

Dynamic Controllers Design for STATCOM

S. A. Al-Mawsawi, M. R. Qader, and G. M. Ali

Abstract—This paper deals with a modern approach of controlling the power flow in AC transmission lines. The control and distribution of power flow in two parallel transmission lines can be implemented by applying one of the flexible AC transmission system (FACTS), which is static compensator (STATCOM) device. The STATCOM device is installed on one line of the two parallel transmission lines to design the controllers for such a system using Electromagnetic Transients Program (EMTP). The closed-loop STATCOM system as a terminal line voltage regulator is designed with two types of controllers, PI with gain scheduling and fuzzy logic. The dynamic performance of the two controllers is tested and compared. It is found that, the fuzzy logic controller forces the system to settle to the steady state value faster than the PI controller with gain scheduling. The fuzzy logic controller is robust; it has a fast response during disturbance and parameters variation. Whereas, the PI controller with gain scheduling has a higher overshoot percentage during transient behavior. Tuning the PI controller with gain scheduling is time consuming and difficult in EMTP, it has a limited range of changing the operating voltage condition due to the tuning difficulty. In the other hand, the fuzzy logic controller can be tuned much faster. Finally, It is claimed that the fuzzy logic controller is a better choice for the STATCOM system compared to the PI controller with gain scheduling.

Index Terms—EMTP, FACTS, STATCOM, PWM, PI controller and Fuzzy logic controller.

I. INTRODUCTION

THE APPLICATION of power electronics, microelectronics, microprocessors and communications in the power distribution and transmission plays an important role to make the system more reliable, more controllable and more efficient [1]. The flexible AC Transmission System (FACTS) becomes an ever increasingly popular solution to our over extended electric power distribution and transmission systems. Because of the flexibility of the system the transmission line can function closer to its thermal limit. The STATCOM is one of the FACTS devices, which can compensate the reactive power in an efficient fast way [2]. It is also called advanced static VAR compensator (STATCOM) [3] or static condenser STATCON [3]. The STATCOM is a shunt FACTS, which consists of a solid-state three-phase source inverter, and it is used as a reactive power compensator. Its power electronic structure is illustrated in Fig. 1 [4].

The STATCOM can either absorb or supply reactive power whose capacitive or inductive output current can be controlled independent of the ac line voltage as indicated in

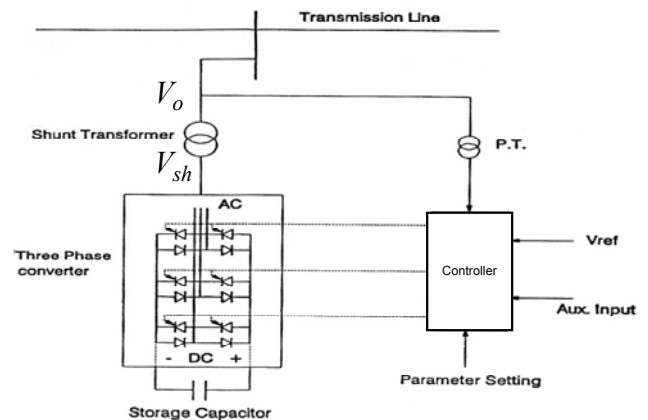


Fig. 1. Basic circuit arrangement of the STATCOM.

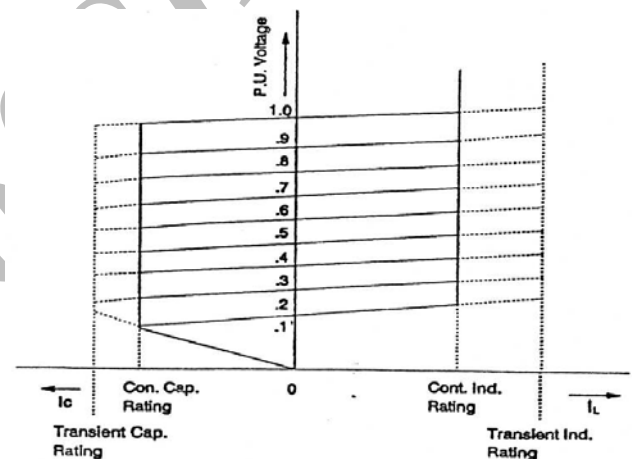


Fig. 2. V-I static characteristics of STATCOM.

the static characteristic in Fig. 2, line voltage versus reactive current.

This paper deals with the design of the dynamic controller for the PWM based STATCOM implemented on parallel transmission lines. The device is connected to one of two parallel transmission lines through a transformer. The design and simulation of the control system is designed and implemented using EMTP program. A system model free controller approach is required to the system, since the model for such a highly non-linear system is difficult to be determined. Moreover, since the STATCOM system operating conditions are varying, the gain of the controller for such a system must be varied to cope with these changes. In this paper two types of controllers are designed and compared:

1. A PI controller with gains scheduling.
2. A fuzzy logic controller.

A. System Model

The single line diagram of the study system on which the STATCOM device is implemented is shown in Fig. 3. A synchronous machine feeds an active power P_1 (40 MW) and reactive power Q_1 to an infinite bus bar via a pair of parallel transmission lines. V_s (66.9 kV) is the

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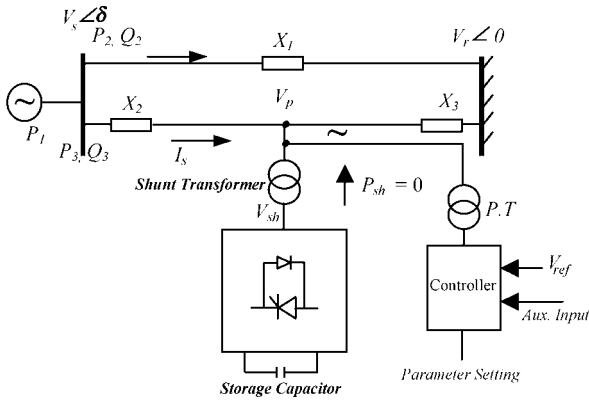


Fig. 3. Single line diagram of the study system and STATCOM.

sending end voltage with load angle d , V_r (65.4 kV) is the receiving end voltage, and X_1 (20 Ω), X_2 (10 Ω), X_3 (10 Ω) are the transmission line impedances, respectively. V_{sh} is the shunt input voltage of converter.

II. PI CONTROLLER WITH GAIN SCHEDULING

The PI controller with a fixed gain is commonly used in industry. The typical equation of the PI controller is

$$y(t) = K_p[e(t) + 1/T_i \int_0^t e(t)dt]. \quad (1)$$

Where K_p is the gain and T_i is the integration time constant, $e(t)$ is the system error and $y(t)$ is the controller output [5].

Since the STATCOM system is controlled by a discrete type controller with the sampling time equal to T_s , the general digital PI controller equation may be written as

$$Y(k) = Y(k-1) + q_0 e(k) + q_1 e(k-1). \quad (2)$$

Hence

$$\begin{aligned} q_0 &= K_p \\ q_1 &= K_p(C_i - 1) \end{aligned} \quad (3)$$

where

$$C_i = T_s/T_i. \quad (4)$$

For a large control deviation $e(k)$, the controlling element is generally driven to saturation and the integral acting term of the control algorithm produces continuously increasing values of the manipulated variable $y(k)$. Therefore, to prevent this, C_i or $e(k-1)$ is usually made equal to zero if $y(k) = y_{\min}$ or $y(k) = y_{\max}$.

In a system such as STATCOM, where the injected voltage V_{sh} is not fixed, V_{sh} has a magnitude varies between $V_{sh\min}$ to $V_{sh\max}$; therefore, it is necessary to design a PI controller so that varying the reference-operating signal changes its parameter gain. This idea is called "gain scheduling", since the scheme was originally used to accommodate changes in process gain only. Gain scheduling is a non-linear feedback of a special form; it has a linear regulator whose parameters are changed as a function of operating conditions in a pre-programmed way [6]. Two tuning rules methods can be used to tune this type of controller based on measured step functions or oscillation test which were proposed by Zielgler and Nichols [6]. In this paper, the oscillation test method was chosen.

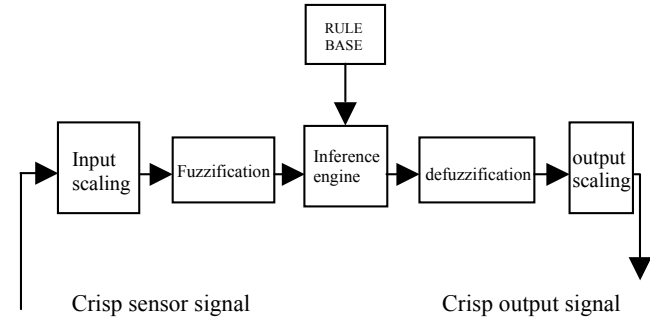


Fig. 4. Block diagram of a fuzzy logic controller.

III. FUZZY LOGIC CONTROLLER

The first paper on fuzzy set wrote by Zadeh [7] on the linguistic approach which is much closer in spirit to human thinking and natural language than the traditional logical systems, it provides an effective means of capturing and approximating the inexact nature of the real world [7]. In a decade after Zadeh's seminal paper on fuzzy sets, many theoretical developments in fuzzy logic took place in Japan, United States and Europe.

More than a decade, fuzzy control has emerged as one of the most active and fruitful areas for the research in the application of fuzzy set theory [7], [8]. Much successful applications in a broad range of areas starting from daily consumer products to aerospace have been developed [9]. Fuzzy sets were first used to solve power systems long-range decision making problems in [10].

When fuzzy logic is used to solve a real problem the following steps should be followed [11]:

1. Describe the original problem. It should be stated mathematically/linguistically.
2. Define the thresholds for the problem variables. For a variable, there is a specific value with the greatest degree of satisfaction evaluated from empirical knowledge and a certain deviation is acceptable with decreasing degree of satisfaction until a value that is completely unacceptable. The two values corresponding to the greatest and least degree of satisfaction are termed thresholds.
3. Proper membership functions are constructed based on the thresholds values. There are different shapes of membership functions such as linear, parabolic, piece-wise linear, trapezoidal, cosinusoidal and so on. The membership functions should reflect the change in the degree of satisfaction with the change in variables evaluated by experts.
4. Select the fuzzy operations. The interpolation of results using fuzzy systems is based on domain experts' reasoning. The most commonly used operations are Mamdani's and Zadeh's.

A. Basic Elements of Fuzzy logic Controller

Fuzzy control systems are rule-based systems in which sets of so-called fuzzy rules represent a linguistic control strategy. The aim of the fuzzy control systems is to replace a skilled operator, expert or experience with a fuzzy rule-based system [12], [13]. The basic elements of a fuzzy logic controller FLC is shown in Fig. 4.

B. Fuzzification

Fuzzification is the process of converting a crisp variable

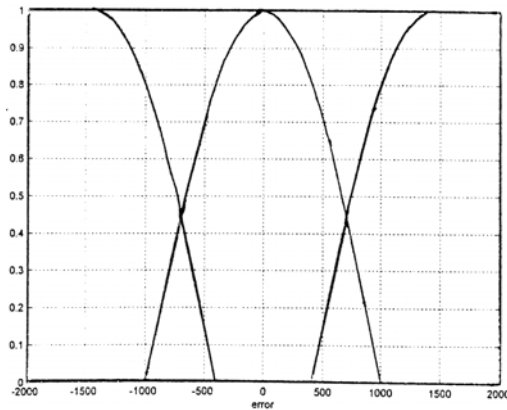


Fig. 5. Fuzzy logic controller membership functions for error.

input into a fuzzy variable. Thus, a crisp input is mapped to a linguistic fuzzy set defined in a certain universe of discourse. In this stage, the crisp inputs are used to determine the degree to which they belong to each of the appropriate fuzzy sets via membership function, the input x is interpreted as a fuzzy set A with membership function $\mu_A(x)$. The error $e(k)$ and the change of error $ce(k) = e(k) - e(k-1)$ are mapped to fuzzy set via membership functions in a certain universe of discourse. There should be an odd number of fuzzy sets to be associated with the variables that is because the error may change its sign. The typical number of fuzzy sets is between three to nine. A greater number of fuzzy sets lead to a much more complex controller with greater computational time.

Each fuzzy set should overlap to a certain degree with its neighbors. This overlap gives a fuzzy controller its smooth and stable surface. The overlap should be between 10% to 50% of the neighboring space and the total sum of any vertical point in the overlap regions must be less than or equal to unity. The grade of membership of fuzzy sets should be highest around the optimal control point of the system and should reduce as the distance increases from the optimal point. The shape of the membership function could be estimated from a histogram of the measured data [10], [14]. For the STATCOM system, it was decided to use three fuzzy sets due to the dimension limitation memory of the EMTP. Figs. 5 and 6 show the fuzzy logic controller membership functions for the error and change of error, respectively. The shape of the membership was chosen to be cosinusoidal because of their simplicity with the measured data histogram and simplicity of expression to be defined in EMTP.

C. Fuzzy Control Rules

The fuzzy control rules is the heart of the fuzzy logic controller where the knowledge base and decision-making logic reside. These rules tie the input fuzzy sets to the output fuzzy sets. These rules are often called fuzzy associative memory (FAM). These rules are defined by using linguistic variables such that *IF* (a set of antecedents are satisfied) *THEN* (a set of consequences can be inferred). Generally, the number of inputs and the number of membership functions determine the number of the system control rules. Consider the STATCOM system where the input variables are error (e) and change of error

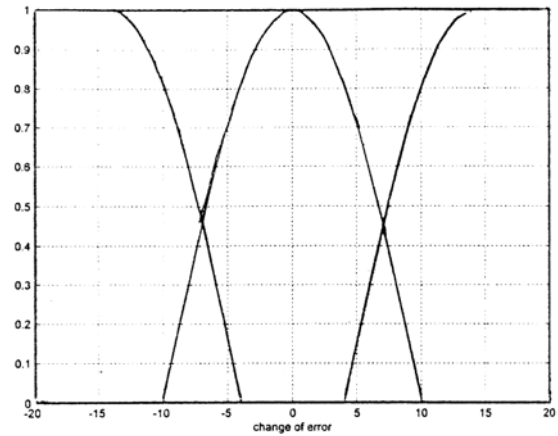


Fig. 6. Fuzzy logic controller membership functions for change of error.

(ce) and each is described by three membership functions Positive Small (PS), Zero (ZE) and Negative Small (NS). This will lead to a number of system control rules $3^2 = 9$. Fuzzy control rules are to be formed based on expert's knowledge, control engineers experience, operators control actions, a fuzzy model of the process or learning.

The fuzzy control rules have the form:

$$R_1: x_1 \text{ is } A_{11} \text{ and } x_2 \text{ is } A_{12} \text{ then } y \text{ is } B_1$$

$$R_2: x_1 \text{ is } A_{21} \text{ and } x_2 \text{ is } A_{22} \text{ then } y \text{ is } B_2$$

$$R_3: x_1 \text{ is } A_{31} \text{ and } x_2 \text{ is } A_{32} \text{ then } y \text{ is } B_3$$

$$R_n: x_1 \text{ is } A_{n1} \text{ and } x_2 \text{ is } A_{n2} \text{ then } y \text{ is } B_n$$

where x_1 , x_2 and y are linguistic variables two process state variables and one control output variable representing; A_{ij} , B_j , are linguistic labels of the linguistic variables x_1 , x_2 and y in the universe of discourse with $i = 1, 2, 3, \dots, n$ and $j = 1, 2$. In the STATCOM system, *IF* error (e) is NS and change in error (ce) is $CEZE$ *THEN* change in output is -35 . All the nine rules of FAM are illustrated in Table I.

D. Inference Engine

The inference engine is used to perform the necessary inference operation on all fuzzy rules. It compares the fuzzified values of the controller inputs error (e) and change of error (ce) as specified by the fuzzy rules described in the previous section. It assigns the degree of fulfillment (DOF) of each rule as the minimum of compared fuzzified values. The DOF is used in the defuzzification process.

E. Defuzzification

Simply, defuzzification is the process of mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of nonfuzzy crisp control actions. Actually, it converts the fuzzified output of the inference engine into a crisp value. The center of area (COA), the maximum criterion (MC) and the mean of maximum (MOM) are the commonly used defuzzification strategies. The widely used strategy is the center of area (COA), which generates the center gravity of possibility distribution of a control action with a better steady state performance [8], [11]. The defuzzified change in output may be expressed as:

$$\Delta U_o(k) = \frac{\sum B_i * F_i}{\sum B_i} \quad (5)$$

TABLE I
A TYPICAL SET OF FUZZY CONTROL RULES FOR DEFUZZIFICATION F_i

		Change of error		
		CENS	CEZE	CEPS
Error	ENS	-70	-35	0
	EZE	-35	0	35
	EPS	0	35	70

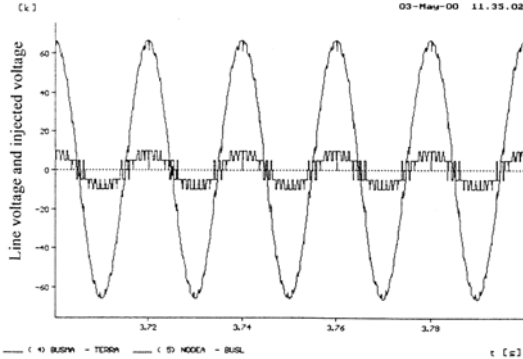


Fig. 7. The transmission line voltage and the injected voltage of fuzzy logic controller in steady state affected by harmonics.

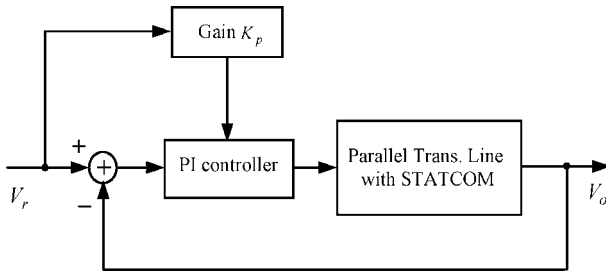


Fig. 8. A block diagram of the system with a PI controller with gain scheduling.

where B_i is the degree of fulfillment of the i -th rule, F_i is the defuzzified value of the output membership function and the summation over all the control rules, refer to Table I. The defuzzified value of the output membership function is the single value that best represents the linguistic description. Typically the abscissa of the membership function's centroid is taken as the defuzzified value [8], [11]. Given the output of the COA operator is $\Delta U_o(k)$, and the output scaling gain is G_f , the input control signal to the plant $U(k)$ can be calculated by:

$$U(k) = G_f * \Delta U_o(k) + U(k-1) \quad (6)$$

where G_f may be selected heuristically or by following the tuning method. Usually, the input membership functions are specified first, followed by their overlap. Second, the rules are formulated and the value of the gain G_f is then chosen. If the specification of input and output fuzzy sets are correct then the required value of the gain G_f would be unity.

IV. CONTROLLER SIMULATION RESULTS

The above two controllers have been simulated and tested in the EMTF program and the dynamic performance of both controllers will be presented. Fig. 7 illustrates the steady state simulation of the terminal voltage and the STATCOM device output voltage. It can be seen that both voltages have been affected by harmonics due to the absence of the filter at the terminal voltage.

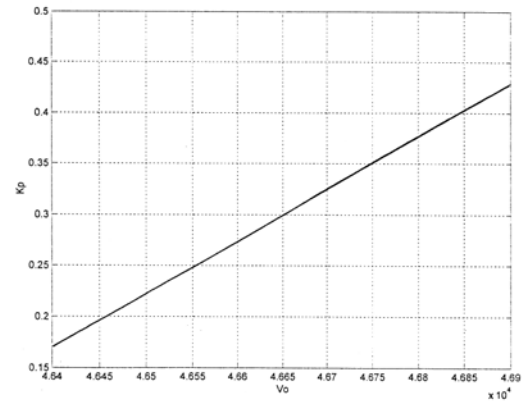


Fig. 9. A curve of the gain K_p of a PI controller with gain scheduling as a function of the reference voltage V_o .

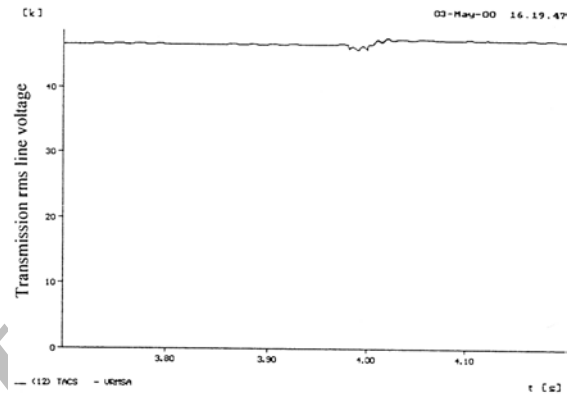


Fig. 10. The transmission line RMS voltage of PI controller in case of terminal voltage disturbance to ground.

A. PI Controller with Gain Scheduling Simulation Results

The procedure described in the above has been used to find the curve fitting for the gain of the controller K_p as a function of the line terminal voltage at which the device is connected as illustrated in Fig. 8. The curve of fitting is actually a straight-line equation as illustrated in Fig. 9 that has been found by using Matlab[®] package program. The mathematical equation of the gain controller as function of V_o which is the terminal line voltage can be written as:

$$K_p = 0.0005186V_o - 23.8927.$$

The simulation results of a typical control strategy of this compensation system gain scheduled PI controller are presented in Figs. 10 and 11. These figures present the simulation results based on sudden terminal voltage to ground disturbances occur at the point of connecting the FACTS device.

B. Fuzzy Logic Controller Simulation Performance Results

The fuzzy logic controller based on cosinusoidal membership functions is designed following the procedure, which has been described above as illustrated in block diagram in Fig. 12. The selected fuzzy membership functions and rules are similar to those shown in Figs. 5 and 6 and Table I.

The simulation results of the fuzzy logic controller for sudden terminal voltage to ground disturbances occur at the point of connecting the STATCOM device are illustrated in Figs. 13 and 14, that is by assuming three phase fault

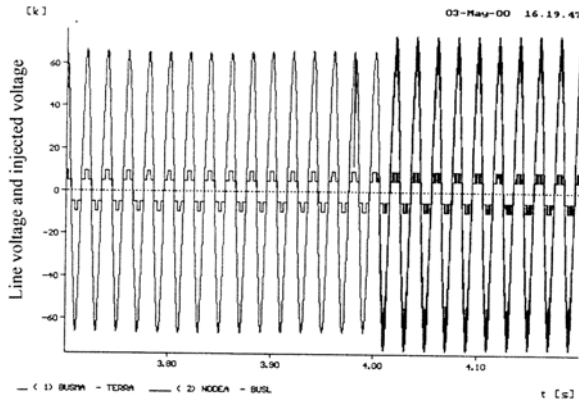


Fig. 11. The transmission line voltage and the injected voltage of PI controller in case of terminal voltage disturbance to ground.

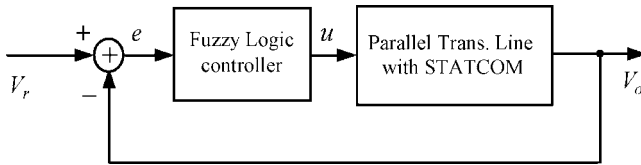


Fig. 12. The transmission line RMS voltage of PI controller in case of terminal voltage disturbance to ground.

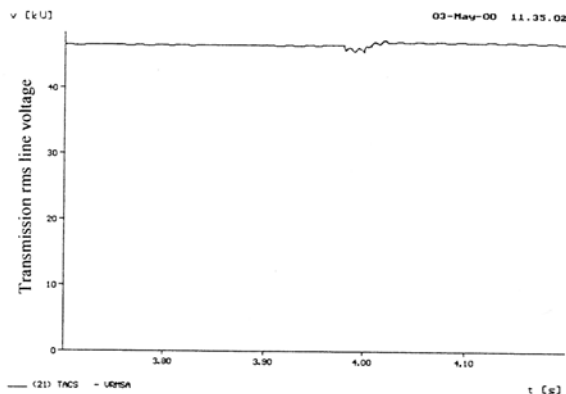


Fig. 13. The transmission line RMS voltage of fuzzy logic controller in case of terminal voltage disturbance to ground.

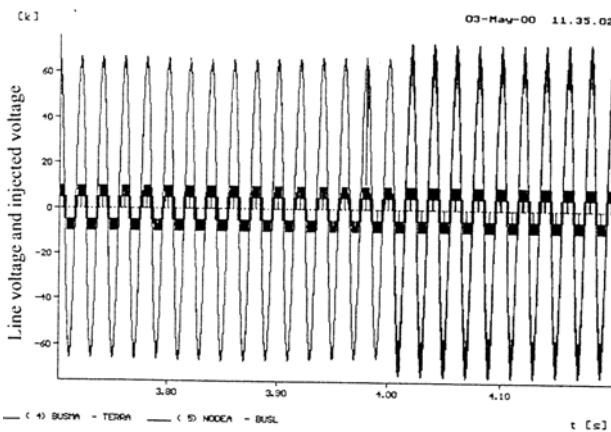


Fig. 14. The transmission line voltage and the injected voltage of fuzzy logic controller in case of terminal voltage disturbance to ground.

between STATCOM bus and ground within one cycle. Furthermore, the simulation results in case of changing the reference voltage 5% and -5% of the setting value are presented in Figs. 15 to 18, respectively.

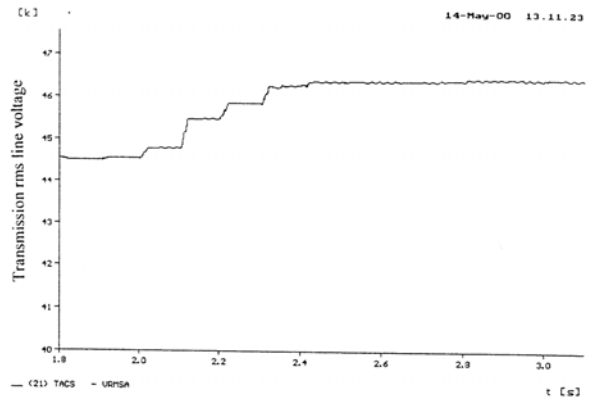


Fig. 15. The transmission line RMS voltage of fuzzy logic controller in case of changing the reference voltage 5%.

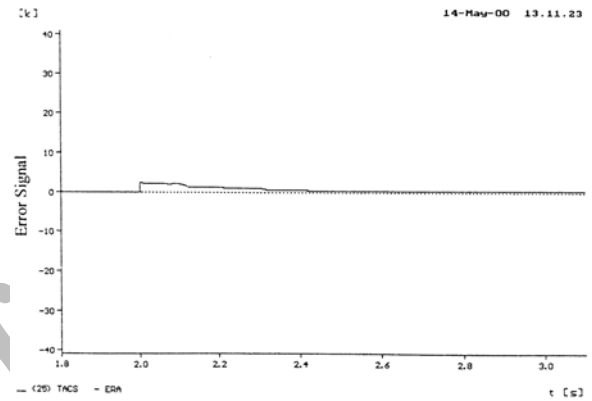


Fig. 16. The error signal of fuzzy logic controller in case of changing the reference voltage 5%.

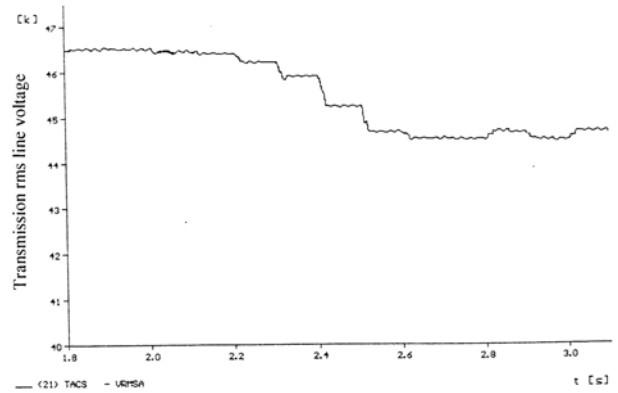


Fig. 17. The transmission line RMS voltage of fuzzy logic controller in case of changing the reference voltage -5%.

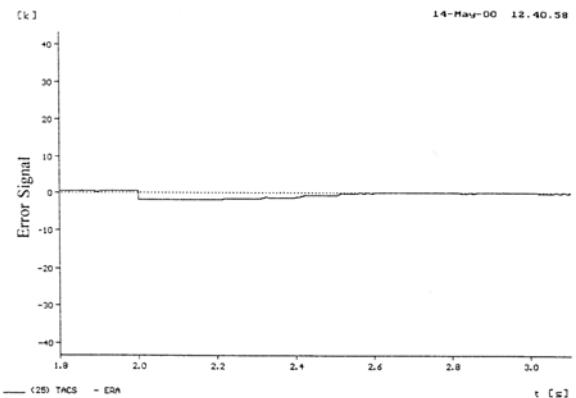


Fig. 18. The error signal of fuzzy logic controller in case of changing the reference voltage -5%.

TABLE II
THE SIMULATION SETTLING TIME RESULTS

The tests	Types of Controllers	
	PI Controller	Fuzzy Logic
Terminal voltage disturbance to ground	0.065 sec	0.027 sec
Transmission line parameters variations	0.04 sec	0.02 sec
Changing voltage operating condition 1%	0.02 sec	0.018 sec
Changing voltage operating condition 5%	—	0.2 sec
Changing voltage operating condition -5%	—	0.3 sec

V. TRANSIENT BEHAVIOR OF THE CONTROLLER

In the transient behavior of the controller, the settling time and the maximum overshoot are considered based on the simulation results obtained and the above two types of controllers are compared.

A. Settling Time

The settle time T_s is defined, as the time required so that the output can stay within 5% of the steady state final value. In the case of sudden terminal voltage is disturbed to ground, it can be seen that the settling time T_s of the fuzzy logic controller is 0.02 second which is half of the PI controller with gain scheduling. In case of changing the transmission line parameter the settling time T_s of the fuzzy logic controller is 0.027 second, which is smaller than that of the PI controller with gain scheduling as indicated in Table II. So, in both tests the fuzzy logic controller forces the system to settle faster to the steady state value rather than PI controller with gain scheduling.

In the case of changing the voltage operating condition 1% the settling time T_s of the fuzzy logic controller is 0.018 second and 0.02 second for of the PI controller with gain scheduling as indicated in Table II. However, for the fuzzy logic controller, when the voltage operating condition of the system is changed within 5% the settle time T_s is 0.2 second. Whereas, in case the voltage operation condition of the system is changed -5 % the $T_s = 0.3$ second.

B. Maximum Overshoot

The maximum overshoot is defined as the largest deviation of the output behavior during transient state. The amount of maximum overshoot is also used as a measure of the relative stability of the system. The maximum overshoot is often represented as a percentage of the steady state final value as follows:

$$\text{percen. max. overshout} = \frac{\text{Maximum overshoot}}{\text{Final value}} * 100\%. \quad (7)$$

High overshoot values may lead to the saturation of some components. In addition, they also lead the system to have higher ratings due to transient. Consequently, overshoot values are not desirable. Table III represents the simulation results of the percentage maximum overshoot values in case of terminal voltage disturbance to ground. It can be recognized that the fuzzy logic controller is more able to reduce the maximum overshoot in the system performance.

TABLE III
THE SIMULATION RESULTS OF THE OVERSHOOT VALUES PERCENTAGE

The Tests	Types of Controllers	
	PI Controller	Fuzzy Logic
Terminal voltage disturbance to ground	1.7%	0.9%

C. Steady State Error

The simulation results in the previous subsections show that PI with gain scheduling and the fuzzy logic controllers are capable to push the steady state error signal value close to zero by maintaining the transmission line voltage close to the reference value. For example, the percentage of steady state error in case of terminal voltage disturbance to ground is 0.64% and 0.85% for the fuzzy logic controller and PI with gain scheduling controller respectively.

D. Tuning the Controller

From the design procedure and simulation results it is clear that tuning the PI with gain scheduling controller is time consuming to determine the controller parameters under different operating conditions. Indeed, the tuning for the PI controller with gain scheduling had been done over a limited range of changing the operating conditions (injected voltage) due to its long time requirement during the tuning. In the other hand, fuzzy logic controller can be tuned easily consuming short time only and it can be controlled over a wide range of operating conditions.

VI. OVERALL PERFORMANCE OF THE CONTROLLERS

The simulation results of the PI with gain scheduling and fuzzy logic controllers reflect that both controllers are capable of controlling the system with the following conclusions:

1. The fuzzy logic controller forces the system to settle to the steady state value faster than the PI controller with gain scheduling.
2. The PI controller with gain scheduling has a higher percentage overshoot during transient behavior rather than the fuzzy logic controller.
3. The fuzzy logic controller is robust; it has a fast response time during disturbances and parameter variations.
4. Tuning the PI controller with gain scheduling is time consuming and difficult. Whereas, the fuzzy logic controller can be tuned much faster.
5. The PI controller with gain scheduling has a limited range of changing the operating voltage condition due to its tuning difficulty.
6. The fuzzy logic controller is a better choice for the ASVC system compared to the PI controller with gain scheduling.

VII. CONCLUSION

The STATCOM has been modeled with two parallel transmission lines using EMTP package. In this case a PWM scheme has been used to control the operation of the inverter of the STATCOM. The closed-loop STATCOM system as a terminal line voltage regulator has been designed with two controllers, PI with gain scheduling and fuzzy logic. The dynamic performance of the two

controllers have been tested and compared by using EMTP program. The fuzzy logic controller forces the system to settle to the steady state value faster than the PI controller with gain scheduling. The fuzzy logic controller is robust, it has a fast response during disturbance and parameters variation. Whereas, the PI controller with gain scheduling has a higher overshoot percentage during transient behavior. Tuning the PI controller with gain scheduling is time consuming and difficult in EMTP, it has a limited range of changing the operating voltage condition due to the tuning difficulty. In the other hand, the fuzzy logic controller can be tuned much faster. Finally, It can be claimed that the fuzzy logic controller is a better choice for the STATCOM system compared to the PI controller with gain scheduling.

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