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Abstract — **A Mamdani based fuzzy logic controller is designed and implemented for controlling a STATCOM, which is connected to a 10 bus multimachine power system. Such a controller does not need any prior knowledge of the plant to be controlled and can efficiently provide control signals for the STATCOM during different disturbances in the network. The proposed controller is implemented using the M67 DSP board and is interfaced to the multimachine power system simulated on a Real-Time Digital Simulator (RTDS). Experimental results are provided, showing that the proposed controller provides more effective damping than the conventional PI controller in a typical large scale disturbance, i.e., a three phase short circuit.**

***Keywords-** Mamdani fuzzy logic controller; Static Compensator; Multimachine power system; Real time digital simulator; DSP implementation.*

I. Introduction

Static Compensators (STATCOMs) are power electronics 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 reactive power injected into the network and the active power drawn from it by this device, provides control over the line voltage as well as the DC bus voltage inside the device respectively [1]. A power system containing generators and FACTS devices is a highly 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 in order to have the best possible performance [2]-[4]. The drawback of such PI controllers is that 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. Moreover, most of these designs require a mathematical model of the plant to be controlled [5]-[7].

Fuzzy logic controllers offer solutions to the above problems. They are able to deal with such a nonlinear plant, with no need for prior information, and can provide efficient control over a wide range of system operating conditions. In earlier papers, the authors simulated fuzzy logic based controllers for a STATCOM in a multimachine power system and showed that the proposed controllers are more efficient than the conventional PI controller in damping transient and dynamic disturbances in the network [8],[9].

This paper deals with hardware implementation of a Mamdani fuzzy logic based controller for a STATCOM connected to a multimachine power system. The fuzzy controller is implemented using the M67 DSP card and is interfaced with the power system which is implemented on a Real-Time Digital Simulator (RTDS). The performance of the fuzzy controller is compared with that of the conventional PI controller for different disturbances.

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 system [10] and is simulated in the RSCAD environment. The generators are modeled together with their automatic voltage regulator (AVR), exciter, governor and turbine dynamics taken into account.

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 the actual and reference values of the power network line voltage and the DC link voltage (inside the STATCOM) respectively, and are then passed through two PI controllers (Fig. 2), their outputs (Δe_d and Δe_q) in turn determine the modulation index and inverter output phase shift applied to the PWM module:

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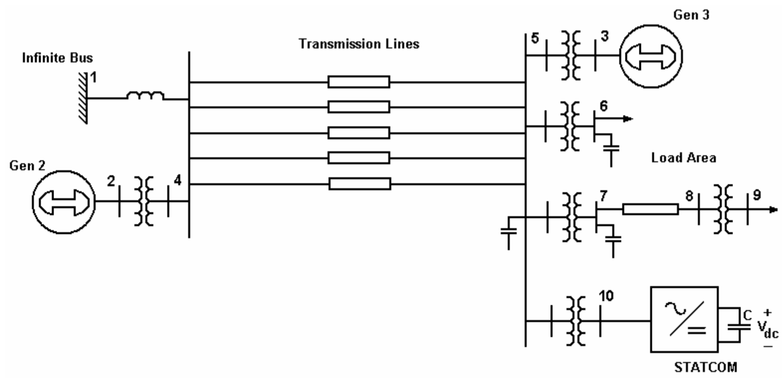

Figure 1. STATCOM connected to a multimachine power system.

$$m_a = \frac{\sqrt{\Delta e_d^2 + \Delta e_q^2}}{V_{dc}},$$

$$\alpha = Cos^{-1}\left(\frac{\Delta e_d}{\sqrt{\Delta e_d^2 + \Delta e_q^2}}\right). \quad (1)$$

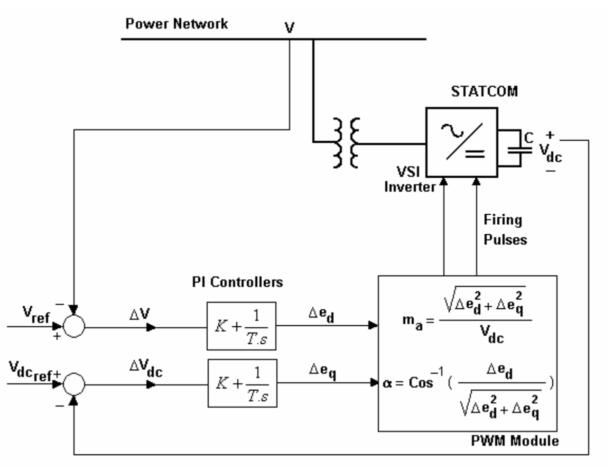

Figure 2. STATCOM internal controller.

Controlling the voltage at the point of connection to the network is the main objective of this STATCOM. Parameters of the STATCOM's two conventional PI controllers are derived (at a specific operating point) so that the controller provides a 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 CONTROLLER

Analytical approaches have always 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 and/or approximating a higher order system by a low order model. Even under such conditions the solution will not necessarily be trivial, and sometimes uncertainties associated with real life problems further exacerbate the reliability of such approaches.

Fuzzy logic, like neural networks, is a tool that can compensate for the above problems, since it is a technique that deals with imprecise, vague or "fuzzy" information. 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 [11].

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 [12]. Also, as opposed to most neural network based controllers, in most of the cases fuzzy logic controllers do not need an identified 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. (2)

Using different standard or non-standard 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.

A. Fuzzy Controller Structure

The fuzzy controller designed in this study, replaces the line voltage PI controller of the STATCOM. The second PI controller in Fig. 2 (DC link voltage) is not replaced by a fuzzy logic controller. The PI controller is able to maintain the capacitor voltage within defined limits and unlike the power network, the STATCOM topology does not change.

The fuzzy controller has two inputs, the line voltage deviation $\Delta V(t)$ and the change in the line voltage error $\Delta E(t)$, i.e. $\Delta V(t) - \Delta V(t-1)$. Using $\Delta E(t)$ helps the controller to respond faster and more accurately to disturbances in the system. In turn the controller generates a control signal to the plant, i.e. Δe_d. Figure 3 shows the schematic diagram of the proposed fuzzy controller.

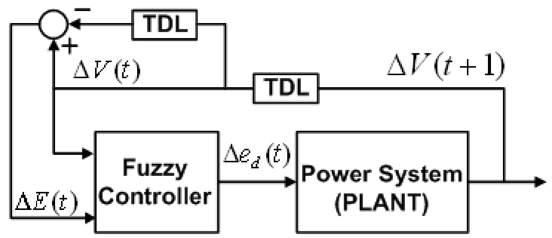

Figure 3. Fuzzy controller structure for line voltage deviation control.

B. *Shrinking Span Membership Functions*

Seven linguistic characteristics are defined for each input/output variable; namely, negative big, negative medium, negative small, zero, positive small, positive medium and positive big.

Due to simplicity, most researchers tend to design the input/output fuzzy membership sets using the standard equal-span mathematical functions, such as triangular or Gaussian functions. However, these functions do not 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 [13]. 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, in order to be able to provide smoother results with less oscillations.

Shrinking span membership functions (SSMFs) are used in this study in order to compensate for the above problems [14]. This method creates 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. SSMFs were used in the authors' earlier work in [8] for designing a Takagi-Sugeno fuzzy logic controller and the results proved to be more efficient than the conventional membership functions.

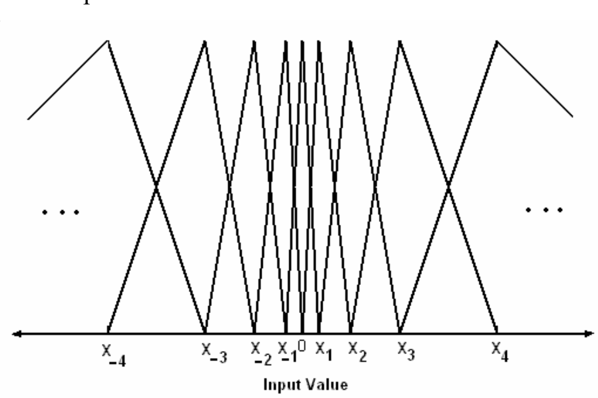

Figure 4. Shrinking span membership functions.

The details of designing a SSMF fuzzy controller in a general case (multiple input multiple output systems) is rigorously described in [14]. Nevertheless, it is briefly revisited here for this specific problem (multiple-input-single-output system).

Different triangular functions for each input variable can be expressed as in (3):

$$F_i = \Delta(x; x_{i-1}, x_i, x_{i+1}), \text{ for } i = -m,...,m. \quad (3)$$

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 *3*, therefore *7* shrinking span membership functions are assigned to each input variable.

The function Δ is a triangular function defined as in equation (4):

$$\Delta(x;a,b,c) = \begin{cases} \frac{x-a}{c-a} & if \quad x < a \\ \frac{d-x}{d-c} & if \quad a \le x < c \\ 0 & otherwise \end{cases} \quad (4)$$

and the subintervals x_i's are derived as following:

$$x_i = \frac{i}{m} \times s^{m-|i|}, \quad (5)$$

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 factor of *0.7* is selected for this work.

C. *Fuzzy Rule Base*

The following rule base for selecting the output of the fuzzy controller is used in this paper.

TABLE I. FUZZY RULE BASE

ΔE \ ΔV	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	NS	Z
NS	NB	NB	NM	NS	NS	Z	Z
Z	NB	NM	NS	Z	PS	PM	PB
PS	Z	Z	PS	PS	PM	PB	PB
PM	Z	PS	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

D. *Mamdani Inference System*

A zero order Sugeno fuzzy model is used for the inference system, which is a special case of the Mamdani fuzzy inference system. In this approach each rule's consequent is specified by a fuzzy singleton. The output of such a model is a smooth function of its input variables as long as the neighboring membership functions have enough overlap [15]. This is ensured using the shrinking span membership functions.

Using the Mamdani inference mechanism, the output of the controller can be written as follows:

$$u(t) = \frac{\sum_{i=-m}^{m} w_i . \beta_j}{\sum_{i=-m}^{m} w_i}, \qquad (6)$$

where w_i and β_i are the rule firing strength and the consequent parameters respectively.

IV. Hardware Implementation

The proposed controller is implemented and evaluated in a laboratory setup (Fig. 5) which consists of a real-time power system simulator and a fuzzy logic controller board.

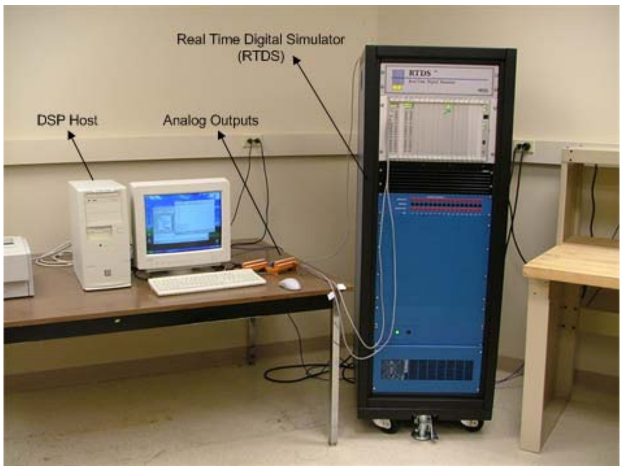

Figure 5. Laboratory setup.

A. *Real Time Digital Simulator (RTDS®)*

The RTDS® is a fully digital electromagnetic transients power system simulator that operates in real time. It has a custom parallel processing hardware architecture assembled in modular units called racks. Power system equipment and network designs can be evaluated and accurately tested. Due to the fact that the RTDS® simulator works in continuous, sustained real time, it can solve the power system equations fast enough to continuously produce output conditions that realistically represent conditions in the real network. Because the solution is real time, the simulator can be connected directly to power system control equipment [16].

The RTDS® simulator uses a graphical user interface, the RSCAD software suite, as the user's main interface with the RTDS® hardware. The multimachine power system with the STATCOM in Fig. 1 is modeled on the RTDS® in the RSCAD environment.

B. *Fuzzy Logic Controller*

The Mamdani fuzzy logic controller is implemented on the Innovative Integration M67 card [17] based on the TMS320C6701 digital signal processor operating at 160 MHz, hosted on a Pentium III 433 MHz personal computer. The M67 DSP card is equipped with two A4D4 OMNIBUS A/D and D/A conversion modules [18].

Each A4D4 OMNIBUS module provides the target card processor with four channels of high speed 200 kHz 16-bit resolution A/D output conversion per module slot, as well as four channels of high speed 200 kHz 16-bit resolution D/A conversion. Figure 6 shows the block diagram of the laboratory setup.

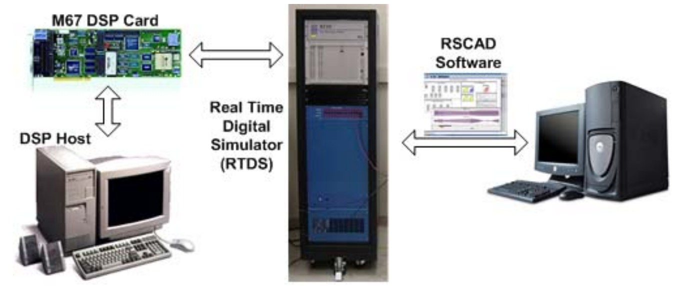

Figure 6. Experimental setup block diagram.

V. EXPERIMENTAL RESULTS

The conventional PI controller is fine tuned at one operating point, so that it can respond to step changes in the reference values with the least overshoot and in the fastest time. Several tests are carried out in order to compare the efficiency of the proposed fuzzy controller with that of the PI controller. Naturally, the performance of the latter degrades by a change in the operating conditions. Various disturbances such as switching on/off a transmission line or a shunt load, or a more severe disturbance, such as a three phase short circuit, can change the operating conditions of the power system.

A. *Case Study 1*

A *100* ms three phase short circuit is applied after 1.3 sec at bus *5* in Fig. 1, where the STATCOM and synchronous generator *3* are connected to. Figures 7-9 compare the performances of the two STATCOM controllers.

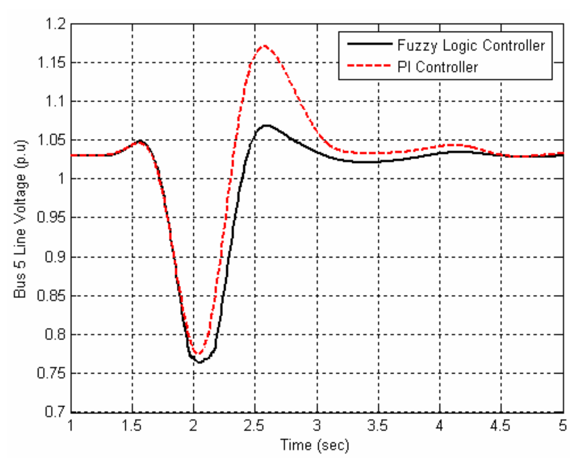

Figure 7. Bus 5 line voltage (Fig. 1) during a 100 ms three phase short circuit.

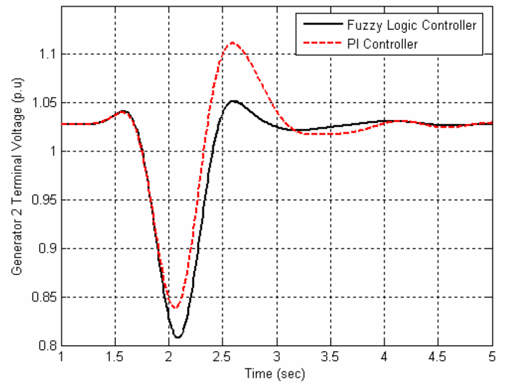

Figure 8. Generator 2 terminal voltage during a 100 ms three phase short circuit at bus 5.

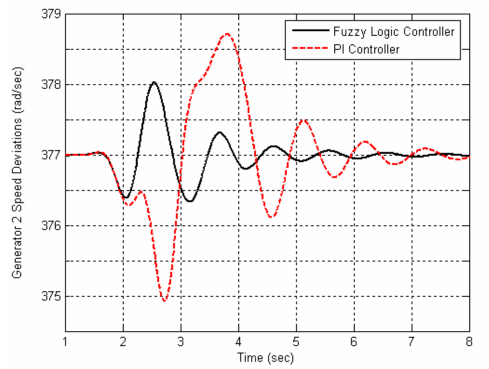

Figure 9. Generator 2 speed deviations during a 100 ms three phase short circuit.

The performance of the two controllers can also be compared in terms of the control effort provided by each one. The reactive power injected during the fault by the STATCOM equipped with each controller in turn, is compared in Fig. 10. These results show that the PI controller injects a considerably larger amount of reactive power into the power system, which in turn means higher currents through the inverter switches. Therefore in the case of the conventional controller, switches with higher current ratings are required.

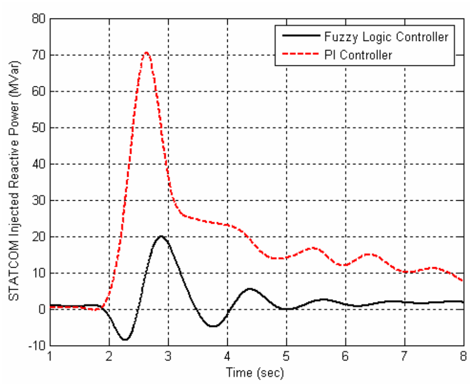

Figure 10. Reactive power injected by the STATCOM during a 100 ms three phase short circuit.

B. Case Study 2

The system is now subjected to a 100 ms three phase short circuit at the load area (bus *8* in Fig. 1). Figures 11-13 compare the performances of the two controllers.

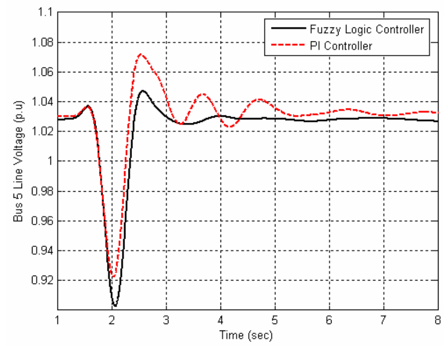

Figure 11. Bus 5 line voltage (Fig. 1) during a 100 ms three phase short circuit at bus 8.

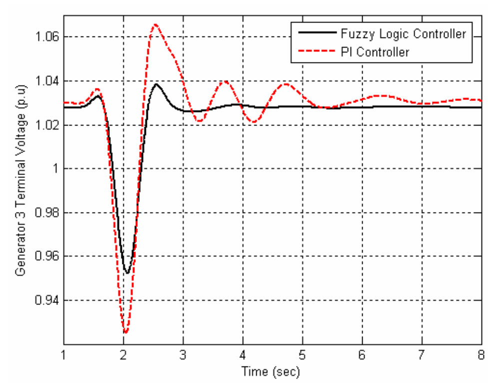

Figure 12. Generator 3 terminal voltage during a 100 ms three phase short circuit at bus 8.

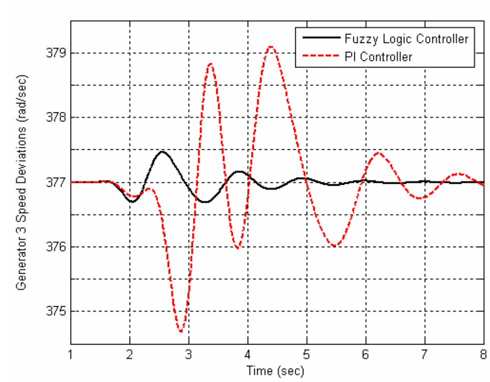

Figure 13. Generator 3 speed deviations during a 100 ms three phase short circuit at bus 8.

The modulation index of the STATCOM inverter in Fig. 14 shows that the conventional controller responds with a much larger change in the modulation index. For cases where the inverter is working close to a modulation index of unity, such a large change might lead to over modulation which in turn results in serious harmonic distortion.

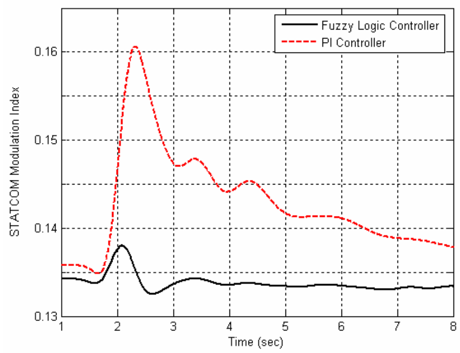

Figure 14. STATCOM inverter modulation index during a 100 ms three phase short circuit at bus 8.

C. Performance Index

The performance of the fuzzy controller depends on the chosen sampling frequency. In order to study the effect of the frequency on the control results, a performance index (P.I.) is defined as:

$$P.I. = 1 \Bigg/ \frac{\sum_{k=1}^{N} (\omega_k - \omega_{Base})^2 + \sum_{k=1}^{N} (V - V_{Base})^2}{N}, \qquad (7)$$

where N is the number of samples obtained.

The performance index is calculated for the fuzzy controller during a *100* ms three phase short circuit at bus *5* in Fig. 1. Only the voltage at bus *5* and the speed of the generator *3* are taken into account, since these are the quantities most affected by the STATCOM performance.

Table II summarizes the results. As expected, by increasing the sampling frequency (on the DSP card) the performance of the controller is improved and the deviations are reduced.

TABLE II. PERFORMANCE INDEX FOR DIFFERENT SAMPLING FREQUENCIES

Sampling Frequency (Hz)	Performance Index
20	0.22
50	0.19
100	0.26
200	0.28
500	0.30

VI. CONCLUSIONS

A Mamdani based fuzzy logic controller is designed and implemented in hardware for controlling a STATCOM, which is connected to a 10 bus multimachine power system. The controller is implemented on a DSP card and is interfaced to the power system, implemented on a Real-Time Digital Simulator (RTDS). Such a controller does not need any prior knowledge of the plant to be controlled, does not depend on the operating condition of the network and can efficiently provide control signals for the STATCOM during different disturbances in the network.

Experimental results are provided, showing that the proposed Mamdani based fuzzy logic controller is more effective than the conventional PI controller in typical large scale disturbances, i.e., a three phase short circuit. The fuzzy logic controller has a better performance with less overshoot during transient faults. Moreover, it provides less control effort for the same fault. This means less reactive power injected which in turn results in smaller currents passing through the STATCOM switches. Thus, the cost of the STATCOM is reduced.

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