A COMPARATIVE STUDY OF CONVENTIONAL, OPTIMAL, SUBOPTIMAL, AND FUZZY LOGIC POWER SYSTEM STABILIZERS FOR MULTIMACHINE SYSTEMS

S.KAMAL SALMAN ALMUSAWI

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By

S.KAMAL SALMAN MOHAMED HUSAIN ALMUSAWI

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CERTIFICATE

I certify that the work presented in the thesis entitled "***A comparative study of conventional, optimal, suboptimal, and fuzzy logic power system stabilizers for multimachine systems***" in partial fulfillment of the requirements for the award of the degree of Master of Science in Electrical Engineering submitted to the Department of Electrical and Electronics Engineering, Bahrain University, Bahrain, is an authentic record of my own work carried out under the supervision of ***Dr. JAWAD TALAQ.***

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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

UNIVERSITY OF BAHRAIN

College of Engineering

Thesis

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

By

Syed Kamal Salman Almusawi

Approved by

External Examiner:

Abu Hamed Abdur-Rahim, Professor

Internal Examiner:

Khaled Zehar, Professor

Supervisor:

Jawad Talaq, Associate Professor

Prof. Nader Al-Bastaki

Dean , College of Engineering

Dr. Sana Al-Mansoori

Chairperson, Electrical & Electronics Eng. Department

Dated: December 27th, 2012

To

MY PARENTS

AND

MY WIFE

(Who offered me unconditional love and support)

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THESIS ABSTRACT

Damping of low frequency power system oscillations have been one of the major concerns in modern power system operation. The low frequency power system oscillations may be local to a single generator (local oscillations), or they may involve a number of generators widely separated geographically (inter-area oscillations). The traditional solution to this problem is the application of power system stabilizer (PSS), which is used to generate supplementary control signals for the excitation system in order to damp the low frequency power system oscillations and to improve the power system dynamics performance.

In this thesis, various types of power system stabilizers (PSS) are designed at the same operating conditions based on different control methodologies. These power system stabilizers are namely, the conventional power system stabilizer (CPSS) utilizes the rotor speed ($\Delta\omega_r$) which is based on the classical control theory. The optimal power system stabilizer (OPSS) utilizes the full states of the machine model, while the sub-optimal power system stabilizer (SOPSS) utilizes partial states of the machine model which are based on the modern control theory. The fuzzy power system stabilizer (FPSS) uses fuzzy logic theory to provide the required control signal.

Detailed analysis has been done to the single machine and multi machine systems for the quadrature and direct currents (I_q and I_d) gains, in addition, the mathematical model according to model 1.1, exciter, and the proposed power system stabilizer are analyzed and the state space representation has been derived in presence of power system stabilizer and without.

The effectiveness of these four different power system stabilizers are compared through the simulation of a single machine system, and multi machine systems when they are subjected to small disturbance of 5% in the mechanical torque. Moreover the comparison of the designed power system stabilizers have been done by considering the speed droop in the modeling of the power system while the same comparison have been done again when the speed droop is neglected. The comparison of the proposed power system stabilizers show that optimal power system stabilizer (OPSS) and the fuzzy power system stabilizer (FPSS) can give adequate performance for damping the low frequency power system oscillations.

TABLE OF CONTENTS

CHAPTER (1) : INTRODUCTION

1.1 Electrical power system 1
1.2 Basic power plant components 2
1.3 Electrical power system control 3
1.4 Motivation and scope of the thesis 4
1.5 Thesis outline 5

CHAPTER (2) : MODELING OF POWER SYSTEMS

2.1 Introduction 6
2.2 Modeling of power system components 9
2.2.1 Synchronous machine model 9
2.2.2 Exciter model 12
2.2.3 Power system stabilizer (PSS) 12
2.2.4 Speed droop model 13
2.3 Power system models for low frequency oscillations studies 14
2.4 State space representation 16

CHAPTER (3) : POWER SYSTEM STABILIZER

3.1 Conventional power system stabilizer 18
3.1.1 State space representation of conventional power system stabilizer 19
3.1.2 Determination of conventional power system stabilizer parameters 22
3.2 State feedback controllers 24
3.2.1 Optimal power system stabilizer 24
3.2.2 Sub-optimal power system stabilizer 26
3.2.3 State space representation of optimal and sub-optimal power system stabilizers 28
3.3 Fuzzy power system stabilizer 33
3.3.1 Introduction to fuzzy set theory 33
3.3.2 Fuzzy logic controller 34
3.3.3 Fuzzy power system stabilizer 36

CHAPTER (4) : Simulation and results

4.1 Single machine system 42
4.1.1 Single machine system models 42
4.1.2 Systems parameters 43
4.1.3 Eigenvalues analysis 43
4.1.4 Computer simulation results of SMIB 44
4.1.4.1 SMIB simulation results - Case-1 44
4.1.4.2 SMIB simulation results - Case-2 49
4.1.4.3 Simulation discussion 54

4.1.5 Computer simulation results of SMIS 55
4.1.5.1 SMIS simulation results -Case-1 55
4.1.5.2 SMIS simulation results -Case-2 58
4.1.5.3 Simulation discussion 61
4.2 Multi-Machine system 64
4.2.1 Multi-machine system models 64
4.2.2 Systems parameters 65
4.2.3 Eigenvalues analysis 65
4.2.4 Computer simulation results of two machine system 66
4.2.4.1 Two machine system simulation results - Case-1 66
4.2.4.2 Two machine system simulation results - Case-2 75
4.2.4.3 Simulation discussion 84
4.2.5 Computer simulation results of two machine system 88
4.2.5.1 Three machine system simulation results - Case-1 88
4.2.5.2 Three machine system simulation results - Case-2 101
4.2.5.3 Simulation discussion 114

CHAPTER (5) : CONCULSION AND RECOMMENDATIONS
5.1 Summary and Conclusion 119
5.2 Recommendations for future research 121
5.3 Thesis contributions 122

REFRENCES 123

APPENDICES
APPENDIX (A) Simplified model of single machine infinite bus 127
APPENDIX (B) I_q and I_d gains analysis for single machine isolated system 139
APPENDIX (C) I_q and I_d gains analysis for multi-machine system 141
APPENDIX (D) Power systems parameters 156
APPENDIX (E) Equations summary 162
APPENDIX (F) Initial conditions results 164
APPENDIX (G) I_q and I_d gains results 167
APPENDIX (H) Eigen-values results 170
APPENDIX (I) A – matrix results 179

LIST OF TABLES

Table		Pages
3.1	Decision rules for the proposed fuzzy power system stabilizer	37
3.2	Membership function for stabilizer inputs	39
4.1	The SMIS eigenvalues (without PSS)	62
4.2	The SMIS eigenvalues (with PSS)	63
4.3	The two machine system eigenvalues (without PSS)	85
4.4	The two machine system eigenvalues (with PSS)	87
4.5	The three machine system eigenvalues (without PSS)	116
4.6	The three machine system eigenvalues (with PSS)	118

LIST OF FIGURES

Figure		Page
1.1	Schematic diagram of an electric power plant	2
2.1	Synchronous generator equivalent circuits with resistance neglected	9
2.2	Configuration of excitation system (exciter)	12
2.3	General structure of conventional power system stabilizer (CPSS)	13
2.4	Angular speed deviation block diagram	14
2.5	System configuration for single machine infinite bus system (SMIB)	14
2.6	System configuration for single machine isolated system (SMIS)	15
2.7	System configuration for multi-machine system	15
3.1	Speed input conventional power system stabilizer (CPSS)	19
3.2	Washout block of conventional power system stabilizer	19
3.3	Equivalent diagram for washout block for CPSS	19
3.4	Phase lead block of conventional power system stabilizer (stage 2)	20
3.5	Equivalent diagram for phase lead block (stage 2)	20
3.6	Phase lead block of conventional power system stabilizer (stage 3)	21
3.7	Equivalent diagram for phase lead block (stage 3)	21
3.8	General structure of optimal power system stabilizer (OPSS)	24
3.9	General structure of sub-optimal power system stabilizer (SOPSS)	26
3.10	General structure of state feedback power system stabilizer	28
3.11	Washout block of state feedback power system stabilizer	28
3.12	Equivalent diagram for washout block	28
3.13	Phase lead block of state feedback power system stabilizer (stage 2)	29
3.14	Equivalent diagram for phase lead block (stage 2)	29
3.15	Phase lead block of state feedback power system stabilizer (stage 3)	30
3.16	Equivalent diagram for phase lead block (stage 3)	30
3.17	General diagram of fuzzy logic controller	35
3.18	Fuzzy power system stabilizer (FPSS) diagram	37
3.19	Membership function shape of $(\Delta\omega_r)$	38
3.20	Membership function shape of $(\Delta\dot{\omega}_r)$	38
3.21	Membership function shape of FPSS output	39
3.22	Graphical illustration of fuzzification and inference phase	41
4.1	Single machine infinite bus (SMIB) model	42
4.2	Single machine isolated system (SMIS) model	42
4.3	Rotor angle deviations after 5% step change in the mechanical torque (T_m) with no speed droop	45
4.4	Rotor angle deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	45
4.5	Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop	46
4.6	Angular speed deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	46
4.7	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) with no speed droop	47

4.8	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	48
4.9	Rotor angle deviations after 5% step change in the mechanical torque (T_m) with no speed droop	50
4.10	Rotor angle deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	50
4.11	Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop	51
4.12	Angular speed deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	51
4.13	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) with no speed droop	52
4.14	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	53
4.15	Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop	56
4.16	Angular speed deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	57
4.17	Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop	59
4.18	Angular speed deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	60
4.19	The system response before and after exciter gain reduction	62
4.20	The system response with CPSS	63
4.21	Two machine system model	64
4.22	Three machine system model	64
4.23	Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) with no speed droop	67
4.24	Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) – including the speed droop of 4%	68
4.25	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop	69
4.26	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	70
4.27	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	71
4.28	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) – including the speed droop	72
4.29	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	73
4.30	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	74

4.31	Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) with no speed droop	76
4.32	Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) – including the speed droop of 4%	77
4.33	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop	78
4.34	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	79
4.35	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	80
4.36	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	81
4.37	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	82
4.38	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	83
4.39	The system response before and after exciter gain reduction	85
4.40	The system response with CPSS	87
4.41	Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) with no speed droop	89
4.42	Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) – including the speed droop of 4%	90
4.43	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop	91
4.44	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	92
4.45	Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) with no speed droop	93
4.46	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	94
4.47	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	95
4.48	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	96
4.49	Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	97
4.50	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	98

4.51	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) with no speed droop	99
4.52	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	100
4.53	Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) with no speed droop	102
4.54	Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) – including the speed droop of 4%	103
4.55	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop	104
4.56	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	105
4.57	Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) with no speed droop	106
4.58	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop	107
4.59	Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	108
4.60	Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	109
4.61	Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	110
4.62	Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	111
4.63	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) with no speed droop	112
4.64	Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) – including the speed droop of 4%	113
4.65	The system response before and after exciter gain reduction	115
4.66	The system response with CPSS	117
A.1	System configuration of single machine infinite bus	127
A.2	The $\Delta\dot{E}_q$ block diagram	134
A.3	The $\Delta\dot{E}_d$ block diagram	135
A.4	The $\Delta\dot{\omega}_r$ block diagram	136
A.5	The $\Delta\dot{\delta}$ block diagram	137
A.6	The $\Delta\dot{V}_t$ block diagram	137
A.7	The $\Delta\dot{E}_{fd}$ block diagram	136
A.8	The block diagram of the simplified model of SMIB	138
B.1	System configuration of single machine isolated system	139
F.1	Phasor diagram	164

LIST OF SYMBOLS

Δ	Change from nominal value
w_b	Base angular speed (rad/sec)
w_r	Rotor angular speed (p.u)
δ	Load angle (rad)
T_e	Electrical torque
T_m	Mechanical torque
V_t	Terminal voltage
V_{ref}	Reference input voltage
u	Control signal
M	Machine inertia constant
D	Damping coefficient
E_{fd}	Excitation field voltage
$\grave{E}_q$	Quadrature (q) axis transient voltage (p.u)
$\grave{E}_d$	Direct (d) axis transient voltage (p.u)
$\grave{T}_{q0}$	Quadrature (q) axis transient open circuit damper time constant (sec)
$\grave{T}_{d0}$	Direct (d) axis transient open circuit field time constant (sec)
K_A	Gain of excitation system
T_A	Time constant of excitation system
V_q	Quadrature (q) axis component of the terminal voltage
V_d	Direct (d) axis component of the terminal voltage
I_q	Quadrature (q) axis component of the armature current
I_d	Direct (d) axis component of the armature current
X_q	Quadrature (q) axis reactance of generator
X_d	Direct (d) axis reactance of generator
$\grave{X}_q$	Quadrature (q) axis transient reactance
$\grave{X}_d$	Direct (d) axis transient reactance
T_w	Washout time constant of power system stabilizer
T_1, T_2, T_3, T_4	Phase compensator time constant of power system stabilizer
D_{pss}	Power system stabilizer gain
I_G	Injected generator current
V_{bus}	Bus voltage
S_G	Apparent power of the generator
K_D	Speed droop gain
$\emptyset_{pss}$	The phase lead of the power system stabilizer
T_{z1}, T_{z2}	The zeros time constant of power system stabilizer
T_{p1}, T_{p2}	The poles time constant of power system stabilizer

ABBREVIATIONS

LFO	Low frequency oscillations
PSS	Power system stabilizer
CPSS	Conventional power system stabilizer
OPSS	Optimal power system stabilizer
SOPSS	Sub-optimal power system stabilizer
FPSS	Fuzzy power system stabilizer
AVR	Automatic voltage regulator
SMIB	Single machine infinite bus
SMIS	Single machine isolated system
SG	Synchronous generator
Y bus	Bus admittance matrix
Yr	Reduced bus admittance matrix
G	Real part of the bus admittance matrix
B	Imaginary part of the bus admittance matrix

CHAPTER 1

INTRODUCTION

1.1 ELETRICAL POWER SYSTEM

Nowadays, electricity is one of the most popular forms of energy that is used in too many sectors such as industrial, domestic, commercial, and transportation sectors, because it can be transported easily at high efficiency and reasonable cost.

The commercial use of electricity began in the late 1870s when the first complete electric power system was built by Thomas Edison – the historic pearl street station in New York City - which was supplying lighting load in the lower Manhattan area. This station was a dc power system consisting of a steam engine - driven dc generator supplying electric power (110 Volts) to 59 customers within an area roughly 1.5 km in radius (Anderson & Fouad, 2003; Kundur, 1993).

Electrical power reaches customer from electric power stations through three stages, these are: generation (in the power station), transmission (through overhead or underground cables), and distribution of electrical power.

The invention of the transformer and induction motor contributed to the huge evolution of the electric power system, with the invention of the transformer (William Stanley, 1885) to raise the level of ac voltage for transmission and distribution and the invention of the induction motor (Nicola Tesla, 1888) to replace the dc motor.

The load, which consisted entirely of incandescent lamps, was supplied at 110V through an underground cable system. Within few years, similar electric power systems were in operation in most large cities throughout the world (Anderson & Fouad, 2003; Bergen, 2000; Kundur, 1993; Saadat, 1999).

At present, electrical power systems are highly interconnected which will expose them to effect by disturbances which may cause unacceptable system operation. Over the past decades, a number of challenging power system control problems have been reported. These problems lead to the development of various control devices to enhance the power system performance based on classical control, modern control, and artificial intelligent based control.

1.2 BASIC POWER PLANT COMPONENTS

The basic components of any electrical power plant are prime mover, alternator, and transformer. The source of the mechanical power, commonly known as prime mover, may be steam turbines whose energy comes from the burning of coal, gas and nuclear fuel, gas turbines, or occasionally internal combustion engines burning oil and hydraulic turbines at waterfalls.

The alternator function is to convert the mechanical power generated by the prime mover to electrical power.

For controlling operation, some components can be added to the electrical power plant such as, governor which is controlling the feeding operation of the fuel, exciter and automatic voltage regulator (AVR) to control the reactive power flow and maintain the generator terminal voltage (Bergen,2000; Chakrabarti & Halder,2008; Machowski, Bialek, & Bumby,2008).

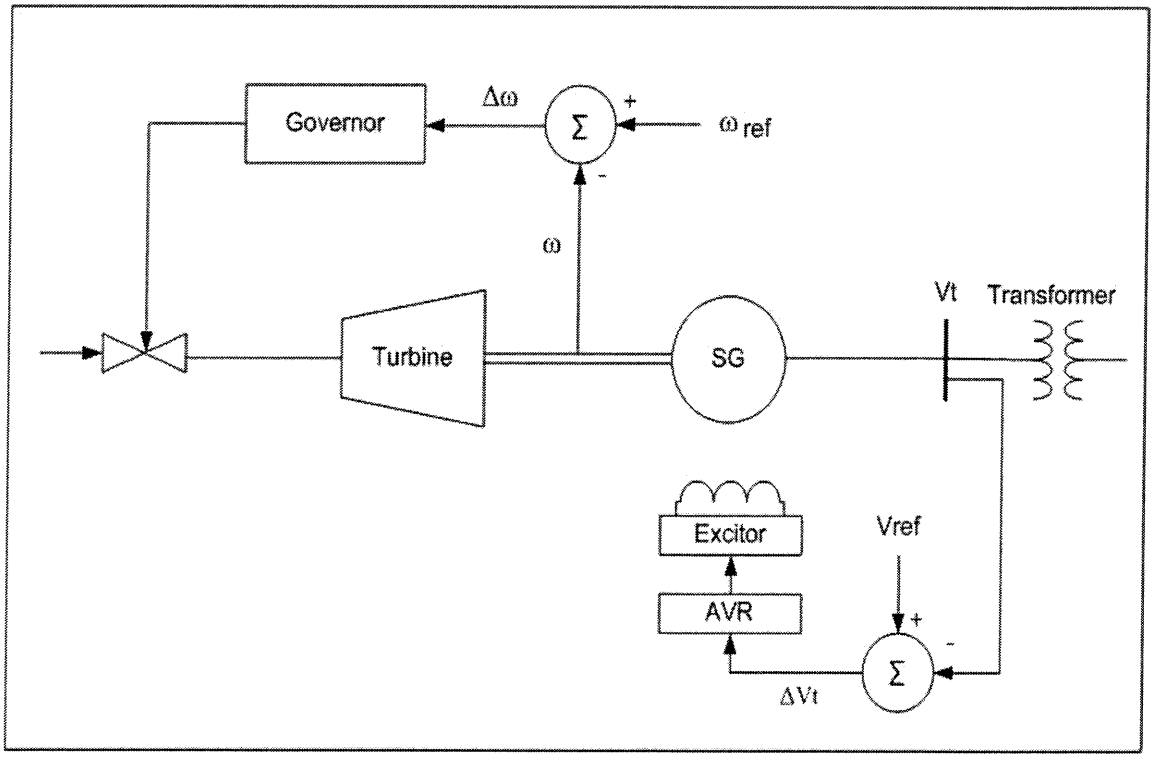


Fig. 1.1 Schematic diagram of an electric power plant

1.3 POWER SYSTEM CONTROL

In power systems, there are several control operations and devices that are used to maintain the constancy of frequency and voltage such as prime mover control and the excitation control.

The prime mover control is concerned with speed regulation and control of energy supply system variables such as boiler pressure, temperature, and flows through the governor control loop that uses the speed deviation signal ($\Delta\omega$) as control signal.

The excitation system control is used to regulate the generator terminal voltage and the reactive power output. The excitation system control loop consists of an exciter and automatic voltage regulator (AVR) with terminal voltage deviation signal (ΔV_t) which is a control signal.

In any control process for power system control problems, there is an analytical solution to the control problem, i.e. there is a mathematical formulation to the control problem under certain assumptions. Based on this result and by using the classical control theory or the modern control theory, several control solutions have been developed (Kundur, 1993; Machowski et al., 2008; Padiyar, 2008).

In recent years, much more uncertainties in power system control problems have been taking place such as the complexity, non-linearity, geographical distribution of power plants, and unexpected events. All these uncertainties make the solution for power system control problems through strict mathematical formulation alone difficult and ineffective. The fuzzy logic control theory and the artificial neural network control theory solve these power system control problems successfully.

1.4 MOTIVATION AND SCOPE OF THE THESIS

This work was motivated by the need to design an effective power system stabilizer based on modern or intelligent control theory to provide an adequate performance to solve one of power system control problems which is the low frequency power system oscillations (LOF) that are initiated by disturbances that occur in power systems. Moreover the requirement of power system stabilizer becomes more urgent than before, and many of generators are equipped with power system stabilizers. In addition, the need for alternative control schemes that do not require model identification, require less computational efforts and easier to be implemented causing to spend more and more time on research in this area.

The focus of this thesis is the application of power system stabilizers (PSS) based on different control methodologies for damping the low frequency oscillations which have been considered as one of the major concerns in power system control and to improve overall system dynamics performance and stability. Four power system stabilizers are proposed for investigations in this thesis. The conventional power system stabilizer (CPSS) is based on the classical control theory. The optimal power system stabilizer (OPSS) and the sub-optimal power system stabilizer (SOPSS) are based on the modern control theory. The fuzzy power system stabilizer (FPSS) is based on the fuzzy logic control theory.

The quadrature and direct currents ($I_q$and I_d) gains for the synchronous machine have been derived according to case (1) and case (2) based on model 1.1. The exciter, and the proposed power system stabilizer are analyzed and the state space representation has been derived.

The effectiveness of the proposed power system stabilizers are compared through the simulation of a single machine system, and multi machines system when they are subjected to small disturbance of 5% change in the mechanical torque. Moreover the comparison of the designed power system stabilizers have been done by considering the speed droop in the modeling of the power system while the same comparison have been done again when the speed droop is neglected.

1.5 THESIS OUTLINE

The thesis outline is divided mainly into five chapters, and each chapter can be described as follows:

(1) Chapter (1): In this chapter, general overviews on the electrical power system, electrical power system components, and the control methods of electrical power system.

(2) Chapter (2): The focus in this chapter is on the problem of electrical power system stability (low frequency oscillations), and then the four power system models are presented including the model of each of the electrical power system components such as synchronous machine, exciter, the power system stabilizer, and the speed droop.

(3) Chapter (3): In this chapter, all proposed power system stabilizers are introduced. The full mathematical model for conventional power system stabilizer, state feedback power system stabilizers (optimal and sub-optimal power system stabilizers) are presented. Also an overview of fuzzy logic theory and the proposed fuzzy power system stabilizer are introduced.

(4) Chapter (4): This chapter includes the simulation results of all the proposed electrical power system models of this thesis.

(5) Chapter (5): Finally the conclusion and the recommendations are presented in this chapter.

CHAPTER 2

MODELLING OF POWER SYSTEMS

2.1 INTRODUCTION

Power systems, in their early days, were simple and relatively local. That is, power was generated beside the load center and, hence, exportation and importation of power through long transmission lines were rare. Nowadays, power demand has grown rapidly and therefore the need for more complex and interconnected power systems has arisen. With the advent of interconnection of large and distantly located power systems, they are subject to many different types of disturbances, which give many new problems to emerge such as low frequency oscillations (LFO).

The change in the torque of synchronous machine following a disturbance can be resolved by a damping torque component in phase with speed deviation, the lack of damping torque results in low frequency oscillations. These low frequency oscillations if not well damped may keep growing in magnitude until loss of synchronism results.

Low frequency oscillations are generator rotor angle oscillations having a frequency between 0.1 -2.0 Hz. The root cause of electrical power oscillations are the unbalance between power demand and available power at a period of time. In the earliest era of power system development, the power oscillations are almost non observable because generators are closely connected to loads, but nowadays, large demand of power to the farthest end of the system that forces to transmit huge power through a long transmission line, which results an increasing power oscillations.

The LFO can be classified as local and inter-area modes:

1) Local modes are associated with the swinging of units at a generating station with respect to the rest of the power system. Oscillations occurred only to the small part of the power system. Typically, the frequency range is 1-2 Hz.

2) Inter area modes are associated with swinging of many machines in one part of the system against machines in other parts. It generally occurs in weak interconnected power systems through long tie lines. Typical frequency range is 0.1-1 Hz.

In the recent years many efforts have been dedicated to damp these low frequency oscillations. Addition of positive damping is required which can be provided by supplementary excitation control. In the late 1950's and early 1960's most of power systems used automatic voltage regulators (AVR) to provide useful damping to the power system to maintain the overall stability of the power system. Although ordinarily the inherent positive damping predominates, in some circumstances the net damping can become negative. With net negative damping, low frequency oscillations of the machine, instead of declining, increases either until equilibrium amplitude reached or synchronism is lost.

The mitigation of these low frequency oscillations is commonly performed with 'supplementary stabilizing signals' and the networks used to generate these signals have come to be known as 'Power system stabilizer' networks. Since the 1960's, power system stabilizers have been used to add damping to the low frequency oscillations. They act through the generator's excitation system to generate a component of electrical torque proportional to speed change.

Nowadays power system stabilizer (PSS) is one of the most important controllers in modern power systems for damping low frequency oscillations with several kinds of supplementary signals (speed deviations, frequency deviations, power deviations, and accelerating power deviations) have been used as input signals to the power system stabilizers.

Extensive researches have been carried out on the applications of power system stabilizers in power systems, which can be summarized as follows:

In 1969, de Mello and Concordia (Demello & Concordia,1969) introduced an extensive analysis of the phenomenon of synchronous machine stability under small signal disturbance; their work founded the requirement of supplementary stabilizing action based on the concept of damping torques.

Larsen and Swann (Larsen & Swann,1981) discussed the general concepts associated with power system stabilizers, the concepts of applying and tuning power system stabilizers utilizing speed, frequency, and power input signals have been described.

In 1989, Kundur and others (Kundur, Klien, Rogers, & Zywno,1989) presented a detailed analytical work to determine the parameters of the phase – lead power system stabilizers. They concluded that by proper tuning, the fixed parameters power system stabilizer can satisfy the requirements for wide range of system conditions.

Two year later, Klein and others (Klein, Rogers, & Kundur,1991) investigated the effect of power system stabilizers on inter area and local modes of low frequency oscillations in interconnected power systems. Recently, Kundur (Kundur,1999) examined the choice of input signals of power system stabilizers.

Traditionally, the conventional power system stabilizer (CPSS) was mostly used to obtain damping to the system using ($\Delta\omega_r$) as a stabilizing signal (Abdel Magid, Abido, & Mantawy,2000; Demello & Concordia,1969; Kundur et al.,1989; Rogers,2000). The conventional power system stabilizer (CPSS) will enhance the performance and the stability of the system. Optimal control theory has been utilized for the design of optimal power system stabilizers (Lewis & Syrmos,1995; Mahabuba & Khan,2008; Huang & Hsu,1990 ; Huang, Hwang, & Yang,1991) to obtain optimal performance.

In the optimal power system stabilizer (OPSS), all state variables of the system are used as input signals to the power system stabilizer, whereas in the sub optimal power system stabilizer (SOPSS), the state variables ($\Delta\omega_r, \Delta E_{fd}$ and ΔPss) of the system are used as input signals to the power system stabilizer. Recently, an alternative control scheme that does not require model identification, and require less computational efforts than the self-tuning controllers such as fuzzy logic based power system stabilizers (Altas & Sharaf,2007; Corcua & Stoenescu,2007; Ganesh,2006; Gupta & Jain,2010; Hoang & Tomsovic,1996; Hsu & Cheng,1990; HusseinZadeh & Kalam,1999; Jantzen,1998; Lakshmi & Khan,1998; Lee,1990; Lee, Lin, & Chuang,2002; Metwally & Malik,1994; Petriu,2009; Prasertwong & Mithulananthan,2009; Ross,2010; Sambariya, Gupta, & Sharma,2009; Sivanandam, Sumathi, & Deepa,2007).

Most of previous studies in this field concentrated on the behavior of the conventional power system stabilizer (CPSS) in providing damping to the power system. In most of these studies the power system considered is a single machine infinite bus (SMIB) or multi-machine system with classical model for the synchronous machine (model 1.0).

In this thesis, the design and effectiveness of the following power system stabilizers have been carried out for different types of power system models (single machine and multi-machines).

(1) Conventional Power System Stabilizer (CPSS).
(2) Optimal Power System Stabilizer (OPSS).
(3) Sub-Optimal Power System Stabilizer (SOPSS).
(4) Fuzzy Power System Stabilizer (FPSS).

2.2 MODELING OF POWER SYSTEM COMPONENTS

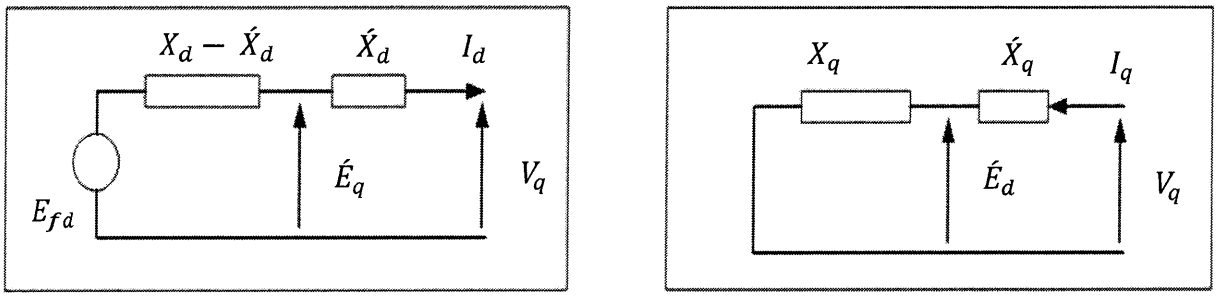
The power system model for low frequency oscillation studies consists of the synchronous machine model, the excitation system (exciter) model, and the power system stabilizer (PSS) model (Anderson, 2011; Demiroren & zeynelgil,2002; Mon & Aung,2008; Panda & Padhy,2007; Patel, Bhatti, & Kothari,2002; Sadikovic,2003; Sauer & Pai,2003).

2.2.1 Synchronous machine model

Depending on the degree of detail used, the synchronous machine can be modeled by several models using either its transient or sub-transient emfs acting behind appropriate reactances. To analyze the synchronous machine, several assumptions can be used. The assumption is the synchronous machine to be studied is represented by model 1.1, noted that in the classification of the machine models, the first number indicates the number of windings on the d – axis while the second number indicates the number of windings on the q - axis. The second assumption is the armature resistance (R_a) is equal to zero.

- **Synchronous machine mathematical model**

Mathematical model of a synchronous machine varies from the classical model to the detailed model depending on the degree of detail used. Moreover, the synchronous machine can be expressed by the fourth order model (δ, ω_r, $\acute{E}_q$, and$\acute{E}_d$), in this model the generator is represented by the transient emfs $\acute{E}_q$ and $\acute{E}_d$ behind the transient reactances $\acute{X}_q$ and $\acute{X}_d$ as shown in the figures below.



(a) d- axis equivalent circuit (b) q- axis equivalent circuit

Fig.2.1 Synchronous generator equivalent circuits with resistances neglected

The modified armature voltage equations can be expressed as follows:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \acute{E}_d \\ \acute{E}_q \end{bmatrix} - \begin{bmatrix} 0 & -\acute{X}_q \\ \acute{X}_d & 0 \end{bmatrix} \cdot \begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad (2.1)$$

In this thesis the investigations of the proposed power system stabilizers performance are mainly done based on two main assumptions for modeling the synchronous machine (Kundur,1993), these are:

- The first assumption made is that the per unit value of the angular rotor speed of the synchronous machine (ω_r) is equal to 1.0 (i.e. $\omega_r = \omega_s\, rad/s$) in the stator voltage equations. This is not the same as saying that the angular speed is constant, it assumes that the angular speed changes are small and do not have a significant effect on the stator voltages. The results based on this assumption are called Case (1).

- The second assumption made is that the per unit value of the angular rotor speed of the synchronous machine (ω_r) is not equal to 1.0 (i.e. $\omega_r \neq \omega_s\, rad/s$) in the stator voltage equations. It assumes that the angular speed changes have a significant effect on the stator voltages. The results based on this assumption are called Case (2).

Based on the above assumptions the Synchronous machine model is described by the following four differential equations (state equations) and three boundary equations as follows (Anderson, 2011; Demiroren & zeynelgil,2002; Mon & Aung,2008; Panda & Padhy,2007; Patel, Bhatti, & Kothari,2002; Sadikovic,2003; Sauer & Pai,2003):

- **State space representation for synchronous machine**

$$\dot{\delta} = \omega_b.(\omega_r - 1) \tag{2.2}$$

$$M.\dot{\omega}_r = T_m - T_e - D.\omega_r - K_D.\omega_r \tag{2.3}$$

$$\dot{T}_{d0}.\dot{E}_q^{`} = -\dot{E}_q - (X_d - \dot{X}_d).I_d + E_{fd} \tag{2.4}$$

$$\dot{T}_{q0}.\dot{E}_d^{`} = -\dot{E}_d + (X_q - \dot{X}_q).I_q \tag{2.5}$$

where

$\dot{E}_q^{`}$: represent the derivation of voltage behind q-axis transient reactance.

$\dot{E}_d^{`}$: represent the derivation of voltage behind d-axis transient reactance.

D: represent the damping coefficient.

K_D: represent the speed droop.

- **Boundary equations for synchronous machine**

Start with

$$V_q = \psi_d . \omega_r \tag{2.6}$$
$$V_q = \left(-X_d . I_d + X_{md} . I_{fd}\right) . \omega_r \tag{2.7}$$
$$V_q = \left(-X_d . I_d + E_{fd}\right) . \omega_r \tag{2.8}$$

From Equation (2.4) at steady state

$$0 = -\grave{E}_q - \left(X_d - \grave{X}_d\right) . I_d + E_{fd} \tag{2.9}$$
$$\grave{E}_q - \grave{X}_d I_d = -X_d I_d + E_{fd} \tag{2.10}$$

Substituting Equation (2.10) into Equation (2.8)

$$V_q = \left(\grave{E}_q - \grave{X}_d . I_d\right) . \omega_r = \grave{E}_q . \omega_r - \grave{X}_d . I_d . \omega_r \tag{2.11}$$

Start with

$$V_d = -\psi_q . \omega_r \tag{2.12}$$
$$V_d = -\left(-X_q . I_q\right) . \omega_r = \left(X_q . I_q\right) . \omega_r \tag{2.13}$$
$$V_d = \left(X_q . I_q\right) . \omega_r \tag{2.14}$$

From Equation (2.5) at steady state

$$0 = -\grave{E}_d + \left(X_d - \grave{X}_q\right) . I_q \tag{2.15}$$
$$\grave{E}_d - \grave{X}_q I_q = X_q I_q \tag{2.16}$$

Substituting Equation (2.16) into Equation (2.14)

$$V_d = \left(\grave{E}_d + \grave{X}_q . I_q\right) . \omega_r = \grave{E}_d . \omega_r + \grave{X}_q . I_q . \omega_r \tag{2.17}$$

Start with

$$P_e = V_q I_q + V_d I_d \tag{2.18}$$
$$P_e = \left(\left(\grave{E}_q - \grave{X}_d . I_d\right) . \omega_r\right) I_q + \left(\left(\grave{E}_d + \grave{X}_q . I_q\right) . \omega_r\right) I_d \tag{2.19}$$
$$P_e = \left(\grave{E}_q I_q + \grave{E}_d I_d - \left(\grave{X}_d - \grave{X}_q\right) I_q I_d\right) \omega_r \tag{2.20}$$
$$T_e = \left(\frac{1}{\omega_r}\right) P_e = \grave{E}_q I_q + \grave{E}_d I_d - \left(\grave{X}_d - \grave{X}_q\right) I_d I_q \tag{2.21}$$

2.2.2 Exciter Model

The basic function of an excitation system is to provide direct current to the synchronous machine field winding which will contribute in regulating the terminal voltage (V_t) and the reactive power output. The excitation system (exciter) model can be represented by a single time constant system as shown below:

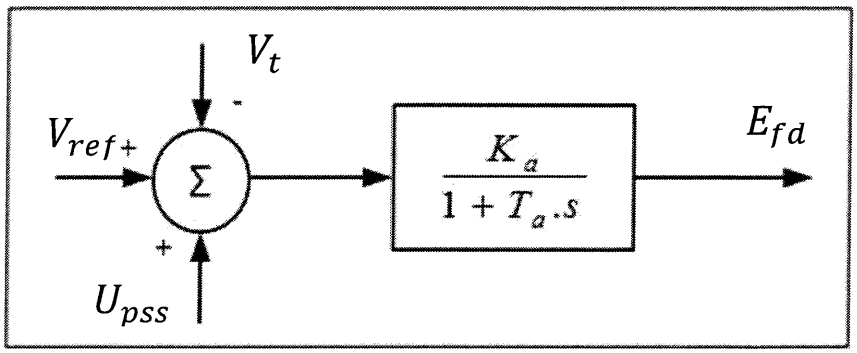


Fig. 2.2 Configuration of excitation system (exciter)

The exciter model can be represented mathematically by one state equation as shown below:

$$\dot{E}_{fd} = \left[\frac{K_a}{T_a}\right](V_{ref} + U_{pss} - V_t) - \left[\frac{1}{T_a}\right].E_{fd} \qquad (2.22)$$

2.2.3 Power system stabilizer model (PSS)

The main function of a power system stabilizer (PSS) is to introduce a component of electrical torque in the synchronous machine rotor that is proportional to the deviation of the actual speed from synchronous speed. When the rotor oscillates, power system stabilizer will damp these oscillations.

- **Structure of power system stabilizer**

The most commonly used structure of a power system stabilizer (PSS) is shown in Figure 2.3. This comprises a gain, a washout filter, and phase compensation blocks.

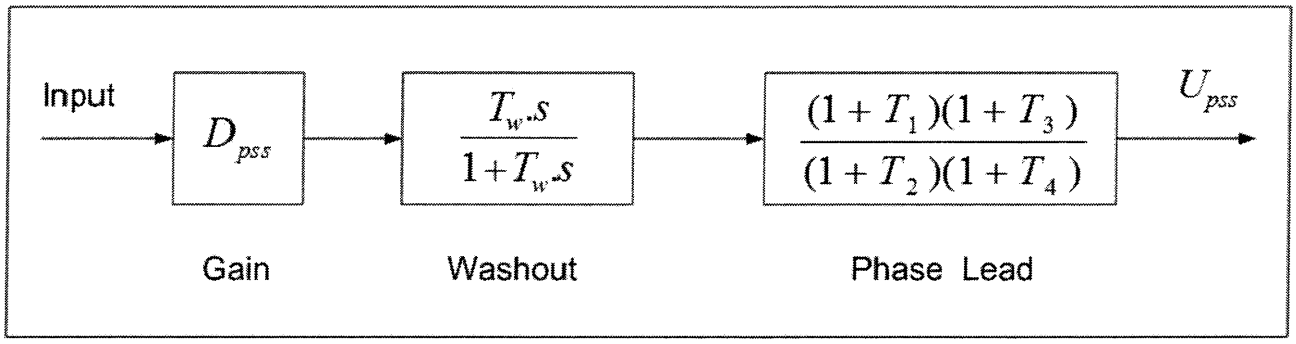


Fig.2.3 General structure of a conventional power system stabilizer (CPSS)

Gain block: the power system stabilizer gain determines the amount of damping introduced in the power system stabilizer (PSS).

Signal washout block: this block serves as high pass filter, with the time constant (T_W) high enough to allow signal associated with oscillations in ω_r to pass unchanged.

Phase compensation block: this block provides the appropriate phase – lead to compensate for the phase lag between the exciter input and the machine torque. In practice, two or more first order blocks may be used to achieve the desired phase compensation.

For the input to the power system stabilizer (PSS), three signals are widely used for the design of power system stabilizer (PSS); these signals are rotor speed deviation, frequency deviation, and the accelerating power deviation. In most of power system stabilizers (PSS) design, the rotor speed deviation is used as feedback signal to the power system stabilizer (PSS).

2.2.4 Speed droop model

Speed droop is a governor function which is a decrease in speed or frequency, proportional to the load. That is, as the load increase, the speed or frequency decreases (droops) to provide stable operation. Speed droop is expressed as the percentage reduction in speed versus the speed set point that occurs when the generator is fully loaded versus the speed that occurs when the generator is unloaded. The speed droop percentage is the range of 3% to 5% of the reference speed.

In this thesis, the speed droop effect can take place through negative feeding back the angular speed deviation ($\Delta\omega_r$) to the speed loop as shown in figure 2.4.

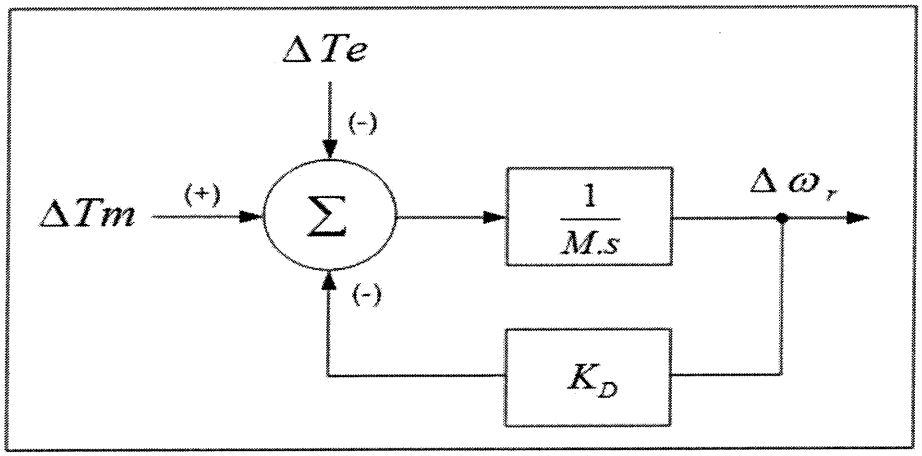


Fig.2.4 Angular speed deviation block diagram

2.3 POWER SYSTEM MODELS FOR LOW FREQUENCY OSCILLATIONS STUDIES

In this thesis, to achieve the research objective, three models of power system are used, these are as shown below:

1) Single machine infinite bus model (SMIB): this power system model consists of a single machine (synchronous generator) including an excitation system (exciter) connected to an infinite bus through transmission line (link) and supply a load or admittance (y) at its terminal as shown in Figure 2.5.

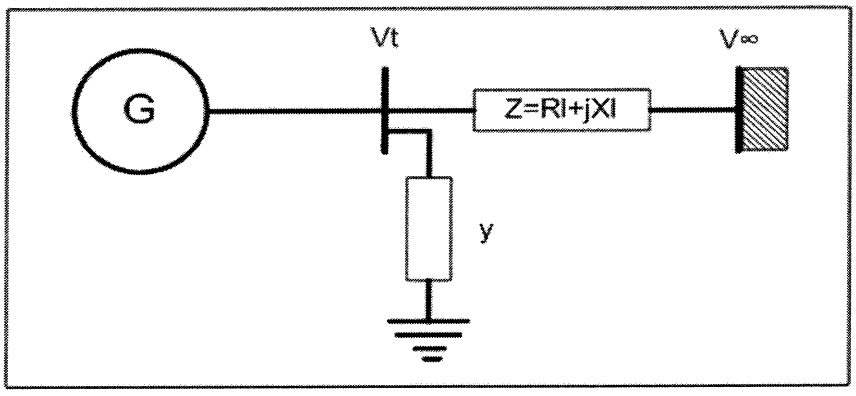


Fig.2.5 System configuration for single machine infinite bus system (SMIB)

2) Single machine isolated system model (SMIS): this power system model consists of a single machine (synchronous generator) including an excitation system (exciter) connected to a load as shown in Figure 2.6.

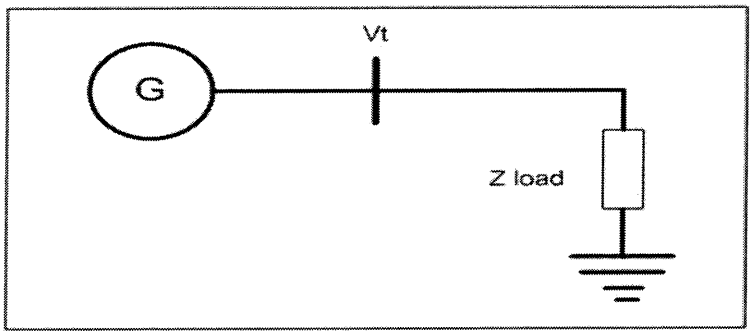


Fig. 2.6 System configuration for single machine isolated system (SMIS)

3) Multi-machine model: the multi-machine systems consist of synchronous generators including an excitation system (exciter) in each machine; these machines are supplying several loads through transmission lines (links). The general multi-machine model is shown in Figure 2.7.

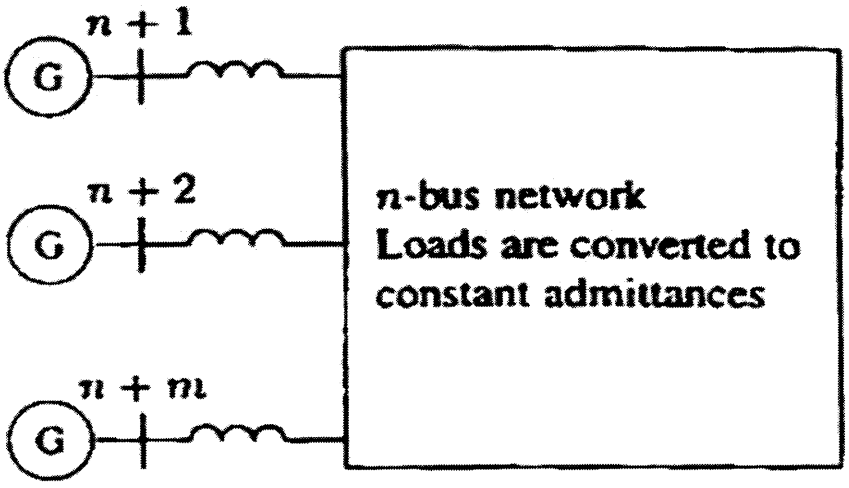


Fig.2.7 General model for multi-machines system

2.4 STATE SPACE REPRESENTATION

The single machine infinite bus system (SMIB) and the single machine isolated system (SMIS) can be represented by state space equations as follows:

$$\dot{x}\,(t) = A\,x(t) + B\,u(t) \tag{2.23}$$

$$y\,(t) = C\,x\,(t) + D\,u\,(t) \tag{2.24}$$

$$x\,(t) = [\Delta\delta\,;\ \Delta\omega_r; \Delta\grave{E}_q; \Delta\grave{E}_d] \quad -for\ SMIB \tag{2.25}$$

$$x\,(t) = [\,\Delta\omega_r; \Delta\grave{E}_q; \Delta\grave{E}_d] \quad -for\ SMIS \tag{2.26}$$

$$x\,(0) = x^0 \tag{2.27}$$

$$u\,(t) = [\Delta E_{fd}; \Delta T_m] \tag{2.28}$$

If a power system stabilizer (PSS) is included in the system, the state vector and the disturbance vector will be as shown below:

$$x\,(t) = [\Delta\delta\,;\ \Delta\omega_r; \Delta\grave{E}_q; \Delta\grave{E}_d; \Delta E_{fd}; \Delta X_6; \Delta X_7; \Delta X_8] \quad -for\ SMIB \tag{2.29}$$

$$x\,(t) = [\,\Delta\omega_r; \Delta\grave{E}_q; \Delta\grave{E}_d; \Delta E_{fd}; \Delta X_6; \Delta X_7; \Delta X_8] \quad -for\ SMIS \tag{2.30}$$

$$u\,(t) = [\Delta V_{ref}; \Delta T_m] \tag{2.31}$$

The multi machine system can be represented by state space equations as follows:

$$\dot{x}\,(t) = A\,x(t) + B\,u(t) \tag{2.32}$$

$$y\,(t) = C\,x\,(t) + D\,u\,(t) \tag{2.33}$$

$$x_k\,(t) = [\Delta\delta_k\,;\ \Delta\omega_{rk}; \Delta\grave{E}_{qk}; \Delta\grave{E}_{dk}] \quad k = 1 \rightarrow NG \tag{2.34}$$

$$x\,(t) = [x_1; x_2; x_3\ \cdots\cdots\ x_{NG}] \tag{2.35}$$

$$x\,(0) = x^0 \tag{2.36}$$

$$u\,(t) = [\Delta E_{fdk}; \Delta T_{mk}] \quad k = 1 \rightarrow NG \tag{2.37}$$

If a power system stabilizer (PSS) is included in the system, the state vector and the disturbance vector will be as shown below:

$$x_k\,(t) = \left[\Delta\delta_k\ ;\ \Delta\omega_{rk}; \Delta\grave{E}_{qk}; \Delta\grave{E}_{dk}; \Delta E_{fdk}; \Delta X_{6k}; \Delta X_{7k}; \Delta X_{8k}\right] \quad k = 1 \rightarrow NG \quad (2.38)$$

$$u\,(t) = \left[\Delta V_{refk}; \Delta T_{mk}\right] \qquad k = 1 \rightarrow NG \quad (2.39)$$

where

$x\,(t) \rightarrow$ *is the state vector*
$u(t) \rightarrow$ *is the disturbance vector*
$y\,(t) \rightarrow$ *is the output vector*
$A, B, C, D \rightarrow$ *are constant matrices*
$x^0 \rightarrow$ *is the initial condition vector*
$NG \rightarrow$ *is the total number of machines*

- The simplified model of single machine infinite bus (SMIB) for small signal analysis is shown in details in appendix [A].
- The full detail of I_q and I_d current gains analysis for single machine isolated system is shown in appendix [B].
- The full detail of I_q and I_d current gains analysis for multi-machine system is shown in appendix [C].

CHAPTER 3

POWER SYSTEM STABILIZER

3.1 CONVENTIONAL POWER SYSTEM STABILIZER

As mentioned previously, in the late 1950's and early 1960's most of the new generating machines added to electric power system were equipped with automatic voltage regulator (AVR) to damp the low frequency oscillations. In the large power systems, it became apparent that the automatic voltage regulator (AVR) action has an impact upon stability (Chakrabarti & Halder,2008).

Later, power system stabilizers (PSS) were developed to aid in damping these low frequency oscillations via modulations of excitation system of generators. The action of a PSS is to extend the angular stability limits of a power system by providing supplemental damping to the low frequency oscillations of synchronous machine rotors through the generator excitation. To provide damping, these stabilizers must produce a component of electrical torque on the rotor which is in phase with speed variations. This supplementary control is very useful during disturbances such as line outages (Lakshmi & Khan,1998; Prasertwong & Mithulananthan,2009).

The conventional power system stabilizer (CPSS) design is based on the concept of the classical control theory. This stabilizer provide suitable supplementary control signal derived from the power, speed and frequency of the operating generator either alone or in various combinations as input signals so as to generate an additional rotor torque to damp out the low frequency oscillations. The gain and the required phase lead/lag of the stabilizers are tuned by using appropriate mathematical models. The principle of operation of this stabilizer is based on the concepts of damping and synchronizing torques within the generator (Hooshmand & Ataei,2009; Kodsi & Canizares,2003; Murdoch, Venkataraman, & Lawson,1999; Panda & Padhy,2007).

The structure of the conventional power system stabilizer (CPSS) consists of three main blocks: a gain block (used to determine the amount of damping introduced by the power system stabilizer), a signal washout block (used to prevent any steady change in speed, frequency, and power affecting the field voltage because of the power system stabilizer action), and a phase compensation block (used to provide the required phase lead of the power system stabilizer) (Kundur,1993).

3.1.1 STATE SPACE REPRESENTATION OF CONVENTIONAL POWER SYSTEM STABILIZER

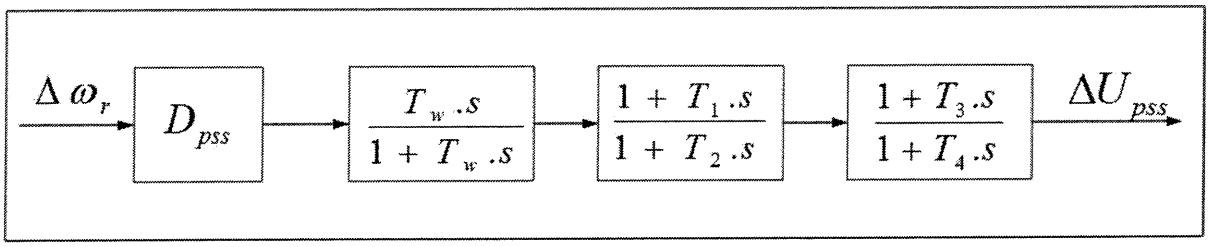


Fig. 3.1 Speed input conventional power system stabilizer (CPSS)

Stage (1): gain and washout block

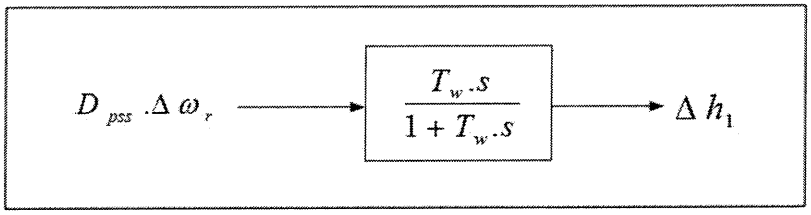


Fig. 3.2 Washout block of conventional power system stabilizer

The washout block can be represented as follows:

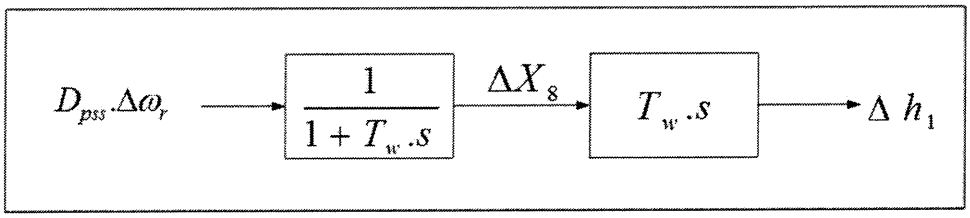


Fig. 3.3 Equivalent diagram for washout block for CPSS

From the previous block diagram, the state equation for state variable $(\Delta\dot{X}_8)$ can be derived as follows:

$$\Delta\dot{X}_8 = \frac{1}{T_w}\left(D_{pss}.\Delta\omega_r\right) - \frac{1}{T_w}.\Delta X_8 \qquad (3.1)$$

The equation of (Δh_1) can be derived as follows

$$\Delta h_1 = T_w.\Delta\dot{X}_8 \qquad (3.2)$$

Substitute Equation (3.1) into Equation (3.2)

$$\Delta h_1 = D_{pss}.\Delta\omega_r - \Delta X_8 \tag{3.3}$$

Stage (2): phase lead block (stage-1)

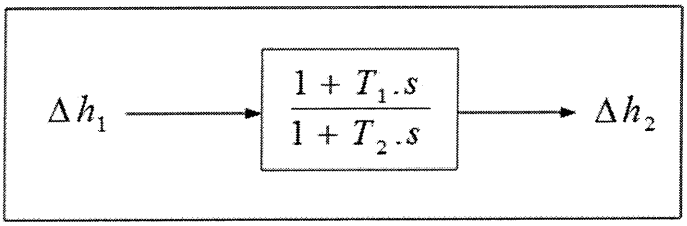


Fig. 3.4 Phase lead block of conventional power system stabilizer (stage-1)

The first stage of the phase lead block can be represented as follows:

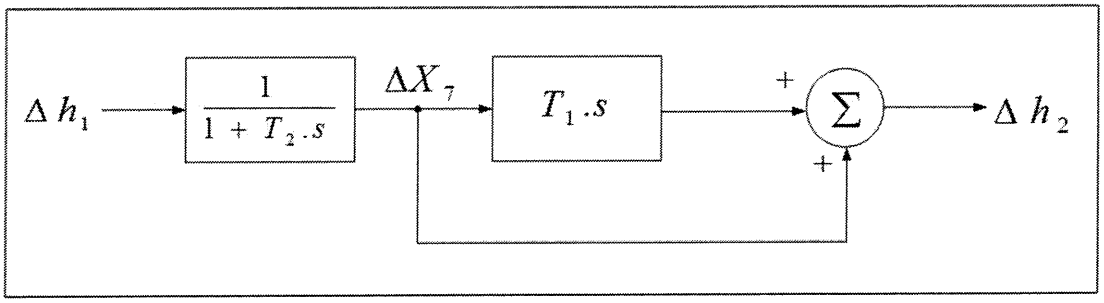


Fig. 3.5 Equivalent diagram for phase lead block (stage 1)

From the previous block diagram, the state equation for the state variable $(\Delta\dot{X}_7)$ can be derived as follows:

$$\Delta\dot{X}_7 = \left(\frac{D_{pss}}{T_2}\right)\Delta\omega_r - \left(\frac{1}{T_2}\right)\Delta X_7 - \left(\frac{1}{T_2}\right)\Delta X_8 \tag{3.4}$$

The equation of (Δh_2) can be derived as follows:

$$\Delta h_2 = T_1.\Delta\dot{X}_7 + \Delta X_7 \tag{3.5}$$

Substituting Equation (3.4) into Equation (3.5):

$$\Delta h_2 = \left(\frac{D_{pss}.T_1}{T_2}\right)\Delta\omega_r + \left(1 - \frac{T_1}{T_2}\right)\Delta X_7 - \left(\frac{T_1}{T_2}\right)\Delta X_8 \tag{3.6}$$

Stage (3): phase lead block (stage-2)

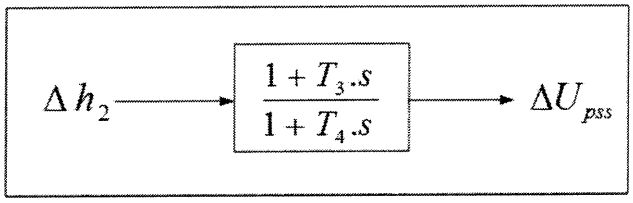


Fig. 3.6 Phase lead block of conventional power system stabilizer (stage-2)

The second stage of the phase lead block can be represented as follows:

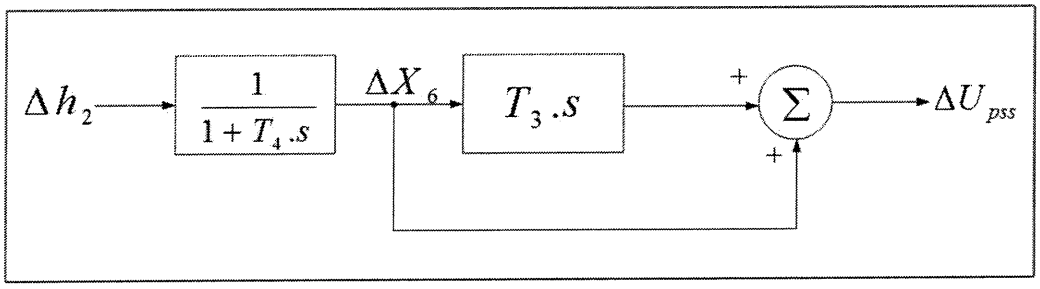


Fig. 3.7 Equivalent diagram for phase lead block (stage-2)

From the previous block diagram, the state equation for the state variable $(\Delta\dot{X}_6)$ can be derived as follows:

$$\Delta\dot{X}_6 = \left(\frac{D_{pss}.T_1}{T_2.T_4}\right)\Delta\omega_r - \left(\frac{1}{T_4}\right)\Delta X_6 + \left(\frac{1}{T_4} - \frac{T_1}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1}{T_2.T_4}\right)\Delta X_8 \qquad (3.7)$$

The equation of (ΔU_{pss}) can be derived as follows:

$$\Delta U_{pss} = T_3.\Delta\dot{X}_6 + \Delta X_6 \qquad (3.8)$$

Substituting Equation (3.7) into Equation (3.8):

$$\Delta U_{pss} = \left[\left(\frac{D_{pss}.T_1.T_3}{T_2.T_4}\right)\Delta\omega_r + \left(1 - \frac{T_3}{T_4}\right)\Delta X_6 + \left(\frac{T_3}{T_4} - \frac{T_1.T_3}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1.T_3}{T_2.T_4}\right)\Delta X_8\right] \qquad (3.9)$$

3.1.2 DETERMINATION OF POWER SYSTEM STABILIZER PARAMETERS

The power system stabilizer provides phase lead compensation, so first the phase lag contributed by the exciter and the open circuit d-axis transient time constant ($\grave{T}_{do}$) should be determined. From appendix [A], the transfer function between ΔV_{ref} and $\Delta \grave{E}_q$ is determined as follows (Sauer & Pai,2003):

$$G_E = \frac{K_2 \, . K_a}{(1 + s.\grave{T}_{do}.K_2)(1 + s.T_a) + K_2 K_{12} K_a} \tag{3.10}$$

Step (1): by neglecting the damping due to all other sources, find the undamped natural frequency (ω_n) in rad/sec of the torque angle loop as follows:

$$\left(\frac{M}{\omega_s}\right).\Delta\dot{\omega}_r = -\Delta T_e = -K_7 \Delta\delta \tag{3.11}$$

$$\omega_n = \sqrt{\frac{K_7 \omega_s}{M}} \tag{3.12}$$

Step (2): find the phase lag of G_E at $s = j\omega_n$

$$Phase\ lag = \angle G_E = \theta_E \tag{3.13}$$

Step (3): the phase lead of the power system stabilizer is:

$$\emptyset_{pss} = -\theta_E \tag{3.14}$$

Step (4): determine the damping gain (D_{Pss}), Let the damping introduced by the power system stabilizer at $s = j\omega_n$ be D_E.

$$D_E = K_9 D_{Pss}.|G_C|.|G_E| \tag{3.15}$$

Where

$$G_C = \left(\frac{T_w s}{1 + T_w s}\right)\left(\frac{1 + T_{z1} s}{1 + T_{p1} s}\right)\left(\frac{1 + T_{z2} s}{1 + T_{p2} s}\right) \tag{3.16}$$

Now the mechanical mode is:

$$\left(\frac{M}{\omega_s}\right).\Delta\dot{\omega}_r = -K_7\Delta\delta - \left(\frac{D_E}{\omega_s}\right)\Delta\omega_r \tag{3.17}$$

$$\left(\frac{M}{\omega_s}\right).\Delta\ddot{\delta} = -K_7\Delta\delta - \left(\frac{D_E}{\omega_s}\right)\Delta\dot{\delta} \tag{3.18}$$

$$s^2 + 2\xi\omega_n.s + \omega_n^2 = 0 \tag{3.19}$$

where $$D_E = 2\xi\omega_n M \tag{3.20}$$

From Equation (3.12), M can be expressed as follows:

$$M = \frac{K_7\omega_s}{\omega_n^2} \tag{3.21}$$

Substitute Equation (3.21) into Equation (3.20), yields:

$$D_E = \frac{2\xi K_7\omega_s}{\omega_n} \tag{3.22}$$

where ξ is the damping ratio, and it is in the range of $(0.1 \rightarrow 0.3)$.

Using two phase lead stages, each stage must contribute by $(\frac{\emptyset_{Pss}}{2})$. To find the time constants, set $T_{p1} = T_{p2} = T_p$ equal to suitable value then find the $\angle(1 + T_p s)$ *at* $s = j\omega_n$. Let $T_{z1} = T_{z2} = T_z$, find T_z as follows:

$$\angle(1 + T_z s) = \left(\frac{\emptyset_{Pss}}{2}\right) + \angle(1 + T_p s) \quad at\ s = j\omega_n \tag{3.23}$$

$$T_z = \frac{tan(\left(\frac{\emptyset_{Pss}}{2}\right) + \angle(1 + T_p s))}{\omega_n} \tag{3.24}$$

By choosing a suitable value for washout time constant (T_w), then find G_C , finally the damping gain can be found using the following formula:

$$D_{Pss} = \frac{D_E}{K_9|G_C|.|G_E|} \tag{3.25}$$

3.2 STATE FEEDBACK CONTROLLERS

To enhance the system damping of low frequency oscillations, the generators units are equipped with power system stabilizer that provide supplementary feedback stabilizing signals in the excitation systems. Several approaches based on modern control theory have been applied to the power system stabilizer design to improve the performance of the power system stabilizer. One of these approaches is the power system stabilizer with state feedback control scheme. The power system stabilizer with state feedback control can be either full state feedback controller (optimal power system stabilizer) or partial state feedback controller (sub-optimal power system stabilizer) (Ganjefar & Judi,2009; Huang et al.,1991; Lewis & Syrmos,1995).

3.2.1 OPTIMAL POWER SYSTEM STABILIZER

The optimal power system stabilizer (OPSS) is designed by feeding back all the system states (Lewis & Syrmos,1995) to the inputs of the washout circuit and the phase lag-lead stages of the conventional PSS through an optimal gain matrix (K) as shown in Figure 3.8.

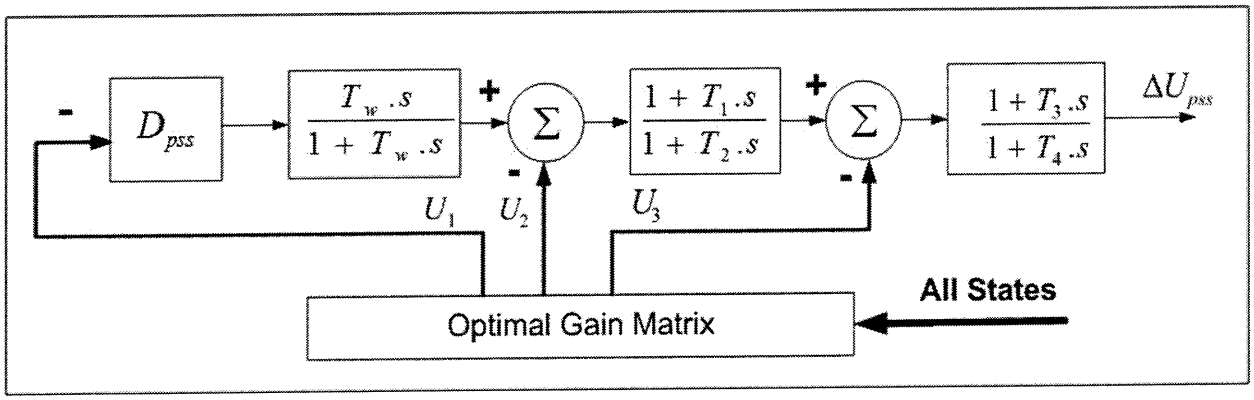


Fig. 3.8 General structure of optimal power system stabilizer (OPSS)

Consider a system whose dynamics is described by:

$$\dot{x}(t) = A\,x(t) + B\,u(t) \tag{3.26}$$

$$y(t) = C\,x(t) + D\,u(t) \tag{3.27}$$

where A is the state matrix, B is the input matrix, C is the output matrix, and D is the feed through matrix.

The control law can be expressed as follows:

$$u = -Kx \tag{3.28}$$

where K is the state feedback gain. Equation 3.26 can be rewritten as follows:

$$\dot{x} = (A - BK)x \tag{3.29}$$

To find the optimal gain matrix (K), the following algebraic Riccati equation (ARE) is solved for the symmetric matrix P.

$$PA + A^T P + Q - PBR^{-1}B^T P = 0 \tag{3.30}$$

where R and Q are positive and semi-positive definite matrices.

The state vector has eight states for each machine. These states are

$$x_k = \left[\delta_k \; \omega_{rk} \; \acute{E}_{qk} \; \acute{E}_{dk} \; E_{fdk} \; X_{6k} \; X_{7k} \; X_{8k}\right]^T \tag{3.31}$$

and

$$x = \left[x_1^T \; x_2^T \; x_3^T \; \ldots\ldots\ldots \; x_{NG}^T\right]^T \tag{3.32}$$

The matrix A has the following form

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} & \cdots \\ A_{21} & A_{22} & A_{33} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix} \tag{3.33}$$

where A_{kk} is the self-state matrix of the k^{th} machine and A_{kj} represents the coupling between k and j machines. The last three states of x_k belong to the power system stabilizer of the k^{th} machine. Each machine has three control input signals as shown in Figure 3.8. The optimal gain matrix K is

$$K = R^{-1}B^T P \tag{3.34}$$

To find the optimal gain matrix (K), the algorithm used is as follows (Lewis & Syrmos,1995):

1) Select the design parameters (R) and (Q) which are minimizing the performance index (J), then solve the following (ARE) for (P).
$$PA + A^T P + Q - PBR^{-1}B^T P = 0$$
2) Determine the optimal gain matrix
$$K = R^{-1}B^T P$$
3) Check the system stability for$(A - BK)$.
4) If the system is unstable, choose different values for (Q) and (R) matrices and repeat the same procedure.

3.2.2 SUB-OPTIMAL POWER SYSTEM STABILIZER

The gain matrix of the optimal power system stabilizer is a full matrix which requires feeding back all the states to the input. Some of these states may be neglected leading to a suboptimal design (Lewis & Syrmos,1995) which may be sufficient enough to achieve adequate damping.

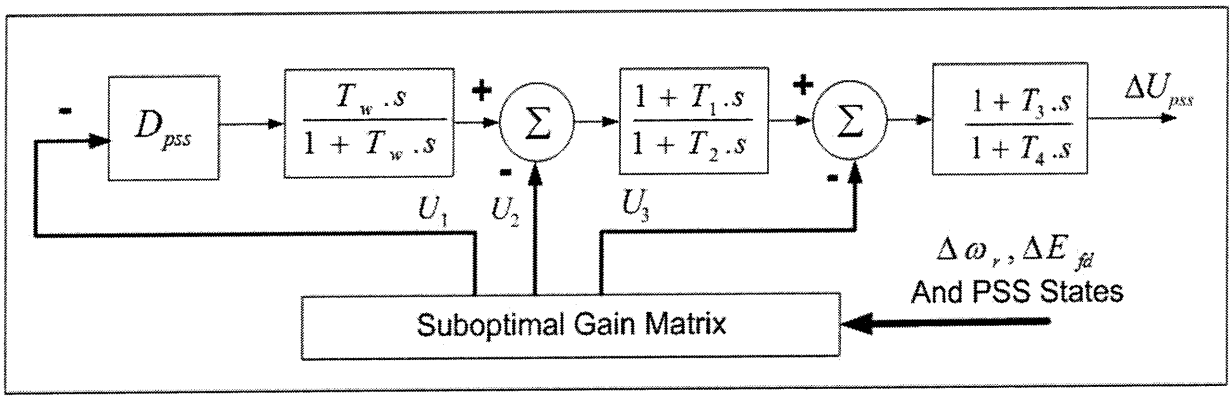


Fig. 3.9 General structure of sub-optimal power system stabilizer (SOPSS)

The proposed suboptimal power system stabilizer (SOPSS) neglects the coupling between machines in the design process. The 8x8 diagonal blocks of the individual machines of matrix A of (3.33) are used. The rotor speed ($\Delta\omega$), the excitation voltage (ΔE_{fd}) and the power system stabilizer states (ΔX_6, ΔX_7 , and ΔX_8) are used for the feedback (Ganjefar & Judi,2009; Huang et al.,1991; Lewis & Syrmos,1995).

$$\dot{x}_k = A_{kk}\, x_k + B_k\, u_k \tag{3.35}$$

$$y_k = C\, x_k + D\, u_k \tag{3.36}$$

and

$$C = \begin{bmatrix} 0\,1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0\,0\,1\,0 \\ 0\,0\,0\,0\,0\,0\,0\,1 \end{bmatrix} \tag{3.37}$$

where (y_k) is the output representing the states needed for the feedback.

$$y_k = \left[\, \omega_{rk}\ E_{fdk}\ X_{6k}\ X_{7k}\ X_{8k} \right]^T \tag{3.38}$$

The output is fed back to the control through the suboptimal gain matrix (K_{sub}):

$$u_k = -K_{sub}.y_k \tag{3.39}$$

This yields the closed loop state matrix (A_k):

$$A_k = A_{kk} - B_k.K_{sub}.C \tag{3.40}$$

and

$$\dot{x} = A_k.x_k \tag{3.41}$$

Equations 3.42 and 3.43 are Lyapunov functions that can be solved iteratively for P and S. Then by using Equation 3.44 to find the sub-optimal gain (K_{sub}).

$$A_k^T.P + P.A_k + Q + C^T.K_{sub}^T.R.K_{sub}.C = 0 \tag{3.42}$$

$$A_k.S + S.A_k^T + X_k = 0 \tag{3.43}$$

$$R.K_{sub}.C.P.C^T - B_k^T.P.S.C^T = 0 \tag{3.44}$$

If R is positive definite and $C \cdot P \cdot C^T$ is non-singular, then

$$K_{sub} = R^{-1}.B_k^T.P.S.C^T.(C.P.C^T)^{-1} \tag{3.45}$$

To find the sub-optimal gain matrix (K_{sub}), the algorithm used is as follows (Lewis & Syrmos,1995):

1) Initialize (k=0), determine a gain (K_{subo}) so that (A-BK_{sub} C) is stable.
2) k^{th} iteration:
   Set $A_k = A - BK_{subk}C$
   Solve for P_k *and* S_k *in*:

$$A_k^T.P_k + P_k.A_k + Q + C^T.K_{subk}^T.R.K_{subk}.C = 0$$

$$A_k.S_k + S_k.A_k^T + X_k = 0$$

   Evaluate the gain update:

$$\Delta K_{sub} = R^{-1}.B_k^T.P.S.C^T.(C.P.C^T)^{-1} - K_{subk}$$

   Update the gain by:

$$K_{subk+1} = K_{subk} + \alpha \Delta K_{sub}$$

   where (α) is chosen so that: (A-BK_{subk+1} C) is stable.
   otherwise, set k=k+1 and go to step (2).
3) Terminate: if $K_{sub\,k} - K_{sub\,k+1} < tolerance$
   Set $K_{sub} = K_{subk+1}$

3.2.3 STATE SPACE REPRESENTATION OF OPTIMAL AND SUB-OPTIMAL POWER SYSTEM STABILIZERS

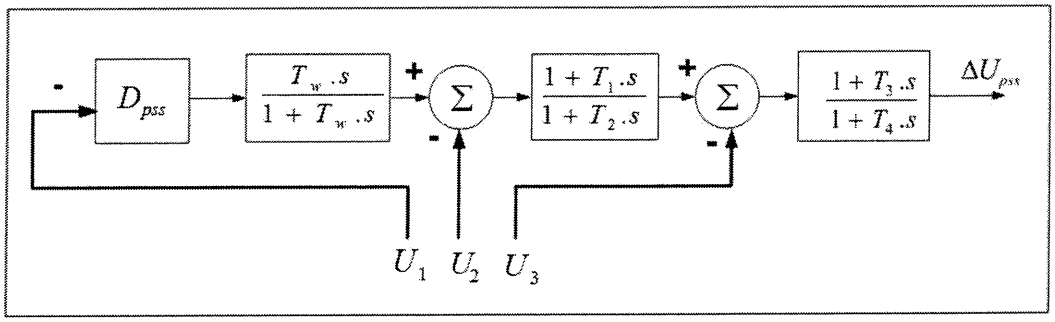


Fig. 3.10 General structure of state feedback power system stabilizer

Stage (1): gain and washout block

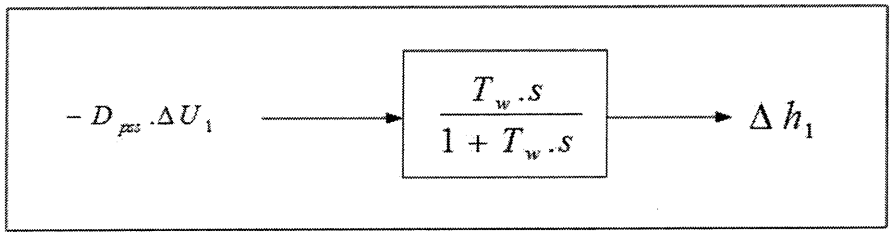


Fig. 3.11 Washout block of state feedback power system stabilizer

The gain and washout block can be represented as follows:

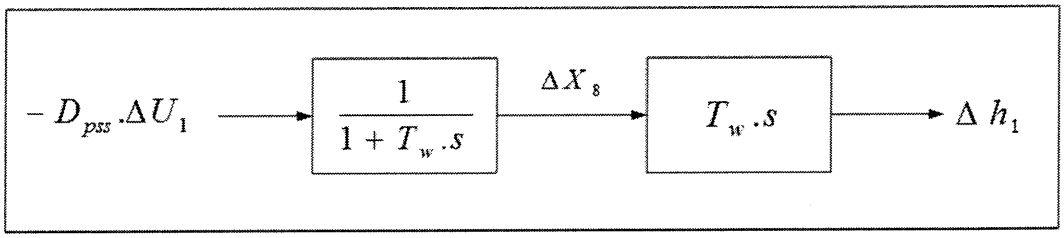


Fig. 3.12 Equivalent diagram for washout block

From the previous block diagram, the state equation for state variable $(\Delta\dot{X}_8)$ can be derived as follows:

$$\Delta\dot{X}_8 = -\frac{1}{T_w}(D_{pss}.\Delta U_1) - \frac{1}{T_w}.\Delta X_8 \qquad (3.46)$$

The Equation of (Δh_1) can be derived as follows:

$$\Delta h_1 = T_w.\Delta\dot{X}_8 \qquad (3.47)$$

Substituting Equation (3.46) into Equation (3.47):

$$\Delta h_1 = -D_{pss}.\Delta U_1 - \Delta X_8 \tag{3.48}$$

Stage (2): phase lead block (stage-1)

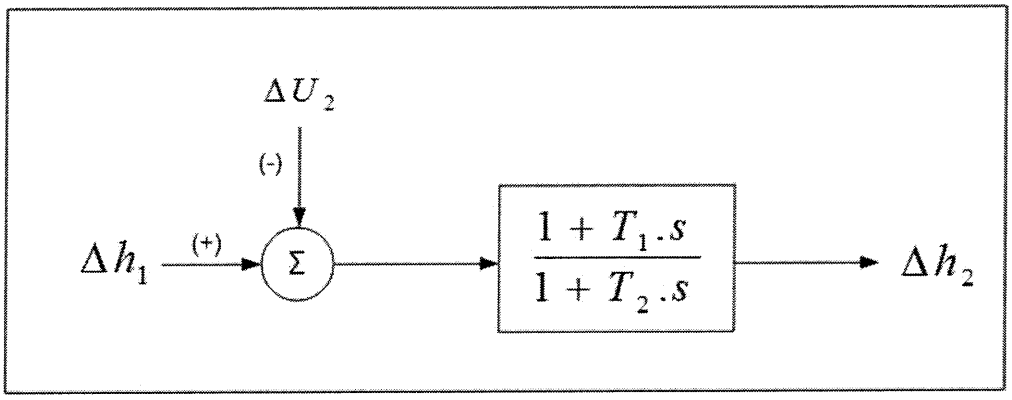


Fig. 3.13 Phase lead block of state feedback power system stabilizer (stage 1)

The first block of the phase lead block can be represented as follows:

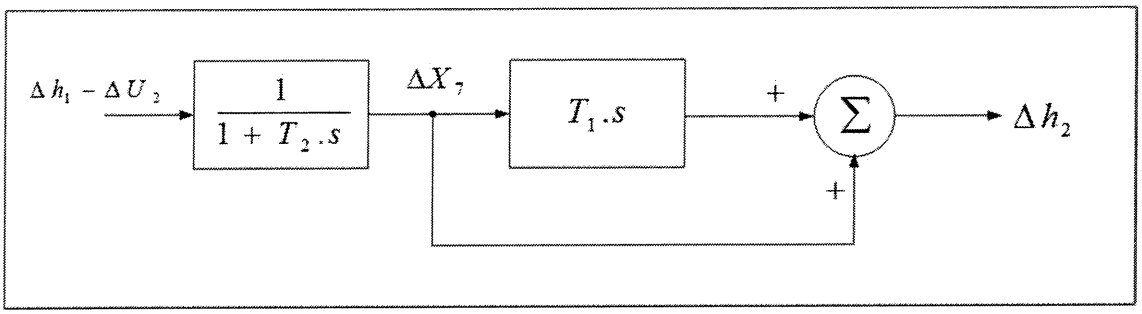


Fig. 3.14 Equivalent diagram for phase lead block (stage 1)

From the previous block diagram, the state equation for state variable $(\Delta\dot{X}_7)$ can be derived as follows:

$$\Delta\dot{X}_7 = \frac{1}{T_2}\left((\Delta h_1 - \Delta U_2) - \Delta X_7\right) \tag{3.49}$$

Substituting Equation (3.48) into Equation (3.49) :

$$\Delta\dot{X}_7 = \left(\frac{-D_{pss}}{T_2}\right)\Delta U_1 - \left(\frac{1}{T_2}\right)\Delta U_2 - \left(\frac{1}{T_2}\right)\Delta X_7 - \left(\frac{1}{T_2}\right)\Delta X_8 \tag{3.50}$$

The Equation of (Δh_2) can be derived as follows:

$$\Delta h_2 = T_1.\Delta\dot{X}_7 + \Delta X_7 \tag{3.51}$$

Substitute Equation (3.50) into Equation (3.51):

$$\Delta h_2 = -\left(\frac{D_{pss}.T_1}{T_2}\right)\Delta U_1 - \left(\frac{T_1}{T_2}\right)\Delta U_2 + \left(1 - \frac{T_1}{T_2}\right)\Delta X_7 - \left(\frac{T_1}{T_2}\right)\Delta X_8 \tag{3.52}$$

Stage (3): phase lead block (stage-2)

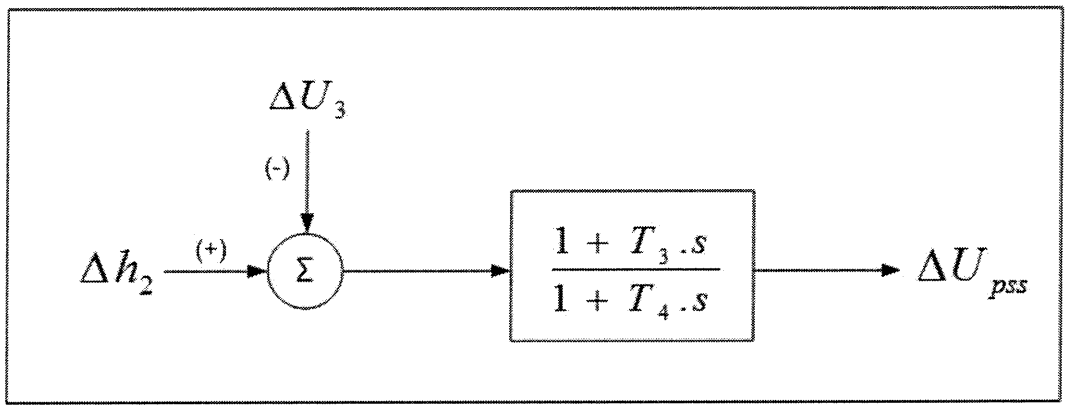


Fig. 3.15 Phase lead block of state feedback power system stabilizer (stage 2)

The second block of the phase lead block can be represented as follows:

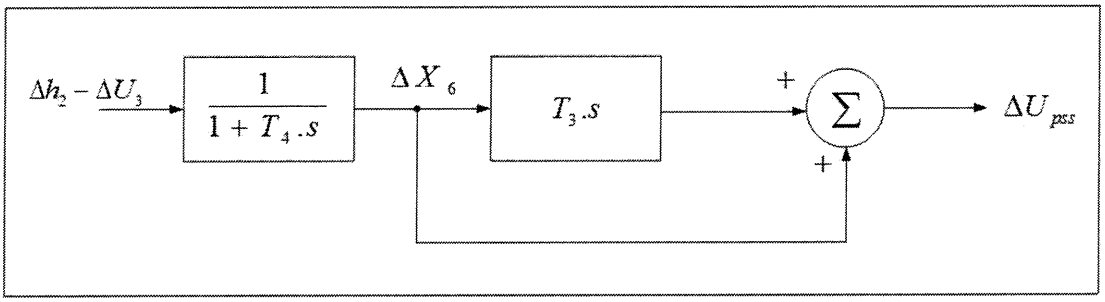


Fig. 3.16 Equivalent diagram for phase lead block (stage 2)

From the previous block diagram, the state equation for the state variable $(\Delta\dot{X}_6)$ can be derived as follows:

$$\Delta\dot{X}_6 = \frac{1}{T_4}\left((\Delta h_2 - \Delta U_3) - \Delta X_6\right) \tag{3.53}$$

Substituting Equation (3.52) into Equation (3.53):

$$\Delta\dot{X}_6 = \begin{pmatrix} \left(\frac{-D_{pss}.T_1}{T_2.T_4}\right)\Delta U_1 - \left(\frac{T_1}{T_2.T_4}\right)\Delta U_2 - \left(\frac{1}{T_4}\right)\Delta U_3 - \left(\frac{1}{T_4}\right)\Delta X_6 \\ + \left(\frac{1}{T_4} - \frac{T_1}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1}{T_2.T_4}\right)\Delta X_8 \end{pmatrix} \quad (3.54)$$

The Equation of (ΔU_{pss}) can be derived as follows:

$$\Delta U_{pss} = T_3.\Delta\dot{X}_6 + \Delta X_6 \quad (3.55)$$

Substituting Equation (3.54) into the previous Equation:

$$\Delta U_{pss} = \left(\frac{-D_{pss}.T_1.T_3}{T_2.T_4}\right)\Delta U_1 - \left(\frac{T_1.T_3}{T_2.T_4}\right)\Delta U_2 - \left(\frac{T_3}{T_4}\right)\Delta U_3 + \left(1 - \frac{T_3}{T_4}\right)\Delta X_6 + \left(\frac{T_3}{T_4} - \frac{T_1.T_3}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1.T_3}{T_2.T_4}\right)\Delta X_8 \quad (3.56)$$

The optimal power system stabilizer (OPSS) and suboptimal power system stabilizer (SOPSS) can be modelled by three state equations, these are:

$$\Delta\dot{X}_6 = \left(\frac{-D_{pss}.T_1}{T_2.T_4}\right)\Delta U_1 - \left(\frac{T_1}{T_2.T_4}\right)\Delta U_2 - \left(\frac{1}{T_4}\right)\Delta U_3 - \left(\frac{1}{T_4}\right)\Delta X_6 + \left(\frac{1}{T_4} - \frac{T_1}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1}{T_2.T_4}\right)\Delta X_8$$

$$\Delta\dot{X}_7 = \left(\frac{-D_{pss}}{T_2}\right)\Delta U_1 - \left(\frac{1}{T_2}\right)\Delta U_2 - \left(\frac{1}{T_2}\right)\Delta X_7 - \left(\frac{1}{T_2}\right)\Delta X_8$$

$$\Delta\dot{X}_8 = -\frac{1}{T_w}(D_{pss}.\Delta U_1) - \frac{1}{T_w}.\Delta X_8$$

where

$$U = -Kx$$

$$x = [x_1^T\ x_2^T\ x_3^T \dots\dots\dots\ x_{NG}^T]^T \quad \rightarrow k = 1 \cdots NG\ (total\ number\ of\ machines)$$

$$U = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix}$$

For optimal power system stabilizer (OPSS)

$$x_k = [\delta_k\ \omega_{rk}\ \acute{E}_{qk}\ \acute{E}_{dk}\ E_{fdk}\ X_{6k}\ X_{7k}\ X_{8k}]^T$$

$$K : Optimal\ gain\ matrix$$

For sub-optimal power system stabilizer (SOPSS)

$$x_k = [\ \omega_{rk}\ E_{fdk}\ X_{6k}\ X_{7k}\ X_{8k}]^T$$

$$K : Suboptimal\ gain\ matrix$$

3.3 FUZZY POWER SYSTEM STABILIZER

During the past few years, fuzzy logic control has emerged as one of the most active and fruitful areas for research in the applications of fuzzy set theory. Moreover in recent years, fuzzy logic has emerged as a powerful tool and is starting to be used in various power system applications.

Fuzzy logic is based on fuzzy set theory that was established by Lofti Zadeh in 1965 (father of fuzzy logic), after Zadeh a lot of research was conducted on this subject in the several years by Mamdani in 1975, and others (Sugeno and Murakami 1985, Evans 1989, Lee 1990, etc.) (Ganesh,2006; HusseinZadeh & Kalam,1999; Lee,1990; Metwally & Malik,1994; Ross,2010; Sivanandam et al.,2007).

Unlike the classical control, which requires the plant model represented by the exact mathematical model to design controller, fuzzy logic incorporates an alternative way which allows one to design a controller using higher level of abstraction without knowing the exact mathematical representation for the power plant system (HusseinZadeh & Kalam,1999).

3.3.1 INTRODUCTION TO FUZZY SET THEORY

What is fuzzy set?

Let X be a collection of objects, then a fuzzy set A in X is defined to be a set of ordered pairs:

$$A= \{(x, \mu_A(x)), x \epsilon X\} \quad (3.57)$$

where $\mu_A(x)$ is called the membership function of x in A. The numerical interval X which is relevant for the description of a fuzzy variable is commonly named universe of discourse. The membership function $\mu_A(x)$ denotes the degree to which x belongs to A and it is normally limited to values between 0 and 1. A value of $\mu_A(x)$ close to one means it is very likely for x to be in A and a value of $\mu_A(x)$ nearer to zero denote non membership (Ganesh,2006; Sivanandam et al.,2007).

Fuzzy set operation

Suppose A and B are two fuzzy sets with membership functions $\mu_A(x)$ and $\mu_B(x)$ respectively then,

1- AND operation (Intersection): the membership function of the intersection on these two fuzzy sets (C = A ∩ B), is defined by:

$$\mu_C(x) = \min \{\mu_A(x), \mu_B(x)\} \ , x \ \epsilon X \quad (3.58)$$

2- OR operation (Union): the membership function of the union of these two sets (D = A ∪ B), is defined by:

$$\mu_B(x) = \max\{\mu_A(x), \mu_B(x)\} \quad , x \in X \tag{3.59}$$

3- NOT operation (complement): the membership function of the complement of A, Ā, is defined by:

$$\mu_{\bar{A}} = 1 - \mu_A(x) \quad , x \in X \tag{3.60}$$

4- Fuzzy relation: a fuzzy relation R from A to B can be considered as a fuzzy graph and characterized by the membership function $\mu_R(x, y)$, which satisfies the composition rule as follows:

$$\mu_B(y) = \max\{ min\,[\mu_R(x, y), \mu_A(x)]\} \quad , x \in X \tag{3.61}$$

3.3.2 FUZZY LOGIC CONTROLLER

Fuzzy control systems are rule based systems in which a set of fuzzy rules represent a control decision mechanism to adjust the effects of certain system disturbances. The aim of fuzzy control systems is normally to replace a skilled human operator with a fuzzy rule based system. The fuzzy logic controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. The basic configuration of a fuzzy logic controller consists of a fuzzification interface, a knowledge base, decision making logic, and a defuzzification interface as shown in Figure 3.17 (Altas & Sharaf,2007; Corcua & Stoenescu,2007; Ganesh,2006; Gupta & Jain,2010; Hiyama & Nakano,1988; Hoang & Tomsovic,1996; Hsu & Cheng,1990; HusseinZadeh & Kalam,1999; Jantzen,1998; Lakshmi & Khan,1998; Lee,1990; Lee et al.,2002; Menniti, Burgio, Pinnarelli, Principe, Scordino, & Sorrentino,2002; Metwally & Malik,1994; Petriu,2009; Prasertwong & Mithulananthan,2009; Ross,2010; Sambariya et al.,2009; Sivanandam et al.,2007; Taher & Shemshadi,2007;Toliyat, Sadeh, & Ghazi,1996).

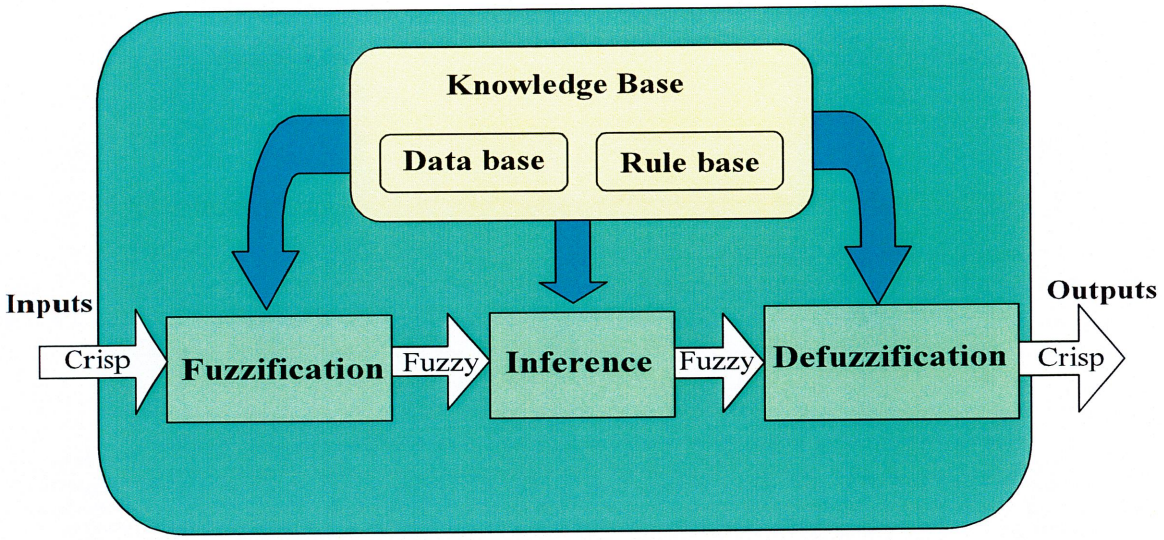


Fig. 3.17 General diagram of fuzzy logic controller

1) **Fuzzification:** fuzzification is the process of transforming the crisp input to fuzzy by mapping of the actual crisp input value to a degree of membership via an input membership function. The resulting degree of membership then becomes an input to the inference stage.

2) **Knowledge Base:** it consists of a data base and rule base. The data base provides necessary definitions which are used to define linguistic control rule and fuzzy data manipulation in a fuzzy logic controller. The rule base defines the relation between the inputs and outputs of a fuzzy logic controller. Linguistic variables are used to define the rules of fuzzy logic controller in the form of if – then format as shown below:

If (a set of conditions are satisfied), Then (a set of consequences can be inferred)

Generally, the number of rules depends on the number of input and the number of membership functions that express each variable and it should cover all possible combination of input values.

3) **Inference:** in the inference stage, the fuzzy logic controller performs the necessary inference operation on all fuzzy rules. Moreover it compares the fuzzified values of the controller inputs by the base rules.

4) **Defuzzification:** defuzzification is the process of transforming the fuzzy control action to crisp output by mapping of a degree of membership to crisp output via an output membership functions.

- **Membership function:** the membership function is a characteristic function of a fuzzy set. A membership function associated with a given fuzzy set, maps an input value (x) to it is corresponding membership value.

Recently fuzzy logic controllers have been widely used in many applications, including the power system stabilizer which is used to enhance the damping characteristic of the power system through the application of a supplementary stabilizing signal to its excitation control loop. The application of fuzzy logic control for power system stabilizers was motivated by the work of Hiyama and Nakano (Hiyama & Nakano,1988). Their proposed fuzzy controller has been demonstrated to be suitable for damping low frequency oscillations of the power system.

3.3.3 FUZZY POWER SYSTEM STABILIZER

The Hsu and Cheng fuzzy power system stabilizer (Hsu & Cheng,1990) is one of the power system stabilizers (Altas & Sharaf,2007; Corcua & Stoenescu,2007; Ganesh,2006; Gupta & Jain,2010; Hiyama & Nakano,1988; Hoang & Tomsovic,1996; Hsu & Cheng,1990; HusseinZadeh & Kalam,1999; Jantzen,1998; Lakshmi & Khan,1998; Lee,1990; Lee et al.,2002; Menniti et al.,2002; Metwally & Malik,1994; Petriu,2009; Prasertwong & Mithulananthan,2009; Ross,2010; Sambariya et al.,2009; Sivanandam et al.,2007; Taher & Shemshadi,2007;Toliyat et al.,1996) based on the concept of fuzzy logic theory. The fuzzy excitation controller proposed by Hsu and Cheng is shown in Figure 3.18 where the measured generator angular speed deviation ($\Delta\omega$) and the calculated acceleration ($\Delta\dot{\omega}$) are used as input signals. These signals are first expressed in some linguistic variables using membership functions in fuzzy set notations before they are processed by the fuzzy controller. A set of decision rules expressed in linguistic variables are established based on previous experience with the study system to related input signals with output (control) signal. These decision rules are converted into a fuzzy relation matrix (R) which can be stored in computer memory. Then, using the fuzzified input variables with the relation matrix, the membership values of the controller output signal expressed in fuzzy linguistic terms can be obtained. Finally the control signal is converted from linguistic term to numerical value before it is fed into the system. From Figure 3.18, the scaling factors Sf1, Sf2 and Sf3 are the normalizing or scaling factors whose values are to be selected to get the optimal system performance.

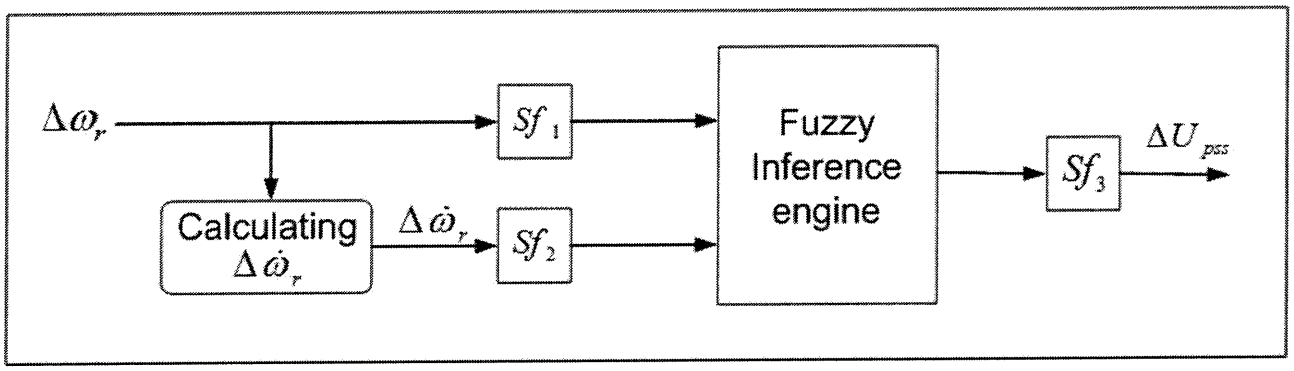


Fig.3.18 Fuzzy power system stabilizer (FPSS) diagram

The design of the proposed power system stabilizer can be described as follows:

1) Calculation of the speed acceleration ($\Delta\dot{\omega}$): from two measured samples of the speed deviation ($\Delta\omega$), the acceleration ($\Delta\dot{\omega}$) can be calculated using the following relationship:

$$\Delta\dot{\omega}(k) = \frac{\Delta\omega(k) - \Delta\omega(k-1)}{T_s} \tag{3.62}$$

Where $\Delta\,\omega(k)$ = the speed deviation at $t = k*T_s$, T_s = sampling time.

2) The decision rules: the decision rules represented by linguistic variables which are established to relate the controller input signals to the controller output. These decision rules are expressed using linguistic variables such as large positive (LP), medium positive (MP), small positive (SP), zero (Z), small negative (SN), medium negative (MN), and large negative (LN). The combination of the two input signals which generates seven linguistic terms (LN,MN,SN,Z,SP,MP, and LP), so 49 decision rules which are presented in the following table:

		Speed Acceleration ($\Delta\dot{\omega}$)						
		LN	**MN**	**SN**	**Z**	**SP**	**MP**	**LP**
Speed deviation $\Delta\omega$	**LP**	Z	SP	MP	LP	LP	LP	LP
	MP	SN	Z	SP	MP	MP	LP	LP
	SP	MN	SN	Z	SP	SP	MP	LP
	Z	MN	MN	SN	Z	SP	MP	MP
	SN	LN	MN	SN	SN	Z	SP	MP
	MN	LN	LN	LN	MN	SN	Z	SP
	LN	LN	LN	LN	LN	MN	SN	Z

Table 3.1 Decision rules for the proposed fuzzy power system stabilizer

For example, rule (1) can be read as follows:

IF $\Delta\omega$ is LP and $\Delta\dot{\omega}$ is LN, THEN ΔU_{pss} (stabilizer output) is Z (3.63)

3) The fuzzy relation matrix: using the fuzzy set notation and the decision rules table (Table 3.1) a fuzzy relation matrix can be implemented as shown in Table 2 presented in (Hsu & Cheng,1990)

The controller output can be obtained when a particular rule applied by using the fuzzy relation matrix as shown below:

IF $\Delta\omega$ is LP, and $\Delta\dot{\omega}$ is LN, then the controller output can be characterized by the fuzzy set:

{(LN, 0), (MN, 0), (SN, 0.5), (Z, 1), (SP, 0.5), (MP, 0), (LP, 0)} (3.64)

4) Membership functions of the stabilizer input signals: to express the power system stabilizer inputs in linguistic variables, the two crisp inputs ($\Delta\omega$ and $\Delta\dot{\omega}$) are normalized then scaled by the input scaling factors ($Sf_1 and\ Sf_2$). These scaling factors are to be selected from the tuning process. The fuzzy power system stabilizer inputs can be described by triangular membership function for the linguistic variables (7- fuzzy sets, as the number of sets increased the accuracy of the controller also increased and it consumed more time) as shown in the figure below.

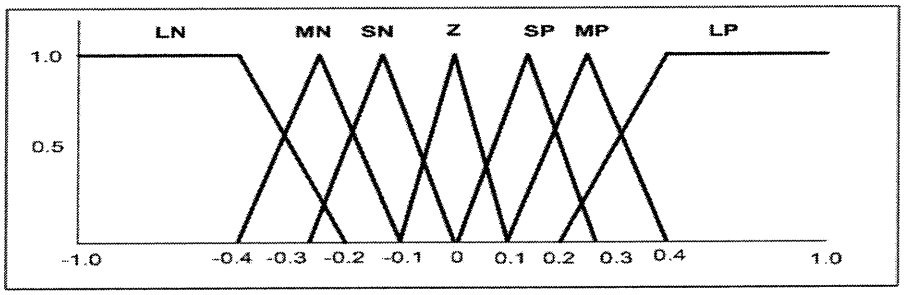


Fig. 3.19 Membership function shape of $\Delta\omega$

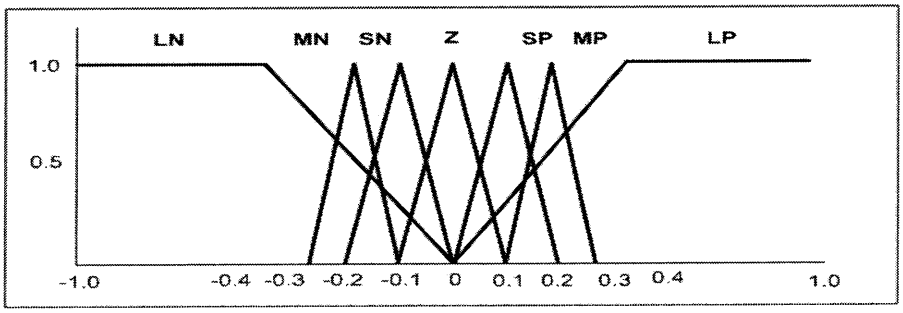


Fig. 3.20 Membership function shape of $\Delta\dot{\omega}$

5) Membership function of the stabilizer output: the membership function of the power system stabilizer output can be determined by considering the contribution of all the rules. Based on these membership values the stabilizer output is expressed in linguistic variables which are converted later to numerical values and scaled by the output scaling factor (Sf_3) before it is fed into the system.

The fuzzy power system stabilizer output can be described by triangular membership function for the linguistic variables as shown in the figure below.

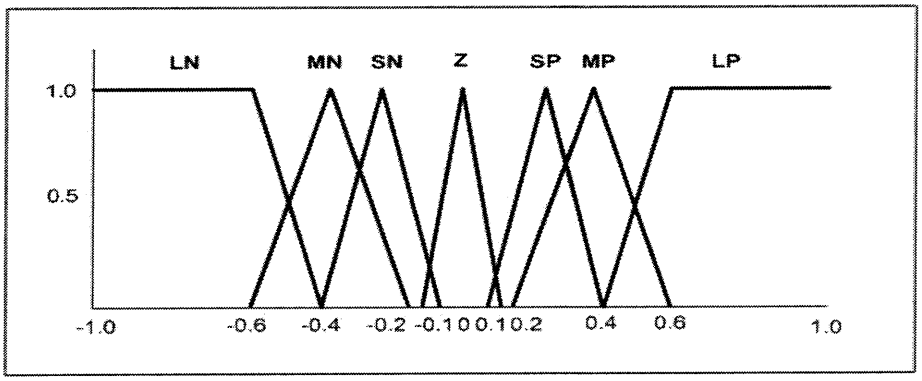


Fig. 3.21 Membership function shape of fuzzy power system stabilizer (FPSS) output

The following is an example for how to compute the output of a fuzzy power system stabilizer:
Suppose that at a particular sampling instant, the sampled stabilizer inputs are $\Delta\omega$ is 0.2 p.u. and $\Delta\dot{\omega}$ is -0.1 p.u. then the degree of membership functions for this sampling instant are:

	LN	MN	SN	Z	SP	MP	LP
$\Delta\omega$	0	0	0	0	0.4	0.67	0
$\Delta\dot{\omega}$	0.22	0	1.0	0	0	0	0

Table 3.2 Membership function for stabilizer inputs

The two stabilizer inputs with respect to Table 3.2 can be described by the following fuzzy sets:

$$\Delta\omega = \{(\text{LN}, 0), (\text{MN}, 0), (\text{SN}, 0), (\text{Z}, 0), (\text{SP}, 0.4), (\text{MP}, 0.67), (\text{LP}, 0)\} \quad (3.65)$$

$$\Delta\dot{\omega} = \{(\text{LN}, 0.22), (\text{MN}, 0), (\text{SN}, 1), (\text{Z}, 0), (\text{SP}, 0), (\text{MP}, 0), (\text{LP}, 0)\} \quad (3.66)$$

To find the membership function of the stabilizer output it is required to find the membership degree for the condition part of each rule, for example;

$$\mu(x_1) = \mu(\Delta\omega \; is \; LP \; and \; \Delta\dot{\omega} \; is \; LN) = \min\big(\mu(\Delta\omega \; is \; LP), \mu(\Delta\dot{\omega} \; is \; LN)\big) \quad (3.67)$$

$$\mu(x_1) = \min(0,0.22) = 0 \quad (3.68)$$

Using Table (2) presented in (Hsu & Cheng,1990), the membership values for the stabilizer output can be obtained for each rule. For example:

$$\Delta U_{c1}(LN) = \min\big(\mu_R(x_1, LN), \mu(x_1)\big) = \min(0,0) = 0 \quad (3.69)$$

This is the membership value of the stabilizer output (LN) if only rule (1) exists. In order to take all the 49 rules into account, the membership values for the condition part of all other 48 rules must be considered as well.
Using equation (3.61) the final value for the stabilizer output (LN) can be evaluated as shown below

$$\mu_{U_c}(LN) = \max_{x_i}\{ min \; [\mu_R \; (x_i, LN), \mu \; (x_i)]\} = 0.22 \quad (3.70)$$

The membership values for the other six variables can be similarly calculated as:

$$\mu_{U_c}(MN) = 0.22 \qquad \mu_{U_c}(SN) = 0.4 \qquad \mu_{U_c}(Z) = 0.5$$
$$\mu_{U_c}(SP) = 0.67 \qquad \mu_{U_c}(MP) = 0.67 \qquad \mu_{U_c}(LP) = 0$$

To obtain the crisp output value for the stabilizer output from the calculated membership values that were obtained in the previous step, a mechanism called defuzzification is used. For the proposed fuzzy power system stabilizer (FPSS), the output is defuzzified according to the membership function shown in Figure (3.21) and the center of area (centroid) method is used for defuzzification. In this defuzzification method, the output of the stabilizer is the center of the area bounded by the membership function curve which is computed using the following formula:

$$y^* = \frac{\int \mu(x)\, x dx}{\int \mu\,(x) dx} = -0.0474 \quad (3.71)$$

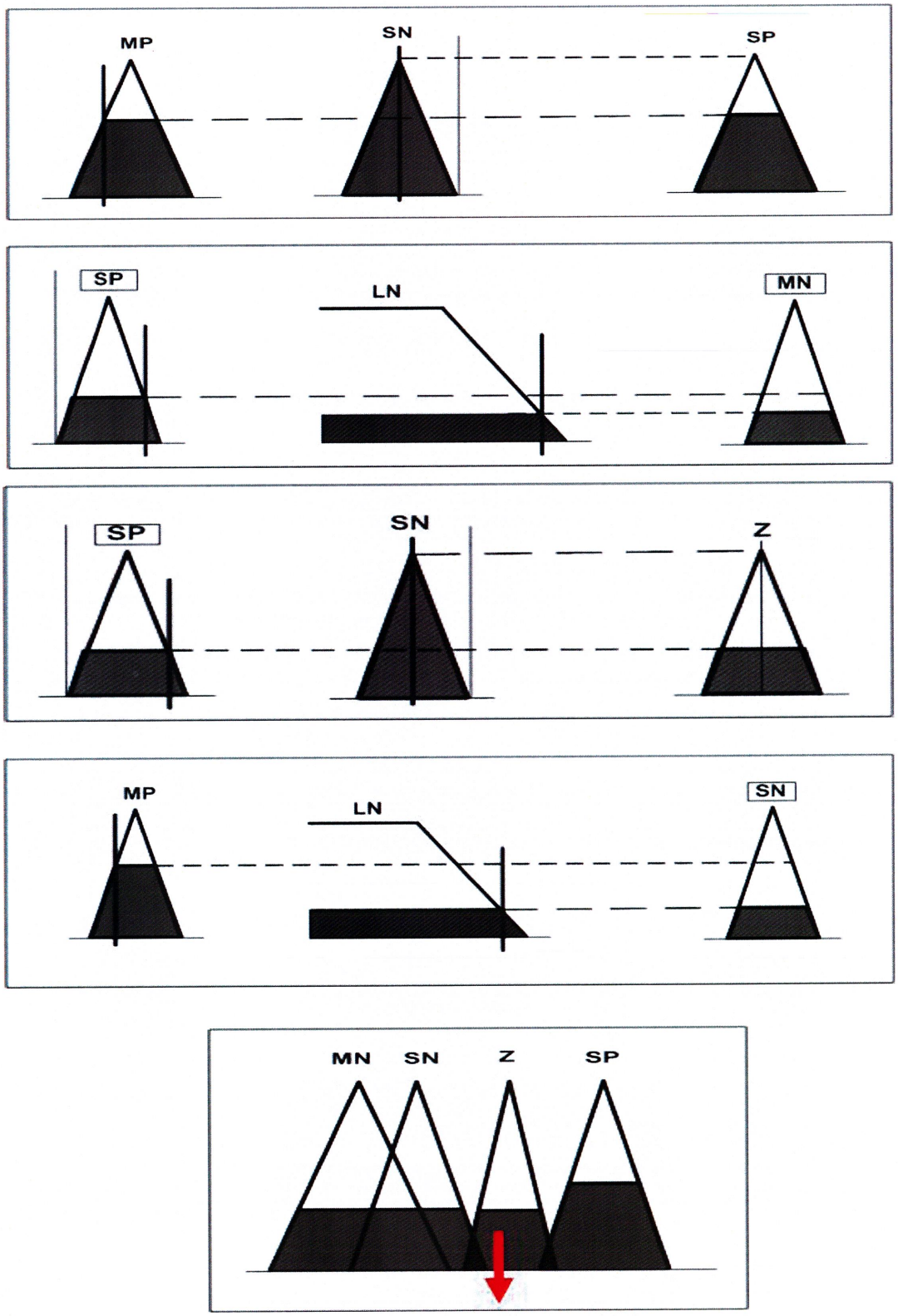


Fig. 3.22 Graphical illustration of fuzzification and inference phase

CHAPTER 4

SIMULATION AND RESULTS

4.1 SINGLE MACHINE SYSTEM

In order to compare the effectiveness and performance of the power system stabilizers, a computer simulation (using MATLAB R2007b) is performed to a single machine connected to infinite bus system and to a single machine isolated system with a small disturbance of 5% step change in the mechanical torque (ΔT_m).

4.1.1 SINGLE MACHINE SYSTEM MODELS

1) Single machine infinite bus model (SMIB): this power system model consists of a single machine (synchronous generator) including an excitation system (exciter) connected to an infinite bus through transmission line (link) as shown in Figure 4.1.

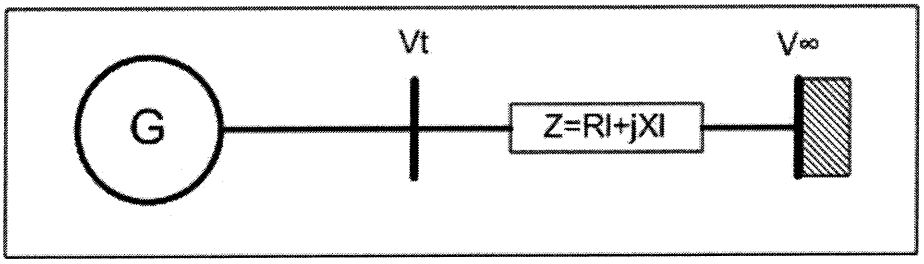


Fig.4.1 Single machine infinite bus (SMIB) model

2) Single machine isolated system model (SMIS): this power system model consists of a single machine (synchronous generator) including an excitation system (exciter) connected to a load as shown in Figure 4.2.

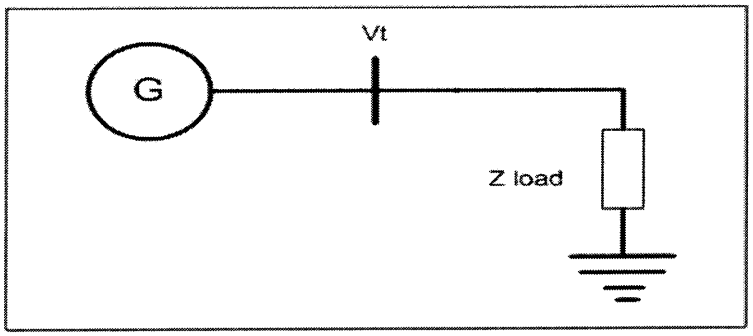


Fig. 4.2 Single machine isolated system (SMIS) model

- The simplified model of single machine infinite bus (SMIB) for small signal analysis is shown in details in appendix [A].

- The full details of I_q and I_d current gains analysis for single machine isolated system are given in appendix [B].

- The I_q and I_d current gains results for single machine system are shown in appendix [G].

4.1.2 SYSTEMS PARAMETERS

The parameters of the stabilizers have been tuned at the nominal operating condition. For the conventional power system stabilizer (CPSS) the parameters of the phase lead compensator are calculated as per the design procedure given in section 3.1.2. For the optimal power system stabilizer (OPSS) and the sub-optimal power system stabilizer (SOPSS), the control weighting (R) is chosen as unity and the state matrix (Q) is found through several trial and error procedures to give the best dynamic performance. The fuzzy power stabilizer scaling factors are found by several trial and error procedures to have the best performance.

- The parameters of single machine system models are shown in appendix [D].

- The initial conditions calculations and results of single machine system models are shown in appendix [F].

- A summary of equations for single machine system models simulation is shown in appendix [E].

4.1.3 EIGENVALUES ANALYSIS

The eigenvalues analysis is done to investigate the mode of oscillations, the damping characteristics, and the stability of the investigated system achieved by the conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), suboptimal power system stabilizer (SOPSS), and fuzzy power system stabilizer (FPSS).

- The full details of the eigenvalues analysis results of single machine system models are shown in appendix [H].
- The A matrix results of single machine system models are shown in appendix [I].

4.1.4 COMPUTER SIMULATION RESULTS OF SMIB

4.1.4.1 SMIB Simulation results (Case-1)

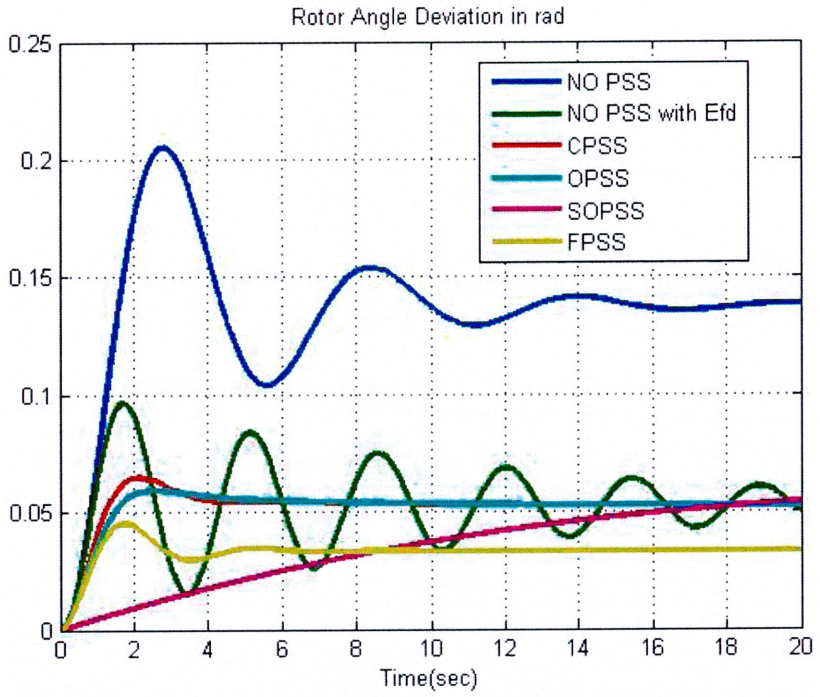


Fig.4.3 Rotor angle deviations after 5% step change in the mechanical torque (T_m) with no speed droop

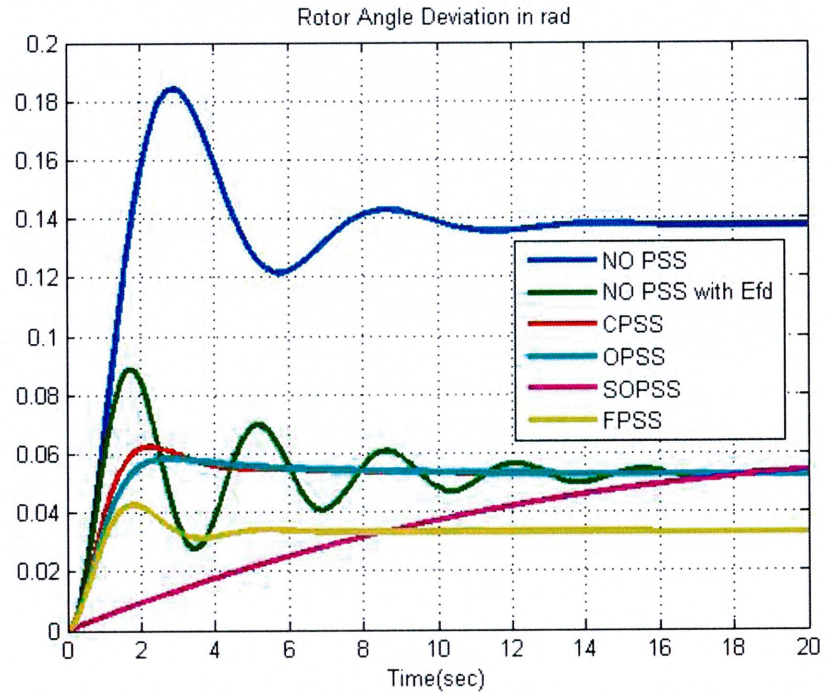


Fig.4.4 Rotor angle deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

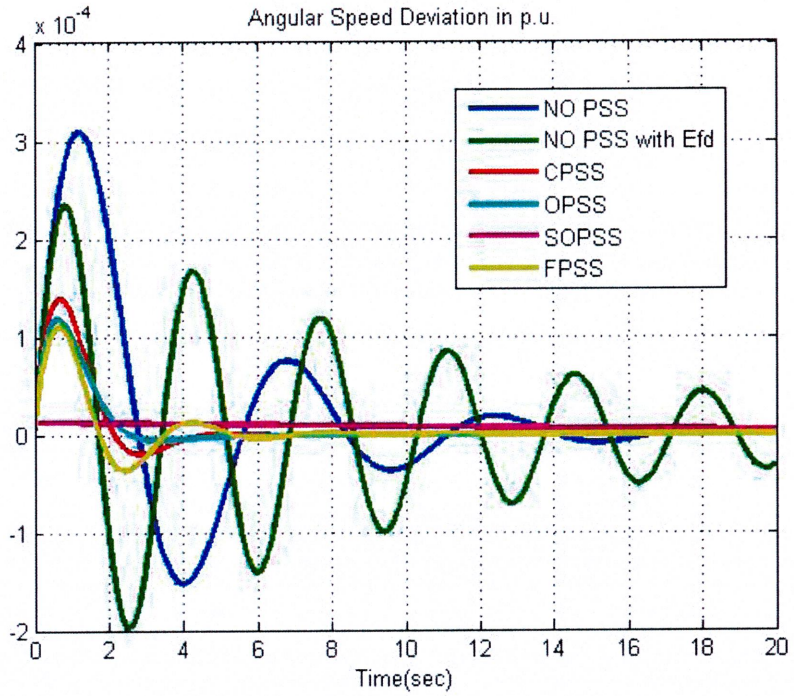


Fig.4.5 Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop

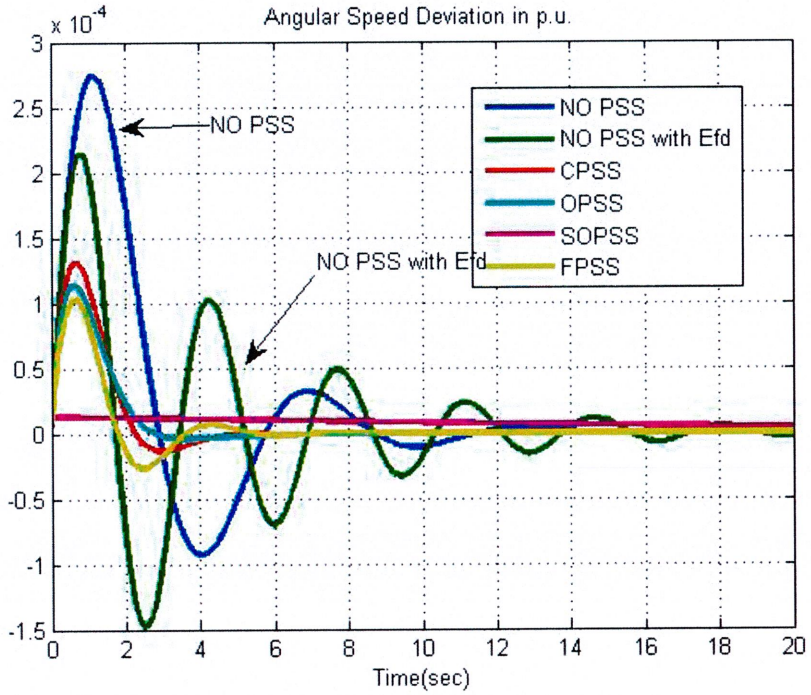


Fig.4.6 Angular speed deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

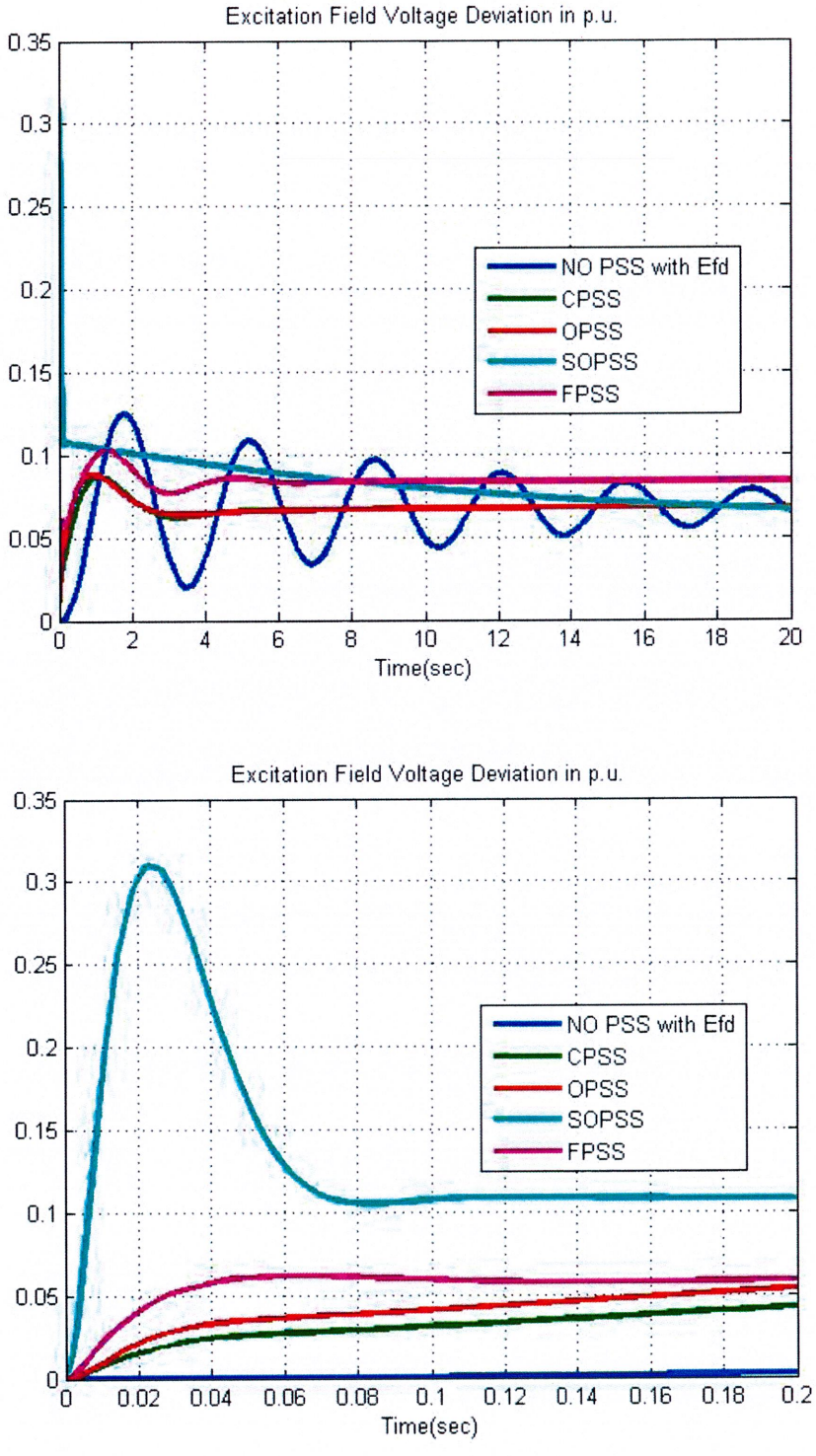


Fig.4.7 Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) with no speed droop

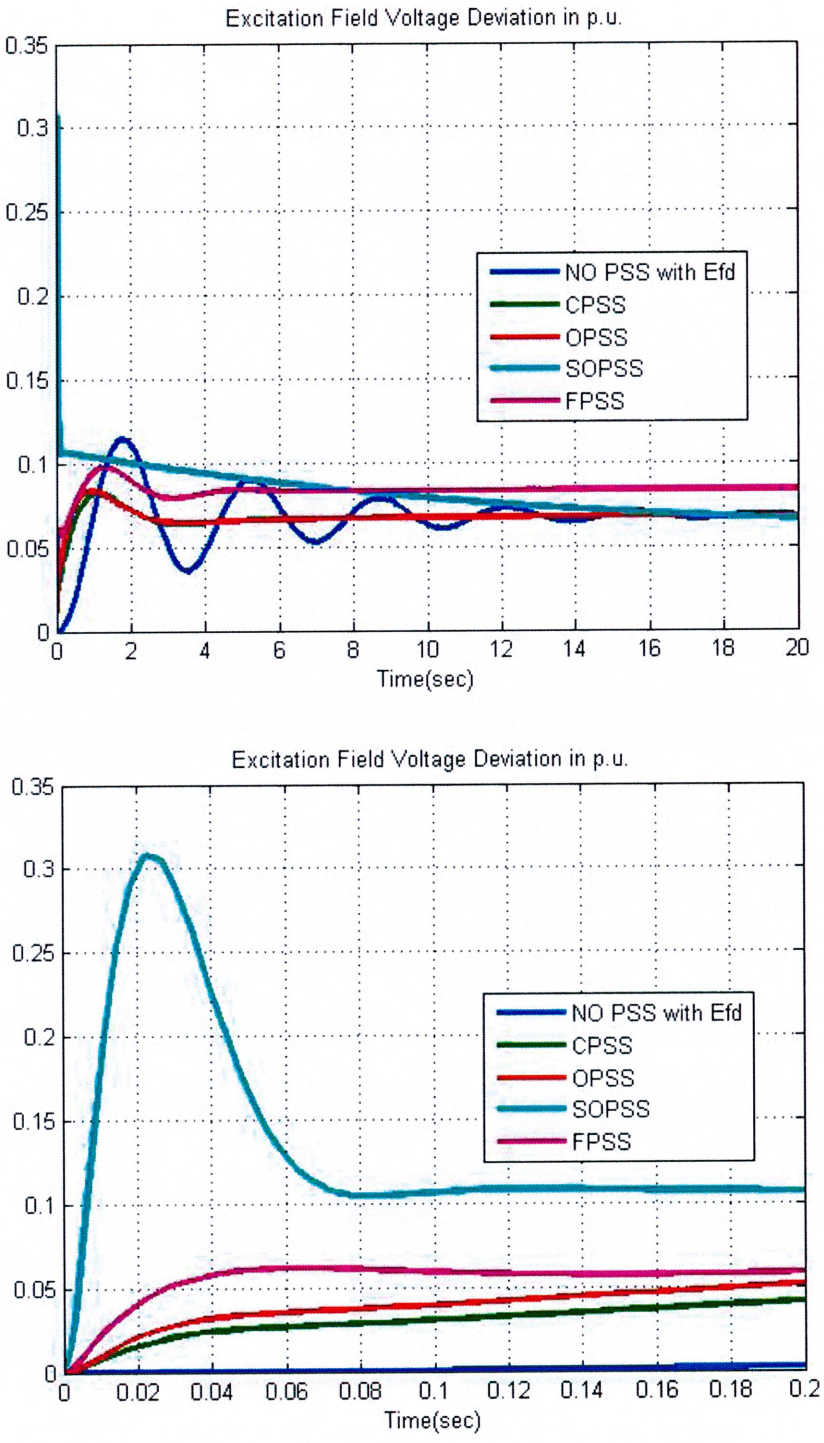


Fig.4.8 Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.1.4.2 SMIB Simulation results (Case-2)

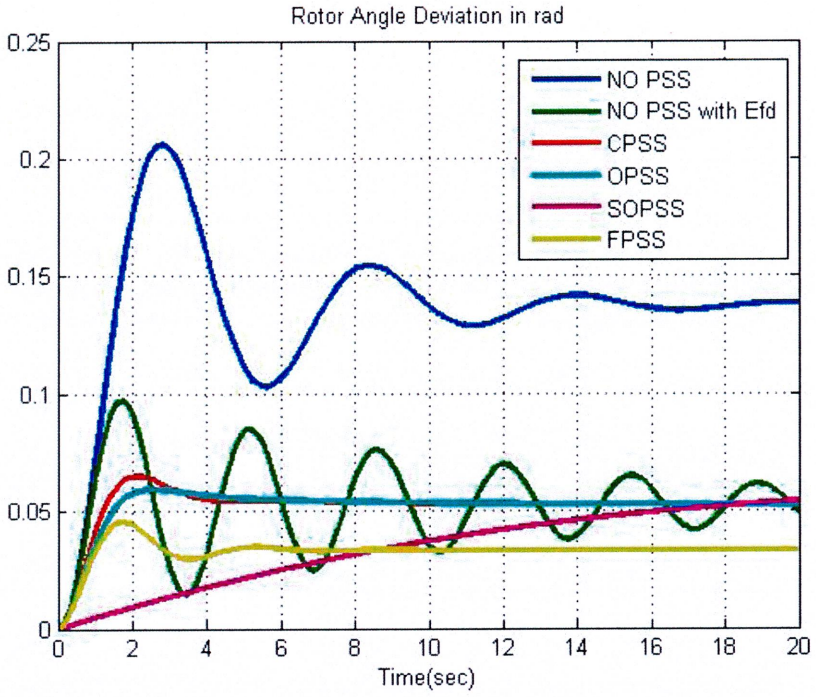


Fig.4.9 Rotor angle deviations after 5% step change in the mechanical torque (T_m) with no speed droop

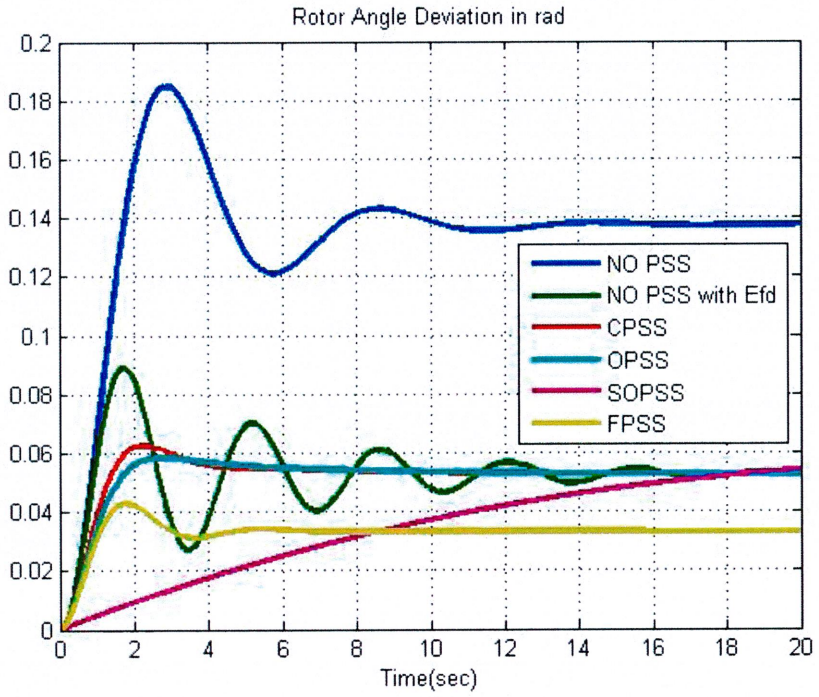


Fig.4.10 Rotor angle deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

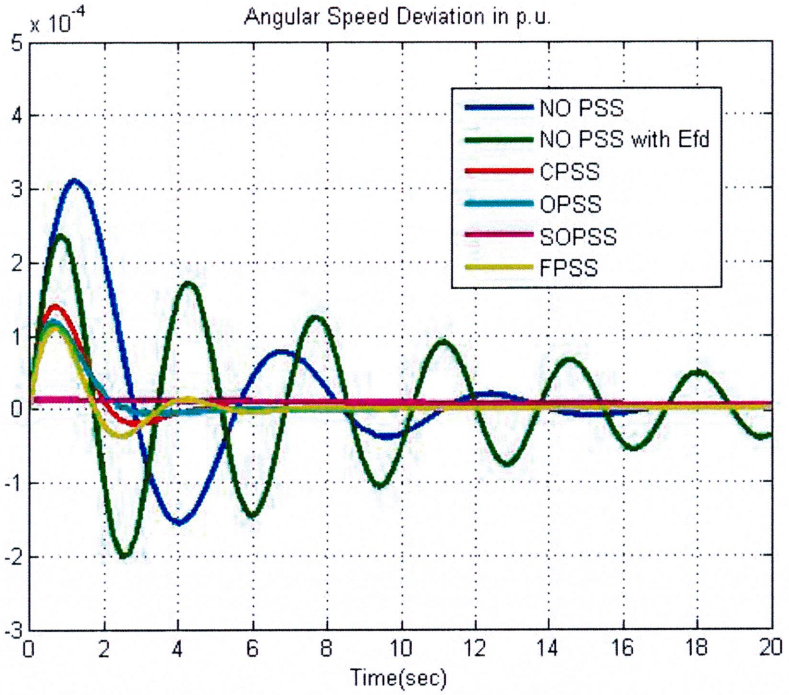


Fig.4.11 Angular speed deviations after 5% step change in the mechanical torque (T_m) with no droop

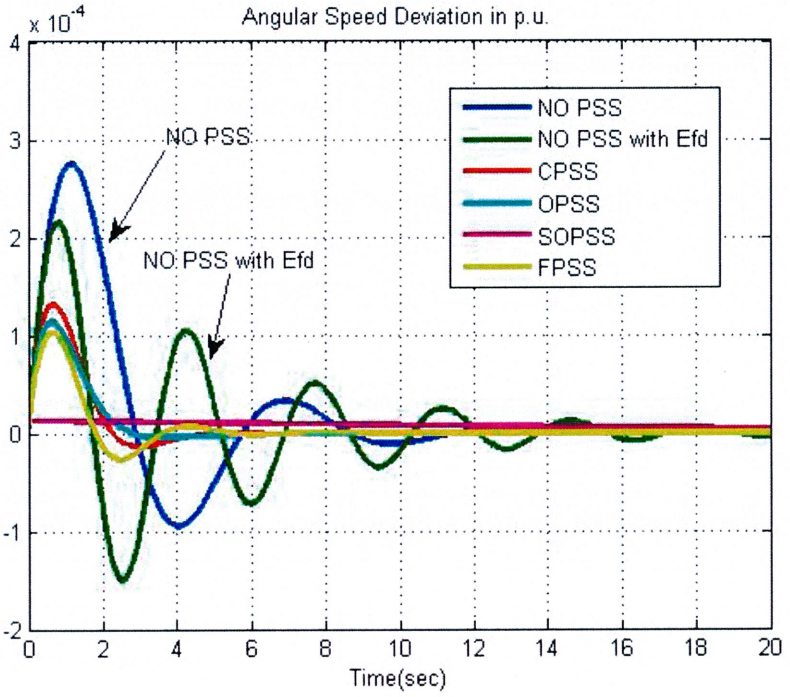


Fig.4.12 Angular speed deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

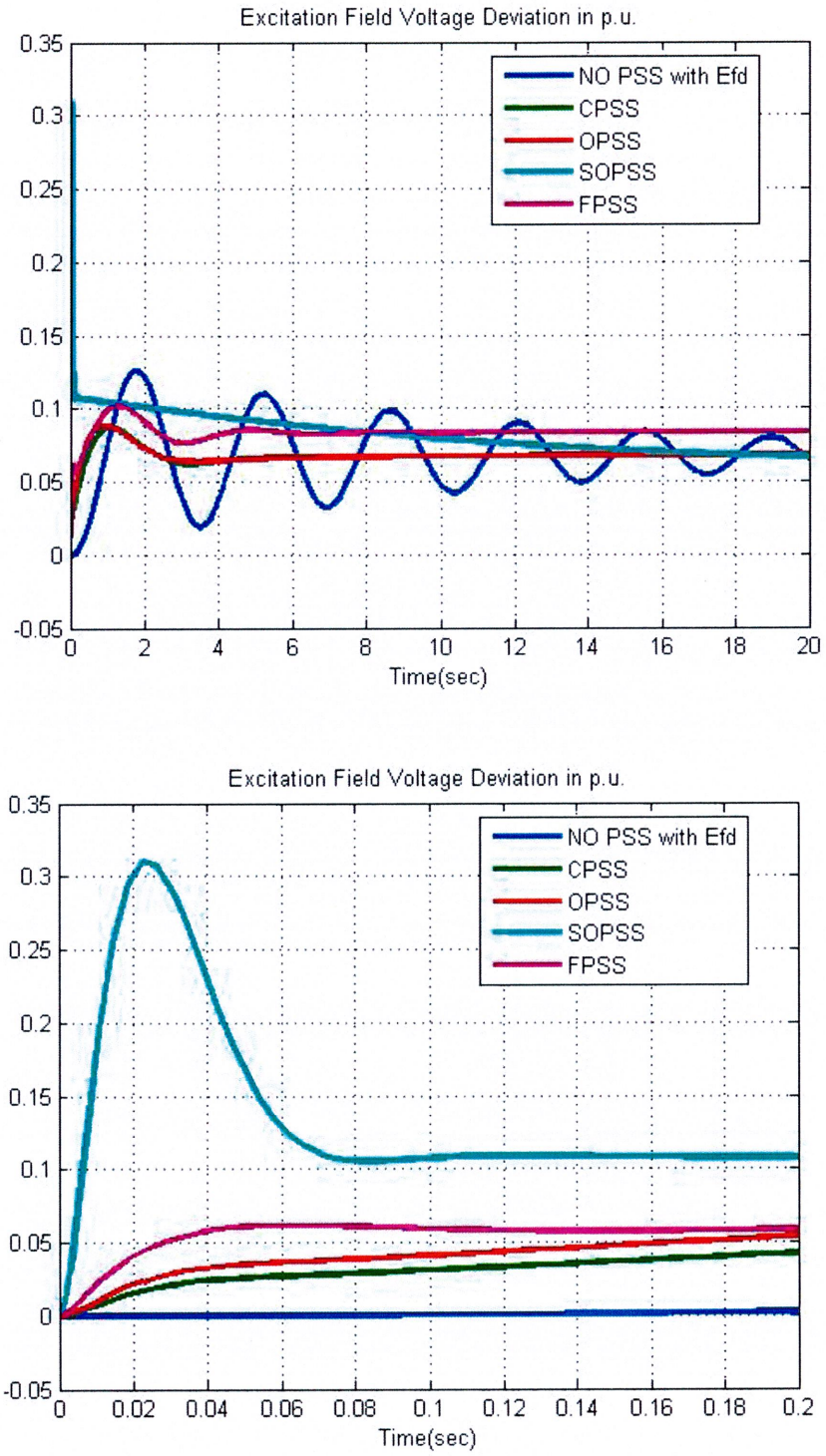


Fig.4.13 Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) with no speed droop

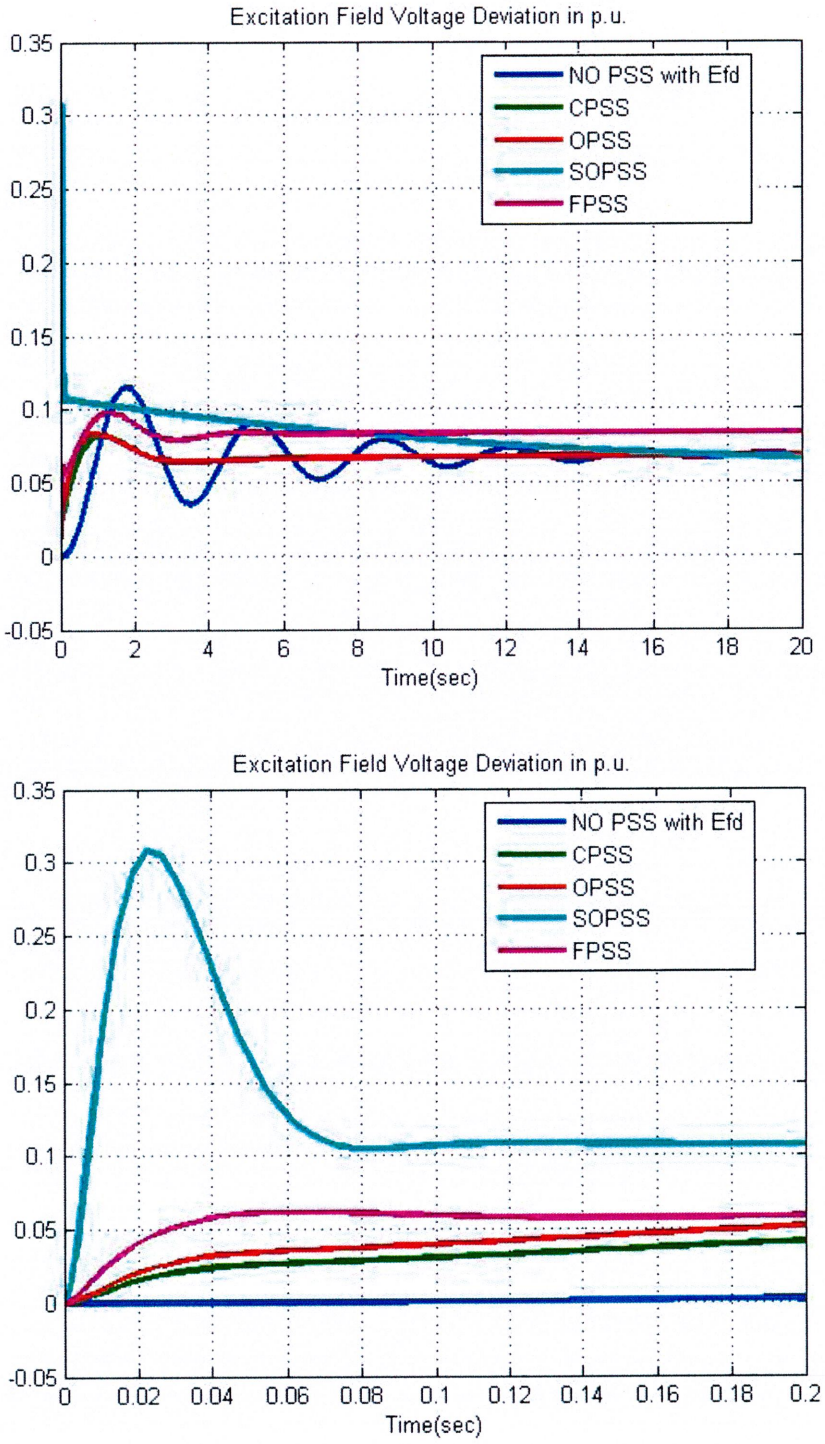


Fig.4.14 Excitation field voltage deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.1.4.3 SIMULATION DISCUSSION

- The eigenvalue analysis is done to investigate the stability of the Single machine infinite bus (SMIB) achieved by no control (constant field voltage), exciter control only, conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), and sub-optimal power system stabilizer (SOPSS). The eigenvalue analysis results are shown in appendix [H], these results indicate that the system is stable even when no power system stabilizer included in the system. The margin of stability is extended when a power system stabilizer is used.

- The figures (4.3 - 4.14) shows the simulation results following a small disturbance (5 % step change in the mechanical torque (ΔT_m)). All figures show the system response when there is no power system stabilizer, and when the proposed power system stabilizers are used.

- From the simulation results, it can be figured out that the single machine infinite bus (SMIB) has the same system response in both cases (Case (1) and Case (2)).

- It is clear from these figures that, the system is poorly damped when no power system stabilizer. Low frequency oscillations are effectively suppressed with the application of conventional, optimal, and fuzzy power system stabilizers. The same figures show that, the power system stabilizers are still required even when speed droop is included.

- The speed droop effect can be seen clearly from the rotor angle, angular speed, and field voltage deviations figures. The settling time and deviation in magnitudes during transients are reduced when speed droop is included.

- Simulation results prove that fuzzy power system stabilizer provide a comparable robustness and adequate performance as the conventional, and optimal power system stabilizers.

4.1.5 COMPUTER SIMULATION RESULTS OF SMIS

4.1.5.1 SMIS Simulation results (Case-1)

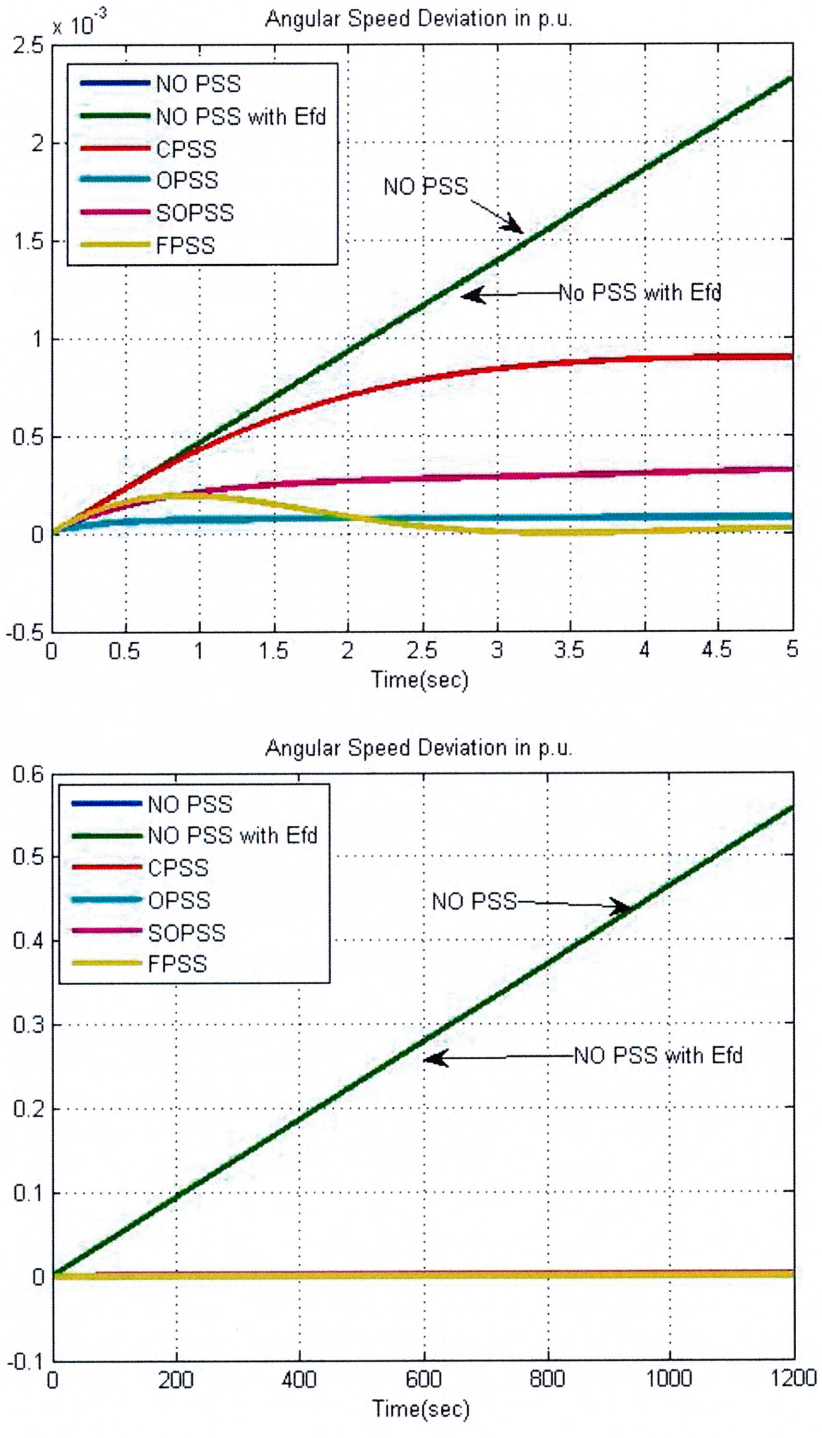


Fig.4.15 Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop

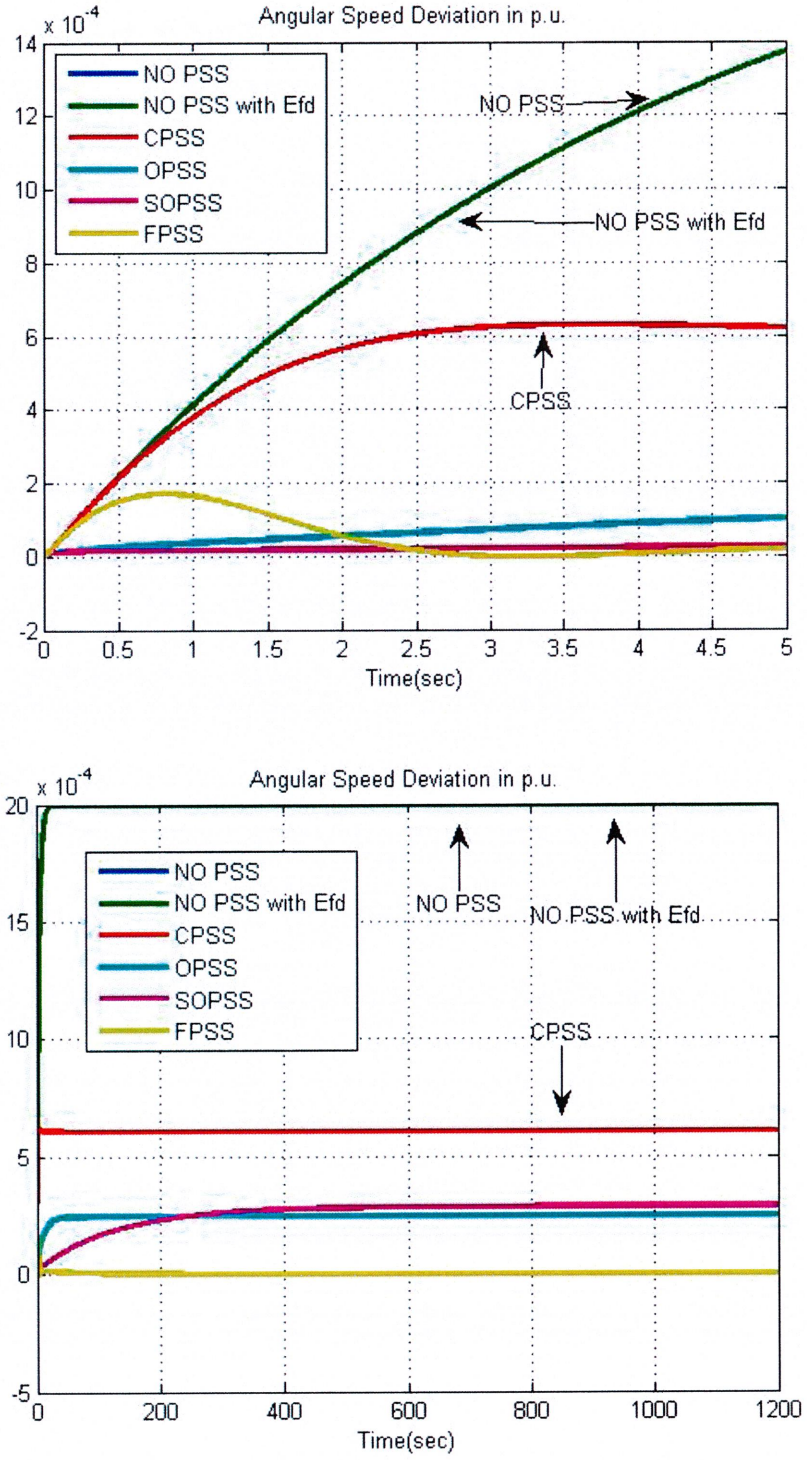


Fig.4.16 Angular speed deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.1.5.2 SMIS Simulation results (Case-2):

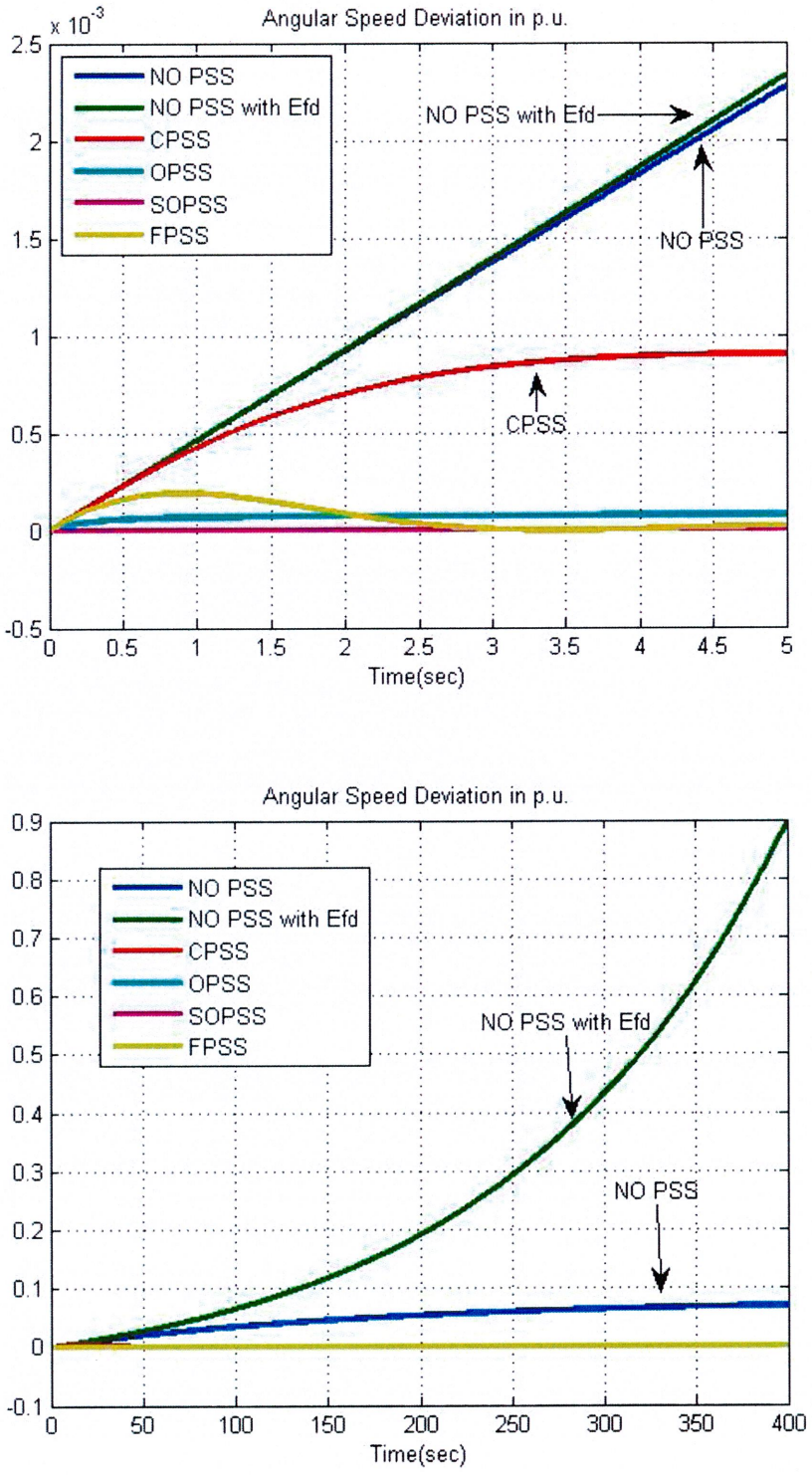


Fig.4.17 Angular speed deviations after 5% step change in the mechanical torque (T_m) with no speed droop

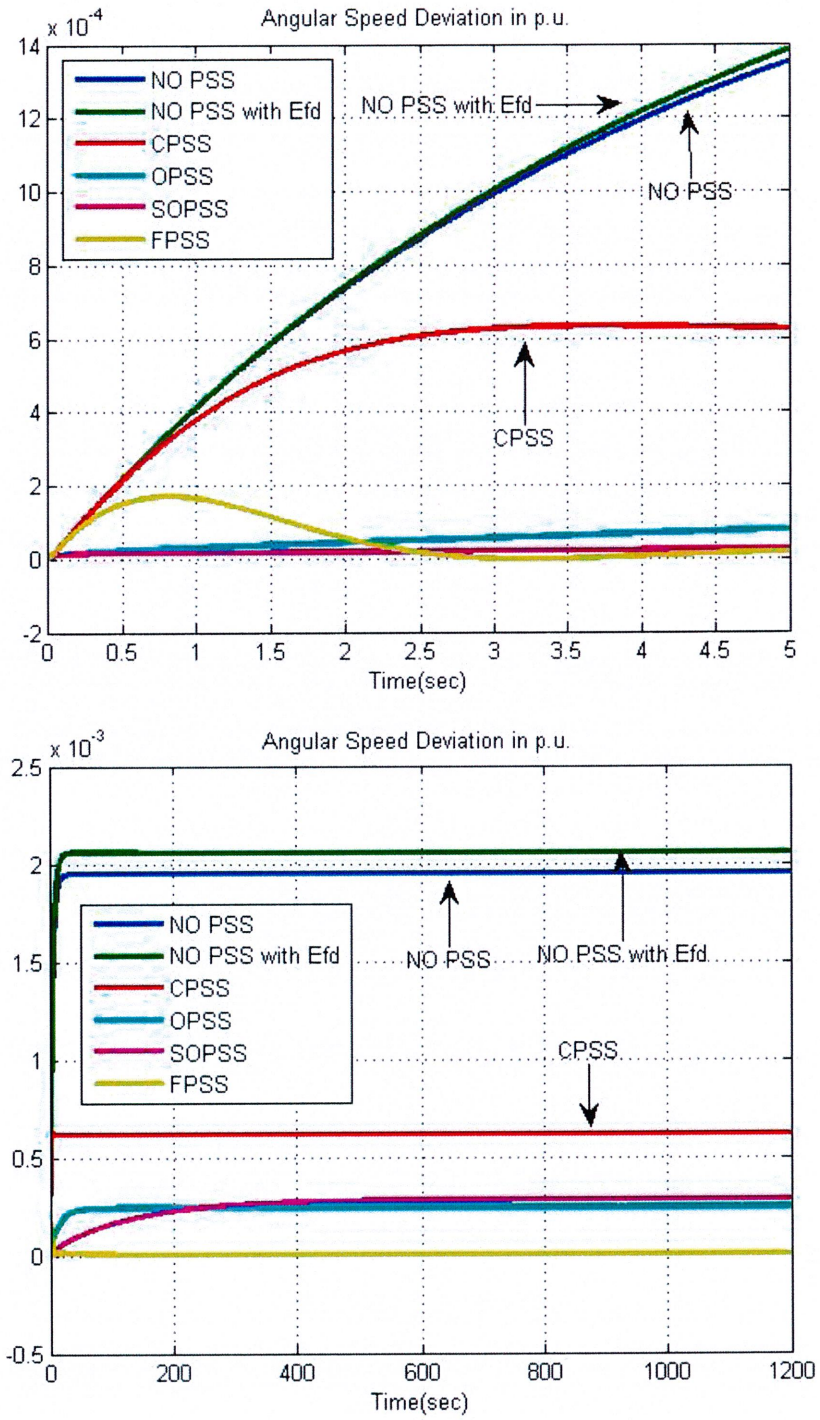


Fig.4.18 Angular speed deviations after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.1.5.3 SIMULATION DISCUSSION

- The eigenvalue analysis is done to investigate the stability of the Single machine isolated system (SMIS) achieved by no control (constant field voltage), exciter control, conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), and sub-optimal power system stabilizer (SOPSS). The eigenvalue analysis results are shown in appendix [H].

- The figures (4.15 - 4.18) shows the simulation results following a small disturbance (5 % step change in the mechanical torque (ΔT_m)). All figures show the system response when there is no power system stabilizer, and when the proposed power system stabilizers are used.

❖ SMIS-case (1)

- Eigenvalue analysis results indicate that the system is unstable in case of no power system stabilizer is equipped in the system. The speed droop stabilizes the system even when there is no power system stabilizer. The stability of the system is improved when a power system stabilizer is used.

- The simulation results show that when no power system stabilizer with constant field voltage (no exciter control) and no power system stabilizer with exciter control cases have an identical response.

- It is clear from the figures (4.15-4.16) that, the optimal and fuzzy power system stabilizers effectively damp out the low frequency oscillations under this disturbance. Also same figures show that both stabilizers can give adequate performance. In addition, the oscillations are significantly damped when the speed droop model included in the system.

- The settling time and deviation in magnitudes during transients are improved when speed droop is included.

❖ SMIS-case(2)

- The eigenvalues analysis results show that the system is unstable when no power system stabilizer with exciter control. However, the system is stable if the field voltage is constant (no exciter control). When the speed droop model is included, the system becomes stable for all cases. The margin of stability is extended when a power system stabilizer is used.

- By reducing the exciter gain (K_a) to be in the range of (0.1 – 0.8) in case of no power system stabilizer is equipped in the power system with exciter control only, the system will be stable as shown figure (4.19). Table (4.1) shows the eigenvalues of the system before and after the reduction of the exciter gain.

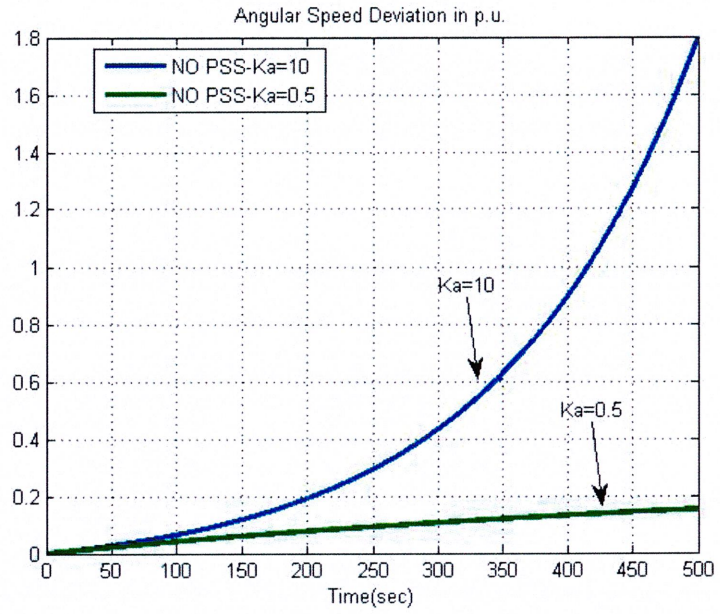


Fig.(4.19) The system response before and after exciter gain reduction

Case(2) – Ka=10	**Case(2) – Ka=0.5**
-4.8746e1	-4.994e1
6.568e-3	-2.7415
-1.4445	-1.6739e-3
-2.7063	-2.0813e-1

Table 4.1 The SMIS eigenvalues (without PSS)

- It is clear from the figures (4.17-4.18) that, the optimal and fuzzy power system stabilizers significantly improve the power system stability by providing good damping characteristics to low frequency oscillations under this disturbance. These figures show that both stabilizers have dynamic performance superior to other power system stabilizers. The same figures clearly show that, the oscillations are significantly damped when the speed droop model is included in the system.

- When the conventional power system stabilizer (CPSS) is equipped in the single machine isolated system (SMIS) in both cases (Case (1) and Case (2)), the system will remain unstable (practically all machines include the speed

droop control which is stabilize the system). To stabilize the system simply a positive feedback stabilizing signal from the speed deviation through a gain to the input of the exciter circuit without washout circuit and phase lead – lag stages (CPSS-Dpss only). Moreover also the system can be stabilized by using the conventional power system stabilizer beside of using a positive stabilizing signal from the speed deviation through a gain to the exciter input (CPSS- with Dcon) where the gain is equal to CPSS gain (Dpss). Figure (4.20) shows the system response for each case of stabilizing the system by using the conventional power system stabilizer and the modified CPSS. Table (4.2) shows the eigenvalues of the system for each case of stabilizing the system by using the conventional power system stabilizer and the modified CPSS. The modified CPSS is simply a CPSS with washout and two phase – lead blocks with a positive feedback stabilizing signal from the speed deviation through a gain (Dcon) equal to CPSS gain (Dpss) to the input of the exciter.

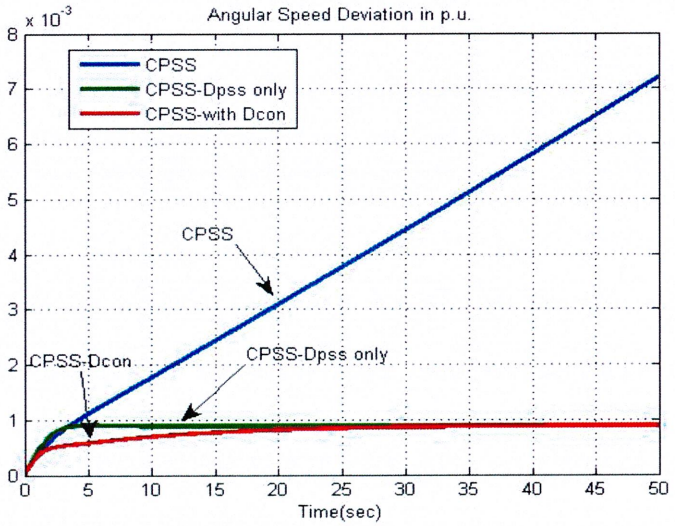


Fig. (4.20) The system response with CPSS

Case (1)		Case (2)	
CPSS	**Modified CPSS**	**CPSS**	**Modified CPSS**
-1.239e2	-1.239e2	-1.239e2	-1.239e2
-6.225e1+j1.9046e1	-6.225e1+j1.9048e1	-6.225e1+j1.9048e1	-6.225e1+j1.905e1
-6.225e1-j1.9046e1	-6.225e1-j1.9048e1	-6.225e1-j1.9048e1	-6.225e1-j1.905e1
4.732e-12	-2.7199	**1.8303e-3**	-2.1794
-8.985e-1	-9.271e-1+j7.877e-1	-8.4629e-1	-9.315e-1+j7.784e-1
-1.0748	-9.271e-1-j7.877e-1	-1.1372	-9.315e-1-j7.784e-1
-2.7071	-9.4198e-2	-2.7063	-9.343e-2

Table 4.2 The SMIS eigenvalues (with PSS)

4.2 MULTI-MACHINE SYSTEM

The effectiveness and performance of the proposed power system stabilizers are compared through the simulation of a two machine system and a three machine system with a small disturbance of 5% step change in the mechanical torque (ΔT_m). The computer simulation has been done by using MATLAB R2007b package.

4.2.1 MULTI-MACHINE SYSTEM MODELS

The multi-machine systems consist of synchronous generators including an excitation system (exciter) in each machine; these machines are supplying several loads through transmission lines (links). The two machine model is shown in Figure 4.21 and the three machine system is the popular Western System Coordinating Council (WSCC) 3-machines, 9-bus system as shown in Figure 4.22.

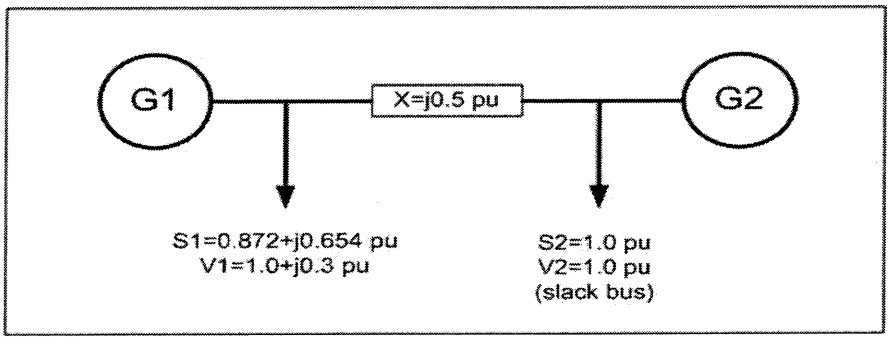


Fig.4.21 Two machine system model

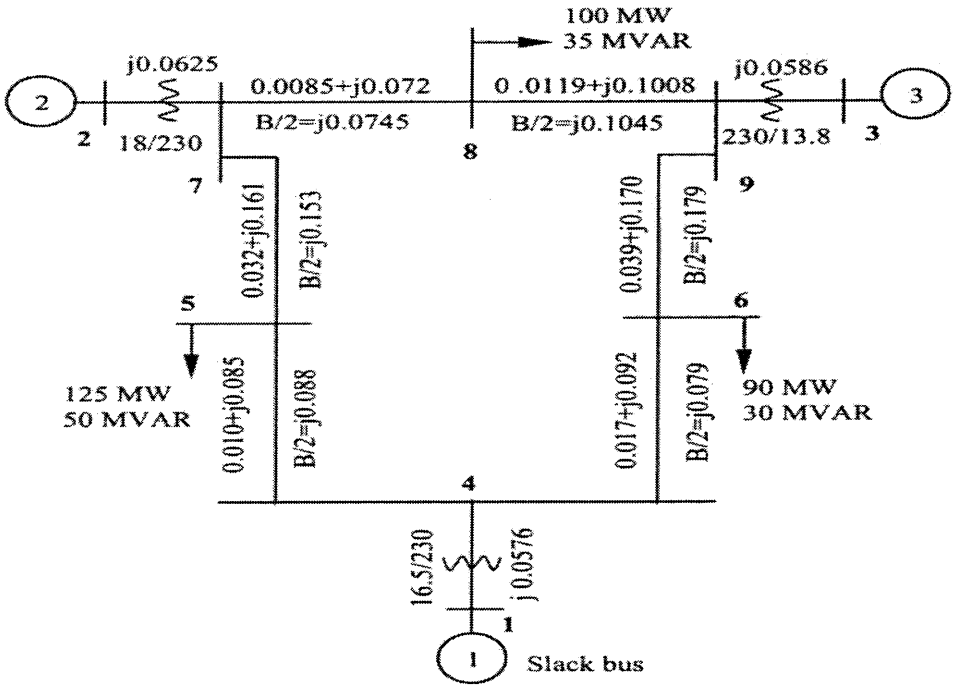


Fig.4.22 Three machine system model

- The full detail of I_q and I_d current gains analysis for multi-machine system is shown in appendix [C].
- The I_q and I_d current gains results for multi-machine system is shown in appendix [G].

4.2.2 SYSTEMS PARAMETERS

The parameters of the stabilizers have been tuned at the nominal operating condition. For the conventional power system stabilizer (CPSS) the parameters of the phase lead compensator are calculated as per the design procedure given in section 3.1.2. For the optimal power system stabilizer (OPSS) and the sub-optimal power system stabilizer (SOPSS), the control weighting (R) is chosen as unity and the state matrix (Q) is found through several trial and error procedures to give the best dynamic performance. The fuzzy power stabilizer scaling factors are found by several trial and error procedures to have the best performance.

- The parameters of multi-machine system models are shown in appendix [D].

- The initial conditions calculations and results of multi-machine system models are shown in appendix [F].

- A summary of equations for multi-machine system models simulation is shown in appendix [E].

4.2.3 EIGENVALUES ANALYSIS

The eigenvalues analysis is done to investigate the mode of oscillations, the damping characteristics, and the stability of the investigated system achieved by the conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), suboptimal power system stabilizer (SOPSS), and fuzzy power system stabilizer (FPSS).

- The full details of the eigenvalues analysis results of multi machine system models are shown in appendix [H].

- The A matrix results of multi machine system models are shown in appendix [I].

4.2.4 COMPUTER SIMULATION RESULTS OF THE TWO MACHINES SYSTEM

4.2.4.1 Two Machines System simulation results (Case-1)

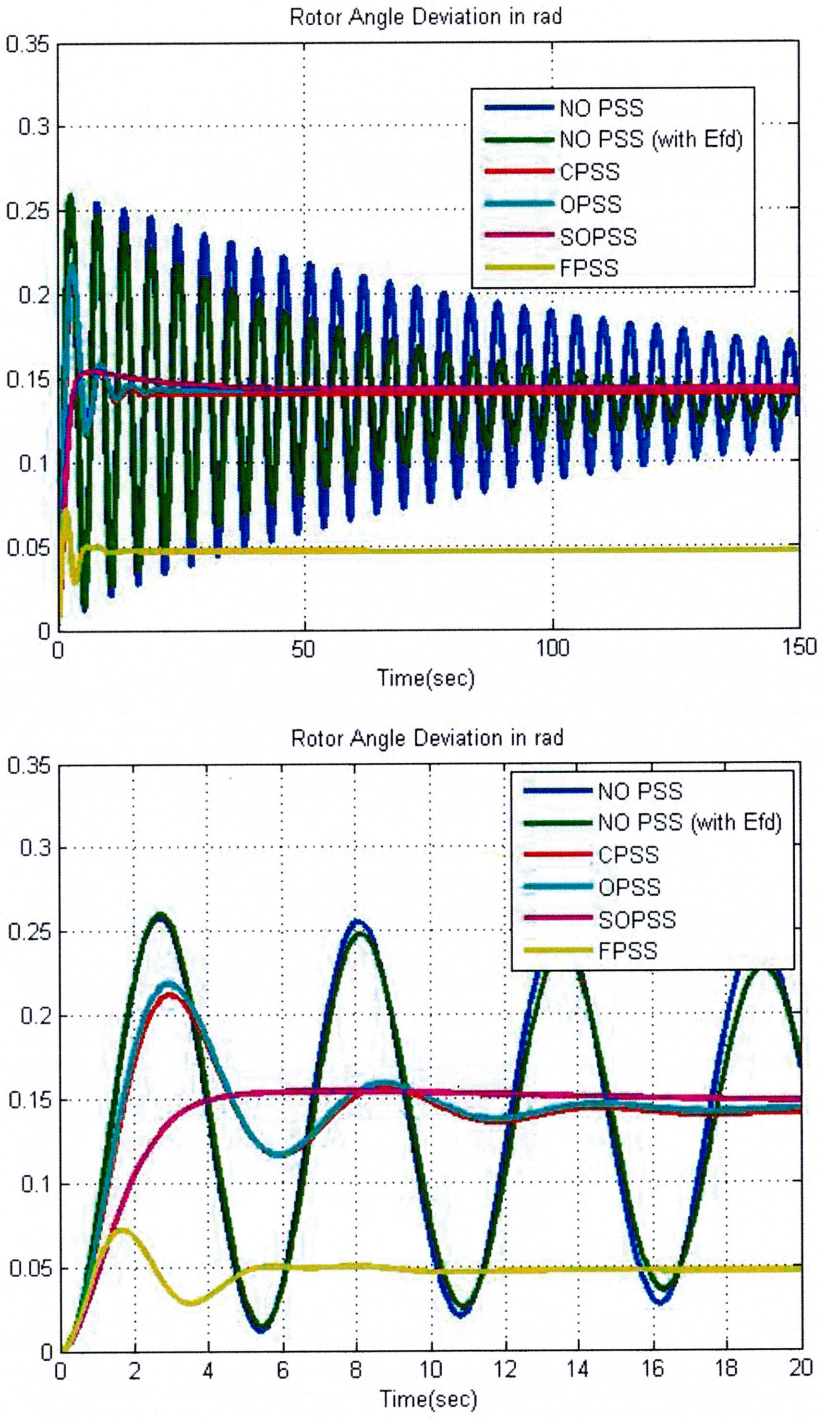


Fig.4.23 Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) with no speed droop

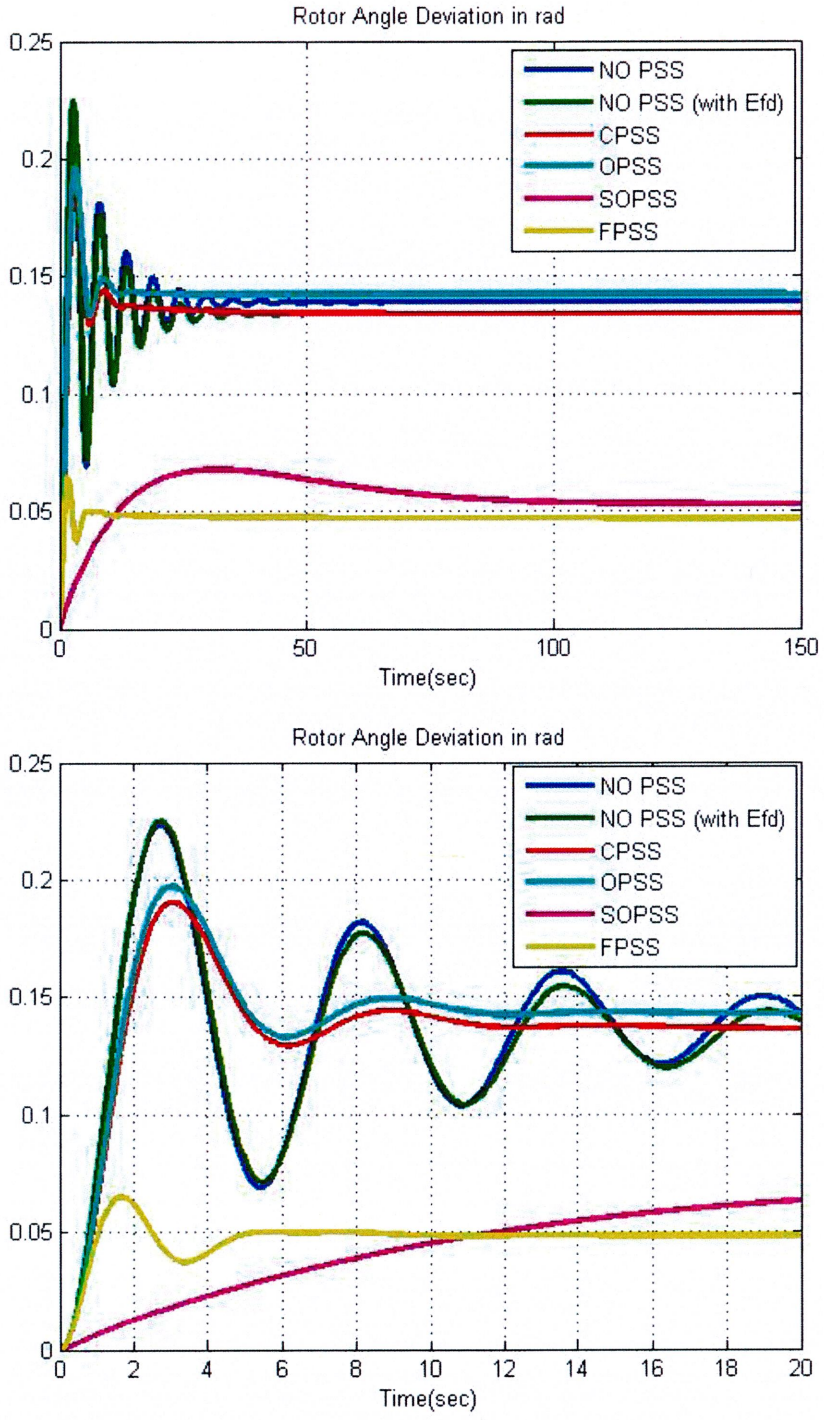


Fig.4.24 Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) including the speed droop of 4%

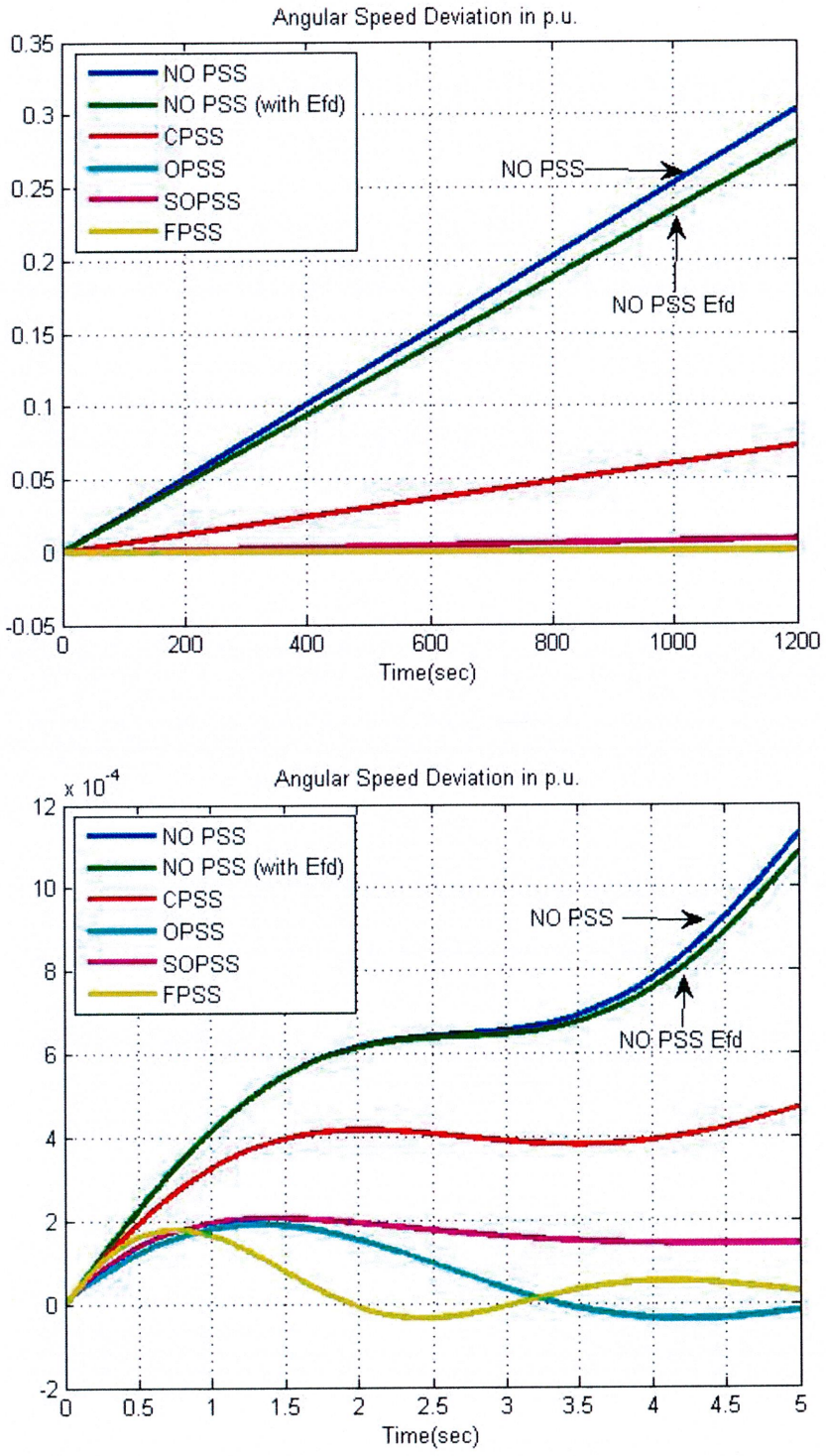


Fig.4.25 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop

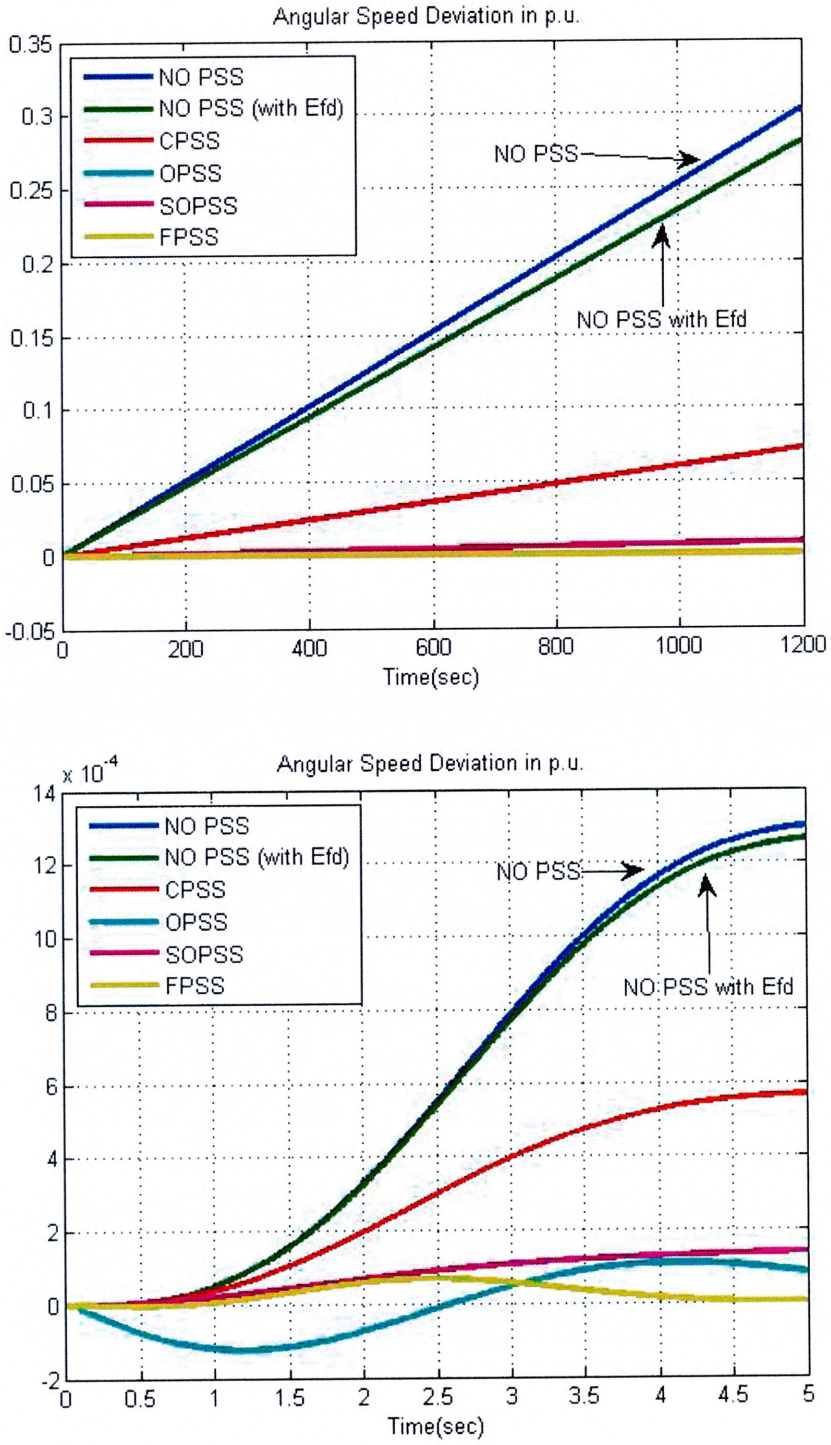


Fig.4.26 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

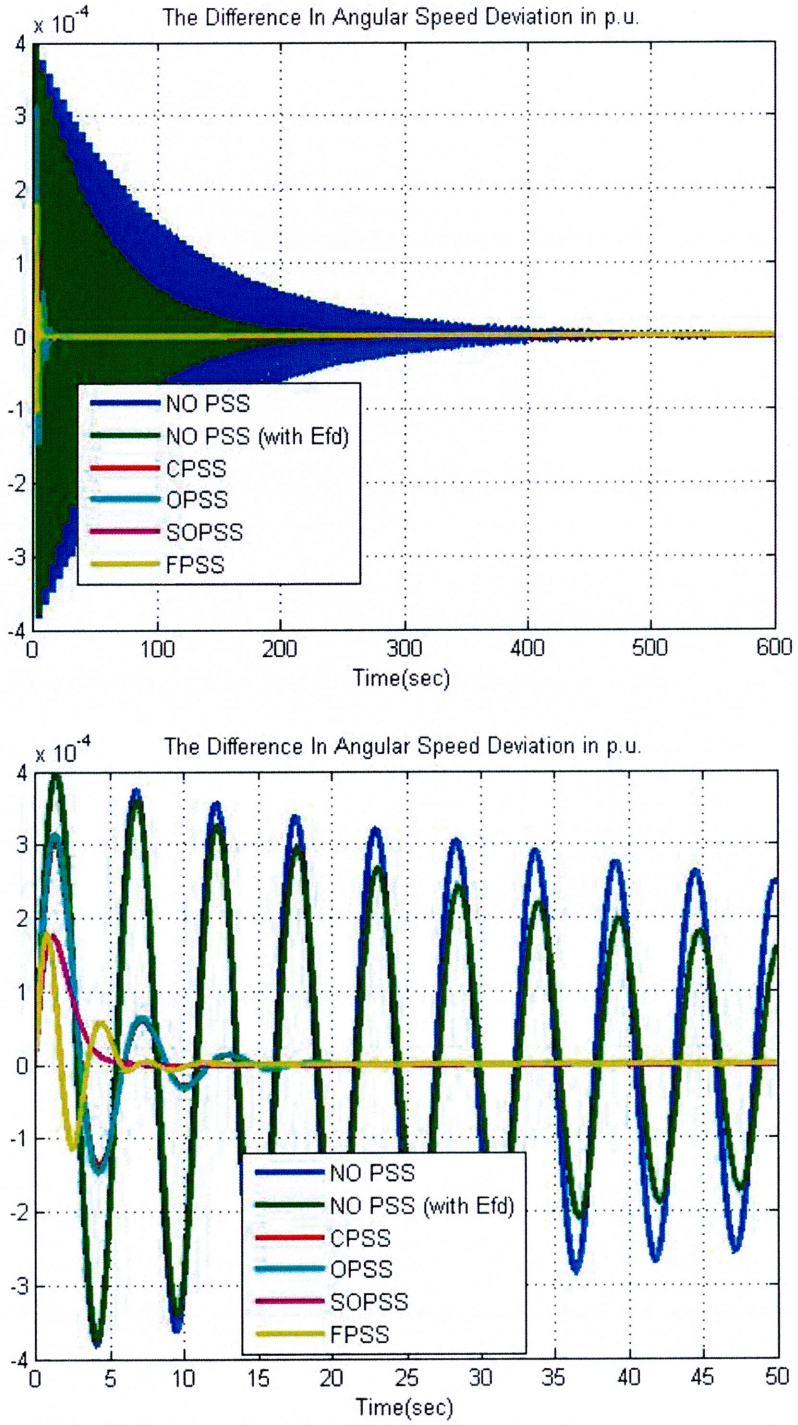


Fig.4.27 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

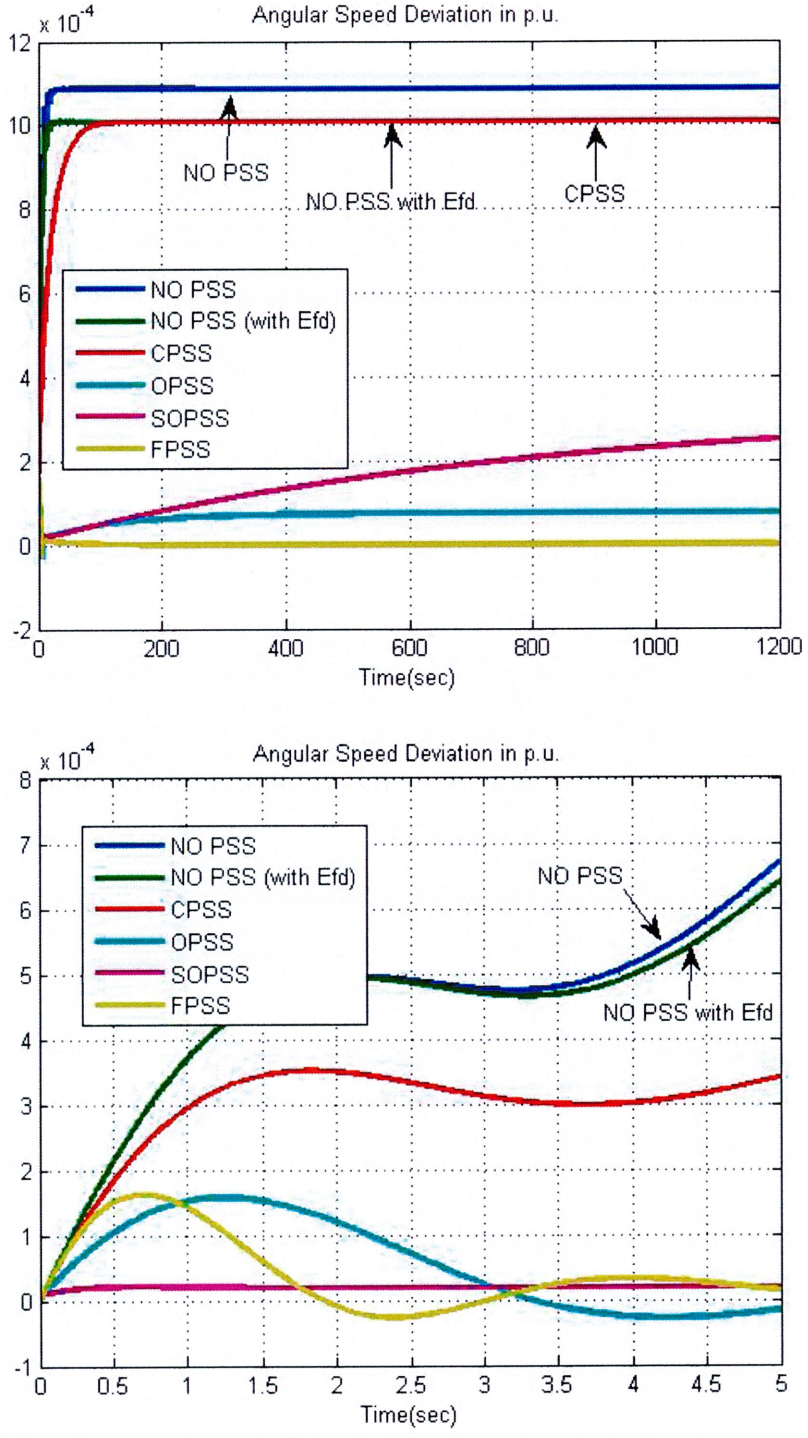
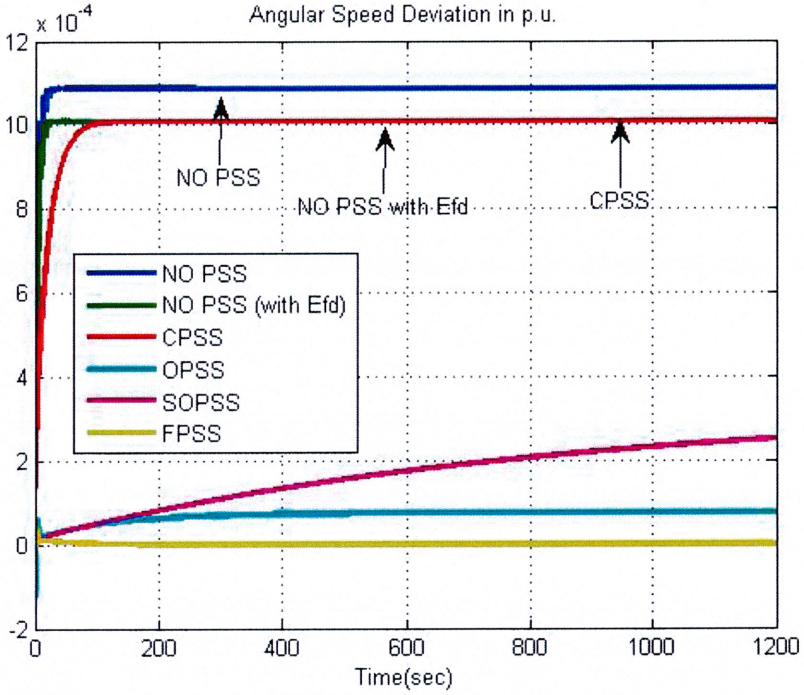


Fig.4.28 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%



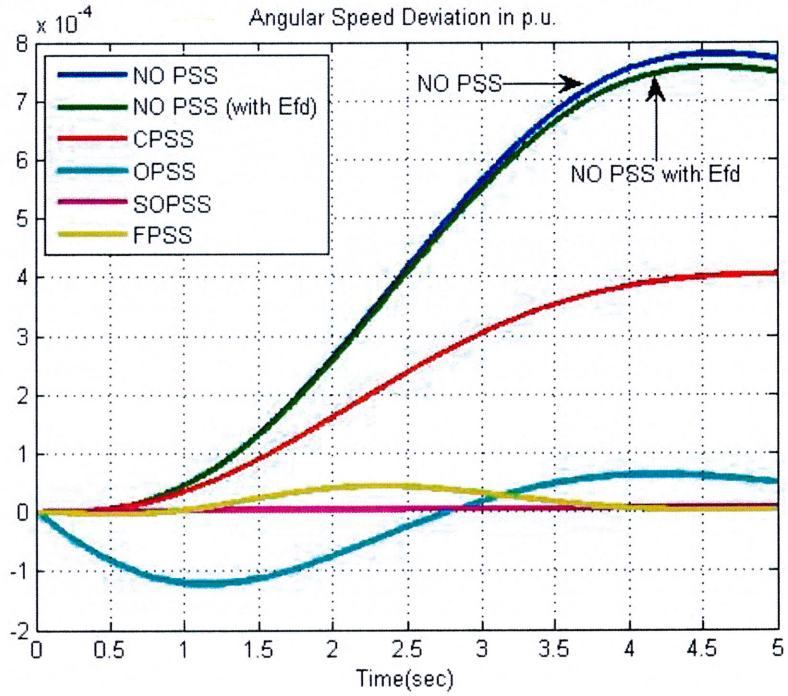


Fig.4.29 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

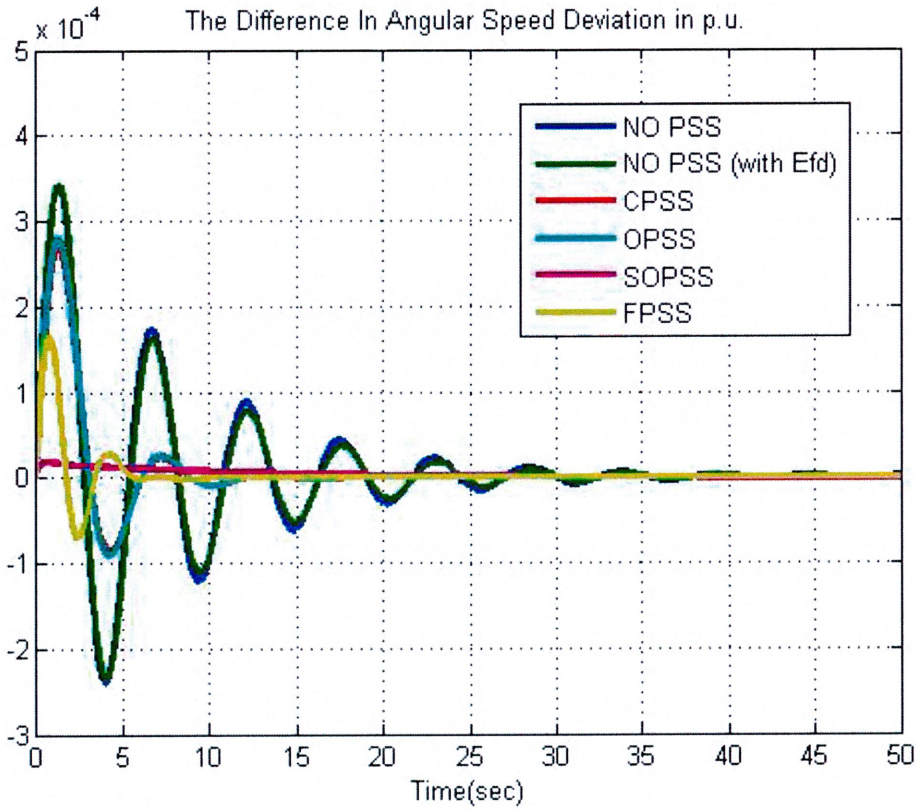


Fig.4.30 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.2.4.2 Two Machines System simulation results (Case-2)

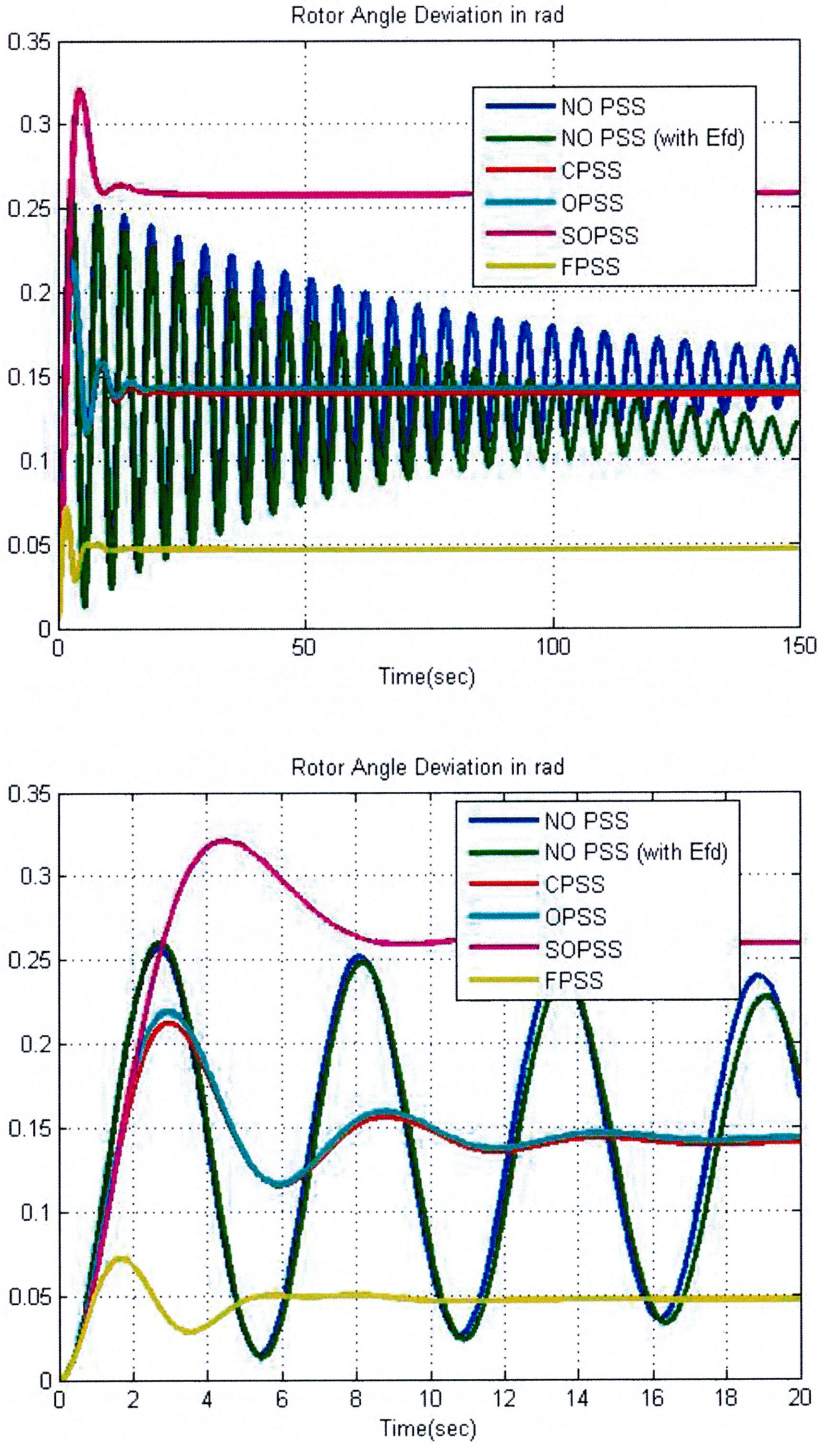


Fig.4.31 Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) with no speed droop

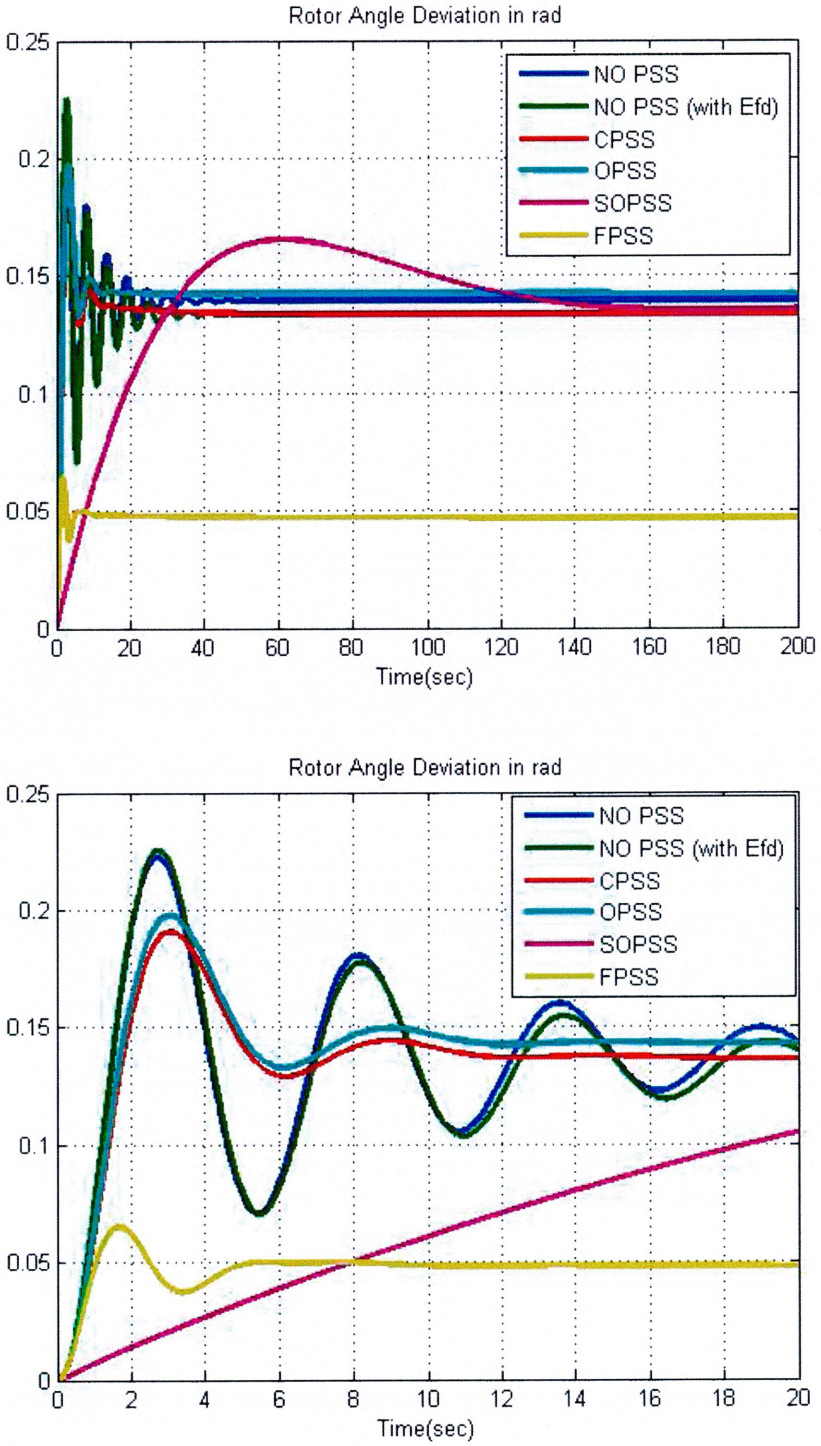


Fig.4.32 Rotor angle deviations of machine (1) after 5% step change in the mechanical torque (T_m) with respect to machine (2) including the speed droop of 4%

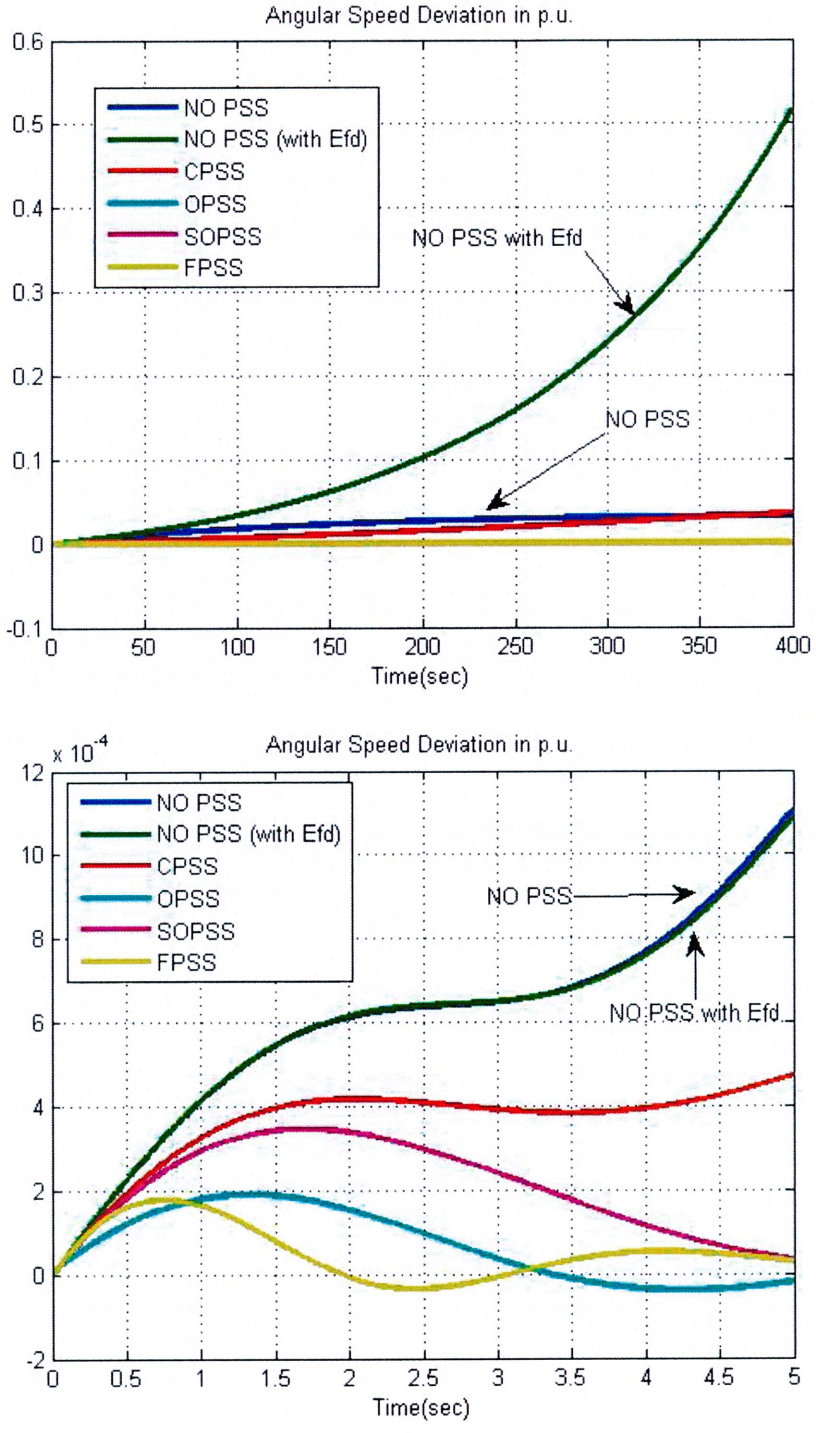


Fig.4.33 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop

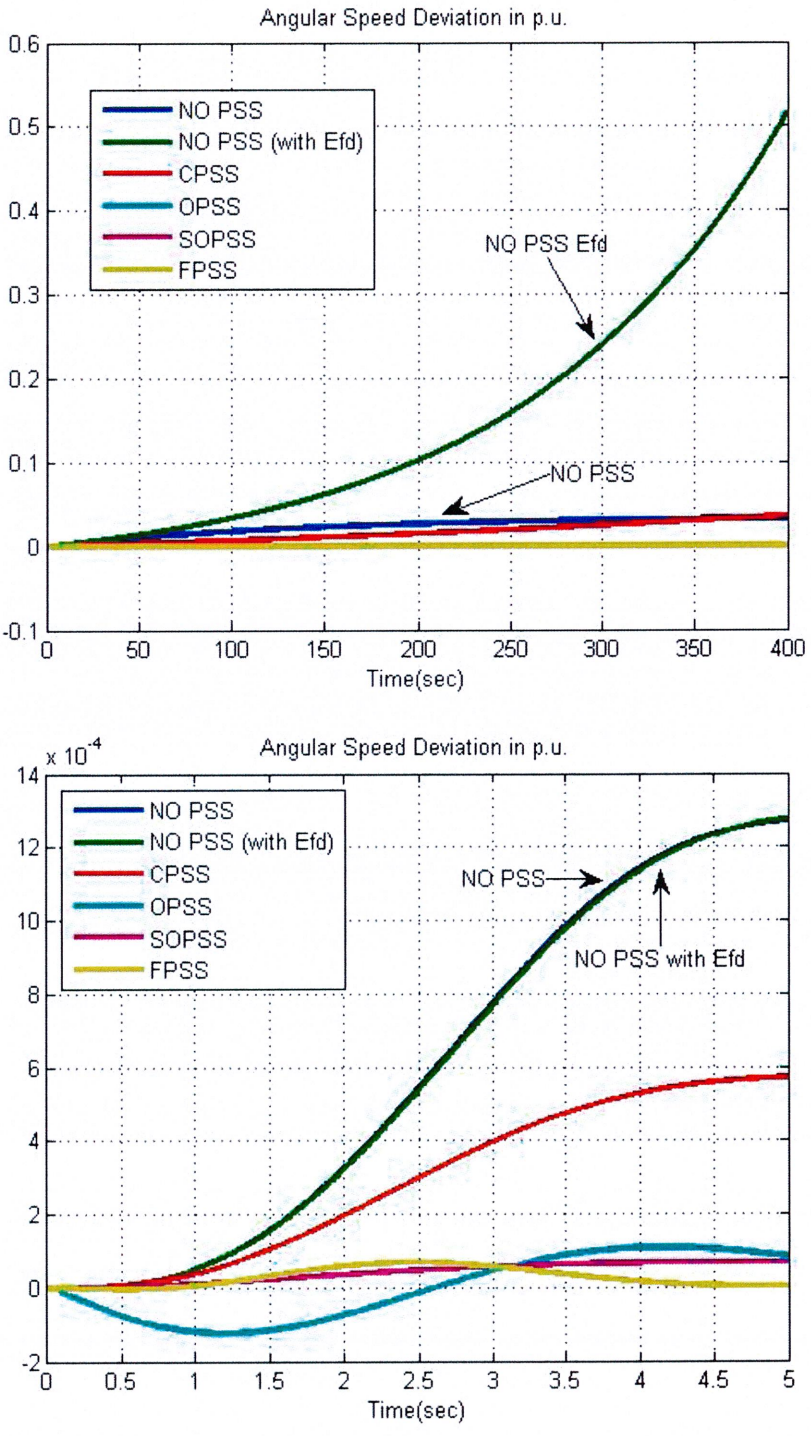


Fig.4.34 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

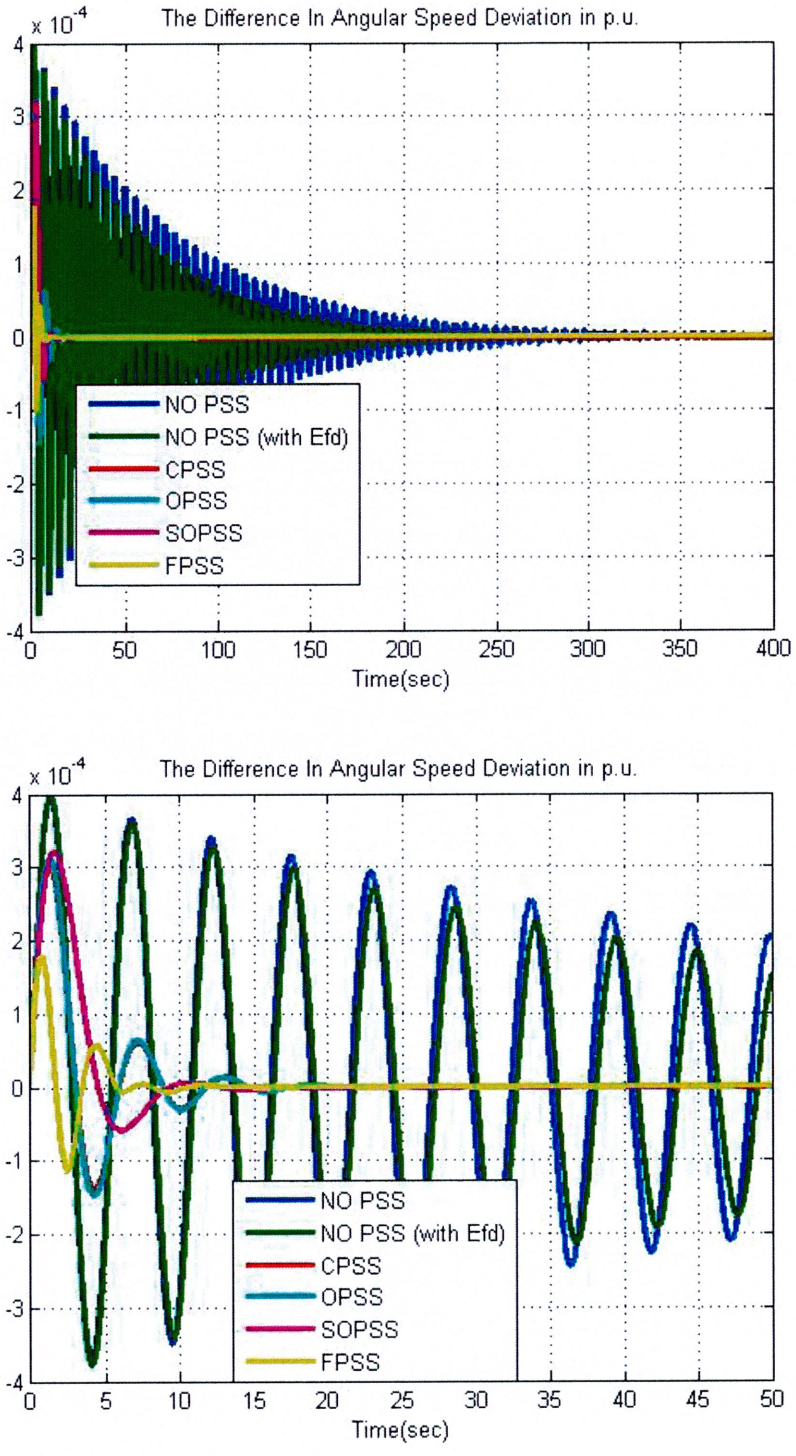


Fig.4.35 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

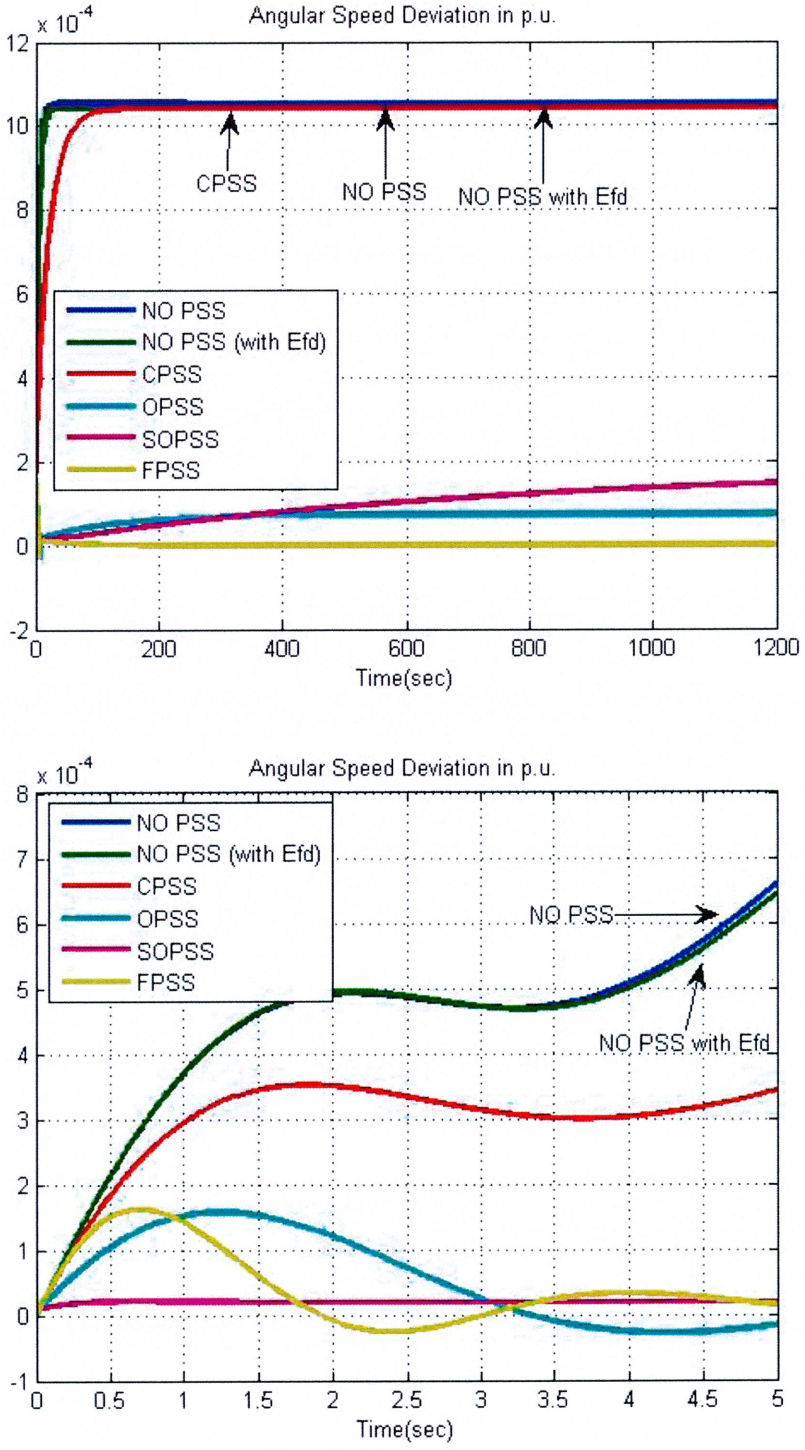


Fig.4.36 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

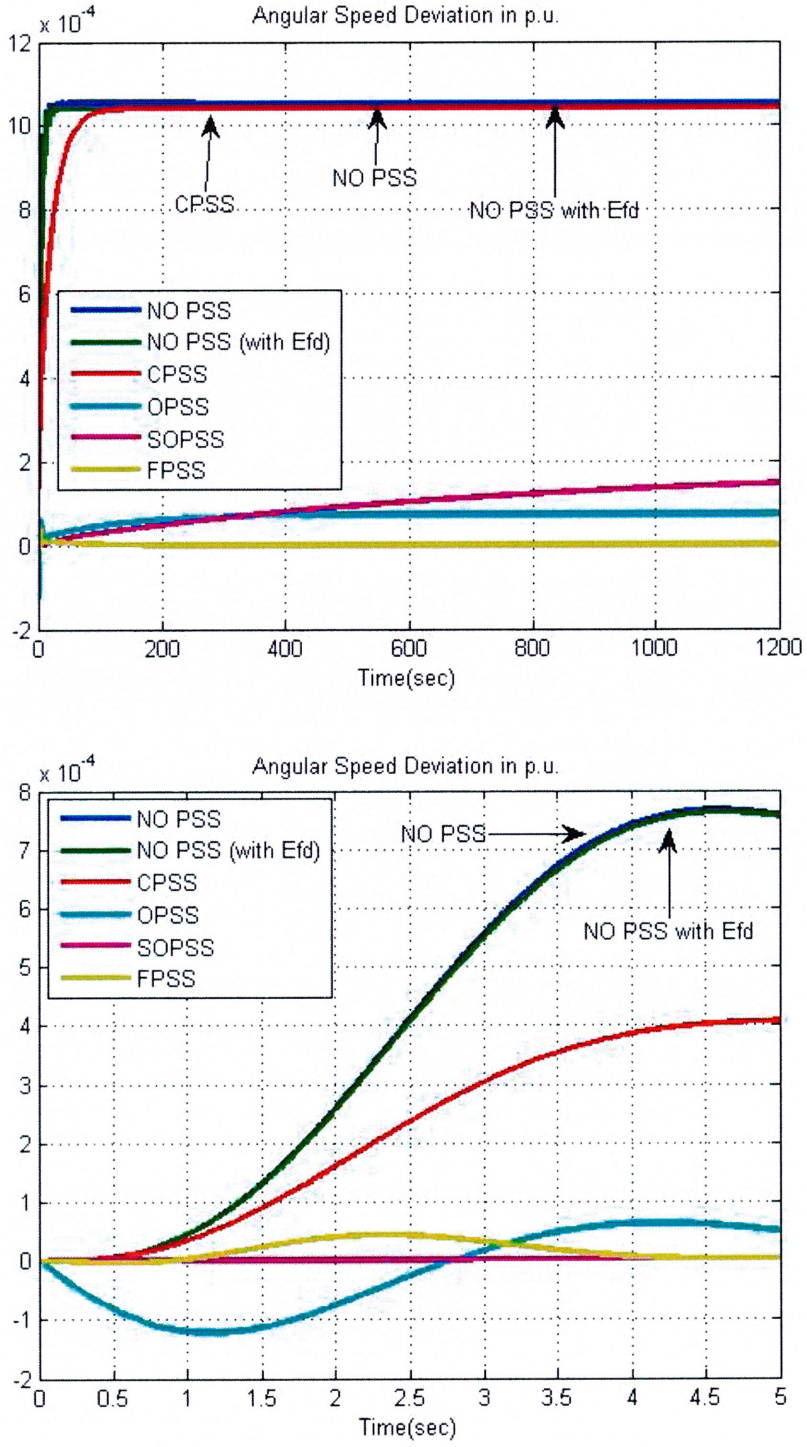


Fig.4.37 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

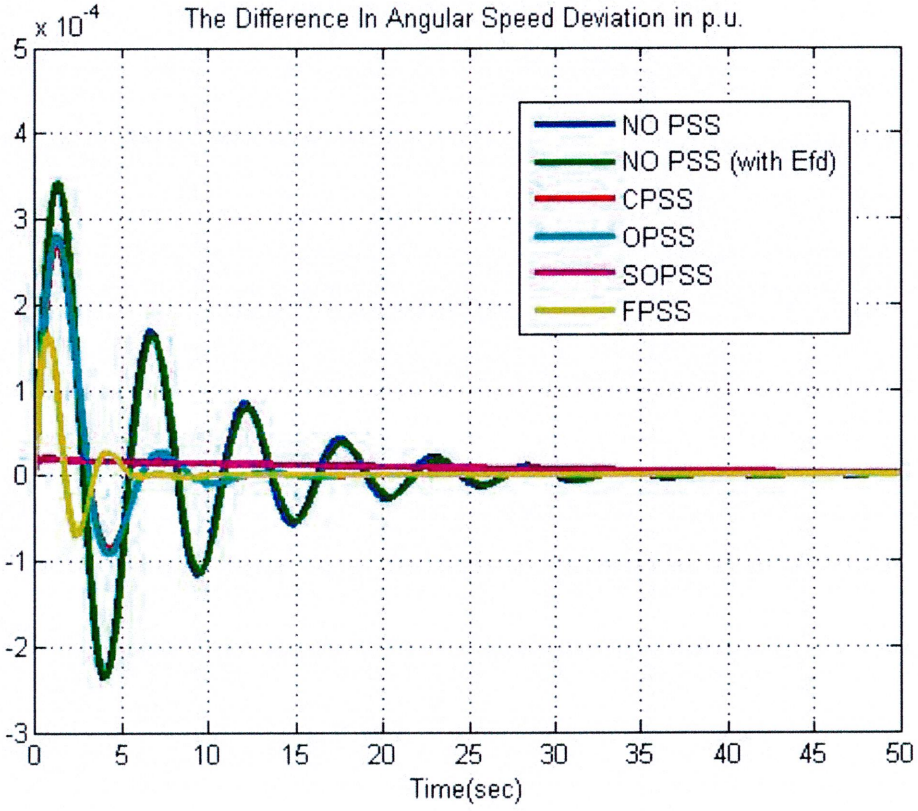


Fig.4.38 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.2.4.3 SIMULATION DISCUSSION

- The eigenvalue analysis is done to investigate the stability of the multi-machine system (two machine system) achieved by no control (constant field voltage), exciter control, conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), and sub-optimal power system stabilizer (SOPSS). The eigenvalue analysis results are shown in appendix [H].

- The figures (4.21 - 4.36) show the simulation results following a small disturbance (5 % step change in the mechanical torque (ΔT_m)). All figures show the system response when there is no power system stabilizer, and when the proposed power system stabilizers are used.

❖ Two machine system-case (1)

- Eigenvalue analysis results indicate that the system is unstable in case of no power system stabilizer equipped in the system and also when the conventional power system stabilizer is used. The system is stabilized even when there is no power system stabilizer when the speed droop model included in the system. The stability of the system is improved when a power system stabilizer is used.

- It is clear from the figures (4.21-4.28) specially (4.21) that, the system is poorly damped when no power system stabilizer under this disturbance, so a power system stabilizer is required to damp the low frequency power system oscillations.

- The angular speed deviation ($\Delta\omega_r$) figures (4.23-4.24) show that, with maintaining the load constant the conventional power system stabilizer (CPSS) did not provide a good damping characteristics to low frequency oscillations under this disturbance. As a results from adding the speed droop model to the system the conventional power system stabilizer (CPSS) provide a good damping characteristics to low frequency oscillations under the same disturbance as shown in figures (4.26-4.27).

- The same figures show that, the optimal and fuzzy power system stabilizers provide the best performance and outperform the other stabilizers. The low frequency oscillations are significantly damped when the speed droop effect is included in the system.

❖ Two machine system-case (2)

- Eigenvalue analysis results indicate that the system is unstable in case of no power system stabilizer with exciter control only and also when the conventional power system stabilizer is used. The system is stabilized even when there is no power system stabilizer equipped in the power system when the speed droop model is included in the system. The stability of the system is improved when a power system stabilizer is used.

- By reducing the exciter gain (K_a) to be in the range of $(0.1 - 0.8)$ in case of no power system stabilizer is equipped in the power system with exciter control only, the system will be stable as shown in Figure (4.39). Table (4.3) shows the eigenvalues of the system before and after the reduction of the exciter gain.

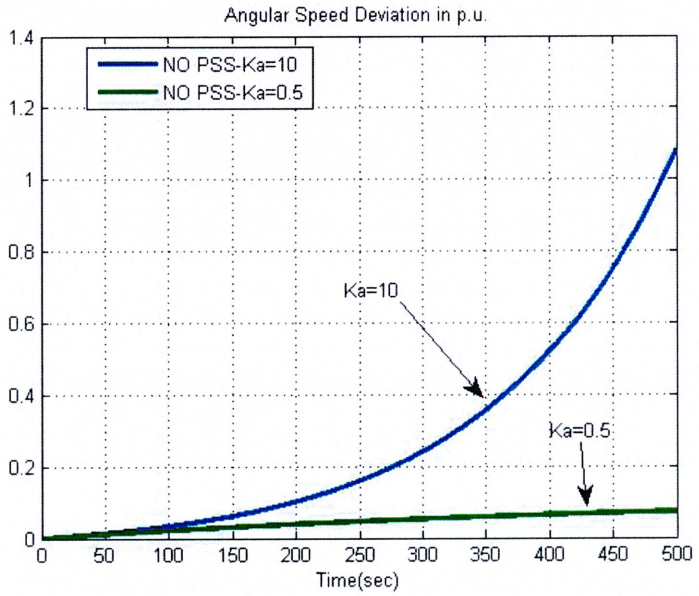


Fig. (4.39) The system response before and after exciter gain reduction

Case(2) – Ka=10	Case(2) – Ka=0.5
-4.8756e1	-4.9938e1
-4.8736e1	-4.9939e1
-1.8e-2+j1.2	-2.8347
-1.8e-2-j1.2	-2.5626
-2.8097	-1.4234e-2+j1.1646
-2.4972	-1.4234e-2-j1.1646
-1.4031	-2.1257e-3
-1.4704	-1.9302e-1
7.0473e-3	-2.0277e-1

Table 4.3 The two machine system eigenvalues (without PSS)

- It is clear from the figures (4.29-4.36) specially (4.29) that, the system did not have a good characteristic to damp the system oscillations when no power system stabilizer under this disturbance, so a power system stabilizer is required to damp the low frequency power system oscillations.

- The angular speed deviation ($\Delta\omega_r$) figures (4.31-4.32) show that, the conventional power system stabilizer (CPSS) did not provide a good damping characteristics to low frequency oscillations for the isolated system (constant load) under this disturbance. By adding the speed droop model to the power system the conventional power system stabilizer (CPSS) provide a good damping characteristics to low frequency oscillations under the same disturbance as shown in figures (4.34-4.35).

- The same figures show that, the optimal and fuzzy power system stabilizers provide the best performance and outperform the other stabilizers. The low frequency oscillations are significantly damped when the speed droop effect is included in the system.

- The settling time and deviation in magnitudes during transients are improved when speed droop is included.

- When the conventional power system stabilizer (CPSS) is equipped in the two machine system in both cases (Case (1) and Case (2)), the system will remain unstable (practically all machines include the speed droop control which is stabilize the system). The system can be stabilized by using the conventional power system stabilizer beside of using a positive stabilizing signal from the speed deviation through a gain to the exciter input (CPSS with Dcon) where the gain is equal to the CPSS gain (Dpss). Figure (4.40) shows the system response for each case of stabilizing the system by using the conventional power system stabilizer and the modified CPSS as seen from the results by adding the speed droop in the system model. Table (4.4) shows the eigenvalues of the system for each case of stabilizing the system by using the conventional power system stabilizer and the modified CPSS. The modified CPSS is simply a CPSS with washout and two phase – lead blocks with a positive feedback stabilizing signal from the speed deviation through a gain (Dcon) equal to CPSS gain (Dpss) to the input of the exciter.

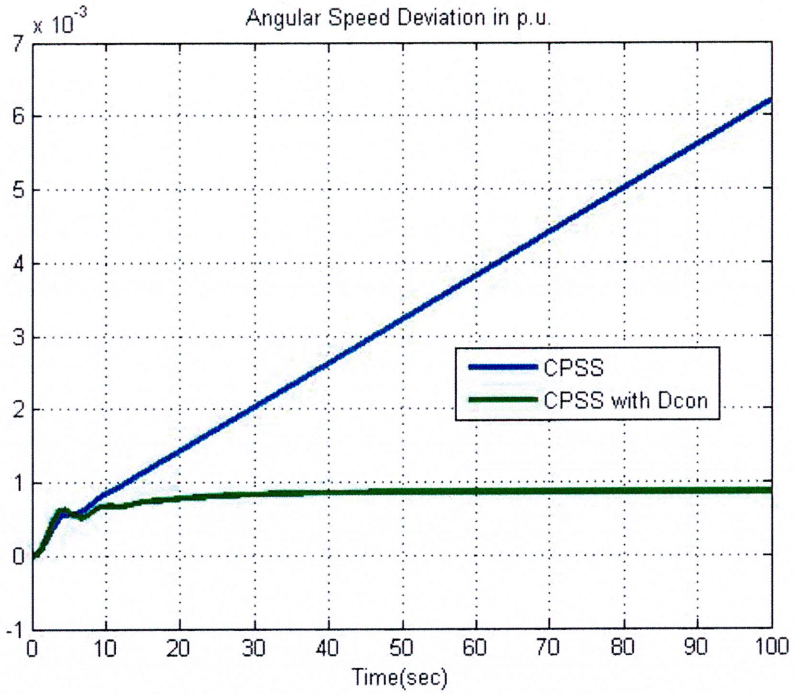


Fig. (4.40) The system response with CPSS

Case (1)		Case (2)	
CPSS	**Modified CPSS**	**CPSS**	**Modified CPSS**
-1.2603e2	-5.0e1	-1.2603e2	-5.0e1
-1.2404e2	-1.0e2	-1.2404e2	-1.0e2
-6.1e1+j2.2e1	-1.0e2	-6.1e1+j2.2e1	-1.0e2
-6.1e1-j2.2e1	-2.0e-1	-6.1e1-j2.2e1	-2.0e-1
-6.2e1+j1.9e1	-1.2399e2	-6.2e1+j1.9e1	-1.2399e2
-6.2e1-j1.9e1	-6.221e1+j1.919e1	-6.2e1-j1.9e1	-6.221e1+j1.919e1
-2.8099	-6.221e1-j1.919e1	-2.8097	-6.221e1-j1.919e1
-2.4996	-2.8132	-2.4978	-2.8131
-2.7e-1+j1.1	-2.5639	-2.7e-1+j1.1	-2.5635
-2.7e-1-j1.1	-2.403e-1+j1.118	-2.7e-1-j1.1	-2.393e-1+j1.118
-1.2501	-2.403e-1-j1.118	-1.2617	-2.393e-1-j1.118
-1.0+j1.4e-1	-6.933e-1+j6.003e-1	-1.0+j5.9e-2	-7.027e-1+j5.918e-1
-1.0-j1.4e-1	-6.933e-1-j6.003e-1	-1.0-j5.9e-2	-7.027e-1-j5.918e-1
-2.2143e-1	-8.6635e-2	-2.2138e-1	-8.64e-2
-5.5e-12	-1.3386e-1	**1.8270e-3**	-1.3415e-1

Table 4.4 The two machine system eigenvalues (with PSS)

4.2.5 COMPUTER SIMULATION RESULTS OF THE THREE MACHINES SYSTEM

4.2.5.1 Three Machines System simulation results (Case-1)

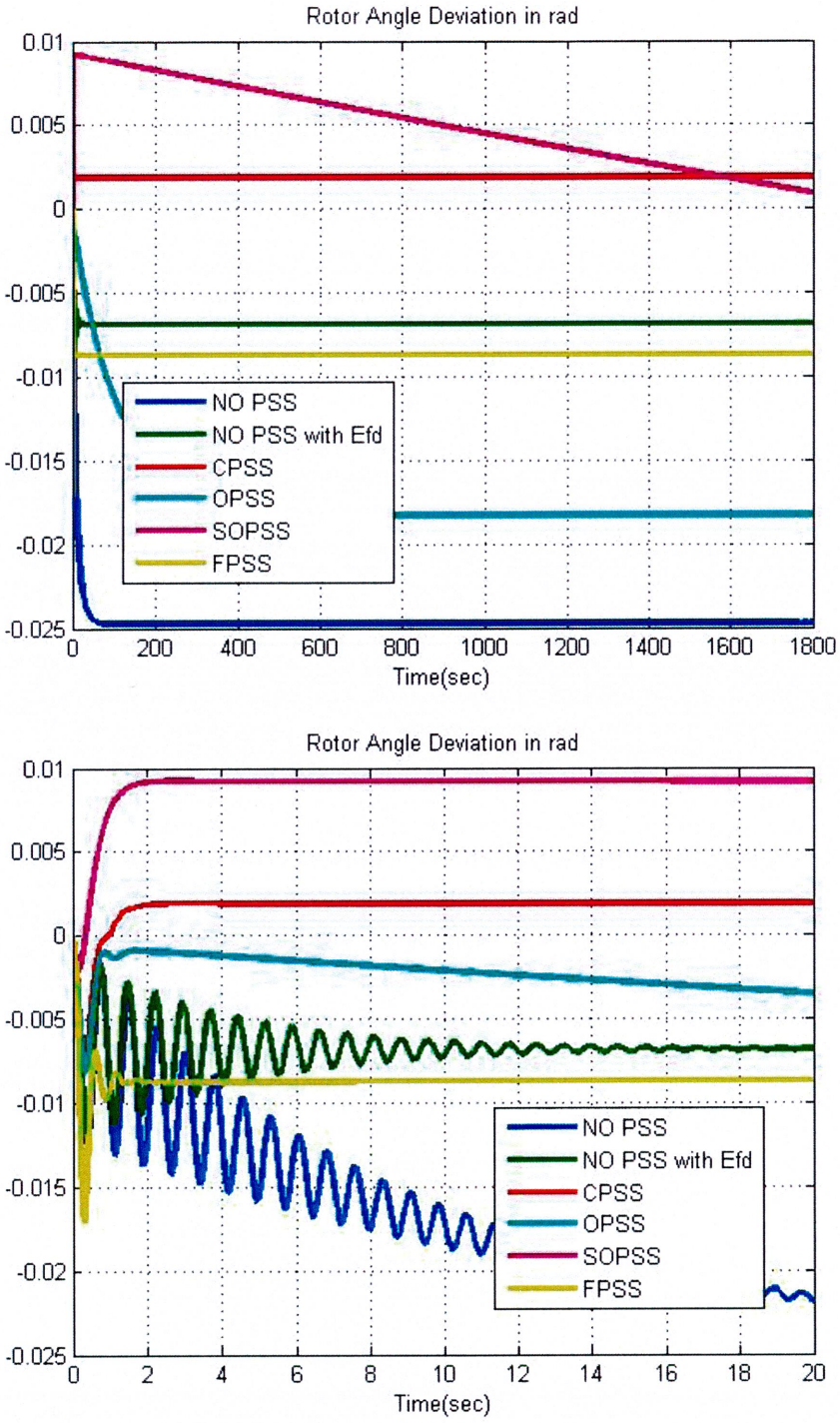


Fig.4.41 Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) with no speed droop

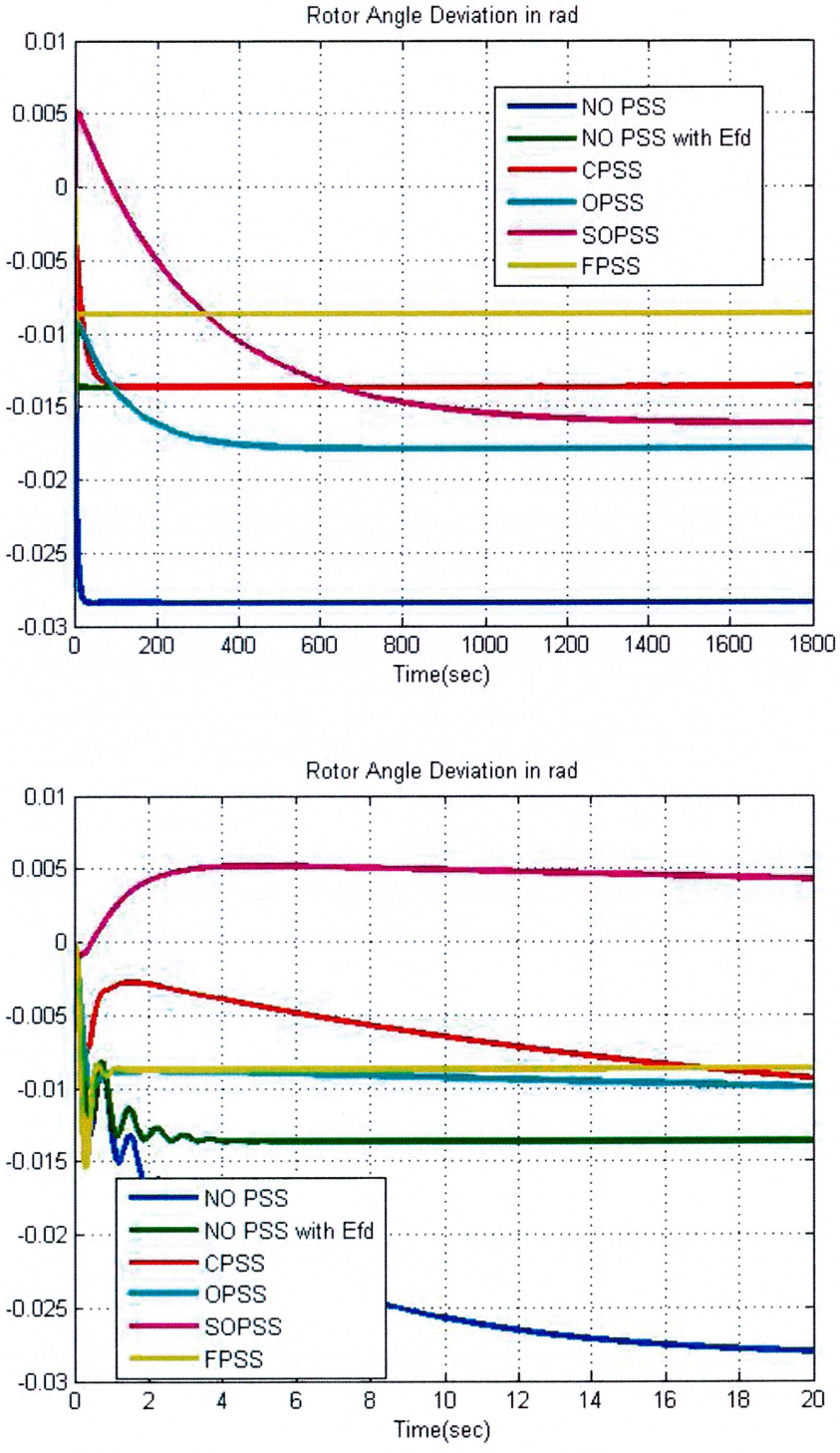


Fig.4.42 Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) including the speed droop of 4%

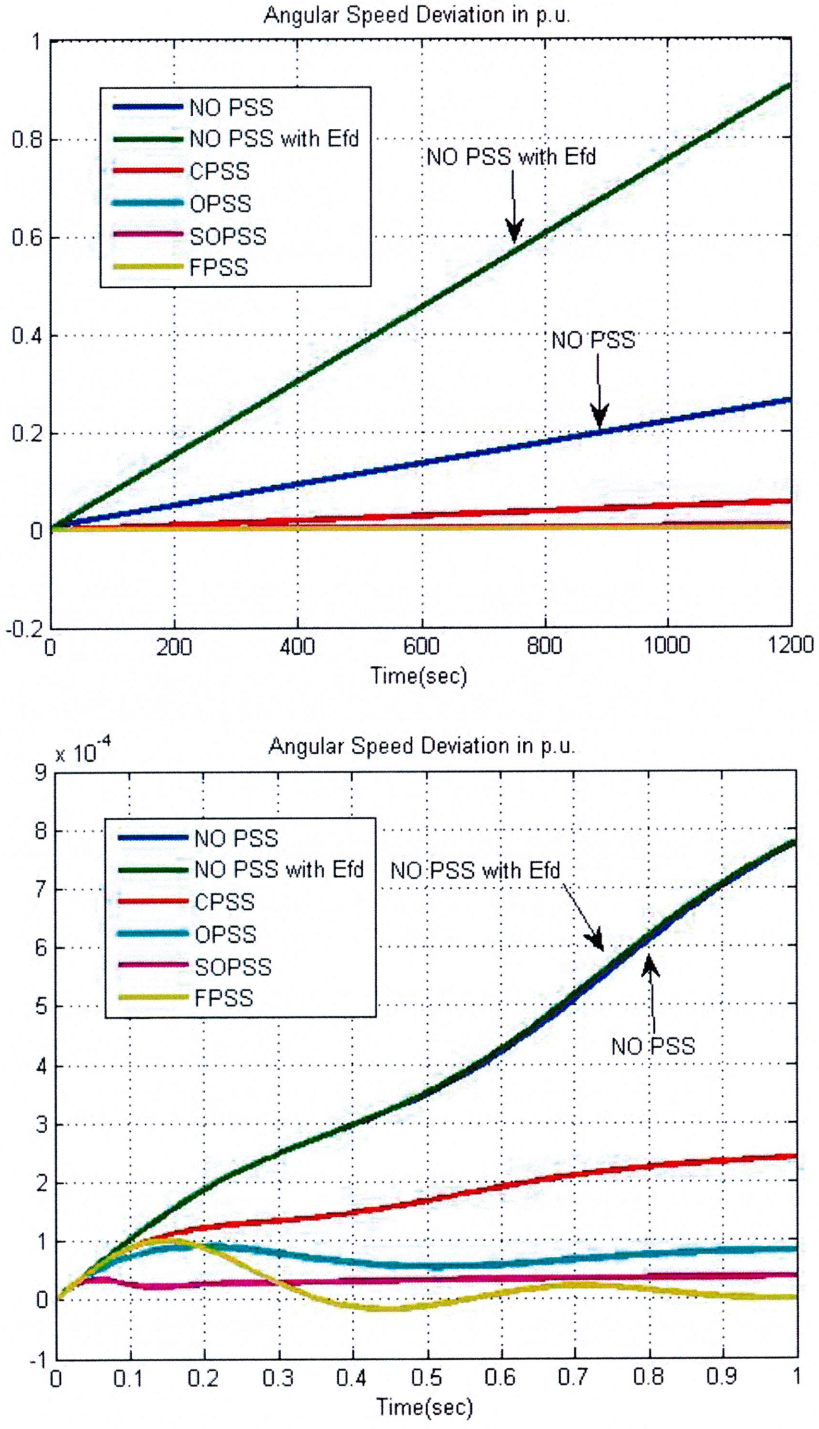


Fig.4.43 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop

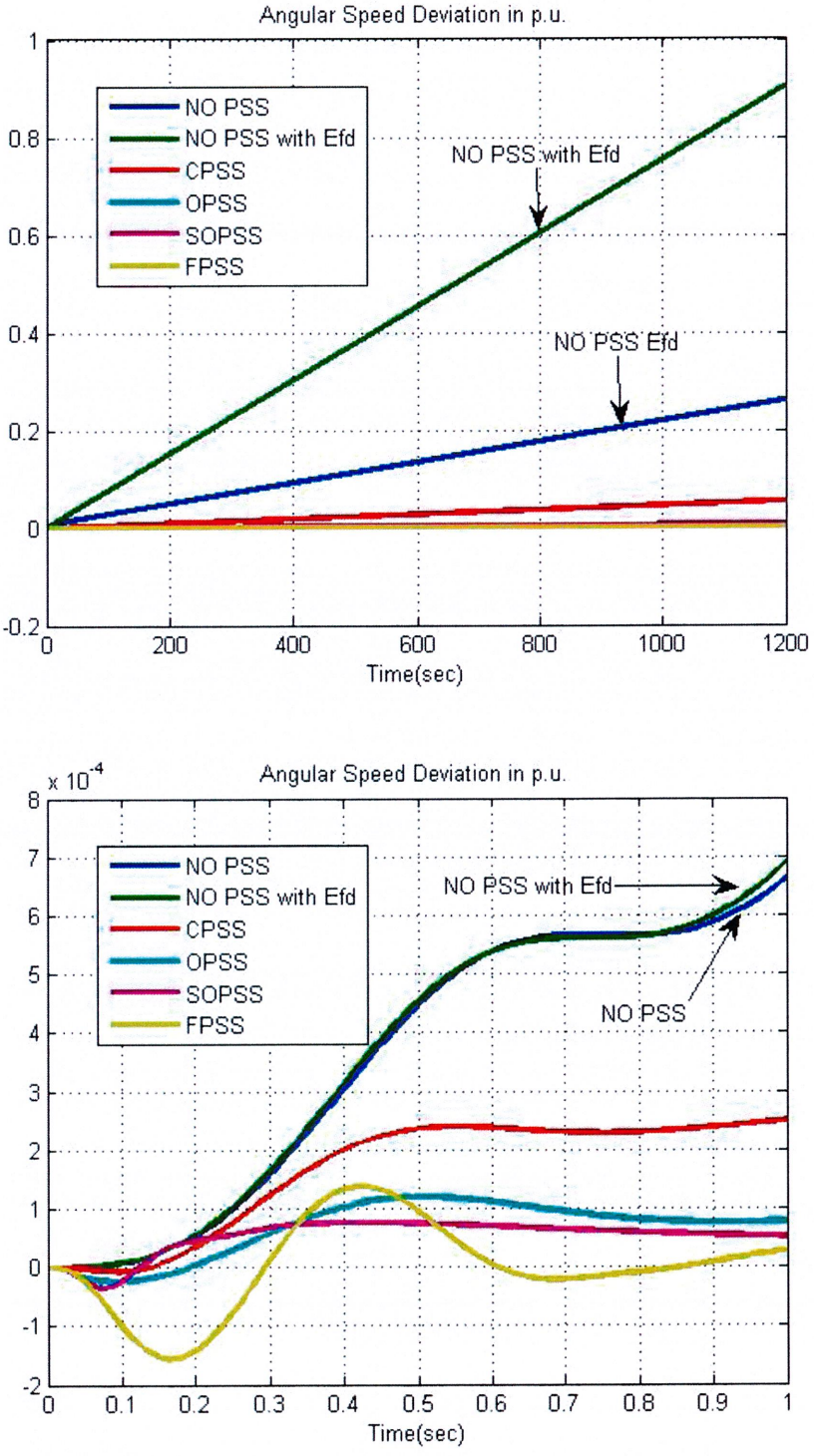


Fig.4.44 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

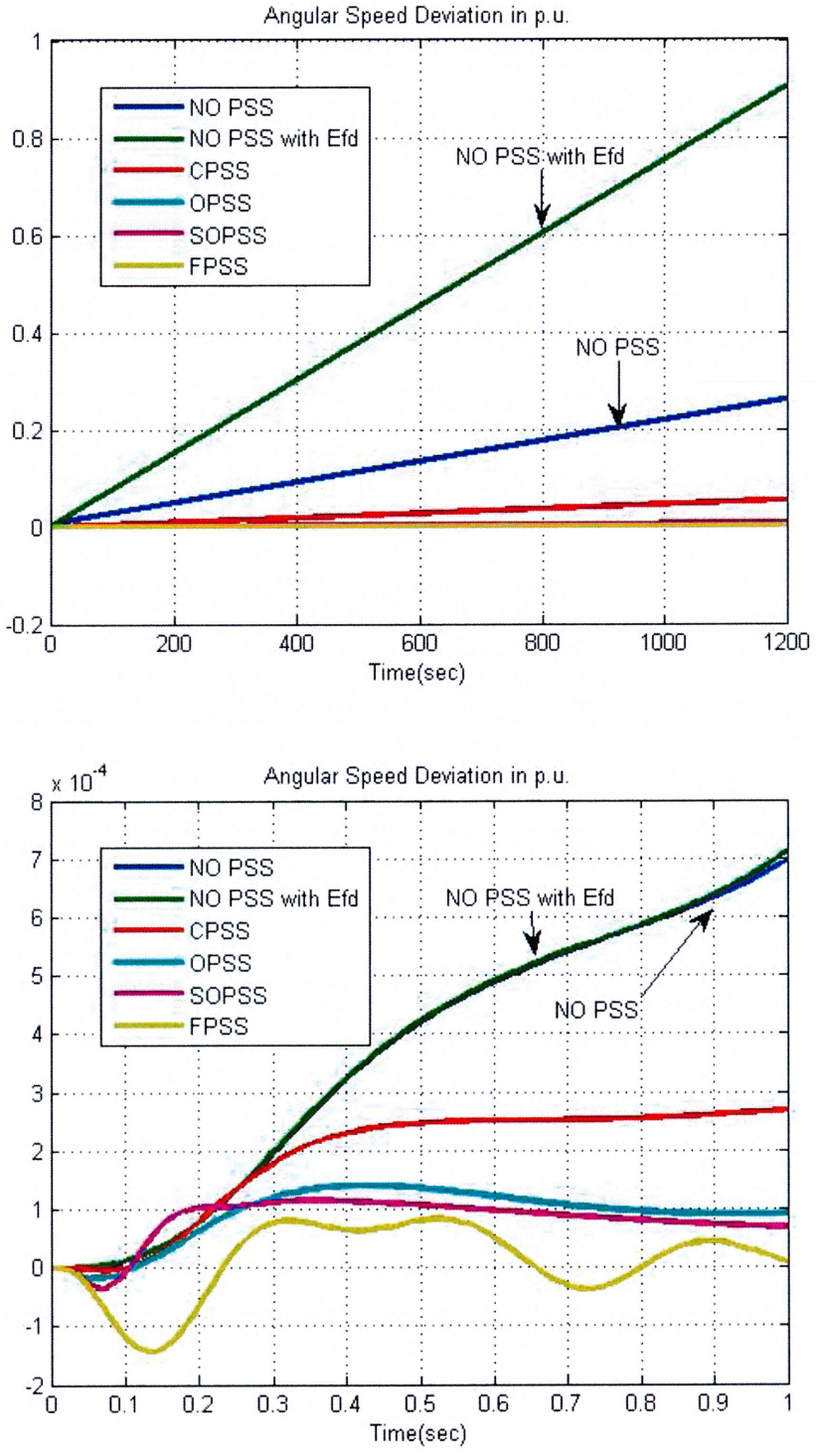


Fig.4.45 Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) with no speed droop

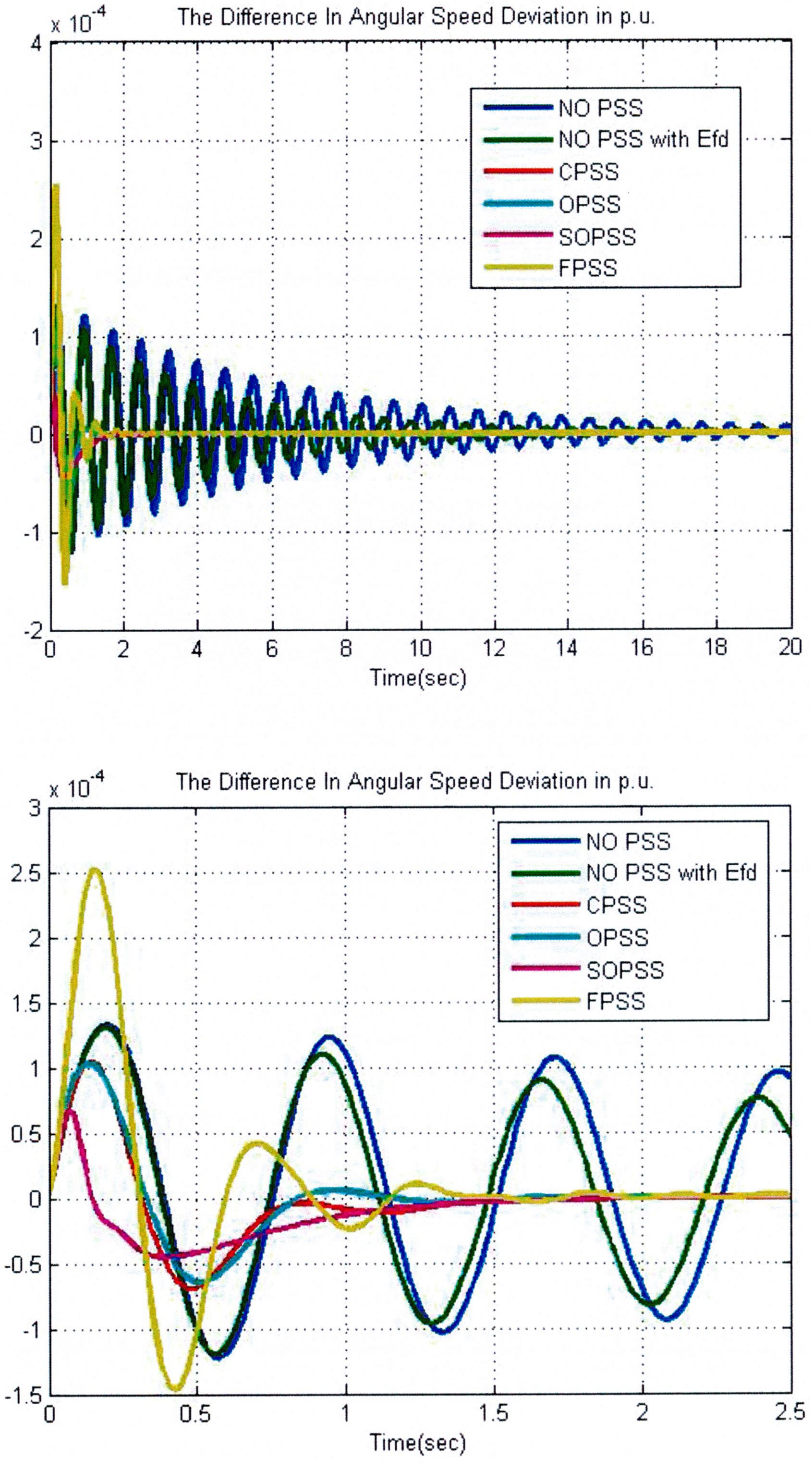


Fig.4.46 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

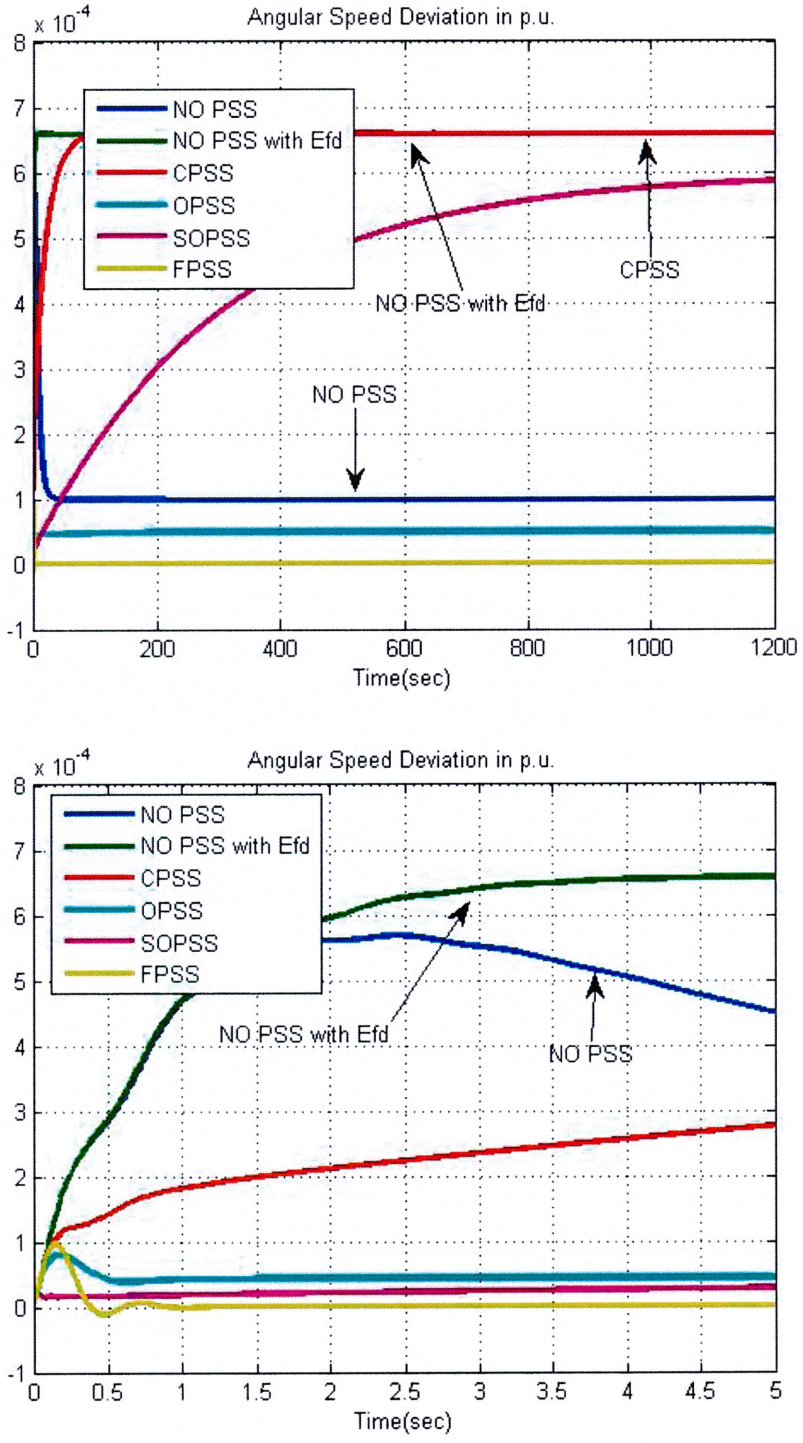
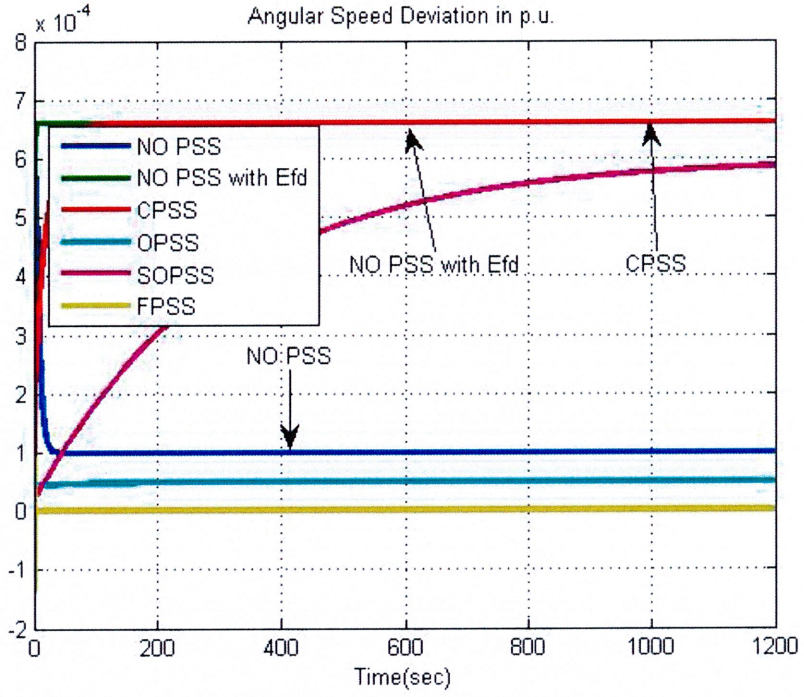


Fig.4.47 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%



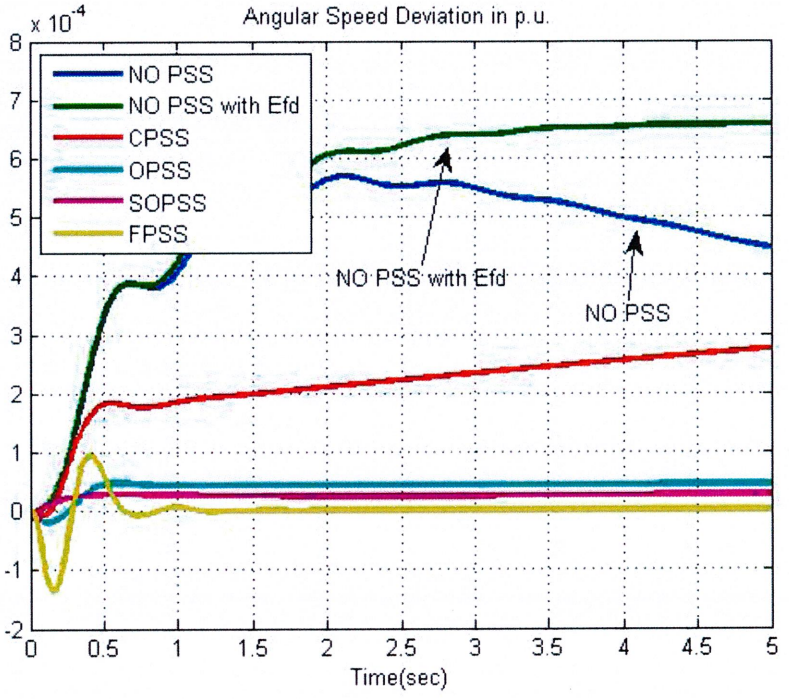


Fig.4.48 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

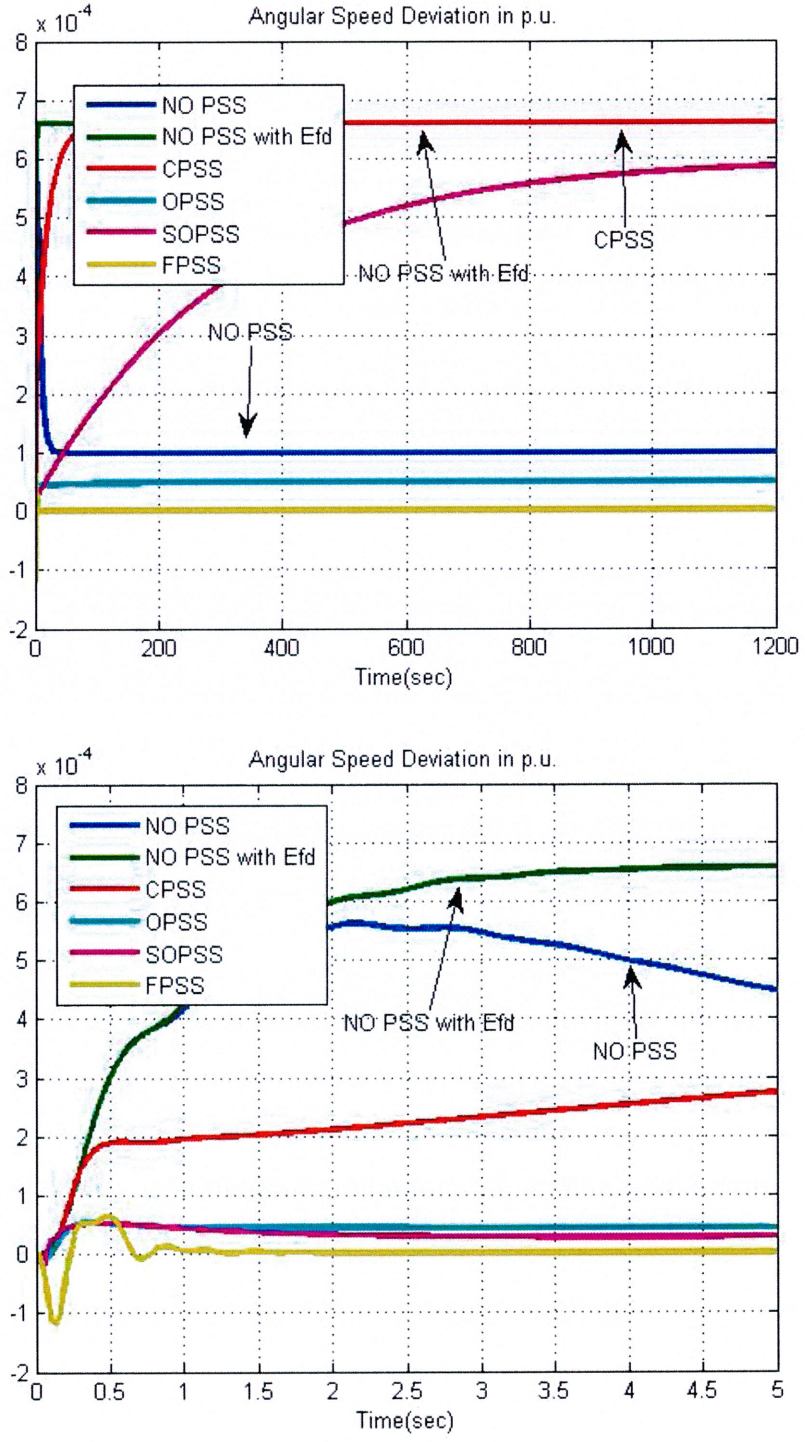


Fig.4.49 Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

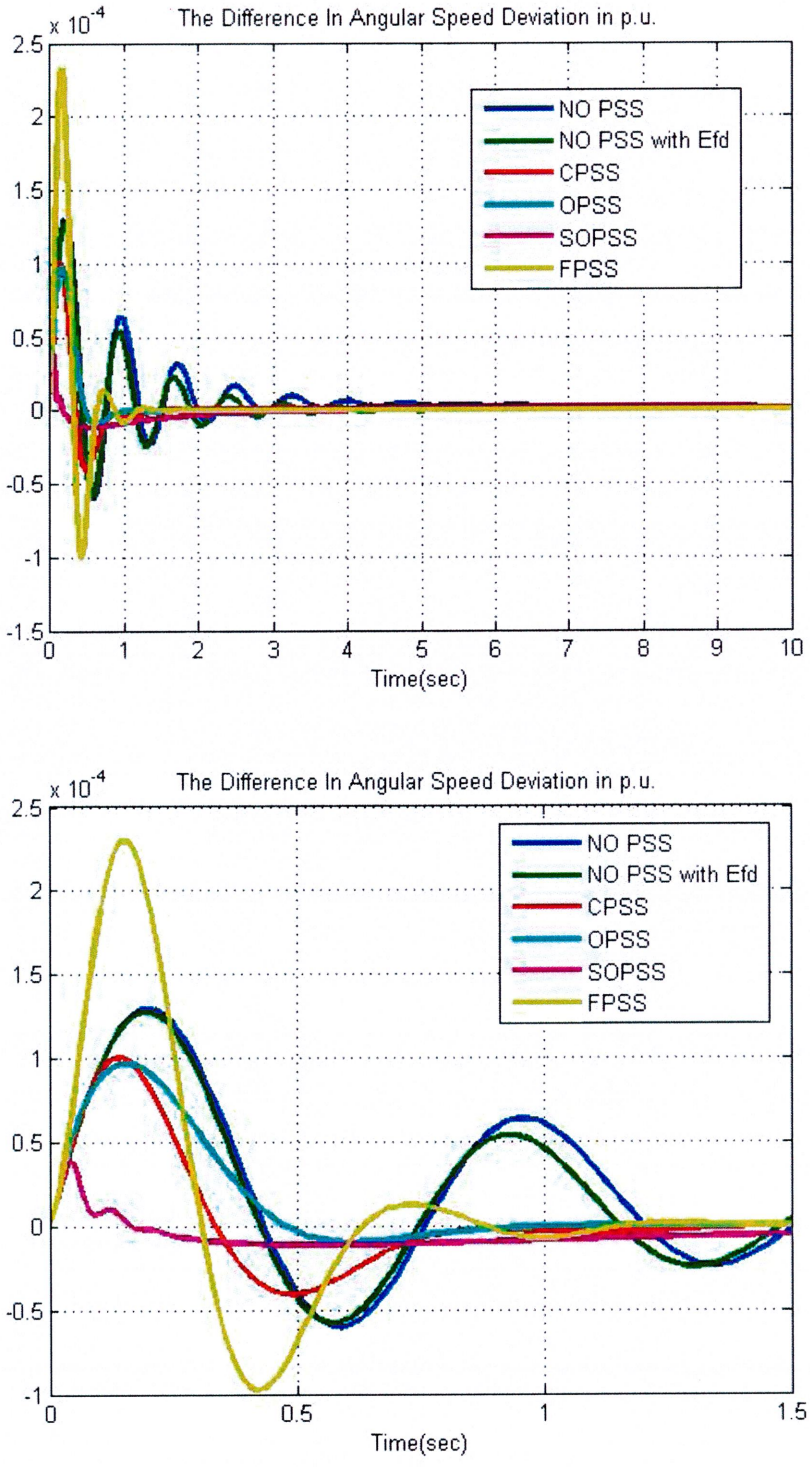


Fig.4.50 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

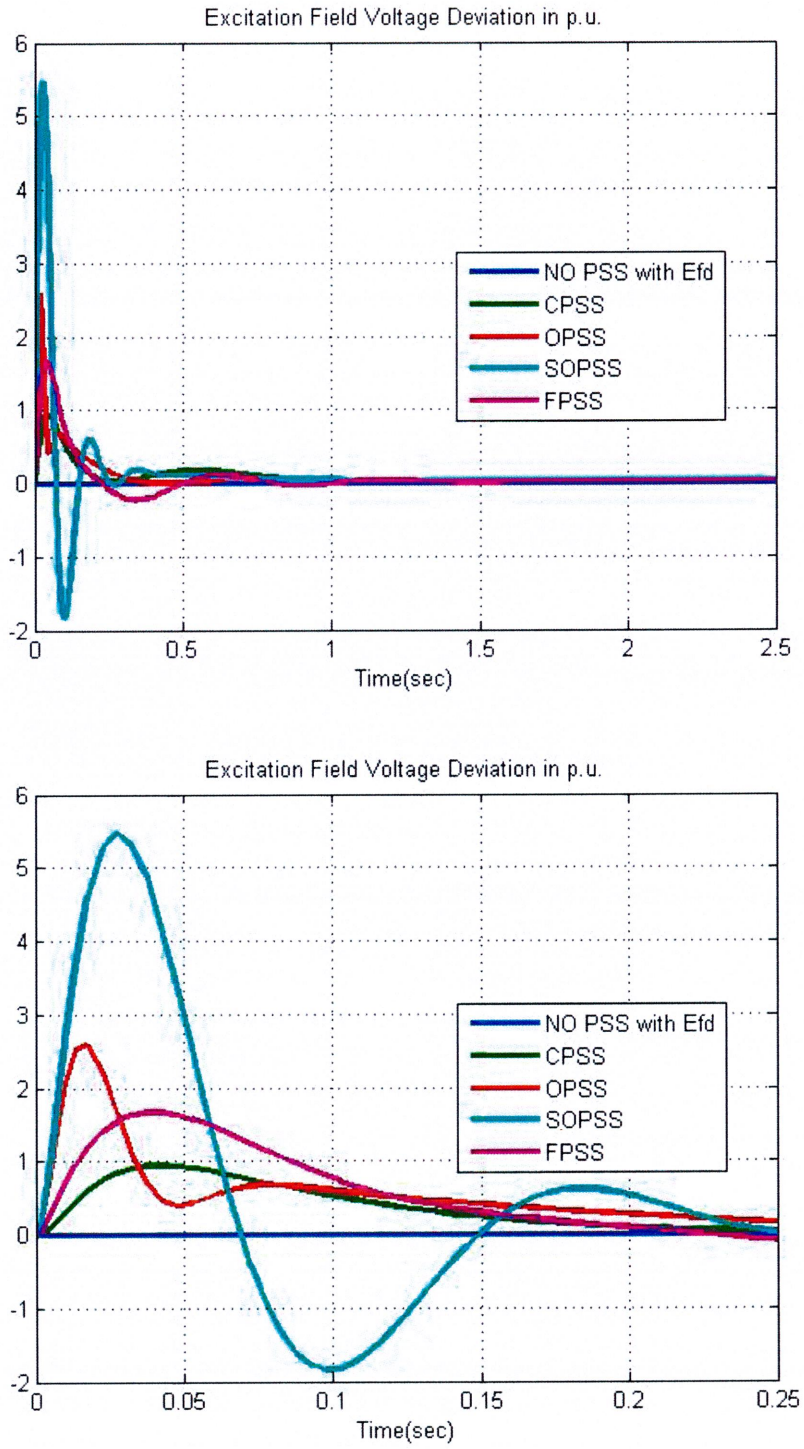


Fig.4.51 Excitation field voltage deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop

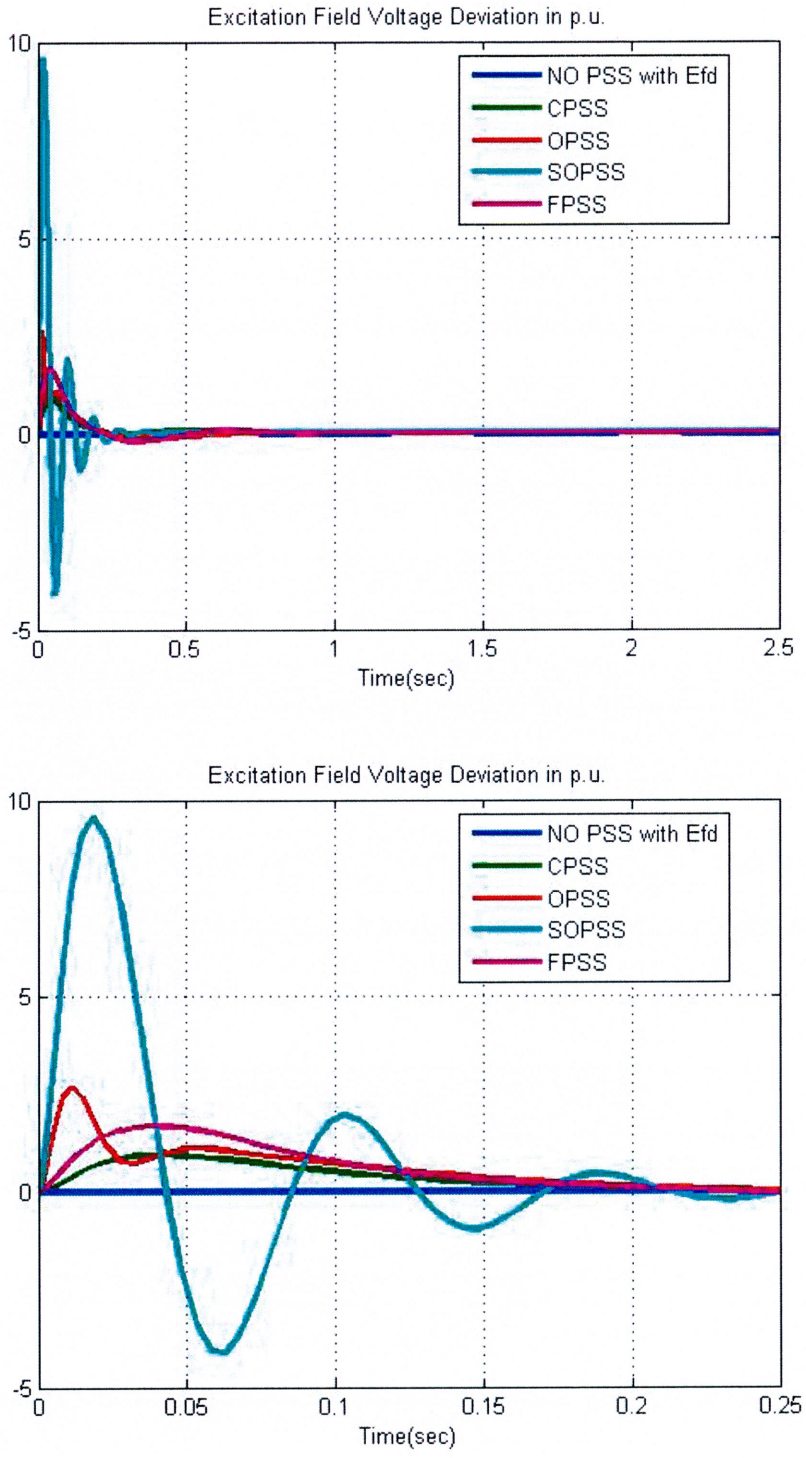


Fig.4.52 Excitation field voltage deviations of machine (1) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.2.5.2 Three Machines System simulation results (Case-2)

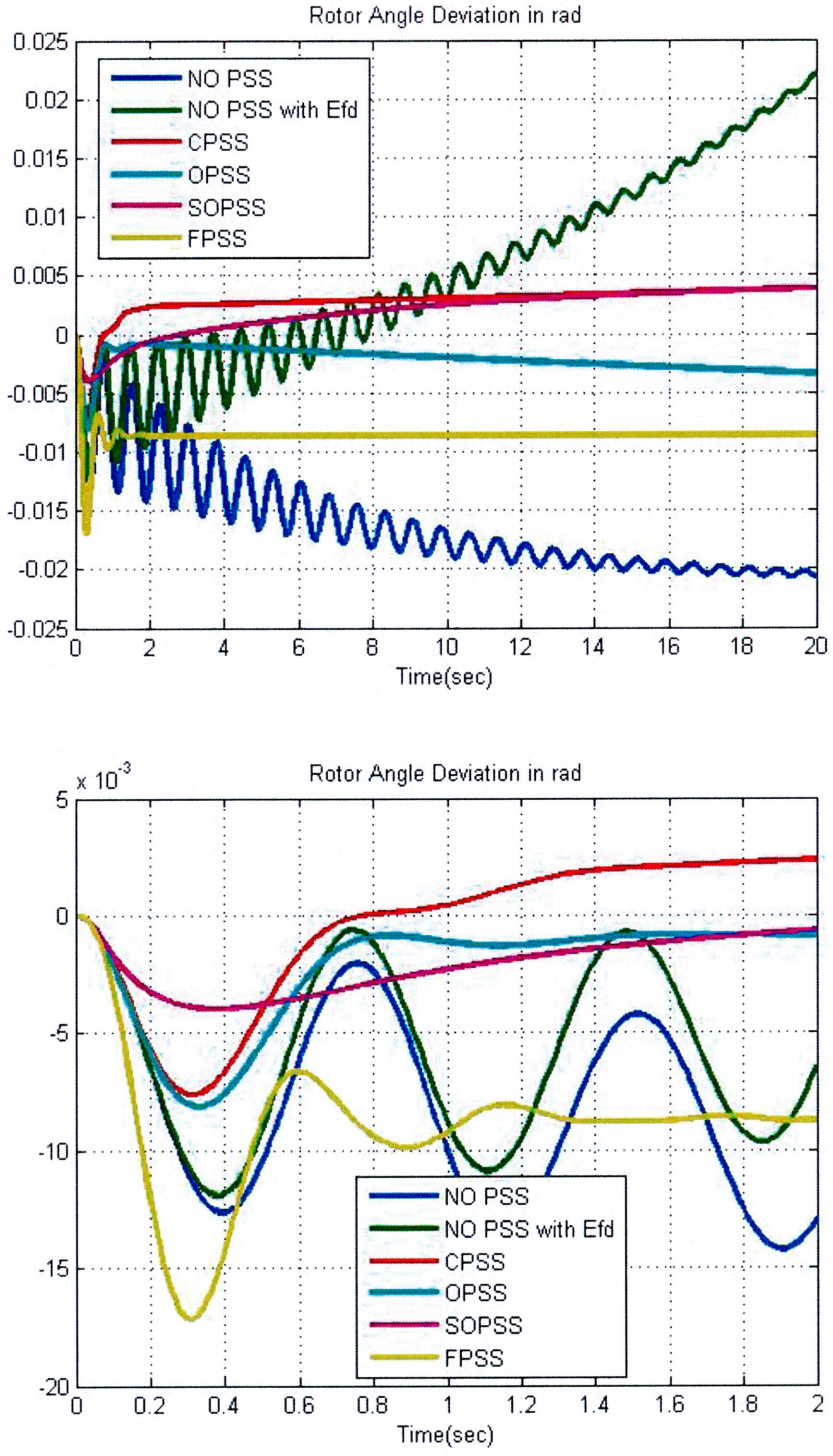


Fig.4.53 Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) with no speed droop

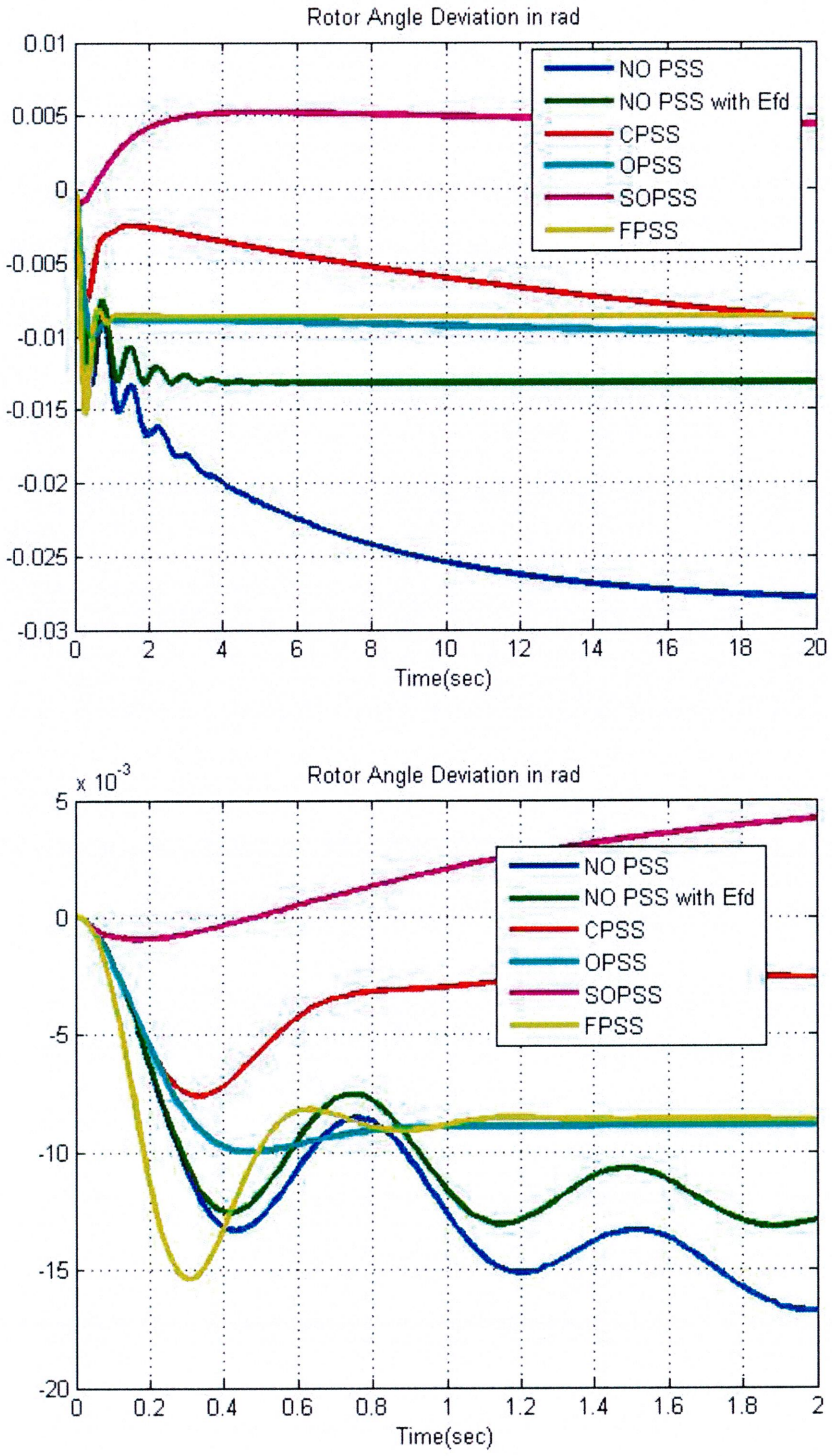


Fig.4.54 Rotor angle deviations of machine (2) after 5% step change in the mechanical torque (T_m) with respect to machine (1) including the speed droop of 4%

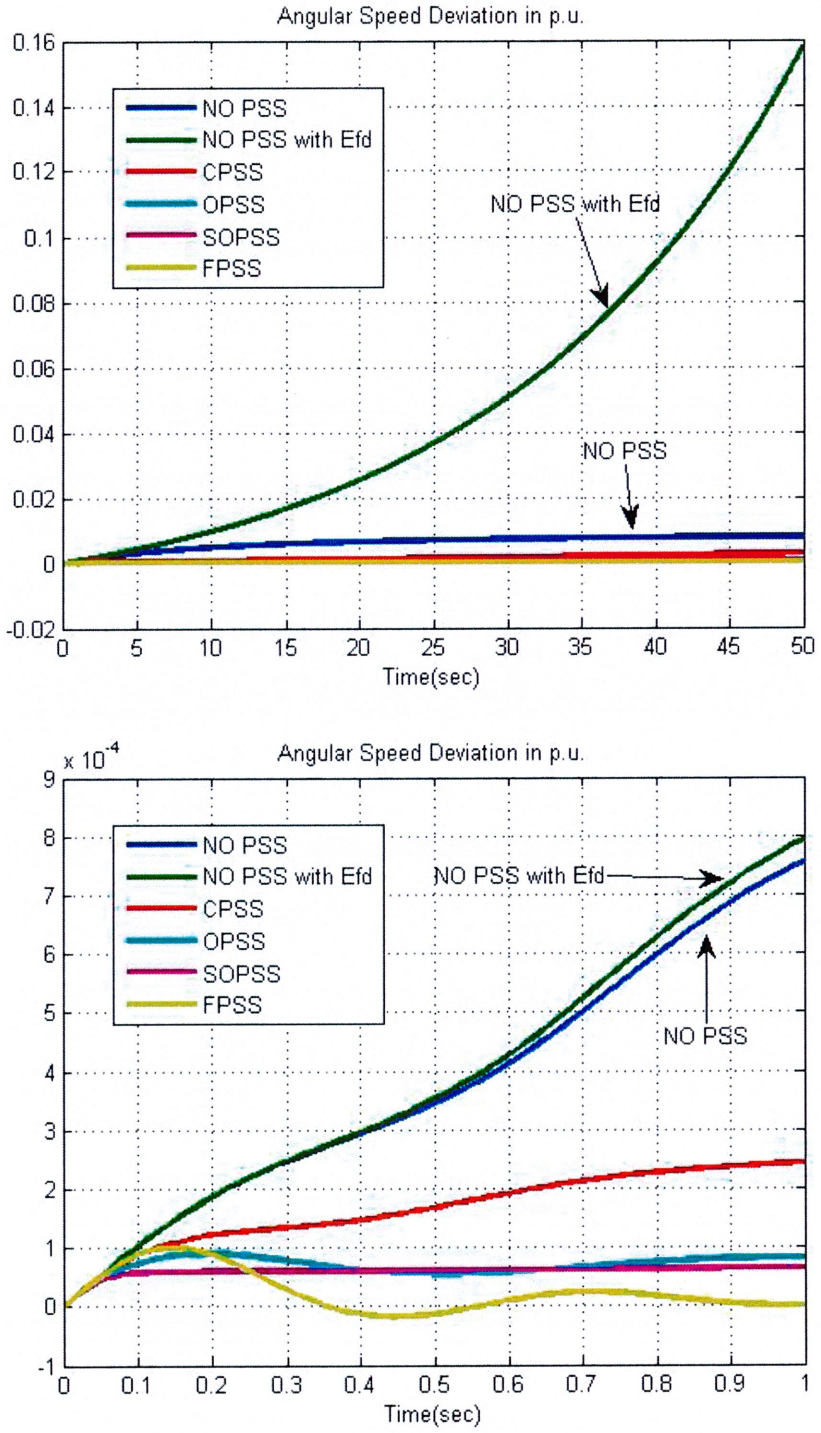


Fig.4.55 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop

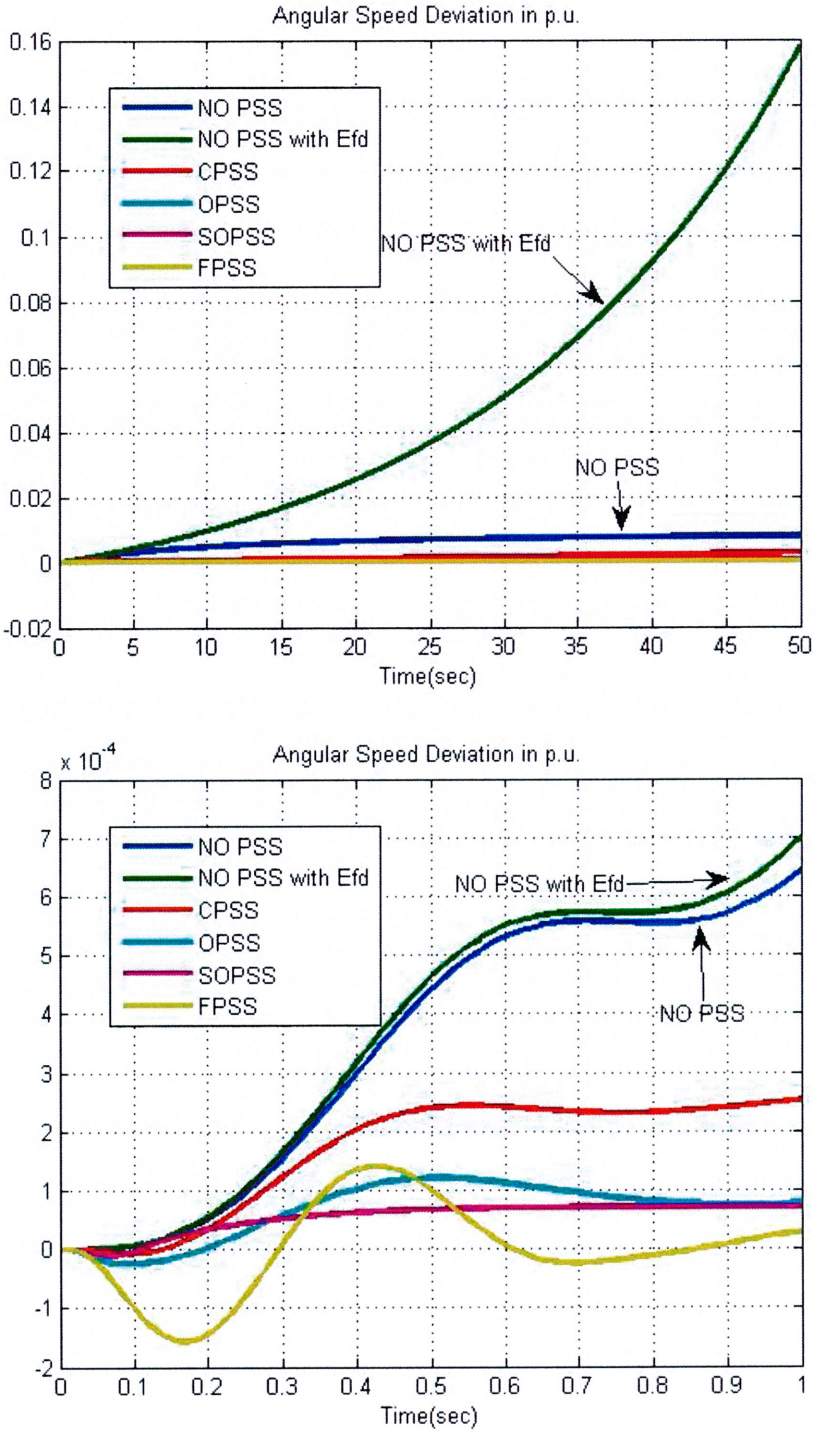


Fig.4.56 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

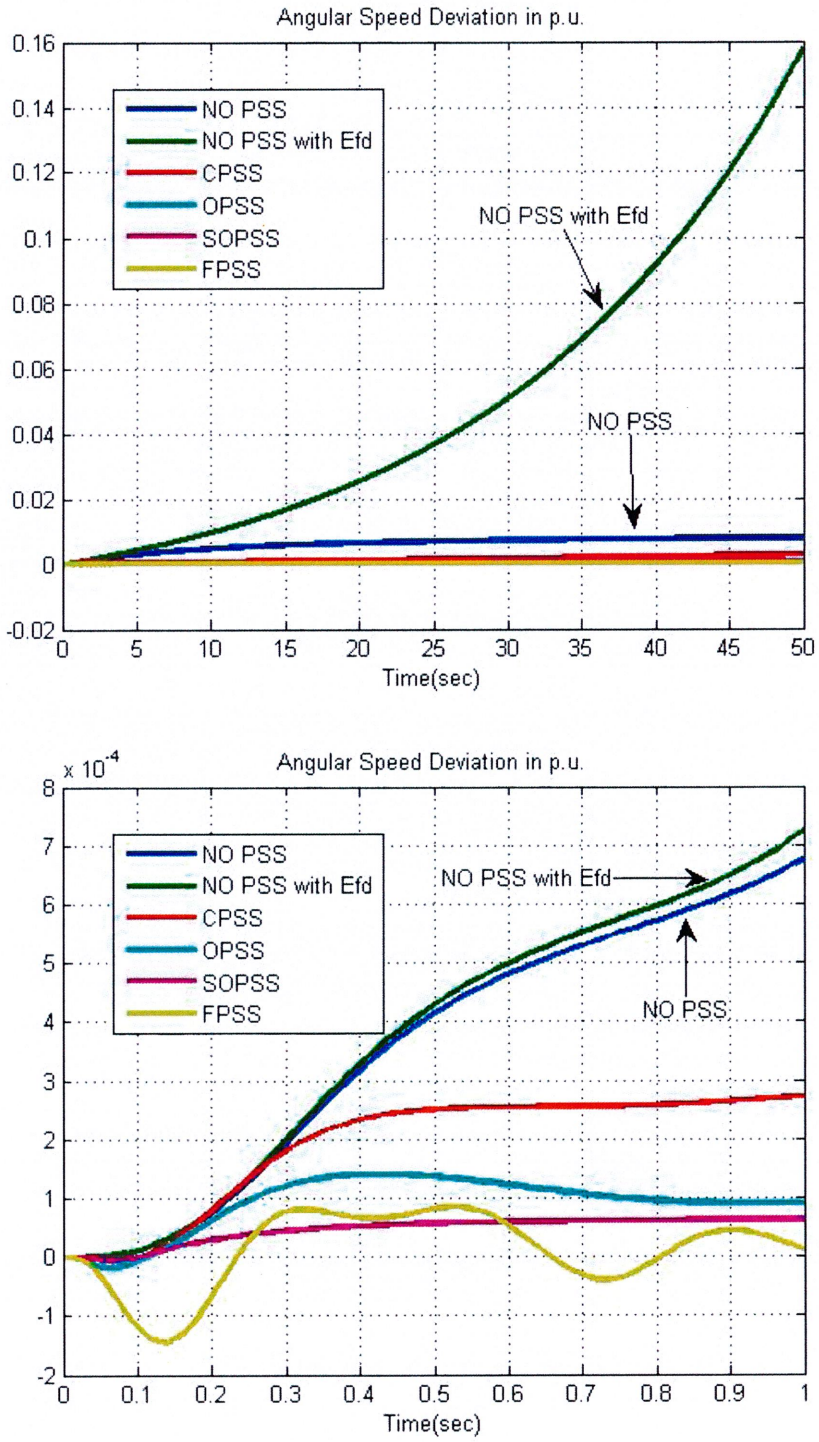


Fig.4.57 Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) with no speed droop

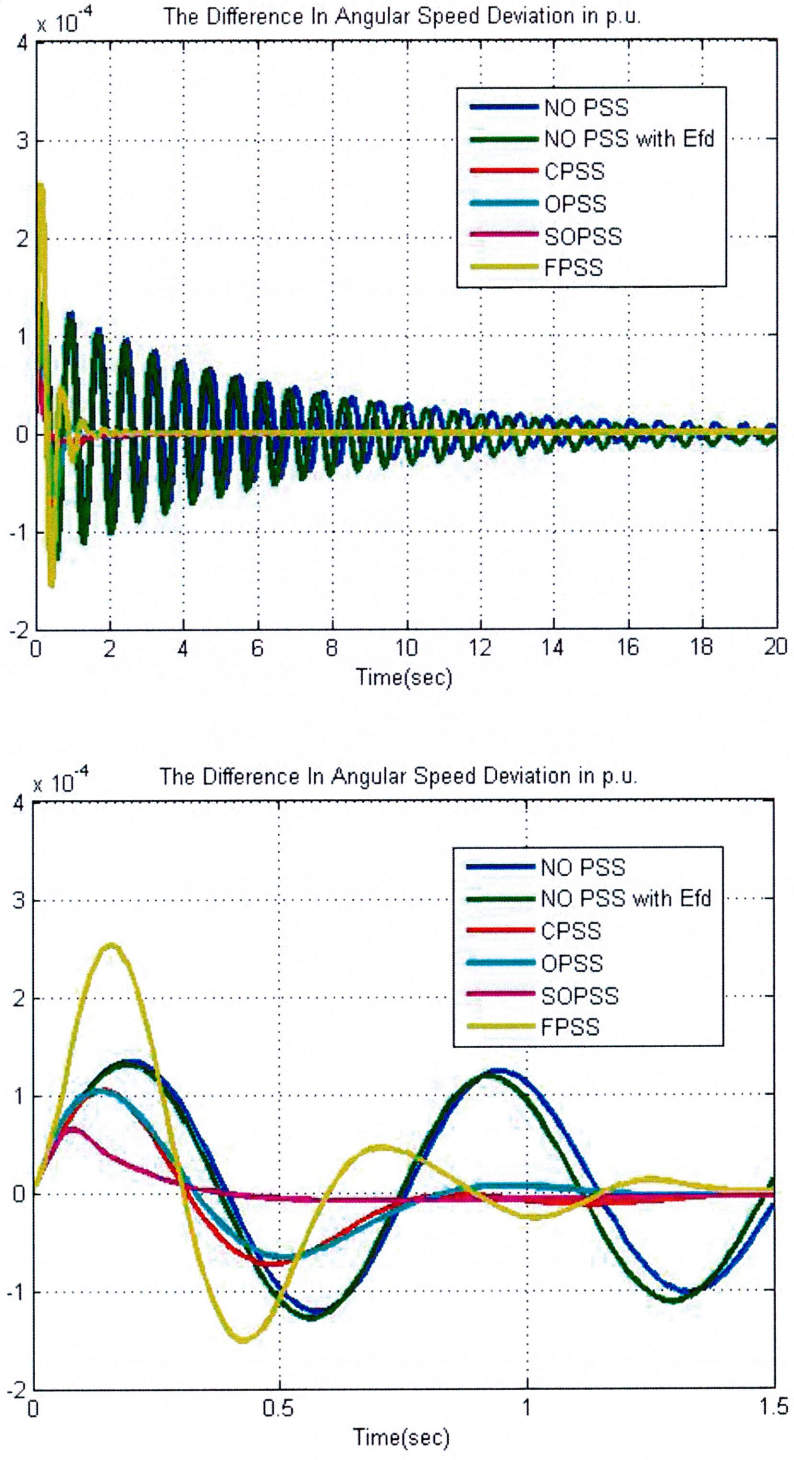


Fig.4.58 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) with no speed droop

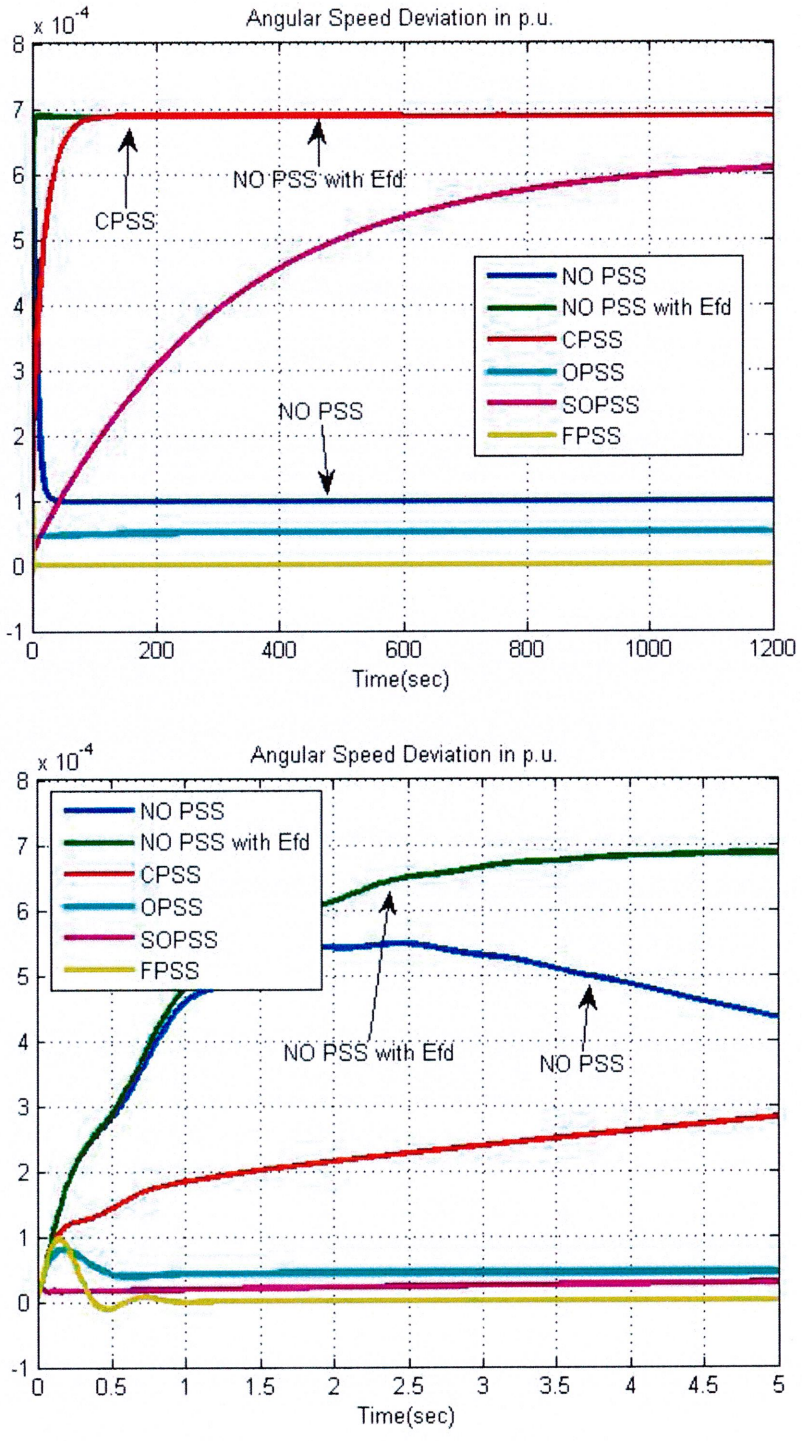


Fig.4.59 Angular speed deviations of machine (1) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

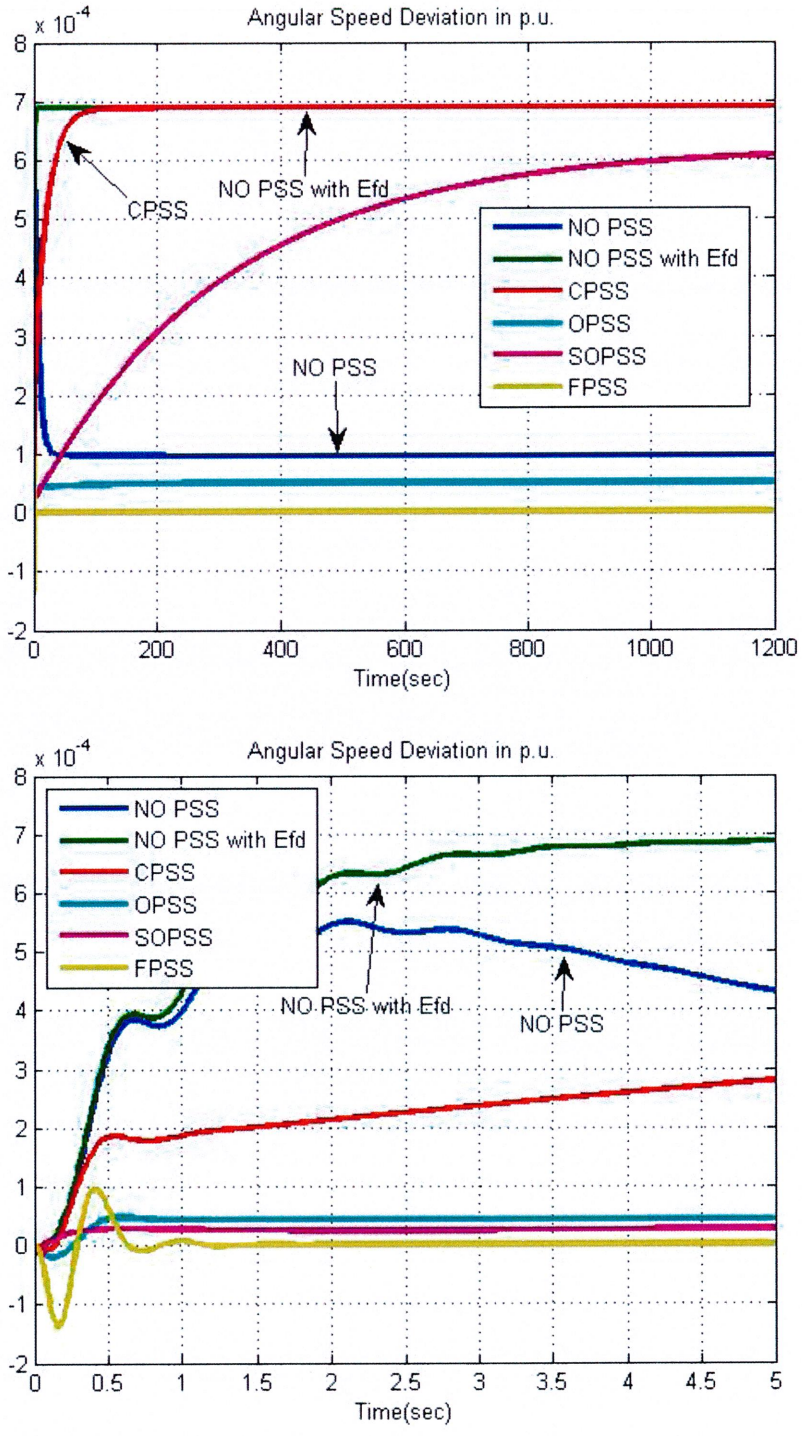


Fig.4.60 Angular speed deviations of machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

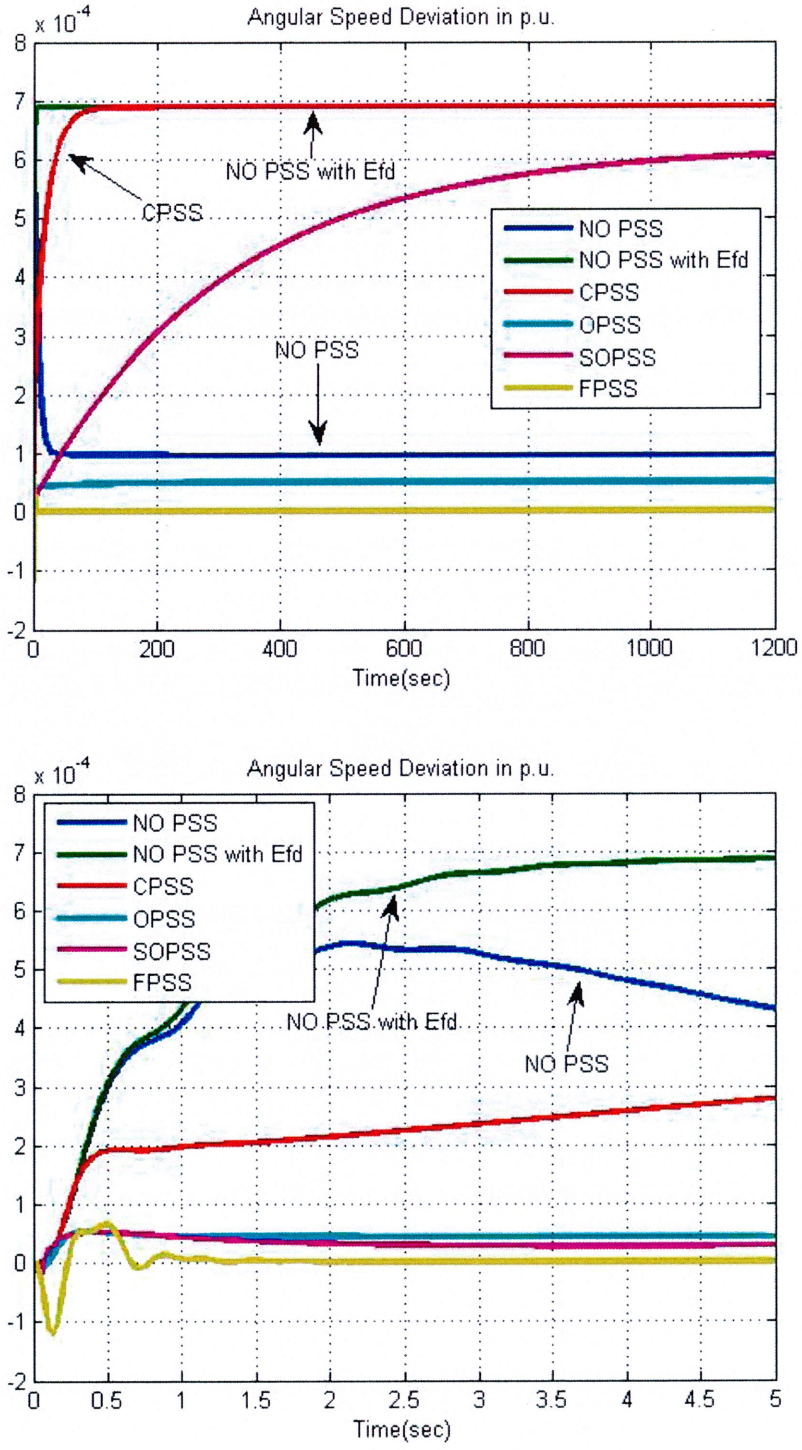


Fig.4.61 Angular speed deviations of machine (3) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

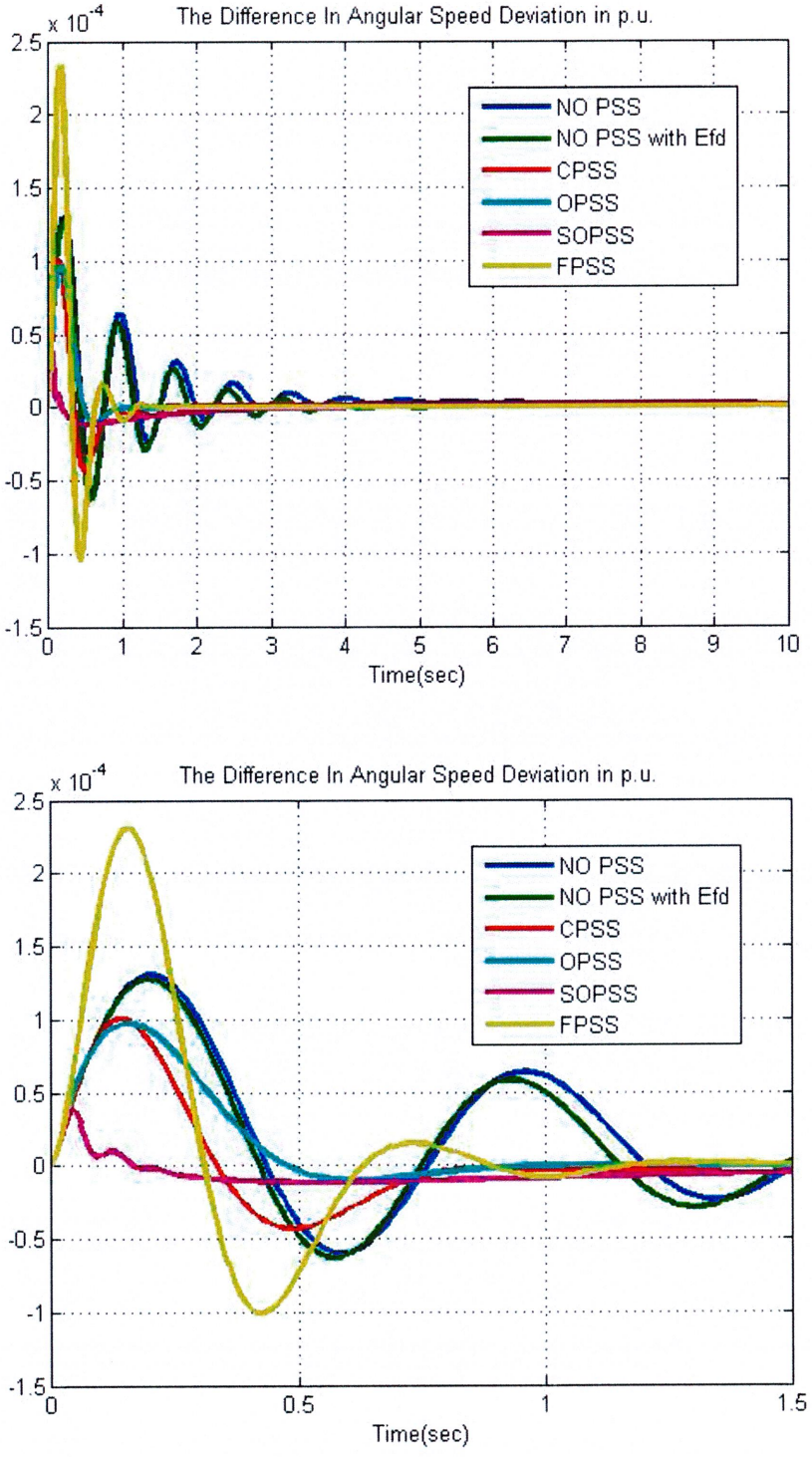


Fig.4.62 Angular speed difference deviations between machine (1) and machine (2) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

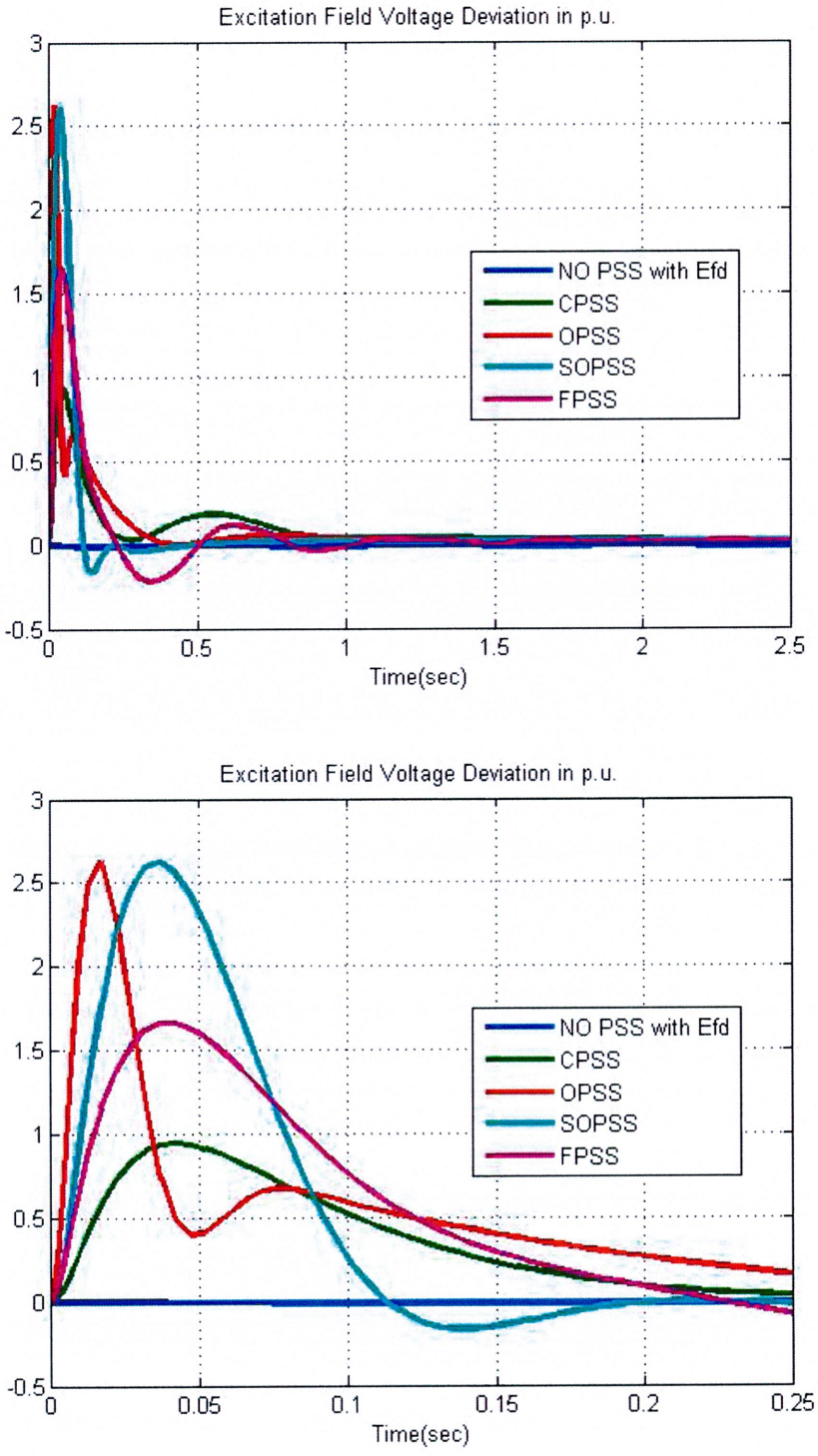


Fig.4.63 Excitation field voltage deviations of machine (1) after 5% step change in the mechanical torque (T_m) with no speed droop

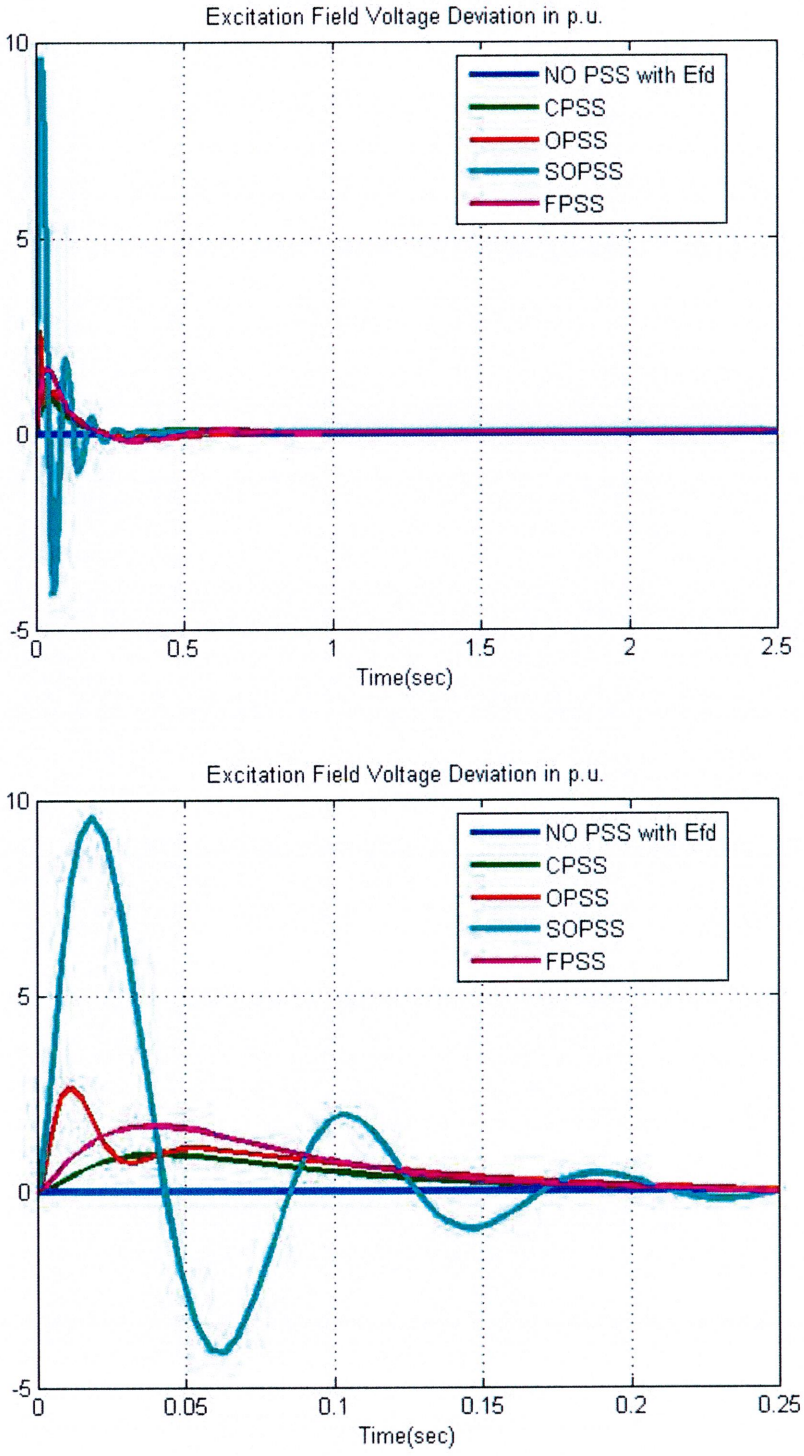


Fig.4.64 Excitation field voltage deviations of machine (1) after 5% step change in the mechanical torque (T_m) including the speed droop of 4%

4.2.5.3 SIMULATION DISCUSSION

- The eigenvalue analysis is done to investigate the stability of the multi-machine system (three machine system) achieved by no control (constant field voltage), exciter control, conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), and sub-optimal power system stabilizer (SOPSS). The eigenvalue analysis results are shown in appendix [H].

- The figures (4.37 - 4.60) show the simulation results following a small disturbance (5 % step change in the mechanical torque (ΔT_m)). All figures show the system response when there is no power system stabilizer, and when the proposed power system stabilizers are used.

- **Three machine system-case (1)**

- Eigenvalue analysis results indicate that the system is unstable in case of no power system stabilizer equipped in the system and also when the conventional power system stabilizer is used. The investigated power system is stabilized even when there is no power system stabilizer in case of the speed droop model is included in the power system. The stability of the system is improved when a power system stabilizer is used.

- It is clear from rotor angle deviation figure (4.37) and the angular speed difference deviation figure (4.42) that, the system is poorly damped when no power system stabilizer is used under this disturbance, so a power system stabilizer is required to damp the low frequency power system oscillations.

- The angular speed deviation ($\Delta\omega_r$) figures (4.39-4.41) show that, the conventional power system stabilizer (CPSS) did not provide a good damping characteristics to low frequency oscillations under this disturbance (with maintaining the load constant). As a results from adding the speed droop model to the power system, the conventional power system stabilizer (CPSS) provide a good damping characteristics to low frequency oscillations under the same disturbance and condition as shown in figures (4.43-4.45).

- The effect of adding the speed droop in the investigated power system is shown clearly in figures (4.38, 4.46) which show that the speed droop significantly suppresses the system oscillations in the rotor angle and the angular speed difference deviations and provides a good damping characteristic to low frequency oscillations by stabilizing the power system much faster.

- The field voltage deviations figures (4.47, 4.48) show that, the oscillations magnitudes of the optimal and sub-optimal power system stabilizers are magnified when the speed droop model added to the investigated power system (when the speed droop included, the Q matrix weight is higher than the Q matrix weight when the speed droop is neglected).

- The figures (4.37-4.48) show that, the optimal and fuzzy power system stabilizers provide the best performance and outperform the conventional power system stabilizer. The low frequency oscillations are significantly damped when the speed droop effect included in the system.

- **Three machine system-case (2)**

- Eigenvalue analysis results indicate that the system is unstable in case of no power system stabilizer with exciter control only and also when the conventional power system stabilizer is used. The investigated power system is stabilized even when there is no power system stabilizer in case of the speed droop model is included in the power system. The stability of the system is improved when a power system stabilizer is used.

- By reducing the exciter gain (K_a) to be in the range of $(0.1 - 0.2)$ in case of no power system stabilizer is equipped in the power system with exciter control only, the system will be stable as shown in Figure (4.65). Table (4.5) shows the eigenvalues of the system before and after the reduction of the exciter gain.

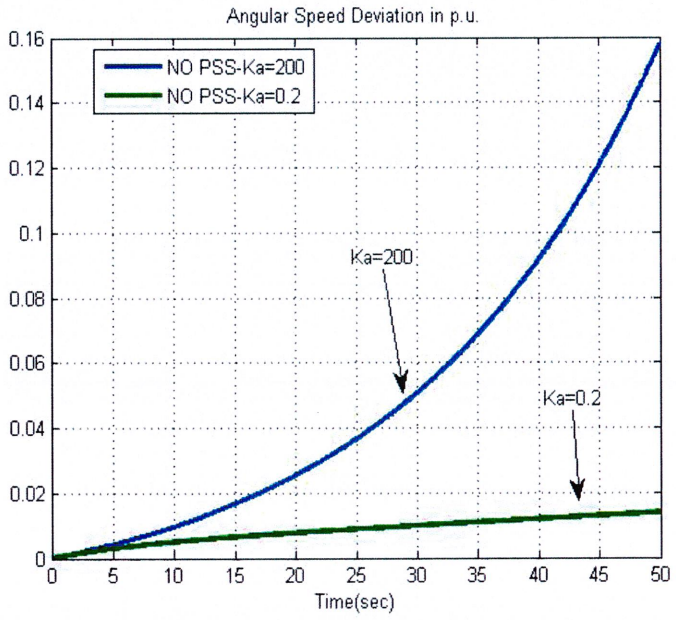


Fig. (4.65) The system response before and after exciter gain reduction

Case(2) – Ka=200	Case(2) – Ka=0.2
-2.5e1+j2.4e1	-4.9976e1
-2.5e1-j2.4e1	-4.9985e1
-3.4229e1	-4.9989e1
-2.5e1+j1e1	-7.058e-1+j1.278e1
-2.5e1-j1e1	-7.058e-1-j1.278e1
-1.8058e1	-1.611e-1+j8.296
-8.4e-1+j1.3e1	-1.611e-1-j8.296
-8.4e-1-j1.3e1	-5.1278
-1.5e-1+j8.5	-3.5542
-1.5e-1-j8.5	-2.8827e-3
-3.6296	-1.6284e-1+j7.8392e-3
-2.5641	-1.6284e-1-j7.8392e-3
4.8206e-2	-1.8112e-1
-2.00	-2.00

Table 4.5 The three machine system eigenvalues (without PSS)

- It is clear from rotor angle deviation figure (4.49) and the angular speed difference deviation figure (4.54) that, the system is poorly damped when no power system stabilizer is used under this disturbance, so a power system stabilizer is required to damp the low frequency power system oscillations.

- The angular speed deviation ($\Delta\omega_r$) figures (4.51-4.53,4.55-4.57) show that, as a result from adding the speed droop model to the investigated power system, the conventional power system stabilizer (CPSS) provide a good damping characteristics to low frequency oscillations outperform the same stabilizer without including the speed droop model under the same disturbance and condition.

- The effect of adding the speed droop in the investigated power system is shown clearly in figures (4.50, 4.58) which show that the speed droop significantly suppresses the system oscillations in the rotor angle and the angular speed difference deviations and provides a good damping characteristic to low frequency oscillations by stabilizing the power system much faster.

- The field voltage deviations figures (4.59, 4.60) show that, the oscillations magnitudes of the optimal and sub-optimal power system stabilizers are magnified when the speed droop model added to the investigated power system (when the speed droop included, the Q matrix weight is higher than the Q matrix weight when the speed droop is neglected).

- The figures (4.49-4.60) show that, the optimal and fuzzy power system stabilizers provide the best performance and outperform the conventional power system stabilizer. The low frequency oscillations are significantly damped when the speed droop effect included in the system.

- When the conventional power system stabilizer (CPSS) is equipped in the three machine system in both cases (Case (1) and Case (2)), the system will remain unstable (practically all machines include speed droop control which is stabilize the system). The system can be stabilized by using the conventional power system stabilizer beside of using a positive stabilizing signal from the speed deviation through a gain to the exciter input. Figure (4.66) shows the system response for each case of stabilizing the system by using the conventional power system stabilizer and the modified CPSS as seen from the results by adding the speed droop in the system model. Table (4.6) shows the eigenvalues of the system for each case of stabilizing the system by using the conventional power system stabilizer and the modified CPSS. The modified CPSS is simply a CPSS with washout and two phase – lead blocks with a positive feedback stabilizing signal from the speed deviation through a gain (Dcon) equal to CPSS gain (Dpss) to the input of the exciter.

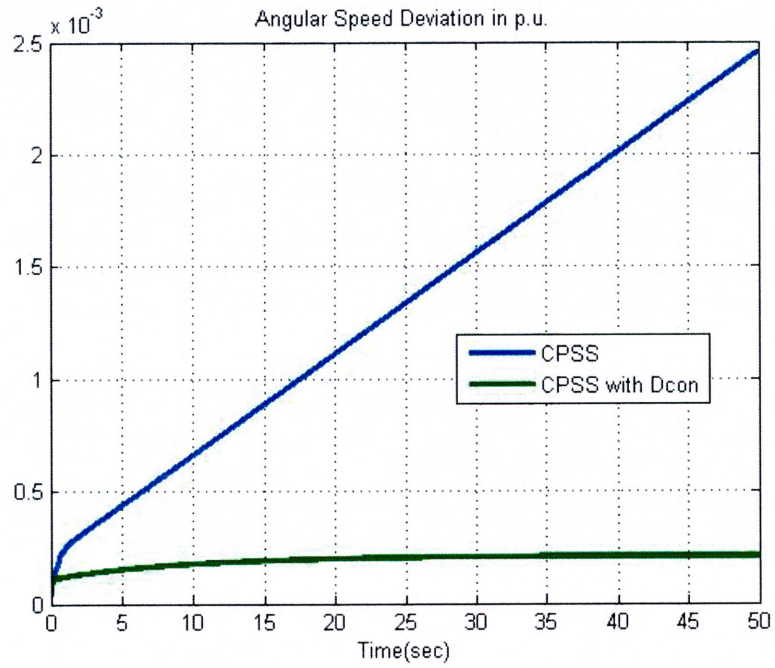


Fig.(4.66) The system response with CPSS

Case (1)		Case (2)	
CPSS	**Modified CPSS**	**CPSS**	**Modified CPSS**
-1.2768e2	-1.213e2+j4.645	-1.2768e2	-1.213e2+j4.645
-1.2e2+j4.6	-1.213e2-j4.645	-1.2e2+j4.6	-1.213e2-j4.645
-1.2e2-j4.6	-1.2793e2	-1.2e2-j4.6	-1.2792e2
-7.4e1+j5.7	-7.308e1+j6.118	-7.4e1+j5.6	-7.309e1+j6.112
-7.4e1-j5.7	-7.308e1-j6.118	-7.4e1-j5.6	-7.309e1-j6.112
-5.7387e1	-5.826e1+j1.343e1	-5.7617e1	-5.821e1+j1.337e1
-4.1335e1	-5.826e1-j1.343e1	-4.0564e1	-5.821e1-j1.337e1
-2.5e1+j2.3e1	-3.9818e1	-2.5e1+j2.3e1	-3.9605e1
-2.5e1-j2.3e1	-2.088+j2.9285e1	-2.5e1-j2.3e1	-2.121+j2.919e1
-2.6e1+j1.5e1	-2.088-j2.9285e1	-2.6e1+j1.5e1	-2.121-j2.919e1
-2.6e1-j1.5e1	-2.345e1+j2.0483e1	-2.6e1-j1.5e1	-2.349e1+j2.0561e1
-6.3+j1.5e1	-2.345e1+j2.0483e1	-6.2+j1.5e1	-2.349e1+j2.0561e1
-6.3-j1.5e1	-6.789+j2.124e1	-6.2-j1.5e1	-6.844+j2.108e1
-1.5459e1	-6.789-j2.124e1	-1.6218e1	-6.844-j2.108e1
-3.54+j9.2	-6.729+j2.578	-3.4+j9.1	-6.752+j2.547
-3.54-j9.2	-6.729+j2.578	-3.4-j9.1	-6.752+j2.547
-3.13+j3e-1	-6.977	-3.1+j3.3e-1	-7.0123
-3.13-j3e-1	-1.9043	-3.1-j3.3e-1	-1.9103
-1.9778	-9.663e-1	-1.9845	-9.685e-1
2.15e-14	-1.0591e-1	**2.9239e-3**	-1.0591e-1
-2.0576e-1	-2.0434e-1	-2.0575e-1	-2.0434e-1
-2.0405e-1	-2.0663e-1	-2.0404e-1	-2.0663e-1
-2.00	-2.00	-2.00	-2.00

Table 4.6 The three machine system eigenvalues (with PSS)

CHAPTER 5

CONCLUSION AND RECOMENDATIONS

5.1 SUMMARY AND CONCLUSION

Power system stabilizer (PSS) is one of the most important controllers in modern power system control that is used for providing suitable damping for low frequency oscillations and enhancing the overall stability of the power system.

A comparative analysis (theoretical and simulation) have been carried out for four different power system stabilizers (PSSs), these stabilizers are the conventional power system stabilizer (CPSS), optimal power system stabilizer (OPSS), sub-optimal power system stabilizer (SOPSS), and fuzzy power system stabilizer (FPSS).

The comparative analysis for the proposed power system stabilizers have been applied to different models of power systems, these power systems are single machine infinite bus system (SMIB), single machine isolated system (SMIS), and multimachine system (two machines system and three machines system).

The conventional power system stabilizer (CPSS) has been successfully applied to the power system models. This stabilizer provides damping to the low frequency oscillations and improves the stability of the power systems under small disturbance.

The optimal power system stabilizer (OPSS) and the sub-optimal power system stabilizer (SOPSS) have been successfully applied to the selected power system models. In fact the difficulty in these types of power system stabilizers is the selection of the performance index weighting matrices (R and Q matrices). Trial and error technique is used to select the weighting matrices for these stabilizers which guarantee high performance, but not optimal response.

The fuzzy power system stabilizer (FPSS) has been successfully applied to the selected power system models. The proposed fuzzy power system stabilizer (FPSS) provides adequate damping for the low frequency oscillations for all the selected power system models. The main problem of constructing a fuzzy power system

stabilizer (FPSS) is finding the optimum parameters, such as values of the scaling factors, shape of membership function for the inputs and output of the stabilizer. These parameters are chosen by trial and error techniques. Moreover the scaling factors are very sensitive to a very small variation in its values, so the performance of the fuzzy power system stabilizer is affected by these scaling factors.

For the single machine infinite bus system (SMIB) a comparison between the four power system stabilizers has been carried out. The simulation results show that case (1) and Case (2) are almost have the same response moreover the controllers improve the damping. The optimal power system stabilizer (OPSS) and the fuzzy power system stabilizer (FPSS) can give adequate performance and provide suitable damping for low frequency oscillations. Note that the system response in each case has been improved when the speed droop is included.

The simulation results of the single machine isolated system (SMIS) show that the uncontrolled system of Case (1) is not stable while it is stable for Case (2). When the exciter state is added without including power system stabilizer destabilizes the system of Case (2).The conventional power system stabilizer with phase lead – lag stages dose not stabilize the system. However by adding a conventional power system stabilizer with feedback with gain only to the exciter from the speed deviation stabilizes both systems of case (1) and Case (2). Moreover also the system can be stabilized by using the conventional power system stabilizer beside of using a positive stabilizing signal from the speed deviation through a gain to the exciter input. In the speed droop case, the system is stable for both Case (1) and Case (2) for uncontrolled cases. However the controllers improve the damping of the low frequency oscillations and the system stability is improved after adding the optimal and fuzzy power system stabilizers.

For multimachine (two machines and three machines), the uncontrolled case is stable for Case (2) which is not stable for Case (1). When the speed droop gain included Case (1) and Case (2) are stable with increasing in the deviation in the excitation voltage (this very clear especially for machine 1 of three machines case as $X_q = \grave{X}_q$ – meaning no damper winding in q-axis). The system can be stabilized by using the conventional power system stabilizer beside of using a positive stabilizing signal from the speed deviation through a gain to the exciter input. The controllers improve the damping of the low frequency oscillations and the system stability is improved after adding the optimal and fuzzy power system stabilizers.

Finally, it can be clearly seen that the optimal power system stabilizer (OPSS) and the fuzzy power system stabilizer (FPSS) provide adequate performance and much better than the other power system stabilizers.

After comparison between the four stabilizers applied to the three machines system, the simulation results showed that the optimal power system stabilizer (OPSS) and the fuzzy power system stabilizer (FPSS) can damp low frequency oscillations better than other stabilizers. The system response in each case has been improved when the speed droop is included.

A comparison between both cases (Case (1) and Case (2)) has been carried out on all the proposed power systems, for the four power system stabilizers. The simulation results prove that the conventional, optimal, and fuzzy power system stabilizers give a comparable performance in both cases in each power system model.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Research on optimal control, fuzzy logic, and artificial intelligent in control systems has grown rapidly in the recent years. In power system control, the applications of these techniques are still limited and they need to be conducted in order to put them into practical use.

Based on the work done in this thesis, the following are recommended as further research topics:

1) Further research in the area of merging between the fuzzy logic control and the artificial intelligent such as artificial neural network for improving the performance of the fuzzy power system stabilizer (FPSS).

2) Further research in the area of merging between the fuzzy logic control and the modern control such as optimal control by using the state feedback technique to improve the performance of the fuzzy power system stabilizer (FPSS).

3) In the fuzzy power system stabilizer, further research is required for the effect of the shape of membership function such as bell shaped, Z shaped, S shaped, and trapezoidal shaped functions, also the effect of the number of rules that are used in the performance of the power system stabilizer.

4) Adaptive fuzzy logic power system stabilizer is an area for further research for damping the low frequency oscillations and enhancing the stability of the power system.

5.3 THESIS CONTRIBUTIONS

The major contributions of this thesis are:

1) The synchronous machine has been modeled by model 1.1(field winding and one damper winding on the q - axis) and the fourth order model (δ, ω_r , $\acute{E}_q$, and$\acute{E}_d$), whereas most of researches in this area use model 1.0 for modeling the synchronous machine.

2) The synchronous machine has been modeled by assuming that the per unit value of the angular rotor speed of the synchronous machine (ω_r) is equal to 1.0 (i.e. $\omega_r = \omega_s\, rad/s$) in the stator voltage equations (the angular speed changes are small), which most of the previous researches done in this area based on this assumption. Moreover, also the synchronous machine has been modeled by assuming that the per unit value of the angular rotor speed of the synchronous machine (ω_r) is not equal to 1.0 (i.e. $\omega_r \neq \omega_s\, rad/s$) in the stator voltage equations (the angular speed changes have a significant effect on the stator voltages).

3) Full details analysis for the current gains based on the per unit value of the angular rotor speed of the synchronous machine (ω_r) is not equal to 1.0 (i.e. $\omega_r \neq \omega_s\, rad/s$) for multi machine system has been presented in this work.

4) The single machine isolated system and the multi machine system with exciter control only have been effectively stabilized by reducing the exciter gain (K_a) to suitable gain range.

5) The single machine isolated system and the multi machine systems with using the conventional power system stabilizer (CPSS) have been effectively stabilized by using a modified CPSS which is simply a CPSS with washout and two phase – lead blocks with a positive feedback stabilizing signal from the speed deviation through a gain (Dcon) equal to CPSS gain (Dpss) to the input of the exciter.

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APPENDIX A

Simplified model of single machine infinite bus

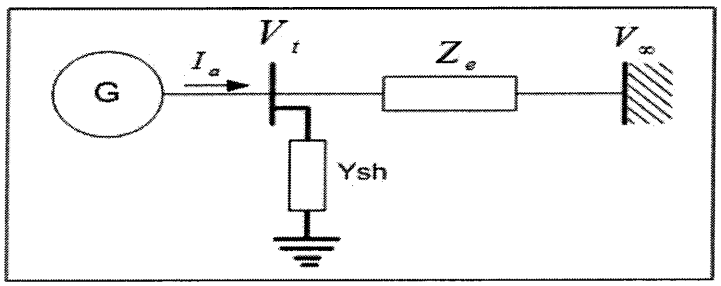


Fig. (A.1) System configuration of single machine infinite bus

From the above figure the current (I_a) is equal to:

$$I_a = \frac{V_t - V_\infty}{Z_e} + y_{sh}.V_t \quad \rightarrow\rightarrow \quad Z_e.I_a = V_t - V_\infty + Z_e y_{sh} V_t$$

where $Z_e = R_e + jX_e \qquad let\ R_e = 0 \quad \rightarrow\rightarrow \quad Z_e = jX_e$

$$jX_e.I_a = V_t - V_\infty + jX_e y_{sh} V_t \quad \rightarrow\rightarrow \quad V_t = (V_\infty + jX_e.I_a)/(1 + + jX_e y_{sh})$$

Assuming $y_{sh} = 0;$

where $V_t = V_q - jV_d \ ; \ I_a = I_q - jI_d \ ; \ V_\infty = V_\infty.\cos\delta - jV_\infty.\sin\delta$

$$V_q - jV_d = jX_e(I_q - jI_d) + (V_\infty.\cos\delta - jV_\infty.\sin\delta)$$

$$V_q - jV_d = jX_e I_q + X_e I_d + (V_\infty.\cos\delta - jV_\infty.\sin\delta)$$

$$\boldsymbol{V_q = X_e I_d + V_\infty.\cos\delta} \qquad (A-1)$$

$$-jV_d = jX_e I_q - jV_\infty.\sin\delta \quad \rightarrow\rightarrow \quad \boldsymbol{V_d = V_\infty.\sin\delta - X_e I_q} \qquad (A-2)$$

Also we have

$$\boldsymbol{V_q = (\grave{E}_q - \grave{X}_d I_d).\omega_r} \qquad (A-3)$$
$$\boldsymbol{V_d = (\grave{E}_d + \grave{X}_q I_q).\omega_r} \qquad (A-4)$$

Let Equation (A-2) = Equation (A- 4)

$$V_\infty . \sin\delta - X_e I_q = \left(\grave{E}_d + \grave{X}_q I_q\right). \omega_r$$
$$V_\infty . \sin\delta - X_e I_q = \grave{E}_d . \omega_r + \grave{X}_q I_q . \omega_r$$

After linearization

$$(V_\infty . \cos\delta)\Delta\delta - X_e \Delta I_q = \grave{E}_{d0} . \Delta\omega_r + \Delta\grave{E}_d + \grave{X}_q \Delta\grave{I_q} + \grave{X}_q I_{q0} . \Delta\omega_r$$

$$(V_\infty . \cos\delta)\Delta\delta - \left(\grave{E}_{d0} + \grave{X}_q I_{q0}\right)\Delta\omega_r - \Delta\grave{E}_d = (X_e + \grave{X}_q)\Delta I_q$$

$$\Delta I_q = \left[\frac{(V_\infty . \cos\delta)}{(X_e + \grave{X}_q)}\right]\Delta\delta + \left[\frac{-1}{(X_e + \grave{X}_q)}\right]\Delta\grave{E}_d + \left[\frac{-(\grave{E}_{d0} + \grave{X}_q I_{q0})}{(X_e + \grave{X}_q)}\right]\Delta\omega_r$$

$$\boldsymbol{\Delta I_q = C_1 . \Delta\delta + C_2 . \Delta\grave{E}_d + C_3 . \Delta\omega_r} \qquad \boldsymbol{(A-5)}$$

where

$$C_1 = \left[\frac{(V_\infty . \cos\delta)}{(X_e + \grave{X}_q)}\right] \; ; \; C_2 = \left[\frac{-1}{(X_e + \grave{X}_q)}\right] \; ; \; C_3 = \left[\frac{-(\grave{E}_{d0} + \grave{X}_q I_{q0})}{(X_e + \grave{X}_q)}\right] = \left[\frac{-V_{d0}}{(X_e + \grave{X}_q)}\right]$$

Let Equation (A-1) = Equation (A-3)

$$V_\infty . \cos\delta + X_e I_d = \left(\grave{E}_q - \grave{X}_d I_d\right). \omega_r$$
$$V_\infty . \cos\delta + X_e I_d = \grave{E}_q . \omega_r - \grave{X}_d I_d . \omega_r$$

After linearization

$$-(V_\infty . \sin\delta)\Delta\delta + X_e \Delta I_d = \grave{E}_{q0} . \Delta\omega_r + \Delta\grave{E}_q - \grave{X}_d \Delta\grave{I_d} - \grave{X}_d I_{d0} . \Delta\omega_r$$

$$(V_\infty . \sin\delta)\Delta\delta + \left(\grave{E}_{q0} - \grave{X}_d I_{d0}\right)\Delta\omega_r + \Delta\grave{E}_q = (X_e + \grave{X}_d)\Delta I_d$$

$$\Delta I_d = \left[\frac{(V_\infty . \sin\delta)}{(X_e + \grave{X}_d)}\right]\Delta\delta + \left[\frac{1}{(X_e + \grave{X}_d)}\right]\Delta\grave{E}_q + \left[\frac{(\grave{E}_{q0} - \grave{X}_d I_{d0})}{(X_e + \grave{X}_d)}\right]\Delta\omega_r$$

$$\boldsymbol{\Delta I_d = C_4 . \Delta\delta + C_5 . \Delta\grave{E}_q + C_6 . \Delta\omega_r} \qquad \boldsymbol{(A-6)}$$

where

$$C_4 = \left[\frac{(V_\infty . \sin\delta)}{(X_e + \grave{X}_d)}\right] \; ; \; C_5 = \left[\frac{1}{(X_e + \grave{X}_d)}\right] \; ; \; C_6 = \left[\frac{(\grave{E}_{q0} - \grave{X}_d I_{d0})}{(X_e + \grave{X}_d)}\right] = \left[\frac{V_{q0}}{(X_e + \grave{X}_d)}\right]$$

From $(\dot{E}_q^{`})$ equation

$$\grave{T}_{d0}\,.\dot{E}_q^{`} = -\grave{E}_q - (X_d - \grave{X}_d).I_d + E_{fd}$$

After linearization

$$\boldsymbol{\grave{T}_{d0}\,.\Delta\dot{E}_q^{`} = -\Delta\grave{E}_q - (X_d - \grave{X}_d).\Delta I_d + \Delta E_{fd}} \qquad (\boldsymbol{A-7})$$

Substitute Equation (A- 6) into Equation (A- 7)

$$\grave{T}_{d0}\,.\Delta\dot{E}_q^{`} = -\Delta\grave{E}_q - (X_d - \grave{X}_d).(C_4.\Delta\delta + C_5.\Delta\grave{E}_q + C_6.\Delta\omega_r) + \Delta E_{fd}$$

$$\Delta\dot{E}_q^{`} = \left[\frac{-(X_d-\grave{X}_d)C_4}{\grave{T}_{d0}}\right]\Delta\delta + \left[\frac{-(X_d-\grave{X}_d)C_5-1}{\grave{T}_{d0}}\right]\Delta\grave{E}_q + \left[\frac{-(X_d-\grave{X}_d)C_6}{\grave{T}_{d0}}\right]\Delta\omega_r + \left[\frac{1}{\grave{T}_{d0}}\right]\Delta E_{fd}$$

$$\boldsymbol{\Delta\dot{E}_q^{`} = K_1\Delta\delta + K_2\Delta\grave{E}_q + K_3\Delta\omega_r + \left[\frac{1}{\grave{T}_{d0}}\right]\Delta E_{fd}} \qquad (\boldsymbol{A-8})$$

Where

$$K_1 = \left[\frac{-(X_d-\grave{X}_d)C_4}{\grave{T}_{d0}}\right];\ K_2 = \left[\frac{-(X_d-\grave{X}_d)C_5-1}{\grave{T}_{d0}}\right];\ K_3 = \left[\frac{-(X_d-\grave{X}_d)C_6}{\grave{T}_{d0}}\right]$$

From ($\dot{E}_d^{`}$) equation

$$\grave{T}_{q0}\,.\ \dot{E}_d^{`} = -\grave{E}_d + (X_q - \grave{X}_q).I_q$$

After linearization

$$\boldsymbol{\grave{T}_{q0}\,.\Delta\dot{E}_d^{`} = -\Delta\grave{E}_d + (X_q - \grave{X}_q).\Delta I_q} \qquad (\boldsymbol{A-9})$$

Substitute Equation (A- 5) into Equation (A- 9)

$$\grave{T}_{q0}\,.\Delta\dot{E}_d^{`} = -\Delta\grave{E}_d + (X_q - \grave{X}_q).(C_1.\Delta\delta + C_2.\Delta\grave{E}_d + C_3.\Delta\omega_r)$$

$$\Delta \dot{E}_d^{`} = \left[\frac{(X_q - \dot{X}_q)C_1}{\dot{T}_{q0}}\right]\Delta\delta + \left[\frac{(X_q - \dot{X}_q)C_2 - 1}{\dot{T}_{q0}}\right]\Delta \dot{E}_d + \left[\frac{(X_q - \dot{X}_q)C_3}{\dot{T}_{q0}}\right]\Delta\omega_r$$

$$\boldsymbol{\Delta \dot{E}_d^{`} = K_4\Delta\delta + K_5\Delta\dot{E}_d + K_6\Delta\omega_r} \qquad \boldsymbol{(A-10)}$$

Where

$$K_4 = \left[\frac{(X_q - \dot{X}_q)C_1}{\dot{T}_{q0}}\right] ; \; K_5 = \left[\frac{(X_q - \dot{X}_q)C_2 - 1}{\dot{T}_{q0}}\right] ; \; K_6 = \left[\frac{(X_q - \dot{X}_q)C_3}{\dot{T}_{q0}}\right]$$

From the (T_e) equation

$$T_e = \dot{E}_q I_q + \dot{E}_d I_d - (\dot{X}_d - \dot{X}_q) I_d I_q$$

After linearization

$$\Delta T_e = \dot{E}_{q0}\Delta I_q + I_{q0}\Delta\dot{E}_q + \dot{E}_{d0}\Delta I_d + I_{d0}\Delta\dot{E}_d - (\dot{X}_d - \dot{X}_q)I_{d0}\Delta I_q - (\dot{X}_d - \dot{X}_q)I_{q0}\Delta I_d$$

$$\Delta T_e = (\dot{E}_{q0} - (\dot{X}_d - \dot{X}_q)I_{d0})\Delta I_q + (\dot{E}_{d0} - (\dot{X}_d - \dot{X}_q)I_{q0})\Delta I_d + I_{q0}\Delta\dot{E}_q + I_{d0}\Delta\dot{E}_d$$

Let $X_1 = \dot{E}_{q0} - (\dot{X}_d - \dot{X}_q)I_{d0}$

$X_2 = \dot{E}_{d0} - (\dot{X}_d - \dot{X}_q)I_{q0}$

$$\boldsymbol{\Delta T_e = X_1\Delta I_q + X_2\Delta I_d + I_{q0}\Delta\dot{E}_q + I_{d0}\Delta\dot{E}_d} \qquad \boldsymbol{(A-11)}$$

Substitute Equation (A- 5) and Equation (A - 6) into Equation (A-11)

$$\Delta T_e = X_1.(C_1.\Delta\delta + C_2.\Delta\dot{E}_d + C_3.\Delta\omega_r) + X_2.(C_4.\Delta\delta + C_5.\Delta\dot{E}_q + C_6.\Delta\omega_r) + I_{q0}\Delta\dot{E}_q + I_{d0}\Delta\dot{E}_d$$

$$\Delta T_e = (X_1.C_1 + X_2.C_4)\Delta\delta + (X_1.C_2 + I_{d0})\Delta\dot{E}_d + (X_2.C_5 + I_{q0})\Delta\dot{E}_q + (X_1.C_3 + X_2.C_6)\Delta\omega_r$$

$$\boldsymbol{\Delta T_e = K_7\Delta\delta + K_8\Delta\dot{E}_d + K_9\Delta\dot{E}_q + K_{10}\,\Delta\omega_r} \qquad \boldsymbol{(A-12)}$$

where

$$K_7 = X_1.C_1 + X_2.C_4 \; ; \quad K_8 = X_1.C_2 + I_{d0}$$

$$K_9 = X_2.C_5 + I_{q0} \; ; \quad K_{10} = X_1.C_3 + X_2.C_6$$

From ($\dot{\omega}_r$) equation

$$M.\dot{\omega}_r = T_m - T_e - D.\omega_r$$

After linearization

$$\boldsymbol{M.\Delta\dot{\omega}_r = \Delta T_m - \Delta T_e - D.\Delta\omega_r} \qquad \boldsymbol{(A-13)}$$

Substitute Equation (A-12) into Equation (A-13)

$$M.\Delta\dot{\omega}_r = \Delta T_m - (K_7\Delta\delta + K_8\Delta\grave{E}_d + K_9\Delta\grave{E}_q + K_{10}\,\Delta\omega_r) - D.\Delta\omega_r$$

$$\Delta\dot{\omega}_r = \left[\frac{-K_7}{M}\right]\Delta\delta + \left[\frac{-K_8}{M}\right]\Delta\grave{E}_d + \left[\frac{-K_9}{M}\right]\Delta\grave{E}_q + \left[\frac{-(D+K_{10})}{M}\right]\Delta\omega_r + \left[\frac{1}{M}\right]\Delta T_m \qquad \boldsymbol{(A-14)}$$

The terminal voltage (V_t) equation

$$V_t = V_q - jV_d$$

$$V_t^2 = V_q^2 + V_d^2$$

$$2V_{t0}.\Delta V_t = 2V_{q0}.\Delta V_q + 2V_{d0}.\Delta V_d$$

$$\boldsymbol{\Delta V_t = \frac{V_{q0}}{V_{t0}}.\Delta V_q + \frac{V_{d0}}{V_{t0}}.\Delta V_d} \qquad \boldsymbol{(A-15)}$$

From (V_q) equation

$$V_q = (\grave{E}_q - \grave{X}_d.I_d).\omega_r = \grave{E}_q.\omega_r - \grave{X}_d.I_d.\omega_r$$

After linearization

$$\Delta V_q = \Delta\grave{E}_q - \grave{X}_d.\Delta I_d + (\grave{E_{q0}} - \grave{X}_d.I_{d0}).\Delta\omega_r$$

$$\boldsymbol{\Delta V_q = \Delta\grave{E}_q - \grave{X}_d.\Delta I_d + V_{q0}.\Delta\omega_r} \qquad \boldsymbol{(A-16)}$$

From (V_d) equation

$$V_d = (\grave{E}_d + \grave{X}_q . I_q) . \omega_r = \grave{E}_d . \omega_r + \grave{X}_q . I_q . \omega_r$$

After linearization

$$\Delta V_d = \Delta \grave{E}_d + \grave{X}_q . \Delta I_q + (\grave{E}_{d0} + \grave{X}_q . I_{q0}) . \Delta \omega_r$$

$$\boldsymbol{\Delta V_d = \Delta \grave{E}_d + \grave{X}_q . \Delta I_q + V_{d0} . \Delta \omega_r} \qquad \boldsymbol{(A-17)}$$

Substitute Equation (A-16) and Equation (A-17) into Equation (A-15)

$$\Delta V_t = \left(\frac{V_{q0}}{V_{t0}}\right) . [\Delta \grave{E}_q - \grave{X}_d . \Delta I_d + V_{q0} . \Delta \omega_r] + \left(\frac{V_{d0}}{V_{t0}}\right) . [\Delta \grave{E}_d + \grave{X}_q . \Delta I_q + V_{d0} . \Delta \omega_r]$$

$$\boldsymbol{\Delta V_t = \left(\frac{V_{q0}}{V_{t0}}\right) . \Delta \grave{E}_q + \left(\frac{V_{d0}}{V_{t0}}\right) . \Delta \grave{E}_d - \left(\frac{V_{q0}}{V_{t0}}\right) . \grave{X}_d . \Delta I_d + \left(\frac{V_{d0}}{V_{t0}}\right) . \grave{X}_q . \Delta I_q + \left(\frac{V_{q0}^2}{V_{t0}} + \frac{V_{d0}^2}{V_{t0}}\right) . \Delta \omega_r} \qquad \boldsymbol{(A-18)}$$

Substitute Equation (A-5) and Equation (A-6) into Equation (A-18)

$$\Delta V_t = \left(\frac{V_{q0}}{V_{t0}}\right) . \Delta \grave{E}_q + \left(\frac{V_{d0}}{V_{t0}}\right) . \Delta \grave{E}_d - \left(\frac{V_{q0}}{V_{t0}}\right) . \grave{X}_d . (C_4 . \Delta \delta + C_5 . \Delta \grave{E}_q + C_6 . \Delta \omega_r) + \left(\frac{V_{d0}}{V_{t0}}\right) . \grave{X}_q . (C_1 . \Delta \delta + C_2 . \Delta \grave{E}_d + C_3 . \Delta \omega_r) + \left(\frac{V_{q0}^2}{V_{t0}} + \frac{V_{d0}^2}{V_{t0}}\right) . \Delta \omega_r$$

$$\Delta V_t = \left(\frac{V_{d0}}{V_{t0}} . \grave{X}_q . C_1 - \frac{V_{q0}}{V_{t0}} . \grave{X}_d . C_4\right) \Delta \delta + \left(\frac{V_{q0}}{V_{t0}} - \frac{V_{q0}}{V_{t0}} . \grave{X}_d . C_5\right) . \Delta \grave{E}_q + \left(\frac{V_{d0}}{V_{t0}} + \frac{V_{d0}}{V_{t0}} . \grave{X}_q . C_2\right) . \Delta \grave{E}_d + \left(\frac{V_{q0}^2}{V_{t0}} + \frac{V_{d0}^2}{V_{t0}} + \frac{V_{d0}}{V_{t0}} . \grave{X}_q . C_3 - \frac{V_{q0}}{V_{t0}} . \grave{X}_d . C_6\right) . \Delta \omega_r$$

$$\boldsymbol{\Delta V_t = K_{11} . \Delta \delta + K_{12} . \Delta \grave{E}_q + K_{13} . \Delta \grave{E}_d + K_{14} . \Delta \omega_r} \qquad \boldsymbol{(A-19)}$$

where

$$K_{11} = \left(\frac{V_{do}}{V_{to}}.\grave{X}_q.C_1 - \frac{V_{qo}}{V_{to}}.\grave{X}_d.C_4\right) \;;\; K_{12} = \left(\frac{V_{qo}}{V_{to}} - \frac{V_{qo}}{V_{to}}.\grave{X}_d.C_5\right)$$

$$K_{13} = \left(\frac{V_{do}}{V_{to}} + \frac{V_{do}}{V_{to}}.\grave{X}_q.C_2\right) \;;\; K_{14} = \left(\frac{V_{qo}^2}{V_{to}} + \frac{V_{do}^2}{V_{to}} + \frac{V_{do}}{V_{to}}.\grave{X}_q.C_3 - \frac{V_{qo}}{V_{to}}.\grave{X}_d.C_6\right)$$

From $(\dot{\delta})$ equation

$$\dot{\delta} = \omega_b.(\omega_r - 1)$$

After linearization

$$\Delta\dot{\boldsymbol{\delta}} = \boldsymbol{\omega_b}.\Delta\boldsymbol{\omega_r} \qquad (\boldsymbol{A-20})$$

From the excitation field voltage $(\dot{E}_{fd})$ equation

$$\dot{E}_{fd} = \left[\frac{K_a}{T_a}\right](V_{ref} + U_{pss} - V_t) - \left[\frac{1}{T_a}\right].E_{fd}$$

After linearization

$$\Delta\dot{E}_{fd} = \left[\frac{K_a}{T_a}\right](\Delta V_{ref} + \Delta U_{pss} - \Delta V_t) - \left[\frac{1}{T_a}\right].\Delta E_{fd}$$

$$\Delta\dot{\boldsymbol{E}}_{\boldsymbol{fd}} = \left[\frac{\boldsymbol{K_a}}{\boldsymbol{T_a}}\right](\Delta\boldsymbol{V_{ref}} + \Delta\boldsymbol{U_{pss}} - \boldsymbol{K_{11}}.\Delta\boldsymbol{\delta} - \boldsymbol{K_{12}}.\Delta\grave{\boldsymbol{E}}_{\boldsymbol{q}} - \boldsymbol{K_{13}}.\Delta\grave{\boldsymbol{E}}_{\boldsymbol{d}} - \boldsymbol{K_{14}}.\Delta\boldsymbol{\omega_r}) - \left[\frac{\boldsymbol{1}}{\boldsymbol{T_a}}\right].\Delta\boldsymbol{E_{fd}} \qquad (\boldsymbol{A-21})$$

BLOCK DIAGRAM OF SIMPLIFIED MODEL OF SMIB:

The $(\Delta\dot{E}_q^{`})$ block diagram: from equation (A-8)

$$\Delta\dot{E}_q^{`} = K_1\Delta\delta + K_2\Delta\grave{E}_q + K_3\Delta\omega_r + \left[\frac{1}{\grave{T}_{d0}}\right]\Delta E_{fd}$$

$$s.\Delta\grave{E}_q - K_2\Delta\grave{E}_q = K_1\Delta\delta + K_3\Delta\omega_r + \left[\frac{1}{\grave{T}_{d0}}\right]\Delta E_{fd}$$

$$(s - K_2)\Delta\grave{E}_q = K_1\Delta\delta + K_3\Delta\omega_r + \left[\frac{1}{\grave{T}_{d0}}\right]\Delta E_{fd}$$

$$\Delta\grave{E}_q = \left[\frac{1}{(s - K_2)}\right](K_1\Delta\delta + K_3\Delta\omega_r + \left[\frac{1}{\grave{T}_{d0}}\right]\Delta E_{fd}) \qquad (A-22)$$

From Equation (A-22)

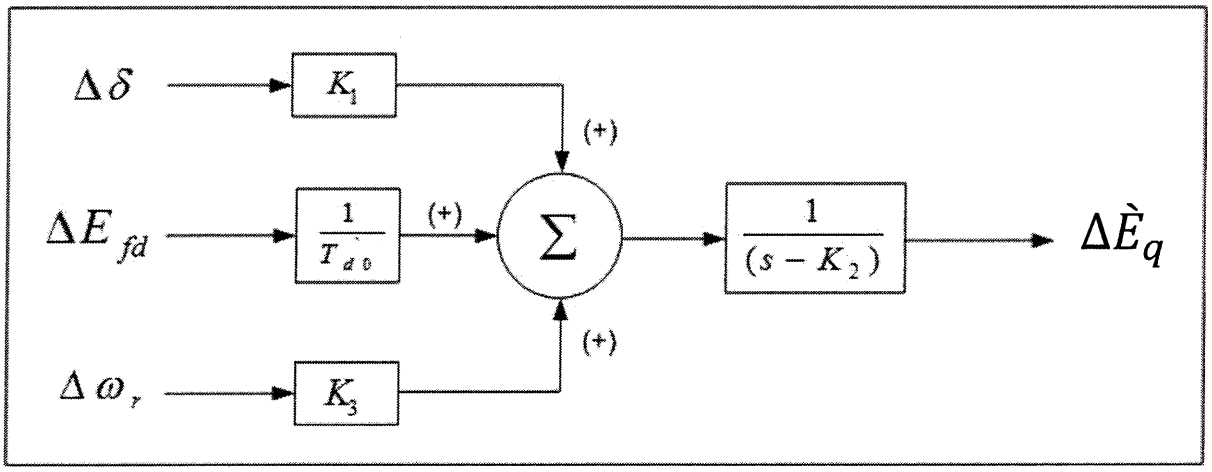


Fig. (A.2) The $(\Delta\dot{E}_q^{`})$ block diagram

The $(\Delta\dot{E}_d^{`})$ block diagram: from Equation (A-10)

$$\Delta\dot{E}_d^{`} = K_4\Delta\delta + K_5\Delta\grave{E}_d + K_6\Delta\omega_r$$

$$s.\Delta\grave{E}_d - K_5\Delta\grave{E}_d = K_4\Delta\delta + +K_6\Delta\omega_r$$

$$(s - K_5)\Delta\grave{E}_d = K_4\Delta\delta + +K_6\Delta\omega_r$$

$$\Delta \dot{E}_d = \left[\frac{1}{(s - K_5)}\right](K_4 \Delta\delta + + K_6 \Delta\omega_r) \qquad (A-23)$$

From Equation (A-23)

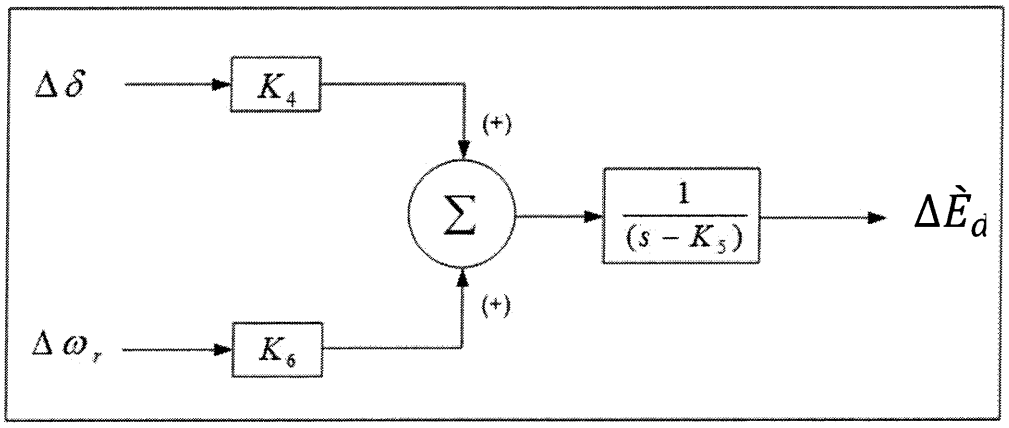


Fig. (A.3) The ($\Delta \dot{E}_d$) block diagram

The speed deviation ($\Delta \dot{\omega}_r$) block diagram: from Equation (A-14)

$$\Delta \dot{\omega}_r = \left[\frac{-K_7}{M}\right]\Delta\delta + \left[\frac{-K_8}{M}\right]\Delta \dot{E}_d + \left[\frac{-K_9}{M}\right]\Delta \dot{E}_q + \left[\frac{-(D + K_{10})}{M}\right]\Delta\omega_r + \left[\frac{1}{M}\right]\Delta T_m$$

$$\Delta \dot{\omega}_r = \left(\tfrac{1}{M}\right)\left[-K_7\Delta\delta - K_8\Delta \dot{E}_d - K_9\Delta \dot{E}_q - (D + K_{10})\Delta\omega_r + \Delta T_m\right]$$

$$M.\Delta \dot{\omega}_r + (D + K_{10})\Delta\omega_r = \left[-K_7\Delta\delta - K_8\Delta \dot{E}_d - K_9\Delta \dot{E}_q + \Delta T_m\right]$$

$$M.s.\Delta\omega_r + (D + K_{10})\Delta\omega_r = \left[-K_7\Delta\delta - K_8\Delta \dot{E}_d - K_9\Delta \dot{E}_q + \Delta T_m\right]$$

$$(M.s + D + K_{10})\Delta\omega_r = \left[-K_7\Delta\delta - K_8\Delta \dot{E}_d - K_9\Delta \dot{E}_q + \Delta T_m\right]$$

$$\Delta\omega_r = \left(\frac{1}{(M.s + D + K_{10})}\right)\left[-K_7\Delta\delta - K_8\Delta \dot{E}_d - K_9\Delta \dot{E}_q + \Delta T_m\right] \qquad (A-24)$$

From Equation (A-24)

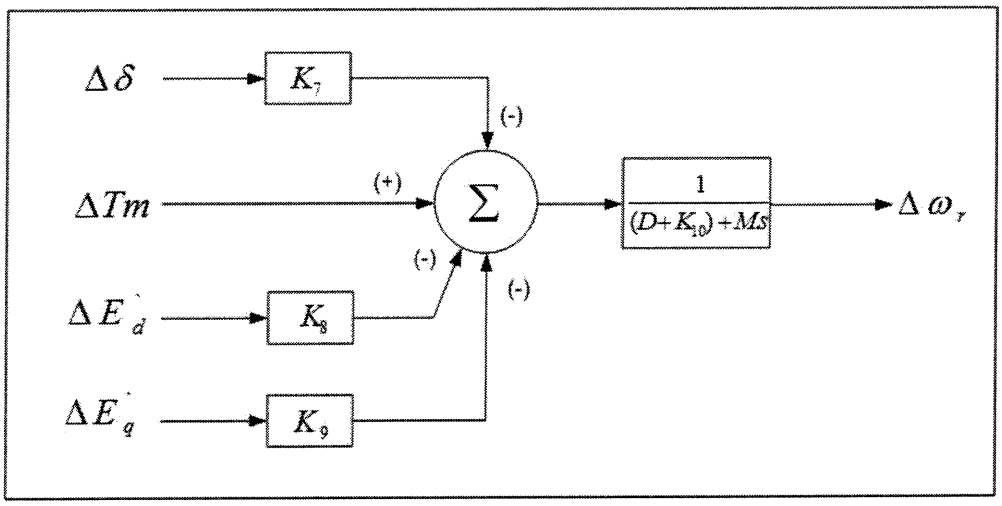


Fig. (A.4) The speed deviation $(\Delta\dot{\omega}_r)$ block diagram

The $(\Delta\dot{\delta})$ block diagram: from Equation (A-20)

$$\Delta\dot{\delta} = \omega_b.\Delta\omega_r \;\rightarrow\rightarrow\; s.\Delta\delta = \omega_b.\Delta\omega_r \;\rightarrow\rightarrow\; \boldsymbol{\Delta\delta = \left(\frac{\omega_b}{s}\right)\Delta\omega_r} \qquad \boldsymbol{(A-25)}$$

From equation (A-25)

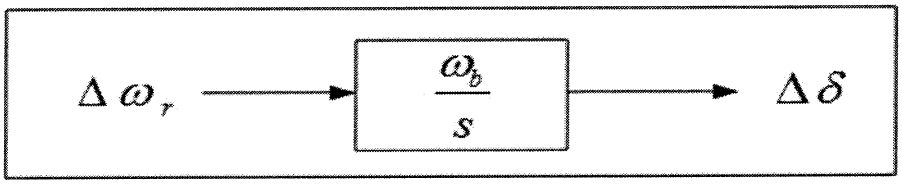


Fig. (A.5) The $(\Delta\dot{\delta})$ block diagram

The (ΔV_t) block diagram: from Equation (A-19)

$$\Delta V_t = K_{11}.\Delta\delta + K_{12}.\Delta\grave{E}_q + K_{13}.\Delta\grave{E}_d + K_{14}.\Delta\omega_r$$

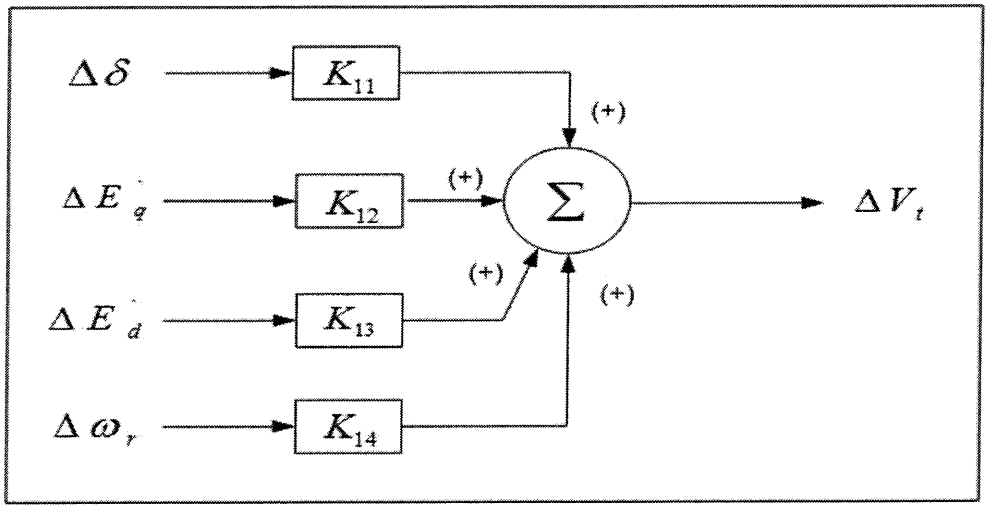


Fig. (A.6) The (ΔV_t) block diagram

The (ΔE_{fd}) block diagram: from Equation (A-21)

$$\Delta \dot{E}_{fd} = \left[\frac{K_a}{T_a}\right]\left(\Delta V_{ref} + \Delta U_{pss} - K_{11}.\Delta\delta - K_{12}.\Delta \dot{E}_q - K_{13}.\Delta \dot{E}_d - K_{14}.\Delta\omega_r\right) - \left[\frac{1}{T_a}\right].\Delta E_{fd}$$

$$T_a.\Delta \dot{E}_{fd} = K_a\left(\Delta V_{ref} + \Delta U_{pss} - \Delta V_t\right) - \Delta E_{fd}$$

$$T_a.s.\Delta E_{fd} + \Delta E_{fd} = K_a\left(\Delta V_{ref} + \Delta U_{pss} - \Delta V_t\right)$$

$$(1 + T_a.s)\Delta E_{fd} = K_a\left(\Delta V_{ref} + \Delta U_{pss} - \Delta V_t\right)$$

$$\boldsymbol{\Delta E_{fd} = \left[\frac{K_a}{(1 + T_a.s)}\right]\left(\Delta V_{ref} + \Delta U_{pss} - \Delta V_t\right)} \qquad \boldsymbol{(A-26)}$$

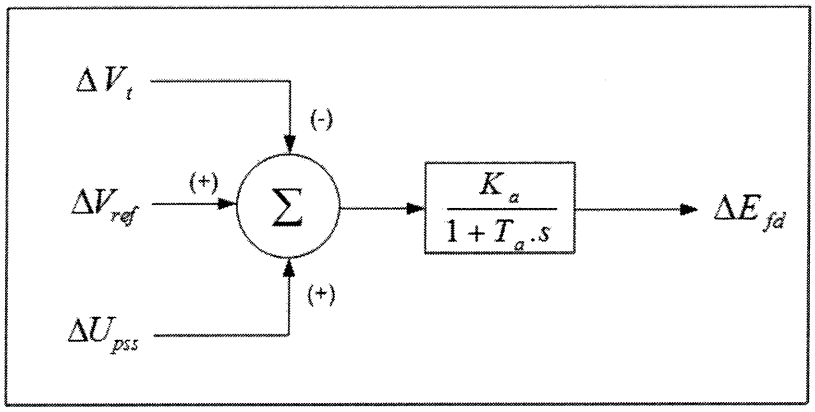


Fig. (A.7) The (ΔE_{fd}) block diagram

The full block diagram

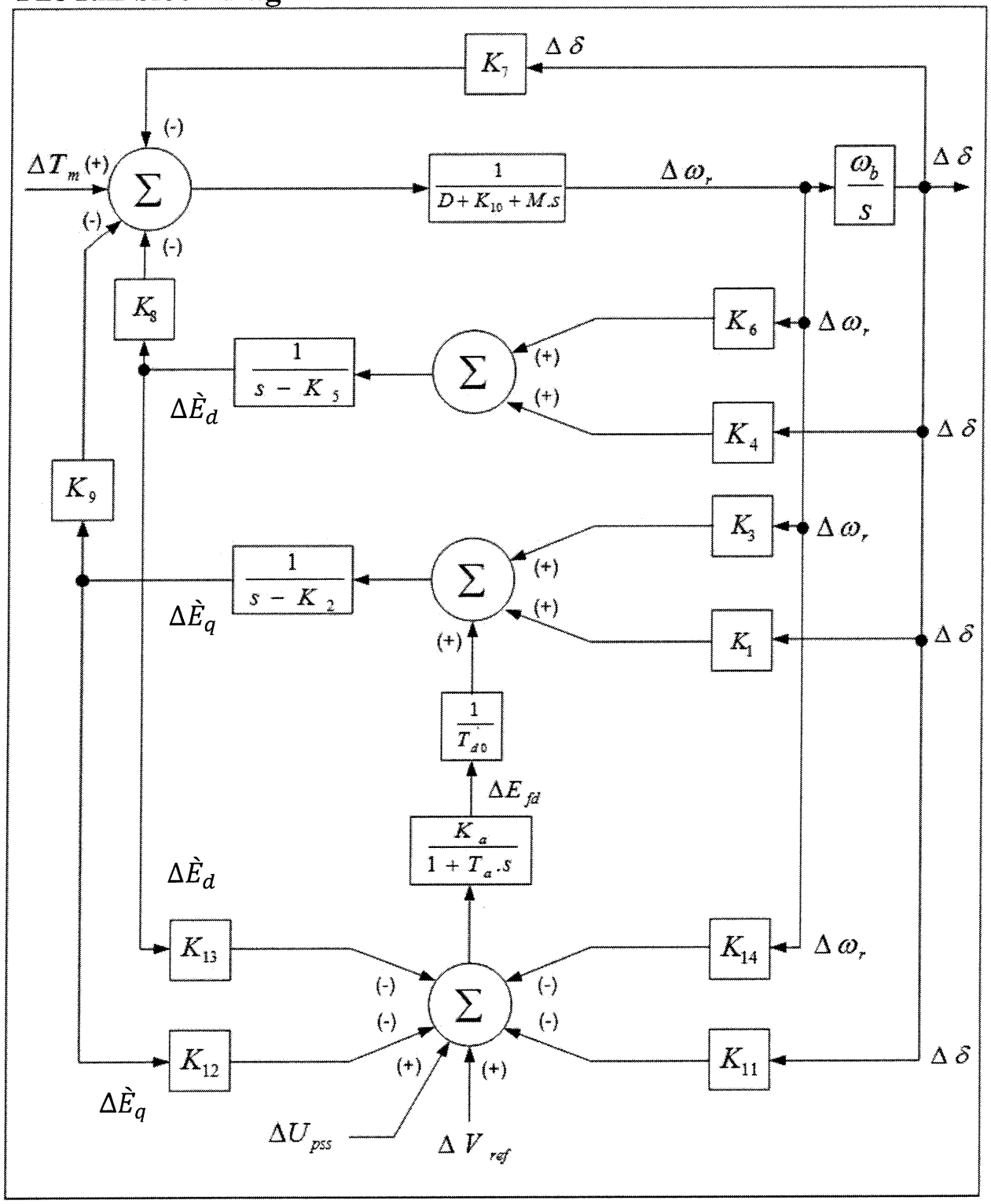


Fig. (A.8) The block diagram of simplified model of SMIB

APPENDIX B

Iq and Id gains analysis for single machine isolated system

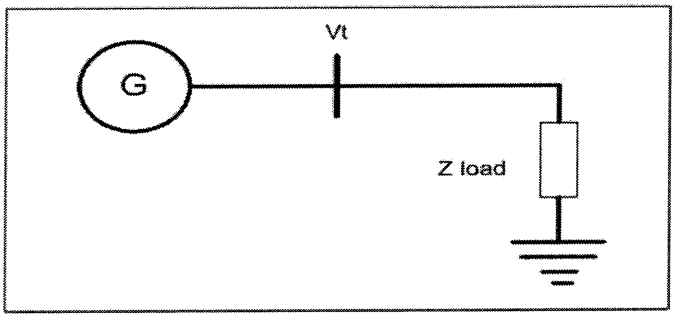


Fig. (B.1) System configuration of single machine isolated system

From the above figure:

$$Y = Z_{load}^{-1} = G + jB \qquad (B-1)$$

$$(I_q - jI_d) = Y.V_t \qquad (B-2)$$

$$(I_q - jI_d) = (G + jB).(V_q - jV_d) \qquad (B-3)$$

$$(I_q - jI_d) = (G.V_q + B.V_d) - j(-B.V_q + G.V_d) \qquad (B-4)$$

$$I_q = (G.V_q + B.V_d) \qquad (B-5)$$

$$I_d = (-B.V_q + G.V_d) \qquad (B-6)$$

After linearizing Equation (B-5) and Equation (B- 6)

$$\Delta I_q = (G.\Delta V_q + B.\Delta V_d) \qquad (B-7)$$

$$\Delta I_d = (-B.\Delta V_q + G.\Delta V_d) \qquad (B-8)$$

Also we have

$$V_q = (\grave{E}_q - \grave{X}_d I_d).\omega_r \qquad (B-9)$$

$$V_d = (\grave{E}_d + \grave{X}_q I_q).\omega_r \qquad (B-10)$$

After linearizing Equation (B-9) and Equation (B- 10)

$$\Delta V_q = \Delta \grave{E}_q - \grave{X}_d \Delta I_d + \left(\grave{E}_{q0} - \grave{X}_d I_{d0}\right).\Delta\omega_r \qquad (B-11)$$

$$\Delta V_q = \Delta \grave{E}_q - \grave{X}_d \Delta I_d + V_{q0}.\Delta\omega_r \qquad (B-12)$$

$$\Delta V_d = \Delta \grave{E}_d + \grave{X}_q \Delta I_q + \left(\grave{E}_{d0} + \grave{X}_{q0} I_q\right).\Delta\omega_r \qquad (B-13)$$

$$\Delta V_d = \Delta \grave{E}_d + \grave{X}_q \Delta I_q + V_{d0}.\Delta\omega_r \qquad (B-14)$$

Substituting Equation (B-12) and Equation (B-14) into Equation (B-7)

$$\Delta I_q = \begin{pmatrix} G.\left(\Delta \grave{E}_q - \grave{X}_d \Delta I_d + V_{q0}.\Delta\omega_r\right) \\ +B.\left(\Delta \grave{E}_d + \grave{X}_q \Delta I_q + V_{d0}.\Delta\omega_r\right) \end{pmatrix} \qquad (B-15)$$

$$(1 - B.\grave{X}_q)\Delta I_q + (G.\grave{X}_d)\Delta I_d = \left(G.\Delta \grave{E}_q + B.\Delta \grave{E}_d + \left(G.V_{q0} + B.V_{d0}\right)\Delta\omega_r\right) \qquad (B-16)$$

$$\Delta I_d = \begin{pmatrix} -B.\left(\Delta \grave{E}_q - \grave{X}_d \Delta I_d + V_{q0}.\Delta\omega_r\right) \\ +G.\left(\Delta \grave{E}_d + \grave{X}_q \Delta I_q + V_{d0}.\Delta\omega_r\right) \end{pmatrix} \qquad (B-17)$$

$$(-G.\grave{X}_q)\Delta I_q + (1 - B.\grave{X}_d)\Delta I_d = \left(-B.\Delta \grave{E}_q + G.\Delta \grave{E}_d + \left(-B.V_{q0} + G.V_{d0}\right)\Delta\omega_r\right) \qquad (B-18)$$

$$\begin{bmatrix} (1 - B.\grave{X}_q) & (G.\grave{X}_d) \\ (-G.\grave{X}_q) & (1 - B.\grave{X}_d) \end{bmatrix} . \begin{bmatrix} \Delta I_q \\ \Delta I_d \end{bmatrix} = \begin{bmatrix} G & B & \left(G.V_{q0} + B.V_{d0}\right) \\ -B & G & \left(-B.V_{q0} + G.V_{d0}\right) \end{bmatrix} \begin{bmatrix} \Delta \grave{E}_q \\ \Delta \grave{E}_d \\ \Delta\omega_r \end{bmatrix} \qquad (B-19)$$

$$\begin{bmatrix} \Delta I_q \\ \Delta I_d \end{bmatrix} = X^{-1}.\bar{G} \begin{bmatrix} \Delta \grave{E}_q \\ \Delta \grave{E}_d \\ \Delta\omega_r \end{bmatrix} \qquad (B-20)$$

where

$$X = \begin{bmatrix} (1 - B.\grave{X}_q) & (G.\grave{X}_d) \\ (-G.\grave{X}_q) & (1 - B.\grave{X}_d) \end{bmatrix} \; ; \; \bar{G} = \begin{bmatrix} G & B & \left(G.V_{q0} + B.V_{d0}\right) \\ -B & G & \left(-B.V_{q0} + G.V_{d0}\right) \end{bmatrix}$$

APPENDIX C

Iq and Id gains analysis for multi-machine system

1) Reduction of the power system network:

The electrical loads are considered as constant impedances.

$$y_{lk} = \frac{S_{lk}^*}{V_k^2} \qquad (C-1)$$

where $S_{lk}^* = apperent\ power\ (VA) of\ the\ electrical\ load\ at\ bus\ k.$

The bus admittance matrix is modified to include the bus loads by adding y_{lk} to the corresponding diagonal element of y_{bus}.

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} * \begin{bmatrix} V_G \\ V_L \end{bmatrix} \qquad (C-2)$$

where

$$I_G = \begin{bmatrix} I_{g1} \\ I_{g2} \\ \vdots \\ I_{gNG} \end{bmatrix} \quad I_L = \begin{bmatrix} I_{l1} \\ I_{l2} \\ \vdots \\ I_{lNL} \end{bmatrix} \quad V_G = \begin{bmatrix} V_{g1} \\ V_{g2} \\ \vdots \\ V_{gNG} \end{bmatrix} \quad V_L = \begin{bmatrix} V_{l1} \\ V_{l2} \\ \vdots \\ V_{lNL} \end{bmatrix}$$

After including the loads in y_{bus} , the external injection for the load buses become zero.

$$\begin{bmatrix} I_G \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} * \begin{bmatrix} V_G \\ V_L \end{bmatrix} \qquad (C-3)$$

$$I_G = Y_{GG}V_G + Y_{GL}V_L \qquad (C-4)$$

$$0 = Y_{LG}V_G + Y_{LL}V_L \qquad (C-5)$$

From equation (C-5):

$$V_L = -Y_{LL}^{-1}Y_{LG}V_G \qquad (C-6)$$

Substitute equation (C-6) into equation (C-4), yields:

$$I_G = Y_{GG}V_G + Y_{GL}(-Y_{LL}^{-1}Y_{LG}V_G)$$

$$I_G = (Y_{GG} - Y_{GL}Y_{LL}^{-1}Y_{LG}).V_G$$

$$I_G = Y_R.V_G \qquad (C-7)$$

where
Y_R is the reduced electrical system network matrix, with the order of the system machines. Y_R is considered constant during the dynamics.

2) <u>d – q axis components:</u>

The generator terminal voltages are transformed to the d – q axis of the individual machines.
If the reference voltage is the voltage of bus (1), i.e. bus (1) is the swing bus:

$$V_1 = |V_1|\angle 0 \quad \bar{E}q_1 = |\bar{E}q_1|\angle\delta_1$$
$$V_{1dq} = |V_1|\cos(\delta_1 - \theta_1) - j|V_1|\sin(\delta_1 - \theta_1)$$

For the k^{th} bus:

$$V_k = |V_k|\angle\theta_k \quad \bar{E}q_k = |\bar{E}q_k|\angle\delta_k$$
$$V_{kdq} = |V_k|\cos(\delta_k - \theta_k) - j|V_k|\sin(\delta_k - \theta_k) \qquad (C-8)$$

$$V_{kdq} = |V_k|\angle -(\delta_k - \theta_k) = V_k\angle -\delta_k = V_k e^{-j\delta_k} \qquad (C-9)$$

$$V_{dq} = T.V \qquad (C-10)$$
$$V = T^{-1}.V_{dq} \qquad (C-11)$$

where

$$V_{dq} = \begin{bmatrix} V_{q1} - jV_{d1} \\ V_{q2} - jV_{d2} \\ \vdots \\ V_{qn} - jV_{dn} \end{bmatrix} \quad V = \begin{bmatrix} V_{g1} \\ V_{g2} \\ \vdots \\ V_{gn} \end{bmatrix}$$

$$T = \begin{bmatrix} e^{-j\delta_1} & 0 & 0 & 0 \\ 0 & e^{-j\delta_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{-j\delta_n} \end{bmatrix} = Transformation\ matrix$$

Similarly for the current

$$I_{dq} = T.I \qquad (C-12)$$
$$I = T^{-1}.I_{dq} \qquad (C-13)$$

where $I^T = [I_{g1}\ I_{g2} \ldots\ldots I_{gn}]$ are the generator output currents.
The current can be expressed in term of Y_R *and* V as follows:

$$I = Y_R.V \qquad (C-14)$$

Substituting Equation (C-11) and Equation (C-13) into Equation (C-14), yields:

$$T^{-1}.I_{dq} = Y_R.T^{-1}.V_{dq}$$

$$I_{dq} = T.Y_R.T^{-1}.V_{dq} = T.Y_R.T^*.V_{dq}$$

$$I_{dq} = Y_{dq}.V_{dq} \qquad (C-15)$$

where $$Y_{dq} = T.Y_R.T^* \qquad (C-16)$$

Note that:

$$T^{-1} = T^* = \begin{bmatrix} e^{j\delta_1} & 0 & 0 & 0 \\ 0 & e^{j\delta_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{j\delta_n} \end{bmatrix}$$

By using Equation (C-16):

$$Y_{dq} = \begin{bmatrix} e^{-j\delta_1} & 0 & 0 & 0 \\ 0 & e^{-j\delta_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{-j\delta_n} \end{bmatrix} * \begin{bmatrix} y_{11} \dots & \dots y_{1n} \\ y_{21} \dots & \dots y_{2n} \\ \vdots & \vdots \\ y_{n1} \dots & \dots y_{nn} \end{bmatrix} * \begin{bmatrix} e^{j\delta_1} & 0 & 0 & 0 \\ 0 & e^{j\delta_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{j\delta_n} \end{bmatrix}$$

$$Y_{dq} = \begin{bmatrix} y_{11}e^{-j\delta_1} & \dots & y_{1n}e^{-j\delta_1} \\ y_{21}e^{-j\delta_2} & \dots & y_{2n}e^{-j\delta_2} \\ \vdots & \vdots & \vdots \\ y_{n1}e^{-j\delta_n} & \dots & y_{nn}e^{-j\delta_n} \end{bmatrix} * \begin{bmatrix} e^{j\delta_1} & 0 & 0 & 0 \\ 0 & e^{j\delta_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{j\delta_n} \end{bmatrix}$$

$$Y_{dq} = \begin{bmatrix} y_{11} & y_{12}e^{-j\delta_{12}} & \dots & y_{1n}e^{-j\delta_{1n}} \\ y_{21}e^{-j\delta_{21}} & y_{22} & \dots & y_{2n}e^{-j\delta_{2n}} \\ & & & \\ y_{n1}e^{-j\delta_{n1}} & \dots & \dots & y_{nn} \end{bmatrix} = Y_R.* e^{-j\delta_{kj}} \qquad (C-17)$$

where:

(.*) denotes element by element multiplication, and $\delta_{kj} = \delta_k - \delta_j$.

$$e^{-j\delta_{kj}} = \begin{bmatrix} e^{-j\delta_{11}} & e^{-j\delta_{12}} & .... & e^{-j\delta_{1n}} \\ e^{-j\delta_{21}} & e^{-j\delta_{22}} & .... & e^{-j\delta_{2n}} \\ & & & \\ e^{-j\delta_{n1}} & .... & .... & e^{-j\delta_{nn}} \end{bmatrix} = \cos\delta_{kj} - j\sin\delta_{kj}$$

where:

$$\cos\delta_{kj} = \begin{bmatrix} \cos\delta_{11} & \cos\delta_{12} & .... & \cos\delta_{1n} \\ \cos\delta_{21} & \cos\delta_{22} & .... & \cos\delta_{2n} \\ & & & \\ \cos\delta_{n1} & .... & .... & \cos\delta_{nn} \end{bmatrix} ; \quad \sin\delta_{kj} = \begin{bmatrix} \sin\delta_{11} & \sin\delta_{12} & .... & \sin\delta_{1n} \\ \sin\delta_{21} & \sin\delta_{22} & .... & \sin\delta_{2n} \\ & & & \\ \sin\delta_{n1} & .... & .... & \sin\delta_{nn} \end{bmatrix}$$

Note that:

$$\cos\delta_{kk} = 1 \qquad \sin\delta_{kk} = 0$$

The reduced admittance matrix Y_R can be expressed as follows:

$$Y_R = G + jB \qquad (C-18)$$

Substituting Equation (C-18) into Equation (C-17), yields:

$$Y_{dq} = [G + jB].* e^{-j\delta_{kj}}$$

$$Y_{dq} = [G + jB].* [\cos\delta_{kj} - j\sin\delta_{kj}]$$

$$Y_{dq} = [G.*\cos\delta_{kj} + B.*\sin\delta_{kj}] + j[B.*\cos\delta_{kj} - G.*\sin\delta_{kj}] \qquad (C-19)$$

Substituting Equation (C-19) into Equation (C-15):

$$I_{dq} = ([G.*\cos\delta_{kj} + B.*\sin\delta_{kj}] + j[B.*\cos\delta_{kj} - G.*\sin\delta_{kj}]).V_{dq}$$

Note that:

$$I_{dq} = I_q - jI_d \qquad and \qquad V_{dq} = V_q - jV_d$$

$$(I_q - jI_d) = ([G.*\cos\delta_{kj} + B.*\sin\delta_{kj}] + j[B.*\cos\delta_{kj} - G.*\sin\delta_{kj}]).(V_q - jV_d)$$

So, the I_q and I_d can be expressed as follows:

$$I_q = [G.* \cos\delta_{kj} + B.* \sin\delta_{kj}].V_q + [B.* \cos\delta_{kj} - G.* \sin\delta_{kj}].V_d \qquad (C-20)$$

$$I_d = -[B.* \cos\delta_{kj} - G.* \sin\delta_{kj}].V_q + [G.* \cos\delta_{kj} + B.* \sin\delta_{kj}].V_d \qquad (C-21)$$

3) Linearization of I_q and I_d:

- Linearization of I_q

$$I_q = [G.* \cos\delta_{kj} + B.* \sin\delta_{kj}].V_q + [B.* \cos\delta_{kj} - G.* \sin\delta_{kj}].V_d$$

With respect to V_q:

$$\Delta I_q = [G.* \cos\delta_{kj} + B.* \sin\delta_{kj}].\Delta V_q = \bar{G}_{qq}.\Delta V_q$$

With respect to V_d:

$$\Delta I_q = [B.* \cos\delta_{kj} - G.* \sin\delta_{kj}].\Delta V_d = \bar{G}_{qd}.\Delta V_d$$

With respect to δ_{kj}:

$$I_q = [G.* \cos\delta_{kj} + B.* \sin\delta_{kj}].V_q + [B.* \cos\delta_{kj} - G.* \sin\delta_{kj}].V_d$$

$$= \left[\begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} .* \begin{bmatrix} \cos\delta_{11} & \cos\delta_{12} & \cos\delta_{13} \\ \cos\delta_{21} & \cos\delta_{22} & \cos\delta_{23} \\ \cos\delta_{31} & \cos\delta_{32} & \cos\delta_{33} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} .* \begin{bmatrix} \sin\delta_{11} & \sin\delta_{12} & \sin\delta_{13} \\ \sin\delta_{21} & \sin\delta_{22} & \sin\delta_{23} \\ \sin\delta_{31} & \sin\delta_{32} & \sin\delta_{33} \end{bmatrix}\right] * \begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q3} \end{bmatrix}$$

$$- \left[\begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} .* \begin{bmatrix} \cos\delta_{11} & \cos\delta_{12} & \cos\delta_{13} \\ \cos\delta_{21} & \cos\delta_{22} & \cos\delta_{23} \\ \cos\delta_{31} & \cos\delta_{32} & \cos\delta_{33} \end{bmatrix} - \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} .* \begin{bmatrix} \sin\delta_{11} & \sin\delta_{12} & \sin\delta_{13} \\ \sin\delta_{21} & \sin\delta_{22} & \sin\delta_{23} \\ \sin\delta_{31} & \sin\delta_{32} & \sin\delta_{33} \end{bmatrix}\right] * \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \end{bmatrix}$$

Note that: $\cos\delta_{kk} = 1$ and $\sin\delta_{kk} = 0$

$$I_q = \left[\begin{bmatrix} G_{11} & G_{12}.\cos\delta_{12} & G_{13}.\cos\delta_{13} \\ G_{21}.\cos\delta_{21} & G_{22} & G_{23}.\cos\delta_{23} \\ G_{31}.\cos\delta_{31} & G_{32}.\cos\delta_{32} & G_{33} \end{bmatrix} + \begin{bmatrix} 0 & B_{12}.\sin\delta_{12} & B_{13}.\sin\delta_{13} \\ B_{21}.\sin\delta_{21} & 0 & B_{23}.\sin\delta_{23} \\ B_{31}.\sin\delta_{31} & B_{32}.\sin\delta_{32} & 0 \end{bmatrix}\right] * \begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q3} \end{bmatrix}$$

$$+\left[\begin{bmatrix} B_{11} & B_{12}.\cos\delta_{12} & B_{13}.\cos\delta_{13} \\ B_{21}.\cos\delta_{21} & B_{22} & B_{23}.\cos\delta_{23} \\ B_{31}.\cos\delta_{31} & B_{32}.\cos\delta_{32} & B_{33} \end{bmatrix} - \begin{bmatrix} 0 & G_{12}.\sin\delta_{12} & G_{13}.\sin\delta_{13} \\ G_{21}.\sin\delta_{21} & 0 & G_{23}.\sin\delta_{23} \\ G_{31}.\sin\delta_{31} & G_{32}.\sin\delta_{32} & 0 \end{bmatrix}.\right] * \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \end{bmatrix}$$

$$I_q = \begin{bmatrix} G_{11} & G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12} & G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13} \\ G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21} & G_{22} & G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23} \\ G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31} & G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32} & G_{33} \end{bmatrix} * \begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q3} \end{bmatrix}$$

$$+\begin{bmatrix} B_{11} & B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12} & B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13} \\ B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21} & B_{22} & B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23} \\ B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31} & B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32} & B_{33} \end{bmatrix} * \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \end{bmatrix}$$

$$I_q = \begin{bmatrix} G_{11}.V_{q1} + (G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12}).V_{q2} + (G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13}).V_{q3} \\ (G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21}).V_{q1} + G_{22}.V_{q2} + (G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23}).V_{q3} \\ (G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31}).V_{q1} + (G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32}).V_{q2} + G_{33}.V_{q3} \end{bmatrix}$$

$$+\begin{bmatrix} B_{11}.V_{d1} + (B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12}).V_{d2} + (B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13}).V_{d3} \\ (B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21}).V_{d1} + B_{22}.V_{d2} + (B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23}).V_{d3} \\ (B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31}).V_{d1} + (B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32}).V_{d2} + B_{33}.V_{d3} \end{bmatrix}$$

$$I_q = \begin{bmatrix} A_{11} + A_{12} + A_{13} \\ A_{21} + A_{22} + A_{23} \\ A_{31} + A_{32} + A_{33} \end{bmatrix}$$

$$A_{11} = G_{11}.V_{q1} + B_{11}.V_{d1}$$
$$A_{12} = (G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12}).V_{q2} + (B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12}).V_{d2}$$
$$A_{13} = (G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13}).V_{q3} + (B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13}).V_{d3}$$

$$A_{21} = (G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21}).V_{q1} + (B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21}).V_{d1}$$
$$A_{22} = G_{22}.V_{q2} + B_{22}.V_{d2}$$
$$A_{23} = (G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23}).V_{q3} + (B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23}).V_{d3}$$

$$A_{31} = (G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31}).V_{q1} + (B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31}).V_{d1}$$
$$A_{32} = (G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32}).V_{q2} + (B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32}).V_{d2}$$
$$A_{33} = G_{33}.V_{q3} + B_{33}.V_{d3}$$

$$A_{11} = G_{11}.V_{q1} + B_{11}.V_{d1}$$

linearization of A_{11} *with respect to* $\delta_1 = 0$
linearization of A_{11} *with respect to* $\delta_2 = 0$
linearization of A_{11} *with respect to* $\delta_3 = 0$

$$A_{12} = (G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12}).V_{q2} + (B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12}).V_{d2}$$

linearization of A_{12} *with respect to* δ_1

$$= [(-G_{12}.\sin\delta_{12} + B_{12}.\cos\delta_{12}).V_{q2} + (-B_{12}.\sin\delta_{12} - G_{12}.\cos\delta_{12}).V_{d2}].\Delta\delta_1$$

linearization of A_{12} *with respect to* δ_2

$$= [(G_{12}.\sin\delta_{12} - B_{12}.\cos\delta_{12}).V_{q2} + (B_{12}.\sin\delta_{12} + G_{12}.\cos\delta_{12}).V_{d2}].\Delta\delta_2$$

linearization of A_{12} *with respect to* $\delta_3 = 0$

$$A_{13} = (G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13}).V_{q3} + (B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13}).V_{d3}$$

linearization of A_{13} *with respect to* δ_1

$$= [(-G_{13}.\sin\delta_{13} + B_{13}.\cos\delta_{13}).V_{q3} + (-B_{13}.\sin\delta_{13} - G_{13}.\cos\delta_{13}).V_{d3}].\Delta\delta_1$$

linearization of A_{13} *with respect to* $\delta_2 = 0$

linearization of A_{13} *with respect to* δ_3

$$= [(G_{13}.\sin\delta_{13} - B_{13}.\cos\delta_{13}).V_{q3} + (B_{13}.\sin\delta_{13} + G_{13}.\cos\delta_{13}).V_{d3}].\Delta\delta_3$$

$$A_{21} = (G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21}).V_{q1} + (B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21}).V_{d1}$$

linearization of A_{21} *with respect to* δ_1

$$= \left[(G_{21}.\sin\delta_{21} - B_{21}.\cos\delta_{21}).V_{q1} + (B_{21}.\sin\delta_{21} + G_{21}.\cos\delta_{21}).V_{d1}\right].\Delta\delta_1$$

linearization of A_{21} *with respect to* δ_2

$$= \left[(-G_{21}.\sin\delta_{21} + B_{21}.\cos\delta_{21}).V_{q1} + (-B_{21}.\sin\delta_{21} - G_{21}.\cos\delta_{21}).V_{d1}\right].\Delta\delta_2$$

linearization of A_{21} *with respect to* $\delta_3 = 0$

$$A_{22} = G_{22}.V_{q2} + B_{22}.V_{d2}$$

linearization of A_{22} *with respect to* $\delta_1 = 0$
linearization of A_{22} *with respect to* $\delta_2 = 0$
linearization of A_{22} *with respect to* $\delta_3 = 0$

$$A_{23} = (G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23}).V_{q3} + (B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23}).V_{d3}$$

linearization of A_{23} *with respect to* $\delta_1 = 0$

linearization of A_{23} *with respect to* δ_2

$$= \left[(-G_{23}.\sin\delta_{23} + B_{23}.\cos\delta_{23}).V_{q3} + (-B_{23}.\sin\delta_{23} - G_{23}.\cos\delta_{23}).V_{d3}\right].\Delta\delta_2$$

linearization of A_{23} *with respect to* δ_3

$$= \left[(G_{23}.\sin\delta_{23} - B_{23}.\cos\delta_{23}).V_{q3} + (B_{23}.\sin\delta_{23} + G_{23}.\cos\delta_{23}).V_{d3}\right].\Delta\delta_3$$

$$A_{31} = (G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31}).V_{q1} + (B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31}).V_{d1}$$

linearization of A_{31} *with respect to* δ_1

$$= \left[(G_{31}.\sin\delta_{31} - B_{31}.\cos\delta_{31}).V_{q1} + (B_{31}.\sin\delta_{31} + G_{31}.\cos\delta_{31}).V_{d1}\right].\Delta\delta_1$$

linearization of A_{31} *with respect to* $\delta_2 = 0$

linearization of A_{31} *with respect to* δ_3

$$= \left[(-G_{31}.\sin\delta_{31} + B_{31}.\cos\delta_{31}).V_{q1} + (-B_{31}.\sin\delta_{31} - G_{31}.\cos\delta_{31}).V_{d1}\right].\Delta\delta_3$$

$$A_{32} = (G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32}).V_{q2} + (B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32}).V_{d2}$$

linearization of A_{32} *with respect to* $\delta_1 = 0$

linearization of A_{32} *with respect to* δ_2

$$= \left[(G_{32}.\sin\delta_{32} - B_{32}.\cos\delta_{32}).V_{q2} + (B_{32}.\sin\delta_{32} + G_{32}.\cos\delta_{32}).V_{d2}\right].\Delta\delta_2$$

linearization of A_{32} *with respect to* δ_3

$$= \left[(-G_{32}.\sin\delta_{32} + B_{32}.\cos\delta_{32}).V_{q2} + (-B_{32}.\sin\delta_{32} - G_{32}.\cos\delta_{32}).V_{d2}\right].\Delta\delta_3$$

$$A_{33} = G_{33}.V_{q3} + B_{33}.V_{d3}$$

linearization of A_{33} *with respect to* $\delta_1 = 0$
linearization of A_{33} *with respect to* $\delta_2 = 0$
linearization of A_{33} *with respect to* $\delta_3 = 0$

$$\Delta I_q = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} * \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\delta_3 \end{bmatrix} \qquad (C-22)$$

$$B_{11} = [(-G_{12}.\sin\delta_{12} + B_{12}.\cos\delta_{12}).V_{q2} + (-B_{12}.\sin\delta_{12} - G_{12}.\cos\delta_{12}).V_{d2}] + [(-G_{13}.\sin\delta_{13} + B_{13}.\cos\delta_{13}).V_{q3} + (-B_{13}.\sin\delta_{13} - G_{13}.\cos\delta_{13}).V_{d3}]$$

$$B_{12} = [(G_{12}.\sin\delta_{12} - B_{12}.\cos\delta_{12}).V_{q2} + (B_{12}.\sin\delta_{12} + G_{12}.\cos\delta_{12}).V_{d2}]$$

$$B_{13} = [(G_{13}.\sin\delta_{13} - B_{13}.\cos\delta_{13}).V_{q3} + (B_{13}.\sin\delta_{13} + G_{13}.\cos\delta_{13}).V_{d3}]$$

$$B_{21} = [(G_{21}.\sin\delta_{21} - B_{21}.\cos\delta_{21}).V_{q1} + (B_{21}.\sin\delta_{21} + G_{21}.\cos\delta_{21}).V_{d1}]$$

$$B_{22} = [(-G_{21}.\sin\delta_{21} + B_{21}.\cos\delta_{21}).V_{q1} + (-B_{21}.\sin\delta_{21} - G_{21}.\cos\delta_{21}).V_{d1}] + [(-G_{23}.\sin\delta_{23} + B_{23}.\cos\delta_{23}).V_{q3} + (-B_{23}.\sin\delta_{23} - G_{23}.\cos\delta_{23}).V_{d3}]$$

$$B_{23} = [(G_{23}.\sin\delta_{23} - B_{23}.\cos\delta_{23}).V_{q3} + (B_{23}.\sin\delta_{23} + G_{23}.\cos\delta_{23}).V_{d3}]$$

$$B_{31} = [(G_{31}.\sin\delta_{31} - B_{31}.\cos\delta_{31}).V_{q1} + (B_{31}.\sin\delta_{31} + G_{31}.\cos\delta_{31}).V_{d1}]$$

$$B_{32} = [(G_{32}.\sin\delta_{32} - B_{32}.\cos\delta_{32}).V_{q2} + (B_{32}.\sin\delta_{32} + G_{32}.\cos\delta_{32}).V_{d2}]$$

$$B_{33} = [(-G_{31}.\sin\delta_{31} + B_{31}.\cos\delta_{31}).V_{q1} + (-B_{31}.\sin\delta_{31} - G_{31}.\cos\delta_{31}).V_{d1}] + [(-G_{32}.\sin\delta_{32} + B_{32}.\cos\delta_{32}).V_{q2} + (-B_{32}.\sin\delta_{32} - G_{32}.\cos\delta_{32}).V_{d2}]$$

$$\Delta I_q = \left[\begin{bmatrix} 0 & B_{12} & B_{13} \\ B_{21} & 0 & B_{23} \\ B_{31} & B_{32} & 0 \end{bmatrix} + \begin{bmatrix} B_{11} & 0 & 0 \\ 0 & B_{22} & 0 \\ 0 & 0 & B_{33} \end{bmatrix}\right] * \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\delta_3 \end{bmatrix} = \bar{G}_{q\delta}.\Delta\delta \qquad (C-23)$$

- Linearization of Id

$$I_d = -[B.*\cos\delta_{kj} - G.*\sin\delta_{kj}].V_q + [G.*\cos\delta_{kj} + B.*\sin\delta_{kj}].V_d$$

With respect to V_q:

$$\Delta \mathrm{I_d} = -[B.*\cos\delta_{kj} - G.*\sin\delta_{kj}].\Delta V_q = \bar{G}_{dq}.\Delta V_q = -\bar{G}_{qd}.\Delta V_q$$

With respect to V_d:

$$\Delta \mathrm{I_d} = [G.*\cos\delta_{kj} + B.*\sin\delta_{kj}].\Delta V_d = \bar{G}_{dd}.\Delta V_q = \bar{G}_{qq}.\Delta V_q$$

With respect to δ_{kj}:

$$I_d = -[B.*\cos\delta_{kj} - G.*\sin\delta_{kj}].V_q + [G.*\cos\delta_{kj} + B.*\sin\delta_{kj}].V_d$$

$$= -\left[\begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} .* \begin{bmatrix} \cos\delta_{11} & \cos\delta_{12} & \cos\delta_{13} \\ \cos\delta_{21} & \cos\delta_{22} & \cos\delta_{23} \\ \cos\delta_{31} & \cos\delta_{32} & \cos\delta_{33} \end{bmatrix} - \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} .* \begin{bmatrix} \sin\delta_{11} & \sin\delta_{12} & \sin\delta_{13} \\ \sin\delta_{21} & \sin\delta_{22} & \sin\delta_{23} \\ \sin\delta_{31} & \sin\delta_{32} & \sin\delta_{33} \end{bmatrix}\right] * \begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q3} \end{bmatrix}$$

$$-\left[\begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} .* \begin{bmatrix} \cos\delta_{11} & \cos\delta_{12} & \cos\delta_{13} \\ \cos\delta_{21} & \cos\delta_{22} & \cos\delta_{23} \\ \cos\delta_{31} & \cos\delta_{32} & \cos\delta_{33} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} .* \begin{bmatrix} \sin\delta_{11} & \sin\delta_{12} & \sin\delta_{13} \\ \sin\delta_{21} & \sin\delta_{22} & \sin\delta_{23} \\ \sin\delta_{31} & \sin\delta_{32} & \sin\delta_{33} \end{bmatrix}\right] * \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \end{bmatrix}$$

Note that: $\cos\delta_{kk} = 1$ and $\sin\delta_{kk} = 0$

$$I_d = -\left[\begin{bmatrix} B_{11} & B_{12}.\cos\delta_{12} & B_{13}.\cos\delta_{13} \\ B_{21}.\cos\delta_{21} & B_{22} & B_{23}.\cos\delta_{23} \\ B_{31}.\cos\delta_{31} & B_{32}.\cos\delta_{32} & B_{33} \end{bmatrix} - \begin{bmatrix} 0 & G_{12}.\sin\delta_{12} & G_{13}.\sin\delta_{13} \\ G_{21}.\sin\delta_{21} & 0 & G_{23}.\sin\delta_{23} \\ G_{31}.\sin\delta_{31} & G_{32}.\sin\delta_{32} & 0 \end{bmatrix}\right] * \begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q3} \end{bmatrix}$$

$$+\left[\begin{bmatrix} G_{11} & G_{12}.\cos\delta_{12} & G_{13}.\cos\delta_{13} \\ G_{21}.\cos\delta_{21} & G_{22} & G_{23}.\cos\delta_{23} \\ G_{31}.\cos\delta_{31} & G_{32}.\cos\delta_{32} & G_{33} \end{bmatrix} + \begin{bmatrix} 0 & B_{12}.\sin\delta_{12} & B_{13}.\sin\delta_{13} \\ B_{21}.\sin\delta_{21} & 0 & B_{23}.\sin\delta_{23} \\ B_{31}.\sin\delta_{31} & B_{32}.\sin\delta_{32} & 0 \end{bmatrix}\right] * \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \end{bmatrix}$$

$$I_d = -\begin{bmatrix} B_{11} & B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12} & B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13} \\ B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21} & B_{22} & B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23} \\ B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31} & B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32} & B_{33} \end{bmatrix} * \begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q3} \end{bmatrix}$$

$$+\begin{bmatrix} G_{11} & G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12} & G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13} \\ G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21} & G_{22} & G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23} \\ G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31} & G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32} & G_{33} \end{bmatrix} * \begin{bmatrix} V_{d1} \\ V_{d2} \\ V_{d3} \end{bmatrix}$$

$$I_d = -\begin{bmatrix} B_{11}.V_{q1} + (B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12}).V_{q2} + (B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13}).V_{q3} \\ (B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21}).V_{q1} + B_{22}.V_{q2} + (B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23}).V_{q3} \\ (B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31}).V_{q1} + (B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32}).V_{q2} + B_{33}.V_{q3} \end{bmatrix}$$

$$+\begin{bmatrix} G_{11}.V_{d1} + (G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12}).V_{d2} + (G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13}).V_{d3} \\ (G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21}).V_{d1} + G_{22}.V_{d2} + (G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23}).V_{d3} \\ (G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31}).V_{d1} + (G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32}).V_{d2} + G_{33}.V_{d3} \end{bmatrix}$$

$$I_d = \begin{bmatrix} C_{11} + C_{12} + C_{13} \\ C_{21} + C + {}_{22}\, C_{23} \\ C_{31} + C_{32} + C_{33} \end{bmatrix}$$

$$C_{11} = -B_{11}.V_{q1} + G_{11}.V_{d1}$$
$$C_{12} = -(B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12}).V_{q2} + (G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12}).V_{d2}$$
$$C_{13} = -(B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13}).V_{q3} + (G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13}).V_{d3}$$

$$C_{21} = -(B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21}).V_{q1} + (G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21}).V_{d1}$$
$$C_{22} = -B_{22}.V_{q2} + G_{22}.V_{d2}$$
$$C_{23} = -(B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23}).V_{q3} + (G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23}).V_{d3}$$

$$C_{31} = -(B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31}).V_{q1} + (G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31}).V_{d1}$$
$$C_{32} = -(B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32}).V_{q2} + (G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32}).V_{d2}$$
$$C_{33} = -B_{33}.V_{q3} + G_{33}.V_{d3}$$

$$C_{11} = -B_{11}.V_{q1} + G_{11}.V_{d1}$$

Linearization of C_{11} *with respect to* $\delta_1 = 0$
Linearization of C_{11} *with respect to* $\delta_2 = 0$
Linearization of C_{11} *with respect to* $\delta_3 = 0$

$$C_{12} = -(B_{12}.\cos\delta_{12} - G_{12}.\sin\delta_{12}).V_{q2} + (G_{12}.\cos\delta_{12} + B_{12}.\sin\delta_{12}).V_{d2}$$

Linearization of C_{12} *with respect to* δ_1

$$= [-(-B_{12}.\sin\delta_{12} - G_{12}.\cos\delta_{12}).V_{q2} + (-G_{12}.\sin\delta_{12} + B_{12}.\cos\delta_{12}).V_{d2}].\Delta\delta_1$$

Linearization of C_{12} *with respect to* δ_2

$$= [-(B_{12}.\sin\delta_{12} + G_{12}.\cos\delta_{12}).V_{q2} + (G_{12}.\sin\delta_{12} - B_{12}.\cos\delta_{12}).V_{d2}].\Delta\delta_2$$

Linearization of C_{12} *with respect to* $\delta_3 = 0$

$$C_{13} = -(B_{13}.\cos\delta_{13} - G_{13}.\sin\delta_{13}).V_{q3} + (G_{13}.\cos\delta_{13} + B_{13}.\sin\delta_{13}).V_{d3}$$

Linearization of C_{13} *with respect to* δ_1

$$= [-(-B_{13}.\sin\delta_{13} - G_{13}.\cos\delta_{13}).V_{q3} + (-G_{13}.\sin\delta_{13} + B_{13}.\cos\delta_{13}).V_{d3}].\Delta\delta_1$$

Linearization of C_{13} *with respect to* $\delta_2 = 0$

Linearization of C_{13} *with respect to* δ_3

$$= [-(B_{13}.\sin\delta_{13} + G_{13}.\cos\delta_{13}).V_{q3} + (G_{13}.\sin\delta_{13} - B_{13}.\cos\delta_{13}).V_{d3}].\Delta\delta_3$$

$$C_{21} = -(B_{21}.\cos\delta_{21} - G_{21}.\sin\delta_{21}).V_{q1} + (G_{21}.\cos\delta_{21} + B_{21}.\sin\delta_{21}).V_{d1}$$

Linearization of C_{21} *with respect to* δ_1

$$= \left[-(B_{21}.\sin\delta_{21} + G_{21}.\cos\delta_{21}).V_{q1} + (G_{21}.\sin\delta_{21} - B_{21}.\cos\delta_{21}).V_{d1}\right].\Delta\delta_1$$

Linearization of C_{21} *with respect to* δ_2

$$= \left[-(-B_{21}.\sin\delta_{21} - G_{21}.\cos\delta_{21}).V_{q1} + (-G_{21}.\sin\delta_{21} + B_{21}.\cos\delta_{21}).V_{d1}\right].\Delta\delta_2$$

Linearization of C_{21} *with respect to* $\delta_3 = 0$

$$C_{22} = -B_{22}.V_{q2} + G_{22}.V_{d2}$$

Linearization of C_{22} *with respect to* $\delta_1 = 0$
Linearization of C_{22} *with respect to* $\delta_2 = 0$
Linearization of C_{22} *with respect to* $\delta_3 = 0$

$$C_{23} = -(B_{23}.\cos\delta_{23} - G_{23}.\sin\delta_{23}).V_{q3} + (G_{23}.\cos\delta_{23} + B_{23}.\sin\delta_{23}).V_{d3}$$

Linearization of C_{23} *with respect to* $\delta_1 = 0$

Linearization of C_{23} *with respect to* δ_2

$$= \left[-(-B_{23}.\sin\delta_{23} - G_{23}.\cos\delta_{23}).V_{q3} + (-G_{23}.\sin\delta_{23} + B_{23}.\cos\delta_{23}).V_{d3}\right].\Delta\delta_2$$

Linearization of C_{23} *with respect to* δ_3

$$= \left[-(B_{23}.\sin\delta_{23} + G_{23}.\cos\delta_{23}).V_{q3} + (G_{23}.\sin\delta_{23} - B_{23}.\cos\delta_{23}).V_{d3}\right].\Delta\delta_3$$

$$C_{31} = -(B_{31}.\cos\delta_{31} - G_{31}.\sin\delta_{31}).V_{q1} + (G_{31}.\cos\delta_{31} + B_{31}.\sin\delta_{31}).V_{d1}$$

Linearization of C_{31} *with respect to* δ_1

$$= \left[-(B_{31}.\sin\delta_{31} + G_{31}.\cos\delta_{31}).V_{q1} + (G_{31}.\sin\delta_{31} - B_{31}.\cos\delta_{31}).V_{d1}\right].\Delta\delta_1$$

Linearization of C_{31} *with respect to* $\delta_2 = 0$

Linearization of C_{31} *with respect to* δ_3

$$= \left[-(-B_{31}.\sin\delta_{31} - G_{31}.\cos\delta_{31}).V_{q1} + (-G_{31}.\sin\delta_{31} + B_{31}.\cos\delta_{31}).V_{d1}\right].\Delta\delta_3$$

$$C_{32} = -(B_{32}.\cos\delta_{32} - G_{32}.\sin\delta_{32}).V_{q2} + (G_{32}.\cos\delta_{32} + B_{32}.\sin\delta_{32}).V_{d2}$$

Linearization of C_{32} *with respect to* $\delta_1 = 0$

Linearization of C_{32} *with respect to* δ_2

$$= \left[-(B_{32}.\sin\delta_{32} + G_{32}.\cos\delta_{32}).V_{q2} + (G_{32}.\sin\delta_{32} - B_{32}.\cos\delta_{32}).V_{d2}\right].\Delta\delta_2$$

Linearization of C_{32} *with respect to* δ_3

$$= \left[-(-B_{32}.\sin\delta_{32} - G_{32}.\cos\delta_{32}).V_{q2} + (-G_{32}.\sin\delta_{32} + B_{32}.\cos\delta_{32}).V_{d2}\right].\Delta\delta_3$$

$$C_{33} = -B_{33}.V_{q3} + G_{33}.V_{d3}$$

$Linearization\ of\ C_{33} with\ respect\ to\ \delta_1 = 0$
$Linearization\ of\ C_{33} with\ respect\ to\ \delta_2 = 0$
$Linearization\ of\ C_{33} with\ respect\ to\ \delta_3 = 0$

$$\Delta I_d = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} * \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\delta_3 \end{bmatrix} \qquad (C-24)$$

$$D_{11} = [-(-B_{12}.\sin\delta_{12} - G_{12}.\cos\delta_{12}).V_{q2} + (-G_{12}.\sin\delta_{12} + B_{12}.\cos\delta_{12}).V_{d2}] + [-(-B_{13}.\sin\delta_{13} - G_{13}.\cos\delta_{13}).V_{q3} + (-G_{13}.\sin\delta_{13} + B_{13}.\cos\delta_{13}).V_{d3}]$$

$$D_{12} = [-(B_{12}.\sin\delta_{12} + G_{12}.\cos\delta_{12}).V_{q2} + (G_{12}.\sin\delta_{12} - B_{12}.\cos\delta_{12}).V_{d2}]$$

$$D_{13} = [-(B_{13}.\sin\delta_{13} + G_{13}.\cos\delta_{13}).V_{q3} + (G_{13}.\sin\delta_{13} - B_{13}.\cos\delta_{13}).V_{d3}]$$

$$D_{21} = [-(B_{21}.\sin\delta_{21} + G_{21}.\cos\delta_{21}).V_{q1} + (G_{21}.\sin\delta_{21} - B_{21}.\cos\delta_{21}).V_{d1}]$$

$$D_{22} = [-(-B_{21}.\sin\delta_{21} - G_{21}.\cos\delta_{21}).V_{q1} + (-G_{21}.\sin\delta_{21} + B_{21}.\cos\delta_{21}).V_{d1}] + [-(-B_{23}.\sin\delta_{23} - G_{23}.\cos\delta_{23}).V_{q3} + (-G_{23}.\sin\delta_{23} + B_{23}.\cos\delta_{23}).V_{d3}]$$

$$D_{23} = [-(B_{23}.\sin\delta_{23} + G_{23}.\cos\delta_{23}).V_{q3} + (G_{23}.\sin\delta_{23} - B_{23}.\cos\delta_{23}).V_{d3}]$$

$$D_{31} = [-(B_{31}.\sin\delta_{31} + G_{31}.\cos\delta_{31}).V_{q1} + (G_{31}.\sin\delta_{31} - B_{31}.\cos\delta_{31}).V_{d1}]$$

$$D_{32} = [-(B_{32}.\sin\delta_{32} + G_{32}.\cos\delta_{32}).V_{q2} + (G_{32}.\sin\delta_{32} - B_{32}.\cos\delta_{32}).V_{d2}]$$

$$D_{33} = [-(-B_{31}.\sin\delta_{31} - G_{31}.\cos\delta_{31}).V_{q1} + (-G_{31}.\sin\delta_{31} + B_{31}.\cos\delta_{31}).V_{d1}] + [-(-B_{32}.\sin\delta_{32} - G_{32}.\cos\delta_{32}).V_{q2} + (-G_{32}.\sin\delta_{32} + B_{32}.\cos\delta_{32}).V_{d2}]$$

$$\Delta I_d = \left[\begin{bmatrix} 0 & D_{12} & D_{13} \\ D_{21} & 0 & D_{23} \\ D_{31} & D_{32} & 0 \end{bmatrix} + \begin{bmatrix} D_{11} & 0 & 0 \\ 0 & D_{22} & 0 \\ 0 & 0 & D_{33} \end{bmatrix}\right] * \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\delta_3 \end{bmatrix} = \bar{G}_{d\delta}.\Delta\delta \qquad (C-25)$$

After linearizing of I_q and I_d with respect toV_q,V_d and δ, we obtain:

$$\Delta I_q = \bar{G}_{qq}.\Delta V_q + \bar{G}_{qd}.\Delta V_d + \bar{G}_{q\delta}.\Delta\delta \qquad (C-26)$$

$$\Delta I_d = \bar{G}_{dq}.\Delta V_q + \bar{G}_{dd}.\Delta V_d + \bar{G}_{d\delta}.\Delta\delta \qquad (C-27)$$

where

$$\Delta I_q = \begin{bmatrix} \Delta I_{q1} \\ \Delta I_{q2} \\ \vdots \\ \Delta I_{qn} \end{bmatrix} \quad \Delta I_d = \begin{bmatrix} \Delta I_{d1} \\ \Delta I_{d2} \\ \vdots \\ \Delta I_{dn} \end{bmatrix} \quad \Delta V_q = \begin{bmatrix} \Delta V_{q1} \\ \Delta V_{q2} \\ \vdots \\ \Delta V_{qn} \end{bmatrix} \quad \Delta V_d = \begin{bmatrix} \Delta V_{d1} \\ \Delta V_{d2} \\ \vdots \\ \Delta V_{dn} \end{bmatrix} \quad \Delta \delta = \begin{bmatrix} \Delta \delta_1 \\ \Delta \delta_2 \\ \vdots \\ \Delta \delta_n \end{bmatrix}$$

Recall that:

$$Vq = (Eq` - Xd`.Id) * \omega_r$$

$$Vd = (Ed` + Xq`.Iq) * \omega_r$$

After linearization:

$$\Delta Vq = \Delta Eq` - Xd`.\Delta Id + Vq_0.\Delta\omega_r \qquad (C-28)$$

$$\Delta Vd = \Delta Ed` + Xq`.\Delta Iq + Vd_0.\Delta\omega_r \qquad (C-29)$$

Substitute Equations (C-28) and (C-29) into Equation (C-26):

$$\Delta Iq = \bar{G}qq.\Delta Vq + \bar{G}qd.\Delta Vd + \bar{G}q\delta.\Delta\delta$$

$$\Delta Iq = \bar{G}qq.[\Delta Eq` - Xd`.\Delta Id + Vq_0.\Delta\omega_r] + \bar{G}qd.[\Delta Ed` + Xq`.\Delta Iq + Vd_0.\Delta\omega_r] + \bar{G}q\delta.\Delta\delta$$

$$\Delta Iq - \bar{G}qd.diag(Xq`).\Delta Iq + \bar{G}qq.diag(Xd`).\Delta Id = \bar{G}qq.\Delta Eq` + \bar{G}qd.\Delta Ed` + [\bar{G}qq.diag(Vq_0) + \bar{G}qd.diag(Vd_0)].\Delta\omega_r + \bar{G}q\delta.\Delta\delta$$

$$(I - \bar{G}qd.diag(Xq`).).\Delta Iq + (\bar{G}qq.diag(Xd`).).\Delta Id = \bar{G}qq.\Delta Eq` + \bar{G}qd.\Delta Ed` + \bar{G}q\omega.\Delta\omega_r + \bar{G}q\delta.\Delta\delta \qquad (C-30)$$

where:

$$\bar{G}q\omega = \bar{G}qq.diag(Vq_0) + \bar{G}qd.diag(Vd_0)$$

Substitute Equations (C-28) and (C-29) into Equation (C-27):

$$\Delta Id = \bar{G}dq.\Delta Vq + \bar{G}dd.\Delta Vd + \bar{G}d\delta.\Delta\delta$$

$$\Delta Id = \bar{G}dq.[\Delta Eq` - Xd`.\Delta Id + Vq_0.\Delta\omega_r] + \bar{G}dd.[\Delta Ed` + Xq`.\Delta Iq + Vd_0.\Delta\omega_r] + \bar{G}q\delta.\Delta\delta$$

$$\Delta Id + \bar{G}qd.diag(Xd`).\Delta Id - \bar{G}dd.diag(Xq`).\Delta Iq = \bar{G}dq.\Delta Eq` + \bar{G}dd.\Delta Ed` + [\bar{G}dq.diag(Vq_0) + \bar{G}dd.diag(Vd_0)].\Delta\omega_r + \bar{G}d\delta.\Delta\delta$$

$$(-\bar{G}dd.diag(Xq`)).\Delta Iq + (I - \bar{G}dq.diag(Xd`)).\Delta Id = \bar{G}dq.\Delta Eq` + \bar{G}dd.\Delta Ed` + \bar{G}d\omega.\Delta\omega_r + \bar{G}d\delta.\Delta\delta \qquad (C-31)$$

where:

$$\bar{G}d\omega = \bar{G}dq.diag(Vq_0) + \bar{G}dd.diag(Vd_0)$$

By using equations (C-30) and (C-31):

$$(I - X\grave{q}.\bar{G}qd).\Delta Iq + (X\grave{d}.\bar{G}qq).\Delta Id = \bar{G}qq.\Delta E\grave{q} + \bar{G}qd.\Delta E\grave{d} + \bar{G}q\omega.\Delta\omega_r + \bar{G}q\delta.\Delta\delta$$

$$(-X\grave{q}.\bar{G}dd).\Delta Iq + (I - X\grave{d}.\bar{G}dq).\Delta Id = \bar{G}dq.\Delta E\grave{q} + \bar{G}dd.\Delta E\grave{d} + \bar{G}d\omega.\Delta\omega_r + \bar{G}d\delta.\Delta\delta$$

$$Z.\Delta I = X \qquad (C-32)$$

Where:

$$\Delta I = \begin{bmatrix} I_q \\ I_d \end{bmatrix} \qquad Z = \begin{bmatrix} I - X\grave{q}.\bar{G}qd & X\grave{d}.\bar{G}qq \\ -X\grave{q}.\bar{G}dd & I - X\grave{d}.\bar{G}dq \end{bmatrix} \qquad X = \begin{bmatrix} \bar{G}qq & \bar{G}qd & \bar{G}q\delta & \bar{G}q\omega \\ \bar{G}dq & \bar{G}dd & \bar{G}d\delta & \bar{G}d\omega \end{bmatrix} \begin{bmatrix} \Delta E\grave{q} \\ \Delta E\grave{d} \\ \Delta\delta \\ \Delta\omega_r \end{bmatrix}$$

Finally, I_q and I_d can be expressed in term of $\Delta\grave{E}_q$,$\Delta\grave{E}_d$,$\Delta\omega_r$ and $\Delta\delta$ as follows:

$$\Delta I_q = G_{qq}.\Delta\grave{E}_q + G_{qd}.\Delta\grave{E}_d + G_{q\delta}.\Delta\delta + G_{q\omega}.\Delta\omega_r \qquad (C-33)$$

$$\Delta I_d = G_{dq}.\Delta\grave{E}_q + G_{dd}.\Delta\grave{E}_d + G_{d\delta}.\Delta\delta + G_{d\omega}.\Delta\omega_r \qquad (C-34)$$

APPENDIX D

Power systems parameters

SMIB - Machine data (60 Hz)

M = 108	D = 0	$X_d = 1.8$	$X_q = 1.7$
$\grave{X}_d = 0.17$	$\grave{X}_q = 0.23$	$\grave{T}_{d0} = 0.4$	$\grave{T}_{q0} = 0.1$
$X_e = 0.25$	$P_t = 1.0$	$V_t = 1.0$	$V_\infty = 1.0$
P.F=0.992 (leading)	$K_D = 25$ (4%)		

Exciter

$K_a = 10.0$	$T_a = 0.02$

Power system stabilizer

$D_{pss} = 70.0$	$T_w = 5.0$	$T_1 = 0.04$	$T_2 = 0.01$
$T_3 = 0.04$	$T_4 = 0.01$		

SMIS - Machine data (60 Hz)

M = 108	D = 0	$X_d = 0.2$	$X_q = 0.18$
$\grave{X}_d = 0.03$	$\grave{X}_q = 0.02$	$\grave{T}_{d0} = 8.0$	$\grave{T}_{q0} = 0.4$
$K_D = 25$ (4%)			

Exciter

$K_a = 10.0$	$T_a = 0.02$

Power system stabilizer

$D_{pss} = 38.0$	$T_w = 5.0$	$T_1 1 = 0.352$	$T_2 = 0.01$
$T_3 = 0.352$	$T_4 = 0.01$	$D_{con} = 38.0$	

Load

$V_t = 1.044$	$S_l = 0.872 + j0.654$	P.F=0.8 (lagging)

Two Machines - Machine data (60 Hz) - (Unit 2 is the slack machine)

	Unit (1)	Unit (2)
M	108.0	108.0
D	0.0	0.0
X_d	0.2	0.2
$\grave{X}_d$	0.03	0.03
X_q	0.18	0.18
$\grave{X}_q$	0.02	0.02
$\grave{T}_{d0}$	8.0	8.0
$\grave{T}_{q0}$	0.4	0.4
K_D	25 (4%)	25 (4%)

Exciter

	Unit (1)	Unit (2)
K_a	10.0	10.0
T_a	0.02	0.02

Power system stabilizer

	Unit (1)	Unit (2)
D_{pss}	38.0	38.0
T_w	5.0	5.0
T_1	0.352	0.352
T_2	0.01	0.01
T_3	0.352	0.352
T_4	0.01	0.01
D_{con}	38.0	38.0

Bus admittance matrix

Y bus	
0.8-j0.8	0+j0.2
0+j0.2	1.0-j0.2

Yr	
0.8-j0.8	0+j0.2
0+j0.2	1.0-j0.2

Three Machines - Machine data (60 Hz) (Unit 1 is the slack machine)

	Unit (1)	Unit (2)	Unit (3)
M	47.28	12.8	6.02
D	0.0	0.0	0.0
X_d	0.146	0.8958	1.3125
$\grave{X}_d$	0.0608	0.1198	0.1813
X_q	0.0969	0.8645	1.2578
$\grave{X}_q$	0.0969	0.1969	0.25
$\grave{T}_{d0}$	8.96	6.0	5.89
$\grave{T}_{q0}$	0.5	0.535	0.6
K_D	25 (4%)	25 (4%)	25 (4%)

Exciter

	Unit (1)	Unit (2)	Unit (3)
K_a	200.0	200.0	200.0
T_a	0.02	0.02	0.02

Power system stabilizer

	Unit (1)	Unit (2)	Unit (3)
D_{pss}	69.0	11.0	8.0
T_w	5.0	5.0	5.0
T_1	0.04	0.04	0.04
T_2	0.01	0.01	0.01
T_3	0.04	0.04	0.04
T_4	0.01	0.01	0.01
D_{con}	69.0	11.0	8.0

Bus admittance matrix (9- bus system)

Y bus =G + jB

G		
G11	G12	G13
G21	G22	G23
G31	G32	G33

B		
B11	B12	B13
B21	B22	B23
B31	B32	B33

G

G11		
0	0	0
0	0	0
0	0	0

G12		
0	0	0
0	0	0
0	0	0

G13		
0	0	0
0	0	0
0	0	0

G21		
0	0	0
0	0	0
0	0	0

G22		
3.3074	-1.365	-1.942
-1.365	3.8129	0
-1.942	0	4.1012

G23		
0	0	0
-1.187	0	0
0	0	-1.282

G31		
0	0	0
0	0	0
0	0	0

G32		
0	-1.187	0
0	0	0
0	0	-1.282

G33		
2.8047	-1.617	0
-1.617	3.7410	-1.155
0	-1.155	2.4371

B

B11		
-17.36	0	0
0	-16.0	0
0	0	-17.06

B12		
17.361	0	0
0	0	0
0	0	0

B13		
0	0	0
16.0	0	0
0	0	17.065

B21		
17.361	0	0
0	0	0
0	0	0

B22		
-39.31	11.60	10.51
11.60	-17.84	0
10.51	0	-16.13

B23		
0	0	0
5.9751	0	0
0	0	5.5882

B31		
0	16.0	0
0	0	0
0	0	17.065

B32		
0	5.9751	0
0	0	0
0	0	5.5882

B33		
-35.44	13.70	0
13.70	-23.64	9.78
0	9.78	-32.15

Yr (reduced matrix)

1.1047-j4.6954
0.0963+j2.2572
0.0044+j2.2749

0.0963+j2.2572
0.7354-j5.1142
0.1229+j2.8258

0.0044+j2.2749
0.1229+j2.8258
0.7213-j5.0231

Scaling factors of fuzzy power system stabilizer (FPSS)

- **Scaling factors for FPSS of SMIB and SMIS systems**

	SMIB	SMIS
Sf1	15	8
Sf2	0.001	0.001
Sf3	0.8	3.795

- **Scaling factors for FPSS of two machines system**

	M1	M2
Sf1	12.0	6.5
Sf2	0.001	0.001
Sf3	4.972	1

- **Scaling factors for FPSS of three machines system**

	M1	M2	M3
Sf1	6.0	6.5	6.5
Sf2	0.001	0.001	0.001
Sf3	2.11	1	1

APPENDIX E

Equations summary

E.1 QUADRATURE AND DIRECT CURRENTS ANALYSIS

The equations of the quadrature and direct axis components of the armature current (I_q *and* I_d) can be expressed with respect to (V_q, V_d *and* δ) as follows:

$$I_q = \bar{G}_{qq}.V_q + \bar{G}_{qd}.V_d + \bar{G}_{q\delta}.\delta \qquad (E.1)$$

$$I_d = \bar{G}_{dq}.V_q + \bar{G}_{dd}.V_d + \bar{G}_{d\delta}.\delta \qquad (E.2)$$

After linearization, the above equations can be expressed with respect to state space variables of the system model ($\Delta\grave{E}_q$, $\Delta\grave{E}_d$, $\Delta\delta$ *and* $\Delta\omega_r$) as follows:

$$\Delta I_q = G_{qq}.\Delta\grave{E}_q + G_{qd}.\Delta\grave{E}_d + G_{q\delta}.\Delta\delta + G_{q\omega}.\Delta\omega_r \qquad (E.3)$$

$$\Delta I_d = G_{dq}.\Delta\grave{E}_q + G_{dd}.\Delta\grave{E}_d + G_{d\delta}.\Delta\delta + G_{d\omega}.\Delta\omega_r \qquad (E.4)$$

For Case 1, the current gains with respect to the state variable ($\Delta\omega_r$) are equal to zero, so the current equations are as follows:

$$\Delta I_q = G_{qq}.\Delta\grave{E}_q + G_{qd}.\Delta\grave{E}_d + G_{q\delta}.\Delta\delta \qquad (E.5)$$

$$\Delta I_d = G_{dq}.\Delta\grave{E}_q + G_{dd}.\Delta\grave{E}_d + G_{d\delta}.\Delta\delta \qquad (E.6)$$

- The full detail of I_q and I_d current gains analysis for single machine isolated system is shown in appendix [B].
- The full detail of I_q and I_d current gains analysis for multi-machine system is shown in appendix [C].

E.2 STATE SPACE EQUATIONS

- Machine equations

$$\Delta\dot{\delta} = \omega_b \Delta\omega_r \qquad (E.7)$$

$$\Delta\dot{\omega}_r = \frac{1}{M}[\Delta T_m - \Delta T_e - D\Delta\omega_r - K_D\Delta\omega_r] \qquad (E.8)$$

$$\Delta\dot{\grave{E}}_q = \frac{1}{\grave{T}_{d0}}[\Delta E_{fd} - \Delta\grave{E}_q - (X_d - \grave{X}_d)\Delta I_d] \qquad (E.9)$$

$$\Delta\dot{\grave{E}}_d = \frac{1}{\grave{T}_{q0}}[-\Delta\grave{E}_d + (X_q - \grave{X}_q)\Delta I_q] \qquad (E.10)$$

- CPSS equations

$$\Delta\dot{X}_6 = \left(\frac{D_{pss}.T_1}{T_2.T_4}\right)\Delta\omega_r - \left(\frac{1}{T_4}\right)\Delta X_6 + \left(\frac{1}{T_4} - \frac{T_1}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1}{T_2.T_4}\right)\Delta X_8 \qquad (E.11)$$

$$\Delta\dot{X}_7 = \left(\frac{D_{pss}}{T_2}\right)\Delta\omega_r - \left(\frac{1}{T_2}\right)\Delta X_7 - \left(\frac{1}{T_2}\right)\Delta X_8 \qquad (E.12)$$

$$\Delta\dot{X}_8 = \frac{1}{T_w}(D_{pss}.\Delta\omega_r) - \frac{1}{T_w}.\Delta X_8 \qquad (E.13)$$

- OPSS and SOPSS equations

$$\Delta\dot{X}_6 = \left(\frac{-D_{pss}.T_1}{T_2.T_4}\right)\Delta U_1 - \left(\frac{T_1}{T_2.T_4}\right)\Delta U_2 - \left(\frac{1}{T_4}\right)\Delta U_3 - \left(\frac{1}{T_4}\right)\Delta X_6 + \left(\frac{1}{T_4} - \frac{T_1}{T_2.T_4}\right)\Delta X_7 - \left(\frac{T_1}{T_2.T_4}\right)\Delta X_8 \qquad (E.14)$$

$$\Delta\dot{X}_7 = \left(\frac{-D_{pss}}{T_2}\right)\Delta U_1 - \left(\frac{1}{T_2}\right)\Delta U_2 - \left(\frac{1}{T_2}\right)\Delta X_7 - \left(\frac{1}{T_2}\right)\Delta X_8 \qquad (E.15)$$

$$\Delta\dot{X}_8 = -\frac{1}{T_w}(D_{pss}.\Delta U_1) - \frac{1}{T_w}.\Delta X_8 \qquad (E.16)$$

$$\Delta U = -k\Delta x \qquad \textit{where } k \textit{ is the gain matrix} \qquad (E.17)$$

APPENDIX F

Initial conditions calculation and results

F.1 INITIAL CONDITIONS CALCULATION

In power system dynamic analysis, the fixed inputs and initial conditions of the state space variables are normally found from a base case load flow solution.

The first step in computing the initial conditions is the calculation of the generator current (I_G) as follows:

$$I_G\, e^{j\emptyset} = \frac{S_G^*}{V_{bus}^*} \qquad (F.1)$$

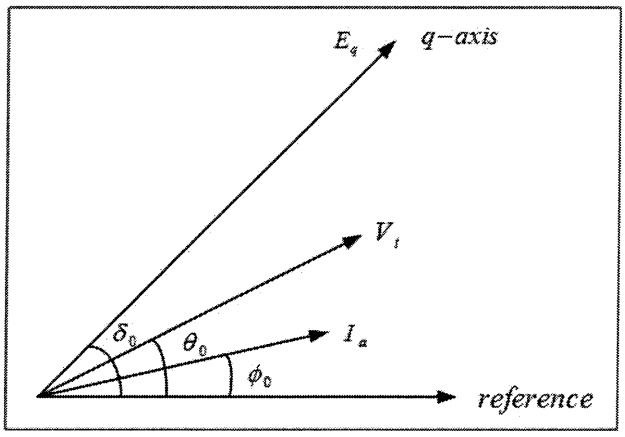


Fig. F.1 Phasor diagram

Based on the phasor diagram of Figure F.1, the second step is the calculation of the load angle (δ_0) as follows:

$$\delta_0 = Angle\left(V_{bus}\, e^{j\theta} + j\, X_q I_G e^{j\emptyset}\right) \qquad (F.2)$$

The third step is the calculation of the quadrature and direct components of the armature current ($I_{q0}\ and\ I_{do}$) as follows:

$$I_{q0} - jI_{d0} = I_G e^{j\emptyset} e^{-j\delta_0} \qquad (F.3)$$

The fourth step is the calculation of the quadrature and direct components of the terminal voltage (V_{q0} *and* V_{do}) also the terminal voltage (V_{t0}) as follows:

$$V_{q0} - jV_{d0} = V_{bus}e^{j\theta}e^{-j\delta_0} \tag{F.4}$$

$$V_{t0} = V_{q0} - jV_{d0} \tag{F.5}$$

The fifth step is the calculation of the quadrature component of the transient voltage ($\grave{E}_{q0}$) as follows:

$$\grave{E}_{q0} = V_{q0} + \grave{X}_d I_{d0} \tag{F.6}$$

The sixth step is the calculation of the direct component of the transient voltage ($\grave{E}_{d0}$) as follows:

$$\grave{E}_{d0} = (X_q - \grave{X}_q)I_{q0} \tag{F.7}$$

The seventh step is the calculation of the excitation field voltage (E_{fd0}) as follows:

$$E_{fd0} = \grave{E}_{q0} + (X_d - X_q)I_{d0} \tag{F.8}$$

F.2 INITIAL CONDITIONS RESULTS

Single Machine System

	SMIB	SMIS
V_{q0}	0.5818	1.0353
V_{d0}	0.8134	0.1346
I_{q0}	0.4785	0.7475
I_{d0}	0.8873	0.7288
$\grave{E}_{q0}$	0.7326	1.0572
$\grave{E}_{d0}$	0.7033	0.1196
δ_0	1.2026	0.1292
V_{t0}	1	1.044
E_{fd0}	2.1788	1.1811

Two Machines System

	Unit (1)	Unit (2)
V_{q0}	1.0353	0.9842
V_{d0}	0.1345	0.1772
I_{q0}	0.7475	0.9842
I_{d0}	0.7288	0.1772
$\acute{E}_{q0}$	1.0572	0.9895
$\acute{E}_{d0}$	0.1196	0.1575
δ_0	0.4207	0.1781
V_{t0}	1.044	1.0
E_{fd0}	1.1811	1.0196

Three Machines System

	Unit (1)	Unit (2)	Unit (3)
V_{q0}	1.0380	0.6337	0.6659
V_{d0}	0.065	0.8056	0.7793
I_{q0}	0.6708	0.9318	0.6196
I_{d0}	0.3021	1.2903	0.5613
$\acute{E}_{q0}$	1.0563	0.7883	0.7677
$\acute{E}_{d0}$	0.0	0.6221	0.6244
δ_0	0.0625	1.0665	0.9457
V_{t0}	1.04	1.025	1.025
E_{fd0}	1.0821	1.7896	1.4027

APPENDIX G

Iq and Id gains results

Case (1)

SMIB System

Gain qEq	Gain qEd	Gain qdelta	Gain qw
0.0	-2.0833	0.7499	0.0

Gain dEq	Gain dEd	Gain ddelta	Gain dw
2.3810	0.0	2.2214	0.0

SMIS

Gain qEq	Gain qEd	Gain qdelta	Gain qw
0.77625	-0.61129	0.0	0.0

Gain dEq	Gain dEd	Gain ddelta	Gain dw
0.60159	0.77625	0.0	0.0

Two Machines System

Gain qEq	
0.7688	0.0551
-0.0381	0.9895

Gain qEd	
-0.8048	0.1875
0.1925	-0.228

Gain qdelta	
0.1769	-0.1769
-0.2064	0.2064

Gain qw	
0.0	0.0
0.0	0.0

Gain dEq	
0.7922	-0.1866
-0.1899	0.2174

Gain dEd	
0.7686	0.0552
-0.0387	0.9896

Gain ddelta	
0.0824	-0.0824
0.0197	-0.0197

Gain dw	
0.0	0.0
0.0	0.0

Three Machines System

Gain qEq		
0.9159	-0.9842	-0.6997
1.2603	0.3347	0.2861
1.0389	0.0749	0.2458

Gain qEd		
-2.634	0.8383	0.7901
0.4573	-2.1885	0.7672
0.5131	0.8066	-1.9653

Gain qdelta		
2.531	-1.4270	-1.1039
-0.4574	0.8855	-0.4282
-0.5223	-0.6639	1.1862

Gain qw		
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0

Gain dEq		
2.8487	-1.1177	-0.9997
-0.4578	2.6855	-1.0755
-0.5529	-1.1407	2.3472

Gain dEd		
0.6965	-0.9526	-0.7466
1.3215	0.4113	0.3621
0.9900	0.1149	0.2751

Gain ddelta		
-0.005587	0.06988	-0.06429
-1.4215	2.4307	-1.0039
-1.0701	-0.8935	1.9636

Gain dw		
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0

Case (2)

SMIB System

Gain qEq	Gain qEd	Gain qdelta	Gain qw
0.0	-2.0833	0.4799	-1.6945

Gain dEq	Gain dEd	Gain ddelta	Gain dw
2.3810	0.0	2.2214	1.3851

SMIS System

Gain qEq	Gain qEd	Gain qdelta	Gain qw
0.77625	-0.61129	0.0	0.7214

Gain dEq	Gain dEd	Gain ddelta	Gain dw
0.60159	0.77625	0.0	0.72727

Two Machines System

Gain qEq	
0.7688	0.0551
-0.0381	0.9895

Gain qEd	
-0.8048	0.1875
0.1925	-0.228

Gain qdelta	
0.1769	-0.1769
-0.2064	0.2064

Gain qw	
0.6877	0.0875
-0.0135	0.9334

Gain dEq	
0.7922	-0.1866
-0.1899	0.2174

Gain dEd	
0.7686	0.0552
-0.0387	0.9896

Gain ddelta	
0.0824	-0.0824
0.0197	-0.0197

Gain dw	
0.9235	-0.1738
-0.2018	0.3892

Three Machines System

Gain qEq		
0.9159	-0.9842	-0.6997
1.2603	0.3347	0.2861
1.0389	0.0749	0.2458

Gain qEd		
-2.634	0.8383	0.7901
0.4573	-2.1885	0.7672
0.5131	0.8066	-1.9653

Gain qdelta		
2.531	-1.4270	-1.1039
-0.4574	0.8855	-0.4282
-0.5223	-0.6639	1.1862

Gain qw		
0.7795	0.05158	0.1498
1.3377	-1.5511	0.7884
1.1117	0.6973	-1.3680

Gain dEq		
2.8487	-1.1177	-0.9997
-0.4578	2.6855	-1.0755
-0.5529	-1.1407	2.3472

Gain dEd		
0.6965	-0.9526	-0.7466
1.3215	0.4113	0.3621
0.9900	0.1149	0.2751

Gain ddelta		
-0.005587	0.06988	-0.06429
-1.4215	2.4307	-1.0039
-1.0701	-0.8935	1.9636

Gain dw		
3.0021	-1.4757	-1.2475
-0.3893	2.0330	-0.4340
-0.5095	-0.6303	1.7775

APPENDIX H

Eigen -values results

SMIB (Case-1)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-4.0608e1	-9.9e-2+j1.8	-1.1675e2	-1.1678e2	-1.5422e2	-4.0438e1
-2.5e-1+j1.12	-9.9e-2-j1.8	-3.3e1+j8.85e1	-3.3e1+j8.85e1	-5.9e1+j5.7e2	-3.1e1+j8.5
-2.5e-1-j1.12	-4.0438e1	-3.3e1-j8.85e1	-3.3e1-j8.85e1	-5.9e1-j5.7e2	-3.1e1-j8.5
-1.1715e1	-3.1e1+j8.5	-7.8775e1	-7.8647e1	-4.0469e1	-9.9e-2+j1.83
	-3.1e1-j8.5	-4.0358e1	-1.3e-1+j1.12	-6.2e-1+j6.0	-9.9e-2-j1.83
		-9.5e-1+j1.43	-1.3e-1-j1.12	-6.2e-1-j6.0	
		-9.5e-1-j1.43	-4.0354e1	-2.3e-1+j4.3	
		-2.2656e-1	-2.2930e-1	-2.3e-1-j4.3	

SMIB (Case-1) – including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-4.0608e1	-3.1e1+j8.5	-1.1676e2	-1.1680e2	-1.5411e2	-3.1e1+j8.5
-3.7e-1+j1.08	-3.1e1-j8.5	-3.3e1+j8.85e1	-3.3e1+j8.84e1	-5.9e1+j5.7e2	-3.1e1-j8.5
-3.7e-1-j1.08	-4.0437e1	-3.3e1-j8.85e1	-3.3e1-j8.84e1	-5.9e1-j5.7e2	-4.0437e1
-1.1705e1	-2.1e-1+j1.8	-4.0355e1	-7.8609e1	-4.0469e1	-2.1e-1+j1.8
	-2.1e-1-j1.8	-7.8737e1	-1.4e-1+j1.01	-6.2e-1+j6.0	-2.1e-1-j1.8
		-1.1e-1+j1.34	-1.4e-1-j1.01	-6.2e-1-j6.0	
		-1.1e-1-j1.34	-4.0352e1	-2.3e-1+j4.3	
		-2.2712e-1	-2.2985e-1	-2.3e-1-j4.3	

SMIB (Case-2)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-4.0603e1	-4.0392e1	-1.1675e2	-1.1678e2	-1.5431e2	-4.0392e1
-2.5e-1+j1.1	-3.1e1+j8.5	-3.3e1+j8.85e1	-3.3e1+j8.84e1	-5.9e1+j5.7e2	-3.1e1+j8.5
-2.5e-1-j1.1	-3.1e1-j8.5	-3.3e1-j8.85e1	-3.3e1-j8.84e1	-5.9e1-j5.7e2	-3.1e1-j8.5
-1.1725e1	-9.3e-2+j1.8	-4.0291e1	-7.8649e1	-4.0431e1	-9.3e-2+j1.8
	-9.3e-2-j1.8	-7.877e1	-1.3e-1+j1.13	-6.2e-1+j6.0	-9.3e-2-j1.8
		-9.5e-1+j1.43	-1.3e-1-j1.13	-6.2e-1-j6.0	
		-9.5e-1-j1.43	-4.0287e1	-2.3e-1+j4.3	
		-2.2654e-1	-2.2927e-1	-2.3e-1-j4.3	

SMIB (Case-2) – including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-4.0603e1	-4.0391e1	-1.1676e2	-1.1680e2	-1.5419e2	-4.0391e1
-3.7e-1+j1.1	-3.1e1+j8.5	-3.3e1+j8.84e1	-3.3e1+j8.83e1	-5.9e1+j5.7e2	-3.1e1+j8.5
-3.7e-1-j1.1	-3.1e1-j8.5	-3.3e1-j8.84e1	-3.3e1-j8.83e1	-5.9e1-j5.7e2	-3.1e1-j8.5
-1.1725e1	-2.1e-1+j1.8	-4.0288e1	-7.8611e1	-4.0432e1	-2.1e-1+j1.8
	-2.1e-1-j1.8	-7.8740e1	-1.4e-1+j1.02	-6.2e-1+j6.0	-2.1e-1-j1.8
		-1.1e-1+j1.34	-1.4e-1-j1.02	-6.2e-1-j6.0	
		-1.1e-1-j1.34	-4.0284e1	-2.3e-1+j4.3	
		-2.2709e-1	-2.2982e-1	-2.3e-1-j4.3	

SMIS (Case-1)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
0.0	0.0	-4.8762e1	-1.284e2	-1.7075e2	0.0
-2.7426	-4.8746e1	-7.0e-1+j5.1e-1	-6.44e1+j3.47e1	-4.82e1+j3.34e1	-4.8746e1
-1.398e-1	-1.4289	-7.0e-1-j5.1e-1	-6.44e1-j3.47e1	-4.82e1-j3.34e1	-1.4289
	-2.7071	-2.7199	-4.9917e-3	-6.8103e-3	-2.7071
			-2.171+j8.31e-1	-1.297+j7.44e-1	
			-2.171-j8.31e-1	-1.297-j7.44e-1	
			-2.7083	-2.7072	

SMIS (Case-1) - including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.315e-1	-2.3148e-1	-2.7209	-1.4631e2	-1.5887e2	-2.3148e-1
-2.7426	-4.8746e1	-4.8762e1	-7.32e1+j6.98e1	-6.94e1+j6.93e1	-4.8746e1
-1.398e-1	-1.4289	-8.15e-1+j6.4	-7.32e1-j6.98e1	-6.94e1-j6.93e1	-1.4289
	-2.7071	-8.15e-1-j6.4	-9.3646e-2	-7.2929e-3	-2.7071
			-2.751+j4.35e-1	-2.704+j5.94e-1	
			-2.751-j4.35e-1	-2.704-j5.94e-1	
			-2.7127	-2.7105	

SMIS (Case-2)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.7424	-4.8746e1	-4.8761e1	-1.284e2	-5.3106e2	-4.8746e1
-1.417e-1	6.568e-3	-7.05e-1+j4.9e-1	-6.44e1+j3.47e1	-2.62e2+j4.43e2	-2.7063
-5.973e-3	-1.4445	-7.05e-1-j4.9e-1	-6.44e1-j3.47e1	-2.62e2-j4.43e2	-1.4445
	-2.7063	-2.7194	-3.9623e-3	-7.4718e-3	6.5682e-3
			-2.173+j8.26e-1	-2.857+j1.79e-1	
			-2.173-j8.26e-1	-2.857-j1.79e-1	
			-2.7065	-2.729	

SMIS (Case-2) - including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.7424	-4.8746e1	-4.8761e1	-1.4631e2	-1.5889e2	-4.8746e1
-2.420e-1	-2.22e-1	-8.19e-1+j6.3e-1	-7.32e1+j6.98e1	-6.94e1+j6.93e2	-2.22e-1
-1.372e-1	-1.4475	-8.19e-1-j6.3e-1	-7.32e1+j6.98e1	-6.94e1-j6.93e2	-1.4475
	-2.7062	-2.7203	-6.4658e-2	-7.9013e-3	-2.7062
			-2.752+j4.3e-1	-2.704+j5.93e-1	
			-2.752+j4.3e-1	-2.704+j5.93e-1	
			-2.7128	-2.7097	

Two machines system (Case-1)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.8353	-4.8757e1	-1.2603e2	-1.3379e2	-1.8e2+j1.2e-1	-4.8757e1
-2.5643	-4.8737e1	-1.2404e2	-1.2493e2	-1.8e2-j1.2e-1	-4.8737e1
-9.4e-3+j1.2	-1.8e-2+j1.2	-6.1e1+j2.2e1	-6.6e1+j4.6e1	-4.7e1+j3.5e1	-1.8e-2+j1.2
-9.4e-3-j1.2	-1.8e-2-j1.2	-6.1e1-j2.2e1	-6.6e1-j4.6e1	-4.7e1-j3.5e1	-1.8e-2-j1.2
-1.3e-1+j4.3e-3	-2.8099	-6.2e1+j1.9e1	-6.2e1+j2.1e1	-4.7e1+j3.4e1	-2.8099
-1.3e-1-j4.3e-3	-2.4990	-6.2e1-j1.9e1	-6.2e1-j2.1e1	-4.7e1-j3.4e1	-2.4990
-3.12e-19	-1.3935	-2.8099	-2.7e-1+j1.1	-2.8099	-1.3935
	-1.4523	-2.4996	-2.7e-1-j1.1	-2.5010	-1.4523
	-1.81e-15	-2.7e-1+j1.1	-2.5+j7.3e-1	-9.7e-1+j10e-1	-1.81e-15
		-2.7e-1-j1.1	-2.5-j7.3e-1	-9.7e-1-j10e-1	
		-1.2501	-2.5153	-1.34+j7.9e-1	
		-1.0+j1.4e-1	-2.8099	-1.34-j7.9e-1	
		-1.0-j1.4e-1	-1.2510	-6.4537e-1	
		-2.2143e-1	-2.2143e-1	-7.1198e-2	
		-5.5e-12	-7.3990e-3	-7.9136e-5	

Two machines system (Case-1) – including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.8347	-4.8737e1	-1.2605e2	-1.5958e2	-6.0e1+j6.9e1	-4.8737e1
-2.5643	-4.8757e1	-1.2406e2	-1.2502e2	-6.0e1+j6.9e1	-4.8757e1
-1.3e-1+j1.16	-1.4e-1+j1.2	-6.1e1+j2.2e1	-7.9e1+j8.9e1	-4.9e1+j4.6e1	-1.4e-1+j1.2
-1.3e-1-j1.16	-1.4e-1-j1.2	-6.1e1-j2.2e1	-7.9e1-j8.9e1	-4.9e1+j4.6e1	-1.4e-1-j1.2
-1.3e-1+j4.4e-3	-2.8099	-6.2e1+j1.9e1	-6.2e1+j2.1e1	-2.12+j1.02	-2.8099
-1.3e-1-j4.4e-3	-2.4996	-6.2e1-j1.9e1	-6.2e1-j2.1e1	-2.12+j1.02	-2.4996
-2.3148e-1	-1.3893	-2.8099	-2.8+j3.1e-1	-1.9363e2	-1.3893
	-1.4514	-2.5003	-2.8-j3.1e-1	-1.8331e2	-1.4514
	-2.315e-1	-3.9e-1+j1.05	-3.9e-1+j1.1	-2.6+j7.4e-1	-2.315e-1
		-3.9e-1-j1.05	-3.9e-1+j1.1	-2.6+j7.4e-1	
		-4.7811e-2	-2.5564	-5e-2+j2.6e-2	
		-1.1+j3.0e-1	-2.8100	-5e-2+j2.6e-2	
		-1.1-j3.0e-1	-1.2243	-2.8099	
		-1.2242	-2.2251e-1	-2.5102	
		-2.2251e-1	-7.6354e-3	-1.2353e-3	

Two machines system (Case-2)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.8354	-4.8756e1	-1.2603e2	-1.3379e2	-1.8504e2	-4.8756e1
-2.5641	-4.8736e1	-1.2404e2	-1.2493e2	-1.4650e2	-4.8736e1
-1.4e-2+j1.17	-1.8e-2+j1.2	-6.1e1+j2.2e1	-6.6e1+j4.6e1	-4.9e1+j4.6e1	-1.76e-2+j1.2
-1.4e-2-j1.17	-1.8e-2-j1.2	-6.1e1-j2.2e1	-6.6e1-j4.6e1	-4.9e1-j4.6e1	-1.76e-2-j1.2
-1.3e-1+j4.2e-3	-2.8097	-6.2e1+j1.9e1	-6.2e1+j2.1e1	-5.5e1+j2.7e1	-2.8097
-1.3e-1-j4.2e-3	-2.4972	-6.2e1-j1.9e1	-6.2e1-j2.1e1	-5.5e1-j2.7e1	-2.4972
-7.1519e-3	-1.4031	-2.8097	-2.7e-1+j1.07	-2.10+j1.03	-1.4031
	-1.4704	-2.4978	-2.7e-1-j1.07	-2.10-j1.03	-1.4704
	7.0473e-3	-2.7e-1+j1.1	-2.5+j7.27e-1	-2.8097	7.0473e-3
		-2.7e-1-j1.1	-2.5-j7.27e-1	-2.5040	
		-1.2617	-2.5141	-4e-1+j7.1e-1	
		-1.0+j5.9e-2	-2.8097	-4e-1-j7.1e-1	
		-1.0-j5.9e-2	-1.2630	-1.1624	
		-2.2138e-1	-2.2139e-1	-1.5972e-1	
		1.8270e-3	-7.4010e-3	-3.1784e-4	

Two machines system (Case-2) – including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.8348	-4.8736e1	-1.2605e2	-1.5958e2	-2.8098	-4.8736e1
-2.5640	-4.8756e1	-1.2406e2	-1.2502e2	-2.5210	-4.8756e1
-1.3e-1+j1.16	-1.3e-1+j1	-6.1e1+j2.2e1	-8.0e1+j8.9e1	-1.95e2+j1.63	-1.3e-1+j1
-1.3e-1-j1.16	-1.3e-2-j1	-6.1e1-j2.2e1	-8.0e1-j8.9e1	-1.95e2-j1.63	-1.3e-2-j1
-1.3e-1+j4.2e-3	-2.8098	-6.2e1+j1.9e1	-6.2e1+j2.1e1	-6.4e1+j7.6e1	-2.8098
-1.3e-1-j4.2e-3	-2.4977	-6.2e1-j1.9e1	-6.2e1-j2.1e1	-6.4e1-j7.6e1	-2.4977
-2.4219e-1	-1.4000	-2.8098	-2.81+j3.1e-1	-6.0e1+j6.9e1	-1.4000
	-1.4729	-2.4984	-2.81-j3.1e-1	-6.0e1-j6.9e1	-1.4729
	-2.2133e-1	-3.9e-1+j1.0	-3.9e-1+j1.1	-2.5e-2+j2.7e-2	-2.2133e-1
		-3.9e-1-j1.0	-3.9e-1-j1.1	-2.5e-2+j2.7e-2	
		-2.2245e-1	-2.5559	-2.6+j7.5e-1	
		-1.1+j2.7e-1	-2.8099	-2.6-j7.5e-1	
		-1.1-j2.7e-1	-1.2380	-2.6+j7.0e-1	
		-4.6534e-2	-2.2245e-1	-2.6-j7.0e-1	
		-1.2376	-7.6230e-3	-1.3007e-3	

Three machines system (Case-1)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-7e-1+j1.3e1	-2.5e1+j2.4e1	-1.2768e2	-1.5410e2	-2.6286e2	-2.5e1+j2.4e1
-7e-1-j1.3e1	-2.5e1-j2.4e1	-1.2e2+j4.6	-7e1+j9.2e1	-1.6374e2	-2.5e1-j2.4e1
-1.6e-1+j8.3	-3.4665e1	-1.2e2-j4.6	-7e1-j9.2e1	-1.1669e2	-3.4665e1
-1.6e-1-j8.3	-2.5e1+j1e1	-7.4e1+j5.7	-1.2802e2	-4.2e1+j5e1	-2.5e1+j1e1
-5.1389	-2.5e1-j1e1	-7.4e1-j5.7	-1.1602e2	-4.2e1-j5e1	-2.5e1-j1e1
-3.5591	-1.7442e1	-5.7387e1	-7.9993e1	-6.0931e1	-1.7442e1
-1.87e-15	-9.4e-1+j1.3e1	-4.1335e1	-5.6e1+j6.9	-1.4e1+j3.7e1	-9.4e-1+j1.3e1
-8.1828e-2	-9.4e-1-j1.3e1	-2.5e1+j2.3e1	-5.6e1-j6.9	-1.4e1-j3.7e1	-9.4e-1-j1.3e1
-1.7418e-1	-2.5e-1+j8.6	-2.5e1-j2.3e1	-3.4769e1	-4.2e1+j1.8e1	-2.5e-1+j8.6
-1.5373e-1	-2.5e-1-j8.6	-2.6e1+j1.5e1	-6.9+j1.4e1	-4.2e1-j1.8e1	-2.5e-1-j8.6
-2.00	-3.6370	-2.6e1-j1.5e1	-6.9-j1.4e1	-1.9e1+j1.6e1	-3.6370
	-2.5616	-6.3+j1.5e1	-2.5e1+j3.0	-1.9e1-j1.6e1	-2.5616
	-2.061e-15	-6.3-j1.5e1	-2.5e1-j3.0	-2.26e1+j5.7	-2.061e-15
	-2.00	-1.5459e1	-1.7997e1	-2.26e1-j5.7	-2.00
		-3.54+j9.2	-1.1958e1	-1.0906e1	
		-3.54-j9.2	-3.4+j7.5	-6.6+j3.07	
		-3.13+j3e-1	-3.4-j7.5	-6.6-j3.07	
		-3.13-j3e-1	-2.8328	-2.3533	
		-1.9778	-1.8694	-1.5185	
		2.15e-14	-9.1020e-3	-7.6442e-5	
		-2.0576e-1	-2.0576e-1	-2.0874e-1	
		-2.0405e-1	-2.0406e-1	-2.0379e-1	
		-2.00	-2.00	-2.00	

Three machines system (Case-1) – including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.6+j1.3e1	-2.5e1+j2.3e1	-1.2802e2	-2.0384e2	-3.0212e2	-2.5e1+j2.3e1
-2.6-j1.3e1	-2.5e1-j2.3e1	-1.2e2+j4.6	-1e2+j1.5e2	-2.3945e2	-2.5e1-j2.3e1
-1.04+j8.23	-3.4632e1	-1.2e2-j4.6	-1e2+j1.5e2	-1.9554e2	-3.4632e1
-1.04-j8.23	-2.5e1+j1e1	-7.3e1+j5.7	-1.2833e2	-8.5e1+j1e2	-2.5e1+j1e1
-5.0628	-2.5e1-j1e1	-7.3e1-j5.7	-1.1594e2	-8.5e1+j1e2	-2.5e1-j1e1
-3.6638	-1.7674e1	-5.4551e1	-7.9329e1	-3.1844e1	-1.7674e1
-9.6171-1	-2.8+j1.3e1	-4.3174e1	-5.5e1+j8.85	-6e1+j10e1	-2.8+j1.3e1
-1.8080e-1	-2.8-j1.3e1	-2.5e1+j2.3e1	-5.5e1+j8.85	-6e1-j10e1	-2.8-j1.3e1
-1.6e-1+2e-2	-1.17+j8.54	-2.5e1-j2.3e1	-3.4455e1	-1.7e1+j7.4e1	-1.17+j8.54
-1.6e-1+2e-2	-1.17+j8.54	-2.6e1+j1.5e1	-9.9+j1.5e1	-1.7e1-j7.4e1	-1.17+j8.54
-2.00	-1.1779	-2.6e1-j1.5e1	-9.9-j1.5e1	-2.5e1+j4.1e1	-1.1779
	-2.3630	-8.5+j1.5e1	-2.5e1+j1.0	-2.5e1-j4.1e1	-2.3630
	-3.5544	-8.5-j1.5e1	-2.5e1-j1.0	-2.4e1+j3.14	-3.5544
	-2.00	-1.5485e1	-1.9357e1	-2.4e1-j3.14	-2.00
		-4.5121	-9.8286	-1.4319e1	
		-2.8140	-5.8+j6.75	-1.4153e-1	
		-4.5+j9e-1	-5.8+j6.75	-1.3376e-1	
		-4.5-j9e-1	-2.0411e-1	-7.2954	
		-1.80140	-2.6554	-5.7000	
		-5.1557e-2	-1.5600	-8.4951e-1	
		-2.0411e-1	-8.4857e-3	-6.6486e-1	
		-2.0582e-1	-2.0583e-1	-3.3478e-1	
		-2.00	-2.00	-2.00	

Three machines system (Case-2)					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-7e-1+j1.3e1	-2.5e1+j2.4e1	-1.2768e2	-1.5410e2	-1.1e2+j1.6e2	-2.5e1+j2.4e1
-7e-1-j1.3e1	-2.5e1-j2.4e1	-1.2e2+j4.6	-7e1+j9.1e1	-1.1e2-j1.6e2	-2.5e1-j2.4e1
-1.6e-1+j8.3	-3.4229e1	-1.2e2-j4.6	-7e1-j9.1e1	-2.4116e2	-3.4229e1
-1.6e-1-j8.3	-2.5e1+j1e1	-7.4e1+j5.6	-1.2802e2	-2.0931e2	-2.5e1+j1e1
-5.1240	-2.5e1-j1e1	-7.4e1-j5.6	-1.1602e2	-1.9418e2	-2.5e1-j1e1
-3.5543	-1.8058e1	-5.7617e1	-7.9995e1	-4.4e1+j5.8e1	-1.8058e1
-1.5211e-2	-8.4e-1+j1.3e1	-4.0564e1	-5.6e1+j6.8	-4.4e1-j5.8e1	-8.4e-1+j1.3e1
-1.2396e-1	-8.4e-1-j1.3e1	-2.5e1+j2.3e1	-5.6e1-j6.8	-2.3e1+j3.5e1	-8.4e-1-j1.3e1
-1.7432e-1	-1.5e-1+j8.5	-2.5e1-j2.3e1	-3.4094e1	-2.3e1-j3.5e1	-1.5e-1+j8.5
-1.4970e-1	-1.5e-1-j8.5	-2.6e1+j1.5e1	-6.8+j1.4e1	-2.5e1+j3.9	-1.5e-1-j8.5
-2.00	-3.6296	-2.6e1-j1.5e1	-6.8-j1.4e1	-2.5e1-j3.9	-3.6296
	-2.5641	-6.2+j1.5e1	-2.5e1+j3.2	-2.7078e1	-2.5641
	4.8206e-2	-6.2-j1.5e1	-2.5e1+j3.2	-2.5117e1	4.8206e-2
	-2.00	-1.6218e1	-1.8811e1	-1.7089e1	-2.00
		-3.4+j9.1	-1.2076e1	-1.0429e1	
		-3.4-j9.1	-3.4+j7.52	-7.1000	
		-3.1+j3.3e-1	-3.4-j7.52	-6.7849	
		-3.1-j3.3e-1	-2.8375	-1.4757	
		-1.9845	-1.8720	-5.7276e-1	
		2.9239e-3	-8.9477e-3	-2.9427e-3	
		-2.0575e-1	-2.0576e-1	-9.6557e-2	
		-2.0404e-1	-2.0406e-1	-1.8924e-1	
		-2.00	-2.00	-2.00	

Three machines system (Case-2) – including the speed droop					
No PSS	**No PSS (with E_{fd})**	**CPSS**	**OPSS**	**SOPSS**	**FPSS**
-2.6+j1.3e1	-2.5e1+j2.4e1	-1.2e2+j4.6	-2.0384e2	-8.5e1+j1e2	-2.5e1+j2.4e1
-2.6-j1.3e1	-2.5e1-j2.4e1	-1.2e2-j4.6	-1e2+j1.5e1	-8.5e1-j1e2	-2.5e1-j2.4e1
-1.04+j8.23	-3.4148e1	-7.4e1+j5.7	-1e2-j1.5e1	-5.9e1+j9.9e1	-3.4148e1
-1.04-j8.23	-2.5e1+j1e1	-7.4e1-j5.7	-1.2832e2	-5.9e1-j9.9e1	-2.5e1+j1e1
-5.0468	-2.5e1-j1e1	-2.5e1+j2.3e1	-1.1594e2	-1.7e1+j7.4e1	-2.5e1-j1e1
-3.6618	-1.8374e1	-2.5e1-j2.3e1	-7.9331e1	-1.7e1-j7.4e1	-1.8374e1
-1.0235	-2.7+j1.3e1	-2.6e1+j1.5e1	-5.5e1+j8.72	-2.5e1+j3.8	-2.7+j1.3e1
-1.6e-1+j2e-2	-2.7-j1.3e1	-2.6e1-j1.5e1	-5.5e1-j8.72	-2.5e1-j3.8	-2.7-j1.3e1
-1.6e-1-j2e-2	-1.06+j8.5	-8.3+j1.5e1	-3.3648e1	-2.4e1+j3.2	-1.06+j8.5
-1.7886e-1	-1.06-j8.5	-8.3-j1.5e1	-9.9+j1.5e1	-2.4e1-j3.2	-1.06-j8.5
-2.00	-1.1203	-4.3+j8.95	-9.9-j1.5e1	-3.0236e2	-1.1203
	-3.5464	-4.3-j8.95	-2.5e1+j1.12	-2.4186e2	-3.5464
	-2.3688	-1.2801e2	-2.5e1-j1.12	-1.9730e2	-2.3688
	-2.00	-5.4966e1	-2.0331e1	-3.1572e1	-2.00
		-4.2148e1	-2.0408e-1	-1.4196e1	
		-2.0582e-1	-5.7+j6.77	-7.3449	
		-1.6371e1	-5.7-j6.77	-5.7157	
		-4.4321	-9.9289	-8.5095e-1	
		-2.8255	-2.6601	-6.6441e-1	
		-1.8139	-1.5627	-3.2243e-3	
		-4.9881e-2	-8.4962e-3	-1.4155e-1	
		-2.0410e-1	-2.0581e-1	-1.3371e-1	
		-2.00	-2.00	-2.00	

APPENDIX I

A – Matrix Results

Axx (1,1) or Axx (2,2)	
→	No Speed droop
→	With speed droop

Axx (5,1) or Axx (5,2)	
→	No PSS with Efd, FPSS
→	CPSS (Dpss only – 5 states)
→	CPSS (8 states)

Single Machine infinite Bus (SMIB) - Case (1)

SMIB (CPSS)							
0	3.7699e2	0	0	0	0	0	0
-2.051e-2	0 -2.32e-1	-2.057e-2	6.9434e-3	0	0	0	0
-9.05210	0	-1.2202e1	0	2.50	0	0	0
1.1023e1	0	0	-4.0625e1	0	0	0	0
3.970e1	0 5.60e5	-1.731e2	-2.118e2	-50.00	-1.50e3	-6.0e3	-8.0e3
0	2.80e4	0	0	0	-100	-300	-400
0	7000	0	0	0	0	-100	-100
0	1.4e1	0	0	0	0	0	-0.20

Kopt							
-3.374e-6	3.835e-1	-3.496e-4	1.419e-4	-1.642e-5	2.378e-4	2.632e-4	6.788e-9
-2.959e-6	5.540e-3	-5.095e-6	2.079e-6	-2.405e-7	3.494e-6	3.836e-6	7.792e-6
-4.277e-6	5.123e-3	-4.996e-6	2.085e-6	-2.429e-7	3.578e-6	3.802e-6	1.155e-5

Kopt (including the speed droop)							
-5.10e-6	3.514e-1	-3.193e-4	1.291e-4	-1.494e-5	2.159e-4	2.404e-4	6.593e-9
-2.702e-6	5.076e-3	-4.653e-6	1.891e-6	-2.188e-7	3.172e-6	3.504e-6	7.056e-6
-3.896e-6	4.671e-3	-4.561e-6	1.899e-6	-2.215e-7	3.260e-6	3.475e-6	1.049e-5

Ksub				
3.085e1	1.418e-3	-3.521e-2	1.931e-2	5.414e-3
4.435e-1	2.059e-5	-5.119e-4	2.840e-4	7.490e-5
2.072e-1	1.242e-5	-3.139e-4	2.047e-4	8.439e-5

Ksub(including the speed droop)				
3.065e1	1.411e-3	-3.504e-2	1.923e-2	5.373e-3
4.406e-1	2.049e-5	-5.094e-4	2.827e-4	7.368e-5
2.059e-1	1.236e-5	-3.125e-4	2.039e-4	8.336e-5

Single Machine infinite Bus (SMIB) - Case (2)

SMIB (CPSS)							
0	3.7699e2	0	0	0	0	0	0
-2.051e-2	2.94e-3 -2.30e-1	-2.057e-2	6.9434e-3	0	0	0	0
-9.05210	-5.6444	-1.2202e1	0	2.50	0	0	0
1.1023e1	-2.491e1	0	-4.0625e1	0	0	0	0
3.970e1	-2.73e2 5.5973e5	-1.731e2	-2.118e2	-50.00	-1.50e3	-6.0e3	-8.0e3
0	2.80e4	0	0	0	-100	-300	-400
0	7000	0	0	0	0	-100	-100
0	1.4e1	0	0	0	0	0	-0.20

Kopt							
-3.593e-6	3.850e-1	-3.511e-4	1.425e-4	-1.649e-5	2.388e-4	2.643e-4	6.841e-9
-2.973e-6	5.563e-3	-5.117e-6	2.088e-6	-2.415e-7	3.509e-6	3.853e-6	7.831e-6
-4.296e-6	5.145e-3	-5.017e-6	2.094e-6	-2.439e-7	3.593e-6	3.818e-6	1.161e-5

Kopt (including the speed droop)							
-4.978e-6	3.528e-1	-3.206e-4	1.297e-4	-1.50e-5	2.169e-4	2.414e-4	5.642e-9
-2.713e-6	5.096e-3	-4.671e-6	1.899e-6	-2.197e-7	3.186e-6	3.518e-6	7.089e-6
-3.913e-6	4.690e-3	-4.579e-6	1.908e-6	-2.224e-7	3.273e-6	3.489e-6	1.054e-5

Ksub				
3.085e1	1.418e-3	-3.521e-2	1.931e-2	5.418e-3
4.435e-1	2.059e-5	-5.119e-4	2.841e-4	7.502e-5
2.073e-1	1.242e-5	-3.139e-4	2.048e-4	8.449e-5

Ksub(including the speed droop)				
3.065e1	1.412e-3	-3.504e-2	1.923e-2	5.377e-3
4.4067-1	2.049e-5	-5.094e-4	2.828e-4	7.379e-5
2.059e-1	1.236e-5	-3.125e-4	2.039e-4	8.346e-5

Single Machine Isolated System (SMIS) - Case (1)

SMIS (CPSS)						
0 -2.32e-1	-1.509e-2	-1.612e-3	0	0	0	0
0	-1.378e-1	-1.649e-2	0.125	0	0	0
0	3.1050e-1	-2.7445	0	0	0	0
0 1.90e4 2.3542e7	-4.8789e2	-5.2105e1	-5.0e1	-1.71e4	-6.0192e5	-6.1952e5
1.3376e5	0	0	0	-100	-3.42e3	-3.52e3
3.8e3	0	0	0	0	-100	-100
6.7	0	0	0	0	0	-0.2

Kopt						
9.0269	-1.596e-3	6.183e-3	-3.531e-5	5.71e-3	1.482e-2	2.182e-2
4.169e-1	-2.555e-3	7.892e-4	-6.287e-6	1.068e-3	1.244e-3	1.242e-2
2.669e-1	-2.584e-3	7.882e-4	-6.446e-6	1.101e-3	1.131e-3	1.242e-2

Kopt (including the speed droop)						
2.8845e1	-3.377e-3	-3.70e-3	2.293e-5	-4.779e-3	1.382e-2	-8.305e-2
3.6511	-3.246e-2	-8.459e-3	-8.065e-5	1.376e-2	1.465e-2	2.047e-1
3.0103	-3.289e-2	-8.530e-3	8.204e-5	1.401e-2	1.458e-2	2.071e-1

Ksub				
2.4063	1.1028e-7	-2.1578e-4	1.8010e-3	1.4787e-2
3.3924e-1	-2.3573e-7	1.9309e-6	-4.6243e-5	1.6730e-2
3.1816e-1	-2.5443e-7	5.8429e-6	-7.6589e-5	1.6754e-2

Ksub (including the speed droop)				
3.00524e1	1.4759e-5	-3.458e-3	1.6456e-2	1.5279e-2
1.1062	4.7101e-7	-1.2316e-4	7.5616e-4	1.6840e-2
4.3783e-1	1.556e-7	-5.2435e-5	5.1477e-4	1.7033e-2

Single Machine Isolated System (SMIS) - Case (2)

SMIS (CPSS)						
-7.768e-3 -2.393e-1	-1.509e-2	-1.612e-3	0	0	0	0
-1.546e-2	-1.378e-1	-1.649e-2	1.25e-1	0	0	0
2.8856e-1	3.1050e-1	-2.7445	0	0	0	0
-5.1e2 1.8488e4 2.3541e7	-4.8789e2	-5.2105e1	-5.0e1	-1.71e4	-6.0192e5	-6.1952e5
1.3376e5	0	0	0	-100	-3.42e3	-3.52e3
3.8e3	0	0	0	0	-100	-100
6.7	0	0	0	0	0	-0.2

Kopt						
9.0185	-1.281e-2	-7.627e-3	-2.697e-5	4.242e-3	1.478e-2	2.205e-2
3.805e-1	-1.823e-3	-6.689e-4	-4.409e-6	7.428e-3	1.069e-3	9.943e-3
2.305e-1	-1.853e-3	-6.564e-4	-4.573e-6	7.766e-4	9.559e-4	9.934e-3

Kopt (including the speed droop)						
2.933e1	-3.479e-3	-2.50e-4	5.293e-6	-1.807e-3	1.629e-2	-4.784e-2
2.766	-2.484e-2	1.781e-3	-6.194e-5	1.059e-2	1.043e-2	1.423e-1
2.1145	-2.517e-2	1.809e-3	-6.308e-5	1.080e-2	1.031e-2	1.438e-1

Ksub				
3.1643e3	4.285e-4	-8.063-2	-3.019e-2	2.196e-2
8.3609e1	1.143e-5	-2.162e-3	-4.012e-4	1.857e-2
2.9317	3.968e-7	-8.021e-5	1.120e-4	1.866e-2

Ksub (including the speed droop)				
3.0521e1	1.476e-5	-3.458e-3	1.6457e-2	1.551e-2
1.1073	4.715e-7	-1.233e-4	7.5783e-4	1.6912e-2
4.3894e-1	1.561e-7	-5.259e-5	5.1647e-4	1.707e-2

Two Machines System (CPSS) - Case (1)

A11

0	3.77e2	0	0	0	0	0	0
-1.81e-3	0 -2.32e-1	-1.52e-2	-2.77e-4	0	0	0	0
-1.75e-3	0	-1.42e-1	-1.63e-2	0.1250	0	0	0
7.08e-2	0	3.08e-1	-2.8220	0	0	0	0
9.98e-1	0 2.3542e7	-4.85e2	-5.197e1	-50.00	-1.7100e4	-6.0192e5	-6.1952e5
0	1.3376e5	0	0	0	-100	-3420.0	-3520.0
0	3800	0	0	0	0	-100	-100
0	7.6000	0	0	0	0	0	-0.2000

A12

-3.77e2	0	0	0	0	0	0
0	-3.43e-4	-1.88e-3	0	0	0	0
0	3.97e-3	-1.17e-3	0	0	0	0
0	2.21e-2	7.50e-2	0	0	0	0
0	-2.8463	0.5804	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

A21

1.86e-3	0	6.08e-4	-1.71e-3	0	0	0	0
-4.18e-4	0	4.04e-3	8.23e-4	0	0	0	0
-8.26e-2	0	-1.52e-2	7.70e-2	0	0	0	0
6.56e-1	0	-2.7359	-9.13e-1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A22

0 -2.32e-1	-1.85e-2	-9.08e-4	0	0	0	0
0	-1.30e-1	-2.10e-2	0.1250	0	0	0
0	3.96e-1	-2.591	0	0	0	0
0 2.3542e7	-4.91e2	-7.36e1	-50.00	-1.710e4	-6.0192e5	-6.1952e5
1.3376e5	0	0	0	-100	-3420.0	-3520.0
3800	0	0	0	0	-100	-100
7.6000	0	0	0	0	0	-0.2000

Kopt (machine-1)							
-1.449e-3	6.3940	-9.344e-3	-9.492e-5	-2.029e-5	3.263e-3	8.600e-3	1.556e-2
-3.888e-5	2.897e-1	-1.548e-3	5.376e-6	-3.788e-6	6.423e-4	7.837e-4	8.302e-3
-1.027e-5	1.669e-1	-1.499e-3	1.042e-6	-3.729e-6	6.359e-4	6.918e-4	8.192e-3

Kopt (machine-2)						
6.767	-4.728e-3	-1.226e-3	-7.168e-6	9.090e-4	9.150e-3	7.685e-3
2.976e-1	-1.771e-3	-3.219e-5	-4.305e-6	7.277e-4	9.463e-4	1.017e-2
1.675e-1	-1.871e-3	-1.910e-5	-4.645e-6	7.918e-4	8.779e-4	1.027e-2

Kopt (machine-1, including the speed droop)							
-3.321e-3	2.079e1	-1.359e-2	1.289e-4	-2.569e-5	3.955e-3	1.204e-2	2.056e-2
-8.651e-5	6.634e-1	-1.613e-3	1.024e-5	-3.814e-6	6.407e-4	8.530e-4	8.182e-3
-8.027e-6	1.781e-1	-1.455e-3	-1.023e-6	-3.609e-6	6.150e-4	6.825e-4	7.936e-3

Kopt (machine-2, including the speed droop)						
2.2578e1	-1.186e-3	-2.004e-3	9.460e-6	-2.279e-3	1.014e-2	-1.584e-3
7.107e-1	-1.636e-3	-5.201e-5	-3.761e-6	6.257e-4	9.555e-4	9.621e-3
1.828e-1	-1.833e-3	-2.004e-5	-4.540e-6	7.731e-4	8.773e-4	9.969e-3

Ksub (machine-1)				
2.3736	-1.014e-7	-1.859e-4	1.481e-3	1.847e-2
6.611e-2	6.506e-9	-6.506e-6	5.618e-5	1.948e-4
4.460e-2	-8.861e-9	-3.015e-6	3.059e-5	-1.091e-4

Ksub (machine-2)				
2.3670	2.230e-7	-2.641e-4	2.10e-3	1.852e-2
6.598e-2	1.542e-8	-8.698e-6	7.404e-5	2.413e-4
4.205e-2	-4.755e-9	-4.102e-6	4.173e-5	-3.246e-5

Ksub (machine-1, including the speed droop)				
3.059e1	1.242e-5	-3.026e-3	1.14e-2	2.393e-2
8.502e-1	3.808e-7	-9.226e-5	4.361e-4	2.488e-3
1.866e-1	9.562e-8	-2.753e-5	2.675e-4	2.425e-3

Ksub (machine-2, including the speed droop)				
8.943	4.457e-6	-1.293e-3	8.346e-3	2.30e-2
2.488e-1	1.420e-7	-3.919e-5	2.753e-4	9.090e-4
9.501e-2	4.361e-8	-1.589e-5	1.604e-4	7.583e-4

Two Machines System (CPSS) - Case (2)

A11

0	3.77e2	0	0	0	0	0	0
-1.81e-3	-7.64e-3 -2.39e-1	-1.52e-2	-2.77e-4	0	0	0	0
-1.75e-3	-1.96e-2	-1.42e-1	-1.63e-2	0.1250	0	0	0
7.08e-2	2.751e-1	3.08e-1	-2.8220	0	0	0	0
9.98e-1	-5.09e2 2.3541e7	-4.85e2	-5.197e1	-50.00	-1.7100e4	-6.0192e5	-6.1952e5
0	1.3376e5	0	0	0	-100	-3420.0	-3520.0
0	3800	0	0	0	0	-100	-100
0	7.6000	0	0	0	0	0	-0.2000

A12

-3.77e2	0	0	0	0	0	0
-6.70e-4	-3.43e-4	-1.88e-3	0	0	0	0
3.694e-3	3.97e-3	-1.17e-3	0	0	0	0
3.50e-2	2.21e-2	7.50e-2	0	0	0	0
-2.6984	-2.8463	0.5804	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

A21							
1.86e-3	3.99e-4	6.08e-4	-1.71e-3	0	0	0	0
-4.18e-4	4.29e-3	4.04e-3	8.23e-4	0	0	0	0
-8.26e-2	-5.40e-3	-1.52e-2	7.70e-2	0	0	0	0
6.56e-1	-2.9553	-2.7359	-9.13e-1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A22						
-9.07e-3 -2.41e-1	-1.85e-2	-9.08e-4	0	0	0	0
-8.27e-3	-1.30e-1	-2.10e-2	0.1250	0	0	0
3.734e-1	3.96e-1	-2.591	0	0	0	0
-4.96e2 2.3541e7	-4.91e2	-7.36e1	-50.00	-1.710e4	-6.0192e5	-6.1952e5
1.3376e5	0	0	0	-100	-3420.0	-3520.0
3800	0	0	0	0	-100	-100
7.6000	0	0	0	0	0	-0.2000

Kopt (machine-1)							
-1.449e-3	6.3940	-9.371e-3	-9.655e-5	-2.036e-5	3.275e-3	8.609e-3	1.583e-2
-3.876e-5	2.90e-1	-1.551e-3	5.376e-6	-3.797e-6	6.438e-4	7.853e-4	8.324e-3
-1.018e-5	1.672e-1	-1.503e-3	1.082e-6	-3.737e-6	6.373e-4	6.933e-4	8.209e-3

Kopt (machine-2)						
6.769	-4.807e-3	-1.224e-3	-7.370e-6	9.438e-4	9.178-3	8.035e-3
2.979e-1	-1.776e-3	-3.217e-5	-4.317e-6	7.298e-4	9.483e-4	1.019e-2
1.678e-1	-1.874e-3	-1.913e-5	-4.654e-6	7.932e-4	8.794e-4	1.029e-2

Kopt (machine-1, including the speed droop)							
-3.324e-3	2.079e1	-1.358e-2	1.217e-4	-2.566e-5	3.949e-3	1.203e-2	2.086e-2
-8.650e-5	6.635e-1	-1.615e-3	1.008e-5	-3.819e-6	6.415e-4	8.538e-4	8.204e-3
-7.972e-6	1.784e-1	-1.457e-3	-9.865e-7	-3.615e-6	6.160e-4	6.835e-4	7.951e-3

Kopt (machine-2, including the speed droop)						
2.2578e1	-1.233e-3	-2.005e-3	9.340e-6	-2.259e-3	1.016e-2	-1.717e-3
7.108e-1	-1.639e-3	-5.204e-5	-3.771e-6	6.274e-4	9.571e-4	9.635e-3
1.829e-1	-1.836e-3	-2.005e-5	-4.547e-6	7.742e-4	8.785e-4	9.987e-3

Ksub (machine-1)				
4.161e-1	-3.273e-7	6.956e-6	-1.268e-4	7.578e-3
1.175e-2	-4.297e-9	-4.835e-7	3.745e-6	3.605e-5
9.474e-3	-2.925e-9	-5.222e-7	5.343e-6	-1.294e-4

Ksub (machine-2)				
9.175	4.547e-6	-1.326e-3	8.637e-3	2.362e-2
2.557e-1	1.450e-7	-4.023e-5	2.847e-4	9.515e-4
9.844e-2	4.456e-8	-1.635e-5	1.646e-4	7.948e-4

Ksub (machine-1, including the speed droop)				
3.058e1	1.242e-5	-3.025e-3	1.139e-2	2.395e-2
8.499e-1	3.808e-7	-9.225e-5	4.361e-4	2.488e-3
1.865e-1	9.568e-8	-2.754e-5	2.676e-4	2.424e-3

Ksub (machine-2, including the speed droop)				
3.059e1	1.478e-5	-3.507e-3	1.139e-2	2.366e-2
8.480e-1	4.504e-7	-1.068e-4	4.565e-4	2.874e-3
1.654e-1	1.067e-7	-2.987e-5	2.877e-4	2.827e-3

Three Machines System (CPSS) - Case (1)

A matrix

A11	A12	A13
A21	A22	A23
A31	A32	A33

A11						
0 -5.288e-1	-3.63e-2	5.27e-2	0	0	0	0
0	-1.39e-1	-6.62e-3	1.116e-1	0	0	0
0	0	-2.00	0	0	0	0
0 1.1040e7	-8.307e3	-4.291e1	-5.0e1	-3.0e4	-1.20e5	-1.60e5
2.76e4	0	0	0	-1.0e2	-3.0e2	-4.0e2
6.90e3	0	0	0	0	-1.0e2	-1.0e2
1.380e1	0	0	0	0	0	-2.0e-1

A12

3.22e-2	0	2.28e-2	-1.84e-2	0	0	0	0
-6.65e-4	0	1.063e-2	9.058e-3	0	0	0	0
0	0	0	0	0	0	0	0
1.288e2	0	-6.1863e2	-6.2883e2	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A13

2.495e-2	0	1.631e-2	-1.75e-2	0	0	0	0
6.114e-4	0	9.506e-3	7.099e-3	0	0	0	0
0	0	0	0	0	0	0	0
2.7851e1	0	-5.6426e2	-5.009e2	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A21

-3.77e2	0	0	0	0	0	0
0	-6.26e-2	-1.03e-1	0	0	0	0
0	5.922e-2	-1.71e-1	0	0	0	0
0	1.5724	5.707e-1	0	0	0	0
0	-2.2892e3	2.7106e2	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

A22

0	3.77e2	0	0	0	0	0	0
-1.93e-1	0 -1.9531	-2.42e-1	2.87e-2	0	0	0	0
-3.14e-1	0	-5.14e-1	-5.32e-2	1.6667e-1	0	0	0
1.1050	0	4.18e-1	-4.6001	0	0	0	0
4.3002e2	0 1.760e6	-4.7116e3	-4.1682e3	-5.0e1	-3.0e4	-1.20e5	-1.60e5
0	4.40e3	0	0	0	-1.0e2	-3.0e2	-4.0e2
0	1.10e3	0	0	0	0	-1.0e2	-1.0e2
0	2.20	0	0	0	0	0	-2.0e-1

A23

0	0	0	0	0	0	0	0
8.44e-2	0	3.85e-2	-7.28e-2	0	0	0	0
1.31e-1	0	1.39e-1	-4.68e-2	0	0	0	0
-5.34e-1	0	3.57e-1	9.57e-1	0	0	0	0
-8.4942e1	0	-1.2393e3	-9.1906e2	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A31

-3.77e2	0	0	0	0	0	0
0	-7.79e-2	-1.78e-1	0	0	0	0
0	1.06e-1	-1.90e-1	0	0	0	0
0	1.7450	8.62e-1	0	0	0	0
0	-2.6257e3	1.9094e2	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

A32

0	0	0	0	0	0	0	0
1.88e-1	0	1.16e-1	-1.21e-1	0	0	0	0
1.72e-1	0	2.19e-1	-2.21e-2	0	0	0	0
-1.1151	0	1.26e-1	1.3549	0	0	0	0
2.0941e2	0	-1.4859e3	-1.3977e3	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A33

0	3.77e2	0	0	0	0	0	0
-3.76e-1	0 -4.1528	-3.96e-1	1.40e-1	0	0	0	0
-3.77e-1	0	-6.21e-1	-5.28e-2	1.6978e-1	0	0	0
1.9924	0	4.13e-1	-4.9678	0	0	0	0
5.8366e1	0 1.280e6	-4.199e3	-3.543e3	-5.0e1	-3.0e4	-1.20e5	-1.60e5
0	3.20e3	0	0	0	-1.0e2	-3.0e2	-4.0e2
0	8.0e2	0	0	0	0	-1.0e2	-1.0e2
0	1.60	0	0	0	0	0	-2.0e-1

Kopt (machine-1)						
9.751	-3.597e-2	6.168e-2	-4.692e-5	1.051e-2	1.766e-2	1.893e-2
-3.849	7.297e-3	-3.380e-2	1.282e-5	-3.373e-3	-4.744e-3	1.00e-2
-2.171	7.283e-3	-3.805e-2	1.324e-5	-3.575e-3	-4.684e-3	4.105e-3

Kopt (machine-2)							
-1.401e-2	3.9523	-1.848e-2	-9.152e-3	-2.896e-5	4.717e-3	1.443e-2	2.156e-2
1.065e-2	1.571	-2.229e-3	-4.104e-3	-4.917e-6	1.268e-3	1.458e-3	-1.507e-2
2.923e-3	1.591	-5.60e-3	4.303e-4	-1.404e-5	3.605e-3	5.122e-3	-2.731e-3

Kopt (machine-3)							
5.964e-2	2.6291	6.489e-2	-4.462e-2	2.469e-4	-7.123e-2	-9.443e-2	-6.973e-2
-3.323e-2	1.9215	-4.059e-2	1.990e-2	-1.109e-4	2.90e-2	4.184e-2	3.369e-2
-3.471e-2	1.2932	-3.251e-2	2.402e-2	-9.838e-5	2.726e-2	3.481e-2	6.017e-2

Kopt (machine-1, including the speed droop)						
1.973e1	-6.057e-2	8.756e-2	-6.193e-5	1.259e-2	2.186e-2	3.495e-2
-1.716e1	2.574e-2	-1.345e-1	4.342e-5	-1.111e-2	-1.649e-2	6.584e-3
-9.0639	2.308e-2	-1.306e-1	4.095e-5	-1.087e-2	-1.485e-2	-9.892e-3

Kopt (machine-2, including the speed droop)							
1.105e-4	1.9259e1	-6.431e-2	-4.216e-2	-7.874e-5	1.177e-2	4.747e-2	-8.793e-2
3.223e-2	4.283	1.343e-2	-3.403e-4	2.483e-5	-3.453e-3	-1.717e-2	-1.995e-2
1.093e-2	4.6128	-2.969e-3	5.122e-3	-5.408e-6	1.689e-3	-4.453e-4	-6.946e-3

Kopt (machine-3, including the speed droop)							
7.882e-2	1.248e1	9.834e-2	-5.038e-2	3.754e-4	-9.968e-2	-1.666e-1	-6.116e-2
-1.284e-1	8.7676	-1.681e-1	6.694e-2	-4.173e-4	1.019e-1	1.692e-1	6.952e-2
-1.224e-1	5.2326	-1.233e-1	7.695e-2	-3.484e-4	9.252e-2	1.303e-1	1.705e-1

Ksub (machine-1)				
1.0438e1	5.360e-5	-3.164e-2	2.525e-2	-2.362e-3
1.515e-1	7.722e-7	-4.559e-4	3.631e-4	-1.729e-4
7.985e-2	6.457e-7	-3.697e-4	3.331e-4	-2.996e-4

Ksub (machine-2)				
2.3993	5.188e-5	-2.892e-2	4.762e-3	-2.056e-2
2.179e-1	3.061e-6	-1.692e-3	-5.716e-4	-1.945e-3
1.368e-1	-7.636e-6	4.246e-3	-6.067e-3	-1.613e-3

Ksub (machine-3)				
2.1973	4.123e-5	-1.202e-2	-3.478e-2	-4.207e-2
2.739e-1	4.547e-6	-1.109e-3	-4.790e-3	-5.289e-3
1.405e-1	-4.462e-6	3.909e-3	-7.781e-3	-3.332e-3

Ksub (machine-1, including the speed droop)				
3.5014e1	9.370e-5	-5.006e-2	2.528e-2	-6.288e-3
5.077e-1	1.351e-6	-7.219e-4	3.628e-4	-3.302e-4
1.720e-1	7.038e-7	-3.668e-4	2.291e-4	-2.701e-4

Ksub (machine-2, including the speed droop)				
3.131e1	4.522e-4	-2.038e-1	-3.960e-2	-1.094e-1
2.8358	3.476e-5	-1.504e-2	-7.203e-3	-9.031e-3
1.066	-7.519e-7	1.251e-3	-9.670e-3	-1.134e-3

Ksub (machine-3, including the speed droop)				
2.884e1	4.343e-4	-1.567e-1	-2.316e-1	-1.785e-1
3.59658	4.712e-5	-1.567e-2	-3.298e-2	-1.994e-2
1.2292	-3.796e-5	2.315e-2	-4.088e-2	-2.339e-3

Three Machines System (CPSS) - Case (2)

A11

-1.91e-2 -5.479e-1	-3.63e-2	5.27e-2	0	0	0	0
-2.85e-2	-1.39e-1	-6.62e-3	1.12e-1	0	0	0
0	0	-2.00	0	0	0	0
-8.6555e3 1.1031e7	-8.307e3	-4.291e1	-5.0e1	-3.0e4	-1.20e5	-1.60e5
2.76e4	0	0	0	-1.0e2	-3.0e2	-4.0e2
6.90e3	0	0	0	0	-1.0e2	-1.0e2
1.380e1	0	0	0	0	0	-2.0e-1

A12

3.22e-2	-4.08e-4	2.28e-2	-1.84e-2	0	0	0	0
-6.65e-4	1.403e-2	1.063e-2	9.058e-3	0	0	0	0
0	0	0	0	0	0	0	0
1.288e2	-8.9861e2	-6.1863e2	-6.2883e2	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A13

2.495e-2	-2.74e-3	1.631e-2	-1.75e-2	0	0	0	0
6.114e-4	1.186e-2	9.506e-3	7.099e-3	0	0	0	0
0	0	0	0	0	0	0	0
2.7851e1	-7.6609e2	-5.6426e2	-5.009e2	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A21

-3.77e2	0	0	0	0	0	0
-7.17e-2	-6.26e-2	-1.03e-1	0	0	0	0
5.036e-2	5.922e-2	-1.71e-1	0	0	0	0
1.6692	1.5724	5.707e-1	0	0	0	0
-2.3585e3	-2.2892e3	2.7106e2	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

A22

0	3.77e2	0	0	0	0	0	0
-1.93e-1	-2.66e-3 -1.9558	-2.42e-1	2.87e-2	0	0	0	0
-3.14e-1	-2.63e-1	-5.14e-1	-5.32e-2	1.6667e-1	0	0	0
1.1050	-1.9353	4.18e-1	-4.6001	0	0	0	0
4.3002e2	-6.344e-3 1.7537e6	-4.7116e3	-4.1682e3	-5.0e1	-3.0e4	-1.20e5	-1.60e5
0	4.40e3	0	0	0	-1.0e2	-3.0e2	-4.0e2
0	1.10e3	0	0	0	0	-1.0e2	-1.0e2
0	2.20	0	0	0	0	0	-2.0e-1

A23

0	0	0	0	0	0	0	0
8.44e-2	-3.11e-2	3.85e-2	-7.28e-2	0	0	0	0
1.31e-1	5.61e-2	1.39e-1	-4.68e-2	0	0	0	0
-5.34e-1	9.84e-1	3.57e-1	9.57e-1	0	0	0	0
-8.4942e1	-1.5415e3	-1.2393e3	-9.1906e2	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A31

-3.77e2	0	0	0	0	0	0
-9.24e-2	-7.79e-2	-1.78e-1	0	0	0	0
9.78e-2	1.06e-1	-1.90e-1	0	0	0	0
1.8673	1.7450	8.62e-1	0	0	0	0
-2.7130e3	-2.6257e3	1.9094e2	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

A32

0	0	0	0	0	0	0	0
1.88e-1	-2.36e-2	1.16e-1	-1.21e-1	0	0	0	0
1.72e-1	1.21e-1	2.19e-1	-2.21e-2	0	0	0	0
-1.1151	1.1712	1.26e-1	1.3549	0	0	0	0
2.0941e2	-2.0676e3	-1.4859e3	-1.3977e3	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

A33

0	3.77e2	0	0	0	0	0	0
-3.76e-1	-1.37e-2 -4.1665	-3.96e-1	1.40e-1	0	0	0	0
-3.77e-1	-3.41e-1	-6.21e-1	-5.28e-2	1.6978e-1	0	0	0
1.9924	-2.2976	4.13e-1	-4.9678	0	0	0	0
5.8366e1	-5.557e3 1.2744e6	-4.199e3	-3.543e3	-5.0e1	-3.0e4	-1.20e5	-1.60e5
0	3.20e3	0	0	0	-1.0e2	-3.0e2	-4.0e2
0	8.0e2	0	0	0	0	-1.0e2	-1.0e2
0	1.60	0	0	0	0	0	-2.0e-1

Kopt (machine-1)						
9.8286	-3.596e-2	6.134e-2	-4.688e-5	1.049e-2	1.766e-2	1.866e-2
-3.905	7.449e-3	-3.443e-2	1.311e-5	-3.449e-3	-4.845e-3	9.837e-3
-2.197	7.423e-3	-3.881e-2	1.352e-5	-3.653e-3	-4.779e-3	3.834e-3

Kopt (machine-2)							
-1.461e-2	3.9636	-1.886e-2	-8.891e-3	-3.00e-5	4.996e-3	1.482e-2	2.247e-2
1.081e-2	1.604	-2.385e-3	-4.128e-3	-5.337e-6	1.379e-3	1.616e-3	-1.572e-2
2.911e-3	1.626	-5.799e-3	5.136e-4	-1.461e-5	3.762e-3	5.323e-3	-3.010e-3

Kopt (machine-3)							
5.943e-2	2.578	6.550e-2	-4.422e-2	2.481e-4	-7.145e-2	-9.498e-2	-6.784e-2
-3.374e-2	1.9519	-4.119e-2	2.026e-2	-1.127e-4	2.949e-2	4.246e-2	3.432e-2
-3.531e-2	1.3186	-3.300e-2	2.446e-2	-9.992e-5	2.769e-2	3.532e-2	6.131e-2

Kopt (machine-1, including the speed droop)						
1.971e1	-6.037e-2	8.694e-2	-6.154e-5	1.248e-2	2.173e-2	3.495e-2
-1.722e1	2.587e-2	-1.355e-1	4.367e-5	-1.117e-2	-1.658e-2	5.961e-3
-9.0869	2.319e-2	-1.315e-1	4.117e-5	-1.093e-2	-1.493e-2	-1.048e-2

Kopt (machine-2, including the speed droop)							
1.291e-4	1.932e1	-6.523e-2	-4.208e-2	-9.022e-5	1.238e-2	4.841e-2	-9.034e-2
3.220e-2	4.3019	1.365e-2	-3.248e-4	2.539e-5	-3.592e-3	-1.741e-2	-1.880e-2
1.093e-2	4.6367	-2.831e-3	5.095e-3	-5.047e-6	1.598e-3	-5.901e-4	-6.268e-3

Kopt (machine-3, including the speed droop)							
7.798e-2	1.243e1	9.87e-2	-4.954e-2	3.755e-4	-9.962e-2	-1.669e-1	-6.139e-2
-1.289e-1	8.8322	-1.691e-1	6.726e-2	-4.203e-4	1.027e-1	1.703e-1	7.333e-2
-1.232e-1	5.2823	-1.243e-1	7.747e-2	-3.509e-4	9.319e-2	1.312e-1	1.746e-1

Ksub (machine-1)				
2.508	1.624e-5	-1.014e-2	9.094e-3	2.931e-3
3.651e-2	2.173e-7	-1.367e-4	1.203e-4	-2.724e-5
2.774e-2	1.587e-7	-1.006e-4	8.966e-5	-1.824e-4

Ksub (machine-2)				
9.7403	2.910e-4	-1.520e-1	6.559e-2	-6.118e-2
8.827e-1	2.308e-5	-1.193e-2	3.969e-3	-5.595e-3
3.946e-1	5.425e-6	-2.612e-3	-1.377e-3	-2.279e-3

Ksub (machine-3)				
9.933e1	7.383e-4	-1.787e-1	-7.788e-1	-2.401e-1
1.239e1	7.806e-5	-1.465e-2	-1.052e-1	-1.982e-2
4.544	-2.489e-4	1.388e-1	-1.761e-1	3.282e-3

Ksub (machine-1, including the speed droop)				
3.5014e1	9.380e-5	-5.015e-2	2.541-2	-6.292e-3
5.077e-1	1.353e-6	-7.233e-4	3.647e-4	-3.303e-4
1.718e-1	7.061e-7	-3.681e-4	2.306e-4	-2.695e-4

Ksub (machine-2, including the speed droop)				
3.138e1	4.653e-4	-2.114e-1	-3.139e-2	-1.089e-1
2.8422	3.598e-5	-1.574e-2	-6.447e-3	-8.997e-3
1.0628	3.690e-7	6.566e-4	-9.054e-3	-1.102e-3

Ksub (machine-3, including the speed droop)				
2.888e1	4.318e-4	-1.559e-1	-2.318e-1	-1.779e-1
3.60078	4.654e-5	-1.542e-2	-3.317e-2	-1.986e-2
1.241	-4.018e-5	2.429e-2	-4.206e-2	-2.363e-3