Fuzzy Logic Control of Static Var Compensator for Power System Damping

N.Karpagam , D.Devaraj

Abstract—Static Var Compensator (SVC) is a shunt type FACTS device which is used in power system primarily for the purpose of voltage and reactive power control. In this paper, a fuzzy logic based supplementary controller for Static Var Compensator (SVC) is developed which is used for damping the rotor angle oscillations and to improve the transient stability of the power system. Generator speed and the electrical power are chosen as input signals for the Fuzzy Logic Controller (FLC). The effectiveness and feasibility of the proposed control is demonstrated with Single Machine Infinite Bus (SMIB) system and multimachine system (WSCC System) which show improvement over the use of a fixed parameter controller.

Keywords—FLC, SVC, Transient stability, SMIB, PID controller.

I. INTRODUCTION

POWER System Stability is the ability of the system to regain its original operating conditions after a disturbance to the system. Power system transient stability analysis is considered with large disturbances like sudden change in load, generation or transmission system configuration due to fault or switching [1]. Dynamic voltage support and reactive power compensation have been identified as a very significant measure to improve the transient stability of the system. Flexible AC Transmission Systems (FACTS) devices with a suitable control strategy have the potential to increase the system stability margin [2,3]. Shunt FACTS devices play an important role in reactive power flow in the power network. In large power systems, low frequency electro-mechanical oscillations often follow the electrical disturbances. Generally, power system stabilizers (PSS) are used in conjunction with Automatic Voltage Regulators (AVR) to damp out the oscillations [3]. However, during some operating conditions this device may not produce adequate damping and other effective alterations are needed in addition to PSS [4,5]. Another means to achieve damping is to use the same shunt FACTS device Static Var Compensator (SVC) designed with auxiliary controllers [6]. Therefore SVC is more effective and if accommodated with supplementary controller, by adjusting

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the equivalent shunt capacitance, SVC will damp out the oscillations and improves the overall system stability [7]. The system operating conditions change considerably during disturbances. Various approaches are available for designing auxiliary controllers in SVC. In [8] a proportional – integral – derivative (PID) was used in SVC. It was found that significant improvements in system damping can be achieved by the PID based SVC. Although PID controllers are simple and easy to design, their performances deteriorate when the system operating conditions vary widely and large disturbances occur. Fuzzy logic control approach is an emerging tool for solving complex problems whose system behavior is complex in nature. An attractive feature of fuzzy logic control is its robustness in system parameters and operating conditions changes [9, 10]. Fuzzy logic controllers are capable of tolerating uncertainty and imprecision to a greater extent [11]. This paper presents a method based on fuzzy logic control for SVC controller which damp out the oscillations at a faster rate. Global input signals such as machine speed (ω) and electrical power (Pe) are given as input to the fuzzy controller. Simulation results for a Single Machine Infinite Bus System (SMIB) and a Multi machine system (WSCC system) are presented and discussed. Finally a comparative study has been carried out between the PID controller and fuzzy controller.

II. MODELING AND CONTROL OF SVC

The Static Var Compensator is basically a shunt connected variable Var generator whose output is adjusted to exchange capacitive or inductive current to the system. One of the most widely used configurations of the SVC is the FC- TCR type in which a Fixed Capacitor (FC) is connected in parallel with 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

$$B_L(\alpha) = \frac{2\pi - 2\alpha + \sin 2\alpha}{\pi X_S} \tag{1}$$

for $\Pi/2 \le \alpha \le \Pi$ where $X_S = \dfrac{V_S^2}{Q_L}$ V_S= SVC bus bar voltage

and Q_L = MVA rating of reactor. As the SVC uses a fixed capacitor and variable reactor combination (TCR- FC), the effective shunt admittance is

$$B_S = \frac{1}{X_C} - B_L(\alpha) \tag{2}$$

where X_C=Capacitive reactance.

An SVC with firing control system can be represented, for the sake of simplicity by a first order model characterized by a gain K_{SVC} and time constants T_1 and T_2 as shown in Fig.1 The controller send firing control signals to the thyristor switching unit to modify the equivalent capacitance of the SVC. The fuzzy controller provides a auxiliary control, which is in addition to the voltage feedback loop.
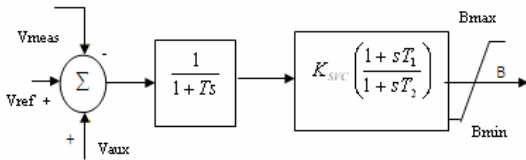

Fig.1 Block representation of SVC control

The auxiliary control loop of the SVC uses stabilizing signals, such as speed, frequency, phase angle difference etc... to improve the dynamic performance of the system.

III. REVIEW OF FUZZY LOGIC

Fuzzy set theory provides an excellent means for representing uncertainty due to vagueness in the available data or unknown behavior of a system. It can represent the human control processes and also allows experimental knowledge in adjusting the controller parameters.

A. Fuzzy sets

A fuzzy set is a collection of distinct elements with a varying degree of relevance or inclusion. If X is a set of elements, then a fuzzy set A in X is defined to be a set of ordered pairs,

$A = \{(x, \mu_A(x)) | x \in X\}$ where $\mu_A(x)$ is called the membership function of x in A. This membership function can take $\mu_A(x)$ denotes the degree to which x belongs to A and is normally limited to values between 0 and 1.A high value of $\mu_A(x)$ implies that it is very likely for x to be in A.

B. Fuzzy If – Then rules

In the fuzzy model the knowledge relating the input features and the output class are represented by the fuzzy if – then rules of the form R_j: if x_{pl} is A_{jl} and x_{pn} is A_{jn}, then class C_j with CF = CF_j where $A_{j1},…A_{jn}$ are antecedent fuzzy sets in the unit interval [0 ,1], C_j is one of the class codes and CF_j is the grade of certainty of the rule. A collection of such statements replace the usual mathematical model of system theory. The knowledge required to generate the fuzzy if – then rules can be derived from an expert operator and a design engineer or by an off – line simulation.

C. Fuzzy Inference system

With cause effect relationship expressed as a collection of fuzzy if – then rules , in which the preconditions uses linguistic variables and the consequent have class labels, qualitative reasoning is performed to infer the results. In our model Mamdani inference system with product t-norm and max t-co norm is used. Here, the set of sensor input is matched against the if part of each if – then rule, and the response of each rule is obtained through fuzzy implication operation. The response of each rule is weighted according to the extent to which each rule fires. The response of all the fuzzy rules for a particular output class are combined to obtain the confidence with which the sensor input is classified to that fault class.

D. Defuzzification

The output of a fuzzy rule based system is generally imprecise and fuzzy. As a fuzzy set cannot directly be used to take the decisions, the fuzzy conclusions of rule based systems have to be converted in to precise quantity. This is called Defuzzification. There are various methods like centroid method, weighted average method and max-membership method etc… for this purpose.

IV. FLC BASED DAMPING CONTROLLER DESIGN

Fig.2 shows the schematic diagram of a SVC along with Fuzzy logic based damping controller. Generator speed deviation (Δω) and (ΔP) are taken as the input signals of the fuzzy controller.
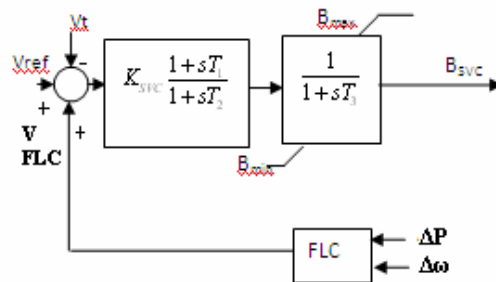

Fig. 2 Block diagram of proposed Fuzzy logic controller

The number of membership functions for each variable determines the quality of control which can be achieved using fuzzy logic controllers. In the present investigation, five membership functions are defined for the input and output variables. Fig.3 shows the membership functions defined. The mentioned membership functions are used to specify a set of rules called a rule base. The rules developed are based on the knowledge and experience. With two inputs and five linguistic terms, 25 rules were developed which is given in Table 1. In inference mechanism all the rules are compared to the inputs to determine which rules apply to the current situation. After the matching process the required rules are fired. The controlled output Bsvc is determined for the different input conditions. The defuzzification produces the final crisp output of FLC with the fuzzified input. Centroid method is employed where the output will be calculated as

$$O/P = \frac{\sum_{i=1}^{5} b_i \int \mu_{(i)}}{\sum_{i=1}^{5} \int \mu_{(i)}} \qquad (3)$$
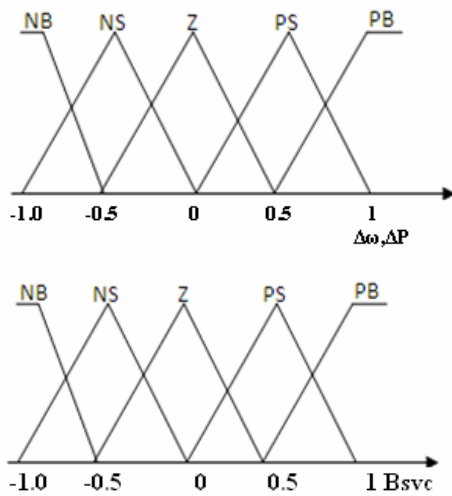
Fig. 3 Membership functions of $\Delta\omega$, ΔP and Bsvc

TABLE 1
FUZZY INFERENCE RULES

Output (B $_{SVC}$)		ΔP				
		NB	NS	Z	PS	PB
	NB	NB	NS	NB	NS	Z
	NS	NS	NB	Z	Z	PS
$\Delta\omega$	Z	NS	Z	Z	PS	PS
	PS	Z	Z	PS	PS	PS
	PB	Z	PS	PS	PS	PB

V. SIMULATION RESULTS

To assess the effectiveness of the proposed controller, simulation studies are carried out for the most severe fault conditions and overload conditions in both SMIB system and Multi machine system. The details of the simulation are presented here.

A. .SMIB system

A SMIB system, equipped with Generator, Transmission line and SVC at the midpoint of the line is shown in Fig.4 The SVC with its controller is place at the midpoint of the transmission line. The fuzzy damping controller for the SVC is developed using MATLAB / SIMULINK and its block diagram is shown in Fig.5. A three phase fault is simulated at the load end at t= 0.1 sec. and cleared after 0.05 sec. The system response without SVC is oscillatory and leads to instability.
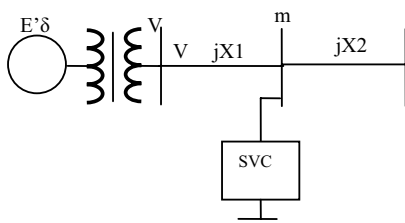
Fig.4 SMIB system with SVC - single line diagram
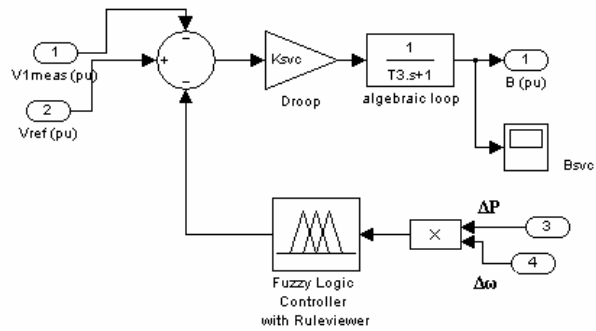
Fig.5 SIMULINK model of FLC controller for SVC

When the SVC with conventional PID controller is placed at bus 1 and the same fault condition is simulated, it is observed that the damping is improved but still oscillations are present. With the FLC based SVC the oscillations are fully damped out and the system comes back to original steady state. Figs 6 and 7 show the dynamic response of the power angle δ and the speed deviation $\Delta\omega$, under fault conditions with different controllers.
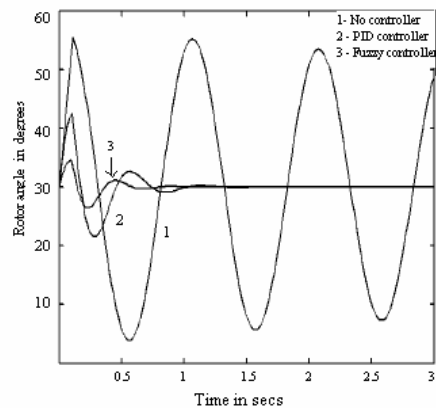
Fig .6 Variation in rotor angle for   different controllers of SVC

B. Multimachine system

The same SVC controller with FLC is implemented in the 3 machine nine bus system (WSCC system). The one line diagram of WSCC system is given Fig.8.

Fig.7 Variation in speed deviation (Δω) for different controllers
        of SVC

Power system data is given in [8]. Power system stabilizers with IEEE type DC1 exciter are equipped with the generators.
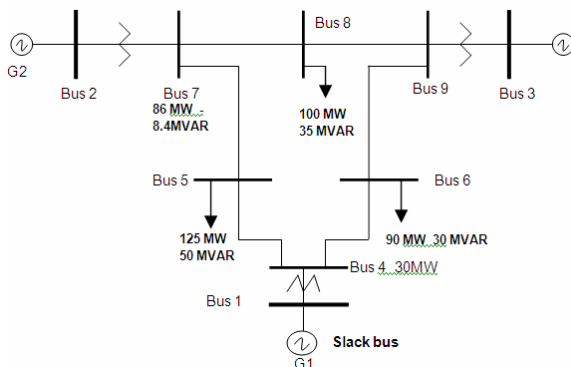
Fig. 8 One line diagram of WSCC system

Case 1: The FLC based SVC is installed at bus 8 near the generator 2. With the initial power flow conditions, a three phase to ground short circuit was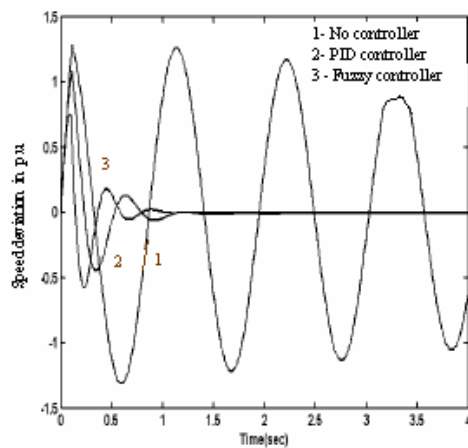 simulated near bus 7. In Figs 9 to 12 the variation of rotor angle δ, SVC voltage, speed deviation Δω, and the suceptance Bsvc of SVC with PID controller and with FLC based SVC controller are plotted. In this study case, fault condition at 0.3 seconds, existing for the period of 0.1 second and cleared at 0.4 seconds is shown in Fig.9. It is clear that the rotor angle damping using fuzzy controller is more effective than PID controller. The settling time of both controllers is found to be same, but the amplitude of rotor angle is reduced in FLC controller.
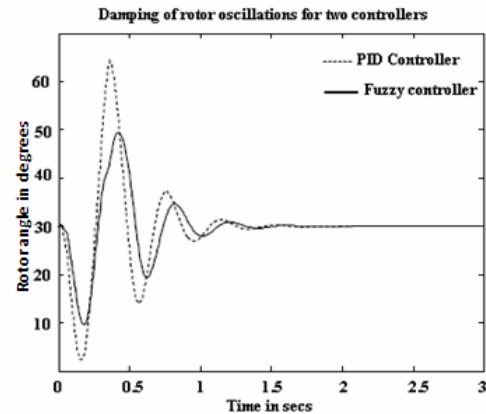
Fig.9. Damping of rotor angle oscillations for FLC- SVC
        for three phase fault at bus 7

From Fig.10, it is observed that the bus voltage of SVC with the proposed FLC is reduced during fault conditions. If PID controllers employed, the SVC voltage increases during fault period which causes additional voltage injection in the system instead of current injection. This will be the remarkable advantage while using a FLC based controller.
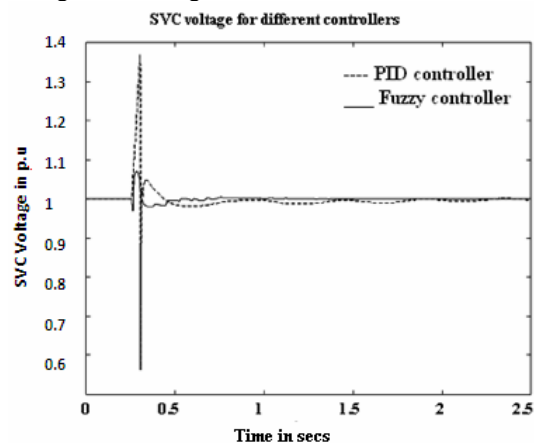
Fig.10 SVC voltage in p.u fault with FLC for 3 – phase fault
        at bus 7

From Fig.11, it is identified that the angular speed deviations Δω will be same for the two controllers and in post fault period, the angular speed deviations are quickly reduced using FLC controller.

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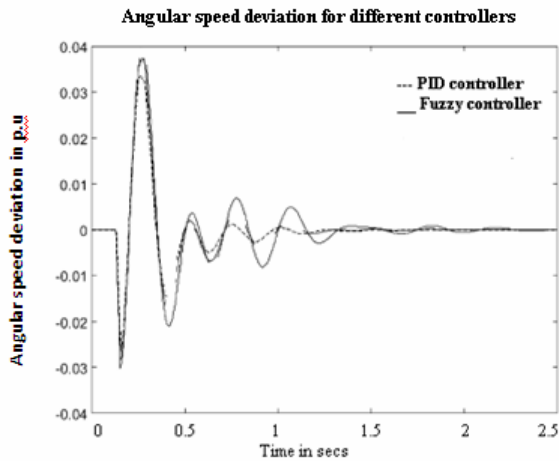
Fig.11 Angular speed deviation in p.u for 3 – phase fault at bus 7

From Fig.12, the injection of B_{SVC} during fault condition is demonstrated. When the fault occurs, the suceptance injected will be at maximum of 1.25 p.u and due to the firing angle control through FLC, it was immediately thrown of to inductive effect from capacitive effect.
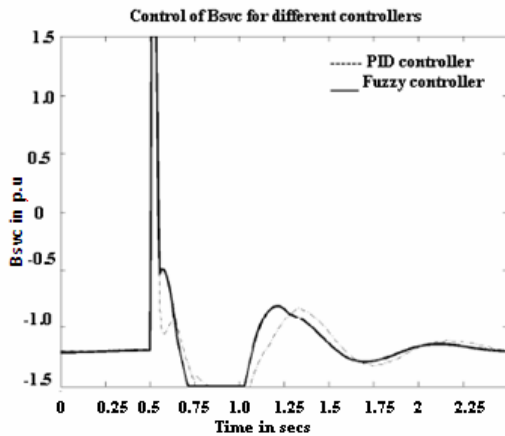
Fig.12. Control of Bsvc with FLC based SVC for three phase Fault at bus 7

Case 2: In this case, with the same location of SVC at bus 8, power of load bus 7 is increased to 1.5 p.u at 0.5 second with 0.5 second duration. The system response is studied with both PID and FLC based SVC controller. For this overloaded condition also, SVC supplies reactive power during this period and quickly maintains the system stability. From the Fig.13, it can be seen that, complete damping of rotor angle oscillations occur at 2.25 seconds only with PID controller whereas with FLC controller damp out the oscillations at 1.5 seconds. From the Fig.14, it can be observed that the suceptance Bsvc included in the system is increased from 0.5 p.u to 1.0 p.u at 0.5 second at which the disturbance is occurring.
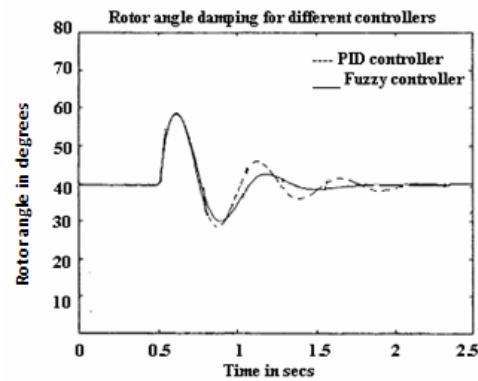
Fig.13 Damping of rotor angle oscillations for FLC- SVC for loading condition of 1.5 p.u

For the time interval of 0.5seconds, the suceptance is included and at the period of 1 second, the capacitive effect is changed over to inductive effect and regains its original state at quicker time with the presence of FLC –SVC controller.
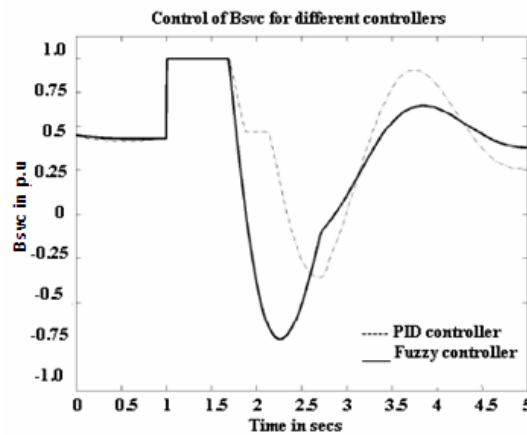
Fig. 14 Control of Bsvc for loading condition of 1.5 p.u

VI. CONCLUSION

This paper presents the application of a fuzzy logic based auxiliary control for an SVC to achieve transient stability enhancement. The proposed FLC for SVC is proved to be very effective and robust in damping power system oscillations and thereby enhancing system transient stability. Fuzzy rules are easily derived from the measurable global signals like line active power flow, and remote generator speed deviation. The performance of various controllers is then compared based on non linear simulation results which are shown in Fig.6 to 14. Among these the performance of the proposed controller is found to be better and damp out the system oscillations at faster rate. It was also observed that for both SMIB system and multimachine system, SVC controller works accurately. Digital computer simulations were performed using MATLAB/ SIMULINK software.

APPENDIX

I. Modeling of Power System Components

A. Generator

The generator is represented by third order model comprising the electromechanical swing equation and the generator internal voltage equations [10] are

$$\dot{\delta} = \omega_0 \omega \tag{4}$$

$$\dot{\omega} = \frac{1}{M}(P_m + G + K_d\omega - P_e) \tag{5}$$

$$\dot{E}_q' = \frac{1}{T_{do}'}[E_{fd} - (x_d - x_d')i_d - E_q'] \tag{6}$$

where
δ=Rotor angle in degrees
ω= angular speed in rad/sec
P_m=Mechanical power developed by the generator
K_d= Damping constant of the generator
P_e = Electrical Power delivered in p.u
X_d, X_q= Direct and quadrature axis reactance of the generator in p.u
E_d, E_q = Direct and quadrature axis voltages behind the transient reactance in p.u

B. Exciter and PSS

The block diagram representing IEEE type 1 DC exciter and Power System Stabilizer (PSS) accommodated with the generator is shown in Fig.15 which is modeled with the following equations

$$\dot{E}_{fd} = \frac{K_A}{T_A}(V_{ref} - V_t + U_{PSS}) - \frac{E_{fd}}{T_A} \tag{7}$$

$$P_e = v_d i_d + v_q i_q \tag{8}$$

and

$$V_t = (v_d^2 + v_q^2)^{1/2} \tag{9}$$

with $v_d = E\sin\delta - (x_q i_q)D_s$ and

$$v_q = E_q' - x_d' i_d$$

$$G = (K_{G1} + \frac{K_{G2}}{1 + sT_G})\dot{\delta} \tag{10}$$

Fig.15. IEEE type DC1 exciter

$$U_{PSS} = -\frac{1}{K_P}\left(\frac{sT_1}{1 + sT_2}\right)\left(\frac{1 + sT_3}{1 + sT_4}\right)\dot{\delta} \tag{11}$$

where
K_A and T_A = gain and time constants of the exciter
V_{ref} = reference voltage in p.u
V_t = Terminal voltage in p.u
E_{fd} = Field voltage of the generator in p.u
K_{G1}, K_{G2}= Gain constants of the Governor
$K_{P=}$ Gain of the PSS
T_1,T_2,T_3 and T_4 = Time constants of the PSS
Ds = Damping coefficient of PSS
U_{PSS}= Output of PSS in p.u

II. Solution for Multimachine Systems

In the multimachine system model, the loads are assumed to be constant impedance and converted in to admittances as

$$\bar{y}_{Li} = \frac{-(P_{Li} - jQ_{Li})}{V_i^2} \text{ where i-1,....m.} \tag{12}$$

The network equations for the new augmented network can be written as

$$\begin{bmatrix} \bar{I}_A \\ 0 \end{bmatrix} = \begin{bmatrix} \bar{Y}_A & \bar{Y}_B \\ \bar{Y}_C & \bar{Y}_D \end{bmatrix} \begin{bmatrix} \bar{E}_A \\ \bar{V}_B \end{bmatrix} \tag{13}$$

which can be reduced to

$$\bar{I}_A = (\bar{Y}_A - \bar{Y}_B\bar{Y}_B\bar{Y}_D^{-1}\bar{Y}_C)\bar{E}_A = \bar{Y}_{int}\bar{E}_A \tag{14}$$

Where the elements of the $\bar{I}_A$ and $\bar{E}_A$ are

$$\bar{I}_i = (I_{di} + jI_{qi})e^{j(\delta_i - \pi/2)} \tag{15}$$

$$\bar{E}_i = E_i\angle\delta_i \tag{16}$$

The elements of $\bar{Y}_{int\,i}$ are

$$\bar{Y}_{ij_i} = G_{ij} + jB_{ij_i} \tag{17}$$

For the simulation of multi machine system, first the admittance matrix (Y) of the system is calculated and the complexity of transient stability analysis is reduced by considering all the rotor angles of synchronous machines coincides with angle of the voltage behind the transient reactance and all the machines are assumed to swing at coherent. The power flow equation of ith machine is calculated by

$$P_{ei} = \sum_{j=1}^{m} |E_i'||E_j'||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{18}$$

And the swing equation is

$$\frac{H_i}{\pi f_0}\frac{d^2\delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m} |E_i'||E_j'||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{19}$$

III. System data

Synchronous machine data

X_d=1.8	X_d'=0.3	X_d"=0.15
Xq=1.8	X_q'=0.0	X_q"=0.15
T_{do}'=6.0	T_{do}"0.04	H=4
T_{qo}'=0.2	T_{do}"=0.0	
R=0.002	X_1=0.0	K_d=0.0

Exciter IEEE Type DC 1 Data (p.u)

K_A=200 T_A=0.02

K_F=0.028 T_F=0.92

K_E=0.0 T_E=0.05

SVC data
K_{SVC}=100 T_1 =0.0 T_2 = 0.05 Bsvc=±1.5

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