PHASE PLANE METHOD STABILITY ANALYSIS OF FUZZY LOGIC PSS

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Abstract: *This paper presents a novel approach to investigate the stability of fuzzy logic based power system stabilizers using phase plane method and limit cycle analysis. Fuzzy logic controller (FLC) is highly non-linear and eigen values of the system cannot be obtained. The phase plane method is utilized for the stability analysis of fuzzy controller and for the development of effective rule base of the fuzzy power system stabilizers (PSSs). The limit cycles with definite area and trajectory in the phase-plane plot not converging towards the origin, is the unstable fuzzy stabilizer. Modifying the linguistic variables in the non-converging region of limit cycle by an opposite linguistic variables (e.g. NS to PS), the unstable fuzzy controller can be converted into a stable fuzzy controller. The effect of fired rules on stability and minimization of non-converging areas of the limit cycles is illustrated and tested for Multi Machine Power System (MMPS).*

Key words: *fuzzy logic controller, limit cycles, phase-plane plots, power system stabilizer.*

1. Introduction

Power system stabilizers are generally provided to damp out the rotor mechanical low frequency oscillations, which are in the range of 0.1 to 2.5Hz. They basically consists of phase lead compensators along with the wash out circuit and hence produces additional electrical torque component which cancels the negative damping torque produced by the large gain AVR excitation system. The state variable modeling of the entire system along with these stabilizers can be obtained and based on its eigen values system stability is determined. Fuzzy logic control is emerging to be a versatile and better control methodology. This method is realized by mapping the inputs and outputs of this controller by a set of linguistic rules. This method is model independent i.e., when there is no exact mathematical model of the physical system this method can be attempted. The power system operating conditions and topologies is time varying and the disturbances are unpredictable. These uncertainties make it very difficult to effectively deal with power system stability problems through conventional controller, which is based on linearized system model and for single operating condition. Hence the fuzzy logic control approach is emerging to be a complement to conventional approach. The most important advantage of fuzzy controller is that it is an intelligent controller. The fuzzy controller is a non-linear controller and not so sensitive to system topology, parameters and to the varying operating conditions. There is a very little mathematical computation involved in this method and this control method will not increase the order of the system. It is realized that this method of control can perform very effectively when the operating conditions are changing rapidly and also when the system non-linearities are significant. These features of fuzzy logic controller make it very attractive for power system applications. Therefore the applications of fuzzy logic in power system control grow rapidly [2]. However, till now the investigation of fuzzy logic applications in power system control design is mainly in excitation control and for PSS design. Investigation of stability of fuzzy controllers is still a challenge in research area.

M.J. Gibbard et al [1] have reconciled various methods of compensation for PSS in multi-machine systems which complement each other and assess their relative merits. M.A.M Hassan et al [2] have given a way to replace the conventional power system stabilizer with fuzzy logic based stabilizer. They have used the standard fuzzy membership function to compute the stabilizing signal of PSS and made simulations for SMIB system for different operating conditions. M. A. Abido et al [3] introduced a hybrid Neuro-Fuzzy power system stabilizer for multi machine power systems. A. Hariri et al [5] have proposed a fuzzy logic based power system stabilizer with learning ability by introducing a standard subjective membership function and a self-tuned parameter. Y. Y. Hsu et al [6] has designed fuzzy power system stabilizers for multi machine power systems without model identification. The proposed fuzzy PSS uses two real-time measurements viz., generator speed deviation and acceleration as input signals. The basic control actions of fuzzy logic controllers are in the form of linguistic rules and are hence flexible. The rules are generally framed by domain experts or heuristically or by observing the performance of conventional controller and modifying the rules, which is a cumbersome process. Harikrishna D et al proposed a novel approach to dynamic stability enhancement using PID damped fuzzy susceptance controlled static VAR compensator [15]. The main drawback of fuzzy method is in the rule base development. This can be achieved with the help of phase-plane plots of the input variables, which are given to the fuzzy controller. The rules are modified till a stabilized phase-plane plot is obtained. The method is illustrated and tested for MMPS.

2. Mathematical modeling

The linearized mathematical modeling of the MMPS is carried out by linearizing the equations around the operating point and hence obtained the required state equations [11]. A three-machine nine-bus system is considered for the linearized modeling of MMPS, and hence its state equations are obtained. The order of MMPS is eleventh order.

Modeling of MMPS is obtained by considering the three machine nine bus system [11]. Generator 1 is taken as reference and hence is modeled as classical model, Generators 2 & 3 are modeled as two-axis models [11]. The excitation system on machines 2 and 3 is modeled as one time lag transfer function. The rotor dynamics of machines 2 and 3 are studied with respect to machine 1 [12][14][15]. Thus the state equation of the form

$$\dot{X} = AX + BU \quad (1)$$

$$\text{and } Y = CX + DU \quad (2)$$

are obtained for the three machine nine bus system. The state vector X and the input vector U are as follows:

$$X^T = [\Delta\omega_1\ \Delta E'_{q2}\ \Delta E'_{d2}\ \Delta\omega_2\ \Delta E'_{q3}\ \Delta E'_{d3}\ \Delta\omega_3\ \Delta\delta_{12}\ \Delta\delta_{13}\ \Delta E_{FD2}\ \Delta E_{FD3}]$$

$$\text{and } U^T = [\Delta T_{m1}\ \Delta T_{m2}\ \Delta V_{ref4}\ \Delta T_{m3}\ \Delta V_{ref5}] \quad (3)$$

Perturbations on change in d-axis stator voltages are negligible. So eliminating $\Delta E'_{d2}$ and $\Delta E'_{d3}$ and rearranging the state equation, the Unified Philips Heffron model for the MMPS is obtained [14] and the new state vector X and the input vector U are as follows:

$$X^T = [\Delta\omega_1\ \Delta E'_{q2}\ \Delta\omega_2\ \Delta E'_{q3}\ \Delta\omega_3\ \Delta\delta_{12}\ \Delta\delta_{13}\ \Delta E_{FD2}\ \Delta E_{FD3}]$$

$$\text{and } U^T = [\Delta T_{m1}\ \Delta T_{m2}\ \Delta V_{ref4}\ \Delta T_{m3}\ \Delta V_{ref5}]. \quad (4)$$

The state equations obtained for Unified Philips Heffron model for the MMPS are as follows:

$$\Delta\dot{\delta} = \omega_B * \Delta\omega \quad (5)$$

$$\Delta\dot{\omega} = -0.5[H]^{-1}[K_1]\Delta\delta - 0.5[H]^{-1}[D]\Delta\omega - 0.5[H]^{-1}[K_2]\Delta E'_q + 0.5[H]^{-1}\Delta T_m \quad (6)$$

$$\Delta\dot{E}'_q = -[T'_{do}]^{-1}[K_4]\Delta\delta - [T'_{do}]^{-1}[K_3]\Delta E'_q + [T'_{do}]^{-1}\Delta E_{FD} \quad (7)$$

$$\Delta\dot{E}_{FD} = -[T_E]^{-1}[K_E][K_5]\Delta\delta - [T_E]^{-1}[K_E][K_6]\Delta E'_q - [T_E]^{-1}\Delta E_{FD} - [T_E]^{-1}[K_E][\Delta V_{ref} + \Delta V_S] \quad (8)$$

$$\text{where, } \Delta\delta = [\Delta\delta_1\ \Delta\delta_2\ \Delta\delta_3]^T \quad (9)$$

$$\Delta\omega = [\Delta\omega_1\ \Delta\omega_2\ \Delta\omega_3\ ]^T \quad (10)$$

$$\Delta E'_q = [\Delta E'_{q1}\Delta E'_{q2}\Delta E'_{q3}]^T \quad (11)$$

$$\Delta E_{FD} = [\Delta E_{FD1}\Delta E_{FD2}\Delta E_{FD3}]^T \quad (12)$$

$$[\omega_B] = \begin{bmatrix} \omega_{B1} & 0 & 0 \\ 0 & \omega_{B2} & 0 \\ 0 & 0 & \omega_{B3} \end{bmatrix} \quad (13)$$

$$[H] = \begin{bmatrix} H_1 & 0 & 0 \\ 0 & H_2 & 0 \\ 0 & 0 & H_3 \end{bmatrix} \quad (14)$$

suffixes 1, 2 and 3 refer to machine 1, machine 2 and machine 3 respectively.

When the fuzzy logic based stabilizer is placed on machine 2, the FLC inputs are $\Delta\omega_{12}$ and $\Delta\dot{\omega}_{12}$ and FLC output is the stabilizing signal ΔV_{S2}. When the fuzzy logic based stabilizer is placed on machine 3, the FLC inputs are $\Delta\omega_{13}$ and $\Delta\dot{\omega}_{13}$ and FLC output is the stabilizing signal ΔV_{S3}. The constants $[K_1]$ to $[K_6]$ are matrices of order (3 X 3) and are calculated for different operating conditions.

3. Stability of Fuzzy PSS - Proposed Algorithm

Fuzzy control systems are essentially non-linear systems hence it is difficult to obtain general results on the analysis and design of fuzzy control systems. Furthermore, the knowledge of the dynamic behavior of the process to be controlled is normally poor. Therefore, the robustness of the fuzzy control system should be incorporated to guarantee stability in spite of variations in system dynamics.

The fuzzy control system can be represented by means of a non-linear function $u = \phi(x)$. This can be analyzed by the dynamic behavior of closed-loop system consisting of (i) Fuzzification, (ii) Inference engine and (iii) Defuzzification.

Stability analysis of a fuzzy control system requires characterization of the relation between the rules and the state-space associated with the dynamic system under control. This relationship is based on the relative influence of each rule of the rule-base on the control action produced by fuzzy inference engine.

A closed-loop system trajectory can be mapped on the position space shown in Fig. 1. A sequence of rules obtained according to the order in which they are fired forms the so-called linguistic trajectory, which corresponds to a certain system trajectory. From the design point of view, this method provides interesting guidelines for the analysis of fuzzy control system. Non-cooperative rules (rules not fired) can be easily modified.

Let us consider the closed-loop system represented as

$$\frac{dx}{dt} = f(x) + bu \qquad (15)$$

where $u = \phi(x)$, f(x) is a non-linear function which represents the plant dynamics with f(0) = 0, x and b are vectors of fuzzified input of the controller obtained from the crisp input x*, then $\phi(x)$ = Defuzzification (μ_x * o μ_R (x,u)), closed-loop behavior will depend on the nature of f(x) and $\phi(x)$.

The dynamic behavior of a stable feedback system can be designed by modifying with opposite sign of rules, in the limit cycle area. In this paper the triangular membership functions are utilized for the fuzzy controller.

The proposed algorithm

The equations for MMPS are linearized and solved using Runga – Kutta 4th order method for different operating conditions.

1) The phase plane plots shown in Fig. 1 and Fig. 5 are obtained for the uncontrolled case for MMPS.
2) The rule base mapping is done in the areas of the limit cycle trajectory of the phase plane plots thus obtained for MMPS.
3) The fuzzy logic controller is simulated along with the equations of MMPS.
4) The phase plane plots shown in Fig. 2 and Fig. 6 for MMPS are obtained with this fuzzy logic controller.
5) These phase plane plots are superimposed on the phase plane plots of uncontrolled MMPS, and the rules falling in the non-converging areas are determined.
6) These rules are modified and stage 1 phase plane plots i.e. Fig. 3 and Fig. 7 for MMPS are obtained.
7) Steps 3) to 4) are repeated till the stabilized phase plane plots i.e. Fig. 4 and Fig. 8 for MMPS are obtained.

4. Limit cycle investigation of fuzzy PSS

The non-linear system subjected to a disturbance is said to be stable after the disturbance if it comes back to equilibrium position or at least staying within the tolerable limit and may exhibit a special behavior of following a close trajectory or limit cycle. The limit cycle describes the oscillation of non-linear system that is why it is most crucial factor in the design and for the stability analysis of non-linear systems. There are number of graphical ways of finding out the existence of limit cycles for non-linear systems.

The phase plane method is a powerful tool for stability study of non-linear system and provides the designer with a deeper physical insight into the system behavior. This is basically a graphical method from which information about transient behavior and stability is easily obtained by constructing phase plane trajectories.

In this paper, a closed-loop system trajectory has been mapped on the position space, for a rule base of uncontrolled machine 2 and machine 3 of MMPS system as shown in Fig. 1 and Fig. 5 respectively. It can be seen that certain areas of the position space relate to the system trajectory. A sequence of rules, obtained according to the order in which they are fired, forms the linguistic trajectory which corresponds to a certain system trajectory. From design point of view this method provides interesting guidelines for the analysis of a fuzzy controller. Non-operative rules (non-fired rules) can be easily modified. This dynamic behavior suggests modifications in the fuzzy sets representing the linguistic values of $\Delta\omega_{12}$ and $\Delta\dot{\omega}_{12}$ for machine 2 and $\Delta\omega_{13}$ and $\Delta\dot{\omega}_{13}$ for machine 3 in the non-converging area.

5. Simulation and results

The equations for MMPS (3 machine 9 bus system) are linearized and solved. The step size of integration is chosen to be 0.001 seconds and the simulations are carried out for 20 seconds. For the input and output variables of fuzzy controller, triangular membership functions distributed in seven linguistic variables viz. negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB) are chosen with fifty percent overlap and centroid method of defuzzification is used. The ranges of inputs given to fuzzy controller are chosen from the responses of uncontrolled cases.

MMPS is analyzed by considering, a case study of limit cycles. The rules are framed heuristically in the areas of the limit cycle trajectories as shown in the phase-plane plots of Fig. 1 and Fig. 5, for uncontrolled cases of machine 2 and machine 3 respectively. The resultant phase-plane plots with fuzzy logic based stabilizers are shown in Fig. 2 and Fig. 6 respectively. These figures have non-converging areas in their limit cycle trajectories. Hence those rules which fall in these non-converging areas needs to be modified.

Each rule in these areas is modified exactly by an opposite inference. Hence, after modifying the rules, which are in these non-converging areas of limit cycle trajectories, the resultant phase-plane plots shown in Fig. 3 and Fig. 7 are obtained. This method of rule base modification is repeated until the resultant phase-plane plots are stabilized shown in Fig. 4 and Fig. 8. The stabilized plots were obtained within two stages of such rule base modifications for MMPS.

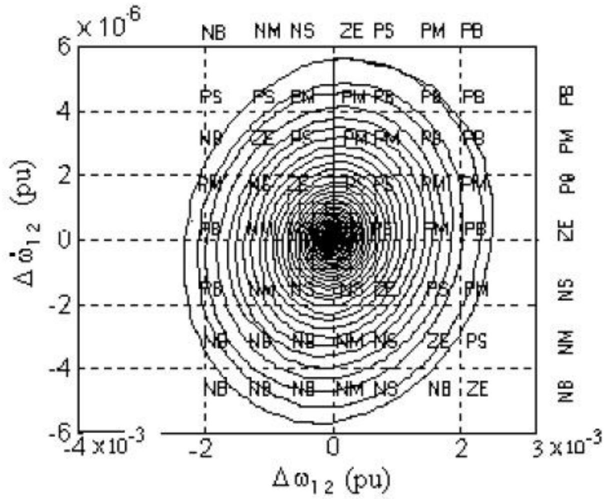

Fig. 1. MMPS rule base mapping of uncontrolled machine 2

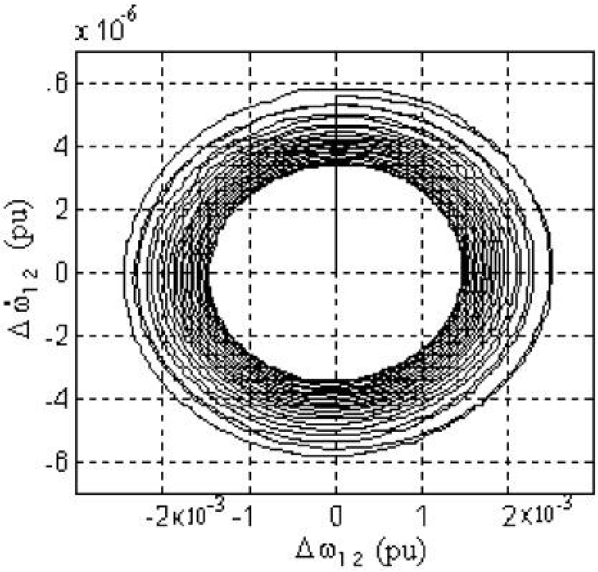

Fig. 2. MMPS unstable fuzzy stabilizer of machine 2

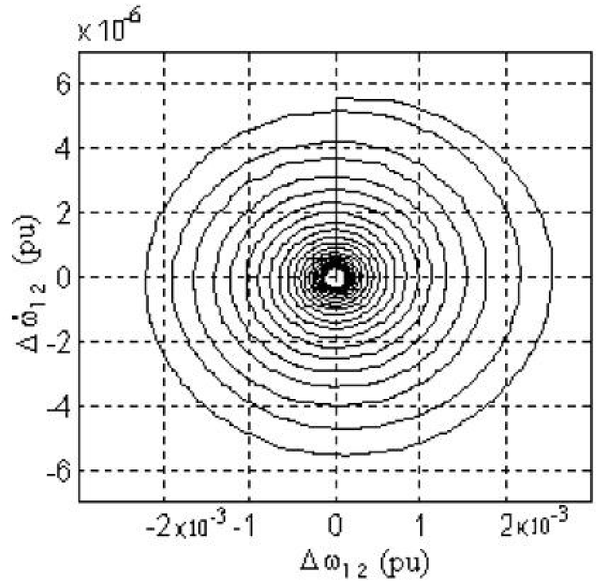

Fig. 3. MMPS unstable fuzzy stabilizer of machine 2 with modified rules stage 1

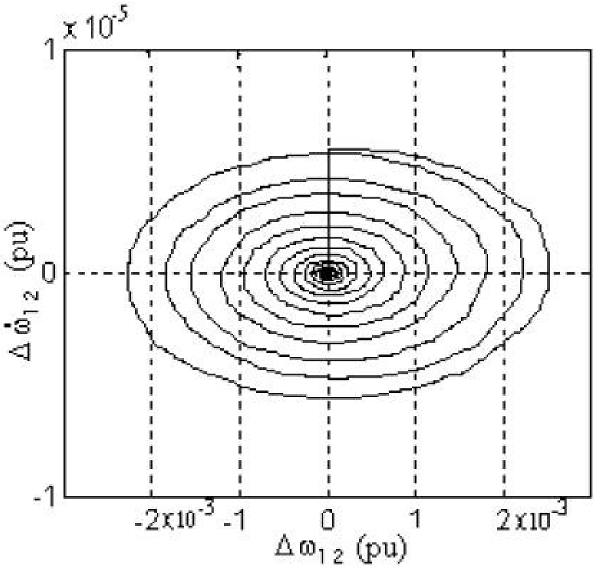

Fig. 4. MMPS stable fuzzy stabilizer of machine 2 with modified rules stage 2

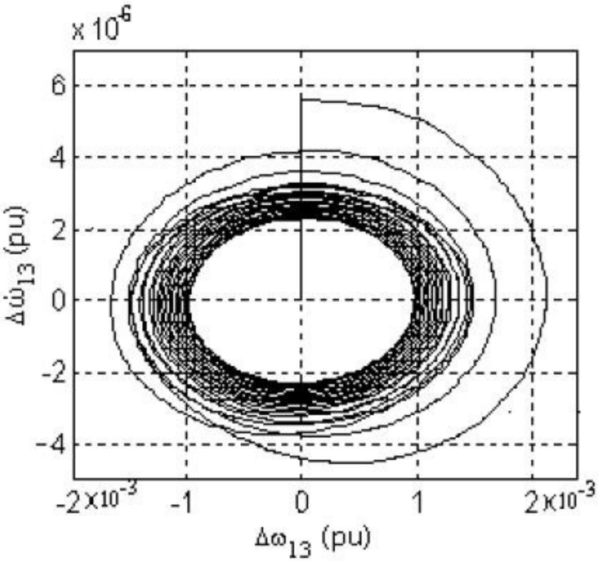

Fig. 6. MMPS unstable fuzzy stabilizer of machine 3

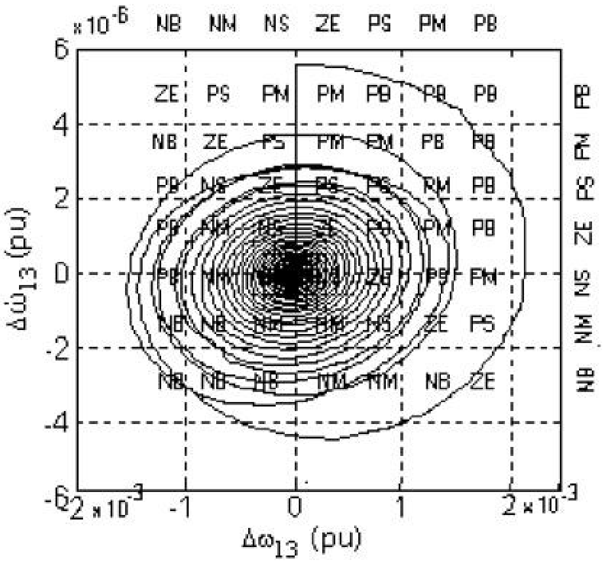

Fig. 5. MMPS rule base mapping of uncontrolled machine 3

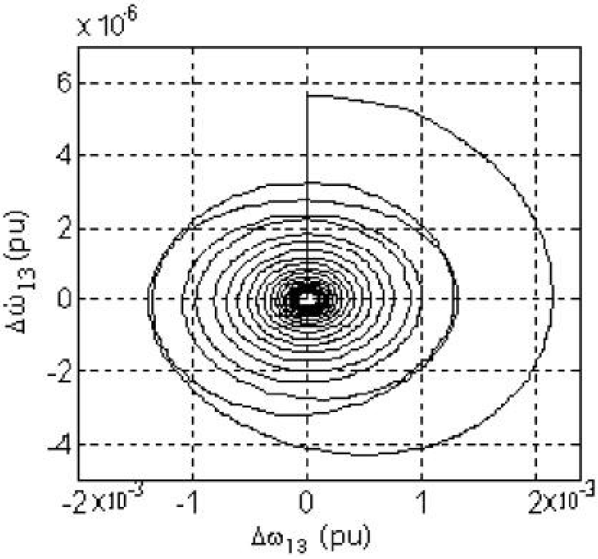

Fig. 7. MMPS unstable fuzzy stabilizer of machine 3 with modified rules stage 1

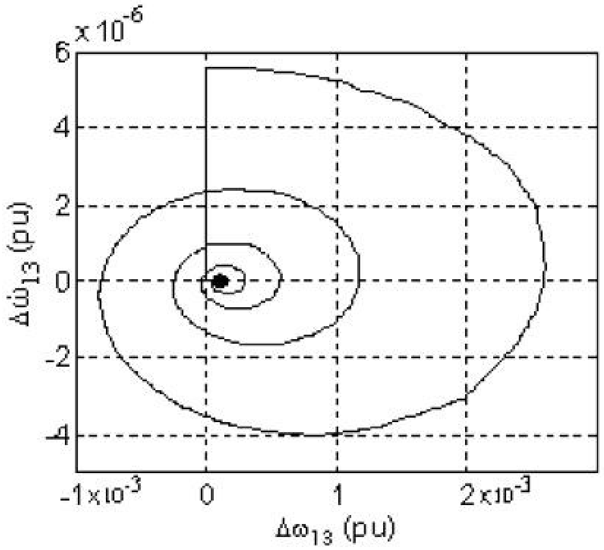

Fig. 8. MMPS stable fuzzy stabilizer of machine 3 with modified rules stage 2

6. Conclusion

In this paper phase-plane method and the limit cycle analysis have been investigated for the stability of fuzzy controlled power system stabilizer. The fuzzy controller inference engine has been designed even when no expert knowledge is available. The effectiveness of the phase-plane analysis has been demonstrated for MMPS. The conclusions are:

1) The stabilized phase plane plots assure asymptotic stability of MMPS which also assures small signal stability.
2) The rule base stabilization (fuzzy inference engine) can be obtained in few steps of rule base modifications.
3) The rules need to be modified are the rules falling in the non-converging areas of the limit cycles trajectories and not the entire rule base.
4) Without the expert knowledge rule base can be designed.
5) The tedious conventional design of fuzzy rules can be avoided.
6) This method of rule base modification and rule base stabilization can be attempted for any fuzzy controlled system.

Hence, fuzzy controlled power system stabilizers can be utilized for the real-time control of power systems.

Appendix

Nomenclature:

K_1 = Change in Electrical Power for a change in rotor angle with constant flux linkage.

K_2 = Change in Electrical Power for a change in the direct axis flux linkage with constant rotor angle.

τ'_{do} = Direct axis open circuit time constant of the machine.

K_3 = An Impedance factor, and K_4 = Demagnetizing effect of a change in rotor angle (At steady state).

K_e = Regulator Gain, T_e = Regulator Time constant.

$V_{t\Delta}$ = Change in Synchronous machine terminal Voltage.

$K_5 = V_{t\Delta}/\delta_\Delta$ = Change in the terminal Voltage with change in rotor angle for constant E'_Δ.

$K_6 = V_{t\Delta}/E'_\Delta$ = Change in the terminal voltage with change in E' for constant δ.

Data for 3-machine 9-bus system: - (All flows are in MW & MVAR)

Generator 1 (G1): 71.6 + j27, Generator 2 (G2): 163 + j6.7 and Generator 3 (G3): 85 – j10.9

Load A: 125 + j50, Load B: 90 + j30 and Load C: 100 + j35

$\Delta\omega_{12}$ and $\Delta\dot{\omega}_{12}$ are the change and the rate of change in the angular velocity of machine 2 w.r.t. machine 1.

$\Delta\omega_{13}$ and $\Delta\dot{\omega}_{13}$ are the change and the rate of change in the angular velocity of machine 3 w.r.t. machine 1.

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