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Modified Takagi-Sugeno Fuzzy Logic Based Controllers for a Static Compensator in a Multimachine Power System

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Abstract- **Takagi-Sugeno (TS) based fuzzy logic controllers have been designed for controlling a STATCOM in a multimachine power system. Such controllers do not need any prior knowledge of the plant to be controlled and can efficiently control a STATCOM during different disturbances in the network. Two different approaches for the TS fuzzy logic controller are proposed: a conventional TS fuzzy logic design and a modified TS fuzzy logic design based on shrinking span membership functions. Simulation results, along with a comparison of the conventional TS fuzzy logic controller performance with that of the proposed controller are presented.**

Keywords- Takagi-Sugeno fuzzy logic controller; shrinking span fuzzy membership functions; Static Compensator; multimachine power system.

I. INTRODUCTION

Static Compensators (STATCOMs) are power electronic based shunt Flexible AC Transmission System (FACTS) devices which can control the line voltage at the point of connection to the electric power network. Regulating the reactive power injected to the network and the active power drawn from it by this device, provides control over the ac line voltage and the DC bus voltage inside the device respectively [1]. A power system containing generators and FACTS devices is a nonlinear system. It is also a non-stationary system since the power network configuration changes continuously as lines and loads are switched on and off.

In recent years most of the papers have suggested methods for designing STATCOM controllers using linear control techniques, in which the system equations are linearized at a specific operating point and based on the linearized model, PI controllers are tuned at that point in order to have the best possible performance [2]-[4].

The drawback of such PI controllers is that their parameters are mostly tuned based on a trial and error approach. Moreover, their performance degrades as the system operating conditions change. Nonlinear adaptive controllers on the other hand can give good control capability over a wide range of operating conditions, but they have a more sophisticated structure and are more difficult to implement compared to linear controllers. In addition, they need a mathematical model of the system to be controlled [5]-[7].

Fuzzy logic controllers offer solutions to this problem. They are nonlinear controllers and need no prior plant information. Moreover, they can provide efficient control over a wide range of system operating conditions. Conventional fuzzy logic controllers have been widely applied in power systems [8]-[11].

This paper designs a conventional and two modified Takagi-Sugeno fuzzy logic based controllers for a STATCOM connected to a multimachine power system, using Shrinking Span Membership Functions (SSMF) [12] and backpropagation (steepest descent) training method [18],[13]. Simulation results are provided to compare the performance of both the conventional and the modified TS fuzzy controllers with that of the conventional PI controller.

II. STATCOM IN A MULTIMACHINE POWER SYSTEM

Figure 1 shows a STATCOM connected to a multimachine power system. The system is a 10 bus, 500 kV, 5000 MVA power network and is simulated in the PSCAD environment. The generators are modeled together with their automatic voltage regulator (AVR), exciter, governor and turbine dynamics taken into account. Detailed parameters of the network can be found in [14].

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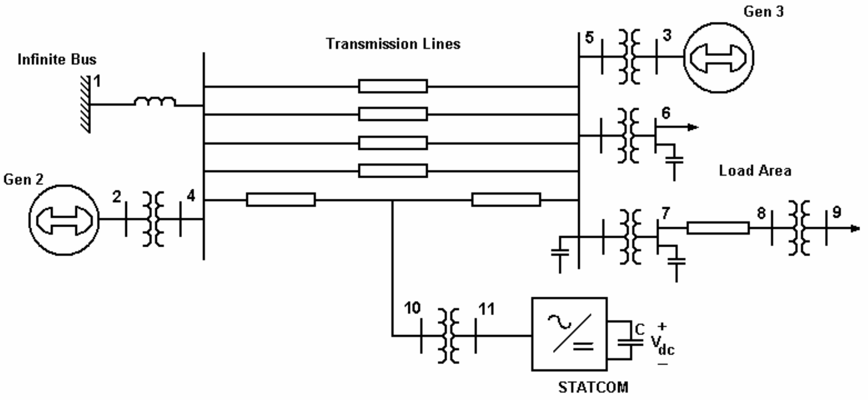

Fig 1. STATCOM in the multimachine system

The STATCOM is first controlled using a conventional PI controller as described in [2]. D-axis and Q-axis voltage deviations are derived from the difference between actual and reference values of the power network line voltage and the DC bus voltage (inside the STATCOM) respectively, and are then passed through two PI controllers (Fig. 2). Those values in turn determine the modulation index and inverter output phase shift applied to the PWM module. Controlling the voltage *V* at the point of connection to the network is the main objective of the STATCOM considered in this paper.

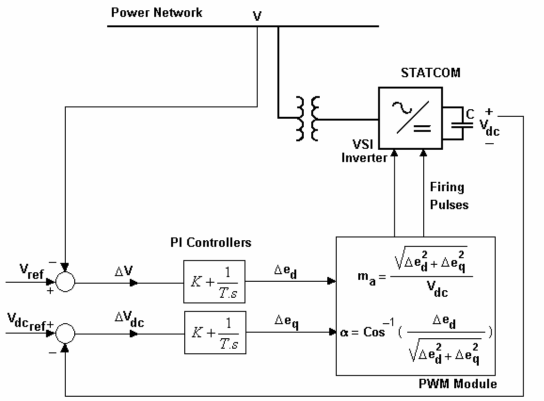

Fig 2. STATCOM internal control structure

Parameters of the STATCOM PI controllers are tuned at one specific operating point, so that the controller provides satisfactory and stable performance when the system is exposed to small changes in reference values as well as large disturbances such as a three phase short circuit on the power network.

III. FUZZY LOGIC CONTROLLERS

Analytical approaches have traditionally been used for modeling and control of power networks. However, these mathematical models/equations are achieved under certain restrictive assumptions, such as linearizing a nonlinear system, or approximating a low order model for a higher order system. Even in such conditions the solution is not necessarily trivial, and sometimes uncertainties associated with real life problems further exacerbate the reliability of such approaches.

Fuzzy logic is a tool that can compensate for the above problems, since it is the only technique that can deal with imprecise, vague or fuzzy information [15]. Fuzzy logic controllers consist of a set of linguistic control rules based on fuzzy implications and the rule of inference. By providing an algorithm, they convert the linguistic control strategy based on expert knowledge into an automatic control strategy [16].

In contrast to the mathematical models or other expert systems, fuzzy logic controllers allow the representation of imprecise human knowledge in a logical way, with approximate terms and values, rather than forcing the use of precise statements and exact values; thus making them more robust, more compact and simpler [17].

Also, as opposed to most neural network based controllers, in most of the cases fuzzy logic controllers do not need a model of the plant to be controlled.

Fuzzy logic systems provide a nonlinear mapping from a set of crisp inputs to a set of crisp outputs, using both intuition and mathematics. In order to do that, each fuzzy logic system is associated with a set of rules, which heuristically define the dynamics of the plant to be controlled. For instance in a multi-input single output fuzzy system:

Rule j: **If** u_1 is F_1^j, ..., and **If** u_n is F_n^j, **Then** y is G^j.

Using different fuzzifiers such as *Singleton*, *Gaussian* and *Triangular* fuzzifiers, any set of crisp inputs is mapped to a fuzzy set. Various rules in the rule base are applied to the fuzzy input data, in order to create a fuzzy output. This output is in turn defuzzified to generate a crisp output value. A defuzzifier is a mapping that, given a fuzzy set, determines the best crisp representative of that set. *Maximum*, *Center of Gravity* and *Centroid* are the most popular defuzzifiers applied to fuzzy logic systems. Triangular fuzzifiers and the centroid defuzzifier are used in this paper as the mapping techniques.

Two distinct fuzzy logic methods for designing controllers are the Mamdani method and the Takagi-Sugeno method [16],[18]. Some of the advantages of both methods are as follows:

Mamdani Method:
- Is intuitive,
- Has widespread acceptance,
- Is well suited to human input.

Takagi-Sugeno Method:
- Is computationally efficient,
- Works well with linear, adaptive and optimization techniques,
- Has guaranteed continuity of the output surface,
- Is well suited to mathematical analysis.

In short, the Mamdani method is the better option for static systems (with slow changing dynamics) and the Takagi-Sugeno method is more efficient for dynamic systems (with fast changing dynamics). Due to the above mentioned issues and the fact that a STATCOM (or any other FACTS device) in a power system goes through fast changes in terms of system parameters and dynamics, the latter method is selected for designing the STATCOM fuzzy logic controller in this paper.

IV. STATCOM FUZZY LOGIC CONTROLLER

A. Conventional Takagi-Sugeno Controller

Fuzzy variables are as $\Delta \mathrm{V}, \Delta \mathrm{V}_{\mathrm{dc}}, \Delta e_d, \Delta e_q$, and fuzzy sets with linguistic characteristics of *negative big*, *negative small*, *zero*, *positive small* and *positive big* are assigned to each variable and equal-span triangular functions have been selected as the fuzzy membership functions (Fig. 3).

Both inputs of the fuzzy controllers have the same membership function description as in Fig. 3, however the subintervals x_i's are heuristically selected based on the characteristics of each control loop in order to provide the best damping/stabilization performance. A Takagi-Sugeno (TS) type fuzzy rule base is been assigned for each combination of input/output variable [16]. As an example for the line voltage loop:

Rule *1*: **If** ΔV is *negative big*, **Then** Δe_d is $f_1(\Delta V)$,
Rule *2*: **If** ΔV is *negative small*, **Then** Δe_d is $f_2(\Delta V)$,
Rule *3*: **If** ΔV is *zero*, **Then** Δe_d is $f_3(\Delta V)$,
Rule *4*: **If** ΔV is *positive small*, **Then** Δe_d is $f_4(\Delta V)$,
Rule *5*: **If** ΔV is *positive big*, **Then** Δe_d is $f_5(\Delta V)$.

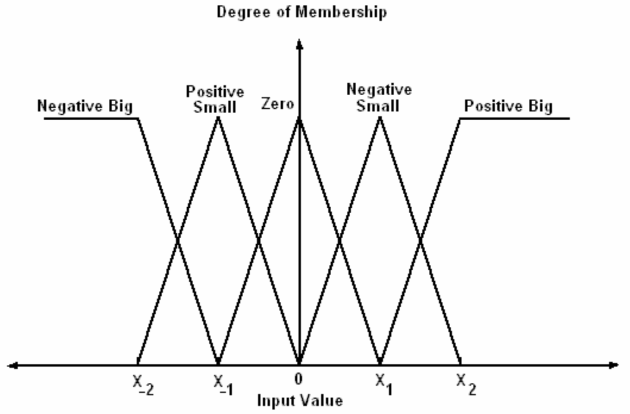

Fig 3. Membership functions of the input fuzzy sets

Where the f_i's are typical linear functions whose coefficients are selected in a way that provides optimal performance. Using the most popular centroid defuzzifier, the final control output is given by (1):

$$\Delta e_d = \frac{\sum_{i=1}^{5} w_i . f_i(\Delta V)}{\sum_{i=1}^{5} w_i}, \tag{1}$$

where the w_i's are the membership values of each rule for a certain value of the input signal ΔV.

The same rule base is used for the second controller (i.e., DC link voltage control).

B. Shrinking Span Membership Function (SSMF) Takagi-Sugeno Controller

There are several different design parameters associated with a fuzzy logic controller, each of which play an important role in the efficiency of the controller. Selecting the proper fuzzy membership functions, subintervals and the defuzzification method, are some of them.

Due to simplicity, most researchers tend to design the input/output fuzzy membership functions using the equal-span triangular functions. However, these functions do not

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necessarily provide the optimum solution for all problems. Instead a prior knowledge of the plant to be controlled, and its dynamics, might lead to different standard or non-standard fuzzy membership functions with various physical shapes in order to design a more efficient fuzzy logic controller.

Moreover, when the control response is closer to the system set point, it can be intuitively seen that the fuzzy membership functions for that specific linguistic term should have narrower spans [19], in order to be provide smoother result with less oscillations.

Shrinking span membership functions (SSMFs) are proposed in order to compensate for the above problems[12]. This method creates triangular membership functions with shrinking spans (Fig. 4), in a way that the controller generates large and fast control actions when the system output is far from the set point and makes moderate and slow changes when it is near the set point. [12]

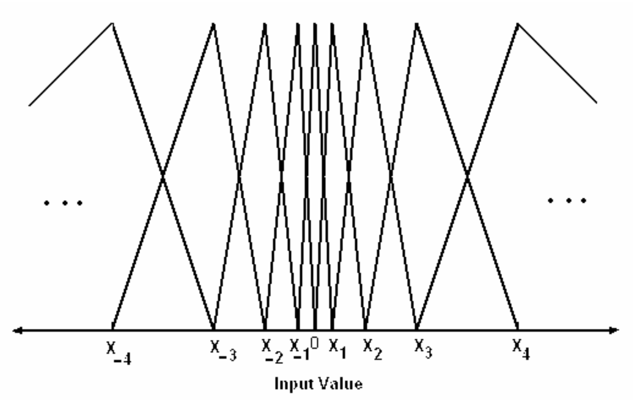

Fig 4. Shrinking span membership functions

The details of designing a SSMF fuzzy controller in a general case (multiple input multiple output systems) is rigorously described in [12]. Nevertheless, it is briefly revisited here for this specific problem (single input single output system).

Different triangular functions for the input variable can be expressed as in (2):

$$F_i = \Delta(x; x_{i-1}, x_i, x_{i+1}), \quad \text{for } i = -m, \ldots, m \tag{2}$$

where m is the index for the input set, resulting in $2m+1$ linguistic terms for that input variable x. In this work, the parameter m is selected to be 5, therefore 11 shrinking span membership functions are assigned to the input variable.

The function Δ is a triangular function defined as in equation (3):

$$\Delta(x; a, b, c) = \begin{cases} \dfrac{x-a}{c-a} & if \quad x < a \\ \dfrac{d-x}{d-c} & if \quad a \le x < c \\ 0 \quad otherwise & \end{cases} \tag{3}$$

and the subintervals x_i's are derived as following:

$$x_i = \frac{i}{m} \times s^{m-|i|}, \tag{4}$$

where $s \in [0,1]$ is the shrinking factor for the input variable x. By applying different shrinking spans to an input variable, different results are achieved. A typical shrinking span of *0.7* is selected for this work.

It should be noted that with the mathematical definition of the membership functions in (2) and (4), the universe of discourse is limited to [-1,1], however this can easily be changed by introducing a scaling factor.

Using a similar approach, membership functions can be defined for the output variable [12], although in the Takagi-Sugeno method, linear functions are applied as a mapping tool between the input and the output.

C. Adaptive Takagi-Sugeno Controller

Both the conventional and SSMF fuzzy logic controllers proposed above, have time invariant membership functions and output mappings between input and output, in other words all the design parameters, remain constant throughout the control performance.

However in a more realistic approach, especially in a control process with fast changing dynamics, an adaptive design will result in a more efficient and a more robust performance.

In an adaptive fuzzy logic controller, the membership functions and the linear mappings can be a function of time. Several training techniques have been proposed in the literature in order to update the fuzzy controller parameters [18],[13]. The backpropagation method is selected for this specific control problem.

In this approach, an error function is defined and the fuzzy controller parameters are trained in a way that the error function is minimized. Line voltage deviation at the middle of the transmission line, i.e., ΔV , is assumed as the error function.

A conventional Takagi-Sugeno fuzzy controller is selected as explained in section A. The coefficients of the input-output mapping linear functions (equation (1)) are assumed to be the time variant parameters of the controller. It should be noted that the subintervals of the fuzzy membership functions (Fig. 3) can be trained and updated as well. However due to the simple structure of the controller in this work, these parameters are considered to be constant and only the mapping functions coefficients undergo training. All the coefficients are updated in a direction that minimizes ΔV .

V. SIMULATION RESULTS

In order to evaluate the performance of different controllers, a *150* ms three phase short circuit is applied to the system at the middle of the transmission line, where the STATCOM is connected. Simulation results for the different controllers appear in Fig. 5.

Figure 5 shows that the fuzzy controllers are more successful than the PI controller in damping the line voltage swings at the point of connecting the STATCOM. This is because the PI controller has been fine tuned at only one operating point, while a severe fault like a three phase short circuit changes the operating condition of the network drastically.

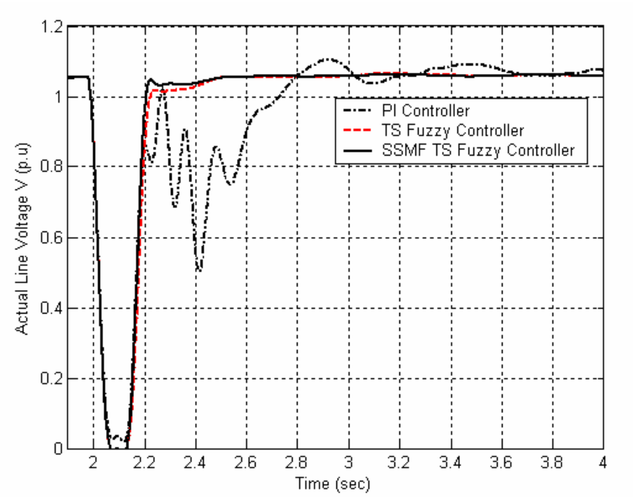

Fig 5. Line voltage during a 150 ms three phase short circuit at the middle of the transmission line.

Although the modified Takagi-Sugeno method works more efficiently, due to the rather simple structure of the controller and straightforward rule base, the conventional Takagi-Sugeno controller works almost equally effective. Even changing the number of membership functions or the shrinking factor does not make a significant difference in the performance of the SSMF fuzzy controller. Figures 6 and 7 show some of the typical waveforms of the generators.

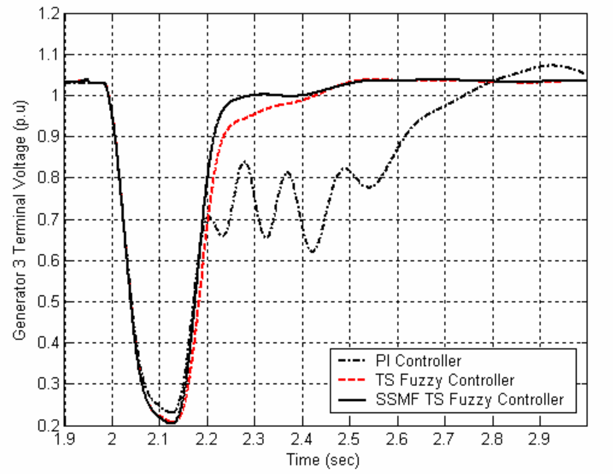

Fig 6. Generator 3 terminal voltage during the fault

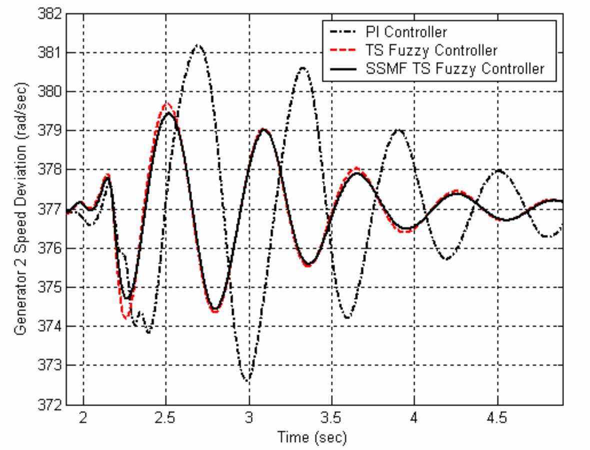

Fig 7. Generator 3 speed deviations during the fault

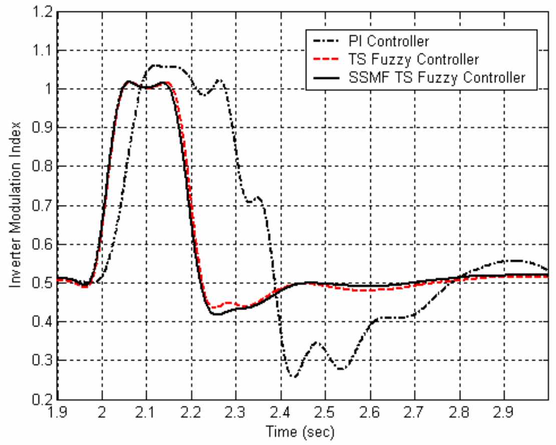

Fig 8. Inverter modulation index during the fault

The controllers can also be compared in terms of the control action generated by each one. The modulation index applied to the STATCOM inverter is a measure of control action and it is clear from Fig. 8 that the fuzzy controllers are faster in sending the appropriate control signal, which in turn means less control action provided.

VI. CONCLUSION

Different Takagi-Sugeno based fuzzy logic designs are proposed for a STATCOM connected to a multimachine power system: a conventional design, a SSMF design and an adaptive controller using the backpropagation (steepest descent) method. The first two controllers are simulated and the results show better and faster damping compared to that of the conventional PI controller.

SSMF fuzzy controllers can adapt to almost all problems with different natures and prove to be more effective than the conventional approach, especially when there is not enough information available on the dynamics and behavior of the plant to be controlled.

Even though both conventional and SSMF fuzzy controllers designed and simulated in this work, tend to rely on the fuzzy inference and reasoning, they still slightly depend on the nature of the plant. In other words, a better knowledge of the dynamics of the STATCOM in this specific power system will lead to a better tuning of the controller, which in turn produces better results at different operating conditions and under various faults applied to the system.

A solution to this problem can be an adaptive fuzzy controller whose design parameters start from an initial set, but can be updated and trained based on the real time performance of the controller. Such a controller will further eliminate the dependency of the design on the expert knowledge on the system and its dynamics.

Simulations are carried out by the authors in order to implement the adaptive Takagi-Sugeno fuzzy logic controller using the backpropagation method. Further results will be provided in the follow up papers.

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