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Performance Analysis of Two-Generator Three-Bus System using Fuzzy Controlled Shunt FACTS Device

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Abstract
In the power and energy field, electrical power system networks have become more and more complex due to growing demand and shortcomings in the construction of new transmission lines. Hence, the power system stability is one of the major concerns to maintain and regulate the challenges in the power system network. The transient stability of the power system has a significant effect on the power quality. Transient stability regulation played a vital role to secure the stable operation of the power system during the faulty condition. A Flexible AC Transmission System (FACTS) provides an effective solution to enhance power transfer capability which leads to enhance the performance of the power system under faulty conditions. In this article, the Performance Analysis of Two Generator Three Bus power systems for transient stability with Static Synchronous compensator (STATCOM) and Static VAR Compensator (SVC) has been carried out under abnormal conditions. To generate the control signal for the shunt FACTS device, an advanced control technique of Fuzzy Logic Controller (FLC) is implemented with STATCOM and SVC. The proposed technique has been validated and verified through MATLAB/Simulink environment. The result has been compared to conventional PI control STATCOM and SVC with advanced Fuzzy Logic Control. The latter method has shown better results in terms of peak overshoot and settling time.

Keywords: *FACTS, STATCOM, SVC, FLC, Power System Stability.*

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I. INTRODUCTION

Nowadays, the complexity of electrical power systems is increasing due to increased power demands and shortcomings in the construction of new transmission lines. Therefore it is essential to focus on the quality of power transfer. Transmission of power at high voltage confronts several challenges of power system stability. Transient stability regulation is one of the challenges that present-day engineers are overlooked at the time of the transmission of power at high voltage. Transient stability is the conditions that characterize the dynamics of a power system subjected to an abnormal condition such as disturbance on the transmission line, sudden loss of large load, loss of excitation [1], [2]. Due to abnormal condition, power system response to the large increase in the rotor angles of the generator, increase in the power flow, variation in bus voltage, and other system variables [2]. Different methods are available to study the transient stability in power systems under faulty conditions. The two most commonly used methods are the direct method and the time-based Simulation method. These methods have some advantages and some deficiencies. The Direct method is quicker than time-based simulation and it is mainly based on stability analysis of Lyapunov theory. However time-based simulation method is model-based. The model-based simulation method is more realistic until unless model would become more accurate [3]. Model-based simulation needs several measured parameters to analyze the performance of the system and it is the major drawback of this method [4].

A FACTS is the most commonly used technique to improve the Power system stability. FACTS devices are externally connected to the transmission network. Static Synchronous Compensator (STATCOM) and Static VAR Compensator (SVC) are shunt-connected FACTS devices that are used for voltage regulation as well as power system stability improvement by injecting or absorbing reactive power to the network [5]. Different controllers have been used to give control signal to STATCOM and SVC such as conventional PI controller, Energy function-based controller, Rule-based controller [6]–[8].

In this article, the performance analysis of a Two-generator Three-bus power system with STATCOM and SVC is carried out under Faulty conditions using MATLAB/Simulink software. An advanced control technique of Fuzzy Logic Controller is implemented to generate the control signal for STATCOM and SVC.

This article is organized in the following manner i.e. Section-II covers the STATCOM and SVC operation. Section-III describes the advanced control technique of the Fuzzy Logic Controller and its strategy to control STATCOM and SVC for transient stability improvement under faulty conditions. Section-IV represents the proposed modelling of a two-generator three-bus power system with a Fuzzy Control shunt FACTS device. Section-V presents simulation results and discussion. Section-VI covers the conclusion.

II. SHUNT FACTS CONTROLLER

2.1 Static Synchronous Compensator (STATCOM)

Static Synchronous Compensator (STATCOM) is a shunt-connected Flexible AC Transmission device. It controls the flow of power with the help of a power electronic device like IGBT, GTO, etc. STATCOM balances the voltage of the connection terminal of the power system by managing the flow of reactive power so that the transient stability of the system is efficiently regulated. STATCOM operation includes continuous monitoring of system terminal voltage. When system terminal voltage is low, reactive power is generated by STATCOM i.e. STATCOM work in capacitive mode. However, when system terminal voltage is high, reactive power is absorbed by STATCOM i.e. STATCOM work in inductive mode [9]. In STATCOM, Reactive power exchanged is controlled by a Voltage Sourced Converter (VSC) connected on another side of the coupling transformer. STATCOM Control Model is shown in Fig. 1.

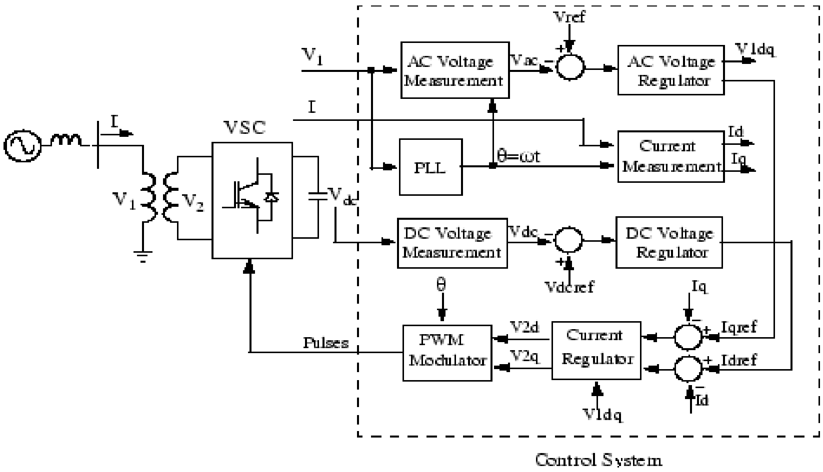

Figure 1 STATCOM Control Model

STATCOM control model is operated in three different modes. Its operation includes the flow of reactive power between a source V1 and V2. In the control model, V1 represents the power system voltage which is to be regulated and V2 represents the VSC voltage. Under the steady-state condition, VSC voltage V2 is in phase with V1 so that no transfer of reactive power takes place. When VSC voltage V2 is lower than V1, reactive power transfers from power system voltage V1 to VSC voltage V2 i.e. STATCOM absorbing the reactive power, and when VSC voltage V2 is higher than V1, reactive power flow from V2 to V1 i.e. STATCOM generating the reactive power [5].

STATCOM control model includes AC and DC voltage and current measurement unit to measure the positive sequence d & q component of voltage (Vd & Vq) and current (Id & Iq). Outer AC and DC voltage regulator provides Iqref and Idref for the current regulator. The current regulator predicts the voltage generated from Iqref and Idref current produced by AC and DC voltage regulator.

2.2 Static VAR Compensator (SVC)

Static VAR Compensator (SVC) is a shunt-connected Flexible AC Transmission device and it controls the flow of power. SVC balances the voltage by managing the flow of the reactive power so that the transient stability of the power system is efficiently regulated. SVC operation includes the continuous monitoring of system terminal voltage. SVC is operated in two modes. In capacitive mode, system terminal voltage is low so that the reactive power is generated by SVC. In Inductive mode, system terminal voltage is high so that the reactive power is absorbed by SVC [9]. In SVC, reactive power variation is controlled by switching inductor and capacitor attached on another side of a coupling transformer. SVC Control Model is shown in Fig. 2.

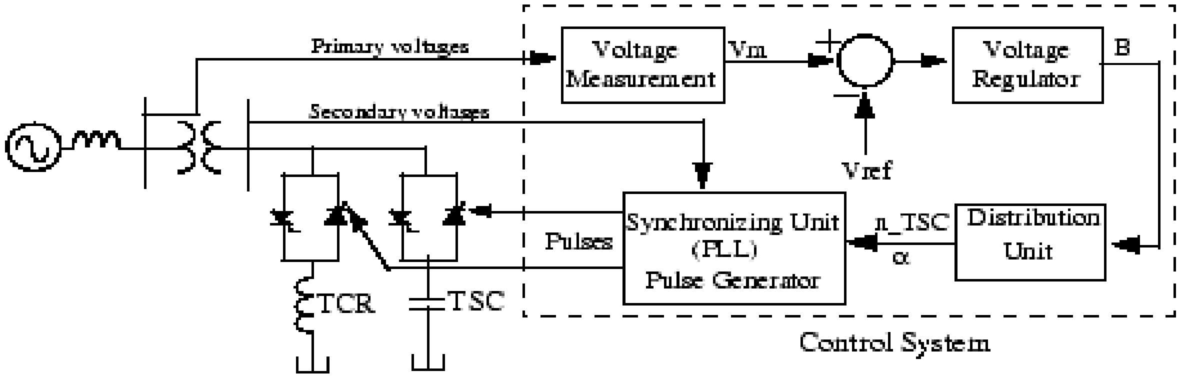

Figure 2 SVC Control Model

In the SVC control model, a voltage measurement unit is used to measure the positive sequence voltage. The measured voltage compared with the reference voltage and error signal is fed to the voltage regulator unit which is used to determine the Susceptance (Beq). A distribution unit determines the switching sequence and accordingly computes the firing angle. The Phase-locked loop synchronized the secondary voltage in the synchronizing unit and the appropriate pulse sends to the thyristor. The equivalent Susceptance (Beq) of SVC is set on the firing angle of the thyristor. When the demand for reactive power at bus continuously changes, Susceptance (Beq) is always changed according to the limits. The SVC absorbs or feeds reactive power to the bus where it is connected by a continuously controlled thyristor.

III. FUZZY LOGIC CONTROLLER

Fuzzy Logic Control is the advanced approach generally used to control the operation of STATCOM and SVC for solving the nonlinear problem in the power system. As Conventional PI Controller with constant parameters does not produce accurate results when there is any change in operating condition. FLC works like a human and it controls the system by self-tunning [10], [11]. The control circuit of the FLC is shown in Fig. 3. FLC includes the following stages.

i. Fuzzifier **-** Converting the crisp value into fuzzy value (Fuzzification)
ii. Fuzzy Knowledge Base **-** Store input-output fuzzy member relationship
iii. Fuzzy Rule Base **-** Store the information about the operation of the process
iv. Inference Engine **-** Simulate the decision by performing the action
v. Defuzzifier **-** Converting the fuzzy value into crisp value (Defuzzification)

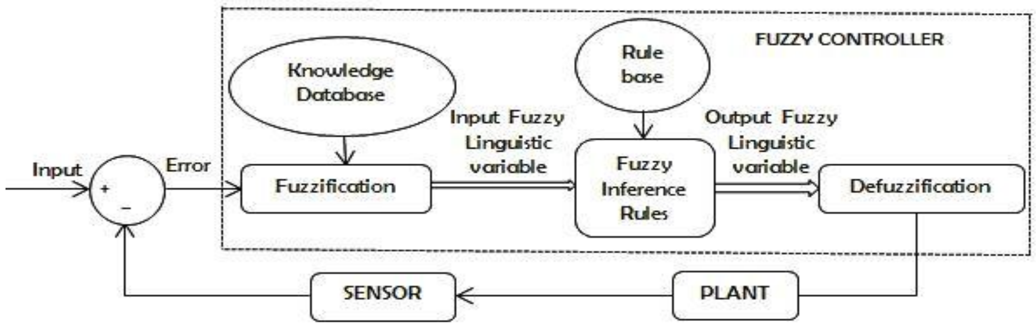

Figure 3 Control Circuit of Fuzzy Logic Controller

3.1 Fuzzy Logic Controller for STATCOM

The fuzzy Logic Controller for STATCOM is designed by using the Mamdani method of the Fuzzy interface. In this method, input is mapped into the Fuzzy domain with the help of the membership function. The inputs taken are generator speed and change in generator speed for FLC and the output is angle Alpha. The inference engine performs the function of infers the control action according to the fuzzy rule base. FLC produces output in a linguistic variable i.e. fuzzy domain. To convert the fuzzy value to crisp value centroid method of defuzzification is used. In this method of Defuzzification, outputs of inference engine translate into crisp value using normalized membership function by control action [10], [12]. Simulink Model of Fuzzy Logic Controller for STATCOM is shown in Fig. 4.

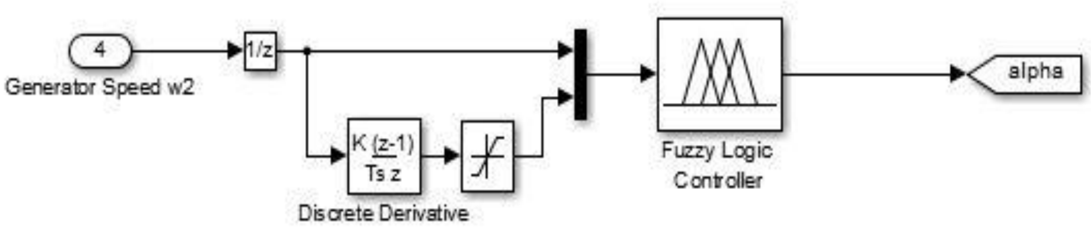

Figure 4 Simulink Model of FLC in STATCOM

3.2 Fuzzy Logic Controller for SVC

The Fuzzy Logic Controller for SVC is designed by using the Mamdani method of the Fuzzy interface. In this method, input is mapped into the fuzzy domain with the help of the membership function. The inputs taken are voltage error (i.e. measured voltage minus reference voltage) and change in voltage error for FLC and the output is the Susceptance (Beq). The inference engine performs the function of infers the control action according to the fuzzy rule base. The fuzzy domain output of FLC is converted into crisp output using the Centroid method of defuzzification by control action [13]-[16]. Simulink Model of Fuzzy Logic Controller for SVC is shown in Fig. 5.

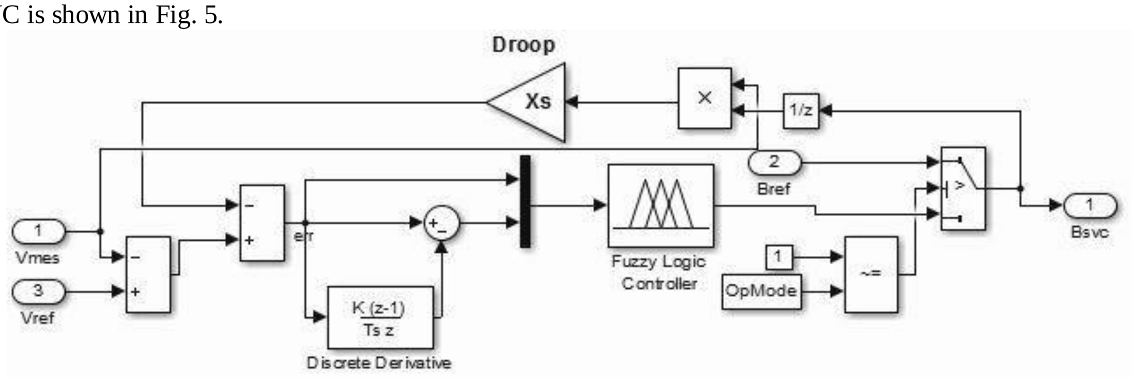

Figure 5 Simulink Model of FLC in SVC

IV. SYSTEM MODELLING

The single line diagram (SLD) of the test system having a Two-Generator Three-Bus is shown in Fig. 6. It consists of Generator-1 (G-1) of 1000MVA hydraulic unit connected to Generator-2 (G-2) of 5000MVA hydraulic unit through 500kV, 700km long transmission line.

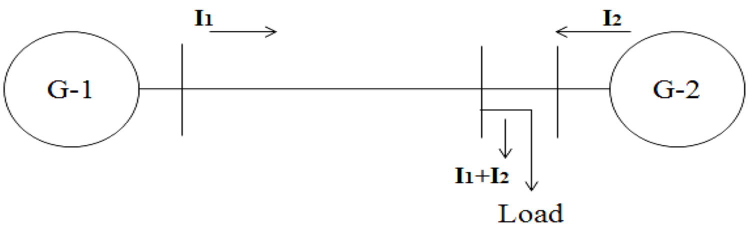

Figure 6 SLD of Two-Generator Three-Bus System

A resistive load of 5000MW is connected near generator-2. The system is initialized by the initialization method so that the transmission line carries 950MW of power. A three-phase fault (L-L-L fault) is made to occur near bus-1 for 0.1 sec from a time interval of 0.6sec to 0.7 sec. To maintain the stability of the power system under faulty conditions, 200 MVA capacities STATCOM and SVC are tie up at the mid-point of the system alternately. The system is simulated in MATLAB/Simulink environment. The Simulink diagram of the Two-Generator Three-Bus system with FLC STATCOM is as shown in Fig. 7.

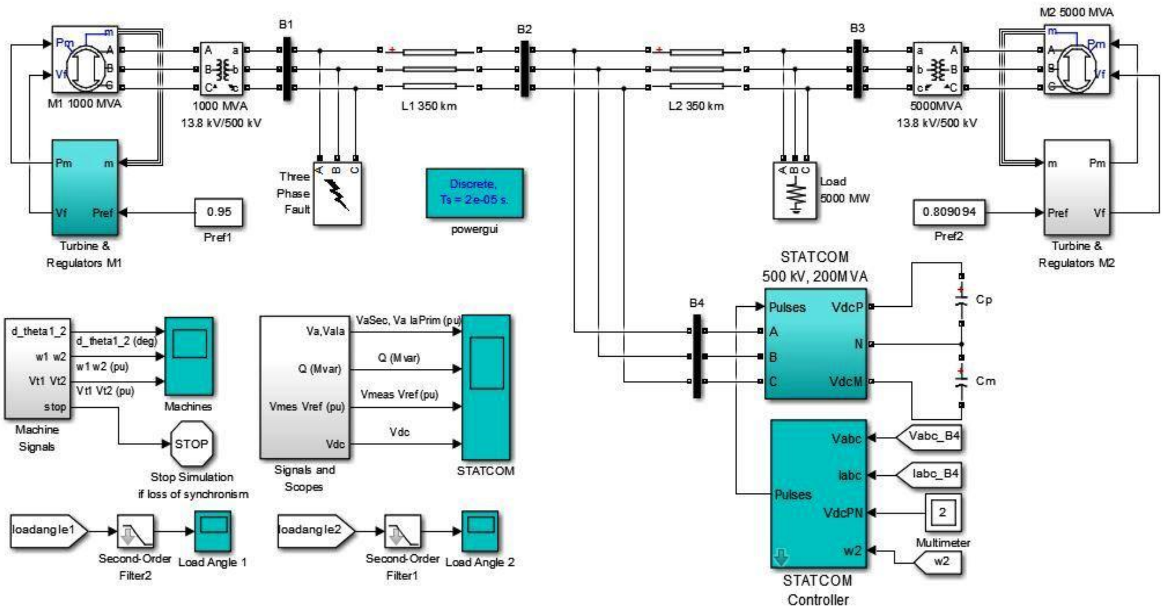

Figure 7 Simulink Diagram of Two-Generator Three-Bus system with FLC STATCOM

Inputs to the FLC of STATCOM are generator-2 (G-2) speed (w2) and change in speed (i.e. derivative). However, angle alpha is taken as output. Membership Functions of Generator-2 speed, change in speed and angle alpha are shown in Fig. 8, 9, and 10 respectively. Rule-based on which FLC of STATCOM is designed as shown in Table. I. The logic behind the rule is as follows.

R1: if w2 is PH and dw is PH then output angle alpha is PH.

R2: if w2 is NH and dw is PVH then output angle alpha is PH.

When the frequency is high and increases rapidly, the system is in a critical state as the mechanical input of the generator is greater than the electrical output.

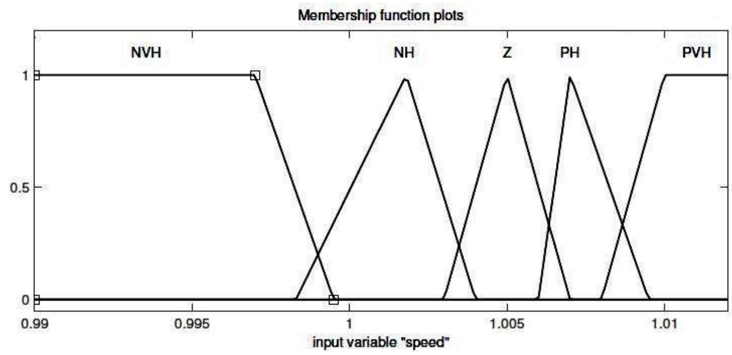

Figure 8 Membership Function of G-2 Speed

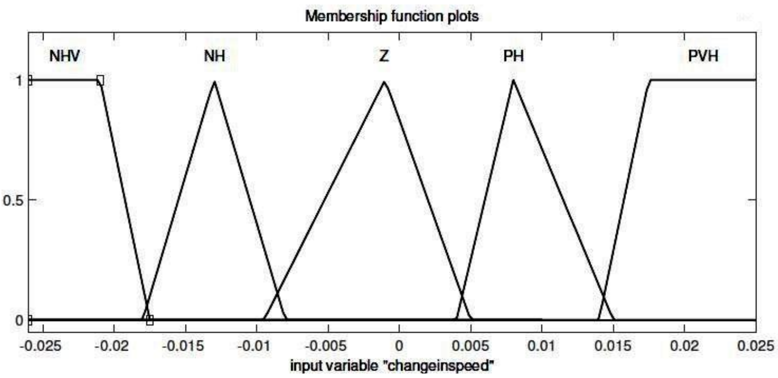

Figure 9 Membership Function of Change in Speed

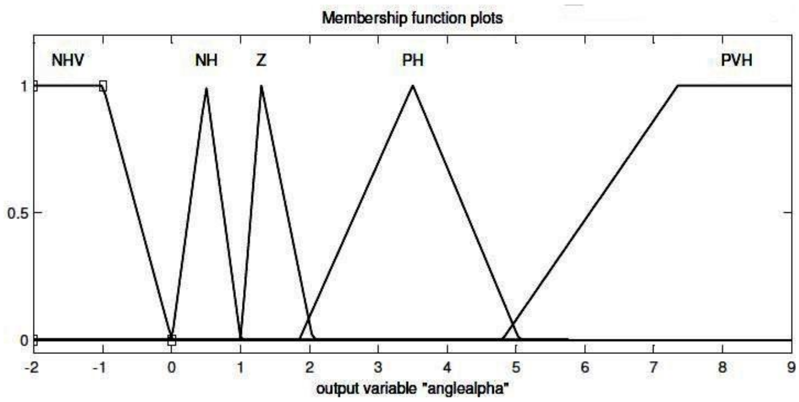

Figure 10 Membership Function of Angle Alpha

Table I Fuzzy Rule-based of STATCOM

Generator speed(w_2) / Change in speed(dw)	NVH	NH	Z	PH	PVH
NVH	NH	NH	NH	NH	NH
NH	NH	NH	NH	NH	NH
Z	NH	NH	Z	PH	PH
PH	PH	PH	PH	PH	PVH
PVH	PH	PH	PH	PH	PVH

The Simulink diagram of Two-Generator Three-Bus system with Fuzzy Logic Control SVC is as shown in Fig. 11.

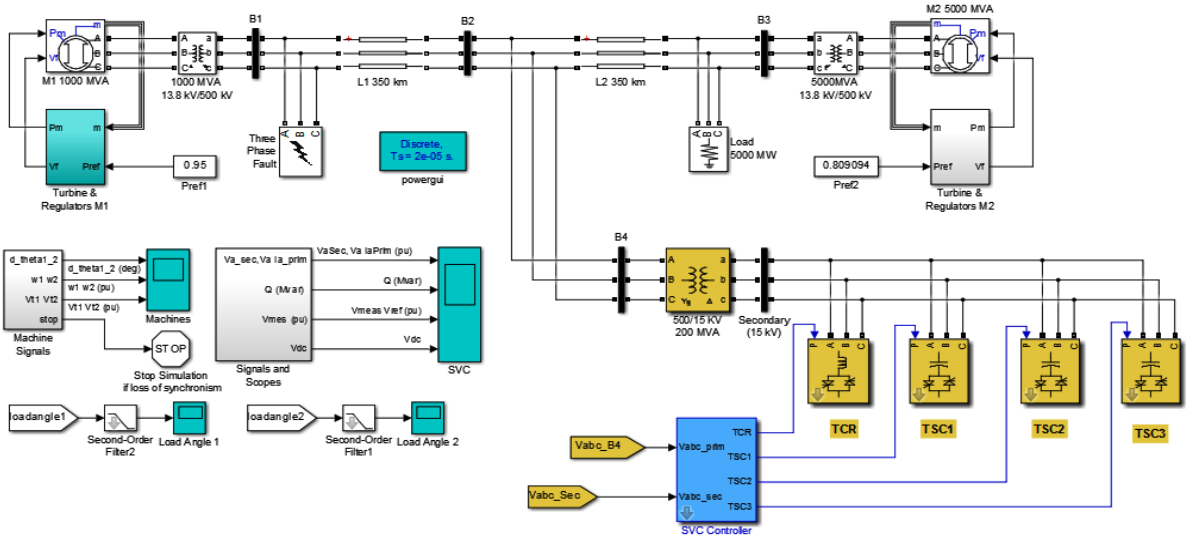

Figure 11 Simulink Diagram of Two-Generator Three-Bus system with FLC SVC

Inputs to the Fuzzy Logic Controller of SVC are Voltage error (e) and change of error (de) whereas Susceptance (Beq) is taken as output. The Membership Function of voltage error, change in voltage error and the Susceptance is shown in Fig. 12, 13, and 14 respectively. Rule-based on which the FLC of SVC is designed as shown in Table. II. The logic behind the rule is as follows.

R1: if voltage error is PS and change of error is PM then output susceptance is PS.

R2: if voltage error is NS and change of error is PS then output susceptance is PS.

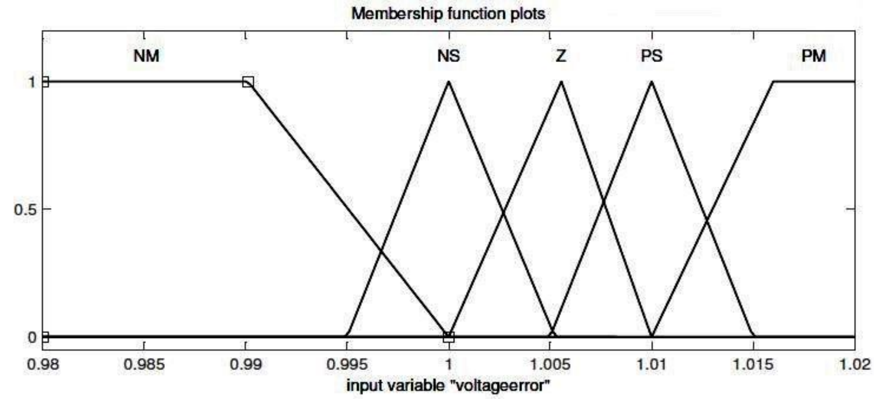

Figure 12 Membership Function of Voltage Error

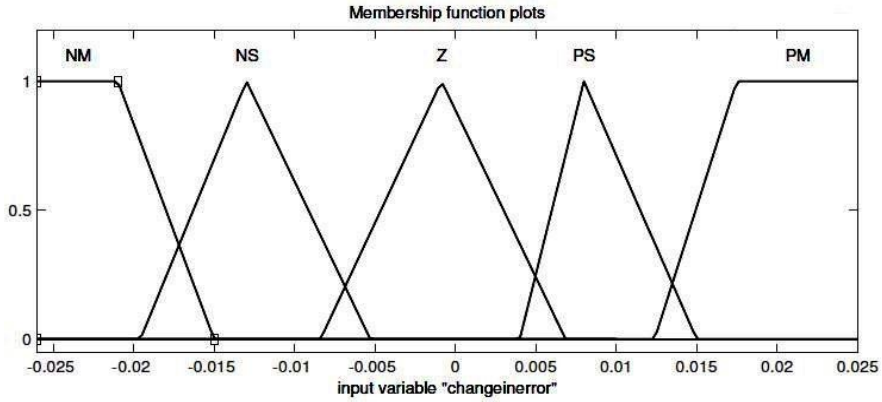

Figure 13 Membership Function of Change in speed

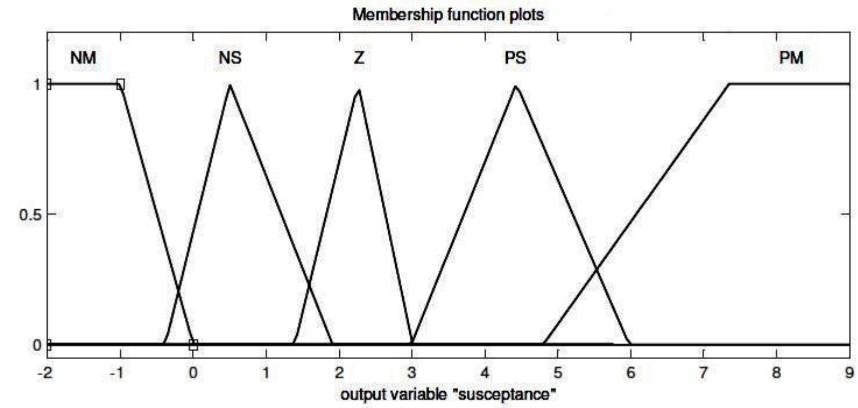

Figure 14 Membership Function of Susceptance

Table II Fuzzy Rule-based of SVC

voltage error (e) change in error (de)	NM	NS	Z	PS	PM
NM	NS	NS	NS	NS	NS
NS	NS	NS	NS	NS	NS
Z	NS	NS	Z	PS	PS
PS	PS	PS	PS	PS	PM
PM	PS	PS	PS	PS	PM

The results obtained from the simulation of the Two-generator Three-bus system with Fuzzy Logic Control STATCOM and SVC are compared for rotor angle difference (d_theta) of Generator-1 and 2 and the variation of the terminal voltage of Generator-1 and 2.

V. RESULT AND DISCUSSION

The rotor angle difference (d_theta) of Generator-1 (G-1) and Generator-2 (G-2) of the test system under the faulty condition with Fuzzy control and convention PI control STATCOM and SVC is shown in Fig. 15 and 16 respectively. For a three-phase fault (i.e. L-L-L Fault) that is created at 0.6 seconds, both the generator will quickly loose the synchronism. The loss of synchronism of the test system is analyzed with the measurement of peak overshoot and settling time. The peak overshoot and settling time for the test system with FLC and PI control STATCOM as well as SVC is shown in Table III.

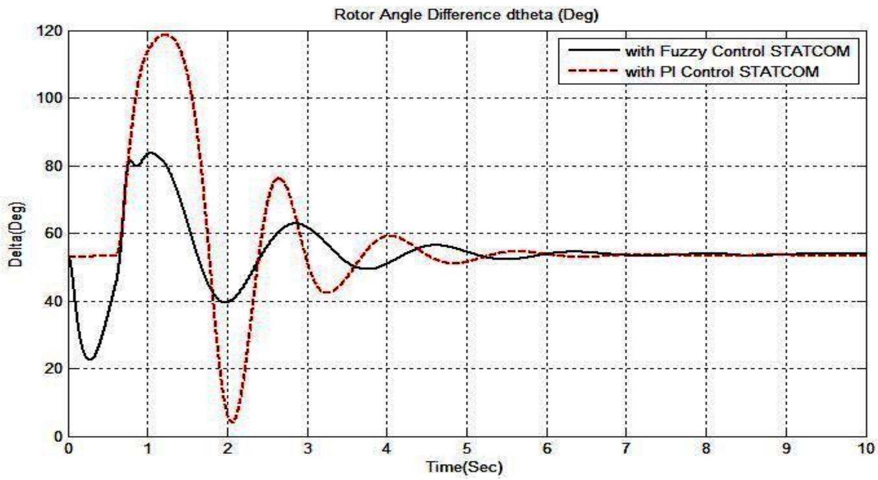

Figure 15 Comparison of rotor angle difference of G-1 and G-2 with FLC and PI control STATCOM

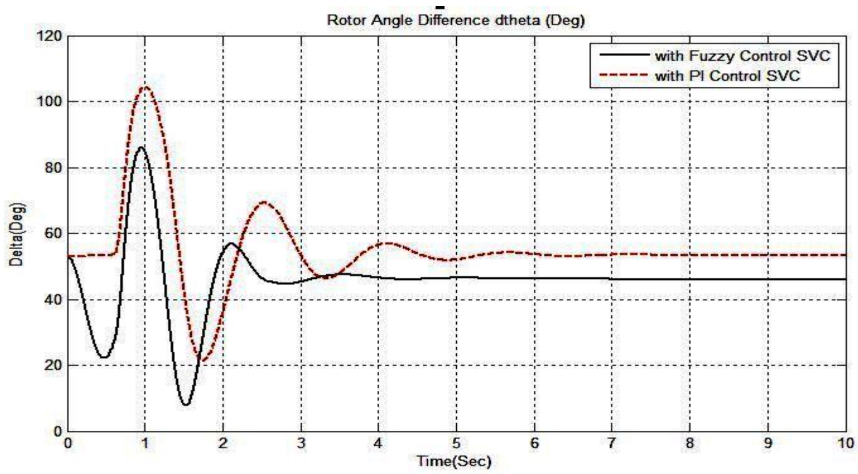

Figure 16 Comparison of rotor angle difference of G-1 and G-2 with FLC and PI control SVC

Table III Comparison of Various Controller wrt peak overshoot and settling time

Control Techniques	d_theta (Peak overshoot) in degree	Settling time in seconds
With PI control STATCOM	116	6.6
With Fuzzy Control STATCOM	85	5.5
With PI Control SVC	108	6.1
With Fuzzy Control SVC	86	4.6

In the STATCOM control Two-generator Three-bus system, the peak overshoot under a fault condition is reduced to 85 degrees from 116 degrees with the use of the FLC technique compared to the conventional PI control technique. Also settling time for the system to be stable after fault is reduced to 5.5 seconds from 6.6 seconds. Hence it is clear that FLC control STATCOM improves the power system transient stability under the faulty condition as quickly as compared to conventional PI control STATCOM. Furthermore, similar behavior is observed when SVC is used for the power system transient stability improvement.

In the SVC control Two-generator Three-bus system, peak overshoot under a fault condition is reduced to 86 degrees from 108 degrees, and settling time is reduced to 4.6seconds from 6.1 seconds with the use of the FLC technique compared to the conventional PI control technique.

In general, FLC STATCOM and SVC reduces the peak overshoot in the range of 20-26% and settling time in the range of 15-23% as compared to conventional PI control STATCOM and SVC. Hence transient stability of the power system is getting improved.

Furthermore, Improvement in the transient stability of the power system is analyzed by comparing the terminal voltage of G-1 and G-2. When a three-phase fault occurs, the variation of terminal voltage Vt of Generators-1 and Generator-2 for FLC and conventional PI control STATCOM and SVC is represented in Fig. 17 and 18 respectively. With the use of the FLC controller in STATCOM and SVC, the oscillation in the terminal voltage is minimized and quick stabilization of the system occurred.

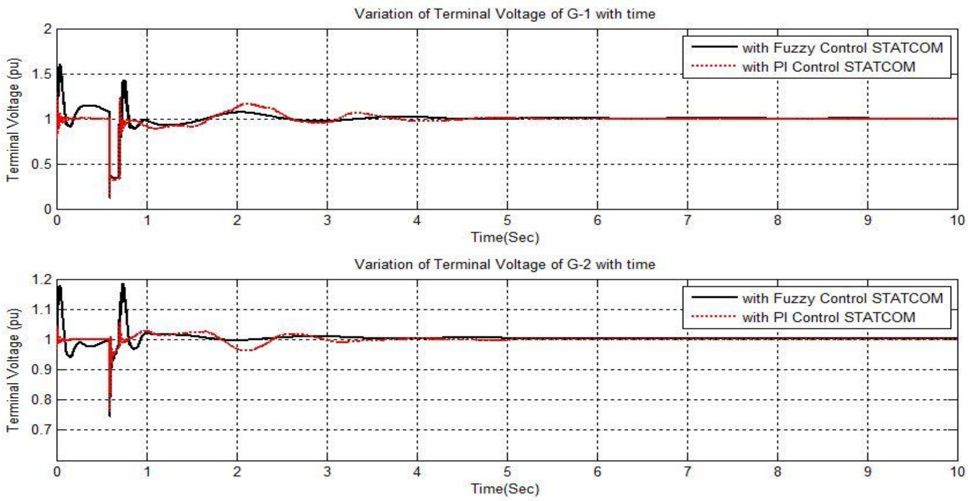

Figure 17Comparison of Terminal Voltage of G-1 and G-2 with FLC and PI Control STATCOM

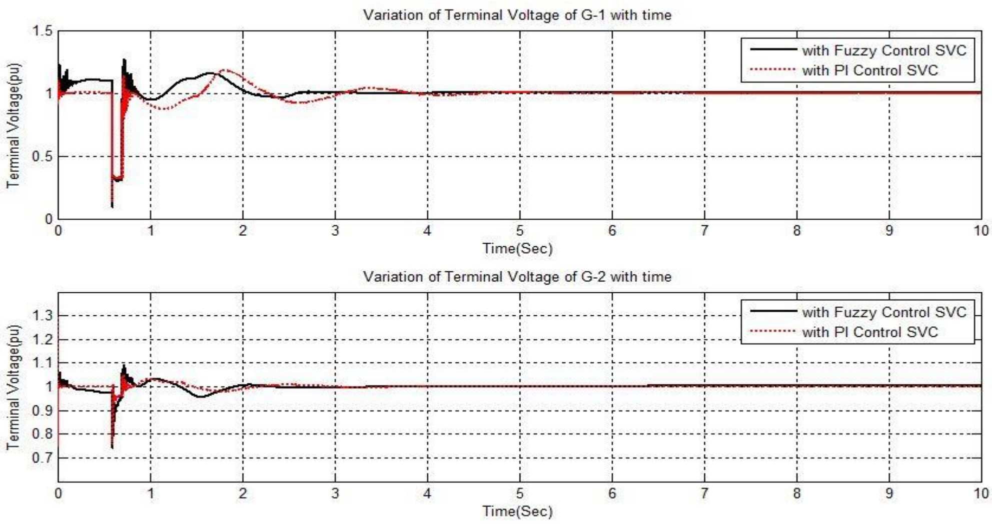

Figure 18 Comparison of Terminal Voltage of G-1 and G-2 with FLC and PI Control SVC

VI. CONCLUSION

In this paper, the transient performance of a Two-generator Three-bus system with conventional PI control STATCOM and SVC has been studied. The advanced control technique of FLC has been employed for controlling STATCOM and SVC. A comparison study between conventional PI control and FLC has been carried out. The results indicate that FLC has excellent performance with less overshoot and reduced settling time under fault conditions. Also, the FLC technique provides better damping of oscillation. In the FLC technique, Peak overshoot is 20-26%, and settling time is 15-23% lower than the conventional PI control technique. Furthermore, the FLC technique provides quick recovery of terminal voltage after the power system is subjected to a fault. Finally, it can be said that FLC techniques provide better performance than conventional PI control techniques.

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