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Steady-state stability enhancement at light-load operation

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ABSTRACT

This paper addresses the choice of both location and magnitude of inductive reactors. These reactors are needed to enhance system steady-state stability by providing a means to absorb the reactive power surplus at light-load operation. The choice is based upon the sensitivity of the reactive power absorbed by system generators with respect to the reactor location. The spring load condition of SCECO-C power system in Saudi Arabia is used to demonstrate the effectiveness of the method.

INTRODUCTION

Operating power systems is a real challenge in both heavy and light-load conditions. The load condition of SCECO-C power system is affected mainly by the weather conditions. At summer time, the peak takes place due to the heavy use of air conditioning equipment. In spring time, the peak load drops to around $\frac{1}{4}$ of the summer peak. At light-load operation, reactive power surplus, due to existence of high-voltage lines and cable-charging current may lead to steady-state instability as well as increasing system voltage level (US Department of Energy 1978). At light operation, the steady-state instability of the system is mainly due to huge absorption of the reactive power by the system generators. This causes the generators to operate in the under-excitation mode. Under-excitation operation reduces the stiffness of the synchronous generators and consequently the inherent damping in both torque angle and interaction modes.

There are many countermeasures for the reactive power surplus problem. Installing inductive reactors in the system network can provide a way to absorb the reactive power surplus. The choice of both reactor location and magnitude is not an easy task.

In this paper, the steady-state stability problems at light-load operation for SCECO-C power system are investigated. The sensitivities of the reactive power are used as a guide to locate the inductive reactors and optimally choose their magnitudes in order to enhance the system steady-state stability.

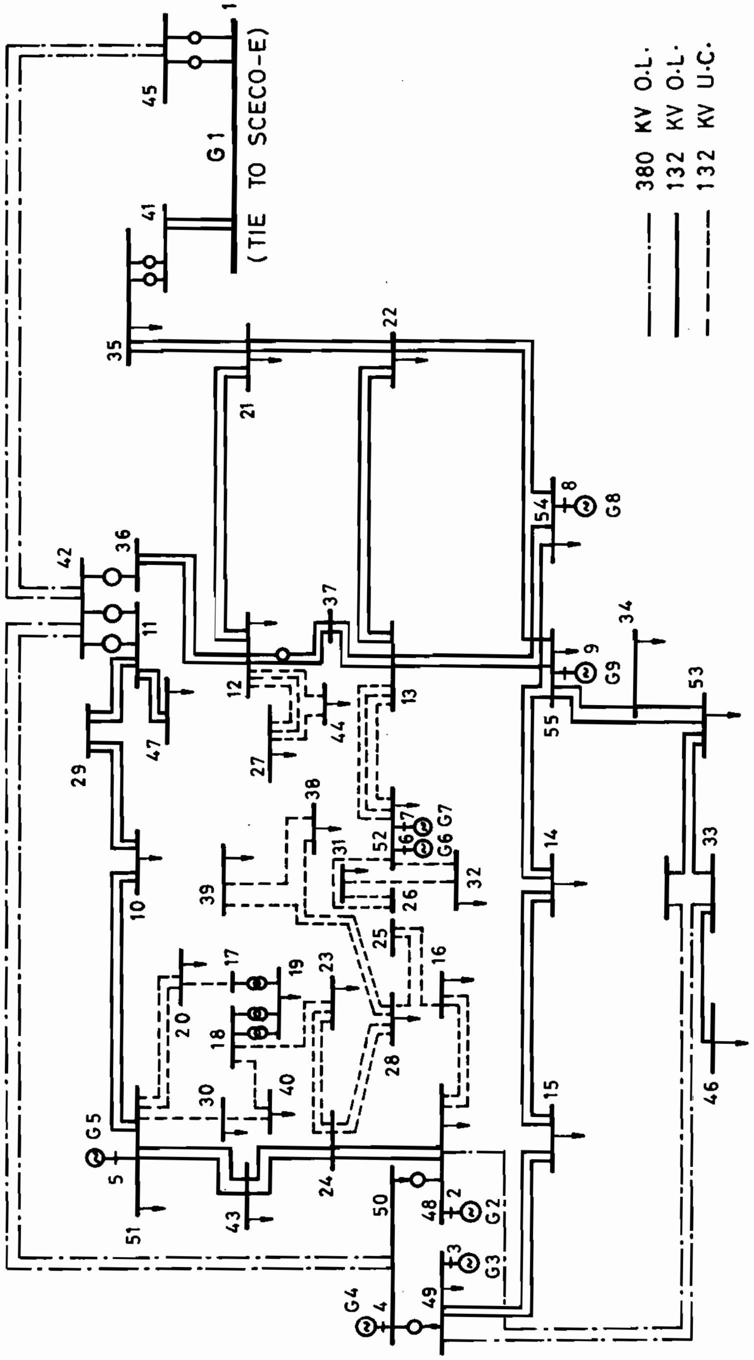

Fig. 1. SCECO-C network configuration.

Table 1. System active and reactive power generation at light load

Generator	I.B	G_5	G_2	G_3	G_4	G_9	G_8	G_7	G_6
P MW	95	125	75	75	44	75	75	54	23
Q MVAR	−423	−268	−230	−107	−105	−88·5	−81	−58	−25

SYSTEM DESCRIPTION

SCECO-C power system consists of a complete ring of 132 kV subtransmission network enclosed by a semi-ring of 380 kV transmission network. Moreover, the system is interconnected with another large power system (SCECO-E), via 380 kV double-circuit lines. The SCECO-E system is considered as infinite bus system (I.B) in this study. The generation in SCECO-C is from eight gas turbine power plants. The system configuration is shown in Fig. 1. The system transmission network parameters and load data are documented elsewhere (Elrazaz *et al.* 1986).

LIGHT-LOAD OPERATION

A large part of the subtransmission network is underground cables, which is the main source of trouble at light-load condition due to the surplus in the reactive power. Data for active and reactive power generation at light-load condition, without switching in any reactors, are given in Table 1, and are ranked according to

Table 2. Generators reactive power constraints

Generator	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9
Max. MVAR	75	75	44	23	54	54	75	75
Min. MVAR	−60	−60	−30	−105	−16	−39	−26	−26

Table 3. System dominant modes at light-load operation

No compensation	250 MVAR compensation level	1000 MVAR compensation level
0·707 ± j0·070	0·460 ± j0·030	0·488 ± j0·0
0·217 ± j0·604	0·300 ± j0·360	−0·046 ± j0·0
0·215 ± j0·843	0·091 ± j0·630	−0·169 ± j0·0
−0·143 ± j0·000	−0·095 ± j0·005	−0·157 ± j3·3
−0·168 ± j0·139	−0·185 ± j0·411	−0·175 ± j4·2

Table 4. Bus voltage at light load

Bus #	16	17	23	24	25	28	30	38	39	40	42	43	48
Voltage in p.u.	1·058	1·059	1·06	1·06	1·058	1·07	1·056	1·072	1·070	1·058	1·05	1·05	1·05

the largest reactive power absorbed by each generator. Table 1 indicates that all the generating units absorb reactive power due to the huge surplus in the reactive power in the system. The generators reactive power constraints as given by the manufacturer are in Table 2. Comparison between Table 1 and Table 2 indicates huge violation in the MVARS constraints of all units. The dynamics of these generators, at this operating condition are the source of the system steady-state instability. Table 3 (1st column) shows the system dominant eigenvalues in descending order. The damping coefficients of these modes are decreased such that some of the modes move to the positive side of the S-plane, indicating system instability. These modes are associated with the interaction between the generator dynamics. Moreover, the load flow analysis at light load shows that the voltage limit at thirteen buses has been violated. Table 4 shows the voltage in p.u. for these buses. Some of these buses are very close to the generating buses, while the others are the buses of underground cable terminals.

Overvoltage may cause flashover or insulation breakdown. Also, saturation of transformers subjected to overvoltage can produce high currents rich in harmonics and in the presence of sufficient capacitance, there is a risk of ferroresonance as well as of harmonic resonance (Illiceto & Cinieno 1977).

REACTIVE POWER COMPENSATION

Reactive power compensation means the modification of the electrical characteristics of the network to improve system stability by increasing the maximum transmissible power and produce a substantially flat voltage profile at all levels of loads.

In the planning phase of SCECO-C system, the planners recommended shunt reactor installation as given in Table 5 to be used at light loads. These reactors were sufficient to solve the reactive power surplus in the network before the new expansion (Al-Ohaly & Elrazaz 1987). Switching on these reactors for the new expanded system does not alleviate the instability as can be seen from Table 3 (2nd column). Table 3 indicates that the instability has been decreased but the system is still unstable. Table 6 shows the new distribution of the reactive power among the various generating units after installing these reactors. The reactive power constraints are violated for some of the generating units as can be seen by comparing

Table 5. Reactors installed in the existing system

Bus #	18	20	27	28	41	48	52
MVARS	40	40	20	40	30	40	40

Table 6. System active and reactive power generated at light load after switching system reactors

Generator	I.B	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9
P MW	93·7	75	75	44	125	23	54	75	75
Q MVAR	−379	−167	−93	−93	−186	−19	−42·5	−63·5	−69·8

the results in Table 6 and Table 2. So switching system reactors at light-load condition (spring load) will not stabilize the system. The system generators still absorb reactive power which affects the steady-state stability as indicated in Table 3. Moreover, at two load buses, voltage level is still above the standard limit (±5%).

It is evident that the installed reactors are not enough to absorb the excess in the reactive power at the specific operating condition (spring load). One way to overcome the problem is to increase the reactor values while keeping their location unchanged.

Several attempts have been made towards changing the reactor values, keeping the sum of reactors at 10 p.u. (1000 MVARS) and the same locations. The results of the simulation show that the voltage level of the system is acceptable but the system is still unstable as indicated in the third column of Table 3.

Increasing the total magnitude of the existing reactors beyond 1000 MVARS results in an unstable system. The preceding discussion indicates that the existing reactor locations in the system are not appropriate for the new expanded system and other locations besides or instead of these locations are needed. This is mainly because the huge network expansion was not anticipated by the system planners. So, the original reactor locations are not suitable for the new expanded system. In their original reactor locations, they mainly relied on the steady-state voltage profile, without considering the stability problem. The following section in the paper addresses the problem of choosing other locations to install the reactors.

INDUCTIVE REACTOR LOCATION

Several criteria have been presented in the literature (Brein & Ledwich 1985; Al-Ohaly & Elrazaz 1987; El-Sulaiman 1988) for shunt compensation location. One criterion is based upon calculating the voltage change at all load buses for a small change in the active power generated by each generator in turn (SENS) (Brein & Ledwich 1985). Another criterion for choosing chunt reactor location is based directly upon the total amount of reactive power (Al-Ohaly & Elrazaz 1987) relieved from being absorbed by the system generators (ΔQ_t). Appendices A and B explain the basis of these criteria. Applying both SENS and ΔQ_t criteria results in choosing buses 19, 47, 46, 53, 33, and 42 for SENS (Table A1) and buses 28, 25, 42, 24, 39, and 18 for ΔQ_t (Table B1) as candidates for reactor locations. A recent criterion based upon DL, the sensitivities of the reactive power relieved from each generator with respect to reactor location, has been proposed (Elrazaz & Al-Ohaly 1989). This method is described in Appendix C. Moreover, the reactor magnitudes have been obtained by minimizing an objective function taking into account the reactive power constraint of each generating unit. This DL criterion results in choosing buses 39, 28, 18, 42, 27, and 33 (Table C1) as candidates for reactor location. Table 7 shows the reactive power distribution among the generating units using the three criteria SENS, ΔQ_t, and DL for different compensation levels. The 100% compensation level is for the case in which the total rating of the reactors is 1000 MVARS.

Adopting SENS criterion results in violation of voltage constraints as given in Table 8, while the steady-state stability of the system at 100% compensation is stable as shown in Table 9. Decreasing the level of system compensation will

Table 7. System generators reactive power at various levels of compensation using various methodologies

GR		SENS		ΔQ_t		DL	
G	MW	100%	75%	100%	75%	100%	75%
I.B.	95	−272·90	−308·40	−281·0	−315·2	−263·10	−273·60
G_2	75	−66·50	−103·50	+80·7	7·5	−15·60	−75·40
G_3	75	+20·37	−8·10	−24·4	−44·1	−7·11	−31·20
G_4	44	−10·79	−32·96	−9·5	−32·3	−2·89	−23·79
G_5	125	−24·57	−80·12	61·2	−16·5	−21·39	−85·45
G_6	23	−11·21	−14·41	−16·5	−18·5	−3·42	−8·21
G_7	54	−26·02	−33·45	−38·3	−43·1	−7·91	−19·10
G_8	75	−23·28	−36·60	−47·9	−55·9	−7·00	−23·97
G_9	75	21·30	−3·43	−48·1	−55·7	−4·16	−26·50

decrease the damping and result in unstable operation at 75% compensation as shown in Table 9.

Moreover, comparison between Table 7 and Table 2 indicates violations in the generator reactive power constraints. On the other hand, using the DL criterion

Table 8. Voltage level in p.u. at some critical buses using SENS criterion

	Level of compensation	
Bus #	100%	75%
39	0·88	0·92
33	0·87	0·9
34	0·90	0·92
46	0·82	0·87
47	0·94	0·96
53	0·87	0·91

Table 9. System dominant eigenvalues for different compensation levels

	Level of compensation	
Criterion	100%	75%
SENS	−0·15±j0·6 −0·19±j5·6 −0·11±j4·3	0·45±j5.8 −0·10±j6·1 −0·23
ΔQ_t	−0·21 −0·19±j5·6 −0·23±j9·6	−0·18±j5·8 −0·22±j9·0 −0·23
DL	−0·17±j3·3 −0·19±j5·7 −0·19±j4·3	0·05 −0·11±j0·4 −0·17±j4·5

indicates no violations in the generators MVARS and bus voltage constraint even with 75% compensation level but the system is marginally unstable. Applying ΔQ_t criterion at 75% level results in violation in the MVARS generator constraints for G_7, G_8 and G_9 power plants. On the other hand, the system is stable as can be seen from Table 9. This result is in contradiction to that obtained for transient stability case (Elrazaz & Al-Ohaly 1989), where the system was less transiently stable compared with the case obtained by using the DL method. This is mainly due to the effect of MVARS on both the synchronizing and the damping component of the generator electric torque.

CONCLUSIONS

Various criteria for inductive reactor installations have been applied to enhance SCECO-C steady-state stability. It has been shown that increasing the reactor rating at the previously planned locations does not stabilize the system and more locations are needed for the new expanded system. Moreover, the paper reveals the importance of updating system reactive power compensation equipment regarding both location and ratings for adequate system performance.

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Table A1. Reactor location priority list using SENS criterion

		Generator buses							
B.N.	I.B.	2	3	4	5	6	7	8	9
19	−4·8	−4·2	−4·6	−4·6	−4·0	−5·2	−4·9	−4·8	−4·6
47	−4·3	−4·6	−4·3	−4·1	−4·7	−4·7	−4·0	−4·3	−4·4
46	−3·8	−2·6	−3·4	−3·3	−3·0	−4·4	−4·1	−4·1	−3·9
53	−3·6	−2·3	−3·3	−3·2	−2·8	−4·2	−3·9	−3·9	−3·6
33	−3·4	−2·2	−3·1	−3·0	−2·7	−4·0	−3·8	−3·8	−3·5
39	−3·3	−2·6	−3·1	−3·0	−2·9	−3·5	−3·3	−3·3	−3·2
38	−3·3	−2·6	−3·0	−3·0	−2·9	−3·5	−3·3	−3·3	−3·2
25	−3·3	−2·5	−3·0	−3·0	−3·0	−3·5	−3·3	−3·3	−3·2
34	−3·2	−2·2	−3·0	−2·9	−2·6	−3·7	−3·4	−3·5	−3·0
28	−3·2	−2·5	−3·0	−3·0	−2·9	−3·5	−3·2	−3·2	−3·2
24	−2·8	−2·2	−2·7	−2·6	−2·4	−3·1	−2·9	−2·8	−2·8
18	−2·9	−2·4	−2·7	−2·7	−2·3	−3·1	−2·9	−2·9	−2·9
51	−2·1	−1·9	−2·0	−2·0	−1·3	−2·3	−2·1	−2·1	−2·1
55	−1·6	−1·3	−1·6	−1·5	−1·4	−1·4	−1·3	−1·4	−0·2
42	−1·7	−1·0	−1·3	−1·3	−1·1	−1·6	−1·6	−1·7	−1·6

APPENDIX A

The SENS criterion is based upon calculating the voltage change at all load buses for small change in the active power generated by each generator in turn. The sensitivities of the voltages with respect to the power changes are written as follows:

$$\mathrm{SENS}(i, j) = \frac{\Delta V_i}{\Delta P_j}, \qquad \begin{array}{l} i = 1, \ldots, n \\ j = 1, \ldots, m \end{array}$$

where

m = number of generating units,
n = number of load buses.

Table A1 shows the voltage sensitivities for some of the possible location candidates. Column 1 of this table shows the priority list of the load buses for inductive reactor installation. The main idea is to identify the buses where poor voltage regulation with respect to generator active power may contribute to system instability. Busbar # 19 has the worst voltage regulation as can be seen from the first row of the table. It should be mentioned that there is no precise relationship between these sensitivities and system stability behaviour.

APPENDIX B

The ΔQ_t criterion for placement of shunt reactors is based upon the total reactive power relieved from being absorbed by the system generating units. This is the main source for system instability. The reactive power relieved from each generator can be written as

$$\Delta Q_t(j) = \sum_{i=1}^{m} Q_i^1 - Q_i^2, \qquad j = 1, 2, \ldots, n$$

Table B1. Reactor location priority list using ΔQ_i criterion

Bus Loc.	28	45	24	39	18	51	19	55	53	52	49	50	27	42
Q_{MVAR}	−188	−186	−186	−185	−184	−180	−166	−166	−162	−161	−158	−149	−147	−139
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14

where

n = number of load buses,
m = number of generating units,
Q_i^1 = the reactive power of the ith unit before switching in the shunt reactor,
Q_i^2 = the reactive power of the ith unit after switching in the shunt reactor.

A priority list is obtained in which the locations are ranked according to the change in the total reactive power absorbed by the system generators as shown in Table B1.

Bus # 28 appears as the first choice which can be verified since this bus is located in the load center zone of the underground cable network.

APPENDIX C

The DL criterion for choosing the shunt reactors is based upon the sensitivities of reactive power relieved from each generator with respect to reactor values at various locations. These sensitivities can be written as

$$S(i, j) = \frac{\Delta Q_i}{\Delta X_j} = \frac{Q_{bi} - Q_{ai}}{\Delta X_j} \qquad \begin{array}{l} i = 1, \ldots, m \\ j = 1, \ldots, n \end{array}$$

where

$S(i, j)$ = the (i, j) element of sensitivity matrix S,
m = number of generating units,
n = number of candidate locations,
$Q_{bi}(Q_{ai})$ = the p.u. absorbed reactive power of the ith generating unit before (after) switching in shunt reactors,
ΔX_j = reactor value at location J.

Using these sensitivities, a matrix S can be constructed with (m) rows and (n) columns. This matrix is used as a guide in the selection of static VAR compensation locations. Table C1 contains the sensitivity element of the matrix $S(i, j)$.

Table C1. Appropriate selection of reactor locations

Location generator	45	51	48	49	50	55	54	52
IB	0·92	0·06	0·07	0·11	0·25	0·10	0·10	0·15
G_5	0·03	0·70	0·30	0·06	0·13	0·03	0·03	0·03
G_2	0·20	0·21	0·55	0·06	0·12	0·04	0·03	0·03
G_3	0·03	0·04	0·06	0·52	0·19	0·10	0·09	0·07
G_4	0·04	0·10	0·06	0·09	0·24	0·03	0·03	0·04
G_9	0·01	0·02	0·04	0·09	0·06	0·49	0·16	0·21
G_8	0·01	0·02	0·02	0·08	0·06	0·16	0·51	0·21
G_7	0·01	0·01	0·01	0·63	0·03	0·09	0·09	0·24
G_6	0·00	0·00	0·01	0·01	0·02	0·04	0·04	0·10
$S_j = \sum_i \frac{\Delta Q_i}{\Delta X_j}$	1·05	1.11	1·13	1·06	1·10	1·06	1·06	1·09

تعضيد إستقرارية الحالة الثابتة لحالات التشغيل ذات الحمل الخفيف

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خلاصة

يتطرق هذا البحث لاختيار أماكن وقيم الممانعات الحثية، وذلك لأن هذه الممانعات ضرورية لتعضيد استقرارية الحالة الثابتة لكونها قادرة على امتصاص الزيادة في القدرة غير الفعالة لحالات التشغيل ذات الحمل الخفيف.

ولقد بني هذا الإختيار على حساسية القدرة غير الفعالة الممتصة بمولدات النظام بالنسبة إلى أماكن هذه الممانعات. ولقد استخدمت ظروف التشغيل في فصل الربيع لنظام المنطقة الوسطى بالمملكة العربية السعودية لبيان كفاءة هذه الطريقة في اختيار أماكن وقيم الممانعات.