Fuzzy Logic Controller for Power System Stability Enhancement

by

Muhammad Shoaib

A Thesis Presented to the

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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MASTER OF SCIENCE

In

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This Humble Work Is Dedicated

To

My Parents

Acknowledgments

All praise be to Allah the Lord of the Worlds, for having guided me at every stage of my life. I seek His mercy, favor and forgiveness. I feel privileged to glorify His name in the sincerest way through this small accomplishment.

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ABSTRACT

NAME: Muhammad Shoaib

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Fuzzy logic controllers have been designed for power system stability enhancement. The proposed fuzzy PSS was tested on a single machine as well as multimachine systems.

A closed loop optimal control strategy is taken as a knowledge base for the fuzzy design. The designing of membership functions and set of rules which are selected from the information using minimum time strategy. Three different fuzzy logic controllers were developed and tested. The response for a single machine infinite bus system with these control strategies are compared with the method reported in the literature. A simplified algorithm which is computationally efficient, has also been examined.

From simulation of the proposed fuzzy algorithm on the single machine and multimachine systems it has been observed that the proposed minimum time based fuzzy logic controller is robust. It can provide a simple and effective method of stabilization and is computationally very efficient.

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خلاصة الرسالة

اسم الطالب الكامل : محمد شعيب

عنوان الرسالة : استخدام المنطق الغير واضح في التحكم في مثبتات نظم القوى الكهربائية .

التخصص : الهندسة الكهربائية

تاريخ الشهادة : يونيو ١٩٩٧م

لقد تم في هذا البحث تصميم مثبتات نظم القوى ذات المنطق غير الواضح وذلك لتحسين إتزان أنظمة القوى الكهربائية وتم إختبار هذه المتحكمة على أنظمة ذات مكائن منفردة ومتعددة ، وأختيرت طريقة التحكم الأمثل ذات الدوائر المغلقة كقاعدة معلومات لتصميم المنطق غير الواضح . وأستخدمت المعلومات المرتبطة بطريقة الوقت الأقصر في تصميم دوال العضوية ومجموعة القواعد ، وتم مقارنة نتائج هذه المتحكمة مع ماتم نشره في هذا المجال .

وللتحقق من قوة آداء هذه المتحكمة تمت محاكاة الخوارزمي المقترح وذلك للتحكم في توازن الأنظمة بطريقة سهلة ومؤثرة وذات كفاءة عالية من الناحية الحسابية .

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Chapter 1

Introduction

Modern power systems are highly vulnerable to large disturbances which can propagate through the large network of interconnection in the absence of adequate safeguards. In order to have reliable generation and transmission, a power system should be stable. Most present day power generators are equipped with power system stabilizers (PSS) for controlling slowing oscillating type instability. This thesis uses fuzzy logic techniques along with standard optimization methods to design such PSS.

1.1 Power System Stability

Power System stability refers to the ability of the synchronous machines to remain in synchronism while delivering power at normal voltage and frequency[1]. Depending on the type of disturbance, power system stability is classified into the following:

- Steady state stability
- Transient stability
- Oscillating (dynamic) stability

Steady state stability[1] involves slow or gradual changes in power without loss of stability or synchronism of machine. Steady state stability studies ensure that phase angles across transmission lines are not too large, bus voltages are close to nominal values and that generators, transmission lines, transformers, and other equipment are not overloaded.

Oscillating stability[2] is the ability of a system to maintain stability when subjected to small disturbances such as small change in mechanical torque. The action of the turbine governors, excitation systems, tap changing transformers and controls from a power system dispatch center can interact to stabilize or destabilize a power system several minutes after a disturbance has occurred. Control of excitation, static var control(SVC) and fast valving are some of the methods for controlling slowly changing oscillations.

Transient stability involves major disturbances such as loss of generation, line switching operations, faults and sudden load changes. The objective of a transient stability study is to determine whether or not the machines will return to synchronous frequency with new steady state power angles. Usually the regulating devices are not fast enough to function during transient period and nonlinear modes of system operation are encountered during this period. The system may lose its stability at first swing unless an effective counter-measure is taken such as dynamic resistance braking, or load shedding.[3]

1.2 Power System Stabilizers

Excitation control involves feeding an extra stabilizing control with the automatic voltage regulator(AVR). This generally is derived from a power system stabilizer(PSS). How much an excitation control signal affects the stabilization process of the machine, depends upon the response of excitation system, available field energy, and maximum and minimum allowable limits of excitation voltage. On occurrence of the fault on a system, the voltage at all buses is reduced, which is sensed by the AVR. The AVR then acts to restore the generator terminal voltage. The general effect of excitation system is to reduce the initial rotor angles swing following the fault. This is done by boosting the field voltage. The increased airgap flux exerts a restraining torque on the rotor which tend to slow down the rotor motion. This method is more effective for smaller disturbances[4].

The use of PSS to improve the dynamic performance of power systems has increased steadily since the sixties when they were first presented. Since then, extensive research has been carried out in this area. Conventional types are designed with fixed structure and constant parameters tuned for optimal operating conditions. Since the operating point of a power system changes nonlinearly as loads and generating units are connected /disconnected, and since unpredictable faults occur, the performance of a fixed structure PSS varies greatly. It is desirable to adapt the stabilizer parameters in real time based on on-line measurements in order to maintain good dynamic performance over a wide range of operating conditions. This motivated the development of a self tuning stabilizer. Although the self tuning PSS is capable of offering better dynamic performance than a fixed gain PSS, it suffers from a major drawback of requiring model identification in real time which is very time consuming, especially for a microcomputer with limited computational capability. Some of the artificial intelligence based alternatives of designing PSS which have been reported in the literature are:

1. Rule based
2. Neural Network
3. Fuzzy Logic

1.3 Fuzzy Logic PSS

Fuzzy logic control(FLC) has found its application in power industry in recent years. Several reportings have been made about design of PSS involving fuzzy control theory. Its simplicity and performance makes it attractive for implementation[5].

The fuzzy PSS has four basic components in it. These are:

1. Fuzzifier
2. Knowledge Base
3. Inference Engine
4. Defuzzifier

The input to the PSS which normally are speed, acceleration, power etc. are converted to fuzzy signals through the fuzzifier.

The expert knowledge about the PSS control strategy are normally stored in knowledge base. It consists of data base and rule base. The rule base guides us about the decision making logic, i.e. a set of rules and from the data base we know about thresholds, shape and number of membership functions.

The fuzzy logic inference engine infers the proper control action based on the available fuzzy rules.

Since the input to the excitation system is crisp, the fuzzy signal obtained, through the above procedure is defuzzified and fed to the AVR.

1.4 Motivation and Objectives

As mentioned, application of FLC to PSS design is a relatively new development. On-line implementation of fuzzy logic power system stabilizer(FLPSS) to a power system demands that the design should be robust and at the same time it should be simple. For the control to be effective in damping the power oscillations, the control decision stored at the knowledge base should be good. Also, for simplicity of calculation, the rules at the knowledge base should be simple and limited in number. The objective of this research is to design a simple FPSS in the light of these factors.

The core of the FLC is the knowledge base. This is where the expert knowledge is incorporated in the control design in terms of linguistic variables through appropriate membership functions. The selection of the membership functions and their thresholds can effectively control the system response. Complicated or inappropriate membership functions can make the decision making logic quite complicated rendering the gain made by FLC algorithms marginal compared to conventional PSS.

The knowledge base may be selected from actual operator experience in the fields or simulation studies. Some of the optimization studies reported in the literature can be incorporated in the knowledge base. The control thus obtained may provide satisfactory response. However, the incorporation of this optimum studies should not put additional burden in computation. In this study, one such crisp optimum excitation control study, derived from a minimum time strategy, has been incorporated in the knowledge base. It is expected that the information from the optimal strategy into the knowledge base will help provide good damping control at the same time minimizing the computation burden on the decision logic.

1.5 Scope of the Thesis

Chapter 2 of the thesis presents a literature review on stability methods, power system stabilizers, fuzzy logic control and application of fuzzy logic to power systems. Chapter 3 gives a brief theory on fuzzy logic control. Chapter 4 presents single and multimachine power system models. Results on single machine system are presented in chapter 5, while those for multimachine systems are given in chapter 6. Chapter 7 includes conclusions and recommendations.

Chapter 2

Literature Review

A great deal of work has been reported on the issue of power system stability and control. In this chapter, we present a review of the stability methods, power system stabilizers, fuzzy logic control and its power application. The last section is devoted to fuzzy power system stabilizer.

2.1 Stability Methods

A reliable power system should be able to restore itself to normal operating conditions following a disturbance. This can be done only if the system is equipped with effective control tools. Research on improvement of power system stability can be categorized into two types. Transmission side modification & generation side modification[6].

The transmission side modification can be subdivided as:

1. Insertion of series capacitance
2. Insertion of series resistance
3. Dynamic braking resistors
4. Single pole or selective pole trip
5. Phase rotation
6. Parallel usage of AC and DC systems
7. Thyristor controlled VAR system
8. Thyristor controlled quadrature voltage injection
9. Superconducting Magnetic Energy Storage(SMES)

The generation side modification can be subdivided as:

1. Turbine Valve Control
2. Excitation Control

2.2 Power System Stabilizers

Different types of power system stabilizers have been designed and reported in the literature in an effort to improve the system performance under smaller and larger disturbances. Some of the related literature on the topic is presented.

Schlief showed that damping and stability are greatly improved by supplementary excitation control with a specially derived function of frequency derivation[7]. De-Mello & Concordia established understanding of stabilizing requirements, and included the voltage regulator gain parameters and transfer function characteristics for a machine speed derived signal superposed on the voltage regulator gain reference for providing damping of machine oscillations[8]. They addressed the problem of the most effective selection of generating units to be equipped with excitation system stabilizers in multimachine system[9].

Larson & Swann presented the performance objectives of PSS in terms of types of oscillations and operating conditions and developed relationship between phase compensation tuning and root locus analysis[10].

Chan & Hsu designed on optimal variable structure stabilizer by increasing the damping torque of synchronous machine. The stabilizer minimizes quadratic performance index in sliding mode operation[11]. D. Xia & G. T. Heydt minimized the cost function which incorporates fluctuations of input, output and setpoint with the system parameters identified in real time by recursive least square algorithm[12].

C. M. Lim presented a method of designing decentralized stabilizers in multimachine power systems[13]. Proportional Integral PSS was first reported by Hsu. He used two approaches, the root locus method & the suboptimal regulator method[14].

So far as self tuning stabilizers are concerned, a significant amount of work has been done and these were the center of attention of power system researches in late eighties.

Chen & Hsu[15] designed an adaptive output feedback PSS using local signal of generator e-g. speed or power. A. Gosh[16] and S. J. Chen etal[17] gave adaptive pole shifting self tuning PSS. References [18,19] suggested dual rate sampling self tuning regulator.

Wu & Hsu designed a self tuning PID PSS for a multimachine power system. The proposed stabilizer had a decentralized structure and only local measurements within each generating unit was required[20]. S.Lefbvre proposed an approach of simultaneously selecting the parameters of all the stabilizers in multimachine power system. He formulated the parameter optimization problem into eigenvalue assignment problem and developed algorithm enabling exact assignment of selected system modes[21].

Q.Lu used differential geometry for his multimachine PSS[22]. Zhou used SPE(Sensitivity of PSS Effect) to select the location of PSS and tuning of PSS parameters in multimachine system[23].

Recently, some work is reported in the literature on rule base[24,25] and neural network[26] in an effort to get rid of model dependence and in turn reduce the calculation time of control.

2.3 Fuzzy Logic Control

To view the developments in fuzzy control in a proper perspective, a bit of history is in order. When Zadeh wrote his first paper *on fuzzy sets* in 1965[27], his expectation was that most of the applications of the theory would be in those fields in which the conventional mathematical techniques are of limited effectiveness. This was, and still is, the case in biological and social sciences, linguistics, psychology, economics and more generally in the soft sciences. In such fields, the variables are hard to quantify and the dependencies are too ill defined to admit precise characterization in terms of difference or differential equations.

It did not take that long, however, to realize that even in those fields in which the dependencies between variables are well-defined, it may be necessary or advantageous to employ fuzzy rather than crisp algorithms to arrive at a solution. The main reason for this state of affairs is that in most real world settings *precision* is illusory. For example in the case of car parking problem, although the kinematics of the car and the geometry of the problem are well defined, the final position and the orientation of the car are not specified precisely. Thus, it is imprecision of the goal that makes it possible for humans to park a car without any measurements or numerical computations. What we see, then, is that human possess a remarkable innate ability to exploit the tolerance for imprecision to achieve tractability, robustness and low solution cost, whereas the traditional control techniques fail to do so when they employ crisp rather than fuzzy algorithms to arrive at a solution[5].

In papers published in 1973 and 1974, Zadeh has outlined the basic ideas underlying fuzzy control[28-30]. Among them, were the concept of a linguistic variable, fuzzy If-Then rules, fuzzy algorithms, the compositional rule of inference, and the execution of fuzzy instructions. However, it was the seminal work of Mamdani and Assilian in 1975 that showed how these ideas could be translated into a working control system[31]. The contributions of Professor Mamdani and his associates at Queen Mary College and those of Professor Sugeno and his associates at Tokyo Institute of Technology, played a key role in the developments of fuzzy control and its early evolution[32].

During the past several years, fuzzy logic has found numerous applications in fields ranging from finance to earthquake engineering[33]. As mentioned earlier, Mamdani and Assilian[31], were the first to apply the fuzzy set theory to control problems (e.g., the control of a laboratory steam engine). This experiment triggered a number of other applications such as the warm water process control[34], activated sludge wastewater treatment process [35], traffic junction control[36], cement kiln[37], automobile speed control[38], water purification process[39], elevator control[40], model car parking control[32], aircraft flight control[41], robot control[42-46], power systems and nuclear reactor control[47, 48], two dimensional ping pong game playing[49], control of biological processes[50], fuzzy memory devices[51-53] and fuzzy computer [54].

In this connection, it should be noted that the first industrial application of FLC was in the cement kiln control system developed by Danish Cement Plant manufacturer F.L. Smidth in 1979[37]. An ingenious application of FLC is in Suggeno's fuzzy car[32] which has the capability of learning from examples. More recently predictive fuzzy control systems have been proposed and successfully applied to automatic train operations systems and automatic crane operation systems [55]. In parallel with this development, a great deal of progress has been made in the design of fuzzy hardware and its use in so called fuzzy computers [54].

2.4 Fuzzy Control to Power Applications

One of the earliest application of fuzzy logic in power system and nuclear control was in 1988[44-45]. Later, the fuzzy technique was applied in almost all the power related areas, such as, planning, scheduling, reliability, contingency analysis, VAR/Voltage control, stability evaluation, load forecasting, load management, decision making support, monitoring & control, unit commitment, state estimation, transformer diagnosis, machine diagnoses and fault analysis[56].

Fuzzy logic has been applied in power system expansion planning[57-59]. The decision making process in power system expansion planning is, to a large extent, qualitative and can be described more flexibly and intuitively by fuzzy set concepts.

Power system long/mid term scheduling problems such as yearly maintenance scheduling, seasonal fuel and mid term operation mode studies are usually solved by various optimal and heuristic methods but it is more reasonable to represent constraints in fuzzy expressions. The combination of conventional methods with fuzzy sets may constitute an effective approach to solve these problems[60-62].

The present practice in dynamic security assessment(DSA) is to perform off-line studies for a wide range of likely system conditions and network configurations. In on-line applications the operators are allowed to rely on their own judgment and knowledge acquired in off-line studies and experience gathered during long time operation. Fuzzy set theory may be useful in building an expert system for DSA based on the operator's empirical knowledge[63-66].

Power system load demand is influenced by many factors such as weather, economic & social activities and different load component(residential, industrial and commercial etc.). Fuzzy logic approach has shown advantages over conventional methods. The numerical aspects and uncertainties of this problem appear suitable methodologies[67-68].

Human experts play central role in trouble shooting or fault analysis. In power systems, it is required to diagnose equipment malfunctions as well as disturbances. Equipment malfunctions are caused by many factors and information available to perform diagnoses is incomplete. In addition, the conditions that induce faults may change with time. Subjective conjectures based on experience are necessary. Accordingly, the expert systems approach has to be useful. As stated previously, fuzzy set concepts can lend itself to the representation of knowledge and the building of an expert system[69-71].

In traditional controller design, a system model needs to be constructed and control laws are derived from the analysis of the model. Because of the non-linearities it is nearly always necessary to linearize the system model and then the linear controllers are used to control the non-linear system. Fuzzy logic controllers have received much attention in recent years, since they are more model-independent, show high robustness, and can adapt. Fuzzy logic controllers are mainly used for power system excitation and converter controls[72-74]. T.Hiyama and his colleagues presented an application of a fuzzy logic control scheme for switched series capacitor modules to enhance overall stability of electrical power system[75]. Desh presented a new approach to the design of FLC for HVDC transmission link using fuzzy logic[76]. The fuzzy controller relates variables like speed & acceleration of generator to a control signal for the rectifier current regulator loop using fuzzy membership functions.

2.5 Fuzzy Power System Stabilizer

One of the earliest articles which present a PSS other than the conventional design, was from Takashi Hiyama in 1989[24]. He presented a rule based stabilizing controller to electrical power system. The control scheme utilized was a bang bang strategy for a single machine infinite bus model. The input signal considered was speed deviation and acceleration. Later he modified the strategy by considering the weighted acceleration[77]. He extended his work on rule based fuzzy control to multimachine system[25] and refined his work through several other publications[26,78-80].

Hassan [81] improved Hiyama's work[77] by changing the shape of the membership functions. Standard non-linear continuous membership functions which are more suitable for synchronous machine. He later, also proposed a self tuned PSS[82], and implemented the controller in the laboratory. Shi[83] also reproduced Hiyama's work[77], by changing the shape of membership functions.

One of the first articles which reported a PSS design, based entirely on fuzzy logic control was from Hsu in 1990[84]. He used the concepts of fuzzification and defuzzification in the PSS design and compared the results with conventional stabilizer. A number of membership functions were employed making the computation complicated. Hoang[85] and Toliyat[86] reported a FLPSS in line with Hsu's work[84].

Sharaf presented a hybrid of conventional and fuzzy PSS design for damping electromechanical modes of oscillations and enhancing power system stability[87]. Kitauchi developed a fuzzy excitation control scheme, for the purpose of further improving the stability to large disturbances[88]. His fuzzy stabilizer was multi-input multi-output(MIMO) type and consists of two subcontrollers using basic concept of AVR & PSS. The inputs to the fuzzy AVR were change in terminal voltage and its rate of change while the input to FPSS were change in electrical power and rate of change in electrical power. Finally the two output signals were added. Iskandar, Ortmeyer reported hybrid PSS's which take care of small as well as large disturbances[89,90]. In order to get rid of measurement noise in speed signal at smaller disturbances, two stabilizers were designed[89]-one speed deviation input fuzzy controller and other electrical power deviation input analog-type PSS.A fuzzy judgment mechanism was suggested which help select one of two controllers for large and small disturbances, respectively.

Hariri's adaptive network based stabilizer[91,92] combines the advantages of artificial neural network and fuzzy logic control together. Fuzzy PSS having learning ability is trained directly from the input and output of the generating unit. Park's self organizing power system stabilizer(SOPSS) use the fuzzy Auto Regressive model[93]. The control rules and the membership functions of the proposed controller are generated automatically without using any plant model. The generated rules are stored in the fuzzy rule space and updated on-line by a self organizing procedure.

P.K.Desh designed an anticipatory fuzzy control PSS which differs from traditional fuzzy control in that, once the fuzzy control rules have been used to generate a control value, a prediction routine built into the controller is called for anticipating its effect on the system output and hence updating the rule base or input-output membership functions in the event of unsatisfactory performance[94].

Other developments in the related area are Metwally[95,96] & Hiyama's advanced FLPSS[97,98],etc.

Chapter 3

Fuzzy logic and Fuzzy Control

3.1 Introduction

Fuzzy logic system(FLS) is a convenient way to map an input space into an output space[99]. This means for the given conditions or sample inputs of the system, the designed fuzzy logic system would lead to the crisp output, no matter how non-linear or stochastic in nature the system is. In order to understand the working properly, it should be noted that FLS is not the only way of solving problems. If it were replaced with a black box, there may be a number of things in that box solving the problem, such as linear systems, expert system, neural network, differential equations, interpolating multidimensional look up tables, etc. Now the question arises, to what sort of problems fuzzy logic should be applied and to which problem it's not beneficial. The answer is, when the problem is simple enough and a crisp mathematical expression solves the problem more effectively, fuzzy logic should be avoided. When problem is very complex, ambiguous and information available is imprecise, fuzzy reasoning provides a way to understand system behavior by allowing interpolation between input and output situations.

3.1.1 Fuzzy Logic Control

A layout of a general fuzzy logic control system is given in Figure 3.1.

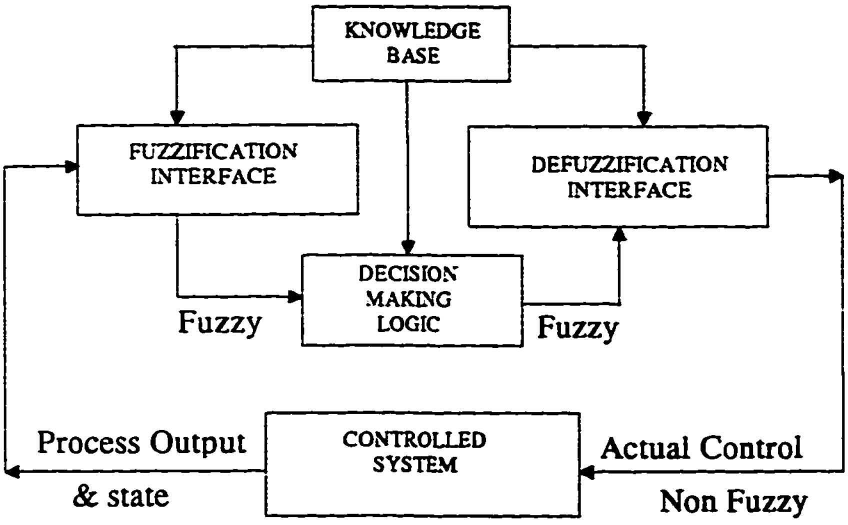


Figure 3. 1 The Basic Configuration of a FLC.

FLC comprises of four principal components. These are: a fuzzification interface, a knowledge base(KB), decision making logic, and a defuzzification interface[30].

1)The fuzzification interface involves the following functions:

- measures the values of input variables(Process Output),
- performs a scale mapping that transfers the range of values of input variables into corresponding universes of discourse,
- performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets.

2)The knowledge base comprises of knowledge of the application domain and the attendant control goals. It consists of a "data base" and a "linguistic (fuzzy) control rule base:"

- the data base provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in FLC.
- the rule base characterizes the control goals by means of a set of linguistic control rules.

3)The decision making logic is the kernel of an FLC, it has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.

4)The defuzzification interface performs the following functions:

- a scale mapping, which converts the range of values of output variables into corresponding universes of discourse,
- defuzzification, which yields a nonfuzzy control action from an inferred fuzzy control action.

Before we proceed with the application of FLC to the power system stability, a brief background on the fuzzy control theory, the fuzzification and defuzzification procedure, etc. is given in the following sections.

3.2 Fuzzy Logic Theory

3.2.1 Fuzzy Sets versus Crisp Sets

The classical mathematical set theory is known as theory of crisp sets. The crisp set has some well defined boundaries, i.e., there is no uncertainty in the prescription or location of boundaries of the set. Any element of the universe of discourse is either present in that crisp set or not. So the membership value of any element is either one or zero. It can be described by its characteristics function as follows:

$$\mu_C : U \Rightarrow \{0,1\} \qquad (3.1)$$

The characteristic function μ_C is called the membership function. Let us denote temperatures 25°C or greater as "hot". Any temperature less than 25°C is then not hot. Then the membership function of crisp set "hot" can be shown as in Fig. 3.2.

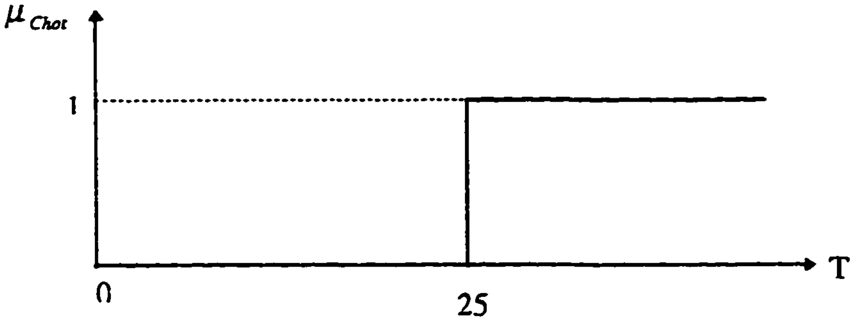


Figure 3. 2 The Characteristic Function μ_{Chot}

In contrast to crisp set, fuzzy set does not have well defined boundaries rather it is prescribed by vague or somewhat ambiguous boundaries. A fuzzy set.

then is a set containing elements that have varying degrees of membership in the set.

The definition of a fuzzy set[24] is given by the characteristics function

$$\mu_F : U \Rightarrow \{0-1\} \qquad (3.2)$$

If now the characteristics function of $\mu_{Fhot}$is considered. one can express the human opinion, being for example that 24 degrees is still fairly hot and 26 degrees is hot but not as 30 degrees and higher. This results in gradual transition from full membership (1) to non-membership(0). Fig. 3.3 shows an example of membership function μ_{Fhot} of the fuzzy set μ_{Fhot}. The membership function has a linear transition, however, every individual can construct a different transition according to his own opinion.

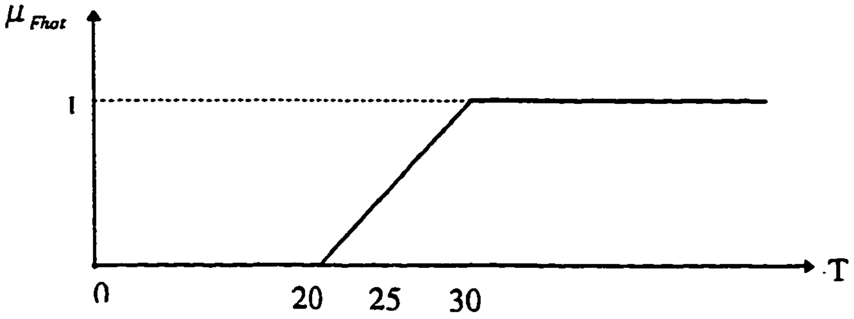


Figure 3. 3 The Membership Function μ_{Fhot}

3.2.2 Fuzzy Set Operations

Just like the traditional crisp sets, logical operations, e.g., union, intersection and complement, can be applied to fuzzy sets [24]. Since some of these operations are used for fuzzy control , the necessary operations are discussed in this section.

Union: The union of two fuzzy sets A and B with the membership functions $\mu_A(x)$ and $\mu_B(x)$ of variable x is a fuzzy set C, written as $C = A \cup B$, whose membership function is related to those of A and B as follows:

$$\mu_C(x) = \max[\mu_A(x), \mu_B(x)] \tag{3.3}$$

The operator in this equation is referred to as the ***max operator***.

Intersection: According to the ***min-operator***, the intersection of two fuzzy sets A and B with respectively the membership functions $\mu_A(x)$ and $\mu_B(x)$ is a fuzzy set C, written as $C = A \cap B$, whose membership function is related to those of A and B as follows:

$$\mu_C(x) = \min[\mu_A(x), \mu_B(x)] \tag{3.4}$$

Both the intersection and the union operations are explained by Figure 3.4

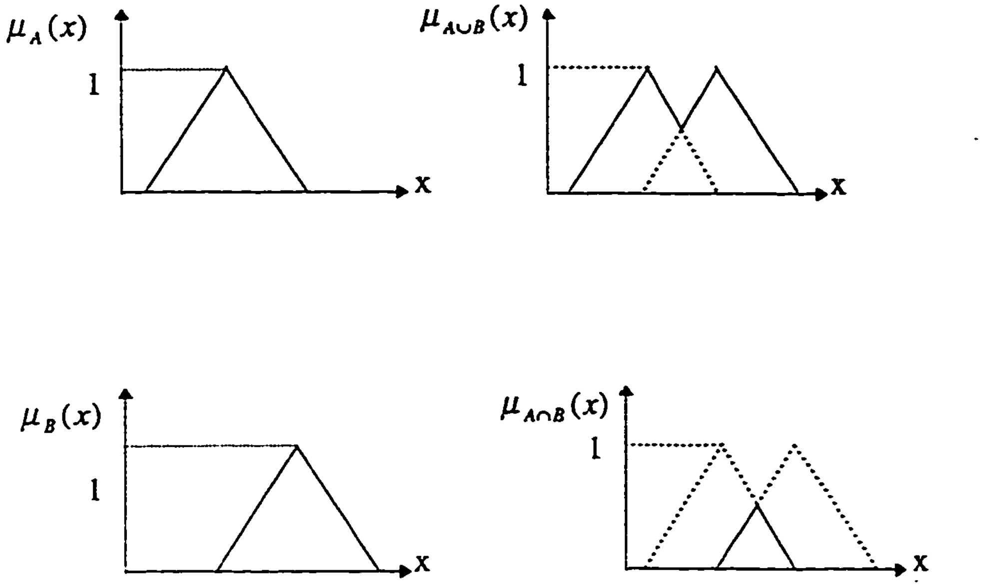


Figure 3. 4 The Fuzzy Set Operations of Union and Intersection

Complement: The complement of a fuzzy set A is denoted $\bar{A}$ as with a membership function defined as

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \qquad (3.5)$$

The complement of a set is explained in Fig. 3.5.

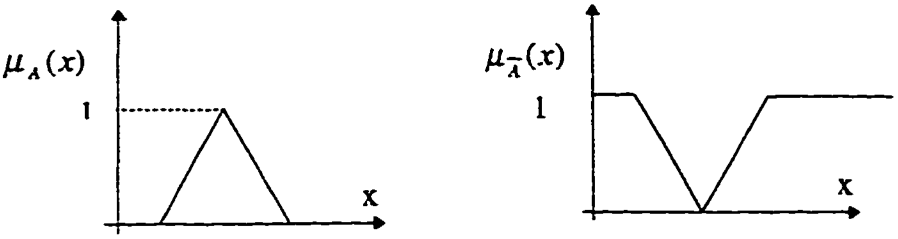


Figure 3. 5 The Fuzzy Set and its Complement.

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

$$\mu_B(y) = \max\{\min[\mu_R(x, y), \mu_A(x)]\} \qquad (3.6)$$

3.2.3 Linguistic Variables

Variables whose values are not numbers but words or sentences are called linguistic variables. The motivation of the use of words or sentences rather than numbers is that linguistic characterization are, in general, less specific than numerical ones.

A linguistic variable is usually decomposed into a set of terms which cover its universe of discourse. For example, a control variable can be represented as:

U(control variable)={Large positive, Medium positive, Small positive, Very small,

Small negative, Medium negative, Large negative}

where each term in U is characterized as fuzzy set.

Similarly, we can construct an example of pressure(P). The universe of discourse is P=[100 psi-2300 psi].

It can be decomposed into the following set of terms.

P(pressure): { Very low, low, medium, high, Very high} ,

It might be interpreted as

Very low as a pressure below 200 psi

Low as a pressure close to 700 psi

Medium as a pressure close to 1050 psi

High as a pressure close to 1500 psi

Very high as a pressure above 2200 psi

3.2.4 Membership functions

The characteristic function of a fuzzy set is called the membership function, as it gives the degree of membership for each element of the universe of discourse. The x-axis of membership function shows thresholds of linguistic variables and y-axis show the membership value for that linguistic variable.

The most commonly used shapes for membership functions are monotonic, triangular, trapezoidal or bell shaped, etc., as shown in Fig. 3.6. Membership functions are chosen by the users, based on the users experiences, perspectives, cultures, etc., hence, the membership functions for two users could be quite different for the same problem[99].

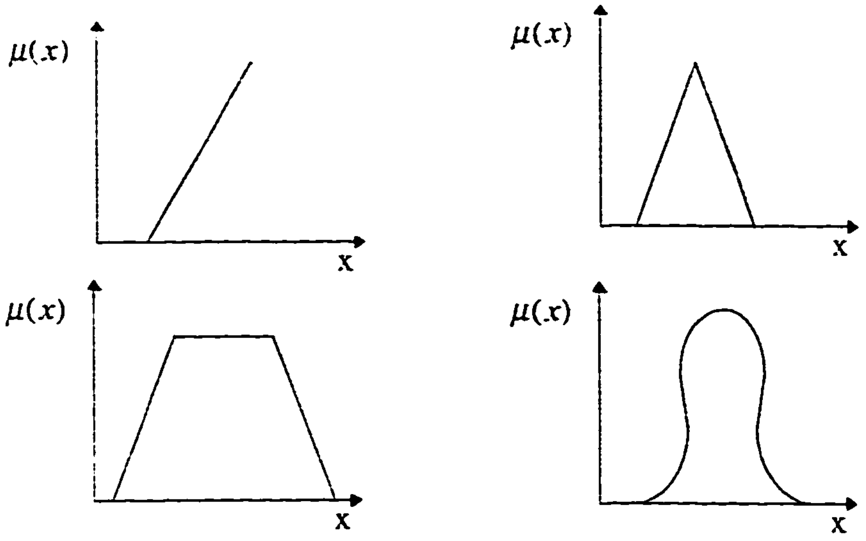


Figure 3. 6 The Different Shapes of Membership Functions.

How many membership functions should be used to represent a certain variable depend upon the user. Greater resolution is achieved by using more membership functions at the price of greater computational complexity. Membership functions do not overlap in crisp set theory but one of greater strength of fuzzy logic is that membership functions can be made to overlap.

In most control systems, the input variables of a FLC are error signals and their derivatives or their integral. These variables can be supported by terms like Large Negative(LN), Medium Negative(MN), Small Negative(SN), Zero(Z), Small Positive(SP), Medium Positive(MP), Large Positive(LP). In Figure 3.7 a set of triangular shaped membership functions are given to describe the above given linguistic variables and these are equally distributed over the universe of discourse. Using other membership function shapes can change the behavior of the FLC considerably. Furthermore, the width of the triangles and the way they are distributed are of great influence as well.

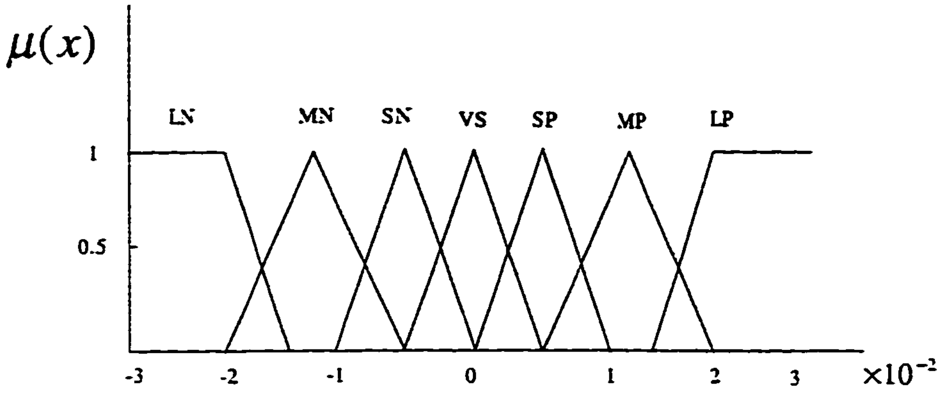


Figure 3. 7 A Set of Triangular Membership Functions

3.3 Knowledge Base and Control Rules

Knowledge Base is the foundation of a fuzzy logic system. It provides

- A data base which helps in constructing linguistic variables and ultimately membership functions.
- Rule base which helps in constructing all the control rules.

Generally speaking, the intelligent system (modern AI) gains much useful knowledge from numerous experiences and stores them in a large scale memory. The information processing is achieved in the symbolic manner. In other words, an inference is achieved by exact matching between input data and antecedents in the knowledge base (or variables in IF-clause of an IF-THEN rule in the knowledge base). In order to infer the conclusion from input data, the knowledge base of the system is necessarily of a large scale because boundaries of all the linguistic terms used are clear.

Human beings can gain a much smaller amount of useful knowledge from numerous experiences by *summarization.* Summarization is to cut off a less important portion from the raw information, to emphasize a more important point and to extract the essence of information. Summarization process converges much similar information obtained from experiences to one simple piece of information which includes a very important essence. This allows us to store a small amount of know-how efficiently. It is also remarkably significant that know-how obtained by summarization is usually represented by fuzzy linguistic terms. Otherwise, the know-how is the expression of only one experience and reduction of know-how cannot be guaranteed.

With the help of knowledge base which may contain an expert opinion or some other solution, information is obtained about the shape and thresholds of membership functions. From human reasoning plus information from knowledge base, the control rules are developed which are required in decision making process. For example, if x_1 and x_2 are two inputs and 'u' is the output of the FLC and three linguistic variables are chosen to describe each input variable {Positive(P), Zero(Z), Negative(N)} and five linguistic variables {PB, P, Z, N, NB} are selected to describe output, then a rule can be of the form

$$\text{IF } (x_1 \text{ is P}) \text{ and } (x_2 \text{ is Z}) \text{ THEN } (u \text{ is P})$$

In the above rule, the condition given just after 'IF' is called antecedent and statement given after 'THEN' is called consequent. To deal with every possible situation one has to define rules for all possible combinations of input variables. In this example, there are three linguistic variables for each input, so the total possible rules are nine. As mentioned earlier, rules are stored in the knowledge base through human reasoning and other information about the system. Table 3.1 gives an example of the possible set of rules for the problem mentioned.

Table 3. 1 Decision Table

x_1 \ x_2	P	Z	N
P	PB	P	Z
Z	P	Z	N
N	Z	N	NB

3.4 Fuzzification and Inference

The fuzzification and inference phase go hand in hand. In this section, the well known *max-min* approach for fuzzification, will be discussed.

The fuzzification process converts the crisp input to linguistic variables and then checks which rules of the rule-base have a truth value above zero. The higher the 'truth' value of a rule, the more the final output signal will be influenced by this rule. This phase results in a fuzzy output signal. First an example with figure is given and then the general formula for the max-min approach is derived.

Consider a FLC . Suppose at a certain moment both e and Δe have a crisp value between the centers of the fuzzy sets Z and P. In the particular case of a FLC described before , rules will be fired, meaning, will have a truth value above zero. In order to provide a clear explanation of the fuzzification and inference phase , only the following two of the four rules will be taken into account.

If e is Z and Δe is Z THEN u is Z.

If e is Z and Δe is P THEN u is P

For these two rules the fuzzification is graphically explained by Fig. 3.8 using the min-max approach. First for each rule , the minimum is taken of the antecedent's membership values related with the crisp inputs. Then the consequent of membership function is cut off above this minimum(clipped). The last step builds up a combined fuzzy output set by calculating the union of the sets.

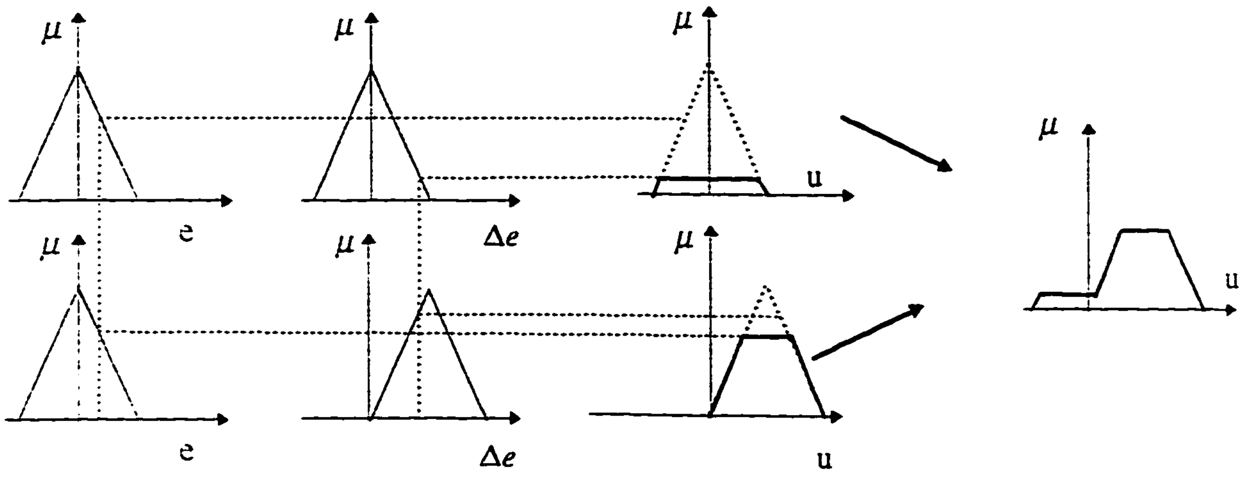


Figure 3. 8 Fuzzification & Inference according to min-max

To generalize the procedure, let

R_j: IF x_1 is A_{j1} and x_2 is A_{j2} and ... and x_n is A_{jn} THEN y is B_j

where $x_1 \ldots x_n$ are the crisp inputs , y is the output variable and $A_{j1} \ldots A_{jn}$ and b_j are the fuzzy sets of any shape. If U is the universe of discourse of the output , the following equation determines the output membership function $\mu_{output}(y)$ according to the max-min approach:

$$\mu_{output}(y) = \bigcup_{j=1}^{r} \left\{ \min(\mu_{A_{j1}}(x_1), \mu_{A_{j2}}(x_2), \ldots \mu_{A_{jn}}(x_n), \mu_{B_j}(y)) \right\}$$

Notice that for union operation in above equation, the max-operator has to be used. The next section deals with obtaining a crisp output from the output membership function $\mu_{output}(y)$

3.5 Defuzzification Methods

Defuzzification is the conversion of a fuzzy quantity to a crisp quantity. There are many popular methods which have been reported in literature[5.100] for defuzzifying fuzzy output functions. Some of them are:

1. Max-membership principal
2. Centroid Method
3. Weighted average method
4. Mean-max membership
5. Center of sums
6. Center of largest area
7. First (or last) of maxima

Three of the above methods which are extensively used for defuzzification are summarized below.

Centroid Method:

This method determines the center of gravity(COG) of the area below the combined membership function $\mu_{output}(y)$. The corresponding y-value is the crisp output y_{crisp} of the fuzzy controller. With U as universe of discourse of the output variable, the following equation represents the COG method:

$$y_{crisp} = \frac{\int_U (y.\mu_{output}(y))dy}{\int_U \mu_{output}(y)dy}$$

Weighted Average Method:

The method is only valid for symmetrical output membership functions. It is given by the algebraic sum

$$y_{crisp} = \frac{\sum \mu_{output}(y) \cdot y}{\sum \mu_{output}(y)}$$

The weighted average method is formed by weighting each membership function in the output by its respective maximum membership value.

Center of Sums:

This is faster than many defuzzification methods that are presently in use. This process involves the algebraic sum of individual output fuzzy sets, instead of their union. One drawback of this method is that the intersecting areas are added twice. The defuzzified value is given by the following equation:

$$y_{crisp} = \frac{\int_U \left(y.\sum_{j=1}^{r} \mu_j(y) \right) dy}{\int_U \sum_{j=1}^{r} \mu_j(y) dy}$$

This method is similar to the weighted average method, except that in the center of sums methods the weights are the areas of the respective membership functions, whereas in the weighted average method the weights are individual membership values.

3.6 Summary

The steps which are involved in the designing of a fuzzy logic controller can be summarized as follows:

Step 1 Choose the input signals to the controller.

Step 2 Decide the linguistic variables which can describe the input variables. These linguistic variables are used to transform the crisp values of the inputs to fuzzy quantities. The number of these linguistic variables specifies the quality of the control. As the number of linguistic variables increases, the computational time and required memory increases. Therefore, a compromise between the quality of control and computational time is needed to choose the number of linguistic variables.

Step 3 Choose the membership functions to represent the inputs and outputs of the controller. This includes the shape and thresholds of the membership functions. The thresholds are decided from the data history of the system.

Step 4 Fuzzify the crisp input of the controller and obtain the corresponding membership values.

Step 5 Construct the IF-THEN rules, for all possible combinations of inputs. The rules are stored in the knowledge base. If LV1 and LV2 are the number of linguistic variables for first and second input of stabilizer respectively, then total number of rules are LV1*LV2.

Step 6 Find the membership value of condition part of each rule. If the two antecedents of each rule are connected by 'and', then take the minimum of membership value of each antecedent. This is the membership value of the rule.

$\mu(x_i) = \mu(rule_i)$ =min[μ (first antecedent) , μ (second antecedent)]

The length of vector $\mu(x)$ is equal to total number of rules.

Step 7 Find membership value for each stabilizer output using the fuzzy relation matrix. Fuzzy relation matrix describes the relation between inputs and outputs as given by equation 3.6, as

$$\mu_{V_{PSS}}(LN) = \max_{x_i}\{\min[\mu_R(x_i, LN), \mu(x_i)]\}$$

The vector $\mu_{V_{PSS}}$ is of the same length as the number of linguistic variables for output membership functions.

Step 8 Defuzzify the output fuzzy variables by any of the suitable defuzzification technique.

Chapter 4

Power System Model

4.1 Introduction

For power system dynamic study, a proper and adequate power system model must be chosen to include all significant components relevant to the problem. For example, for study of low frequency oscillations of a large electric power system as an equivalent single machine infinite bus model, mechanical model with only one inertia constant, one field circuit equation, and a first order exciter is, generally, sufficient. On the other hand, for the study of torsional oscillations of a steam turbine-generator plant with a capacitor-compensated transmission system, the simple model for the low frequency study is neither proper nor adequate. For this study, the turbines and generator sets must be considered as a multiple mass spring system, and all generator windings, transmission lines and the capacitor compensation must be described by adequate differential equations[3].

In the following, we include models for the single machine and multimachine systems which are normally employed for stability studies.

4.2 Single Machine Model

The single line diagram of single machine infinite bus system considered for this study is shown in Figure 4.1. It consists of a synchronous generator feeding a power system through a transmission line. The generator is assumed to be equipped with a static excitation system. Speed governor and turbine models are also included.

a) Synchronous Machine model

The synchronous generator is modeled through d-q axis transient voltage equations (E'_d, E'_q) and the electromechanical swing equations.

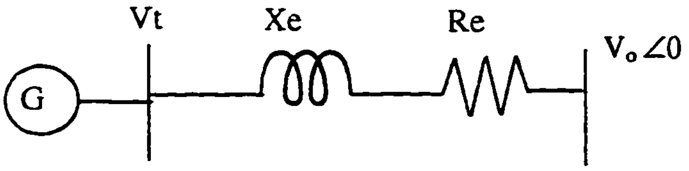


Figure 4. 1 Single machine infinite bus power system

The dynamic relationship of the internal voltages are given as[101]:

$$\dot{E}'_d = \left[-E'_d + (X_q - X'_d) I_q\right] / T'_{qo} \tag{4.1}$$

$$\dot{E}'_q = \left[E_{fd} - E'_q - (X_d - X'_d) I_d\right] / T'_{do} \tag{4.2}$$

where E'_d and E'_q are direct and quadrature axis transient voltages.

X_d and X_q are direct and quadrature axis synchronous reactances.

X'_d and X'_q are direct and quadrature axis transient reactances.

E_{fd} is the direct axis field voltage as seen from the armature.

I_d and I_q are the direct and quadrature axis armature current.

The electromechanical swing equation is

$$M\ddot{\delta} + D\dot{\delta} = P_m - P_e \qquad (4.3)$$

where δ is rotor angle, M and D are inertia and damping constant respectively. P_m is the prime mover mechanical input and P_e is the electrical output.

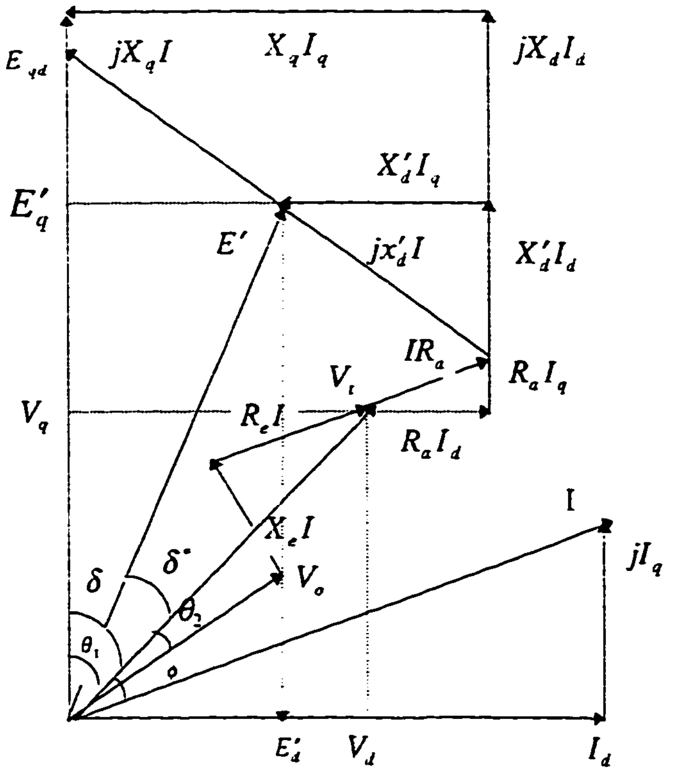


Figure 4. 2 Phaser Diagram for synchronous machine in transient state

The state variables chosen for the generator equations are $[E'_d, E'_q, \delta, \omega]$. The non-state variables like I_d, I_q, P_e are expressed in terms of the selected state variables through the following analysis.

Referring to the phaser diagram given in Fig. 4.2

$$I = \frac{S_o^*}{V_t} \tag{4.4}$$

$$E_{qd} = V_t + R_a I + jX_q I = |E_{qd}|\angle\theta_1 \tag{4.5}$$

$$V_o = V_t - (R_a + jX_e)I = |V_o|\angle\theta_2 \tag{4.6}$$

$$\delta = \theta_1 + \theta_2 \tag{4.7}$$

$$E' = V_t + (R_a + jX'_d)I = |E'|\angle\delta^* \tag{4.8}$$

$$E'_{do} = |E'|Sin(\theta_1 - \delta^*) \tag{4.9}$$

$$E'_{qo} = |E'|Cos(\theta_1 - \delta^*) \tag{4.10}$$

$$E_{fdo} = E'_{qo} + (X_d - X'_d)I_{do} \tag{4.11}$$

$$I_{do} = |I_o|Sin(\phi + \theta_1) \tag{4.12}$$

$$I_{qo} = |I_o|Cos(\phi + \theta_1) \tag{4.13}$$

The electrical power output of the generator is related to the voltages and currents by

$$P_e = E'_d I_d + E'_q I_q \tag{4.14}$$

The terminal voltage relating the transmission line and generator quantities are:

$$V_d = E'_d - R_a I_d + X'_q I_q \tag{4.15}$$

$$V_d = V_o Sin\delta + R_e I_d - X_e I_q \tag{4.16}$$

$$V_q = E'_q - R_a I_q + X'_d I_d \tag{4.17}$$

$$V_q = V_o Cos\delta + R_e I_q + X_e I_d \tag{4.18}$$

$$V_t = \sqrt{V_d^2 + V_q^2} \tag{4.19}$$

Equating (4.15) with (4.16) and (4.17) with (4.18) results in:

$$\begin{bmatrix} R_a + R_e & -(X_e + X'_d) \\ X_e + X'_d & R_a + R_e \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} E'_d - V_o Sin\delta \\ E'_q - V_o Cos\delta \end{bmatrix} \tag{4.20}$$

$$\Delta = (R_a + R_e)^2 + (X_e + X'_d)^2 \tag{4.21}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} R_a + R_e & -(X_e + X'_d) \\ X_e + X'_d & R_a + R_e \end{bmatrix} \begin{bmatrix} E'_d - V_o Sin\delta \\ E'_q - V_o Cos\delta \end{bmatrix} \tag{4.22}$$

$$A_d = \frac{R_a + R_e}{\Delta} \tag{4.23}$$

$$A_q = \frac{X_e + X'_d}{\Delta} \tag{4.24}$$

$$I_d = A_d(E'_d - V_o Sin\delta) + A_q(E'_q - V_o Cos\delta) \tag{4.25}$$

$$I_q = -A_q(E'_d - V_o Sin\delta) + A_d(E'_q - V_o Cos\delta) \tag{4.26}$$

The non state variables (I_d & I_q) are eliminated by substituting (4.25) & (4.26) into (4.1) & (4.2)

$$\begin{aligned} \dot{E}'_d = {} & \frac{A_q(X_q - X'_d)V_o}{T'_{qo}} Sin\delta - \frac{A_d(X_q - X'_d)V_o}{T'_{qo}} Cos\delta \\ & - \frac{1 + A_q(X_q - X'_d)}{T'_{qo}} E'_d + \frac{A_d(X_q - X'_d)}{T'_{qo}} E'_q \end{aligned} \tag{4.27}$$

$$\begin{aligned} \dot{E}'_q = {} & \frac{A_d(X_d - X'_d)V_o}{T'_{do}} Sin\delta - \frac{A_q(X_d - X'_d)V_o}{T'_{do}} Cos\delta \\ & + \frac{1}{T'_{do}} E_{fd} - \frac{1 + A_q(X_d - X'_d)}{T'_{do}} E'_q + \frac{A_d(X_d - X'_d)}{T'_{do}} E'_d \end{aligned} \tag{4.28}$$

Equation (4.14) becomes

$$\begin{aligned} P_e = {} & A_d(E_d'^2 + E_q'^2) - A_d V_o E_d' Sin\delta + A_q V_o E_q' Sin\delta \\ & - A_q V_o E_d' Cos\delta - A_d V_o E_q' Cos\delta \end{aligned} \qquad (4.29)$$

The mechanical rotating system is represented as a single solid shaft so that the torsional oscillation effects are neglected. Thus, the mechanical rotating system is essentially modeled by a second order differential equation to reflect the dominant electromechanical oscillations during the transient disturbances. The electromechanical swing equation given in equation (4.3) can be split up into two as

$$\dot{\omega} = \frac{1}{M}(P_m - D\omega - P_e) \qquad (4.30)$$

$$\dot{\delta} = \omega_o(\omega - 1) \qquad (4.31)$$

Substituting P_e from (4.29) into (4.30) we get

$$\begin{aligned} \dot{\omega} = {} & -\frac{D}{M}\omega + \frac{A_d V_o}{M} E_d' Sin\delta - \frac{A_q V_o}{M} E_q' Sin\delta + \frac{A_q V_o}{M} E_d' Cos\delta + \frac{A_d V_o}{M} E_q' Cos\delta \\ & - \frac{A_d}{M} E_d'^2 - \frac{A_d}{M} E_q'^2 + \frac{1}{M} P_m \end{aligned} \qquad (4.32)$$

The state model of the generator only can be represented by equations (4.27), (4.28), (4.31) and (4.32).

b) Excitation system

The IEEE Type 1 excitation system given in Figure 4.3 is considered in this study

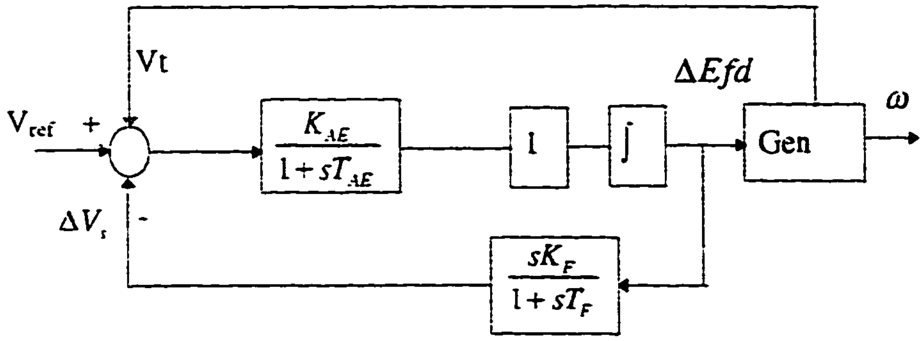


Figure 4. 3 The IEEE Type 1 Excitation Block Diagram

Mathematically the exciter block diagram can be expressed as

$$\Delta \dot{E}_{fd} = \frac{K_{AE}}{T_{AE}}(V_{tr} - V_t) - \frac{1}{T_{AE}}\Delta E_{fd} - \frac{K_{AE}}{T_{AE}}\Delta V_s \qquad (4.34)$$

$$\Delta \dot{V}_s = \frac{K_F}{T_F}\Delta \dot{E}_{fd} - \frac{1}{T_F}\Delta V_s \qquad (4.35)$$

c) Turbine and Governor System

The steam turbine and governor system model considered is shown by the block diagram in Figure 4.4. The governor system is represented by time constants corresponding to the speed relay, servomotor, steam chest and turbine.

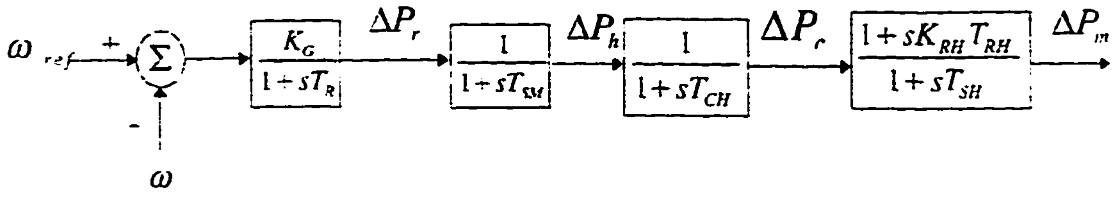


Figure 4. 4 Steam Turbine and Governor System

This can be expressed in terms of the following state equations.

$$\Delta \dot{P}_r = -\frac{K_G}{T_{SR}}\Delta\omega - \frac{1}{T_{SR}}\Delta P_r \tag{4.36}$$

$$\Delta \dot{P}_h = \frac{1}{T_{SM}}\Delta P_r - \frac{1}{T_{SM}}\Delta P_h \tag{4.37}$$

$$\Delta \dot{P}_c = \frac{1}{T_{CH}}\Delta P_h - \frac{1}{T_{CH}}\Delta P_c \tag{4.38}$$

$$\Delta \dot{P}_m = \frac{1}{T_{RH}}\Delta P_c + K_{RH}\Delta \dot{P}_c - \frac{1}{T_{RH}}\Delta P_m \tag{4.39}$$

The single machine infinite bus system is then expressed through a 10th order state model

$$\dot{x} = f(x,u) \tag{4.40}$$

where x is a vector of $\left[\omega, \delta, E'_d, E'_q, E_{fd}, V_s, P_r, P_h, P_c, P_m\right]^T$

and u is the input to the power system stabilizer.

The differential equations were solved by Rang-Kutta method. A computer program was developed in FORTRAN to simulate the power system.

4.3 Multimachine system model

In the past few decades, when computing facilities were not much developed, a simple model of a constant voltage behind a transient reactance was used for a synchronous machine and it was adequate for approximate studies. Now due to revolutionary changes in the world of computing tools, a detailed and accurate model can be adapted. Changes in field winding may be accounted for and also the inclusion of automatic voltage regulator and speed governor may improve the results.

The synchronous generator, in this study, is modeled through d-q axis transient voltage equations and the electromechanical swing equation. The excitation system, governor and turbine are also considered. Transmission lines are represented by its equivalent Π circuits in the positive phase sequence. Other loads are represented as fixed impedances. Differential equations are used to describe the rotational motion of the machines. Algebraic equations describe the network relationships.

4.3.1 Synchronous Machine Model

The swing equation of each synchronous machine can be rewritten in terms of two first order differential equations as,

$$M_i\ddot{\delta}_i = P_i - P_{ei} - D_i\dot{\delta}_i \qquad (4.41)$$

where i=1,2,.....n n is the number of machines.

The machine speeds are written as

$$\dot{\delta}_i = \omega_i \qquad (4.42)$$

where i=1,2,.....,n

The above two equations represent the mechanical motion of the machine.

where

$$P_i = P_{mi} - |E_i|^2 G_{ii} \qquad (4.43)$$

$$P_{ei} = \sum_{\substack{j=1 \\ j\neq i}}^{n} [A_{ij} \sin(\delta_i - \delta_j) + B_{ij} \cos(\delta_i - \delta_j)] \qquad (4.44)$$

$$A_{ij} = |E_i||E_j||Y_{ij}| \sin\phi_{ij} \qquad (4.45)$$

$$B_{ij} = |E_i||E_j||Y_{ij}| \cos\phi_{ij} \qquad (4.46)$$

Equations of the transient voltages as derived in the single machine model, are

$$\dot{E}'_d = \left[-E'_d + (X_q - X'_d)I_q\right] / T'_{qo} \qquad (4.47)$$

$$\dot{E}'_q = \left[E_{fd} - E'_q - (X_d - X'_d)I_d\right] / T'_{do} \qquad (4.48)$$

where,

E_{fd} = machine field voltage

X_d , X_q = direct and quadrature synchronous reactances respectively.

T'_d, T'_q = direct and quadrature axes transient time constant.

The phaser diagram of machine operating in transient state is similar to Fig. 4.2.

4.3.2 AVR, Speed Governor And Turbine Model

Figure 4.5 shows the IEEE type 2 excitation system model as used in this study

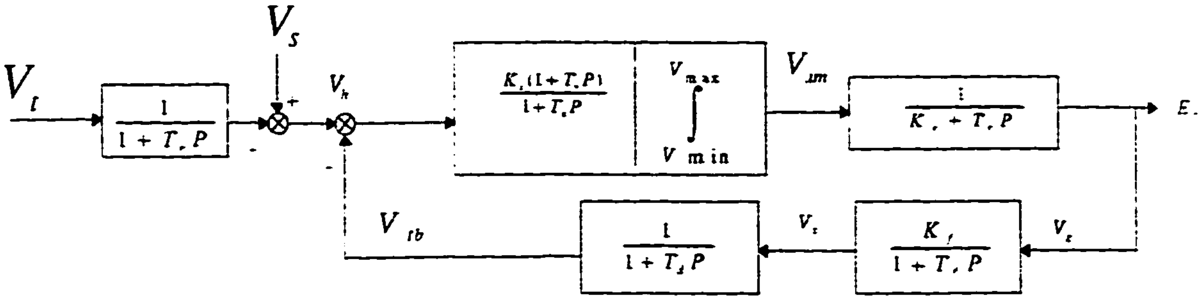


Figure 4. 5 A Block Diagram of Automatic Voltage Regulator.

A speed governor includes the effect of the turbine which is assumed to produce constant shaft power. Figure 4.6 shows a block diagram of the speed governor model adopted in this study.

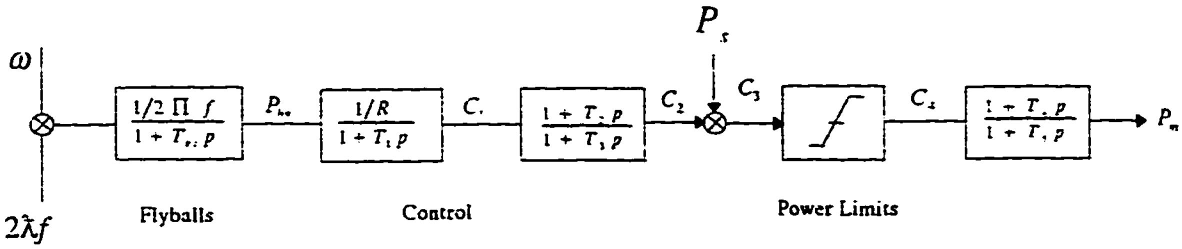


Figure 4. 6 A Block Diagram of Composite Speed Governor.

The excitation system contributes 3 differential equations and the speed governor and the steam turbines are represented by 4th order model each.

4.3.3 Network

The network is expressed in the normal modal admittance form, the equation is given as

$$I=Y \cdot V \tag{4.49}$$

where I and V are complex injected current and nodal voltage vectors respectively, and Y is the admittance matrix of the transmission network.

The synchronous machine equations are written in a synchronously rotating frame of reference. The transformation into real and imaginary components of the network equation is given by

$$\begin{bmatrix} V_r \\ V_m \end{bmatrix} = \begin{bmatrix} \sin\delta & \cos\delta \\ -\cos\delta & \sin\delta \end{bmatrix} \cdot \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{4.50}$$

for both currents and voltages.

where δ is the machine rotor angle.

V_d and V_q are direct and quadrature axis nodal voltages respectively.

The electrical power output for each generator is obtained by adding the real power flow of each line[102].

A load flow solution of the predisturbed system is done by a fast decoupled Newton-Raphson technique. The differential equations are converted to algebraic equations. These, along with the network equations, are solved through trapezoidal integration iteratively at every integration step. Solution is advanced if the necessary convergence criterion is met.

Chapter 5

Fuzzy PSS for Single Machine System

5.1 Introduction

The single machine system given in Figure 5.1 is considered for this study. The system data is given in Appendix A. Stabilizing control obtained through fuzzy logic theory was used to stabilize the system for the following disturbances.

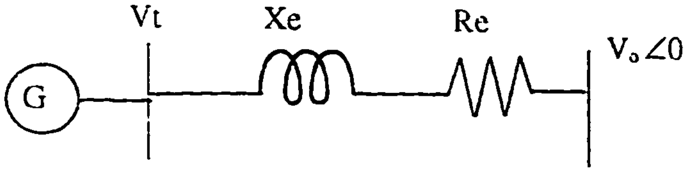


Figure 5. 1 Single machine infinite bus power system

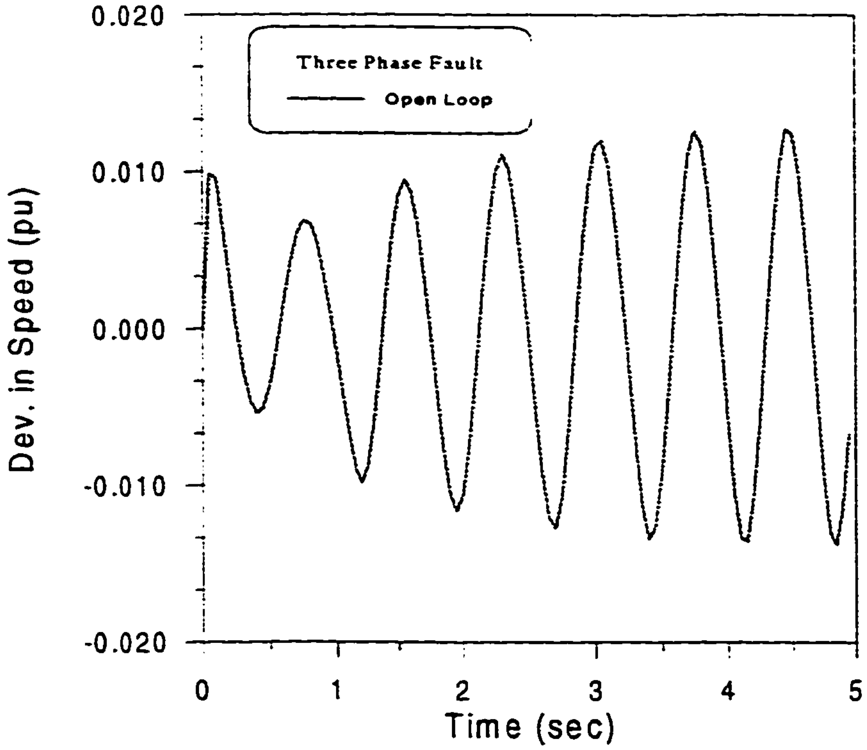
- A 50% torque pulse for a duration of 0.06 secs. The linear system model was used for simulation. This disturbance is small because of relatively smaller excursion of rotor angle.
- A three phase fault at generator bus for 0.06 secs. Since this is a very large disturbance, the nonlinear system model was considered.

The first step in designing fuzzy logic controller is the selection of inputs for the fuzzy controller. The inputs should be so selected that they are representative of system dynamics. Change in shaft speed and acceleration are considered as the inputs to FPSS in this study.

The linguistic variables and the membership functions for the inputs are obtained from an open loop study. For a symmetric three phase fault, the speed and acceleration variables obtained from an open loop simulation are shown in Fig. 5.2 and Fig.5.3 respectively. Linguistic variables and corresponding membership functions are selected from these records.

The linguistic variables for the control signal and the consequent decision table in the fuzzy algorithm are generated in two different ways. These are

1. Through a method reported in the literature by Hsu[84], and Toliyat[86]. This has been termed as 'General method' in this work.
2. The decision variables obtained from a minimum time stabilization strategy are converted to linguistic variables along with the corresponding linguistic variables and stored in the knowledge base. The fuzzy algorithm for stabilization developed with expert knowledge is termed as minimum time based fuzzy logic power system stabilizer(MTB FPSS).



3.

Figure 5. 2 Deviation in Speed (Open Loop Study)

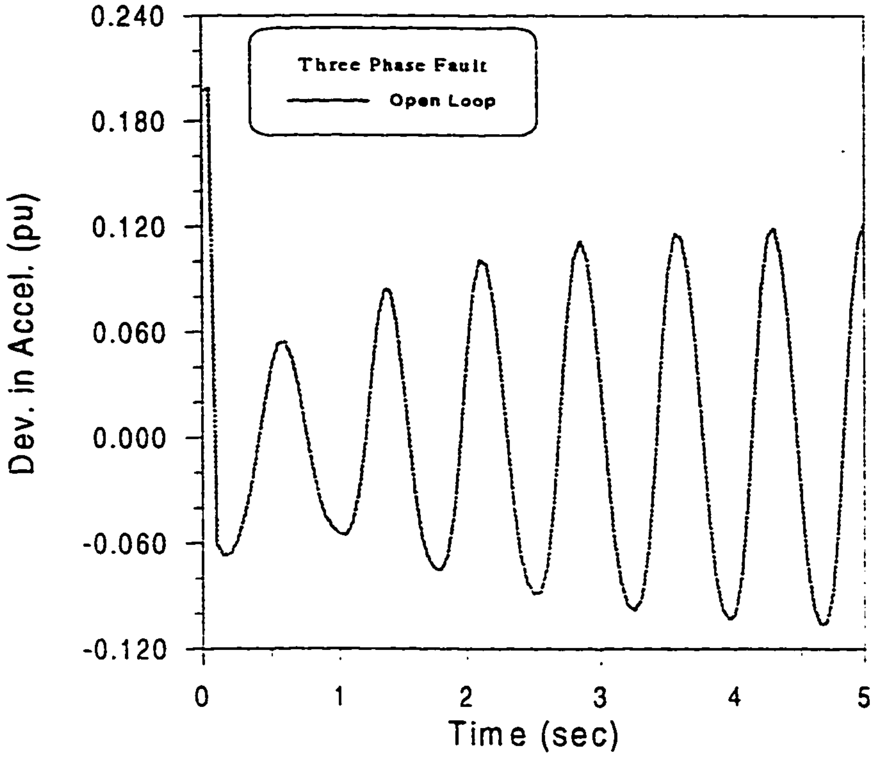


Figure 5. 3 Deviation in Acceleration (Open Loop Study)

5.2 FPSS Using the General Method

5.2.1 FPSS Design

Designing of the FPSS constitutes construction of the following:

1. The input membership functions.
2. The output membership functions.
3. The decision table.
4. The fuzzy relation matrix.

The designing of membership functions for the stabilizer input is done by keeping in view the minimum and maximum of stabilizer inputs. In order to find the minimum and maximum of stabilizer inputs ($\Delta\omega, \Delta\dot{\omega}$), open loop simulation results given in Figs. 5.2 and 5.3 were used. The fuzzy sets for these variables in terms of linguistic variables are then specified. In this study, seven linguistic variables[LN,MN,SN,Z,SP,MP,LP] were considered for the states. Triangular shapes are taken for the degree of membership. The membership functions for two stabilizers inputs are shown in Figures 5.4 & 5.5. The thresholds for the decision variable as reported in Toliyat's work[86] are

$$V_{PSS} = [-0.1 \quad -0.04 \quad -0.02 \quad 0 \quad 0.02 \quad 0.04 \quad 0.1] \qquad (5.1)$$

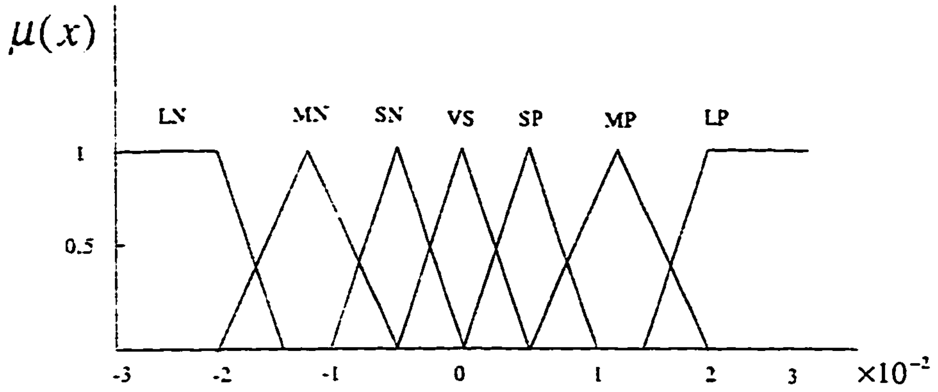


Figure 5. 4 Membership Function for Deviation in Speed

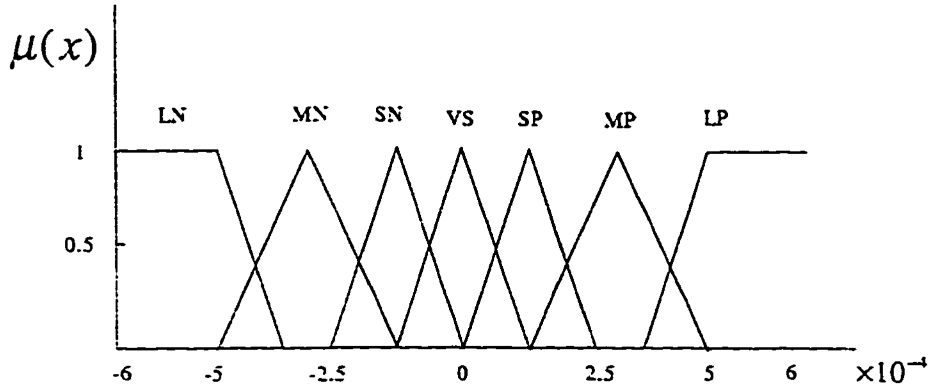


Figure 5. 5 Membership Function for Deviation in acceleration.

The decision table as used in this reference[86] is given in Table 5.1. The 49 combinations of the states are entered in the fuzzy relationship matrix of Table5.2.

Table 5. 1 Decision Table for General Method

$\Delta\dot{\omega}$ $\Delta\omega$	LN	MN	SN	VS	SP	MP	LP
LN	LN	LN	LN	LN	MN	SN	VS
MN	LN	LN	MN	MN	SN	VS	SP
SN	LN	MN	SN	SN	VS	SP	MP
VS	MN	MN	SN	VS	SP	MP	MP
SP	MN	SN	VS	SP	SP	MP	LP
MP	SN	VS	SP	MP	MP	LP	LP
LP	VS	SP	MP	LP	LP	LP	LP

Table 5. 2 Fuzzy Relation matrix for General Method

X_i	Stabiliser Input	Stabiliser Output						
		LN	*MN*	*SN*	*VS*	*SP*	*MP*	*LP*
		Membership value						
		$m_R(x_i, LN)$	$m_R(x_i, MN)$	$m_R(x_i, SN)$	$m_R(x_i, VS)$	$m_R(x_i, SP)$	$m_R(x_i, MP)$	$m_R(x_i, LP)$
x_1	(LN, LN)	1	0.5	0	0	0	0	0
x_2	(LN, MN)	1	0.5	0	0	0	0	0
x_3	(LN, SN)	1	0.5	0	0	0	0	0
x_4	(LN, VS)	1	0.5	0	0	0	0	0
x_5	(LN, SP)	0.5	1	0.5	0	0	0	0
x_6	(LN, MP)	0	0.5	1	0.5	0	0	0
x_7	(LN, LP)	0	0	0.5	1	0.5	0	0
x_8	(MN, LN)	1	0.5	0	0	0	0	0
x_9	(MN, MN)	1	0.5	0	0	0	0	0
x_{10}	(MN, SN)	0.5	1	0.5	0	0	0	0
x_{11}	(MN, VS)	0.5	1	0.5	0	0	0	0
x_{12}	(MN, SP)	0	0.5	1	0.5	0	0	0
x_{13}	(MN, MP)	0	0	0.5	1	0.5	0	0
x_{14}	(MN, LP)	0	0	0	0.5	1	0.5	0
x_{15}	(SN, LN)	1	0.5	0	0	0	0	0
x_{16}	(SN, MN)	0.5	1	0.5	0	0	0	0
x_{17}	(SN, SN)	0	0.5	1	0.5	0	0	0
x_{18}	(SN, VS)	0	0.5	1	0.5	0	0	0
x_{19}	(SN, SP)	0	0	0.5	1	0.5	0	0
x_{20}	(SN, MP)	0	0	0	0.5	1	0.5	0
x_{21}	(SN, LP)	0	0	0	0	0.5	1	0.5
x_{22}	(VS, LN)	0.5	1	0.5	0	0	0	0
x_{23}	(VS, MN)	0.5	1	0.5	0	0	0	0
x_{24}	(VS, SN)	0	0.5	1	0.5	0	0	0
x_{25}	(VS, VS)	0	0	0.5	1	0.5	0	0
x_{26}	(VS, SP)	0	0	0	0.5	1	0.5	0
x_{27}	(VS, MP)	0	0	0	0	0.5	1	0.5
x_{28}	(VS, LP)	0	0	0	0	0.5	1	0.5
x_{29}	(SP, LN)	0.5	1	0.5	0	0	0	0
x_{30}	(SP, MN)	0	0.5	1	0.5	0	0	0
x_{31}	(SP, SN)	0	0	0.5	1	0.5	0	0
x_{32}	(SP, VS)	0	0	0	0.5	1	0.5	0
x_{33}	(SP, SP)	0	0	0	0.5	1	0.5	0
x_{34}	(SP, MP)	0	0	0	0	0.5	1	0.5
x_{35}	(SP, LP)	0	0	0	0	0	0.5	1
x_{36}	(MP, LN)	0	0.5	1	0.5	0	0	0
x_{37}	(MP, MN)	0	0	0.5	1	0.5	0	0
x_{38}	(MP, SN)	0	0	0	0.5	1	0.5	0
x_{39}	(MP, VS)	0	0	0	0	0.5	1	0.5
x_{40}	(MP, SP)	0	0	0	0	0.5	1	0.5
x_{41}	(MP, MP)	0	0	0	0	0	0.5	1
x_{42}	(MP, LP)	0	0	0	0	0	0.5	1
x_{43}	(LP, LN)	0	0	0.5	1	0.5	0	0
x_{44}	(LP, MN)	0	0	0	0.5	1	0.5	0
x_{45}	(LP, SN)	0	0	0	0	0.5	1	0.5
x_{46}	(LP, VS)	0	0	0	0	0	0.5	1
x_{47}	(LP, SP)	0	0	0	0	0	0.5	1
x_{48}	(LP, MP)	0	0	0	0	0	0.5	1
x_{49}	(LP, LP)	0	0	0	0	0	0.5	1

Sample Calculation

A numerical example for calculating the crisp stabilizer output from a crisp set of input using the fuzzy algorithm is given in the following. The steps followed are as in section 3.6

For, $\Delta\omega = 0.65 \times 10^{-2}$ and $\Delta\dot{\omega} = 0.4 \times 10^{-1}$

The two stabilizer inputs in terms of linguistic variables shown in Fig. 5.4 & 5.5 respectively, would be described by the following fuzzy sets:

$$\{\Delta\omega\} = \{(LN,0),(MN,0),(SN,0),(VS,0.0298),(SP,0.9745),(MP,0),(LP,0)\}$$
$$\{\Delta\dot{\omega}\} = \{(LN,0),(MN,0),(SN,0),(VS,0),(SP,0),(MP,0),(LP,1)\}$$

The membership value for the condition part of 49 rules are obtained as:

$\mu(x_1) = \mu\,(\Delta\omega$ is LN and $\Delta\dot{\omega}$ is LN)

=min[$\mu\,(\Delta\omega$ is LN), $\mu\,(\Delta\dot{\omega}$ is LN)]

=min[0,0]= 0

For rule 28,

$\mu(x_{28}) = \mu\,(\Delta\omega$ is VS and $\Delta\dot{\omega}$ is LP)

=min[$\mu\,(\Delta\omega$ is VS), $\mu\,(\Delta\dot{\omega}$ is LP)]

=min[0.0298,1]=0.0298

Similarly,

$\mu(x_{35})$ =0.9745

All other membership values from 1 to 49 except 28 & 35, are zero, as $\mu(x)$ is a column vector of length 49.

To find the membership values for the stabilizer output characterized by the seven linguistic variables LN, MN, SN, VS, SP, MP, LP. The fuzzy relation matrix given as Table 5.2 is employed

For example

$\mu_{u_{PSS,28}}$(LN)=min[$\mu_R(x_1, LN), \mu(x_1)$]=min[0,0.0298]=0

This is the membership value of the stabilizer output LN if only Rule 28 exists. In order to take all the 49 rules into account, the membership values for the condition part of all the other 48 rules must be considered. The final value for stabilizer output LN can be evaluated using following equation

$$\mu_{u_{PSS}}(LN) = \max_{x_i}\left\{\min\left[\mu_R(x_i, LN), \mu(x_i)\right]\right\}$$

Repeating the procedure for other linguistic variables of the decision variable, their membership values can be calculated as:

$\mu_{u_{PSS}}(LN)=0$ $\quad\mu_{u_{PSS}}(MN)=0$ $\quad\mu_{u_{PSS}}(SN)=0$

$\mu_{u_{PSS}}(VS)=0$ $\quad\mu_{u_{PSS}}(SP)=0.0298$ $\quad\mu_{u_{PSS}}(MP)=0.5$

$\mu_{u_{PSS}}(LP)=0.9745$

By applying the weighted average defuzzification method, get the final value of control output as

$$u_{PSS} = \frac{0\times-(0.1)+0\times-(0.04)+0\times(-0.02)+0\times 0+0.0298\times 0.02+0.5\times 0.04+0.9745\times 0.1}{0+0+0+0+0.298+0.5+0.9745}$$

=0.0785

5.2.2 Simulation Results

The FPSS with the general method was tested for the two types of disturbances-50% torque pulse and three phase fault. Plots for deviation in speed for no control and with fuzzy logic control by general method, for 50% torque pulse are shown in Fig. 5.6. Plots of deviation in speed for no control and with fuzzy logic control for three phase fault are shown in Figure 5.7. The results show generally good damping characteristics for both types of faults. The settling time is observed to be large in case f the torque pulse.

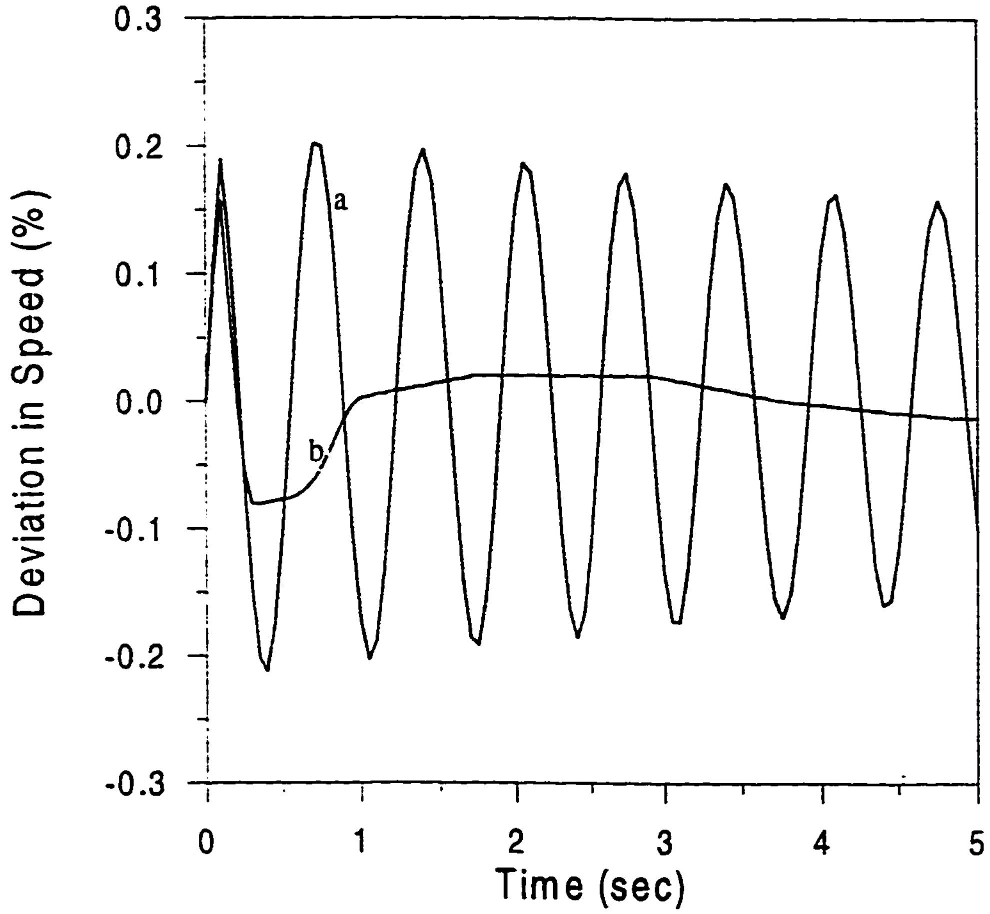


Figure 5. 6 Deviation in Speed for 50% Torque Pulse

a)No control

b)Fuzzy logic control

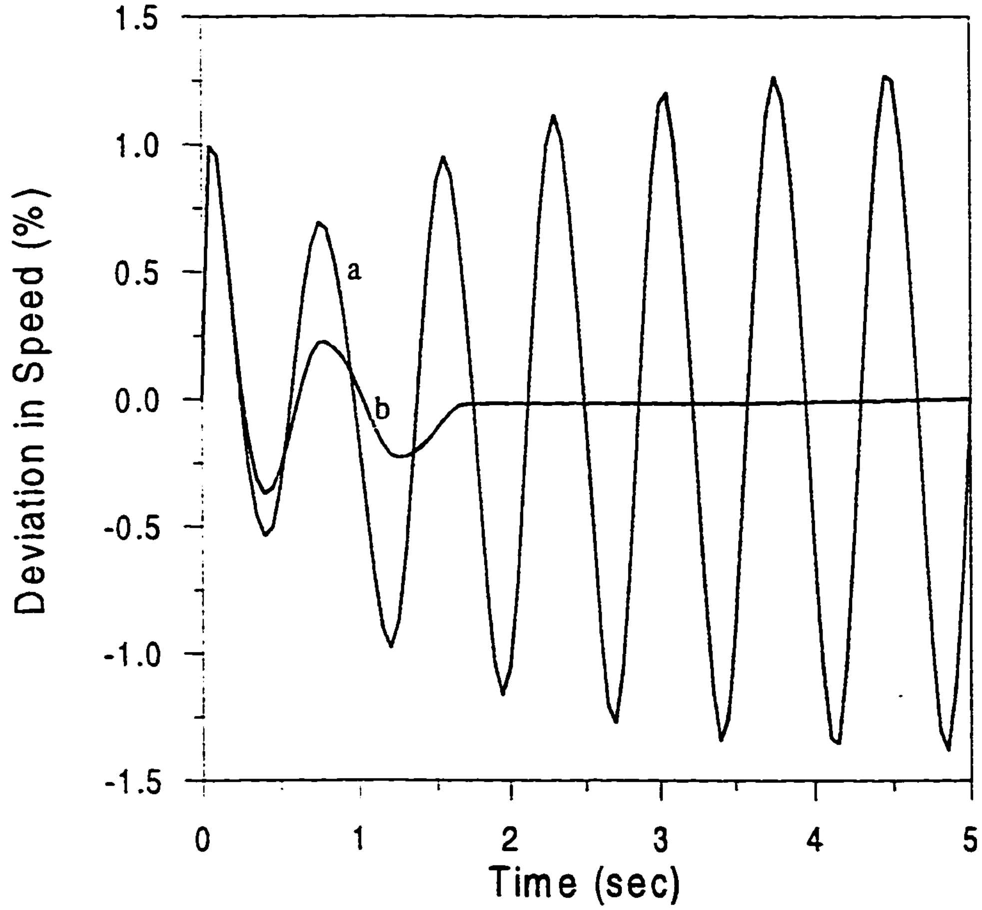


Figure 5. 7 Deviation in Speed for Three Phase Fault.

a)No control

b)Fuzzy logic control

5.3 Minimum Time Based Fuzzy PSS

The fuzzy PSS designed in the previous sections using 7 linguistic variables requires a 49x7 fuzzy relation matrix. Since the procedure of determining the control through steps 4 to 8, presented in section 3.6 have to be repeated at each sampling instant, it may be computationally burdensome. This may offset the gain achieved by the fuzzy stabilizer design.

In the following section an attempt is made to design a FPSS which requires less number of linguistic variables for states as well as control, thus making the algorithm computationally efficient. The decision variables are obtained through a classical optimization procedure which ensures that the control will provide adequate damping to the system.

5.3.1 The optimum control strategy and fuzzy matrices

The power system model in the state space can be represented by the nonlinear function as:

$$\dot{x} = f(x,u) \tag{5.1}$$

where x is the state vector.

u is the stabilizing control to the AVR

The constraint on the normalized control is

$$-1 \leq u_i \leq 1 \tag{5.2}$$

One way to define a stability problem is: Given the initial values of x_o, find the admissible control u which brings the change in speed and acceleration to zero in minimum possible time or minimizes the performance index.

$$J = \int_{t_o}^{t_f} dt \tag{5.3}$$

A closed form solution of the above control problem is not possible because of the complexity of the system equations and also because of its dependence on the nature of disturbances. A simple procedure to find the control in a closed form proposed in the reference[102] is briefly summarized below.

Consider the speed variation equation in the electromechanical swing equation

$$\dot{\omega} = \frac{1}{M}\left[P_m - P_e - P_D\right] \tag{5.4}$$

where $P_e = v_d i_d + v_q i_q$

The damping torque P_D is often neglected and P_m is constant input power. Differentiating the speed equation and substituting appropriate relationship of voltage, current and other states from(5.4), and after some algebraic manipulations we can write[103]

$$\ddot{\omega} = L(x) + b(x)u \tag{5.5}$$

where

$$L(x) = \frac{v_d e_i}{x'_d T'_{do} T_m} + \frac{v_q e_d}{T_m x'_q T'_{qo}} + \frac{2 \cdot i_d e_d}{T_m T'_{qo}}$$

$$b(x) = -\frac{v_d}{T_m x'_d T'_{do}}$$

A quasi optimum minimum time control for (4) can be written as[103]

$$u = \begin{cases} u_{\max}, & \text{if } \Sigma > 0 \\ u_{\min}, & \text{if } \Sigma < 0 \end{cases}$$

where, $$\Sigma = \Delta\omega - \frac{(\Delta\dot{\omega})^2}{2[L(x) + b(x)\cdot \operatorname{sgn}\{\Delta\dot{\omega}\}]}$$

The above control strategy can be demonstrated by Figure 5.8. The switch curves(Σ) are located in second and fourth quadrants of the state space. If both speed and acceleration are positive i.e., the trajectory is the first quadrant(R+), the control is positive. It is negative in the third quadrant(R-). In the second or fourth quadrant the control may be positive or negative depending on the switch curve. Moreover, it should be noted that switch curve depends on $L(x)$ and $b(x)$ which are state dependent.

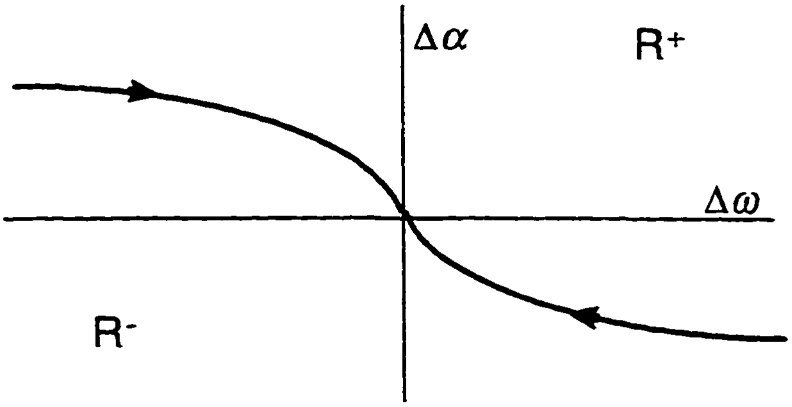


Figure 5. 8 Switch Curve

If $\Delta\omega - \Delta\alpha$ plane is converted to polar coordinates of R-θ plane where

$$R = \sqrt{\Delta\omega^2 + (\alpha\Delta\dot{\omega})^2}$$

$$\theta = \tan^{-1}\left(\frac{\alpha\Delta\dot{\omega}}{\Delta\omega}\right) \tag{5.6}$$

The above control algorithm in fuzzy notation can be expressed by Fig. 5.9

where P stands for positive and N for negative controls. The parameter α can be adjusted for scaling the acceleration of the machines.

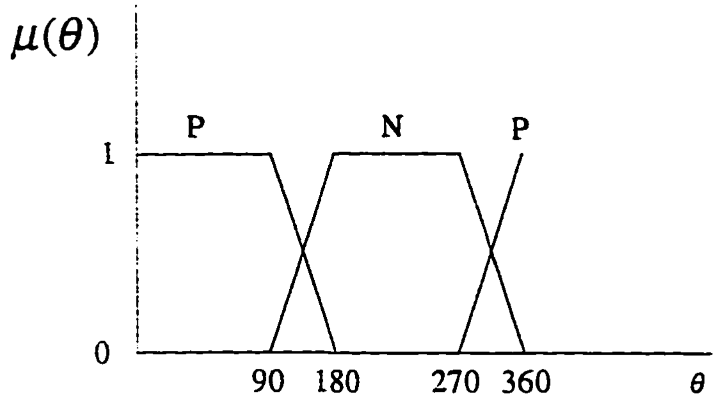


Figure 5. 9 Membership Function of Angle (θ)

The time optimum 'bang bang' control is not suitable from application viewpoint because the transition of AVR control is not smooth. Also, it is not required to drive the exciter to the ceilings when the oscillations have died down. A sub-optimal control given as

$$u = K\Sigma \tag{5.7}$$

which is proportional to the switch function is used in the simulation studies. The value of K is obtained by trail and error such that for large perturbations the exciter reaches the ceilings.

For a three phase fault on the remote bus for a duration of 0.06 secs(3.6 cycles) the generator speed deviation is shown in Fig. 5.10. Curve 'a' is without any control and the time optimum control is given in 'b'. The variation of the time optimum control is shown in Fig. 5.11.

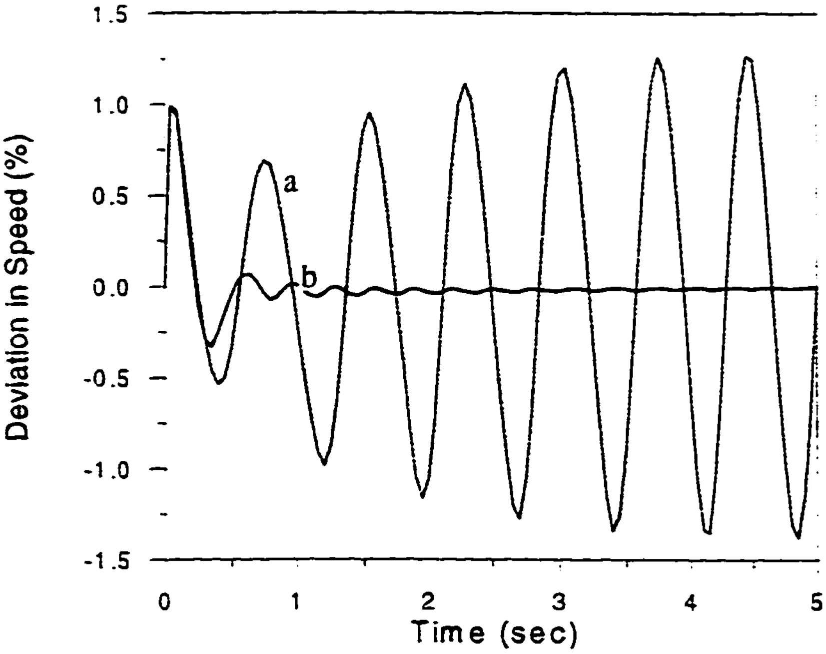


Figure 5. 10 Deviation in Speed for Minimum Time Controller

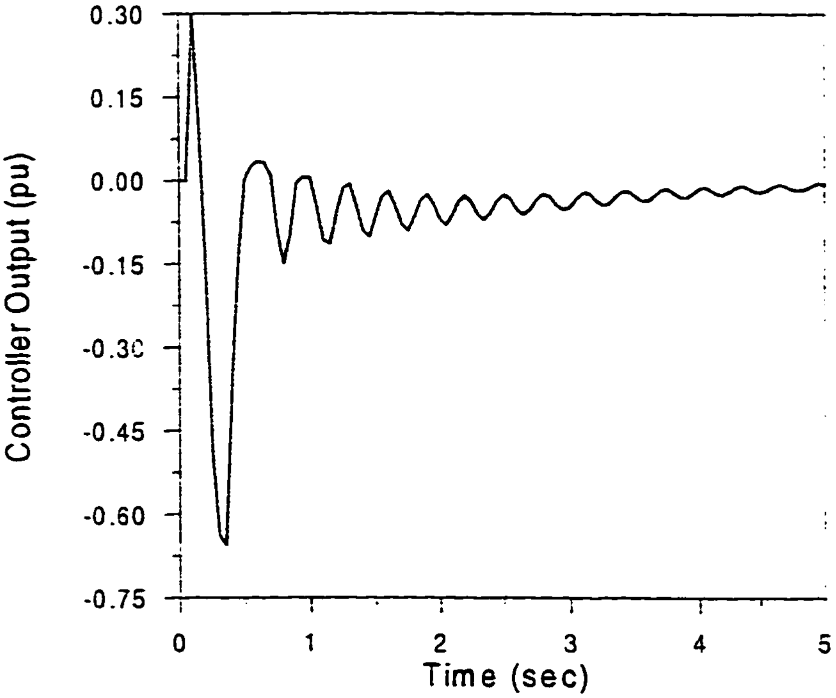


Figure 5. 11 Output of Minimum Time Controller

The thresholds for R and u_{PSS} are obtained from the open loop and optimal responses of Figures 5.10 & 5.11 respectively. The thresholds of R with the membership functions are shown in Figure 5.12.

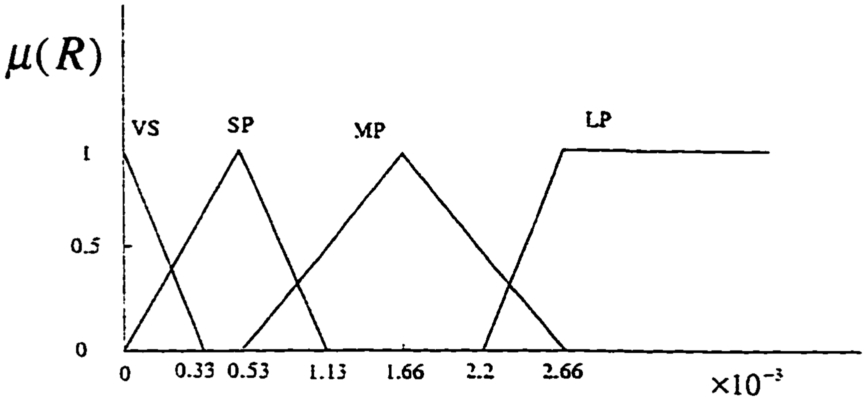


Figure 5. 12 Membership Function of R

The thresholds for the control are selected as,

$$u_{PSS} = [-0.6 \quad -0.24 \quad -0.06 \quad 0 \quad 0.06 \quad 0.12 \quad 0.3] \qquad (5.2)$$

The decision table is given in Table 5.3. The order of this decision table is only 4x2. Compare this the general method given in Table 5.1 which is 7x7.

Table 5. 3 Decision Table for Minimum Time Strategy

R \ θ	P	N
VS	VS	VS
SP	SP	SN
MP	MP	MN
LP	LP	LN

The fuzzy relation matrix derived from the decision table for 7 linguistic variables is shown in Table 5.4. It is an 8x7 matrix. For general method it is 49x7. It is not necessary to have 7 variables for the decision. It will be shown later that less number of variables can also be chosen.

Table 5. 4 Fuzzy Relation Matrix for Minimum Time Strategy

Stabilizer Outputs

Stabilizer Inputs	LN	MN	SN	VS	SP	MP	LP
VS,P	0	0	0.5	1	0.5	0	0
VS,N	0	0	0.5	1	0.5	0	0
SP,P	0	0	0	0.5	1	0.5	0
SP,N	0	0.5	1	0.5	0	0	0
MP,P	0	0	0	0	0.5	1	0.5
MP,N	0.5	1	0.5	0	0	0	0
LP,P	0	0	0	0	0	0.5	1
LP,N	1	0.5	0	0	0	0	0

Sample Calculation

For $\Delta\omega = 0.65\times10^{-2}$, $\Delta\dot{\omega} = 0.4\times10^{-1}$, $\alpha = 0.15$

we have,

$$R=\sqrt{\Delta\omega^2 + (\alpha\Delta\dot{\omega})^2} = 8.846\times10^{-3}$$

$$\theta = \tan^{-1}\left(\frac{\alpha\Delta\dot{\omega}}{\Delta\omega}\right) = 42.71^{\circ}$$

The two stabilizer inputs in Figure 5.9 & Figure 5.12 respectively would be described by the following fuzzy sets:

$$\{R\} = \{(VS,0),(SP,0),(MP,0),(LP,1)\}$$
$$\{\theta\} = \{(P,1),(N,0),\}$$

For four linguistic variables for R and two for θ, there are 8 rules. The membership values for the condition part of each rule are

$$\mu_{x_i} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0]^T$$

The final value for stabilizer output for any linguistic variable, say, LN, can be evaluated using following equation

$$\mu_{u_{PSS}}(LN) = \max_{x_i}\{\min[\mu_R(x_i, LN), \mu(x_i)]\}$$

The membership values for all the seven linguistic variables are calculated as:

$\mu_{u_{PSS}}(LN) = 0$ $\mu_{u_{PSS}}(MN) = 0$ $\mu_{u_{PSS}}(SN) = 0$

$\mu_{u_{PSS}}(VS) = 0$ $\mu_{u_{PSS}}(SP) = 0$ $\mu_{u_{PSS}}(MP) = 0.5$

$\mu_{u_{PSS}}(LP) = 1$

By applying the weighted average defuzzification method we get the final value of control output as

$$u_{PSS} = \frac{0\times-(0.06)+0\times-(0.24)+0\times(-0.06)+0\times0+0\times0.06+0.5\times0.12+1\times0.3}{0+0+0+0+0+0.5+1}$$

$$=0.24$$

5.3.2 Simulation Results

A 50% input torque pulse for 6 cycles was simulated on a single machine infinite bus system. A three phase fault on the remote bus was also simulated for a duration of 6 cycles. Fig. 5.13 shows the comparison of deviation of speed for smaller disturbance and Figure 5.14 shows the comparison of deviation of speed for three phase fault. In each of these figures, the responses with the following three different controllers are compared.

a) FPSS with general method.

b) General method FPSS but thresholds from minimum time strategy.

c) Proposed FPSS from minimum time based fuzzy variables.

Figures 5.13 and 5.14 give comparison of the responses with the three strategies. The general method based with the fuzzy variables reported in the literature stabilizing the system but the response is poor. When the fuzzy thresholds for the general method selected from the quasi-optimum minimum time strategy, the response is significantly improved (curve b). The best damping characteristics are obtained with the proposed FPSS derived entirely from the minimum time strategy(curve c). As mentioned earlier, the proposed controller also has less number of fuzzy variables and hence computationally also much faster.

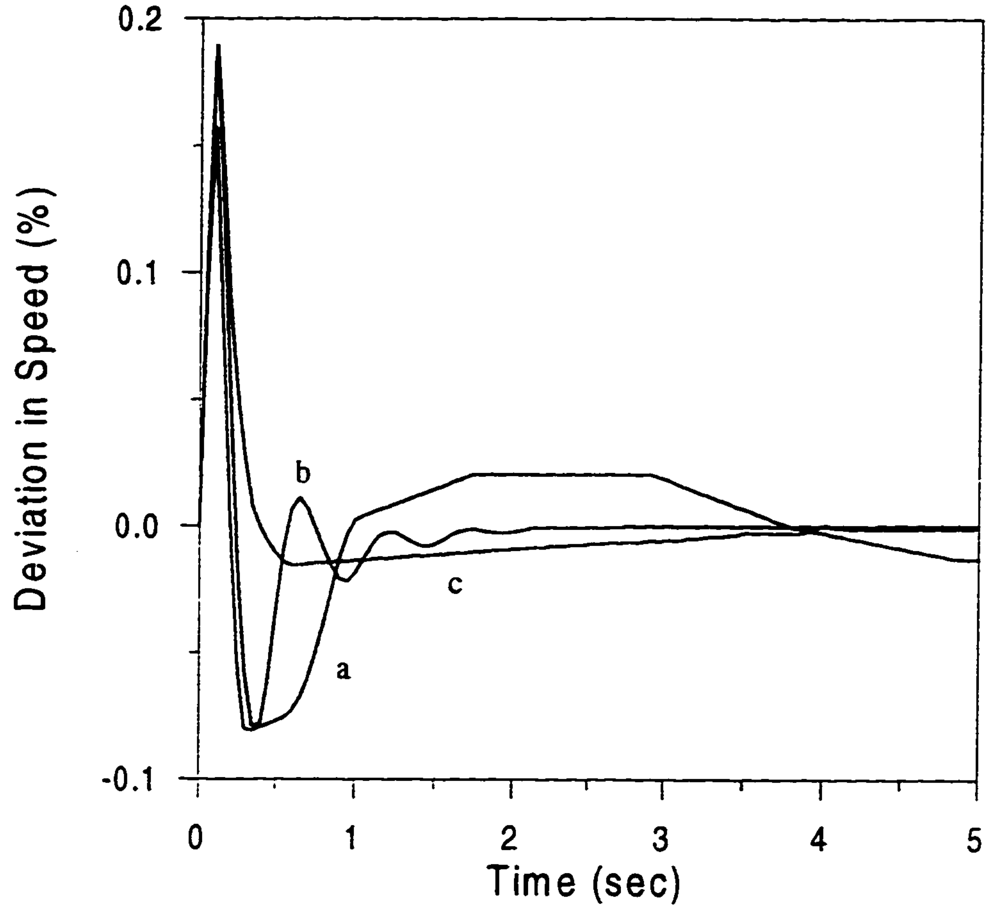


Figure 5. 13 Deviation in Speed for 50% input Torque

a)General method based FPSS

b)General method based with minimum time thresholds

c)Minimum time based FPSS

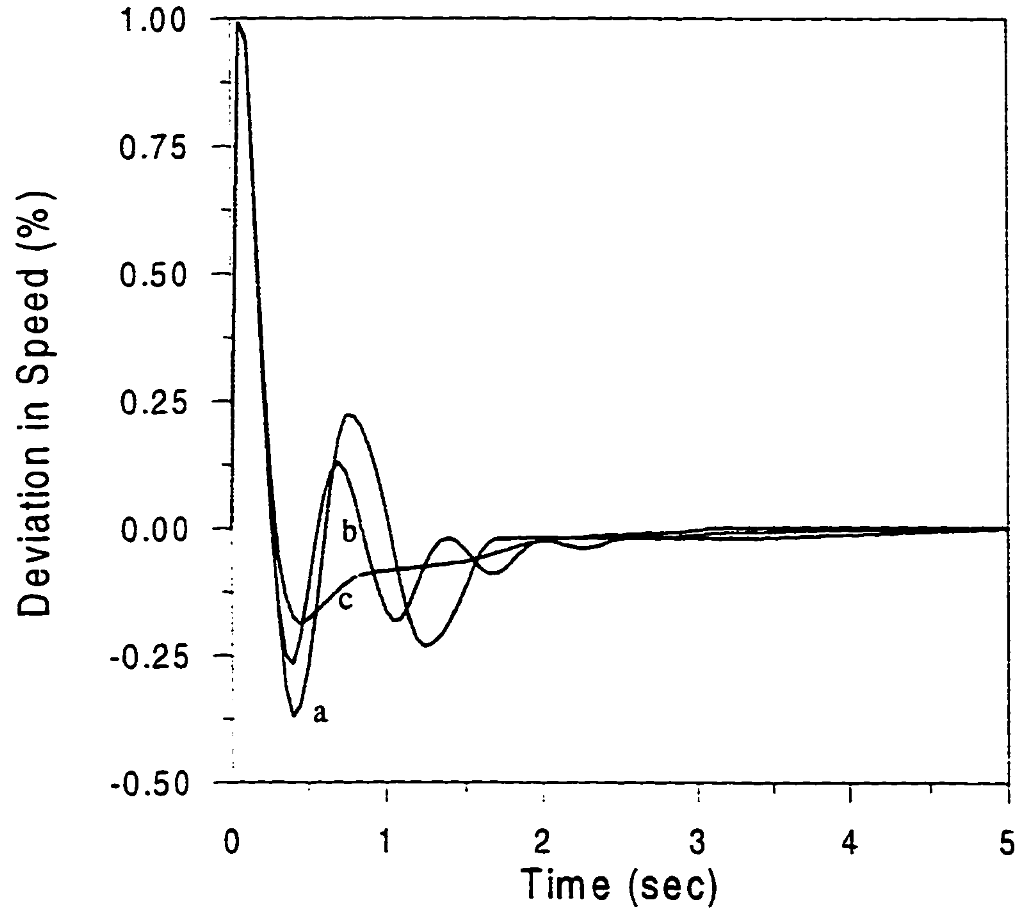


Figure 5. 14 Deviation in Speed for Three Phase Fault.

a)General method based FPSS

b)General method based with minimum time thresholds

c)Minimum time based FPSS

The decision table in the FLC is made from the expert knowledge. The success of the FPSS depends. to a large extent, on this decision process. Theoretically, selection of a very large number of fuzzy variables should resemble to the crisp control. However. such a process may worsen the situation rather helping it because of too many number of variables, the decision table may not be judiciously made.

Figure 5.15 shows the speed variation of the generator with two sets of linguistic variables for the decision(control). Curves 'a' and 'b' are with the general method based FPSS with 7 and 5 linguistic variables, respectively. The control thresholds are obtained from the minimum time strategy. Curves 'c' and 'd' are with the proposed minimum time based FPSS with the two cases, respectively. In either case. 5 variables give a slightly better response which may be ascribed to the inaccuracy of the selection of the decision variables.

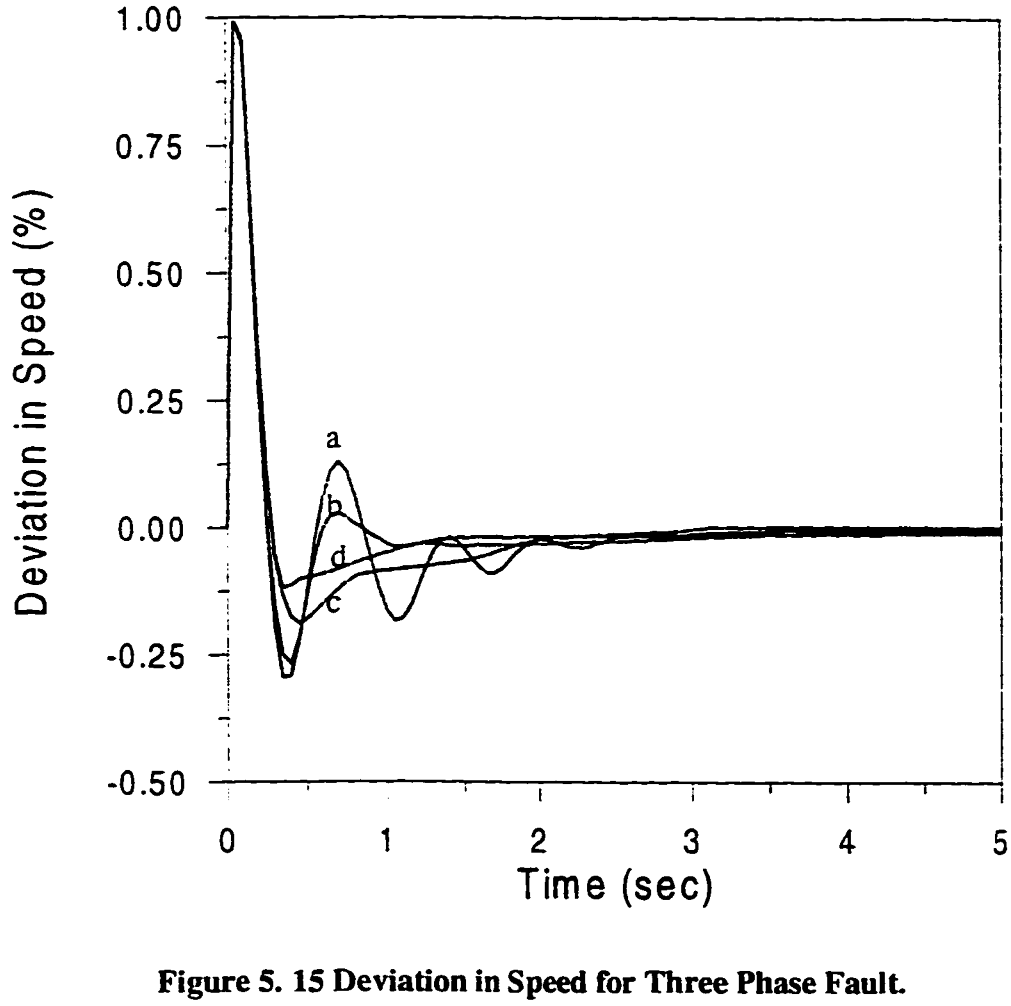


Figure 5. 15 Deviation in Speed for Three Phase Fault.

a, b)General method with 7 and 5 decision variables respectively

c, d)Proposed method with7 and 5 decision variables respectively

5.4 A Simplified Algorithm

The minimum time based FPSS which have been designed in section 5.3 shows very good damping characteristics and the settling time is reasonably low. Though the computational requirements has been very improved, possibility of further improvement is investigated through a method reported in the literature[5]. Consider a rule extracted from the decision table

IF ($\Delta\omega$ is LP) and ($\Delta\dot{\omega}$ is MN) THEN u is SN

This rule states that if the states belong to LP and LN, respectively the membership value of u in SN is 1. However, because of the fuzzy nature of the membership functions selected in Figure 5.12, SN also overlaps with VS and MN, the membership values of which are 0.5 each. The dependence of each state on different decision variables can be clearly seen in the fuzzy relationship matrix given in Table 5.4. A normal fuzzification procedure involves calculation of each and every possible state for each and every decision (control) through the composition rules.

Ross[5] suggested a procedure of calculation neglecting the dependence on other variables excepting where it has a full membership of 1. In the above example, it means, no contribution from SN and VS terms. This makes calculation of the fuzzy PSS very simple and the generation of the fuzzy relationship matrix is not even necessary. An example is worked below to slow the procedure.

Sample Calculation

For $\Delta\omega = 0.65 \times 10^{-2}$, $\Delta\dot{\omega} = 0.4 \times 10^{-1}$, $\alpha = 0.15$

we have,

$$R=\sqrt{\Delta\omega^2 + (\alpha\Delta\dot{\omega})^2} = 8.846 \times 10^{-3}$$

$$\theta = \tan^{-1}\left(\frac{\alpha\Delta\dot{\omega}}{\Delta\omega}\right) = 42.71^\circ$$

Step 1 The two stabilizer inputs from Figure 5.9 & Figure 5.12 respectively would be described by the following fuzzy sets:

$$\{R\} = \{(VS,0),(SP,0),(MP,0),(LP,1)\}$$
$$\{\theta\} = \{(P,1),(N,0),\}$$

Step 2 For four linguistic variables for R and two linguistic variables for θ, there are 8 rules. The membership value for the condition part of each rule are:

IF (R=VS) & (θ=P) THEN u =VS	min(0,1)=0(VS)
IF (R=VS) & (θ=N) THEN u =VS	min(0,1)=0(VS)
IF (R=SP) & (θ=P) THEN u =SP	min(0,1)=0(SP)
IF (R=SP) & (θ=N) THEN u =SN	min(0,1)=0(SN)
IF (R=MP) & (θ=P) THEN u =MP	min(0,1)=0(MP)
IF (R=MP) & (θ=N) THEN u =MN	min(0,1)=0(MN)
IF (R=LP) & (θ=P) THEN u =LP	min(0,1)=0(LP)
IF (R=LP) & (θ=N) THEN u =LN	min(0,1)=0(LN)

Step 3 Membership value of each output linguistic variable are

$\mu_{u_{PSS}}(LN)=0$ $\mu_{u_{PSS}}(MN)=0$ $\mu_{u_{PSS}}(SN)=0$

$\mu_{u_{PSS}}(VS)=0$ $\mu_{u_{PSS}}(SP)=0$ $\mu_{u_{PSS}}(MP)=0$

$\mu_{u_{PSS}}(LP)=1$

Step 4 For the threshold in (5.2), the weighted average defuzzification method gives

$$u_{PSS}=\frac{0\times-(0.06)+0\times-(0.24)+0\times(-0.06)+0\times0+0\times0.06+0\times0.12+1\times0.3}{0+0+0+0+0+0+1}$$

$$=0.3$$

5.4.1 Simulation Results

Figure 5.16 shows the speed deviation for the generator for the 3-phase fault condition with the simplified fuzzy PSS. The three cases plotted are for

a) No control

b) Minimum time based FPSS presented in the previous section.

c) The simplified FPSS

The comparison shows that normal minimum time based FPSS gives better damping characteristics compared to simplified strategy. This is expected because the simplification has actually has lost a lot of fuzzy information while this saves a lot of computation, gives poor transient response. However, for very large multimachine systems where a great deal of computation is involved, the method may be looked into.

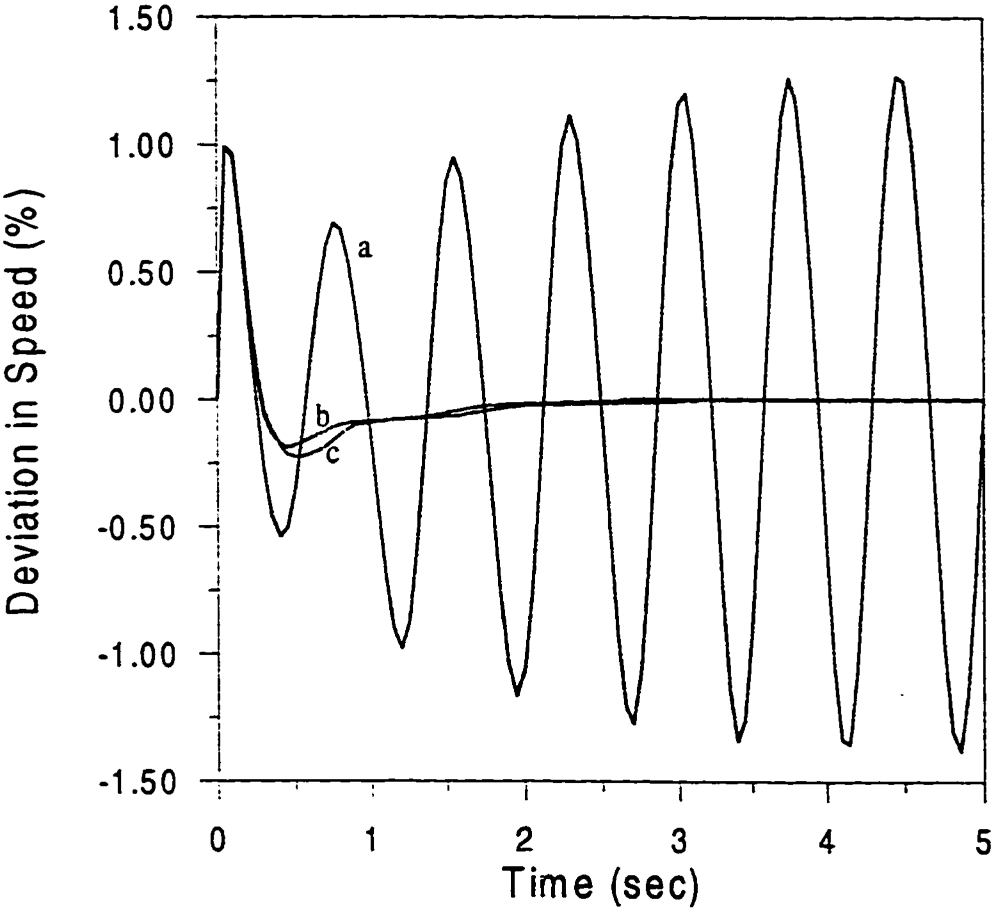


Figure 5. 16 Deviation in Speed for Three Phase Fault

a) No Control

b) Minimum time based FPSS

c) Simplified FPSS

5.5 Comparison of Results

Four different FPSS strategies were developed for a single machine model in this chapter. These are

a)FPSS based on general method

b)Same as 'a' but thresholds from minimum time strategy.

c)Minimum time based FPSS

d) Simplified FPSS

Figure 5.17 redraws the speed deviation characteristics of the generator with the above four strategies. This is shown only for the sake of comparison.

The comparison of the two general FPSS strategies (a), (b) indicate that the one which uses the minimum time based thresholds in the knowledge base (b), gives better response. Cases (c) and (d) both employ the minimum time based fuzzy strategies, d involving simplified calculations. It is clear that the proposed minimum time based fuzzy PSS provides the best transient response.

We conclude that the minimum time based FPSS can be implemented on real system because of not only good damping characteristics achieved, but also due to reduction of calculation time as compared to general methods reported in the literature. Specifically, with the proposed strategy

- Computation time is saved in fuzzification process because of reduction of input linguistic variables.
- Computation time is reduced in the defuzzification process because of reduced number of output linguistic variables.

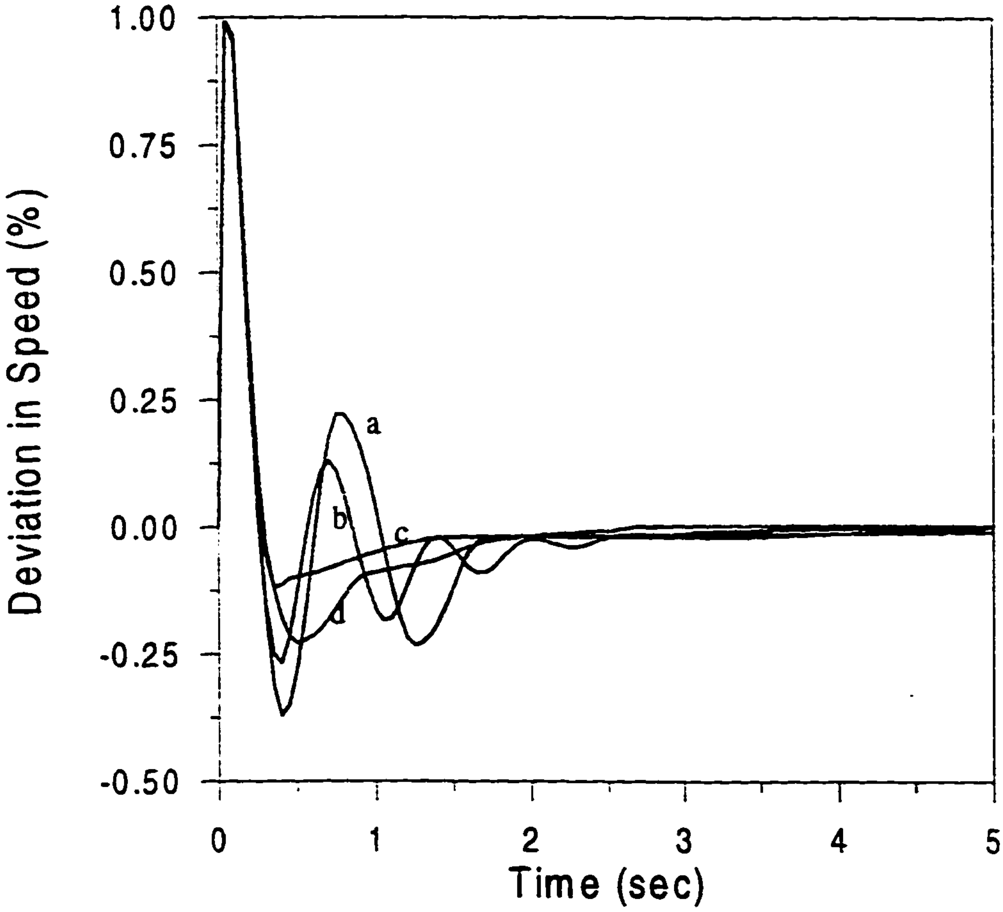


Figure 5. 17 Deviation in Speed for Three Phase Fault

a)General method based FPSS

b)General method based with minimum time thresholds

c)Minimum time based FPSS

d)Simplified FPSS

Chapter 6

Fuzzy PSS for Multimachine Power System

6.1 Introduction

The FPSS designed and tested on a single machine system in the previous chapter, is then extended to multimachine systems. The following test systems were considered

1. Multimachine system I- The CIGRE system. It has 4 generators and 6 buses.
2. Multimachine system II - The Bnile system. It has six machines and 20 buses and is relatively complex as compared to system I.

In the single machine study, we found that the minimum time based FPSS is suited from computational viewpoint as well as damping control. So only the minimum time based FPSS's were employed. The following three cases were considered

a) General method with minimum time based thresholds.

b) Minimum time based FPSS.

c) Simplified FPSS.

6.2 System I

The four machine CIGRE system is shown in the single line diagram of Fig. 6.1

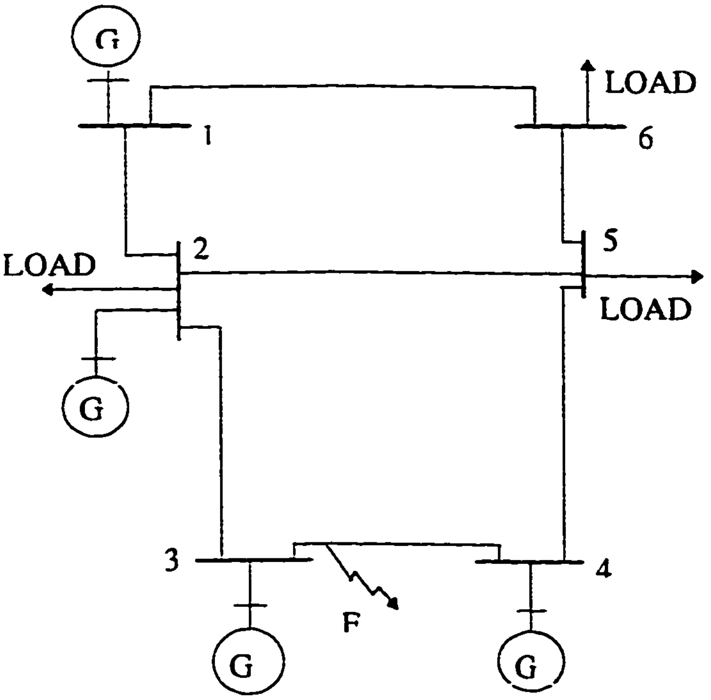


Figure 6. 1 Single Line Diagram of System I

The line constants, machine details, the loads, governor & AVR parameters, switching operations etc. is given in Appendix B.

Generator 1 is a very large machine with respect to rest of the generators. It is also considered as the reference for this study. A three phase fault is simulated on bus3 for a duration of 0.25 secs., cleared by itself.

6.2.1 Results: Generation of Thresholds

The design starts with determination of linguistic variables and their thresholds for each machine. The thresholds are obtained from a symmetrical three phase fault on bus 3. Only speed and acceleration of generators 2 & 3 are shown in Figures. 6.2, 6.3 and 6.4 respectively. Thresholds for output membership functions are obtained by the time optimal controller output, which serves as the knowledge base for this study. The results of optimal control for generator 2 & 3 are shown in Figure 6.5.

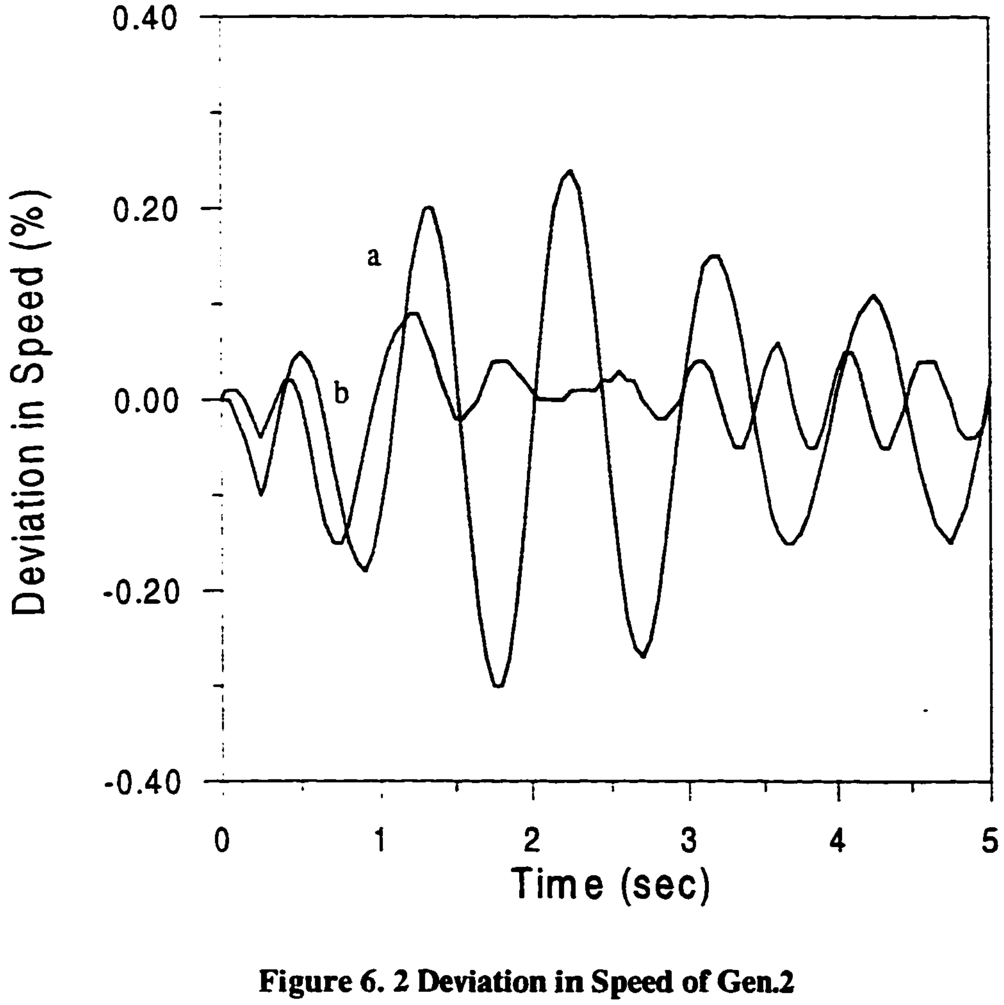


Figure 6. 2 Deviation in Speed of Gen.2

a) Uncontrolled

b) Minimum time control

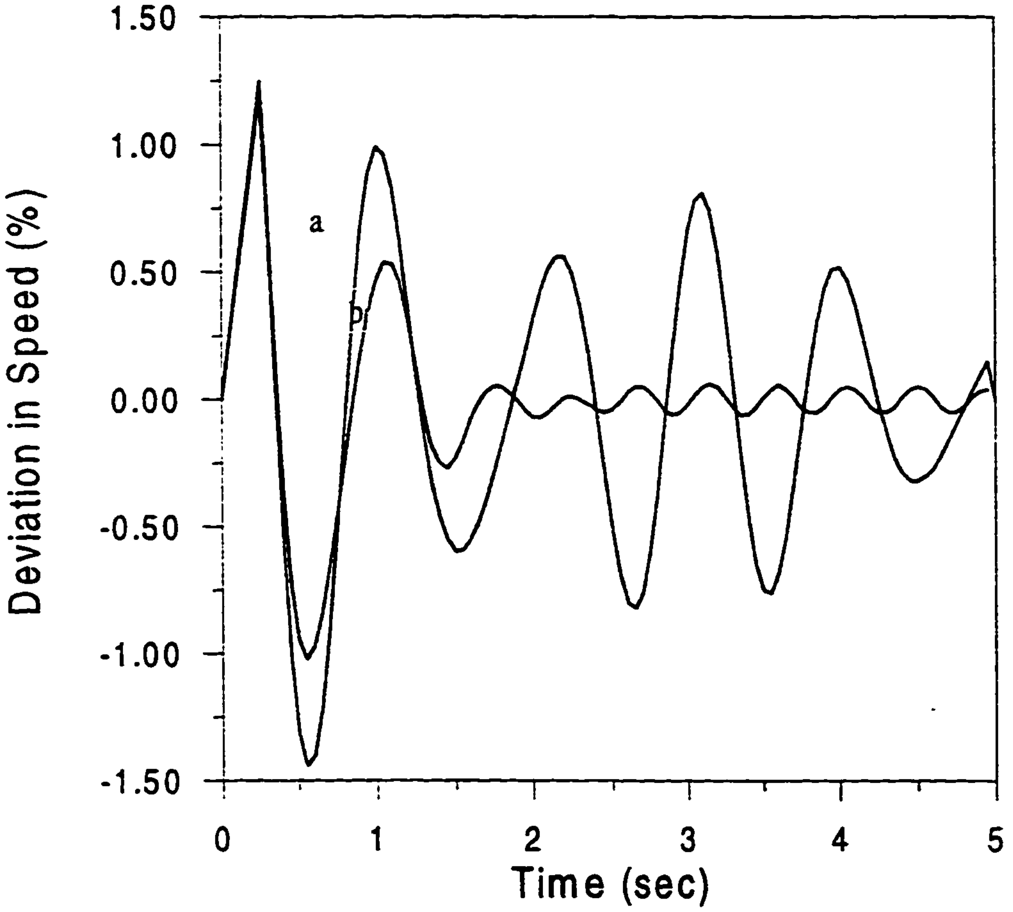


Figure 6. 3 Deviation in Speed of Gen.3

a) Uncontrolled

b) Minimum time control

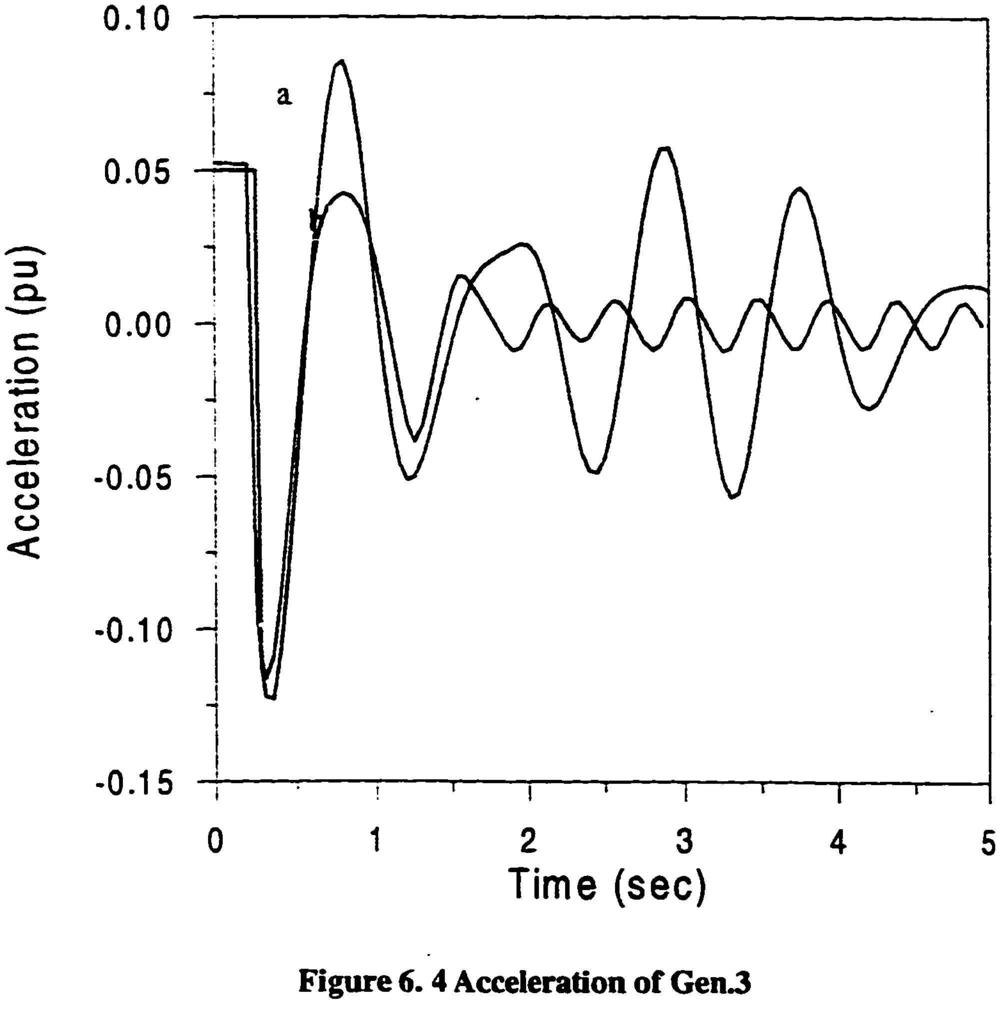


Figure 6. 4 Acceleration of Gen.3

a) Uncontrolled

b) Minimum time control

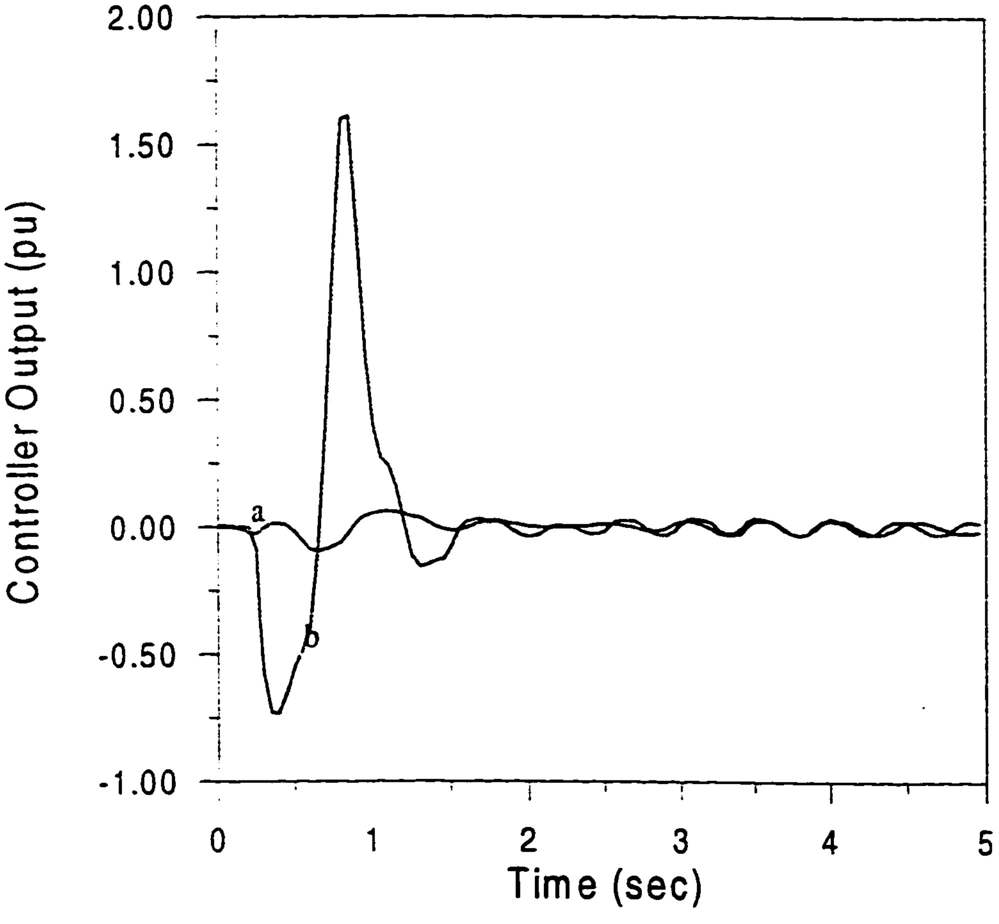


Figure 6. 5 Minimum Time Controller Output

a) Controller output of generator 2

b) Controller output of generator 3

6.2.2 Results: Simulation Studies with FPSS

The minimum time based FPSS is tested for multimachine system I. A three phase fault is simulated on bus3 and the fault is cleared after 0.25 secs. Various minimum time based schemes mentioned were tested and the results are compared.

The speed deviation for generator 3 is given in Fig. 6.6. The responses are:

a) General case involving 7 linguistic variables for each of states and decision. Note the thresholds for the decision variable are taken from the minimum time control study.

b) The minimum time based FPSS involving 4,2 linguistic variables for input states.

c) Scheme (b) with further reduction in computation due to Ross's method.

Scheme (b) and (c) are basically the same, except (c) is slightly computationally faster.

Figures 6.7 and 6.8 show the rotor angle variations for generator 2 and 3. Symbols a, b, c are as in Fig 6.6.

The comparison of results shown in Figs. 6.6 to 6.8 show that case (b) with minimum time based FPSS provides better damping compared to the others. The reduced calculation case (c) appears to be equally effective in terms of damping properties.

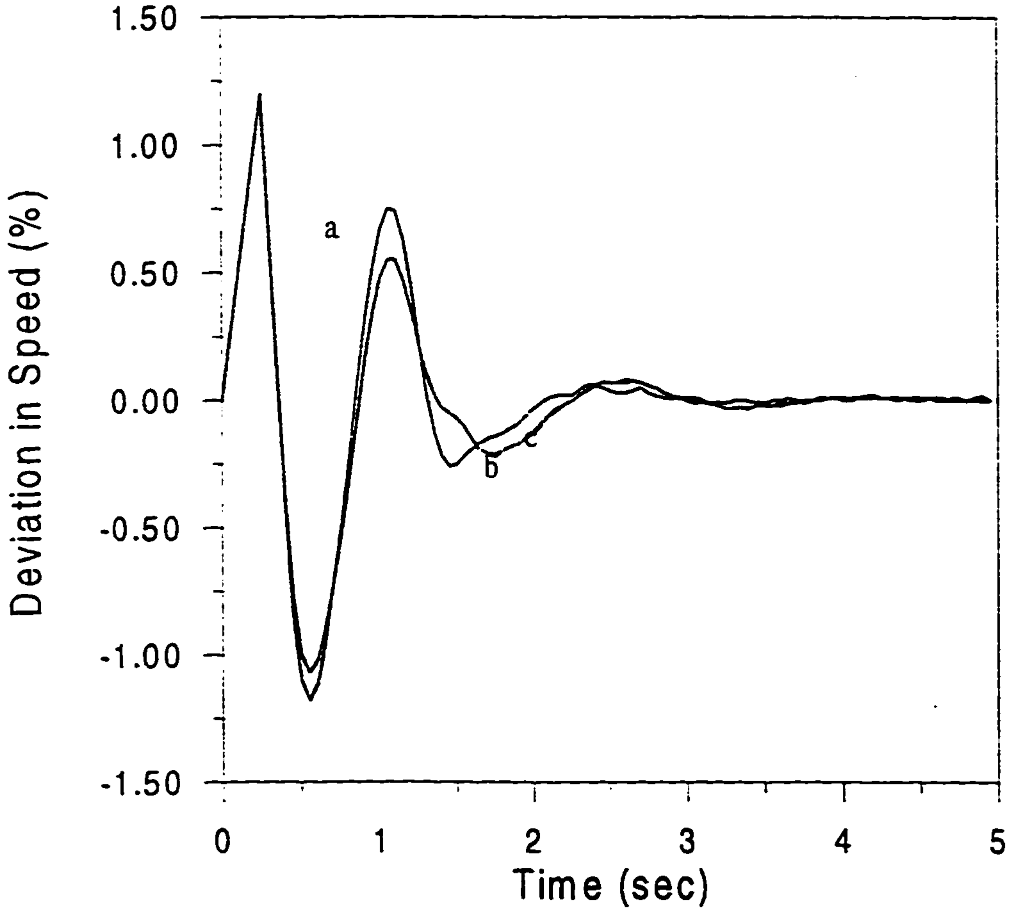


Figure 6. 6 Deviation in Speed for Generator 3

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

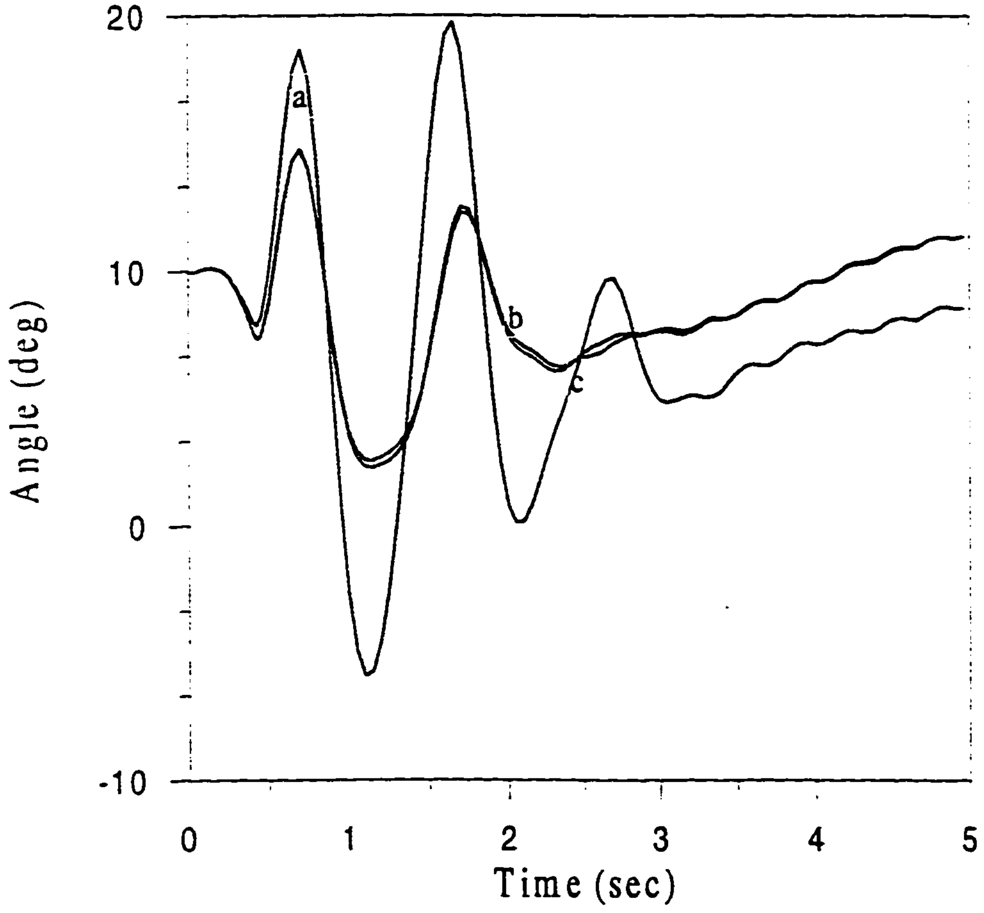


Figure 6. 7 Rotor Angle Response for Generator 2

Symbols are as in Figure 6.6

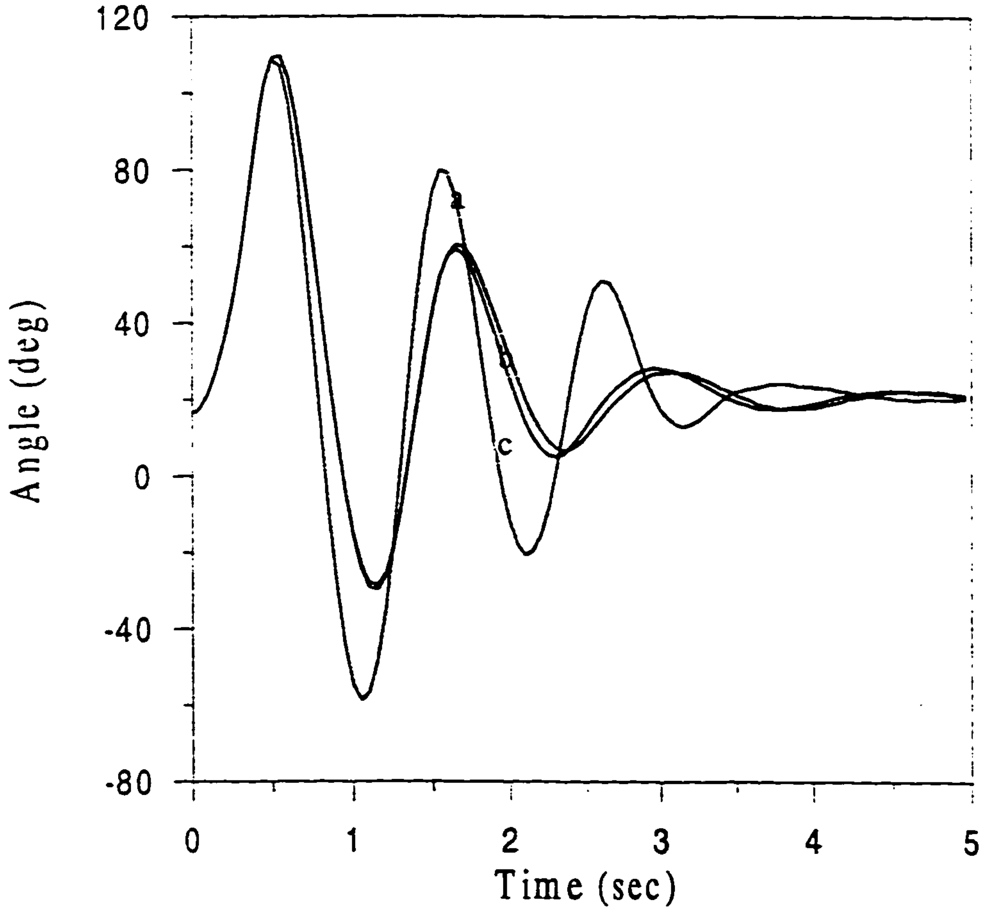


Figure 6. 8 Rotor Angle Response for Generator 3

Symbols are as in Figure 6.6

6.3 System II

The second multimachine system considered is the six machine Bnile system. Single line diagram of the system is shown in Figure 6.9. The system data is given in Appendix C. Three phase faults were simulated and the performance of FPSS is evaluated. The bus "BURS" at generating station A is taken as reference bus.

The developed fuzzy control scheme was tested on this system for various fault conditions and also for various operating conditions.

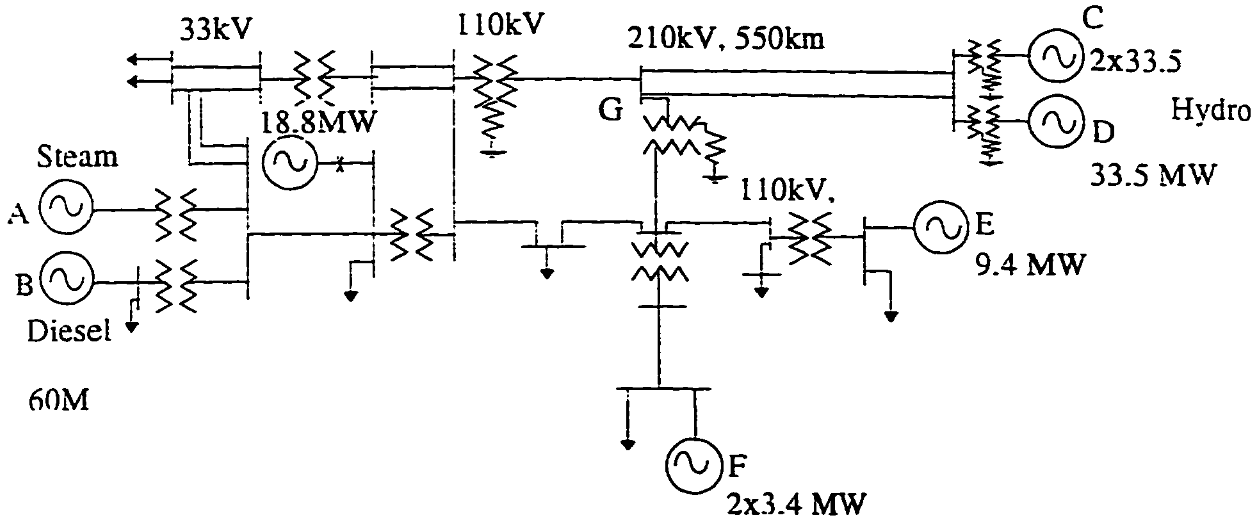


Figure 6. 9 Single Line diagram for System II

6.3.1 Results: Generation of Thresholds

The thresholds of the input membership functions are taken from open loop simulation for different initial conditions. The procedure is same as given for test system I. The results of deviation in speed without control & with optimal control for Gen. B & Gen. C for three phase fault are shown in Figures 6.10, & 6.11 respectively.

The thresholds for stabilizer output are obtained from the minimum time controller as shown in Figure 6.12.

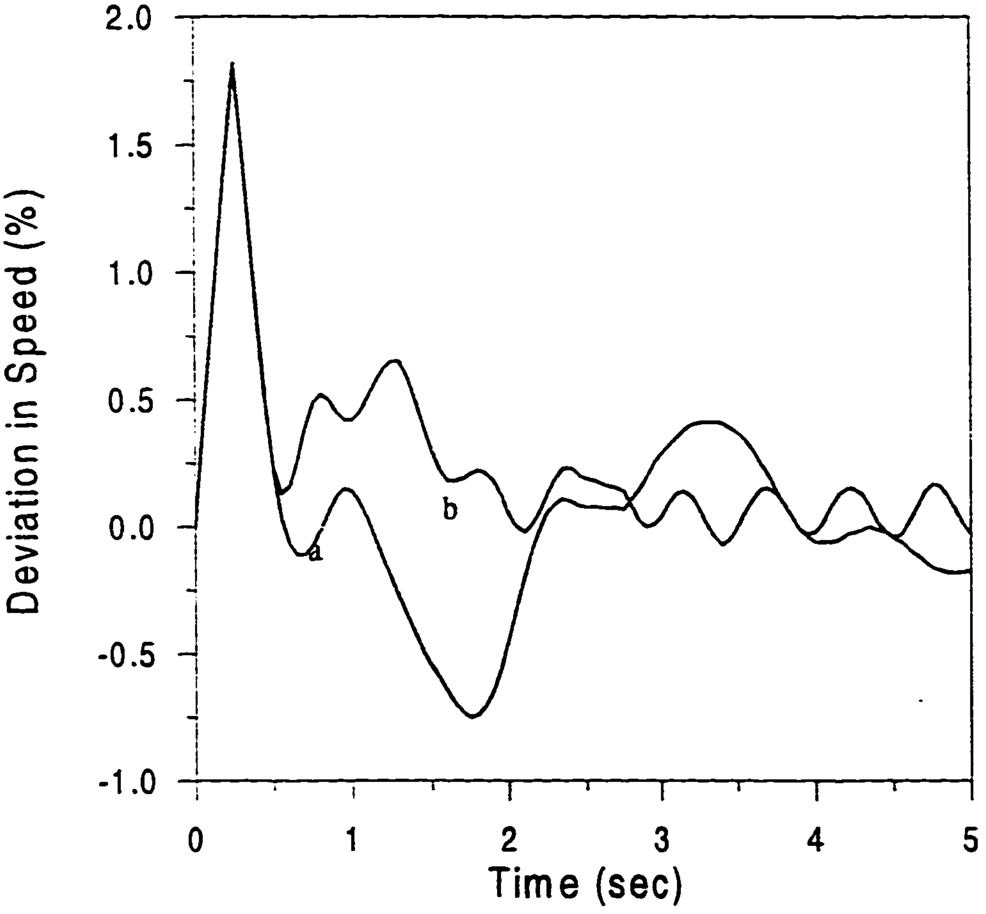


Figure 6. 10 Deviation in Speed of Gen. B

a) Uncontrolled

b) Minimum time control

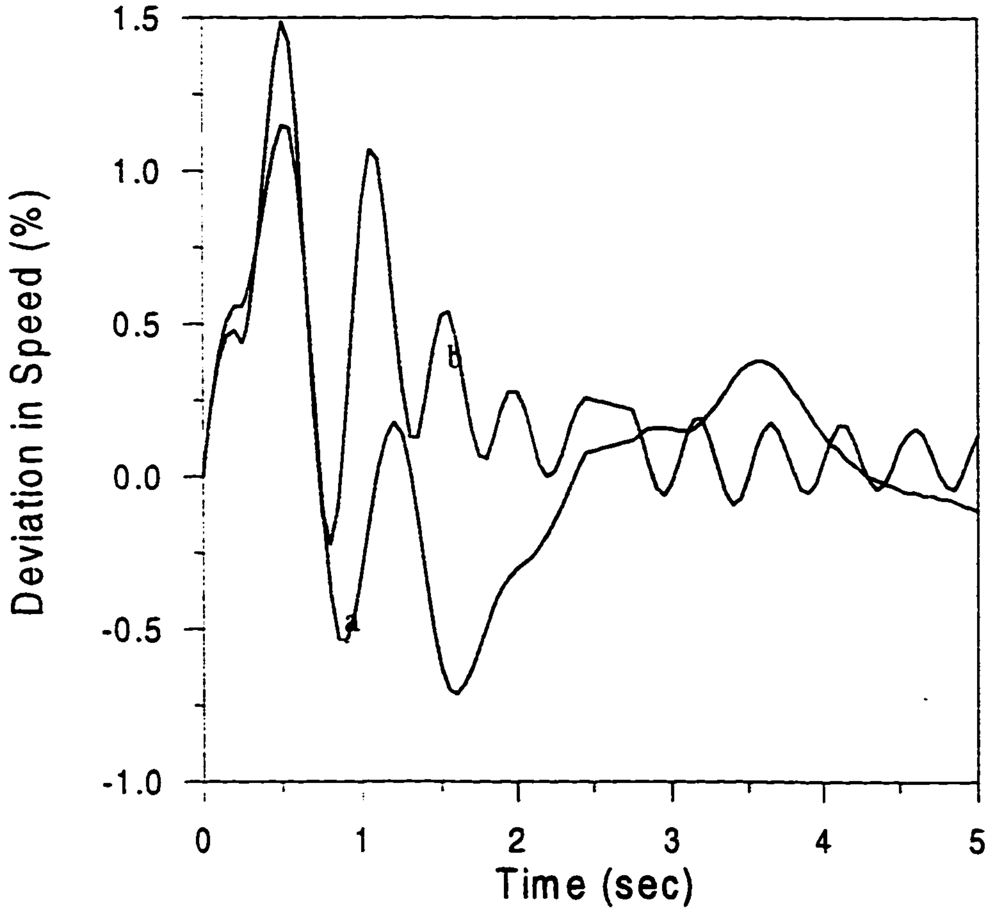


Figure 6. 11 Deviation in Speed of Gen. C

a) Uncontrolled

b) Minimum time control

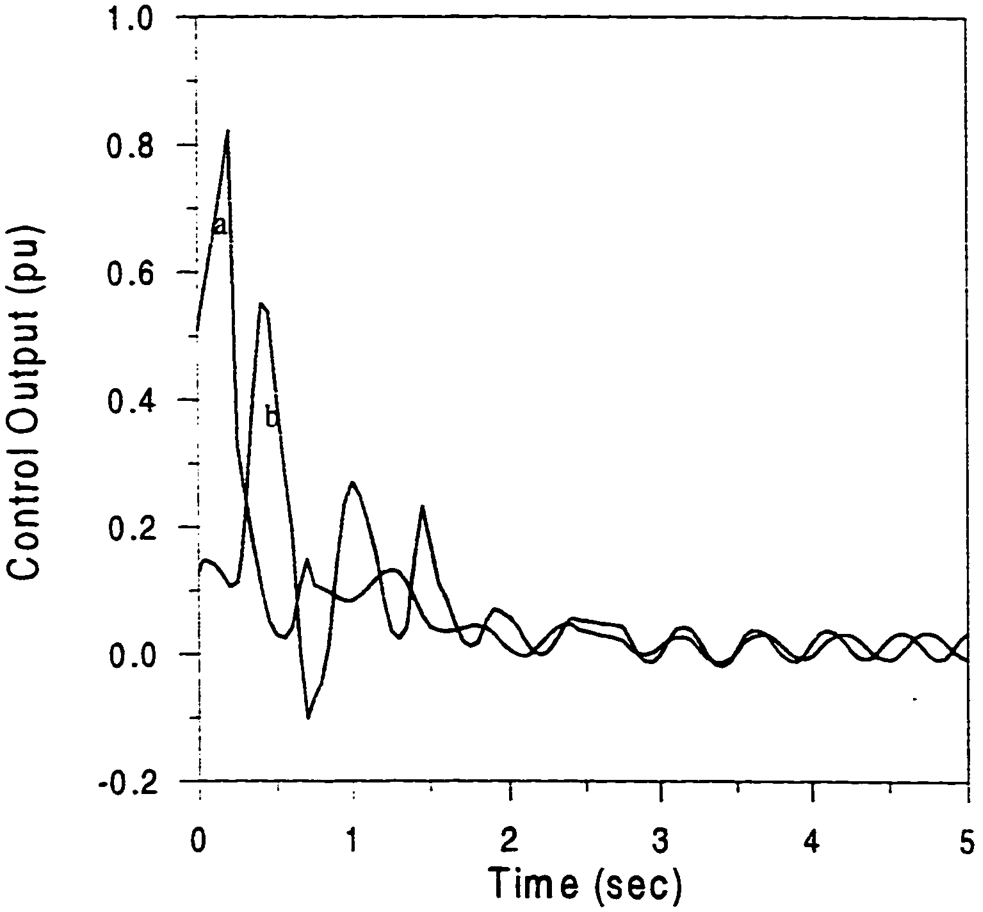


Figure 6. 12 Output of Minimum Time Controller

a) Control for Gen. B

b) Control for Gen. C

6.3.2 Simulation Results with FPSS: Case I

There are 20 buses on this 6 machine system out of which 9 are load buses. Moreover, shunt reactors are also installed at 4 buses. The system has a variety of generators i.e. steam, diesel and hydel. Very long transmission lines connect generators C&D to the rest of the system.

A 0.25 secs., 3-phase fault, simulated on high tension side of CD, was cleared by removal of line G-CD. The three minimum time based FPSS , mentioned in section 6.2.2 for multimachine system I, were used.

The speed deviation responses of Gen. B & D are shown in Figs. 6.13 & 6.14 respectively. The rotor angle responses of the generators B & D are shown in Figures 6.15 & 6.16 respectively. As in system I, the cases studied were

a) General case involving 7 linguistic variables for each of states and decision. Note the thresholds for the decision variable are taken from the minimum time control study.
b) The minimum time based FPSS involving 4,2 linguistic variables for input states.
c) Scheme (b) with further reduction in computation due to Ross's method.

A comparison of the figures indicate that case (b) provide best damping characteristics. Case (c) gives results which are very close to case (b).

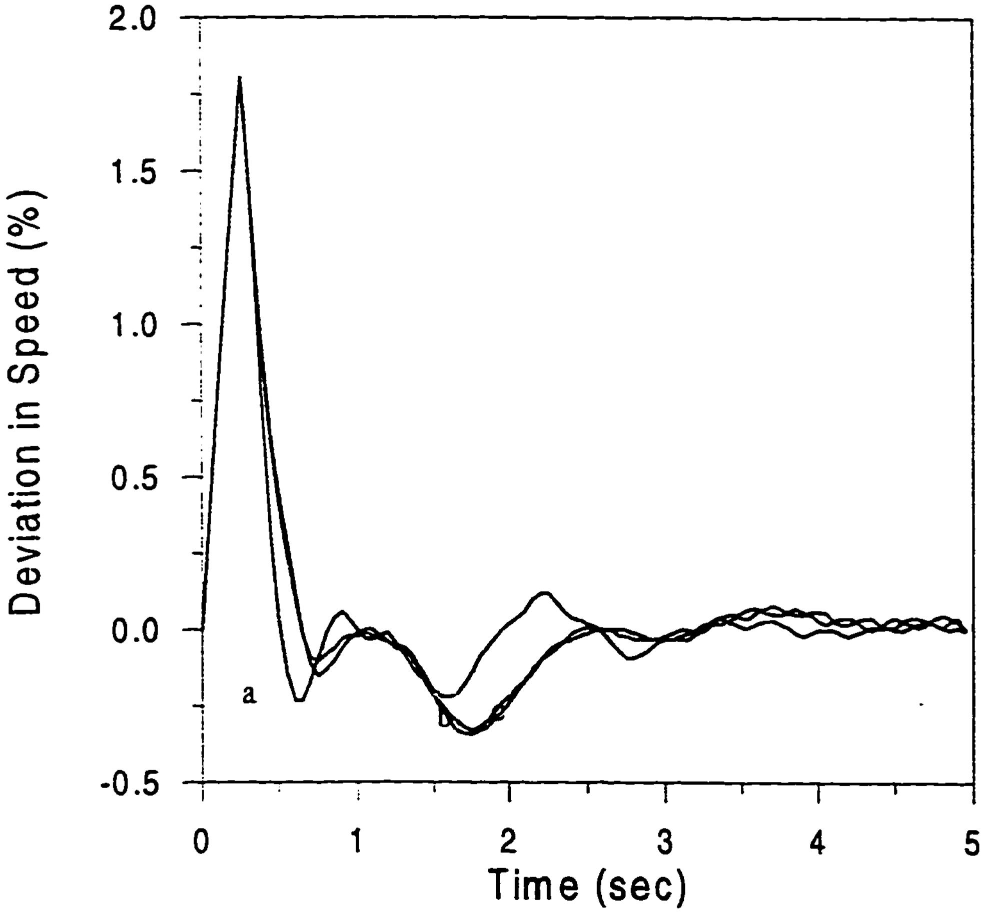


Figure 6. 13 Deviation in Speed for Generator B

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

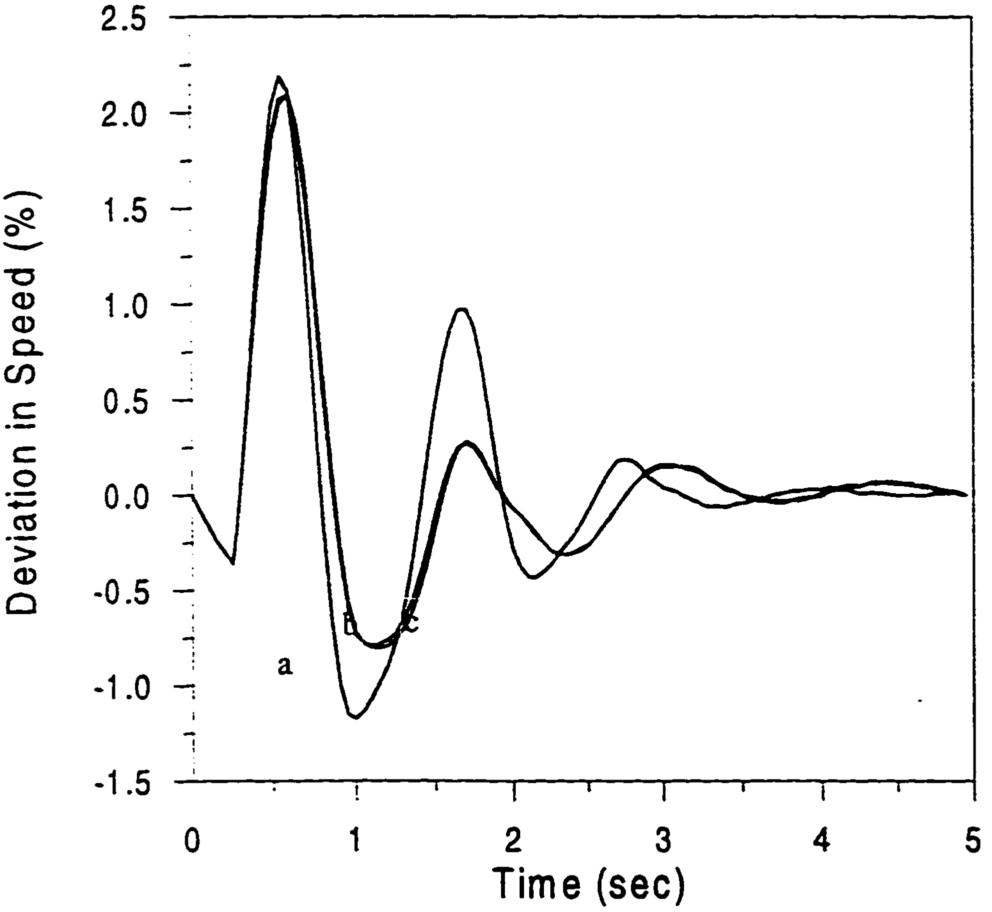


Figure 6. 14 Deviation in Speed for Generator D

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

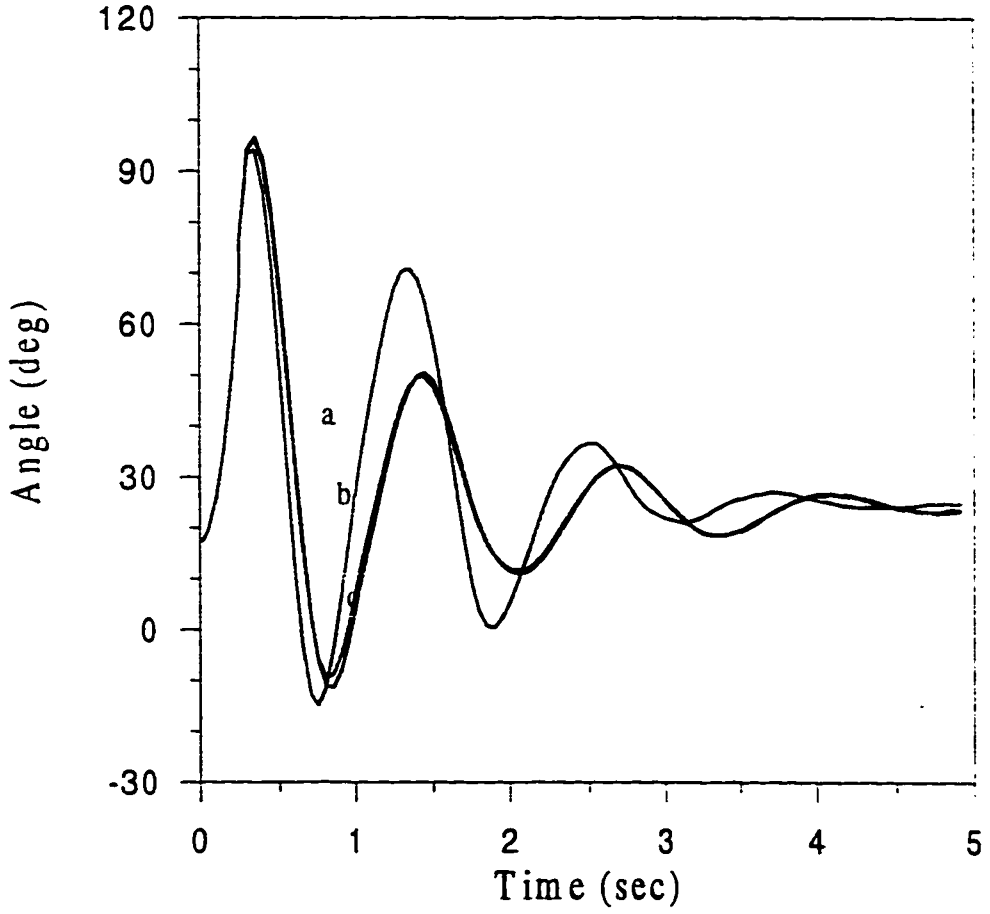


Figure 6. 15 Rotor angle Response for Generator B

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

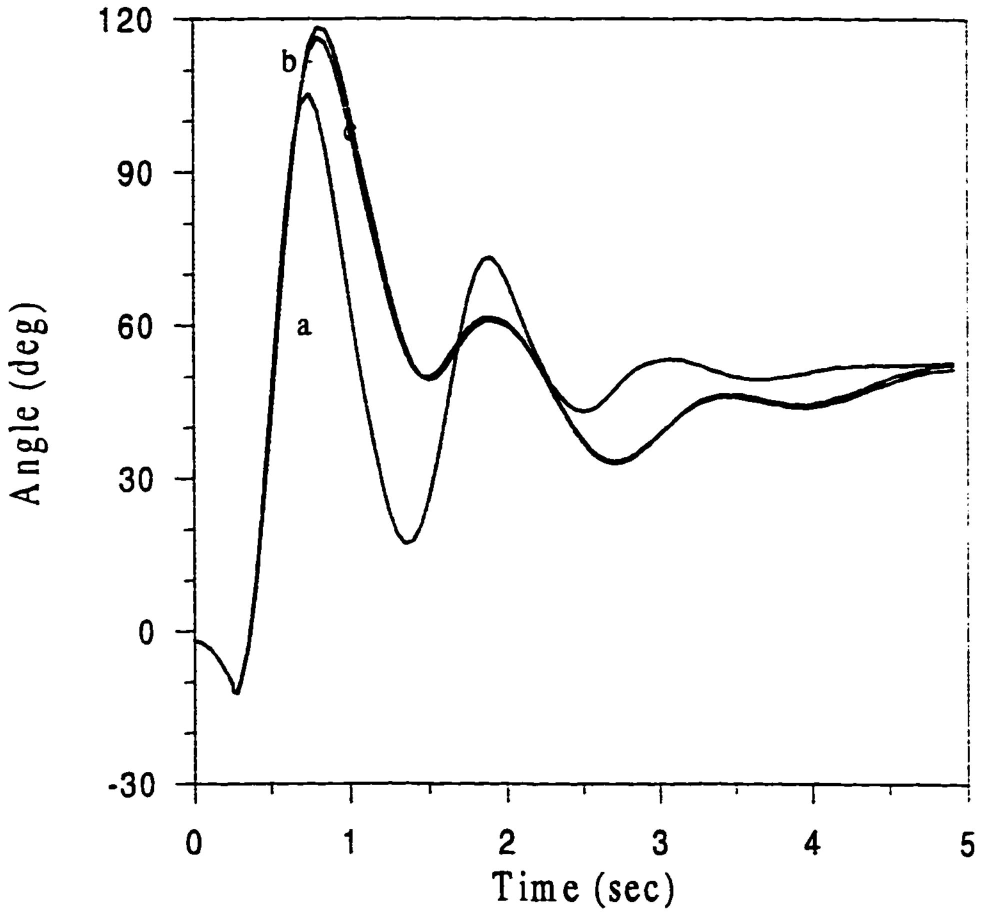


Figure 6. 16 Rotor angle Response for Generator D

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

6.3.3 FPSS for System II : Case II

The performance of FPSS was evaluated for another operating condition on system II. The loading is different in this case. The operating conditions are given in Appendix D. In this case also, a three phase fault was simulated on high tension side of CD link and it was cleared after 0.25 secs. by removal of line G-CD.

Figures 6.17 & 6.18 present the comparison of deviation in speed for generators B & D respectively. The comparison of rotor angle response for generators B & D is shown in Figs. 6.19 & 6.20 respectively.

From all the above simulation studies it can be observed that the minimum time based fuzzy PSS provides fastest damping control. The response with case (c), again is very near to case (b).

From two multimachine system studies, on different operating conditions, we conclude that the proposed FPSS is robust and is operating point independent.

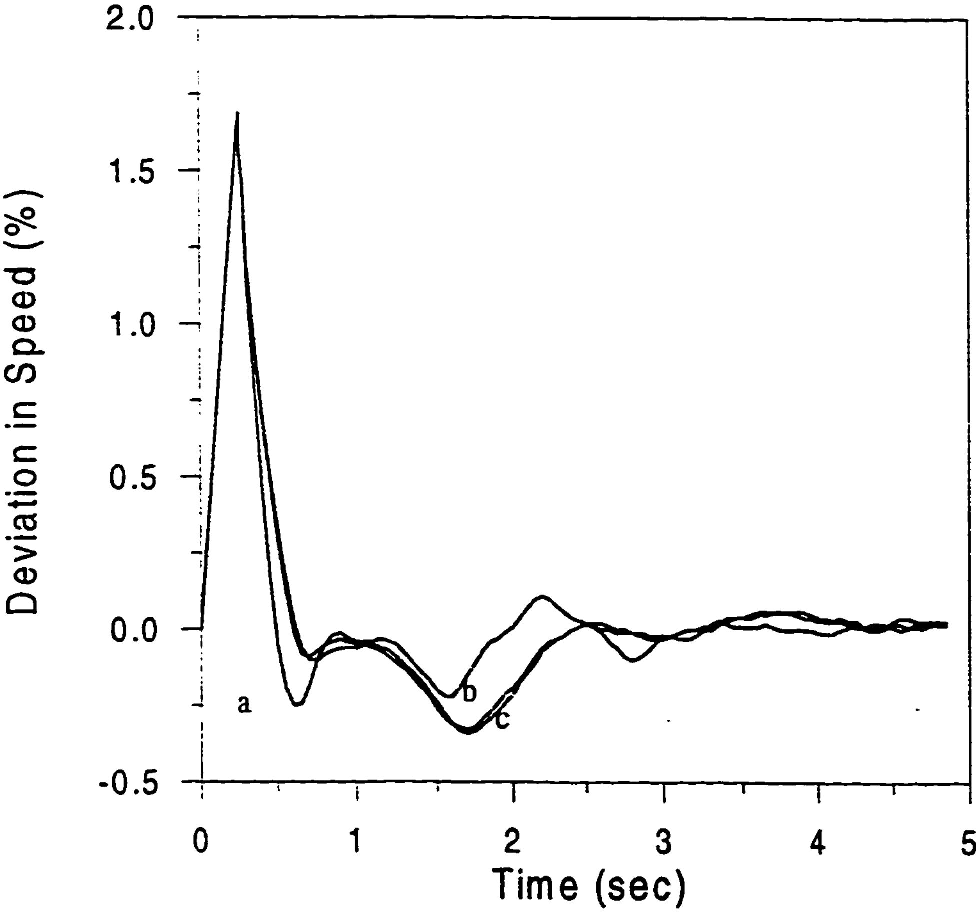


Figure 6. 17 Deviation in Speed for Generator B

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

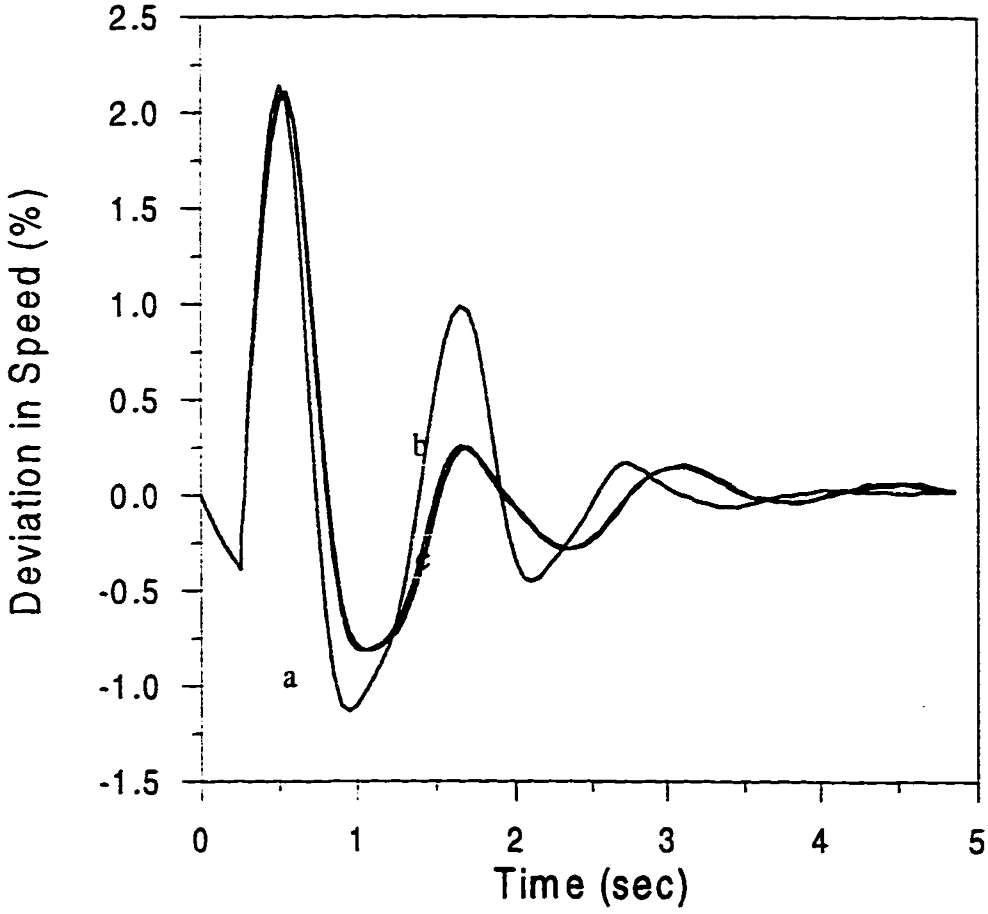


Figure 6. 18 Deviation in Speed for Generator D

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

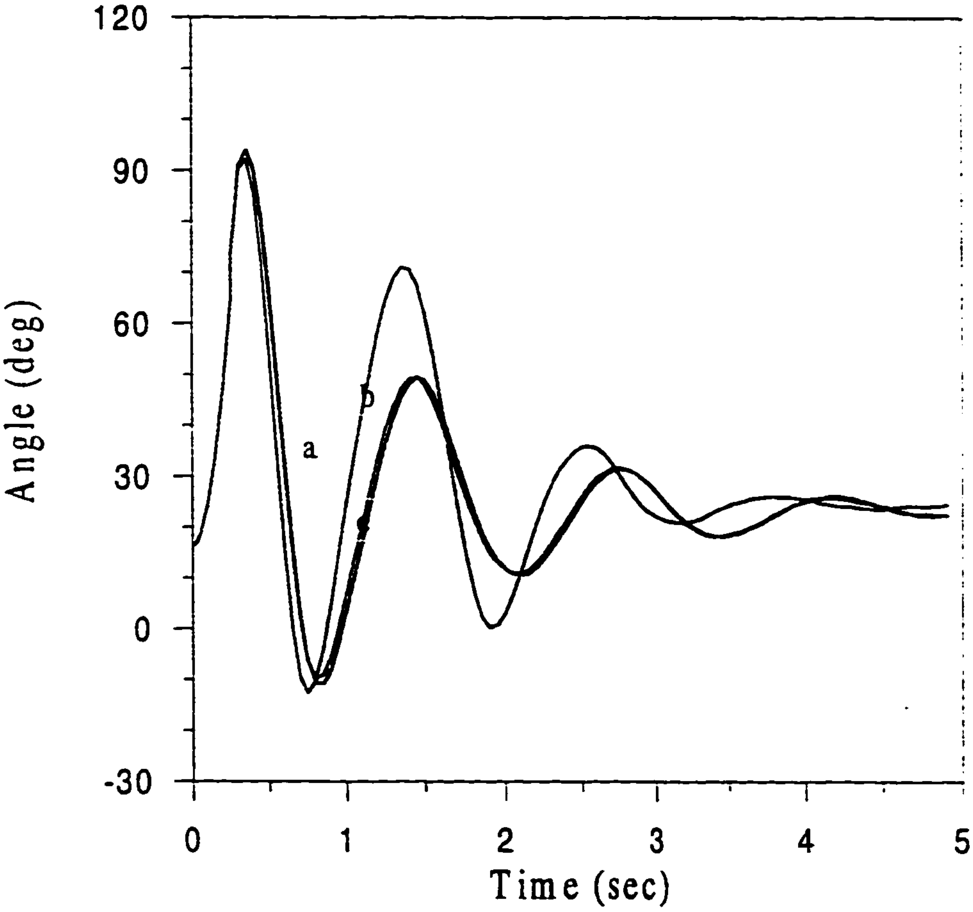


Figure 6. 19 Rotor angle Response for Generator B

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

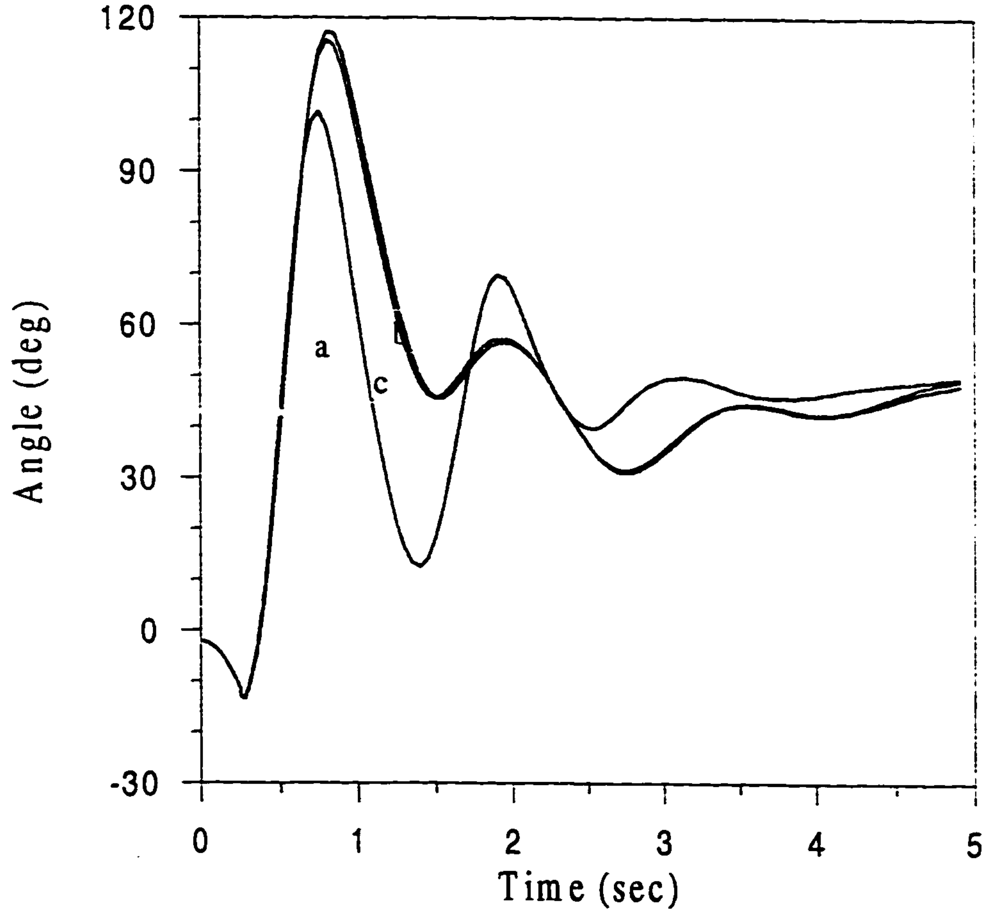


Figure 6. 20 Rotor angle Response for Generator D

a) FPSS based on general method

b) Minimum time based FPSS

c) Simplified FPSS

6.4 Summary of Multimachine System Studies

In this chapter, FPSS was tested for two multimachine systems. System I is a relatively smaller with 4 machine and 6 bus as system II is a six machine & 20 bus system. It has variety of generators i.e., diesel, steam and hydel and of different ratings. Moreover the system is connected with long transmission lines. For System II, the FPSS was tested for two operating conditions to make sure that it can perform in all possible situations. In both the multimachine systems, three phase faults were simulated for a time of 0.25 seconds. Results show that FPSS design was equally successful at both the operating conditions. This proves its robustness. Also, it provided good damping characteristics for both the multimachine systems.

Chapter 7

Conclusions and Recommendations

A fuzzy logic power system stabilizer is designed and tested for stabilization of power system when subjected to small as well as large disturbances. The fuzzy logic control scheme is based on minimum time control which acts as a knowledge base for the fuzzy logic system. The inputs to stabilizer are synchronous machine speed and acceleration. The fuzzy logic controller is tested on a single machine infinite system and then the work is extended to multimachine systems.

In order to evaluate the proposed fuzzy logic stabilizer, it was compared with a fuzzy PSS reported in the literature.. The proposed minimum time based fuzzy PSS was shown to be computationally faster. Simulation results on a single machine system show that minimum time based FPSS provides better damping characteristics for small perturbation as well as severe three phase faults.

The fuzzy logic controllers developed for the single machine system were also tested for two multimachine systems - a 4 generator system and another six generator system with various operating conditions. The results indicate that minimum time based FPSS effectively control the multimachine system damping properties. Moreover, it was shown that the performance of the FPSS is independent of the operating point. This demonstrates the robustness of the proposed controller.

The minimum time based FPSS is not only very effective in stabilization but also computationally efficient compared to reported methods. In terms of physical realization of controller this means reduced number of components. This will also make it cost effective. It has been demonstrated that further improvements in terms of computation can be made by modifying the minimum time based FPSS but the damping properties are slightly deteriorated.

To summarize: the proposed FPSS is totally model and operating conditions independent. The thresholds of the controllers can be automatically generated by the minimum time controller located in the knowledge base. The controller is also simple in terms of realization.

Further Research

In the following, some recommendations are given for future research in the area.

1. The minimum time based fuzzy logic controller developed in this work, should also be implemented in the laboratory to evaluate its real time performance.
2. In this study, only min-max technique of fuzzy logic was used, max-dot technique can also be tried to see if it can help to improve the results.

3. Different defuzzification techniques can be tried to find out which is most suitable to the power system applications.
4. Shapes other than triangular functions such as bell shaped, etc., can also be tried to find out which function suits speed and acceleration of machines.
5. Fuzzy logic controllers can also be used for other dynamic security assessment techniques such as
    a) Dynamic braking
    b) Static var compensators
    c) HVDC links.

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Appendix A

Single Machine Data

Following are the parameters for Single machine system study.

S_o=(1, 0.61974)

V_o=1.0

ω_s=377

ra=0.001096

re=0.02

xd=1.7

xq=1.64

xd'=0.245

xe=0.4

Tdo'=5.9

Tqo'=0.075

Dg=0

M=4.74

Kg=3.5

Krh=0.3

Tae=0.05 Kae=400

Tf=1.0 Kf=0.025

Trh=8.0 Tsm=0.2

Tch=0.05 Tsr=0.1

APPENDIX-B

```
                         ELECTRICAL POWER-SYSTEM TRANSIENT-STABILITY STUDY
                         ----------------------------------------------

                                    POWER-SYSTEM LABORATORY
                               DEPARTMENT OF ELECTRICAL ENGINEERING
                              UNIVERSITY OF PETROLEUM AND MINERALS
                                         SYSTEM NO. 1
                                         ------------

                                     TRANSIENT STABILITY
                                        STUDY FOR AN
                                      ARBITRARY SYSTEM


                              SYSTEM FREQUENCY   =  50.00HERTZ
                              M.V.A. BASE        =  100.0M.V.A.


                                  STEADY-STATE SYSTEM DATA
                                  ------------------------

                                      BUSBAR DATA INPUT

  BUSBAR      VOLTAGE      ANGLE      GEN MW      GEN MVAR      LOAD MW     LOAD MVAR

  BUS1       1.00000      .00000    33.20000      9.10000       .00000       .00000
  BUS2       1.00200     -.12000    10.00000      5.00000     20.00000     10.00000
  BUS3       1.08400     4.62000    30.00000     20.00000       .00000       .00000
  BUS4       1.02500     1.41000    20.00000     10.00000       .00000       .00000
  BUS5        .95630    -2.80000      .00000       .00000     40.00000     15.00000

  BUS6        .95300    -2.30000      .00000       .00000     30.00000     10.00000

                                      LINE DATA INPUT

      SENDING RECEIVING    RESISTACE     REACTANCE     SUSCEPTANCE     TAP
      BUSBAR  BUSBAR         P.U.          P.U.            P.U.        P.C.

       BUS1    BUS2         .05000        .20000          .00000        .00
       BUS2    BUS3         .10000        .50000          .00000        .00
       BUS3    BUS4         .20000        .80000          .00000        .00
       BUS4    BUS5         .10000        .30000          .00000        .00
       BUS5    BUS6         .20000        .40000          .00000        .00

       BUS6    BUS1         .10000        .15000          .00000        .00
       BUS2    BUS6         .20000        .50000          .00000        .00


                                  SYNCHRONOUS MACHINE DATA
                                  ------------------------

                                       M/C PARAMETERS

BUSBAR MACHINE INERT -------------REACTANCES(P.U.) -------------) ARM.-----     (O/C TCS (SECS) ----)
NAME     MVA   CONST.   TRANSIENT   SYNCHRONOUS SUB-TRANSIENT  POT- RESIST    TRANSIENT   SUB-TRANSIENT
         BASE  KWS/KVA D-AXIS Q-AXIS D-AXIS Q-AXIS D-AXIS Q-AXIS  IER  (P.U.)D-AXIS Q-AXIS D-AXIS Q-AXIS

BUS1   100.00 95.300   .0040  .0100  .0400  .0100  .0040  .0100  .000  .0000  30.00 30.000  .0000  .0000
BUS2   100.00  1.500 1.0000 2.0000 3.0000 2.0000 1.0000 2.0000  .000  .0000   5.00  5.000  .0000  .0000
BUS3   100.00  2.997  .5000 1.0000 2.0000 1.0000  .5000 1.0000  .000  .0000   5.00  5.000  .0000  .0000
BUS4   100.00  2.000  .4000  .8000 1.5000  .8000  .4000  .8000  .000  .0000   5.00  5.000  .0000  .0000


                        BUSBAR      M/C  POWER OUTPUT      DAMPING
                        NAME        MW            MVAR      FACTOR

                        BUS1     33.20000       9.10000      .00
                        BUS2     10.00000       5.00000      .03
                        BUS3     30.00000      20.00000      .01
                        BUS4     20.00000      10.00000      .00
```

```
                                   AUTOMATIC VOLTAGE REGULATOR DATA

BUSBAR MC AVR FILTER REG.     REG. T.CS.       REG. LIMITS          EXCITER     F/BK  F/BK T.CS. EXCITER LIMITS
 NAME  NO TYPE  T.C.   GAIN     TA      TB    MAX     MIN    RATE   GAIN  T.C.  GAIN   TF     TD      MAX     MIN

 BUS1 1  1    .0000  200.00  .100    .000  6.000 -6.000****** 1.000  .000  .010 5.000  .000   6.000 -6.000
 BUS2 1  1    .0000  200.00  .100    .000  6.000 -6.000****** 1.000  .000  .010 5.000  .000   6.000 -6.000
 BUS3 1  1    .0000  200.00  .100    .000  6.000 -6.000****** 1.000  .000  .010 5.000  .000   6.000 -6.000
 BUS4 1  1    .0000  200.00  .100    .000  6.000 -6.000****** 1.000  .000  .010 5.000  .000   6.000 -6.000


                                THERMAL TURBINE GOVERNOR PARAMETERS

            BUSBAR      SPEED         FLYBALL          CONTROL SYSTEM T.CS.        THERMAL  TURBINE
             NAME     REGULATION   GAIN     T.C.      T1        T2       T3         T.C.    LIMIT(MW)

             BUS1       .0500     1.0000  1.0000  16.0000   4.0000    .5000       .8500    99.9900
             BUS2       .0400     1.0000  1.0000  16.0000   2.4000    .9200       .3000    99.9900
             BUS3       .0400     1.0000  1.0000  16.0000   3.0000    .7500       .6000    99.9900
             BUS4       .0400     1.0000  1.0000  16.0000   3.0000    .8000       .5000    99.9900


                                          SHUNT LOADS
                                          -----------

                                  BUSBAR    MEGAWATTS     MEGAVARS

                                   BUS2     20.00000     10.00000
                                   BUS5     40.00000     15.00000
                                   BUS6     30.00000     10.00000


                                     SYSTEM NO.  1 CASE NO.  1
                                     -------------  -----------

                                   REF. M/C = NO.  1ON BUS BUS1
                                   INTEGRATION STEP (SEC) =  .050000
                                   STUDY DURATION    (SEC) = 5.000000
                                   PRINT INTERVAL    (SEC) =  .100000
                                   SYNCH. M/C ANGLE LIMIT =  360.DEG


                                   SPECIFIED SWITCHING OPERATIONS
                                   ------------------------------

      SWITCH       SWITCH      SENDING     RECEIVING            RESITANC       REACTANCE
       TIME        IN/OUT      BUSBAR        BUSBAR               P.U.            P.U.

       0000         IN        BUS3                          .00000          .00000

       2500         OUT       BUS3                          .00000          .00000
```

APPENDIX-C

```
                    ELECTRICAL POWER-SYSTEM TRANSIENT-STABILITY STUDY
                    -------------------------------------------------

                              POWER-SYSTEM LABORATORY
                        DEPARTMENT OF ELECTRICAL ENGINEERING
                        UNIVERSITY OF PETROLEUM AND MINERALS
                                  SYSTEM NO.  1
                                  -------------

                                TRANSIENT STABILITY
                                    STUDY FOR
                                   BNILE SYSTEM


                        SYSTEM FREQUENCY   =  50.00HERTZ
                        M.V.A. BASE        =  100.0M.V.A.


                              STEADY-STATE SYSTEM DATA
                              ------------------------

                                BUSBAR DATA INPUT

BUSBAR    VOLTAGE     ANGLE       GEN MW       GEN MVAR      LOAD MW    LOAD MVAR

 BURS     1.00000   -12.86000     4.00000      2.02100        .00000      .00000
 BURD     1.00000   -14.36500     1.99100      7.61400       7.00000     4.00000
 BURM      .99230   -13.74900      .00000       .00000      13.00000    10.00000
 SWSN      .98890   -13.49500      .00000       .00000      20.00000    20.00000
 KILM     1.05200   -13.81300      .00000       .00000       6.00000     6.00000

 KUKM      .99410   -13.43200      .00000       .00000      12.00000    10.00000
 KUKI     1.06520   -11.20800      .00000       .00000        .00000      .00000
 KILH     1.11410    -9.29200      .00000       .00000        .00000    15.00000
 KILI     1.07100   -10.79400      .00000       .00000        .00000      .00000
 MERH     1.13430    -7.84700      .00000       .00000        00000     15.00000

 ROSH     1.11300    -3.48100      .00000       .00000        .00000      .00000
 ROSL     1.05000     -.27700    22.00000     -1.72000        .00000    20.00000
 ROLL     1.04000      .00000    47.34000     -9.81100        .00000    40.00000
 HASI     1.09530    -9.99800      00000        .00000        .00000      .00000
 HASL     1.11770   -11.71300      00000        .00000       6.00000     4.00000

 MERM     1.11590    -9 18700      .00000       .00000        .00000      .00000
 WADM     1.03000   -11.66400     2.99000     -3.76500       7.00000     5.00000
 SENM     1.10000    -9.35500      00000        .00000        .00000      .00000
 RAEK     1.09350    -9.91170      00000        .00000       3.00000     2.00000
 SENL     1.00000    -9.35500    12.00000      1.71800      12.00000     8.00000


                                 LINE DATA INPUT

   SENDING RECEIVING    RESISTACE     REACTANCE     SUSCEPTANCE    TAP
   BUSBAR  BUSBAR          P.U           P.U.           P.U.       P.C.

    BURS    BURM          00000        .38400         .00000        .00
    BURD    BURM          .00000       .21300         00000         .00
    BURM    KILM          .21300       .35800         .00000        00
    BURM    SWSN          .04000       .02900         00000         .00
    BURM    KUKM          04000        .06330         00000         .00

    SWSN    KUKM          .02000       .01450         .00000        .00
    KUKM    KUKI          .00000       .11060         .00000      -5.00
    KUKI    KILI          .00470       .02330         .01000        .00
    KILI    KILM          .00000       .40250         .00000      -5.00
    KILI    KILH          .00000       .06500         .00000      -2.00

    KILH    MERH          .02400       .14100         .23620        .00
    KILH    MERH          .02400       .14100         .23620        .00
    MERH    ROSH          .04420       .26000         .43200        .00
    MERH    ROSH          .04420       .26000         .43200        .00
    ROSH    ROLL          .00000       .14850         00000         .00

    ROSH    ROSL          .00000       .29700         00000         .00
    MERH    MERM          .00000       .15600         00000         .00
    MERM    HASI          .14000        18600         01750         00
    HASI    KILI          20700        .40700         02100         .00
    HASI    HASL          00000        .63500         00000       -4.00

    MERM    WADM          00000       1.26500         .00000      -2.00
    MERM    SENM          25050         33300         03120         00
    SENM    RAEK          26900         37800         03140         00
    SENM    SENL          00000       1.10000         .000         3 00
```

SYNCHRONOUS MACHINE DATA

M/C PARAMETERS

BUSBAR NAME	MACHINE MVA BASE	INERT. CONST. KWSKVA	REACTANCES(P.U.) TRANSIENT D-AXIS		SYNCHRONOUS D-AXIS		SUB-TRANSIENT D-AXIS		POT-IER	ARM. RESIST (P.U.)	O/C TCS (SECS) TRANSIENT D-AXIS		SUB-TRANSIENT D-AXIS	
				Q-AXIS		Q-AXIS		Q-AXIS				Q-AXIS		Q-AXIS
ROSL	33.50	4.500	.2800	.4000	.7700	.4000	.2800	.4000	.000	.0000	4.80	4.800	.0000	.0000
ROLL	33.50	9.000	.1400	.2000	.3850	.2000	.1400	.2000	.000	.0000	4.80	4.800	.0000	.0000
SENL	9.90	4.440	.1500	.2950	.5100	.2950	.1500	.2950	.000	.0000	5.00	5.000	.0000	.0000
BURS	12.50	10.200	.0730	.6670	.6690	.6670	.0730	.6670	.000	.0000	6.00	6.000	.0000	.0000
BURD	3.75	5.500	.0720	.3740	.3100	.3740	.0720	.3740	.000	.0000	4.00	4.000	.0000	.0000
WADM	3.39	2.100	.1380	.4120	.7325	.4120	.1380	.4120	.000	.0000	3.40	3.399	.0000	.0000

BUSBAR NAME	M/C NO.	M/C POWER OUTPUT MW	MVAR	DAMPING FACTOR
ROSL	1	22.00000	-1.72000	.01
ROLL	1	47.34000	-9.81100	.01
SENL	1	12.00000	1.71800	.01
BURS	1	4.00000	2.02100	.01
BURD	1	1.99100	7.61400	.01
WADM	1	2.99000	-3.76500	.01

AUTOMATIC VOLTAGE REGULATOR DATA

BUSBAR NAME	MC NO	AVR TYPE	FILTER T.C.	REG. GAIN	REG. T.CS. TA	TB	REG. LIMITS MAX	MIN	RATE	EXCITER GAIN	T.C.	F/BK GAIN	F/BK T.CS. TF	TD	EXCITER LIMITS MAX	MIN
ROSL	1	1	.0000	200.00	.100	.000	6.000	-6.000	******	1.000	.000	.100	1.600	.000	6.000	-6.000
ROLL	1	1	.0000	200.00	.100	.000	6.000	-6.000	******	1.000	.000	.100	1.600	.000	6.000	-6.000
SENL	1	1	.0000	124.50	.100	.000	6.000	-6.000	******	1.000	.000	.066	.375	.000	6.000	-6.000
BURS	1	1	.0000	300.00	.100	.000	6.000	-6.000	******	1.000	.000	.050	10.000	.000	6.000	-6.000
BURD	1	1	.0000	300.00	.100	.000	6.000	-6.000	******	1.000	.000	.050	10.000	.000	6.000	-6.000
WADM	1	1	.0000	300.00	.100	.000	6.000	-6.000	******	1.000	.000	.050	10.000	.000	6.000	-6.000

THERMAL TURBINE GOVERNOR PARAMETERS

BUSBAR NAME	M/C NO	SPEED REGULATION	FLYBALL GAIN	T.C.	CONTROL SYSTEM T.CS. T1	T2	T3	THERMAL T.C.	TURBINE LIMIT(MW)
ROSL	1	.0400	1.0000	2.5000	.1000	.1000	.1000	.1000	99.9900
ROLL	1	.0400	1.0000	2.5000	.1000	.1000	.1000	.1000	99.9900
SENL	1	.0400	1.0000	2.5000	.1000	.1000	.1000	.1000	99.9900
BURS	1	.0400	1.0000	2.5000	.1000	.1000	.1000	.1000	99.9900
BURD	1	.0400	1.0000	2.5000	.1000	.1000	.1000	.1000	99.9900
WADM	1	.0400	1.0000	2.5000	.1000	.1000	.1000	.1000	99.9900

SHUNT LOADS

BUSBAR	MEGAWATTS	MEGAVARS
BURD	7.00000	4.00000
BURM	13.00000	10.00000
SWSN	20.00000	20.00000
KILM	8.00000	6.00000
KUKM	12.00000	10.00000
KILH	.00000	15.00000
MERH	.00000	15.00000
ROSL	.00000	20.00000
ROLL	.00000	40.00000
HASL	6.00000	4.00000
WADM	7.00000	5.00000
RABK	3.00000	2.00000
SENL	12.00000	8.00000

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                              SYSTEM NO.  1 CASE NO   1
                              -------------  -----------

                           REF. M/C = NO.  1 ON BUS BURS
                           INTEGRATION STEP (SEC) =  .050000
                           STUDY DURATION     (SEC) = 5.000000
                           PRINT INTERVAL     (SEC) =  .100000
                           SYNCH. M/C ANGLE LIMIT =  160.DEG


                             SPECIFIED SWITCHING OPERATIONS
                             ------------------------------

    SWITCH      SWITCH   SENDING   RECEIVING    RESITANCE   REACTANCE    SUSCEPTANCE    TAP
     TIME       IN/OUT   BUSBAR     BUSBAR        P.U.        P.U.          P.U.        P.C.

     .0000       IN      ROSH                    .00000       .00000

      2500       OUT     ROSH                    .00000       .00000

     .2500       OUT     MERH                    .04420       .26000
                                    ROSH                                    .43200       00
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APPENDIX-D

STEADY-STATE SYSTEM DATA

BUSBAR DATA INPUT

BUSBAR	VOLTAGE	ANGLE	GEN MW	GEN MVAR	LOAD MW	LOAD MVAR
BURS	1.00000	-13.64831	4.00000	.84594	.00000	.00000
BURD	1.00000	-15.14456	1.99000	5.49634	7.00000	4.00000
BURM	.99687	-14.53119	.00000	.00000	15.00000	7.00000
SWSN	.99700	-14.38748	.00000	.00000	20.00000	20.00000
KILM	1.01656	-13.86952	.00000	.00000	8.00000	6.00000
KUKM	1.00399	-14.37914	.00000	.00000	15.00000	11.00000
KUKI	1.04200	-11.56722	.00000	.00000	.00000	.00000
KILH	1.07959	-9.35511	.00000	.00000	.00000	15.00000
KILI	1.05227	-11.09160	.00000	.00000	.00000	.00000
MERH	1.10788	-7.75980	.00000	.00000	.00000	13.00000
ROSH	1.09763	-3.33120	.00000	.00000	.00000	.00000
ROSL	1.05000	.36237	25.00000	3.96796	.00000	20.00000
ROLL	1.03000	.00000	44.23835	-5.62034	.00000	40.00000
HASI	1.07421	-9.66785	.00000	.00000	.00000	.00000
HASL	1.04935	-11.80781	.00000	.00000	6.00000	4.00000
MERM	1.09422	-8.66071	.00000	.00000	.00000	.00000
WADM	1.03000	-8.22658	2.99000	-.24426	2.00000	5.00000
SENM	1.07326	-8.81516	.00000	.00000	.00000	.00000
RABK	1.05579	-9.62075	.00000	.00000	5.00000	3.00000
SENL	1.00000	-7.64067	14.00000	1.36019	12.00000	8.00000

BUSBAR NAME	M/C NO.	M/C POWER OUTPUT MW	MVAR	DAMPING FACTOR
ROSL	1	25.00000	3.96790	.01
ROLL	1	44.23800	-5.62000	.01
SENL	1	14.00000	1.36010	.01
BURS	1	4.00000	.84590	.01
BURD	1	1.99100	5.49630	.01
WADM	1	2.99000	-.24430	.01

SHUNT LOADS

BUSBAR	MEGAWATTS	MEGAVARS
BURD	7.00000	4.00000
BURM	15.00000	7.00000
SWSN	20.00000	20.00000
KILM	8.00000	6.00000
KUKM	15.00000	11.00000
KILH	.00000	15.00000
MERH	.00000	13.00000
ROSL	.00000	20.00000
ROLL	.00000	40.00000
HASL	6.00000	4.00000
WADM	2.00000	5.00000
RABK	5.00000	3.00000
SENL	12.00000	8.00000