

ENHANCEMENT OF LOADABILITY CRITERION OF TRANSMISSION & DISTRIBUTION LINES BY USING FUZZY LOGIC CONTROLLER WITH STATCOM

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Abstract: Due to the rapid technological progress, the consumption of electric energy increases continuously. But the transmission systems are not extended to the same extent because building of new lines is difficult for environmental as well as political reasons. Hence, the systems are driven closer to their limits resulting in congestions and critical situations endangering the system security. Power Flow Control devices such as Flexible AC Transmission Systems (FACTS) provide the opportunity to influence power flows and voltages and therefore to enhance system security, e.g. by resolving congestions and improving the voltage profile. Even though the focus lies on Static Var Compensators (SVC), Thyristor-Controlled Series Compensators (TCSC) and Thyristor-Controlled Phase Shifting Transformers (TCPST), the developed methods can also be applied to any arbitrary controllable devices. In order to benefit from these devices, an appropriate control is necessary. In this thesis, an Optimal Power Flow problem is formulated and solved to find the optimal device settings. Two types of FACTS devices, SVC and TCSC, can be installed on buses and transmission lines to enhance the transmission loadability (TL) of power systems, respectively through injecting reactive power and changing line reactance. In this paper, there are three main steps in the FACTS devices installation strategy proposed. In step 1, based on the peak-load state, the CPF technique is used to formulate the maximum transmission loadability (MTL) problem to maximize the TL increased from the peak-load through installation of the FACTS devices. Here, the MTL without FACTS device installed is first calculated. While in step 2, based on the power flow solution for the MTL obtained in step 1, the positions proper to place SVCs and TCSCs are determined using the tangent vector technique and real power flow performance index (PI) sensitivity factors, respectively. Various FACTS devices installation schemes are then built with these candidate positions and, for each scheme, the MTL is solved by determining the ratings for the SVCs and TCSCs installed. Finally in step 3, by comparing the ratios of the investment costs to the TLs increased between various schemes, a correspondingly most advantageous scheme is suggested. Also, to further validate the effectiveness of the proposed method, a static voltage stability analysis is given.

Index Terms: Transient Stability, Fuzzy Logic Controller, STATCOM, Uncertainty, Oscillation damping.

I. INTRODUCTION

Transient stability analysis is considered when the power system is confronted with large disturbances. Sudden changes in load, generation or transmission system configuration due to fault or switching are examples of large disturbances. Power system should retain its synchronism during and after all these kind of disturbances. Therefore transient stability is an important security criterion in power systems design. Different methods have been used for transient stability analysis in power systems. Time Domain simulation and direct method are two important methods that have some benefits and shortcomings. In the time domain simulation power system elements are modeled in the proper software and transient stability is checked for each contingency. As simulation is based on the model of the system, the more exact the model, the more actual the results if the complexity of the system does not provoke numerical problems. Simulation time is also an important issue in this type of analysis and in many cases limits the application of the online study. These problems become more important when studying larger systems. In direct method there is no need to solve dynamic equations of system, so it is faster than time domain simulation. This method is mainly based on Lyapunov stability analysis theory and needs to form the system energy function as a Lyapunov function [1]. If energy function is derived, power system stability can be checked by monitoring this function and its rate of decent. Model based characteristics and the need to several measured parameters are the main shortcoming of this method. Recently, some researchers have performed this method using adaptive or robust techniques to decrease the model based characteristic and use some local measurements to obtain stability criteria and design a control strategy. Flexible AC Transmission System (FACTS) devices are used to control power flow along transmission lines and improve power system stability [4]. STATCOM is one of the parallel FACTS devices that are usually used for voltage regulation. It is also used to improve power system stability by injecting or absorbing reactive power. This function of STATCOM needs some more supplementary input signals [4]. Several controllers have been used to perform this control strategy such as conventional PI controller [5], rule based controller [6] and energy function based controller [7]. Uncertainty exists in almost every physical system. It can be the result of different phenomenon according to system nature, lack of information or measurements. Power systems are large scale systems with high nonlinearity, so there is a considerable uncertainty

in every part of them. Fuzzy logic performs as a powerful tool to confront these uncertainties [8]. This paper presents a fuzzy logic based control strategy for STATCOM to improve power system stability and performance. The fuzzy logic approach provides a model free method for STATCOM control and can be effective over a wide range of power system changes. Fuzzy logic approach allows the designer to incorporate experimental knowledge in adjustment of controller parameters. Selection of proper control signals for Fuzzy Logic Controller (FLC) is very important because controller design, system response and sensitivity depend directly on it. In [9] FLC is designed based on the line active power measurement and its derivative. Simulation results are compared with conventional energy function based method. In this work frequency and its derivative are chosen as FLC inputs. In part II STATCOM model is presented for transient stability is expressed. In part III some fuzzy logic principles and control strategies are introduced. This strategy is based on Mamdani's FLC. The advantage of this controller is that it doesn't need detailed information about the system. In part IV the proposed method is implemented for a sample network and simulation results are expressed.

II. MODELING

A. Power system model with STATCOM

STATCOM can be represented by a controlled shunt current source as shown in Fig. 1. The STATCOM current is always in quadrature with its terminal voltage and can be written as:

$$I_{STATCOM} = I_{STATCOM} e^{j(\delta + 90)} \quad (1)$$

Positive and negative signs are for inductive and capacitive modes respectively. In capacitive mode the voltage magnitude (V_m) and angle of bus m (δ) can be expressed by:

$$V_m = \frac{E'X_2 \cos(\delta - \delta_m) + VX_1 \cos \delta_m + X_1X_2 I_{STATCOM}}{X_1 + X_2} \quad (2)$$

$$\delta_m = \tan^{-1} \left(\frac{E'X_2 \sin \delta}{VX_1 + E'X_2 \cos \delta} \right) \quad (3)$$

Where $E_1, E, V_m, \delta, \delta_m$ are the generator internal voltage, infinite bus voltage, STATCOM bus voltage, generator internal angle. The controller design for power system stability studies requires suitable mathematical representation so as to include all significant components of power system.

B. SMIB with STATCOM

A Single Machine Infinite Bus (SMIB) system shown in Figure 1 is considered. The STATCOM is connected at the mid-point of the transmission line.

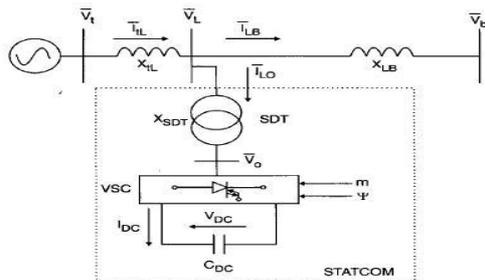


Figure: 1. STATCOM installed in a SMIB system

C. Synchronous Generator and its Excitation System

The synchronous generator is modeled as q-axis component of voltage behind transient reactance and electromechanical swing equation representing motion of the rotor. The internal voltage equation of the generator is written as,

$$\dot{E}'_q = [E'_{fd} - E'_q - (x_d - x'_d)I_d] \frac{1}{T'_{do}} \quad (4)$$

where, E'_q is the voltage behind the transient reactance, subscripts d and q represents the direct and quadrature axis of the machine, I_d is the current along the d-axis. x_d, x'_d and T'_{do} are d-axis synchronous reactance, transient reactance and open circuit field time constants respectively. The electromechanical swing equation is broken into two first order differential equations and is written as,

$$\begin{aligned} \dot{\omega} &= \frac{1}{M} [P_m - P_e - D(\omega - 1)] \\ \dot{\delta} &= \omega_b (\omega - 1) \end{aligned} \quad (5)$$

where, P_m and P_e are the input and output powers of the generator respectively; M and D the inertia constant and damping coefficient; ω_b the synchronous speed; δ and ω are the rotor angle and speed; The electrical power output is,

$$P_e = V_{td}I_d + V_{tq}I_q \quad (6)$$

where, V_{td} and V_{tq} are components of generator terminal voltage (V_t) and I_q is current along the q-axis. The IEEE Type ST1 excitation system is considered in this work. The dynamic model of the excitation system is

$$\dot{E}'_{fd} = \frac{1}{T_A} [K_A (V_{ref} - V_t) - E'_{fd}] \quad (7)$$

where, V_{ref} represents the steady state (reference) value of terminal voltage, K_A and T_A are the gain constant and time constant of exciter respectively.

D. The STATCOM System

The STATCOM installed in a SMIB system shown in Figure 1 consists of a step down transformer (SDT) with leakage reactance X_{SDT} , a three phase GTO based voltage source converter (VSC) and a DC capacitor.

The VSC generates a controller AC voltage behind the leakage reactance.

$$V_0(t) = V_0(\sin(\omega t - \psi))$$

The voltage difference between the STATCOM bus voltage V_0 and the bus voltage V_L produces active and reactive power exchange between STATCOM and the power system, which can be controlled by adjusting the magnitude V_0 and phase ψ . The voltage current relationship in the STATCOM are expressed as,

$$\dot{V}_{DC} = \frac{I_{DC}}{C_{DC}} = \frac{c}{C_{DC}} (I_{LOd} \cos \psi + jI_{LOq} \sin \psi)$$

where,

$$c = mk, \quad k = \frac{AC \text{ voltage}}{DC \text{ voltage}}$$

m = modulation ratio defined by PWM, ψ = angle defined by PWM, I_{LOd} and I_{LOq} are components of STATCOM current. The relation b/n STATCOM AC voltage V_0 and V_{DC} is

$$V_0 = c V_{DC} \angle \psi \tag{8}$$

The d-q components of generator and STATCOM currents can be expressed in the form,

$$I_{tLd} = \frac{\left(1 + \frac{X_{LD}}{X_{SDT}}\right) E'_q - V_B \cos \delta - \frac{X_{LD}}{X_{SDT}} c V_{DC} \sin \psi}{X_{tL} + X_{LB} + X_{tL} \frac{X_{LB}}{X_{SDT}} + \left(1 + \frac{X_{LB}}{X_{SDT}}\right) X'_d} \tag{9}$$

$$I_{tLq} = \frac{V_B \sin \delta + \frac{X_{LD}}{X_{SDT}} c V_{DC} \cos \psi}{X_{tL} + X_{LB} + X_{tL} \frac{X_{LB}}{X_{SDT}} + \left(1 + \frac{X_{LB}}{X_{SDT}}\right) X'_d} \tag{10}$$

$$I_{LOd} = \frac{E'_q}{X_{SDT}} - \frac{X'_d + X_{tL}}{X_{SDT}} I_{tLd} - \frac{c V_{DC} \sin \psi}{X_{SDT}} \tag{11}$$

$$I_{LOq} = \frac{c V_{DC} \cos \psi}{X_{SDT}} - \frac{X_q + X_{tL}}{X_{SDT}} I_{tLq} \tag{12}$$

The set of equations (1),(2),(3),(5),(7) form the non-linear model of SMIB system with STATCOM. This can be written as

$$\dot{x} = f(x, u) \tag{13}$$

III. STATCOM CONTROL SYSTEM

The converter and step down transformer in STATCOM can be modeled with a voltage source and a reactance for an operating point. Changing modulation ratio can change the amplitude of the output voltage of converter and so the active power absorbed by the system. By changing the converter voltage angle, reactive power exchanging with system can be controlled. In this study, the P-I controllers are used for voltage regulation.

A. Terminal voltage controller

AC voltage controller regulates the voltage of terminal according to reference which it accomplishes through changing of the converter output voltage magnitude. The terminal voltage controller is shown in Figure 2(a).

The AC damping stabilizer of STATCOM is shown in Figure 2(b) is used to create an additional damping signal for STATCOM. This damping stabilizer has a structure similar to conventional PSS. In this stabilizer $\Delta\omega$ and u_{dc} are the stabilizer input and output signals respectively.

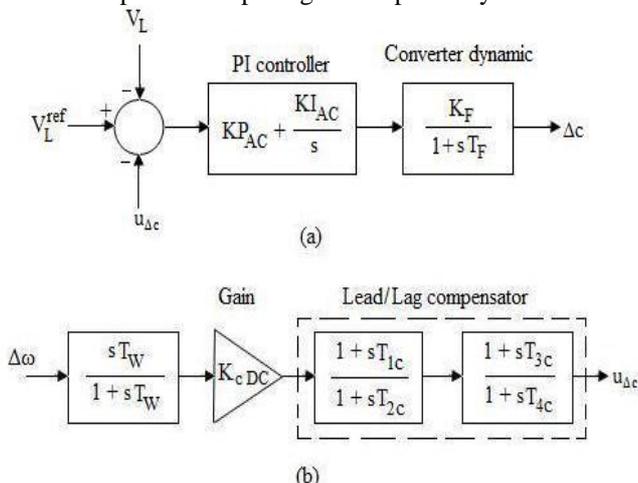


Figure 2. (a) AC Voltage Controller (b) AC Damping Stabilizer

B. Capacitor Voltage Controller

The inner DC voltage controller regulates the voltage of capacitor. The converter phase angle $\Delta\psi$ is calculated according to the reference capacitor voltage with capacitor voltage. The capacitor voltage controller is as shown in Figure 3.

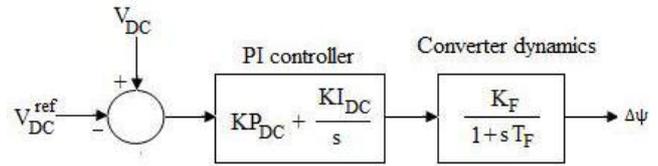


Figure 3. Capacitor voltage controller.

C. The Linearized Equations

The linearized model for SMIB with STATCOM is obtained by linearizing the set of equations (13) around a nominal operating point. The linearized system equations are written as,

$$\begin{aligned} \Delta \dot{\delta} &= \omega_B \Delta \omega \\ \Delta \dot{\omega} &= \frac{1}{M} (-\Delta P_e - D \Delta \omega) \\ \Delta \dot{E}'_q &= \frac{1}{T'_{do}} (-\Delta E_q + \Delta E_{fd}) \\ \Delta \dot{E}_{fd} &= -\frac{1}{T_A} (\Delta E_{fd}) - \frac{K_A}{T_A} (\Delta V_t) \end{aligned} \tag{14}$$

where,

$$\begin{aligned} \Delta P_e &= K_1 \Delta \delta + K_2 \Delta E'_q + K_{pDC} \Delta V_{DC} + K_{pc} \Delta c + K_{p\psi} \Delta \psi \\ \Delta E_q &= K_4 \Delta \delta + K_3 \Delta E'_q + K_{qDC} \Delta V_{DC} + K_{qc} \Delta c + K_{q\psi} \Delta \psi \\ \Delta V_t &= K_5 \Delta \delta + K_6 \Delta E'_q + K_{vDC} \Delta V_{DC} + K_{vc} \Delta c + K_{v\psi} \Delta \psi \\ \Delta V_{dc} &= K_7 \Delta \delta + K_8 \Delta E'_q + K_9 \Delta V_{DC} + K_{dc} \Delta c + K_{d\psi} \Delta \psi \end{aligned} \tag{15}$$

Arranging the state equations in matrix form gives,

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega} \\ \Delta \dot{E}'_q \\ \Delta \dot{E}_{fd} \\ \Delta \dot{V}_{DC} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ \frac{K_7}{K_8} & 0 & -\frac{1}{K_8} & -\frac{1}{T_A} & -\frac{K_9}{K_8} \end{bmatrix} x + \begin{bmatrix} 0 \\ -\frac{K_{pc}}{M} \\ -\frac{K_{qc}}{M} \\ -\frac{K_A K_{vc}}{T_A} \\ \frac{K_{dc}}{K_8} \end{bmatrix} \begin{bmatrix} \Delta c \\ \Delta \psi \end{bmatrix} \tag{16}$$

The above equation can be written as:

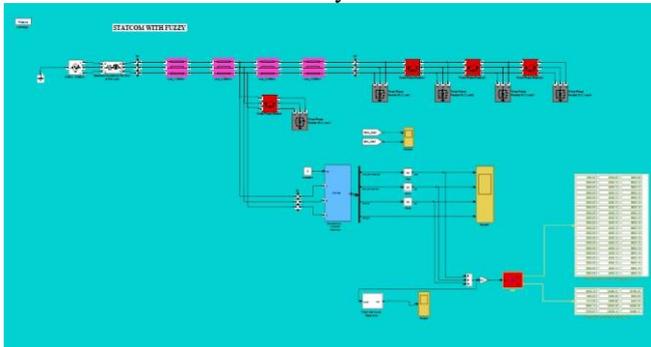
$$\dot{x} = Ax + Bu \tag{17}$$

where x is the perturbation of the states in equation (14) and u is the vector of control $[\Delta c, \Delta \psi]^T$.

The block diagram of linearized Philips Heffron model of SMIB system with STATCOM is shown in Figure 4.

V. RESULTS & CASE STUDIES

The effect of Voltage Regulator and Fuzzy STATCOM controller are evaluated. We firstly consider a simulink model of STATCOM with fuzzy controller



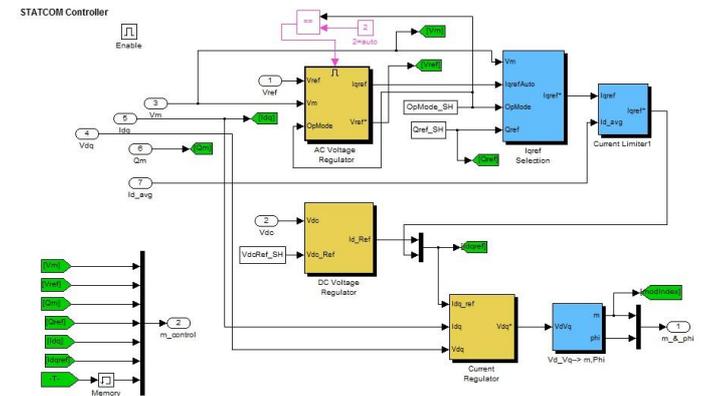
In the first part of our paper we designed a power system with single source of 230 KV/ 100 MVA with transmission lines upto 800 Km. long. The source is connected at one end of the line & load is connected to the other end of the line. A STATCOM connected at one center of the line (at 400KM from source) the rating of STATCOM is 100 MVA at 230 KV. Now the step is used to analyze the performance of STATCOM to improve the system performance of STATCOM to improve the system performance in terms of stability of voltage fluctuation with variation of load & with excessive reactive load. For load variation the line load from 25MVA is increased to 100 MVA in step of 25 MVA at line step of 20 cycles. In second scenario the reactive load of rating 50 MVA is switched to line. For both scenario the following parameters are measured & compared with & without STATCOM (1) Peak voltage swing (2) Settling time (3)Voltage variation at load.

In the second part of the paper a fuzzy based controller is designed for same. STATCOM for the improvement of AC Regulation block in simulink. Then the comparison is performed for same parameters as explained in first part. The fuzzy controller regulates the I_q ref according to it's input error voltage between measured & reference & change in error. The fuzzy input is scaled with triangular function with seven categories (Negative Large, Negative medium, Negative large, Zero position small, Zero position medium, Zero position low) both inputs & output uses the same method.

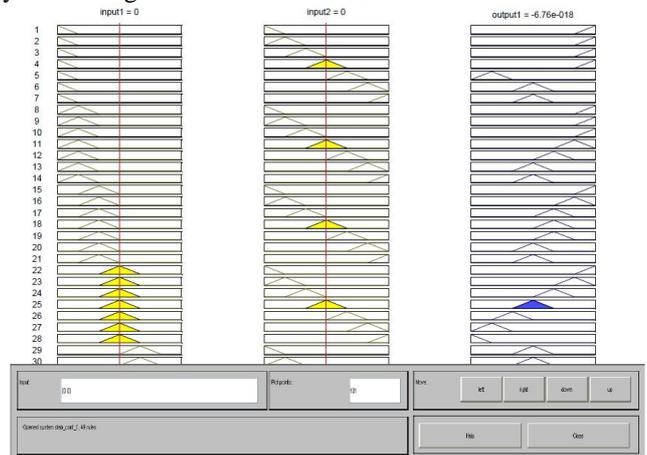
A. Effect of Voltage Regulator

Long transmission line presents a problem of unequal voltage along the length. The voltage at intermediate points along the line may exceed beyond safe limits causing flashovers. Once energized the shunt capacitance of the line becomes a source of reactive power (VAr). Under low load conditions the VAr generation exceeds the VAr consumption. If we consider a symmetric line which has controlled bus voltage at both ends. Without compensation under light load conditions the midpoint voltage may exceed the upper permissible voltage limit & under heavy load conditions the voltage may dip below the lower permissible limit. The voltage profile of the line becomes flat at surge impedance load. Therefore the problem arises how to control over voltages over long length

of line. This is solved by the connection of shunt reactors at intermediate buses. Mid-point controlled shunt compensation of long lines improve the voltage profile. It also enhances the power transfer capability of a long line by giving voltage support. The dark line show the voltage profile along the line without mid-point compensation for (1) Low load (Upper dark line). (2) Middle flat dark line (natural load). (3) Lower dark line (Heavy load , $P = 1.5 P_n$).



The DC-voltage regulator controls the DC voltage across the DC capacitor of the STATCOM Figure 3 shows the dynamic model of the DC-voltage regulator, which adopts PI control. The DC-voltage regulator functions by exchanging active power between the STATCOM and the power system. Hence its influence on power system oscillation damping should be expected and can be investigated based on the Phillips-Heffron model. For example, if it is assumed that the active power input to the STATCOM installed in the SMIB power system of Figure 1 is $P_{com} = V_{dc} I_{dc}$.



The power balance equation of the power system should be $P_m - P_e = P_{acc} + P_{com}$, where P_{m0} (constant) is the mechanical power input to the generator, P_e is the electric power output from the generator and P_{acc} is the accelerating power to the rotor movement of the generator. In the steady-state operation mode, $P_{m0} - P_{e0} = 0$ since $P_{acc} = 0$ and $P_{com0} = V_{dc0} I_{dc0} = 0, (I_{dc0} = 0)$. However, during the dynamic process, power balance is achieved to ensure that $\Delta P_e + \Delta P_{acc} + \Delta P_{com} = 0$. ΔP_{com} varies inversely with ΔP_e as does ΔP_{acc} so that the active power is kept in balance.

Therefore, ΔP_{com} is opposite to ΔP_e in phase and thus in 90° of phase lead with respect to generator speed $\Delta\omega$ from eqn. 7 it can obtain

$$\begin{aligned} \Delta P_{com} &= V_{DC0}\Delta I_{DC} + I_{DC0}\Delta V_{DC} = V_{DC0}\Delta I_{DC} \\ &= CV_{DC0}\Delta \dot{V}_{DC} = sCV_{DC0}\Delta V_{DC} \end{aligned} \quad (19)$$

Thus, ΔV_{DC} lags ΔP_{com} by 90° in phase and hence is in phase with $\Delta\omega$ which can be expressed as $\Delta V_{DC}=K_{DCw}\Delta\omega$. Therefore, from Figure 1 and Figure 3 it can obtain the 'direct electric- torque' contribution from the DC-voltage regulator to the electromechanical oscillation loop of the generator (converter dynamics is neglected, $T_c = 0$)

$$\begin{aligned} \Delta P_{com} &= V_{DC0}\Delta I_{DC} + I_{DC0}\Delta V_{DC} = V_{DC0}\Delta I_{DC} \\ &= CV_{DC0}\Delta \dot{V}_{DC} = sCV_{DC0}\Delta V_{DC} \end{aligned} \quad (20)$$

Since, with increasing $\psi\psi$, more active power is sent into the power system from the STATCOM, $K_P=\partial P_e\partial>0$ which indicates that the proportional control of the DC voltage regulator of the STATCOM provides the power system with negative damping torque, while the integral control of the DC-voltage regulator contributes no damping to system oscillations. The conclusion obtained above from the simple analysis can be confirmed by MATLAB simulation. The parameters of single-machine infinite-bus power system are given in the Appendix A1. The simulation results for the linearized model of eqn. 16, with different cases of STATCOM are shown in Figure 6. From the simulation results it can be concluded that:

- 1) The STATCOM DC-voltage regulator contributes negative damping to the power system. From Figure 6(i) it is observed that installation of STATCOM DC-voltage regulator results more oscillations in to the system.
- 2) The STATCOM DC-voltage regulator with integral control has very less effect on system damping as shown in Figure 6(ii).

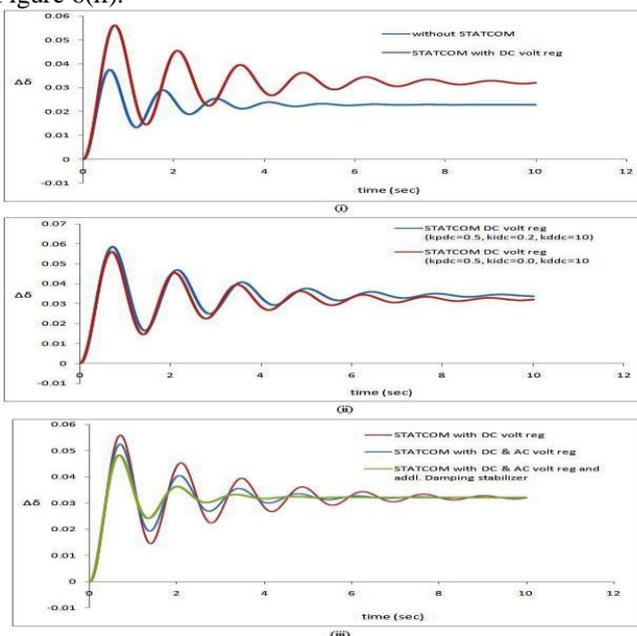


Figure 6. Responses showing (i) Effect of DC Voltage Regulator (ii) Effect of integral control of DC Voltage Regulator (iii) Effect of STAT-COM damping stabilizer

3) It can be observed from Figure 6(iii) that STATCOM AC voltage controller has a little influence on system damping. It is also observed that the negative damping effect is further reduced by providing an auxiliary damping stabilizer to STATCOM AC voltage controller.

B. Performance of Fuzzy STATCOM Controller

The performance of the fuzzy AC damping controlled STATCOM is evaluated with Fuzzy logic controller (FLC) by MATLAB simulation studies. The SMIB system was tested with the FLC for nominal operating condition. The system data is given in the Appendix A1. The dynamic performance of the rotor angle variation ($\Delta\delta$), rotor speed variation ($\Delta\omega$), terminal voltage variation (ΔV_t), and DC capacitor voltage (ΔV_{dc}) variations are compared with and without fuzzy controller for the nominal operating point following 1% mechanical disturbance are shown in Figure 7. It is clearly seen that with the inclusion of FLC, electromechanical damping characteristics of the system is improved.

It can be observed the fuzzy control scheme gives very good damping profile for nominal operating conditions. Philips-Heffron model has been designed for Single Machine Infinite Bus system with STATCOM located at the midpoint of the transmission line. The effect of STATCOM AC and DC voltage regulator and with an additional AC-damping stabilizer were presented and discussed for power system dynamics stability studies. It is observed from the simulation results that STAT-COM DC voltage regulator contributes negative damping to the power system.

The STATCOM DC voltage regulator with integral control has very less effect on system damping. The STATCOM along with DC voltage regulator and AC voltage regulator without any additional control has little influence on system damping. By adding additional AC damping controller to the AC voltage regulator, the negative damping effect is further reduced. In this paper fuzzy AC damping controlled STATCOM is designed for stabilization of power system oscillations in a SMIB system where additional AC damping controller of AC voltage regulator is replaced by the proposed fuzzy logic controller.

The SMIB system was tested with pro-posed fuzzy AC damping controlled STATCOM for nominal operating conditions. The change in rotor speed, rotor angle, terminal voltage and DC capacitor voltage fluctuations are compared with and without fuzzy logic control. It is observed that proposed fuzzy AC damping controlled STATCOM is capable of further enhancing the power system dynamic stability. It is fast and better option for damping out the electro-mechanical low frequency oscillations of power system. Hence, it can also be implemented in real-time control of power system.

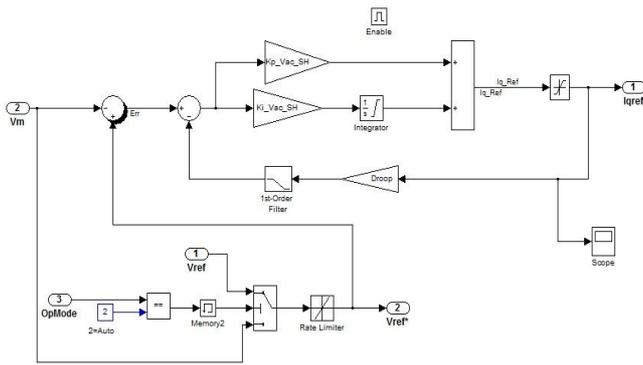


Figure 7: STATCOM WITHOUT FUZZY LOGIC CONTROLLER

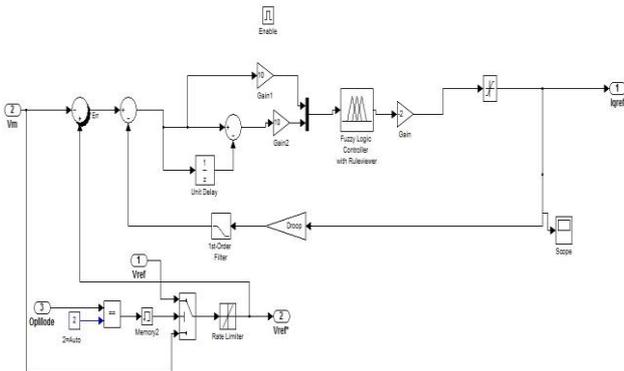
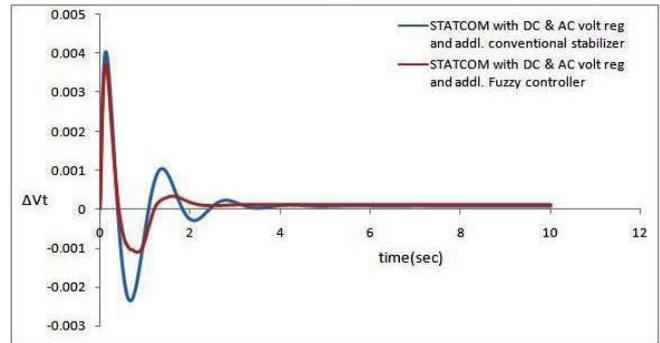
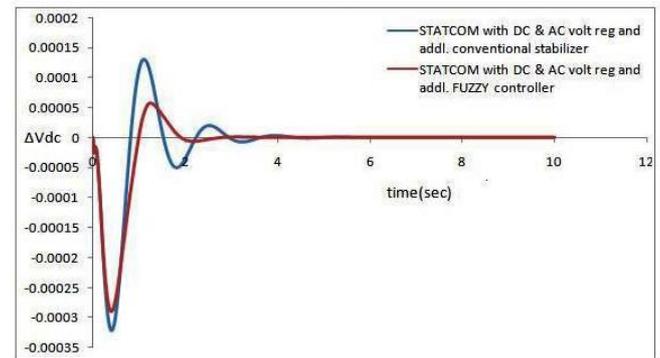


Figure 8: STATCOM WITH FUZZY LOGIC CONTROLLER INTRODUCED



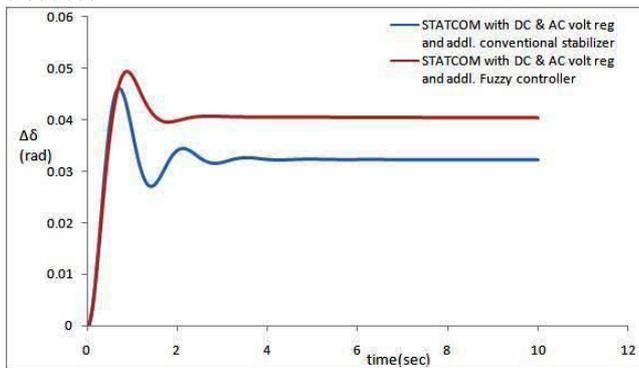
(iii)



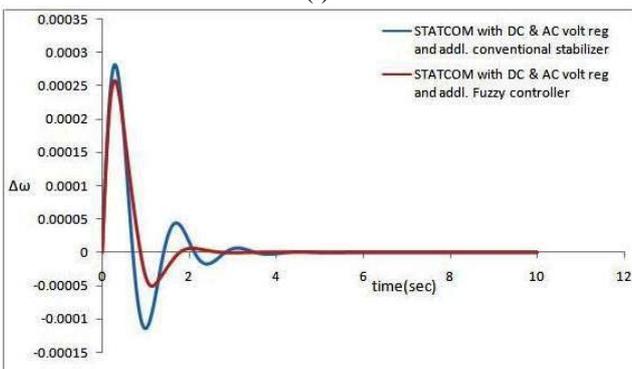
(iv)

Figure: 9. Comparison of responses for a 1% disturbance with and without fuzzy (i) Rotor angle variation (ii) Rotor speed variation (iii) Terminal voltage variation (iv) DC Capacitor voltage variation. Conclusions

Output Waveforms as seen with Fuzzy logic controllers introduced



(i)



(ii)

VI. CONCLUSION

In this paper, a fuzzy logic controller is proposed to control STATCOM for improving power system transient stability and system damping. Fuzzy logic controller works according to system behavior. Controller input parameters are carefully chosen to provide considerable damping for power system. The range of each controller is determined based on simulation results of the fuzzification process. Simulation results indicate that this controller can improve stability margin of the system in the case of transient stability and provide considerable damping of power oscillation.

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