Applications of fuzzy logic control for damping power system oscillations
by Jie Lu

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
This thesis is concerned with applications of fuzzy logic control to enhance the damping of low frequency electro-mechanical oscillations in electric power systems. The objective is to develop power system stabilizers and damping controllers with fuzzy logic control so that they can be improved over conventional stabilizers in terms of adaptiveness and robustness.

Two fuzzy adaptive control schemes are developed. One scheme is based on direct tuning of stabilizer parameters and the other is based on an optimal combination of damping signals. In the first scheme, the Prony method is used to identify linear models of the power system under study, and then a root locus method is used to design conventional stabilizers at various operating points. A genetic algorithm is then used to optimize the fuzzy parameter tuner so that damping ratios are maximized regardless of changes in the operating condition. In the second scheme, a frequency-domain phase compensation method is used to identify the optimal characteristics of stabilizers at different operating points and to design conventional stabilizers for two extremes of these points. Then a fuzzy signal synthesizer is developed to optimally blend damping signals from the two independent conventional stabilizers, and therefore the stabilizer/controller can retain optimality even when the operating point drifts.

These two schemes are applied to develop power system stabilizers and/or SVC damping controllers, and extensive simulations on several systems demonstrate the effectiveness of these two schemes and show better performance than conventional stabilizers/controllers.

APPLICATIONS OF FUZZY LOGIC CONTROL FOR DAMPING POWER SYSTEM OSCILLATIONS

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

M. Hashem Nehrir, Ph.D. *M. Hashem Nehrir* 7/24/00
Chairperson, Graduate Committee (Signature) Date

Approved for the Department of Electrical and Computer Engineering

James N. Peterson, Ph.D. *James N. Peterson* 7/24/00
Head, ECE Dept. (Signature) Date

Approved for the College of Graduate Studies

Bruce R. McLeod, Ph.D. *Bruce R. McLeod* 7-25-00
Graduate Dean (Signature) Date

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ABSTRACT

This thesis is concerned with applications of fuzzy logic control to enhance the damping of low frequency electro-mechanical oscillations in electric power systems. The objective is to develop power system stabilizers and damping controllers with fuzzy logic control so that they can be improved over conventional stabilizers in terms of adaptiveness and robustness.

Two fuzzy adaptive control schemes are developed. One scheme is based on direct tuning of stabilizer parameters and the other is based on an optimal combination of damping signals. In the first scheme, the Prony method is used to identify linear models of the power system under study, and then a root locus method is used to design conventional stabilizers at various operating points. A genetic algorithm is then used to optimize the fuzzy parameter tuner so that damping ratios are maximized regardless of changes in the operating condition. In the second scheme, a frequency-domain phase compensation method is used to identify the optimal characteristics of stabilizers at different operating points and to design conventional stabilizers for two extremes of these points. Then a fuzzy signal synthesizer is developed to optimally blend damping signals from the two independent conventional stabilizers, and therefore the stabilizer/controller can retain optimality even when the operating point drifts.

These two schemes are applied to develop power system stabilizers and/or SVC damping controllers, and extensive simulations on several systems demonstrate the effectiveness of these two schemes and show better performance than conventional stabilizers/controllers.

CHAPTER 1

INTRODUCTION

Background

This thesis is concerned with the development of intelligent control strategies, and more specifically, fuzzy logic control to enhance the damping of low frequency electromechanical oscillations in electric power systems.

Within an interconnected power system, the power flow over a tie-line should be maintained near a constant level under normal conditions. However, low frequency electromechanical oscillations may occur spontaneously under certain circumstances. When such oscillations occur, electric power can be transmitted back and forth over the tie-line, demonstrating an active power fluctuation in a frequency range of 0.1 ~ 1 Hz. Accompanying this, generators within a regional system may swing against each other with a slightly higher frequency (up to 3 Hz), which also greatly disturbs the normal operation of a power system. Once such oscillations begin, they may die out by themselves after a short period, may persist for a long time until some condition changes, or may keep intensifying in magnitude, destabilizing the system, and may eventually break the interconnected system into regional islands.

The fundamental cause of this kind of oscillation is the generation of negative damping by some components, which cancels out the inherent positive damping of the system and therefore causes very light or even negative system damping. This phenomenon is more likely to happen in some specially structured systems, for example, a weak interconnection between two regional systems, or a power plant connected to a load center over a long geographical distance. Generally speaking, low frequency oscillations are associated with the dynamics of the turbine governors, excitation systems and automatic excitation regulators. Negative damping may be introduced when their parameters are improperly set.

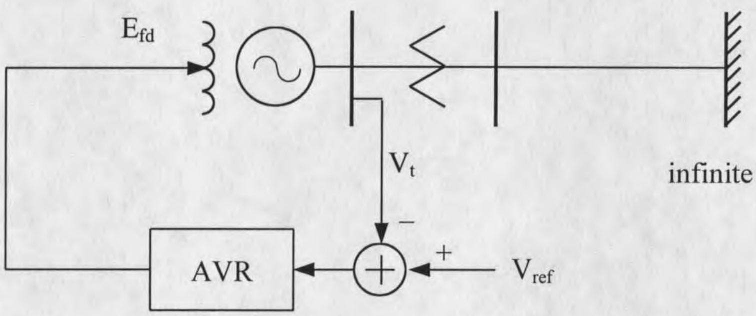
Undamped oscillations can result in great damage to interconnected systems, and they are very severe events in terms of economic loss. Power system engineers have been working on this important issue since the 1960's and have conducted numerous theoretical studies and field tests. However, research on this issue remains active because of the complexity of the problem and the advent of new control techniques and new fast-response devices not available when the problem was first studied. Among the former are intelligent (knowledge-based) control schemes such as fuzzy logic control (FLC) and digital control techniques that make logic-based control possible in industrial applications. Among the latter are Static VAR Compensators (SVC), Thyristor Controlled Series Compensators (TCSC), and other Flexible AC Transmission System (FACTS) devices, a common feature of which is short response time, which benefits control greatly.

The Nature of Low Frequency Oscillations

Prior to the actual design of a control scheme to suppress such low frequency oscillations, a full understanding of the nature of these oscillations is necessary. For precise mathematical analysis, a linearization followed by eigenvalue analysis is often desirable. However, for the purpose of understanding, a physical analysis on a one-machine system is more appealing, since it introduces useful physical concepts and reveals how the physical quantities interact with each other to develop negative damping. It is also useful in developing remedial measures against these negatively damped oscillations.

Consider the following simple system.

Figure 1. A simple system.



E_{fd}: excitation field voltage.
V_t: terminal voltage.
V_{ref}: reference voltage.
AVR: automatic voltage regulator.

Neglecting all minor details and assuming no immediate mechanical torque change following a small perturbation (which is justified by the slow response of turbine governors), linearized equations characterizing this system are as follows:

$$\frac{2H}{\omega_0}\Delta\dot{\omega} + D\Delta\omega = -\Delta T_e \tag{1.1}$$

$$\Delta\dot{\delta} = \Delta\omega \tag{1.2}$$

where

H is the inertia of the generator,

ω is the angular speed,

ω_0 is the nominal angular speed,

δ is the rotor angle,

D is the inherent damping, and

T_e is the electrical torque.

Since here we are talking about a linearized representation of the system, the electrical torque T_e can be further expressed as a linear combination of the other two variables ω and δ as follows:

$$\Delta T_e = K_S \cdot \Delta\delta + K_D \cdot \Delta\omega \tag{1.3}$$

where K_S and K_D are coefficients, which are highly sensitive of operating points, network parameters and excitation system parameters. The first term on the right-hand side of (1.3) is called synchronizing torque while the second term is called damping torque.

By substituting (1.2) and (1.3) into (1.1), we have

$$\frac{2H}{\omega_0}\Delta\ddot{\delta} + (D + K_D) \cdot \Delta\dot{\delta} + K_S \cdot \Delta\delta = 0 \tag{1.4}$$

For this second-order system to be stable, $(D+K_D)$ and K_S should both be positive. If the synchronizing torque is negative, the characteristic equation has (at least) one positive real root, and therefore the generator slips out of synchronism without any oscillation. If the damping coefficient $(D+K_D)$ is negative, the characteristic equation guarantees to have roots whose real parts are positive, which correspond to unstable modes. If the roots are complex, the system exhibits oscillations. Usually the synchronizing torque is safely large due to the action of the generator AVR, and therefore of less concern than the damping torque. On the other hand, it is exactly the same action of the AVR that under certain conditions could deteriorate the damping torque to such a degree that the generator becomes vulnerable to small disturbances in the system.

In the above analysis, we concentrated on the electrical torque and neglected the mechanical torque. In fact, the mechanical torque can be decomposed as synchronizing and damping torque as well. Therefore, similar analysis can also be carried out for the mechanical torque; the only difference is that the resultant coefficients would depend on different factors like turbine governor parameters rather than excitation system parameters. This is the reason that in some cases low frequency oscillations are due to improper mechanical subsystem settings.

The whole matter is much more complicated if more than one machine is involved; the order of the system is higher, and interactions between machines have to be considered. However, the physical nature of the oscillation remains the same. Hence some concepts developed with the single machine case are still applicable, and the control methodologies based on them may be extended to multi-machine systems.

Measures against Low Frequency Oscillations

There are two philosophies in developing power system stabilizers for improving system damping: one is based on control theories; and the other is to follow the understanding of the physical nature of low-frequency oscillations.

The underlying thought of the former is to view the problem from the perspective of control theories, where a mathematical model of the whole system is obtained and analyzed, and based on its characteristics appropriate control theories are applied to design a controller. In other words, the problem is put into a general frame of control problems, and an optimal solution is sought in that framework. One advantage of this approach is that so many control methodologies are readily available, among which some may fit well to the particular problem at hand. These control methodologies usually have well-defined procedures to follow in controller design. Classical examples include using root locus to develop stabilizers based on the zero-pole representation of the system and using linear quadratic regulation theory to design an optimal stabilizer based on the system state-space representation.

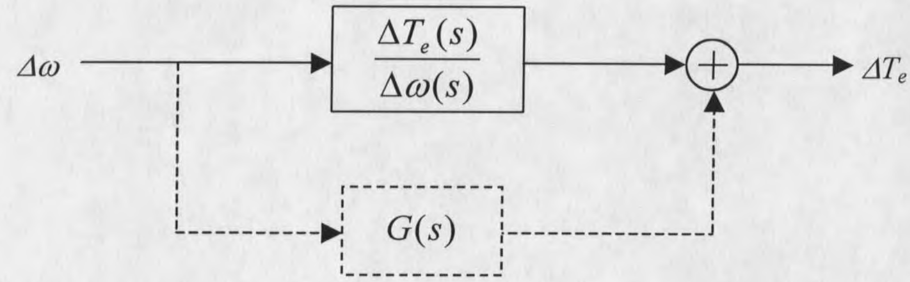
In contrast, the other category of approaches views the problem from a physical perspective, especially focuses on why and how oscillations develop, what is the key driving force behind the power oscillations, and what are physically suitable remedies. For example, after the interaction between the voltage regulation and the machine speed is unveiled, a heuristic controller might be designed to give supplementary control to the excitation system utilizing a phase-plane representation of the machine speed and acceleration.

In particular, a methodology for power system stabilizer design is worthy of mention since it serves as a basis of an adaptive controller, which a part of this thesis concerns. From (1.3) we can see that the coefficient K_D is actually defined as:

$$K_D = \frac{dT_e}{d\omega} \tag{1.5}$$

Equation (1.5) shows how much damping would be introduced in the electrical torque if a deviation of machine speed takes place. This implies that by adding a parallel compensatory signal path with a positive gain in addition to the inherent signal path from

Figure 2. Compensatory signal path added to improve damping.



ω to T_e, damping can be improved. This is illustrated in Fig. 2, where the dotted path is the added-in compensatory one.

By incorporating (1.2) and (1.3) and performing Laplace transformations, we obtain the following expression, assuming the oscillation of concern is sinusoidal:

$$F(j\Omega) \triangleq \frac{\Delta T_e(j\Omega)}{\Delta\omega(j\Omega)} = \frac{K_S}{j\Omega} + K_D \tag{1.6}$$

where Ω is the angular frequency of oscillation[1]. It follows that

$$K_D = \mathrm{Re}[F(j\Omega)] \tag{1.7}$$

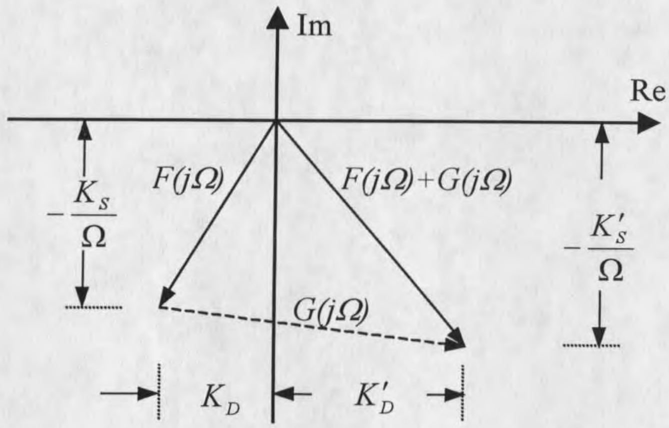
and

$$K_S = -\Omega\,\mathrm{Im}[F(j\Omega)] \tag{1.8}$$

where Re(·) and Im(·) denote the real and imaginary parts of a complex number respectively. Suppose the complex gain of the compensatory path is $G(j\Omega)$, then, as shown in the phasor diagram given in the Fig. 3, it is clear that the best angle of the $G(j\Omega)$ phasor should be negative and approaching zero, so that the damping is enhanced

[1] To avoid confusion, a capital Ω is used here to denote the angular oscillation frequency, since ω is already denoting the angular speed of the generator.

Figure 3. Phasor diagram of complex gains.



K'_D, K'_S: Coefficients after compensation

without having an undermining effect on synchronous torque. Here the compensatory path includes not only a controller but also some unalterable part of the system. Frequency domain methods are used to design the compensator so that the complex gain of the path is close to real.

Controllers have to be actually attached to physical devices such as a generator excitation unit, an SVC, a Static Synchronous Compensator (STATCOM), or a TCSC. These devices except the first one are categorized as FACTS devices. Controllers based on excitation units have the advantage of being a low-cost option, and they are applied most widely for the purpose of damping low-frequency oscillations. On the other hand, FACTS devices, which are high power electronic devices, have fast response time and potential to yield better control performance. They are expensive, and therefore it is generally infeasible to install them solely for the purpose of damping low frequency oscillations. However, if there are FACTS devices already in operation for other purposes like voltage support, supplementary controllers can be designed for them to enhance damping. In this thesis, consideration is given to excitation unit-based and SVC-based controllers, since these two are the most available options at present time.

Fuzzy Logic Control

Fuzzy logic control (FLC) is a powerful tool in modeling and controlling those imprecise systems that are difficult to represent in traditional mathematical models. It is based upon fuzzy set theory that mathematically establishes the definitions and manipulation rules of fuzzy sets representing imprecise objects or terms in real life. For example, the statement "if A is very high and B is medium, then C is moderately high," which might be impossible to translate into conventional mathematical languages, is expressible with the fuzzy set theory. With the definition of fuzzy terms and inference rules, just like the IF-THEN statement above, expertise given by a human being or experience learned by other means can be stored and applied by a computer.

In control applications, fuzzy logic is fairly flexible. In the statement above, if A and B are measurements, then C could be an output, or it could be a control signal. In the former case the rule is a part of a fuzzy model, and in the latter case it is a control law. The two forms can be (and usually are) used jointly in controller design: based on a model rule, a fuzzy control law is developed. A paradigm is as follows: if measurement A is very high, and measurement B is medium, then the output is moderately high and therefore the control effort should be moderately low.

There are two forms of fuzzy logic systems: Mamdani type and Takagi-Sugeno type. The difference between them is with the consequent (THEN) part of rules: in the former the output variable is specified with a fuzzy term, and it needs to be defuzzified to obtain a crisp value. In the latter type the output is given as a crisp (as opposed to fuzzy) linear combination of the input variables. The two forms both have their own advantages: the Mamdani type is easy to construct based on human language description of an object, whereas the Takagi-Sugeno type is useful when some traditional mathematical representation of an object is involved. With this type, a design pattern is often followed:

(1) Determine a proper division of state space so that in every subspace the object in study is linear or quasi-linear. For each subspace a rule is given to specify the subspace in the antecedent (IF) part and describe the linear relationship in the consequent part as follows:

If $\overline{X}$ is ..., then $\overline{Y} = F(\overline{X})$, where $F(\cdot)$ is a linear function.

(2) Based on the model rules given in (1), for every subspace a controller H is designed optimally in some sense.

(3) The control laws are then constructed, followed by any optimization (if necessary) of the fuzzy membership functions:

If $\overline{X}$ is ..., then $H = H(\overline{X}, \overline{Y})$, where $H(\cdot)$ is the control function.

This procedure is used in this thesis to develop adaptive stabilizers.

Literature Review on Control for System Damping

This section will review some published work on damping low frequency oscillations. Most of them are focused on intelligent control schemes for damping purposes, while some others are included due to their relevance to this thesis.

DeMello and Concordia [1] were among the first to analyze the nature and remedies of the low frequency electro-mechanical oscillations. In their paper, they presented, in the form of a block diagram, a linearized model of a synchronous generator and its excitation system connected to an infinite bus. Detailed explanations were given on parts of their diagram and on the physical significance of the constants appeared therein. They introduced the concepts of synchronous and damping torques, and pointed out that lack of adequate damping torque caused oscillation or instability. Using these concepts and the block diagram, the authors developed expressions for torques and thus revealed the effect of the excitation system on stability: under certain conditions, high voltage regulator gain jeopardized stability by lowering damping inadvertently when attempting to increase synchronizing torque. Based on this understanding, the authors used frequency domain methods to develop speed-based power system stabilizers (PSS) to compensate this negative impact on damping torque and demonstrated the effectiveness through analog simulations.

Kundur, et al., [2] described in detail analytical work and a design procedure to determine PSS parameters for a large power generation station. The frequency response method outlined in their paper is based on and is similar to the stabilizers proposed in [1], but the authors obtained the frequency characteristics with the model of a whole system instead of a single machine model. This created a more accurate representation of the generator of interest. The authors also put emphasis on simultaneous damping of inter-area and local modes and robustness of PSS design. It was pointed out by the authors that if the time constant of the washout filter was too small then damping was adversely affected on inter-area modes by over-compensation. In their paper, the effect of transient gain reduction was also discussed, and the authors showed that it did not provide any major benefit. As the authors reported, the frequency response method (that mainly aimed to compensate the lag from the excitation input to the electrical torque) was fairly robust. This meant that a PSS with proper frequency characteristics could be universal regardless of external conditions or mode of oscillations.

Trudnowski, et al., [3] presented an interesting identification method and a method of designing PSS other than frequency domain based ones. The authors used a pulse of a short time period as the excitation to a generator in a multi-machine system to obtain a response, and based on this input-output relationship, generated a transfer function that was optimal in the sense of least-squares error of time domain fit. A root locus method together with a decentralized sequential control technique was used to demonstrate the procedure to use transfer functions acquired above for damping controller design. The authors clearly showed the effectiveness of their design method by presenting simulation results, FFT analysis on those and a root locus plot for a 16-machine 27-bus test system.

Hsu and Cheng [4] proposed a PSS based on fuzzy set theory. This paper attempted to use a classical Mamdani type fuzzy system to build a mapping relationship from measurement inputs to control output. The authors chose the normalized values of speed deviation $\Delta\omega$ and its derivative as two inputs to a fuzzy logic inference machine, which gave a fuzzy value of PSS control signal. A seven-by-seven rule table was employed, and the authors determined all the membership functions based on their design experience and no optimization on these membership functions was intended or mentioned in their paper. A two-machine nine-bus system including an infinite bus was used as the test system to simulate a three-phase fault. The results reported showed good damping as compared with a conventional lead-lag PSS.

Hiyama published a series of papers on applying rule-based and fuzzy logic controllers to stabilize power systems. He proposed [5] the following control scheme: First, the speed deviation is selected as the input signal, and then a phase plane is constructed based on speed deviation and its first-order derivative, i.e., the acceleration of the generator. The phase plane is divided into six sectors, which respectively represent different speed and acceleration combination states and therefore demand for different control strategies: strong accelerating control, slight accelerating control, slight decelerating control, and strong decelerating control. Dividing lines are defined to divide the phase plane, and the positioning of these lines are parameterized and subject to subsequent optimizations. Naturally the sign of the control reflects whether it was an accelerating or decelerating control. Two gain levels, high and low, were used to implement "strong" and "slight" controls respectively. The gain of the controller is also dependent of how far the state is from the origin of the phase plane, which represents the equilibrium point of the generator: the gain is proportional to the distance from the origin within a given threshold, and is a constant beyond that. This threshold is also subject to optimizations. To achieve optimal performance, all the parameters including those mentioned above undergo an optimization to determine the optimal setting. A time-domain summation of squared errors is used as the performance index, and the parameters are optimized sequentially. Simulations showed impressive damping improvement over conventional stabilizers. In [6] the same design was extended into multi-machine cases and it also showed good results.

In [7] Hiyama presented a modified version of the rule-based stabilizers. Use of the phase plane, with speed deviation as the input signal, and the concepts of strong or slight controls, accelerating or decelerating controls remained the same. However, instead of using two gain levels and sign of the control signal to realize the control strategy as reported above, he introduced a fuzzy logic scheme to describe the transition of different controls. Two terms were defined to represent strong positive and strong negative control respectively, and their respective trapezoidal membership functions complemented each other and determined the control signal in states that are between the two extreme ones. The same sequential optimization technique was again used to get a minimal oscillation, though the parameters to be optimized were slightly different. The author also presented in detail his implementation in an experimental system using digital control, and showed that the approach yielded good performances. In [8], the author discussed the application of this approach to a multi-machine system, and based on the simulation results, it was claimed that the approach was robust over a wide range of operating conditions, though no theoretical analysis was presented. In [9] the author reported inferior performances or even instability associated with a condition where the acceleration and speed deviation were close to zero while the phase was not at its steady-state value. To correct this situation, further modifications were made to his scheme: the phase information or the integration of the speed deviation was introduced (hence the name PID Type stabilizer since an integration was involved) and the origin of the phase plane was moved leftward or rightward depending on the sign of the integral. This shift was to force the phase integration to zero by applying accelerating or decelerating controls when the integration drifted from zero towards negative or positive sides respectively. The author did both