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Hardware Implementation of a Mamdani Fuzzy Logic Controller for a Static Compensator in a Multimachine Power System

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***Abstract*—A Mamdani-type fuzzy logic controller is designed and implemented in hardware for controlling a static compensator (STATCOM), which is connected to a ten-bus multimachine power system. Such a controller does not need any mathematical model of the plant to be controlled and can efficiently provide control signals for the STATCOM over a wide range of operating conditions of the power system and during different disturbances. The proposed controller is implemented using the M67 digital signal processor board and is interfaced to the multimachine power system simulated on a real-time digital simulator. Experimental results are provided, showing that the proposed Mamdani fuzzy logic controller provides superior damping compared to the conventional proportional–integral (PI) controller for both small and large scale disturbances. In addition, the proposed controller manages to restore the power system to the steady state conditions with less control effort exerted by the STATCOM, which, in turn, leads to smaller megavar rating and, therefore, less cost for the device. The matrix pencil method analysis of the damping provided by the different controllers indicates that the proposed controller provides higher damping than the PI controller and also mitigates the modes present with the conventional PI control.**

***Index Terms*—Digital signal processor (DSP) implementation, Mamdani fuzzy logic controller, matrix pencil analysis, multimachine power system, real-time digital simulator (RTDS), static compensator (STATCOM).**

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 nonstationary 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, proportional–integral (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 access to the mathematical model of the plant, which, in most cases, is very difficult to obtain [5]–[7].

Fuzzy logic controllers offer solutions to the aforementioned problems. They are able to deal with such a nonlinear plant, with little or no need for prior information, and can provide efficient control over a wide range of system operating conditions. Fuzzy logic controllers have been designed and implemented as power system stabilizers in computer simulations [8]–[10]. Moreover, 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 effective than the conventional PI controller in damping transient and dynamic disturbances in the network [11], [12].

This paper deals with the *hardware implementation* of a Mamdani-type fuzzy logic controller for a STATCOM connected to a multimachine power system. The objective of this paper is to show the effectiveness of employing fuzzy controllers for practical applications in power systems. The validation of the efficiency and superiority of the STATCOM fuzzy controller in a hardware-in-the-loop laboratory setup is demonstrated. This phase is the necessary step and a prerequisite for installing a prototype controller in an actual STATCOM on a power system. The fuzzy controller is implemented on the M67 digital signal processor (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

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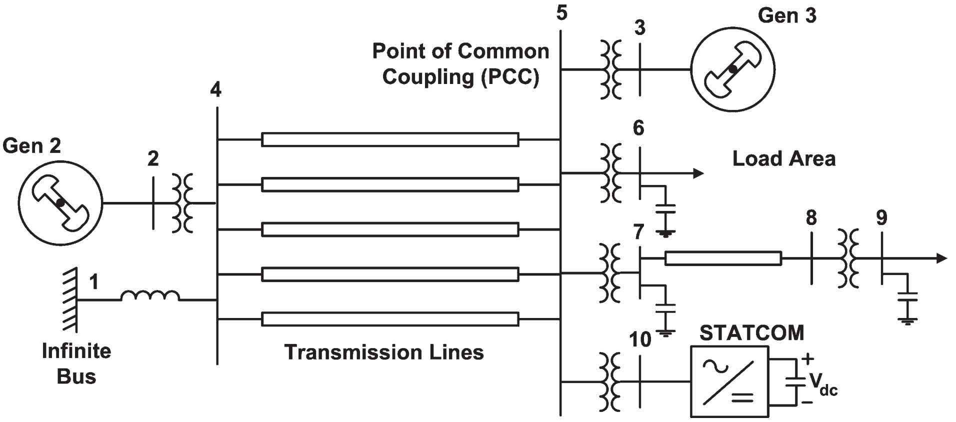

Fig. 1. STATCOM connected to a multimachine power system.

is compared with that of the conventional PI controller for different disturbances. In addition, the matrix-pencil-method-based analysis of the damping provided by the two controllers is presented.

The multimachine power system and the STATCOM studied in this paper are intentionally selected since, together, they portray a nonlinear nonstationary system with unknown parameters and uncertainties associated with it. An intelligent controller, such as the fuzzy controller proposed and implemented in this paper, is not only capable of providing superior control for the STATCOM over a wide range of operating conditions but is also able to reduce the control effort exerted by the device during large scale disturbances, which, in turn, leads to smaller megavar rating and, therefore, less capital investment required for the STATCOM. The aforementioned issues emphasize the fact that intelligent controllers enable the power system to utilize its current capacity in a more effective yet economical way.

The rest of this paper is organized as follows. Some of the key concepts and advantages behind fuzzy control techniques in power systems are discussed in Section II. The details of the multimachine power system and the control structure of the STATCOM are provided in Section III. The structure of the proposed fuzzy controller is presented in Section IV of this paper. Section V discusses the procedure for implementing the fuzzy controller in hardware. The experimental results along with the quantitative analysis of the results are provided in Section VI. Some practical considerations are listed in Section VII. Finally, concluding remarks appear in Section VIII of this paper.

II. FUZZY CONTROL IN POWER SYSTEMS: A REALITY?

This paper primarily addresses the implementation of a fuzzy controller for a power system application. However, as the first step, it is appropriate to discuss in this section why a fuzzy controller would be a desirable solution for real-world applications in power systems.

Analytical approaches have been traditionally used for modeling and controlling power system components. However, these mathematical models/equations are determined 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 aforementioned problems, since it is a technique that deals with imprecise, vague, or “fuzzy” information [13], [14]. 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 [15]. Moreover, as opposed to most neural-network-based controllers, fuzzy logic controllers often do not need an identified model of the plant to be controlled.

Another advantage of fuzzy controllers, which distinguishes them from other intelligent techniques, is their white box approach, where the design engineer can obtain a clear *qualitative* understanding on the relationship between the inputs and outputs of the controller and the impact of the rules and fuzzy set parameters on the overall output of the controller. The aforementioned fact makes fuzzy controllers appropriate alternatives for the traditional PI derivative (PID) controllers, for which electrical engineers and technicians in general have a very clear understanding on the performance and its design parameters. Hence, fuzzy controllers can be viewed as the first step of employing intelligent control techniques for real-world power system applications, and by building the trust, they can pave the way for incorporating more intelligence in power system control.

III. STATCOM IN A MULTIMACHINE POWER SYSTEM

Fig. 1 shows a STATCOM connected to a multimachine power system. The system is a ten-bus 500-kV 5000-MVA system [16] and is simulated in the RSCAD environment [17]. The generators are modeled together with their automatic voltage regulator, exciter, governor, and turbine dynamics taken into account.

The STATCOM is first controlled using a conventional PI controller, as described in [2]. The d- and q-axis voltage deviations are derived from the differences 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 PI_d and PI_q in Fig. 2,

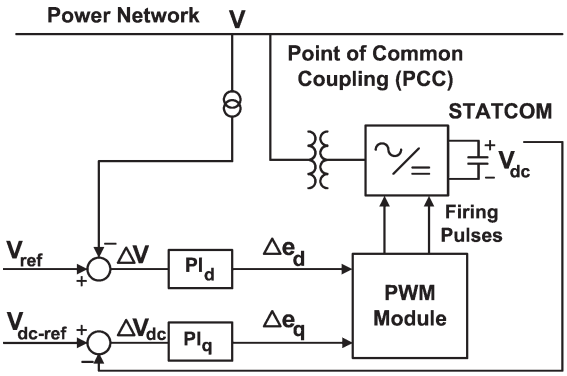

Fig. 2. STATCOM conventional control structure.

whose corresponding outputs are Δe_d and Δe_q. These values, in turn, determine the modulation index and the inverter output phase shift applied to the pulsewidth modulation module

$$m_a = \frac{\sqrt{\Delta e_d^2 + \Delta e_q^2}}{V_{\mathrm{dc}}}$$
$$\alpha = \cos^{-1}\left(\frac{\Delta e_d}{\sqrt{\Delta e_d^2 + \Delta e_q^2}}\right). \quad (1)$$

Controlling the voltage at the point of connection to the network, i.e., point of common coupling (PCC), is the main objective of the STATCOM in this paper. The 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 the reference values, as well as large disturbances such as a three-phase short circuit on the power network. The details of the procedure for fine tuning the PI controllers appear in the Appendix.

IV. STATCOM FUZZY LOGIC CONTROLLER

A. Structure of the Fuzzy Controller

The fuzzy controller designed in this paper replaces the line voltage PI_d controller of the STATCOM. The second PI controller in Fig. 2 (dc link voltage PI_q) is not replaced here. This is due to the fact that this controller is able to maintain the capacitor voltage within the defined limits, and unlike the power network, the STATCOM topology does not change and remains stationary.

The fuzzy controller has two inputs, which are 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 return, the controller generates a command signal $u(t)$ to the plant, which replaces the signal $\Delta e_d(t)$ in Fig. 2. Fig. 3 shows the schematic diagram of the proposed fuzzy controller.

B. SSMFs

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.

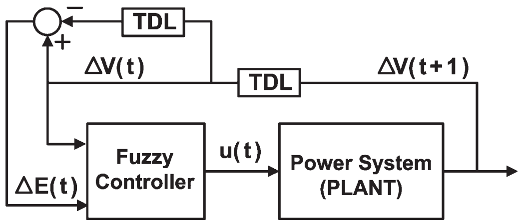

Fig. 3. Fuzzy controller structure for line voltage deviation control.

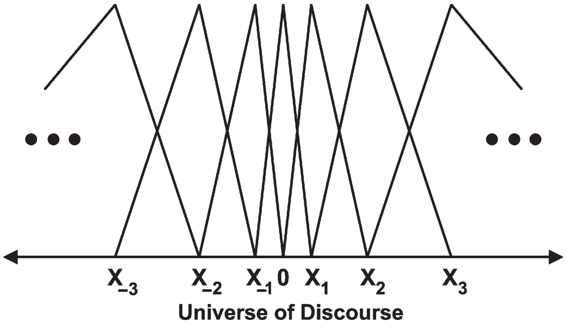

Fig. 4. SSMFs.

Clearly, changing any of the parameters associated with a fuzzy controller can change its performance. However, it has been shown that the membership functions have a dominant effect [20]. Due to simplicity, most researchers tend to design the input/output fuzzy membership sets using the standard equal-span mathematical functions, such as the 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 nonstandard fuzzy membership functions with various physical shapes in order to design a more efficient controller [18]. Moreover, when the system is closer to its set point, it can be intuitively seen that the fuzzy membership functions for those specific linguistic terms should have narrower spans, in order to be able to provide smoother results with less oscillations.

For this purpose, shrinking span membership functions (SSMFs) [21] are used in this paper. 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 state is far from the set point and makes moderate and slow changes when it is near the set point. SSMFs are used in the authors' earlier work in [10] for designing a Takagi–Sugeno fuzzy logic controller, and the results proved to be more efficient than the conventional fuzzy membership functions.

The details of designing an SSMF fuzzy controller in a general case (multiple-input–multiple-output systems) are rigorously described in [21]. 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

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

where m is the index for the input set, resulting in $2m+1$ linguistic terms for that input variable x. In this paper, the

TABLE I
FUZZY RULE BASE

ΔV / ΔE	**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

parameter m is selected to be three; therefore, seven SSMFs are assigned to each input variable.

The function Δ is a triangular function defined as in

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

where $a<b<c$, and the subintervals x_i's are derived as follows:

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

where $s\in[[0,1]]$ is the shrinking factor for the input variable x. Naturally, different shrinking spans lead to different results. After trial and error, a shrinking factor of 0.7 was selected in this paper.

C. Fuzzy Rule Base

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

D. Mamdani Inference System

A zero-order Takagi–Sugeno fuzzy model is used for the inference system, which is a special case of the Mamdani fuzzy inference system [22]. In this approach, each rule's consequent parameter 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 [22]. This is ensured using the SSMFs.

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

$$u(t)=\frac{\sum\limits_{i=-m}^{m} w_i\cdot\beta_j}{\sum\limits_{i=-m}^{m} w_i} \tag{5}$$

where w_i and β_i are the firing strength and the consequent parameter of the ith rule, respectively.

V. HARDWARE IMPLEMENTATION

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

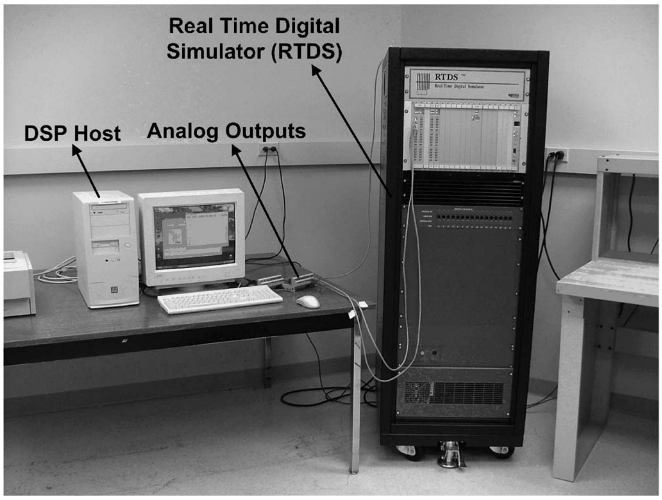

Fig. 5. Laboratory setup. The fuzzy controller is implemented on the DSP board, which sits on the DSP host PC, and is interfaced to the RTDS, where the rest of the power system is modeled.

A. RTDS

The RTDS is a fully digital electromagnetic transient 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 [23].

The RTDS software is divided into two main categories: the graphical user interface and the underlying solution algorithms for network equations and component models. All aspects of simulator operation, from constructing simulation circuits to recording simulation results, are controlled through the graphical interface and the RSCAD software suite as the user's main interface with the RTDS hardware. There are two main RSCAD modules: the Draft and the RunTime. The Draft software module is used for circuit assembly and parameter entry. The RunTime software module is used to control the operation of the RTDS simulator. Through the RunTime module, the user performs actions such as starting and stopping the simulation cases, initiating system disturbances, changing system set points, online monitoring of system quantities, and suchlike.

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 [24] based on the TMS320C6701 DSP 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 [25]. Each A4D4 OMNIBUS module provides the target card processor with four channels of high-speed 200-kHz

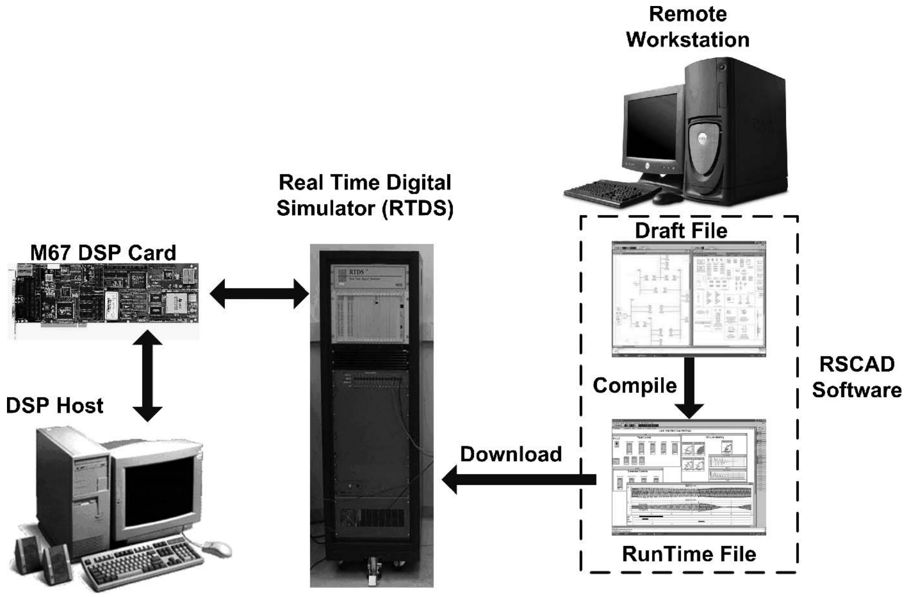

Fig. 6. Experimental setup block diagram.

16-b resolution A/D output conversion per module slot, as well as four channels of high-speed 200-kHz 16-b resolution D/A conversion. Fig. 6 shows the block diagram of the laboratory setup.

For the system studied in this paper, a time step of 50 μs is selected for simulating the multimachine power system on the RTDS, while the sampling frequency for interfacing the fuzzy controller on the DSP board with the rest of the system is assumed to be 50 Hz.

VI. EXPERIMENTAL RESULTS

The conventional PI_d 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. The procedure for tuning the PI controller is explained in more details in the Appendix. Moreover, the PI controllers in this study are equipped with hard limiters so as to limit the control effort generated by each one.

Several tests are carried out in order to compare the efficiency of the proposed fuzzy controller with that of the PI_d 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, thereby affecting the effectiveness of the PI_d controller in providing damping for the system.

A. Case Study 1

A 100-ms temporary three-phase short circuit is applied after 1.3 s at bus 5 in Fig. 1, where the STATCOM and synchronous generator 3 are connected via buses 10 and 3, respectively. Figs. 7 and 8 show the performances of the two STATCOM controllers and show that the fuzzy controller damps out the oscillations faster and with less overshoot.

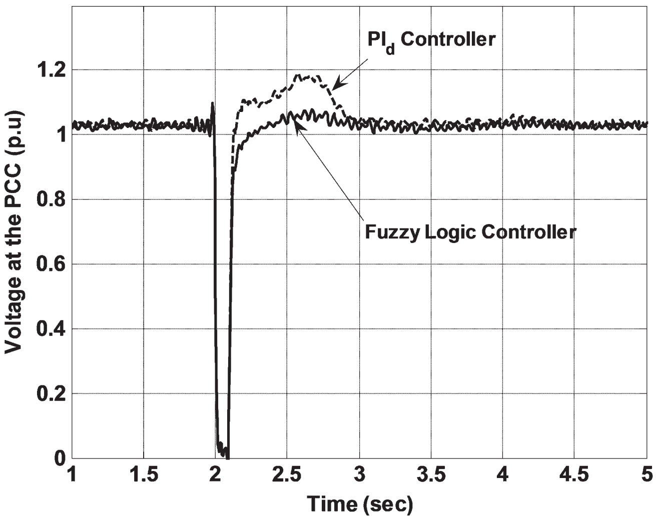

Fig. 7. Bus 5 voltage (Fig. 1) during case study 1.

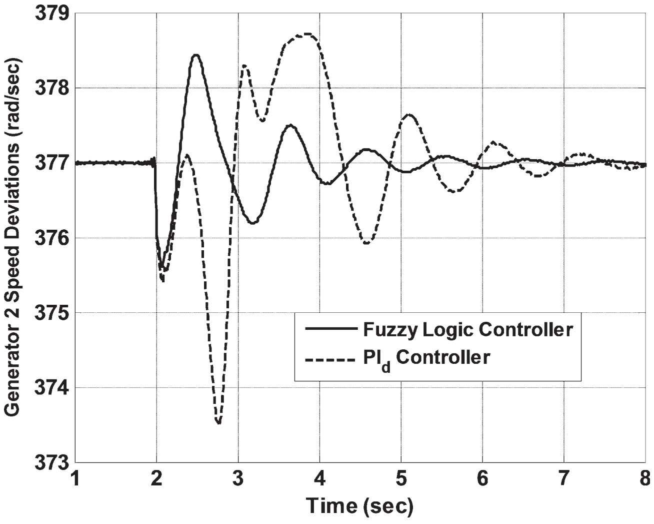

Fig. 8. Generator 2 speed deviations during case study 1.

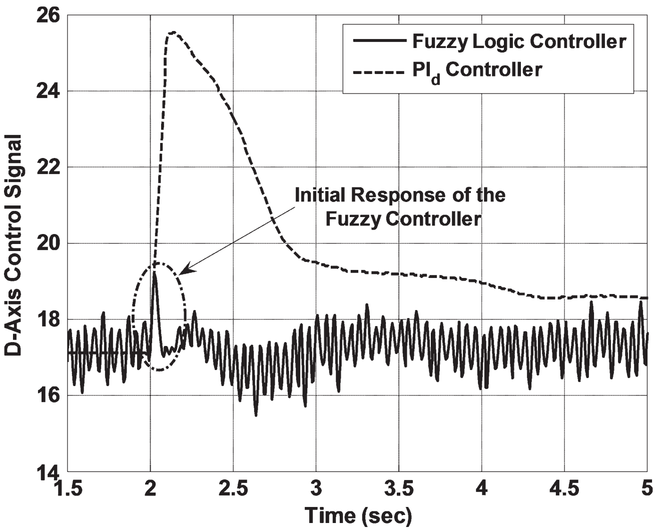

Fig. 9. D-axis control signal during case study 1.

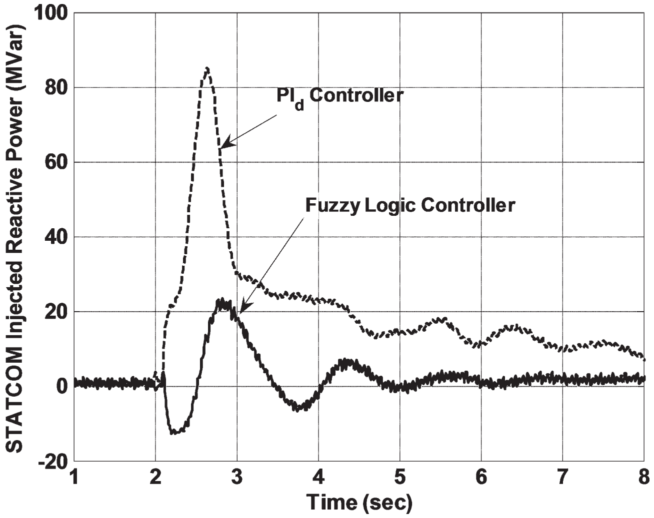

Fig. 10. Reactive power injected by the STATCOM during case study 1.

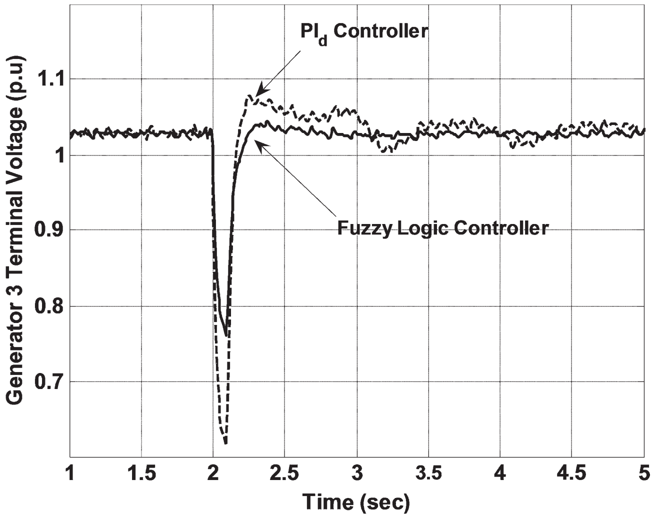

Fig. 11. Generator 3 terminal voltage during case study 2.

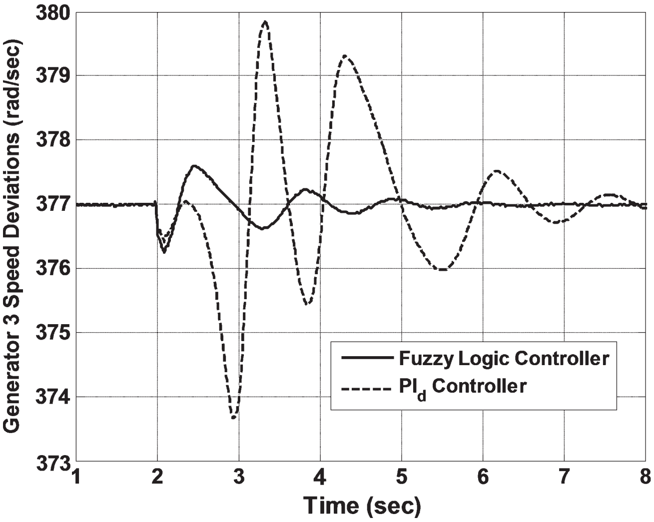

Fig. 12. Generator 3 speed deviations during case study 2.

The performance of the two controllers can also be compared in terms of the control effort provided by each one. The control signal generated by the d-axis controller and the reactive power injected during the fault by the STATCOM equipped with each controller in turn is shown in Figs. 9 and 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. Simulation results indicate that the STATCOM controlled by the fuzzy controller reduces the peak reactive power injection by almost 60 Mvar. Based on a typical conservative price of 50 $/kvar, this reduction results in approximate savings of $4 000 000.

It is also interesting to observe in Fig. 10 that the fuzzy logic controller causes a drop in the reactive power injected by the STATCOM right after the fault occurs. This control action is the exact opposite of the expected response otherwise provided by the PI controller, i.e., a boost in the amount of reactive power injection. However, it helps the power system to restore to the steady state conditions faster and shows the impact of intelligence incorporated into the controller performance by fuzzy logic modeling and reasoning.

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). Figs. 11–13 show the performances of the two controllers and show that the fuzzy controller provides more damping during the short circuit compared to the conventional PI_d controller. This happens since the PI_d controller is fine tuned, assuming a linear model for the system, while in a large-scale disturbance such as a three-phase short circuit, the system is moved away from its steady state operating point and the linear control assumptions no longer provide optimal performance. The results show that the conventional controller responds with a much larger control effort. This is due to the fact that the PI controller is fine tuned at a single operating condition by applying step changes to the power system (see the Appendix). For cases where the inverter is working close to a modulation index of unity, such

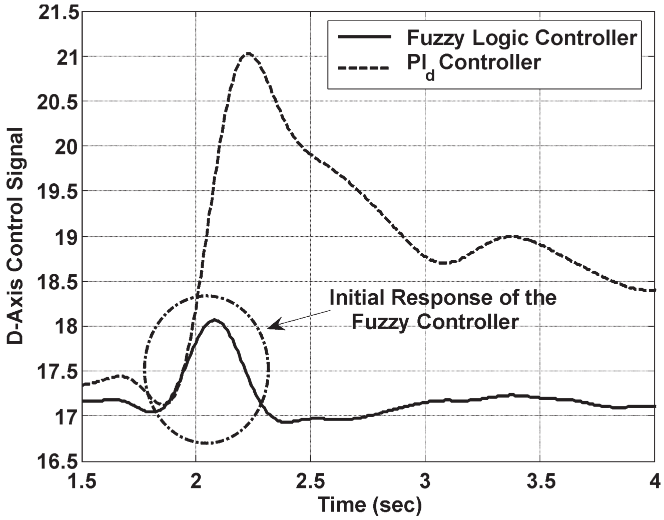

Fig. 13. *d*-axis control signal during case study 2.

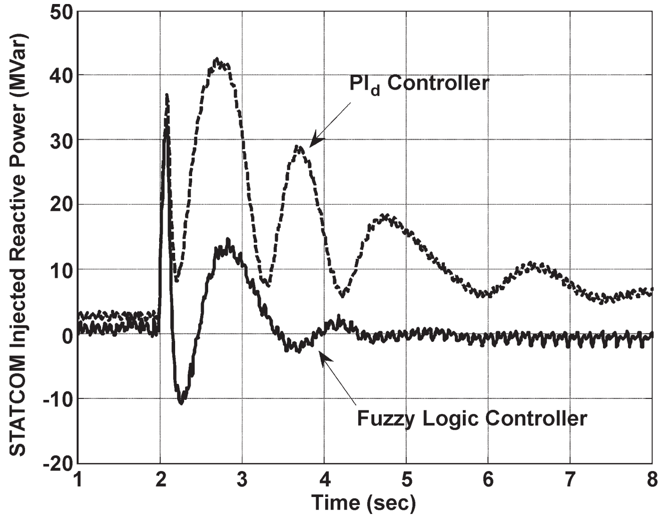

Fig. 14. Reactive power injected by the STATCOM during case study 2.

a large change might lead to overmodulation, which, in turn, results in serious harmonic distortion. This has been shown in simulations in the authors' previous work in [12]. Fig. 14 shows the reactive power injected by the STATCOM, comparing the performances of the two controllers. As expected, the PI_d controller injects a much higher reactive power. Observing the peak-compensated reactive power in cases 1 and 2, about three times less current rating is required when fuzzy logic control is used in comparison to the PI_d control.

The performance of the PI controller can be further improved by adopting an antiwindup mechanism [27]; however, due to the nature of the PI controller that is trained at a single operating point, this improvement is limited and can vary under different operating conditions. For more information and a detailed comparison, the reader is referred to [28].

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

$$P.I. = \left(\frac{\sum_{k=1}^{N} (\omega_k - \omega_{\text{Base}})^2 + \sum_{k=1}^{N} (V_k - V_{\text{Base}})^2}{N} \right)^{-1} \tag{6}$$

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

TABLE III
FREQUENCIES AND DAMPING OF DOMINANT MODES OF GENERATOR NUMBER 2 FOR A 100-ms SHORT CIRCUIT UNDER DIFFERENT CONTROL SCHEMES

PI		FLC	
Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
0.42	26.05	-	-
0.74	8.98	-	-
-	-	0.80	12.30
1.02	5.85	-	-
-	-	1.17	11.27
1.62	6.52	-	-

D. Stability Analysis Using the Matrix Pencil Method

The stability of the closed loop system with the different controllers applied in this paper for STATCOM control has been investigated using the *matrix pencil* method. This analytical tool provides the modes of the system from the impulse response. During a short circuit, the system faces impulsive force, and the postfault time domain response is used to find the modes of the system and, thereby, the oscillation frequencies and damping associated with each mode. This mathematical entity has been applied by many researchers in array processing and spectral estimation [29], [30].

Different fault responses for both case studies are investigated with the matrix pencil method. A comparison between Tables III and IV shows the improvement in damping with the fuzzy logic controller with respect to the PI controller for a 100-ms short circuit. In Tables III and IV, the blank cells under frequency and damping represent the modes which are not visible under that control scheme, which means that the specific mode has been mitigated.

TABLE IV
FREQUENCIES AND DAMPING OF DOMINANT MODES OF GENERATOR NUMBER 3 FOR A 100-ms SHORT CIRCUIT UNDER DIFFERENT CONTROL SCHEMES

PI		FLC	
Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
0.36	20.38	-	-
0.65	7.25	-	-
-	-	0.89	7.23
0.99	15.90	-	-
1.29	13.71	-	-
2.00	4.32	-	-

VII. PRACTICAL CONSIDERATIONS

A. Installment Cost

Implementing a fuzzy controller like the one proposed in this paper requires a larger amount of capital investment compared to a PI controller. However, it should be noted that the installment cost of a DSP-based fuzzy controller for a STATCOM is negligible compared to the capital investment required for the FACTS device itself. Moreover, the fuzzy controller improves the overall performance of the system by reducing the amount of reactive power injected by the STATCOM, which, in turn, reduces the ratings of the inverter switches and, hence, its cost.

B. Design Steps for the Controller

A fuzzy controller such as the one proposed in this paper can be initially designed using expert knowledge and engineering judgment on the dynamics of the power system. Using power system simulators such as the RTDS, its performance can then be validated under actual tests/disturbances, and if necessary, the parameters can be modified. This process is similar to the procedure followed for designing conventional PID controllers in power systems. Once the experimental results are satisfactory, the controller can be commissioned for the actual application. Due to the nature of the fuzzy controller, which, in fact, provides a nonlinear gain scheduling control scheme, a realistically designed fuzzy system is guaranteed to outperform a PID controller.

C. Fixed Versus Evolving Fuzzy Controller

A fuzzy controller outperforms a finely tuned PI controller since, as a nonlinear gain scheduling controller, it can provide robust control over a wide range of operating conditions. However, a fuzzy controller with fixed structure designed based on a human expert might not be able to provide the best performance under all contingencies. The parameters of such a controller can be adaptively evolved offline or online while it is performing in the power system. Clearly, changing any of the parameters associated with a fuzzy controller can change its performance. However, it has been shown that altering the membership functions has a dominant effect [20]. Many researchers have tried to address this issue by applying partitioning techniques for the input and output spaces [13]–[15]. Others have proposed methods to take the uncertainty of the membership function into account [18]. However, it has also been shown in the literature that the connectionist system theory can be applied to adaptively adjust the parameters of a fuzzy controller, including its membership functions, while the controller is operating in the system [22], [31]–[33]. The authors have used approximate dynamic programming to adaptively evolve the parameters of a fuzzy controller for a STATCOM in a multimachine power system and have shown through computer simulations that such a controller outperforms a fuzzy controller with a fixed structure [34], [35]. Using the RTDS, such schemes can be effectively implemented in hardware for real-world applications.

D. Size of the Power System

The design procedure set forth in this paper can be applied to a larger scale power system equally well. Since the STATCOM controller relies solely on local measurements, the design procedure and the controller performance are largely insensitive to the size of the multimachine power system. In an earlier work in [36], Mohagheghi *et al*. have successfully implemented the fuzzy logic controller for a STATCOM in the 45-bus section of the Brazilian power system.

VIII. CONCLUSION

A Mamdani-type fuzzy logic controller has been designed and implemented in hardware for controlling a STATCOM, which is connected to a ten-bus multimachine power system. The controller is implemented on a DSP card and is interfaced to the power system, which is implemented on an RTDS. Such a controller does not need any prior knowledge of the plant to be controlled, does not depend on the operating conditions of the network, and can provide efficient control signals for the STATCOM during different faults/disturbances in the power system.

Experimental results are provided, showing that the proposed Mamdani-type fuzzy logic controller is more effective than the conventional PI controller for small, as well as large scale, disturbances. The fuzzy logic controller has a better performance with less overshoot during transient faults. The matrix pencil analysis of the time domain response under different disturbances shows that the fuzzy controller provides better damping and, in addition, mitigates the modes present in the network when the STATCOM is PI controlled. Moreover, the fuzzy controller requires 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. Clearly, a smaller STATCOM kilovoltampere rating implies less cost.

The main objective of this paper is to show through actual hardware implementation that fuzzy controllers are dependable alternatives for the traditional PI controllers commonly employed in power systems. They are nonlinear gain scheduling controllers that can provide nonlinear robust control over a wide range of operating conditions in the power system. A fuzzy controller can be readily implemented on a DSP board and used for different controllable components in the network, such as the STATCOM. With negligible implementation cost compared to the actual cost of the FACTS device itself, the fuzzy controller enables the power system to utilize its current capacity in a more effective yet economical way.

APPENDIX
TUNING THE PI CONTROLLER

The PI controller is fine tuned at a single operating condition. Step changes are applied to the line voltage reference of the STATCOM in Fig. 2 (with 0.05 per unit magnitude), and the parameters of the PI controller are tweaked by observing the power system response in the time domain. The transfer function used for each PI controller is

$$G(s) = k_P + \frac{k_I}{s}. \tag{7}$$

The algorithm used for tuning the PI controllers is a common industry procedure for large scale nonlinear systems, which is as follows.

Step 1) Reduce the integral gain k_I to zero.

Step 2) Increase the proportional gain k_P in small steps, and repeatedly apply step changes to the power system until the first overshoot is observed in the line voltage at the PCC.

Step 3) Reduce k_P to 50% of its value.

Step 4) Increase k_I in small steps, and repeatedly apply step changes to the power system until the steady state error ΔV in Fig. 2 is zero.

Step 5) Repeat Step 2) until a critically damped response with zero steady sate error is found.

A more detailed analytical design optimization method using pole placement, for example, could also be used, but the power system is nonlinear and nonstationary; therefore, whatever tuning technique is used, it soon degrades as conditions change.

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