STABILIZATION OF SUBSYNCHRONOUS RESONANCE OSCILLATIONS BY REACTIVE POWER MODULATION

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الخلاصـــة :

تقدم هذه الورقة تقنية جديدة لتحديد أشكال الأنماط للنظام الميكانيكي للمولِّد التوربيني ، ولتصميم نظام تحكم بالقوة المفاعلة لتخميد الاهتزازات التوافقية التحت تزامنية في أنظمة القوى الكهربائية التي تحتوي على مكثف متصل على التوالي مع خطوط النقل .

وتبيِّن هذه الورقة أنَّ طرق الاستجابة الترددية تعطي معلومات نافذة عن تأثيرات التخميد لمختلف إشارات السرعة والتي تستعمل لتغيير معامل الحثّ لـمُحِثٍّ موصولٍ على التوازي عند المولِّد ، وذلك لتخميد النمط المهاج وتأكيد التخميد الموجب لبقية أنماط الاهتزازات . وتقدم هذه الطرق أيضا دلائل على كيفية ضبط إشارة السرعة المنتقاة بحيث تفى بمتطلبات نظام التحكم .

ABSTRACT

This paper presents a new technique for the determination of the mode shapes of the mechanical system of the turboalternator and the design of control schemes for static var controllers to suppress subsynchronous resonance oscillations in series compensated power systems. It is shown that the frequency response methods can specify the mode shapes and develop insights into the damping effects of the different speed signals available for use to modulate the inductance of a shunt reactor connected at the alternator terminals so as to stabilize the excited mode and to provide positive damping for the remaining modes of oscillation. These methods also provide guidance on how the selected signal should be adjusted to satisfy the control scheme basic requirements.

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NOTATION

i_{dm}, i_{gm} Direct and quadrature axes machine currents, p.u.
i_{dl}, i_{ql} Direct and quadrature axes reactor currents, p.u.
i_{fd} Field current, p.u.
i_{kd}, $i_{kq_{1,2}}$ Direct and quadrature axes damper windings currents, p.u.
$\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$ Speeds at different locations rad s^{-1}
$\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6$ Angular displacements at different locations in radians
V_{cd} Direct axis capacitor voltage, p.u.
V_{cq} Quadrature axis capacitor voltage, p.u.
E_{fd} Field voltage, p.u.
T_m Mechanical torque, p.u.
T_e Electrical torque, p.u.
f_n Natural frequency of oscillation rad s^{-1}
I_m Machine current, p.u.
I_l Reactor current, p.u.
X_c Reactance of the series capacitor, p.u.
P_g Power generated, p.u.
ΔL Change in the inductance of the reactor (phase), p.u.
ΔX_L Change in the reactance of the reactor, p.u.
$\Delta\omega_i$ ($i = 1-6$) Speed change depending on location on the shaft, rad s^{-1}
X_{Lo} Steady state value of the reactance of the reactor, p.u.
f_o Synchronous frequency

1. INTRODUCTION

Reactive power control is an essential requirement for efficient, reliable, and economic operation of modern power systems. Among the features afforded by such control, depending on the adopted strategy, are: leveling the voltage profile, improvement of stability limits, and counteracting subsynchronous resonance (SSR).

SSR oscillations occur in series compensated power systems due to the interaction between the subharmonic currents of the R–L–C transmission circuit and the rotor flux of the alternator, to produce subharmonic torques which may excite one of the turbo-alternator shaft modes, thus giving rise to a phenomenon usually referred to as SSR. Many countermeasures including excitation control [1, 2] series passive filter [3], control of DC links [4] NGH method [5] and active [6] and reactive power control [7–9] are employed to damp these oscillations. In the reactive power control method, the reactive power absorbed by a shunt reactor connected to the alternator terminals is modulated, usually in proportion to the generator speed signal, to modify the alternator current and prevent the harmful interaction effects with the rotor flux.

One of the control schemes [7] is arrived at by using the experimentally determined relation between the inductance of the reactor and torque perturbations. Such a scheme was capable of providing optimum damping of the excited mode but was ineffective in damping other modes of oscillation. To overcome this difficulty, it was necessary to use composite speed signals or torsional monitors [8]. In another scheme [9], the critical phase shift is determined and the mode stability zones are identified. More recently, optimal output feedback techniques [10] are employed for the design of the controller.

In this paper a new method making use of the frequency responses of the outputs of interest is introduced for the determination of the mode shapes and the choice of the most appropriate speed signal depending on its location along the shaft, and for the design of the controller. The aim is to stabilize the excited mode and at the same time provide a positive damping effect for other unexcited modes of oscillation.

A single machine connected to an infinite busbar through a series-compensated circuit is considered for the purpose of defining the problem, designing the controller, and demonstrating its effectiveness. This system is considered as a control system whose inputs are the exciter and speed error signals. The exciter error signal is taken as a reference and the frequency response of the different speed signals and currents are used to design the control scheme. The stability of both modulated and unmodulated systems is checked using the eigenvalue analysis of the small perturbation of the linearized equations describing the power system model.

2. DESCRIPTION OF THE STUDIED SYSTEM

The system considered is the IEEE first benchmark model for computer simulation of SSR [11] as shown in Figure 1. The generator is represented in terms of Park's equations in which the rate of change of flux in the stator winding is taken into account. The machine has two quadrature and one direct axes damper windings. The mechanical system is modeled by six elements in a lumped mass model. The mechanical damping (mainly steam and material hysteretic damping) is considered to be zero so as to represent a worst case condition and ensure that the designed stabilizer is capable of stabilizing the most severe oscillations. The transmission circuit is represented by lumped R−L−C elements. Each phase of the delta connected static var compensator consists of a reactor in series with parallel back-to-back thyristors connected to the alternator terminals. The reactor has a 50 MVA rating, which is equivalent to 5.6% of the alternator capacity. The reactive power of this reactor is modulated in accordance with a speed signal and the terminal voltage, when the voltage control loop is closed. For simplification, the dead and the delay times of the thyristor circuit are considered to be zero.

For the small disturbance analysis, the nonlinear equations expressed in a rotor frame of reference are linearized and arranged in the standard state space form:

$$\dot{X} = Ax + Bu$$

$$Y = Cx + Du$$

where

$$X^t = \{i_{dm}, i_{qm}, i_{fd}, i_{kd}, i_{kq1}, i_{kq2}, V_{cd}, V_{cq}, \omega_1, \delta_1, \omega_2, \delta_2, \omega_3, \delta_3, \omega_4, \delta_4, \omega_5, \delta_5, \omega_6, \delta_6, i_{dl}, i_{ql}\}$$

$$U^t = \{E_{fd}, T_m\}$$

$$y^t = \{I_m, I_l, T_e, E_t, \omega_i\} \; i = 1-6 \; .$$

A, B, C, D are matrices of appropriate dimensions.

Control over the terminal voltage E_t is provided by an exciter in accordance with an exciter error signal which is the difference between E_t and the reference voltage. Similarly, control over the synchronous speed is performed by the governor/turbine control system in accordance with a speed error signal which is the difference between the actual speed and the reference speed. However, it should be emphasized that this governor loop has no significant influence on SSR oscillations due to the excessive attenuation at the torsional frequency range. The block diagram representation of the complete control system is shown in Figure 2. In the Figure, $G(s)$ relates the input $U(s)$ to the output $Y(s)$:

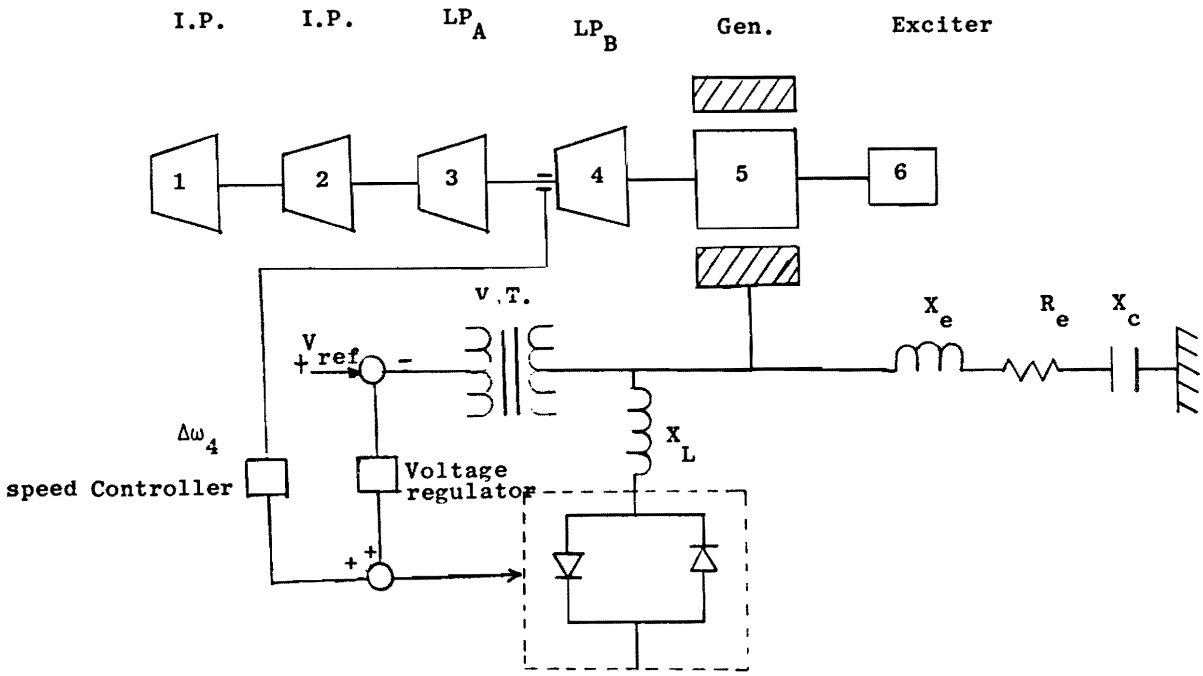

Figure 1. Model for the Studied Power System.

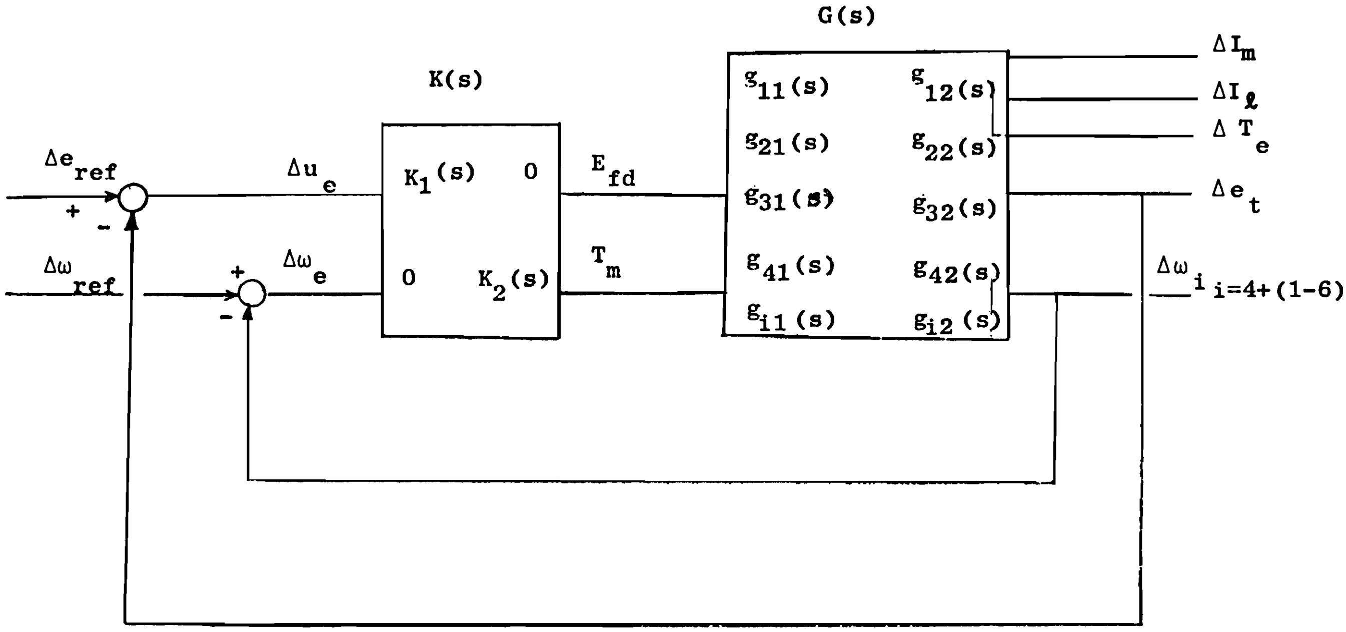

Figure 2. Block Diagram Representation of the Power System with Controls.

$$Y(s) = G(s)\,U(s)$$

$$G(s) = C(sI-A)^{-1}\,B+D\,.$$

$K(s)$ represents the excitation and governor control systems:

$K_1(s)$: transfer function of the thyristor excitation system $= k_{ex}/(1+sT_{ex})$

$K_2(s)$: transfer function of the turbine-governor system $= k_g/(1+sT_g)\,(1+sT_t)$

where $k_{ex} = 200$, $T_{ex} = 0.05$ s, $k_g = 25$, $T_g = 0.2$ s, $T_t = 0.3$ s.

The frequency response of any output w.r.t. the voltage error signal is obtained from the mapping of $g_{n1}(s)k_1(s)$; n denotes the output as specified in Figure 2 or in Y^t. Similarly, the frequency response of any output w.r.t. the speed error signal is obtained from the mapping of $g_{n2}(s)k_2(s)$. Substituting $j\omega$ for s, $g(j\omega)\,k(j\omega)$ is computed at predetermined frequencies and plotted in the form shown in the frequency response figures of this paper.

3. MODE SHAPES

The system has six mechanical modes of oscillation. Mode 0 corresponds to the classical hunting mode of oscillation of all the masses of the turbogenerator as one unit against the electrical system. Modes 1–5 correspond to intermasses torsional oscillations at frequencies of 98.27, 126.99, 160.52, 202.85, and 298.12 rad s^{-1}. The mode shapes defining the relative directions and amplitudes of oscillation of the different masses with respect to each other are obtained from the frequency response of the different speed signals, considered as outputs as specified in Y^t or Figure 2 and derived from the different mass locations along the turbogenerator shaft, relative to the exciter error signal Δu_e as shown in Figure 3. At each critical frequency of oscillation, comparison of the magnitude and phase of the response of the different speed signals give the mode shapes. For mode zero all the responses are similar in phase and magnitude at the 7 rad s^{-1} frequency of oscillation, indicating that all the masses are moving as one unit against the electrical system. For other modes the phase and amplitude of responses at each critical frequency are not equal and are either in phase or out of phase (shifted 180° exactly) with respect to each other indicating that the masses move either in the same direction or in opposite directions. For example if we consider column 2 of Figure 3 representing mode 1 of oscillation at approximately 99 rad s^{-1}, the responses of the speed signals at the H.P. tur., I.P. tur., L.P.$_A$ tur., L.P.$_B$ tur., generator, and exciter are 0.07 $\angle 174°$, 0.055 $\angle 174°$, 0.03 $\angle 174°$, 0.01 $\angle -6°$, 0.035 $\angle -6°$, and 0.09 $\angle -6°$, respectively. Comparison of phases and magnitudes of these responses can be expressed in the standard form of Figure 4 which includes also the results of comparison at other modes.

The mode shapes of Figure 4 are usually obtained from the eigenvector matrix. If we consider the equations of the mechanical system only, the eigenvectors matrix Q is given below:

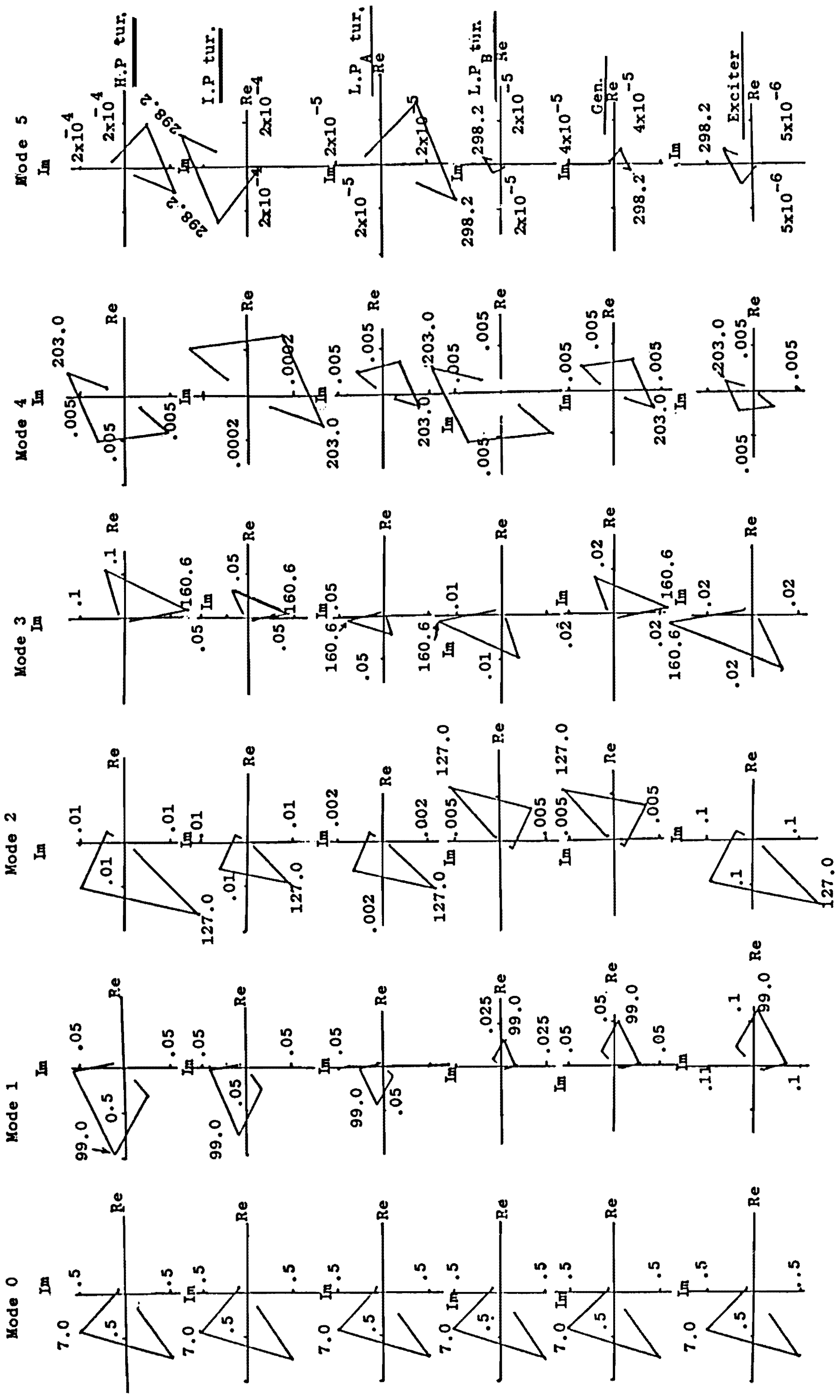

Figure 3. Frequency Response of the Different Speed Signals Relative to the Exciter Error Signal (Figures on the Graph Indicate Frequency in rad s^{-1}) (X_c = 0.0, p = 1.0 p.u., p.f. = 0.9).

$$Q = \begin{vmatrix} 0.163\times10^{-4} & -0.194 & -0.059 & 0.416 & 0.308 & -0.487 \\ 0.163\times10^{-4} & -0.146 & -0.347 & 0.142 & -0.016 & 0.619 \\ 0.163\times10^{-4} & -0.086 & -0.008 & -0.095 & -0.179 & -0.071 \\ 0.163\times10^{-4} & 0.028 & 0.212 & -0.04 & 0.357 & 0.013 \\ 0.163\times10^{-4} & 0.093 & 0.02 & 0.069 & -0.221 & -0.003 \\ 0.163\times10^{-4} & 0.25 & -0.537 & -0.105 & 0.134 & 0.0006 \end{vmatrix}$$

If we consider the elements of column 2 of matrix Q, comparison of these elements results in the same mode 1 shape as concluded from column 2 of Figure 3. Similarly, each column of matrix Q is equivalent to the corresponding column in Figure 3, *i.e.* the ratio between the phasors representing the responses at each frequency of oscillation as derived from Figure 3 correlates exactly withe the ratios between the entries in the columns in matrix Q. Hence Figure 3 could be thought of as the eigenvector matrix; however it gives definite information on the absolute magnitude and exact phase of the angular displacements or speed changes when the system is disturbed. In contrast, the eigenvectors are not unique and the absolute value of the magnitude and phase of the response of the displacements cannot be defined therefrom.

4. SYSTEM STABILITY

Since the masses are displaced with different amplitudes in different directions, torsional torques between the neighboring masses are produced. Usually these torques are positively damped by the mechanical system damping. However, in series compensated systems, the subsynchronous stator current having a natural frequency f_n interacts with the air gap flux rotating at f_0 to produce torques at a frequency of f_0-f_n. If this frequency coincides or is sufficiently near one of the natural frequencies of oscillation of the masses mounted on the shaft, then oscillations at this frequency are excited and may grow in magnitude to damaging levels and cause the shaft failure. The problem is well explained by finding the eigenvalues for the cases x_c = 0.24 p.u. and 0.285 p.u. At x_c = 0.24 p.u., f_0-f_n does not coincide with any of the natural modes of oscillation while at x_c = 0.285 p.u., f_0-f_n coincides almost exactly with the frequency of mode 3. The eigenvalues of the power system with unmodulated reactor in both cases, in addition to the case where x_c = 0.0, are shown in Table 1.

It is evident that with no coincidence between the frequencies of the electrical and mechanical modes, the mechanical modes of oscillation are lightly undamped as they have positive decrement factors. However, the decrement factors will become negative if the mechanical damping effect is taken into account. When f_0-f_n of the electrical mode is coincident with mode 3, its positive decrement factor is appreciably increased, indicating that the mode is excited by the mechanism of SSR. The relation between the value of x_c and the decrement factor around mode 3 is shown in Figure 5. It can be shown that as far as the excited mode damping is concerned, the system behavior is the same whether the unmodulated reactor is incorporated or not.

5. SYSTEM STABILIZATION BY INDUCTANCE MODULATION

Since the instability is caused by the interaction of the subsynchronous stator currents with the main field flux, the most straightforward method to

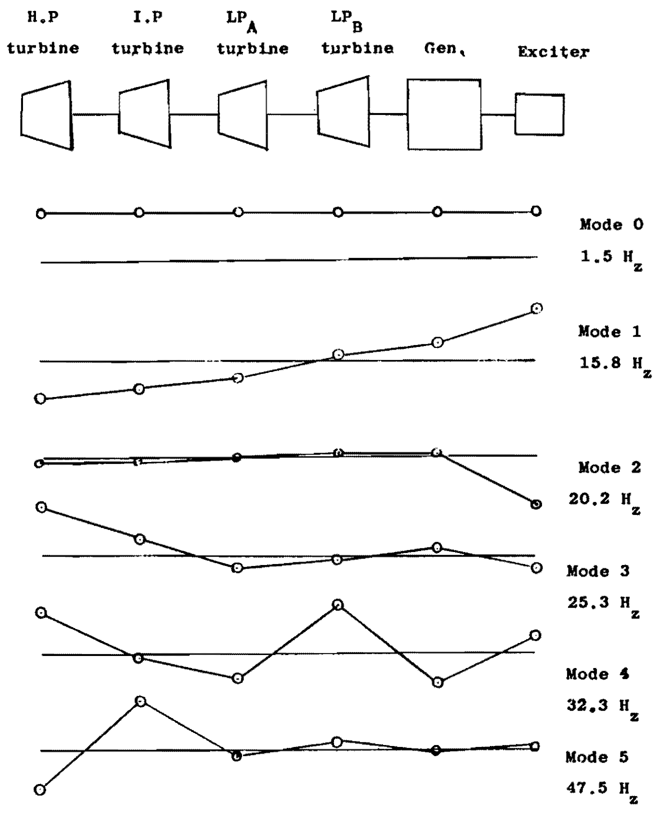

Figure 4. Mode Shapes of the Mechanical System.

Table 1. Eigenvalues of the Power System with Unmodulated Reactor P_g = 1.0, p.f. = 0.9.

x_c = 0.0	x_c = 0.24	x_c = 0.285	Remarks
$-8.56+j376.96$	$-4.64+j570.5$	$-4.67+j592.4$	Stator f_o+f_n
$-10.72+j377$	$-10.72+j377$	$-10.72+j377$	Reactor at f_o
$-0.0+j298.18$	$-0.0+j298.18$	$-0.0+j298.18$	Mode 5
$+0.003+j202.97$	$+0.064+j202.46$	$+0.008+j202.64$	Mode 4
$0.0+j377$	$-3.48+j183.34$	$-4.64+j161.15$	Stator f_o+f_n
$+0.001+j160.6$	$+0.052+j160.87$	$+1.515+j160.72$	Mode 3
$+0.0002+j127.02$	$+0.0027+j127.05$	$+0.0067+j127.08$	Mode 2
$-0.0005+j99.06$	$+0.02+j99.46$	$+0.02+j99.46$	Mode 1
$-0.31+j7.72$	$-0.45+j9.05$	$-0.5+j9.47$	Mode 0
-32.3	-32.68	-32.81	Direct damper
-0.27	-0.283	-0.285	Field
-3.02	-3.59	-3.79	Quad damper 1
-20.29	-20.37	-20.41	Quad damper 2

stabilize the system is to adjust the inductance of the reactor such that the current drawn at the unstable frequency of oscillation is in antiphase with the machine current at this frequency. The reactor current can then be adjusted in magnitude to force the resultant machine current to be in phase opposition to the original machine current. Thus, the electromagnetic torque at the subsynchronous frequency of interest is reversed causing positive damping of the oscillatory mode instead of its original destabilizing effect.

To realize this idea for the case where x_c = 0.285 p.u. the frequency response of the different outputs with respect to the exciter error signal shall be considered. The responses of the different speed signals and the machine and inductor currents are shown in Figures 6*a*, 6*b*, respectively. In these figures, the responses of mode 0 and mode 5 are ignored. The responses for mode 0 are the same at all locations and are of concern only when the reactor is intended for improving the dynamic stability limits. Mode 5 is usually neglected as it can only be excited at very low unpractical values of series compensation.

By inspection of Figures 6*a* and 6*b*, the phase relations between the machine current (row 3 of column 1 of Figure 6*b*) and the LP_B turbine speed signal (row 3 of column 4 of Figure 6*a*) at the frequency of 160.7 rad s^{-1} are summarized in Figure 7. Assuming that the inductance is modulated in accordance with LP_B speed signal (the most appropriate stabilizing signal as will be shown later), the relation between the reactance and the speed can be expressed as:

$$\frac{\Delta X_L}{\Delta\omega} = K * X_{Lo} * \frac{aS+1}{bS+1} ;$$

a, *b* are constants chosen to provide the required phase shift and *K* is the gain adjustment.

The final choice of control scheme is made in view of the following points:

(*a*) The phase shift between the response of the machine current and LP_B speed signal at 160.7 rad s^{-1} is 56°. Other speed signals are shifted 56° or (56° + 180°).

(*b*) The response of the unmodulated reactor current at all the subsynchronous frequencies (as shown in Figure 6) is very small to influence perfor-

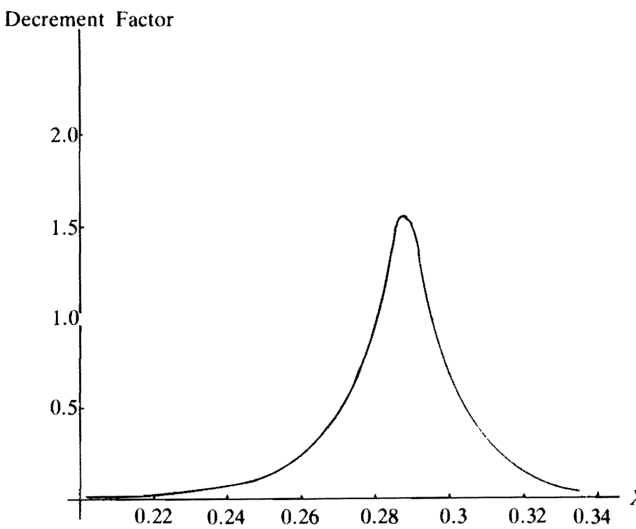

Figure 5. The Relationship Between the Damping of Mode 3 and the Value of X_c *(*P_g *= 1.0 p.u.,* p.f. *= 0.9).*

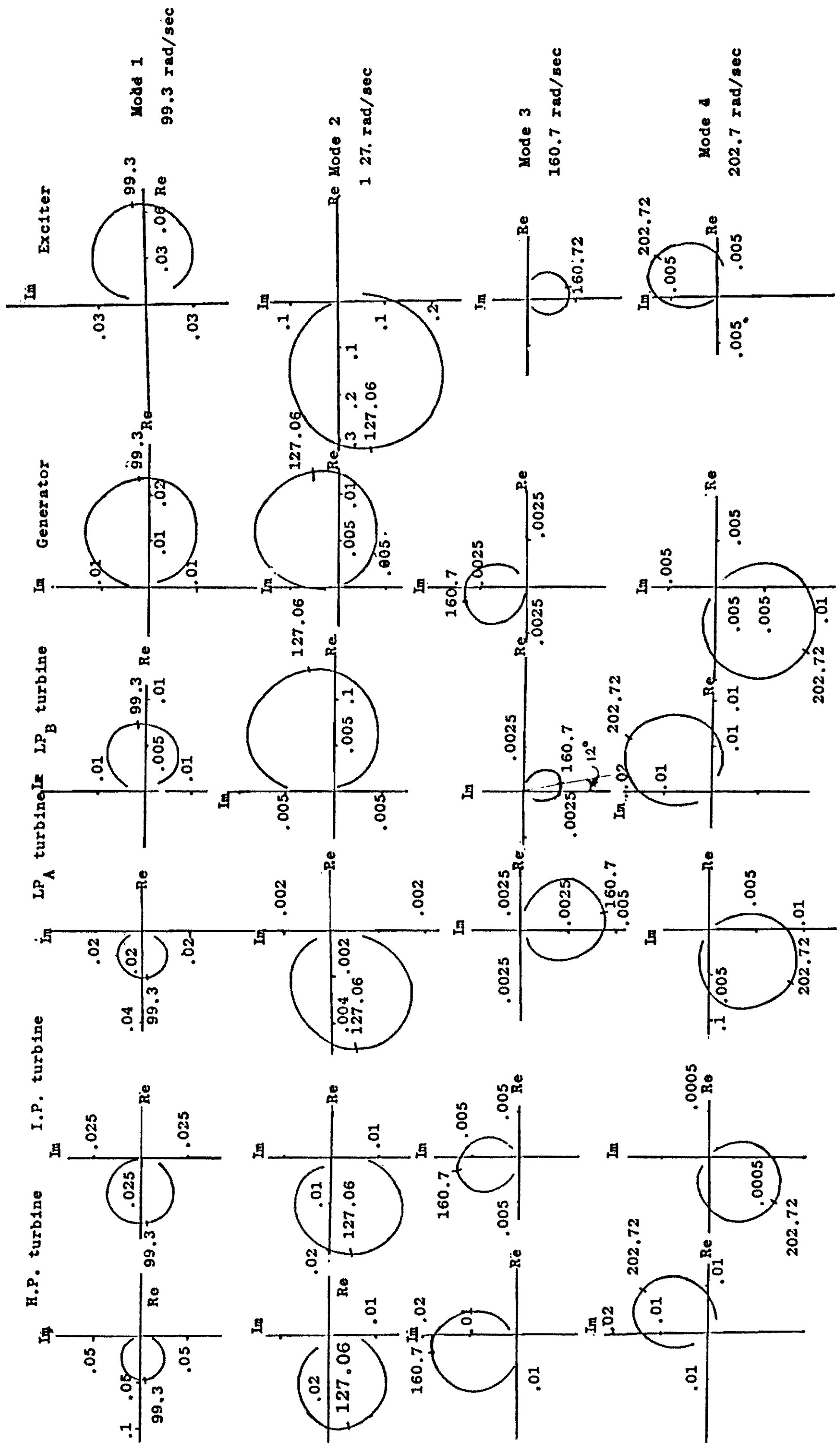

Figure 6(a). Frequency Response of the Different Speed Signals Relative to the Exciter Error Signal (Figures on the Graph Indicate Frequency in rad s^{-1}) ($X_c = 0.285$, $P_g = 1.0$ *p.u.*, p.f. = 0.9).

mance. Therefore, the overall response of the modulated reactor current will be determined by the current component caused by inductance modulation.

(*c*) If the inductance is advanced by a certain angle with respect to a specific signal, the reactor current is expected to be retarded with respect to this signal by the same angle. This is because the current is inversely proportional to the reactance.

(*d*) The speed signal, in proportion to which the inductance is modulated, contains components of all the remaining mechanical modes. Therefore, the machine current at these natural frequencies is also modulated and the damping is affected. The selected stabilizing signal should have a tendency to modulate the current at the remaining modes so as to produce positive damping effects.

In view of the above considerations ΔX_L should be delayed by an angle of 56° with respect to $-\Delta\omega_{LP_B}$ so that the reactor current is advanced by 56° from this signal and hence becomes in direct phase opposition to the machine current at the 160.7 rad s^{-1} frequency of oscillation. In this case the decrement factor at 160.7 rad s^{-1} is -2.64 indicating very efficient damping of the excited mode, however the damping at some other modes of oscillation remained negative. By inspection of the responses of the LP_B speed signal at other modes, it can be concluded that with less phase shift the damping of other modes could be improved. A phase shift of 20° was arrived at, using eigenvalue sensitivity analysis, as a compromise to ensure that all other subsynchronous modes are positively damped and at the same time that the damping of the excited mode remains very satisfactory. In this case, the stabilizer constants are as follows:

$$a = 0.00228\,\text{s},\ b = 0.005\,\text{s},\ k = -6.9\ .$$

The eigenvalues of the stabilized system with this control scheme are given in Table 2. In comparison with Table 1, it is clear that the excited mode is effectively damped and modes 1–4 are now positively damped. The damping of mode 0 is also substantially improved. Mode 5 damping is not affected in agreement with the result obtained by others [9].

The mechanism by which the reactor inductance modulation works to suppress the excited mode of oscillation can be well explained by reference to Figure 8, which shows the frequency response of the electrical torque (Torque = flux × current), considered as an output as specified in Y^t on Figure 2, relative to the exciter error signal and as developed by the alternator with and without modulation. It is evident that the torque with the modulated inductance has been advanced by 210° from the unmodulated case, *i.e.* the torques are approximately out of phase indicating a positive instead of the negative damping effect.

Close examination of the responses of Figure 6*a* indicates that a speed signal from IP turbine has frequency responses opposite to the response of the LP_B turbine speed signal. Therefore, it can be concluded that the inductor modulation could be effected by an

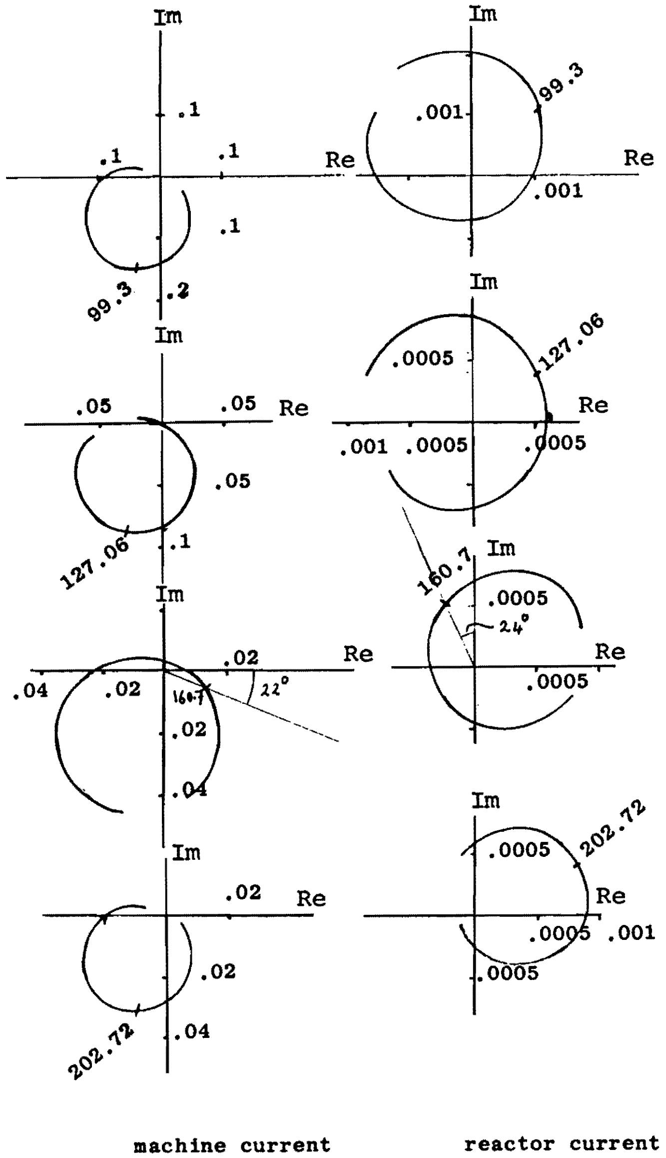

*Figure 6(*b*). Frequency Response of the Machine and Unmodulated Reactor Current Relative to the Exciter Error Signal (Figures on the Graph Indicate Frequency in rads^{-1}) (X_c = 0.285, P_g = 1.0 p.u., p.f. = 0.9).*

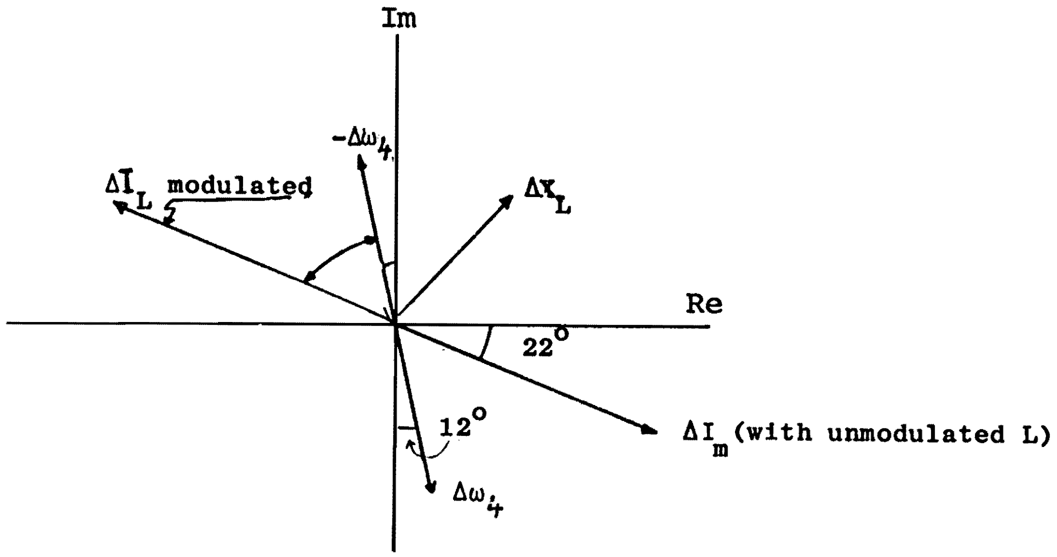

Figure 7. Phase Relations Between Different Signals at 160.7 rad s^{-1} (Mode 3).

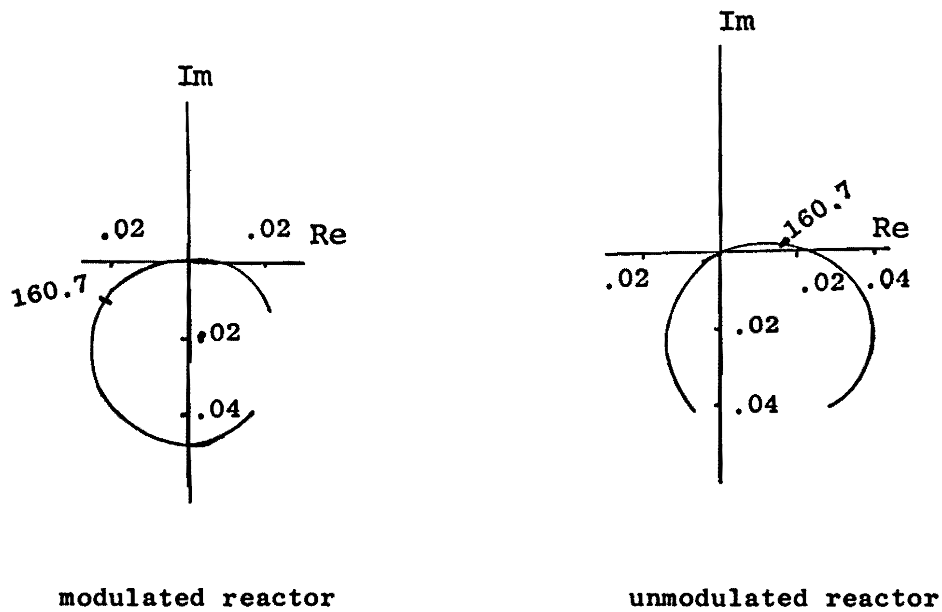

Figure 8. Frequency Response of the Electrical Torque Relative to the Exciter Error Input in the Frequency Range of Mode 3.

I.P. speed signal to provide positive damping for modes 1–4. However, the stabilizer gain K should be positive. The main objection to the use of this signal is that it would have an opposite effect to that of LP_B signal on the damping of mode 0 since the responses at this mode are all similar.

The relative effect of the remaining speed signals if used for modulation can be visualized by assuming that the same control scheme defined above is used utilizing each signal in turn. The eigenvalues for the modes of interest would be as given in Table 3. Inspection of Figure 6 in conjunction with Tables 2 and 3 reveals that with same form of modulation, the generator speed signal would be more effective at mode 1 than the LP_B speed signal. This is concluded from Figure 6*a* because the response of the generator speed in the 99.7 rad s^{-1} range is more pronounced and is in phase with the response of the LP_B signal. The result is confirmed by the values of the decrement factors for both cases (Tables 2 and 3). For mode 2, the effect is almost the same, which is

Table 2. The Eigenvalues of the Power System with the Modulated Reactor in Proportion to LP_B Turbine Speed Signal ($X_c = 0.285$, $P_g = 1.0$, $p.f. = 0.9$) ($K = -6.9$, $a = 0.00228$, $b = 0.005$).

$-4.96 \mp j592.45$
$-10.56 \mp j377$
$-0.0 \mp j298.18$
$-0.077 \mp j202.32$
$-1.25 \mp j161.35$
$-0.83 \mp j158.744$
$-0.126 \mp j127.22$
$-0.396 \mp j99.66$
$-1.288 \mp j9.44$
-32.83
-0.283
-3.814
-20.41
-199.34

indicated by the frequency response as well as the eigenvalues. At the excited modes 3 and 4 of oscillation, the responses are out of phase and so the corresponding eigenvalues indicated a destabilizing effect. This argument can be also extended to the remaining speed signals.

The control strategy, as devised above, relies on the use of a speed signal derived from the LP_B tur. If the LP_B tur. is not accessible, the LP_B signal could be reproduced using a torsional monitor [8]. The stabilized system have sufficient phase and gain margins, and hence it is not expected to be very sensitive for minor errors in the reproduction process.

The above studies were carried out with the voltage control loop of the reactor kept open. Further studies have shown that closing of this loop will have adverse effect on the damping of some shaft torsional modes. Therefore, it is necessary to insert an LP filter in that loop to block the torsional frequencies range. With this voltage regulation loop closed, the damping effect of the stabilizer was found to be satisfactory over a wide range of loading conditions.

6. CONCLUSIONS

This paper has presented a new method for designing a control scheme for modulating the inductance of a shunt reactor to suppress SSR oscillations. The frequency response analysis defines the mode shapes of the mechanical system and allows the choice of the most appropriate speed signal to be used for modulation and gives sufficient information on how the signal should be adjusted, not only to stabilize the excited mode but also to provide positive damping of other modes of oscillation. It is shown that the generator speed stabilizing signal usually used [7, 9] is not necessarily the most suitable signal.

In all studies presented, the mechanical damping was neglected, therefore the results obtained are considered pessimistic.

The control scheme as designed in this paper and the schemes developed by others [6–9] are based on a single machine system. The performance of such stabilization schemes in a practical multimachine power system remains to be checked. However, power system stabilizers designed on the same basis, to suppress low frequency oscillations, work well in practice. This may give an indication that the SSR stabilizer would be also effective in multimachine systems.

The work carried out in this paper can also be extended to a multimachine system, however, as the number of the machines increases the dimensionability of the model becomes a major problem. Model reduction techniques should then be used to reduce the dimension of the system model.

Table 3. Eigenvalues of the Power System with Modulated Inductance Using the Same Control Scheme and Under the Same Conditions of Table 2.

H.P. Signal	I.P. Signal	LP_A Signal	Gen. Signal	Ex. Signal
$-0.053 \mp j203.4$	$0.092 \mp j202.7$	$0.182 \mp j202.32$	$0.192 \mp j202.24$	$-0.02 \mp j203$
$8.15 \mp j163.3$	$4.577 \mp j162.5$	$-0.31 \mp j157.5$	$3.6 \mp j161.6$	$-0.261 \mp j165.17$
$0.17 \mp j126.7$	$0.11 \mp j126.85$	$0.016 \mp j127.02$	$-0.117 \mp j127.2$	$2.9 \mp j123.64$
$1.4 \mp j97.94$	$1.05 \mp j98.78$	$0.566 \mp j98.78$	$-0.937 \mp j100.2$	$-2.8 \mp j101.36$

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