الجمهورية الجزائرية الديمقراطية الشعبية
PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
وزارة التعليم العالي و البحث العلمي
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

MOHAMED KHEIDER University BISKRA

Faculty of Science and Technology

Electric Engineering Department

Field: Electrotechnics

Option: Electrical Networks

Réf: …………

A Dissertation for the Fulfillment of the Requirement of a Master's Degree

Theme

Power System Stabilizer Controlled By Fuzzy Logic

Presented by:
Bechar Mohamed Djihad

Presented on: 04 June 2015

Members of Jury:

Dr. Salhi Ahmed	*University of Biskra*	President
Dr. Naimi Djemai	*University of Biskra*	Supervisor
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Academic Year: 2014 / 2015

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Favorable opinion of the supervisor:

Dr. Naimi Djemai

Favorable opinion of the Jury President

Dr. Salhi Ahmed

Stamp and signature

DEDICATION

To the most supportive and most important people in my life, my parents.

To my dear friends who have been a big part of my life.

To my colleagues whom I spent many years with.

To my teachers whom have been my source of motivation and aspiration.

ACKNOWLEDGMENT

First and foremost, I want to express my gratitude to everyone I know, for their encouragement and support.

The paucity of words does not compromise for extending my thanks to my family and friends whose gave me support, inspiration and helped me in completing this work.

I would like to express my sincere appreciation to my supervisor and advisor *Dr. Naimi Djemai* for his valuable academic suggestions and patient guidance throughout the preparation of this memoire.

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ملـــخـــص:

تتكون أنظمة الطاقة الحديثة من عدة مولدات تعمل بشكل متزامن لتلبية الطلب على الطاقة. لاعتمادية الأنظمة، لا بد من ضمان الاستقرار في حالة الاعطال داخل النظام. أخطاء في نظام تحفز التذبذبات الكهربائية من المولدات الكهربائية. هذه التذبذبات، وتسمى أيضا تقلبات الطاقة يجب أن تثبط بشكل فعال للحفاظ على استقرار النظام. في محاولة للحد من تقلبات النظام، تستخدم المثبتات نظام الطاقة (PSS) لإضافة التخميد عن طريق التحكم في نظام التحفيز. وقد أظهرت الدراسات أن ضبط مثبت نظام الطاقة (PSS) بشكل جيد يمكن أن يحسن بشكل فعال الاستقرار الديناميكي لنظام الطاقة. يوضح هذا العمل كيفية استخدام وحدة تحكم المنطق الضبابي لمراقبة دقيقة وضبط مثبت نظام الطاقة (PSS) وبالتالي تحسين الاستقرار الشامل للنظام الطاقة. وقد أجريت عمليات المحاكاة من على مولد واحد متصل بنظام لانهائي (SMIB) وجدت في المراجع. لقد تمت محاكاة هذا النموذج في بيئة .MATLAB / SIMULINK ويتم مقارنة نتائج المولد دون مثبت نظام الطاقة (PSS) ، مع نتائج مثبت نظام الطاقة (PSS) ومع مثبت نظام الطاقة (PSS) بالإضافة إلى وحدة تحكم المنطق الضبابي. وتشير النتائج إلى أن إدراج المنطق الضبابي المراقب يحسن تخميد التذبذبات الكهربائية التي سببها عطل في النظام، وبالتالي يحسن الاستقرار الكلي للنظام.

الكلمات المفتاحية: استقرار نظام الطاقة، مثبت نظام الطاقة، منظم الجهد الأوتوماتيكي، المنطق الضبابي.

Abstract

Modern power systems consist of several generators working synchronously to meet the power demand. For reliability of these systems, stability must be ensured in case of faults within the system. Faults within a system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability. In an attempt to reduce system oscillations, Power System Stabilizers (PSS) are used to add damping by controlling the excitation system. Studies have shown that a well-tuned PSS can effectively improve power system dynamic stability. This memoire demonstrates how the Fuzzy Logic Controller can be used to fine control and tune the PSS and thus improve the overall stability of a power system. Simulations have been carried out on a single machine connected to infinite bus system (SMIB) found in literature. The model was simulated in a MATLAB/SIMULINK environment. A comparison is carried out on a generator without a PSS, with a PSS and with a PSS plus a Fuzzy Logic Controller. The results indicate that the inclusion of a Fuzzy Logic Controller improves the damping of electromechanical oscillations introduced by a three phase fault in the system, and hence, improves the overall stability of the system.

Key words: Power system stability, power system stabilizer, AVR, fuzzy logic.

Résumé

Systèmes électriques modernes sont constitués de plusieurs générateurs fonctionnant de manière synchrone pour répondre à la demande de puissance. Pour la fiabilité de ces systèmes, la stabilité doit être assurée en cas de défauts dans le système. Défauts dans un système induisent oscillations électromécaniques des générateurs électriques. Ces oscillations, appelées aussi des sautes de puissance, doivent être efficacement amorties pour maintenir la stabilité du système. Dans une tentative pour réduire les oscillations du système, les systèmes stabilisateurs de puissance (PSS) sont utilisés pour ajouter amortissement par la commande du système d'excitation. Des études ont montré qu'un PSS bien réglé peut effectivement améliorer la stabilité dynamique de système. Ce mémoire démontre comment le contrôleur de logique floue peut être utilisé pour un contrôle précis et syntoniser le PSS et d'améliorer ainsi la stabilité transitoire du système d'alimentation. Des simulations ont été réalisées sur une seule machine connectée à un jeu de barre infinie (SMIB) trouvé dans la littérature. Le modèle a été simulé dans un environnement MATLAB / Simulink. Une comparaison est effectuée sur un générateur sans PSS, avec un PSS et avec un PSS basé à la logique floue. Les résultats indiquent que l'incorporation d'un contrôleur floue permet d'améliorer l'amortissement des oscillations électromécaniques introduites par un défaut triphasé (court-circuit) dans le système et, par conséquent, améliore la stabilité globale du système.

Mots-clés: Stabilité de système de puissance, stabilisateur de système de puissance, AVR, logique floue.

General Introduction

GENERAL INTRODUCTION

Electrical energy has become a major form of energy for end use consumption in today's world. There is always a need for making electrical energy generation and transmission, both more economical reliable. Power systems are normally designed so they can operate and survive large disturbances like storms, lightning strikes, equipment failures, and unpredictable fault locations. This usually means that even though some power system equipment will be separated or isolated as a result of automatic protection and control actions, power supply to customers will not be disrupted or, at least, that any such disruptions will be localized.

Power system stability has been recognized as an important problem for secure system operation since the beginning of last century. Many major blackouts caused due to power system instability have illustrated the importance of this phenomenon. The power system is a highly nonlinear system whose dynamic performance is influenced by a wide array of devices with different response rates and characteristics. System stability must be viewed not as a single problem, but rather in terms of its different aspects.

Power system stability had been the primary concern of the utilities for many decades. However, in the last two decades power systems have operated under much more stressed conditions than they usually had in the past. There are number of factors responsible for this: continuing growth in interconnections; increased electricity consumption in heavy load areas (where it is not feasible or economical to install new generating plants); growing use of induction machines.

The phenomenon of electromechanical oscillations between interconnected synchronous generators in power systems is intensively discussed in the literature. The main method used today to guard against small signal instability is the offline tuning of power system stabilizers (PSS). These PSSs are local controllers on the generators. Thus local controllers are used to mitigate system oscillation modes. However, this procedure, in some circumstances, is recognized to have significant disadvantages.

The most commonly used PSS, referred to as conventional PSS (CPSS), is a fixed parameter analog-type device with lead-lag compensation, wash out, and amplifier gains, which are limited and may lose effective damping robustness for overall operation.

New controllers need to be developed that can exploit system-wide inputs (not necessarily more inputs per controller but input signals from further away). Another control concept is to adaptively change the PSS set points according to the power system operating conditions.

Adaptive control can change the controller parameters online based on the changes in system operating conditions. An adaptive controller responds to changes in system operating conditions by determining a new set of control parameters.

In an attempt to cover a wide range of operating conditions, Fuzzy logic control has been suggested as a possible solution to overcome this problem, thereby using linguist information and avoiding a complex system mathematical model, while giving good performance under different operating conditions. In this memoir, a systematic approach to fuzzy logic control design is proposed. The study of fuzzy logic power system stabilizer for stability enhancement of a single machine infinite bus system is presented. In order to accomplish the stability enhancement, the difference between other people work and ours is that the simulation results will be compared and discussed from different sides (time and amplitude), the main advantage of fuzzy logic control design lies in the nonlinearity nature of fuzzy control rules that can manage a wide range of operating conditions.

The content of this work is structured as follows:

Chapter 1 presents a general introduction to the power system stability problem including classification, historical review, and definition of related terms. In addition, an overview of the rotor angle stability especially transient stability, and identifies factors influencing it, and describes modelling consideration and analytical technique applicable. Finally, for the enhancement of stability, we have introduced the power system stabilizer and its types.

Chapter 2 provide an overview to the theory of fuzzy logic, it includes a historical review, concept, definitions and some examples to illustrate the difference between the Boolean logic and Fuzzy logic. We will present the general structure of fuzzy controller and its different applications.

The aim of the last chapter is to describe the design procedure for a fuzzy logic based PSS (FLPSS), to enhance the damping of generator oscillations In order to accomplish a stability enhancement. The proposed technique has the features of a simple structure, and fast response and is evaluated on a Single machine connected to infinite bus (SMIB), and two-machine system, the performance of the fuzzy logic power system stabilizer was compared with the conventional power system stabilizer. Simulation results on SMIB show the effectiveness of the proposed FLPSS.

Chapter 1

Power System Stability

Introduction

At present the demand for electricity is rising phenomenally especially in developing countries. This persistent demand is leading to operation of the power system at its limit. On top of this the need for reliable, stable and quality power is also on the rise due to electric power sensitive industries. In this scenario, meeting the electric power demand is not the only criteria but also it is the responsibility of the power system engineers to provide a stable and quality power to the consumers. These issues highlight the necessity of understanding the power system stability.

This chapter presents a general introduction to the power system stability problem, and the objective of this chapter is to provide an overview of the different types of power system stability, particularly the transient stability phenomena, and the Power System Stabilizer PSS.

1.1 Historical review of stability problems

Power system stability is **[KUN 94b]** a complex subject that has challenged power system engineers for many years. A review of the history of the subject is useful for a better understanding of present-day stability problems.

The stability of power systems was first recognized as an important problem in 1920. Results of the first laboratory tests on miniature systems were reported in 1924; the first field tests on the stability on a practical power system were conducted in 1925.

Early stability problems were associated with remote hydroelectric generating stations feeding into metropolitan load centers over long-distance transmission. For economic reasons, such systems were operated close to their steady-state stability limits. In a few instances, instability occurred during steady-state operation, but it occurred more frequently following short-circuits and other system disturbances.

The stability problem was largely influenced by the strength of the transmission system, with instability being the result of insufficient synchronizing torque. The fault-clearing times were slow, being in the order of 0.5 to 2.0 seconds or longer.

The methods of analysis and the models used were dictated by developments in the art of computation and the stability theory of dynamic systems. Slide rules and mechanical calculators were used; hence, the models and methods of analysis had to be simple. In addition, graphical techniques such as the equal-area criterion and circle diagrams were developed. Such techniques were adequate for the analysis of the simple systems that could be treated separately. The former was related to the slope and peak of the power-angle curve; it was taken for granted that damping was positive.

1.2 Basic Concepts and Definitions of Power System Stability

1.2.1 Definition

Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance **[KUN 94c].** The disturbance mentioned in the definition could be faults, load changes, generator outages, line outages, voltage collapse or some combination of these. Power system stability can be broadly classified into rotor angle, voltage and frequency stability. Each of these three stabilities can be further classified into large disturbance or small disturbance, short term or long term. The classification is depicted in *Figure 1.1* **[IEE 04].**

1.2.2 Classification of stability

Power system stability is **[KUN 94a]** a single problem; however, it is impractical to study it as such. Analysis of stability problems, identification of essential factors that contribute to instability, and formation of methods of improving stable operation are greatly facilitated by classification of stability into appropriate categories. These are based on the following considerations:

- The physical nature of the resulting instability;
- The size of the disturbance considered;
- The devices, processes, and time span that must be taken into consideration in order to determine stability;
- The most appropriate method of calculation and prediction of stability.

Figure 1.1 gives an overall picture of the power system stability problem, identifying its classes and subclasses in terms of the categories.

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There are three categories of stability:

- ❖ Rotor angle stability;
- ❖ Frequency stability;
- ❖ Voltage stability.

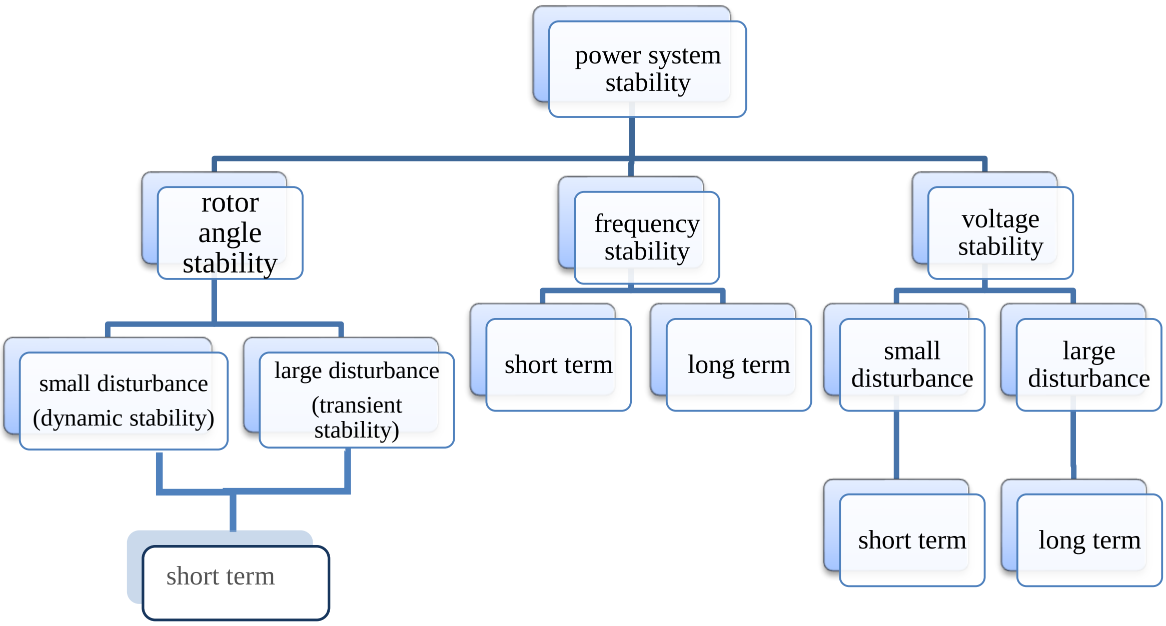


Figure 1.1 Classification of power system stability

1.2.3 Principal causes of instability

Every abrupt disturbance of the mode of operation of an electric system is composed, of transport lines of energy and loads, product of pumping of the synchronous machines. At the times of bad operating conditions, the amplitude of oscillations can be so important that certain machines or a whole station left synchronism. Pumping of the synchronous machines can also appear in the following cases:

- ➢ Large step loading (or loss of load).
- ➢ During the rupture of the line.
- ➢ At the time of disconnection of the transformers.
- ➢ At the time of short-circuit.

Of all these incidents it is the short-circuit which is necessary to be studied in priority.

Therefore, our study of stability will be done especially in the case of transient stability.

1.2.4 Results of instability

In cases of instability, as the generator angles separate, the voltage and current angular relationships at points on the system change drastically. Some of the protective line relays will detect these changes and react as if they were due to fault conditions causing the opening of many transmission lines. The resulting transmission system is usually segmented into two or more electrically isolated islands, some of which will have excess generation and some will be generation deficient.

In excess generation pockets, the frequency will rise. In generation deficient pockets, the frequency will fall. If the frequency falls too far, generator auxiliary systems (motors, fans) will fail, causing generators to be automatically disconnected by their protective devices. Industry practice is to provide for situations where there is insufficient generation by installing under frequency-load-shedding relays. These relays, keyed to various levels of low frequency, will actuate the disconnection of blocks of customer load in an effort to restore the load-generation balance. In situations where the frequency rises because of excess generation, generators will be automatically removed from service by protective devices detecting an over-speed condition. If studies indicate potential excess generation pockets, special, selective generation disconnection controls can be installed ***[UND 03a].***

1.3 Voltage Stability

It is the ability of the system to maintain steady state voltages at all the system buses when subjected to a disturbance **[IEE 82]**. If the disturbance is large then it is called as large-disturbance voltage stability and if the disturbance is small it is called as small-disturbance voltage stability. Unlike angle stability, voltage stability can also be a long term phenomenon. In case voltage fluctuations occur due to fast acting devices like induction motors, power electronic drive, *HVDC* …etc., then the time frame for understanding the stability is in the range of 10-20 s and hence can be treated as short term phenomenon. On the other hand if voltage variations are due to slow change in load, over loading of lines, generators hitting reactive power limits, tap changing transformers …etc., then time frame for voltage stability can stretch from 1 minute to several minutes.

The main difference between voltage stability and angle stability is that voltage stability depends on the balance of reactive power demand and generation in the system where as the angle stability mainly depends on the balance between real power generation and demand.

1.4 Frequency Stability

It refers to the ability of a power system to maintain steady frequency following a severe disturbance between generation and load **[IEE 82]**. It depends on the ability to restore equilibrium between system generation and load, with minimum loss of load. Frequency instability may lead to sustained frequency swings leading to tripping of generating units or loads. During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds like under frequency control to several minutes, corresponding to the response of devices such as prime mover and hence frequency stability may be a short-term phenomenon or a long-term phenomenon.

Though, stability is classified into rotor angle, voltage and frequency stability they need not be independent isolated events. A voltage collapse at a bus can lead to large excursions in rotor angle and frequency. Similarly, large frequency deviations can lead to large changes in voltage magnitude.

1.5 Rotor Angle Stability

It is the ability of the system to remain in synchronism when subjected to a disturbance **[IEE 82]**. The rotor angle of a generator depends on the balance between the electromagnetic torque due to the generator electrical power output and mechanical torque due to the input mechanical power through a prime mover. Remaining in synchronism means that all the generators electromagnetic torque is exactly balanced by the mechanical torque. If in some generator the balance between electromagnetic and mechanical torque is disturbed, due to disturbances in the system, then this will lead to oscillations in the rotor angle.

1.5.1 Equations of motion

The equations of central importance in power system stability analysis are the rotational inertia equations describing the effect of unbalance between the electromagnetic torque and the mechanical torque of the individual machines. We will develop these equations in *per unit* form define parameters that are used to represent mechanical characteristics of synchronous machines in stability studies.

Before we develop the equations of motion of a synchronous machine, it is useful to review the quantities and relationships associated with the mechanics of motion. These are summarized in *Table 1.1*. Since it is easier to visualize quantities associated with rotation by analogy with those associated with more familiar linear motion, the latter are also included in the table.

1.5.2 Swing equation

As we are introducing new per unit equations and parameters, once again we temporarily resort to the use of super-bars to identify per unit quantities.

When there is an unbalance between the torques acting on the rotor, the net torque causing acceleration (or deceleration) is:

$$T_a = T_m - T_e \tag{1.1}$$

Where:

T_a= acceleration torque in N.m.

T_m= mechanical torque in N.m.

T_e=electromagnetic torque in N.m.

In the above equation, $\boldsymbol{T_m}$ and $\boldsymbol{T_e}$ are positive for a generator and negative for a motor. The combined inertia of the generator and prime mover is accelerated by the unbalance in the applied torques. Hence, the equation of motion is:

$$J\frac{d\boldsymbol{\omega_m}}{dt} = T_a = T_m - T_e \tag{1.2}$$

Where:

J= combined moment of inertia of generator and turbine, Kg.m^2.

ω_m= angular velocity of the rotor, mech.rad/s.

T= time, s.

Table 1.1 quantities and relationships associated with the mechanics of motion

Linear Motion				*Rotation*		
Quantity	***Symbol/ Equation***	***Unit***		***Quantity***	***Symbol/ Equation***	***Unit***
Length	S	meter (m)		**Angular displacement**	θ	radian (rad)
Mass	M	kilogram (kg)		**Moment of inertia**	$J=\int r^2 dm$	$kg.m^2$
Velocity	v=ds/dt	meter/second (ms)		**Angular velocity**	ω=dθ/dt	rad/s
Acceleration	a=dv/dt	m/s^2		**Angular acceleration**	α=dω/dt	rad/s^2
Force	F=M.a	Newton (N)		**Torque**	T=J.α	Newton-meter (N.m) or J/rad
Work	$W=\int F ds$	joule (J)		**Work**	$W=\int T d\theta$	J or W.s
Power	P=dW/dt =F.v	watt (W)		**Power**	P=dW/dt =T.w	W

The above equation can be normalized in terms of per unit *inertia constant H*, defined as the kinetic energy in watt-seconds at rated speed divided by the *VA*base. Using ω_{0m} to denote rated angular velocity in mechanical radians per second, the inertia constant is:

$$H = \frac{J\omega_{0\,m}^2}{2_{VAbase}} \qquad (1.3)$$

The moment of inertia *J* in terms of *H* is:

$$J = \frac{2H_{VAbase}}{2\omega_{0m}^2} \qquad (1.4)$$

Substituting the above in *Equation (1.2)* gives:

$$\frac{2H}{\omega_{0\,m}^2} VA_{base}.\frac{d\omega_m}{dt} = T_m - T_e \qquad (1.5)$$

Rearranging yields:

$$2H\frac{d(\frac{\omega_m}{\omega_{0m}})}{dt} = \frac{T_m - T_e}{(\frac{VA_{base}}{\omega_{0m}})} \quad (1.6)$$

Noting that $\boldsymbol{T_{base}=VA_{base}/\omega_{0m}}$, the equation of motion in per unit form is

$$2H\frac{d\acute{\omega}_r}{dt} = \bar{T}_m - \bar{T}_e \quad (1.7)$$

In the above equation,

$$\acute{\omega}_r = \frac{\omega_m}{\omega_{0m}} = \frac{\frac{\omega_r}{Pf}}{\frac{\omega_0}{Pf}} = \frac{\omega_r}{\omega_0} \quad (1.8)$$

Where $\boldsymbol{\omega_r}$ is angular velocity of the rotor in electrical *rad/s*, $\boldsymbol{\omega_0}$ is its rated value, and $\boldsymbol{P_f}$ is number of field poles.

If $\boldsymbol{\delta}$ is the angular position of the rotor in electrical radians with respect to a synchronously rotating reference and $\boldsymbol{\delta_0}$ is its value at $\boldsymbol{t=0}$,

$$\delta = \omega_{rt} - \omega_{0t} + \delta_0 \quad (1.9)$$

Taking the time derivative, we have

$$\frac{d\delta}{dt} = \omega_r - \omega_0 = \Delta\omega_r \quad (1.10)$$

And,

$$\frac{d^2\delta}{dt^2} = \frac{d\omega_r}{dt} = \frac{d\Delta\omega_r}{dt} = \omega_0\frac{d\acute{\omega}_r}{dt} = \omega_0\frac{d\Delta\acute{\omega}_r}{dt} \quad (1.11)$$

Substituting for $\frac{d\acute{\omega}_r}{dt}$ given by the above equation in *Equation (1.7)*, we get

$$\frac{2H}{\omega_0}.\frac{d^2\delta}{dt^2} = \bar{T}_m - \bar{T}_e \quad (1.12)$$

It is often desirable to include a component of damping torque, not accounted for in the calculation of T_e, separately. This is accomplished by adding a term proportional to speed deviation in the above equation as follows:

$$\frac{2H}{\omega_0} \cdot \frac{d^2\delta}{dt^2} = \overline{T}_m - \overline{T}_e - K_D \Delta\acute{\omega}_r \quad (1.13)$$

From *Equation (1.11)*,

$$\Delta\acute{\omega}_r = \frac{\Delta\omega_r}{\omega_0} = \frac{1}{\omega_0}\frac{d\delta}{dt} \quad (1.14)$$

Equation (1.14) represents the equation of motion of a synchronous machine. It is commonly referred to as the *swing equation* because it represents swings in rotor angle $\boldsymbol{\delta}$ during disturbances.

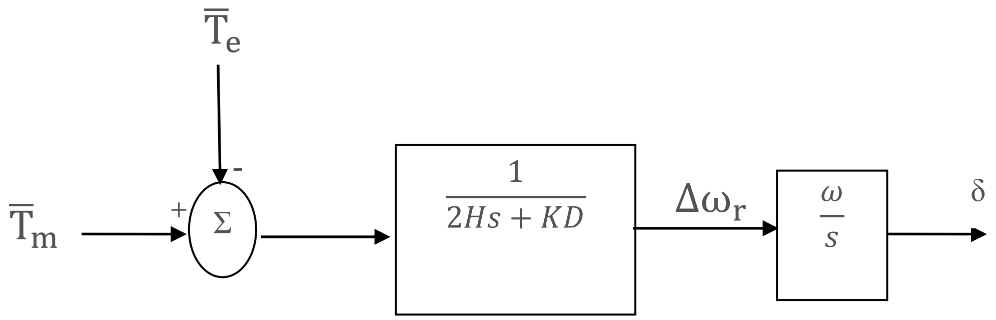


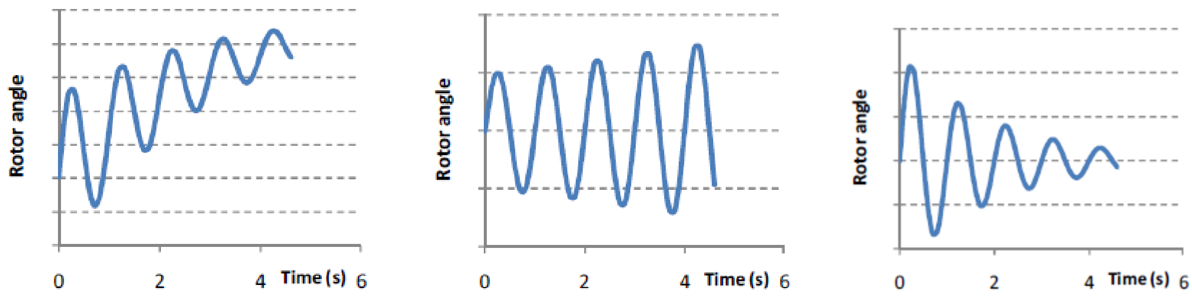
Figure 1.2 Block diagram representation of swing equation

In the block diagram, ***S*** is the Laplace operator; it replaces ***d/dt*** of equations. Symbols T_M and ***M*** are often used in place of ***2H.***

1.5.3 Small-disturbance (or small-signal) stability

It is the ability of the system to remain in synchronism when subjected to small disturbances **[IEE 82]**. If a disturbance is small enough so that the nonlinear power system can be approximated as a linear system, then the study of rotor angle stability of that particular system is called as small-disturbance angle stability analysis. Small disturbances can be small load changes like switching on or off of small loads, line tripping, small generators tripping etc. Due to small disturbances there can be two types of instability: *non-oscillatory instability* and *oscillatory instability*. In non-oscillatory instability the rotor angle of a generator keeps on increasing due to a small disturbance and in case of oscillatory instability the rotor angle oscillates with increasing magnitude.

Positive T_d, Negative T_s Negative T_d, Positive T_s Positive T_d, Positive T_s



(a) *(b)* *(c)*

Figure 1.3 Types of small-disturbance stability

T_d = Damping torque; T_s= synchronizing torque.

The nature of system response to small disturbances depends on a number of factors including the initial operating, the transmission system strength, and the type of generator excitation controls used.

1.5.4 Transient Stability

In the evaluation of stability, the concern is the behavior of the power system when subjected to a transient disturbance.

Transient stability, the main focus of this chapter, is the ability of the system to remain in synchronism when subjected to large disturbances. Large disturbances can be faults, switching on or off of large loads, large generators tripping etc. When a power system is subjected to large disturbances they will lead to large excursions of generator rotor angles.

Since there are large rotor angle changes the power system cannot be approximated by a linear representation like in the case of small-disturbance stability. The time domain of interest in case of large-disturbance as well as small-disturbance angle stability is anywhere between *0.1- 10 s*. Due to this reason small and large-disturbance angle stability are considered to be short term phenomenon **[IEE 04].**

Consider the system shown in *Figure 1.4***,** consisting of a generator delivering power to a large system represented by an infinite bus through two transmission circuits. *An infinite bus is an ideal voltage source that maintains constant voltage magnitude, constant phase, and constant frequency*.

We will present fundamental concepts and principles of transient stability by analyzing the system response to large disturbances, using very simple models. All resistances are neglected. The generator is represented by the classical model and the speed governor effects are neglected. The corresponding system representation is shown in *Figure 1.5 (a)***.** The voltage behind the transient reactance ***(X'$_d$)*** is denoted by ***E'***. The rotor angle $\boldsymbol{\delta}$ represents the angle by which ***E'*** leads $\boldsymbol{E_B}$.

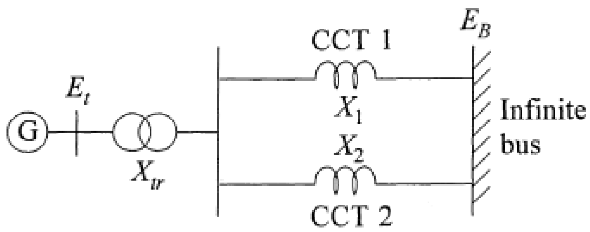
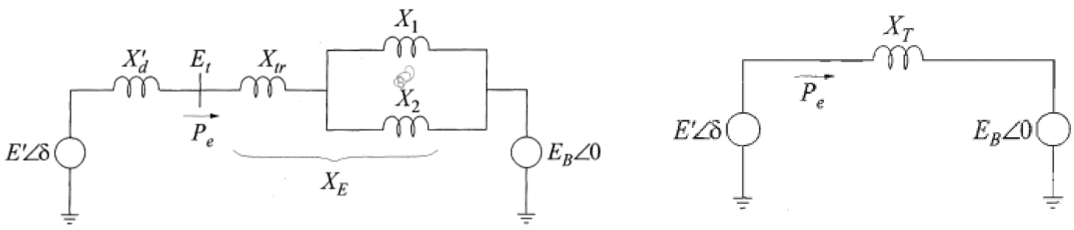


Figure 1.4 Single-machine infinite bus system



(a) Equivalent circuit

(b) Reduced equivalent circuit

$\bar{E}' = \bar{E}_{t0} + jX'_d . \tilde{I}t0$

$X_T = X'_d + X_E$

Figure 1.5 System representation with generator represented by classical model

When the system is perturbed, the magnitude of ***E'*** remains constant at its pre-disturbance value and $\boldsymbol{\delta}$ changes as the generator rotor speed deviates from synchronous speed $\boldsymbol{\omega_0}$.

The system model can be reduced to the form shown in *Figure 5 (b)*. It can be analyzed by using simple analytical methods and is helpful in acquiring a basic understanding of the transient stability phenomenon. The generator's electrical power output is:

$$P_e = \frac{\acute{E}.E_B}{X_T}\sin\delta = P_m - P_{max}.\sin\delta \qquad (1.15)$$

Where:

$$P_{max} = \frac{\acute{E}.E_B}{X_T}$$

Since we have neglected the stator resistance, $\boldsymbol{P_e}$ represents the air-gap power as well as the terminal power. The power-angle relationship with both transmission circuits in service (I/S) is shown graphically in *Figure 1.6* as curve ***1***. With a mechanical power input of $\boldsymbol{P_m}$, the steady-state electrical power output $\boldsymbol{P_e}$ is equal to $\boldsymbol{P_m}$, and the operating condition is represented by point "*a*" on the curve. The corresponding rotor angle is $\boldsymbol{\delta_a}$.

If one of the circuits is out of service (O/S), the effective reactance $\boldsymbol{X_T}$ is higher. The power-angle relationship with circuit **2** out of service is shown in *Figure 1.6* as curve **2.** The maximum power is now lower. With a mechanical power input of Pm, the rotor angle is now $\boldsymbol{\delta_b}$ corresponding to the operating point "*b*" on curve **2**; with a higher reactance, the rotor angle is higher in order to transmit the same steady-state power.

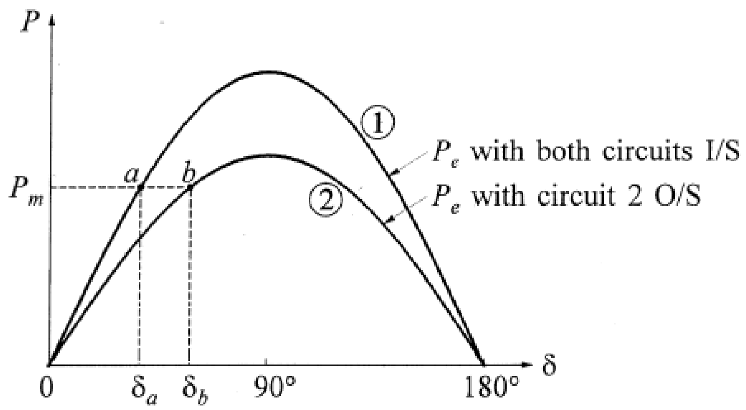


Figure 1.6 Power angle relationship

During a disturbance, the oscillation of $\boldsymbol{\delta}$ is superimposed on the synchronous speed $\boldsymbol{\omega_0}$, but the speed deviation ($\boldsymbol{\Delta\omega_r = d\delta/dt}$) is very much smaller than $\boldsymbol{\omega_0}$. Therefore, the generator speed is practically equal to ω_0, and the *per unit* (*pu*) air-gap torque may be considered to be equal to the pu air-gap power. We will therefore use torque and power interchangeably when referring to the swing equation.

The equation of motion or the swing equation may be written as:

$$\frac{2H}{\omega_0} \cdot \frac{d^2\delta}{dt^2} = P_m - P_{max} \cdot \sin\delta \tag{1.16}$$

Where:

P_m = mechanical power input, in *pu*

P_{max} = maximum electrical power output, in *pu*

H = inertia constant, in MW.s/MVA

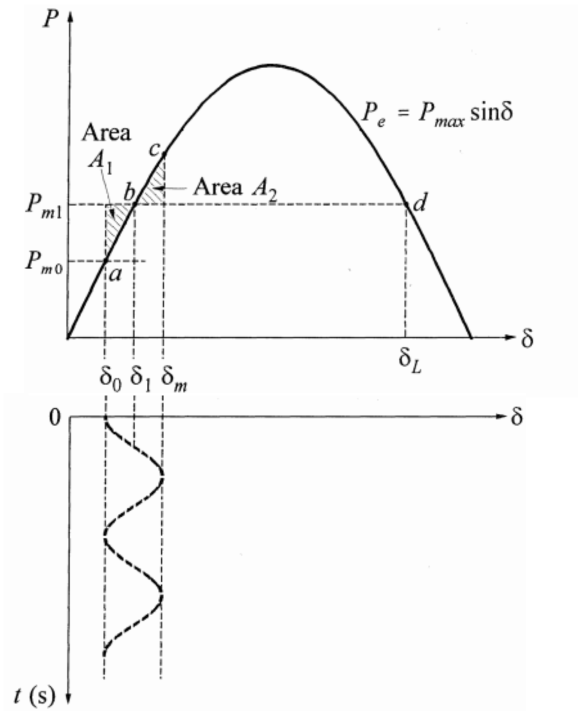
δ = rotor angle, in elec.rad

t = time, in *s*

1.5.5 Response to a step change in P_m

Let us now examine the transient behavior of system, with both circuits in service, by considering a sudden increase in the mechanical power input from an initial value of P_{m0} to P_{m1} as shown in *Figure 1.7 (a)*. Because of the inertia of the rotor, the rotor angle cannot change instantly from the initial value of δ_0 to δ_1 corresponding to the new equilibrium point b at which $P_e = P_{m1}$. The mechanical power is now in excess of the electrical power. The resulting accelerating torque causes the rotor to accelerate from the initial operating point a toward the new equilibrium point b, tracing the P_e-δ curve at *"a"* rate determined by swing equation. The difference between P_{m1} and P_e at any instant represents the accelerating power.

When point **b** is reached, the accelerating power is zero, but the rotor speed is higher than the synchronous speed ω_0 (which corresponds to the frequency of the infinite bus voltage). Hence, the rotor angle continues to increase. For values of δ higher than δ_1, P_e is greater than P_{m1} and the rotor decelerates. At some peak value δ_m, the rotor speed recovers to the synchronous value ω_0, P_e is higher than P_{ml}. point retraces the P_e-δ curve from *"c"* to b and then to *"a"*. The rotor angle oscillates indefinitely about the new equilibrium angle δ_1 with constant amplitude as shown by the time plot of δ in *Figure 1.7(b)*.



(a) Power-angle deviation

(b) Rotor angle time response

Figure 1.7 Present the Power-angle deviation and Rotor angle time response

In our representation of the power system in the above analysis, we have neglected all resistances and the classical model is used to represent the generator. In effect, this neglects all sources of damping. Therefore, the rotor oscillations continue unabated following the perturbation. In practice, there are many sources of positive damping including field flux variations and rotor damper (amortisseurs) circuits. In a system which is small-signal stable, the oscillation damp out.

1.5.6 Equal-area criterion

For the system model considered above, it is not necessary to formally solve the swing equation to determine whether the rotor angle increases indefinitely or oscillates about an equilibrium position. Information regarding the maximum angle excursion (***δm***) and stability limit may be obtained graphically by using the power-angle diagram shown in *Figure 1.7*. Although this method is not applicable to multi-machine systems with detailed representation of synchronous machine, it helps in understanding basic factors that influence the transient stability of any system.

From *Equation (1.16)*, we have the following relationship between the rotor angle and the accelerating power:

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H}(P_m - P_e) \tag{1.17}$$

Now $\boldsymbol{P_e}$ is a nonlinear function of $\boldsymbol{\delta}$, and therefore the above equation cannot be solved directly. If both sides are multiplied by ***2dδ/dt***, then:

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{\omega_0(P_m - P_e)d\delta}{H} \tag{1.18}$$

$$\frac{d}{dt}\left[\frac{d\delta}{dt}\right]^2 = \frac{\omega_0(P_m - P_e)}{H}\frac{d\delta}{dt} \tag{1.19}$$

Integrating gives:

$$\left[\frac{d\delta}{dt}\right]^2 = \int \frac{\omega_0\,(P_m - P_e)}{H}d\delta \tag{1.20}$$

The speed deviation ***dδ/dt*** is initially zero. It will change as a result of the disturbance. For stable operation, the deviation of angle $\boldsymbol{\delta}$ must be bounded, reaching a maximum value (as at point *"c"* in *Figure 1.7*) and then changing direction. This requires the speed deviation ***dδ/dt*** to become zero at some time after the disturbance. Therefore, from *Equation (1.20)*, as a criterion for stability we may write:

$$\int_{\delta_0}^{\delta_m} \frac{\omega_0}{H}(P_m - P_e)d\delta = 0 \tag{1.21}$$

Where $\boldsymbol{\delta_0}$ is the initial rotor angle and $\boldsymbol{\delta_m}$ is the maximum rotor angle, as illustrated in *Figure 1.7*. Thus, the area under the function $\boldsymbol{P_m}$-$\boldsymbol{P_e}$ plotted against $\boldsymbol{\delta}$ must be zero if the system is to be stable. In *Figure 1.7*, this is satisfied when area $\boldsymbol{A_1}$ is equal to area $\boldsymbol{A_2}$. Kinetic energy is gained by the rotor during acceleration when $\boldsymbol{\delta}$ changes from $\boldsymbol{\delta_0}$ to $\boldsymbol{\delta_1}$. The energy gained is:

$$E_1 = \int_{\delta_0}^{\delta_1} (P_m - P_e)d\delta = \text{area } A_1 \tag{1.22}$$

The energy lost during deceleration when $\boldsymbol{\delta}$ changes from $\boldsymbol{\delta_1}$ to $\boldsymbol{\delta_m}$ is:

$$E2 = \int_{\delta_1}^{\delta_m} (P_e - P_m)d\delta = \text{area } A_2 \tag{1.23}$$

As we have not considered any losses, the energy gained is equal to the energy lost; therefore, area $\boldsymbol{A_1}$ is equal to area $\boldsymbol{A_2}$. This forms the basis for the *equal-area criterion*. It enables us to determine the maximum swing of $\boldsymbol{\delta}$ and hence the stability of the system without computing the time response through formal solution of the swing equation.

The criterion can be readily used to determine the maximum permissible increase in $\boldsymbol{P_m}$ for the system of *Figure 1.4*. The stability is maintained only if an area $\boldsymbol{A_2}$ at least equal to $\boldsymbol{A_1}$ can be located above $\boldsymbol{P_{m1}}$. If $\boldsymbol{A_1}$ is greater than $\boldsymbol{A_2}$, then $\boldsymbol{\delta_m > \delta_L}$, and stability will be lost. This is because, for $\boldsymbol{\delta > \delta_L}$, $\boldsymbol{P_{m1}}$ is larger than $\boldsymbol{P_e}$ and the net torque is accelerating rather than decelerating.

We will examine the mechanism of transient instability by considering next the system response to a short-circuit fault on the transmission system, which is more common form of a disturbance considered in transient stability studies.

1.5.7 Response to a short-circuit fault

Let us consider the response of the system to a three-phase fault at location ***F*** on transmission circuit ***2***, as shown in *Figure 1.8* (a). The corresponding equivalent circuit, assuming a classical generator model, is shown in *Figure 1.8* (b). The fault is cleared by opening circuit breakers at both ends of faulted circuit, the fault-clearing time depending on the relaying time and breaker time.

If the fault location ***F*** is at the sending end (*HT bus*) of the faulted circuit, no power is transmitted to the infinite bus. The short-circuit current from the generator flows through pure reactance to the fault. Hence, only reactive power flows and the active power $\boldsymbol{P_e}$ and the corresponding electrical torque $\boldsymbol{T_e}$ at the air-gap are zero during the fault. If we had included generator stator and transformer resistances in our model, $\boldsymbol{P_e}$ would have a small value, representing the corresponding resistive losses.

If the fault location ***F*** is at some distance away from the sending end as shown in *Figures 1.8 (a)* and (b), some active power is transmitted to the infinite bus while the fault is still on.

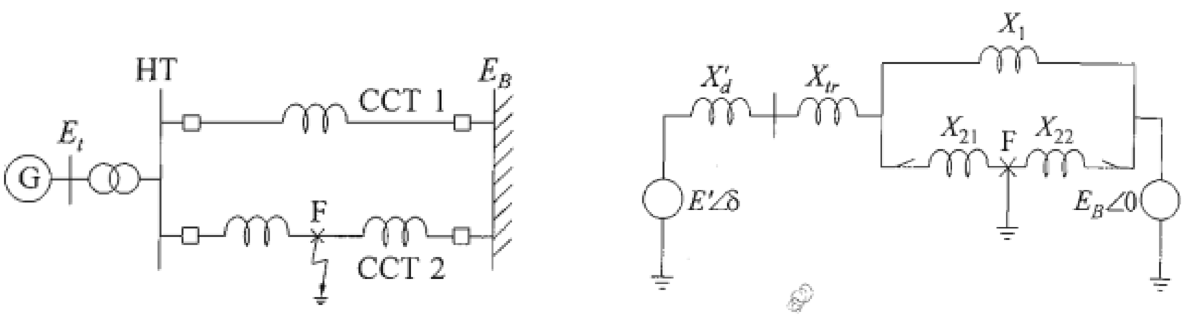
Figures 1.8 (c) and *(d)* show $\boldsymbol{P_e}$-$\boldsymbol{\delta}$ plots for the three network conditions:

- ✓ Pre-fault (both circuits in service).
- ✓ A three-phase fault on circuit ***2*** at a location some distance from the sending end.
- ✓ Post-fault (circuit ***2*** out of service).

Figure 1.8 (c) considers the system performance with a fault-clearing time of $\boldsymbol{t_{c1}}$ and represent a stable case. *Figure 1.8 (d)* considers a longer fault-clearing time $\boldsymbol{t_{c2}}$ such that the system is unstable. In both cases ***Pm*** is assumed to be constant.

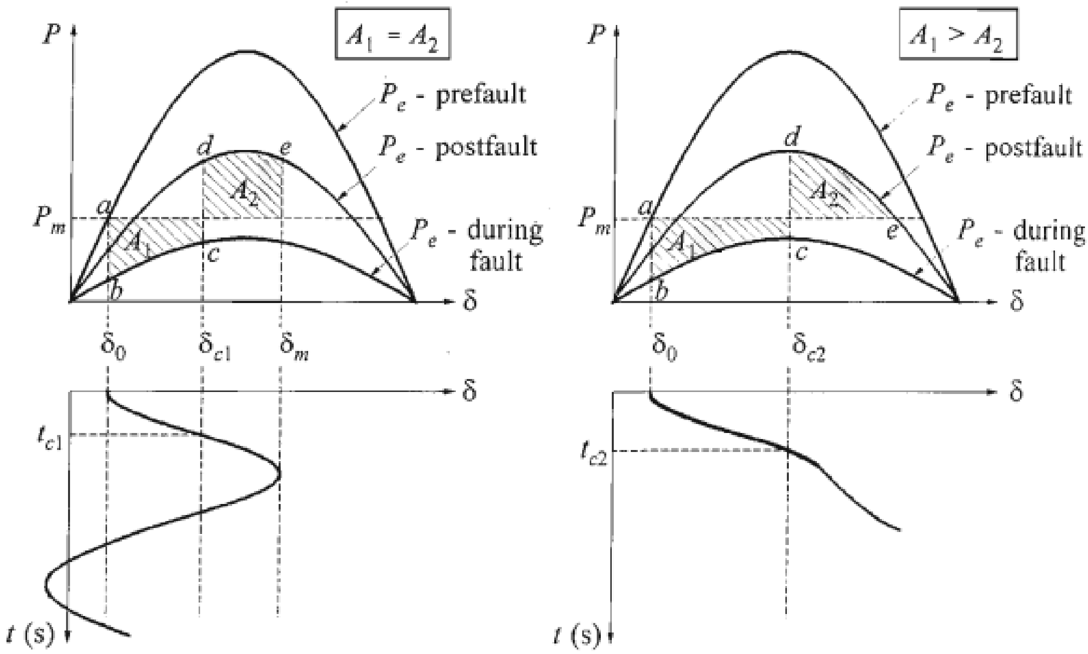
Let us examine the stable case depicted by *Figure 1.8 (c)*. Initially, the system is operating with both circuits in service such that $\boldsymbol{P_e = P_m}$ and $\boldsymbol{\delta = \delta_0}$. When the fault occurs, the operating point suddenly changes from *"a"* to *"b"*. Owing to inertia, angle $\boldsymbol{\delta}$ cannot change instantly. Since $\boldsymbol{P_m}$ is now greater than $\boldsymbol{P_e}$, the rotor accelerates until the operating point reaches c, when the fault is cleared by isolating circuit 2 from the system. The operating point now suddenly shifts to *"d"*. Now, $\boldsymbol{P_e}$ is greater than $\boldsymbol{P_m}$, causing deceleration of the rotor. Since the rotor speed is greater than the synchronous speed $\boldsymbol{\omega_0}$, $\boldsymbol{\delta}$ continues to increase until the kinetic energy gained during the period of acceleration (represented by area $\boldsymbol{A_1}$) is expended by transferring the energy to the system. The operating point moves from *"d"* to *"e"*, such that area $\boldsymbol{A_2}$ is equal to area $\boldsymbol{A_1}$. At point *"e"*, the speed is equal to $\boldsymbol{\omega_0}$ and $\boldsymbol{\delta}$ has reached its maximum value δ_m. Since Pe is still greater than Pm, the rotor continues to retard, with the speed dropping below ω_0. The rotor angle δ decreases, and the operating point retraces the path from e to d and follows the P_e-δ curve for the post-fault system farther down. The minimum value of δ is such that it satisfies the equal-area criterion for the post-fault system. In the absence of any source of damping, the rotor continues to oscillate with constant amplitude.

With a delayed fault clearing, as shown in *Figure 1.8 (d)*, area $\boldsymbol{A_2}$ above $\boldsymbol{P_m}$ is less than $\boldsymbol{A_1}$. When the operating point reaches "*e*", the kinetic energy has not been completely expended; consequently, the speed is still greater than $\boldsymbol{\omega_0}$ and $\boldsymbol{\delta}$ continues to increase. Beyond point ***"e"***, $\boldsymbol{P_e}$ is less than $\boldsymbol{P_m}$, and the rotor begins to accelerate again. The rotor speed and angle continue to increase, leading to loss of synchronism.



(a) Single-line diagram

(b) Equivalent circuit



(c) Response to a fault cleared in tc1 seconds= stable case

(d) Response to a fault cleared in tc2 seconds= unstable case

Figure 1.8 Illustration of transient stability phenomenon

1.5.8 Factors influencing transient stability

From the above discussion, we can conclude that transient stability of the generator is dependent on the following:

- How heavily the generator is loaded.
- The generator output during the fault. This depends on the fault location and type.
- The fault-clearing time.
- The post-fault transmission system reactance.

- The generator reactance. A lower reactance increases peak power and reduces initial rotor angle.
- The generator inertia. The higher the inertia, the slower the rate of change in angle. This reduces the kinetic energy gained during fault.
- The generator internal voltage magnitude (***E'***). This depends on the field excitation.
- -The infinite bus voltage magnitude E_B.

1.6 Power System Control

The function of an electric power system is **[KUN 94]** to convert energy from one of the naturally available forms to the electrical form and to transport it to the points of consumptions. Energy is seldom consumed in the electrical form but is rather converted to other forms such as heat, light, and mechanical energy. The advantage of the electrical form of energy is that it can be transported and controlled with relative ease and with a high degree of efficiency and reliability. A properly designed and operated power system should, therefore, meet the following fundamental requirements:

- The system must be able to meet the continually changing load demand for active and reactive power.

- The system should supply energy at minimum cost and with minimum ecological impact.

- The “quality” of power supply must meet certain minimum standards with regard to the following factors:

- ✓ Constancy of frequency.
- ✓ Constancy of voltage.
- ✓ Level of reliability.

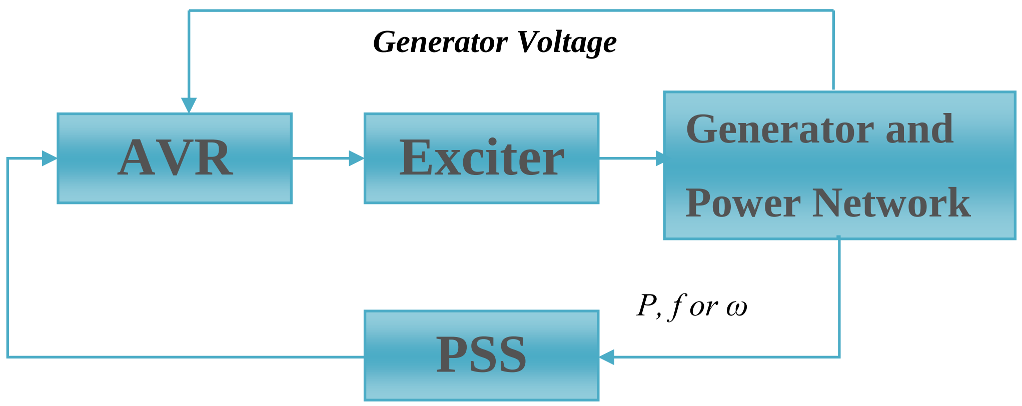


Figure 1.9 the structure diagram of power system control **[Liu 10]**

1.6.1 Synchronous Machine

The Synchronous Machine block operates in generator or motor modes. The operating mode is dictated by the sign of the mechanical power (positive for generator mode, negative for motor mode). The electrical part of the machine is represented by a sixth-order state-space model and the mechanical part is the same as in the Simplified Synchronous Machine block.

When two or more synchronous machines are interconnected, the stator voltages and currents of all the machines must have the same frequency and the rotor mechanical speed of each is synchronized to this frequency. Therefore, the rotors of all interconnected synchronous machines must be in synchronism.

1.6.2 Synchronism

When a number of generators are connected to the same electric grid, they are said to be in synchronism because they operate at the same frequency and the angular differences between the voltage angles of each generator are stable and less than 90 degrees. Units operating in synchronism are magnetically coupled by their connections through the power system. If anyone changes its angle of operation, all the others are affected.

1.6.3 Simplified Synchronous Machine Model Connected To an Infinite Bus

Figure 1.10 shows a simplified model of a synchronous machine, called the classical model that can be used in transient stability studies. As shown, the synchronous machine is represented by a constant internal voltage E' behind its direct axis transient reactance X'_d.

This model is based on the following assumptions:

- ✓ The machine is operating under balanced three-phase positive sequence conditions.
- ✓ Machine excitation is constant.
- ✓ Machine losses, saturation, and saliency are neglected.

In transient stability programs, more detailed models can be used to represent exciters, losses, saturation, and saliency. However, the simplified model reduces model complexity while maintaining reasonable accuracy in stability calculations. The generator in the model is connected to a system consisting of transmission lines, transformers, loads, and other machines. To a first approximation the system can be represented by an ‘‘*infinite bus*’’ behind a system reactance.

Figure 1.10 shows a synchronous generator connected to an infinite bus. The voltage magnitude $\boldsymbol{E_B}$ and $\boldsymbol{0°}$ phase of the infinite bus are constant.

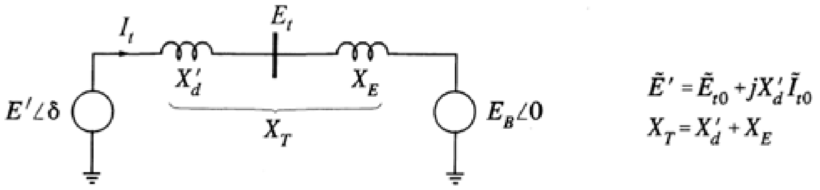


Figure 1.10 Classical model of synchronous generator connected to an infinite bus

The phase angle **δ** of the internal machine voltage is the machine power angle with respect to the infinite bus. The equivalent reactance between the machine internal voltage and the infinite bus is:

$$X_T = (X'_d + X_E) \tag{1.24}$$

The real power delivered by the synchronous generator to the infinite bus is:

$$P_e = \left(\frac{\acute{E}.E_B}{X_T}\right).sin\delta \tag{1.25}$$

During transient disturbances both $\boldsymbol{E'}$ and $\boldsymbol{E_B}$ are considered constant in **(**1.*25***)**. Thus $\boldsymbol{P_e}$ is a sinusoidal function of the machine power angle $\boldsymbol{\delta}$.

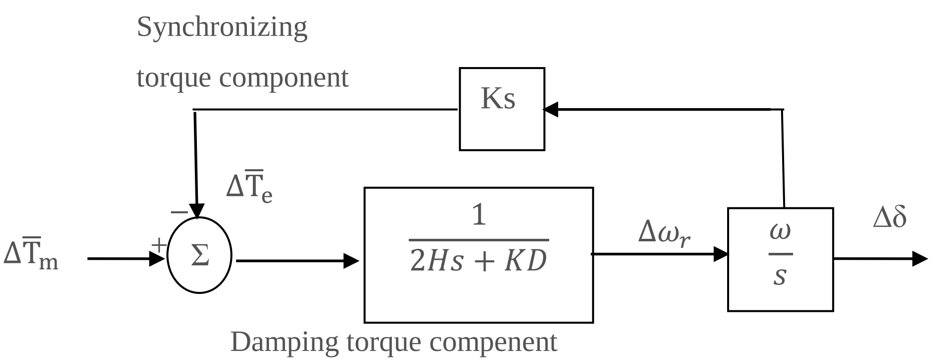


Figure 1.11 Block diagram of a single-machine infinite bus system with classical generator model

K_S = synchronizing torque coefficient in pu torque/rad

K_D = damping torque coefficient in pu torque/pu speed deviation

H = inertia constant in MW.S/MVA

$\Delta\omega_r$ = speed deviation in pu = $(\omega r-\omega_0)/\omega_0$

$\Delta\delta$ = rotor angle deviation in elec.rad

S = Laplace operator.

ω_0 = rated speed in elec.rad/s = $2\pi f_0$

= 377 for a 60 Hz system

1.6.4 Excitation System Model

Excitation system is one of prime importance for the proper operation of synchronous generators. The excitation system can be as simple as a fixed dc power supply connected to the rotor's winding of the synchronous generators. The primary function of a synchronous generator excitation system is to regulate the voltage at the generator output. **The Governor:** A governor, or speed limiter, is a device used to measure and regulate the speed of a machine, such as an engine. A classic example is the centrifugal governor, which uses weights mounted on spring-loaded arms to determine how fast a shaft is spinning, and then uses proportional control to regulate the shaft speed.

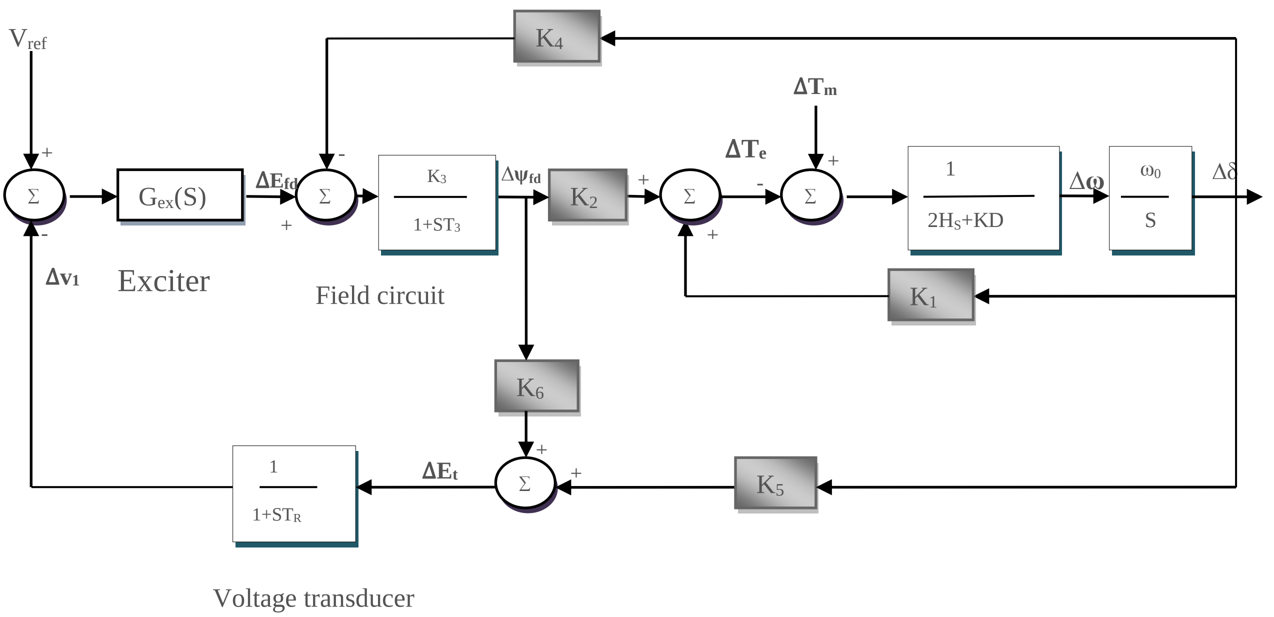


Figure 1.12 Block diagram representation with exciter and AVR **[KUN 94d]**

1.7 Power System Stabilizer

The Generic Power System Stabilizer (PSS) block can be used to add damping to the rotor oscillations of the synchronous machine **[KUN 94]** by controlling its excitation. The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability. The output signal of the PSS is used as an additional input (v_{stab}) to the Excitation System block. The PSS input signal can be either the machine speed deviation, $d\omega$, or its acceleration power, $P_a = P_m - P_e$ (difference between the mechanical power and the electrical power).

The Generic Power System Stabilizer is **[LIU 10]** modeled by the following nonlinear system:

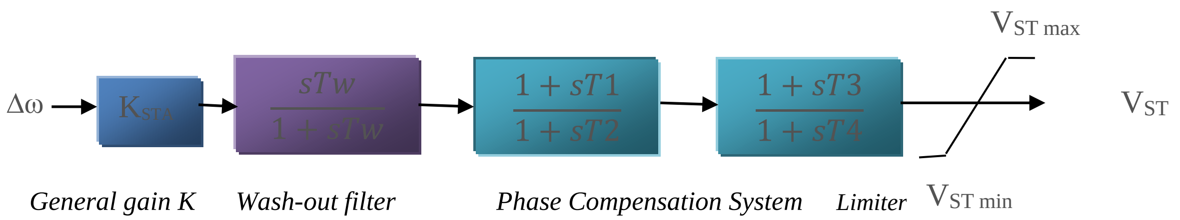


Figure 1.13 General Power System Stabilizer model

To ensure a robust damping, the PSS should provide a moderate phase advance at frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced by the PSS action.

The model consists of a low-pass filter, a general gain, a washout high-pass filter, a phase-compensation system, and an output limiter.

The general gain K determines the amount of damping produced by the stabilizer.

The washout high-pass filter eliminates low frequencies that are present in the $d\omega$ signal and allows the **PSS** to respond only to speed changes.

The phase-compensation system is represented by a cascade of two first-order lead-lag transfer functions used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine.

V_{stab} The output is the stabilization voltage (in *pu*) to connect to the ***Vstab*** input of the Excitation System block used to control the terminal voltage of the synchronous machine.

1.7.1 Operating principle

The basic function of power system stabilizer (PSS) is to add damping to the generator rotor oscillations by controlling its excitation by using auxiliary stabilizing signal(s). Based on the automatic voltage regulator (AVR) and using speed deviation, power deviation or frequency deviation as additional control signals, PSS is designed to introduce an additional torque coaxial with the rotational speed deviation, so that it can increase low-frequency oscillation damping and enhance the stability of power system.

1.7.2 Types of Power System Stabilizer

The type of PSS is distinguished by its detection signal. The simplest and most typical type is the Δp input type unit; however, $\Delta\omega$ and Δf input type units have been introduced to improve the stability of the intra-system oscillation mode. (i.e., long term mode) in view of the large increase in power systems and power re-routing in recent years. Each of the features is outlined below:

A. *Speed-Based ($\Delta\omega$) Stabilizer.*

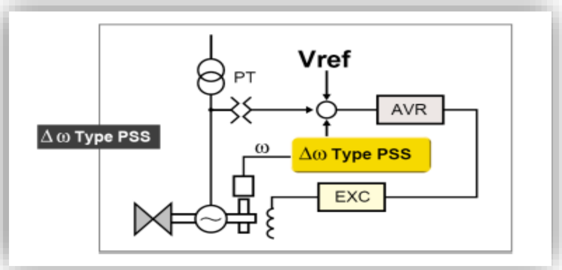


Figure 1.14 PSS type (Δω)

B. *Frequency-Based (Δ_f) Stabilizer.*

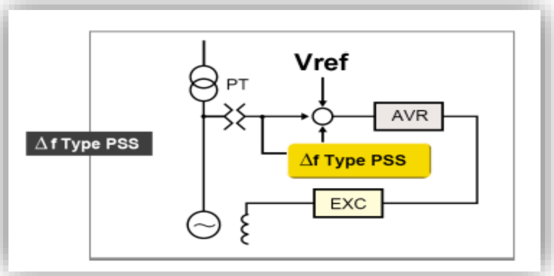


Figure 1.15 PSS type (Δ_f)

C. *Power-Based (Δp) Stabilizer.*

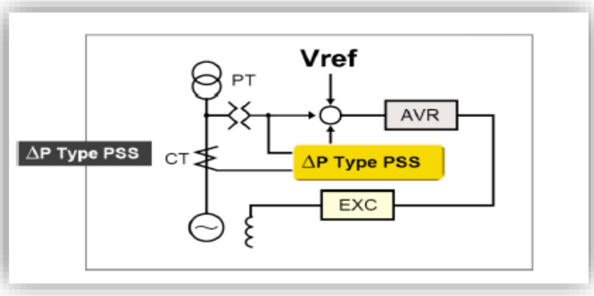


Figure 1.16 *PSS type (ΔP)*

Conclusion

Power system is a complex nonlinear system. It is very hard to establish a complete mathematic model. Although the prediction of power requirement is more accurate than before, the random power oscillation in the power grid still cannot be controlled. As a result, the PSS is the most effective device to prevent these power oscillations in the power grid. In this chapter, we first introduced the basic concepts and definitions of power system stability and its classification, and we focused on the angular stability. We presented also, the power system stabilizer (PSS) which has the ability to enhance the system stability.

Chapter 2

Fuzzy Logic Theory

Introduction

Fuzzy logic has become an important tool for a number of different applications ranging from the control of engineering systems to artificial intelligence.

The entire real world is complex; it is found that the complexity arises from uncertainty in the form of ambiguity. According to Dr. Lotfi Zadeh, Principle of Compatibility, the complexity, and the imprecision are correlated, “the closer one looks at a real world problem, the fuzzier becomes its solution” **[SIV 07].**

In this chapter, we present basic ideas of fuzzy logic, fuzzy sets, fuzzy relations, and fuzzy reasoning, and shows how they may be applied to build a fuzzy logic controller.

2.1 History

Fuzzy logic was introduced in 1965 by Lotfi A.Zadeh in his paper "Fuzzy Sets" **[ZAD 87]**. Zadeh and others continued to develop fuzzy logic at that time. The idea of fuzzy sets and fuzzy logic were not accepted well within academic circles because some of the underlying mathematics had not yet been explored. The applications of fuzzy logic were slow to develop because of this, except in the east. In Japan specifically fuzzy logic was fully accepted and implemented in products simply because fuzzy logic worked, regardless of whether mathematicians agreed or not **[CAL 15].**

- ✓ *1965:* Birth of the first concept of Fuzzy Logic with *Pr. Zadeh Lotfi* (*University of Berkeley California*), He declared that “*an Electro-Mechanic Controller dotted with human reasoning would be much more performing than a classical controller*”, and he introduced the theory of “Fuzzy Sets”.
- ✓ *1973:* Pr. Zadeh published an article in which he mentioned for the first time the ‘linguistic variables’ term (where the value is a word not a number).
- ✓ *1974: Dr. Mamdani* (London University) made an experimental fuzzy controller on a vapor engine.
- ✓ *1980: F.L. Smidth* (Denmark), put into application the Fuzzy Logic theory in the ciment furnace control, it’s the first practical application of this new theory.
- ✓ *In the 1980’s;* numerous applications began to immerge (notably in Japan).
- ✓ *1987:* “explosion of Fuzzy Logic” in Japan (with the Metro of Sendai control), which reached its apogee in 1990.

Today; different varieties of products are labeled “fuzzy products”.

2.2 Concepts and definitions

2.2.1 Definition of fuzzy logic

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth; truth values between "completely true" and "completely false", fuzzy logic is much different from Boolean logic. Fuzzy logic is many-valued logic, which cannot express “true” or “false”, but can express “partially true”. Fuzzy logic value varies from 0 to 1 while the traditional logic 0 or 1. Besides, fuzzy logic also can deal with the linguistic variables, which extremely extended the applications.

2.2.2 Description of Fuzzy Logic

To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalued logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of FL. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalued logical systems **[MAT 15].**

2.2.3 The Need of Fuzzy Logic

Fuzzy logic is **[COX 99]** the way the human brain works, and we can mimic this in machines so they will perform somewhat like humans (not to be confused with Artificial Intelligence, where the goal is for machines to perform exactly like humans).

Fuzzy logic control and analysis systems may be electro-mechanical in nature, or concerned only with data, here a very brief explanation of Fuzzy theory in medical application is presented. A crisp property P can be defined $\mu: x \rightarrow \{0, 1\}$ whereas a fuzzy property can be described by $\mu: x \rightarrow [0, 1]$. $\mu(x)$ indicates the degree to which x has the property. To clarify fuzzy logic in medical science, a simple example of representing a medical concept “high fever” as a fuzzy set is illustrated below **[PHU 01]**:

For example: in case of fever, the linguistic variable is high fever. If the body temperature(x) is greater than 39 degree Centigrade then in medical concept μ(x) for high fever is 1 it means x has surely 'High Fever'. If x is less than 38.5 degree centigrade then μ(x) of medical concept ' High Fever' is 0, which means x surely does not have 'High Fever'. If x is in the interval [38.5 degree Centigrade, 39 degree Centigrade] then x has a property of high fever with some degree (i.e., membership function) between [0, 1].

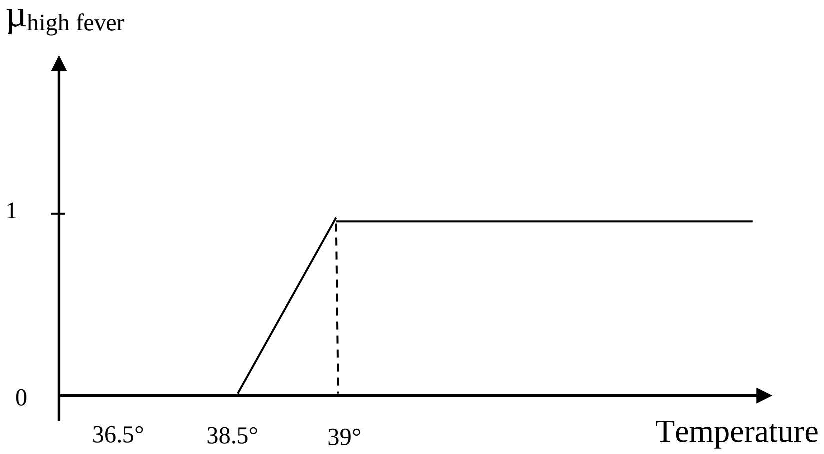


Figure 2.1. Representing a medical concept “High Fever”

A fever - also known as a high fever or a high temperature - is not by itself an illness. Fever is generally not considered dangerous, it's usually a symptom of an underlying condition, most often an infection, but if we use the Boolean logic, the patient fever could be 38.9 and the diagnostic will tell us that he got no fever, so, extreme temperature elevation then becomes a medical emergency requiring immediate treatment to prevent disability or *death.*

2.2.4 Fuzzy Logic Relevance

Here is a list of general observations about fuzzy logic:

✓ Fuzzy logic is conceptually easy to understand.

The mathematical concepts behind fuzzy reasoning are very simple. Fuzzy logic is a more intuitive approach without the far-reaching complexity.

✓ Fuzzy Logic is flexible.

.

With any given system, it is easy to layer on more functionality without starting again from scratch.

- ✓ Fuzzy logic is tolerant of imprecise data.

Everything is imprecise if you look closely enough, but more than that, most things are imprecise even on careful inspection. Fuzzy reasoning builds this understanding into the process rather than tacking it onto the end.

- ✓ Fuzzy logic can model nonlinear functions of arbitrary complexity.

You can create a fuzzy system to match any set of input-output data. This process is made particularly easy by adaptive techniques like Adaptive Neuro-Fuzzy Inference Systems (ANFIS), which are available in Fuzzy Logic Toolbox software.

- ✓ Fuzzy logic can be built on top of the experience of experts.

In direct contrast to neural networks, which take training data and generate opaque, impenetrable models, fuzzy logic lets you rely on the experience of people who already understand your system.

- ✓ Fuzzy logic can be blended with conventional control techniques.

Fuzzy systems don't necessarily replace conventional control methods. In many cases fuzzy systems augment them and simplify their implementation.

- ✓ Fuzzy logic is based on natural language.

The basis for fuzzy logic is the basis for human communication. This observation underpins many of the other statements about fuzzy logic. Because fuzzy logic is built on the structures of qualitative description used in everyday language, fuzzy logic is easy to use.

The last statement is perhaps the most important one. Natural language, which is used by ordinary people on a daily basis, has been shaped by thousands of years of human history to be convenient and efficient. Sentences written in ordinary language represent a triumph of efficient communication **[MAT 15]**.

2.2.5 The Fuzzy Logic Concept

The way that people think is inherently fuzzy **[CAL 15].** The way that we perceive the world is continually changing and cannot always be defined in true or false statements. Take for example the set of all the apples and all the apple cores in the world. Now take one of those apples; it belongs to the set of all apples. Now take a bite out of that apple; it is still an apple, right? If so, it still belongs to the set of apples. After several more bites have been taken and you are left with an apple core and it belongs to the set of apple cores. At what point did the apple cross over from being an apple to being an apple core? What if you could get one more bite out of that apple core, does that move it into a different set?

The definition of the apple and apple core sets are too strictly defined when looking at the process of eating an apple. The area between the two sets is not clearly defined since the object cannot belong to the set of apples and apple cores because, by definition, an apple core is NOT an apple. The sets defining apples and apple cores need to be redefined as fuzzy sets.

2.3 Fuzzy set

A *fuzzy set* is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership.

If the value of 1 is assigned to objects entirely within the set and a 0 is assigned to objects outside of the set **[CAL 15]**, then any object partially in the set will have a value between 0 and 1. The number assigned to the object is called its degree of membership in the set. So an apple with one bite out of it may have a degree of membership of 0.9 in the set of apples. This does not mean that it has to have a degree of membership of 0.1 in the set of apple cores though. However as the apple is eaten it loses its membership in the fuzzy set of apples and gains membership in the fuzzy set of apple cores.

As another example of fuzzy sets **[MAT 15]**, consider the question of seasons. What season is it right now? In the northern hemisphere, summer officially begins at the exact moment in the earth's orbit when the North Pole is pointed most directly toward the sun. It occurs exactly once a year, in late June. Using the astronomical definitions for the season, you get sharp boundaries as shown on the left in the figure that follows. But what you experience as the seasons vary more or less continuously as shown on the right in the following figure (in temperate northern hemisphere climates).

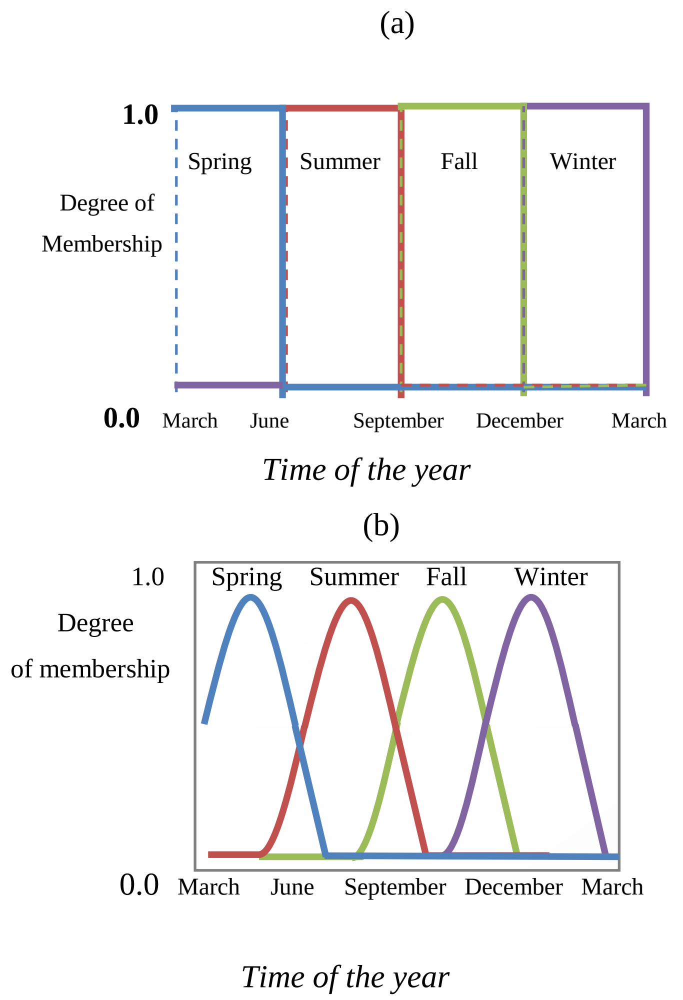


Figure 2.2. Description of temperate climates by fuzzy sets

2.4 Crisp (classical) versus fuzzy sets

Boolean logic includes two kinds of set relations. One, often represented using Venn Diagrams, involves crisp sets of binary variables. X & Y ("X and Y") thus refers to the intersection of sets X and Y. The second kind is fuzzy set relations. Here, the sets X and Y have fuzzy boundaries, or in other words the degree of membership in X is an ordinal index, not a binary variable.

Crisp set requires a deep understanding of a system, exact equation, and precise numeric value, fuzzy logic represents and alternative way of thinking, which allows modeling complex system using a higher level of abstraction originating from our knowledge and experience. Fuzzy logic allows expressing this knowledge with subjective concepts such as very hot, bright red, and a long time which are mapped into exact numeric ranges **[COX 99].**

The differences between crisp and fuzzy may be easily understood by *figure2.3*

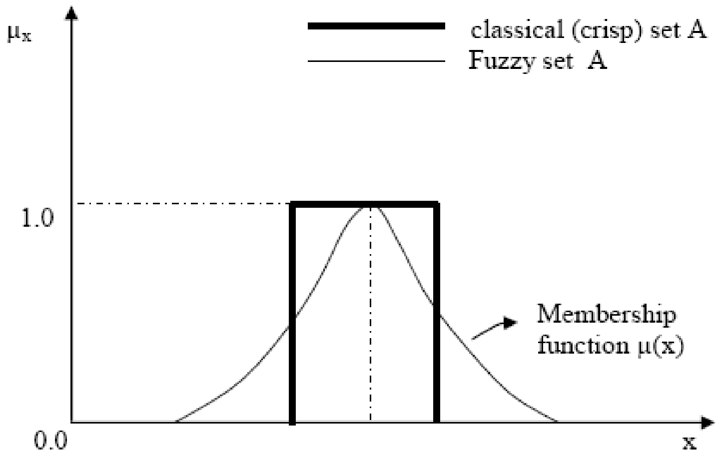


Figure 2.3. Shapes of crisp and fuzzy

2.5 Membership Functions

A *membership function* (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the *universe of discourse*, a fancy name for a simple concept **[MAT 15]**. The membership function is **[COX 99]** a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response.

The fuzzy membership function for the fuzzy linguistic term "cool" relating to temperature may turn out to be as illustrated in the figure bellow:

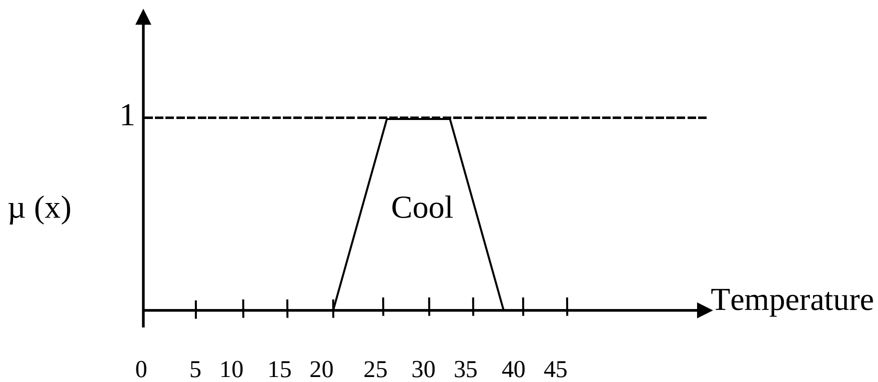


Figure 2.4. Continuous membership functions for "cool".

A membership function can also be given mathematically as: $\mu A(x) = 1/(1+x)^2$

The graph is as shown in *figure 2.5*.

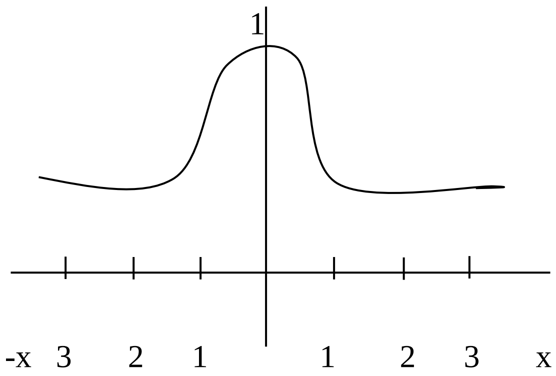
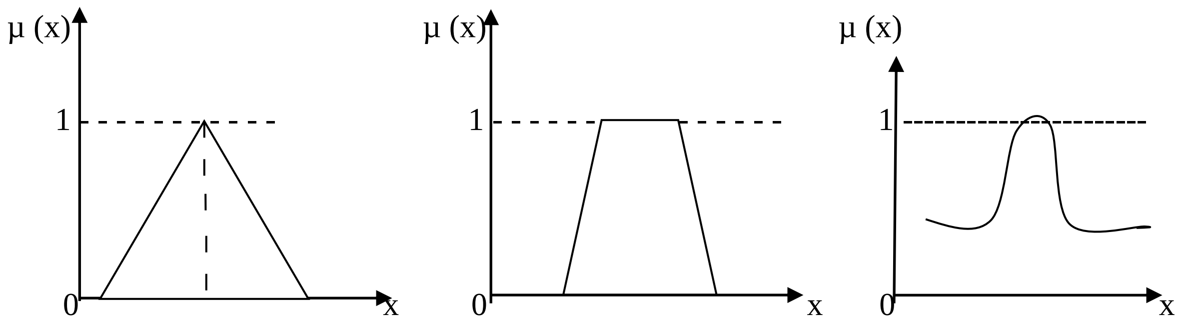


Figure 2.5. Continuous membership function dictated by a mathematical function

Different shapes of membership functions exist. The commonly used shape to describe the membership function is triangular, trapezoidal and Gaussian can also be used as shown in *figure 2.6* with their variation.



a) Triangular M_function b) *Trapezoidal* M_function c) Gaussian M_function

Figure 2.6. Different shapes of membership functions

Human beings make decisions based on rules. Although, we may not be aware of it, but whatever decisions are made are all based on computer like if-then statements. Rules associate ideas and relate one event to another.

Fuzzy machines, which always tend to mimic the behavior of man, also work in the same way. However, the decision and the means of choosing that decision are replaced by fuzzy sets and the rules are replaced by fuzzy rules. Fuzzy rules also operate using a series of if-then statements. For instance, if X is positive then A, and if Y is negative then B, where A & B are all sets of X and Y. fuzzy rules define fuzzy patches, which is the key idea in fuzzy logic **[COX 99].**

2.6 Linguistic Variables

A variable whose values are **[ZAD 75]** words or sentences in natural language. As an example: Temperature is linguistic variable if it takes values hot, cool warm; speed is also a linguistic variable it can take values such us fast, slow … etc.

- x denotes the symbolic name of linguistic variable, μ_x is a fuzzy function that maps linguistic terms of variables to the equivalent crisp values.

2.7 Fuzzy Engineering

There is more to fuzzy logic than some interesting math **[CAL 15]**; it has some impressive applications in engineering. The main application of fuzzy logic in engineering is in the area of control systems. The definition of a control system, given by Richard Dorf in *Modern Control Systems* **[DOR 80]** is: "An interconnection of components forming a system configuration that will provide a desired response." This means that a control system needs to know the desired response (input) and it needs to process this input and attempt to achieve it. The general control system can then be summarized with the following diagram **[CAL 15]**:

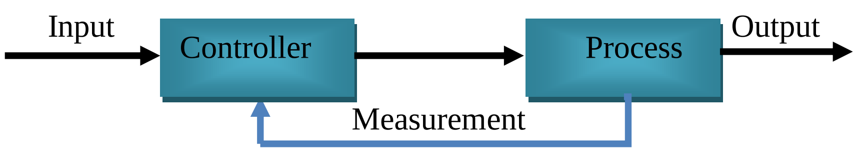


Figure 2.7. Diagram of general control system

The process is the system that is being controlled and cannot typically be changed. The controller then must take the input and also take measurements from the process and use this information to generate the appropriate input to the process. A basic example of a controller would be a summing point that will provide the difference between input and output to the process, whereas a more advanced controller would be a PID controller *(Proportional, Integral and Derivative controller)*. A fuzzy logic based controller will use fuzzy membership functions and inference rules to determine the appropriate process input. Designing a fuzzy controller is a more intuitive approach to controller design since it uses a comprehensible linguistic rule base.

A fuzzy controller can be divided into three main processes. The first of these is the fuzzification; this uses defined membership functions to process the inputs and to fuzzify them. These fuzzified inputs are then used in the second part, the rule-based inference system. This system uses previously defined linguistic rules to generate a fuzzy response. The fuzzy response is then defuzzified in the final process: defuzzification. This process will provide a real number as an output.

2.8 Fuzzy Logic Controller

Almost any control system can be replaced with a fuzzy logic based control system **[CAL 15]**. This may be overkill in many places however it simplifies the design of many more complicated cases. So fuzzy logic is not the answer to everything, it must be used when appropriate to provide better control. If a simple closed loop or PID controller works fine then there is no need for a fuzzy controller. There are many cases when tuning a PID controller or designing a control system for a complicated system is overwhelming, this is where fuzzy logic gets its chance to shine.

Fuzzy control, which directly uses fuzzy rules, is the most important application in fuzzy theory. Using a procedure originated by *Ibrahim Mamdani* in the late 70’s, three steps are taken to create a fuzzy controlled machine:

- ✓ Fuzzification (using membership functions to graphically describe a situation)
- ✓ Rule evaluation (Application of fuzzy rules)
- ✓ Defuzzification (obtaining the crisp or actual results)

The structure of fuzzy control system is **[GER 05]** shown in *Figure 2.8*. Therefore, the basic steps of designing a fuzzy controller are as below:

- ✓ Define the inputs and outputs variables.
- ✓ Choose the fuzzification method.
- ✓ Define the linguistic variable database.
- ✓ Design the control rules database.
- ✓ Design the fuzzy inference mechanism.

✓ Choose the defuzzification method.

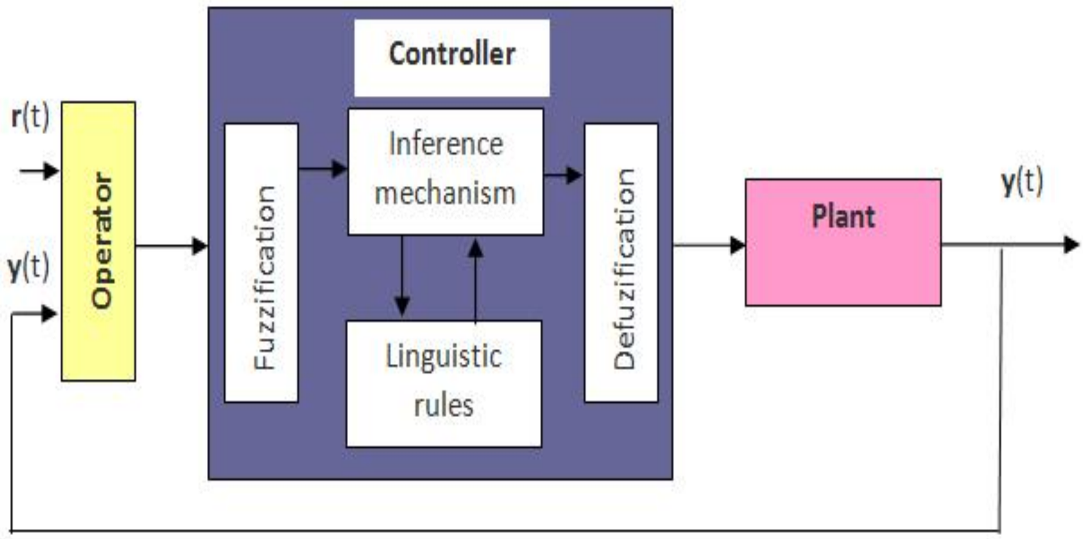


Figure 2.8. Structure of fuzzy control system.

Fuzzy control systems are **[TOU 10]** rule-based systems in which a set of so-called fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimulus. 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.

Figure 2.9 illustrates the basic configuration of a fuzzy logic controller which consists of a fuzzification interface, a knowledge base (consists of data base & rule base), a decision making logic, and a defuzzification interface block applies control signal **[TOU 10]**.

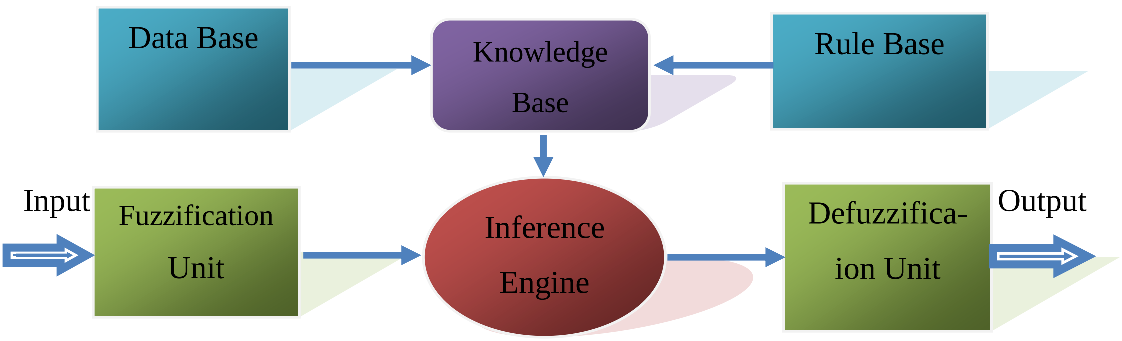


Figure 2.9. Model of fuzzy controller and its blocks

The fuzzy knowledge-based controller is one part of FLC which is composed of three main parts: fuzzification, inference engine and defuzzification.

2.8.1 Fuzzification

Fuzzification is an important concept in the fuzzy logic theory. Fuzzification is the process where the crisp quantities are converted to fuzzy (crisp to fuzzy). By identifying some of the uncertainties present in the crisp values, we form the fuzzy values. The conversion of fuzzy values is represented by the membership functions.

In any practical applications, in industries, etc., measurement of voltage, current, temperature, etc., there might be a negligible error. This causes imprecision in the data. This imprecision can be represented by the membership functions. Hence fuzzification is performed.

Thus fuzzification process may involve assigning membership values for the given crisp quantities.

2.8.2 Creating Fuzzy Rules

Fuzzy rules are a collection of linguistic statements that describe how the FIS should make a decision regarding classifying an input or controlling an output. Fuzzy rules are always written in the following form:

if *(input 1 is membership function 1)* ***and/or*** *(input 2 is membership function 2)* ***and/or*** . . . ***then*** *(output is output membership function)*. For example:

if *temperature is high* ***and*** *humidity is high* ***then*** *room is hot.*

There would have to be membership functions that define high temperature *(input 1)*, high humidity *(input 2)*, and a hot room *(output 1)*. This process of taking an input such as temperature and processing it through a membership function to determine "high" temperature is called fuzzification. Also, "AND"/"OR" in the fuzzy rule should be defined. This is called fuzzy combination.

2.8.3 Defuzzification

Defuzzification means the fuzzy to crisp conversions. The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using defuzzification process. The defuzzification has the capability to reduce a fuzzy to a crisp single-valued quantity or as a set, or converting to the form in which fuzzy quantity is present. Defuzzification can also be called as "rounding off" method. Defuzzification reduces the collection of membership function values in to a single sealer quantity.

As an example: Consider the air conditioner in *Figure 2.10* Let temperature (t) is the linguistic variable which represents the temperature of a room. To qualify the temperature, terms such as \hot" and \cold" are used in real life. These are the linguistic values of the temperature. Then, T (t) = {too-cold, cold, warm, hot, too-hot} can be the set of decompositions for the linguistic variable temperature.

Each member of this decomposition is called a linguistic term and can cover a portion of the overall values of the temperature **[MEN 95]**.

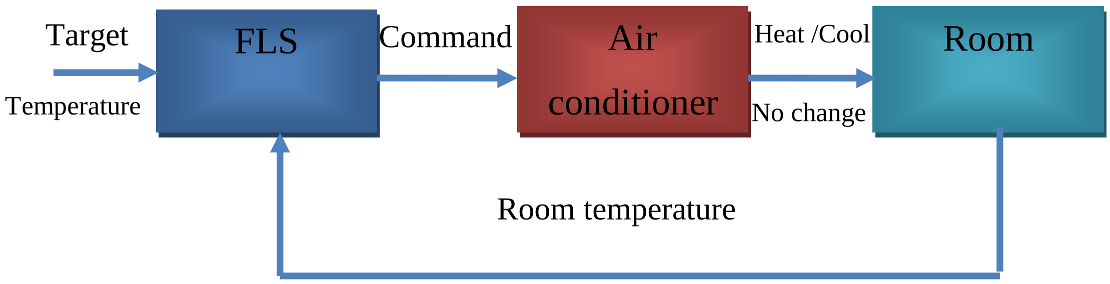


Figure 2.10. A simple FLS to control an air conditioner

For instance, in *Figure 2.11*, membership functions for the linguistic terms of temperature variable are plotted. Note that, an important characteristic of fuzzy logic is that a numerical value does not have to be fuzzied using only one membership function. In other words, a value can belong to multiple sets at the same time.

According to *Figure 2.11*, a temperature value can be considered as "cold" and "too-cold" at the same time, with different degree of memberships.

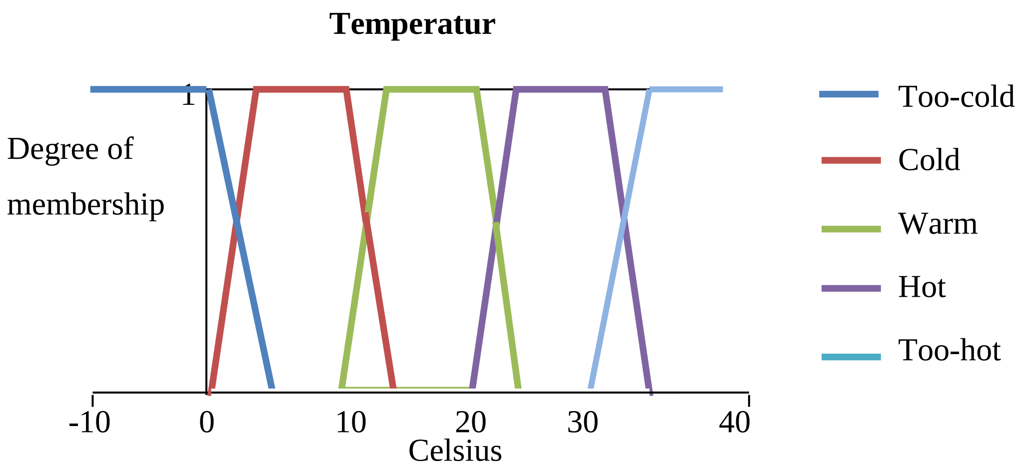


Figure 2.11. Membership function for T (t) = {too-cold, cold, warm, hot, too-hot}

Row captions in the matrix contain the values that current room temperature can take, column captions contain the values for target temperature, and each cell is the resulting command when the input variables take the values in that row and column. For instance, the cell (3, 4) in the matrix can be read as follows: If temperature is cold and target is warm then command is heat.

Table 2.1. Sample fuzzy rules for air conditioner system

	Fuzzy Rules
1.	IF (temperature is *cold* OR *too-cold*) AND (target is *warm*) THEN command is *heat*
2.	IF (temperature is *hot* OR *too-hot*) AND (target is *warm*) THEN command is *cool*
3.	IF (temperature is *warm*) AND (target is *warm*) THEN command is *no-change*

Table 2.2. Fuzzy matrix example

Temperature/Target	**Too-cold**	**Cold**	**Warm**	**Hot**	**Too-hot**
Too-cold	No-change	Heat	Heat	Heat	Heat
Cold	Cool	No-charge	Heat	Heat	Heat
Warm	Cool	Cool	No-change	Heat	Heat
Hot	Cool	Cool	Cool	No-change	Heat
Too-hot	Cool	Cool	Cool	Cool	No-change

2.9 Fuzzy Logic Applications

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation and decision-support systems.

There are other several applications like:

- ✓ The automatism (ABS brakes, conduct of process).
- ✓ Robotics (forms of recognition).
- ✓ The management of road traffic (Red lights).
- ✓ Air traffic control (traffic aerial management).
- ✓ The environment (meteorology, climatology).
- ✓ Medicine (help for diagnostic).

As a final example of fuzzy logic, it can be used in areas other than simply control. Fuzzy logic can be used in any decision making process such as signal processing or data analysis. An example of this is a fuzzy logic system that analyzes a power system and diagnoses any harmonic disturbance issues. The system analyzes the fundamental voltage, as well as third, fifth and seventh harmonics as well as the temperature to determine if there is cause for concern in the operation of the system **[CAL 15].**

Conclusion

In this chapter, we have defined the theory of fuzzy logic and its concept, we illustrated some examples to show the relevance of this theory and to compare it with the classic (Boolean) logic. The fuzzy control is a very powerful theory which provides conclusions and generate responses from vague, incomplete and inaccurate information, where the model of the system is unknown or difficult to formulate.

Chapter 3

Comparative Study

Introduction

This chapter presents the effect of the presence of power system stabilizer with an adaptive PID fuzzy controller on transient stability for different operating conditions of the power system. Various simulations have been performed for multi-machine power system. We will use to types of stabilizers; to enhance the stability, the first PSS will be the conventional one, after that we will use a PSS based on a Fuzzy Logic Controller. After presenting the simulation results for each type; we will compare between them to obtain conclusions.

3.1. Fuzzy Logic Toolbox:

Fuzzy Logic Toolbox™ provides MATLAB® functions, apps, and a Simulink® block for analyzing, designing, and simulating systems based on fuzzy logic. The product guides you through the steps of designing fuzzy inference systems. Functions are provided for many common methods, including fuzzy clustering and adaptive neurofuzzy learning.

The toolbox lets you model complex system behaviors using simple logic rules, and then implement these rules in a fuzzy inference system. You can use it as a stand-alone fuzzy inference engine. Alternatively, you can use fuzzy inference blocks in Simulink and simulate the fuzzy systems within a comprehensive model of the entire dynamic system.

3.1..1. Description Fuzzy Logic Toolbox

Fuzzy Logic Toolbox software is a collection of functions built on the MATLAB technical computing environment. It provides tools for to create and edit fuzzy inference systems within the framework of MATLAB. It can also integrate the fuzzy systems into simulations with Simulink software. This toolbox relies heavily on graphical user interface (GUI) tools to help user accomplish his work, although the user can work entirely from the command line if he prefers. The toolbox provides three categories of tools:

- ✓ Command line functions.
- ✓ Graphical interactive tools.
- ✓ Simulink blocks and examples.

The first category of tools is made up of functions that we can call from the command line or from our own applications. Many of these functions are MATLAB M-files, series of

MATLAB statements that implement specialized fuzzy logic algorithms. We can view the MATLAB code for these functions using the statement *type function_name*

Secondly, the toolbox provides a number of interactive tools that let us access many of the functions through a GUI. Together, the GUI-based tools provide an environment for fuzzy inference system design, analysis, and implementation.

The third category of tools is a set of blocks for use with Simulink. These are specifically designed for high speed fuzzy logic inference in the Simulink environment **[Mat 15]**.

3.1..2. The Fuzzy Logic Designer

The Fuzzy Logic Designer opens and displays a diagram of the fuzzy inference system (FIS) with the names of each input variable on the left, and those of each output variable on the right, as shown in the next figure.

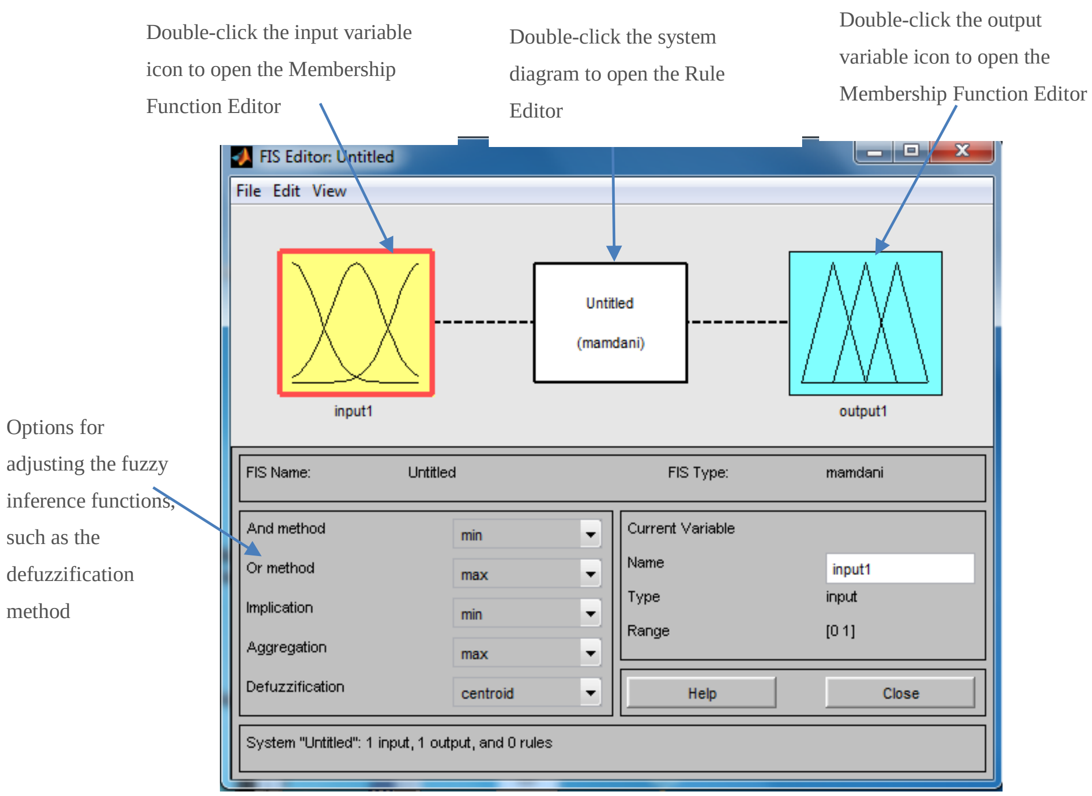


Figure 3.1 fuzzy logic designer window

3.1..3. The Membership Function Editor

The Membership Function Editor is the tool that lets you display and edit all of the membership functions associated with all of the input and output variables for the entire fuzzy inference system. The Membership Function Editor shares some features with the Fuzzy Logic Designer, as shown in the next figure:

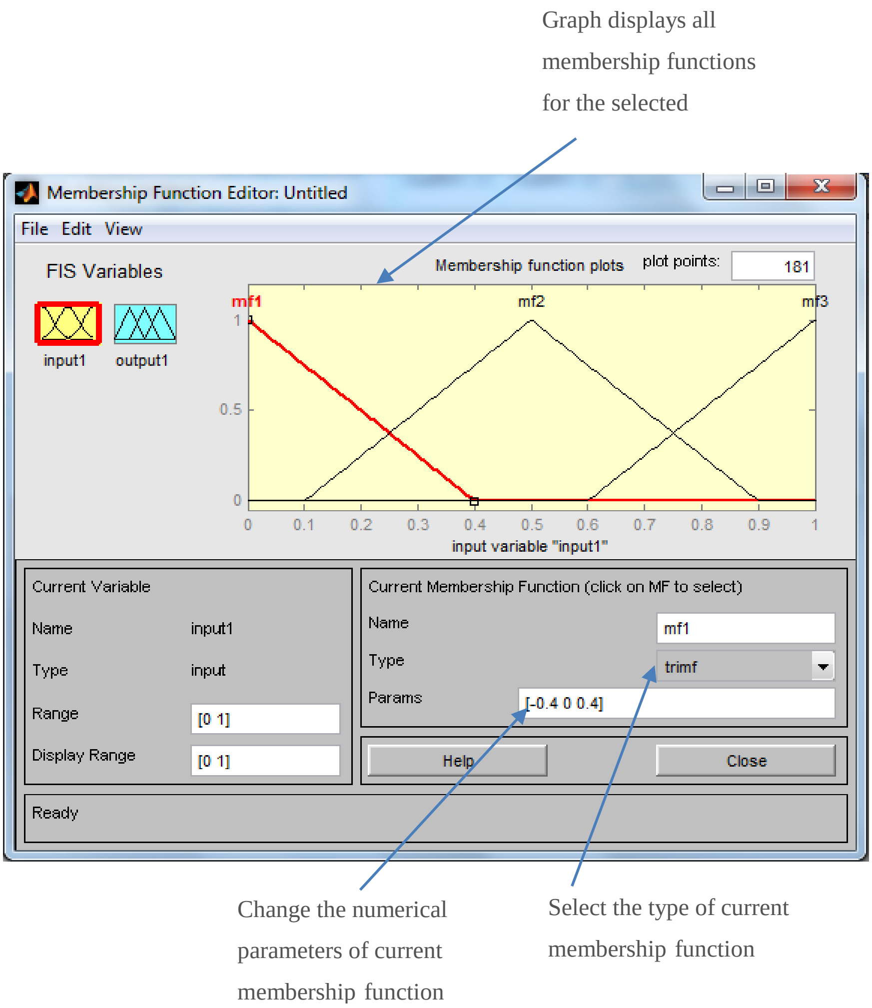


Figure 3.2 Membership Editor Window

3.1..4. The Rule Editor

Constructing rules using the graphical Rule Editor interface is fairly self-evident. Based on the descriptions of the input and output variables defined with the Fuzzy Logic Designer, the Rule Editor allows you to construct the rule statements automatically.

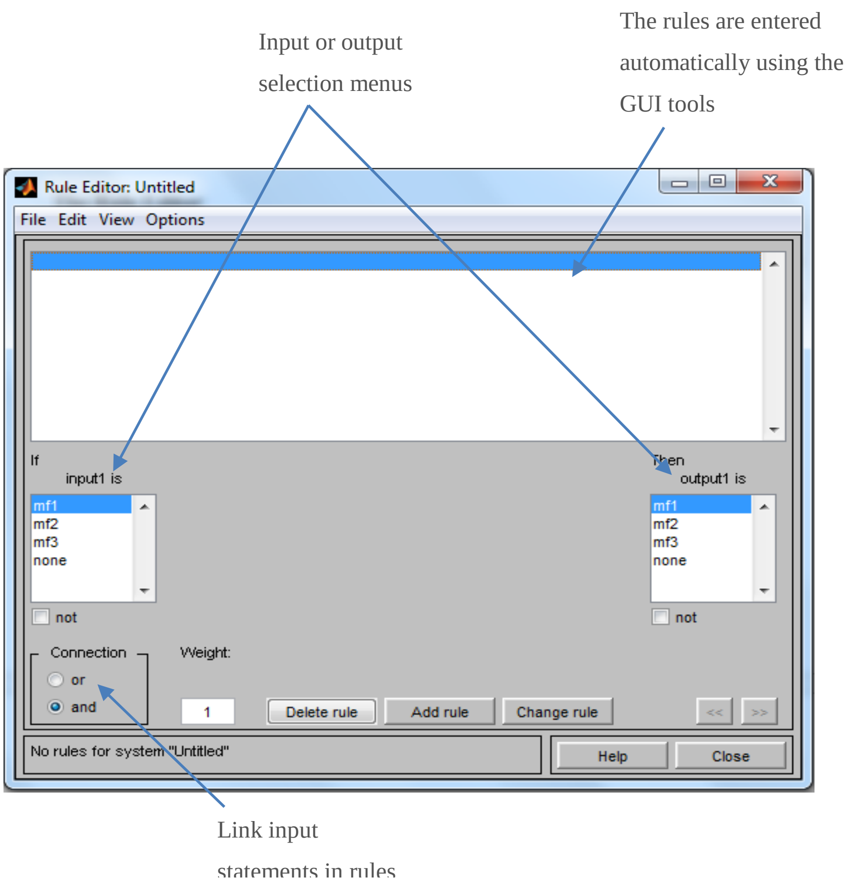


Figure 3.3 Rule Editor Window

3.1..5. The Rule Viewer

The Rule Viewer displays a roadmap of the whole fuzzy inference process.

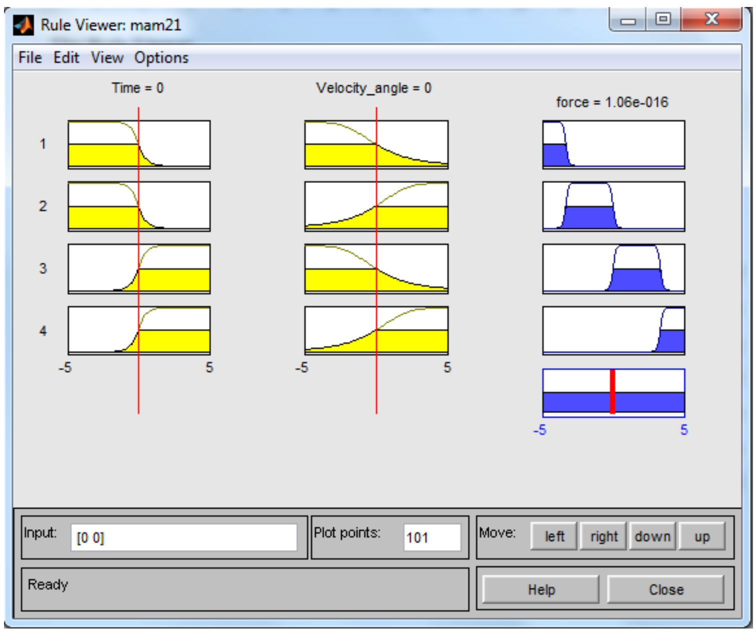


Figure 3.4 Rule Viewer Window

3.1..6. The Surface Viewer

Upon opening the Surface Viewer, you see a three-dimensional curve

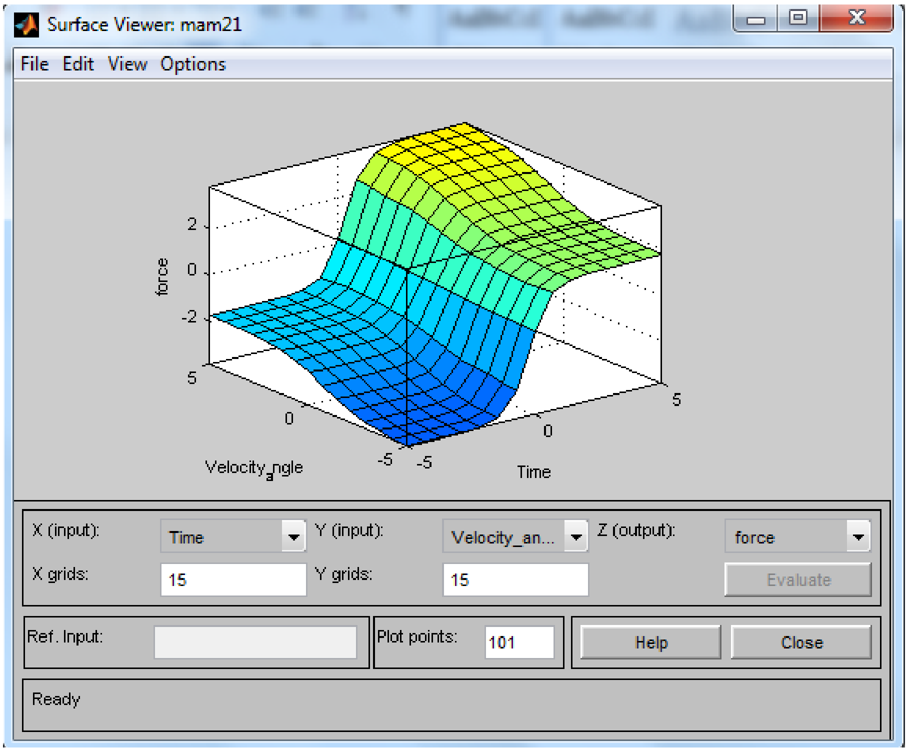


Figure 3.5 Surface Viewer Window

3.1..7. Fuzzy Simulink Controller

To build a Simulink systems that use fuzzy logic, use the blocks in the Fuzzy Logic Toolbox library.

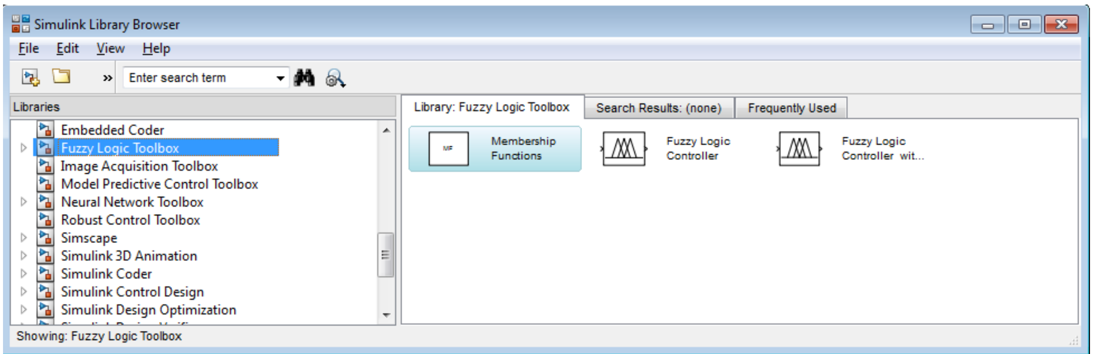


Figure 3.6 Simulink library (fuzzy logic toolbox)

The Fuzzy Logic Toolbox library contains the Fuzzy Logic Controller and Fuzzy Logic Controller with Rule Viewer blocks. It also includes a Membership Functions sub-library that contains Simulink blocks for the built-in membership functions.

3.2.Causes and types of power oscillations

Network faults or network operation close to the stability limits cause active power oscillations between generators and the network. These electromechanical oscillations of the rotor can be reduced by controlled influence of the excitation current. Usually a distinction is made between:

• Local oscillations between a generator and other generators in a power station. Typical oscillation frequency: 0.8 to 2.0 Hz

• Oscillations between neighboring power stations, typical oscillation frequency: 1.0 to 2.0 Hz

• Oscillations between network areas, each comprising several generators. Typical oscillation frequency: 0.2 to 0.8 Hz

• Global oscillations, characterized by collective in phase oscillations of all generators within a network area. Typical oscillation frequency: below 0.2 Hz.

The purpose of the power system stabilizer (PSS) is to measure these power oscillations and derive from these a signal, which influences the set point of the voltage regulator.

Case study:

The test system consists of two synchronous machines linked together by two 500 kV lines of 350 km length. The synchronous machines have identical parameters. The system is connected to a load (5000 MW) through two step-up transformers and two transmission lines, the characteristics of these components are as below:

Machine 1 (M1): nominal power=1000 MVA.

Machine 2 (M2): nominal power=5000 MVA.

Transformer 1: nominal power =1000 MVA.

Transformer 2: nominal power =5000 MVA.

Voltage of windings for the two transformers:

Winding 1=13.8 KV, winding 2=500 KV

Transmission lines:

L1= 350 KM;   L2= 350 KM.

The load (5000 MW) is connected to bus3.

The other parameters of the system are given in the appendix.

Three-Phase to Ground Fault

We have programed a three-phase short-circuit fault (3ph-Short-cicuit) at 1.

Simulation Parameters:

Simulation time: 10 seconds.

Solver: ode3 (Bogacki-Shampine), (ordinary differential equations).

Solver type: fixed-step.

Fixed-step size (fundamental sample time): 0.0001s.

Test system:

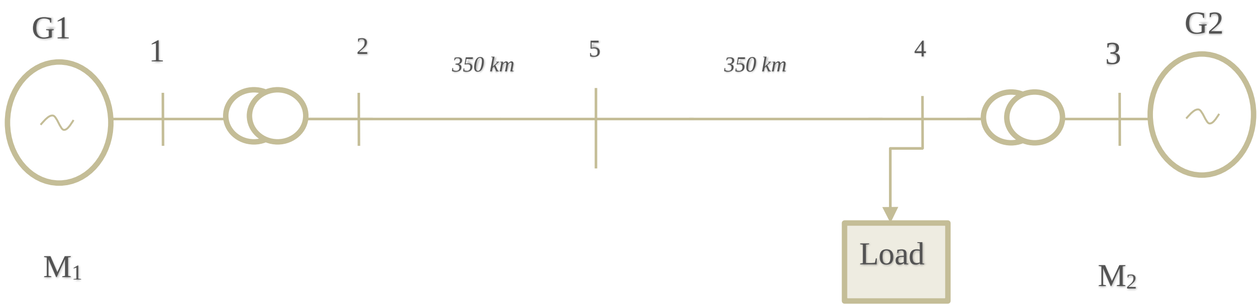


Figure 3.7 single-line representation of the test system

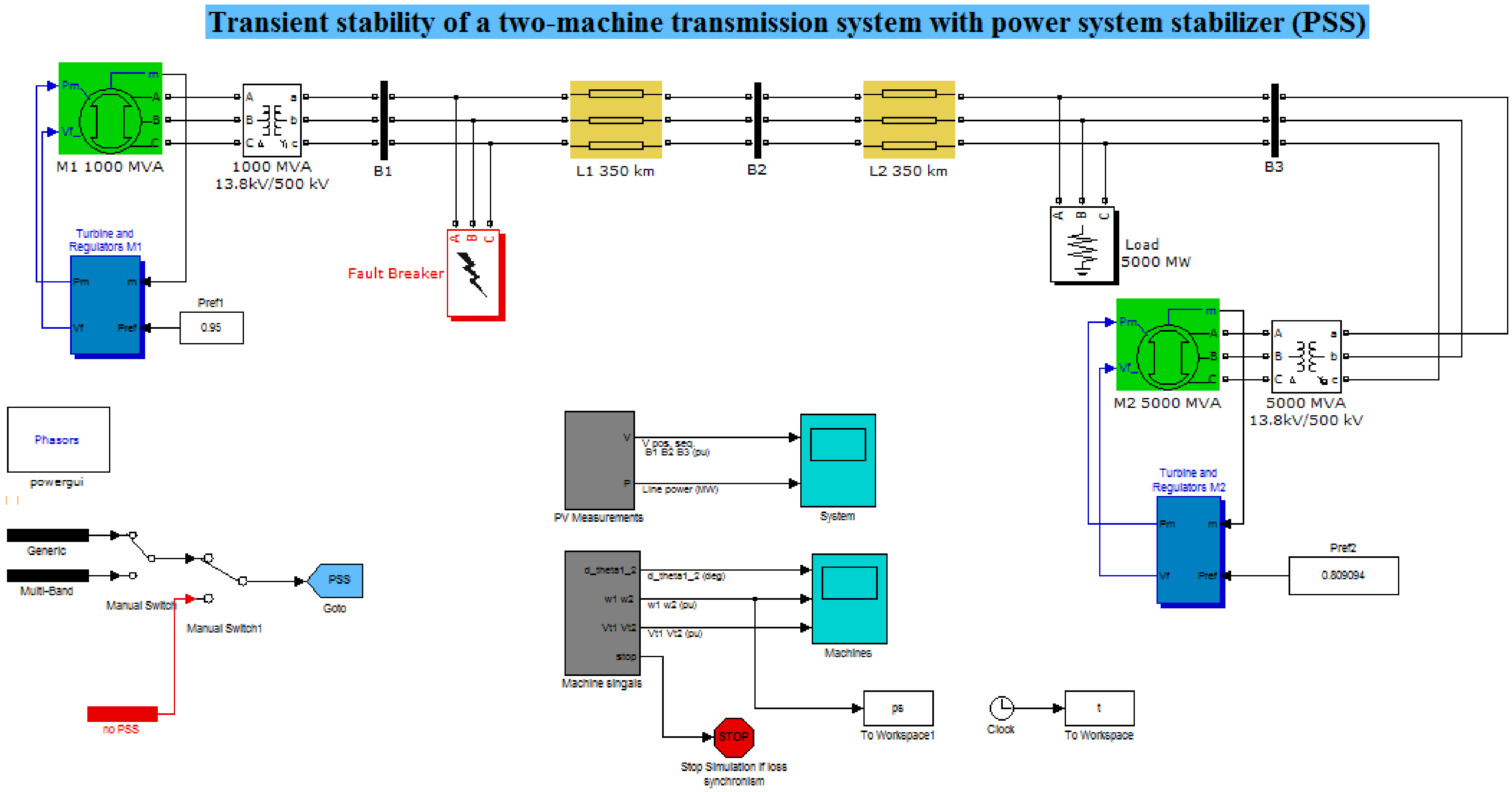


Figure 3.8 Model of transient stability of a Two-Machine system with PSS (Matlab “Simulink”)

The system is simulated using MATLAB (7.9.0)/Simulink toolbox. The models of the synchronous machine, PSS and the excitation system are linked together to form the overall system representation. A number of studies involving variety of tests at different system and operating conditions have been conducted to evaluate the efficacy of the proposed stabilizer. All results are compared with the performance of a conventional PSS. For now onwards, the conventional PSS has been referred to as CPSS and proposed Fuzzy based PSS as FLPSS.

3.3.Running simulation without PSS:

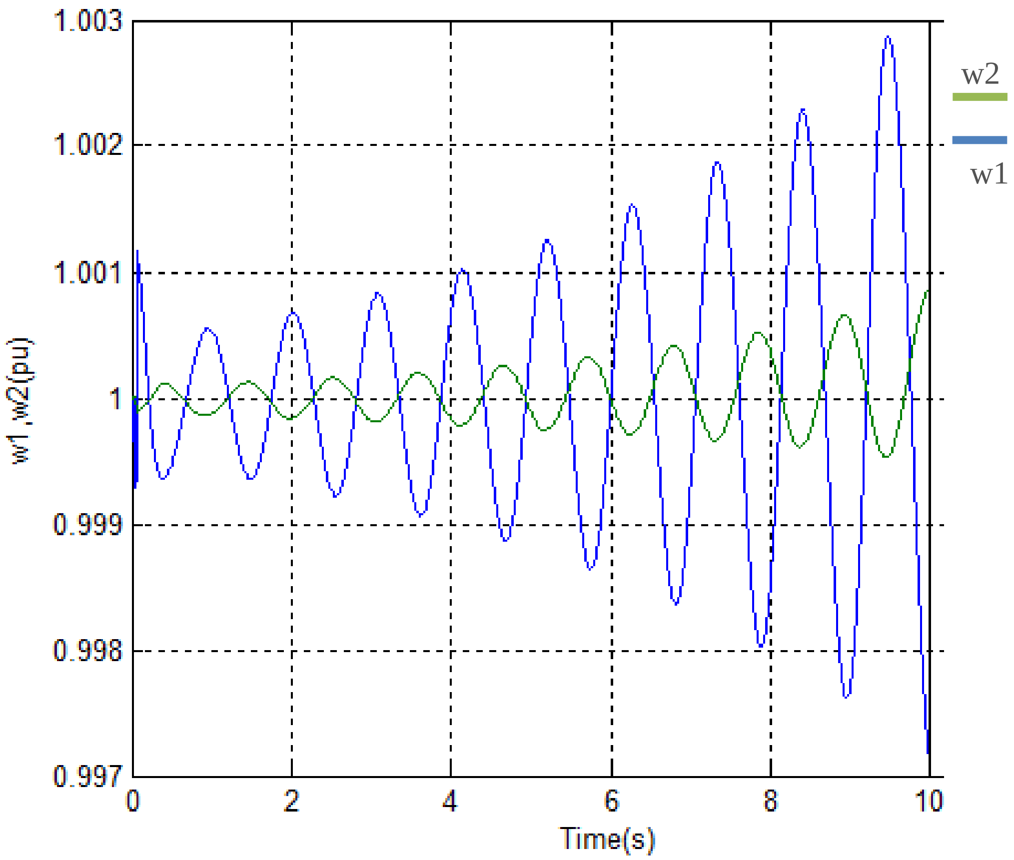


Figure 3.9 Variation of the angular velocity (without PSS)

The change in speed of the generators which follows this disturbance is shown in *Figure 3.9*. Thus, it is clear that the system is unstable and badly depreciated. The system behavior to disturbances clearly shows the instability of the system. The amplitude of first oscillation (M1) is higher than the second one (M2), because the fault is closer to the first generator.

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3.4.Running simulation with PSS:

We use PSS to restore the stability of the system and improve its damping.

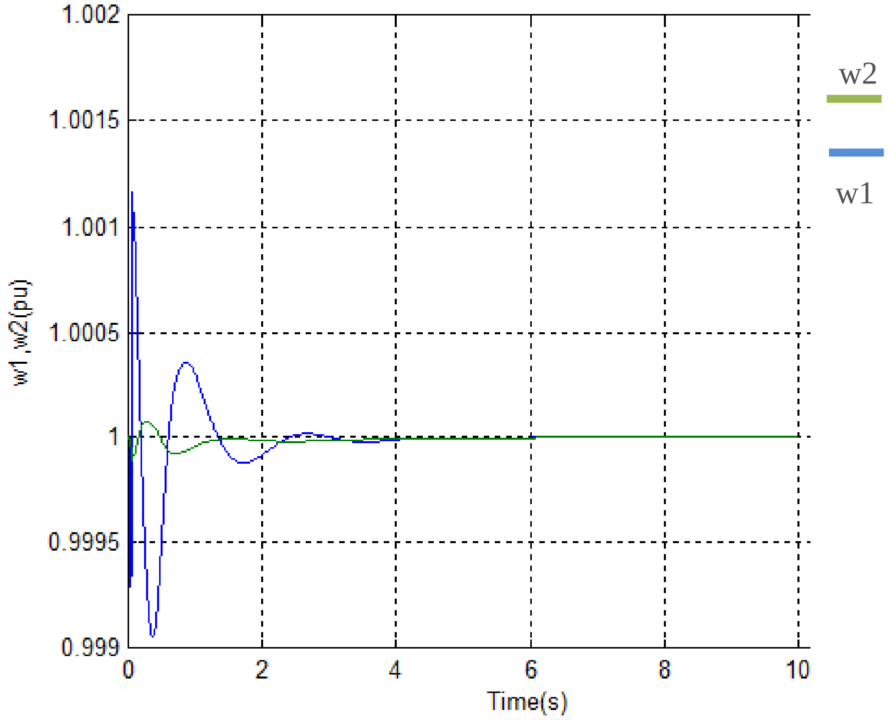

Figure 3.10 Variation of the angular velocity (with PSS)

Simulation results of the *Figure 3.10*shows that after the use of the PSS system becomes stable the system without PSS in a time of between 3 and 4secondes. It follows that the PSS has a good influence on the stability of the system.

Figure 3.11 presents comparison between the variations of the angular velocity of the first machine (M1) when it was without PSS and then with the PSS, the influence of the PSS is clear, and it made the system refers to its stable state in an acceptable time.

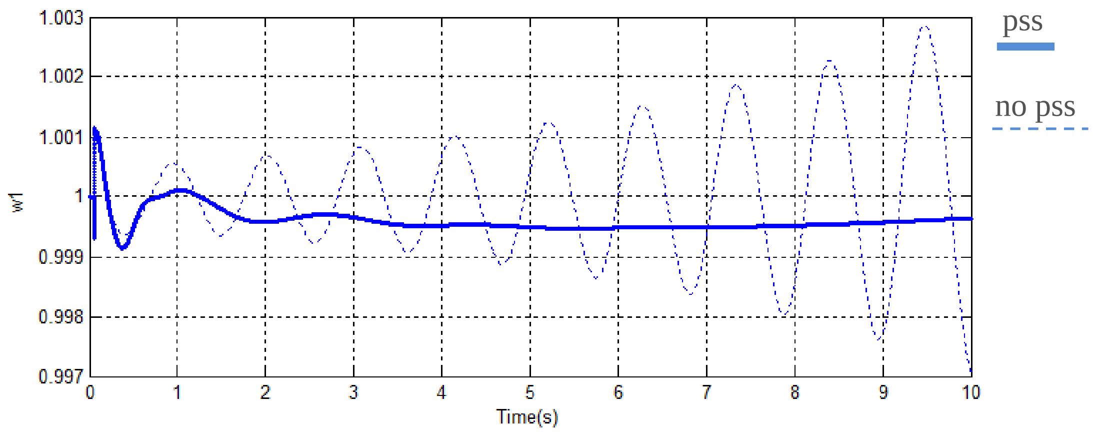

Figure 3.11 comparison between variations of angular velocity of M1.

The above curve shows that the amplitude of oscillation of variation of angular velocity with PSS is greater (more than 1.001 pu) than the other one without PSS, but the PSS had damped the oscillation within 3 to 4 seconds.

3.5. Automatic Voltage Regulator

Every piece of electrical equipment will operate within arrange of voltage levels, however not necessarily with optimal performance. When the voltage level falls outside of its operational range, a device may be unable to start or operate, it may malfunction or the device may be damaged, so the ultimate reason for using voltage regulation is financial to avoid the costs associated with equipment damage and downtime caused by poor voltage levels.

An automatic voltage regulator, AVR for short, is a device that is designed to automatically control, adjust or maintain a constant voltage level.

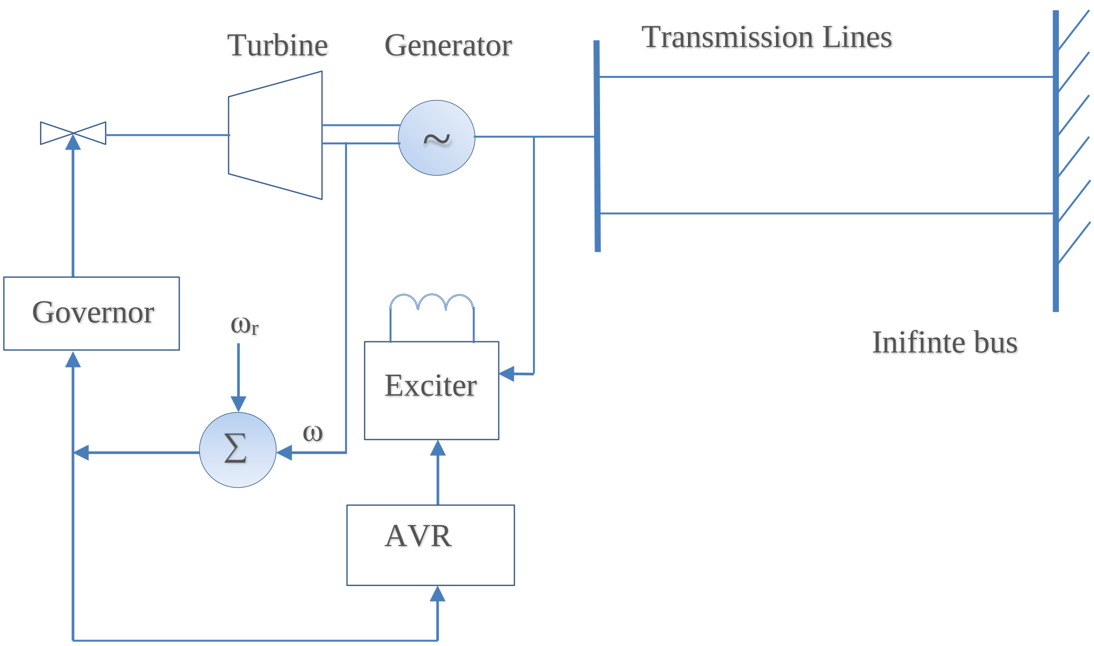

Figure 3.12 Schematic diagram of governor and AVR excitation of synchronous machine

For better comparison between the results that we will obtain after the application of a conventional PSS and a Fuzzy Logic PSS, we will propose to do our study for a single machine connected to infinite bus (SMIB) system.

The Governor or speed limiter, is a device used to measure and regulate the speed of a machine, such as an engine.

The model used in the simulation study the response of the system with the constant voltage as shown in *Figure 3.13*.

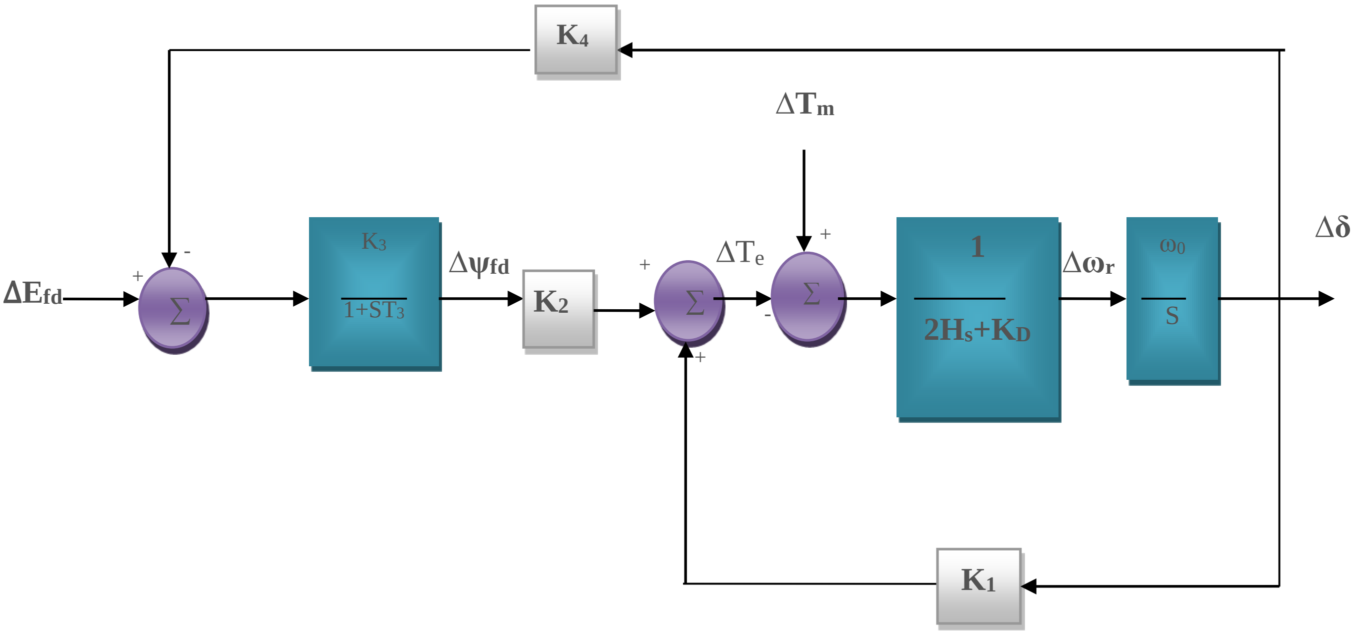

Figure 3.13 presents the block of automatic voltage regulator

3.6. Running with the excitation system (AVR-Governor) without PSS

Figure 3.13 shows the functional block diagram to include the voltage sensor and the automatic voltage regulator with excitement. Such that G (x) is the function of the AVR and the exciter and G_{ex} (S) = $K_{A.}$ The dynamic characteristics of the system are expressed in terms of so-called constant K above: K1, K2 & K4 are pure gains.

K1=1.591; K2=1.5; K3=0.333; K4=1.8; K_D=0.0; H_S=3.0; T3=1.91

The simulation model is shown in the *figure 3.11* and the excitation system parameters are: K_A=200; T_R=0.02; K5=-0.12; K6=0.3

We take the same values of the previous model for constant K (K1, K2, K3 and K4).

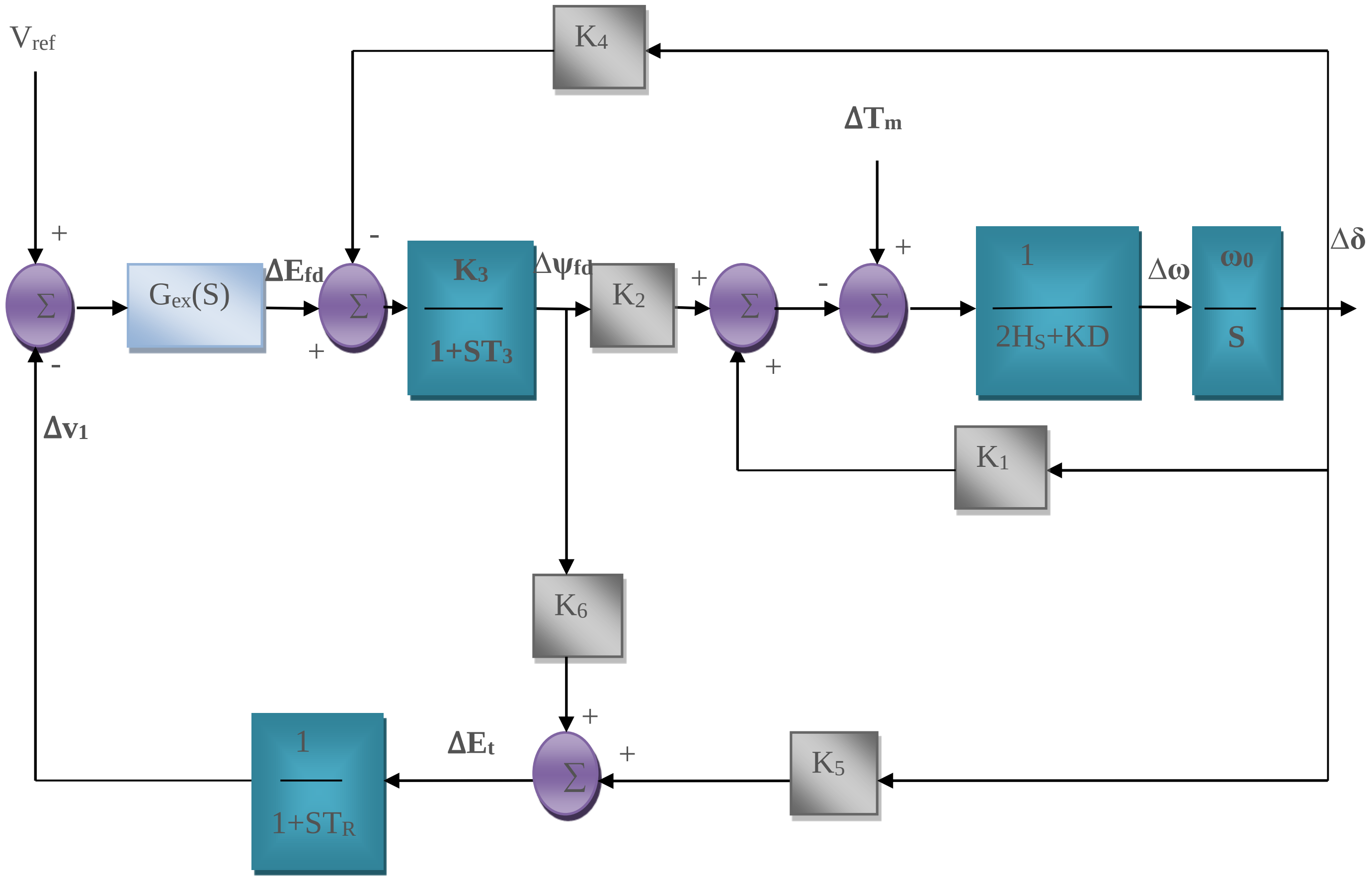

Figure 3.14 Block diagram of excitation system (AVR_Gouvernor) without PSS

The results after execution are shown in figures below:

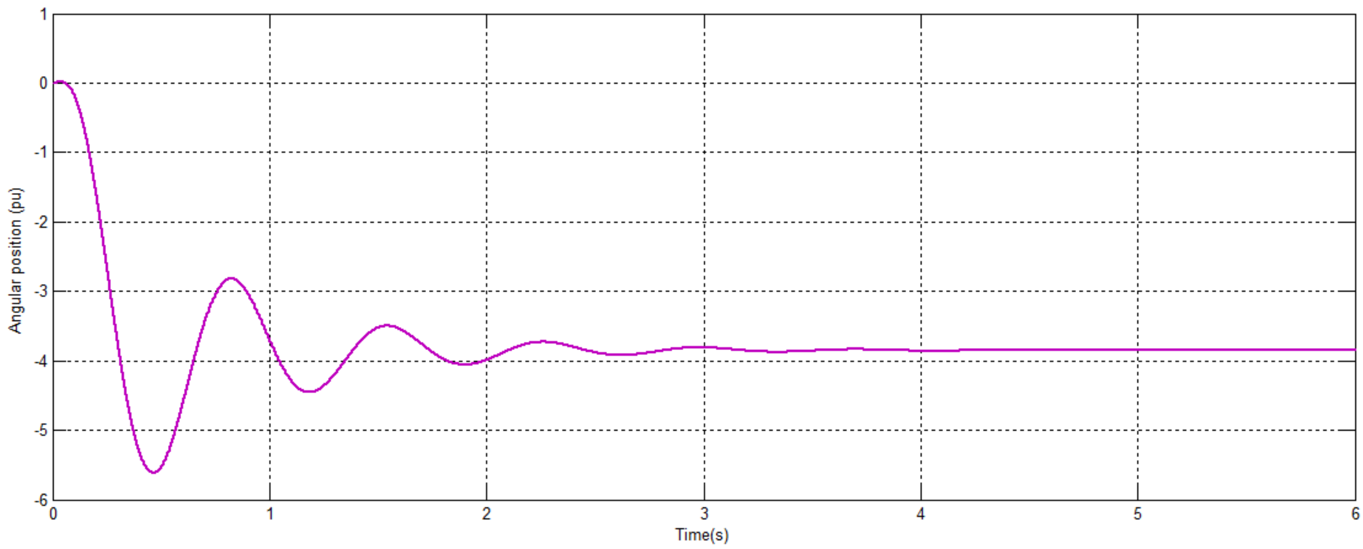

Figure 3.15 Variation of angular position (without PSS)

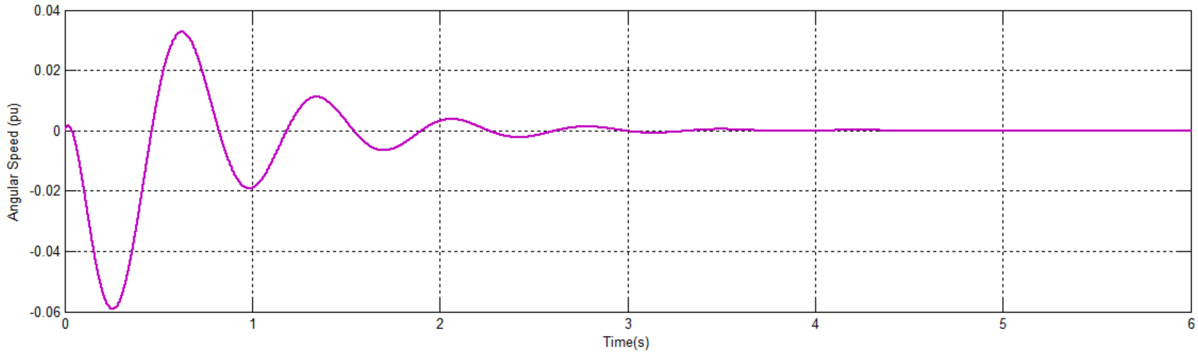

Figure 3.16 Variation of angular speed (without PSS)

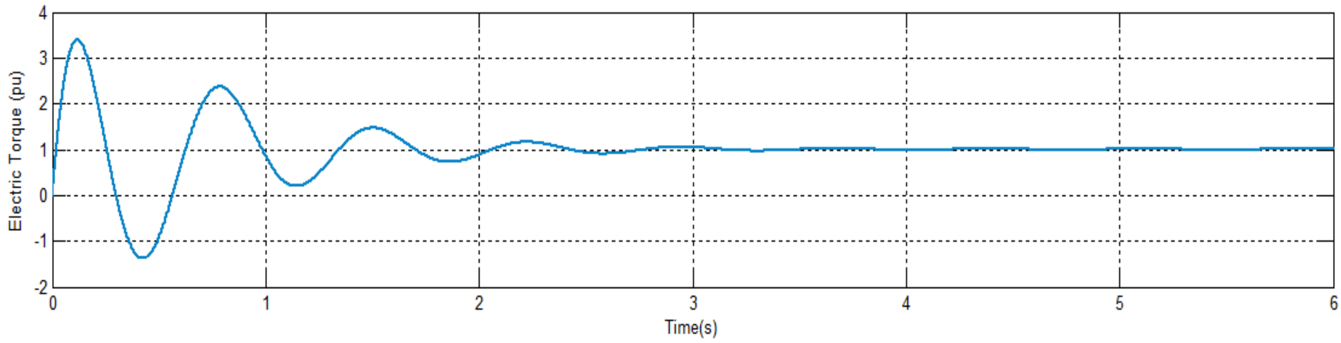

Figure 3.17 Variation of Electric torque (Without PSS)

After the simulation results in *Figures (1.14)-(1.15)-(1.16)* above show that the system becomes stable in a response time of -almost- after 3.5 seconds in the three curves.

3.7. Execution of the excitation system with PSS

The action of a PSS is to extend the angular stability limits of a power system by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation. This damping is provided by an electric torque applied to the rotor that is in phase with the speed variation.

Due to the direct influence on the rotor current of the generator, the power system stabilizer works very effectively. Power oscillations caused by sudden changes in load are quickly damped.

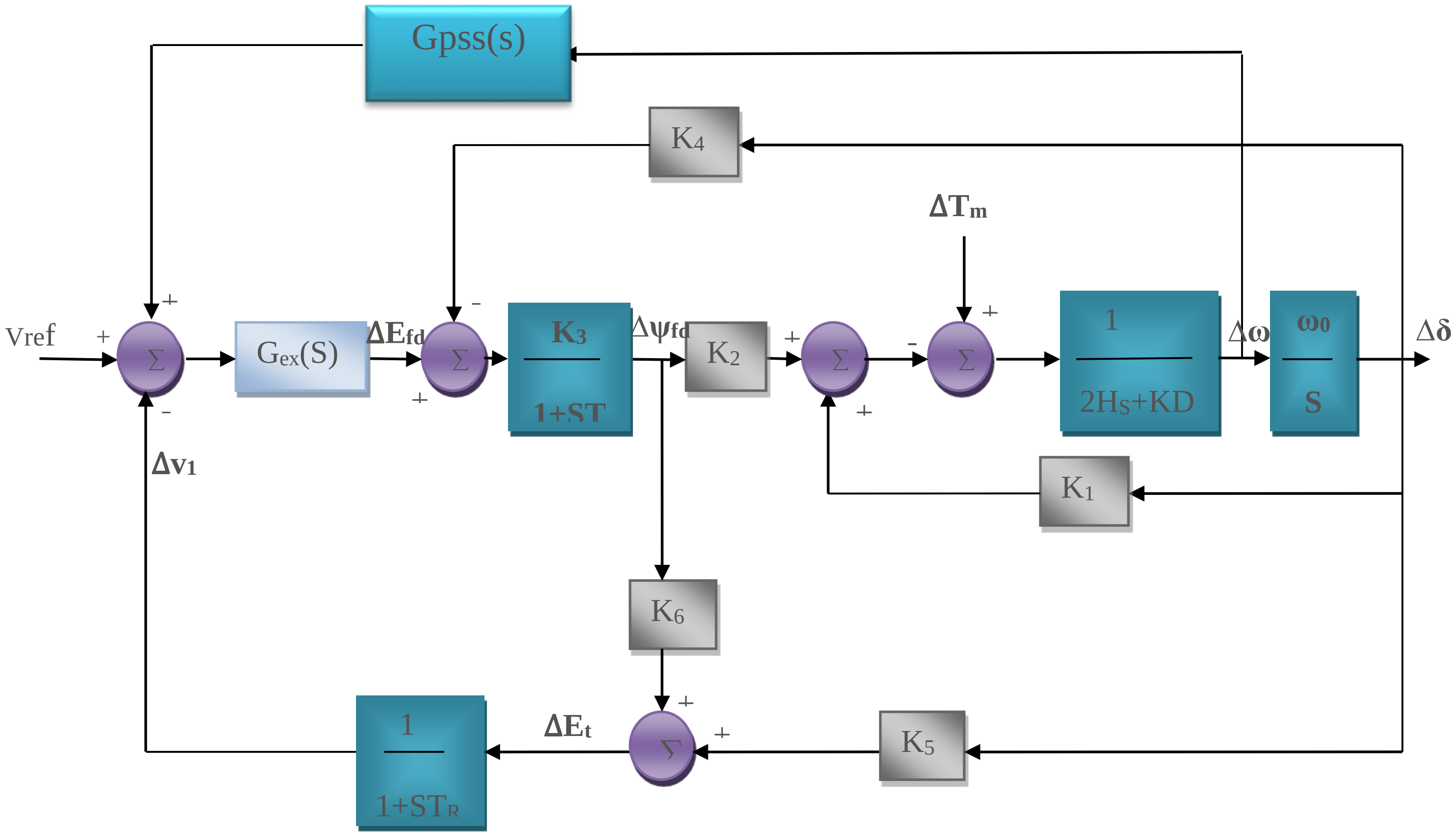

Figure 3.18 Function block diagram with the AVR and PSS

GPSS (S) is the transfer function PSS; the results obtained after running the simulation are as below:

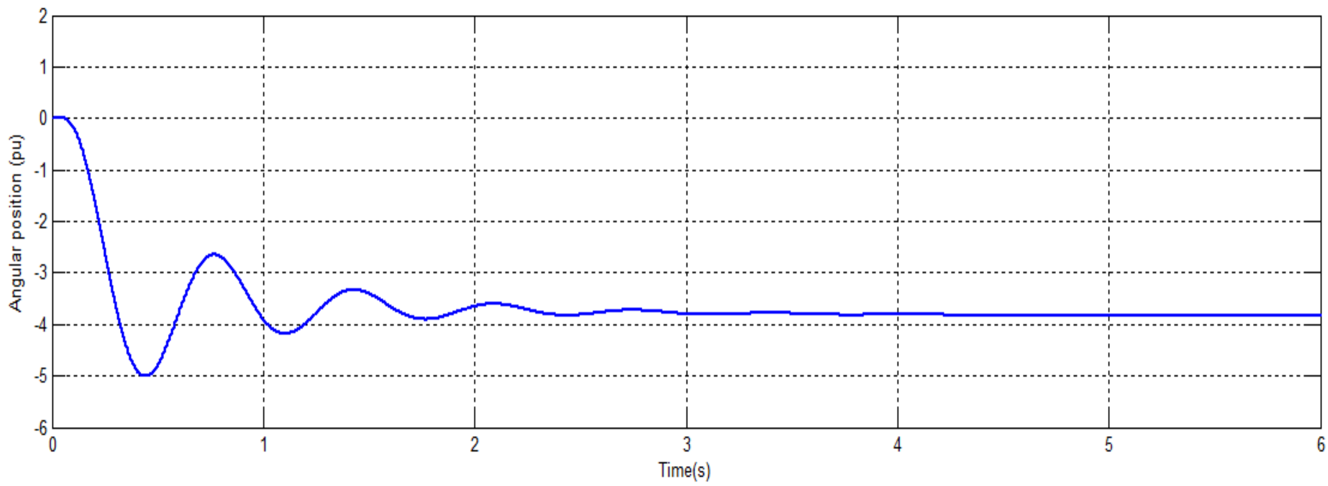

Figure 3.19 Variation in angular position (with PSS)

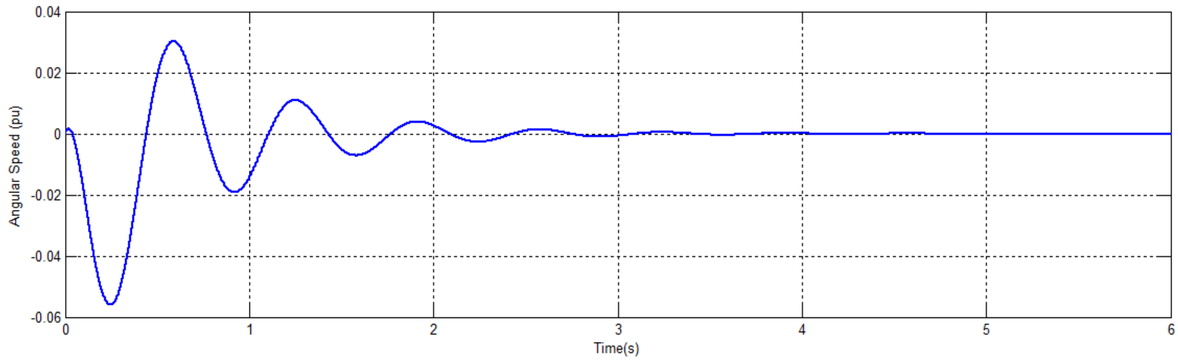

Figure 3.20 Variation in angular speed (with PSS)

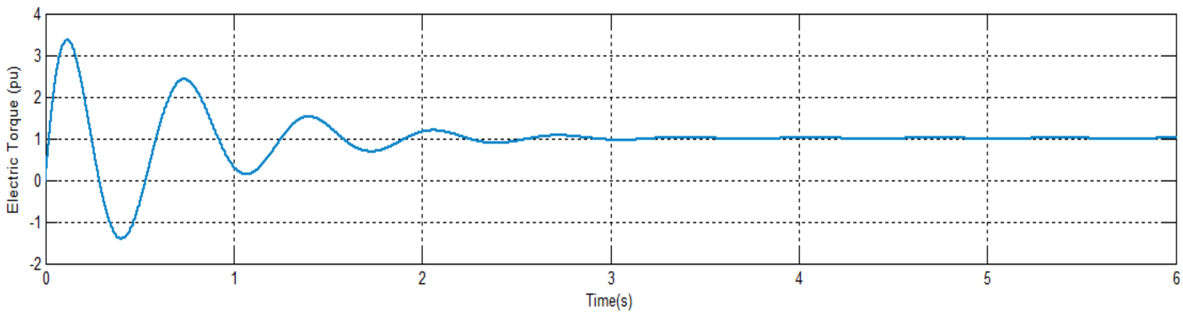

Figure 3.21 The variation in electric torque (with PSS)

Figures (3.19), (3.20) and (3.21) show that after the use of the PSS, system becomes stable comparing to the previous system (without PSS) in a response time is almost equal to 3 seconds so it follows that the PSS had a good influence on the grid stability with a good damping of the oscillations of the angular speed and of the angle.

The peak overshoot for step disturbance without PSS is equal to the other one with PSS.

3.8. Execution of the excitation system with fuzzy PSS

Fuzzification: The initial step in designing the FLPSS is the determination of the state variables which represent the performance of the system. The input signals to the FLPSS are to be chosen from these variables. The input values are normalized and converted into fuzzy variables. Rules are executed to produce a consequent fuzzy region for each variable. The expected value for each variable is found by defuzzifying the fuzzy regions. The angular velocity ($\Delta\omega$) of the synchronous machine and its derivative ($\Delta\dot{\omega}$) are chosen as inputs to the FLPSS and the output is the stabilizing signal V_{PSS}. The value of input error (e) and change of error (Δe) are normalized by an input scaling factor.

The proposed controller also uses 7 linguistic variables such as: Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), Negative Medium (NM) and Negative Big (NB). The membership functions are chosen to be Triangular. The defuzzification of the variables into crisp outputs is tested by using the center of gravity (COG) method. The two inputs: speed deviation and acceleration, result in 49 rules for each machine. Decision *Table 3.1* shows the result of 49 rules, where a positive control signal is for the deceleration control and a negative signal is for acceleration control.

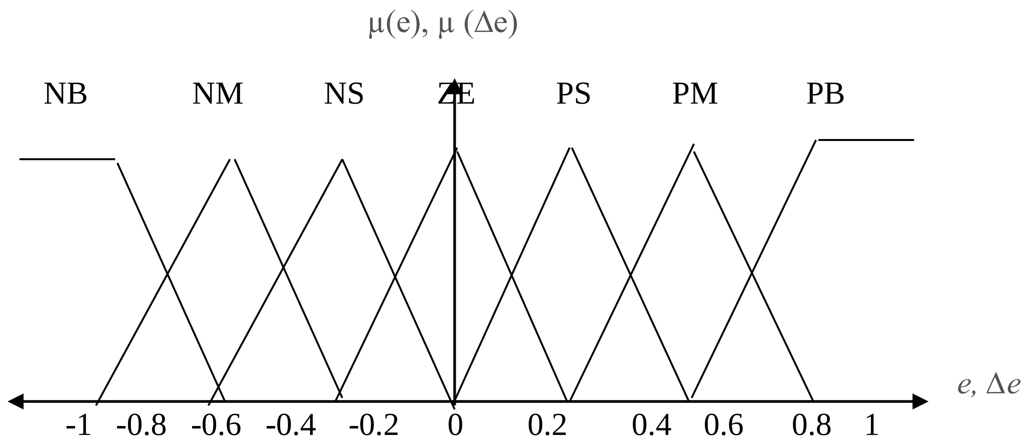

Figure 3.22 Fuzzy logic control membership functions for Input

Inference method: the composition operation is the method by which a control output is generated. The used method is sum-product. *Table 3.1* shows rule base of the FLC.

Table 3.1 Decision table of 49-rules of fuzzy logic controller

error (Speed Deviation)	Δe (Acceleration)						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	ZE
NS	NM	NM	NS	NS	ZE	ZE	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	ZE	ZE	PS	PS	PM	PM
PM	ZE	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PB	PB	PB	PB

Each of the 49 control rules represents the desired controller response to a particular situation.

Defuzzification: for this step we used the method of center of gravity which is given by the relation:

$$\Delta V_{eref} = \frac{.\sum_{i=1}^{l} .C_i \, .\mu_{res}}{.\sum_{i=1}^{l} \mu_{res}} \qquad (3.1)$$

Where:

μ_{res}: fonction d'appartenance résultante.

ΔV_{ref}: the change of control output.

C_i: the peak value of each output.

3.9. Implementation of fuzzy logic controller

The block diagram representation of fuzzy logic controller is shown in *figure 3.20.*The fuzzy module has two inputs namely the angular velocity (angular speed) and its derivative angular acceleration and output parameter as voltage. These are normalized by gain $K_{in}1$, $K_{in}2$ and K_{out} respectively.

The only difference in application of fuzzy controller to single machine infinite bus and conventional power system stabilizer is that in former case the PSS block is replaced by the fuzzy logic controller block.

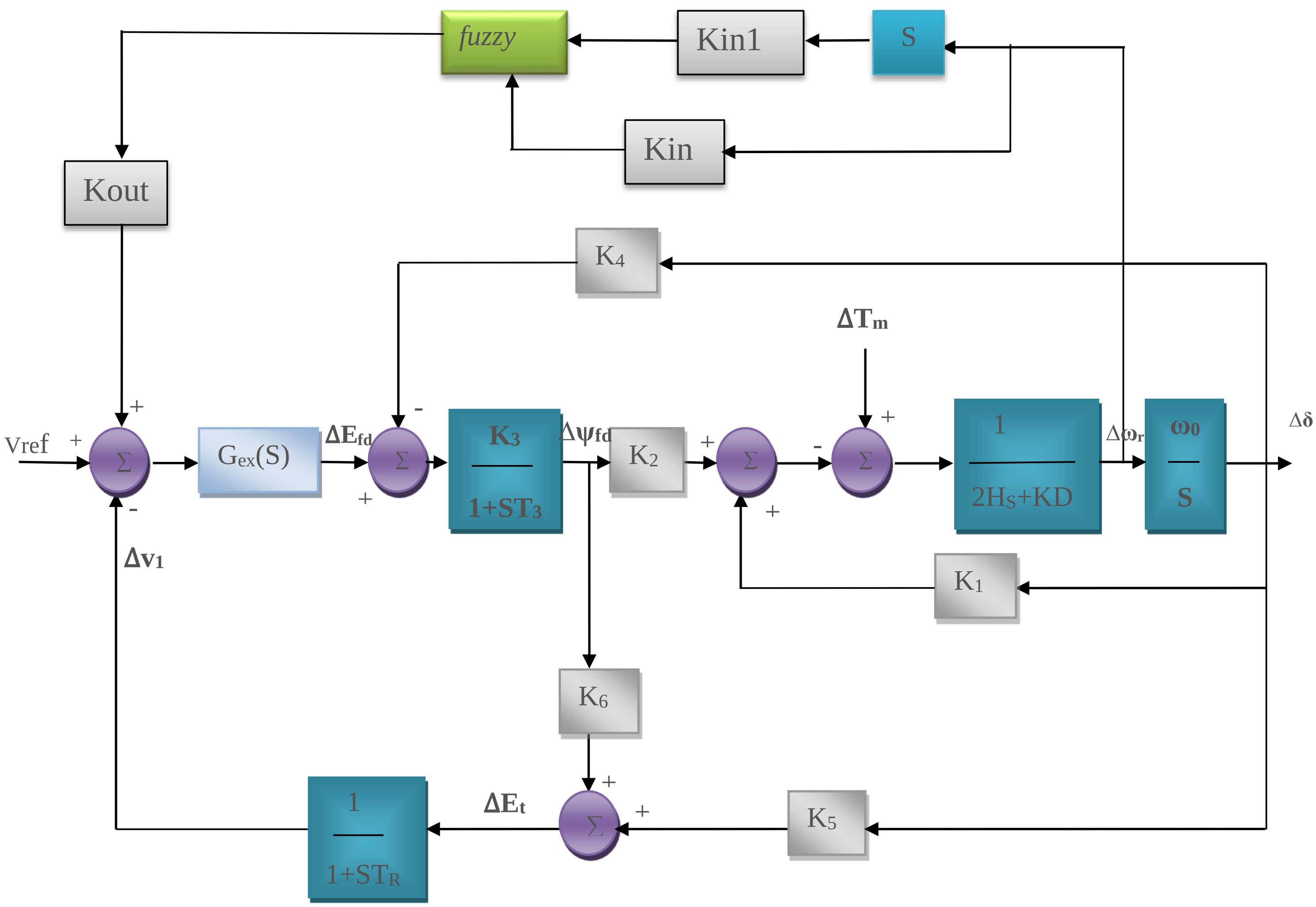

Figure 3.23 Block diagram of PSS based on Fuzzy Logic

➢ *Results and discussion*

The characteristics below will show the performance of the fuzzy logic power system stabilizer (FLPSS), and its influence on the system .We will note the difference between the CPSS and the FLPSS.

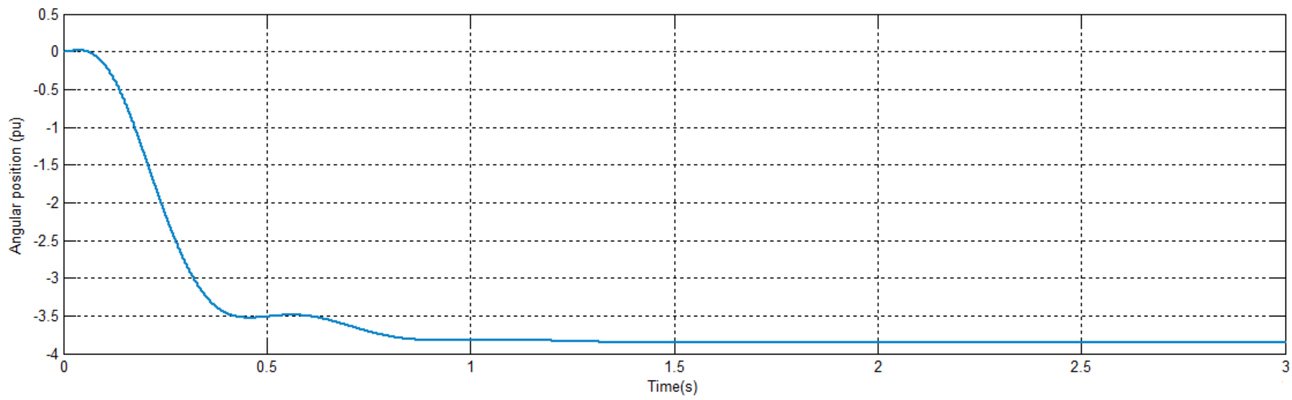

Figure 3.24 Variation in angular position (FLPSS)

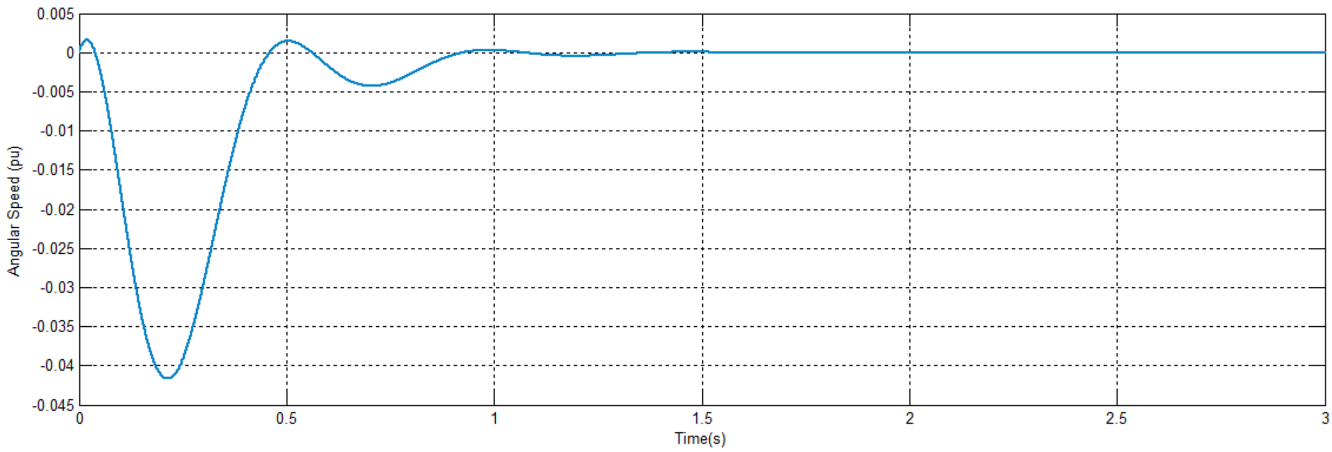

Figure 3.25 Variation in angular speed (FLPSS)

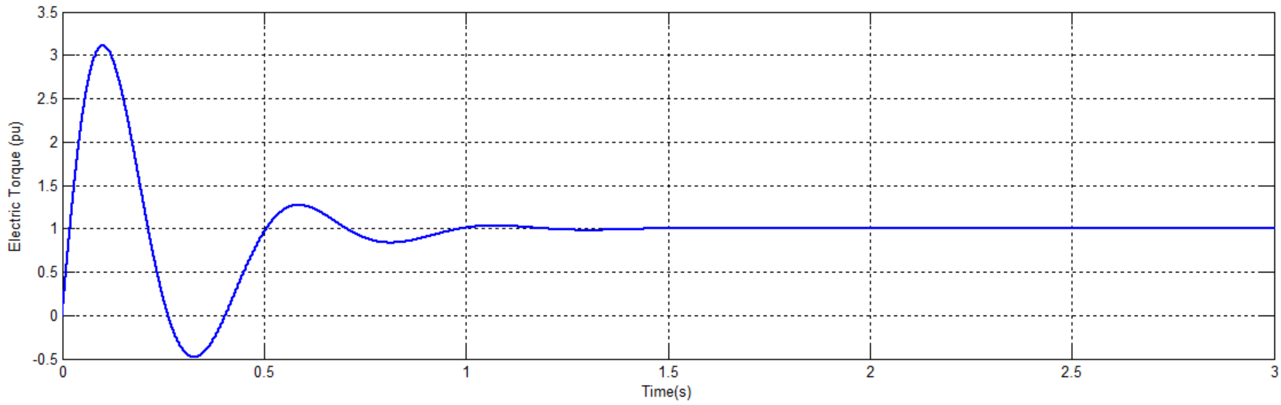

Figure 3.26 Variation in electric torque (FLPSS)

The fuzzy logic power system stabilizer (FLPSS) has increased the damping of the system causing it to settle back to steady state in much less time (1 second) than the conventional power system stabilizer (CPSS). The FLPSS, though rather basic in its control proves that it is indeed a good controller due to its simplicity.

3.10. Comparative study

It contain three cases as below:

Case 1: simulated *figure 3.26* shows the comparison in variation of angular position between FLPSS and conventional power system stabilizer (PSS).

Case 2: simulated *figure 3.27* shows the comparison in variation of angular speed between FLPSS and PSS.

Case 3: simulated *figure 3.28* shows the comparison in variation of electric torque.

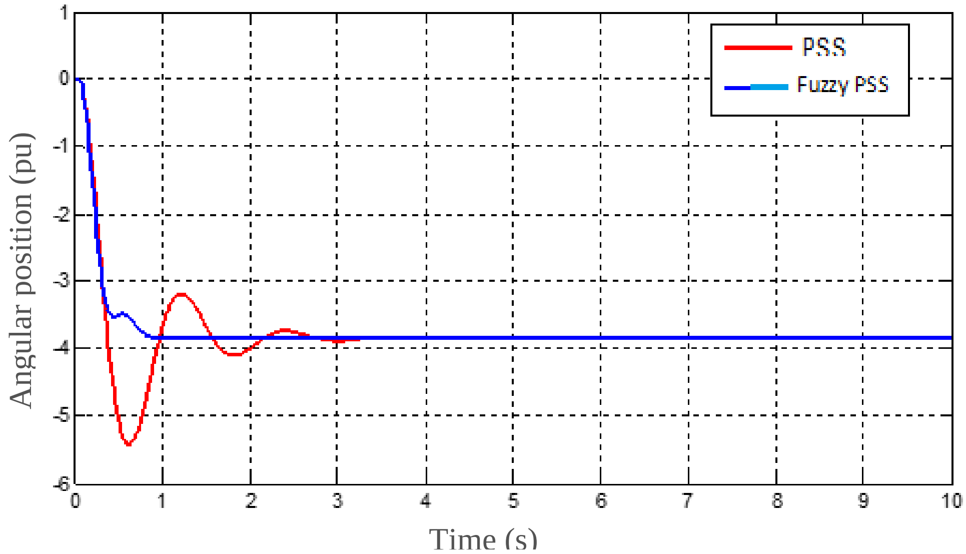

Figure 3.27 Variation of angular position

In the above case, improved fuzzy based PSS provides very good damping (Damping time is 1 second) as compared with the conventional PSS.

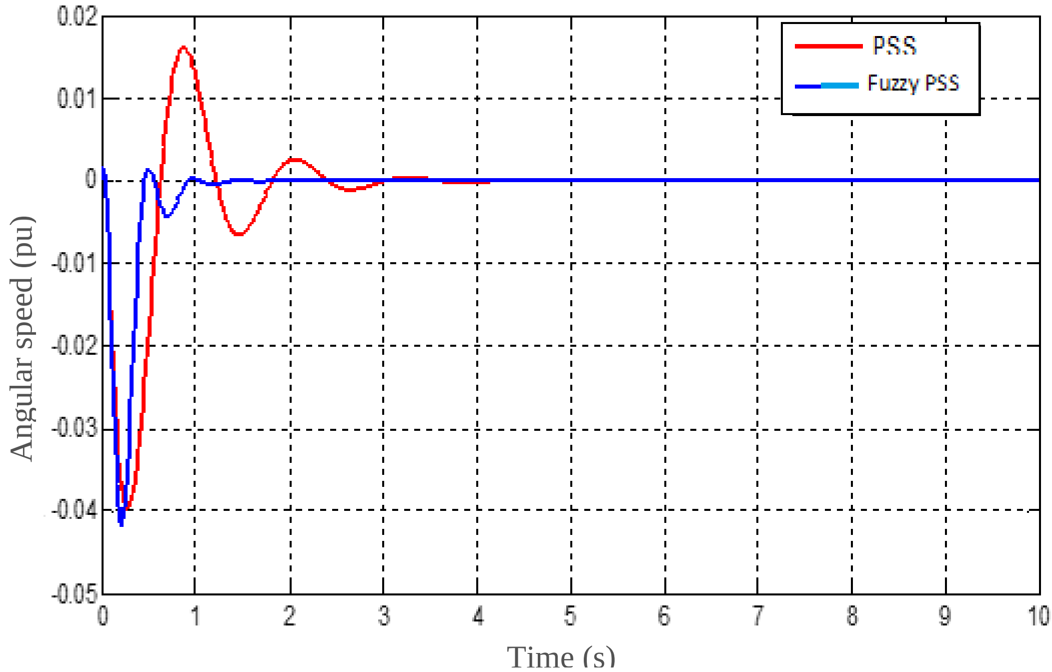

Figure 3.28 Variation in angular speed

In the second case, FLPSS also provides good damping (damping time constant is 1.3 second) as compared with the CPSS.

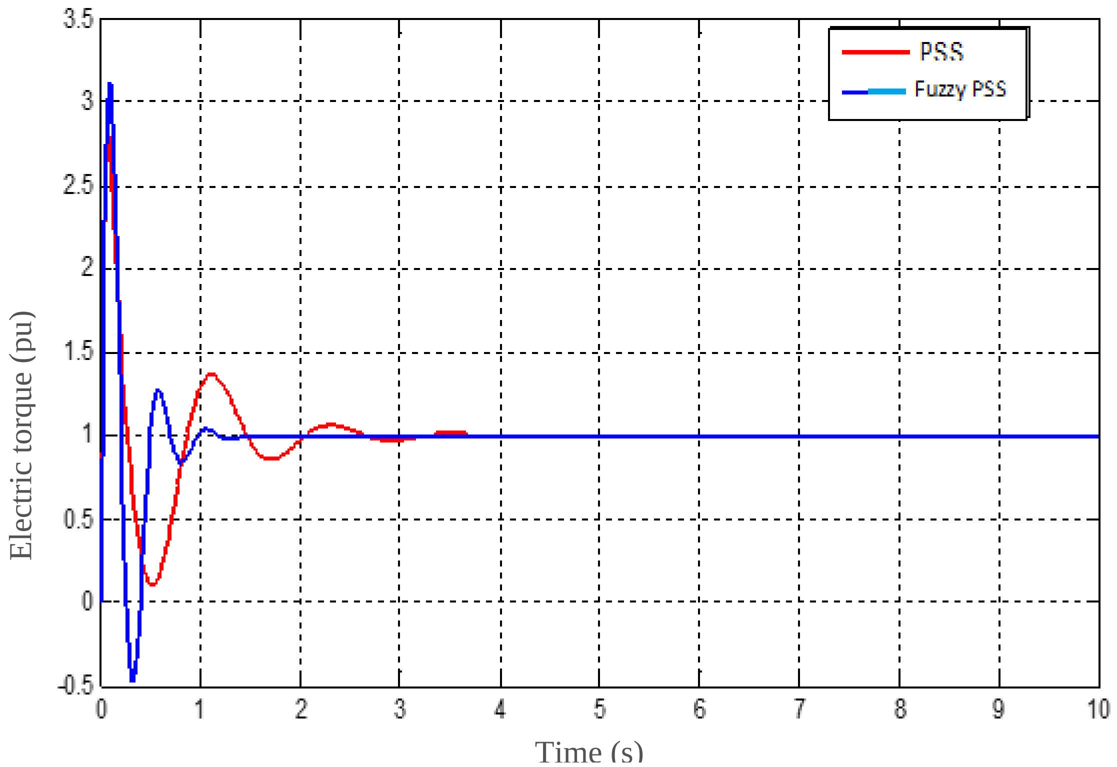

Figure 3.29 Variation in electric torque

In the last case, the simulation results shows that the fuzzy logic controller applied to a power system stabilizer provided better response than the conventional power system stabilizer. Although, *the peak of first oscillation* is greater (3 & -0.5) than the peak of CPSS.

Simulation result shows that for different operating conditions, the fuzzy logic power system stabilizer (FLPSS) has increased the damping of the system causing back to it steady state in much less time than the conventional power system stabilizer (CPSS).

The Comparisons from the *figures 3.27 to 3.29* shows that the "*Settling time*" is more improved for the Fuzzy based method when compared with Conventional based technique. The effect of a PSS based on using the fuzzy rules, greatly improves the system return to its initial position.

After the intervention of the circuit breaker and fault elimination, the system oscillates during a low period than when using a conventional PSS. So we can see that the critical time of the system with FLPSS is very large compared to the conventional PSS. Better and fast damping means that generators *can operate more close to their maximum generation capacity* . This ensures that generators remain stable under severe faults such as three phase short circuits.

Conclusion

The target of the developed work is the damping of oscillations related to power system using a controller based on fuzzy logic theory, we proposed this nonlinear control method in order to enhance more transient stability of a synchronous machine connected to an infinite bus. The simulation results showed that fuzzy stabilizer has a much faster effect than a conventional PSS on transient stability and the damping of the system. The example showed that the application of fuzzy logic further improves transient stability of the system.

Perspective:

We wanted to develop the proposed theory of fuzzy logic controller on the two area four machine test system model presented in [KUN 94e], but we did not have enough time, so, we intend to do it in the future. The one-line diagram model is shown in the figure below:

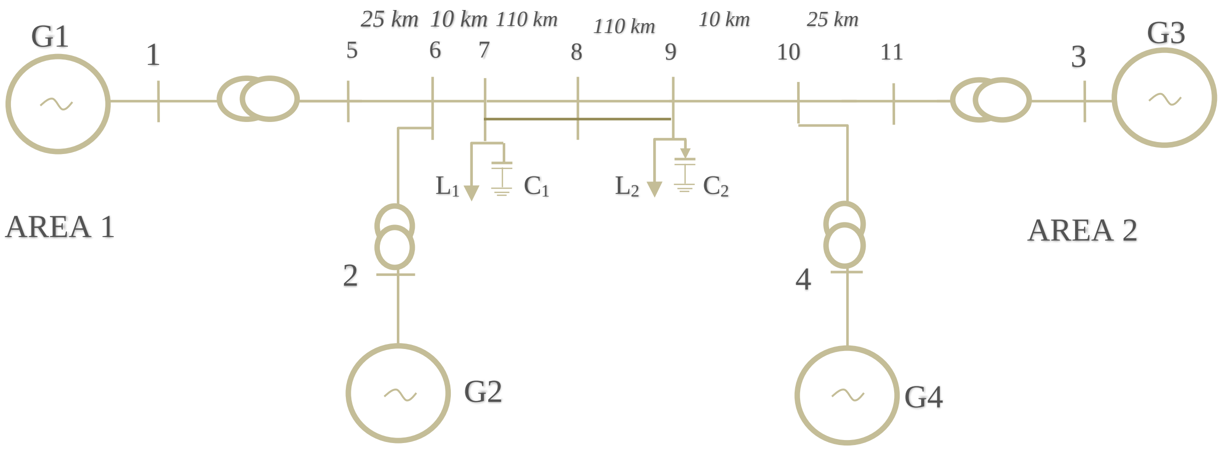

Figure 3.30 One-line diagram of two area 4 machine system

General Conclusion

The stability of power system is the core of power system security protection which is one of the most important problems researched by electrical engineers. As the permanent network extension and ongoing interconnections, the complexity of power system is increasing worldwide. Hence, it becomes more easily to get failures, even the catastrophic failures. The stable systems mean the ability of the system to damp the power oscillatory to a new steady state in finite time. The addition of power system stabilizer is to damp the oscillation of power system.

Essentially, the PSS mechanism can be described as a supplementary control signal that is added to a generator excitation control unit or automatic voltage regulator (AVR). This can improve the overall power system dynamic stability, and particularly to address the control of electromechanical oscillations. Thus, the PSS uses feedback signals such as speed deviation, variation in speed deviation, and electric torque (active power) to change the summing element of the AVR. This is a very effective method of enhancing small-signal stability performance on a power system grid.

The target of the developed work is the damping of oscillations related to power system using a controller based on fuzzy logic theory. Better and fast damping means that generators can operate more close to their maximum generation capacity . This ensures that generators remain stable under severe faults such as three phase short circuits.

This memoire has been proposed a fuzzy logic based power system stabilizer for single machine connected to infinite bus system. The performance of the system during a three-phase fault condition is performed. The resultant characteristics of angular position, angular speed, and electric torque (active power) are observed for the condition mentioned above. For the disturbance investigated, the fuzzy logic power system stabilizer (FLPSS) has increased the damping of the system causing it to settle back to steady state in much less time than the conventional power system stabilizer (CPSS). The FLPSS, though rather basic in its control proves that it is indeed a good controller due to its simplicity.

Work to Be Done in the Future

Although the proposed technique is very easy, simple, and provides a very good damping, it has some bottlenecks like generation of membership function, creation of rules and choice of scaling factors which is done by trial and error method. To overcome these drawbacks fuzzy logic controller can be automatically tuned using the advanced optimization techniques like Genetic Algorithm, Particle Swam Optimization, and Ant Colony Optimization etc.

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APPENDICES

Appendix A

Generators:

The generator parameters in per unit on the rated MVA and kV base are as follows:

Xd=1.305

Xq=0.474

Xl=0.18

Xd’=0.296

Xq’’=0.243

Xd’’=0.252

Rs=0.0028544

Td’=1.01s

Tq0‘’=0.1s

Td’’=0.053s

H=3.7(for G1 and G2)

KD=0

Transformers:

The first step-up transformer function on 1000 MVA and 13.8/500 kV base.

The second step-up transformer function on 5000 MVA and 13.8/500 KV base.

Transmission line:

The length of each line is 350 KM. the parameters of the lines in per unit on, 500 kvbase are:

r= 0.01755 pu/k

Xl = 0.0008737 pu/km

bc= 0.00000001333 pu/km

Appendix B

PSS :

KA=200.0 ; TR=0.02 ; K5=-0.12 ; K6= 0.3.

Appendix C

Synchronous machine connected to infinite bus:

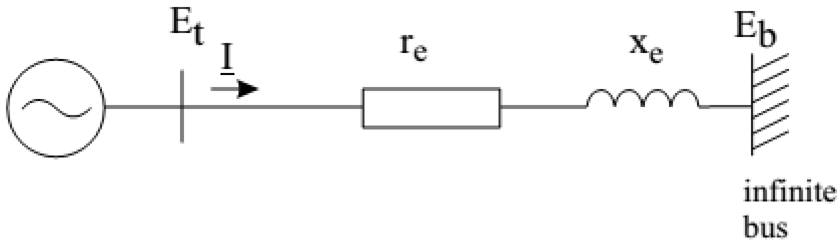
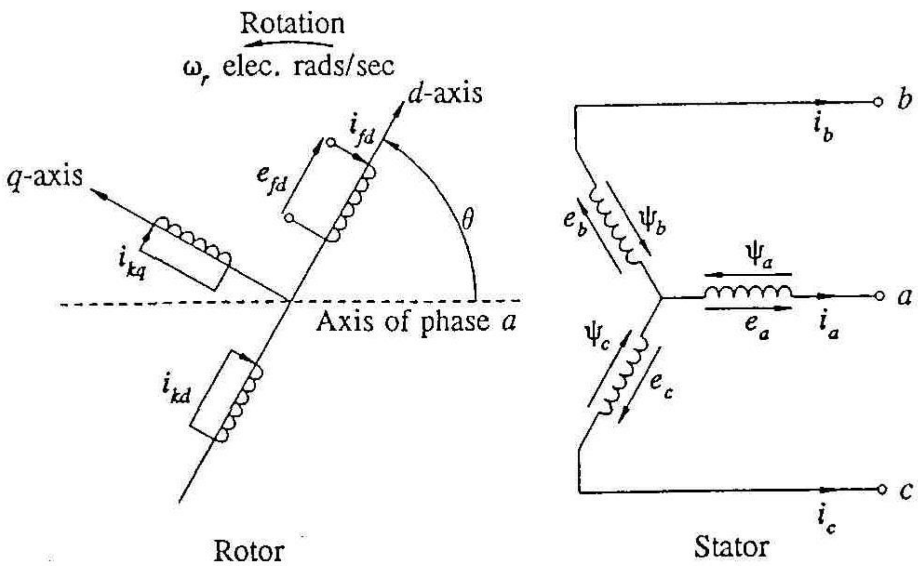


Fig: one-line diagram for a SMIB system.

Appendix D

Mathematical Descriptions of a Synchronous Machine:



-Stator and rotor circuits-

Review of Magnetic Circuit Equations (Single Excited Circuit)

$$\mathbf{e_i = \frac{d\Psi}{dt}}$$

$$\mathbf{e_1 = \frac{d\Psi}{dt} + ri}$$

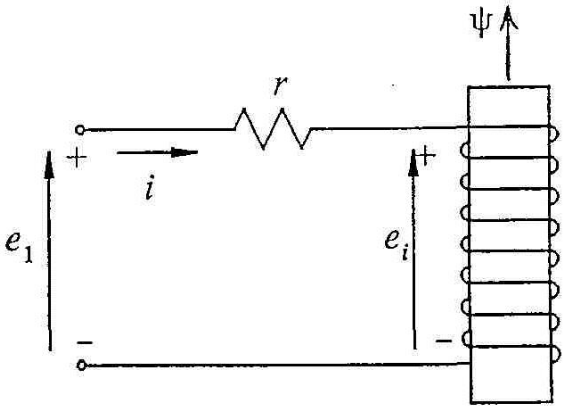
$$\mathbf{\Psi = Li}$$

- The inductance, by definition, is equal to flux linkage per unit current

$$L = N\frac{\phi}{i} = N^2 P$$

where

P	=	permeance of magnetic path
ϕ	=	flux = (mmf) P = NiP



-Single excited magnetic circuit-

Review of Magnetic Circuit Equations (Coupled Circuits)

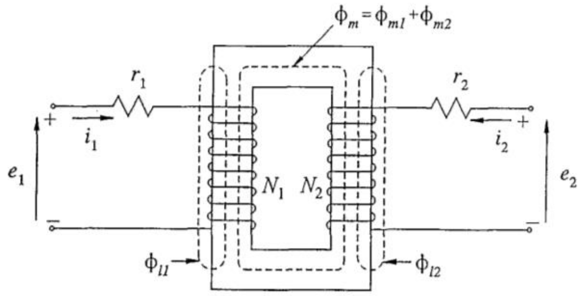
$$e_1 = \frac{d\Psi_1}{dt} + r_1 i_1$$

$$e_2 = \frac{d\Psi_2}{dt} + r_2 i_2$$

$$\Psi_1 = L_{11} i_1 + L_{21} i_2$$

$$\Psi_2 = L_{21} i_1 + L_{22} i_2$$

With L_{11} = self-inductance of winding 1
L_{22} = self-inductance of winding 2
L_{21} = mutual inductance between winding 1 and 2



Magnetically coupled circuit

Basic Equations of a Synchronous Machine

The equations are complicated by the fact that the inductances are functions of rotor position and hence vary with time.

The self and mutual inductances of stator circuits vary with rotor position.

$$I_{aa} = L_{al} + I_{gaa}$$

$$= L_{aa0} + L_{aa2} \cos 2\theta$$

$$I_{ab} = I_{ba} = -L_{ab0} + L_{ab2} \cos\left(2\theta - \frac{2\pi}{3}\right)$$
$$= -L_{ab0} - L_{ab2} \cos\left(2\theta + \frac{\pi}{3}\right)$$

The mutual inductances between stator and rotor circuits vary due to relative motion between the windings.

$$I_{afd} = L_{afd} \cos\theta$$

$$I_{akd} = L_{akd} \cos\theta$$

$$I_{akq} = L_{akq} \cos\left(\theta + \frac{\pi}{2}\right) = -L_{akq} \sin\theta$$

Dynamics of a synchronous machine is given by the equations of the coupled stator and rotor circuits.

Stator voltage and flux linkage equations for phase a (similar equations apply to phase b and phase c).

- Rotor circuit voltage and flux linkage equations:

$$e_{fd} = p\Psi_{fd} + R_{fd} i_{fd}$$

$$0 = p\Psi_{kd} + R_{kd} i_{kd}$$

$$0 = p\Psi_{kq} + R_{kq} i_{kq}$$

$$\psi_{fd} = L_{ffd} i_{fd} + L_{fkd} i_{kd}$$
$$- L_{afd}\left[i_a \cos\theta + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$\psi_{kd} = L_{fkd} i_{fd} + L_{kkd} i_{kd}$$
$$- L_{afd}\left[i_a \cos\theta + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$\psi_{kq} = L_{kkd} i_{kq}$$
$$+ L_{akq}\left[i_a \sin\theta + i_b \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\theta + \frac{2\pi}{3}\right)\right]$$

The mutual inductances between stator and rotor circuits vary due to relative motion between the windings:

$$I_{afd} = L_{afd}\cos\theta$$

$$I_{akd} = L_{akd}\cos\theta$$

$$I_{akq} = L_{akq}\cos\left(\theta + \frac{\pi}{2}\right) = -L_{akq}\sin\theta$$

- Dynamics of a synchronous machine is given by the equations of the coupled stator and rotor circuits
- Stator voltage and flux linkage equations for phase a (similar equations apply to phase b and phase c)

$$e_a = \frac{d\Psi_a}{dt} - R_a i_a = p\Psi_a - R_a i_a$$

$$\Psi_a = -l_{aa}i_a - l_{ab}i_b - l_{ac}i_c + l_{afd}i_{fd} + l_{akd}i_{kd} + l_{akq}i_{kq}$$

Rotor circuit voltage and flux linkage equations:

$$e_{fd} = p\Psi_{fd} + R_{fd}i_{fd}$$

$$0 = p\Psi_{kd} + R_{kd}i_{kd}$$

$$0 = p\Psi_{kq} + R_{kq}i_{kq}$$

$$\psi_{fd} = L_{ffd}i_{fd} + L_{fkd}i_{kd}$$
$$- L_{afd}\left[i_a\cos\theta + i_b\cos\left(\theta - \frac{2\pi}{3}\right) + i_c\cos\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$\psi_{kd} = L_{fkd}i_{fd} + L_{kkd}i_{kd}$$
$$- L_{afd}\left[i_a\cos\theta + i_b\cos\left(\theta - \frac{2\pi}{3}\right) + i_c\cos\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$\psi_{kq} = L_{kkd}i_{kq}$$
$$+ L_{akq}\left[i_a\sin\theta + i_b\sin\left(\theta - \frac{2\pi}{3}\right) + i_c\sin\left(\theta + \frac{2\pi}{3}\right)\right]$$

The dq_o Transformation

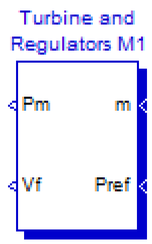
The dq_o transformation, also called Park's transformation, transforms stator phase quantities from the stationary abc reference frame to the dqo reference frame which rotates with the rotor.

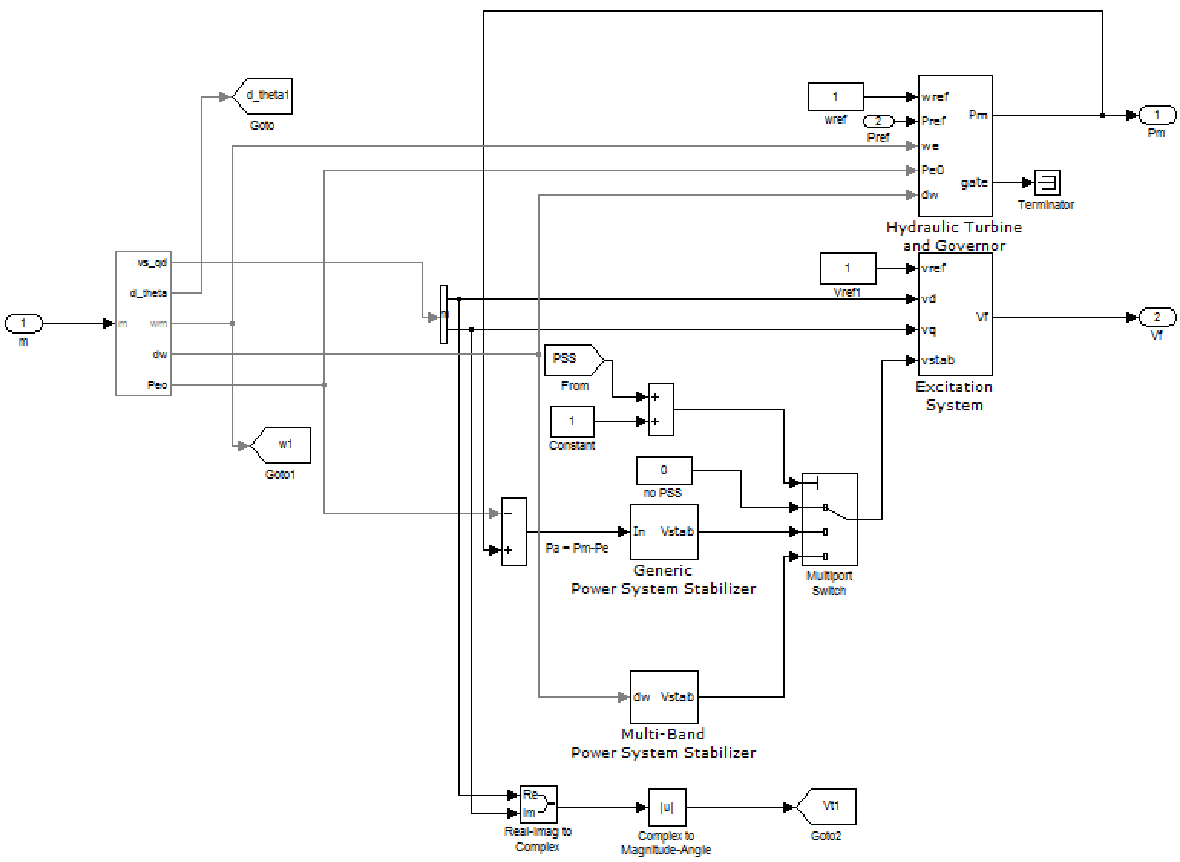
$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The above transformation also applies to stator flux linkages and voltages.

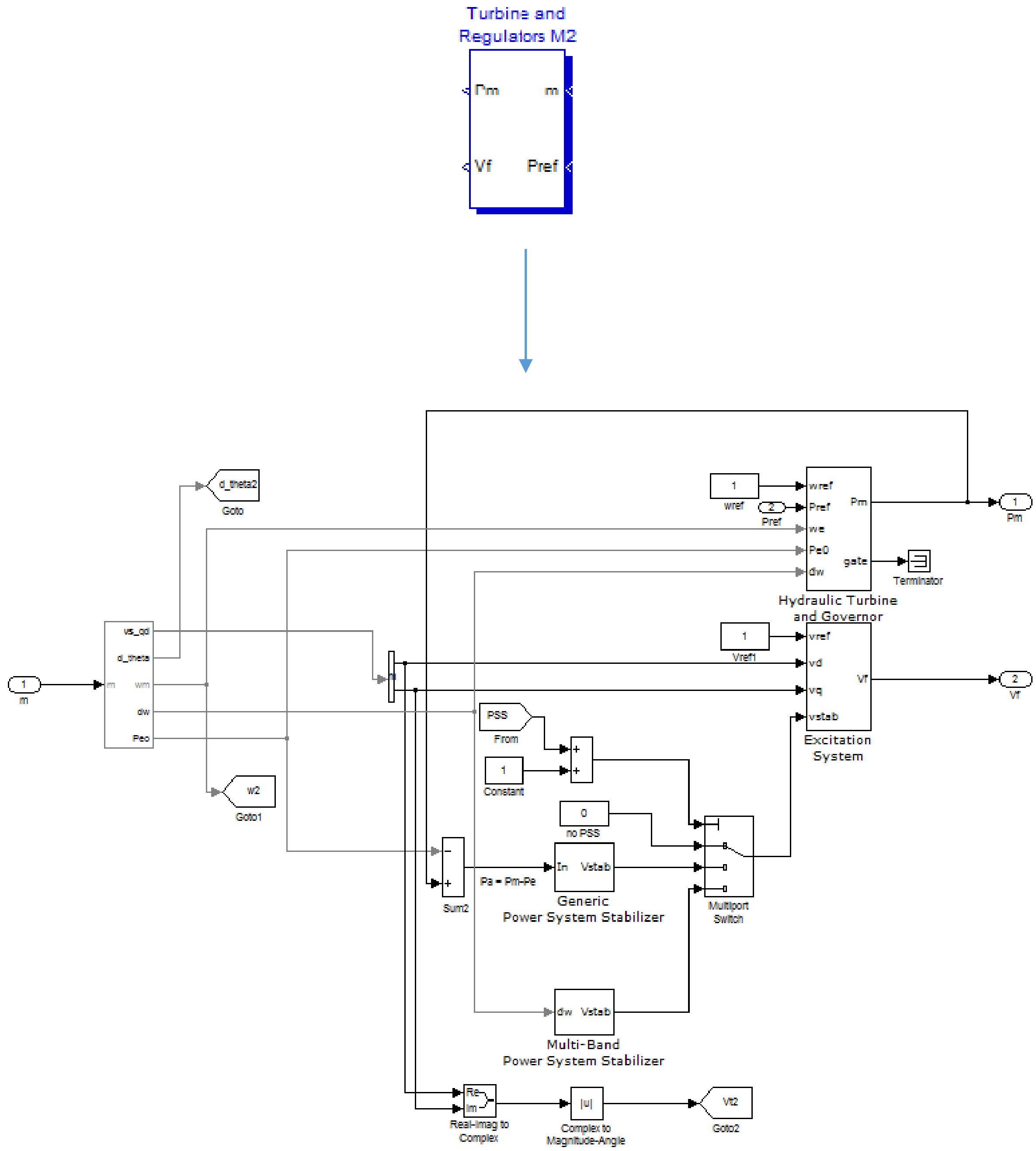
Explain subsystems blocks:

Machine 1:





Machine 2 :


Turbine and
Regulators M2
Pm
m
Vf
Pref
d_theta2
Goto
w2
Goto1
1
m
vs_qd
d_theta
wm
dw
Peo
1
wref
2
Pref
wref
Pref
we
Pe0
dw
Pm
gate
Terminator
Hydraulic Turbine
and Governor
1
Pm
1
Vref1
vref
vd
vq
vstab
Vf
Excitation
System
2
Vf
PSS
From
1
Constant
0
no PSS
Multiport
Switch
Sum2
Pa = Pm-Pe
In
Vstab
Generic
Power System Stabilizer
dw
Vstab
Multi-Band
Power System Stabilizer
Re
Im
Real-Imag to
Complex
|u|
Complex to
Magnitude-Angle
Vt2
Goto2