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Network Stability control using Fuzzy logic

By:

Mr. Haissam Abdeldjelil

Supervised by:

Pr. Sebaa Karim

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Thanks and dedication



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I thank Allah, the Almighty, the Merciful, for

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Dedication

To my family

To my friends

Not to mention all my teachers who contributed and participated in my formation, from primary to present

To all those whom I love, who love me and all those whom I have known.

And to those who share good memories.

Abdeldjelil



Dictionary of technique terms

Dictionary of technique termes

Acronyms:

SMIB	Single Machine Infinite Bus
IEEE	Institute of Electrical and Electronics Engineers
IAE	Integral of Absolute Error
ISE	Integral of Square Error
ITAE	Integral Time multiplied by Absolute Error
SVCs	Static Var Compensator systems
HVDC	High-voltage direct current
AVR	Automatic Voltage Regulator
PSS	Power System Stabilizer
Mamdani	A type of Fuzzy inference
FLPSS	Fuzzy logic PSS
FUZZY	Fuzzy logic
trimf	Triangular mode
trapmf	Trapezoidal mode
gauss2mf	Gaussian mode
psigmf	Sigmoid mode

Symbols:

$E = fem$	Electromotive force of generator (pu)
$EB = E0$	the tension of the infinite busbar (pu)
Efd	The excitation output voltage (pu)
X	Synchronous reactance and transient reactance (pu)
$X_e = X_E$	Line reactance. (Pu)
Xg	Generator reactance (pu)
Pe	Electric power (pu)

Dictionary of technique termes

Pm	Mechanical power (pu)
S	Apparent power (pu)
Te	Electric torque (pu)
TA	The damping torque (pu)
Ts	The synchronizing torque (pu)
Tm	Mechanical torque supplied by the turbine (pu)
Tem	Electromagnetic torque (pu)
KA	Synchronizing torque coefficient (pu)
Ks	Torque coefficient of damping (pu)
KD	Generator damping coefficient (pu)
$KPSS$	Advance phase delay stabilizer gain (pu)
$S\Psi_{fd}$	Synchronous generator circuit flux (pu)
Ψ_d	Stator flux (pu)
L_{ads}	Self-inductances of a stator winding (pu)
i_d	Direct axis generator current (pu)
i_q	Quadratic axis generator current (pu)
R_a	Stator phase resistance (pu)
ω_0	Synchronism speed (pu)
$\Delta\omega$	Rotor speed variation
ω_n	Natural pulse
ω_i	Mode frequency λi in rad / sec
H	Inertia constant
ζ_{cr}	Critical value of the damping factor
δ	Rotor angle Rotor angle
σ_{cr}	Absolute stability margin
Δf	Variation of the busbar frequency
$D_P\%$	Maximum overrun in percent

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ملخص:

في هذا العمل، نقترح طريقة جديدة لتصميم عامل استقرار ذكي وقوي غير خطي يجمع بين المنظم التقليدي والمنظم من خلال منطق ضبابي لأنظمة الطاقة ذات الماكينة الواحدة.

أظهرت نتائج المحاكاة التي تم الحصول عليها لنقاط التشغيل المختلفة بعد التخلص من الخطأ أن المثبت الغامض FPSSالمقترح يضمن ثباتًا جيدًا ويحسن تخميد التذبذبات. تمت مقارنة النتائج التي تم الحصول عليها مع تلك الخاصة بالمثبتات: بدون مثبت طاقة) بدون(PSS ، مع مثبت) PSS مع (PSS ومثبت PSS الضبابي .(FPSS) أظهرت النتائج التي تم الحصول عليها أن المثبت الضبابي PSS يوفر أداءً أفضل بشكل عام مقارنة بالمثبتات المذكورة أعلاه.

الكلمات المفتاحية: مثبت نظام الطاقة (PSS)، مثبت نظام الطاقة المنطق الضبابي (FPSS)، نظام الطاقة.

Abstract:

In this work, we propose a new method of designing a stabilizer intelligent, non-linear robust combining the conventional regulator and the regulator by fuzzy logic for single machine power systems.

The simulation results obtained for different operating points after fault elimination have shown that the proposed FPSS fuzzy stabilizer ensures good stability and improves the damping of oscillations. The results obtained are compared with those of stabilizers: without power stabilizer (without PSS), with PSS stabilizer (with PSS) and PSS fuzzy stabilizer (FPSS). The results obtained show that the fuzzy stabilizer PSS provides overall better performance compared to the aforementioned stabilizers.

Key words: power system stabilizer (PSS), fuzzy logic regulator (FPSS), power system.

Résumé :

Dans ce travail, on à proposer une nouvelle méthode de conception d'un stabilisateur intelligent, non linéaire robuste combinant le régulateur conventionnel et le régulateur par logique floue pour les systèmes de puissance mono machines.

Les résultats de simulation obtenus pour différents points de fonctionnement après élimination de défaut ont montrent que le stabilisateur flou FPSS proposé, assure une bonne stabilité et améliore l'amortissement des oscillations. Les résultats obtenus sont comparés à ceux des stabilisateurs : sans stabilisateur de puissance (sans PSS), avec stabilisateur PSS (avec PSS) et stabilisateur floue PSS (FPSS). Les résultats obtenus ont montrent que le stabilisateur flou PSS assure globalement de meilleures performances comparativement aux stabilisateurs précités.

Mots clés : stabilisateur du système de puissance (PSS), régulateur par logique flou (FPSS), système de puissance.

General Introduction

General Introduction:

For the past twenty years, power systems have had to face very significant challenges. The liberalization of the electricity market creates much more complex operating scenarios than in the past. The permanent increase in electricity dependence in modern society implies that power systems operate at 100% of their capacity and maximum safety. In addition, the quality of electric power has become of great concern to consumers and suppliers today. Consequently, rigorous criteria of development and operation are more and more required.

Under these conditions, the stability of power systems becomes one of the major concerns for electricity suppliers. These systems must remain stable for all small variations in the vicinity of the operating points as well as for severe conditions. New methods and technologies for improving the stability of systems are therefore the subject of extremely important research.

Several of the modern methods have already been the subject of industrial applications in advanced fields such as aeronautics and robotics. We are therefore entitled to wonder about their effectiveness with regard to the problem of the design of voltage and speed regulators which ensure the stability of electrical networks.

The Automatic Voltage Regulator (AVR) and the Speed Regulator or Governor are characterized by a weakly damped exchange of electrical power between two or more zones of the network. This new structure has better performance and dampens local and inter-zone oscillations relatively well.
However. The PSS and the AVR act simultaneously, independently and uncoordinatedly on the excitation of the generator. A compromise is therefore made in order to ensure the proper functioning of the assembly. So. With the addition of PSS, we notice generally some deterioration in the quality of voltage regulation.

Another method of PSS based on fuzzy logic. This is due to the possibility of introducing knowledge expressed in the form of an inference rule to determine membership functions, based on human experience in the field. In particular, the application of fuzzy set theory in the control of processes. By simulation, we will visualize and compare the attenuation time of the oscillations linked to the electrical systems (synchronous machine

connected to an infinite network) when they are subjected to a disturbance, therefore to see the effect of artificial intelligence on the system by compared to conventional, that is to say further improvement of the stability of the power system.

The PSS and fuzzy logic are still considered as an effective means for the damping of local electromechanical modes, but at the same time its role in damping of interregional modes is still considered weak. The objective of our work is thus to ensure a maximum damping of the interregional modes as well as of the local modes. To achieve this goal, we offer an optimal adjustment of the PSS and fuzzy logic " FUZZY ". This makes it possible to ensure satisfactory damping of the rotor oscillations and to guarantee the overall stability of the system for different operating points.

Chapter I

Basic concepts and review of classical methods.

I.1. Basic Concepts

I.1.1. Introduction:

When studying the behavior of electrical energy networks, one of the most important problems that we often encounter is the study of stability. In fact, since the industrial revolution in the middle of the 18th century, the demand for electricity has only increased in order to be able to operate factories and serve households. Electricity networks have obviously experienced significant development. It was therefore urgent to examine at all times the behavior of networks in the face of low and / or large disturbances. These disturbances, which can be of various origins, are the source of a difference between mechanical power (production) and electrical power (consumption).

I.1.2. General

Modern power systems are characterized by extensive system interconnections and increasing dependence on control for optimum utilization of existing resources. The supply of reliable and economic electric energy is a major determinant of industrial progress and consequent rise in the standard of living. The increasing demand for electric power coupled with resource and environmental constraints pose several challenges to system planners. The generation may have to be sited at locations far away from load centers (to exploit the advantages of remote hydro power and pit head generation using fossil fuels). However, constraints on right of way lead to overloading of existing transmission lines and an impetus to seek technological solutions for exploiting the high thermal loading limits of EHV lines [1]. With deregulation of power supply utilities, there is a tendency to view the power networks as highways for transmitting electric power from wherever it is available to places where required, depending on the pricing that varies with time of the day.

Power system dynamics has an important bearing on the satisfactory system operation. It is influenced by the dynamics of the system components such as generators, transmission lines, loads and other control equipment (HVDe and SVC controllers). The dynamic behavior of power systems can be quite complex and a good understanding is essential for proper system planning and secure operation.

I.1.3. Power System Stability

Stability of power systems has been and continues to be of major concern in system operation [2-7]. This arises from the fact that in steady state (under normal conditions) the

average electrical speed of all the generators must remain the same anywhere in the system. This is termed as the synchronous operation of a system. Any disturbance small or large can affect the synchronous operation.

For example, there can be a sudden increase in the load or loss of generation. Another type of disturbance is the switching out of a transmission line, which may occur due to overloading or a fault. The stability of a system determines whether the system can settle down to a new or original steady state after the transients disappear.

The disturbance can be divided into two categories (a) small and (b) large. A small disturbance is one for which the system dynamics can be analyzed from linearized equations (small signal analysis). The small (random) changes in the load or generation can be termed as small disturbances. The tripping of a line may be considered as a small disturbance if the initial (pre-disturbance) power flow on that line is not significant. However, faults which result in a sudden dip in the bus voltages are large disturbances and require remedial action in the form of clearing of the fault. The duration of the fault has a critical influence on system stability.

Although stability of a system is an integral property of the system, for purposes of the system analysis, it is divided into two broad classes [4].

1. Steady-State or Small Signal Stability

A power system is steady state stable for a particular steady state operating condition if, following any small disturbance, it reaches a steady state operating condition which is identical or close to the pre-disturbance operating condition.

2. Transient Stability

A power system is transiently stable for a particular steady-state operating condition and for a particular (large) disturbance or sequence of disturbances if, following that (or sequence of) disturbance(s) it reaches an acceptable steady-state operating condition.

It is important to note that, while steady-state stability is a function only of the operating condition, transient stability is a function of both the operating condition and the disturbance(s). This complicates the analysis of transient stability considerably. Not only system linearization cannot be used, repeated analysis is required for different disturbances that are to be considered.

Another important point to be noted is that while the system can be operated even if it is transiently unstable, small signal stability is necessary at all times. In general, the stability

depends upon the system loading. An increase in the load can bring about onset of instability. This shows the importance of maintaining system stability even under high loading conditions.

I.1.4. States of Operation and System Security

Dy Liacco [5], and Fink and Carlson [6] classified the system operation into 5 states as shown in Fig I.1. The system operation is governed by three sets of generic equations one differential and two algebraic (generally non-linear). Of the two algebraic sets, one set comprise equality constraints (E) which express balance between the generation and load demand. The other set consists of inequality constraints (I) which express limitations of the physical equipment (such as currents and voltages must not exceed maximum limits). The classification of the system states is based on the fulfillment or violation of one or both sets of these constraints.

1. Normal Secure State: Here all equality (E) and inequality (I) constraints are satisfied. In this state, generation is adequate to supply the existing load demand and no equipment is overloaded. Also in this state, reserve margins (for transmission as well as generation) are sufficient to provide an adequate level of security with respect to the stresses to which the system may be subjected. The latter may be treated as the satisfaction of security constraints.

2. Alert State: The difference between this and the previous state is that in this state, the security level is below some threshold of adequacy. This implies that there is a danger of violating some of the inequality (I) constraints when subjected to disturbances (stresses). It can also be said that security constraints are not met. Preventive control enables the transition from an alert state to a secure state.

3. Emergency State: Due to a severe disturbance the system can enter emergency state. Here I constraints are violated. The system, however, would still be intact, and emergency control action (heroic measures) could be initiated to restore the system to alert state. If these measures are not taken in time or are ineffective, and if the initiating disturbance or a subsequent one is severe enough to overstress the system, the system will break down and reach 'In Extremis' state.

4. In Extremis State: Here both E and I constraints are violated. The violation of equality constraints implies that parts of system load are lost. Emergency control action should be directed at avoiding total collapse.

5. Restorative State: This is a transitional state in which I constraints are met from the emergency control actions taken but the E constraints are yet to be satisfied. From this state, the system can transit to either the alert or the I1-ormal state depending on the circumstances.

In further developments in defining the system states [7], the power system emergency is defined as due to either a (i) viability crisis resulting from an imbalance between generation, loads and transmission whether local or system-wide or (ii) stability crisis resulting from energy accumulated at sufficient level in swings of the system to disrupt its integrity.

'In Extremis' state corresponds to a system failure characterized by the loss of system integrity involving uncontrolled is landings (fragmentation) of the system and/or uncontrolled loss of large blocks of load.

It is obvious that the objective of emergency control action should be to avoid transition from emergency state to a failure state (In Extremis). The knowledge of system dynamics is important in designing appropriate controllers. This involves both the detection of the problem using dynamic security assessment and initiation of the control action.

I.1.5. System Dynamic Problems

In the early stages of power system development, (over 50 years ago) both steady state and transient stability problems challenged system planners. The development of fast acting static exciters and electronic voltage regulators overcame to a large extent the transient stability and steady state stability problems (caused by slow drift in the generator rotor motion as the loading was increased). A parallel development in high-speed operation of circuit breakers and reduction of the fault clearing time and reclosing, also improved system stability.

The regulation of frequency has led to the development of turbine speed governors which enable rapid control of frequency and power output of the generator with minimum dead band. The various prime-mover controls are classified as

a) primary (speed governor)

b) secondary (tie line power and frequency)

c) tertiary (economic load dispatch).

However, in well-developed and highly interconnected power systems, frequency deviations have become smaller. Thus tie-line power frequency control (also termed as

automatic generation control) (AGC) has assumed major importance. A well-designed prime mover control system can help in improving the system dynamic performance, particularly the frequency stability.

Over last 25 years, the problems of low frequency power oscillations have assumed importance. The frequency of oscillations is in the range of 0.2 to 2.0 Hz. The lower the frequency, the more widespread are the oscillations (also called inter-area oscillations). The presence of these oscillations is traced to fast voltage regulation in generators and can be overcome through supplementary control employing power system stabilizers (PSS). The design and development of effective PSS is an active area of research.

Another major problem faced by modern power systems is the problem of voltage collapse or voltage instability which is a manifestation of steady-state instability. Historically steady state instability has been associated with angle instability and slow loss of synchronism among generators. The slow collapse of voltage at load buses under high loading conditions and reactive power limitations, is a recent phenomenon.

Power transmission bottlenecks are faced even in countries with large generation reserves. The economic and environmental factors necessitate generation sites at remote locations and wheeling of power through existing networks.

The operational problems faced in such cases require detailed analysis of dynamic behavior of power systems and development of suitable controllers to overcome the problems. The system has not only controllers located at generating stations such as excitation and speed governor controls but also controllers at HVDC converter stations, Static VAR Compensators (SVC). New control devices such as Thyristor Controlled Series Compensator (TCSC) and other FACTS controllers are also available. The multiplicity of controllers also present challenges in their design and coordinated operation. Adaptive control strategies may be required.

The tools used for the study of system dynamic problems in the past were simplistic. Analog simulation using AC network analyzers were inadequate for considering detailed generator models. The advent of digital computers has not only resulted in the introduction of complex equipment models but also the simulation of large-scale systems. The realistic models enable the simulation of systems over a longer period than previously feasible. However, the curse of dimensionality' has imposed constraints on on-line simulation of large systems even with super computers. This implies that on-line dynamic security assessment using simulation is not yet feasible. Future developments on massively parallel computers and

algorithms for simplifying the solution may enable real time dynamic simulation.

The satisfactory design of system wide controllers have to be based on adequate dynamic models. This implies the modelling should be based on 'parsimony' principle include only those details which are essential.

I.2 Review of Classical Methods

In this Part, we will review the classical methods of analysis of system stability, incorporated in the treatises of Kimbark and Crary. Although the assumptions behind the classical analysis are no longer valid with the introduction of fast acting controllers and increasing complexity of the system, the simplified approach forms a beginning in the study of system dynamics. Thus, for the sake of maintaining the continuity, it is instructive to outline this approach.

As the objective is mainly to illustrate the basic concepts, the examples considered here will be that of a single machine connected to an infinite bus (SMIB).

I.2.1 System Model

Consider the system (represented by a single line diagram) shown in Fig. I.1. Here the single generator represents a single machine equivalent of a power plant (consisting of several generators). The generator G is connected to a double circuit line through transformer T. The line is connected to an infinite bus through an equivalent impedance ZT. The infinite bus, by definition, represents a bus with fixed voltage source. The magnitude, frequency and phase of the voltage are unaltered by changes in the load (output of the generator). It is to be noted that the system shown in Fig.I.1 is a simplified representation of a remote generator connected to a load center through transmission line.

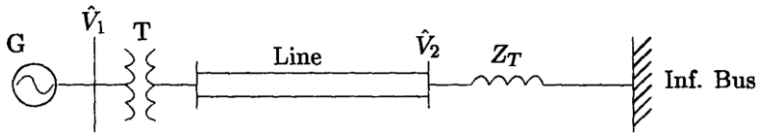


Figure I.1: Single line diagram of a single machine system

The major feature in the classical methods of analysis is the simplified (classical) model of the generator. Here, the machine is modelled by an equivalent voltage source behind an impedance. The major assumptions behind the model are as follows

1. Voltage regulators are not present and manual excitation control is used.

This implies that in steady- state, the magnitude of the voltage source is determined by the field current which is constant.

2. Damper circuits are neglected.

3. Transient stability is judged by the first swing, which is normally reached within one or two seconds.

4. Flux decay in the field circuit is neglected (This is valid for short period, say a second, following a disturbance, as the field time constant is of the order of several seconds).

5. The mechanical power input to the generator is constant.

6. Saliency has little effect and can be neglected particularly in transient stability studies.

Based on the classical model of the generator, the equivalent circuit of the system of Fig. I.1is shown in Fig. I.2. Here the losses are neglected for simplicity. Xe is the total external reactance viewed from the generator terminals. The generator reactance, Xg, is equal to synchronous reactance Xd for steady-state analysis. For transient analysis, Xg is equal to the direct axis transient reactance x'_d . In this case, the magnitude of the generator voltage Eg is proportional to the field flux linkages which are assumed to remain constant (from assumption 4)

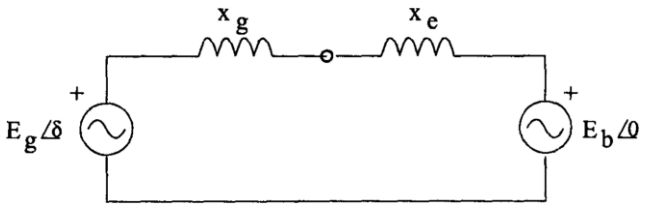


Figure I.2: Equivalent circuit of the system shown in Fig. I.1

For the classical model of the generator, the only differential equation relates to the motion of the rotor.

The Swing Equation

The motion of the rotor is described by the following second order equation

$$J\frac{d^2\theta_m}{dt^2} = T_m - T_e \quad (I.1)$$

where

J is the moment of inertia

θ_m)s the angular position of the rotor with respect to a stationary axis

T_m is the net mechanical input torque

T_{em} is the electromagnetic torque

By multiplying both sides of the Eq. (I.1) by the nominal (rated) rotor speed,ω_m, we get

$$M\frac{d^2\theta_m}{dt^2} = P_m - P_e \quad (I.2)$$

where $M = J\omega_m$ is the angular momentum. It is convenient to express θ_m as

$$\theta_m = \omega_m t + \delta_m \quad (I.3)$$

where ω_m is the average angular speed of the rotor. δ_m is the rotor angle with respect to a synchronously rotating reference frame with velocity ω_m. Substituting Eq (I. 3) in Eq. (I.2) we get

$$M\frac{d^2\delta_m}{dt^2} = P_m - I_e \quad (I.4)$$

This is called the swing equation. Note that M is strictly not a constant.

However, the variation in M is negligible and M can be considered as a constant. (Termed inertia constant).

It is convenient to express Eq (I. 4) in per unit by dividing both sides

by base power S_B. Eq. (I. 4) can be expressed as

$$\frac{M}{S_B}\frac{d^2\delta_m}{dt^2} = \overline{Pm} - \overline{Pe} \quad (I.5)$$

where $\overline{P}m$ and $\overline{Pe}$ are expressed in per unit. The L.H.S. of Eq. (I.5) can be

written as

$$\frac{M}{S_B}\frac{d^2\delta_m}{dt^2} = \frac{J\omega_m}{S_B}\left(\frac{\omega_B}{\omega s}\right)\left(\frac{2}{P}\right)\frac{d^2\delta}{dt^2} = \frac{J\omega_m^2}{S_B\omega p}\frac{(fl\delta}{dt^2} = \left(\frac{2H}{\omega_B}\right)\frac{d^2\delta}{dt^2} \quad (I.6)$$

where

δ is the load angle $= \delta_m \frac{P}{2}$

P is the number of poles

ω_B is the electrical angular frequency $= \frac{P}{2}\omega_m$

H is also termed as the inertia constant given by

$$H = \frac{1}{2}\frac{J\omega_m^2}{S_B} = \frac{kinetic\ energy\ stored\ in\ mega\ joules}{Rating\ in\ MVA}$$

The inertia constant If has the dimension of time expressed in seconds.H varies in a narrow range (2-10) for most of the machines irrespective of their ratings.

From Eq. (I.6), the per unit inertia is given by

$$\overline{M} = \frac{M}{S_B} = \frac{2H}{\omega_B} \quad \text{(I.7)}$$

The above relation assumes that δ is expressed in radians and time in seconds. If δ is expressed in electrical degrees, then the per umt inertia is

$$M^l = \frac{2H}{\omega_B}.\frac{\pi}{180} = \frac{2H}{2\pi f_B}.\frac{\pi}{180} = \frac{H}{180 f_B} \quad \text{(I.8)}$$

where f_B is the rated frequency in Hz.

For convenience, in what follows, all quantities are expressed in per unit and no distinction will be made in the symbols to indicate per unit quantities. Thus, Eq. (I.4) is revised and expressed in $p.u.$ quantities as

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \quad \text{(I.9)}$$

From Fig. 2.2, the expression for P_e is obtained as

$$P_e = \frac{E_g E_b}{(x_g + x_e)}\ sin\ \delta \quad \text{(I.10)}$$

The swing equation, when P_e is expressed using Eq. (I.10), is a nonlinear differential equation for which there is no analytic solution in general.

For $P_m = 0$, the solution can be expressed in terms of elliptic integrals [1]. It is to be noted that the swing equation reduces to the equation of a nonlinear pendulum when $P_m = 0$.

Invariably, numerical methods have to be used for solving the swing equation. However simple techniques exist for the testing of system stability when subjected to small and large disturbances. These will be taken up in the following sections.

I.2.2 Some Mathematical Preliminaries

A nonlinear continuous time dynamic system is denoted by the state equation

$$\dot{x} = f(x, u) \quad \text{(I.11)}$$

where x and f are column vectors of dimension 'n'. u is a vector of dimension 'r' in general. u can be viewed as input vector. If u is a constant vector, the system is said to be autonomous. If the elements of u are explicit functions of time, t, then the system is said to be non-autonomous. If the initial condition is specified, i.e.

$$x(t_o) = x_o \quad \text{(I.12)}$$

then the solution to Eq. (I. 11)is expressed as $\varphi_t(x_o)$ to show explicitly the dependence on initial condition. (Note that since u is constant it can be treated.as parameter and the dependence of the solution on u need not be shown explicitly) f is called the vector fleld and $\varphi_t(x_o\rangle$ is called the trajectory through x_o.

$\varphi_t(x)$ where $x \in R^n$ is called the flow for non-autonomous systems, the trajectory is also a function of time t and is expressed as $\varphi_t(x_o, t_o)$ which indicates the solution passes through x_o at t_o.

In what follows, the attention will be focused only on autonomous systems as power systems can be modelled as autonomous systems. With some mild restrictions on f, the solution of Eq. (I. 11⟩ has the following properties

1. The solution exists for all t

2. At any time t, $\varphi_t(x) = \varphi_t(y)$ if and only if $x = y$. Also, as $\varphi_{(t_1+t_2)} = \varphi_{t_1}.\varphi_{t_2}$,

it follows that a trajectory of an autonomous system is uniquely specified by its initial condition and those distinct trajectories do not intersect.

3. The derivative of a trajectory with respect to the initial condition exists and is nonsingular. For t and t_o fixed, $\varphi_t(x_o)$ is continuous with respect to initial state x_o.

Equilibrium Points ⟨*EP*⟩

An equilibrium point x_e of an autonomous system is a constant solution such that

$$x_e = \varphi_t(x_e) \quad \text{(I.13)}$$

This implies that equilibrium point satisfies

$$0 = f(x_e, u) \quad \text{(I.14)}$$

Eq. (I.14) shows that x_e is a function of u.

In general, there are several equilibrium points which are obtained as real solutions of Eq. (I.14).

Stability of Equilibrium Point

An equilibrium point, x_e is said to be asymptotically stable if all nearby trajectories approach x_e as $t \to \infty$. It is unstable if no nearby trajectories remain nearby.

An unstable equilibrium point is asymptotically stable in reverse time $(as\ t \to -\infty)$. An equilibrium point is non-stable (also called saddle point) if at least one of the nearby trajectories approach x_e in forward time $(as\ t \to \infty)$ and if at least one trajectory approaches x_e in reverse time $(as\ t \to -\infty)$.

The stability of an equilibrium point can be judged by the solution of the linearized system at x_e.

Letting

$$x = x_e + \Delta x \quad \text{(I.15)}$$

and substituting in Eq. (I.11) gives

$$\dot{x} = x_e + \Delta\dot{x} = f(x_e, u) + [\frac{\partial f(x,u)}{\partial x}]_{x=x_e}\Delta x \quad \text{(I.16)}$$

From Eqs. (I.14) and (I.16) we get

$$\Delta\dot{x} = [A(x_e, u)]\Delta x \quad \text{(I.17)}$$

where A is a nxn matrix whose elements are functions of x_e and u. The ii^{th} element of $[A]$ is given by

$$A_{ij}(x_e, u) = \frac{\partial f_i}{\partial x_j}(x_e, u) \quad \text{(I.18)}$$

For a given x_e and u, the $matrix^{\backslash}A$ is constant. The solution of the linearized state equation (I.17) is given by

$$\Delta x(t) = e^{A(t-to)}\Delta x(t_o) \quad \text{(I.19)}$$

$$= c_1 e^{\lambda_1 t} v_1 + c_2 e^{\lambda_2 t} v_2 + \cdots + c_n e^{\lambda_n t} v_n \quad \text{(I.20)}$$

where $c_1, c_2 \ldots c_n$ are constants depending on the initial conditions. λ_i and v_1 are the i^{th} eigenvalue and the corresponding eigehvector of matrix $[A]$. It is assumed that all eigenvalues are distinct.

From Eq. (I.20) it can be seen that if $\Re[\lambda_i] < 0$ for all λ_i, then for all sufficiently small perturbations from the equilibrium point x_e, the trajectories tend to x_e ae $t \to \infty$. Hence, x_e is asymptotically stable.

If $\Re[\lambda_i] > 0$ for all λ_i then any perturbation leads to the trajectory leaving the neighborhood of x_e. Hence x_e is unstable. If there exists i and j such that $\Re[\lambda_i] < 0$ and $\Re[\lambda_j > 0]$ then x_e is a saddle point. If $\Re[\lambda_i] \neq 0$ for all λ_i then the equilibrium point is said to be hyperbolic. No conclusion can be drawn regarding stability of an equilibrium point if it is not hyperbolic and has no λ; with real part greater than zero.

A stable or unstable equilibrium point with no complex eigenvalues is called a $(node)$.

Remarks

1. For all practical purposes, an equilibrium point which is not stable, can be termed as unstable. For a hyperbolic equilibrium point, the number of eigenvalues with positive real parts determines its type. A type 1 Unstable EP (UEP) has one eigenvalue in the RRP of the 's' plane. An EP with all eigenvalues in the R.H.P. is called a source.

2. Equilibrium points are also termed as fixed points. A Stable EP (SEP) is also called a sink.

Steady-state Behavior

The steady state behavior of an autonomous system is obtained from the asymptotic behavior of the system trajectories assuming that the difference between the trajectory and its steady state is called 'transient'.

It is obvious that stable equilibrium points are subsets of steady state behavior. In addition, a system may also exhibit **limit** cycles. A limit cycle is an isolated periodic solution (with the trajectory forming a closed curve in state space).

There can be more complex behavior such as chaos which does not have any fixed pattern in the steady state solution. In general, chaotic systems exhibit sensitive dependence on initial conditions and the spectrum of the steady state solution has a broad-band noise like component [2]

I.2.3 Analysis of Steady State Stability

The swing equation for system shown in Fig. I.2 is

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_{max}\ sin\ \delta \quad \text{(I.21)}$$

where

$$P_{mw} = \frac{E_g E_b}{(x_g + x_e)} \quad \text{(I.22)}$$

Equation (I.21) is same as $Eq.$ (I. 9) except for the addition of a damping Term $D\frac{d\delta}{dt}$. It is assumed that D is small but positive. It can be ignored when the solution of the swing equation is required only for a short period (say 1 to 2 seconds) following a disturbance. Hence D can be neglected in transient stability analysis but needs to be considered in steady state stability analysis.

Equation (I.21) can be expressed in the state space form as

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = -\frac{D}{M}x_2 - \frac{P_{max}}{M}\ sin\ x_1 + \frac{P_m}{M} \quad \text{(I.23)}$$

where

$$x_1 = \delta, x_2 = \frac{d\delta}{dt}$$

The equilibrium points for the system of Eq. (1.23) are given by

$$x_2 = 0$$

$$x_1 = sin^{-1}\frac{P_m}{P_{max}}\} \quad \text{(I.24)}$$

From the power angle curves shown in Fig. 2.3, it can be seen that there are two values of δ corresponding to a specified value of P_m (when $P_m < P_{max}$)

when the range of δ is confined $to -180^o < \delta < 180^o$. Thus, there are two equilibria given by

$$x_e^1 = x_s = (\delta_\theta, 0)$$

$$x_e^2 = x_u = (\delta_u, 0) \qquad \text{(I.25)}$$

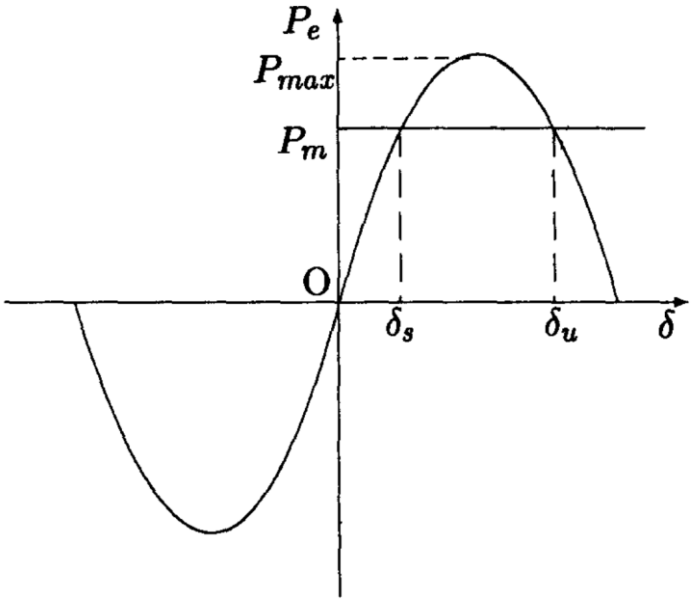


Figure I.3: Power angle curve

It can be shown by linearizing Eq. (I.23) that x_s is a stable equilibrium point and x_u is the unstable equilibrium point. The criterion for stability is an algebraic one given by

$$\frac{dP_e}{d\delta} > 0 \quad \text{(I.26)}$$

Proof: Let $y_1 = \Delta x_1, y_2 = \Delta x_2$

Then,

$$\begin{Bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{Bmatrix} = \begin{Bmatrix} 0 & 1 \\ -\frac{K}{M} & -\frac{D}{M} \end{Bmatrix} \begin{Bmatrix} y_1 \\ y_2 \end{Bmatrix} \quad \text{(I.27)}$$

where

$$K = P_{max} \cos \delta_e \quad \text{(I.28)}$$

δ_e is the angle at equilibrium (δ_s or δ_u)

The eigenvalues of the linearized system are given by

$$\lambda = -\frac{D}{2M} \pm \sqrt{\frac{D^2}{4M^2} - \frac{K}{M}} \quad \text{(I.29)}$$

If K is positive then both eigen values have negative real parts. If K is negative one of the eigenvalues is positive real. For small D, and $K > 0$ eigenvalues are complex given by

$$\lambda = -\sigma \pm j\omega \quad \text{(I.30)}$$

where

$$\sigma = \frac{D}{2M}, \omega = \sqrt{\frac{K}{M} - \frac{D^2}{4M^2}}$$

Hence, for the stability of the equilibrium point, a necessary condition is

$$K > 0 \quad \text{(I.31)}$$

Remarks

1. The expression for K in the general case is given by

$$K = \frac{dP_e}{d\delta}(\delta_e) \quad \text{(I.32)}$$

This shows explicitly the dependence of K on (δ_ε) . In general, P_e can be a nonsinusoidal function of δ, although for the special case considered (neglecting losses and saliency) the power angle curve is sinusoidal.

2. For $\delta_e = \delta_s$, $K > 0$ while for $\delta_e. = \delta_u$, $K < 0$. Hence x_s is a stable equilibrium point while x_u is unstable (a saddle point).

3. The two equilibrium points come closer as P_m (also equal to the steady state power output of the generator) is increased. The maximum power supplied by the generator (steady-state stability limit) is equal to P_{max} and occurs at $\delta^* = 90^o$ (in this particular case). The condition for stability can also be stated as

$$\delta_s < \delta^* \quad \text{(I.33)}$$

The loci of eigenvalues in the s plane as P_m is varied is shown in Fig. I.4

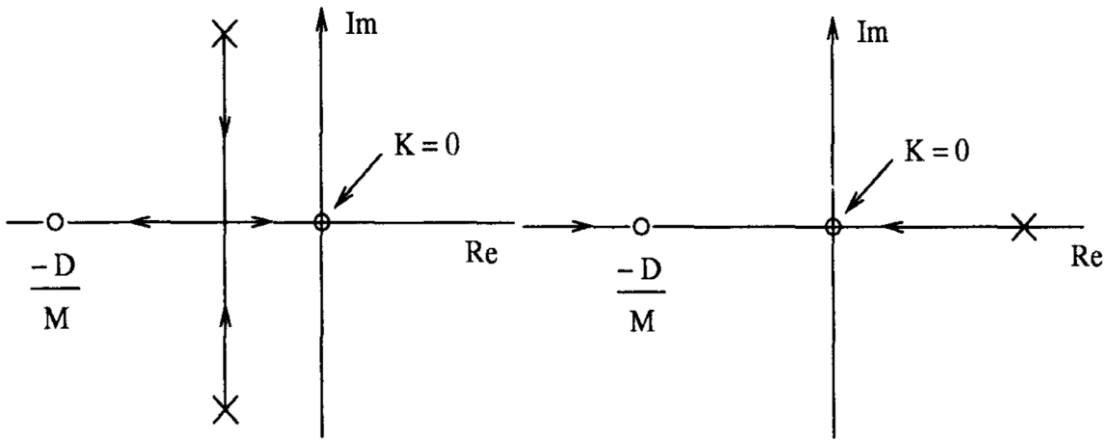
Fig. I.4 (a) shows the loci of eigenvalues calculated at SEP (Stable Equilibrium Point). The eigenvalues are initially complex and split into two real values. One of them reaches origin as P_m is increased to P_{max} (when $K = 0$). The other eigenvalue approaches $(-\frac{D}{M})$

Fig I.4 (b) shows the loci for UEP (Unstable Equilibrium Point). Here both eigenvalues are real. As P_m increases, both move towards the origin.

At $P_m = P_{max}$ one of the values is exactly zero while the other is $(-\frac{D}{M})$. It is to be noted that for $p_m > P_{max}$ there is no equilibrium.

Comments

1. The stability criterion given in (I.26) is an algebraic one. While this is simple and convenient (avoids computation of eigenvalues) it is to be



(a) at SEP **(b) at UEP**

Figure I.4: Loci of eigenvalues

noted that this is derived from dynamic analysis. Hence the extension of this criterion to more complex dynamics (with the relaxation of some of the assumptions given earlier) is not valid. For the general case, the mathematical analysis involving linearization of the system and checking of the system stability cannot be avoided. (It is to be noted that in simple cases, the stability of linear systems can be directly determined, without recourse to eigenvalue computations, i.e., Routh-Hurwitz and Nyquist criteria. However, these still require the knowledge of system equations).

2. It is interesting to note that the limit of steady state stability using the classical model is also equal to the maximum power transferred in the network (neglecting losses). In other words, the steady state stability limit is also the network limit. As it would be practical to maintain stability margin, the network limit must be larger than the maximum power output of the generator.

3. The criterion of $\frac{dP_e}{d\delta} > 0$, can also be derived from 'physical' arguments. If P_m is suddenly increased by a small amount, the rotor initially accelerates (as δ cannot change suddenly). As the velocity and consequently δ increase, the electric power output also increases (if the system is stable) for an equilibrium to be reached. For this to be possible, P_e should increase with increase in δ Similar arguments apply if P_m is suddenly decreased

It is to be noted that such ‘physical’ arguments, although intuitively appealing, can sometimes lead to false conclusions. It will be shown in chapter that the consideration of detailed model of the synchronous generator leads to different criteria for stability than given by (I.26).

I.3 Conclusion:

A major problem faced by modern power systems is the problem of voltage collapse or voltage instability which is a manifestation of steady-state instability. Historically steady-state instability has been associated with angle instability and slow loss of synchronism among generators. The slow collapse of voltage at load buses under high loading conditions and reactive power limitations, is a recent phenomenon.

This approach of reducing the equivalent reactance of the synchronous machine from *Xd* to *Xg* to account for voltage regulation is only accurate in determining the power limit in the absence of oscillatory instability. This implies that the simplified analysis of excitation controllers is not valid and detailed generator models need to be considered. The detailed component models synchronous machine, excitation and prime mover controllers, loads, transmission lines and SVC are taken up in the next chapters.

Chapter II

Analysis and Modulization of Synchronous Machine.

II.1 Modelling of Synchronous Machine

II.1.1 Introduction:

Simple models of the synchronous generators are not adequate for accurate description of the power system dynamics. In this chapter, detailed models of synchronous machine are developed from the basic equations using phase variables and application of Park's transformation. Park's transformation results in time-invariant machine equations which are easier to handle. Also, there is a close connection between Park's variables and the phasors describing voltages and currents in steady state.

In this chapter, the derivation of the machine model is accompanied by its representation using per unit quantities and equivalent circuits on d- and q-axes. Measurement of machine parameters and representation of saturation are also discussed. The application of the model for transient analysis is outlined at the end.

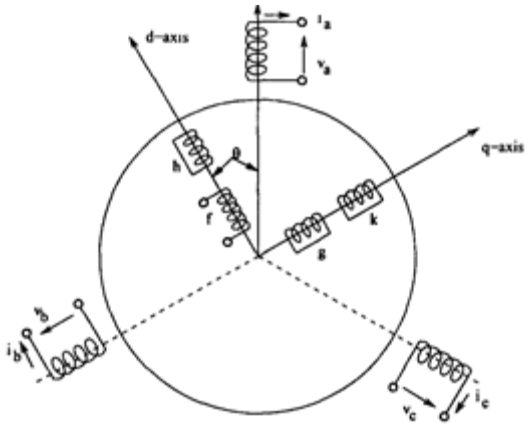


Figure II.1: synchronous machine

II.1.2 Synchronous Machine

The synchronous machine considered is shown in Fig. II.1. This shows three phase armature windings (a, b and c) on the stator and four windings on the rotor including the field winding 'f'. The damper (or damper) circuits in the salient pole machine or the eddy-current effects in the rotor are represented by a set of coils with constant parameters. Three damper coils, *'h'* in the d-axis and g, k on the q-axis is shown in Fig. II.1. The number *of* damper coils represented can vary from zero (in the simplest model) to five or more using Jackson Winchester model [3]. However, the most detailed model used extensively in power system

dynamic studies is limited to 3 damper coils. (It is also easier to obtain the parameters of this and simpler models).

The following assumptions are used in the derivation of the basic equations of the machine.

1. The mmf in the airgap is distributed sinusoidally and the harmonics are neglected.
2. Saliency is restricted to the rotor. The effect of slots in the stator is neglected.
3. Magnetic saturation and hysteresis are ignored.

The representation of the saturation will be considered later in this chapter. In what follows, the machine is assumed to have two poles. There is no loss of generality in doing this as the rotor angle θ (with respect to a stationary axis) is assumed to be the electrical angle and the equations are invariant with respect to the number of poles. The mechanical angle θ_m is related to θ by

$$\theta_m = \frac{2}{P}\theta \qquad \text{(II.1)}$$

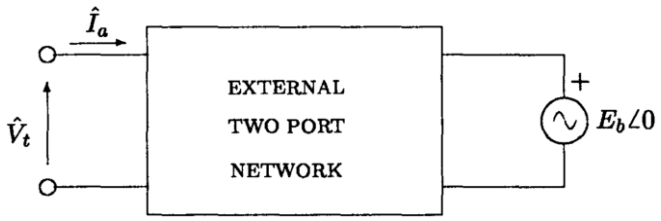
II.2 Dynamics of a Synchronous Generator Connected to Infinite Bus

the dynamics of a synchronous generator is illustrated by taking up the example of a single machine connected to an infinite bus (SMIB).

Although this is the simplest system example that can be considered, it is not entirely unrealistic. For example, a remote power station connected to a load center through a long transmission line can be approximated by SMIB system. Although a power station consists of more than one generator, it is acceptable to assume that, for disturbances external to the power station, the generators can be represented by an equivalent machine.

II.2.1 System Model

The system considered is shown in Fig. II.2. This shows the external network (represented by a black box) with two ports. One port is connected to the generator terminals while the second port is connected to a voltage source E_b(representing the infinite bus). Both the magnitude *Eb* and the phase angle of the voltage source are assumed to be constants. Also, there is no loss of generality in assuming the phase angle of the bus voltage as zero (reference bus). (However, in a general case, where the voltage source is Thevenin's equivalent, both the voltage magnitude and angle may be treated as variable).



$$\hat{y} = (v_q + jv_d)e^{j\delta}, \hat{t} = (i_q + ji_d)e^{j\delta}$$

Figure II.2: External two port network

One of the major assumptions in the analysis of dynamic performance involving low frequency « 5 Hz) behavior of the system, is to neglect the transients in the external network. This simplifies the analysis as the network is modelled by algebraic equations based on single phase representation (see chapter 5). The network equations are conveniently expressed using voltage (and current) phasors with D-Q components (expressed on a synchronously rotating or Kron's reference frame).

II.2.2 Synchronous Machine Model

II.2.2.1 Stator Equations:

The stator equations in Park's reference frame are described. Expressed in per unit, these are:

$$-\frac{1d\psi_d}{\omega_B dt} - \frac{\omega}{\omega_B}\psi_q - R_a i_d = v_d \qquad (II.2)$$

$$-\frac{1d\psi_q}{\omega_B dt} + \frac{w}{\omega_B}\psi_d - R_a i_q = v_q \qquad (II.3)$$

It is assumed that the zero sequence currents in the stator are absent. If stator transients are to be ignored, it is equivalent to ignoring the $p\psi_d$ and $p\psi_q$ terms in Eqs. (II.2) and (II.3) (Note that p is the differential operator$\frac{d}{\mathrm{dt}}$). In addition, it is also advantageous to ignore the variations in the rotor speed ω. This can be justified on the grounds that under disturbances considered the variations in the speed are negligible. (Actually, in some cases neglecting $p\psi_d$ and $p\psi_q$ terms go together with neglecting variations in ω) With these assumptions, Eqs. (II.2) and (II.3) can be expressed as

$$-(1 + S_{mo})\psi_q - R_a i_d = v_d \qquad \text{(II.4)}$$

$$(1 + S_{\pi w})\psi_d - R_a i_q = v_q \qquad \text{(II.5)}$$

where S_{mo} is the imtial operating slip defined as

$$S_{mo} = \frac{\omega_o - \omega_B}{\omega_B} \qquad \text{(II.6)}$$

II.2.2.2 Rotor Equations

Since the stator Eqs. (II.4 and II.5) are algebraic (neglecting stator transients), it is not possible to choose stator currents i_d and i_q as state variables (state variables have to be continuous functions of time, whereas i_d and i_q can be discontinuous due to any sudden changes in the network- this point will be made clear later). As rotor windings either remain closed (damper windings) or closed through finite voltage source (field winding), the flux linkages of these windings cannot change suddenly. This implies that if i_d changes suddenly, the field and damper currents also change suddenly in order to maintain the field and damper flux linkages continuous. The flux linkage immediately after a disturbance remains constant at the value just prior to the disturbance. (This property is termed as the theorem of constant flux linkages in the literature).

II.2.2.3 Calculation of Initial Conditions

The system equations (II.11) are nonlinear and have to be solved numerically. In solving these equations, it is assumed that the system is at a stable equilibrium point (SEP) till time $t = 0$, and a disturbance occurs at $t = 0$ or later. It is necessary to calculate the initial conditions x_o at time $t = 0$ based on the system operating point determined from load (power) flow.

From power flow calculations in steady state, we get the real and reactive power (P_t and Q_t), the voltage magnitude (V_t) and angle (θ) at the generator terminals. Here θ is the angle with respect to the slack (infinite) bus.

In steady state, the derivatives of all the state variables, $\dot{x} = 0$. From this condition, we get

$$E'_{qo} = E_{fde} + (x_d - x'_d) i_{do} \qquad \text{(II.7)}$$

$$E'_{do} = -(x_q - x'_q) i_{qo} \qquad \text{(II.8)}$$

$$T_{mo} = T_{eo} = E'_{qo} i_{qo} + E'_{do} i_{do} + (x'_d - x'_q) i_{do} i_{qo} \qquad \text{(II.9)}$$

In the above equations, the subscript 'o' indicates the operating values. It is to be noted that, in general, the initial slip $S_{m\sigma}$ cannot be determined from Eq. (II.6). It has to be specified separately. As mentioned earlier, it can be taken as zero.

Substituting the previous Eqs, we get

$$E_{fdo} + xdi_{do} - R_a i_{qo} = v_{qo} \quad \text{(II.10)}$$

$$-x_q i_{qo} - R_a i_{do} = v_{do} \quad \text{(II.11)}$$

From the above, one can obtain

$$R_{f^{do}} + (x_d - x_q)i_{do} = (v_{qo} + jv_{do}) + (R_a + jx_q)(i_{qO} + ji_{do})$$

$$= \hat{V}\angle - \delta + (R_a + jx_q)\hat{I}\angle - \delta \qquad \text{(II.12)}$$

Defining

$$E_q\angle\delta = \hat{y} + (R_a + gx_q)\hat{I} \qquad \text{(II.13)}$$

We can express,

$$E_{fdo} = E_{qo} - (x_d - x_q)i_{do} \quad \text{(II.14)}$$

Eq. (II.10) can be used to fix the position of q-axis. The phasor diagram shown in Fig. II.3 represents the Eqs. (II.10) and (II.11). The d- $a1_c d$ q-axis components of the armature current (i_d, i_q) and the terminal voltage (v_d, v_q) are also shown in the diagram.

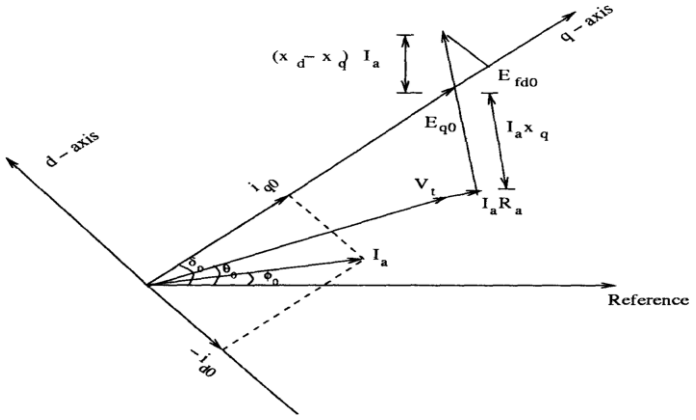


Figure II.3: Phasor Diagram

The procedure for the computation of the initial conditions is given below

1. Compute $\hat{I}$ from

$$\hat{I} = I_{ao}\angle\varphi_0 = \frac{P_t - jQ_t}{V_{to}\angle - \theta_o}$$

2. Compute E_{qo} and δ_o from

$$E_{go}\angle\delta_o = V_{to}\angle\theta_o + (R_w + jx_q)I_{ao}\angle\varphi_0$$

(Note that P_t, Q_t, V_{to} and θ_o are obtained from the power flow analysis in steady $state\rangle$

3. Compute

$$i_{do} = -I_{ao} \sin(\delta_o - \varphi_0\rangle$$

$$i_{qo} = I_{ao} \cos(\delta_o - \varphi_0)$$

$$v_{do} = -V_{to} \sin(\delta_a - \theta_o)$$

$$v_{qo} = V_{to} cos(\delta_o - \theta_o)$$

4. Compute

$$E_{fdo} = E_{qo} - (x - x)i_{do}$$

$$E_{qo}^{'} = E_{fdo} + (x_d - x_d^{'})i_{do}$$

$$E_{do}^{'} = -(x_q - x_q^{'})i_{qo}$$

$$T_{eo} = R_{qo}^{'} i_{qo} + E_{do}^{'} i_{do} + (x_d^{'} - x_q^{'})i_{do} i_{qo} = T_{mo}$$

II.3 Analysis of Single Machine System

II.3.1 Introduction:

With classical model of the synchronous machine, the steady state instability at the limiting power is characterized by a slow monotonic increase (or decrease) in the rotor angle, resulting in loss of synchronism. With the advent of automatic voltage regulators (AVR) it was felt that the steady state stability limit can be enhanced as the AVR acts to overcome the armature reaction. A simplified representation of the effect of AVR is the reduction of generator reactance from x_d to a much smaller value (around $x_d^{'}$).

It is to be noted that without AVRs modern turbo-generators cannot operate at full rated power, as their synchronous reactance are around 2.0 pu. Also, the transient stability is improved by fast acting exciters with high gain AVRs. Unfortunately, such fast acting excitation systems can result in negative damping of the rotor oscillations induced by small disturbances such as random load changes. Thus, system operators started observing spontaneous power oscillations of low frequency in interconnecting ties or long transmission lines. These oscillations have been observed in several systems and are of major concern in

system operation. This is mainly due to the fact that the problem is aggravated at peak loading conditions and high external impedance (connected to a generator).

II.3.2 Small Signal Analysis with Block Diagram Representation

Consider a single machine system shown in Fig. II.4. For simplicity, we will assume a synchronous machine represented by model 1.0 neglecting damper windings both in the d and q axes. (It is possible to approximate the effects of damper windings by a nonlinear damping term, if necessary). Also, the armature resistance of the machine is neglected and the excitation system represented by a single time-constant system shown in Fig. II.5.

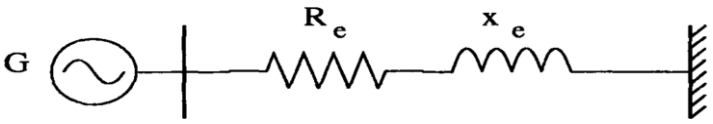


Figure II.4: A single machine system

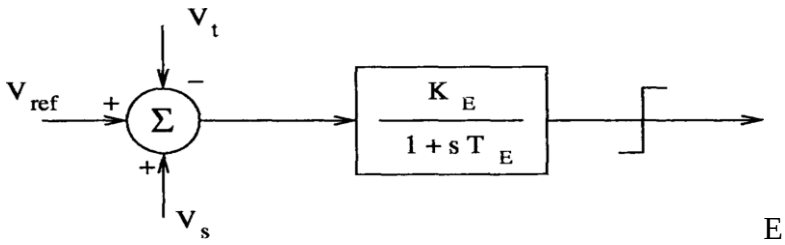


Figure II.5: Excitation system

The algebraic equations of the stator are

$$E_q^{'} + x_d^{'} i_d = v_q \quad \text{(II.15)}$$

$$-x_q i_q = v_d \quad \text{(II.16)}$$

The complex terminal voltage can be expressed as

$$vQ + jv_d = (v_q + jv_d)e^{j\delta} = (i_q + ji_d)(R_e + jx_e)e^{j\delta} + E_b\angle 0$$

From which

$$(v_q + jv_d) = (i_q + ji_d)(R_e + jx_\varepsilon) + E_b e^{-j\delta} \text{ . (II.17)}$$

Separating real and imaginary parts, Eq. (7.3) can be expressed as

$$v_q = R_e i_q - x_e i_d + E_b \cos\delta \quad \text{(II.18)}$$

$$v_d = R_e i_d + x_e i_q - B_b \sin\delta \quad \text{(II.19)}$$

Substituting Eqs. (7.4) and (7.5) in Eqs. (7.1) and (7.2), we get,

$$\begin{Bmatrix} (x_d^{'} + x_e) & -R_e \\ -R_e & -(x_q + x_e) \end{Bmatrix} \begin{Bmatrix} i_d \\ i_q \end{Bmatrix} = \begin{Bmatrix} E_b\, cos\delta - E_q^{'} \\ -sin\delta\, E_b \end{Bmatrix} \quad \text{(II.20)}$$

The expressions for i_d and i_q are obtained from solving (7.6) and are given below

$$i_d = \frac{1}{A}[R_e E_b \sin\delta + (x_q + x_e)(E_b \cos\delta - E_q^{'})] \quad \text{(II.21)}$$

$$i_q = \frac{1}{A}[(x_d^{'} + x_e)E_b \sin\delta - R_e(E_b \cos\delta - Reject_q)] \quad \text{(II.22)}$$

where

$$A = (x_d' + x_e)(x_q + x_e) + R_e^2 \quad \text{(II.23)}$$

Linearizing Eqs. (7.7) and (7.8) we get

$$\Delta i_d = C_1 \Delta\delta + C_2 \Delta f f_q \quad \text{(II.24)}$$

$$\Delta i_q = C_3 \Delta\delta + C_4 \Delta E_q' \quad \text{(II.25)}$$

where

$$C_1 = \frac{1}{A}[R_e E_b \cos\delta_o - (x_q + x_e)B_b \sin\delta_o]$$

$$C_2 = -\frac{1}{A}(x_q + x_e)$$

$$C_3 = \frac{1}{A}[(x_d^{'} + x_e)E_b \cos\delta_o + R_e E_b \sin\delta_o]$$

$$C_4 = \frac{R_e}{A}$$

Linearizing Eqs. (II.15) and (II.16), and substituting from Eqs. (II.24) and (II.25),

we get,

$$\Delta v_q = x_d' C_1 \Delta\delta + (1 + x_d' C_2)\Delta E_q' \quad \text{(II.26)}$$

$$\Delta v_d = -x_q C_3 \Delta\delta - {}_{Xq} C_4 \triangle E_q' \quad \text{(II.27)}$$

It is to be noted that the subscript ‘o’ indicates operating value of the variable.

II.3.2.1 Rotor Mechanical Equations and Torque Angle Loop

The rotor mechanical equations are

$$\frac{d\delta}{dt} = \omega_B(S_m - S_{mo}) \quad \text{(II.28)}$$

$$2H\frac{dS_m}{dt} = -DS_m + T_m - T_e \quad \text{(II.29)}$$

$$T_e = E_q^{'} i_q - (x_q - x_d^{'}) i_d i_q \quad \text{(II.30)}$$

Linearizing $Eq.$ (II. 30) we get

$$\Delta T_e = [E'_{qo} - (x_q - x'_d) i_{do}]\Delta i_q + i_{qo}\Delta E'_q - (x_q - x'_d) i_{qo}\Delta i_d \quad \text{(II.31)}$$

Substituting Eqs(II. 28) and (II.29) in Eq. (II.31), we can express ΔT_e as

$$\Delta T_e = K_1\Delta\delta + K_2\Delta E'_q \quad \text{(II.32)}$$

where

$$K_1 = E_{qo}C_{\$} - (x_q - x_d^{'}) i_{qo} C_1 \quad \text{(II.33)}$$

$$K_2 = E_{qo}C_4 + i_{qo} - (x_q - x_d^{'}) i_{qo} C_2 \quad \text{(II.34)}$$

$$E_{qo} = ff_{qo} - (x_q - x_d^{'}) i_{do} \quad \text{(II.35)}$$

Linearizing Eqs. (II.33) and (II.34) and applying Laplace transform, we get

$$\Delta\delta = \frac{\omega_B}{S}\Delta S_m = \frac{\omega B}{s}\Delta\overline{\omega} \quad \text{(II.36)}$$

$$\Delta S_m = \frac{1}{2Hs}[\Delta T_m - \Delta T_e - D\Delta S_m] \quad \text{(II.37)}$$

The combined Eqs. (II.32), (II.35) and Eq. (II.37) represent a block diagram shown in Fig. II.6. This represents the torque-angle loop of the synchronous machine.

For classical machine model, $\triangle E'_q = 0$ and the characteristic equation given by

$$2Hs^2 + Ds + K_1\omega_B = 0 \quad \text{(II.38)}$$

For stability, both D and K_1 should be positive. If D is negligible, the roots of the characteristic equations are

$$s_1, s_2 = \pm j\sqrt{\frac{K_1 w_B}{2H}} = \pm j\omega_n \quad \text{(II.39)}$$

where ω_n is the natural (radian) frequency of oscillation of the rotor. Typically, the frequency of oscillation lies in the range of 0.5 to 2.0 Hz although extreme values of 0.1 Hz at the low end and 4 Hv at the high end are also possible.

II.3.2.2 Representation of Flux Decay

The equation for the field winding can be expressed as

$$T'_{do}\frac{dE'_q}{dt} = E_{fd} - E'_q + (x_d - x'_d)i_d \quad \text{(II.40)}$$

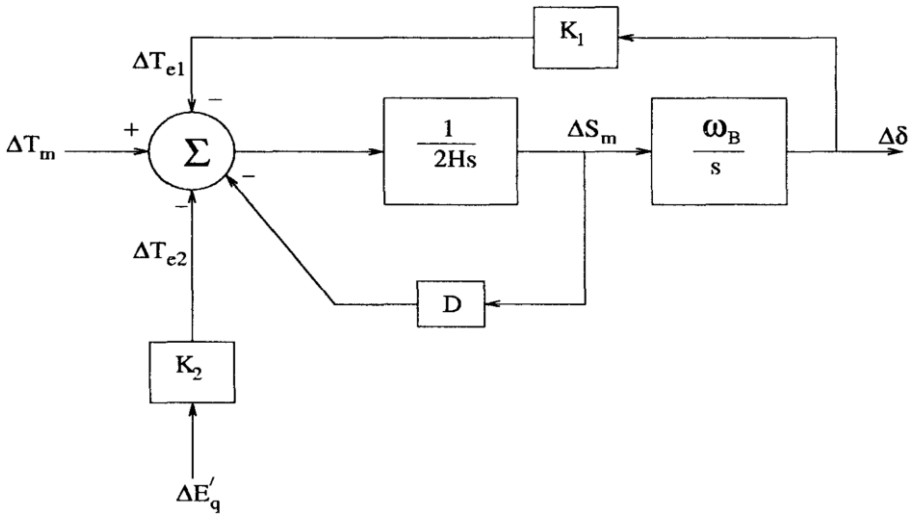


Figure II.6: Torque-angle loop

Linearizing Eq. (II.40) and substituting from Eq. (II.34) we have

$$T'_{do}\frac{d\Delta E'_q}{dt} = \Delta E_{fd} - \Delta ff_q + (xd - x'_d)(C_\lambda \Delta\delta + C_2 \Delta E'_q) \quad \text{(II.41)}$$

Taking Laplace transform of (II.41) we get,

$$(1 + sT'_{do}K_3)\Delta E'_q = K_3\Delta E_{fd} - K_3K_4\Delta\delta \quad \text{(II.42)}$$

where

$$K_3 = \frac{1}{[1-(x_d - x'_d)C_2]} \quad \text{(II.43)}$$

$$K_4 = -(x_d - x'_d)C_1 \quad \text{(II.44)}$$

$Eqs(\text{II. } 40)$ can be represented by the block diagram shown in Fig. II.7.

II.3.2.3 Representation of Excitation System

The block diagram of the excitation system considered is shown in Fig. II.6. The linearized equations of this system can also be represented by the same block diagram omitting the

limiter. For the present analysis we can ignore the auxiliary signal V_s. The perturbation in the terminal voltage V_t can be expressed

as

$$\Delta V_t = \frac{v_{do}}{y_{to}}\Delta v_d + \frac{v_{qo}}{y_{to}}\Delta v_q \quad \text{(II.45)}$$

Substituting from Eqs. (II.40) and (II.42) in (II.45), we get

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q \quad \text{(II.46)}$$

where

$$K_5 = -(\frac{v_{do}}{y_{to}})x_q C_3 + (\frac{v_{qo}}{y_{to}})x'_d C_1 \quad \text{(II.47)}$$

$$K_6 = -(\frac{v_{do}}{V_{to}})x_q C_4 + (\frac{v_{qo}}{y_{to}})(1 + x'_d C_8) \quad \text{(II.48)}$$

Using Eq. (II.45) the block diagram of the excitation system is shown in Fig. II.7. The coefficients K_1 to K_6 defined in Eqs. (II.33), (II.34), (II.43), (II.44), (II.47) and (II.48) are termed as Heffron-Phillips's constants. They are dependent on the machine parameters and the operating conditions. Generally, K_1, K_2, K_3 and K_6 are positive. K_4 is also mostly positive except for cases when R_e is high. K_5 can be either positive or negative. K_5 is positive for low to medium external impedances $(R_e + jx_e)$ and low to medium loadings. K_5 is usually negative for moderate to high external impedances and heavy loadings.

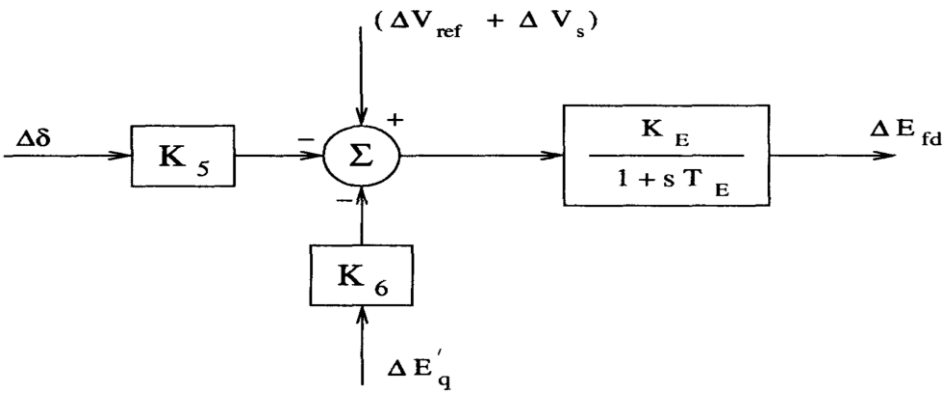


Figure II.7: Excitation system block diagram

II.3.2.4 Computation of Heffron-Phillips Constants for Lossless Network

For $R_e = 0$, the expressions for the constants K_1 to K_6 are simplified. As the armature resistance is already neglected, this refers to a lossless network on the stator side. The expressions are given below.

$$K_1 = \frac{E_b E_{qo} \cos \delta_o}{(x_e + x_q)} + \frac{(x_q - x_d^{'})}{(x_e + x_d)} E_b i_{qo} \sin \delta_o$$

$$K_2 = (x_e + x_d)^{i_{qo}} (x_e + x_q) = \frac{E_b \sin \delta_o}{(x_e + x_d)}$$

$$K_3 = \frac{(x_e + x_d^{'})}{(x_d + x_e)}$$

$$K_4 = \frac{(x_d - x_d^{'})}{(x_d^{'} + x_e)} E_b \sin \delta_o$$

$$K_5 = \frac{-x_q v_{do} E_b \cos \delta_o}{(x_e + x_q) V_{to}} - \frac{x_d^{'} v_{qo} E_b \sin \delta_o}{(x_e + x_d) V_{to}}$$

$$K_6 = \frac{x_e}{(x_e + x_d^{'})} . (\frac{v_{qo}}{V_{to}})$$

It is not difficult to see that for $x_e > 0$, the constants K_1, K_2, K_3, K_4 and K_6 are positive. This is because δ_o is generally less than 90^o and i_{qo} is positive. K_3 is independent of the operating point and less than unity $(as\ x_d' < x_d)$. Note that x_e is generally positive unless the generator is feeding a large capacitive load (which is not realistic).

II.3.2.5 System Representation

The system block diagram, consisting of the representation of the rotor swing equations, flux decay and excitation system, is obtained by combining the component blocks shown in Figs. II.4to II.8. The overall block diagram is shown in Fig. II.8. Here the damping term (*D*) in the swing equations is neglected for convenience. (Actually *D* is generally small and neglecting it will give slightly pessimistic results).

From Fig. II.8, the electrical torque compound ΔT_{e2} is related to $\Delta\delta$ by the following relation

$$\Delta T_{e2}(s) = -\frac{K_2 K_4}{T_{do}} [\frac{s + \frac{1}{T_{\lambda l}}(1 + \frac{K_5 K_E}{K_4})}{s^2 + s(\frac{1}{T_E} + \frac{1}{K_3 T'_{do}}) + (1 + K_3 K_6 K_{I3})/K_3 T'_{do} T_E}] \Delta\delta(s) \qquad \text{(II.49)}$$

For a static exciter, $T_{\mathcal{B}}$ is very small. If $T_{ll} \simeq 0$, the transfer function $\frac{\Delta T_{e2}}{\Delta\delta}$ can be approximated as

$$\frac{\Delta T_{e2}(s)}{\Delta\delta(s)} \simeq -\frac{K_2 K_4}{T_{do}} \frac{(1+K_5 K_{\mathcal{B}}/K_4)}{[s+(1+K_3 K_6 K_{Reject})/K_3 T_{do}]} \quad \text{(II.50)}$$

For large values of K_E, Eq (II. 50) can be further approximated as

$$\frac{\Delta T_{e2}(s)}{\Delta\delta(s)} \simeq -\frac{K_2 K_5 K_E}{(T'_{do} s+K_\delta K_E)} = -\frac{K_2 K_5/K_6}{sT'_{do}/(K_6 K_E)+1} \quad \text{(II.51)}$$

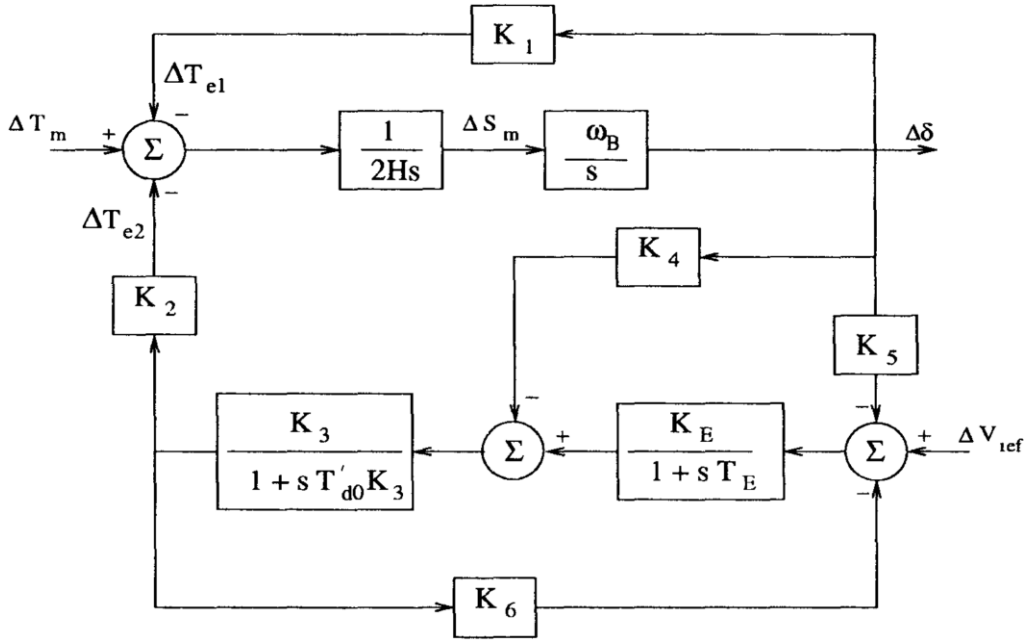


Figure II.8: Overall block diagram

Example 1

A synchronous generator is connected to an infinite bus through an external reactance $x_e = 0.4$ pu. K_1 toK_6 at the operating point

(a) $P_g = 0.5, V_t = 1.0, E_b = 1.0$

(b) $P_g = 1.0, V_t = 1.0, E_b = 1.0$

The machine data: $x_d = 1.6, x_q = 1.55, x'_d = 0.32, T'_{do} = 6.0, H = 5, D = 0, f_B = 60Hz.$

We used this MATLAB script to calculate the initial conditions and the Heffron-Phillips constants

```
clear
clc
Eb=1;Vt0=1;Pt=0.5;Xe=0.4;
Xd=1.6;Xq=1.55;Xdd=0.32;Xqq=0.32;Ra=0;Tdd0=6;Tqq=0.1;H=5;D=0;fb=60;wb=2*pi*fb;

theta0=asin((Pt*Xe)/(Vt0*Eb));
Vt=exp(j*theta0);
Ia=(Vt-Eb)/(j*Xe);abs(Ia);thetaI=angle(Ia)*180/pi;
Eq0=Vt+j*Xq*Ia;abs(Eq0);delta0=angle(Eq0)*180/pi;
id0=-abs(Ia)*sind(delta0-thetaI);
iq0=abs(Ia)*cosd(delta0-thetaI);
Vd0=-Vt0*sind(delta0-theta0*180/pi);
Vq0=Vt0*cosd(delta0-theta0*180/pi);
Efd0=abs(Eq0)-(Xd-Xq)*id0;
Eqq0=Efd0+(Xd-Xdd)*id0;
Edd0=-(Xq-Xqq)*iq0;
Te0=Eqq0*iq0+Edd0*id0+(Xdd-Xqq)*id0*iq0;
K1=(Eb*abs(Eq0)*cosd(delta0))/(Xe+Xq)+(Xq-Xdd)/(Xe+Xdd)*(Eb*iq0*sind(delta0));
K2=(Xe+Xq)/(Xe+Xqq)*iq0;
K3=(Xe+Xdd)/(Xd+Xe);
K4=(Xd-Xdd)/(Xdd+Xe)*Eb*sind(delta0);
K5=((-Xq*Vd0*Eb*cosd(delta0))/((Xe+Xq)*Vt0))-
(Xdd*Vq0*Eb*sind(delta0))/((Xe+Xdd)*Vt0);
K6=(Xe/(Xe+Xdd))*(Vq0/Vt0);
Ke=200;
Te=Eqq0*iq0+Edd0*id0+(Xdd-Xqq)*iq0*id0;
```

II.3.3 Small Signal Model: State Equations

II.3.3.1 Simplified Model

It is possible to express the system equations in the state space form. From the block diagram, shown in Fig. II.8, the following system equations can be derived

$$\dot{x} = [A]x + [B](\Delta V_{ref} + \Delta V_s)$$

where

$$x^t = [\Delta S_m \; \Delta\delta \; \Delta E_q^{'} \; \Delta E_{fd}]$$

$$[A] = \begin{Bmatrix} 0 & -\frac{K_2}{2H} & -\frac{K_1}{2H} & 0 \\ w_b & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T'_{do}} & -\frac{1}{T_{do}^{'}K_3} & \frac{1}{T_{do}} \\ 0 & -\frac{K_e K_5}{T_E} & -\frac{K_e K_6}{T_E} & -\frac{1}{T_E} \end{Bmatrix}$$

$$[B]^t = [0 \; 0 \; 0 \; \frac{K_E}{T_E}]$$

The damping term D, is included in the swing equation. The eigenvalues of the matrix should lie in LHP in the 's' plane for the system to be stable. The effect of various parameters (for example, $K_E \; and \; T_E$) can be examined from eigenvalue analysis. It is to be noted that the elements of matrix $[A]$ are dependent on the operating condition.

II.4 Conclusion:

by taking up the example of a single machine connected to an infinite bus (SMIB) makes the study of stability of electrical network way easier a clearer. In stability studies, where swing curves are of importance, it is acceptable to ignore the transients in the stator. In this case, the stator is described by algebraic equations. Neither $\psi_d, \psi_q \; or \; i_d, i_q$ can be considered as state variables as they can change suddenly in response to step changes in the terminal voltages *Vd* and *Vq*.

The problem of oscillatory instability (which can lead to loss of synchronism) introduced by static excitation systems can be solved utilizing Power System Stabilizers (PSS). This is discussed in the next chapter.

Chapter III

Fuzzy logic stabilization.

III.1 Introduction:

The first applications of fuzzy logic were confined to non-technical fields, such as commerce and management, and it was not until 1974 that it was applied automatically by Mamdani which started with the realization of the first fuzzy controller. In this first section, we deal with two fundamental notions: fuzzy and fuzzy logic and subsets.

Fuzzy logic came into being after Boolean logic. The latter is based on the principle that any proposition can only be true or false (all or nothing), and yet human thought is much more complex and more nuanced than a rigid set of laws because, for a human being, the word "nothing " is not quite white or black, we find in our usual language " big enough, almost hot, not hot… etc. So the propositions require an extension to classical logic.

In this chapter, we will present some theoretical aspect of fuzzy logic, as well as the bases of its application for process control.

III.2 Interests of fuzzy logic [9]:

Fuzzy logic finds its origins in a number of observations:

• The knowledge that a human being has of any situation is generally imperfect, it can be uncertain (he doubts its validity), or imprecise (he has difficulty expressing it clearly).

• Human beings often solve complex problems with the help of approximate data: data precision is often unnecessary. For example, to choose an apartment, he can take into account the surface, the proximity of shops, the distance from the workplace, the rent, without needing a very precise value for each of these data.

• In industry or technology, operators often solve problems complex in a relatively simple way and without the need to model the system.

Likewise, everyone knows that a mathematical model is not necessary to drive a car and yet a car is a very complex system.

• The more the complexity of a system increases, the less it is possible to make assertions precise about his behavior.

From these findings naturally come the following deductions:

• Rather than model the system, it is often interesting to model the behavior of a human operator vis-à-vis the system.

• Rather than by precise numerical values, the operation should be described by global qualifiers reflecting the approximate state of the variables.

III.3 The theory of fuzzy logic:

III.3.1 Principle and definition:

Fuzzy logic is based on the theory of fuzzy sets developed by Zadeh [**10].** Beside of a highly developed mathematical formalism, we prefer to approach the presentation in an intuitive way. The concepts of average temperature or low current are relatively difficult to specify precisely.

We can set thresholds and consider that we attribute such or such a qualifier according to the value of the variable compared to these thresholds.

This can only express a very clear opinion of the qualifier "average temperature" for example. The "vague" aspect of this qualifier is not shown in figure (III.1). We can define the degree to which the variable temperature belongs to the "low" set as the "degree of truth" of the proposition "the temperature is low" [**10].**

In Boolean logic, the degree of membership (μ) can only take two values (0 or 1). The temperature can be:

• low: μ low (T) =1, μ average (T) =0, μ high (T) =0
• average: μ low (T) =0, μ average (T) =1, μ high (T) =0
• high: μ low (T) =0, μ average (T) =0, μ high (T) =1
• It cannot take two qualifiers at the same time.

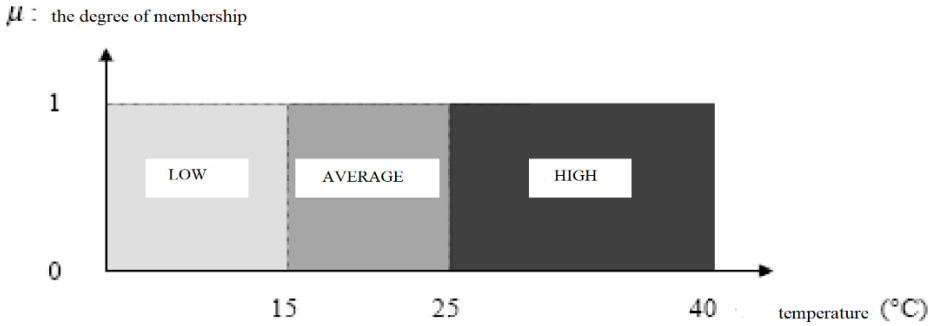


Figure III.1: Example of sets considered in Boolean logic

In fuzzy logic, the degree of membership becomes a function which can take a real value between 0 and 1 inclusive. μ average (T), for example, allows to quantify the fact that the temperature can be considered as average. In this case, the temperature can be considered both as low with a membership degree of 0.2 and as average with a membership degree of 0.8 figure (III.2).

μ low (T) = 0.2, μ average (T) = 0.8, μ high (T) = 0

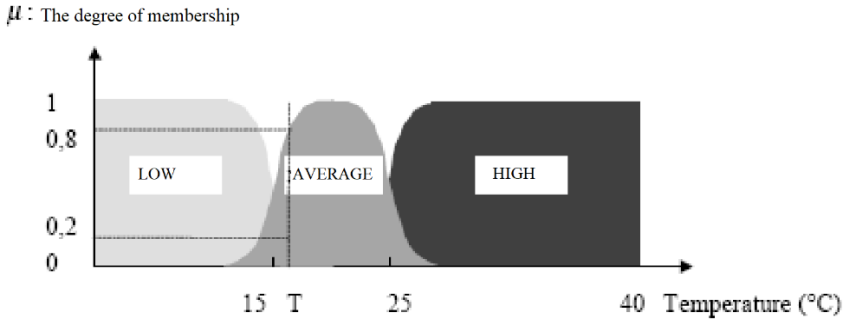


Figure III.2: Example of sets considered in fuzzy logic

For the fuzzy variable x, we define a fuzzy set at on a universe of discourse X by one degree of membership function:

$$x \rightarrow \mu A\ (x)$$

The universe of discourse is the set of real values that the fuzzy variable can take x and μA(x) is the degree of belonging of the element x to the whole fuzzy at figure (III.3). More generally, the domain of definition of μA *(x)* at can be reduced to a subset of X

We can thus have several membership functions, each characterizing a fuzzy subset. It is by the association of all the fuzzy subsets of the universe of discourse, that we obtain the fuzzy set of the fuzzy variable x. By abuse of language, the fuzzy subsets are very often confused with the fuzzy set.

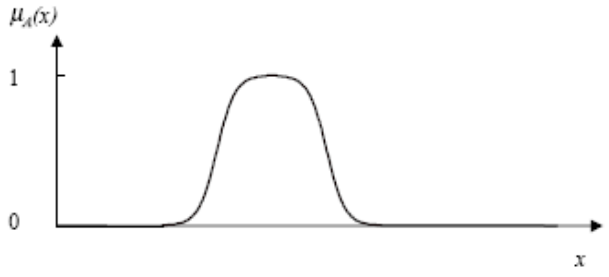


Figure III.3: Representation of a fuzzy set by its membership function

In our example, the fuzzy variable is the temperature, the universe of discourse is the set of reals of the interval [0, 40]. Three fuzzy subsets are attributed to this variable: low, medium and high.

Each is characterized by its degree of membership function:

μ low (T), μ average (T), μ high (T)

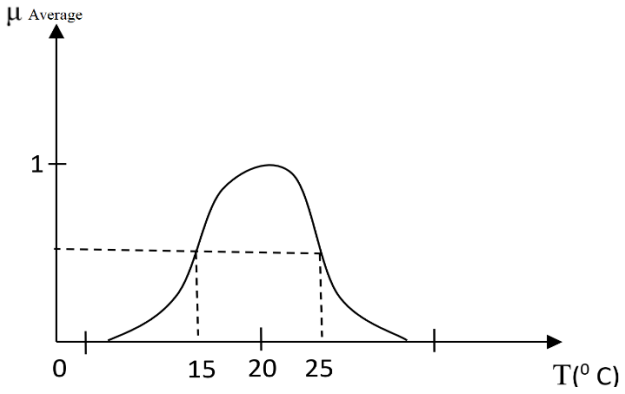


Figure III.4: Case of the "average" fuzzy set of the variable Temperature

We can define the degree of membership function μ average on the whole universe of discourse:

$$\mu_{average}(x) = \begin{cases} \dfrac{1}{1+exp(15-x)}; x\varepsilon[0,20] \\ 1, -\dfrac{1}{1+\exp(25-x)}; x\varepsilon[0,40] \end{cases}$$

III.3.2 Membership function:

The membership function μ between 0 and 1 is associated with the subset E1of T (X) and variable X, whose set of possible values is T (X). It is also called, degree belonging or coefficient of belonging or degree of possibility, which is the possibility that the variable u has the quality associated with the subset E1. It is used to do the mathematical processing of linguistic variables in order to process fuzzy computer inferences.

We attribute to each value of the linguistic variable membership functions μ, a determined value for the variable X will be referred to as the membership factor. There are several forms of the membership function to have [**11]:**

a) Triangular function:

$$\mu(x) = \begin{cases} \frac{x-a}{b-a} & a < x \leq b \\ \frac{c-x}{c-b,} & b < x \leq c \\ 0\ elswhere \end{cases} \qquad \text{(III-1)}$$

b) Trapezoidal membership function:

$$\mu(x) = \begin{cases} \frac{x-a}{b-a} & a < x \leq b \\ \frac{d-x}{d-c} & c < x \leq d \\ 1 \quad b<x\leq c \\ 0\ elswhere \end{cases} \qquad \text{(III-2)}$$

c) Gaussian membership function:

$$\mu(x) = EXP[-(\frac{x-m}{\delta})^2] - \infty < x < +\infty \qquad \text{(III-3)}$$

Figure (III.5) represents the forms of these three types of membership functions

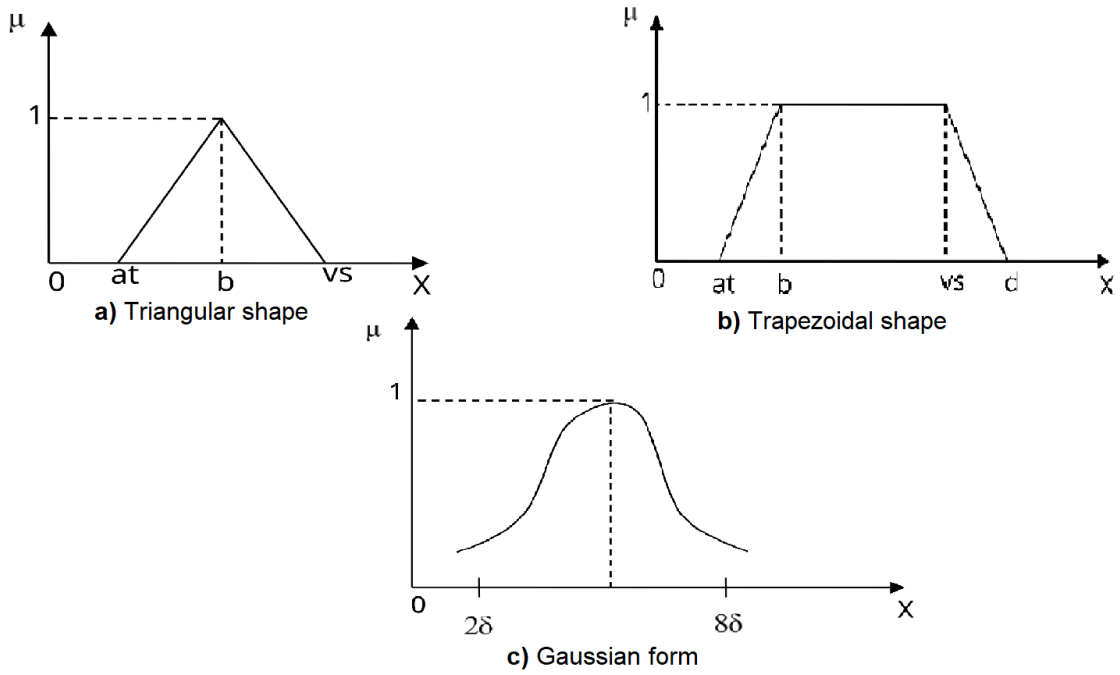


Figure III.5: Different forms of the membership function.

III.3.3 Linguistic variable:

A linguistic variable represents a state in the fuzzy system, its value is defined in linguistic terms which can be words or sentences of a natural or artificial language.
Each linguistic variable is characterized by a set such that: (x, T (x), u) or: x: the variable name T (x): set of variable terms, it is the set of names of linguistic values of x each value of

which is a fuzzy subset defined in U.

U: the universe of discourse.

As an example of a linguistic variable, we take the rotational speed of the engine. Its term set T(speed) can be: T (speed) = {slow, medium, fast,}.

Or each term in T(speed) is characterized by a fuzzy set in a universe of discourse

U = [0.200] for example.

For speeds less than or equal to 80 the linguistic variable (slow) intervenes, and for speeds greater than or equal to 150 the linguistic variable (fast) intervenes. These two terms can be characterized as fuzzy sets whose membership functions are shown in figure (III.6)

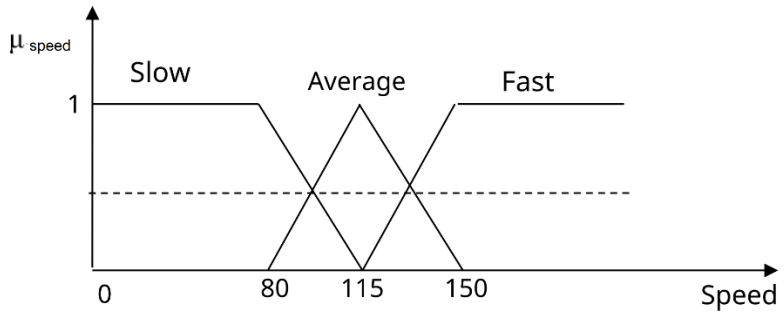


Figure III.6: Representation of linguistic variables.

III.3.4 Fuzzy logic operators:

Linguistic variables are linked to each other at the level of inference rules by operators AND or OR. These are fuzzy logic operators that operate on membership functions representing linguistic variables. In addition, there is the NOT operator which is called (complement, negation, inverse)

Operator OR (The union)

The membership function μA∪B for the fuzzy set A∪B is defined as follows:

$$\mu_{A\cup B}(u) = \max\{\mu_A(u), \mu_B(u)\} \quad \text{(III-4)}$$

AND operator (the intersection)

The membership function μA∩B for the fuzzy set A∩B is defined as follows:

$$\mu_{A\cap B}(u) = m\ln\{\mu_A(u), \mu_B(u)\} \quad \text{(III-5)}$$

NOT operators (complement)

We define the membership function μ_A for the fuzzy set A by:

$$\mu_A(u) = 1 - \mu_A(u) \qquad \text{(III-6)}$$

• **Cartesian product:**

Let A1, ..., An fuzzy sets, in universes of speech u1, ..., un respectively.

The Cartesian product of A1, ..., An is a fuzzy set in the universe of speech $\mu_{1'}\mu_{2'\ldots'}\mu_n$whose membership function is expressed by:

$$\mu A_1, A_2, \ldots\ldots A_n(\mu_{1'}\mu_{2'}\mu_n) = \min\{\mu_{A_1}(\mu_1), \ldots \mu_{A_1}(\mu_n)\} \qquad \text{(III-7)}$$

Or:

$$\mu_{A_1,A_2,\ldots\ldots A_n}(\mu_{1'}\mu_{2'\ldots'}\mu_n) = \mu_{A_1}(\mu_1), \mu_{A_n}(\mu_n)$$

• **Fuzzy relationship:**

A fuzzy relationship is a fuzzy set in the universes of speech $\mu_1, \ldots \mu_n$. it is expressed as follows:

$$R_{u_1,u_2,\ldots\ldots u_n} = \{((u_1, \ldots, u_n)R_{(R_{u_1\ldots\ldots u_n})})/(u_1, \ldots\ldots u_n) \in u_1, \ldots\ldots u_n\} \qquad \text{(III-8)}$$

• **The sup-star composition:**

Let R and S be two fuzzy relations in the speech universes UxV and VxW respectively, the composition of R and S is a fuzzy relation denoted ROS such that:

$$\text{ROS} = \{\lfloor (u, w), sup(\mu R(u,v) * \mu S(v,w))\rfloor u \in U, V, w \in W\} \qquad \text{(III-9)}$$

With: * is an operator belongs to the triangular norm T-norm

III.3.5 Fuzzy logic and approximate reasoning:

Sup-star compositional rule for inference:

If R is a fuzzy relation in Uxy and if x is a fuzzy set in U, then the `` sup-star '' compositional rule for inference states that the fuzzy set y in V can be deduced through: y = XOR Or XOR represents sup-star composition.

III.3.6 Fuzzy implication:

The fuzzy implication is an operator which aims to evaluate a degree of truth of a rule in the form: If x is A then y is B ,This evaluation is given from the values of the premise and that of the conclusion.

$$\mu_R(x,y) = I(\mu_A(x), \mu_B(y)) \qquad \text{(III-10)}$$

Where I is an implication operator

III.4.1 The fuzzy controller:

A fuzzy controller is a particular knowledge-based system using limit-depth reasoning, in a chaining procedure before rules (activation of rules by premises); A representative diagram can be as follows: [**12]**

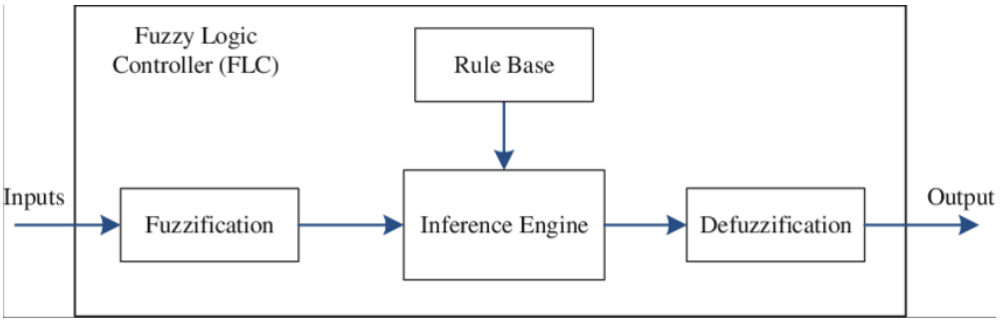


Figure III.7: Basic structure of a fuzzy controller

III.4.1.1 Normalization:

This first step allows the processing of the input variables of the fuzzy controller. For example, calculation of errors (Difference between measured quantities and setpoints) and variation of errors.

The use of normalized domain (Universe of speech included between [-1, 1]) requires a scale transformation, this one is carried out by the intermediary of scale factors of transformation of the physical quantities of the inputs into values normalized belonging to the interval [-1, 1]

III.4.1.2 Fuzzification:

It is the operation of projecting real physical variables onto fuzzy sets characterized by the linguistic values taken by these variables. Two cases can arise depending on whether the measurement of a real physical variable is precise (numerical value) or not. [**12]**

The choice of the form of membership function (triangular, trapezoidal, etc.) is arbitrary. As for the number of membership functions, it is generally odd because they are distributed around zero (3, 5 and 7 are current values). An example of triangular membership functions is given in the following figure:

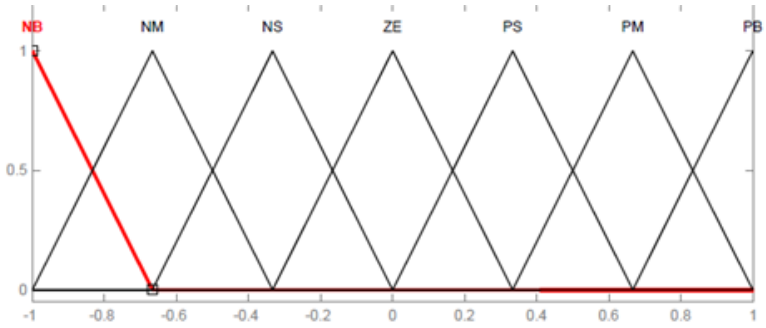


Figure III.8: Example of triangular membership function.

NB, NM..., PB are linguistic values, with:

• NB: Negative big

• NM: Negative middle (negative average)

• NS: Negative small

• Z E: Zero

• PS: Positive small

• PM: Positive middle

• PB: Positive big

III.4.1.3 Inference:

In classical logic, the rule of reasoning of modus ponens allows, from the two assertions,

• X is A'

• Yes x is A so y is B, to conclude that Y is B.

In fuzzy logic, the rule is called modus ponens generalized and allows from assertions.

• X is A'

• Yes x is A so y is B, to conclude that Y is B'.

Inference is the operation of aggregating the rules.

U		T		
		F	M	E
V	F	Z	P	GP
	E	Z	Z	P

Table III.1: Example of rule inference

The rules described in this table are (in symbolic form):

In the example above we have represented the rules which are activated at a given moment by dark boxes:

IF (T is **M** AND **V** is **F)** SO **U** is **P**

Or

IF (T is **E** AND **V** is **F)** SO **U** is **GP**

It happens that all the boxes of the table are not filled, one speaks then about rules of incomplete inferences. This does not mean that the output does not exist, but rather that the membership degree is zero for the rule in question.

It is now a question of defining the degrees of membership of the output variable to its fuzzy subsets. There are several methods of inference such as "Max-Min", "Max-Product", "Max-Sum" which makes it possible to achieve this.

These methods are essentially differentiated by the way in which the operators will be carried out ("AND"And"OR') Used in inference rules.

III.4.1.4 Defuzzification:

Consists of transforming the resulting fuzzy assembly into a precise control quantity. There are also several methods. among:

• The height method

• The first maxima

• The last maxima

• The maximum mean

• Center of gravity

• The center of areas

• The center of maxima

• The center of the largest area

The most used defuzzification methods in fuzzy control are: the center of gravity, the center of the areas and the center of maxima

• **The center of gravity method:**

This method is most often used and generally gives the best results. It consists in taking as a solution the abscissa of the center of gravity of the solutions. It is also the most expensive method in terms of computation. [**12]** The formula for obtaining the center of gravity from the output fuzzy set is

Shown as $$\chi_0 = \frac{\int x.\mu(x)dx}{\int \mu(x)ax}$$

III.4.1.5 Demoralization:

This last step transforms the normalized values of the command variables of the values belonging to their respective physical domain.

III.4.2 The different stages of fuzzy control:

We classically distinguish the steps below in the structure of a fuzzy controller [**8]:**

• identification of variables for input and output.

• the construction of control rules.

• establish the approach to describe the state of the system in terms of fuzzy subsets, or establish the Fuzzification method and fuzzy membership functions.

• selection of the compositional rule of inference.

• method Defuzzification is the step which transforms the fuzzy set, obtained by the preceding calculation, into a control quantity to be applied to the process. In the next section, we can explain the previous steps with PSS based on fuzzy logic.

III.5 PSS based on fuzzy logic:

The power system stabilizer is used to improve the efficiency of the synchronous generator. However, this results in poor performance under various loading conditions which implemented with PSS classic.

For this purpose, the need for fuzzy logic PSS. The fuzzy controller used in electro-power system stabilizer is normally a two input and a single output component. It is generally a system MISO. Both inputs are change of angular velocity and rate of change of angular velocity while the output of fuzzy logic controller is a voltage signal. A change in the feedback voltage to the excitation system as a function of the acceleration power on a unit is used to improve the stability of the system. Stabilization signals are calculated using standard fuzzy membership functions as a function of these variables [**8].**

III.5.1 Selection of input and output variables:

The input and control variables are defined, that is to say, which states of the process are to be observed and which are to be considered as control measures. For models FLPSS, the acceleration and the speed deviation of the generator can be observed and was chosen as the input signal of the PSS blurry. The dynamic performance of the system could be assessed by examining the response curve of these two variables. The voltage is at the output of the

fuzzy logic controller [**8].**

In practice, only axis speed is readily available. The acceleration signal can be derived from the speed signals measured at two successive sampling times using the equation below:

$$\Delta\omega(k) = \frac{(\Delta\omega(k) - \Delta\omega(k-1))}{\Delta T} \qquad \text{(III-11)}$$

III.5.2 Membership function:

The variables chosen for this controller are the speed deviation, acceleration and voltage, in this, the speed deviation and acceleration are the input variables and the voltage is output variable. The number of linguistic variables describing fuzzy subsets of a variable varies depending on the demand (application). Usually, an odd number is used. A reasonable number is seven. However, the multiplication of fuzzy subsets results in a corresponding increase in the number of rules. Each linguistic variable has its fuzzy membership function.

The membership function maps net values into fuzzy variables. Triangular membership functions are used to define the degree of belonging. It is important not that the degree of adhesion plays its important role in the design [**8].**

A blurry controller. Each of the input and output fuzzy variables is assigned seven linguistic fuzzy subsets varying from large negative (NB) to large positive (PB). Each subset is associated with the triangular membership function from a set of seven membership functions for each fuzzy variable.

NB	NEGATIVE BIG
NM	NEGATIVE MEDIUM
NS	NEGATIVE SMALL
Z	ZERO
PS	POSITIVE SMALL
PM	POSITIVE MEDIUM
PB	POSITIVE BIG

Table III.2: Fuzzy variables for the membership function.

The variables are normalized by multiplying with respective gains of K1, K2, K3, so that their value between -1 and 1. The membership functions of the input and output variables have 50% overlap between adjacent fuzzy subsets [**8].** The membership function for acceleration, speed and voltage are shown in the following figure:

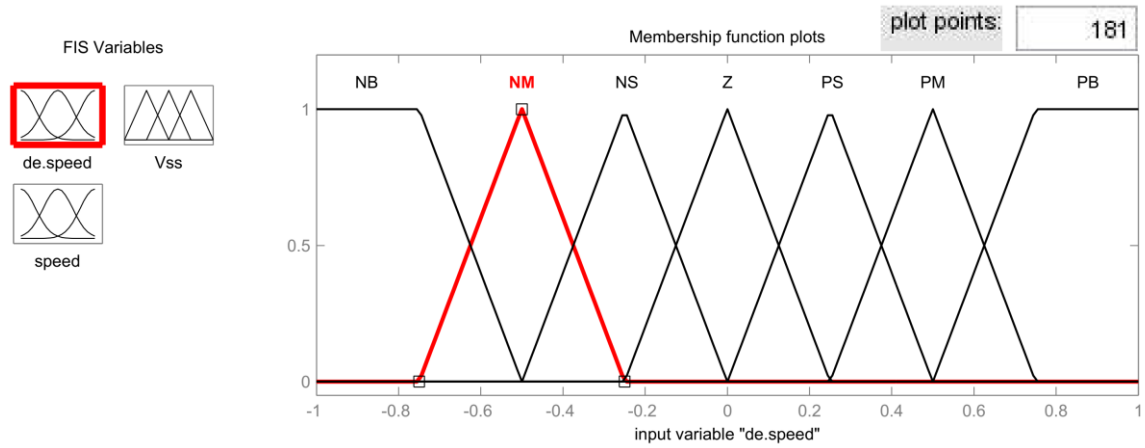


Figure III.9: Membership functions for acceleration.

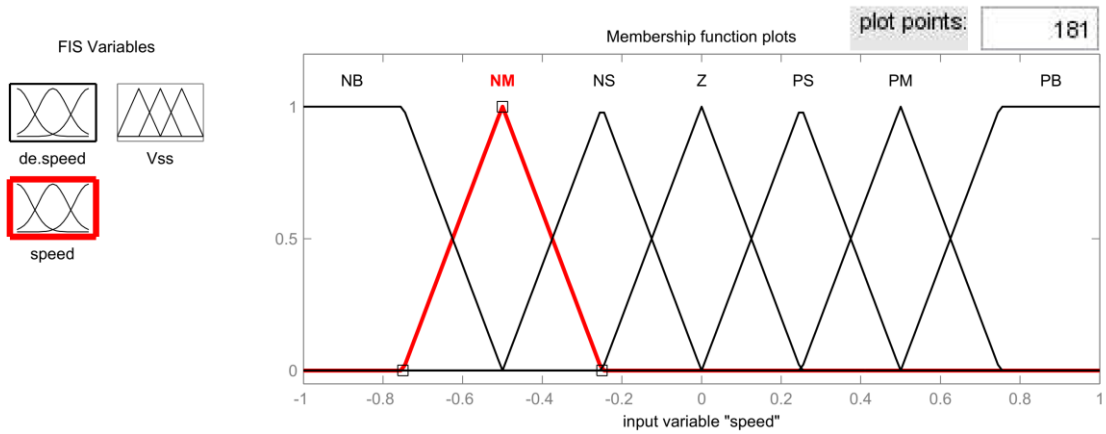


Figure III.10: Membership functions for speed variation.

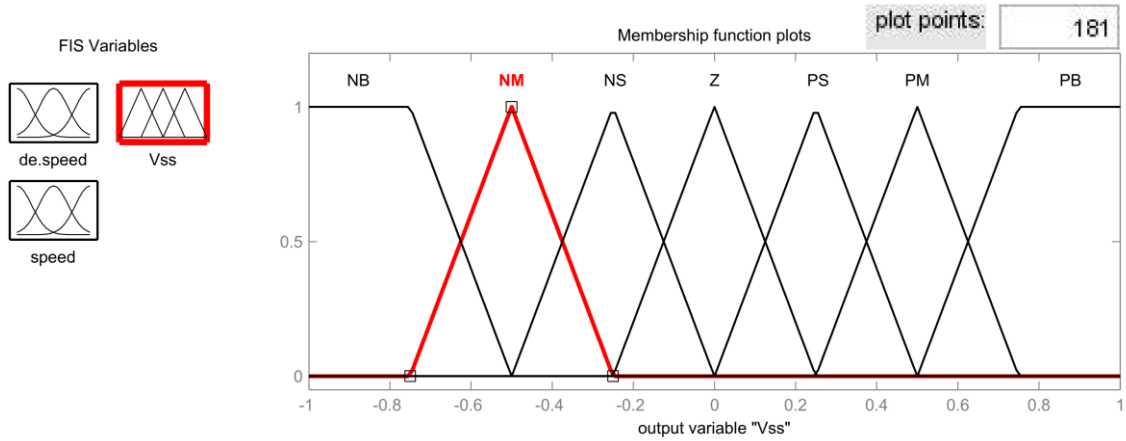


Figure III.11: Membership functions for voltage.

III.5.3 The fuzzy rule base [13]:

A set of rules that define the relationship between the input and output of the fuzzy logic controller can be found using knowledge available in the field of designing. PSS [**8].** These rules are defined using linguistic variables. The two inputs, speed and acceleration, translate (49) rules for each machine. Typical rules have the following structure:

• **Rule (1):** if the speed variation is NB (NEGATIVE BIG), AND acceleration is NB SO voltage (the output of PSS fuzzy) is NB.

• **Rule (2):** if the speed variation is ZE (ZERO), AND acceleration is NS (NEGATIVE SMALL) SO voltage (the output of PSS fuzzy) is NS.

• **Rule (3):** if the speed variation is PB (POSITIVE BIG), AND acceleration is NM (NEGATIVE MEDIUM) SO voltage (the output of PSS fuzzy) is PM (POSITIVE MEDIUM). And so on…

All the 49 rules governing the mechanism are explained in Table (III.3), where all the symbols are defined in basic fuzzy logic terminology.

Variation of speed	Acceleration						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	NS
NM	NM	NB	NM	NM	NS	NS	ZE
NS	NS	NM	NM	NS	ZE	ZE	PS
ZE	ZE	NM	NM	NS	PS	PS	PM
PS	PS	NS	ZE	ZE	PS	PM	PM
PM	PM	ZE	PS	PS	PM	PM	PB
PB	PB	PS	PM	PM	PB	PB	PB

Table III.3: Fuzzy logic controller rule base.

The stabilizer output is obtained by applying a particle rule expressed as membership functions. Finally, the rule's output membership is calculated. This procedure is followed for all rules and with each rule a result is obtained. We use the most commonly used inference mechanism is the so-called "Mamdani ".
Previously, we can know the stages (Fuzzification, degree of activation, implication and aggregation).

III.5.4 Defuzzification:

Generally, the solution of a problem using fuzzy sets is a result expressed in terms of fuzzy values (membership functions). On the other hand, to exploit or apply these results physically, one must use ordinary values. This operation, which consists of converting fuzzy values into ordinary values, is called defuzzification.

The most widely used defuzzification method is certainly the center of gravity method, the principle of which is to take the abscissa of the center of gravity of the surface of the resulting membership function.

In the case of a discreet universe of discourse, this method gives:

$$y = \frac{\Sigma_1^n \mu(x_i) x_i}{\Sigma_1^n \mu(x_i)} \; with: X = (x_1 \, . x_2) \qquad \text{(III-12)}$$

However, this defuzzification method is sometimes complex and requires significant calculations. It is for this reason that another simpler method is often used which is the maximum method, the principle of which is to take the abscissa of the maximum of the resulting membership function [**14].**

III.5.5 the implementation of fuzzy logic [13]:

Single machine (synchronous generator) fuzzy logic controller block diagram representation connected to the infinite network. As in the following figure:

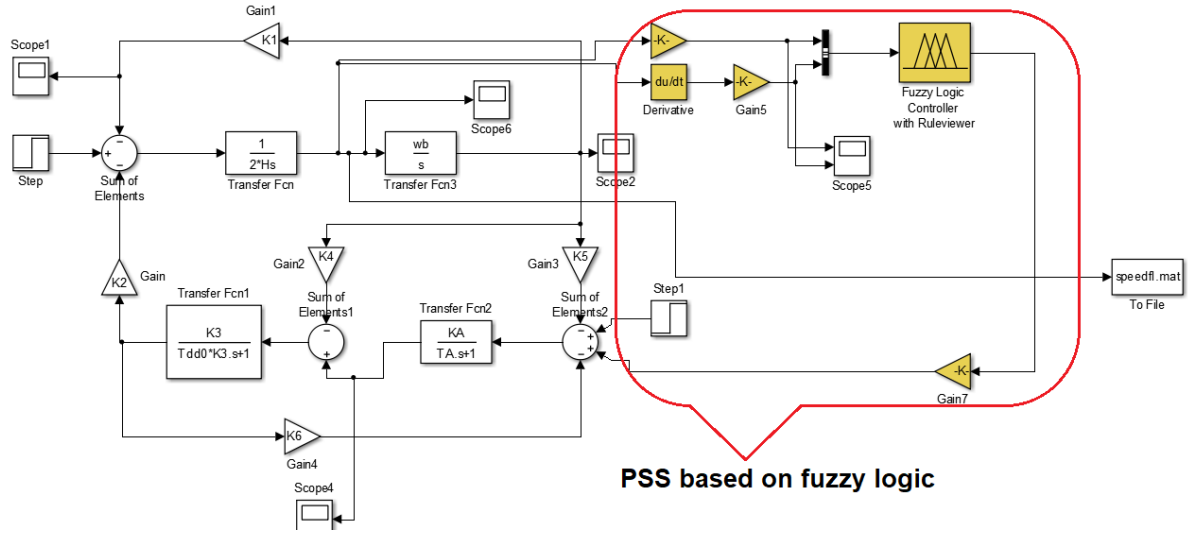


Figure III.12: Running fuzzy logic controller.

III.6 Conclusion

In this chapter we have exposed the main theoretical concepts of fuzzy logic, then after having described a structure of a basic command Fuzzy logic makes it possible to model a complex system, by modeling only the behavior of the human operator facing the system. Classified among the techniques of artificial intelligence, fuzzy logic makes it possible to model and then replace the expertise of process management, coming from the designer or the user.

Chapter IV

Simulation of PSS and PSS Based on Fuzzy Logic.

IV.1 Introduction:

This new structure has better performance and dampens local and inter-zone oscillations relatively well. However. The PSS and the AVR act simultaneously, independently and uncoordinatedly on the excitation of the generator. A compromise is therefore made in order to ensure the proper functioning of the assembly. So. With the addition of PSS, we notice generally some deterioration in the quality of voltage regulation.

In this chapter, we will test the block diagrams of regulators with the reference parameters. Thus, a result of the programming is presented in graphical interface form to simulate and analyze the performance of electrical networks using the technique of visual programming in the MATLAB environment.

IV.2 System execution studied with automatic voltage regulator AVR:

The simulation model studying the response of the system with constant voltage is shown in fig (IV.1). In this representation the dynamic characteristics of the system are expressed in terms of the supposed constant of K.

Pg = 0.5, Vi = 1.0, Eb = 1.0

The machine data: Xd = 1.6, Xq = 1.55, xd = 0.32, Tdo = 6.0, H = 5,
D = 0, fb = 60 Hz.

The data given assumes machine model (1.0). The initial conditions and the Heffron Phillips constants K1 to K6 are obtained from using the MATLAB script from Chapter II

(a) Vt = 1.0∠11.53, fa = 0.5025, Eqo = 1.3279, 80 = 47.240, ido = -0.3328, iqo = 0.3765, Vdo = -0.5836, Vqo = 0.8120
Kl = 0.9346, K2 = 1.0198, K3 = 0.3600, K4 = 1.3053, K5 = 0.0500, K6 = 0.4511

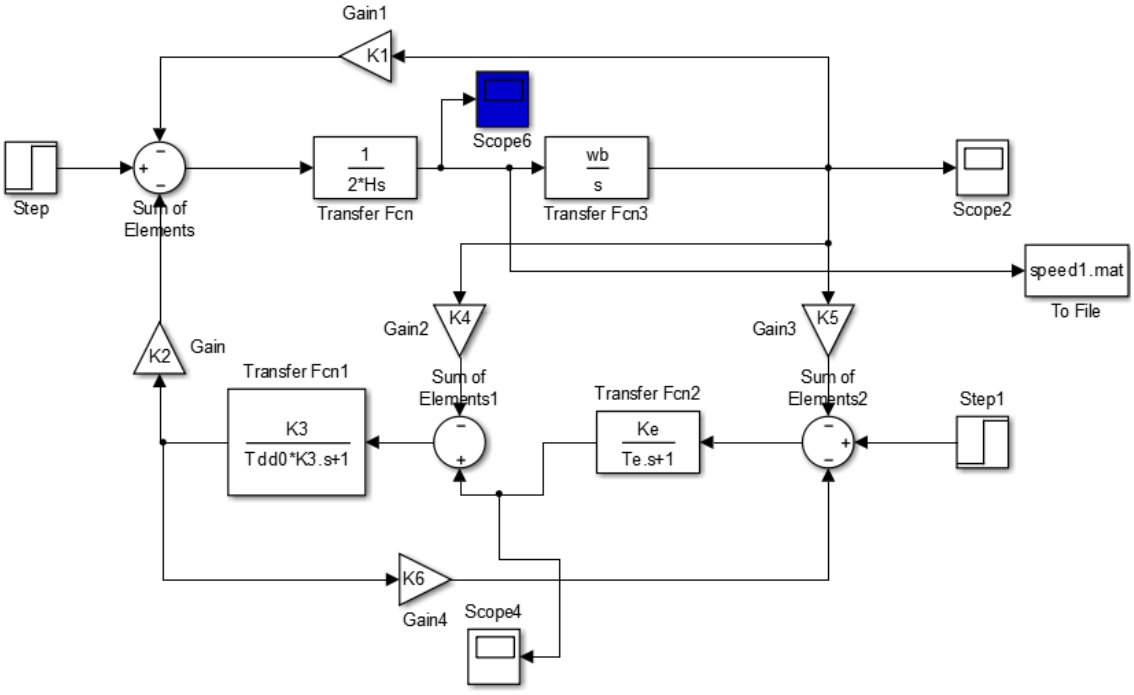


Figure IV.1: Network representation SMIB + AVR on MATLAB / Simulink

The simulation results for each of angular speed and angular speed deviation shown below.

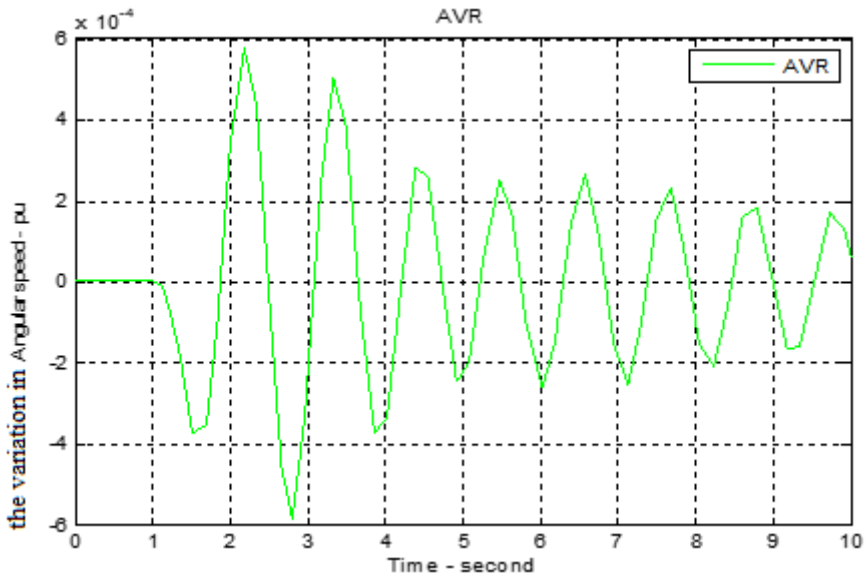


Figure IV.2: Shows the variation in angular velocity.

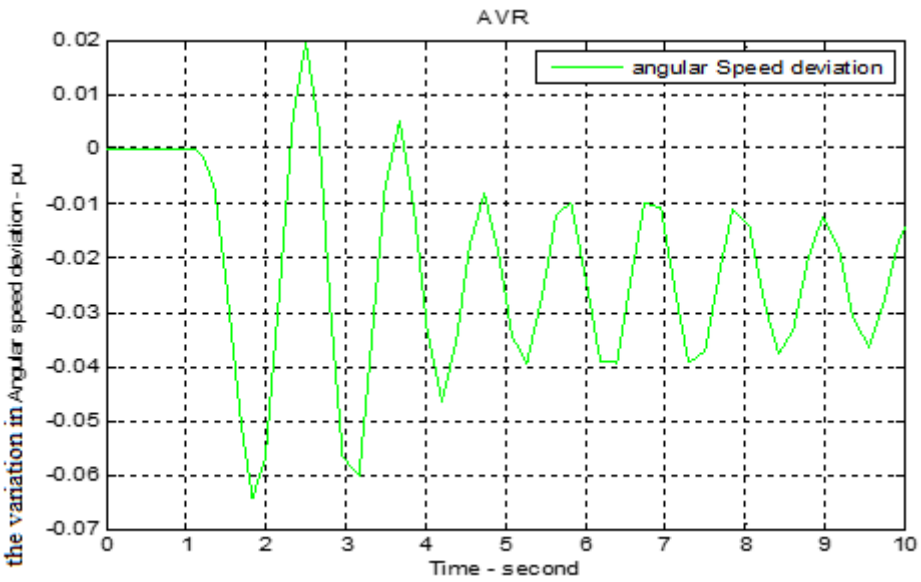


Figure IV.3: Shows the variation of the angular speed deviation.

Notes:

In these results, it clearly appears that the system with automatic voltage regulator exhibits divergent electromechanical oscillations. It is then necessary to place the Power system stabilizer to improve the stability of the system.

IV.3. Execution of the studied system with the excitation system with PSS:

According to the preceding chapter (II), one can use MATLAB / Simulink for the application of the PSS on the same previous example we used for the AVR.

The system data is taken from Example 7.1. The system consists of a single machine connected to an external impedance of 0 + j0.4. The generator is initially supplying power of 0.5 pu with terminal voltage at l.0 pu. The infinite bus voltage is $1.0\angle 0$. A static exciter with a single time constant AVR is considered (KE = 200, TE = 0.05). The time constants Tl and T2 are selected as T1 = 0.078 s, T2 = 0.026 s. The washout circuit time constant Tw is selected as 2.0 s. The root corresponding to the exciter mode moves to the right and crosses imaginary axis at around Ks = 74

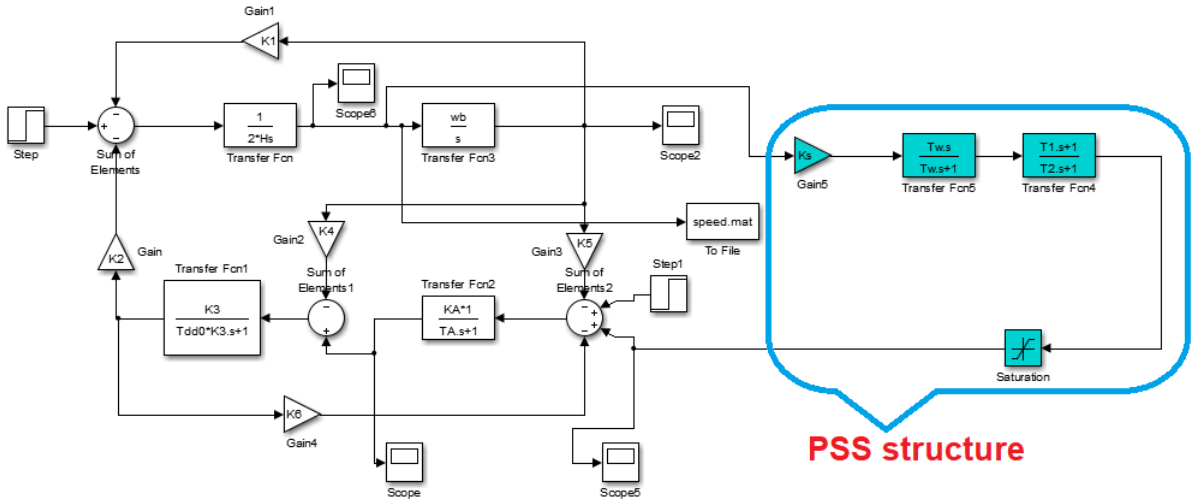


Figure IV.4: Network representation SMIB + PSS on MATLAB / Simulink.

The simulation results for each angular speed and the angular speed deviation shown below.

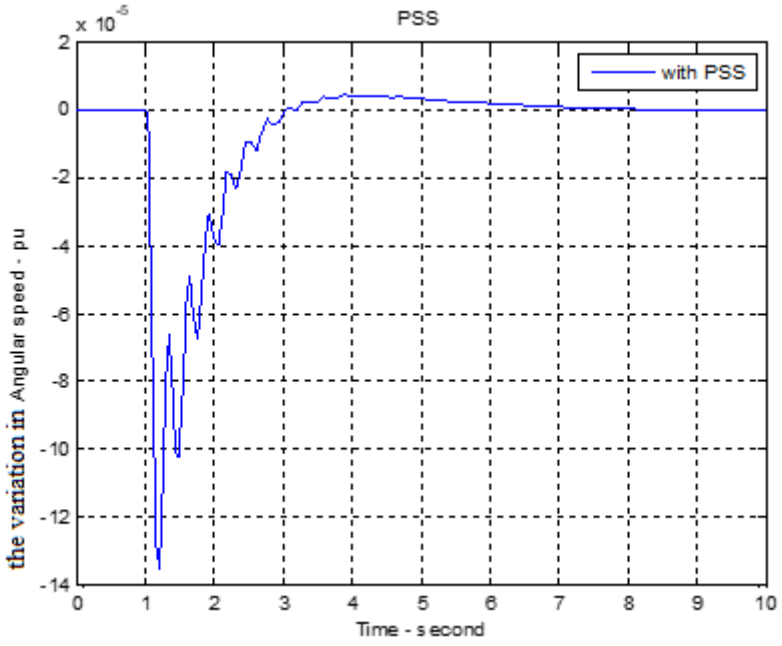


Figure IV.5: Shows the variation of the angular speed.

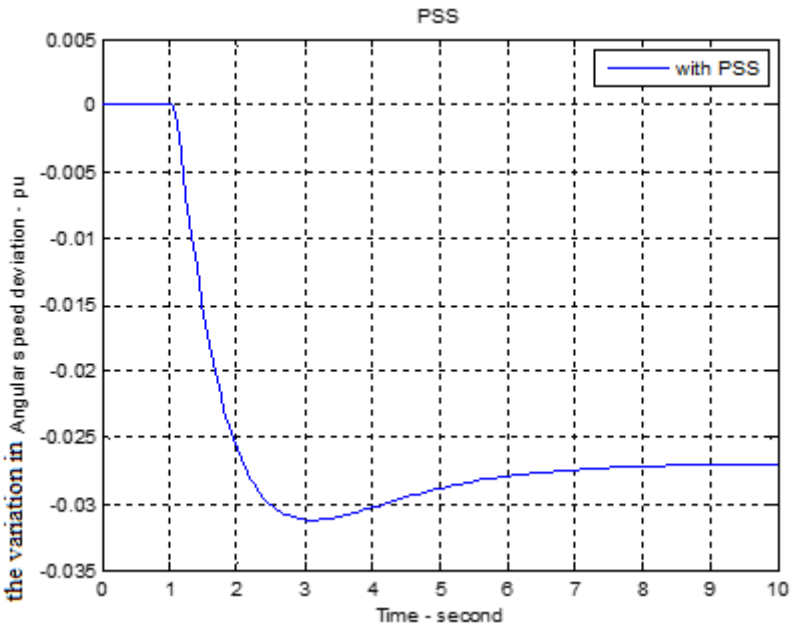


Figure IV.6: Shows the variation of the angular speed deviation.

IV.4. Comparison study of regulation without PSS and regulation with PSS:

We compared between the following two cases, where our system is connected with the regulator PSS and the other without regulator, then choose the most efficient and best choice according to the performance criteria that allow the proper operation of the system. According to the previous chapter (II), one can use MATLAB / Simulink for the application the two block diagrams in figure (II.5), and figure (II.6).

The simulation results in figures (IV.7), (IV.8) are shown below, for each of angular speed and the angular speed deviation, with PSS is without PSS.

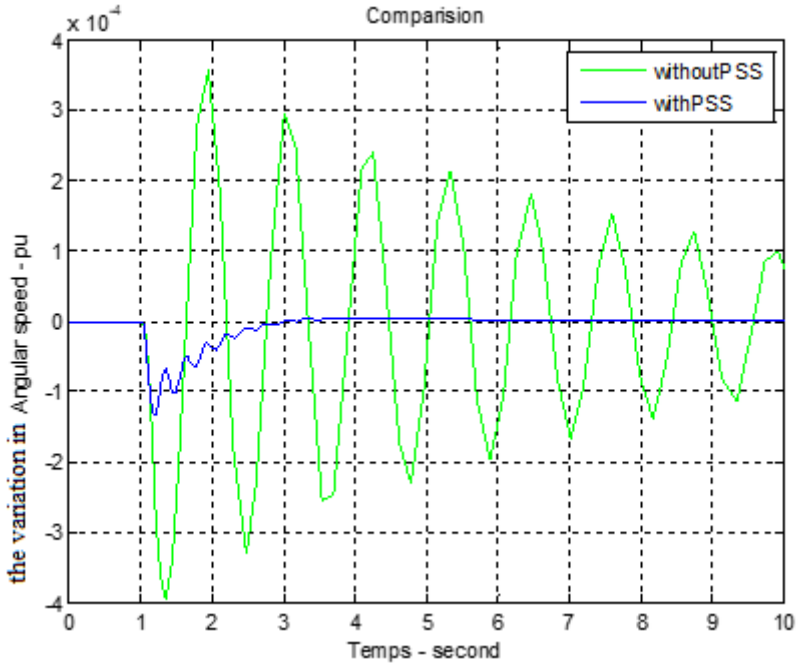


Figure IV.7: Shows the variation of the angular speed.

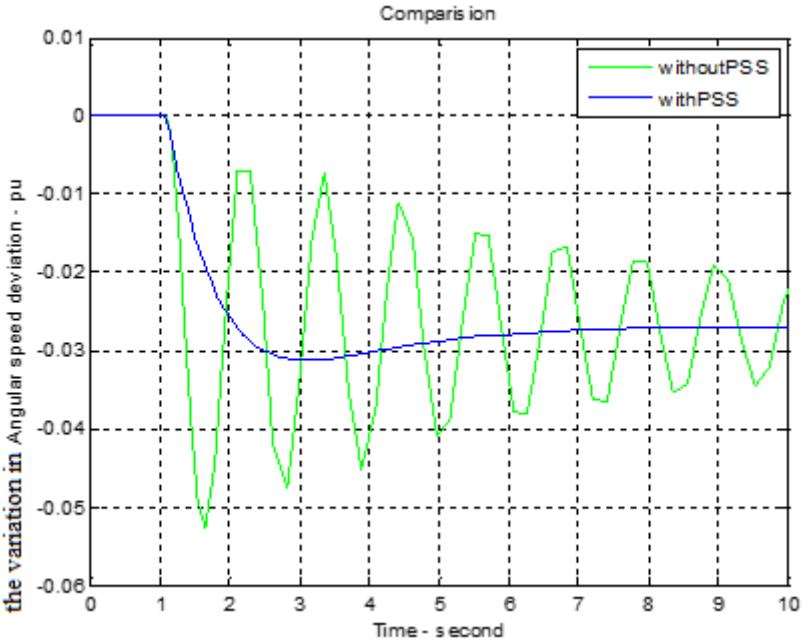


Figure IV.8: Shows the variation in angular speed deviation.

Notes:

The simulation results in the figures above show that after using PSS the system becomes stable than the previous system (without PSS) in a response time between 3 to 4

seconds for the angular speed and angular speed deviation therefore the PSS to a good influence on the power regulation with good damping of the angular velocity oscillation, as well as the load angle.

IV.5 Execution of PSS based on fuzzy logic:

The block diagram used in MATLAB / Simulink to analyze the effect of the fuzzy logic controller by attenuating the small signal oscillation implemented on infinite busbar of single system machine is shown below figure (IV. 9)

• Simulation block diagram parameter:

We use the same example as in the PSS

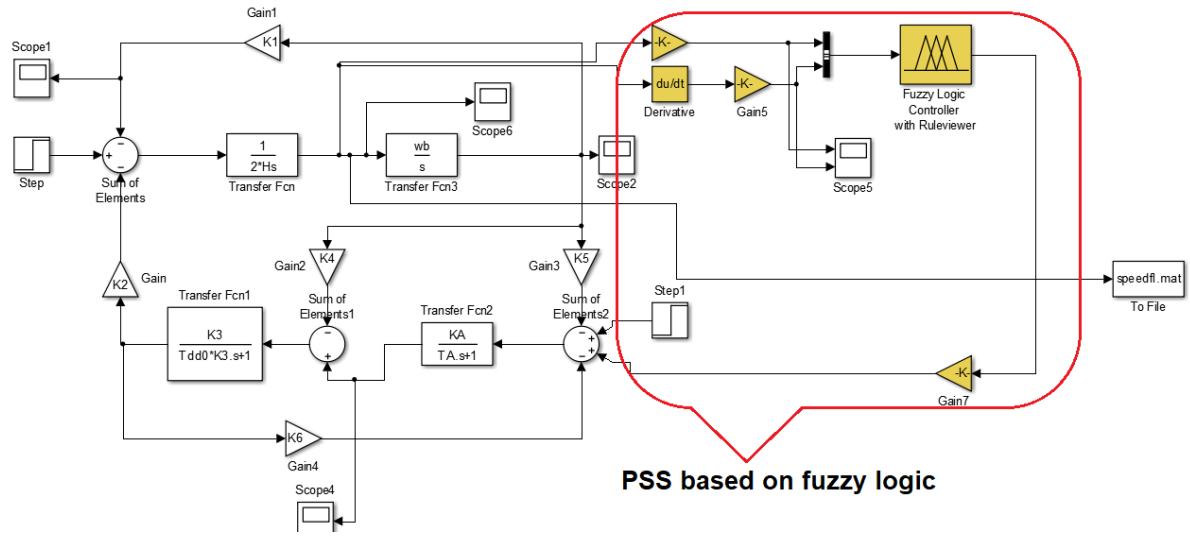


Figure IV.9: Representation of the SMIB + network Fuzzy PSS on MATLAB / Simulink

The simulation results for each angular speed and the angular speed deviation shown below.

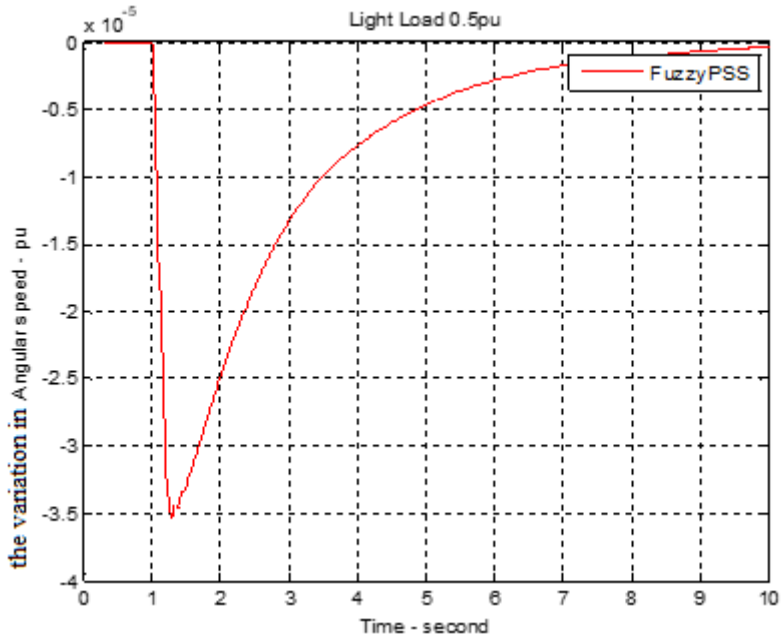


Figure IV.10: Shows the variation of the angular speed.

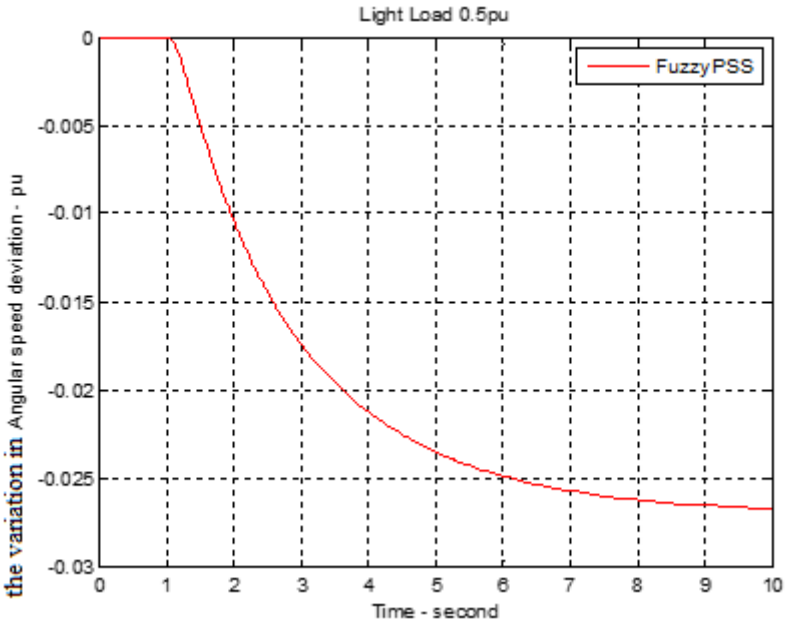


Figure IV.11: Shows the variation of the angular speed deviation.

IV.6 Comparison study of conventional PSS regulation and PSS regulation based on fuzzy logic:

We compared between the two cases: where our system is:

• connected with regulator PSS conventional.

• connected with regulator FLPSS (FuzzyPSS).

Simultaneously, we execute the block diagrams of figures (IV.5), (IV.10) and of figure (IV.6), (IV.11), for the same parameters.

IV.6.1 First case light load using 0.5pu:

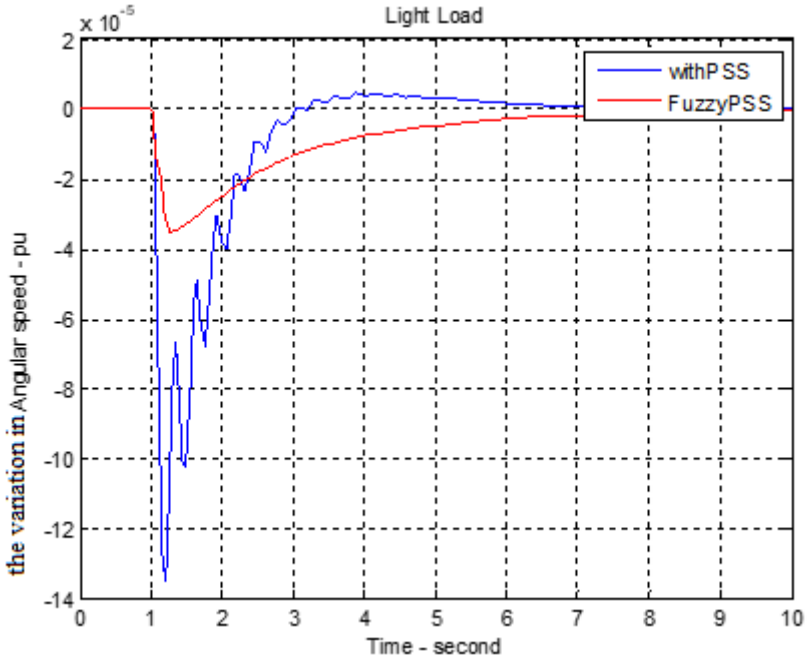


Figure IV.12: Shows the comparison based on the angular speed using light load.

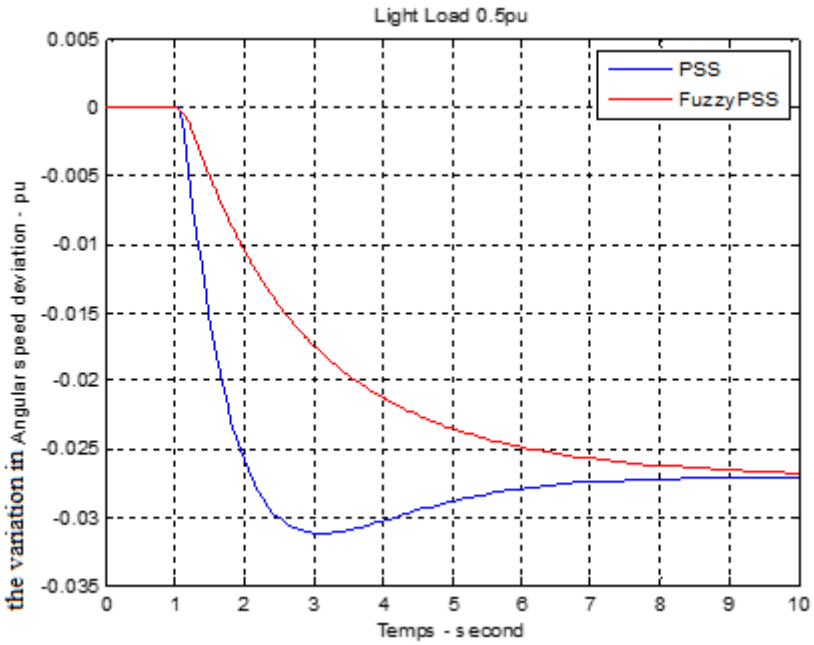


Figure IV.13: Shows the comparison based on the angular speed deviation using light load.

Analyses: we can see in the two figures above **Figure IV.12** and **Figure IV.13** that with the Fuzzy logic PSS is slightly better on the error (smaller damping), on the other hand both Fuzzy PSS and conventional PSS reach stability at nearly the same time.

IV.6.2 Second case medium load using 1pu:

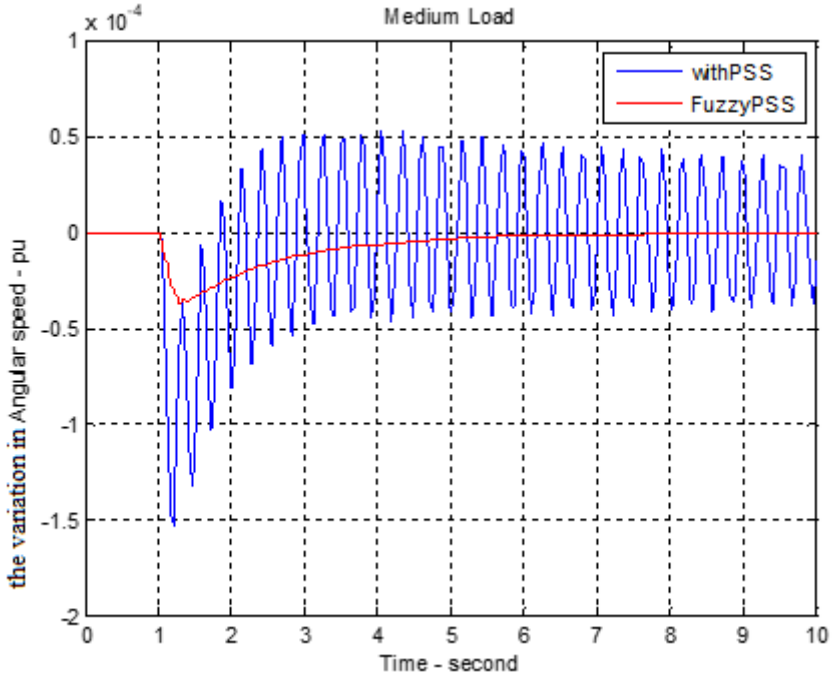


Figure IV.14: Shows the comparison based on the angular speed using medium load.

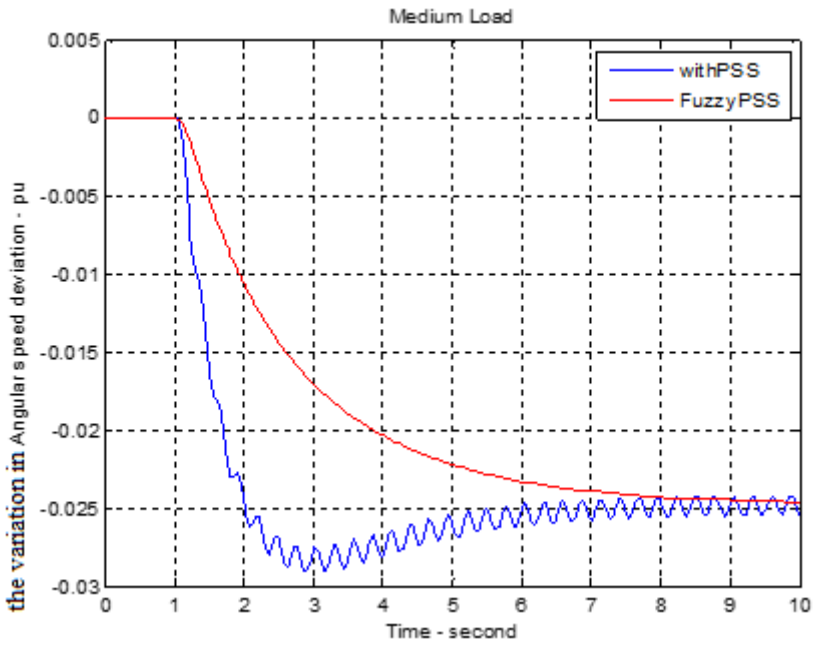


Figure IV.15: Shows the comparison based on the angular speed deviation using medium load.

Analyses: we can see in the two figures above **Figure IV.14, Figure IV.15** that with the Fuzzy logic PSS has a smooth way to stability and the conventional PSS is going through some considerable oscillations,

IV.6.3 Third case heavy load using 1.5pu:

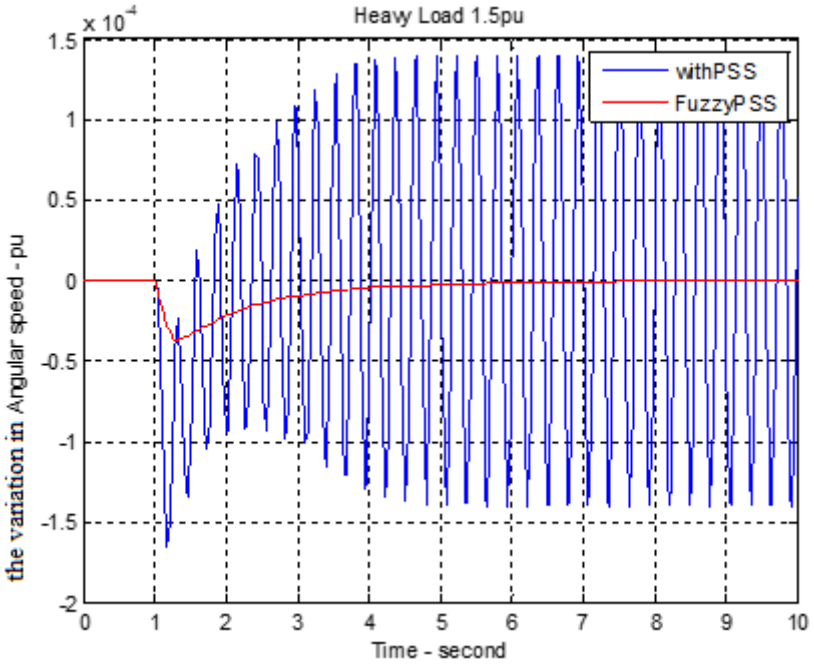


Figure IV.16: Shows the comparison based on the angular speed using heavy load.

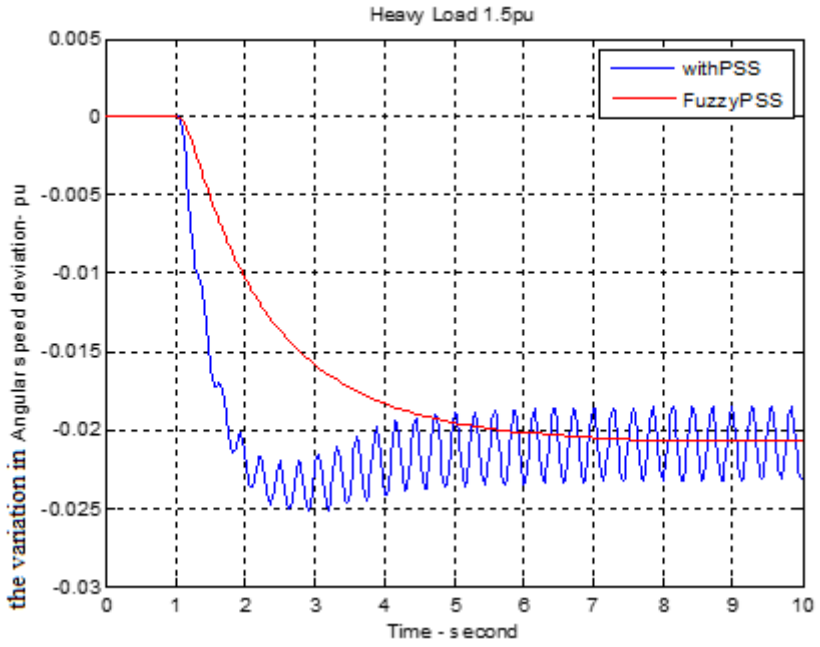


Figure IV.17: Shows the comparison based on the angular speed deviation using heavy load.

Analyses: we can see in the two figures above **Figure IV.16, Figure IV.17** that with the Fuzzy logic PSS has a smooth way to stability and the conventional PSS is going through some very high oscillations.

Note: we can see in the Fuzzy logic PSS that whatever the load is we get the same figure which means that the load does not affect the result of the Fuzzy logic PSS, on the other hand when we use the conventional PSS adding more load makes the signals unstable and the oscillations higher.

IV.7 Conclusion:

In this chapter, we applied a nonlinear approach to the design of a power system stabilizer for damping low frequency electromechanical oscillations based on the combination of PSS control and fuzzy logic control. the AVR can't make good damping improvement. And we concluded that for light loads the conventional PSS gives similar result as the Fuzzy PSS but when the load gets heavier the conventional PSS goes into instability (can't handle heavy loads), in the other hand the Fuzzy PSS gives optimal damping improvements at any load value making it the best stability regulation method.

General conclusion

General conclusion:

Electro-energy systems are constantly developing. The extension of interconnected networks make systems highly sensitive to interregional oscillations. These oscillations can seriously restrict the transport of electrical energy. They can also lead to disturbances extending to the entire electro-energy system if, for example, a cascade of transmission line faults occurs. Under these new conditions, power grid operators often find themselves forced to operate systems at the limits of stability.

Therefore, improving stability to small disturbances, in particular the damping of interregional oscillations, is a priority objective.

The work presented in this thesis concerns the study of the stability of an electro energetic system by power stabilizer "PSS" and fuzzy logic methods. The PSS still represent an effective means for the damping of the local electromechanical modes, but their role in the damping of the interregional modes is still considered of little importance. In this study we have shown that the fuzzy logic method satisfies both the damping of interregional modes and the damping of local modes.

Our research work focused on the following points:

• the modeling of a power system, modeling adapted for the study of stability to small disturbances.

• The application of fuzzy set theory to improve the stability of the mini-machine system.

• Comparison study

In the modeling part, we presented the nonlinear mathematical models of the elements of the power system. We have also developed the associated linear model.

We also recalled the theory of stability, the problems of stability at small disturbances of a power system and the principle of the PSS stabilizer.

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