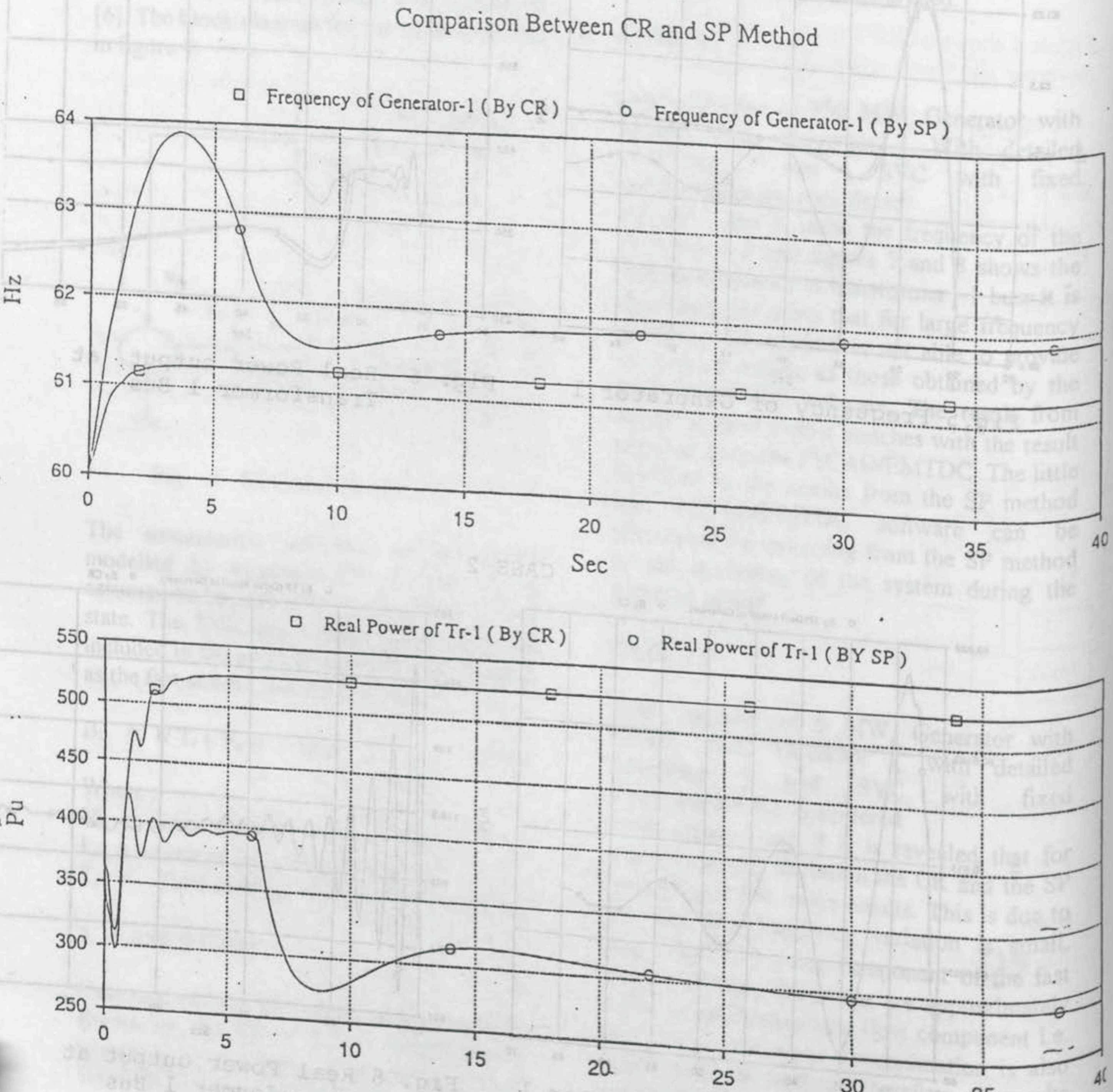
CASE 3 : Load rejection 850 MW,Generator with exciter, PSS,Governor (with detailed modelling) and SVC with detailed model are considered. The SVC setting are : $V_{ref} = 1.1$pu, slope = 10%. The V_{ref} and slope are chosen such that after the disturbance the SVC reaches to it's reactive power (Capacitive) limits.



Comparison Between CR and SP Method

Fig. 9

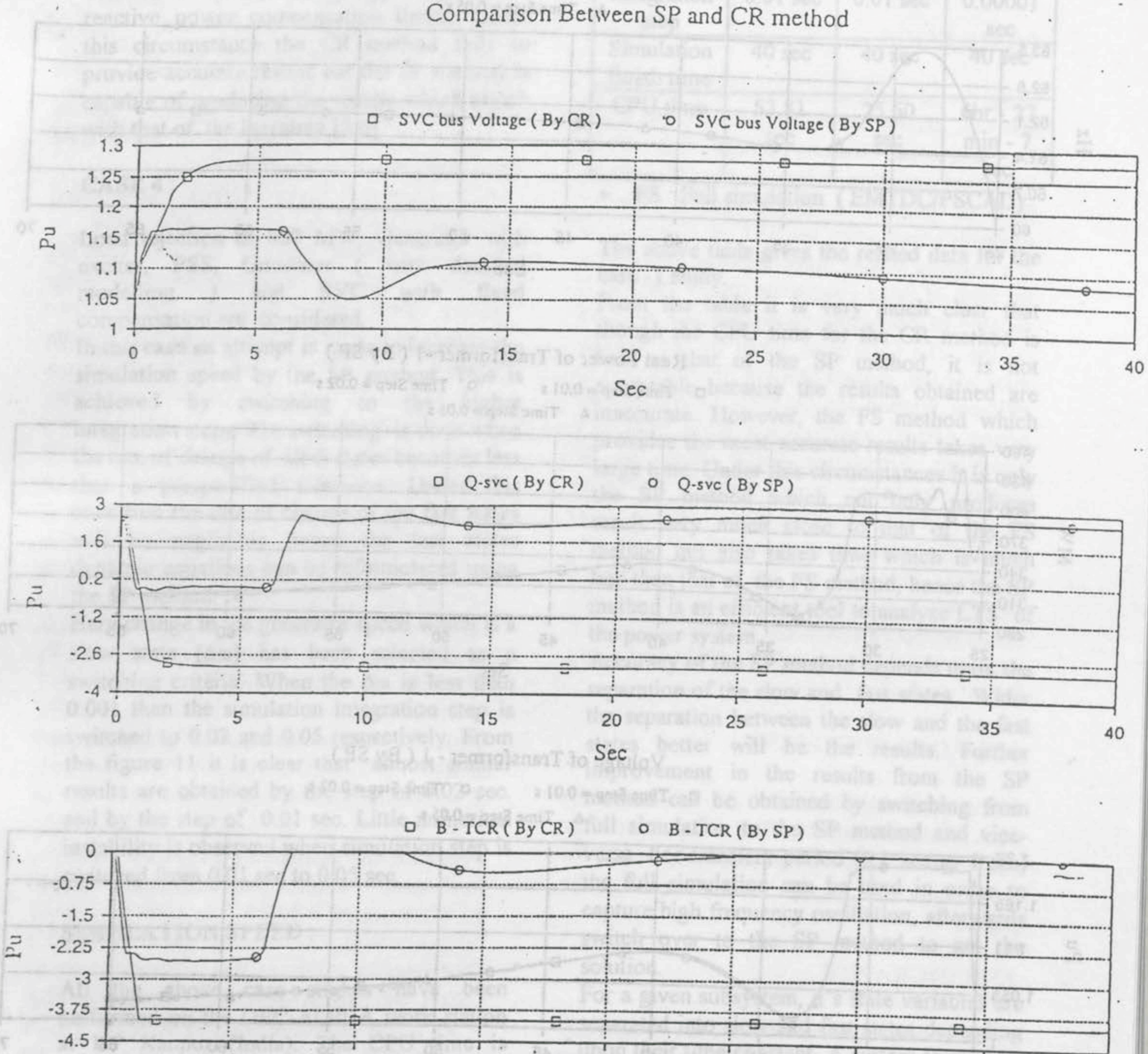

Comparison Between SP and CR method
□ SVC bus Voltage (By CR)
o SVC bus Voltage (By SP)
Pu
1.3
1.25
1.2
1.15
1.1
1.05
1
0
5
10
15
20
25
30
35
40
Sec
□ Q-svc (By CR)
o Q-svc (By SP)
Pu
3
1.6
0.2
-1.2
-2.6
-4
0
5
10
15
20
25
30
35
40
Sec
□ B - TCR (By CR)
o B - TCR (By SP)
Pu
0
-0.75
-1.5
-2.25
-3
-3.75
-4.5
0
5
10
15
20
25
30
35
40
Sec

Fig. 10

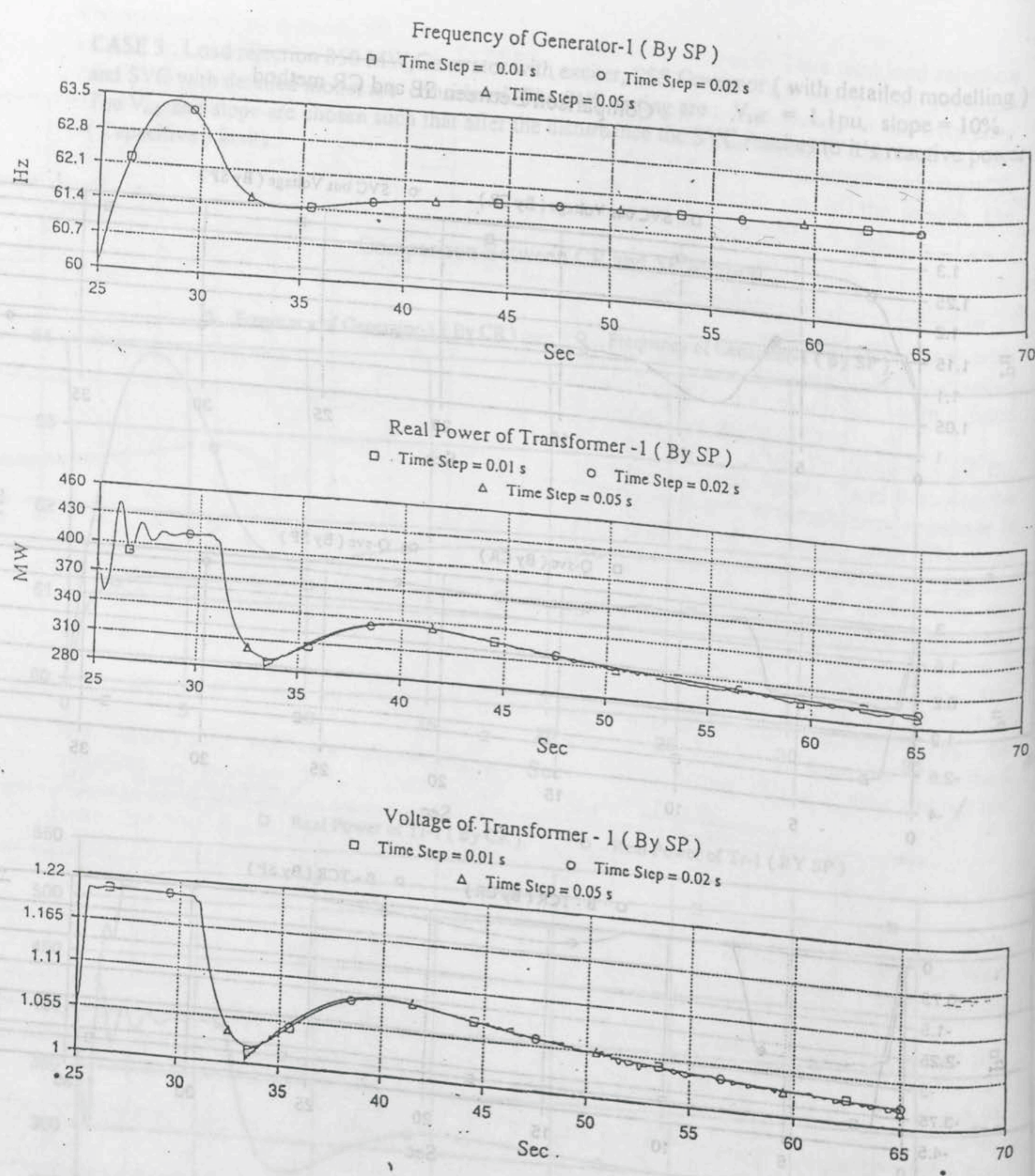


Fig 11 Effects of Switching in Time Step

Generator With Exciter, PSS and Governor (Detail Model)

Figures 9 and 10 represent the case with the detailed model of SVC, operating at it's reactive power compensation limits. Under this circumstance the CR method fails to provide accurate results but the SP method is capable of producing the results which match with that of the literature [5,6].

CASE 4 :

Load rejection of 850 MW, Generator with exciter, PSS, Governor (with detailed modelling) and SVC with fixed compensation are considered.

In this case an attempt is made to increase the simulation speed by the SP method. This is achieved by switching to the higher integration steps. The switching is done when the rate of change of slow states becomes less than a prespecified tolerance. Under this condition the rate of change of the fast states will be negligible hence the fast states dynamic equations can be reformulated using the SP method.

Here change in the generator speed which is a slow state ($\Delta\omega$) has been selected as a switching criteria. When the $\Delta\omega$ is less than 0.001 then the simulation integration step is switched to 0.02 and 0.05 respectively. From the figure 11 it is clear that almost similar results are obtained by the step of 0.02 sec. and by the step of 0.01 sec. Little numerical instability is observed when simulation step is switched from 0.01 sec to 0.05 sec.

SIMULATION SPEED :

All the above case studies have been performed on the DEC-ALPHA work station at IIT Kanpur (India). The CPU time is recorded and tabulated below for the various methods of analysing the long term stability of the power systems, as described above.

Parameter	**SP**	**CR**	**FS**
Integration step	0.01 sec	0.01 sec	0.00001 sec
Simulation finish time	40 sec	40 sec	40 sec
CPU time	53.81 sec	25.60 sec	6hr.- 27 min - 7 sec

- FS : Full simulation (EMTDC/PSCAD)

The above table gives the related data for the case -1 study.

From the table it is very much clear that though the CPU time for the CR method is half as that of the SP method, it is not acceptable because the results obtained are inaccurate. However, the FS method which provides the most accurate results takes very large time. Under this circumstances it is only the SP method which not only produces result very much close to that of the FS method but also takes time which is much less than that of the FS method, hence the SP method is an efficient tool to analyse LTS of the power system.

Accuracy of the SP method depends upon the separation of the slow and fast states. Wider the separation between the slow and the fast states better will be the results. Further improvement in the results from the SP method can be obtained by switching from full simulation to the SP method and vice-versa. For transient period (0.1 sec to 1 sec) the full simulation can be used in order to capture high frequency oscillation, afterwards switch over to the SP method to get the solution.

For a given subsystem, it's state variables are separated into slow and fast states depending upon their time constant. A system formed by subsystems will finally decide how to treat a given state, whether a fast state or a slow state. For example in governor model x_1, x_2 etc. are the fast states, but from the system point of view it is better to treat them as slow states because frequencies of these states are nearer to the frequency of rotor speed, which is treated as slow state in the simulation.

CONCLUSION :

Using the SP method models of the generator, network, exciter and PSS, governor and SVC are presented. Results reveal that when frequency variation is larger, the CR method fails to provide accurate results. Similar situation arises when the SVC is operating at it's reactive power compensation limits. But for both of these conditions the SP method is capable of producing consistent and efficient results. The CPU time taken by the various methods also reports that the SP method is an efficient method for the LTS analysis of the power system experiencing large frequency variations. Simulation speed using the SP method can further be increased by switching to the higher integration step. The switching effects from the integration steps of 0.01 sec. to 0.02 sec and 0.05 sec. are studied. Model of the SVC is developed using the SP method which produces consistent results. This give a way to model the other FACTS devices using the SP method.

ACKNOWLEDGEMENT :

The authors are thankful to Dr. J.J. Patel, Mr. M.A. Rahman and Mr. R.P. Gupta for their full hearted support and encouragement for completing the study and presenting the paper.

BIBLIOGRAPHY :

[1] R.K. Varma, R.M. Mathur, G.J. Rogers, P. Kundur, " Modelling effects of system frequency variation in long term stability studies ", IEEE trans. on power system, vol. 11, no 2, pp 827-832, May 1996

[2] P.V. Kokotovic, J.J. Allemong, J.H. Chow, " Singular perturbation analysis of power system with sustained high frequency oscillations ", Automatica, vol 13, 1978, 271-279

[3] R.S. Ramshaw, K.R. Padiyar, " Generalised system model for slipring machine ", IEE proceedings, vol 120, no 6, June 1973.

[4] P.M. Anderson, A.A. Fouad, " Power system control and stability ", Iowa state university press, Iowa 1977.

[5] P. Kundur, " Power system stability and control ", New York : McGraw Hill, 1994

[6] IEEE special stability controls working group, " Static var compensation models for power flow and dynamic performance simulation ", IEEE trans. on power system, vol 9, no 1, pp 229-240,Feb. 1994

APPENDIX - A :

System Data : Base voltage = 20 kV, Base MVA = 100, Base frequency = 50.0 Hz

Data for Generators (on their own base)

S_n = 900 MVA, V_n = 20 kV, R_a = 0.0025 pu, x_d = 1.8 pu, x_q = 1.7 pu, x_l = 0.2 pu, x_d' = 0.3 pu, x_q' = 0.55 pu, x_d'' = 0.25 pu, x_q'' = 0.025 pu, T_d' = 8.0 sec, T_q' = 0.4 sec, T_d'' = 0.03 sec, T_q'' = 0.05 sec, H = 6.5 MJ/MVA

Data for both transformers (on generator base)

X_t = 0.01667 pu

Transmission line data (on system base)

Resistance = 0.0055 pu, Reactance = 0.0055 pu, Susceptance = 0.09625 pu

SVC data

Q_{svc} = 140.596 MVAR, Q-factor of the TCR = 50, Slope setting = 5%, PI controller gain = 0.00466667, Fixed capacitor rating = 200 MVAR, Inductive limit = 200 MVAR

Exciter and PSS data

k_A = 200.0, T_A = 0.0 sec, T_m = 0.01 sec, k_w = 20.0, T_w = 10.0 sec, T_1=T_3= 0.16 sec, T_2=T_4= 0.02 sec

Governor and Turbines data

k_1 = 15.0, T_1 = 0.1 sec, T_2 = 0.0 sec, T_3 = 0.25 sec, T_4 = 0.42 sec, T_5 = 4.25 sec, T_6 = 0.72 sec, T_7 = 0.0 sec, k_2 = 0.25 sec, k_3 = 0.25 sec, k_4 = 0.5 sec, k_5 = 0.0

Load Data

Local load 1 = 300 MW

Local load 2 = 1100 MW

BIOGRAPHIES :

Manoj Gupta received his B.E. (Electrical) degree from M.B.M. engineering college, JNV University, Jodhpur in 1994 and M.Tech (Power system) degree from IIT Kanpur in 1997. Presently he is working with Corporate R&D, Asea Brown Boveri ltd. , Baroda (India). His fields of interest are reactive power compensation and Controlled switching of the power systems.

R.K. Varma received B.tech (Electrical) and Ph.D. degrees from Indian Institute of Technology (IIT), Kanpur, in 1980 and 1988, respectively. He worked as Research Associate at IIT-Kanpur from 1988-1989 and then joined IIT-Kanpur as Assistant Professor in the Electrical Engineering Department in 1989. During 1992-1994 he worked as a visiting Assistant Professor in the Electrical Engineering Department of the University of Western Ontario (London), Canada, while on a Govt. of India BOYSCAST fellowship for young scientists. His teaching and research interests include Static Var Systems, Power System Dynamics and Control.

Long Term Stability Analysis of Power System Experiencing Large Frequency Variations

Manoj Gupta
Corporate R&D
Asea Brown Bowari Ltd.
Vadodara – 390013 (India)

R.K. Varma (Sr. member, IEEE)
Electrical Engg. Dept.
Indian Institute of Technology (IIT)
Kanpur – 208016 (India)

ABSTRACT :

This paper presents an application of the Singular Perturbation (SP) method to power system simulations. The main focus is on the interaction of the slow and fast states associated with various dynamic devices used in the power systems. Model of the network, the exciter, the Power System Stabiliser (PSS), the governor with turbines and Static Var Compensator (SVC) are reformulated using the SP method. Simulation results are validated by the PSCAD/EMTDC software. The paper presents a comparison study between the conventional method of analysing the transient stability also known as Constant Reactance (CR) method and the SP method for the system undergoing large frequency variation (About 5% and more).

1. INTRODUCTION :

In general, long term stability analysis (LTS) is an extension of the transient stability study. The methods to be used for the LTS studies should be efficient because simulation time may vary from 1 to 3 minutes or more. In this paper it is presented that the CR method gives inaccurate results when frequency variation is large (about 5%) or SVC is operating at it's upper and lower reactive power limits. If all the state equations of the system are solved using suitable numerical method, then the simulation time step must be smaller than the smallest time constant of the system, so that the response of the fastest state can also be obtained accurately. This technique if used for LTS analysis then computation time will be very large, may be in hours. However, it is required to get good accuracy with high simulation speed, the SP method is a tool which fulfil these conditions hence is an efficient technique for LTS studies. In this paper mathematical model of the power system components i.e. generator, network, exciter, PSS, governor with turbine and SVC are reformulated using the SP method. The advantage of the new model is that the reformulated state equations are algebraic ones hence take less time to solve in comparison to the original differential equations. Due to this transformation of the differential equations into the algebraic equations the SP method is also known as an algebraic approximation method. Applications of the SP method in power systems have been presented in [1, 2]. In this paper additional models have been added. Model of the SVC using the SP method is developed. This throws some light on the modelling of the Flexible A.C. Transmission Systems (FACTS) using the SP method. Using the SP method the simulation speed can further be increased by switching to the next higher integration step when the solution is near-by the new equilibrium position after disturbance.

SINGULAR PERTURBATION THEORY

The SP method is also known as Two Time Scale method. This method was used in the power systems a decade ago. The SP method can be used when two dynamic phenomena with large separation (>35) in the frequency

are interacting with each other. In power systems there are rotor mode oscillations with the frequency ranging from 0.2 Hz to 2.0 Hz and network transients having frequency 50 Hz or greater. This separation in frequency is large enough for using the SP method for the analysis of power system stability problems.
The low frequency rotor states are treated as slow states and the higher frequency network states are treated as fast states [1]. A singularly perturbed system possessing a two time scale property due to the simultaneous presence of the slow and fast phenomena is called a 'stiff' system.
The basic mathematical formula of this method is as follows :

$$X'_s = f(X_s, X_n, t),\ X_s(t_0) = X_s^0 \qquad (1.1)$$

$$\varepsilon X'_n = f(X_s, X_n, t),\ X_n(t_0) = X_n^0 \qquad (1.2)$$

ε = a small parameter, defined as

$$\varepsilon = \frac{\text{frequency of slow states}}{\text{frequency of fast states}}$$

X_s = Slow states of the system
X_n = Fast states of the system

Equation 1.2 is an alternative way of representing the exact differential equations of the fast variables. The singular perturbation parameter is extracted from the right hand side of the original differential equation of fast variables and brought to the left-hand side, resulting in the equation 1.2. Because the dynamics of the two phenomena in the power system are widely separated, ε becomes very small and can be approximated as zero. The equations 1.1 and 1.2 then can be expressed in terms of slow components of the respective variables (indicated by an additional subscript 's') as follows :

$$X'_{ss} = f(X_{ss}, X_{ns}, t),\ X_{ss}(t_0) = X_{ss}^0 \qquad (1.3)$$

$$0 = g(X_{ss}, X_{ns}, t) \qquad (1.4)$$

The advantage of doing this is that, now the equation 1.4 is an algebraic equation. Since X_s are slow states of the system

$X_s(t) \cong X_{ss}(t)$ and $X_n = X_{ns} + X_{nf}$
where :

X_{ss} is the steady state value of the slow states.
X_{ns} is the slow component of the fast states (X_n) , which essentially tracks the slow system transients.
X_{nf} is the fast component of the fast states X_n and provides the correction term.

The most accurate solution of equation 1.2 can be obtained by integration but the simulation time will be very long, may be in hours. While the CR method computes only X_{ss} and X_{ns}. The SP method calculates X_{ss}, X_{ns} and X_{nf}. The correction term X_{nf} indeed accounts for the frequency variation effect and contributes to the accuracy of the SP method. Thus the SP method provides a much more accurate solution than the CR method when frequency variation is large. When frequency deviation is very small X_{nf} become negligibly small and hence can be ignored. In this situation the SP and the CR method will provide almost similar solution.

2. SYSTEM MODELLING AND ANALYTICAL METHOD

The two area system as shown in figure 1, is analysed for long term stability studies. The magnitude of local load is chosen such that there is a net flow of power across the tie line in one direction. The generators are considered along with their controllers such as exciter, PSS and governor. The tie line is compensated at the mid-point by a fixed capacitor Thyristor Controlled Reactor (FC-TCR) type of static var compensator .The two area system is divided in separate subsystems for the purpose of analysis as follows :

- Generator (G1, G2)
- Exciter and PSS
- Governor and Turbines
- Network
- Static Var Compensator

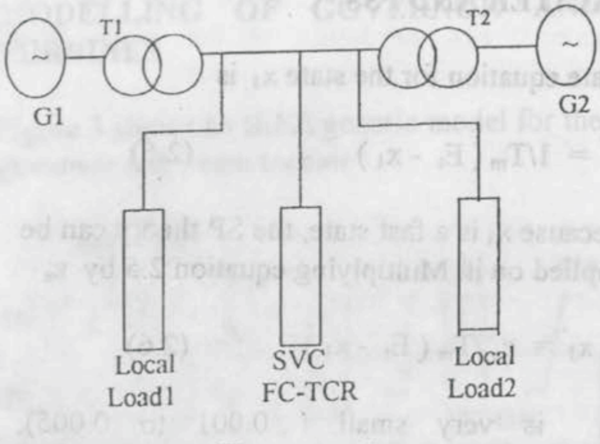


Fig. 1 Two area system

GENERATOR MODEL

The synchronous generator of both the areas are represented by a field winding (f) and a damper winding (h) along with a d-axis and two damper winding (g,k) on the q axis [3,4]

STATOR CIRCUIT

The stator of both the generator are modelled by a dependent current source $I_{i\propto}$ in shunt with the subtransient reactance L''_{di} , where i is an index related to the generator. The stator model is combined with the transmission network model as described in network modelling in the succeeding paragraph.

ROTOR CIRCUIT

The flux linkages (ψ) of different windings relating to generator are defined as :

$$\psi'_{fi} = a_{1i}\,\psi_{fi} + a_{2i}\,\psi_{hi} + b_{1i}\,v_{fi} + b_{2i}\,i_{di}$$

$$\psi'_{hi} = a_{3i}\,\psi_{fi} + a_{4i}\,\psi_{hi} + b_{3i}\,i_{di}$$

$$\psi'_{gi} = a_{5i}\,\psi_{gi} + a_{6i}\,\psi_{ki} + b_{5i}\,iq_i$$

$$\psi'_{ki} = a_{7i}\,\psi_{gi} + a_{8i}\,\psi_{ki} + b_{6i}\,iq_i \qquad (2.1)$$

Here :

i is an index number, i = 1,2

v_{fi} : field excitation voltages of generator

i_{di}, i_{qi} : d, q axis component of the i^{th} generator current.

a_{1i} - a_{8i} : Constants associated with the i^{th} generator

Transforming the d-q frame of reference variables into the synchronously rotating D-Q reference frame equation 2.1 is represented by equation 2.2 in the matrix form

$$\psi'_{gr} = [A_{gr}]\,\psi_{gi} + [A_{gf}]v_f + [H]X_n \qquad (2.2)$$

Where :

$\psi'_{gr} = [\psi_{fi}\ \psi_{hi}\ \psi_{gi}\ \psi_{ki}\ ]$, i = 1,2

$v_f = [\ v_{fi}\ ]$, i = 1,2

X_n is defined in network model. The d-q axis component of the dependent current source $I_{i\propto}$ to the two generator are given by :

$I_{di} = c_{1i}\,\psi_{fi} + c_{2i}\,\psi_{hi}$

$I_{qi} = c_{3i}\,\psi_{gi} + c_{4i}\,\psi_{ki}$, i = 1,2

These currents are also transformed to D-Q axis frame of reference [1].

GENERATOR EQUATION OF MOTION

The generator equations of motion are :

$$\delta'_j = \omega_j - \omega_0$$

$$\omega'_j = (\omega_0 / 2^* H_j)[\,T_{mj} - D_j(\omega_j - \omega_0) - T_{ej}\,], \qquad \ldots\ldots\ldots\ldots (2.3)$$

Where :

j = 1,2

$$T_{ej} = -x''_{di}\,(i_{di}\, I_{qi} - i_{qi}\, I_{di})$$

Because of the slow frequency phenomena equations 2.2 and 2.3 are treated as the slow states of the system.

MODELLING OF EXCITER AND POWER SYSTEM STABILIZER

Figure 2 shows the dynamic model of a static exciter with PSS, corresponding to IEEE type ST1 and PSS1A [5]. Time constants of various states are given in appendix – A. It is clear from the appendix-A that T_w is the maximum, hence x_3 is a slow state as evident from the model below. Because the other time constants are lesser than the T_w. Hence the corresponding states x_1, x_2, x_4 and x_5 are treated as the fast states

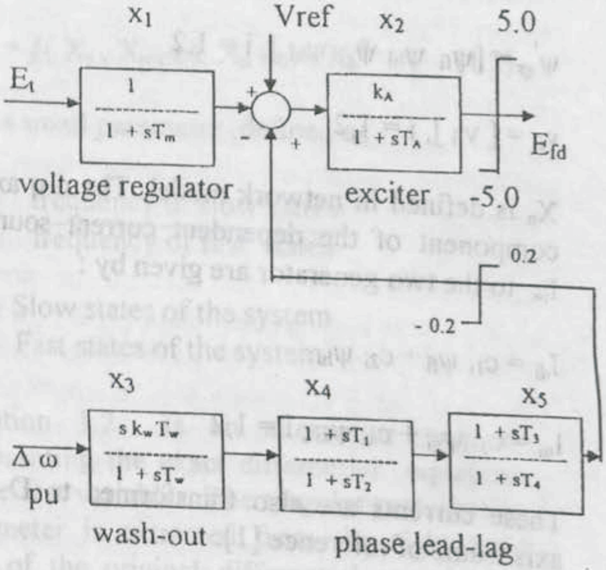


Fig. 2 Exciter and PSS model

The detailed model of exciter and PSS is given by:

$$\varepsilon_e X'_e = [A_e]X_e + [B_e]x_3 + [C_e]Vref + [D_e]E_t \quad (2.4)$$

Where :

$$X_e^T = [\, x_1, x_2, x_4, x_5 \,]$$

$$\varepsilon_e = \frac{\text{Time constant of fast states}}{\text{Time constant of slow states}}$$

ε_e varies from 0.001 to 0.005

TWO TIME SCALE MODEL OF THE EXCITER AND PSS

State equation for the state x_1 is

$$x_1' = 1/T_m\,(E_t - x_1) \quad (2.5)$$

Because x_1 is a fast state, the SP theory can be applied on it. Multiplying equation 2.5 by ε_e

$$\varepsilon_e\, x_1' = \varepsilon_e / T_m\,(E_t - x_1) \quad (2.6)$$

ε_e is very small (0.001 to 0.005), approximating LHS to zero will give the slow tracking component of the x_1 ie x_{1s}

$$0 = 1/T_m\,(E_t - x_{1s})$$

$$x_{1s} = E_t$$

hence $x_{1s} = E_t$ (2.7)

putting $x_1 = x_{1s} + x_{1f}$ and substitute 2.7 in equation 2.6. Neglect the x_{1f}, because x_{1f} decays very fast and solve for the x_{1f}.

$$x_{1f} = - T_m E_t'$$

Adding x_{1s} and x_{1f} will result x_1

$$x_1 = E_t - T_m E_t$$

Similarly using the mathematics explained above, the state equations of all other fast states ie x_2, x_4, x_5 are reformulated. The complete two time scale model of the exciter and PSS is as follows:

$$x_1 = E_t - T_m E_t'$$

$$x_2 = Vref - [E_t - (T_m + T_A)E_t'] + (k_w \Delta\omega - x_{3a}) - [T_A - T_1 + T_2 - T_3 + T_4]\,(k_w \Delta\omega - x_{3a})'$$

$$x_4 = (k_w \Delta\omega - x_{3a}) - T_2\,(k_w \Delta\omega - x_{3a})'$$

$$x_5 = (k_w \Delta\omega - x_{3a}) - (T_4 - T_1 + T_2)(k_w \Delta\omega - x_{3a})'$$

Where :

$x_3 = T_w x_{3a}$

MODELLING OF GOVERNOR AND TURBINES

Figure 3 shows an IEEE generic model for the governor and steam turbine

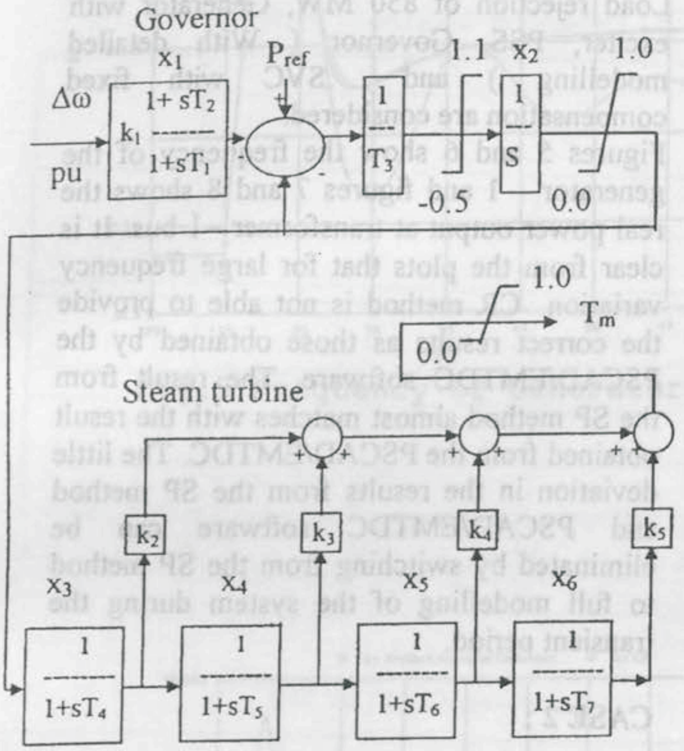


Fig 3 Model of Governor and Turbine

Detailed model of the governor and turbines

$$\varepsilon_g X'_g = [A_g]X_g + [B_g]\Delta\omega + [C_g]P_{ref} \quad (2.8)$$

Where:

$Xg^T = [x_1, x_2, x_3, x_4, x_5]$

$$\varepsilon_g = \frac{\text{Time constant of fast states}}{\text{Time constant of slow states}}$$

ε_g varies from 0.02 to 0.15

TWO TIME SCALE MODEL OF THE GOVERNOR AND TURBINES

Time constant of various states have been given in the Appendix -A. Time constant T_5 is the maximum hence state x_4 is a slow state. All other states x_1, x_2, x_3, x_5 and x_6 are treated as the fast states because their related time constants are lesser than T_5. Reformulated two time scale model of the governor and turbine model is as follows :

$x_1 = k_1\Delta\omega - T_1 k_1 \Delta\omega$

$x_2 = P_{ref} - [k_1\Delta\omega - (T_1 - T_2 + T_3) k_1 \Delta\omega']$

$x_3 = P_{ref} - [k_1\Delta\omega - (T_1 - T_2 + T_3 + T_4) k_1 \Delta\omega']$

$x_5 = x_4 - T_6 x_4'$

$x_6 = x_4 - (T_6 + T_7) x_4'$

NETWORK MODELLING

For network modelling α - axis and β - axis state equations are written. Those state equation are then transformed into D-Q frame of reference [2]. The final states equations in matrix form are as follows :

$$\varepsilon X' = [A_n]X_n + [F_l]\Psi_{gr} + [F_2]v_f \quad (2.9)$$

Where:
X_n is state variable in D-Q frame of reference
Ψ_{gr} is obtained from the equation 2.2
v_f field voltage vector

Applying two-time scale theory on 2.9 will result :

$$X_{ns} = -[A_n]^{-1} [F_l] \Psi_{gr} \quad (2.10)$$

X_{ns} is the slow component of the network states.

X_{nf} the fast components of the X_n is obtained by iterative procedure.

$$X^{(0)}_{nf} = -[A_n]^{-1} [G]$$

$$-[A_n] X^{(1)}_{nf} = [G] - [S_9] X^{(0)}_{nf}$$

All matrices $[A_n]$, $[F_l]$, $[F_2]$, $[G]$ and $[S_9]$ are defined in [2].

The iteration can be continued till
$\mathrm{mod}[X^{(i+1)}_{nf} - X^{(i)}_{nf}] \leq \varepsilon_1$
Where ε_1 is a small tolerance factor
finally X_{ns} and X_{nf} are added to get X_n.

MODELLING OF THE SVC

For SVC IEEE basic model - 1 is considered [6]. The block diagram for the same is shown in figure 4.

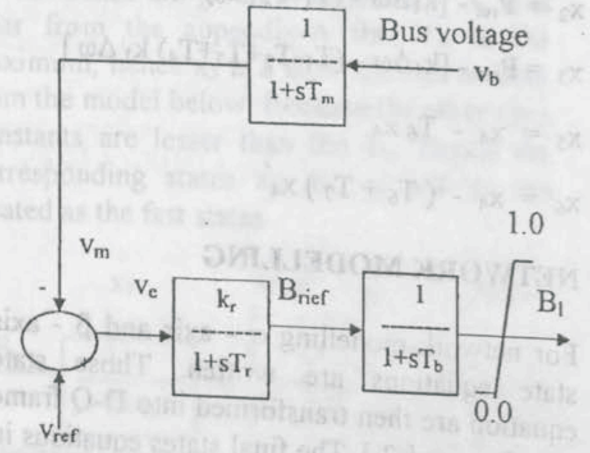


Fig 4 SVC basic model – 1

The susceptance reference output B_l is modelled by equation 2.11 { Here T_b is assumed to be zero }. B_l is treated as a slow state. The SVC bus voltage and current are included in the network modelling and treated as the fast states (included in X_n).

$$B_l^{'} = 1/T_r\,(V_e k_r - B_l) \qquad (2.11)$$

Where :
V_e = Error voltage = $V_{ref} - V_m$
k_r = Gain of the voltage regulator
T_r = Time constant of the voltage regulator

3. CASE STUDY

Case studies have been done on the system as shown by the figure 2.1. A disturbance is simulated by switching off the entire load of 300 MW in area-1 and 550 MW (50% of the total load) in area-2. Thus total load rejection is of 850 MW. This heavy load rejection results in about 5 % change in the frequency of both the generators. The results are obtained for the SP method and the CR method. For validation of the results the PSCAD/EMTDC package is used.

CASE 1:

Load rejection of 850 MW, Generator with exciter, PSS, Governor (With detailed modelling) and SVC with fixed compensation are considered.

Figures 5 and 6 show the frequency of the generator – 1 and figures 7 and 8 shows the real power output at transformer –1 bus. It is clear from the plots that for large frequency variation CR method is not able to provide the correct results as those obtained by the PSCAD/EMTDC software. The result from the SP method almost matches with the result obtained from the PSCAD/EMTDC. The little deviation in the results from the SP method and PSCAD/EMTDC software can be eliminated by switching from the SP method to full modelling of the system during the transient period.

CASE 2 :

Load rejection of 5 MW, Generator with exciter, PSS, Governor (with detailed modelling) and SVC with fixed compensation are considered.

From figure 7 and 8 it is revealed that for small frequency deviation the CR and the SP methods provide same results. This is due to the fact that frequency variation is small, hence $X_{nf} \cong 0$ (fast component of the fast states). Hence, fast states are approximately equal to their respective slow component i.e. $X_n \cong X_{ns}$. The same approximation is also made in the CR methods, therefore, the results for the small frequency deviation are similar from SP and CR methods.

CASE 1

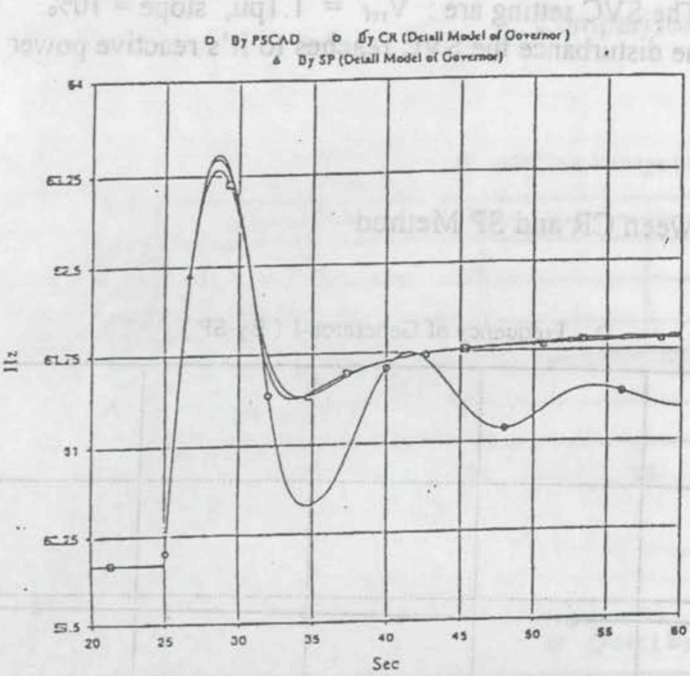


Fig.5 Frequency of Generator 1

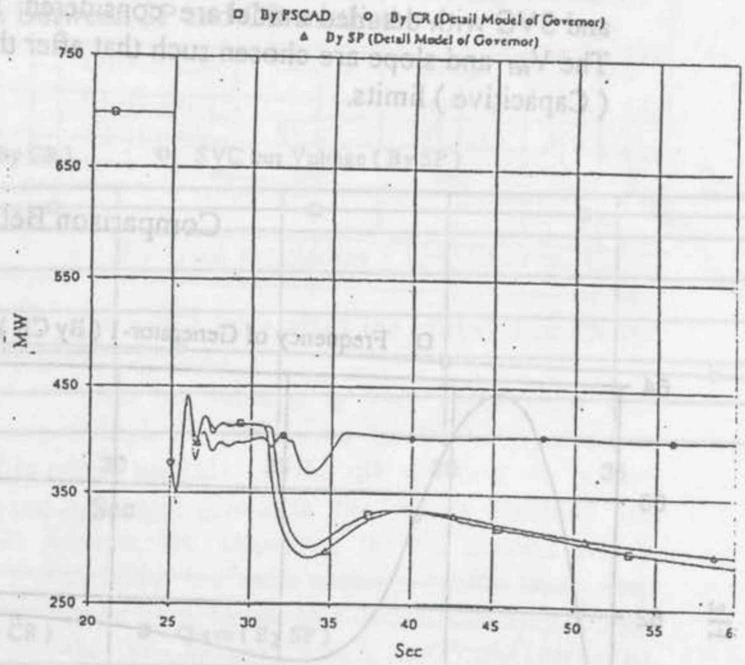


Fig. 6 Real Power output at Transformer 1 Bus

CASE 2

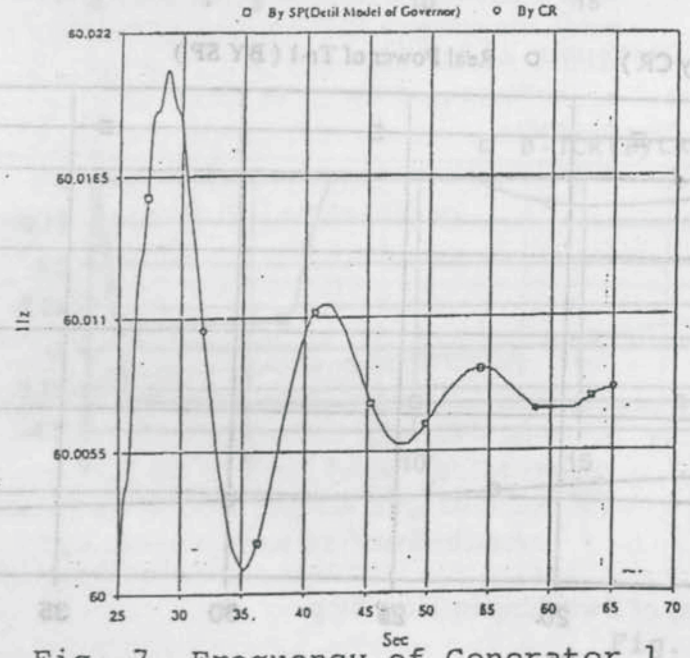


Fig. 7 Frequency of Generator 1

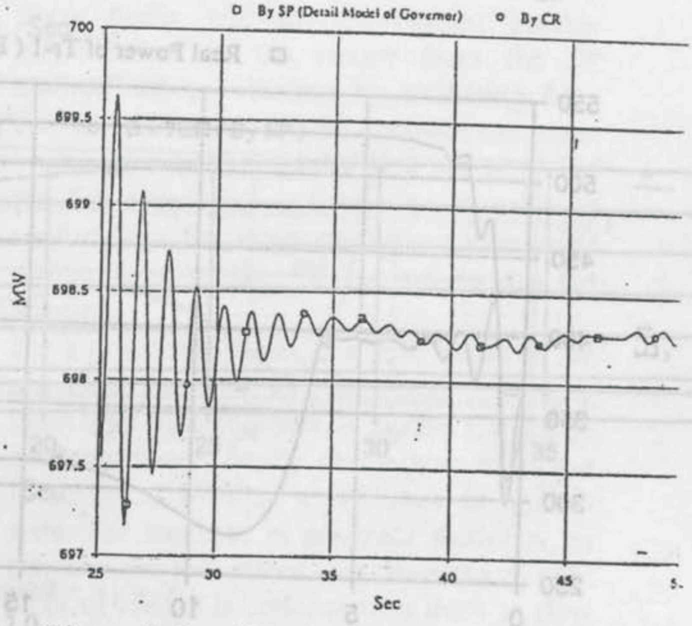


Fig. 8 Real Power output at Transformer 1 Bus