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FACTORS AFFECTING THE NATURAL MACHINE DAMPING POWER IN SERIES COMPENSATED POWER SYSTEMS

BY

A.A.Sallam - Ph.D., MIEEE
Department of Electrical Engineering, University of Suez Canal
Port Said, Egypt.

Abstract

Studies of the application of series capacitor compensation in integrated power systems lead to consideration of the effects of the compensation upon the contribution arising from the natural damping of the generators.

In general, the series compensation is chosen because of the reduction in transfer reactance, but this paper shows that there is also an improvement in the natural positive sequence machine damping. Automatic voltage regulator effects and the effects of feedback signals in such controls have been studied.

The possibility of sub-synchronous resonance is taken into account.

Introduction

The positive sequence damping power of each component synchronous generator is a significant factor in the overall stability of an interconnected synchronous power system. It is seen from equation (1) that it is a function of the machine design [1] and indeed it is usually necessary to design damping into a generator, perhaps the best example being the damper windings built into the pole faces of salient pole generator which have laminated field systems. High speed generatros with solid rotors usually rely upon the damper current paths in the solid rotor. With higher specific outputs in such machines, additional damping has been provided by damper windings in the slots above the field winding, and by long and electrically continuous slot wedges.

$$P_d = E^2 \cdot \frac{1}{360\ f} \cdot \frac{\Delta\delta}{\Delta t} \cdot \omega \left[\frac{(x_d' - x_d'')\ T_{do}''}{(x_d' + x_e)^2} \ \sin^2 \delta + \frac{(x_q' - x_q'')\ T_{qo}''}{(x_q' + x_e)^2} \cos^2 \delta \right] \qquad (1)$$

As damping is affected by the connection to the power system, the transfer impedance must also be of significance, a tightly coupled system being more heavily damped than a tenuous system.

With hydro-generators situated a long way from the main load centre, it is useful to improve the coupling by reducing the transfer reactance, using series capacitor compensation. It is important to understand the effect of such compensation upon damping, and this factor has been studied on a representative system. It is seen that the location of the compensator series capacitor relative to the generator is significant [2] .

No synchronous generator is now connected to a system without an automatic voltage regulator. It is well known that the system and not the generator, decides the busbar voltage, so that the automatic voltage regulator, (or more accurately the automatic excitation control) controls reactive power sharing rather than voltage. It can also make a substantial contribution towards stability by increasing excitation during system distrubances such as faults which tend to reduce busbar voltage [3] . This leads to a substantial reduction in load angle excursion, but at the expense of appreciable negative damping. For this reason, a Δw or similar state-related feedback signal in the excitation control is now standard for all generators except those on a tightly interconnected system. This feed-back signal produces a significant damping contribution and can restore all of the positive damping lost by automatic voltage regulator action.

Finally, no system containing series capacitor compensation is now envisaged unless the possiblity of sub-synchronous resonance can be completely excluded. Early generator shaft failures due to such resonance were associated with series capacitors giving resonant frequencies close to a shaft natural mode of oscillation.

Frequencies around 10, 16, or 23 Herz, which are near to the possible natural modes of oscillation of generator shafts, are to be avoided, and it is necessary for the manufacturer to identify with accuracy all the possible natural frequencies so that they and their harmonics can be avoided under all possible system

State/Space Feedback Signal in A.V.R.

It is well known that the negative damping produced by the A.V.R. effects can be substantially reduced by the use of a $\Delta\omega$ feedback signal, where the effects of rotor velocity and acceleration relative to synchronous speed can be used to improve the stability contribution [6] .

This is clearly seen in Fig. (8) and Fig. (9), whilst Fig. (10) shows that this is achieved without a large machine natural damping contribution. This effect is most clearly seen in Fig. (10). The effects of inclusion of the A.V.R. with and without $\Delta\omega$ feedback are shown, in the absence of any series capcitor compensation. The machine natural damping is seen to be considerably reduced, if Fig. (10) is compared with Fig. (7).

Shaft Torsional Effects

The shaft stiffness and the shaft natural modes of oscillation can no longer be neglected with the modern generators of high specific output, and the problems of shaft life duration are now taken into account in all serious studies.[7]

The mathematical modelling usually represents rigid masses, weightless springs and damping sources. The parameters of such a model are set up in a matrix form covering a specific number of points over the required frequency range. As the basic parameters are not known to any high degree of accuracy, extreme accuracy is not possible in determining natural frequencies of oscillation.

The matrix of the electrical power system is used to determine the eigen values with the preferred magnitude and location of the series compensation. It is then only necessary to ensure that there will be no possibility of resonance between masses described above.

Conclusions - Detailed

The nearest point to the actual generator is the most suitable place for positioning the series compensation to obtain the best improvement in transient stability. This does not conflict with the machine natural damping power contribution, for this is maximized when the compensation lies between the generator and its terminal busbar.

The usual requirement of series compensation to reduce the transfer reactance, also does not conflict with the damping requirements, as machine natural damping is increased by the series compensation.

Conclusions - General

The natural machine damping should be taken into account in determining the magnitude and location of series compensation capacitors in an integrated power system.

When such calculations are made, they may affect the decisions taken purely on grounds of transmission line transfer impedance, important though these may be.

Automatic voltage regulator effects must also be considered, especially with the attenuated transmission lines which are normally associated with the need for series compensation. In such conditions, the A.V.R. may be expected to produce appreciable negative damping, and it will usually be necessary to include a state/space feedback in the excitation control, such as $\Delta\omega$, to restore positive damping from the A.V.R. Even in these circumstances, the natural machine

ion is not negligi

Finally, it is necessary to determine the natural frequencies of oscillations associated with the system including series compensation, and compare these with the natural frequencies inherent in the generator and prime mover shafts to ensure that there is no possibility of sub-synchronous resonance.

Further studies are in progress, on a system which could not be operated without sereis capacitor compensation, and where the multi-machine modes of oscillation are of importance.

References

(1) KIMBARK, "Power System Stability-Synchronous Machines", J.W. 1968, pp 214-245

(2) ANDERSON & FOUARD, "Power System Control & Stability", Iouse State University Press 1977, pp37-43

(3) DANDEND, P.L., KOVIAS, A.N., MCCLYMONT, K.R. & WATSON, W., "Effect of High-Speed Rectifier Excitation Systems on Generator Stability Limits". IEEE Transactions on Power Apperatus and Systems, Vol. 87, No. 1 January 1968 pp 190 - 201

(4) WATSON, W., & Coultes, M.E., "Static Exciter Stabilizing Signals on Large Generators Mechanical Problems", IEEE Power Apparatus and Systems, Vol. PAS 92, Jan/feb 1972, pp204-211

(5) DEMELLO, F.P. & CONCORDIA, C., "Concepts of Synchronous Machine Stability as Affected by Excitation Control", IEEE Trans. Vol. PAS 88, No. 4, April 1969, pp 316-329

(6) GIBBARD, M.J., "Co-ordination of Multi-Machine Stabilizer Gain Settings for a Specified Level of System Damping Performance

IEE IEE Proceedings, Vol. 129, Part C, No. 2, March 1982,pp 45-48

(7) KIMBARK, E.W. "How to Improve System Stability Without Risking Subsynchronous Resonance" IEEE Trans. on Power Apparatus & Systems

Vol. - PAS - 96, No. 5 September / October 1977, pp 1608-1619

Appendicies

Appendix (I) : List of Symbols used

P_d = damping power

E = voltage of terminal bus

f = frequency

$\Delta\delta$ = change of laod angle

ω = 2πx rated frequency

Δt = change of time

X_d' = direct axis transient reactance

X_d'' = direct axis subtransient reactance

X_e = external reactance in series with armature

T_{do}'' = direct axis subtransient open-circuit time constant

δ = rotor angle

X_q' = quad.-axis transient reactance

X_q'' = quad.-axis subtransient reactance

T_{qo}'' = quadrature-axis subtransient open-circuit time constant

Appendix (II)

The data of the system shown in Fig. (1)

a – the impedances in p.u. on a 100 MVA base

Bus				
from	To	R	X	B/2
1	4	0.0	0.0576	0.0
4	5	0.01	0.085	0.088
4	6	0.017	0.092	0.079
5	7	0.032	0.161	0.153
6	9	0.039	0.17	0.179
7	2	0.0000	0.0625	0.0
7	8	0.0085	0.072	0.0745
8	9	0.0119	0.1008	0.1045
9	3	0.0	0.0586	0.0

b - Load data

Load at	P (p.u.)	Q (p.u.)
A	1.25	0.5
B	0.90	0.3
C	1.00	0.35

c - Generators data

Generator	G_1	G_2	G_3
rated MVA	247.5	192.0	128.0
KV	16.5	18.0	13.8
p.f.	1.0	0.85	0.85
Type	hydro	steam	steam
speed	180.0	3600.0	3600.0
X_d	0.146	0.8958	1.3125
X_d'	0.0608	0.1198	0.1813
X_q	0.0969	0.8645	1.2578
X_q'	0.0969	0.1969	0.25
T_{do}'	8.96	6.0	5.89
T_{do}''	0.03	—	—
T_{qo}'	0.0	0.535	0.60
T_{qo}''	0.06	—	—
X_d''	0.0517	0.1018	0.1541
X_q''	0.06	—	—
H	5.55	3.33	2.35

Appendix (III)

The block diagram of the used A.V.R. (excitation control system) in IEEE standards including ω feedback signal is shown in Fig.(11). The values of the parameters K_c , T_c and T_b are determined from computer studies which showed that a gain of these magnitudes was desirable.

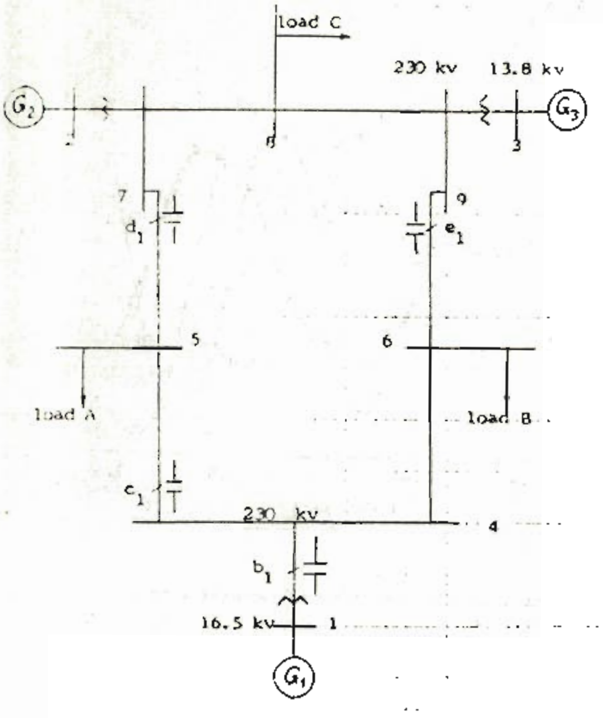


Fig. (1) : System studied

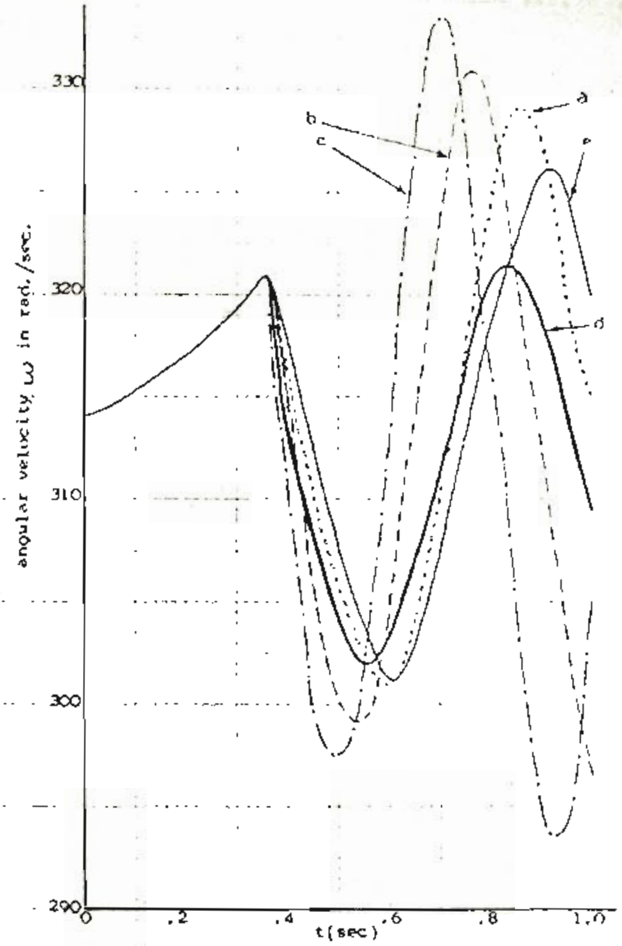


Fig.(3): Rotor angular velocity vs. time,Generator No.1

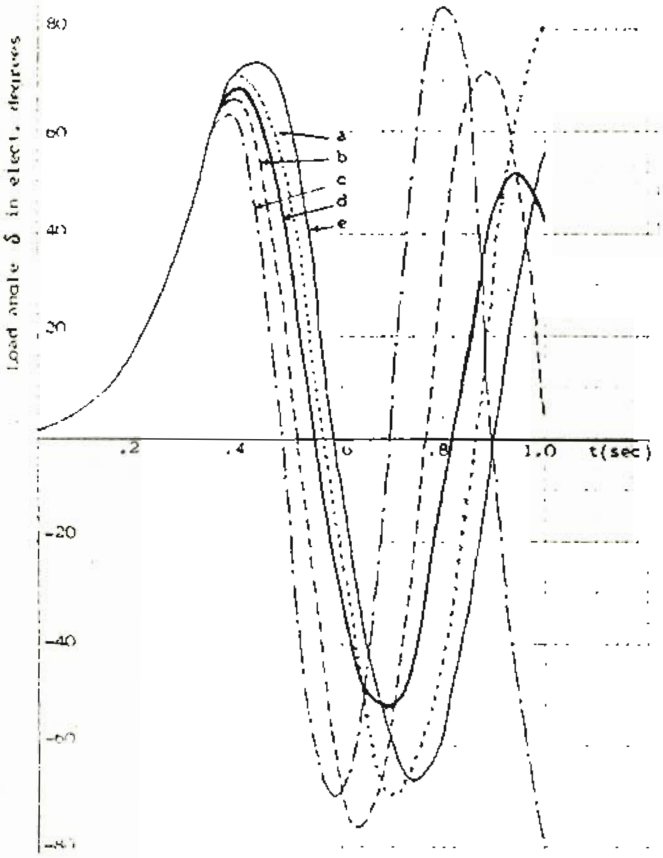
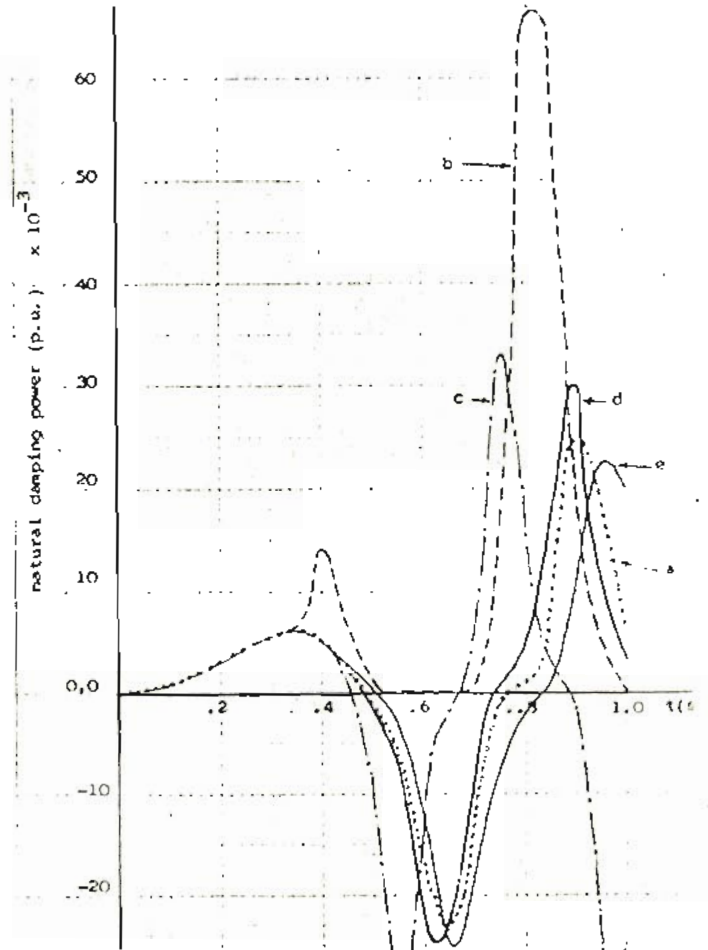


Fig.(2): Load angle oscillations of Generator No.1



Figs. 2,3&4 are drawn for gen. No.1 ,the natural damping is taken into account,while the A.V.R. effect is excluded.
Curve (a) - the system without series compensation
Curve (b) - the system with $X = X$ at location b_1 in Fig(1)

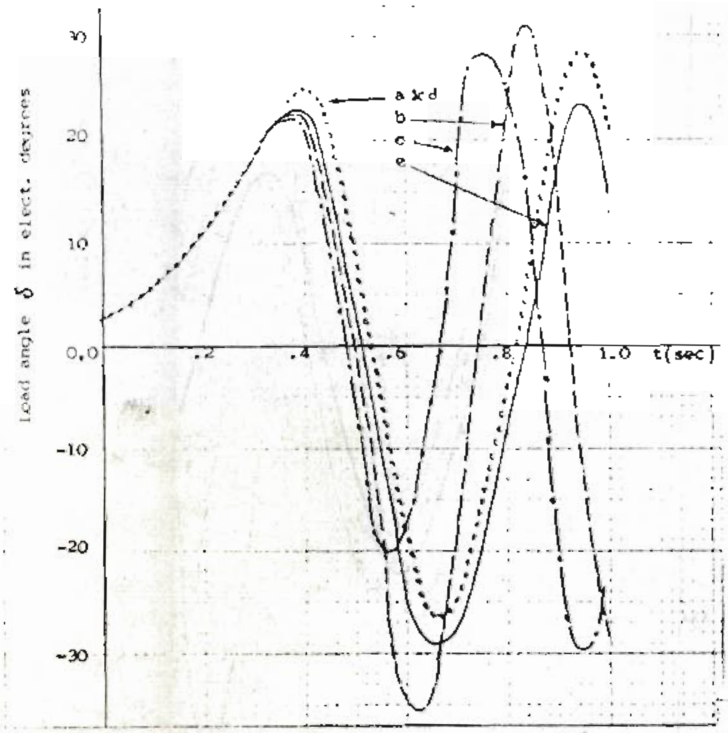
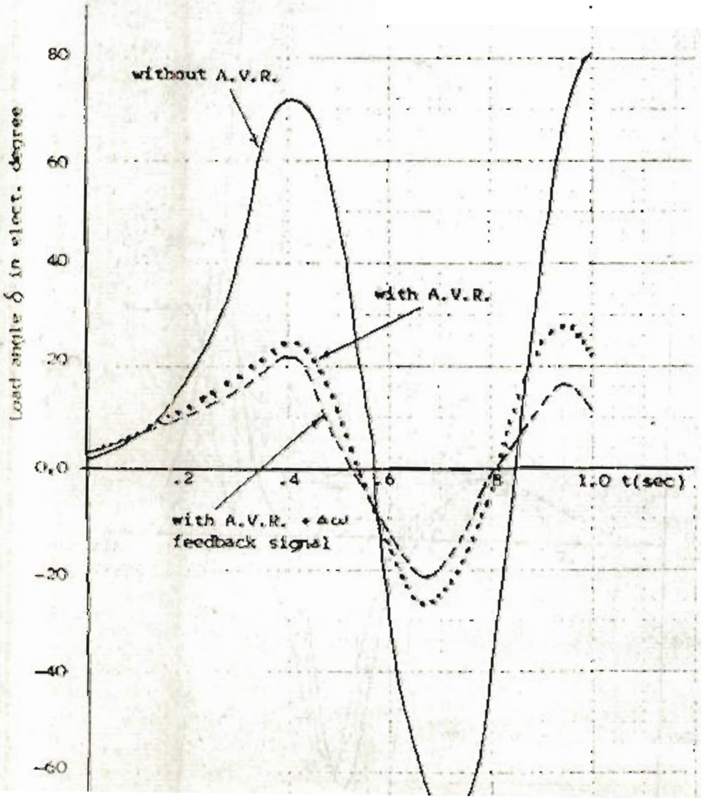


Fig. (5): Load angle oscillations of Generator No.1

Figs.(5,6&7) are drawn for generator No.1,taking into consideration both of positive sequence damping power and A.V.R. effect. The curves a,b,c,d&e are at the same compensation , as in Figs.(2,3 &4) , where X_c is the series capacitive reactance and $X_{i,j}$ is the inductive reactance between the busbars i and j .



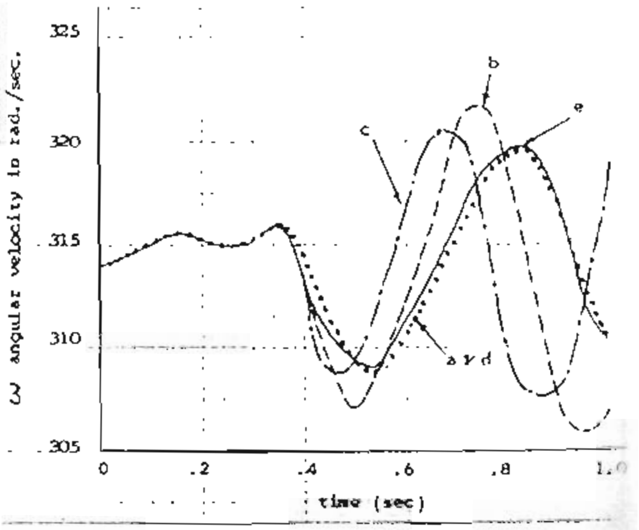


Fig. (6): Rotor angular velocity of Generator No.1

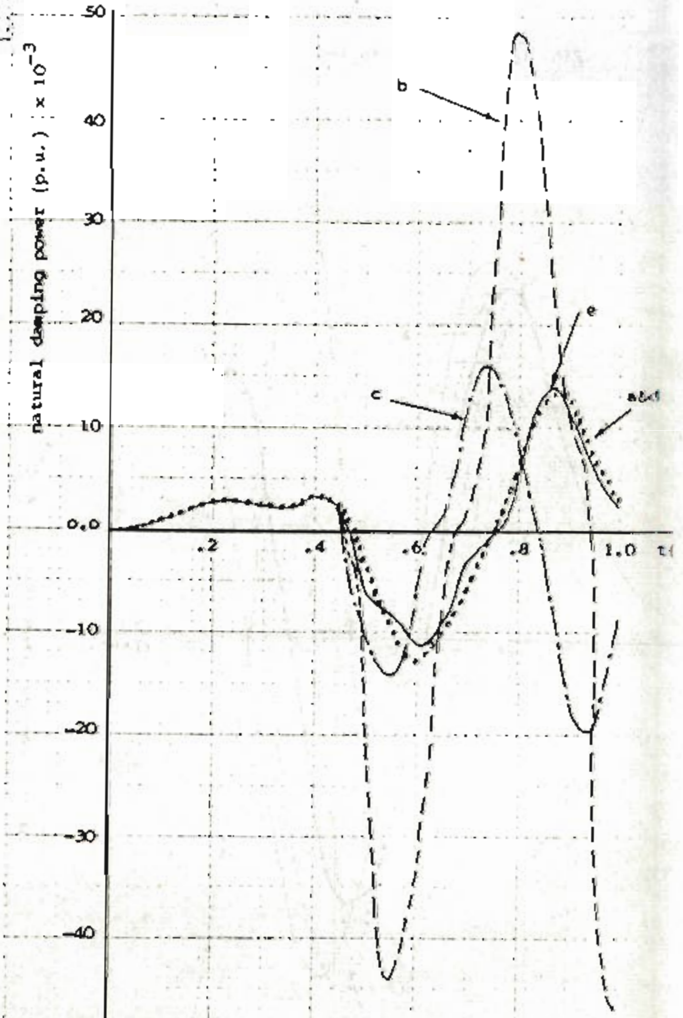


Fig.(7): Natural damping power of Generator No.1

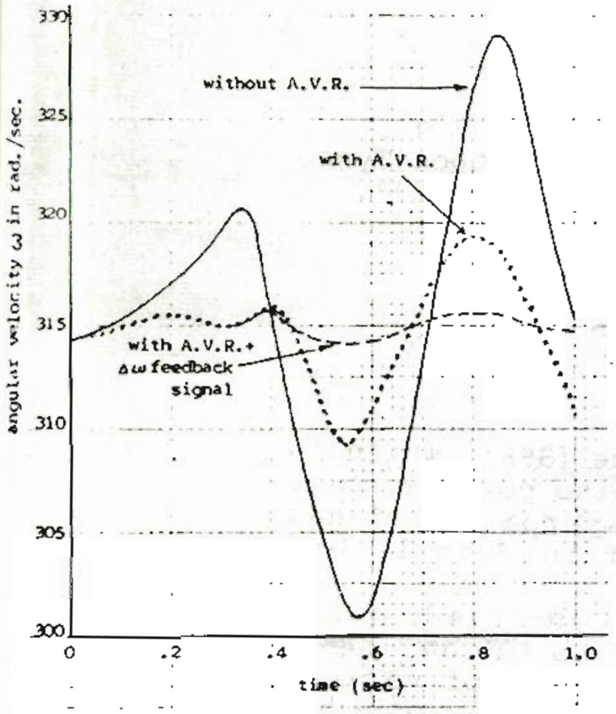


Fig.(9): Rotor angular velocity of Generator No.1 without series compensation in the system.

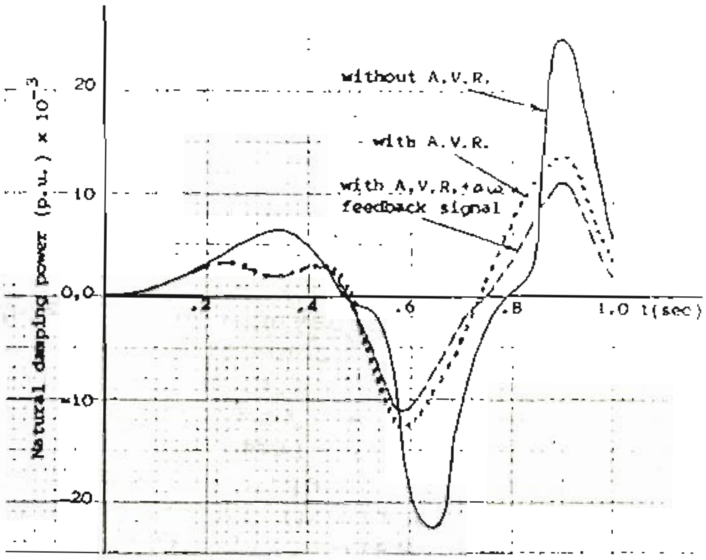


Fig.(10): Natural damping power of Generator No. 1 without series compensation in the system.

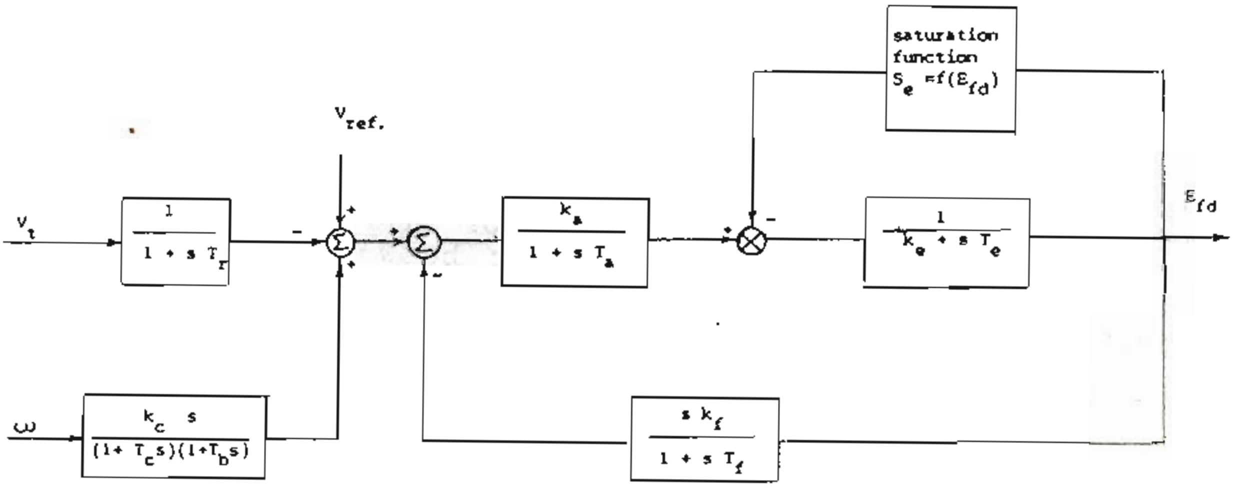


Fig.(11): The block diagram of the excitation control system (IEEE standard)

$T_r = 0$

$T_a = 0.06$

$T_e = 0.5$

$T_f = 1.0$

$T_c = 1.6$

$T_b = 1.5$

$K_a = 25.0$

$K_e = -0.0445$

$K_f = 0.16$

$K_c = 0.1$

$S_e = 0.0016\ e^{1.465\ E_{fd}}$