# SIMULATION STUDIES FOR THE DIGITAL EXCITATION CONTROL OF SYNCHRONOUS GENERATORS

A DISSERTATION

submitted in partial fulfilment of
the requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power System Engineering)

By

NASEER AHMAD LAWAY

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247667 (INDIA)

January, 1988

DEDICATED

TO

MY SISTERS

## CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation entitled **'SIMULATION STUDIES FOR THE DIGITAL EXCITATION CONTROL OF SYNCHRONOUS GENERATORS'** in partial fulfilment of the requirements for the award of the Degree of **Master of Engineering** in **Electrical Engineering** with specialization in **Power Systems Engineering** submitted in the DEPARTMENT OF ELECTRICAL ENGINEERING, UNIVERSITY OF ROORKEE, ROORKEE is an authentic record of my own work carried out for a period of about six months, from August 1987 to January 1988 under the supervision of **Dr. Ambrish Chandra**, Lecturer, Department of Electrical Engineering, University of Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Dated: Jan. 30th 1988

**(NASEER AHMAD LAWAY)**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

**(AMBRISH CHANDRA)**
**LECTURER IN ELECTRICAL ENGG**
**UNIVERSITY OF ROORKEE**
**ROORKEE 247 667 INDIA**

## ABSTRACT

A synchronous machine AVR-CUM-STABILIZER digital excitation controller utilizing the recursive least-squares identification with varying forgetting factor and a self-searching pole-shifting self-tuning control stategy is described in this dissertation.

The use of varying forgetting factor in the identification algorithm improves parameter tracking under both transient and dynamic conditions, and the use of a self-searching pole-shifting self-tuning control increases the flexibility when applied to varying operating conditions encountered in power systems.

Simulation studies are performed with the proposed controller on a single machine infinite bus system. It is observed that better system response is achieved using the proposed controller in comparison to conventional controller.

## ACKNOWLEDGEMENTS

I have a deep feeling of indebtedness to Dr. Ambrish Chandra, Lecturer in Electrical Engineering, for his invaluable guidance, advice, and encouragement given to me in preparing this dissertation. Detailed discussions with him have helped me in understanding the subject well.

I am extremely thankful to all of my friends for their kind advice and encouragement whenever the need arose for the same.

The cooperation extended by the staff of RURCC for carrying out the computational work is appreciated.

For the moral support provided by my parents, the indebtedness is eternal.

NASEER AHMAD LAWAY

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF SYMBOLS

| | |
|---|---|
| $A(Z^{-1})$ | denominator of the transfer function of the system |
| ARMAX | auto-regressive moving average control model |
| AVR | automatic voltage regulator |
| a,b | constants of governor |
| $B(Z^{-1})$ | numerator of the system transfer function |
| $C(Z^{-1})$ | polynomial representing the noise property in an ARMAX model |
| e(t) | an independent random variable with zero mean |
| $F(Z^{-1})$ | polynomial to form the output |
| $G(Z^{-1})$ | polynomial to form the output |
| G | generator |
| g | output of the governor |
| H | machine time constant |
| I,i | current |
| J | performance index of identification, control |
| K(t) | gain matrix |
| k | system delay |
| K | constant used to control the $\alpha$ variation |
| $K_A$ | gain |
| $K_\delta$ | gain of conventional PSS |
| l | inductance |
| L | matrix used to calculate the PS control parameters |
| LR | linear regression model |

| | |
|---|---|
| M | matrix to calculate the PS control parameters |
| MV | minimum variance control |
| MRAC | model reference adaptive control |
| P(t) | error covariance matrix |
| PA | pole assignment control |
| PS | pole-shifting control |
| P | active power output |
| p.f. | power factor |
| PSS | power system stabilizer |
| RLS | recurcive least squares identification |
| r | resistance |
| $T(Z^{-1})$ | desired closed-loop system characteristic polynomial in the PA control |
| T | time constant |
| $T_m$ | mechanical torque |
| $T_Q, T_1, T_2$ | time constants of conventional PSS |
| u(t) | system input |
| $u_{max}$ | upper limit of control output |
| $u_{min}$ | lower limit of control output |
| V,E | voltage |
| X,x | Reactance |
| y(t) | measured system output |
| $\hat{y}(t)$ | estimated system output |

| | |
|---|---|
| $Z$ | control parameter vector in the PS control |
| $\alpha$ | pole-shifting factor |
| $\delta$ | rotor angle |
| $\dot{\delta}$ | $p\,\delta$ |
| $\Delta u$ | control margin |
| $\Delta\alpha$ | pole-shifting factor modification |
| $\epsilon(t)$ | prediction error |
| $\xi$ | white noise |
| $\lambda$ | flux linkage, forgetting factor |
| $\lambda_{min}$ | minimum value of forgetting factor |
| $\theta(t)$ | system parameters |
| $\hat{\theta}(t)$ | identified system parameters |
| $\Sigma_0$ | a variable used to measure the information for identification |
| $\nu, \omega$ | speed |
| $\emptyset(t)$ | measurement vector |
| $(.)_d$ | direct axis variable |
| $(.)_g$ | variables of the governor |
| $(.)_f, (.)_{fd}$ | field coil variables |
| $(.)_o$ | variable of the infinite bus |
| $(.)_{kd}$ | direct axis damping coil variable |
| $(.)_{kq}$ | quadrature axis damping coil variable |
| $(.)_{md}$ | direct axis mutual variable |
| $(.)_{mq}$ | quadrature axis mutual variable |

| | |
|---|---|
| $(.)_{ref}$ | reference variables |
| $(.)_T$ | generator terminal variable |
| $(.)_q$ | quadrature axis variable |

# CHAPTER - 1

# INTRODUCTION

## 1.1 DEVELOPMENT OF POWER SYSTEMS

Power is a pre-requisite for the progress of any society. It is a must for the industrial development which is essential to continual improvement in the standard of living of people everywhere. A major portion of the energy needs of a country is supplied in the form of electrical energy. The energy which is available in some other form like nuclear, hydro, thermal etc. is converted into the electrical energy and the electric power system becomes a tool for converting and transmitting it to the consumers.

The growth of the electric power systems began in America in 1882. In that year the world's first power system was installed to sell energy for incandescent lighting. The system was d.c., three wire, 220/110 volts with total power requirements of 30 KW. The power was generated in steam driven d.c. 'dynamos' and distributed in underground cables. It is interesting to note that the system in its first eight years of operation had only one three-hour outage [24].

With the advent of transformers and the induction motors, the d.c. power systems gave way to the a.c. power systems. The first a.c. power system was put into operation in 1890. Immediately the advantages of a.c. power systems were realized and it was subsequently standardised by the industry.

Until 1917, electric power systems were usually operated as individual units because they started as isolated systems and spread out only gradually to cover the whole country. An operator was quite capable of manually adjusting the outputs of the isolated units to suit the needs of the customer. As the power demand increased the small isolated systems were unable to supply power with sufficient frequency and voltage control. In order to properly meet the large fluctuations in load and to increase the reliability of supply, the power systems were interconnected over a transmission and distribution network.

Interconnection is advantageous economically because fewer machines are required as a reserve for operation at peak loads (reserve capacity) and fewer machines running without load are required to take care of sudden, unexpected jumps in load (spinning reserve).

Interconnection of power systems brought many new problems. Stability was one of them.

## 1.2 STABILITY PROBLEM

As discussed in section 1.1, the generating units were interconnected to improve the quality of power supply and to reduce the overall production cost. This was the time when first indication of the existence of stability problem came into notice. The phenomenon was of spontaneous oscillations.

The interconnected power systems present complex operating and control problems. A disturbance of some sort can perturb the normal operating conditions-terminal voltage or synchronous speed-of the generating units. A good system should have the ability to return to its normal operating condition after a disturbance. The present day tendency of operating generators with a small stability margin has made the stability problem even more serious [2].

The definition of stability, as applied to power systems, is stated as [2],

"If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, the system is said to be stable. If the system is not stable, it is considered unstable".

According to this definition, the system response of continuous oscillation without enough damping is considered to be unstable [42].

A power system is a non-linear system and consists of many components. Some components are combinations of electrical and mechanical parts which have different dynamic behaviour. Due to the interactions between these parts, it is not easy to analyze the power system stability. In order to simplify the analysis, power system stability is considered in its three aspects [22], namely

1. Steady state

2. Transient, and

3. Dynamic stability

The steady-state stability refers to the behaviour of a power system around a fixed operating point , equilibirum point, and no disturbance is considered. Therefore, it depends only upon the system operating conditions.

Transient stability refers to the ability of the power system to survive a large impact. The unstable situation always results in the loss of synchronism during the first one or two swings after the disturbance. Usually this kind of stability depends strongly upon the magnitude and location of the disturbance and to a lesser extent upon the initial state or operating condition of the system [2].

The dynamic stability deals with the stability of a synchronous machine under the condition of small load changes. The unstable situation in this case always results in long term low frequency oscillations [22]. If the damping existing in the system is not strong enough, the long term oscillations will become larger and larger. These electromechanical oscillations pose the following problems.

1. They lead to dynamic instability of the system

2. They give rise to fluctuations in voltages and the phase angles.

3. They cause excessive wear and tear of mechanical control components.

4. They cause inadvertent operation of protection devices on the system or on connected equipment.

5. They excite subharmonic torsional shaft oscillations on large multistage turbine units.

### 1.2.1 Methods to Enhance Power System Stability

The engineers generally use the following methods to enhance the power system stability.

1. Excitation control of synchronous generators [9,17,41]

2. Input power control of synchronous generators [2,11,24]

3. System operating condition and configuration control[35,46].

For a particular problem, any one or more of the above methods can be used. The excitation control is more preferred due to the following reasons:

1. electrical system has much smaller time constant than the mechanical system

2. an electrical control system is more economical and easy to implement than a mechanical control system

3. because of small loop time constant, an electrical system is effectively a continuously acting system, consequently, it gives smooth system response.

## 1.3 EXCITATION CONTROL OF SYNCHRONOUS GENERATORS

The main aim of using excitation control is to achieve an acceptable voltage profile at the consumer terminal and to effectively control the reactive power flow in the system.

Considerable attention has been given in the literature to the excitation system and its ability to improve power system stability. Early researchers found that the 'steady-state' power limits of power networks could be increased by using the then available high-gain continuous-acting voltage regulators [18]. It was also recognised that the voltage regulator gain requirement was different at no-load conditions from that needed for good performance under load. The high gain requirements of the voltage regulator introduced negative damping to inherently weakly damped interconnected systems and thus had a detrimental impact upon the steady-state stability of the power system. It has been observed that the systems are less oscillatory with the voltage regulators turned off than with them operating.

The voltage regulators are part and parcel of modern power systems. As has been already mentioned, the voltage regulator helps to maintain constancy of terminal voltage and thus it cannot be avoided.

It has been suggested that the system damping could be enhanced by an auxiliary signal introduced through the excitation system [17,20,49]. This auxiliary signal is called the 'supplementary stabilizing signal' and the network used to generate this signal is known as the 'power system stabilizer' (PSS).

The basic function of a power system stabilizer is to extend stability limits by modulating generator excitation to provide damping to the oscillations of synchronous machine rotors relative to one another. These oscillations of concern typically occur in the frequency range of approximately 0.2 to 2.5 Hz, and insufficient damping of these oscillations may limit the ability to transmit power. To provide damping, the stabilizer must produce a component of electrical torque on the rotor which is in phase with speed variations [36]. The stabilizing signal is generally derived from speed variations, accelerating power, electrical power or frequency signals. However, for any input signal the transfer function of the stabilizer must compensate for the gain and phase characteristics of the excitation system, the generator, and the power system, which collectively determine the transfer function from the stabilizer output to the component of electrical torque which can be modulated via excitation control [36]. This transfer function is effected by voltage regulator gain, generator power level and ac system strength.

### 1.3.1 Need for the Digital Excitation Controller

The conventional excitation controller (AVR + PSS) is based on the deterministic control theory. This controller has to be designed for some particular operating conditions and it will give excellent performance if tuned to its parameters properly.

The actual power system is a highly non-linear system and its operating conditions may vary over a wide range. Moreover its properties are non-deterministic in nature. Thus the following problems arise when the conventional controllers are used:-

1. selecting the proper transfer function for the controller

2. tuning its parameters

3. tracking the system operating conditions

4. considering the interaction between various machines.

A lot of work has been done to solve these problems. Different transfer functions have been proposed [20,49,13,37]. Excellent methods to tune the controller have been designed [28,8,40]. The mutual cooperation of different controllers in a multimachine environment has also been studied [22]. But the problem of automatic tracking of system operating conditions adjusting the controller parameters simultaneously has remained a little studied area.

All the above mentioned problems can be solved easily and effectively if the controller identifies the system parameters 'on-line' and automatically tunes itself to the identified system parameters. This objective can be achieved by designing a digital excitation controller based on adaptive control theory. Many research papers have been reported in this area in the recent past [14, 15, 20, 29, 50], but still this field is quite open for further research.

One form of adaptive control known as 'self-tuning' control is mostly used for the implementation of the digital excitation controllers. There are many self-tuning control algorithms available, such as pole-assignment, pole-shift, self-searching pole-shifting algorithms etc. [14,29,32,[illegible],52]. These algorithms are being used as the power system stabilizers and they provide a supplementary stabilizing control signal to the existing conventional AVRs. Therefore, it is worthwhile to find and develop an algorithm which can function as an 'AVR-cum-stabilizer' and solve the above mentioned problems more effectively. This is the main aim of the thesis. This is also the aim to study the performance of such a controller under both the dynamic and the transient operating conditions and to compare the performance of this controller with the conventional controller based on the deterministic control theory.

## 1.4 OUTLINE OF THE THESIS

This thesis is composed of five chapters.

In chapter 2, different digital excitation controllers based on adaptive control theory are discussed. Adaptive control theory is reviewed briefly. Various system identification techniques are mentioned and the RLS identification technique is discussed.

In chapter 3, the proposed AVR-cum-Stabilizer digital excitation controller is presented. The variable forgetting factor recurcive least. squares identification technique is used to make the controller suitable for the practical purposes.

Simulation studies have been conducted on a single machine connected to an infinite bus through a double circuit transmission line and the results are presented and discussed in chapter 4.

Conclusions and comments on further research in this field are presented in chapter 5.

# CHAPTER - 2

# DIGITAL EXCITATION CONTROLLERS

## 2.1 INTRODUCTION

The electric power system is a highly complex system. Most of the power systems in a country are interconnected to form power pools. To effectively control such huge, gigantic structures, new control methods are needed. Generally the deterministic control theory is applied to design the controllers for different system components. The main disadvantage with these controllers is that they do not take into consideration the uncertainties which may occur in the system. The problem gets further aggravated, because of the non-linearity of the power system.

The operating conditions of a power system continually change with time. The conventional controllers are designed to operate at some fixed operating condition for which their performance is very good. But their performance deteriorates as the operating conditions change, thus jeopordising the system reliability and system stability.

The ideal controllers used should be able to track the operating conditions of the system and tune their own parameters to generate the requisite control. This is possible if the controller design is based on the adaptive control theory and the tracking of parameters is done on-line. The principles of adaptive control theory can be easily applied through the digital devices such as micrprocessors.

In this chapter, the different excitation controllers based on the adaptive control theory will be surveyed fairly broadly.

## 2.2 ADAPTIVE CONTROL

The adaptive control is a recent addition to the field of modern control theory. It has fascinated the engineers right from its inception. Its appeal lies in the fact that it takes into account the unpredictable system changes and adjusts the control parameters according to the new system conditions. This self-adjusting property of this control makes it best suited for the systems with many unknown parameters that are changing in time. This control theory has found applications in almost all of the engineering fields which deal with systems full of uncertainities and unpredictable operating conditions. Perhaps, it is appropriate here to give a brief review of this control theory.

The word adaptive means to change (onself) so that one's behaviour will conform to new or changed circumstances.

With specific reference to physical systems, the adaptive control is initially defined as follows:

'Intuitively and adaptive regulator can change its behaviour in response to change in the dynamics of the process and the disturbances'.

This definition is not complete and clear. It suggests that all kinds of controls such as open-loop control, closed-loop feedback control with constant parameters, closed-loop feedback control with changing parameters etc. belong to adaptive control, because they have different degrees of ability to change their behaviour, according to the system changes. The definition of adaptive control has been changed to differentiate it from other controls. Astrom defined it simply as [3]:

'adaptive control is simply a special type of non-linear feedback control'. It is a feedback control with variable feedback gains, instead of constant feedback gains.

Conventional control theory deals with the dynamical systems whose mathematical representations are completely known and the adaptive control refers to the control of partially known systems.

The adaptive control is used because there is invariably some uncertainty in the dynamic characteristics of most of the practical systems. The conventional control theory, if used for the design of controllers for such systems, will not give satisfactory performance in the entire range over which the characteristics of the system may vary.

The adaptive control theory was initially applied to design a high performance autopilot aircraft. The ordinary constant gain, linear feedback system works well in the operating condition in which it is set. However, its performance suffers when operating conditions change. The wide range of operating conditions of the aircraft requires the controller to automatically change its control parameters and feedback gains to match the operating condition. Initially the attempt was not successful because of lack of computational facilities for implementation and the underdeveloped theoretical aspects.

With the further development of the adaptive control and the advent of microcomputer technology, the new theory was applied to many systems and the encouraging results were obtained [3,6,7]. Recently, the power system also came under the fold of the adaptive control. The adaptive control was applied to design excitation controllers for better system performance and high reliability.

## 2.3 SYSTEM IDENTIFICATION

The backbone of adaptive control theory is the system identification. The problem of identification can be formulated as the evaluation of a system model representing the essential aspects of an existing system and representing the knowledge of that system in a useful form [4,26]. There are two forms of identification algorithms :

1. off-line system identification algorithm
2. on-line system identification algorithm

The off-line or non-real-time algorithms are generally more accurate than on-line or real-time algorithms since they may reprocess data several times. In self-tuning algorithms, because of real-time application, the recursive on-line algorithms are used.

Many system identification algorithms are available. All algorithms should possess the following requirements [26]:

1. the algoritnm should be mathematically tractable
2. it should be implementable on a microcomputer
3. it should be generally applicable
4. the algorithm should converge to an optimal identification
5. the convergence should be fast.

The following are the three main aspects of system identification [30]:

1. An appropriate mathematical model
2. A proper persistently exciting signal, and
3. A pre-selected identification scheme.

**2.3.1 System and Model**

A system is a physical object which is having measurable output y(t) and measurable input u(t) at any time t. For a stochastic system, any one or both of the input and output may be corrupted with noise as shown in Fig. 2.1.

The knowledge of the properties of a system is generally called a 'Model'. A model can have the following forms:

1. Mathematical model
2. Graphical model

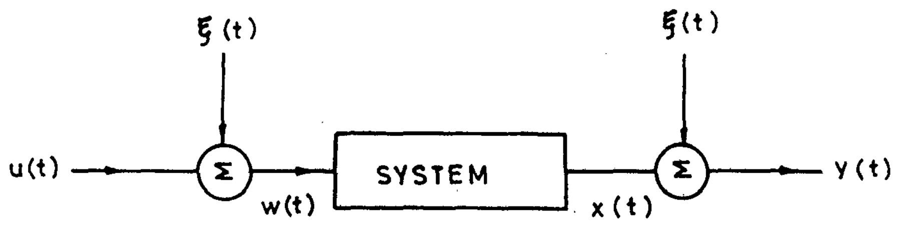



FIG. 2.1 - BLOCK DIAGRAM OF A STOCHASTIC SYSTEM

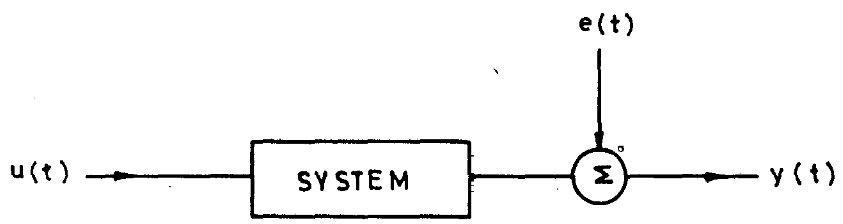



FIG. 2.2 - A BLOCK DIAGRAM OF A LR MODEL

In order to solve a problem, a model of the system is always necessary. Mathematical models are necessary when complex problems, such as power systems are treated.

There are two methods to derive a mathematical model of a complex system. First method is to look into the mechanisms of the system that generate signals and variables and on that basis construct the required model. For systems whose response is unpredictable or the complete mechanism of which is not known, the mathematical model is formed by measuring the signals of the system. The adaptive control technique uses latter method to construct a model.

Many practical systems are multi-input multi-output. The same is the case with the power systems. But as far as excitation control is concerned, it can be treated fairly well by considering it as a single-input single-output system. Due to the digital computer application, the mathematical model considered is of discrete form (difference equations).

The following are the two main kinds of discrete mathematical models frequently used in the self-tuning controller design.

**2.3.1.1 Linear Regression Model (LR)**

The model is assumed to be of the form

$$A(Z^{-1}).y(t) = Z^{-k}.B(Z^{-1}).u(t) + e(t) \tag{2.1}$$

where,

$y(t)$ is the output signal

u(t) is the input signal

e(t) is assumed to be a sequence of independent random variables with zero mean.

k is the system delay

$A(Z^{-1})$ and $B(Z^{-1})$ are polynomials in the delay operator$(Z^{-1})$

A and B are defined as:

$$A(Z^{-1}) = 1 + a_1 Z^{-1} + \dots + a_{na} Z^{-na} \tag{2.2}$$

$$B(Z^{-1}) = b_1 Z^{-1} + \dots + b_{nb} Z^{-nb} \tag{2.3}$$

$n_a$, $n_b$ are the orders of the polynomials A and B respectively. The graphic representation of the model is shown in Fig. 2.2.

#### 2.3.1.2 An ARMAX Model

The block diagram of a stochastic system is as shown in Fig.2.1.

The corrupted input

$$w(t) = u(t) + \xi(t) \tag{2.4}$$

where,

$\xi(t)$ is the white noise and u(t) is the observed input.

The currupted output

$$x(t) = y(t) - \xi(t) \tag{2.5}$$

where,

y(t) is the observed output.

Suppose that the system input and output satisfy the following linear difference equation

$$A(Z^{-1}).x(t) = Z^{-k}.\,B(Z^{-1}).\ w(t) \tag{2.6}$$

Substituting Equations 2.4 and 2.5 in Equation 2.6, we get

$$A(Z^{-1}).[y(t) - \xi(t)] = Z^{-k}.B(Z^{-1})[u(t) + \xi(t)$$

or

$$A(Z^{-1}).y(t) = Z^{-k}.B(Z^{-1}).u(t) + Z^{-k}B(Z^{-1})\ \xi(t) + A(Z^{-1})\ \xi(t)$$

or

$$A(Z^{-1}).y(t) = Z^{-k}.B(Z^{-1}).u(t) + C(Z^{-1}).e(t) \tag{2.7}$$

where,

$C(Z^{-1})$ is a polynomial in $Z^{-1}$

$$C(Z^{-1}) = 1 + C_1.Z^{-1} + \ldots. + C_{nc}Z^{-nc} \tag{2.8}$$

where,

$C_i$, is a function of $a_j$, $b_k$, and K.

The model Equation 2.7 is called the ARMAX (auto regressive moving average exogeneous) model.

Other models, such as the state space model, are generally used for the multi-input multi-output system.

### 2.3.2 Persistently Exciting Signal

To identify a system, it is necessary to excite it by some exciting signal. The signal should excite all modes of the system. By this way, the estimated parameters will converge to the reasonably correct values. The signal should have sufficiently rich frequency content i.e., it should be persistently exciting.

There are many exciting signals such as impulse function, step function, white noise, sinusoidal signal etc., which are being used. In most of the literature white noise is considered to be a suitable signal. Hence white noise has been taken for persistent excitation.

**2.3.3 Identification Methods**

The selection of identification method is mainly dependent upon the mathematical model used. Due to the suitability and reasonable simplicity of Linear Regression Model, it has been used to represent the system model.

There are three main recursive identification algorithms which are generally used [4,25,26,30,31].

1. Recursive Least Squares (RLS) Identification
2. Recursive Extended Least Squares (REL) Identification
3. Recursive Maximum Likelihood (RML) Identification

Generally speaking, more sophisticated identification methods will require more calculation time. For this reason, when designing an on-line system identifier, a compromise must be made between the quality of identification and a reasonable calculation time among all possible identification methods.

The RLS method has the advantages of simple calculation and good convergence properties. It is the preferred technique for use in the design of the self-tuning controller for real-time applications. Hence it has been used for the identification purposes in the present work.

### 2.3.3.1 Recurcive Least Squares (RLS) Identification

This is the most simple and popular method of identification. It has been used for many applications in the literature. It is discussed briefly as follows:

Let y(t) be the sampled output of the system, and is given by

$$y(t) = \theta^T(t)\ \emptyset(t) + e(t) \tag{2.9}$$

where parameter vector θ(t) is given by

$$\theta^T(t) = [a_1, a_2, \ldots, a_{na}, b_1, b_2, \ldots, b_{nb}] \tag{2.10}$$

a's and b's are the actual parameters of the system and the information matrix is given by

$$\emptyset^T(t) = [-y(t-1), \ldots, -y(t-n_a), u(t-k-1), \ldots, u(t-k-n_b)] \tag{2.11}$$

y's and u's are the old or previous outputs and inputs of the system respectively.

The estimate of y(t) is $\hat{y}(t)$ and is given by

$$\hat{y}(t) = \hat{\theta}^T(t)\ \emptyset(t) \tag{2.12}$$

This equation is known as the PREDICTION MODEL of the system. The identified parameter vector is

$$\hat{\theta}^T(t) = [\hat{a}_1, \hat{a}_2, \ldots, \hat{a}_{na}, \hat{b}_1, \hat{b}_2, \ldots, \hat{b}_{nb}] \tag{2.13}$$

where $\hat{a}$'s and $\hat{b}$'s are the identified parameters of the system .

Prediction error

$$\varepsilon(t) = y(t) - \hat{y}(t) = e(t) \quad (2.14)$$

$\hat{\theta}(t)$ is chosen in such a way that the criterion J

$$J = \sum_{t=1}^{m} \varepsilon^2(t) \quad (2.15)$$

is minimized.

The use of RLS technique [48] gives

$$\hat{\theta}(t) = \hat{\theta}(t-1) + k(t)[y(t) - \hat{\theta}^T(t-1)\phi(t)] \quad (2.16)$$

where,

$\hat{\theta}(t-1)$ is the previous identified parameter vector and

$k(t)$ is the gain vector given by

$$k(t) = \frac{P(t-1)\,\phi(t)}{[1 + \phi^T(t)\,P(t-1)\,\phi(t)]} \quad (2.17)$$

$P(t)$ = Error covariance matrix

$$= [1-k(t)\,\phi^T(t)].P(t-1) \quad (2.18)$$

$\hat{\theta}(t)$ is the weighted sum of last estimation $\hat{\theta}(t-1)$ and prediction error $\varepsilon(t)$. For a time-invariant system, as time increases, $\hat{\theta}(t)$ converges towards its true value, and hence, the prediction error $\varepsilon(t)$, gain vector $k(t)$ and covariance matrix $P(t)$ tend to zero. It means that fresh experimental data are continuously in supply but this new information is not making any contribution to the parameter estimation. In time-invariant systems, once the estimated parameters reach the 'true value' it may not be a problem. But the main aim of using the self-tuning control is for time varying systems. This problem affects the parameter tracking. Hence forgetting factor is used to remove the tracking problem. This will be discussed in detail in the next chapter.

## 2.4 CONTROL TECHNIQUES

The application of adaptive control strategy to digital excitation control is attractive because the effective system response changes with load level and system configuration. Whenever an adaptive controller detects the changes in system operating conditions, it responds by determining a new set of control parameters. Adaptive technique ensures that the controller parameters are suboptimal for the operating condition, and thus the system stability is enhanced.

There are two main adaptive control techniques which can be used for the excitation cotrol of synchronous generators. They are

1. Model Reference Adaptive Control (MRAC) [29]
2. Self-tuning Adaptive Control (STAC) [5,6,29,14]

### 2.4.1 Model Reference Adaptive Control Technique

A very useful adaptive control technique is to specify a desired performance and measure the actual performance against this performance. This type of controller follows a model designed for the desired performance. Thus the first step in this control technique is the choice of a reference model. A reference model representing the desired behaviour of the closed-loop system is driven by the same input as the controlled system. The regulator parameters are then adjusted depending upon the error between the system output and the reference model output. A model reference adaptive control is shown in Fig. 2.3.

The task of adaptation is to minimize a function of the difference between the outputs, or the states, of the adjustable system and those of the reference model. This is done by adaptation mechanism that modifies the parameters of the adjustable system. On the basis of the observed output error, this mechanism must be able to determine which way to adjust the controller coefficients and must also remain stable under all operating conditions. Thus the main problem in this mechanism is to design a suitable adaptation mechanism. Use of MRAC technique for the control of power systems is reported in [56].

It has been observed that when the 'ideal reference model'is not achievable due to system limitations, the response of the reference system will be substantially different from that of the actual system. The difference in performance will be interpreted as system fault, and adaptation of the system gains will occur even when the system is at steady state.

The main disadvantage of this technique is that, it cancels the system zeros by the controller poles to get the closed-loop response. Hence it cannot be used to systems which are having the zeros outside the stability region [16,29]. Therefore, this does not seem to be a very suitable technique for excitation control in power systems.

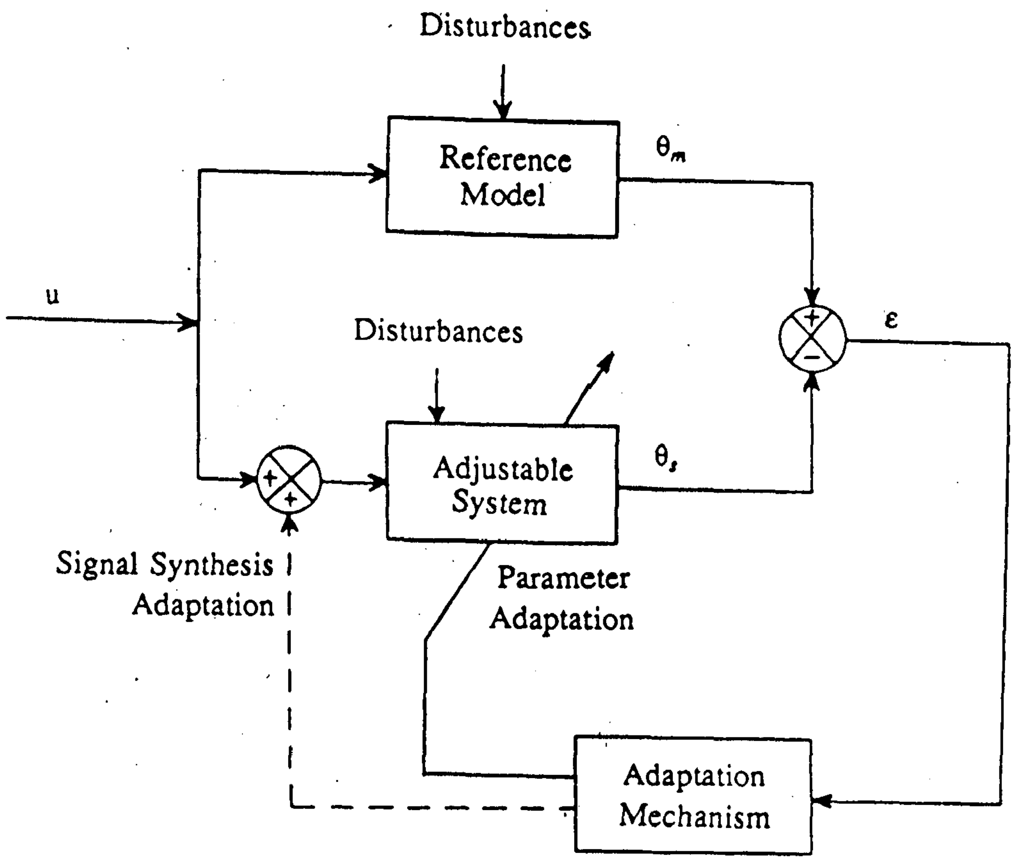



FIG. 2.3 – MODEL REFERENCE ADAPTIVE CONTROL SCHEME

### 2.4.2 Self-Tuning Control Techniques

This control technique is best suited for the digital excitation controller. Lately this method has been used for a variety of engineering problems. Its success can be attributed to the following advantages [32].

1. The algorithms are very simple
2. The mathematical model is available in discrete form, thus it is easily implemented on microcomputers
3. The satisfactory stable performance can be achieved.

The self-tuning adaptive control has the ability of self-adjusting its control parameters according to system conditions. It is a simple and effective technique.

This technique is based on 'certainity equivalence principle' of the stochastic control theory. According to this principle, a stochastic problem can be solved in the following two steps i.e. a system identification problem and a deterministic control problem. The block diagram of a general self-tuning controller is as shown in Fig. 2.4.

Various combinations of identification techniques and control strategies will result in different kinds of self-tuning controllers. In these techniques the parameters of a model of the controlled system are identified on-line and control is calculated using a pre-selected strategy (Fig. 2.4).

The various self-tuning control techniques which can be used for excitation control are as follows:

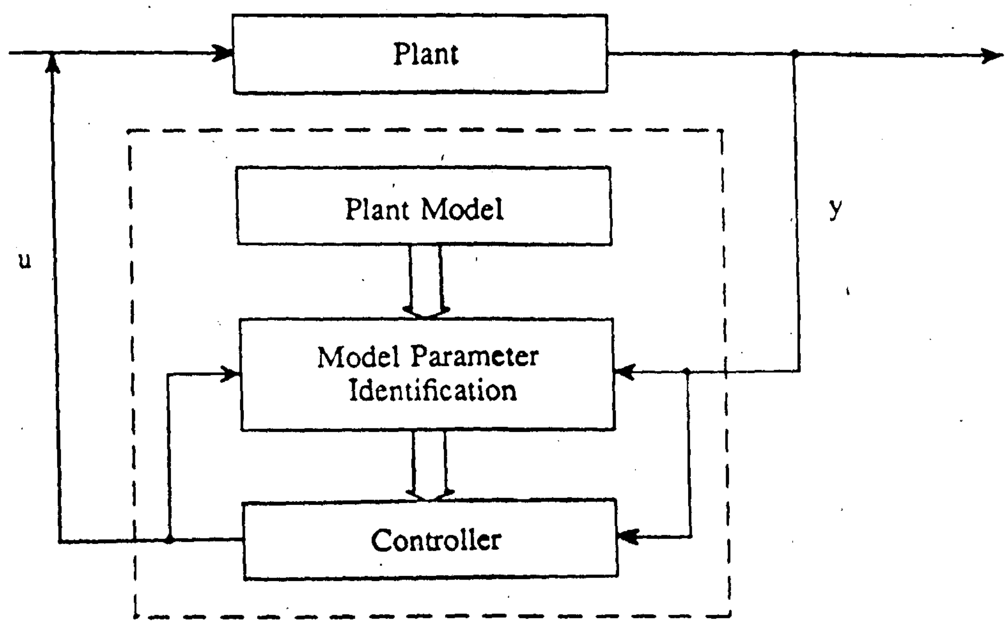



FIG. 2.4 - BLOCK DIAGRAM OF A SELF-TUNING CONTROLLER

### 2.4.2.1 Minimum Variance Control

The original self-tuning control concept presented in Ref [3,5,6] made use of this control method, which minimizes the variance of the output of the process. The controller first predicts the next measurement for zero control, and then choses the control value so that the predicted output error is zero [5]. The RLS identification technique is used for identifying the parameters of the system model.

This method has the following drawbacks [29]:

1. For non-minimum phase systems, unstable poles are used to cancel the zeros outside the unit circle. Any error in the mathematical model will result in an unstable closed loop system.

2. This may produce excessive control inputs.

3. This can be used only for a restricted class of processes

4. The user can only change the sample frequency.

This controller utilizes the following steps:

1. Micro-computers are used to implement the self-tuning algorithms. Thus, the computations are done in discrete time, and the designer must select the sampling frequency. As a guide choose a sampling frequency approximately 10 time the normal system frequency of oscillation.

2. At each sampling instant update the parameter estimates using the RLS algorithm.

3. Compute the control which makes the predicted error zero.

For a plant identified as [5]

$$y(t) = -a_1y(t-1)-a_2y(t-2)+b_1u(t-1)+b_2u(t-2) \tag{2.18}$$

The minimum variance control is given by

$$u(t) = 1/b_1[a_1y(t)+a_2y(t-1)-b_2u(t-1)] \tag{2.19}$$

In Equation 2.19 if the pole at $Z = -b_2/b_1$ is on or outside the unit circle $[|Z|\leqslant 1]$, then control, u(t) increases without bounds. The cancellation of large parameter errors in one sample is impossible due to the control limits of the excitation system. If the control signal is limited, the resulting control, which is always in phase with the predicted error can give rise to poor damping.

**2.4.2.2 Linear Quadratic ( LQ) Control**

Reformulation of the problem by introducing the linear quadratic control strategy may eliminate the problems associated with minimum variance control.

The concept behind this class of controllers is to minimize a linear quadratic performance index of the form

$$J = \sum_{t=1}^{\infty} [y(t)^2 + r\,u(t-1)^2] \tag{2.20}$$

where,

u(t) and y(t) are the input and output of the process.

For $r \neq 0$, the control minimizes the output error subject to the requirement that the control effort be small. For r--> 0, the penalty on large control is reduced, and in the limit gives minimum variance performance. For r --> ∞ control action is taken only to stabilize an unstable system. Thus, with a proper choice of r excessive saturation on the controller may be avoided.

The various steps involved are [55]:

Steps (1) and (2) are the same as for MV controller.

3. The system is described in the state space form as

$$x_{k+1} = Fx_k + gu_k \tag{2.21}$$

$$y_k = h\,x_k \tag{2.22}$$

where matrix F and vectors g and h are determined from estimates in step 2.

4. Obtain steady-state solution of equations

$$K_{k+1} = -[g^T S_k g + r]^{-1} g^T S_k F \tag{2.23}$$

$$S_{k+1} = [F + gK_k]^T S_K F + hT_n \tag{2.24}$$

5. Obtain the control from

$$M_k = K_k\, x_k \tag{2.25}$$

The drawbacks in the control strategy are [29]

1. To obtain steady-state solution of Equations 2.23 and 2.24 requires infinite number of iterations.

2. Large number of iterations are not possible in real time applications.

3. To determine the satisfactory value of r, the simulation studies have to be performed first and the best value of r has to be taken.

### 2.4.2.3 Pole Assigned (PA) Control

This control is similar to that of model reference in that the desirable response is pre-specified. In this technique the closed loop system poles are placed at pre-specified positions depending on the required transient response. The control engineer can easily relate pole locations to the closed-loop transient performance. Whereas the MV Controller shifts all the poles towards the origin, the PA Controller has the freedom to place the poles at other locations [50].This scheme is therefore very robust and can be applied with ease to non-minimum phase systems.

The steps involved are

Steps (1) and (2) are the same as for the MV controller.

3. Compute control which will then place the poles to pre-prescribed locations.

For a single-input single-output system the process is given by the transfer function:

$$y(t) = \frac{B(Z^{-1})}{A(Z^{-1})} u(t) \qquad (2.26)$$

where u(t) is the input and y(t) is the output of the system. The polynomials $A(Z^{-1})$ and $B(Z^{-1})$ are given by

$$A(Z^{-1}) = 1 + a_1 Z^{-1} + \dots + a_{na} Z^{-na}$$
$$B(Z^{-1}) = b_1 Z^{-1} + \dots + b_{nb} Z^{-nb} \tag{2.27}$$

and $Z^{-1}$ is a delay operator

The control is computed from

$$u(t) = - \frac{G(Z^{-1})}{F(Z^{-1})} y(t) \tag{2.28}$$

where polynomials $F(Z^{-1})$ and $G(Z^{-1})$ are given by

$$F(Z^{-1}) = 1 + f_1 Z^{-1} + \dots + f_{nf} Z^{-nf} \; ; \quad nf = nb - 1$$
$$G(Z^{-1}) = g_o + g_1 Z^{-1} + \dots + g_{ng} Z^{-ng} \; ; \quad ng = na - 1 \tag{2.29}$$

The closed loop transfer function from the noise input to the output is represented in the Fig. 2.5 :

Therefore, the transfer function is written as :

$$\frac{y(t)}{e(t)} = \frac{F(Z^{-1})\, B(Z^{-1})}{A(Z^{-1})\, F(Z^{-1}) + B(Z^{-1})\, G(Z^{-1})} \tag{2.30}$$

In the transfer function the transport delay is assumed to be zero. The poles are determined by the characteristic equation

$$A(Z^{-1})F(Z^{-1}) + B(Z^{-1})G(Z^{-1}) = 0 \tag{2.31}$$

According to the desired closed-loop transient properties, select a desired closed-loop system characteristic equation :

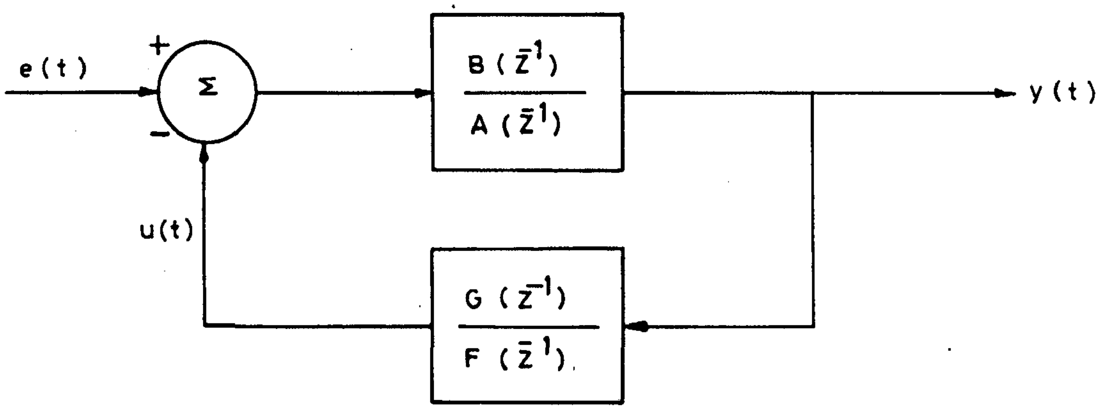



FIG.2.5 - BLOCK DIAGRAM OF PA CONTROL SYSTEM

$$T(Z^{-1}) = (1-\alpha_1 Z^{-1})(1-\alpha_2 Z^{-1}) \ldots (1-\alpha_{nt} Z^{-1})$$

$$= 1 + t_1 Z^{-1} + t_2 Z^{-2} + \ldots + t_{nt} Z^{-nt} \qquad (2.32)$$

where $\alpha_1, \ldots, \alpha_{nt}$ are desired closed loop poles[50].

The control parameters $f_i$ and $g_j$ are computed by comparing the coefficients of Z's in the following equation :

$$A(Z^{-1})F(Z^{-1}) + B(Z^{-1})G(Z^{-1}) = T(Z^{-1}) \qquad (2.33)$$

where $n_t \leqslant n_a + n_b - 1 \qquad (2.34)$

For $n_a = n_b = n$, solution of Equation 2.33 takes the form

$$\begin{bmatrix} 1 & 0 & \ldots & 0 & b_1 & 0 & \ldots & 0 \\ a_1 & 1 & \ldots & 0 & b_2 & b_1 & \ldots & 0 \\ \vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots \\ a_n & a_{n-1} & \ldots & a_2 & b_n & b_{n-1} & \ldots & b_1 \\ 0 & a_n & \ldots & a_3 & 0 & b_n & \ldots & b_2 \\ \vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & \ldots & a_n & 0 & 0 & \ldots & b_n \end{bmatrix} \cdot \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_{n-1} \\ g_0 \\ \vdots \\ g_{n-1} \end{bmatrix} = \begin{bmatrix} t_1 - a_1 \\ t_2 - a_2 \\ \vdots \\ t_n - a_n \\ t_{n+1} \\ \vdots \\ t_{2n-1} \end{bmatrix} \qquad (2.35)$$

Equation 2.35 can be written as

$$M.Z = L$$

where M is a (2n-1) x (2n-1) matrix, and Z and L are vectors having (2n-1) elements.

The solution of the equation is

$$Z = M^{-1}L \tag{2.36}$$

where the inverse in Equation 2.36 exists provided that $A(Z^{-1})$ and $B(Z^{-1})$ have no common factors. Note that, if the elements of L are very small, the coefficients of $F(Z^{-1})$ and $G(Z^{-1})$ are small. With coefficients of $F(Z^{-1})$ small, the roots of $F(Z^{-1})$ are close to zero, and a stable controller is achieved. This controller produces smoother control action which is required for the direct digital control.

### 2.4.2.4 Pole Shifting (PS) Control

In the pole-assignment control the closed-loop poles are placed at pre-specified locations. The amount of control effort is to some extent proportional to the distance of the proposed locations of the closed-loop locations from their open-loop locations. A poor choice of closed-loop locations may result in large control effort. If the desired control cannot be provided, the system may become unstable. This can easily happen when a 'priori' decision on the system transfer function cannot be made, which is always the situations in power systems. Thus the pole-assignment control strategy can be modified to a pole-shifting control strategy. In the pole-shifting strategy the closed-loop poles are shifted radially towards the origin in the Z-domain, and a stable controller is achieved.

Pole-shift control, while retaining the basic advantages of the pole-assignment strategy, eliminates the requirements of specifying the closed-loop pole locations.

$$T(Z^{-1}) = (1-\alpha_1 Z^{-1})(1-\alpha_2 Z^{-1}) \ldots (1-\alpha_{nt}Z^{-1})$$

$$= 1 + t_1 Z^{-1} + t_2 Z^{-2} + \ldots + t_{nt}Z^{-nt} \qquad (2.32)$$

where $\alpha_1, \ldots, \alpha_{nt}$ are desired closed loop poles[50].

The control parameters $f_i$ and $g_j$ are computed by comparing the coefficients of Z's in the following equation :

$$A(Z^{-1})F(Z^{-1}) + B(Z^{-1})G(Z^{-1}) = T(Z^{-1}) \qquad (2.33)$$

$$\text{where } n_t \leqslant n_a + n_b - 1 \qquad (2.34)$$

For $n_a = n_b = n$, solution of Equation 2.33 takes the form

$$\begin{bmatrix} 1 & 0 & \ldots & 0 & b_1 & 0 & \ldots & 0 \\ a_1 & 1 & \ldots & 0 & b_2 & b_1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots \\ a_n & a_{n-1} & \ldots & a_2 & b_n & b_{n-1} & \ldots & b_1 \\ 0 & a_n & \ldots & a_3 & 0 & b_n & \ldots & b_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & \ldots & a_n & 0 & 0 & \ldots & b_n \end{bmatrix} \cdot \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_{n-1} \\ g_0 \\ \vdots \\ g_{n-1} \end{bmatrix} = \begin{bmatrix} t_1 - a_1 \\ t_2 - a_2 \\ \vdots \\ t_n - a_n \\ t_{n+1} \\ \vdots \\ t_{2n-1} \end{bmatrix} \qquad (2.35)$$

Equation 2.35 can be written as

$$M.Z = L$$

where M is a (2n-1) x (2n-1) matrix, and Z and L are vectors having (2n-1) elements.

The solution of the equation is

$$Z = M^{-1}L \tag{2.36}$$

where the inverse in Equation 2.36 exists provided that $A(Z^{-1})$ and $B(Z^{-1})$ have no common factors. Note that, if the elements of L are very small, the coefficients of $F(Z^{-1})$ and $G(Z^{-1})$ are small. With coefficients of $F(Z^{-1})$ small, the roots of $F(Z^{-1})$ are close to zero, and a stable controller is achieved. This controller produces smoother control action which is required for the direct digital control.

#### 2.4.2.4 Pole Shifting (PS) Control

In the pole-assignment control the closed-loop poles are placed at pre-specified locations. The amount of control effort is to some extent proportional to the distance of the proposed locations of the closed-loop locations from their open-loop locations. A poor choice of closed-loop locations may result in large control effort. If the desired control cannot be provided, the system may become unstable. This can easily happen when a 'priori' decision on the system transfer function cannot be made, which is always the situations in power systems. Thus the pole-assignment control strategy can be modified to a pole-shifting control strategy. In the pole-shifting strategy the closed-loop poles are shifted radially towards the origin in the Z-domain, and a stable controller is achieved.

Pole-shift control, while retaining the basic advantages of the pole-assignment strategy, eliminates the requirements of specifying the closed-loop pole locations.

If the open-loop poles are shifted radially towards the origin such that T becomes

$$T = A(\alpha Z^{-1}) = 1 + \alpha a_1 Z^{-1} + \alpha^2 a_2 Z^{-2} + \dots + \alpha^n a_n Z^{-n} + \dots \qquad (2.37)$$

where $\alpha$, called pole-shift factor, is closed to, but less than one, then L in Equation 2.36 becomes

$$L^T = [a_1 (\alpha - 1), a_2(\alpha^2 - 1), \dots, a_n(\alpha^n - 1), 0, \dots, 0] \qquad (2.38)$$

The control u can be calculated as :

$$u(t) = [-u(t-1) \dots -u(t-n-1), -y(t), \dots, -y(t-n-1)][Z]$$

or $$u(t) = x^T(t)Z \qquad (2.39)$$

Though this method has certain problems as discussed in next section, it has been successfully implemented for the excitation control. The results reported are quite satisfactory [29].

**2.4.2.5 Self-Searching Pole-Shifting Control**

As mentioned above, the pole-shifting control strategy gives quite satisfactory results. In this we keep the pole-shifting factor, $\alpha$, constant, which is a major shortcoming of the PS control technique. Ideally, the proper value of the pole-shift factor should depend on the operating conditions of the synchronous generator. Under dynamic conditions, pole-shift factor can be close to zero, i.e. the poles can be shifted very close to the origin. However, under transient conditions this factor cannot be taken so small because of the practical limits on control. These difficulties can be overcome by utilizing a self-searching pole-shift factor strategy [14]. Instead of choosing a fixed value of the pole-shift factor, appropriate value to match system operating conditions is computed every sampling instant.

The idea of introducing the variable pole-shifting technique to the PS control technique is basically the same as that of introducing the variable forgetting factor to the RLS identification. In self-searching pole-shifting control technique, the pole-shifting factor $\alpha(t)$ is calculated recursively every control interval according to the following basic principles:

1. Theoretically, as the closed loop poles are shifted towards the origin of the unit circle in the 'Z' domain the closed loop system becomes more stable.

2. Practically as the poles are shifted to the origin of the unit circle more control effort is required. The control variable has its output limits. If these limits are exceeded, unsatisfactory control action will result and, in the worst case, the system will become unstable.

Based on these principles, the criterion of the variable pole-shifting factor PS Control strategy can be mentioned as

Determine the pole-shift factor which shifts the closed loop system poles as close as possible to the origin of the unit circle in the 'Z' domain without violating the control constraints.

The algorithm for calculating the pole-shifting factor $\alpha(t)$ can be formulated as follows:

Assuming that the practical control constraint is given by

$$u_{min} \leqslant u \leqslant u_{max} \tag{2.40}$$

the control margin is defined as

$$\Delta u = \begin{cases} u_{max} - u & u \geqslant 0 \\ u - u_{min} & u < 0 \end{cases} \tag{2.41}$$

If $\Delta u < 0$, it means that one of the control limits has been hit and the pole-shifting factor has to be increased. If $\Delta u > 0$, it means that the control limits have not been reached and the pole shifting factor can still decrease if $\alpha(t) > 0$.

Modification of $\alpha(t)$ can be formulated as follows:

As already derived in Equation 2.35 we have

$$M.Z = L$$

which means

$$Z = M^{-1}L$$

This equation calculatesthe control parameters, $f_i$ and $g_j$

The control output is given by

$$u(t) = x^T(t).Z$$

To meet tne priciple (2) of subsection (2.4.2.5) a sensitivity function is calculated as

$$\frac{\partial u}{\partial \alpha} = x^T(t) \frac{\partial Z}{\partial \alpha} \tag{2.42}$$

or

$$\frac{\partial u}{\partial \alpha} = x^T(t) \frac{\partial}{\partial \alpha}[M^{-1}L]$$

$$= x^T(t)M^{-1}\frac{\partial L}{\partial \alpha}$$

or

$$\frac{\partial u}{\partial \alpha} = x^T(t).M^{-1}[a_1, 2a_2\alpha, \ldots, na_n\alpha^{n-1}] \tag{2.43}$$

For the control margin calculated in Equation 2.41, the modification of the pole-shifting factor $\alpha$ (t) is given by

$$\Delta\alpha = -K \left| \frac{\partial u}{\partial \alpha} \right|^{-1} . \Delta u \qquad (2.44)$$

where K is a positive constant chosen to avoid excessive variations in $\alpha$ (t)

The variable pole-shifting factor is given by

$$\alpha(t) = \alpha(t-1) + \Delta\alpha \qquad (2.45)$$

This calculation may be repeated every sampling period until the control u is within the limits. However, modifying many times per sampling period is not necessary. In the simulation studies of applying this algorithm to a synchronous machine excitation control, good results were obtained with one iteration [14].

On start up, $\alpha$ can be assigned any value from 0 to 1 The algorithm will automatically search for its best value. When the system to be controlled is operating in the steady state, shifting the closed loop poles even to the origin of the unit circle will result in small control effort.

# CHAPTER - 3

# PROPOSED AVR-CUM-STABILIZER DIGITAL EXCITATION CONTROLLER

## 3.1 INTRODUCTION

Most of the digital excitation control techniques discussed in Chapter 2 have been proven successful in providing supplementary stabilizing signal to the conventional AVR [14,29]. In a way they work as self-tuning power system stabilizers, modulating the excitation signals to produce enough damping. However, the algorithms cannot be called as the total digital excitation controllers of the synchronous machine. Complete excitation control encompasses two functions, i.e. AVR and stabilizer. Hence, it is quite logical to combine the two functions in one device to have a complete digital excitation controller.

In this chapter, the self-searching pole-shifting self-tuning algorithm is modified to work as an AVR-cum-stabilizer, in order to develop a complete digital excitation control of the synchronous generators.

Since the electrical power system is a non-linear and time varying system, the RLS identification part of the algorithm discussed in section 2.3.3.1 is slightly modified to take into account the concept of variable forgetting factor to improve the performance of the adaptive mechanism [14,27,30,39].

## 3.2 PROBLEMS OF IDENTIFICATION-THE USE OF FORGETTING FACTOR

The main aim of using the self-tuning control is for time varying systems. When RLS is used for this type of system, the following problem arises [51,53,54].

As the gain vector K(t), used for up-dating the adaptive parameters, decreases in time, the system model error is less taken into account. This greatly affects the parameter tracking. One way to overcome this problem is to periodically reset the P(t) matrix to either a fixed initial value or a value depending on the latest P(t) matrix. But in this case, all the past information stored in the gain matrix will be lost.

It is worthwhile to consider a criteria in which older values are discounted by an exponential weighting scheme which places heavier emphasis on the more recent data. As a result, the parameter tracking capability is greatly increased.

Consider the performance index

$$J = \sum_{i=1}^{m} \lambda^{m-i} \varepsilon^2(t) \tag{3.1}$$

wnere $\lambda < 1$ is the forgetting factor.

In this criterion the latter errors are given more weight than the earlier ones.RLS identification algorithm with a forgetting factor is better adopted to work in real-time because the gain matrix does not need to be reset. In addition, past errors are gradually forgotten and more attention is paid to the recent information.

Accordingly, the RLS identification algorithm can be modified by changing Equation (2.18) to

$$P(t) = \frac{[\ 1 - K(t).\ \emptyset^T(t)]\ P(t-1)}{\lambda} \qquad (3.2)$$

Now if $\lambda < 1$ then P(t) will not tend to zero and the algorithm is more capable of tracking the parameter variation.

The fixed forgetting factor has already been used successfully in practical applications [39]. Many results show that if the system is always properly excited, this algorithm will give good parameter tracking property for the time varying systems. However, there do exist systems which are not 'properly' excited. These situations always happen in power systems. During the normal operating conditions the system is poorly excited, whereas under the large disturbances, the system is over-excited. The use of fixed forgetting factor RLS identification will face the following problems.

1. It is difficult to choose an appropriate value of $\lambda$, which will give the best identified parameters. A small value of $\lambda$ gives good parameter tracking for the case of large disturbances but also makes the parameters more sensitive to the system noise. A large value of $\lambda$ gives smooth parameter estimation which is useful for the steady-state operations but results in a slow parameter tracking speed.

2. The so called P matrix 'blow-up' sometimes happens. This problem occurs when the fixed forgetting factor $\lambda$ is used and the slowly time-varying system operates in steady-state for a long time.

In this case, as the prediction error tends to zero, Equation 3.2 can be approximately represented by [51]

$$P(t) = \frac{P(t-1)}{\lambda} \tag{3.3}$$

This can be obtained by putting $\emptyset(t) = 0$ in Eqn. (3.2).

This means that P(t) matrix will exponentially tend to infinity. When P(t) becomes very large, any disturbance from the system will result in an inappropriate parameter estimation and then a very undesirable control action. This will sometimes make the system unstable.

In order to avoid such difficulties, a measure for the information content is defined. A forgetting factor can then be chosen at each step such that this is kept constant. Reasonable choice of information measure can prevent P(t) from blowing-up, while still retaining the adaptibility of the algorithm [27,53,54].

The measure of information content can be expressed recurcively as :

$$\Sigma(t) = \lambda(t) \quad \Sigma(t-1) + [1-\emptyset^T(t-1)\ K(t)]\ \varepsilon^2(t) \tag{3.4}$$

By keeping $\Sigma(t)$ constant at $\Sigma_0$, the amount of forgetting will at each step correspond to the amount of new information in the latest measurement, thereby ensuring that the estimation is always based on some amount of information.

Hence

$$\lambda\,(t) = 1 - \frac{[1-\phi^T(t-1)\ K(t)]}{\Sigma_0}\,\varepsilon^2(t) = 1 - \frac{1}{N(t)} \qquad (3.5)$$

If during steady-state error $\varepsilon$ (t) is small, $\lambda$ is close to unity and it retains as much information as possible. Moreover, it prevents P(t) matrix from blowing-up. If due to disturbance, error is large, $\lambda$ is reduced, hence increasing the sensitivity of the estimator until parameters are readjusted and errors become small.

## 3.3 PROPOSED CONTROLLER

The necessary background required for the controller has been explained in chapter 2. The controller is based on the self-searching pole-shifting self-tuning control strategy. Its structure is as given in Fig. 3.1.

y(t) is the system output signal which is sampled and fed to the controller which in turn generates a requisite amount of control signal u(t).

In all the digital excitation controllers discussed in chapter 2, this signal y(t) is either taken as speed, frequency, electric power or accelerating power. Since all the controllers act as power system stabilizers, the sampled signal y(t) is known as the stabilizing signal.

In the proposed controller which has to act as an AVR-cum-stabilizer, the signal y(t) should represent both the functions. Hence y(t), as shown in Fig. 3.2 is formed by amalgamating the

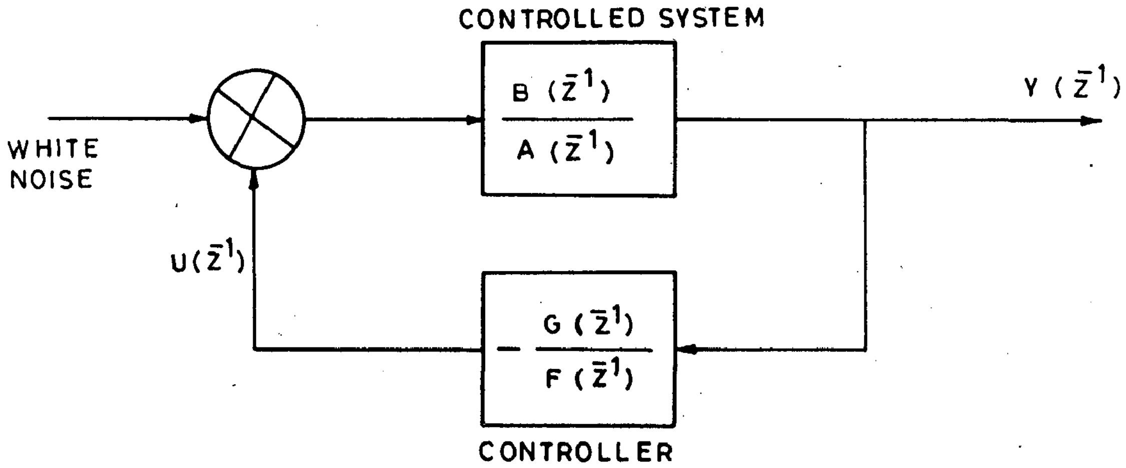



FIG.3.1— STRUCTURE OF THE CONTROLLER

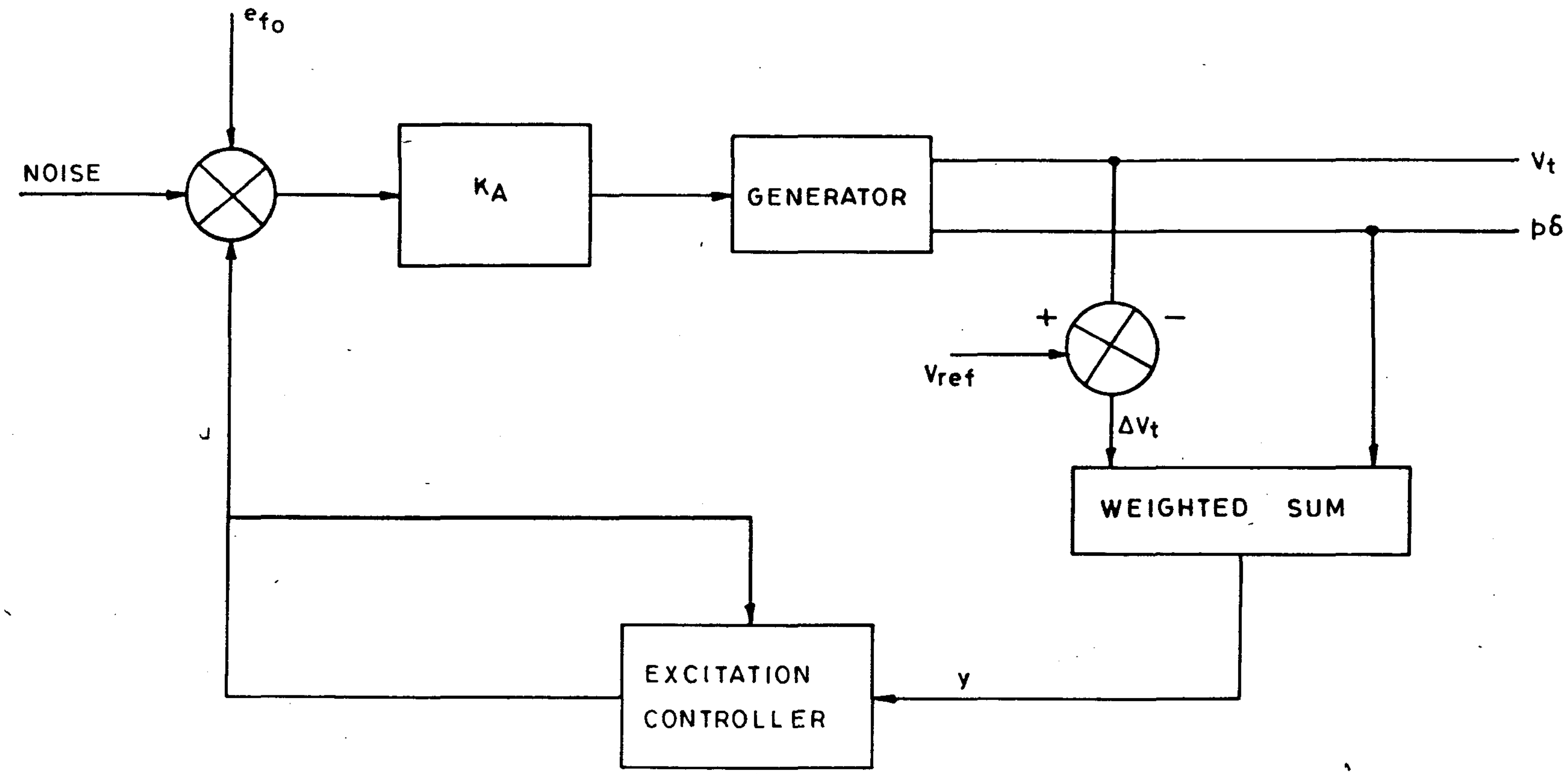



FIG. 3·2 — PROPOSED DIGITAL EXCITATION CONTROLLER stabilizing signal and the voltage error signal. A definite weightage is given to these signals and the weighted sum is taken as y(t). This weighted sum is then sampled and fed to the digital controller.

Damping of the system oscillations will depend very much on the weightage given to each signal. If more weightage is given to the auxiliary stabilizing signal, the damping would be more and the controller will act as a stabilizer and its performance as an AVR will be affected. If more weightage is given to the voltage error signal, the controller will act as a good AVR and its performance as a stabilizer will be poor. Therefore, giving an appropriate weight is very important for the desired operation of the controller.

The complete algorithm for the self-searching pole-shifting self-tuning AVR-cum-stabilizer utilizing RLS identification with variable forgetting is given as below.

### 3.3.1 Algorithm

The algorithm consists of the following steps:

1. Initialize the controlled system parameters
2. Solve the system equations using Runge Kutta method
3. Get $p\,\delta$ and $\Delta Vt$ signals, where $\Delta Vt = V_{ref} - Vt$
4. Sample y(t), where y(t) is a weighted sum of $p\,\delta$ and $\Delta Vt$

$y(t) = \rho_1\, p\,\delta + \rho_2\, \Delta Vt$

The weights $\rho_1$ and $\rho_2$ are to be chosen carefully.

5. The system parameters are estimated, by the use of the RLS identification algorithm as

$$\hat{y}(t) = \hat{\theta}^T(t)\, \emptyset(t) + e(t)$$

where

$\hat{\theta}(t)$ is the identified parameter vector

e(t) is the white noise injected into the system to excite all the modes.

$\emptyset(t)$ = measurement vector

$= [-y(t-1), -y(t-2), \ldots, -y(t-n), u(t-1), u(t-2), \ldots, u(t-n)]$

The prediction error is calculated as

$$\varepsilon(t) = y(t) - \hat{y}(t)$$

$\hat{\theta}(t)$ is recurcively calculated as

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)\, \varepsilon(t)$$

where,

$$K(t) = \text{gain matrix} = \frac{P(t-1)\, \emptyset(t)}{[1 + \emptyset^T(t)\, P(t-1)\, \emptyset(t)]}$$

and P(t) = error covariance matrix

$$= \frac{[1 - K(t)\, \emptyset^T(t)]\, P(t-1)}{\lambda(t)}$$

$\lambda$ is a forgetting factor for exponential weighting of last data values. $\lambda(t)$ is found from

$$\lambda(t) = 1 - \frac{[1 - \emptyset^T(t-1)\, K(t)]}{\Sigma_0}\, \varepsilon^2(t)$$

$\Sigma_0$ is the measure of information content

$$\Sigma(t) = \lambda(t)\ \Sigma(t-1) + [1-\emptyset^T(t-1)\ K(t)]\ \ \varepsilon^2(t)$$

$\Sigma(t)$ is kept constant at $\Sigma_0$.

6. Calculate the control from the equation:-

$$u(t) = x^T(t).Z$$

where, $x^T(t) = [-u(t-1),\ldots,-u(t-n-1),\ -y(t),\ldots,-y(t-n-1)]$

and $Z = M^{-1}L$

Z will contain the control parameters f's and g's.

M is the matrix of identified $\theta(t)$ parameters given by Equation 2.35.

$$L^T = [\ t_1-a_1,\ t_2-a_2,\ldots,t_n-a_n,\ 0,\ldots\ldots,\ 0]$$

7. Set the control limits i.e. set $u_{max}$ and $u_{min}$

8. Calculate $\Delta u$ as

$$\Delta u = \begin{cases} u_{max} - u & u \geqslant 0 \\ u - u_{min} & u < 0 \end{cases}$$

9. The $\alpha$ modification factor is calculated as

$$\Delta\alpha = -K \left| \frac{\partial u}{\partial \alpha} \right|^{-1} . \Delta u$$

where

$$\frac{\theta u}{\partial \alpha} = -x^T.M^{-1}[\ a_1, 2a_2\ \alpha\ , \ldots, na_n\ \alpha^{n-1}\ ]$$

K is a positive constant chosen to avoid excessive variations in $\alpha$ .

10. Calculate $\alpha(t)$ as

$$\alpha(t) = \alpha(t-1) + \Delta\alpha$$

11. Repeat from (2) for incremental value of t.

The initial values to different parameters is chosen carefully. Simulation studies of the algorithm has made it clear that the controller can work as an efficient AVR-cum-stabilizer for the synchronous generator. The results of the study are presented and discussed in the next chapter.

### 3.4 SELECTION OF PARAMETERS

The digital excitation controller uses the self-tuning control algorithm to tune its own various parameters. It seem to be interesting to say that even this self-tuning controller needs to be tuned. The tuning has to be done for several parameters like, selection of system model order, choice of the value for K, choice of initial value for $\alpha$ etc. Once these parameters are tuned properly, the controller will exhibit excellent performance.

### 3.4.1 Selection of the System Model Order

Any known system can be represented by a mathematical model. The more complex the system, the higher will be the order of the system. Although it is desirable that the order of the model be as close as possible to that of the physical system, a reasonable simplification of the model is generally possible and even necessary when designing a self-tuning controller.

The simplification of the mathematical model is necessary because of the following reasons:

1. Self-tuning controller identifies the system parameters on-line. If the order of the model is high, the parameter estimation becomes difficult due to heavy calculation burden.

2. Self-tuning controller requires only the most important part of the system dynamics.

Thus the simplification of the system model is a must for the proper control.

Normally third order system model is taken for the power system. This is based on the consideration that a third order system usually contains a pair of dominant poles and a single pole which represents the main part of the system dynamics.

### 3.4.2 Selection of Minimum Value for $\lambda$

$\lambda$ is another tuning parametr for the self-tuning controller. A limit is put to its minimum value. If a too small value of $\lambda$ is taken, it will discount the old information very fast. This is not an acceptable proposition. This will make the identified parameter too sensitive to the new measurements. If the system noise is high, it may create stability problems. Thus a limit is put to the low value of $\lambda$ . In the present study 0.98 has been taken as the minimum value for $\lambda$ .

### 3.4.3 Selection of K

The pole-shifting modification factor $\Delta\alpha$ (t) is given by

$$\Delta\alpha(t) = -K \left|\frac{\partial u}{\partial \alpha}\right|^{-1} \Delta u$$

where K is a constant chosen to avoid excessive variation in $\alpha$ (t). If we want smooth controller action, $\alpha$(t) should change slowly. Thus it is obvious that the value of K should be small. But how small? Sometimes it becomes a must that $\alpha$(t) should change quickly. Such a situation arises when there is a sudden change in the controlled system. Heavy saturation in the system controlled output can be avoided if $\alpha$(t) increases rapidly. This will bring the control closer to the limits. Sometimes the need arises to decrease $\alpha$(t) rapidly to enhance system damping. Such a situation arises when the system is recovering from a sudden change.

The value of K taken for the present case is 0.05

Its rough value can be calculated from the above mentioned equation.

### 3.4.4 Selection of Initial Value for $\alpha$

$\alpha$ is a variable which can take any value from 0 to 1. The best value for $\alpha$ will be automatically calculated by the controller itself. Any value between 0 to 1 can be assigned to $\alpha$ initially. However, to reduce the initial impact higher value of $\alpha$ is preferable. If higher value of $\alpha$ is chosen, it results in small control output and avoids initial impact on the system. Later-on the algorithm can search for the best value itself.

# CHAPTER - 4

# APPLICATION OF THE PROPOSED CONTROLLER TO A SYNCHRONOUS GENERATOR

## 4.1 INTRODUCTION

The structure of the self-tuning algorithm has been studied fairly broadly in the last chapter. In this chapter, its performance is studied under different dynamic and transient conditions. It is observed that the controller performance in comparison to conventional one is fairly good.

The simulation studies are performed on a single machine connected to an infinite bus through a double circuit transmission line. The results are compared with AVR/stabilizer combination proposed by Ontario Hydro [14] as shown in Fig. 4.1 with fixed transfer functions for AVR and stabilizer.

The parameters used for the simulation studies are given in Appendix.

## 4.2 POWER SYSTEM MODEL

The schematic diagram of the power system considered is shown in Fig. 4.2.

The mathematical model of synchronous generator is a set of seven first order differential equations given as follows[1]:

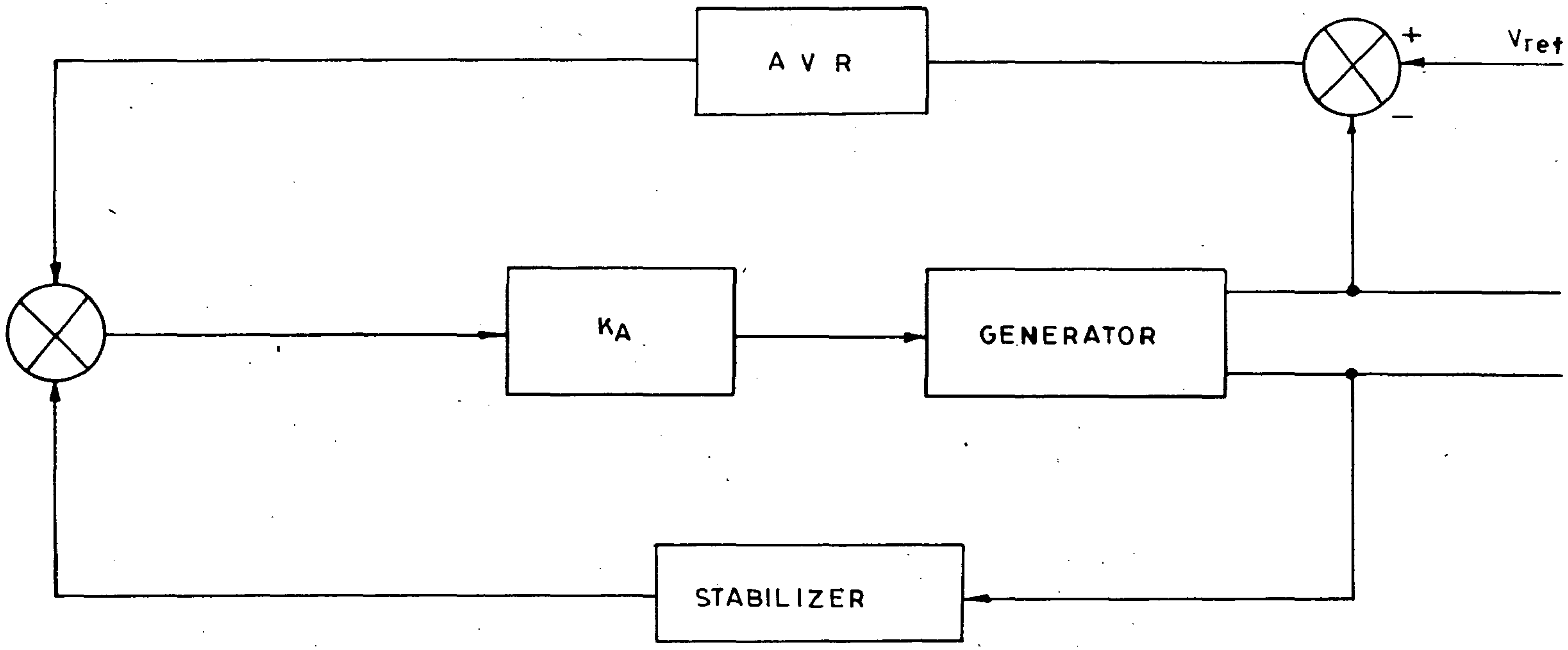



FIG. 4·1 — A CONVENTIONAL AVR AND STABILIZER

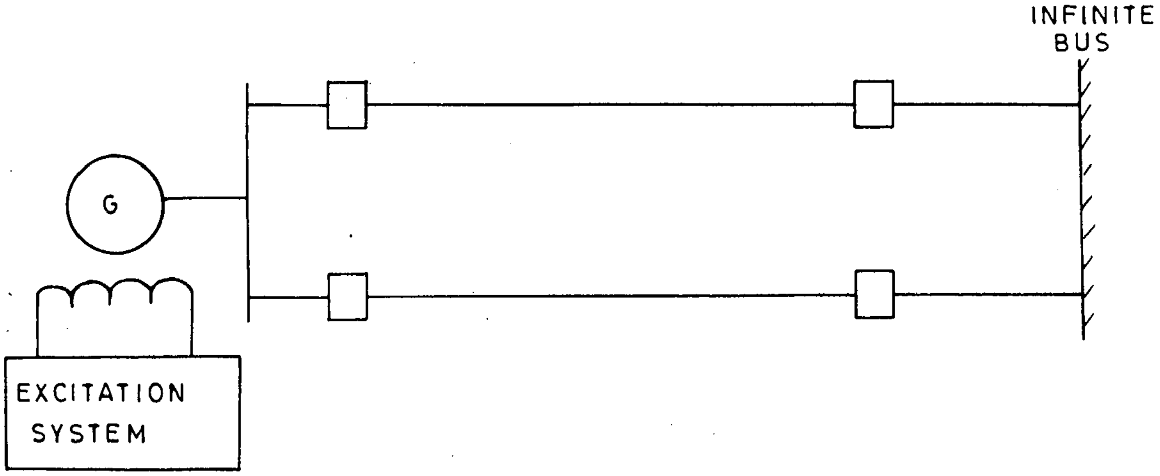



FIG.4·2— SINGLE M/C INFINITE BUS SYSTEM

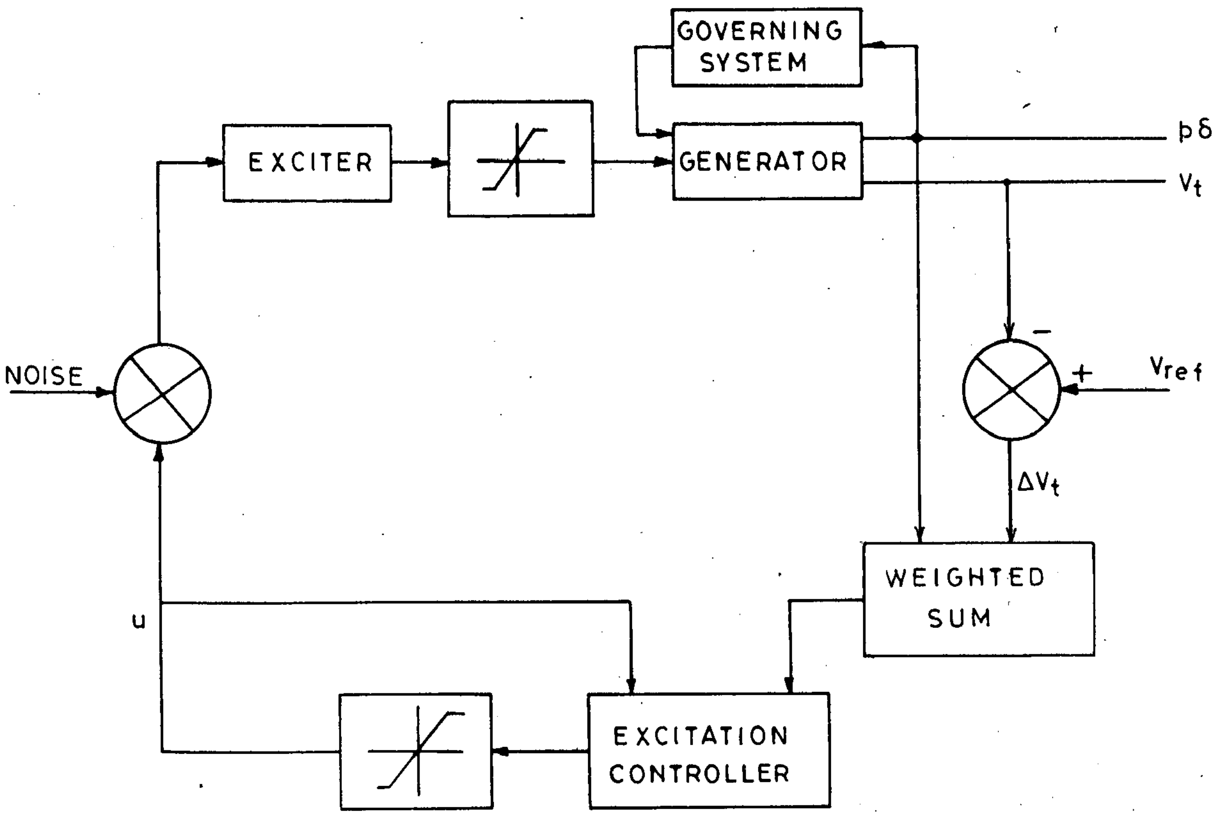



FIG.4·3— CLOSED LOOP SYSTEM

$$\dot{\lambda}_d = -E_0 \sin\delta - (r_a + r_t)\, i_d + x_t i_q + (\omega_0 - \nu)\, \lambda_q \qquad (4.1)$$

$$\dot{\lambda}_{kd} = -r_{kd}\, i_{kd} \qquad .. \qquad (4.2)$$

$$\dot{\lambda}_f = E_f - r_f\, i_f \qquad .. \qquad (4.3)$$

$$\dot{\lambda}_q = E_0 \cos\delta - (r_a + r_t)\, i_q - x_t\, i_d - (\omega_0 - \nu)\, \lambda_d \qquad (4.4)$$

$$\dot{\lambda}_{kq} = -r_{kq}\, i_{kq} \qquad .. \qquad (4.5)$$

$$\dot{\delta} = \nu \qquad .. \qquad (4.6)$$

$$\dot{\nu} = (T_m + g - T_e)\ \omega_0/2H \qquad .. \qquad (4.7)$$

where,

$$T_e = \omega_0/2\, (\lambda_d\, iq - \lambda_q\, id) \qquad .. \qquad (4.8)$$

and

$$\begin{bmatrix} \lambda_d \\ \lambda_{kd} \\ \lambda_f \end{bmatrix} = \begin{bmatrix} l_{md}+l_a & l_{md} & l_{md} \\ l_{md} & l_{md}+l_{kd} & l_{md} \\ l_{md} & l_{md} & l_{md}+l_f \end{bmatrix} \begin{bmatrix} id \\ i_{kd} \\ if \end{bmatrix} \qquad (4.9)$$

$$\begin{bmatrix} \lambda_q \\ \lambda_{kq} \end{bmatrix} = \begin{bmatrix} l_{mq}+l_a & l_{mq} \\ l_{mq} & l_{mq}+l_{kq} \end{bmatrix} \begin{bmatrix} iq \\ i_{kq} \end{bmatrix} \qquad (4.10)$$

These equations are derived by the use of the generalized theory of the alternating current machines [1].

The transfer function of the governor is [14]

$$g = (a + \frac{b}{1 + T_g s}) \, p \, \delta \qquad .. \qquad (4.11)$$

The AVR-exciter combination have the following transfer function [14]

$$E_{fd} = \frac{K_A}{1 + T_A s} \, (V_{ref} - V_t) \qquad .. \qquad (4.12)$$

The closed loop system configuration is as shown in Fig. 4.3.

### 4.3 SIMULATION STUDIES

Computer simulation studies were performed on the above mentioned power system. Its performance was studied by applying the dynamic as well as the transient disturbances. The performance of the proposed controller was compared with a conventional one. The encouraging results were observed.

#### 4.3.1 Dynamic Performance

Small disturbances were given to the system and the response was observed for the dynamic performance of the controller.

The following were the small disturbances applied to the system :

1. A disturbance of 5% step change in the input torque was applied to the synchronous machine. The operating conditions before

the disturbance were 0.6 p.u. active power output and 0.85 lagging power factor. The rotor angle response is shown in Fig. 4.4a. It is clear from the system response that the oscillations are reasonably damped with the proposed controller.

Fig. 4.4b depicts the p $\delta$ response due to the disturbance.

Fig. 4.4c shows the output generated by the controller. Due to the disturbance, the output fluctuates in order to follow the changes in the system response and once the system settles to the new operating condition, the output also settles.

The pole-shift factor and the forgetting factor are shown in Figs. 4.4d and 4.4e respectively. Since the disturbance is small, there are no variations recorded in these parameters. $\alpha$ continues to remain at zero and $\lambda$ continues to remain at 1.0.

2. A disturbance of 5% step change in $V_{ref}$ was applied to the machine. The operating conditions were kept at 0.6 p.u. power output and 0.85 lagging p.f. The response of the rotor angle is shown in Fig. 4.5a. The superiority of the digital controller is evident. The oscillations get damped quicker than the conventional controller. The p $\delta$ response is shown in Fig. 4.5b.

The output of the digital controller and the terminal voltage when this controller is used are depicted in Figs. 4.5 (c) and (d) respectively. It shows that the digital controller performs as an AVR also.

Since the controller does not hit the limits, so the pole shift factor again will remain at zero (Fig. 4.5e).

The forgetting factor registers a change immediately after the disturbance. It is shown in Fig. 4.5f.

System response to the above small disturbances shows that reasonable damping is provided by the proposed controller. This contributes to dynamic stability. More-over, it performs as an AVR also.

### 4.3.2 Transient Performance

To investigate the transient performance of the proposed controller, the following disturbances were given to the synchronous machine :

1. A 50% step change in input torque was applied to the synchronous machine operating at 0.6 p.u. active power output and 0.85 lagging p.f.The rotor angle response to the disturbance plotted in Fig. 4.6a shows the excellent performance of the digital controller. The oscillations are damped out quickly.

Fig. 4.6b depicts the p $\delta$ response. The output of the controller is depicted in Fig. 4.6c. It is seen that the controller hits the limits, so we can see the variation in $\alpha$. Due to the severe disturbance, the proposed controller moves the closed loop poles of the system away from the origin for short duration of time.

The variation of $\alpha$ is shown in Fig. 4.6d. $\lambda$ will also change and its variations are also depicted in Fig. 4.6e.

For this particular case, the variations of the identified A and B parameters are recorded in Figs. 4.6(f) and (g) respectively.

It is observed that the new parameters are identified very quickly and the system settles to the new operating conditions. The forgetting factor $\lambda$ discounts the old information quickly and this makes the identified parameters sensitive to new measurements.

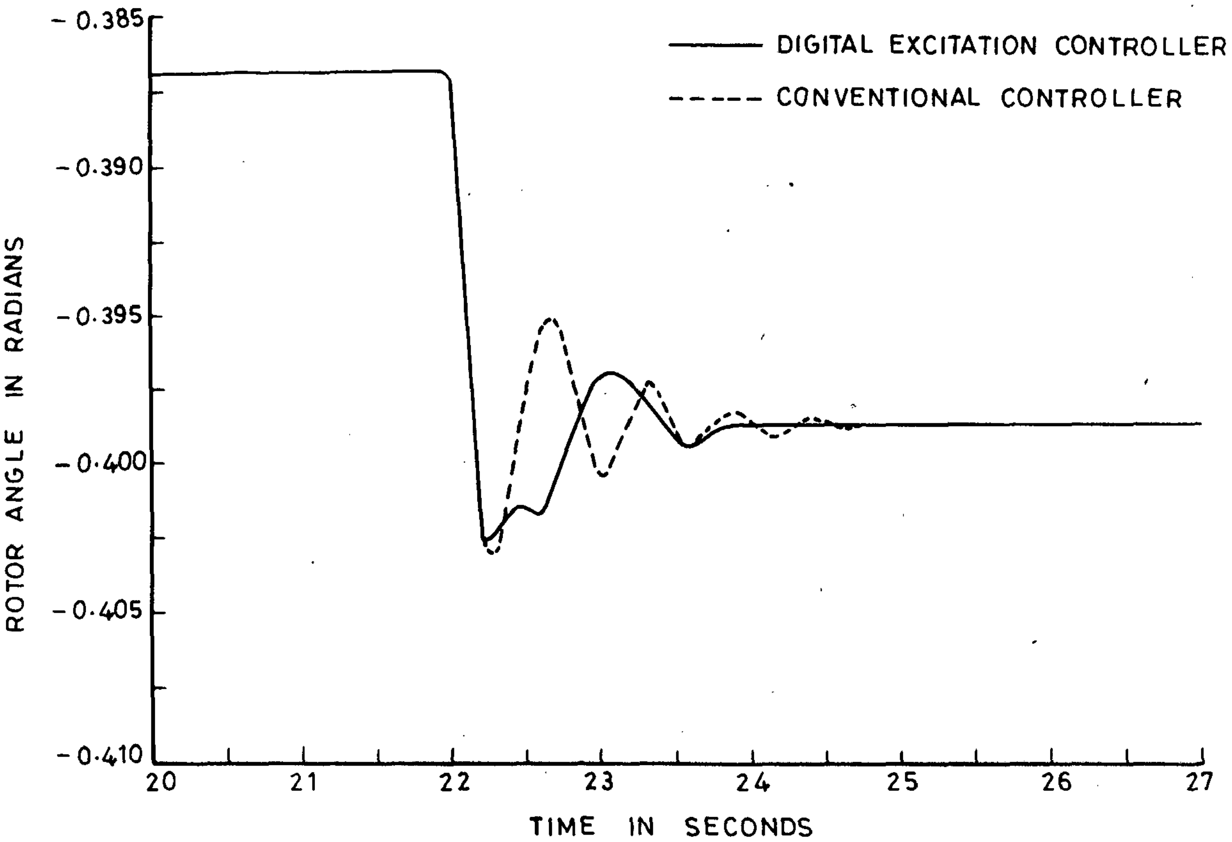
2. A 30% step change in input torque, to study the behaviour of the system under motoring action, was given to the synchronous machine. The responses of rotor angle, $p\delta$, $u$, $\alpha$ and $\lambda$ are shown in Fig.4.7. It is seen that the better system damping is achieved with the proposed controller than with the conventional controller.

3. A three-phase to ground short circuit was applied to the infinite bus side of one of the transmission lines for 0.1 sec. The faulted line was then disconnected from both sides for 0.15 sec. by the protective relays. After that, the faulted line was reclosed successfully. The system response to such a disturbance is shown in Fig. 4.8. In Fig.4.8, $\delta$, $p\delta$, $u$, $V_t$, $\alpha$ and $\lambda$ are depicted.
The operating conditions for such a study was 0.72 p.u. active power output and 0.85 lagging p.f.

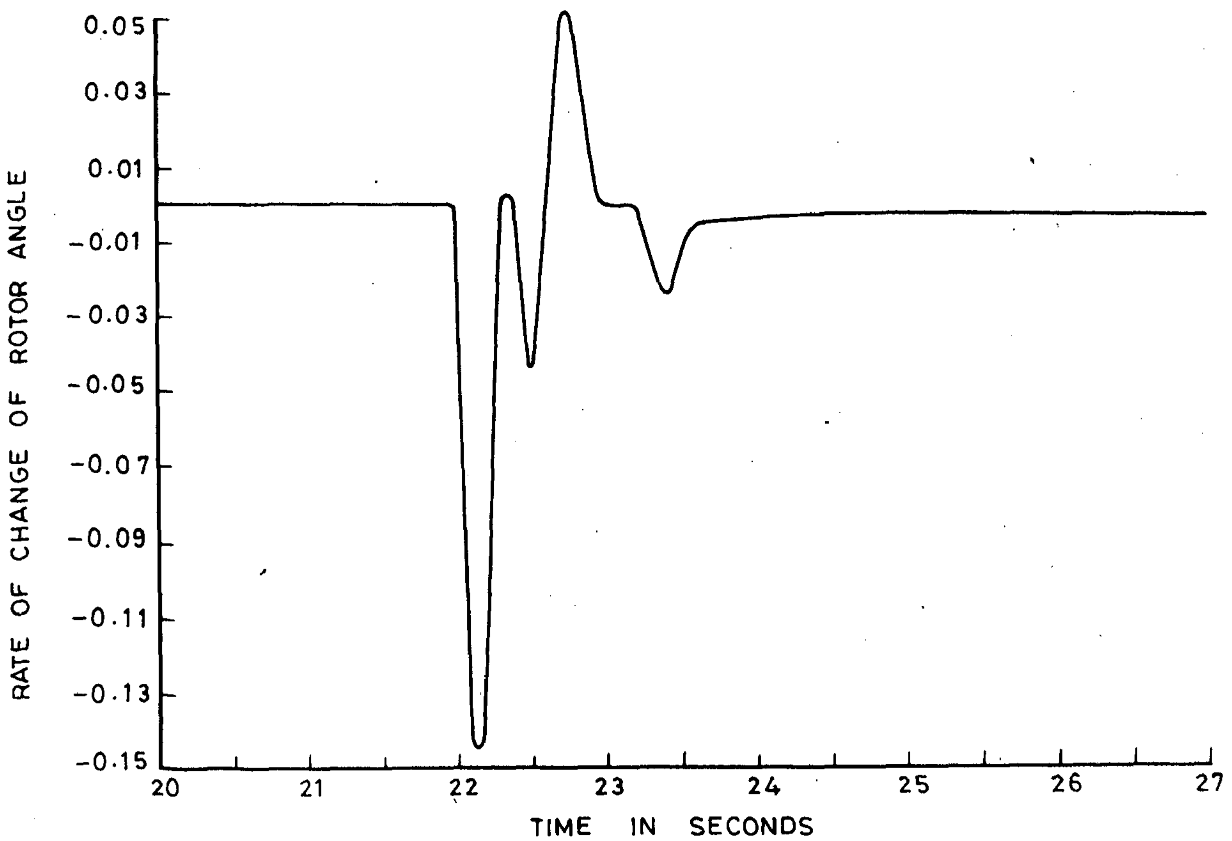
4. A three-phase to ground short circuit was applied again. After the fault is cleared the line is not reconnected back. This simulated the short circuit and one line loss test. The response to this type of disturbance is depicted in Fig. 4.9.

In order to accommodate the large disturbance, the pole-shift factor in the proposed controller has to increase when the control hits the limits. The poles are shifted away from the origin for a small time to avoid excessive output saturation problem of the controller. When the system recovers from the large disturbances, the control output decreases from the ceiling value and the pole-shift control algorithm will rapidly decrease $\alpha$ , in order to bring the poles back closer to the origin.

From the above tests it is evident that the dynamic as well as the transient stability of the system is increased with the help of the proposed controller. It performs well as an AVR as well as a stabilizer.

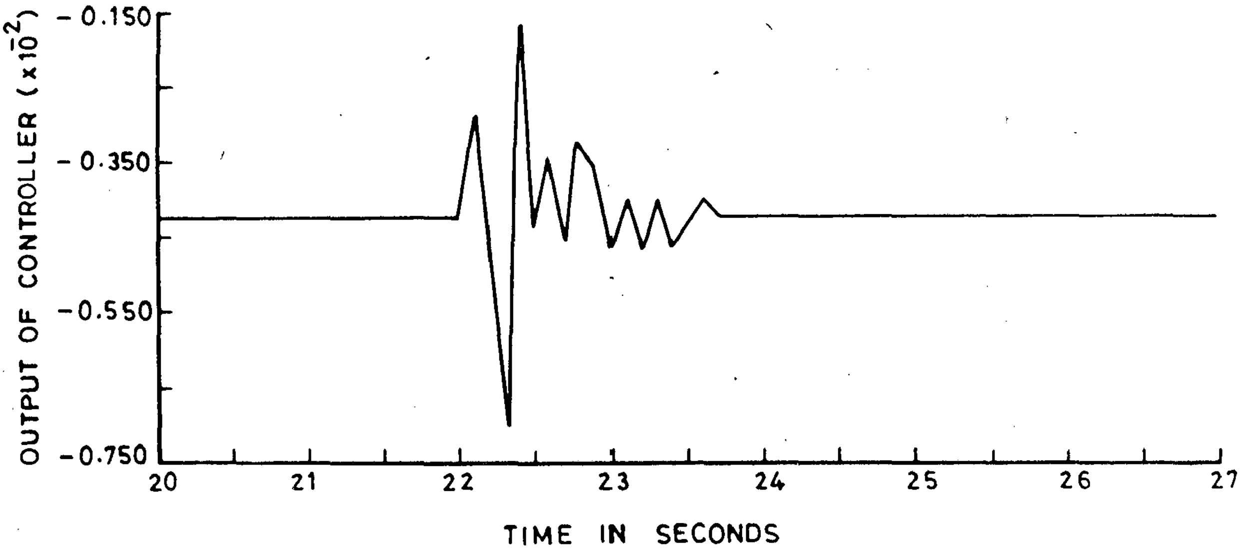



(a) ROTOR ANGLE RESPONSE



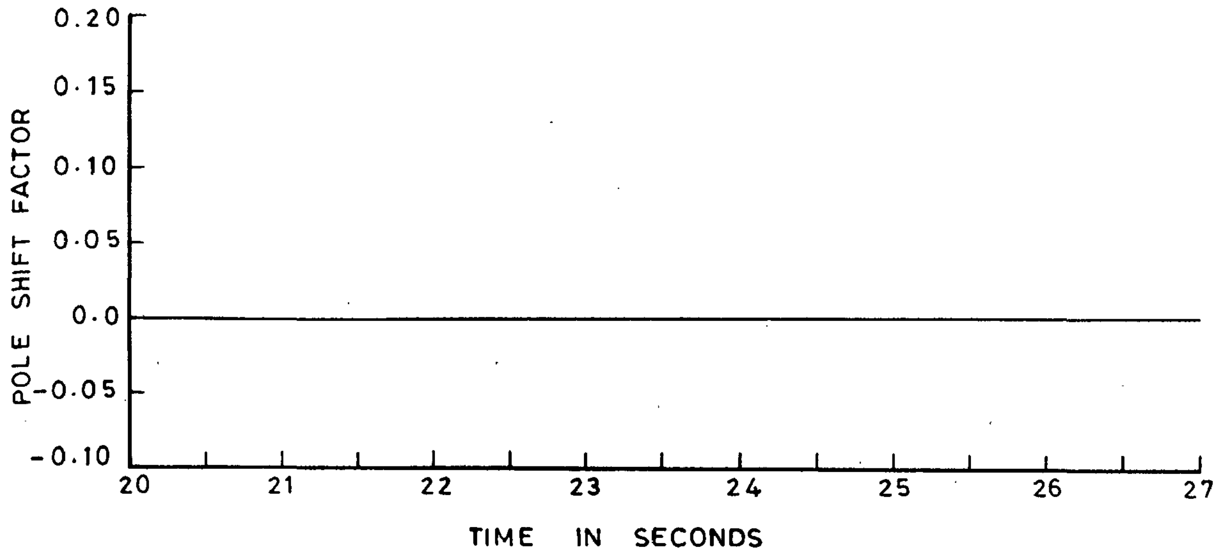

(b) pδ RESPONSE

FIG. 4·4 – RESPONSE TO A 5% STEP CHANGE IN INPUT TORQUE

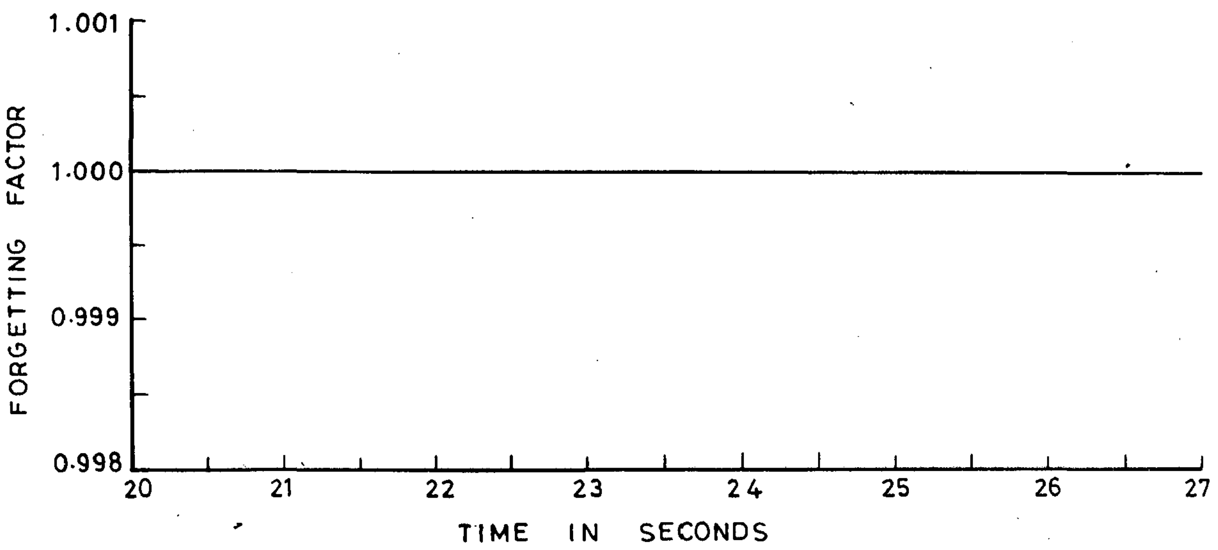



(c) OUTPUT OF DIGITAL CONTROLLER

FIG. 4·4 (CONTINUED)

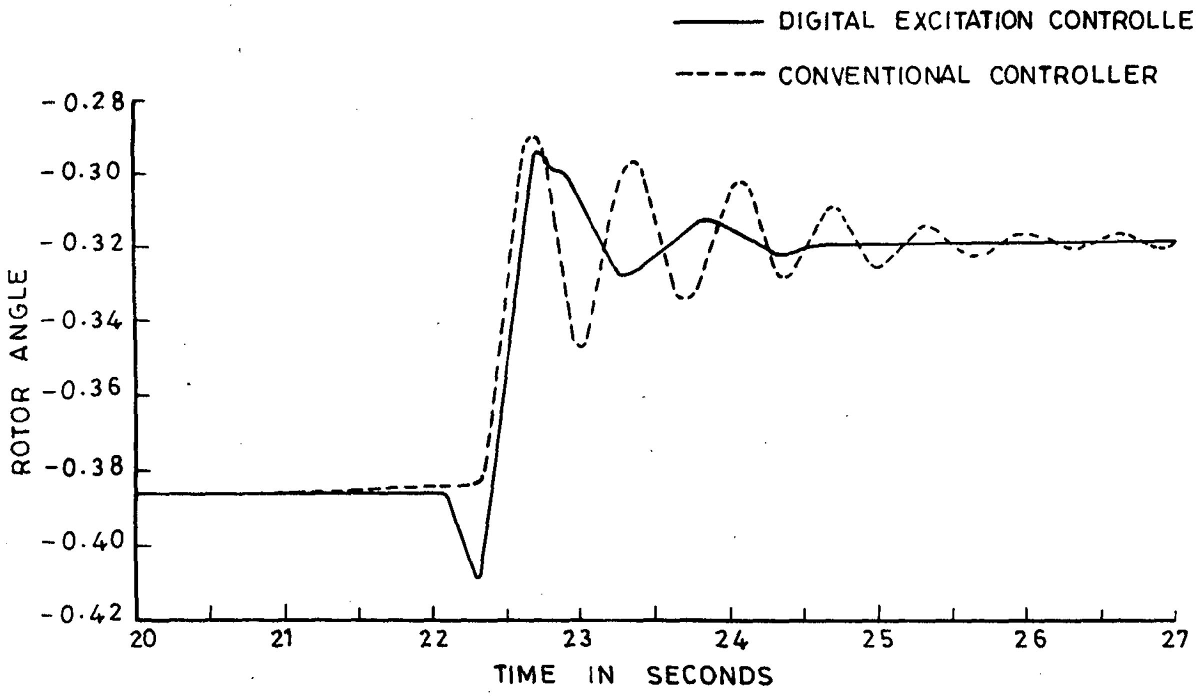



(d) POLE-SHIFTING FACTOR

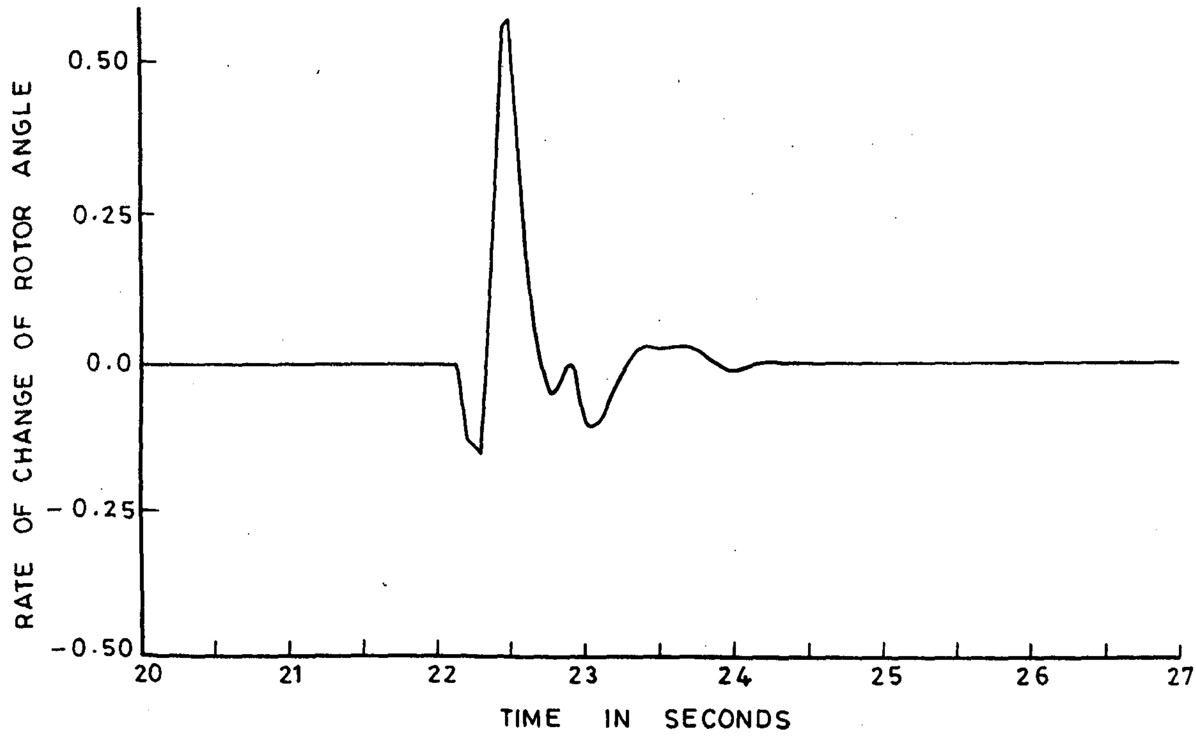



(e) FORGETTING FACTOR

FIG. 4·4 (CONTINUED)

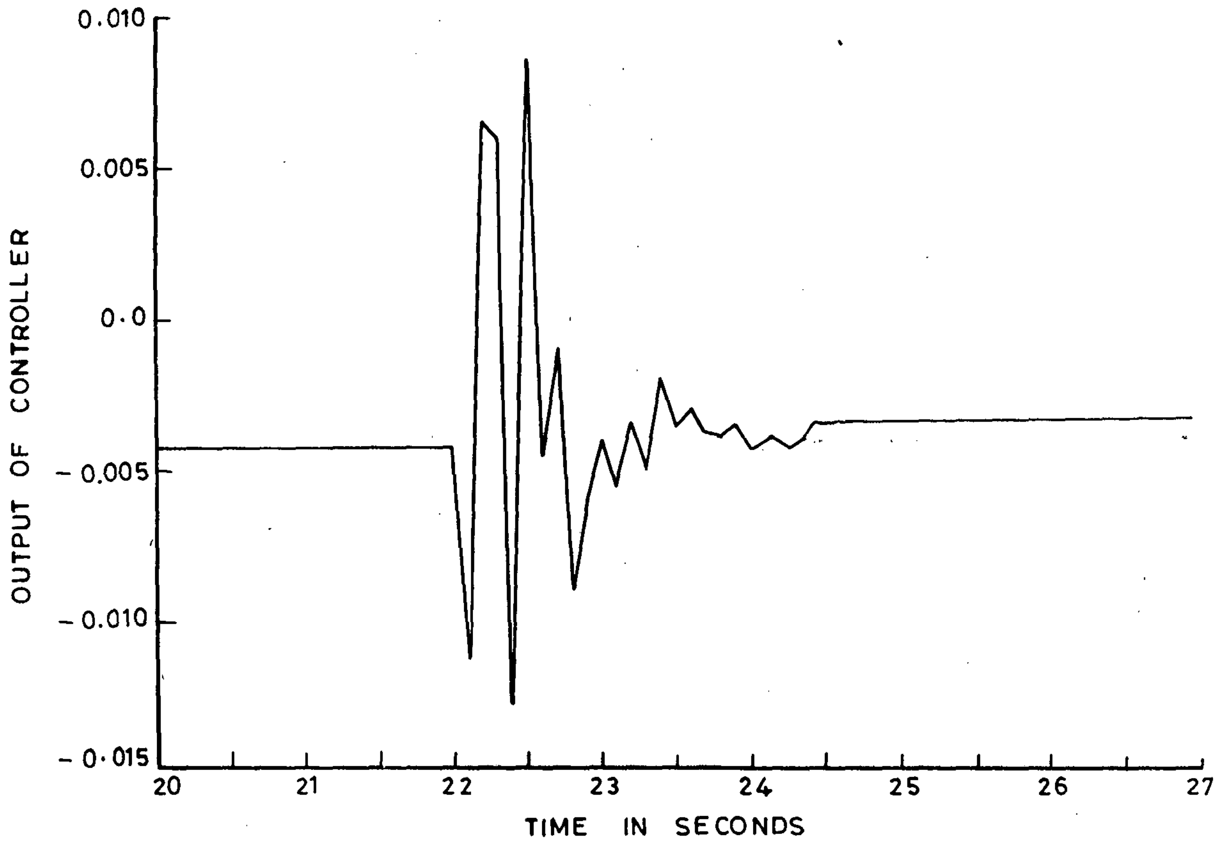



(a) LOAD ANGLE RESPONSE

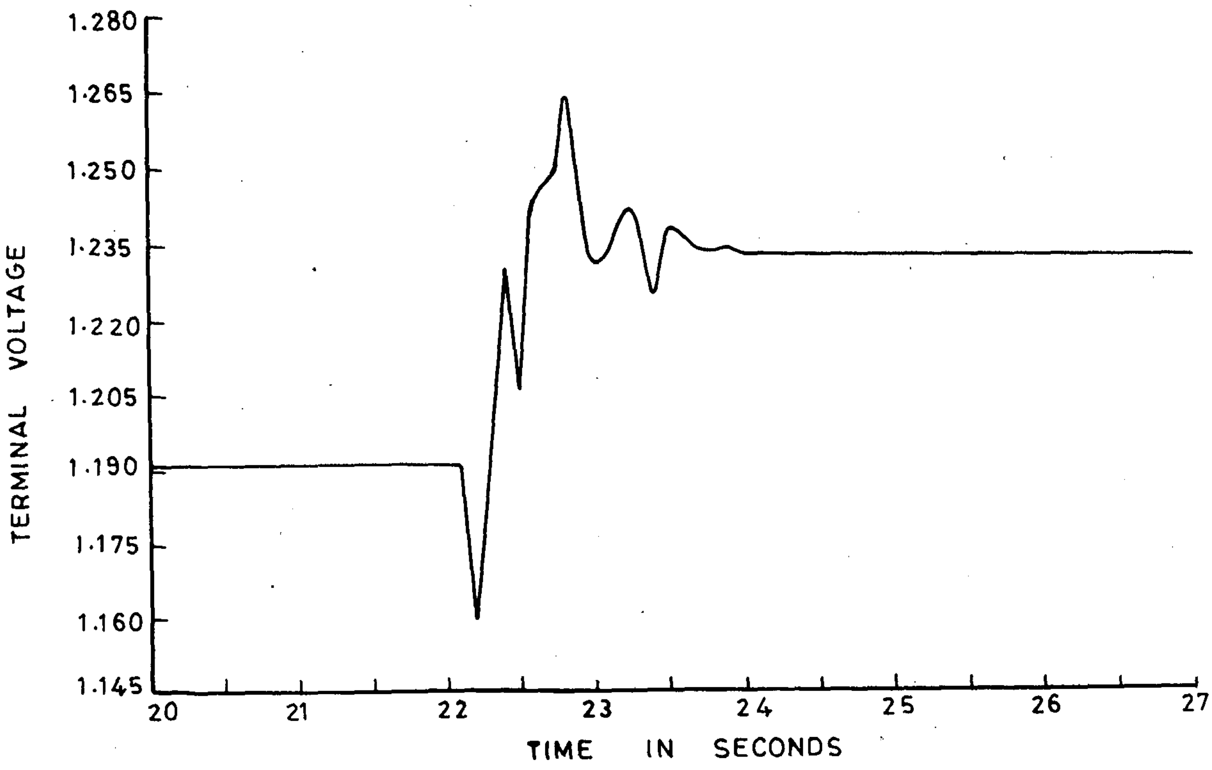



(b) pδ RESPONSE

FIG. 4.5 –RESPONSE TO A 5% STEP CHANGE IN TERMINAL VOLTAGE REFFRENCE

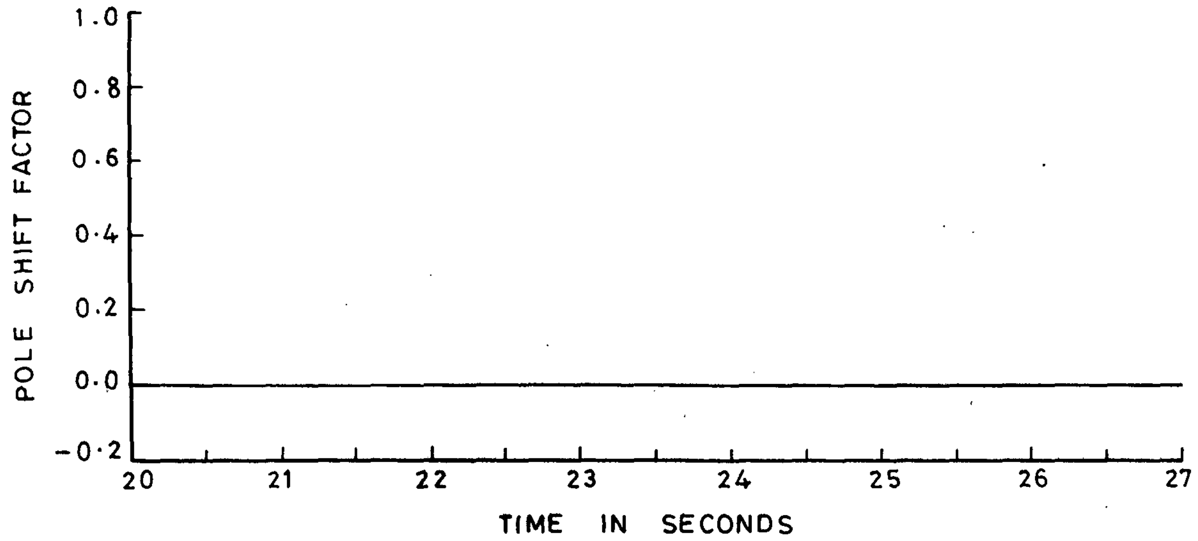



(c) OUTPUT OF DIGITAL CONTROLLER

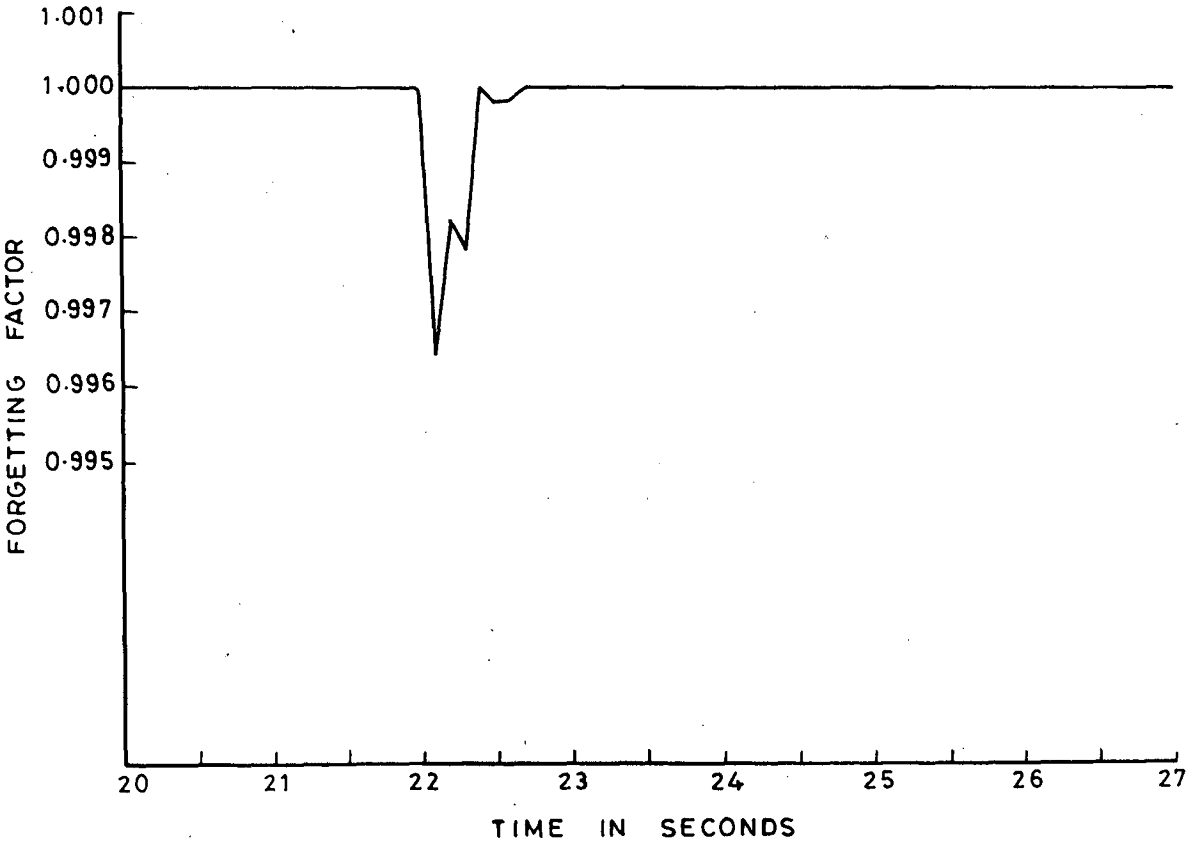



(d) TERMINAL VOLTAGE

FIG. 4.5 (CONTINUED)




(e) POLE SHIFT FACTOR




(f) FORGETTING FACTOR

FIG. 4.5 (CONTINUED)

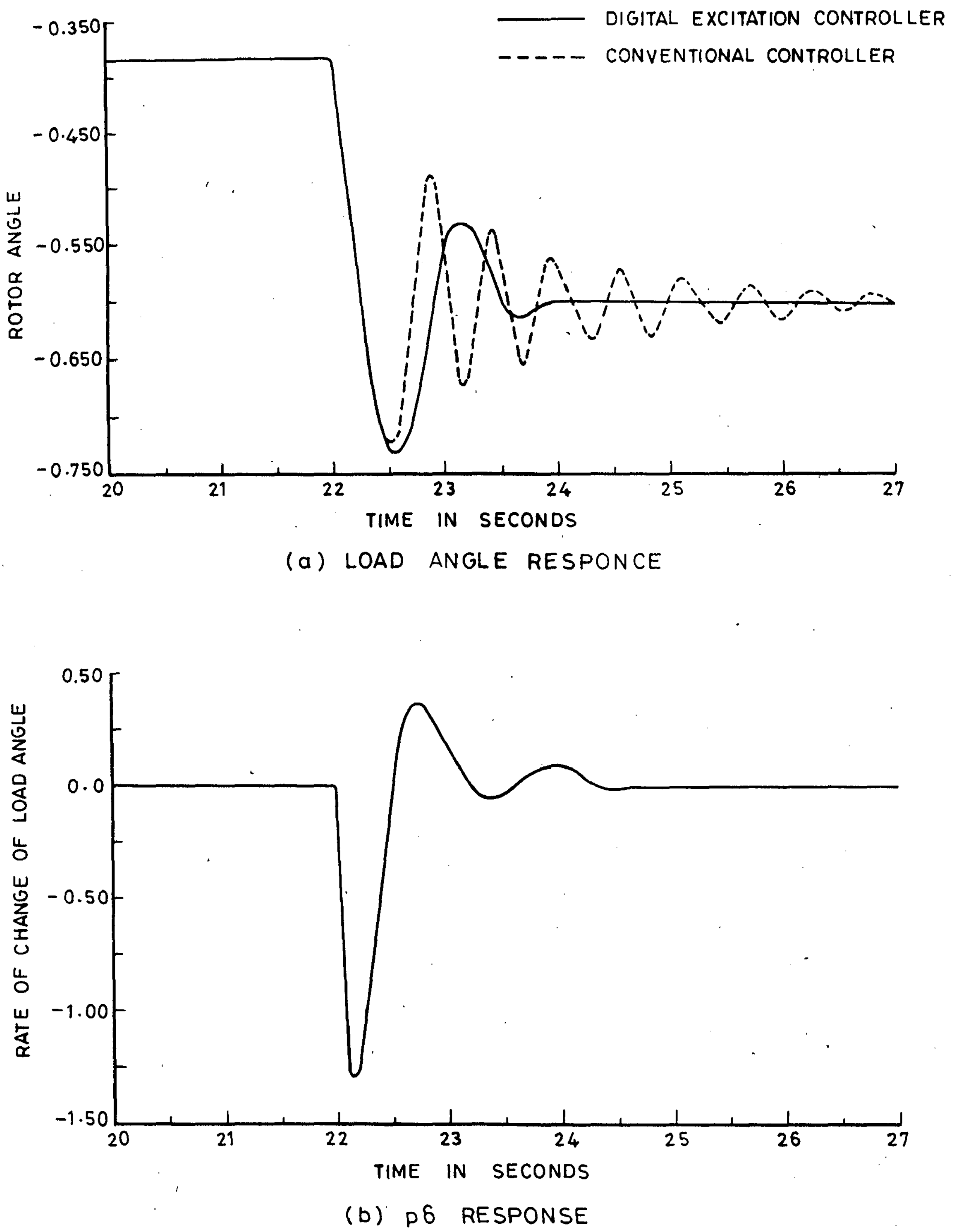
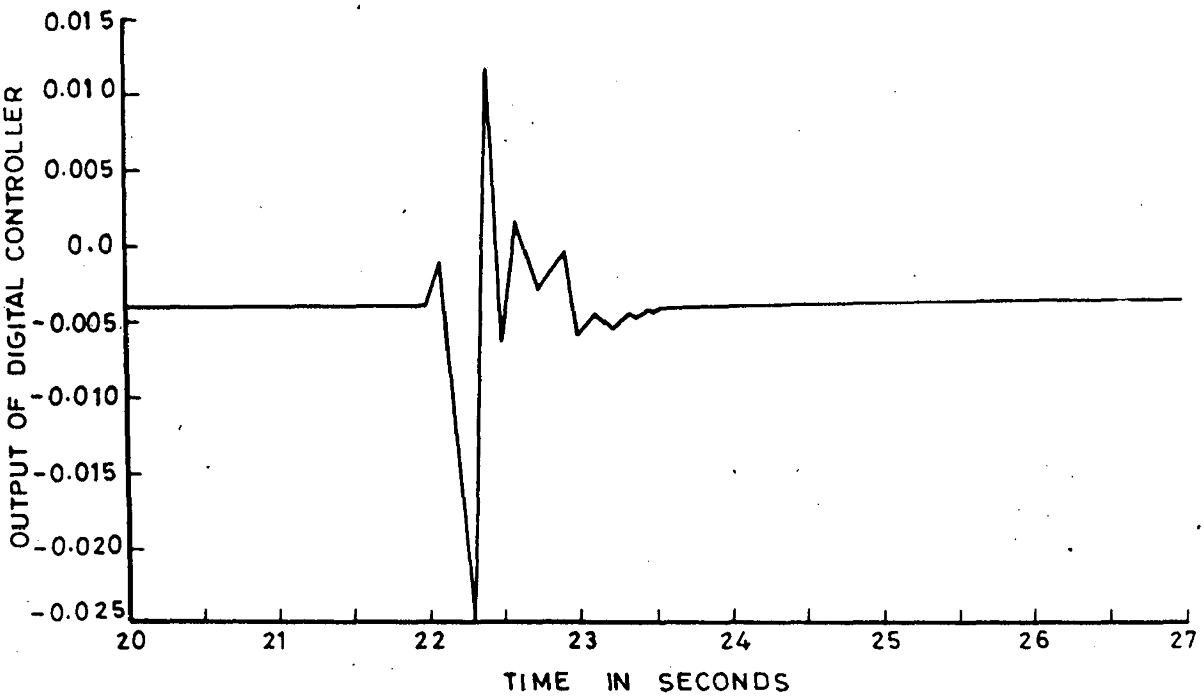
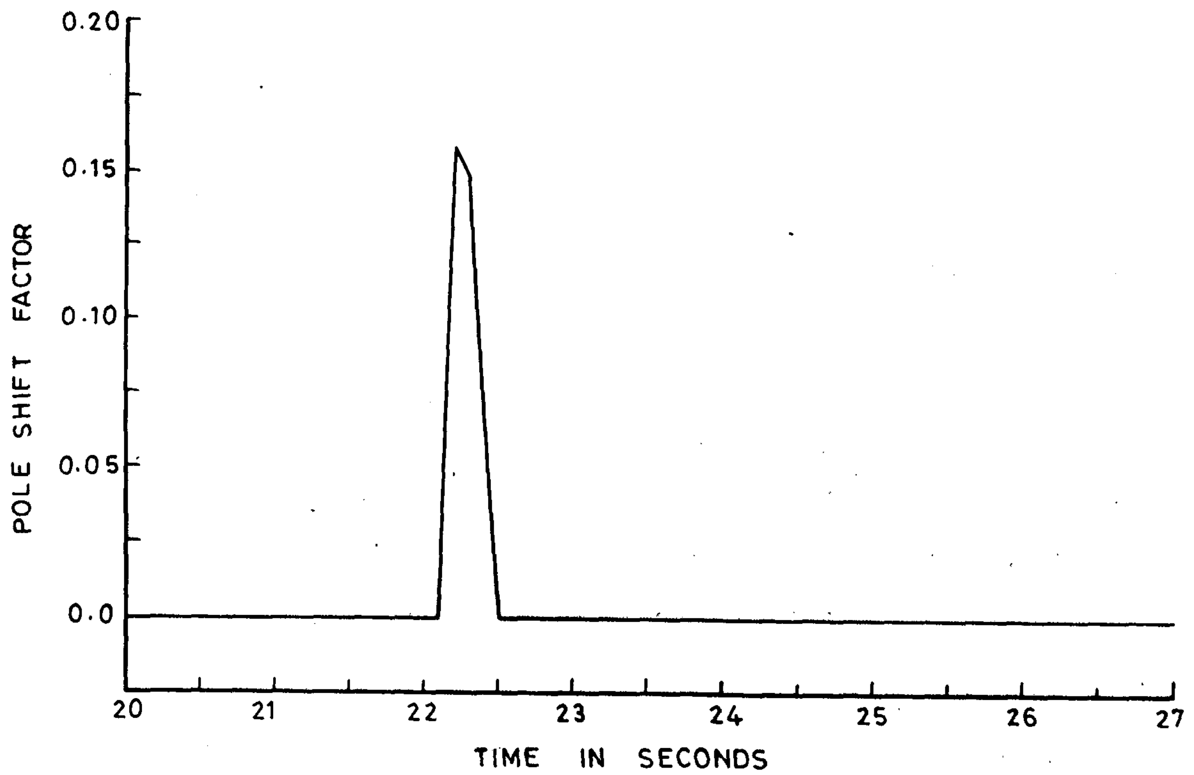



FIG. 4·6 -RESPONSE TO A 50% STEP CHANGE IN INPUT TORQUE

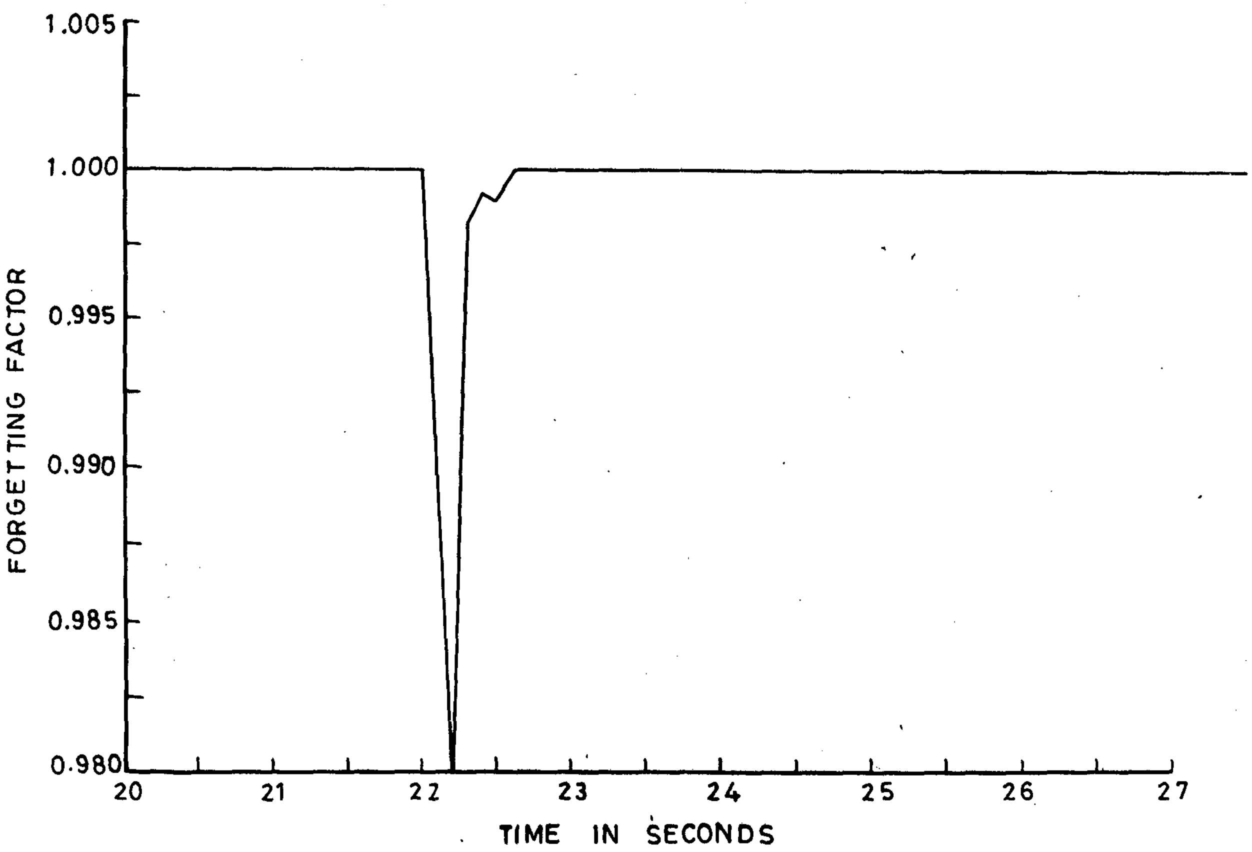



(c) OUTPUT OF THE CONTROLLER

FIG. 4·6 (CONTINUED)

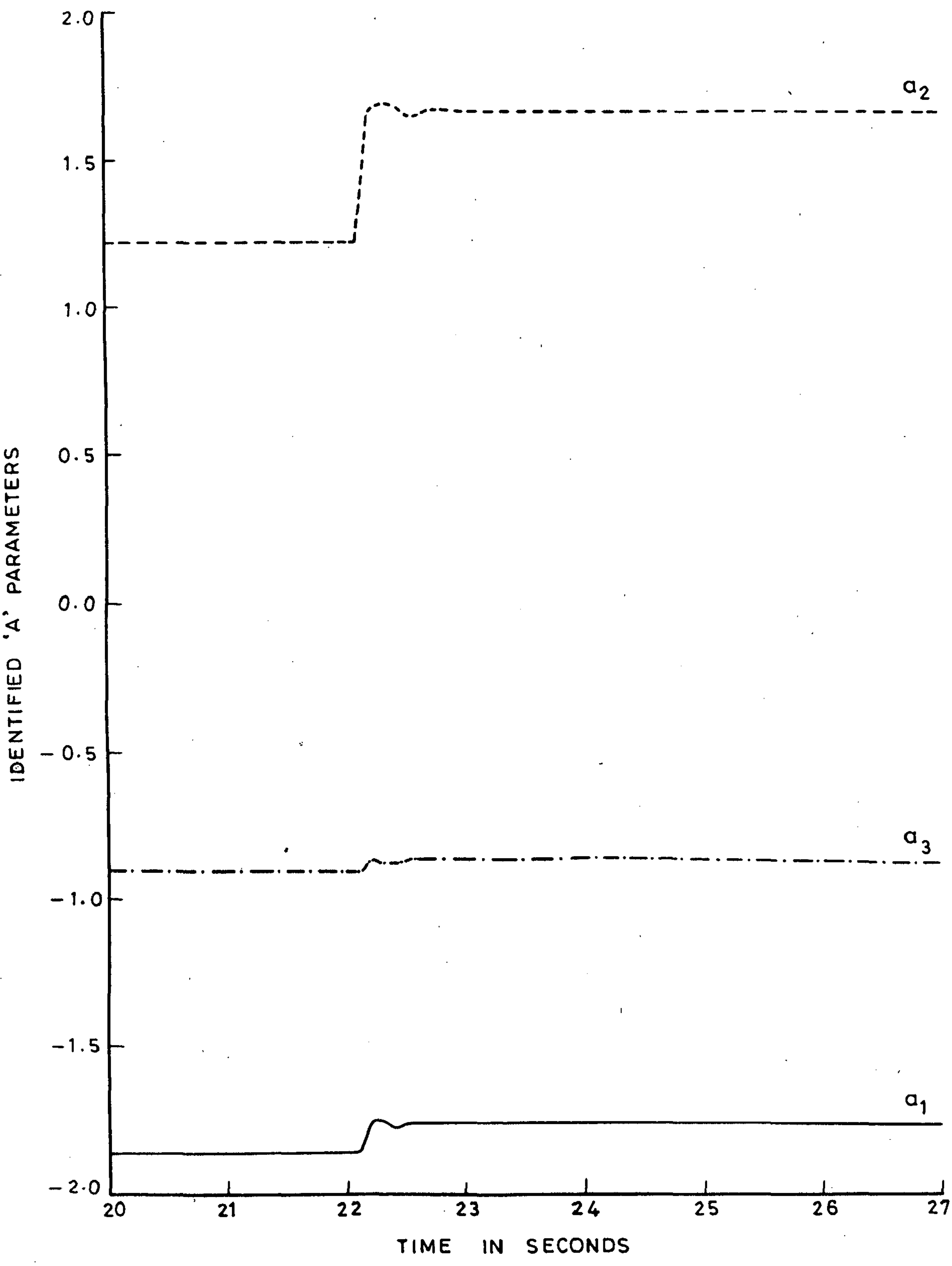



(d) VARIATION IN POLE SHIFT FACTOR



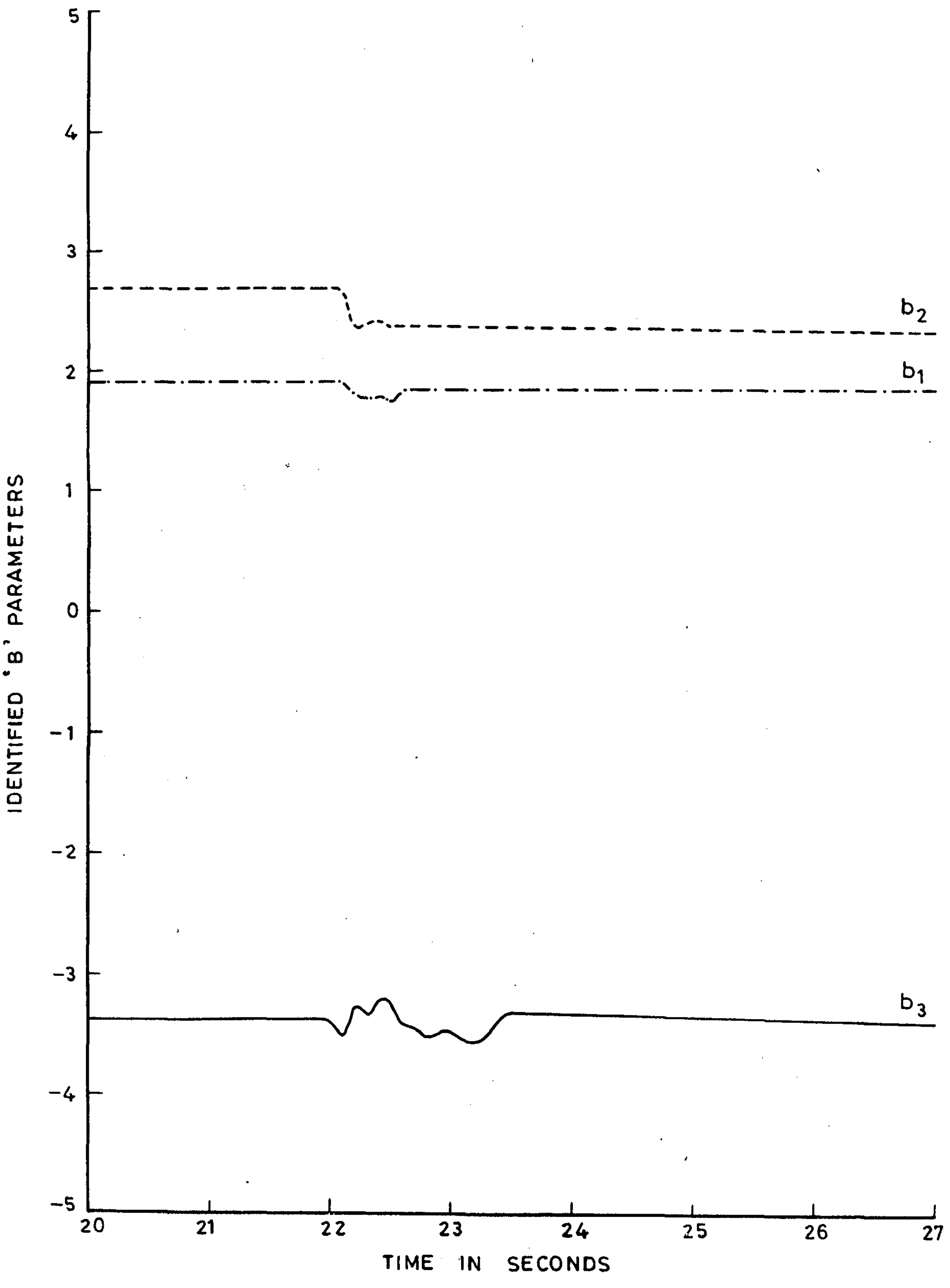

(e) VARIATION IN FORGETTING FACTOR

FIG. 4·6 (CONTINUED)




(f) VARIATION OF 'A' IDENTIFIED PARAMETERS

FIG. 4·6 (CONTINUED)




(g) VARIATION OF 'B' IDENTIFIED PARAMETERS

FIG. 4·6 (CONTINUED)

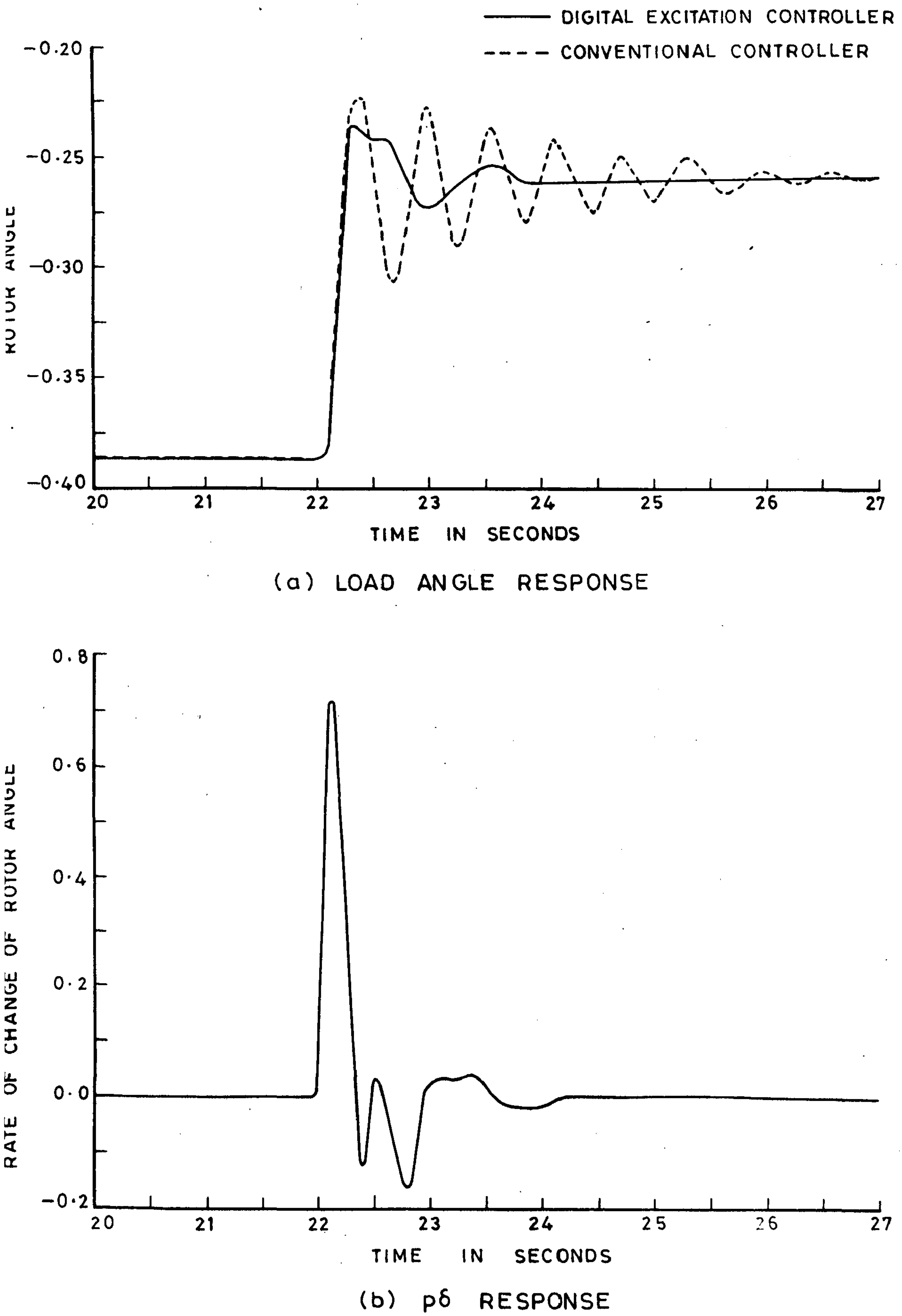
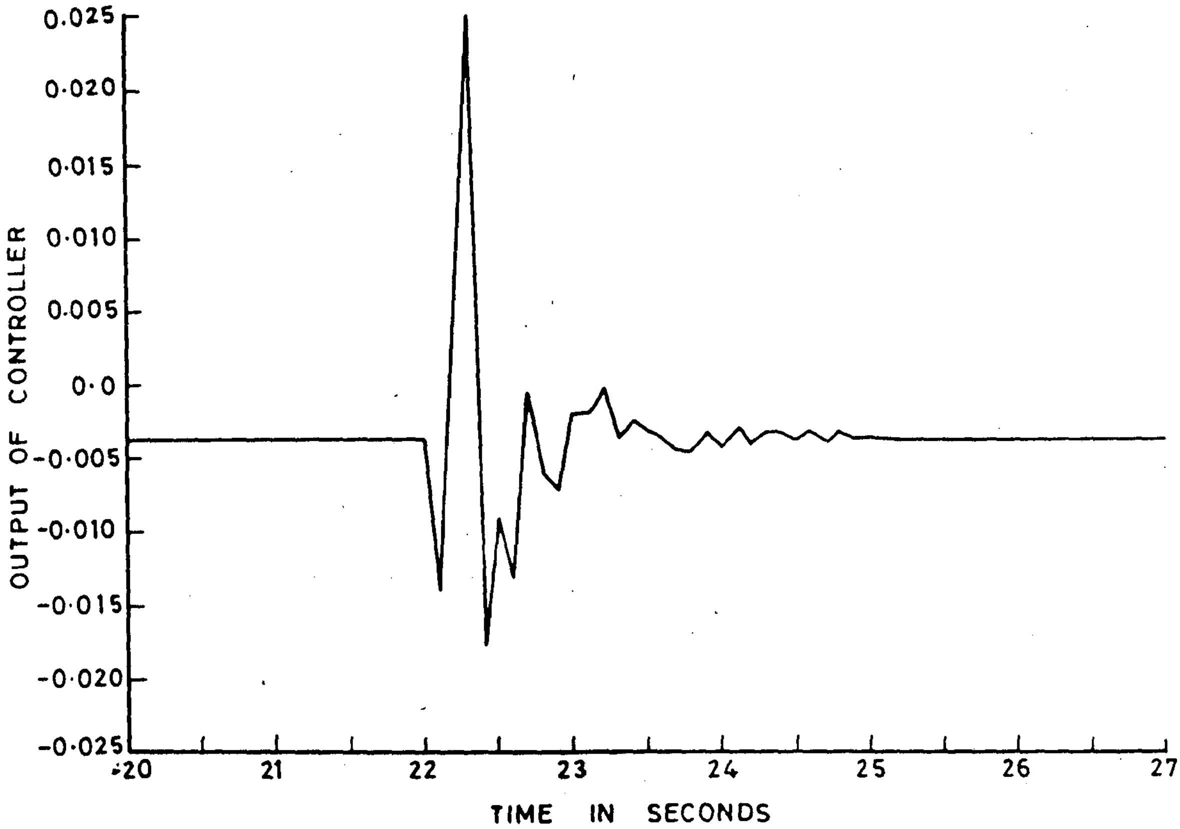
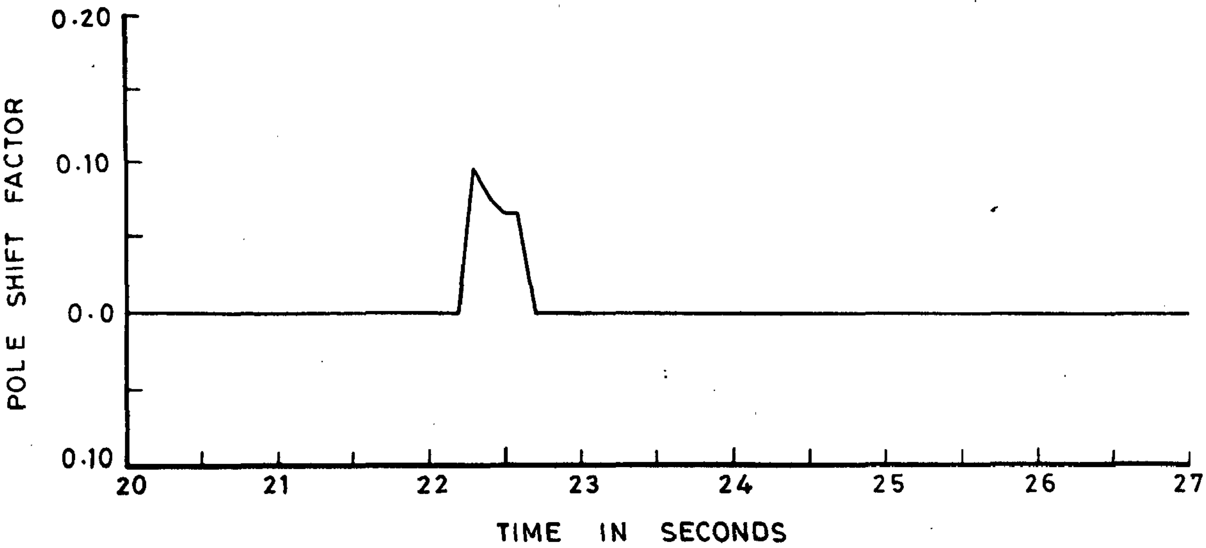



FIG. 4.7 - RESPONSE TO A 30% STEP DECREASE IN INPUT TORQUE

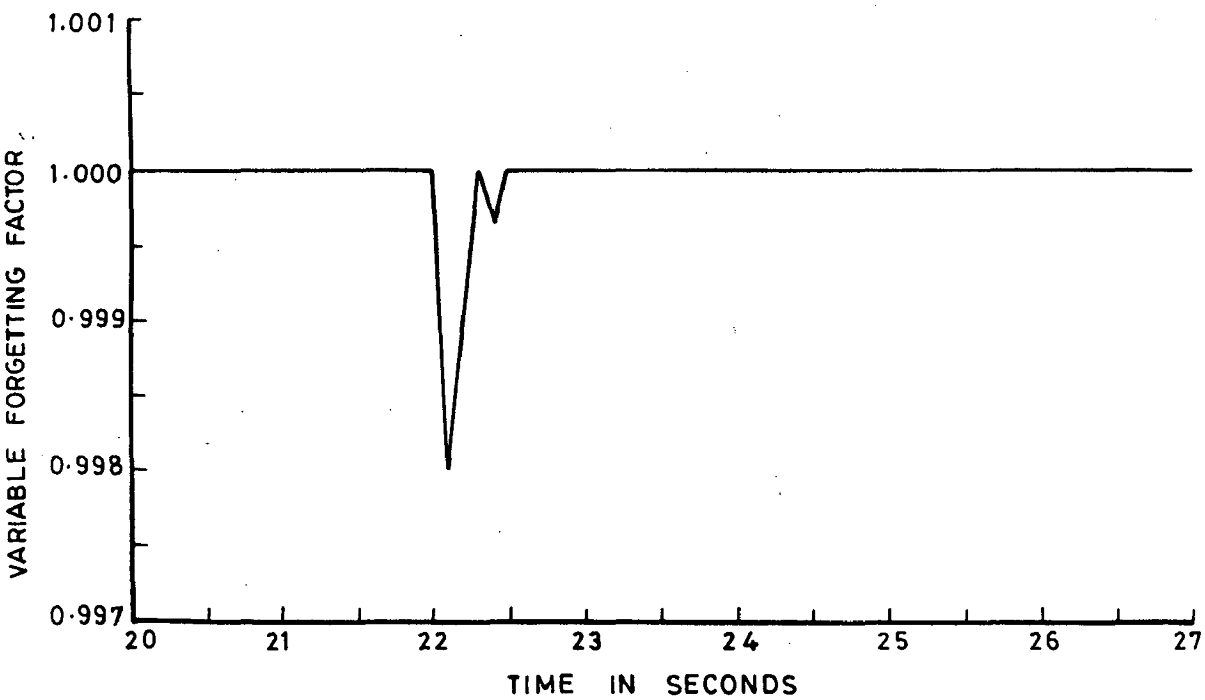



(c) OUTPUT OF DIGITAL CONTROLLER

FIG. 4·7 (CONTINUED)

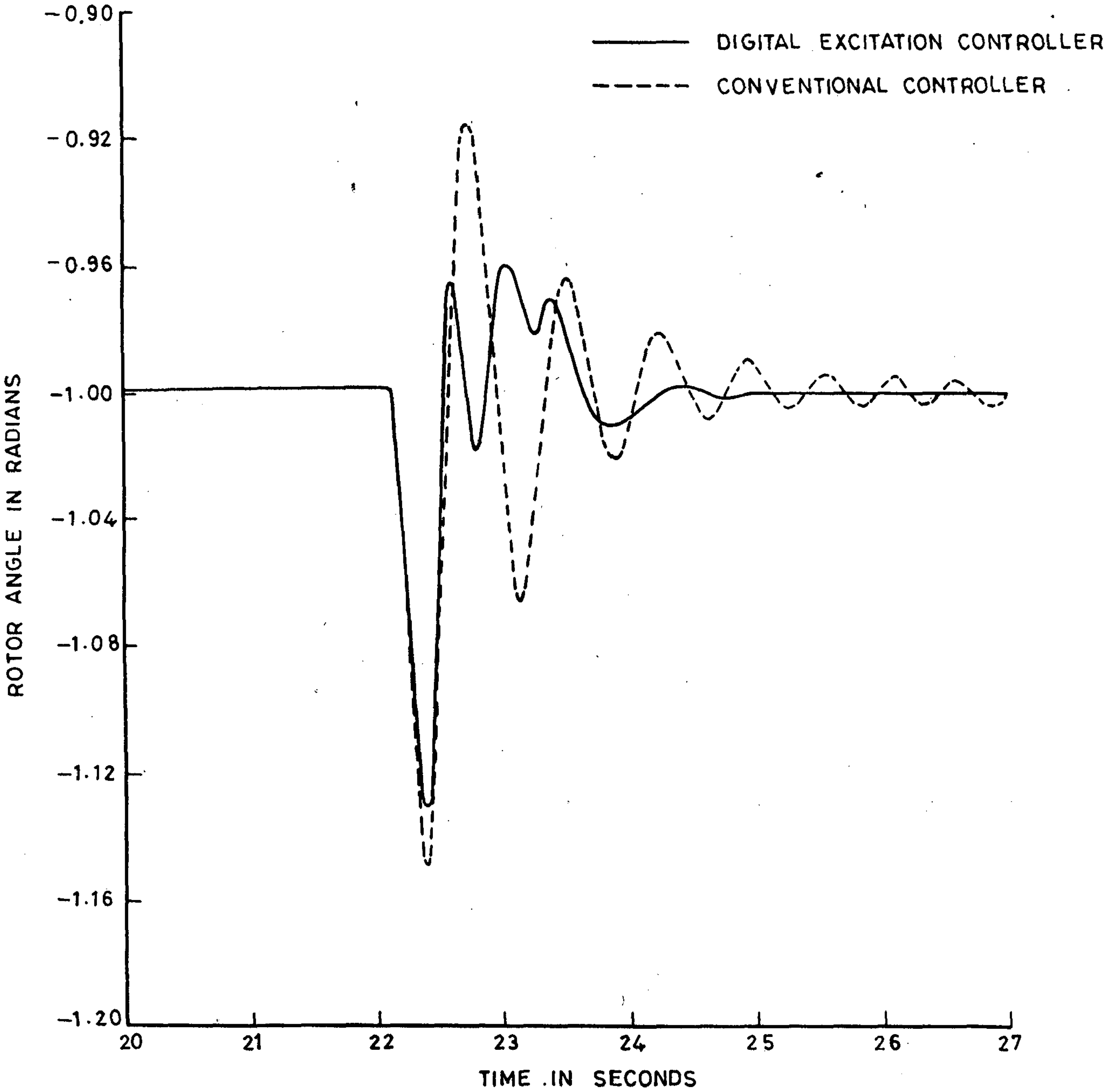



(d) POLE SHIFT FACTOR



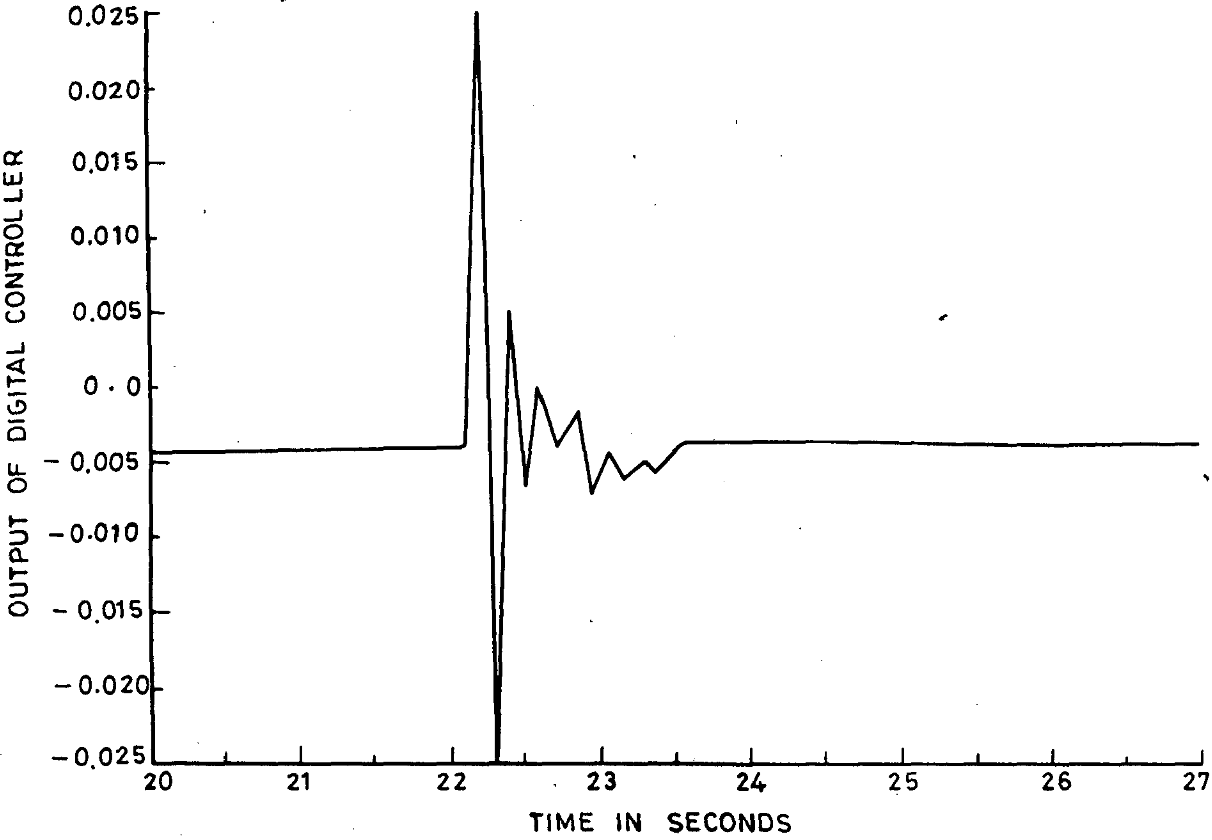

(e) VARIATION OF FORGETTING FACTOR

FIG. 4·7 (CONTINUED)

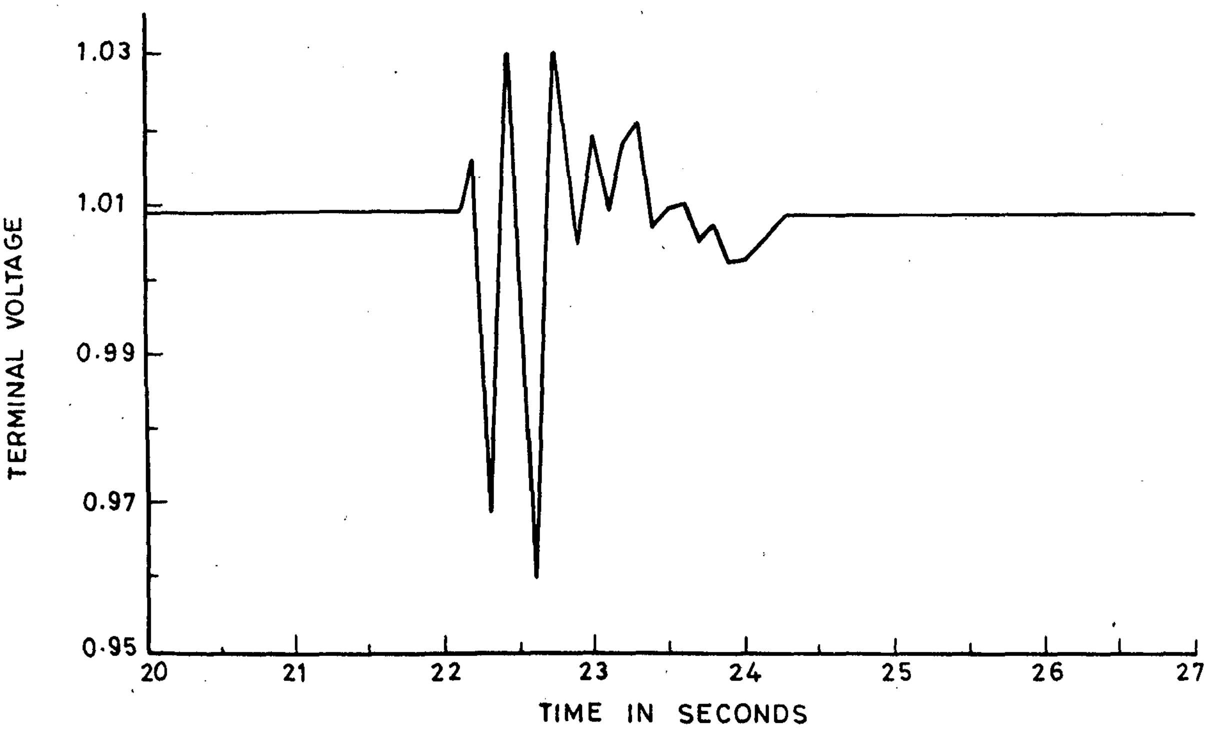



(a) LOAD ANGLE RESPONSE

FIG. 4·8 – RESPONSE TO A THREE PHASE TO GROUND SHORT CIRCUIT WITH SUCCESSFUL RECLOSURE OF CIRCUIT BREAKERS

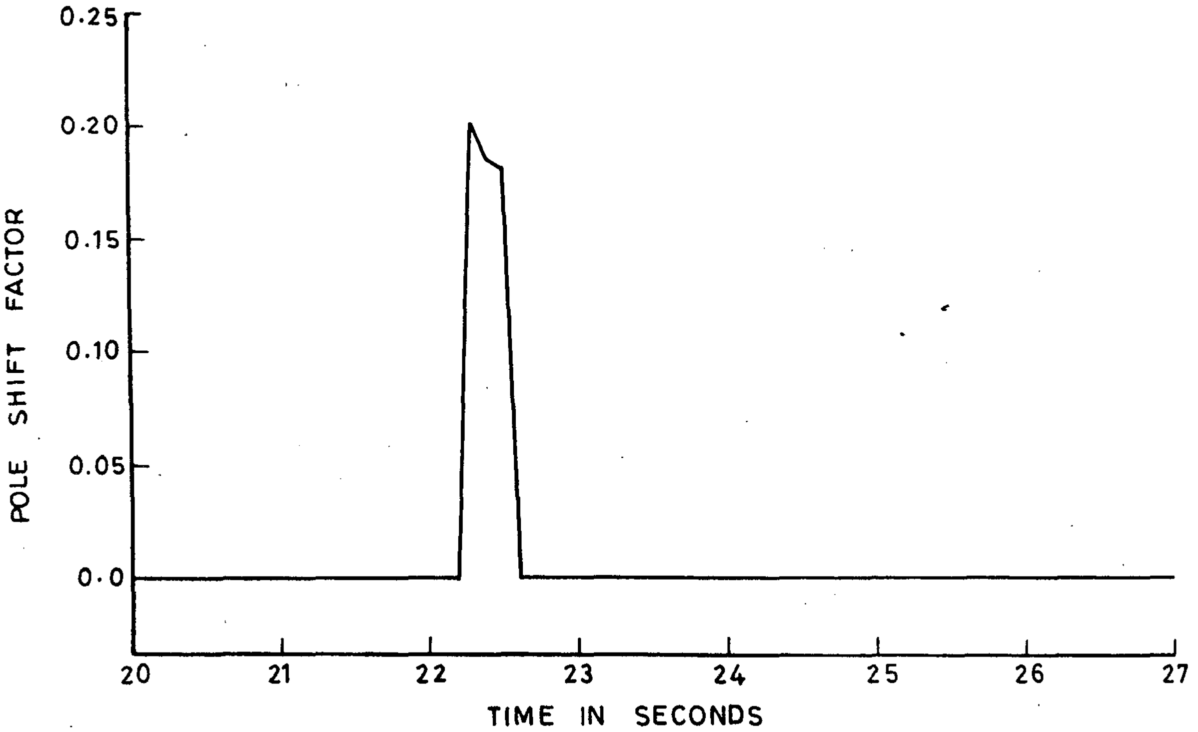



(b) OUTPUT OF DIGITAL CONTROLLER

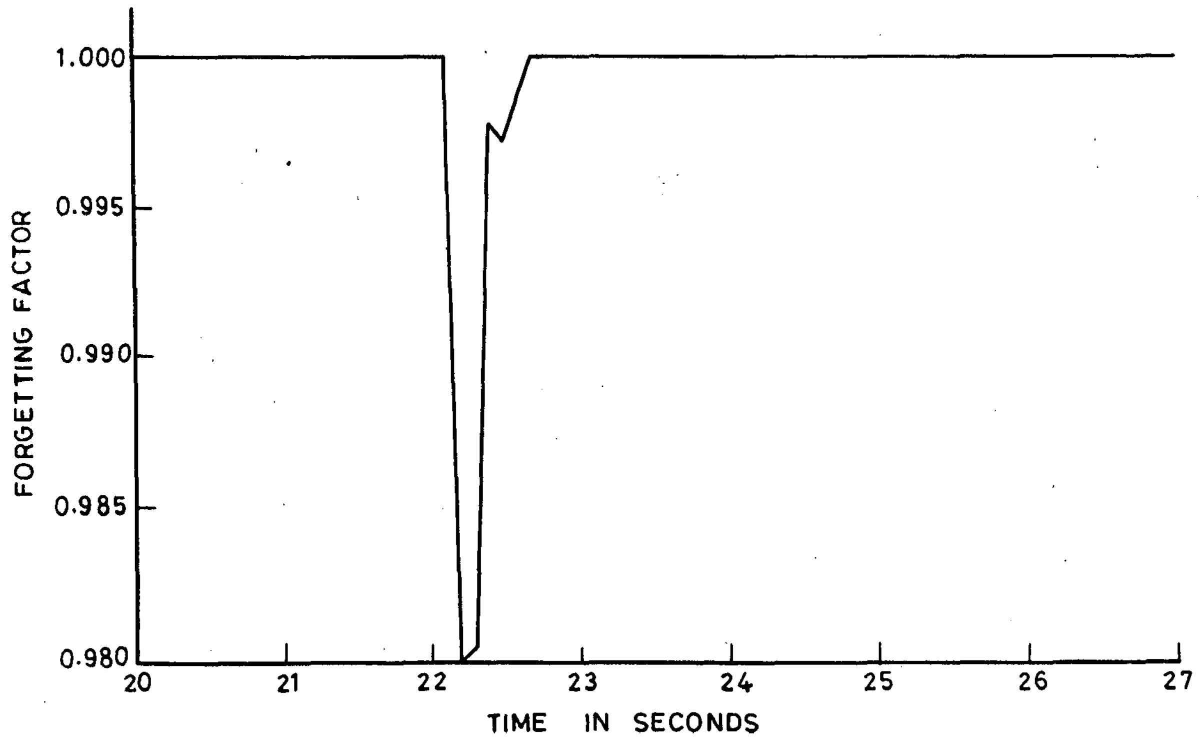



(c) TERMINAL VOLTAGE

FIG. 4·8 (CONTINUED)

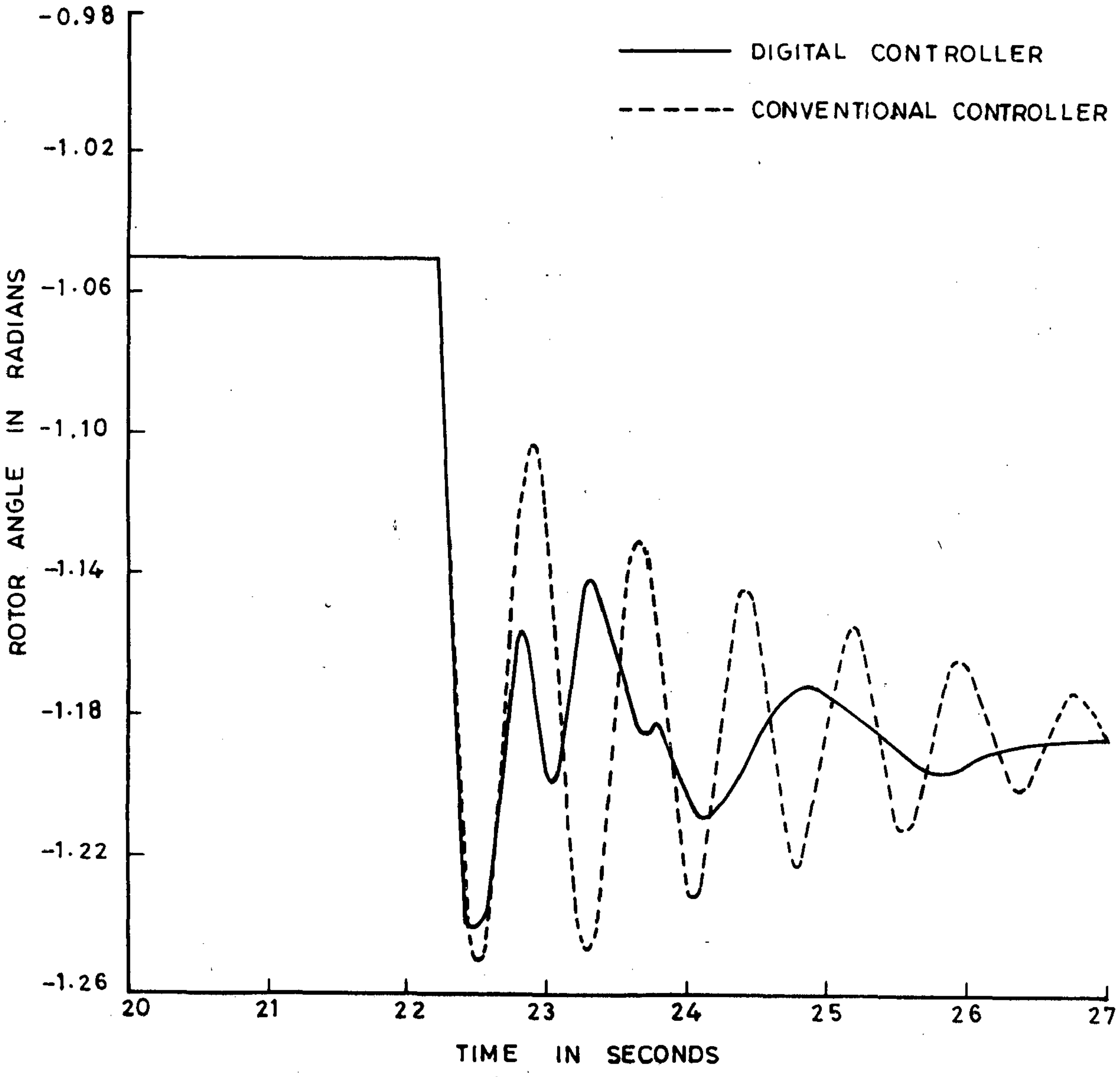



(d) POLE-SHIFT FACTOR



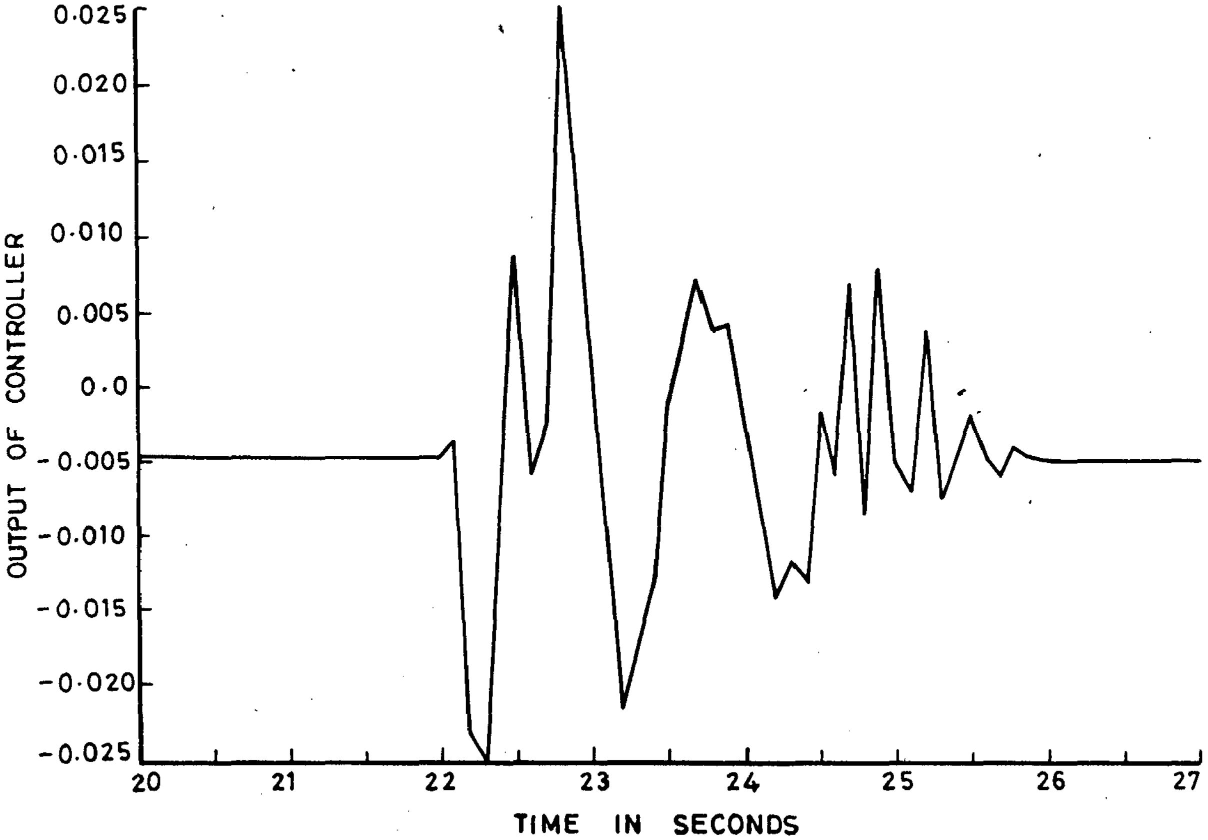

(e) FORGETTING FACTOR

FIG. 4·8 (CONTINUED)

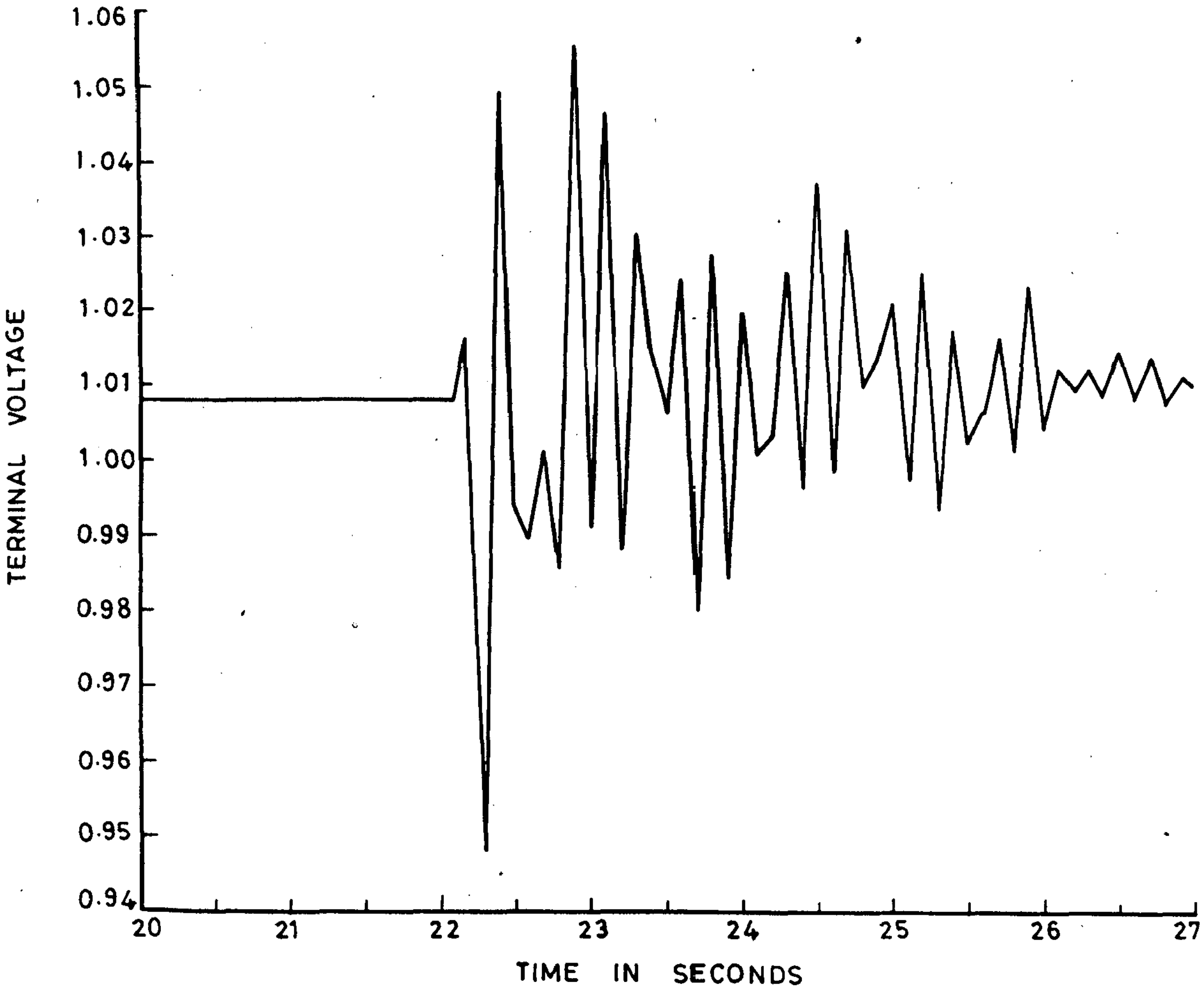



(a) ROTOR ANGLE RESPONSE

FIG. 4.9 – RESPONSE TO A THREE PHASE TO GROUND SHORT CIRCUIT WITH ONE LINE LOSS

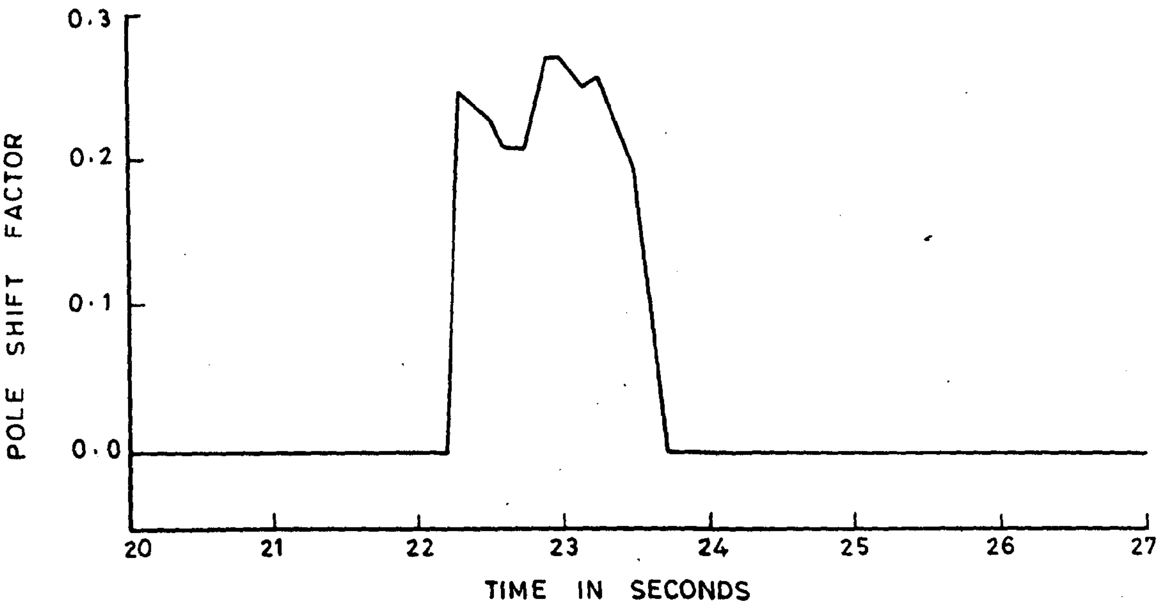



(b) OUTPUT OF DIGITAL CONTROLLER

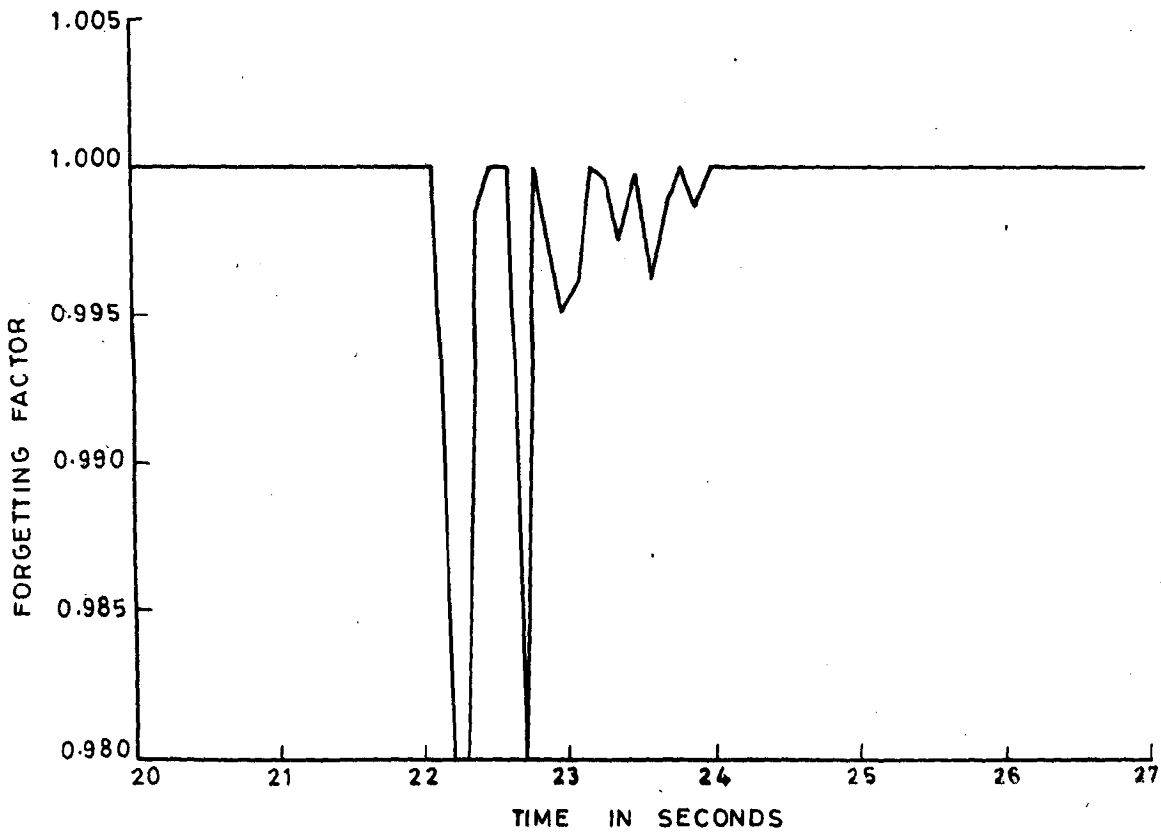



(c) TERMINAL VOLTAGE

FIG. 4·9 (CONTINUED)




(d) POLE SHIFT FACTOR




(e) FORGETTING FACTOR

FIG. 4.9 (CONTINUED)

# CHAPTER - 5

# CONCLUSIONS AND FUTURE WORK

## 5.1 CONCLUSIONS

The problem with the conventional excitation controller is that they are tuned to a fixed operating condition and their control strategy is based upon the deterministic control theory. These cannot provide optimum response when the system operating conditions change.

In the present work, the adaptive control theory is used to design a digital excitation controller. Self-tuning control is one of the most effective and the simplest stochastic control strategies. It has received a lot of interest in many industrial applications in recent years, however its use in power systems is relatively new.

The self-tuning pole-shifting control technique has been used to design a digital excitation controller which performs as an AVR-cum-stabilizer. It tracks the system and computes the control according to the changing operating conditions.

Simulation studies have been performed on a power system to test the proposed controller. The performance of the system is observed for both the dynamic as well as the transient operating conditions. It is concluded that the controller works excellently under the different varying operating conditions.

## 5.2 FUTURE WORK

The application of the self-tuning control technique to power systems is quite new. A lot of research is needed to make the controllers based on this theory suitable for the actual implementation in the field. Thus the field is quite open.

The following are the few recommendations for future work in the field -

1. The proposed controller can be implemented on a micro-machine power system in a laboratory environment and its validity as an efficient controller can be confirmed.

2. Different stabilizing signals can be used to compare the performance of the proposed controller. The stabilizing signals should be either frequency, accelerating power, error in electrical power etc.

3. The proposed controller can be applied to a more practical system such as a multi-machine power system and its performance can be studied.

4. Its behaviour can be studied in power systems which have the sub-synchronous resonance problem.

5. A complete digital machine controller can be designed which can control both the excitation and the governer of the machine.

It is important to do these types of studies in collaboration with industries.

# REFERENCES

1. Adkins and Harley, 'The General Theory of A.C. Machines' John Wiley & Sons, 1975.

2. Anderson and Foud, 'Power System Control and Stability' The Iowa State University Press, Iowa, U.S.A., 1977.

3. Astrom, 'Theory and Application of Adaptive Control—A Survey', Automatica Vol 19, No. 5, 1983, pp 471-486.

4. Astrom and Eykoff, 'System-Identification-A Survey', Automatica Vol 17, 1971, pp 123-162.

5. Astrom and Wittenmark, 'On Self-tuning Regulators', Automatica, Vol 17, 1981, pp 7-21.

6. Astrom, Borison, Ljung, Wittenmark, 'Theory and Applications of Self-tuning Regulator', Automatica Vol 13, 1977, pp 457-476.

7. Astrom and Wittenmark, 'Self-tuning Controllers Based on Pole-zero Placement', Proc. IEE Vol 127, 1980, pp 120-130.

8. Bollinger, Laha, Hamilton, Harras, 'Power Stabilizer Design Using Root Locus Method', IEEE Trans Vol PAS-94, 1975, pp 1484-1488.

9. Bobo, Skooglund, Wagner, 'Performance of Excitation Sytem Under Abnormal Conditions', IEEE Trans Vol PAS-87, No. 2, 1968, pp 547-553.

10. Byerly, Keay, Skooglund, 'Damping of Power Oscillations in Salient-pole Machines with Static Exciters', IEEE Trans Vol PAS-89, No. 6, 1970, pp 1009-1021.

11. Brown, deMello, Lenfest, Mills, 'Effects of Excitation, Turbine Energy Control, and Transmission on Transient Stability', IEEE Trans Vol PAS-89, No. 6, 1970, pp 1247-1252.

12. Bayne, Kundur, Watson, 'Static Excitation Control to Improve Transient Stability', IEEE Trans Vol PAS-94, 1975, pp 1141-1146.

13. Bayne, Lee, Watson, 'A Power System Stabilizer for Thermal Units Based on Deviation of Accelerating Power' IEEE Trans Vol PAS-96, No. 6, 1977, pp 1777-1783.

14. Cheng, Chow, Malik, Hope, 'An Adaptive Synchronous Machine Stabilizer', IEEE Trans Vol PWRS-1 No.3,1986, pp 101-107.

15. Clarke and Gawthrop, 'Implementation and Application of Microprocessor-based Self-tuners', Automatica Vol 17, No. 1, 1981, pp 223-244

16. Clarke and Gawthrop, 'Self-tuning Control', Proc. IEE Vol 122, 1975, pp 929-935.

17. Concordia and deMello, 'Concepts of Synchronous Machine Stability as Affected by Excitation Control ', IEEE Trans, Vol PAS-88, 1969, pp 316-329.

18. Concordia, 'Steady-State Stability of Synchronous Machines as Affected by Voltage Regulator Characteristics', AIEE , Vol 63, 1944, pp 215-220.

19. Czuba, et al, 'Implementation of Power System Stabilizer at the Ludington Pumped Storage Plant', IEEE Trans Vol. PWRS-1, 1986, pp 121-128.

20. deMello, et al, 'A Power System Stabilizer Design Using Digital Control', IEEE Trans Vol PAS-101, 1982, pp 2860-2866.

21. deMello, et al, 'Practical Approaches to Supplementary Stabilizing from Accelerating Power', IEEE Trans Vol PAS-97, No.5, 1978, pp 1515-1522.

22. deMello, Laskowski, 'Concepts of Power System Dynamic Stability', IEEE Trans Vol PAS-94, 1975, pp 827-833.

23. Dandeno, et al, 'Effect of High-speed Rectifier Excitation System on Generator Stability Limits', IEEE Trans Vol PAS-87, No. 1, 1968, pp 190-200.

24. Elgerd, 'Electric Energy Systems Theory', Tata McGraw Hill, 1982.

25. Eykoff, 'Trends and Progress in System Identification', Pergamon Press, Oxford 1981.

26. Eykoff , 'System Identification' Wiley London 1974.

27. Fortesque, Kreshenbaum, Ydstie, 'Implementation of Self-tuning Regulators with Variable Forgetting Factors', Automatica Vol 17, No. 8, 1981 pp 831-835.

28. Gerhart, et al, 'Power System Stabilizer: Field Testing and Digital Simulation', IEEE Trans Vol PAS-90, 1971, pp 2095-2100.

29. Ghosh et al, 'PSS Based on Adaptive Control Techniques', IEEE Trans Vol PAS-103, 1984, pp 1983-1989.

30. Goodwin and Pyne, 'Dynamic System Identification: Experimental Design and Data Analysis', Academic Press, New York, San Francisco, London, 1977.

31. Graupe , Jain, Salahi, 'A Comparative Analysis of Various Least-Squares Identification Algorithms', Automatica, Vol 16, 1980, pp 663-681.

32. Harris and Billings, 'Self-tuning and Adaptive Control', IEE Control Engg Series 15, IEE 1981.

33. Kundur, et al, 'Power System Stabilizers for Thermal Units: Analytical Techniques and On-site Validation', IEEE Trans Vol PAS-100, No. 1, 1981, pp 81-95.

34. Kanniah, Malik, Hope, 'Excitation Control of Synchronous Generators Using Adaptive Regulators', Part 1 & 2, IEEE Trans Vol PAS-103, 1984, pp 897-910.

35. Kimbark, 'Improvement of Power System Stability by Changes in the Network,' IEEE Trans Vol PAS-88, No. 5, 1969, pp 773-781.

36. Larsen and Swann, 'Applying Power System Stabilizer', Part I, II, III, IEEE Trans Vol PAS-100, 1981, pp 3017-3046.

37. Lee, et al 'A PSS Using Speed and Electrical Power Inputs: Design and Field Experience,' IEEE Trans, Vol PAS-100, 1981, pp 4151-4157.

38. Lawson, Swann, Wright, 'Minimization of Power System Stabilizer Torsional Interaction on Large Steam Turbine generator', IEEE Trans Vol PAS-97, No. 1, 1978, pp 183-190.

39. Lezano, 'Independent Tracking and Regulation Adaptive Control with Foregetting Factor', Automatica, Vol 18, 1987, pp 455-459.

40. Mobarak, Thorne, Hill, 'Optimization of Exciter and Stabilizer Parameters of a Large Thermal Generator Station', IEEE Trans Vol PAS-97, No. 4, 1978, pp 1182-1193.

41. Malik, Hope, Huber, 'Design and Test Results of a Software Based Digital AVR', IEEE Trans Vol PAS-95, 1976, pp 634-642.

42. Ogata, 'Modern Control Engg', Prentice Hall, Inc 1970.

43. Schlief, et al, 'Excitation Control to Improve Powerline Stability', IEEE Trans Vol PAS-87, 1968, pp 1426-1434.

44. Schlief, Feelay, et al, 'A PSS Application with Local Mode Cancellation' IEEE Trans Vol PAS-98, 1979. pp 1054-1060

45. Sheriah, Malik et al, 'A Self-tuning Automatic Voltage Regulator', Electric Power System Research, Vol 2, 1979, pp 199-213.

46. Smith, 'Power System Transient Control by Capacitor Switching', IEEE Trans Vol PAS-88, 1969, pp 28-35.

47. Strejc, 'Trends in Identification', Automatica, Vol 17, 1981, pp 7-21.

48. Strejc, 'Least squares Parameter Estimation', Automatica Vol 16, 1980, pp 535-550.

49. Watson, Manchur, 'Experience with Supplementary Damping Signal for Generator Static Excitation Systems', IEEE Trans Vol PAS-92, 1973, pp 199-211.

50. Wellstead, Prager, Zanker, 'Pole-assignment Self-tuning Regulator', Proc. IEE Vol 126, 1979, pp 781-790.

51. Wittenmark, Astrom, 'Practical Issues in the Implementation of Self-tuning Control', Automatica Vol 20, 1984, pp 595-605.

52. Xia, Heydt, 'Self-tuning Controller for Generator Excitation Control', IEEE Trans Vol PAS-102, No. 6, 1983, pp 1877-1885.

53. Ydstie, Sargent, 'Deterministic Convergence of an Adaptive Regulator with Variable Forgetting Factor', IFAC Symposium on Identification and System Parameter Estimation Washington D.C. 1982, pp 259-263.

54. Zarrop, 'Variable Forgetting Factors in Parameter Estimation' Automatica Vol 19, 1983, pp 295-298.

55. Anderson, Moore, 'Linear Optimal Control' Prentice Hall, 1971

56. Malik, Hope, Ramanujam, 'Real Time Model Reference Adaptive Control of Synchronous Machine Excitation' IEEE Power Engg. Society, Winter Meeting New York, 1970, Paper # A70 297-4

# APPENDIX

## Synchronous Machine Parameters in p.u.

| | | |
|---|---|---|
| $r_a = 0.007$ | $l_{md} = 0.00296$ | $l_{mq} = 0.00166$ |
| $r_{kd} = 0.023$ | $l_{kd} = 0.00007$ | $l_{kq} = 0.00007$ |
| $r_f = 0.00089$ | $l_a = 0.00031$ | $l_f = 0.0018$ |
| | | $H = 3.64$ sec |

## Transmission Line Parameters in p.u.

$r_t = 0.024$ $\quad$ $x_t = 0.115$

## AVR and Exciter

$K_A = 200$ $\quad$ $T_A = 0.01$ s

## Governor

$a = -0.001326$; $b = -0.17$ ; $\quad$ $T_g = 0.25$ s

## Conventional Stabilizer

The transfer function of the conventional stabilizer is

$$V(s) = -\frac{K_\delta}{K_A} \cdot \frac{sT_Q}{1+sT_Q} \cdot \frac{1+sT_1}{1+sT_2} \cdot p\,\delta$$

where,

$K_\delta = 0.015$ ; $T_Q = 1.5$ s; $T_1 = 0.3$ s ; $T_2 = 0.06$ s

Stabilizer Output limit = $\pm\, 5/K_A$