Fuzzy Logic based Power Factor Control of Synchronous Machine

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ABSTRACT

In this paper, a fuzzy logic technique is used to control the power factor (PF) that compensate the reactive power of the load by controlling the excitation system of synchronous machine. This fuzzy logic controller can give a fast response compensation to meet the required load reactive power and hence keeping the load bus at constant set point PF value. The V curve of PF is treated in a way to get the flexibility and the limitation the over or under values, as well as time delay could therefore be eliminated with such a control configuration. The results show that fuzzy based power factor controller using synchronous machine is reliable, sensitive, faster and more efficient compare with the other methods such as capacitor groups.

Matlab-Simulink program was adopted for the architecture and learning procedure of fuzzy system depending of construct an input-output mapping based on both knowledge and stipulated input-output data pairs. A model of the synchronous machine was also presented in this paper. The variable DC voltage based excitation field current controller was built based on fuzzy logic controller to generate the firing angle of six-pulse rectifier circuit.

Keywords

Fuzzy logic controller, Power factor controller, Synchronous machine model, and Reactive power compensation.

List of Symbols:

SM = Synchronous machine.

v_a, v_b and v_c = Thee phase terminal voltages (Volt).

i_a, i_b and i_c = Thee phase terminal current (Ampere).

α= Firing angle (degree).

V_f= DC field voltage (volt).

I_f= DC field current (amper).

R_f= Resistance of field circuit (ohm).

L_{ff}= Self of rotor inductance (henry).

L_a, L_b and L_c= Stator self-inductance (static)/ phase (henry).

L_{ab}, L_{bc} and L_{ca}= Mutual inductance between stator Phases (henry).

L_{af}, L_{bf} and L_{cf}= mutual inductances between stator phases and rotor (henry).

L_s= Part of phase inductance harmonic because of salience (henry).

λ_a, λ_b and λ_c= Instantaneous linkage flux for stator phases (Wb).

λ_f = Instantaneous linkage flux for rotor (Wb).

[V]= Voltage matrix (volt).

[R]= Resistance matrix (ohm).

[i]= Current matrix (amper).

[λ]=Linkage flux matrix (Wb).

[L]= Inductance matrix (henry).

Te= Electrical torque (N.m).

TL= Mechanical torque (N.m).

ωs= Synchronous speed (rpm).

ωr= Rotor speed (rpm).

θ= Displacement angle for rotor refers to stator phase (a) (rad).

Vf =DC field voltage (volt).

PL&QL = Real and reactive power load demand respectively (watt, var).

Pm&Qm = Real and reactive power of the Synchronous machine respectively (watt, var).

Pt&Qt = Total real and reactive power for the Synchronous machine and load demand respectively (watt, var).

1. INTRODUCTION

Reactive power is a quantity that is normally only defined for alternating current (ac) electrical systems [1]. In an AC system, the voltages and currents alternate up and down 50 times per second since the frequency of the voltage is 50 Hz. In that sense, these are pulsating quantities. Because of this, the power being transmitted down a single line also pulsates, although it goes up and down 100 times per second rather than 50. This power goes up and down around an average value that is called the real power [2]. Over time, customers pay for this in kilowatt-hours of energy. If this average value is zero, then all of the power being transmitted is called reactive power. Customers would not normally be charged for using reactive power because they are consuming some energy half the time, and giving it all back the other half of the time, for a net use of zero [3]. Voltage and current may not be in phase. When the voltage and current are in phase, only real power is transmitted. When the voltage and current are not in phase, reactive power is being transmitted [4, 5].

Capacitor groups with adjustable inductance can be used for reactive power compensation that can give a smooth

correction without step changes. In industry, most of the reactive power compensation systems have been achieved by using constant capacitor groups, which are controlled by contactors and timers [6]. In this case, the penalties such as time delay, over compensation or lower compensation are always possible because of the step changes of capacitor groups. In addition, capacitors are often less flexible and less economical. On the other hand, synchronous machine (SM) can operate at unity, lagging or leading PF condition, so that the SM can be provide network by the reactive power demand [7].

Presently for the smooth and fast reactive power compensation, SM will be widely used for the reactive power compensation due to low cost of the compact system, SM and controller, as compared with power electronics with capacitor grope, Flexible AC Transmission System (FACTS) [8]. In addition, SM minimal harmonics content and, therefore, require no special filtering [9].

2. DETERMINATION OF CAPACITOR POWER

A system with the installed active power P is to be compensated from a power factor cos φ1 to a power factor cos φ2. The capacitor power necessary for this compensation is calculated as follows: Qc = P · (tan φ1 – tan φ2)

Compensation reduces the transmitted apparent power S, as shown in Figure 1. Ohmic transmission losses decrease by the square of the currents.
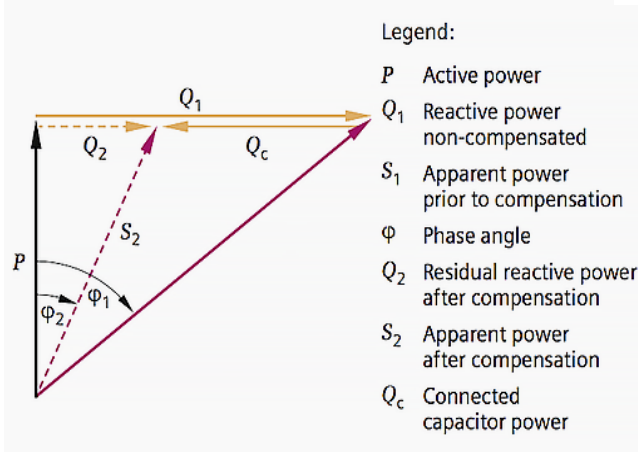

Fig. 1: Power diagram for a non-compensated (1) and a compensated (2) installation.

3. VOLTAGE STABILITY AND POWER FACTOR

In a practical calculation for a complex power system, the fall in system voltage as the load rises must be assumed to operate the on load tap changer (OLTC). When these reach their limits, and VAR Compensator VC equipment reach to limit also, the system voltage will continue to fall as the load rises. The single line diagram of a 2-Bus system is shown in Figure 2. It can be seen form result in Figure 3 that the variation of voltage stability margin is wide for lagging PF values up to unity PF while this margin is narrow for leading PF. Increasing voltage levels by OLTC action can decrease the margin of voltage stability due to the effect of increasing the inductively reactive power in to the load side, in case the VC equipment reaches its limit in providing reactive power [9, 10].

The critical voltage can be kept constant with the variation of both PF and power. Figure 4 shows the variation of reactive power with voltage for different constant values of real power [7, 11].
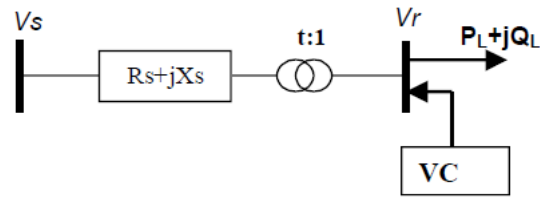

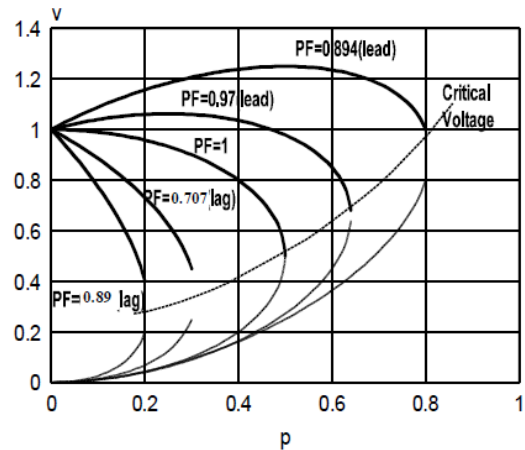**Fig.2: The single line diagram of a 2-Bus system.**

Fig.3: Normalized p-v curves for two bus system,

$$\text{Where} \quad v = \frac{Vs}{Vr} , \quad p = \frac{PXs}{Vs^2} .$$
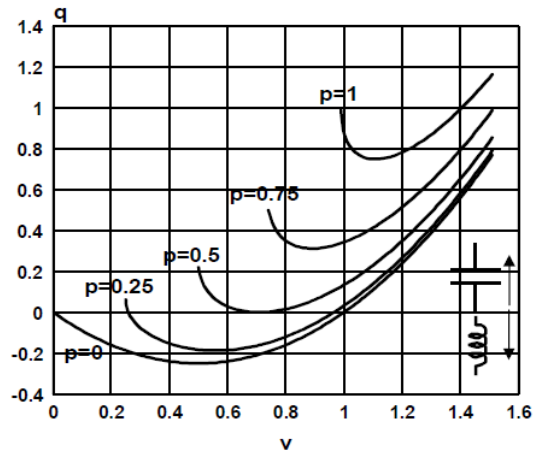

Fig.4: Normalized v-q curves for two bus system, where

$$v = \frac{Vs}{Vr} , \quad q = \frac{QXs}{Vs^2} .$$

4. MODELING OF SYNCHRONOUS MACHINE

The direct 3-phase model of the SM can be represented by the following equations [12]:

$$[V] = [R] \cdot [i] + p\{[L] \cdot [i]\} \qquad \dots(1)$$

$$[V] = [R] \cdot [i] + p[\lambda] \qquad \dots(2)$$

where p represented the derivative pointer.

$$[i] = \begin{bmatrix} i_a & i_b & i_c & i_f \end{bmatrix}^t \qquad \text{...(3)}$$

$$[R] = diag\begin{bmatrix} R_a & R_b & R_c & R_f \end{bmatrix} \qquad \text{...(4)}$$

$$[V] = \begin{bmatrix} v_a & v_b & v_c & V_f \end{bmatrix}^t \qquad \text{...(5)}$$

$$p[\lambda] = \begin{bmatrix} p\lambda_a & p\lambda_b & p\lambda_c & p\lambda_f \end{bmatrix}^t \qquad \text{...(6)}$$

Since, the relationship between leakage flux and current is:

$$[\lambda] = [L] \cdot [i] \qquad \text{...(7)}$$

where [L] matrix given in Table 1.

Differentiating two sides of equation (7) gives:

$$p[\lambda] = [L] \cdot p[i] + \frac{d[L]}{d\theta} \cdot [i] \cdot p\theta \qquad \text{...(8)}$$

where matrix $\dfrac{d[L]}{d\theta}$ is given in Table 1.

Rearranging equation (8) would result in:

$$p[i] = [L]^{-1}\left\{ [V] - [R] \cdot [i]' - \frac{d[L]}{d\theta} \cdot [i] p\theta \right\} \qquad \text{...(9)}$$

The total electrical developed torque would thus be [12]:

$$T_e = 0.5 \cdot \rho \cdot [i]' \cdot \frac{d[L]}{d\theta} \cdot [i] \qquad \text{...(10)}$$

$$T_e = T_m + K \cdot \omega_r + KD\frac{d\delta}{dt} + J\frac{d\omega}{dt} \qquad \text{...(11)}$$

All equations from (1) to (11) were modeled and simulated using MATLAB-Simulink. Figure 5 shows the overall suggestion system and Figure 6 shows the Matlab model.

5. FUZZY LOGIC CONTROLLER

Fuzzy control is one of the most well-known fuzzy logic applications. In 1974, E. H. Mamdani was the first to demonstrate the application of fuzzy logic in control field [13]. A major breakthrough of fuzzy control came in the beginning of 1980's, where a controller development for a cement kiln was the first real application of fuzzy control. Within the next year, several successful applications were presented, where many of them had been exposed during the IFSA (International Fuzzy Systems Association) meeting in Tokyo 1987 [14, 15].

The objective is to design a FLC capable of keeping the plant PF at or above the desired threshold value by compensating load reactive power. The FLC will use both of the PF and error signal (e) of the SM as inputs to obtain the FLC output used to drive six-pulse full wave thyristorized rectifier circuit which can thus control the excitation field voltage. The SM would thus produce kVAR which will achieve the load reactive power at the desired SM PF.

The proposed FIS can construct an input-output mapping based on both human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs, for SM at no load, as shown in Figure 7-a, where the inverse V-curve has been treated in a way that all lagging PF less than unity PF are taken as its values, while all leading PF less than leading unity

were processed in such a way that the zero leading PF value is considered to be equal to 2, the whole leading PF range would thus be in the range of : ...(2.9)

$$2 \geq PFm_{Leading} > 1$$.

The designed FIS has two fuzzy variables (PF and error) and seven linguistic variables for each, PF from very Lag (VLa) to very Lead (VLe) and Error from negative big (NB) to positive big (PB). The FLC attributes and all details are summarized as follows and shown in the in Figure 7-b.

Name: 'PF controller'; type: 'sugeno'.

AndMethod: 'prod'; orMethod: 'max'.

DefuzzMethod: 'wtaver'; impMethod: 'prod'.

AggMethod: 'sum'; input: [1x2 struct].

Output: [1x1 struct]; rule: [1x49 struct].

The membership functions of the input fuzzy variable are shown in Figure 7-c and Figure 7-d. The control surface is defined with 49 rules, as shown in Figure 7-e. A flowchart of reactive power compensation using fuzzy algorithm had been shown in Figure 8.

6. SIMULATION RESULTS

Reactive power compensation of power system based on VAR/PF controller of SM could be made after the complete determination of the power system weak buses with the aid of the analysis and modeling using Q-V sensitivity. A computer program gives the effect of reactive power compensation on weak bus and overall system, which would thus give the state of the system voltage stability.

Simulation results of the SM and IEEE 14-buses sample system, shown in Figure 9, is presented and analyzed in this paper. The weak buses of IEEE 14-bus sample system are determined as shown in Figure 10. Numerous graphs showing in Figure 11 the behavior of the system in various conditions have been included to illustrate the analysis with various values of control action.

7. CONCLUSIONS

PF fuzzy Controller for reactive power compensation is investigated in a single machine connected to infinite bus system with load. A controller introduced depends on the dynamic behavior of SM analysis. This machine is used to control the total reactive power absorbed by the load. An intelligent controller FIS have been designed, and compared to output control signal used to drive six-pulse full wave thyristorized rectifier circuit which can thus control the excitation field voltage. The SM (working as motor) will produce the needed kVAR, for the desired PF to the weak bus.

• Design of FLC give higher performance that overcome output response overshoot in both of the over or under compensations. The main benefits of this designed system would thus exist in more flexibility, fast (about two cycles), more efficient, reliable and economical.

• Synchronous motor can be used as a dynamic reactive power compensator for constant loads and a voltage regulator for variable loads, which would in turn increase the system voltage stability owing to converting this weak load bus into strong bus by overcoming the reactive load demand. The PF remains constant for different load reactive power variations.

• Bifurcation analysis and Q-V sensitivity methods have been used to calculate system weak buses which are characterized by showing higher participation factors to the smallest Eigen-values. These methods have been applied on IEEE 14-Bus

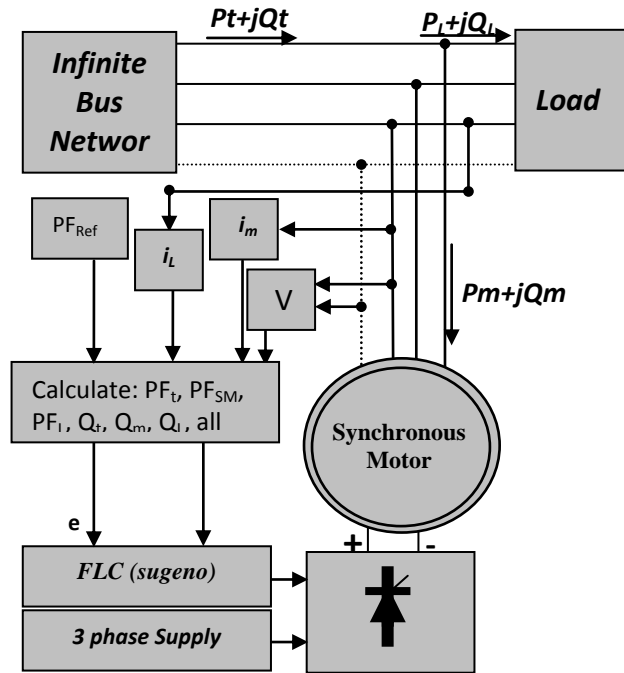MATLAB, PSAT. The weak load bus has been chosen for the SM reactive power compensation that would hence in turn result in improving the overall system voltage stability.
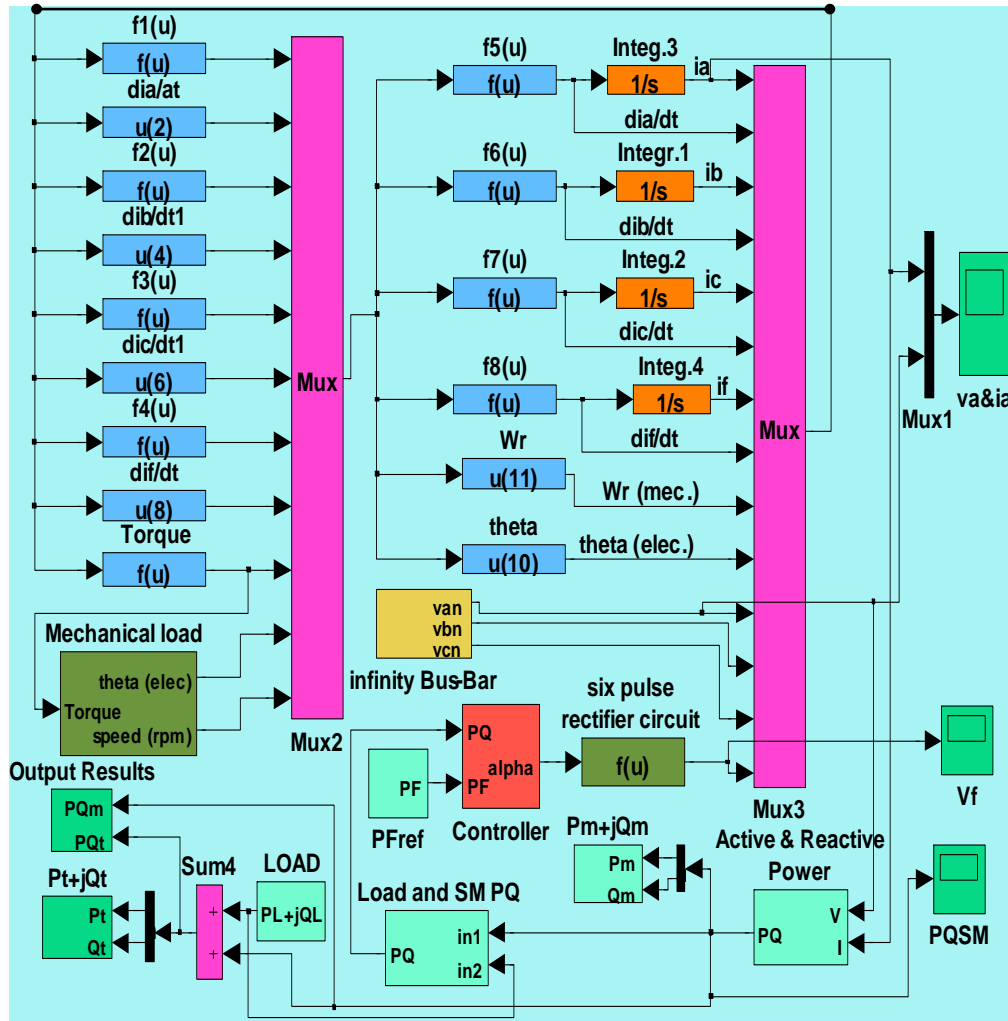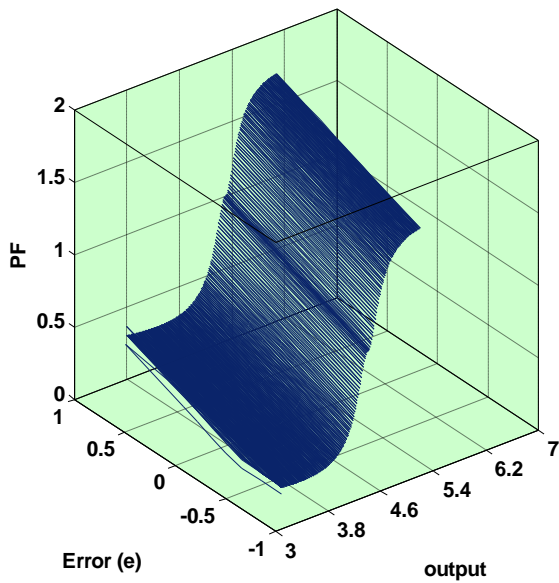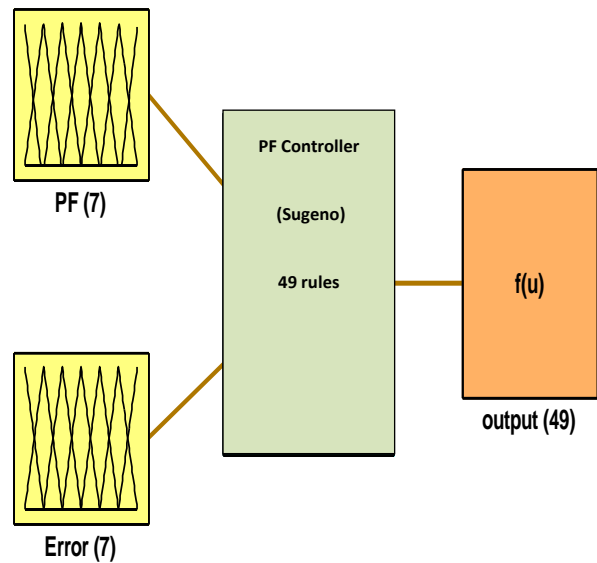

Fig.5: Overall suggested main system.

Fig.6: The overall main system model in MATLAB-Simulink.
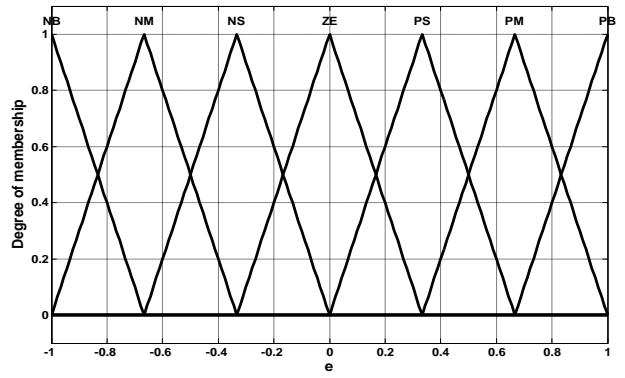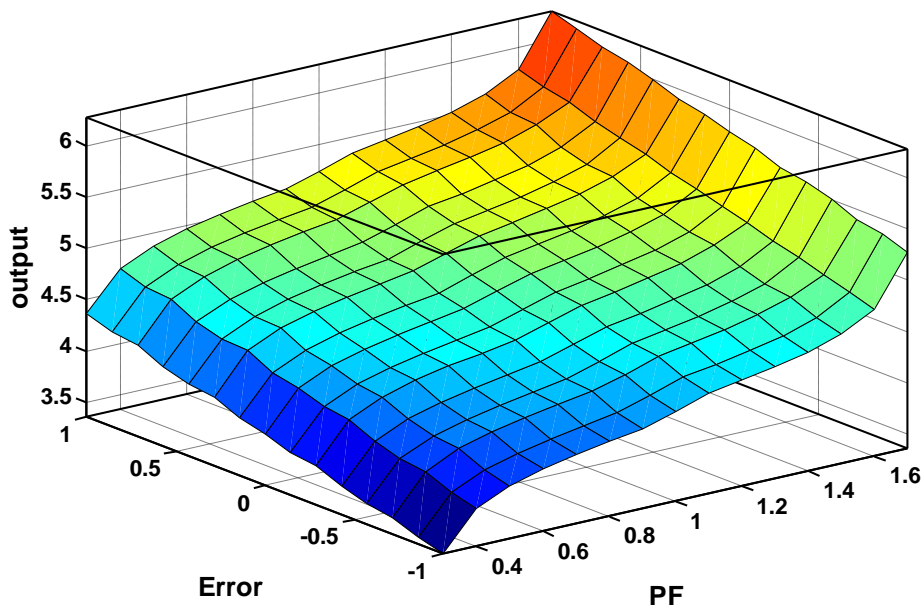

(a)

(b)
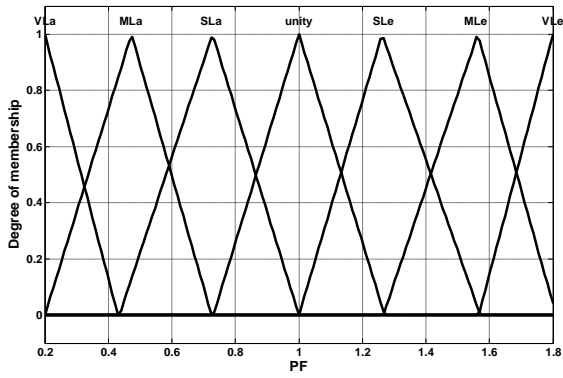
(c)

(d)

(e)

Fig. 7: Proposed FLC where: (a) FIS input-output training, (b) FLC input-output structure, (c) PF fuzzy membership function. (d) Error signal fuzzy membership function. (e) Proposed FLC surface.
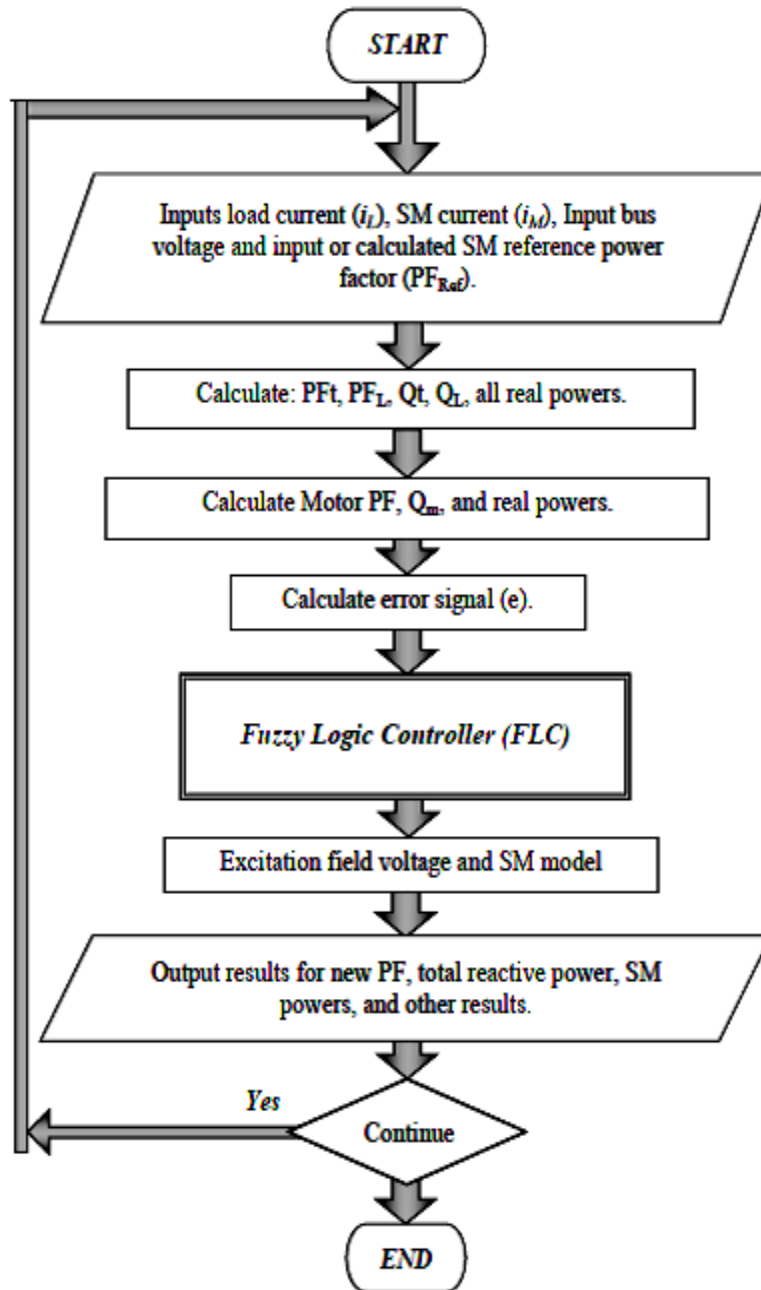
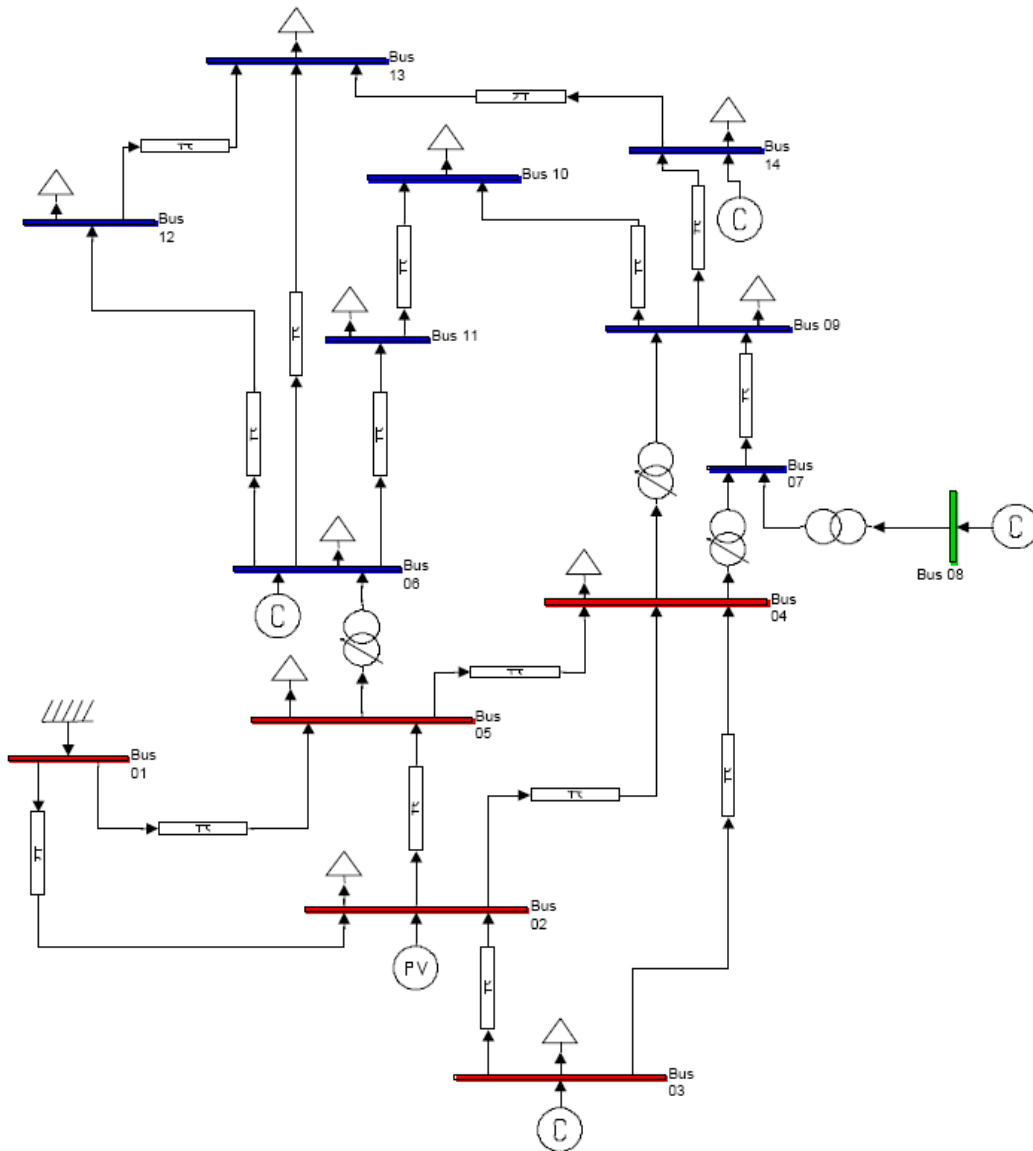**Fig.8: Flowchart of reactive power compensation using fuzzy algorithm.**

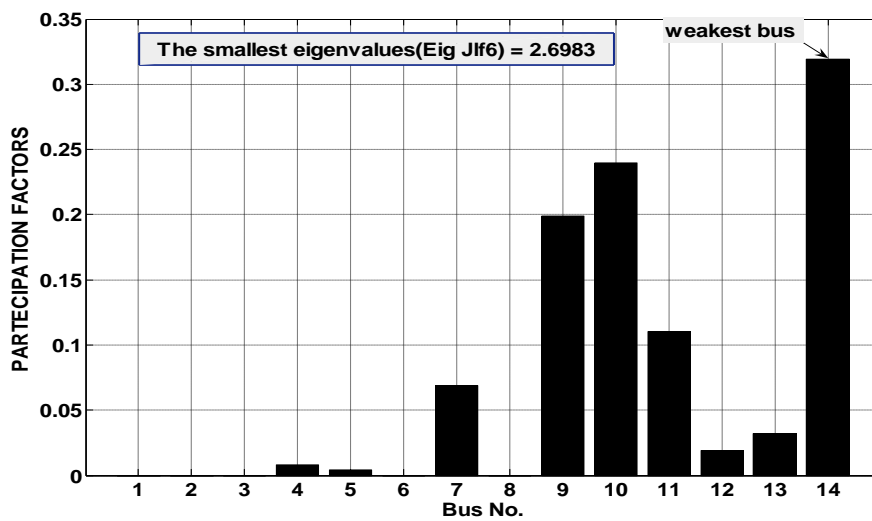**Fig.9: IEEE 14-Bus sample system with SM compensator at 3, 6, 8 and 14.**

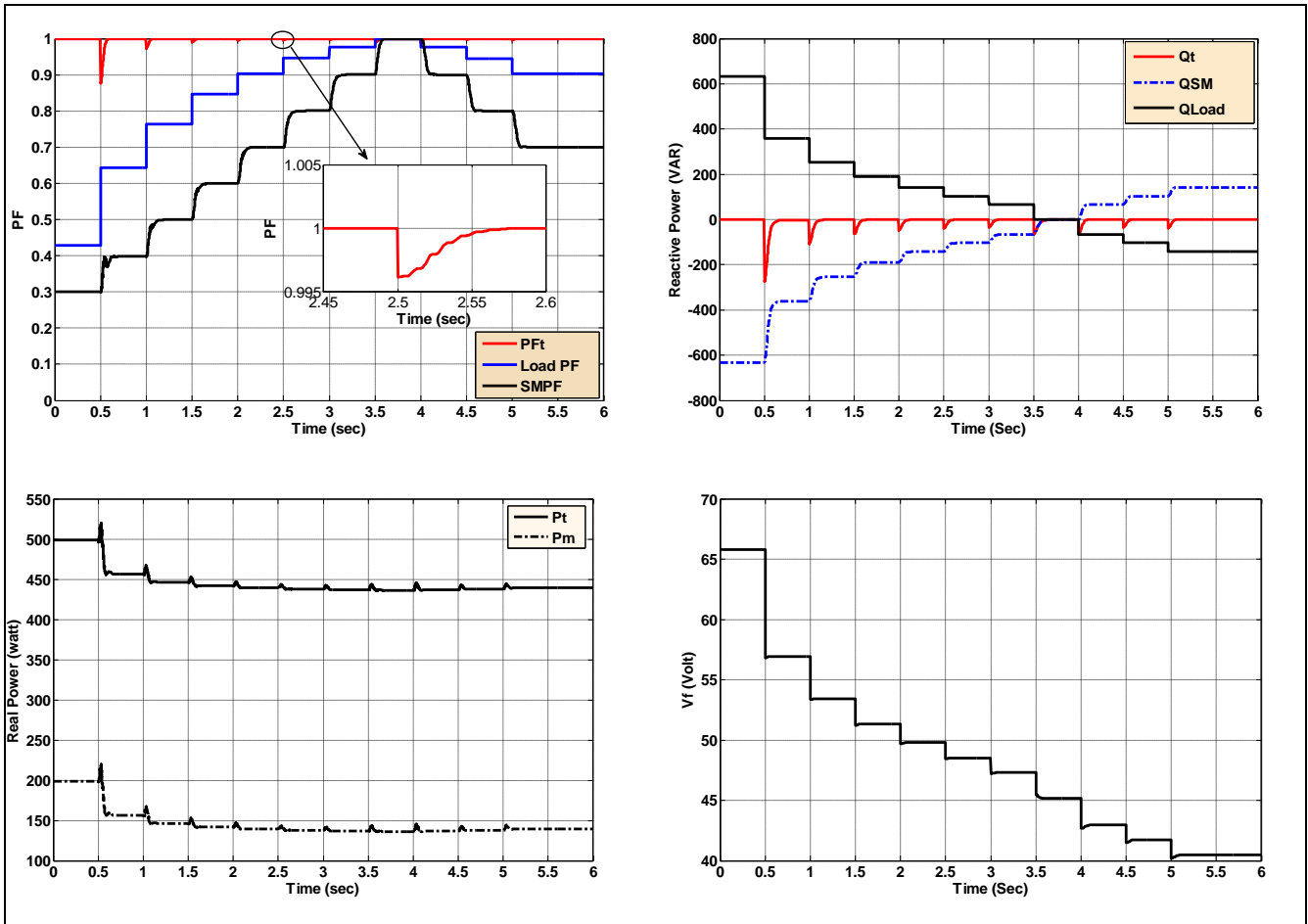**Fig.10: Weak buses for IEEE 14-bus sample system.**

Fig.11: Simulation results for PF, real power, reactive power and field voltage variation vs time using FIS controller.

Table 1: Synchronous machine inductance matrices.

$$[L] = \begin{bmatrix} L_a + L_S \cdot \cos(2\theta) & -L_{ab} + L_S \cdot \cos(2\theta - 2\alpha/3) & -L_{ac} + L_S \cdot \cos(2\theta + 2\alpha/3) & L_{af} \cdot \cos(\theta) \\ -L_{ab} + L_S \cdot \cos(2\theta - 2\alpha/3) & L_b + L_S \cos(2\theta) & -L_{bc} + L_S \cdot \cos(2\theta) & L_{bf} \cdot \cos(\theta - 2\alpha/3) \\ -L_{ac} + L_S \cdot \cos(2\theta + 2\alpha/3) & -L_{bc} + L_S \cdot \cos(2\theta) & L_c + \cos(2\theta) & L_{cf} \cdot \cos(\theta + 2\alpha/3) \\ L_{af} \cdot \cos(\theta) & L_{bf} \cdot \cos(\theta - 2\alpha/3) & L_{cf} \cdot \cos(2\theta + 2\alpha/3) & L_{ff} \end{bmatrix}$$

$$\frac{d[L]}{d\theta} = \begin{bmatrix} -2L_S \cdot \sin(2\theta) & -2L_S \cdot \sin(2\theta - 2\alpha/3) & -2L_S \cdot \sin(2\theta + 2\alpha/3) & -L_{af} \cdot \sin(\theta) \\ -2L_S \cdot \sin(2\theta - 2\alpha/3) & -2L_S \cdot \sin(2\theta + 2\alpha/3) & -2L_S \cdot \sin(2\theta) & -L_{bf} \cdot \sin(\theta - 2\alpha/3) \\ -2l_s \cdot \sin(2\theta + 2\alpha/3) & -2L_S \cdot \sin(2\theta) & -2L_S \cdot \sin(2\theta - 2\alpha/3) & -L_{cf} \cdot \sin(\theta + 2\alpha/3) \\ -L_{af} \cdot \sin(\theta) & -L_{bf} \cdot \sin(\theta - 2\alpha/3) & -L_{cf} \cdot \sin(\theta + 2\alpha/3) & 0 \end{bmatrix}$$

8. ACKNOWLEDGMENTS

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