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Impact of system parameter tuning on steady-state stabilization for rapidly growing power system

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ABSTRACT

This paper investigates multimachine steady-state stability utilizing variation of system parameters through alternative adoption of the generalized axes frame of reference. The effect of system parameters on intermachine modes and the effect of system excitation modeling is presented. The modal analysis is used to recommend system controller parameters for an acceptable operation range.

LIST OF SYMBOLS

λ_i	Eigenvalue of system matrix A.
v_i	Eigenvector of system matrix A.
u_i	Eigenvector of system matrix A^T.
ξ	System parameter.
T_E	Exciter time constant.
K_E	Exciter gain.
G_i	The ith power plant.
K_A, T_A	Amplifier gain and time constant.
K_F, T_F	Stabilizing signal gain and time constant.
BBC	Brown Boveri Company.
GE	General Electric.
AVR	Automatic voltage regulator.
SCECO-C	Saudi Consolidated Electric Company, Central Region.
R	Governor groove.
T_1, T_2	Governor and combustion chamber time constants, s.
T_3	Thermal time constant, s.
K_T	Actuator gain.
L_d	Self inductance in direct axis.
L_F	Field self inductance.
L_q	Self inductance in quadrature axis.
l_d, l_q	Leakage inductances.

R	Armature resistance.
R_F	Field resistance.
H	Machine H-constant, s.
L_{AD}	Mutual inductance in direct axis.
L_{AQ}	Mutual inductance in quadrature axis.

INTRODUCTION

The evaluation and analysis of steady-state stability is essential for both the planning and operation of electric power systems, particularly for fast-growing utilities. The fact is that a fast-growing system is characterized by a rapid increase in its electrical demand which may cause operational problems in a power system. An inappropriate system parameter setting results in the reduction of natural mechanical oscillation damping which may lead to unstable operation.

The objective of this paper is to investigate the steady state stability of the Central Region of Saudi Arabia Utility, since the system network has been largely expanded (in load and transmission) during the last few years. In this paper the multimachine steady-state stability investigation is carried out, utilizing the approach of selecting machine and generalized axes (Anderson & Fouad 1977). The effect of system parameters on intermachine modes, and the effect of system excitation modeling are addressed, utilizing the well known eigenvalue technique. Moreover, the eigenvalues, sensitivities are used to establish system controllers' parameter ranges for acceptable operation.

SYSTEM DESCRIPTION

The system contains 32 main buses connected via a 132 kV double circuit ring transmission network as shown in Fig. 1. Five controlled inductive reactors are

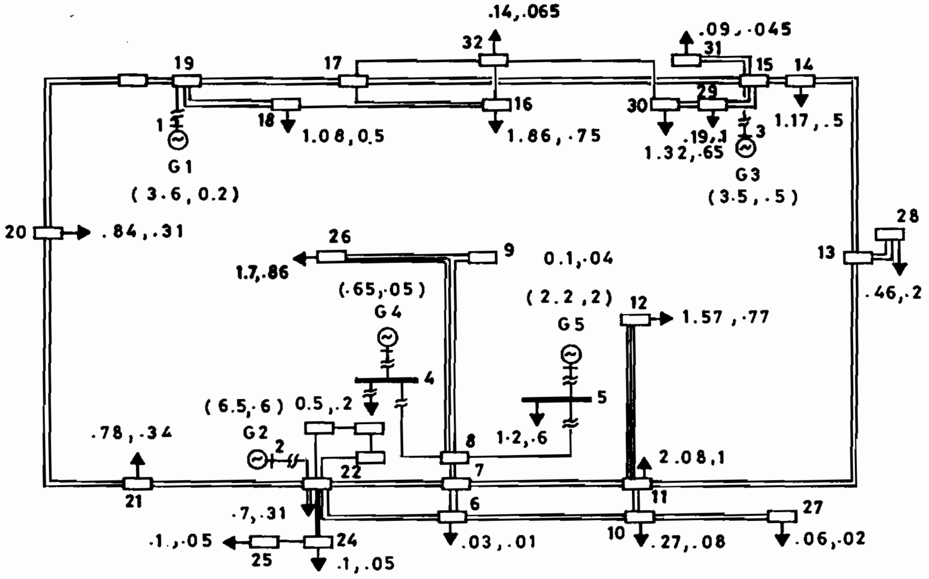

Fig. 1. SCECO-C network configuration (load, generation in p.u., 100 MVA base).

Table 1. The parameters of one-equivalent machine (p.u. values based upon 100 MVA, 132 kV).

G Rating	G_1	G_2	G_3	G_4	G_5
MVA	924	1000	1386	186	413·7
VB K.V.	13·8	13·8	13·8	13·8	13·8
IB K.A.	38·66	41·84	57·97	7·78	17·31
L_d p.u.	0·3041	0·1839	0·2028	1·1675	0·3990
L_F p.u.	0·2914	0·1822	0·1943	1·1200	0·3950
$l_d = l_q$ p.u.	0·0211	0·0129	0·0141	0·0685	0·0241
L_q p.u.	0·2814	0·1728	0·1876	1·1310	0·3294
l_{AD} p.u.	0·2830	0·1710	0·1887	1·0685	0·3704
l_{AQ} p.u.	0·2603	0·1600	0·1735	1·0625	0·3704
R p.u.	0·000216	0·00009	0·000144	0·000535	0·00024
R_F p.u.	0·000036	0·00097	0·000024	0·000092	0·00034
H s	46·477	90·000	69·715	17·942	18·939

installed at buses 8, 12, 16, 19, and 24. These are used to control the reactive power flow by which the system voltage distribution is kept within specified tolerance. These reactors are used to enhance the system performance especially at light-load operation. The loads are modeled as constant impedance as shown in Fig. 1, since ninety percent of the system load is of residential type. The system transmission network parameters are reported in Abu-Alseba (1986). The hierarchical structure of the generation system is composed of five power plants, each containing several identical gas-turbine generating units. Each power plant has been represented by an equivalent machine, since the units are almost always connected to the same bus. Table 1 lists these five equivalent machine parameters on 100 MVA base. The peak load condition occurring in the system has been chosen as the base case and load flow analysis has been obtained as given in Fig. 1. Also, load flow analysis has been carried out for light load condition. The results are given in Table 2. The generating units generate or absorb reactive power depending on whether or not the controlled reactors are being utilized. Fig. 2 shows the reduced system network containing the active internal buses of the generators. Different excitation systems are implemented in the system. The physical description of the excitation units as well as IEEE-models (IEEE 1968, 1981) have been used to construct appropriate computer models to be implemented for the stability studies (Elrazaz *et al.* 1987). Table 3 shows the data for the different power plants' excitation system. The gas turbine model is shown in Fig. 3.

Table 2. System generation at light-load operations in p.u. based upon 100 MVA.

Half-load leading power factor		Half-load lagging power factor	
P_1 = 1·74	Q_1 = −0·77	P_1 = 1·75	Q_1 = 0·90
P_2 = 3·25	Q_2 = −1·04	P_2 = 3·25	Q_2 = 1·53
P_3 = 1·76	Q_3 = −0·94	P_3 = 1·76	Q_3 = 1·07
P_4 = 0·33	Q_4 = −0·10	P_4 = 0·33	Q_4 = 0·20
P_5 = 1·08	Q_5 = −0·35	P_5 = 1·08	Q_5 = 0·80

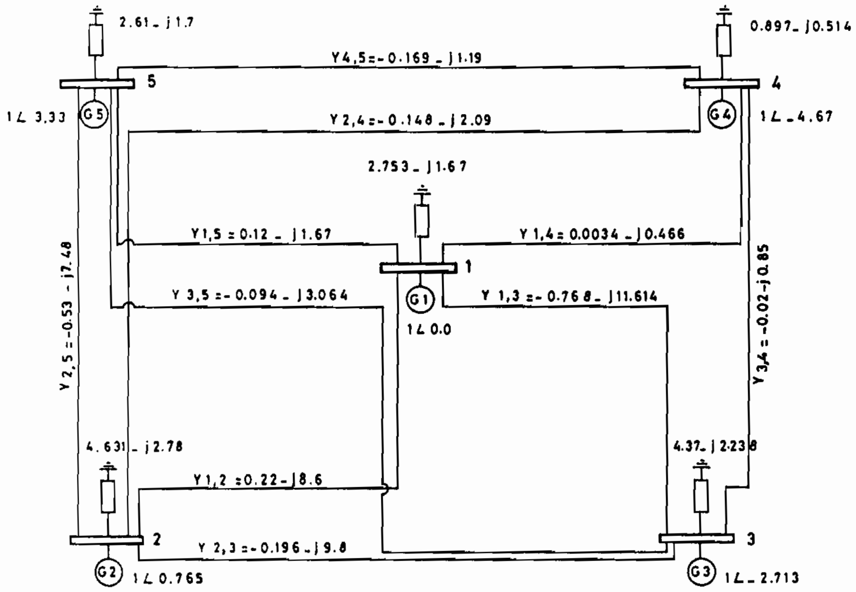

Fig. 2. Reduced active modes network (p.u. values 100 MVA, 132 KV base).

MULTIMACHINE MODELING

The multimachine modeling adopted the choice of both $d - q$ axes and the transformation matrix given in by Anderson & Fouad (1977). This selection is different from that used in most of the literature. One of the advantages of this choice is that the angle between the two frames (machine, generalized frame) is itself the rotor angle. Moreover, the transformation matrix is symmetrical and therefore the machine equation can be realized by an equivalent circuit. It is important to mention that the selection of the axes can be a source of confusion since all the system equations depend on this selection. The state space approach has been used to construct the

Table 3. BBC and GE excitation systems parameters.

BBC rotating rectifier system	GE static excitation system
$K_c = 2$	$K_A = 25$
$K = 290$	$K_F = 0{\cdot}05$
$K_E = 1$	$T_A = 0{\cdot}5\,\mathrm{s}$
$S_E = 0{\cdot}3$	$T_F = 2{\cdot}5\,\mathrm{s}$
$T_E = 1\,\mathrm{s}$	$T_R = 0{\cdot}015\,\mathrm{s}$
$T_1 = 0{\cdot}01\,\mathrm{s}$	
$T_2 = 0{\cdot}02\,\mathrm{s}$	
$T_3 = 10\,\mathrm{s}$	
$T_4 = 0{\cdot}7\,\mathrm{s}$	
$T_5 = 0{\cdot}3\,\mathrm{s}$	
$T_6 = 0{\cdot}03\,\mathrm{s}$	

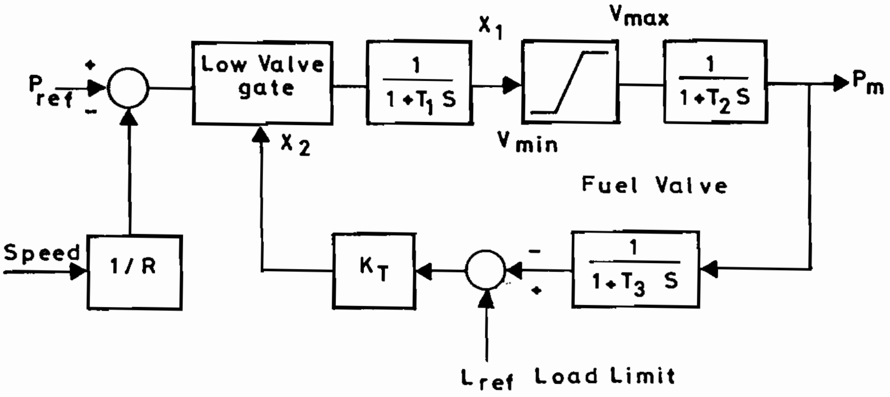

Fig. 3. Gas turbine block diagram.

dynamic model for the system which can be written as $\dot{X} = AX + BU$ where X and U are system state and input vector, respectively. A and B are constant matrices dependent on system parameters and operating condition. The eigenvalues of the matrix A are indicative of system steady state stability performance where the real part represents the amount of damping and the imaginary part indicates the amount of oscillation of the associated mode. Each synchronous machine is represented by a fifth-order model. The excitation systems are modeled by fifth, fourth, or third order model depending on the choice of system representation. The gas turbine is a third order model. The integrated system under study is of fifty-ninth order.

STEADY-STATE STABILITY ANALYSIS

The system non-linear differential equation (Abu-Alseba 1986) has been linearized around the system peak load condition shown in Fig. 1. An efficient eigenvalue technique has been used to obtain the system eigenvalues.

IMPACT OF SMALL DISTURBANCE ON SYSTEM PERFORMANCE

The dominant eigenvalue of system matrix at the peak operating condition are given in Table 4. The eigenvalues of the system can be identified by knowing the behaviour of its governor equation. The eigenvalues associated with network transient are well damped high frequency modes. Also, the low-frequency modes (1–3 Hz) and lightly damped ones are associated with the torque angle loop. Similar identification can be carried for the modes of both excitation and turbine governor dynamics. However, the most important modes to be examined are those eigenvalues associated with the interaction between the different power plants (intermachine modes). These modes are characterized as lightly damped and low-frequency oscillation (about 0·1–0·4 Hz). These are the most sensitive modes for system-operating conditions in which these modes result from merging between different machine dynamics.

The excitation parameters affect the intermachine modes. Changing the time constant or the gain of the stabilizing signal of power plant, G_2, affects several eigenvalues as shown in Figs 4 and 5. As can be seen from Fig. 5, the interaction mode has a non-linear characteristic with turning point at certain gain value. It is important to point out that increasing the gain beyond this point will contribute negative damping in the interaction mode. This should be taken into consideration during operation. Other excitation parameters exhibit different and same features.

The eigenvalue sensitivity with respect to several excitation parameters are listed in Table 5. These sensitivities with respect to system parameter ξ have been obtained using the relation

$$\frac{d\lambda_i}{d\xi} = U_i^T \frac{dA}{d\xi} V_i / U_i^T V_i$$

where U_i, V_i are the eigenvectors of A and A^T corresponding to the eigenvalue λ_i.

The table reveals several interesting points. Variation of the rotating exciter parameters T_E and K_E of the power plant G_1 affects several system modes, among which are the eigenvalues associated with torque angle loop. Moreover, changing T_E, is more pronounced in the two power plants with similar excitation system. Also, it affects other power plants interaction modes with different degrees. The variation of exciter gain affects the torque angle modes of the power plant besides the interaction

Table 4. System dominant modes identification of base case.

1	Network	−18·453	± j 557·95
2	transient		
3		−19·231	± j 573·21
4			
5		−23·95	± j 597·21
6			
7		−53·271	± 649·97
8			
9		−1080·82	
10			
		−2104·02	
11	Torque angle	−0·1309	± j 5·33 A
12	loops		
13		−0·1957	± j 7·72 B
14			
15		−0·367	± j 4·59 C
16			
17		−0·3995	± j 6·37 D
18			
19		−0·5093	± j 7·44 E
20	Interaction	−0·256	± j 0·180 A
21			
22		−0·3282	± j 0·784 B
23			
24		−0·3843	± j 0·187 C
25			
26		−0·4583′	± j 1·616 D
27			
28		−0·708	± j 0·995 E
29			
31		−1·488 ′	± j 0·179 F
32			

Table 5. Eigenvalues (real part) sensitivities with respect to system excitation parameters

	Torque angle modes				Interaction modes				Excitation modes			
PP-Parameter	λ 1,2A	λ 1,2C	λ 1,2D	λ 1,2E	λ 5,13A	λ 5,11B	λ 5,11C	λ 5,13D	λ 21	λ 33	λ 34	λ 30,31
$G_1 - T_E$ +	−0·075			−0·25	−0·2	0·075		−0·25				
$G_1 - K_E$ +				0·02				0·55				
$G_4 - T_E$ −		0·1		−0·70						−2·5		
$G_4 - K_E$ −							0·5					
$G_2 - K_A$*			0·01			+0·003	−0·006		−0·05			0·05
$G_2 - T_A$*	0·040		−0·50			0·040					4·0	2·00
$G_2 - T_F$*			−0·04						0·04	0·7	−0·6	0·20
$G_2 - K_F$*			2·60		7·0			1·00				

+ Rotating exciter
− Old type D·C· exciter
*Static exciter

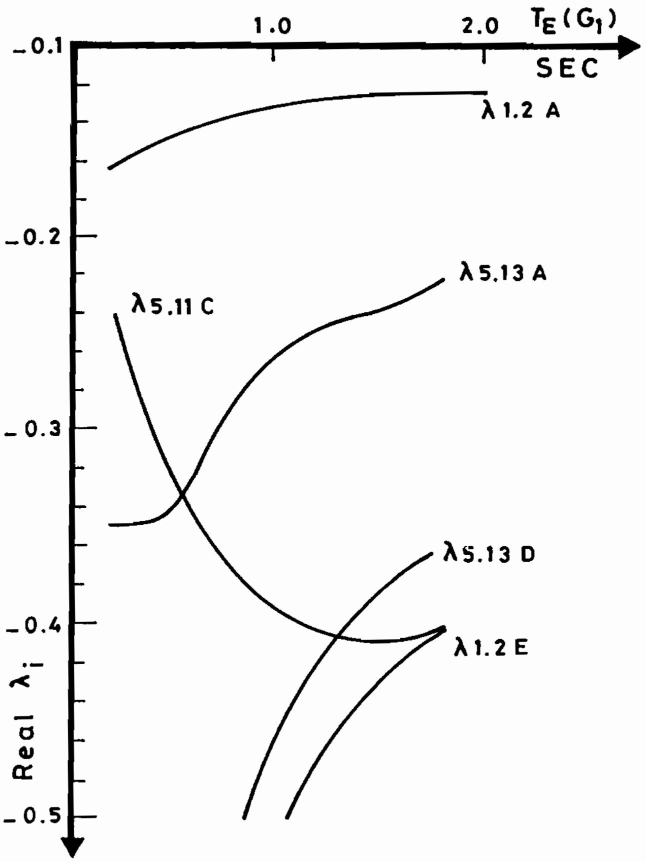

Fig. 4. Effect of T_F on the interaction and excitation modes.

mode in the other power plants. The sensitivity of the interaction mode of G_2 generator is greatly affected by the exciter gains of generator $G_1 (\partial\lambda_{5,13}/\partial K_E = 0{\cdot}55)$.

Varying the excitation system parameter in G_4 (old excitation system) does not have a strong effect on the generator modes. The variation of the modern static excitation system parameters utilized in both G_2 and G_5 power plants affects several system eigenvalues. These eigenvalues are associated with torque angle, interaction, and excitation modes of several power plants. This indicates the importance of implementing static excitation and adequately tuning their parameters for appropriate system performance. It is interesting to point out that varying the excitation parameters in one direction will stabilize some of the system modes and destabilize others. This should be considered with care in tuning several excitation parameters. Table 4 indicates that intermachine modes are among the dominant system's modes. These eigenvalues are due to system machines coupling. These eigenvalues can be changed drastically with system operation. However, tuning system parameters can be used to stabilize the critical eigenvalues of intermachines modes for different operating conditions, bearing in mind that this may destabilize other system modes such as AVR modes. The performance of intercoupling's mode can be taken as a measure to diagnose the system behaviour.

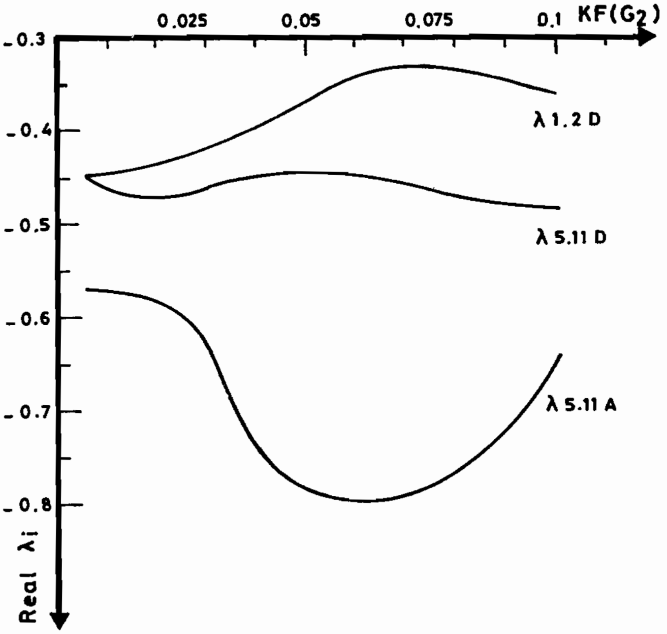

Fig. 5. Effect of K_F on the interaction and torque-angle modes.

EFFECT OF MODELING OF GAS TURBINE AND NETWORK TRANSIENTS ON SYSTEM PERFORMANCE

Analysing the results given in Table 4 reveals that the turbine governor modes are not sensitive to system operation since no fast valving is utilized. These modes have large time constants and will add small attribution to system dynamics. This suggests that detailed simulation of gas turbine for dynamic analysis is not necessary and this will reduce the system order and complexity. Moreover, the transient modes due to stator network can be eliminated, since their attribution to the steady state performance is small, due to their inherent large damping components. A point to be mentioned is that the interface between stator and system network necessitates whether or not both transients' terms should be modeled. In this study, the transients in the network were not modeled. For such a study, it is recommended to eliminate the detailed modeling for both turbine governor and the stator transients.

EFFECT OF SYSTEM EXCITATION MODELING ON SYSTEM PERFORMANCE

Table 6 lists the eigenvalue of the system, neglecting both excitation and turbine system dynamics by considering both the mechanical power and field voltage constant. Table 6 reveals, generally, that the damping in the network transient is decreased while that of the torque angle's eigenvalues is increased relative to that of the detailed modeling case. It can be stated that neglecting the excitation system causes the interaction of the machines modes to disappear. Also the modes associated with the field circuit are characterized by pure damped eigenvalues since the excitation has been neglected. This will manifold much information regarding system characteristics, and modeling the excitation system in detail is a must. More-

Table 6. System modes considering machine dynamics only.

Network transients	−0·77 ± j 380·8
	−1·04 ± j 373·0
	−15·69 ± j 954·3
	−17·44 ± j 552·4
	−51·14 ± j 662·2
Torque angle loops	−0·28 ± j 6·27
	−0·30 ± j 8·89
	−0·31 ± j 5·35
	−0·32 ± j 5·66
	−0·71 ± j 5·03
Field circuit	−0·192
	−0·274
	−0·432
	−0·490
	−1·160

Table 7. Multimachine modes using unified excitation system

Network transients	−18·54 ± j 557·8
	−19·20 ± j 573·5
	−24·26 ± j 597·2
	−54·19 ± j 649·6
	−1099·70
	−2104·90
Torque angle loops	−0·131 ± j 3·00
	−0·197 ± j 5·60
	−0·200 ± j 7·41
	−0·291 ± j 6·54
	−0·460 ± j 4·60
Interaction	−0·331 ± j 0·753
	−0·510 ± j 0·730
	−0·520 ± j 0·395
	−0·192
	−0·363
	−0·855
	−1·000
Excitation systems	−3·44
	−3·57
	−9·99
	−10·00
	−3·68
	−3·69
	−3·95
	−9·94
	−9·97
	−9·98

over, representing all excitation systems by one type may manifold some information about the system. Table 7 lists the eigenvalues of a system by representing all excitation systems by a rotating exciter using D.C generator type (Brown Boveri Company 1974). It can be concluded that the interaction between the field and excitation dynamics has been greatly reduced by representing the system by one excitation type. This can be seen by comparing the interaction modes in Table 7 with those of Table 4. In addition to this, slight variations in torque angle modes are observed.

PARAMETRIC VARIATION

For the excitation system to be effective in improving power system stability, their parameters must be appropriately chosen and optimally coordinated to give the best overall system dynamic performance (Vournas & Papadias 1987). Fig. 6 shows the effect of varying the exciter time constant T_E of BBC excitation system. Eight eigenvalues are sensitive with respect to T_E. It can be stated that the appropriate range for this parameter ($T_E < 1{\cdot}0$ s) is adequate for acceptable operation. Fig. 7 shows the effect of changing the amplifier gain K_A on the eigenvalue spectrum. The figure reveals that changing K_A has a pronounced effect on torque angle, excitation, and the interaction modes. Also it can be said that the range of changing K_A from 25–40 is the most appropriate range for adequate system performance. Similar conclusions can be stated about the effect of changing the amplifier time constant which indicate that the range of T_A from 0·50–0·75 s is the appropriate range for system operation.

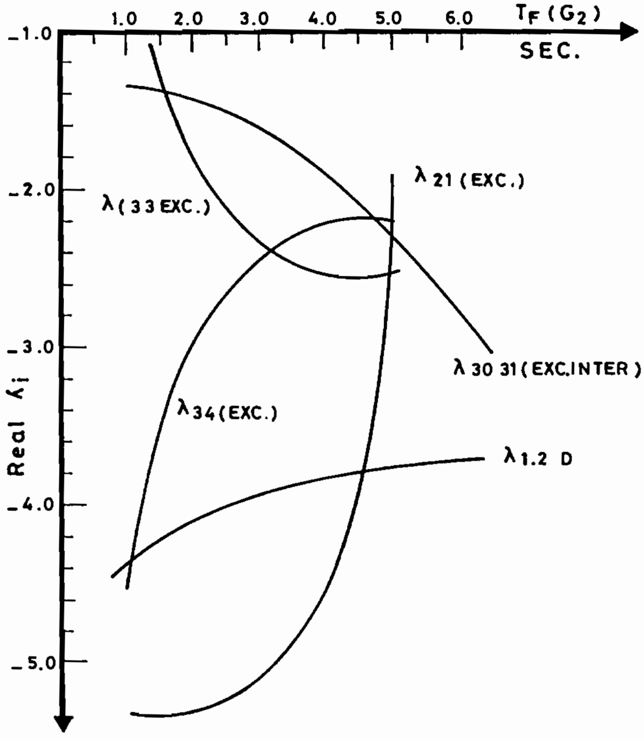

Fig. 6. Effect of BBC exciter time constant on the system modes.

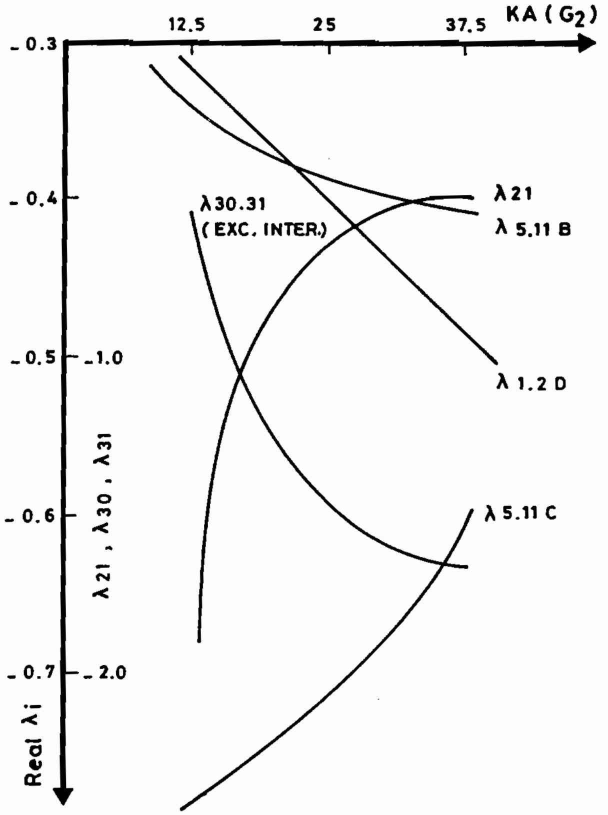

Fig. 7. Effect of amplifier gain on the system modes.

Fig. 4 shows the effect of the excitation feedback stabilizing signal time constant T_F on the system modes. As expected, its effect is pronounced on the interaction, excitation, and swing angle modes. It can be claimed that the appropriate range of T_F is less than 4·0 s. This is because of the effect of T_F on stabilizing and destabilizing different system modes, as can be seen from Fig. 4.

The previous parametric variation analysis can be justified by calculating the eigenvalue sensitivities of the dominant modes with respect to different excitation parameters as given in Table 5. Examining Table 5 reveals that BBC exciter parameters affect several modes. Among these are the torque angle mode of the machine itself as well as the other machines, intermachine modes, and interaction modes between the field and excitation system of several machines. The old type of BBC exciter system installed in G_4 does not affect the interaction mode and torque angle of any other machine. This indicates the improvement in system steady-state stability by installing modern excitation systems.

LIGHT-LOAD OPERATION

Table 8 gives a comparison between the electromechanical modes at half-load operation. Light-load operation is characterized by a large amount of reactive power

Table 8. Electromechanical modes at different operating conditions

Base case peak-load condition	Half-load leading, no reactors	Half-load lagging, reactors installed
−0·1309 ± *j* 5·326	−0·038 ± *j* 4·26	−0·124 ± *j* 3·24
−0·1957 ± *j* 7·723	−0·087 ± *j* 7·27	−0·192 ± *j* 5·94
−0·3670 ± *j* 4·590	−0·100 ± *j* 5·15	−0·217 ± *j* 3·65
−0·3995 ± *j* 6·370	−0·420 ± *j* 6·33	−0·437 ± *j* 4·98
−0·5093 ± *j* 7·440	−0·540 ± *j* 7·23	−0·566 ± *j* 5·87

Table 9. Suggested operation range for excitation system parameters of SCECO-Central

Parameters Excitation system	K_E	T_E	K_F	T_F	K_A	T_A
BBC rotating rectifier exciter	0·5–2·0	0·5–1·0 s	–	–	–	–
BBC rotating exciter using DC generator	0·5–1·5	0·75–1·5 s	–	–	–	–
GE static excitation system	–	–	0·025–0·075	1–3·5 s	25–40	0·5–0·75 s

absorbed by the system generators. This forces the units stiffness. This is indicated in the damping components of the eigenvalues as given in the second column of Table 8. It should be stressed that such operation may lead the system to unstable operation since one of the eigenvalues associated with interaction has positive real part (+0·035). To improve system performance at light-load condition, controlled inductive reactors are installed. This improves the damping components of the electromechanical modes as given in the third column in Table 8.

CONCLUSIONS

This study reveals the following:

1. Excitation parameters affect the intermachine modes as shown in Figs 4 and 5 and Table 5.
2. The interaction mode exhibited a nonlinear characteristic with turning point at a certain gain value after which the gain contributed negative damping.
3. Table 4 indicates that intermachine modes are among the dominant systems modes.
4. Tuning system parameters can be used to stabilize the critical eigenvalues of intermachine modes, bearing in mind that there is no power stabilizer adopted, while disturbance in other system modes such as AVR mode may occur.
5. This work provides acceptable range operations data for system controllers as given in Table 9.

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تأثير ضبط عوامل التحكم على استقرارية الحالة الثابتة لنظم القوى الكهربائية سريعة النمو

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المملكة العربية السعودية

خلاصة

يتطرق هذا البحث لدراسة استقرارية الحالة الثابتة للنظم الكهربائية باستخدام عوامل التحكم في النظام . ويشمل البحث تأثير هذه العوامل على أطوار المواجهة بين مولدات النظام ، وكذلك تأثير تمثيل نظام الاثارة بالمولدات على ذلك . ولقد استخدم التحليل المودلي للحصول على قيم عوامل التحكم التي تعطي ظروف تشغيل مقبولة .