Paper

Fuzzy Logic Controller Based on Observed Signals and a Genetic Algorithm Application with STATCOM for Power System Stabilization

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Fuzzy logic control has been applied to various applications in power systems. Its control rules and membership functions are typically obtained by trial and error methods or experience knowledge. Proposed here is the application of a micro-genetic algorithm (micro-GA) to simultaneously design optimal membership functions and control rules for STATCOM. First, we propose a simple approach to extract membership functions and fuzzy logic control rules based on observed signals. Then a proposed GA will be applied to optimize membership functions and its control rules. To validate the effectiveness of the proposed approach, several simulation studies have been performed on a multimachine power system. Simulation results show that the proposed fuzzy logic controller with STATCOM can effectively and robustly enhance the damping of oscillations.

Keywords: fuzzy logic control, micro-genetic algorithm, power system stabilization, STATCOM

1. Introduction

The growth and continuing evolution of modern power systems have progressively altered their characters. Modern power systems become larger, more complex and deregulated. These are the key factors forcing utilities to operate and utilize their existing facilities at higher efficiency than ever before. In order to keep flexibility, higher stability and reliability in power system operations, the use of FACTS devices in transmission systems is being considered. Among them STATCOM is one type of FACTS devices which resembles in many aspects as rotating synchronous condenser used for voltage control and reactive power compensation. As compared with SVC, many literatures suggested that the size of capacitor of STATCOM may be reduced to about 20 to 30% of that required for a conventional SVC. This implies a great save both in the installation space and the economical uses (1). The mentioned reasons can be considered as important advantages of using STATCOM over the conventional SVC in power system applications. With proper control, STATCOM can enhance power transfer limit and improve dynamic behavior significantly. Over the decades, the linear controller as a lead-lag compensator has been applied to various power system applications due to its simplicity in structure and its easiness in realization. Nevertheless, it is well recognized that the linear controller cannot operate robustly when the power system is subjected to varying operating or control conditions.

Recently, fuzzy logic controllers (FLCs) are rapidly becoming viable alternatives for classical linear controllers. A fuzzy logic controller has several advantages compared to those from many conventional linear controllers; for instance, it offers a convenient way of designing a controller about the process being controlled from operator's experiences and expert's knowledge. This approach can enhance performance, adaptive property, reliability and robustness of the controllers better than conventional linear controllers.

The contribution of this paper is to develop a method for optimal design of FLC of STATCOM by using a micro-genetic algorithm (micro-GA), regarding to enhancing power system stabilities. Here, we firstly propose a fast and simple method to design FLC from without knowledge of the system by extracting membership functions and fuzzy logic control rules based on observed signals. By using the initial design of FLC, which we call a non-optimal FLC, the system dynamic behavior can be improved evidently. However, in order to obtain the better performance, an optimization method should be incorporated to tune membership functions and fuzzy logic control rules simultaneously. GA's are particularly suitable for such optimization and hence automating the design process. The important problem when applying GA's to large power system problems is the calculation time that GA's may take days or weeks to finish the optimization. Typically, most of the time spent by GA's is for calculating the objective function. The idea of using a micro-GA can alleviate this problem because the number of GA population size can be reduced

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substantially [2][3]. Besides, experiences from several computational experiments show that if we put a few good solutions in the initialization process of GA's, the total time to find the final best solution can be improved remarkably. As a result, in this study, we apply a micro-GA with an assigned initial good solution to optimize the membership functions and control rules simultaneously. To demonstrate the effectiveness of the proposed approach, several simulation studies have been carried out on a multimachine power system. Simulation results show that the resulting FLC application with STATCOM can effectively and robustly enhance the damping of oscillations.

2. STATCOM Model

In this paper, the STATCOM is represented by a voltage source connected to a bus through a series reactance X_s as shown in Fig. 1. A new modeling language named Modelica together with Dymola and ObjectStab library

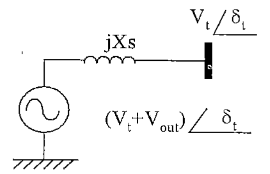


Fig. 1. Equivalent model of STATCOM

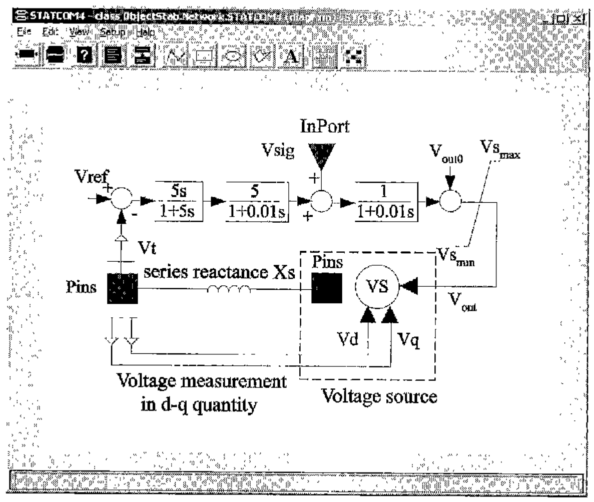


Fig. 2. Model of STATCOM in ObjectStab

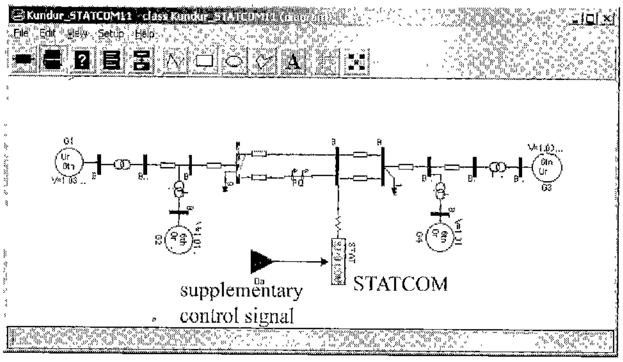


Fig. 3. STATCOM model applied to a power system network

for power system stability studies has been employed to model the STATCOM [4]~[6]. Using traditional ways to model power system devices, one requires to intensively work with ac network interface and to modify the system bus admittance matrix. On the other hand, with Dymola and ObjectStab, the STATCOM can be directly modeled from a free body diagram of Fig. 1. Power system topology and parameter data can be readily entered in one-line diagram form using a graphical editor; besides, all model components are transparent and are easy to be modified. Fig. 2 illustrates the detail of the STATCOM model developed by the authors. It can be seen that the STATCOM model is constructed by use most of standard components in Dymola and ObjectStab, i.e. the transfer function block, the series reactance (X_s), the connectors (*Pins*), the input port (*InPort*), and the limiter, except the model of STATCOM voltage source which is modeled separately in terms of equations. Since the STATCOM model cannot be found in the standard library, here, the authors provide the detailed code of the STATCOM model for interested persons in the Appendix. Once the STATCOM model is established for use as one object, it can be reusable to connect its instance with other standard models to form such complex networks. Fig. 3 illustrates what the STATCOM model looks like when connecting it to a power system network. One of the most benefits of using Dymola and ObjectStab is that all models can be exported for use in Matlab/Simulink, then a full set of Matlab tools can be used which ease the use of genetic algorithm in this study [7]. In order to fully understand some other technical advantages of using Modelica language, Dymola and ObjectStab, one can access to the Modelica Association web site; *http://www.modelica.org.*

3. Power System Model

Fig. 4 illustrates a single line diagram of a test power system. Every generator is equipped with AVR and GOV. The data of this power system network, AVR and GOV are given in Ref. (8). The STATCOM is represented by a voltage source connected to a bus at the middle of transmission line through a series reactance X_s. A three-phase to ground fault occurred at Bus 7 is considered as a disturbance by assuming that the faulted line is cleared after the occurring of fault for a 0.07 s period. To investigate the performance of STATCOM for a wide range of operating conditions, the transfer power between two areas is adjusted for base, heavy and light loading conditions as specified in Fig. 4.

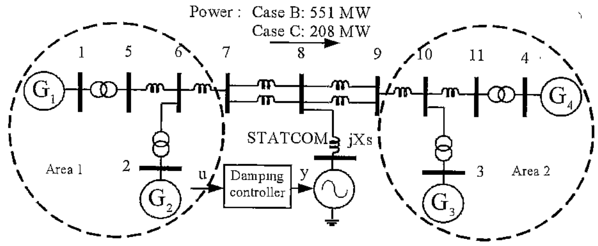
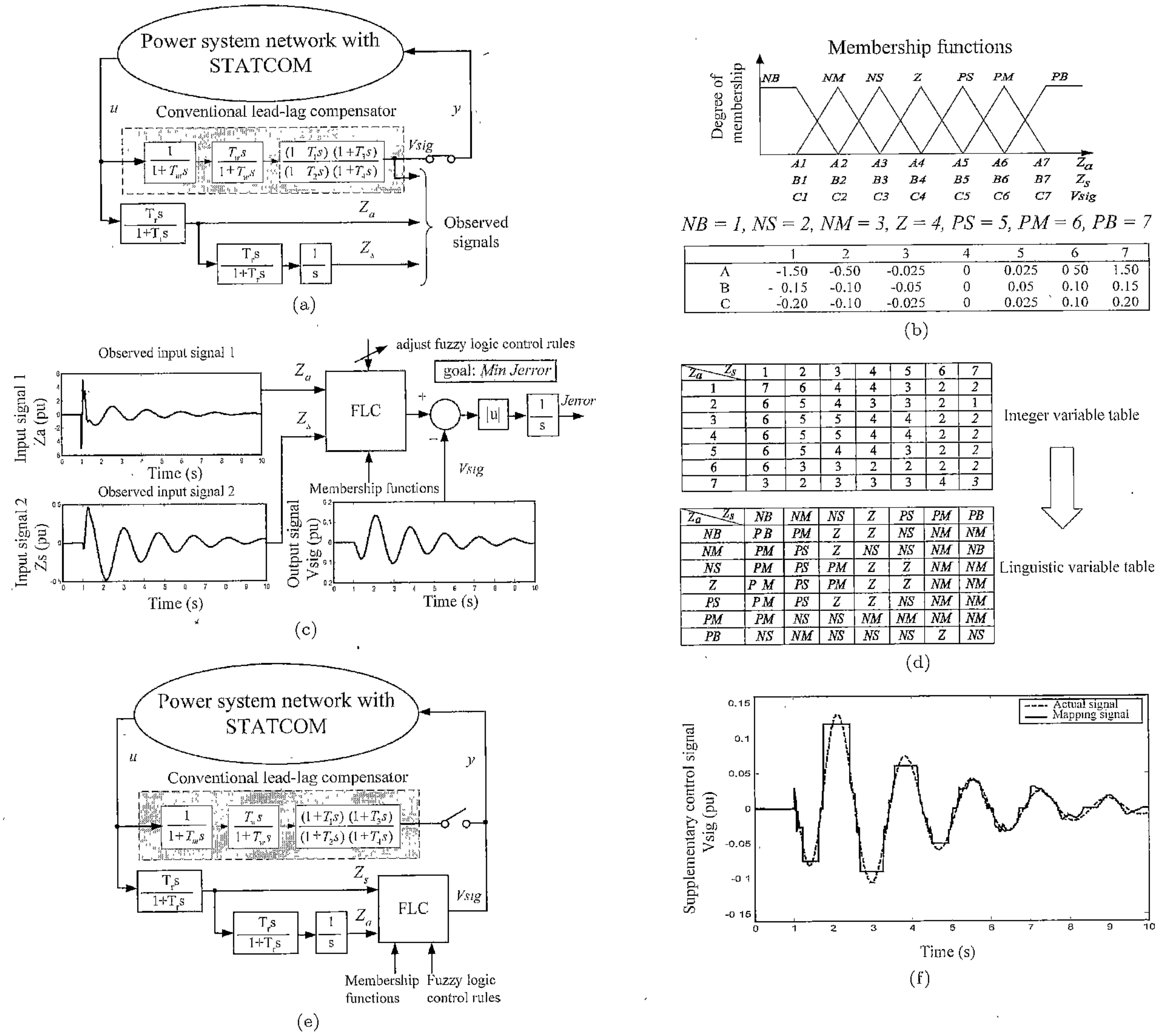


Fig. 4. Power system model used in this study

4. Fuzzy Logic Control Rules from Observed Signals

In FLC design, important steps are how to obtain the membership functions and control rules. Typically, the membership functions and the control rules are obtained by expert's experiences where they are synthesized by the choices of the input-output membership functions and the rule bases. In case of no experts and no or little initial knowledge, FLC design may not be easy for non-experts. This study presents a simple, general and practical approach to extract membership functions and fuzzy logic control rules based on observed signals. Conceptually, we try to invent a FLC that mimics the performance of any black box controllers that will be put into the power system. Though the resulting FLC may not be the optimum; however, it is expected that FLC can deal with for hidden uncertainties when the power system is subjected to changing the operating conditions. The procedure to extract membership functions and fuzzy logic control rules is explained step by step as in Fig. 5. First, we can collect input-output pairs which are served as the samples for an initial FCL design by putting an appropriate conventional lead-lag compensator into the power system. In this study, a local signal of power flowing in the tie line is selected as an synthesized input while the observed input-output signals are calculated from the block diagram in Fig. 5(a). After obtaining input-output responses from a conventional lead-lag compensator, we can determine the universe of discourse for membership functions of each input and output signal roughly. For simplicity, triangle



	1	2	3	4	5	6	7
A	-1.50	-0.50	-0.025	0	0.025	0 50	1.50
B	- 0.15	-0.10	-0.05	0	0.05	0.10	0.15
C	-0.20	-0.10	-0.025	0	0.025	0.10	0.20

Z_a \ Z_s	1	2	3	4	5	6	7
1	7	6	4	4	3	2	2
2	6	5	4	3	3	2	1
3	6	5	5	4	4	2	2
4	6	5	5	4	4	2	2
5	6	5	4	4	3	2	2
6	6	3	3	2	2	2	2
7	3	2	3	3	3	4	3

Z_a \ Z_s	NB	NM	NS	Z	PS	PM	PB
NB	PB	PM	Z	Z	NS	NM	NM
NM	PM	PS	Z	NS	NS	NM	NB
NS	PM	PS	PM	Z	Z	NM	NM
Z	PM	PS	PM	Z	Z	NM	NM
PS	PM	PS	Z	Z	NS	NM	NM
PM	PM	NS	NS	NM	NM	NM	NM
PB	NS	NM	NS	NS	NS	Z	NS

Fig. 5. The procedure to extract membership functions and fuzzy logic control rules: (a) step 1: extract input-output signals from a conventional lead-lag power system damping controller of STATCOM, (b) step 2: determine the universe of discourse for membership functions based on the real magnitude of observed input-output signals, (c) step 3: randomly adjust fuzzy logic control rules by minimizing Jerror, (d) covert the integer variable table to the linguistic variable table based on the fuzzy set notations determined by step 2 (e) validate the fuzzy logic controller by putting the FLC with resulting membership functions and control rules into a power system as a damping controller of STATCOM, (f) compare the actual and mapping signals; if the result is not satisfied then go to step 2 and step 3

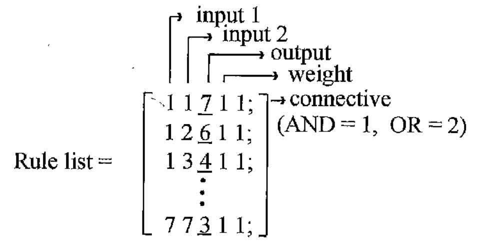


Fig. 6. Rule list in the fuzzy logic toolbox of Matlab

and trapezoidal shaped membership functions have been selected to describe all of linguistic variables. Fig. 5(b) illustrates the fuzzy sets for all of the input and output variables. The input and output signals are divided into seven linguistic variables using the fuzzy set notations as defined in Fig. 5(b). Control rules can be more complicated than membership function determination. Fortunately, the fuzzy logic toolbox in Matlab supports for matrix representation of rule sets. This makes the design procedure easier from the use of an optimization method to obtain the control rule table. For the case of two-input, one-output system, the fuzzy rule set can be shown graphically in a table where every cell show the output membership function of a fuzzy rule with input membership functions. In the fuzzy logic toolbox of Matlab the rules are build from this statement: *if input 1 and input 2 then output 1.*

The rule is turned into a structure as shown in Fig. 6 when applying this idea in the fuzzy logic toolbox. The underlined integer numbers are equivalent to the linguistic variable outputs and are the integer numbers in the control rule table. Since there are 49 rules, there are, therefore, 49 unknown parameters at this stage. In the process of Fig. 5(c), we use the input-output signals that were previously recorded by using the method in step 1. We apply the determined membership functions as in Fig. 5(b) and randomly adjust the rule list in Fig.6 until the output *Jerror* is minimized. The resulting control rules are shown in Fig. 5(d). It is easy to convert the integer variable table to the linguistic variable table by using the fuzzy set notations as determined in Fig. 5(b). The result of the linguistic variable table in Fig. 5(d), which humans can understand, is turned into the initial knowledge obtained from the signal mapping method. In order to verify the performance of the resulting FLC, we then apply the membership functions and the resulting control rules with the FLC and connect the FLC to the power system as in Fig. 5(e). The performance of FLC can be observed from the time domain simulation as depicted in Fig. 5(f). It should be noted that this idea can be applied as long as we have input-output pairs. The speed of calculation based on this approach is considerably fast because power system network does not involve in the optimization. However, in order to obtain the better performance of FLC, an optimization method should be incorporated to adjust the proper shapes of membership functions and its control rules.

5. Designing a FLC using a Micro-GA

5.1 Micro-genetic Algorithm The aim of a micro-GA is to find the optimum as quickly as possible without improving any average performance. It can be done by using a very small size, usually not more than 10, of population in the procedure and using a reinitialization process to keep enough diversity in the population. The point is that, when applying GA's to large-scale problems, most of the time is consumed for calculating the objective function. If the population size can be reduced without effecting the convergence capability of GA's, the total spending time will be decreased considerably. The idea of a micro-GA is extensively discussed and explained in details in our previous papers [(2)(3)]. Here, only some important parts when using a micro-GA particularly how to translate in genetic codes with a specified chromosome structure and how to determine the objective function will be explained.

5.2 Chromosome Structure Every fuzzy set in a fuzzy partitioning is defined by its shape of membership functions. Consequently, the GA designer has to decide which parameters to fix and which parameters to tune. In our study, we employ two shapes of membership functions; triangular and trapezoidal membership functions. Fig. 7 illustrates a chromosome structure used in this study. It contains important information for membership functions of each input-output signal and fuzzy logic control rules. Most of linguistic variables use a triangular membership function, only for *NB* and *PB* linguistic variables use a trapezoidal membership function. A triangular membership function is defined by its three parameters; left base (L), center (C) and right base (R). A trapezoidal membership function is defined by its four parameters; left base (L), center 1 (C_1), center 2 (C_2), and right base (R). The chromosome part for control rules is same as explained in the rule list in section 4. There are 49 unknown parameters for 49 control rules in which each parameter is represented by an integer ranging from 1 to 7 for the corresponding output membership function. All values of the optimized parameters in the chromosome are encoded by integer values. The way to change integer parts to real parts for membership functions is using eq. (1)

$$A_i = \underline{A} + I_{Ai} \times (\overline{A} - \underline{A})/(number\ of\ step) \quad \cdots\cdots (1)$$

where A_i is a real value of the i^{th} decoded parameter, I_{Ai} is the i^{th} integer value which contains in the chromosome, $\underline{A}$ and $\overline{A}$ are upper and lower bound of each parameter in real values respectively, *number of step* is the step required by the designer to determine the accuracy of each decoded parameter.

5.3 Objective function With the study system, there are three different electromechanical modes of oscillations in which the number of modes is less than the number of generators by one. These are two local modes in which generators within the same area oscillate against each other, and one inter-area mode in which the generators in area 1 oscillates against those in area 2.

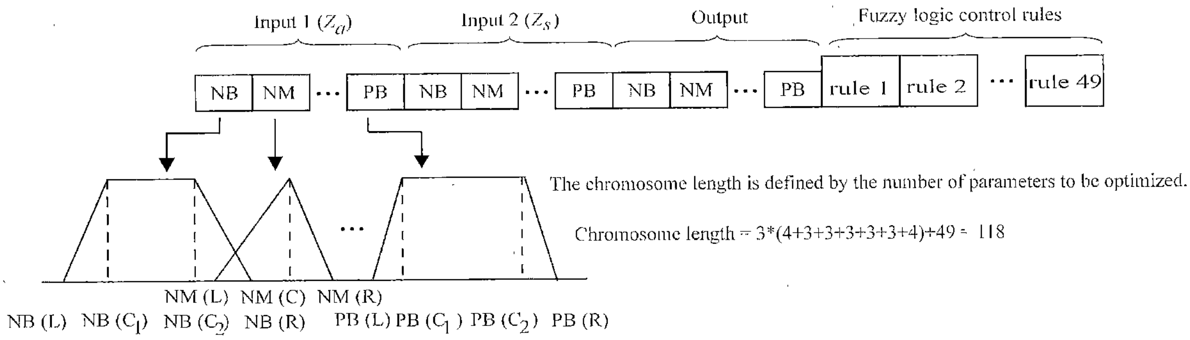


Fig. 7. Chromosome structure

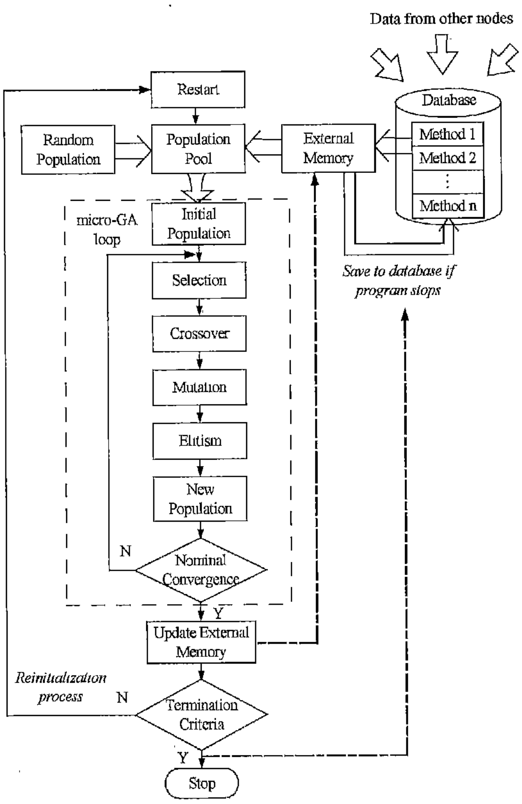


Fig. 8. Micro-GA flowchart

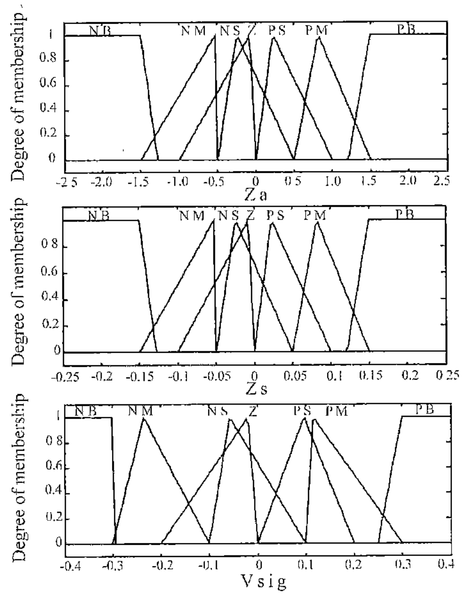


Fig. 9. Optimal membership functions

Based on this nature of oscillations, when the local mode of each area is excited, it is made dominant by observing the generator speed difference within the same area ($\Delta\omega_{12}$ and $\Delta\omega_{34}$). By the same way, when the inter-area mode is excited, it is made dominant by observing the generator speed difference between two areas ($\Delta\omega_{13}$ and $\Delta\omega_{14}$). Here, the design specification of FLC for STATCOM is to meet the objective function in eq. (2). The speed of the generator 1 is taken as a reference. The speed difference between generator 1 and 3 (generator 1 and 4), and the generator 1 and 2 (generator 3 and 4) represent the inter-area and local mode respectively. The objective is to minimize the speed deviation of generators for local and inter-area modes. Based on the eigenvalue analysis, it reveals that two local modes have much higher damping ratios than the inter-area mode. This implies that the inter-area mode is more difficult to be damped. Therefore, the inter-area mode is more concerned in this study resulting to higher weighting values compared to those for the local modes. The weighting values in this study were set to be $k_1 = 0.5$, $k_2 = 1.0$, $k_3 = 1.0$, and $k_4 = 0.5$. However, it is not restricted to such a case, these values can be adjusted arbitrarily depending on the purposes of designers and the nature of problems.

$$\min F = \int_{t=0}^{20} (k_1|\Delta\omega_{12}| + k_2|\Delta\omega_{13}| + k_3|\Delta\omega_{14}| + k_4|\Delta\omega_{34}|)dt \quad \cdots\cdots (2)$$

where k_1, k_2, k_3, and k_4 are weighting values,
$\Delta\omega_{12}$ is the speed difference between generator 1 and generator 2,
$\Delta\omega_{13}$ is the speed difference between generator 1 and generator 3,
$\Delta\omega_{14}$ is the speed difference between generator 1 and generator 4,
$\Delta\omega_{34}$ is the speed difference between generator 3 and generator 4

5.4 Implementation We employed a micro-GA as in the algorithm flowchart in Fig. 8 to solve the optimization problem. Experiences from several computational experiments using a micro-GA show that the time consumed by a micro-GA can be hastened if a few good solutions are used in the GA initialization process. As a result, the result obtained from designing a FLC in section 4 is used as an initial good solution. The time spent in the initialization process will be compensated by substantial improving of the total calculation time. The time in the initialization process is about 0.15 seconds per iteration.

The results presented in this paper have been obtained by the GA settings with the population size of 8 and maximum generation of 120. Recombination is performed using a discrete recombination with the probability of 0.9 and mutation is applied with non-uniform mutation with the probability of 0.01. The selection process uses a tournament selection with the tournament size of 2. These above GA settings were guided by Ref. (9) for the case of small population size. Besides, several computational experiments using these settings in a variety of applications by us show that it appears to be no problems. The necessary time for evaluating one time of objective function is about 1.5 seconds in this step.

Table 1. Optimal fuzzy logic control rules

Z_a \ Z_s	NB	NM	NS	Z	PS	PM	PB
NB	PB	PM	PM	NS	NS	NM	NB
NM	PM	PM	PM	NM	NS	NM	NM
NS	PM	PM	PS	PS	NS	NM	NM
Z	PM	PM	Z	Z	Z	NM	NM
PS	PM	PM	PS	NS	NS	NM	NM
PM	PM	PM	PM	NM	NM	NM	NM
PB	PM	PM	PM	NM	NM	NM	NM

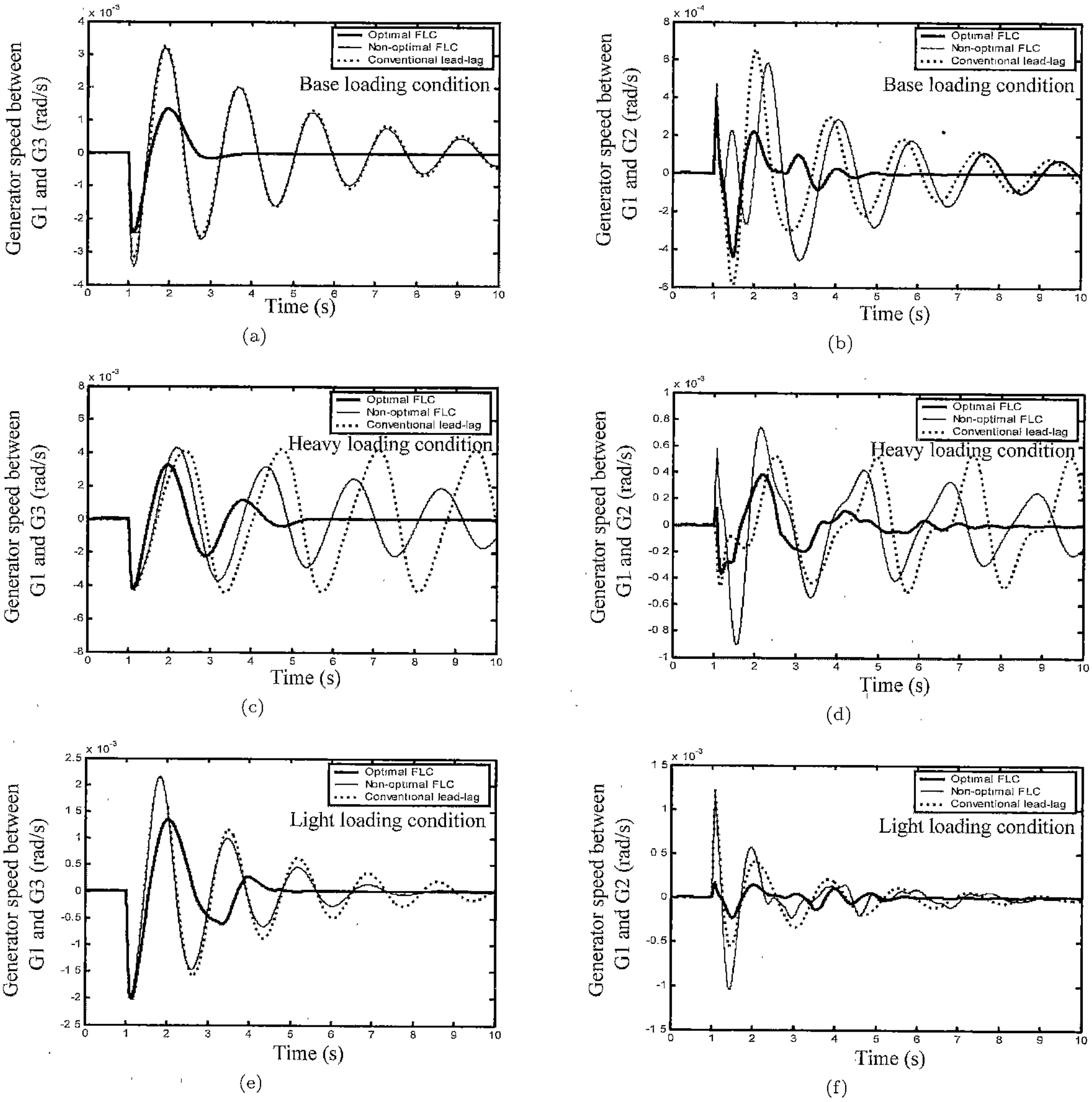


Fig. 10. Generator speed responses in which the generator speed between G1 and G3 represents the inter-area mode and the generator speed between G1 and G2 represents the local mode: (a) inter-area mode for base loading condition, (b) local mode for base loading condition, (c) inter-area mode for heavy loading condition, (d) local mode for heavy loading condition, (e) inter-area mode for light loading condition, and (f) local mode for light loading condition

6. Simulation Results

The optimal FLC, non-optimal FLC and a conventional lead-lag compensator were designed at the base loading condition and then the performance of controllers were tested by varying loading conditions. The non-optimal FLC in this study means the FLC that we obtained from the design method in section 4 based on the observed signals. Fig. 9 shows the final optimal membership functions obtained from a micro-GA and the optimal fuzzy logic control rules are shown in Table 1. A number of studies have been performed with the proposed FLC. The performance of the proposed FLC is compared to those from the non-optimal FLC and the conventional lead-lag compensator. To demonstrate the capability of the proposed FLC in enhancing the system damping over a wide range of operating conditions, three following cases for transmitted power flowing between two areas are considered: (1) Case A (base load): P = 388 MW, (2) Case B (heavy load): P = 551 MW, and (3) Case C (light load): P = 208 MW. From the simulation results in Fig. 10, these points are clarified:

(1) the performance of the non-optimal FLC and the conventional lead-lag compensator is almost identical because the non-optimal FLC is designed based on the observed signals from the conventional lead-lag compensator.

(2) when the operating condition is changed to the heavy loading condition, the conventional lead-lag compensator cannot stabilize inter-area and local modes. Even if using the non-optimal FLC, the system dynamic behavior can be improved evidently.

(3) after optimizing membership functions and control rules by a micro-GA, the optimal FLC can effectively and robustly enhance the damping of oscillations for three loading conditions.

7. Conclusions

In this paper, a micro-GA has been used for developing an optimal fuzzy logic controller of STATCOM. The physical model of STATCOM by Modelica language as an extended version of ObjectStab library has been developed. The proposed technique for designing a FLC helps us save time when compared to those from conventional trial and error design procedures. Another benefit of this approach is that it does not require experts for the design of FLC. A number of studies have been performed with the proposed FLC to test the effectiveness and robustness. Finally, the simulation results show that the proposed FLC is effective, efficient and robust over a wide range of operating conditions.

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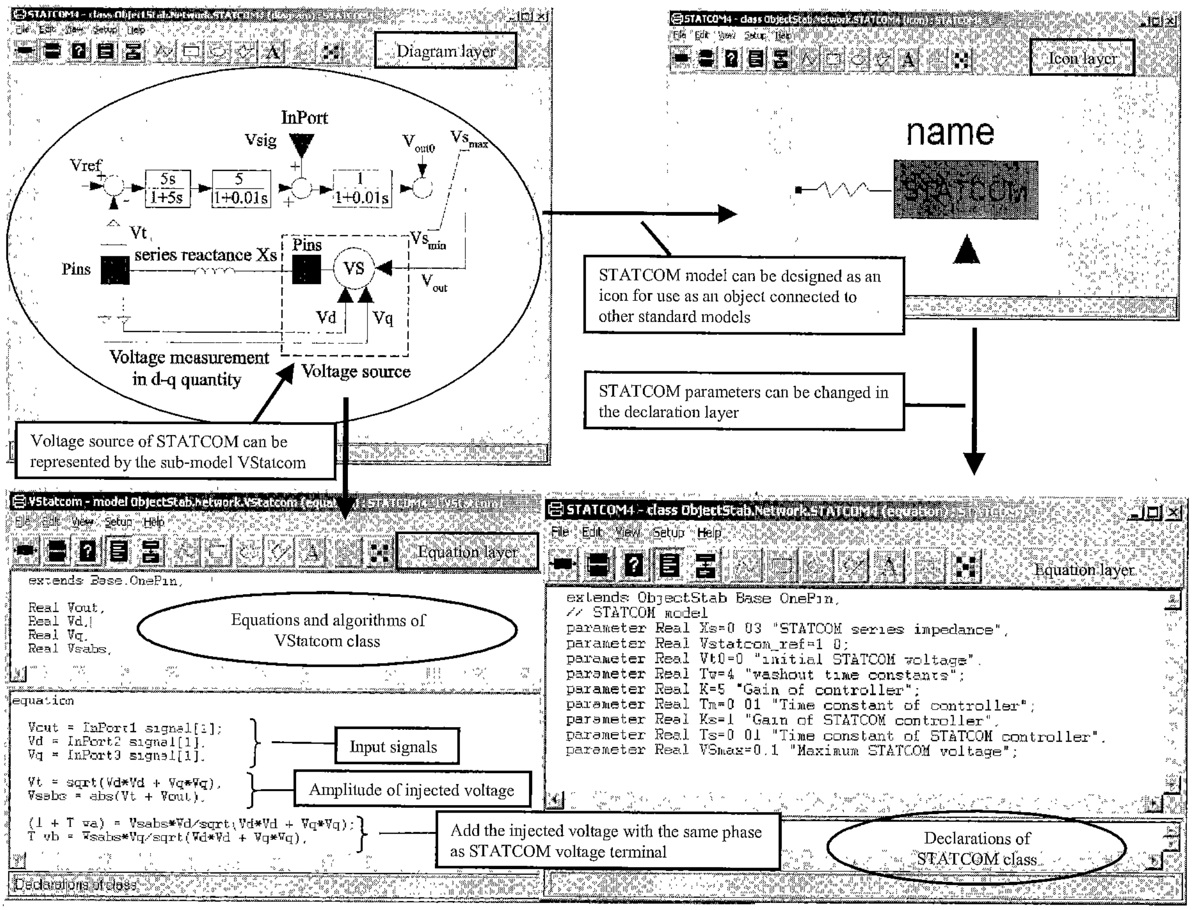
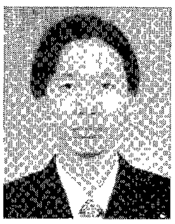
Appendix

The detailed code of the STATCOM model developed by the authors is shown in app. Fig. 1.



app. Fig. 1. The STATCOM model is modeled in Dymola environment by use of standard model components in ObjectStab, i.e. a model of series reactor and Pins connectors, and other model components in Dymola standard library, i.e. transfer function block diagrams, voltage measurement blocks and a limiter. The STATCOM model consists of three important layers; diagram layer, icon layer and equation layer



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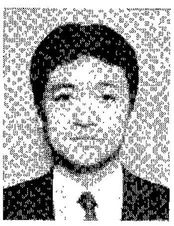

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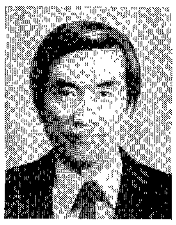

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