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Transient Stability Enhancement Using Fuzzy Controlled SVC and STATCOM

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ABSTRACT—The modern power system is more complex and it presents serious challenges in perspective of power system stability because of growing demand and restrictions in building new lines. Transient stability is regarded as the main source of system insecurity; hence it has to be maintained for ensuring stable operation of power system in the event of large disturbance and faults. In modern power systems, shunt FACTS devices like, Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) are used as supplementary controllers to improve transient stability. This paper proposes an application of Fuzzy Logic Controller (FLC) to determine the control signal of SVC and STATCOM for damping the rotor angle oscillations and thereby to improve the stability of the power system. The proposed controller is tested on 2-machines 3-bus system. The parameters like rotor angle deviation, terminal voltage of buses and transmission line active power are observed. The results obtained are compared with that of conventional PI controller and it is proved that the Fuzzy controlled SVC and STATCOM gives better results than SVC and STATCOM with conventional PI controller. The MATLAB/Simulink software is used to verify the effectiveness of each control method.

KEYWORDS— Transient stability, SVC, STATCOM, Fuzzy Logic Control.

I. INTRODUCTION

Modern power system is a complex non linear interconnected network. It consists of inter connected transmission lines, generating plants transformers and a variety of loads. With the increase in power demand now-a-days some transmission lines are more loaded than their normal limits. With the increased loading of long transmission lines, the problem of transient stability has become a serious limiting factor. Transient stability of a system is defined as the ability of the system to maintain in a stable condition after being subjected to large disturbances such as faults and switching of lines.

This transient stability problem requires evaluation of a power system's ability to withstand disturbances while maintaining the quality of service. Many different techniques have been proposed for transient stability analysis in power systems, especially for a multi-machine system. These methods include the time domain solutions, the extended equal area criteria, and the direct stability methods such as the transient energy function approach. For the improvement of transient stability the general methods adopted are fast acting exciters, circuit breakers and reduction in system transfer reactance[1].

Modern power system is equipped with fast acting static excitation system but they introduce negative damping at the electromechanical oscillation frequencies of the machine. Thus they make the system unstable under local and inter area mode of oscillation. For the machine to remain in synchronism under small disturbance, it is essential to have positive damping for the machine. Power system stabilizer will introduce positive damping to the system. Power system stabilizers (PSS) must be capable of providing stabilization signals over a broad range of operating conditions and disturbance. Under certain conditions the performance of PSS is limited due to nonlinear nature of power system [2].

During the last decade, a number of control devices under the term FACTS technology have been proposed and implemented. Application of FACTS devices in modern power systems leads to better performance of the system. FACTS devices enhances system parameters like Voltage stability, voltage regulation, power system stability and enhancement of damping. There are various forms of FACTS devices, some are connected in series with a line and the others are connected in shunt or a combination of series and shunt. The FACTS technology is not a single high power controller but rather a group of controllers which can be applied individually or in coordination with other to control one or more of the inter related system parameters like impedance, voltage, current, and phase angle, they can damp oscillations at various frequencies below the rated frequency [3].

In this paper, shunt FACTS devices like Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) are discussed. SVC and STATCOM are members of FACTS family that are connected in shunt with the system. A SVC is a shunt FACTS device that is widely used, since it has the capability of enhancing both steady-state capacity and dynamic performance of power systems. The basic principle of A STATCOM, also known as a “Static Synchronous Condenser” is that voltage-sourceinverter generates a controllable AC voltage sourcebehind a transformer-leakage reactance so that thevoltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network [4,5].

For SVC and STATCOM, conventional controllers like PI or PID controller is used as a voltage controller. There are several methods available for tuning of PI or PID controller’s parameters. Even though those parameters are chosen properly, they cannot provide satisfactory performance over a wide range of operation points and under large disturbances since power system is a non-linear system.Now-a-days, Fuzzy based approaches have received much attention. An attractive feature of fuzzy logic control is its robustness when the system parameters and operating conditions changes. Fuzzy logic controllers are capable of tolerating uncertainty and imprecision to a greater extent [6].

Hence in this paper control signals for SVC and STATCOM are provided using fuzzy logic controller. The voltage error and its integral value are given as input to the fuzzy controller. Finally a comparative study is carried out between the PI controller and fuzzy controller in enhancing the transient stability of a 2-bus 3-machine system and the simulation results are presented.

II. STATIC VAR COMPENSATOR

According to IEEE, Static Var Compensator (SVC**)** is defined as “A shunt-connected static var generator or absorberwhose output is adjusted to exchange capacitive or inductive current so as to maintain or controlspecific parameters of the electrical power system (typically bus voltage)” [7].

A. *Construction of SVC*

A Static Var compensator consists of capacitors and reactors connected in shunt, which can be quickly controlled by thyristor switching. In effect SVC is a variable shunt susceptance. The susceptance is varied in response to system voltage conditions by a thyristor controlled reactor in parallel with a combination of fixed and switched capacitors and reactors. Direct and rapid bus voltage control forms the principal basis of SVC for transient stability enhancement. SVC increases power transfer during low voltage conditions while fault on the system by decreasing generator acceleration and vice versa when the fault is cleared. If SVC is on the system, it reduces the adverse impact of the fault on the generator's ability to maintain synchronism. The SVCs in use nowadays are of variable susceptance type [8].

The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. There are two types of the SVC. They are fixed capacitor thyristor controlled reactor (FC-TCR) and thyristor switched capacitor-thyristor controlled reactor (TSC-TCR). The later type is used commonly because it is more flexible than FC-TCR and it uses lower reactor rating. The basic diagram of FC-TCR based SVC is shown in the Fig. 1.

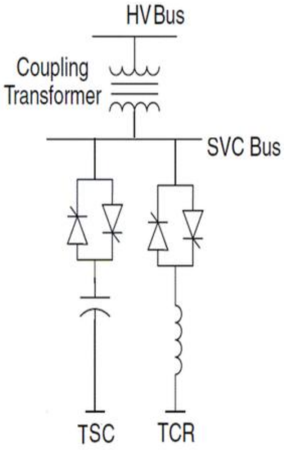

Fig. 1. Basic configuration of SVC

The SVC generates reactive power (capacitive mode) when the system voltage is low and will absorbs reactive power (inductive mode) when the system voltage is high. The variation of the reactive power can be controlled by switching capacitor banks and inductor banks which are connected on the low voltage bus. Reactors are either switched on off by Thyristor Switched Reactor (TSR) or phase controlled Thyristor Controlled Reactor (TCR).

The magnitude of the SVC is inductive admittance B_L (α) is a function of the firing angle α and is given by

$$B_L(\propto) = \frac{2\pi - 2\alpha + \sin 2\alpha}{\pi X_s} for \frac{\pi}{2} \le \alpha \le \pi \quad (1)$$

Where, $X_s = \frac{V_s^2}{Q_L}$, where V_S = SVC bus bar voltage and Q_L is the MVA rating of reactor. As the SVC uses an FC and a variable reactor combination (TCR–FC), the effective shunt admittance is given by,

$$B_s = \frac{1}{X_c} - B_L(\alpha) \tag{2}$$

Where, X_C = capacitive reactance.

B. Control system of SVC

The control system of SVC is shown in Fig. 2. It consists of a measurement system, voltage regulator and synchronizing system. The measurement system measures the positive-sequence voltage to be controlled. A measurement system based on Fourier transformation is used.A voltage regulator that uses the voltage error i.e the difference between the measured voltage V_m and the reference voltage V_{ref} is used to determine the SVC susceptance B, which is needed to keep the system voltage constant. The TSCs (and eventually TSRs) which are to be switched in and out, are determined by a distribution unit that computes the firing angle α of TCRs.A synchronizing system consists of a phase-locked loop (PLL) and a pulse generator, sends appropriate pulses to the thyristors [5].

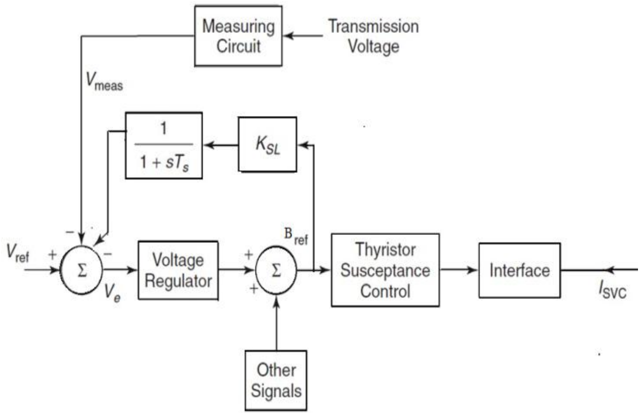

Fig. 2. Control system of SVC

C. Transient stability model of SVC

The transient stability model of SVC shown in Fig. 3 can be obtained by assuming balanced, fundamental frequency operation with sinusoidal voltages [4]. It can be represented by the following set of equations:

$$\begin{bmatrix} \dot{x_c} \\ \dot{\propto} \end{bmatrix} = f_c\left(x_c, \propto, V, V_{ref}\right) \tag{3}$$

$$0 = \begin{bmatrix} P - \frac{2\propto - sin\,2\propto - \pi\left(2 - \frac{X_L}{X_c}\right)}{\pi X_L} \\ I - V_i B_e \\ I - {V_i}^2 B_e \end{bmatrix} \tag{4}$$

Most of the variables used in the equation (3)and (4) are clearly defined on Fig. 3, and the control system variables and equations are represented by $x_c$and f(.)respectively. These equations are used to represent limits notonly on the firing angle, but also on the current I, thecontrol voltage V and the capacitor voltage V_i, as well ascontrol variables other types of controllers such as a reactive power Q control scheme [9].

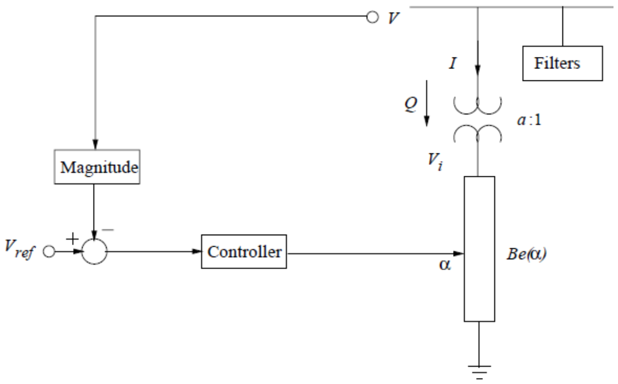

Fig. 3. Transient stability model of SVC

III. STATIC SYNCHRONOUS COMPENSATOR

According to IEEE, Static Synchronous Compensator (STATCOM) is defined as, “A Static synchronous generator operates as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage” [7].

A. Construction of STATCOM

The STATCOM uses semiconductor devices to generate a balanced three-phase voltage whose magnitude and phase angle can be adjusted rapidly. In this way, it can draw or supply the reactive power or real power from/to the power system. This function is similar to the synchronous condenser, but its response time is much faster than that of the synchronous condenser due to the absence of the rotating mass. The traditional STATCOM has no DC source or energy storage devices on its DC side, so it cannot supply/absorb real power to/ from power system [10]. In this paper, the generalized STATCOM is considered which has energy storage on its DC side. In this way, it acts as a static generator with faster response than the synchronous generators.

Fig. 4 shows a simplified configuration of a STATCOM with energy storage on the DC side. The DC interface provides the interface between the DC side of STATCOM and other energy sources, which could be any kind of energy storage device or DC source, such as wind turbines, DC generator, photovoltaic systems, or other power electronics devices. The Voltage Source Inverter (VSI) is a very important part of the STATCOM. It is the interface between the DC source and the AC system. The STATCOM must always absorb real power from the system to compensate for the converter and transformer losses to maintain DC side voltage [11].

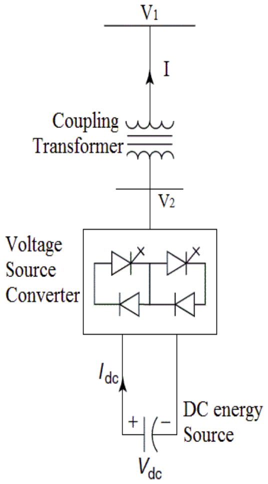

Fig. 4. Basic configuration of STATCOM

B. *Control system of STATCOM*

The control system for STATCOM [11] is shown in Fig. 5. The measurement system measures the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage V_{dc}.An outer regulation loop consists of an AC voltage regulator and a DC voltage regulator. The AC voltage regulator is used to provide the reference current I_{qref} for the current regulator (I_q = current in quadrature with voltage which controls reactive power flow) and the output of the DC voltage regulator is the reference current I_{dref}which is fed as input for the current regulator (I_d = current in phase with voltage which controls active power flow).

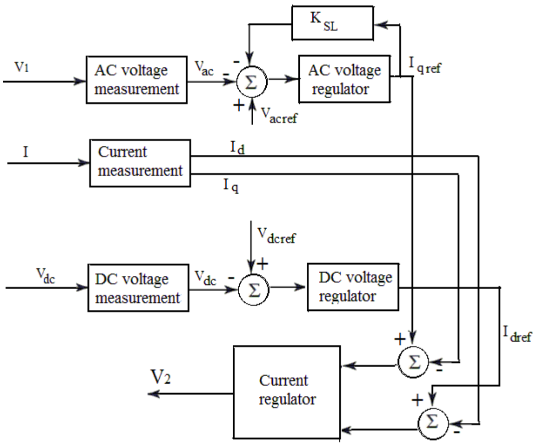

Fig. 5. Control system of STATCOM

An inner current regulation loop consists of a current regulator, which controls the magnitude and phase of the voltage generated by the PWM converter (V_{2d} V_{2q}), from the I_{dref} and I_{qref} reference currents produced respectively by the DC voltage regulator and the AC voltage regulator (in voltage control mode). The current regulator is supported by a feed forward type regulator which predicts the V_2 voltage output (V_{2d} V_{2q}) from the V_1 measurement (V_{1d} V_{1q}) and the transformer leakage reactance [12].

C. *Transient stability model of STATCOM*

The transient stability model of STATCOM is shown in Fig 6. The Differential-Algebraic Equations (DAE) corresponding to this model are,

$$\begin{bmatrix} \dot{x}_c \\ \dot{\propto} \\ \dot{m} \end{bmatrix} = f_c\left(x_c, \propto, m, V, V_{dc}, V_{ref}, V_{dc_{ref}}\right) \qquad (5)$$

$$\dot{V_{dc}} = \frac{VI}{CV_{dc}} cos(\delta - \theta) - \frac{G_c}{C} V_{dc} - \frac{R}{C}\frac{I^2}{V_{dc}} \qquad (6)$$

$$0 = \begin{bmatrix} P - VIcos(\delta-\theta) \\ Q - VIsin(\delta-\theta) \\ P - V^2G + kV_{dc}VGcos(\delta-\alpha) + kV_{dc}VBsin(\delta-\alpha) \\ Q + V^2B - kV_{dc}VBcos(\delta-\alpha) + kV_{dc}VGsin(\delta-\alpha) \end{bmatrix} \qquad (7)$$

Where, $k = \sqrt{3/_8}\, m$ (8)

The transformer impedance is represented by the admittance $G + jB = (R + jX)^{-1}$and switching inertia of the converter is modeled as Gc. The modulation index is given by m, which is used to control ac bus voltage. The function in (2) indicates the internal control system of STATCOM. The phase angle α determines the active power P flowing into the controller and thus it helps in the process of charging and discharging of the capacitor, which in turn used to directly control the dc voltage magnitude. The parameter G_c in this model indicates dc voltage dynamics and this value affects directly the capacitor's charging and discharging time constant [9].

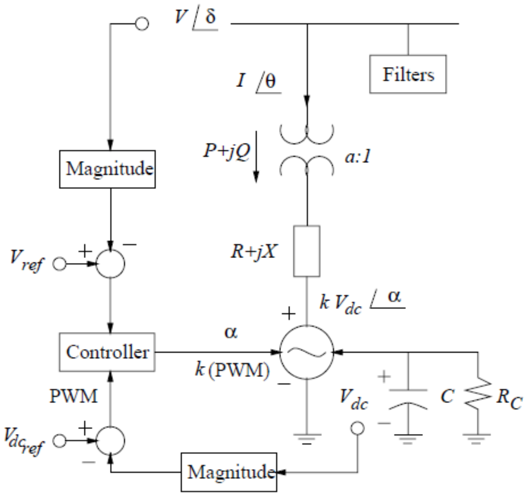

Fig. 6.Transient stability model of STATCOM

IV. FUZZY CONTROLLERS FOR SVC AND STATCOM

One of the most victorious approaches to design a controller which utilizes the qualitative information of a system and solves a problem with imprecision or suspicions is Fuzzy Logic Controller. Here it is used in the control loop of SVC and STATCOM. Fig. 7 shows the basic Fuzzy Logic Controller, which consists of Input fuzzification block (binary-to-fuzzy [B/F] conversion), rule base (knowledge base), fuzzy Inferencing block and output defuzzification (fuzzy-to-binary [F/B] conversion). The voltage error and its integral value are fed as the input signals for the fuzzy controller [13].

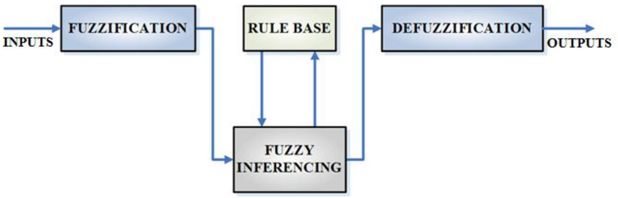

Fig. 7.Basic Fuzzy controller

In this paper, seven membership functions are defined for the input and output variables. Fig.8 shows thedefined membership functions. These membership functions are used to develop a set of rules called a rule base. Withtwo inputs and seven linguistic terms, 49 rules were developed which is given in Table I. In inference mechanism the rules and the input to FLC are compared to determine a proper conclusion to the current situation. For inference engine Mamdani's method is used. The output of inference engine is of fuzzy value, which is to be converted into crisp value using defuzzificationblock. The Centroid method is employed for defuzzification process.

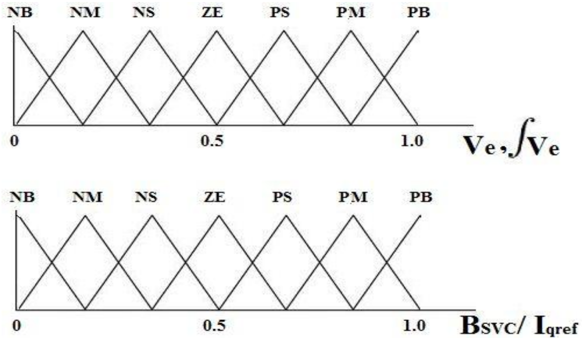

Fig. 8.Memebership functions for FLC

TABLE I

RULES FOR FLC

∫Ve/Ve	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

V. SIMULATION RESULTS

A. *Test System*

The test system used in this paper is 2 machines 3 bus system. It consists of a hydraulic generation plant (M1) having capacity of 1000MW, which is connected to a load via a long 700km transmission line. The load is designed as a 5000MW resistive load. The load is also fed by a local generation of 5000MW (M2). The system has been initialized in such a way that thetransmission line carries 950MW which is nearer to its surge impedance loading of 977MW. To maintain the stability of system after faults, compensation is provided at its midpoint by means of a FACTS device [14].The single line diagram of the proposed system is given in Fig. 9.Table II shows the specifications of the test system.

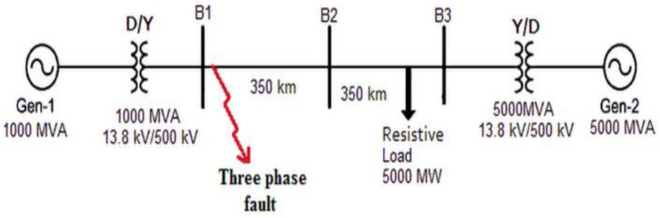

Fig. 9.Single line diagram of test system

TABLE II

SPECIFICATIONS OF TEST SYSTEM

System Parameters	Rating
Load centre	5000MW, Resistive load
Power plant 1 (M1)	1000MW
Power plant 2 (M2)	5000MW
Initial power flow	950MW
Surge Impedance Loading (SIL)	977MW
Power rating of SVC	200MVar
Power rating of STATCOM	100MVar

B. *Simulation results of Fuzzy based SVC and Conventional SVC*

Three phase fault is occurred at t=3s and circuit breaker is made to open at t=3.1s to clear that fault. Both conventional SVC (SVC with PI controller) and Fuzzy based SVC are simulated for the same three phase fault and simulation results are presented. From Fig. 10 and Fig.13 it is inferred that the rotor angle deviation of the system with fuzzy controller is settled faster with settling time of 12s than with the PI controller where the settling time is 8s. Also the amplitude of rotor angle deviation is reduced with fuzzy based SVC. As fault occurred between Bus 1 and Bus 2, terminal voltages $V_{t1}$and V_{t2} are also affected. Observation from Fig. 11 and Fig. 14 shows that those voltages are less oscillated and stabilized faster with the Fuzzy based SVC. Another parameter that also been observed is active power of the transmission line as shown in Fig. 12 and Fig. 15. The line active power is less oscillated and stabilized faster at t=6.5s after subjected to disturbance with the Fuzzy based SVC than PI based SVC where the oscillation of the line power is stabilized at t=10s.Comparison of performance between PI based SVC and FLC based SVC are given in Table III.

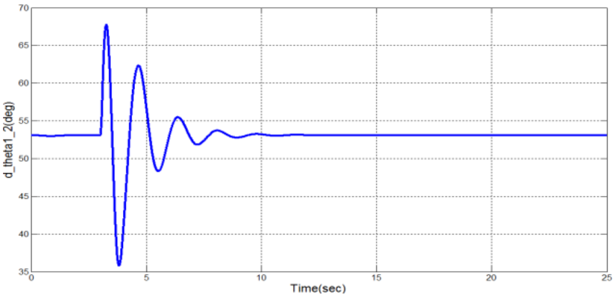

Fig. 10. Rotor angle deviation with PI based SVC

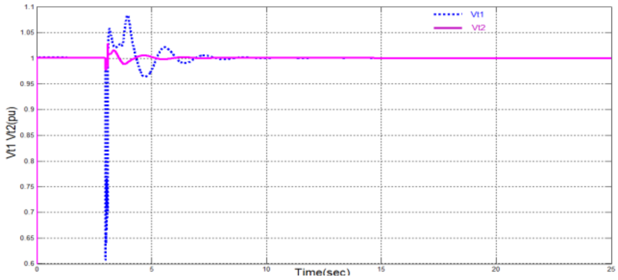

Fig. 11.Terminal voltages with PI based SVC

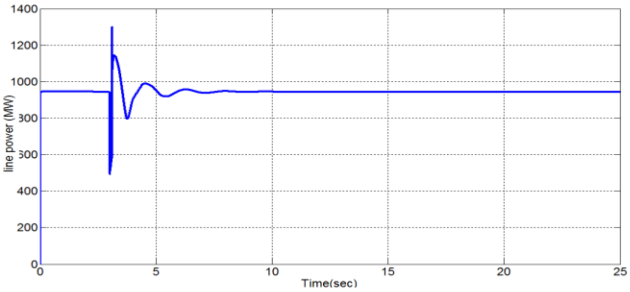

Fig. 12.Transmission line active power with PI based SVC

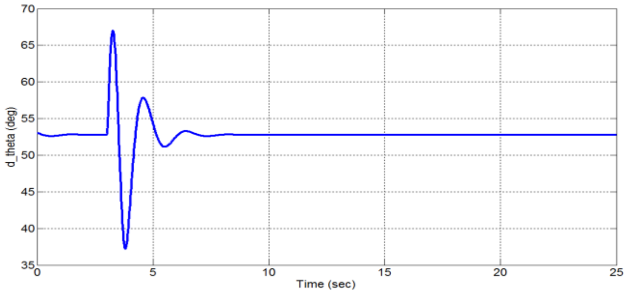

Fig. 13.Rotor angle deviation with FLC based SVC

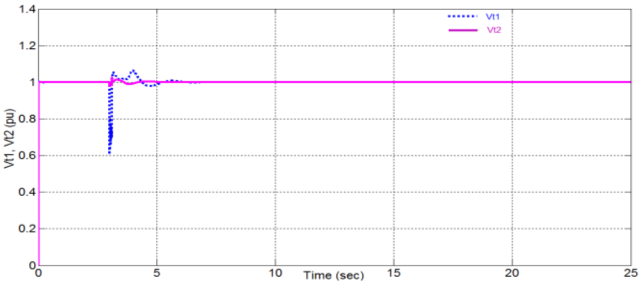

Fig. 14. Terminal voltages with FLC based SVC

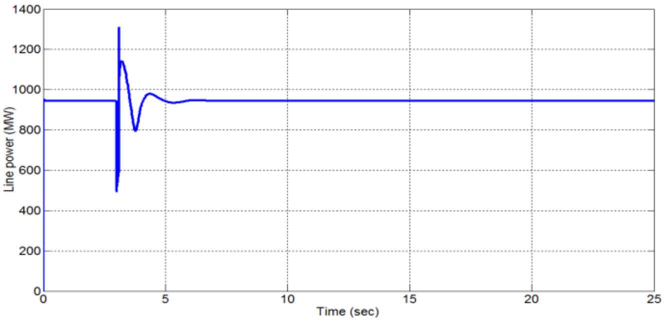

Fig. 15. Line power with FLC based SVC

TABLE III

COMPARISON BETWEEN PI BASED AND FLC BASED SVC

Parameter	**d_theta**		**Vt1**		**Vt2**		**Line power**	
	Peak (deg)	**Ts (sec)**	**Peak (pu)**	**Ts (sec)**	**Peak (pu)**	**Ts (sec)**	**Peak (MW)**	**Ts (sec)**
PI	68	12.0	1.08	11.0	1.03	5.8	1300	10.0
FLC	67	8.0	1.07	7.0	1.02	4.9	1300	6.5

C. Simulation results of Fuzzy based STATCOMand Conventional STATCOM

Similar to SVC, simulations were done using STATCOM with Fuzzy controller and PI controller and the results are presented in figures from Fig. 16-21.Table IV show the comparison of performance between PI based STATCOM and FLC based STATCOM.

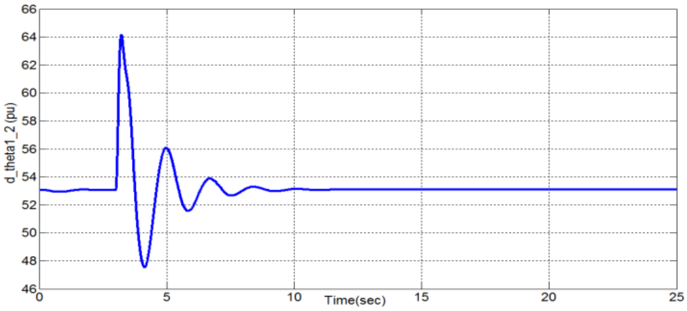

Fig. 16. Rotor angle deviation with PI based STATCOM

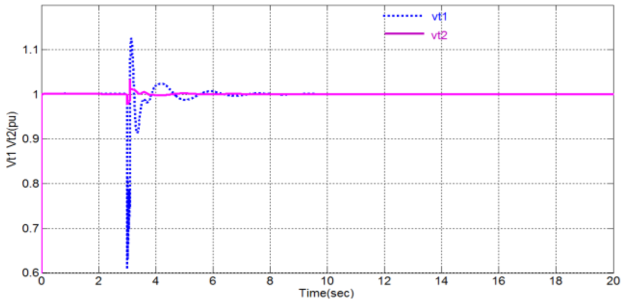

Fig. 17. Terminal voltages with PI based STATCOM

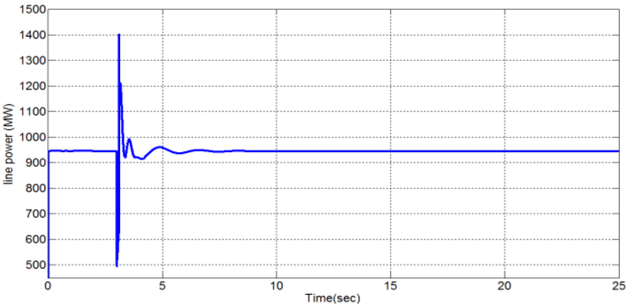

Fig. 18. Line power with PI based STATCOM

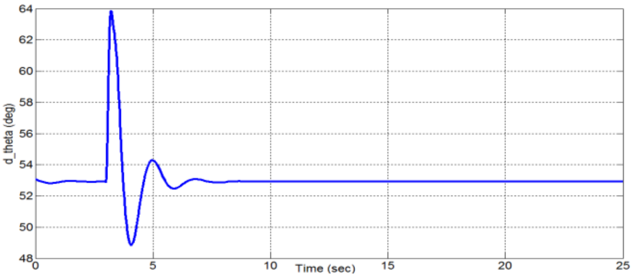

Fig. 19. Rotor angle deviation with FLC based STATCOM

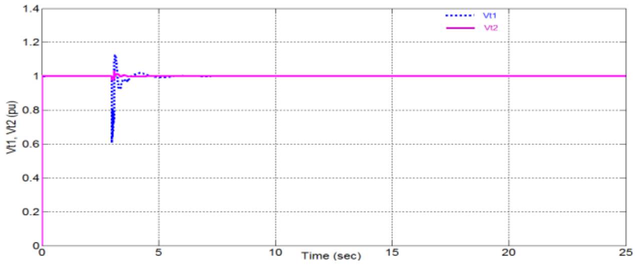

Fig. 20. Terminal voltages with FLC based STATCOM

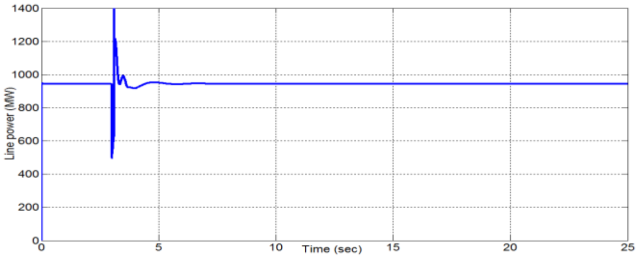

Fig. 21. Line power with FLC based STATCOM

TABLE IV

COMPARISON BETWEEN PI BASED AND FLC BASED STATCOM

Parameter	**d_theta**		**Vt1**		**Vt2**		**Line power**	
	Peak (deg)	**Ts (sec)**	**Peak (pu)**	**Ts (sec)**	**Peak (pu)**	**Ts (sec)**	**Peak (MW)**	**Ts (sec)**
PI	64.0	12.0	1.2	7.5	1.03	5.0	1400	10.0
FLC	63.9	8.0	1.1	7.0	1.02	4.8	1400	7.0

VI. CONCLUSION

In this paper, an application of Fuzzy Logic Controller (FLC) to determine the control signal of SVC and STATCOM for damping the rotor angle oscillations and to improve the transient stability of the Multi-machine power system is presented. The performance of the proposed fuzzy logic controller for SVC and STATCOM was analyzed for a three phase fault in 2-machines 3-bus system. Various parameters like rotor angle deviation, terminal voltage of buses and transmission line active power are observed. The results obtained are compared with that of conventional PI controller and it is proved that the Fuzzy controlled SVC and STATCOM gives better results than SVC and STATCOM with conventional PI controller.

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