Effect of non-utility generator siting on oscillatory stability of Taiwan power system

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The site specific impact that a non-utility generator (NUG) can have upon the oscillatory stability of the Taiwan power system is investigated. The transmission network in Taiwan has been experiencing poorly-damped low frequency oscillations since 1984 due to its longitudinal structure. Therefore, it is essential to evaluate the effect of a non-utility generator on the oscillatory stability of the whole network before it is connected to the system. To do this, an NUG impact evaluation procedure is developed to reach an oscillatory stability index (OSI) which can be employed to evaluate the effect of the NUG at a particular site on system stability. The effectiveness of the proposed impact evaluation procedure is demonstrated by a stability analysis of the Taiwan power system with the NUG installed at different locations. It is expected that the proposed method will provide a valuable quantitative index which can be used to explore the adequacy of the transmission facilities in the utility when an NUG is installed at a specific site. Copyright © 1996 Elsevier Science Ltd

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1. Introduction

Taiwan Power Company (TPC), a state-owned utility, is the sole electric utility in Taiwan. Under the licence from the government, TPC owns all generating plants and operates the entire transmission and distribution network on the island of Taiwan. Due to the continuing economic growth on the island, TPC load demand has been increasing at an annual rate of around 7% in the past few years. On the other hand, construction of several major power plants has been delayed or even cancelled due to protests from environmental protection groups. As a result, power shortages have been experienced over the past five years, especially during the summer peak. Under

pressure from law makers to provide a reliable power supply to consumers and to deregulate all government-owned enterprises including TPC, the Ministry of Economics issued its first announcement to open the electricity generation market to the public in September 1994. Independent power producers (IPP) are now allowed to build non-utility generators (NUG) and sell electricity to TPC. A reviewing committee, comprising members from the government, TPC, universities, and industries is formed to review each NUG project proposed by candidate power producers.

Since the construction and operation of an NUG may cause significant impacts such as air pollution, change in the TPC transmission network loading, risk of system instability, etc., the reviewing committee ought to disapprove those NUG projects which may cause severe environmental pollution or system instability. To help the members in the reviewing committee determine whether a particular NUG project should be approved, ten specific items as described below have been summarized to cover issues related to environmental protection, TPC transmission network security, system stability, etc.

- (1) Check if the independent power producer has enough manpower (managers, engineers, technicians, etc.) and has an adequate financial plan.
- (2) Check if the independent power producer is able to operate the NUG based on the proposed operation plan and previous operation experience.
- (3) Check if the IPP is able to get the land for the power plant.
- (4) Determine the effect of the proposed NUG on the area generation-load balance.
- (5) Check if the scheduled date of commercial operation meets the system requirements and if the type of fuel used by the NUG meets the energy policy.
- (6) Check if the pollution from the NUG meets the pollution standard, as required by the Environmental Protection Bureau, and if the residents around the NUG location will accept the NUG project.
- (7) Check the fuel supply of the NUG is reliable.

- (8) Determine the effect of the NUG on system fault currents and reactive power requirements.
- (9) Check if the current TPC transmission network is capable of transmitting the power from the NUG.
- (10) Check if the IPP is able to build the transmission line between the NUG and TPC substations.

Note that the above items cover economical and environmental, as well as technical aspects related to the NUG. In the present work, we are mainly concerned about the effect of the NUG on area generation-load balance as mentioned in item (4) since the area generation-load balance affects the system oscillatory instability [1–13] to a great extent. The main reason why we are concerned with the oscillatory instability problem is that TPC has been experiencing inter-area low frequency oscillations since 1984 [2,9–13] due to the longitudinal structure of the EHV transmission networks. In fact, these undamped or poorly-damped oscillations have caused a major threat to the reliable operation of the TPC transmission networks. It is observed from previous recordings that inter-area power flows most affect the damping of the oscillations. In other words, the inter-area oscillations can be avoided if the inter-area power flows can be kept to a minimum, by maintaining the generation-load balance in the three regions (north, center and south) of Taiwan. Based on these findings, it seems natural to favor an NUG project which will help improve the area generation-load balance, since the operation of such an NUG will help reduce the risk of inter-area oscillations. Although generation-load balance is only one of the ten items which must be taken into account by the reviewing committee, we want to provide the members of the reviewing committee with a clear picture of how system security and stability will be severely damaged by an NUG which deteriorates the area generation-load balance and causes inter-area oscillations.

In the literature, the site specific impact that an NUG can have upon the Florida Power Corporation's ability to sustain interchange power transactions was reported in Reference 14. The maximum power transfer of the transmission system with and without the NUG were first determined, and the NUG impact on transmission import was computed. It was concluded [14] that the generator location could affect the interchange power transaction capability of the transmission network. In addition, it was recommended that the utility should not bear the adverse burden of an NUG generator connection and the independent power producers should bear the cost for improving the power transfer limit of the transmission network.

Note that load flow, stability and reactive power are taken into account in Reference 14 to find the maximum transfer. In the present work, we propose developing a systematic approach which can be used to evaluate the effect of generator location on the transfer capabilities of the transmission system, as limited by inter-area oscillations, in addition to the factors considered in Reference 14. An impact determination procedure will be developed to reach a quantitative oscillatory stability impact index. It is expected that the proposed oscillatory impact determination procedure can help any utility with a potential inter-area oscillation problem evaluate the site impact of an NUG on its transmission network.

The contents of this paper are arranged as follows. In the next section, the study system is briefly described. The transmission bottleneck caused by inter-area oscillations is studied through eigenvalue–eigenvector analysis. This is followed by the NUG siting problem. Potential locations proposed by independent power producers are given and the relative merits of these NUG locations are briefly described. Then, the proposed impact evaluation procedure is presented in Section IV. In Section V, case studies are presented in order to demonstrate the

Figure 1. Service area of Taiwan Power Company

Table 1. Generation bus data

Area	Generation bus number	Generator type	Real power generation (MW)	
			Peak	Off-peak
North	167	nuclear	660	660
	168	nuclear	660	660
	169	nuclear	985	985
	170	nuclear	985	985
	171	thermal	114	114
	172	thermal	550	134.3
	173	thermal	114	114
	174	thermal	550	114
	175	thermal	35	35
	176	thermal	60	60
	177	thermal	90	90
	178	thermal	300	300
	179	thermal	360	360
Center	180	thermal	160	—
	181	hydro	70	—
	182	thermal	520	520
	183	thermal	520	520
	184	thermal	520	520
	185	thermal	520	520
	186	thermal	278	—
	187	thermal	30	—
	188	thermal	220	—
	189	thermal	220	—
	190	thermal	220	—
	191	thermal	300	—
	192	thermal	300	—
	193	PS	150	–240
	194	PS	150	–240
	195	PS	150	–240
	196	PS	150	–240
	197	PS	270	–260
	198	PS	270	–260
	199	PS	270	–260
	200	hydro	—	—
	201	hydro	100	—
	202	hydro	100	—
	203	hydro	239.5	173.8
	204	hydro	210	—
	205	hydro	40	—
	206	hydro	100	60
	207	hydro	20	—
South	208	nuclear	951	951
	209	nuclear	951	951
	210	thermal	80	—
	211	thermal	550	550
	212	thermal	550	550
	213	thermal	624	624
	214	thermal	624	624
	215	thermal	300	300
	216	thermal	330	330
	217	thermal	82	82
	218	thermal	550	110
	219	thermal	533	110
	220	thermal	80	—
	221	thermal	179	—
	222	thermal	179	—
	223	hydro	115	15

PS: pumped-storage
 —: off-line unit
 203: swing generator

effectiveness of the proposed impact evaluation procedure. Discussion of the results is presented in Section VI.

II. Description of the study system

The service area of TPC covers the entire island of Taiwan, a distance of 400 km from the north to the south and 120 km from the west to the east. As shown in Figure 1, the island is divided into three areas, i.e., the northern area (N), the central area (C), and the southern area (S). The three areas are connected together via 345 kV trunk lines. Since the system is longitudinal in nature, it is vulnerable to inter-area low frequency oscillations [2–8], especially when the trunk lines are heavily loaded.

The generation bus number, geographical area, and type of generator are listed in Table 1. Note that there are four nuclear units (167–170) and some thermal units in the north. Most hydro units, including several pumped-storage units, are located in the central area. In addition to the hydro units, there are some thermal units in the center. In the south, there are two nuclear units and several thermal units. A major load center is located in Taipei, which is the capital of Taiwan.

Figure 2 depicts a typical daily load curve in the summer peak. It is observed from Figure 2 that the peak load (17824 MW) is much higher than the off-peak load (10165 MW) and the load factor is very poor. To improve the load factor, seven pumped-storage units (193–199) have been installed near Sun-Moon Lake in the central area. These pumped-storage units consume the excess power from the nuclear units through pump operation at night and provide load demand through generating operation during peak hours.

To examine the generation-load balance in the three areas, the real power generations, load demands, and the surplus (or deficit) powers are listed in Table 2. It is noted that two typical load patterns, one for peak load condition and the other for off-peak load condition, are considered. It is observed from Table 2 that, under peak load conditions, the surplus power (3611 MW) in the south is transmitted to the center and north through 345 kV trunk lines. The seven pumped-storage units are all operated in the generation mode. During the off-peak period, the central area has a deficit power of 3222 MW because the seven pumped-storage units are now operating in the pumping mode. Most of the deficit power comes from the south. In summary, a significant amount of

Figure 2. Typical daily load curve of TPC

Table 2. Real power generations and load demands

Case	Area	Real power generation		Load demand		Surplus or deficit (–) power (MW)
		(MW)	(%)	(MW)	(%)	
Peak	N	5693	31.2	8109	45.5	–2416
	C	5900	32.3	6648	37.3	–748
	S	6678	36.5	3067	17.2	3611
	Total	18271	100	17824	100	—
Off-peak	N	4611.3	44.4	4280.8	42.1	330.5
	C	573.8	5.5	3796	37.3	–3222.2
	S	5197	50.1	2088.6	20.6	3108.4
	Total	10382.1	100	10165.4	100	—

power (3611 MW) is transmitted from the south to the center and then to the north during peak hours while a somewhat smaller amount of power (3108 MW) is transmitted to the center during the off-peak period.

Since there are heavy power flows over the inter-area trunk lines, it is essential to examine whether the inter-area mode is well-damped. In this work, we compute the eigenvalue, oscillation frequency and normalized generator speeds (eigenvectors) for each electromechanical mode using a modified version of the AESOPS program [1,15,16]. Note that the AESOPS program provides us with the eigenvalues and eigenvectors for all the electromechanical modes. Among these modes, the inter-area mode which affects all generators in the three areas of the system usually has the worst damping, based on our previous experience [2,9,10]. Thus, this inter-area mode will be of major concern in this work. Table 3 gives the eigenvalues, oscillation frequency, and damping ratio for this mode. It is observed from Table 3 that the inter-area mode is poorly damped under both peak load and off-peak load conditions. The oscillation frequency is around 0.85 Hz and the real part of the eigenvalues for this mode are -0.059 and -0.0413 for the peak load case and the off-peak load case, respectively.

To examine how the generators in the three areas interact with each other in the inter-area oscillations, Figure 3a and b depicts the eigenvectors for the inter-area mode under peak load condition and off-peak load condition, respectively. It is observed from Figure 3 that the generators in the northern area and central area form a group which oscillates with the group of generators in the south. This is a rather interesting observation which should be taken into account in determining proper locations for the NUG because the addition of an NUG in a certain area will not only affect inter-area line flows which, in turn, affect the damping for the inter-area mode, but also affect the way a group of generators oscillates with another. The eigenvalues and eigenvectors for other electromechanical modes are not listed because they have much better damping and do not cause oscillatory instability problems in the study system.

III. NUG siting problem

Because running an NUG in Taiwan seems to be highly profitable, at least at the present time, many investors, both local and overseas, have been working on their NUG projects since the government made its announce-

ment to open the NUG market in September 1994. Most investors face two major obstacles in their NUG projects: the land and the fuel for the power plant. Since Taiwan is a small, crowded island with more than twenty million people, land is rather scarce and expensive. On the other hand, the fuel for the plant (coal, oil or gas) must be imported from overseas. Thus, a feasible NUG site must have access to the imported fuel and must be away from towns in order to get relatively cheap land and to avoid protest from the neighbouring residents. In fact, several of TPC's plants have been forced to shut down many times due to the protest from nearby residents. Based on these considerations, most investors may wish to put their NUGs in industrial zones where their own factories are located. In this way, they can get inexpensive land for the

(a) peak load condition

(b) off-peak load condition

Figure 3. Eigenvectors for the inter-area mode. (a) Peak load condition and (b) off-peak load condition

Table 3. Eigenvalues and eigenvectors* (normalized speed deviation) for the inter-area mode

Peak case		Off-peak case	
Eigenvalues	$-0.059 \pm j5.34$	Eigenvalues	$-0.0413 \pm j5.392$
Oscillation frequency	0.85	Oscillation frequency	0.858
Damping ratio	0.01	Damping ratio	0.0076
Generation bus number	Normalized speed deviation	Generation bus number	Normalized speed deviation
167	$0.76 + j0.02$	167	$0.74 - j0.03$
168	$0.76 + j0.02$	168	$0.74 - j0.03$
169	$1.00 + j0.09$	169	$1.00 + j0.05$
170	$1.00 + j0.09$	170	$1.00 + j0.05$
171	$0.78 + j0.04$	171	$0.73 - j0.01$
172	$0.86 + j0.01$	172	$0.74 - j0.01$
173	$0.78 + j0.04$	173	$0.73 - j0.01$
174	$0.86 + j0.01$	174	$0.73 - j0.01$
175	$0.63 + j0.04$	175	$0.61 + j0.00$
176	$0.72 + j0.05$	176	$0.73 + j0.02$
177	$0.76 + j0.05$	177	$0.77 + j0.01$
178	$0.65 + j0.00$	178	$0.63 - j0.04$
179	$0.64 + j0.02$	179	$0.61 - j0.02$
180	$0.59 + j0.01$	203	$0.16 - j0.02$
181	$0.61 - j0.01$	208	$-0.89 + j0.02$
182	$0.12 + j0.00$	209	$-0.89 + j0.02$
183	$0.12 + j0.00$	211	$-0.66 - j0.01$
184	$0.12 + j0.00$	212	$-0.66 - j0.01$
185	$0.12 + j0.00$	213	$-0.60 + j0.01$
187	$0.67 - j0.02$	214	$-0.60 + j0.01$
188	$0.58 - j0.03$	215	$-0.79 + j0.00$
189	$0.58 - j0.03$	216	$-0.77 + j0.00$
190	$0.58 - j0.03$	217	$-0.80 - j0.05$
191	$0.58 - j0.04$	218	$-0.64 - j0.05$
192	$0.58 - j0.04$	219	$-0.64 - j0.05$
193	$0.16 - j0.06$	223	$-0.80 + j0.07$
194	$0.16 - j0.06$		
195	$0.16 - j0.06$		
196	$0.16 - j0.06$		
197	$0.11 - j0.02$		
198	$0.11 - j0.02$		
199	$0.11 - j0.02$		
201	$0.26 - j0.02$		
202	$0.31 - j0.01$		
203	$0.35 - j0.04$		
204	$0.41 - j0.05$		
205	$0.10 + j0.01$		
207	$-0.13 + j0.01$		
208	$-0.63 + j0.07$		
209	$-0.63 + j0.07$		
210	$-0.66 - j0.01$		
211	$-0.45 + j0.04$		
212	$-0.45 + j0.04$		
213	$-0.42 + j0.05$		
214	$-0.42 - j0.05$		
215	$-0.58 + j0.06$		
216	$-0.59 + j0.06$		
217	$-0.61 + j0.02$		
218	$-0.67 - j0.08$		
219	$-0.68 - j0.08$		
220	$-0.54 + j0.00$		
221	$-0.48 + j0.06$		
222	$-0.48 + j0.06$		
223	$-0.91 + j0.00$		

*Only those eigenvectors with magnitudes greater than 0.1 are listed

NUG. Once approved, the NUG provides electricity service to the local factories and sells the excess power to TPC. Up to now, three possible sites (Site 1, Site 2, and Site 3, as shown in Figure 1) have been selected as candidate locations for the NUG by the investors. It is noted that, among the three possible locations for the NUG, Site 1, which is located in the northern area, is closest to the load center in Taipei. Site 2, in the central area, is close to a large petro-chemical plant, while Site 3 in the southern area is close to a large steel mill.

It was mentioned in last section that undamped inter-area low frequency oscillations would be observed when the inter-area power flows are heavy. Since the addition of an NUG at different locations will have a different impact upon the inter-area power flows, it is obvious that the NUG location will affect the damping of the inter-area oscillations to a great extent. Because the damping of inter-area oscillations has a significant impact on the reliable operation of the whole TPC, it is essential to develop a procedure to evaluate quantitatively the impact of NUG location on the damping of inter-area oscillations. This motivates the development of the impact evaluation procedure in the next section.

IV. The proposed NUG impact evaluation procedure

The impact of a generator installation at a given site can be determined using the load flow program and the AESOPS program. The studies are evaluated at representative system conditions and the average impact found. This impact gives an index of how much the damping of the inter-area mode will improve (when the index is positive) or deteriorate (when the index is nega-

Table 4. Summary of the generated powers of the units redispatched
(a) peak load case

Generator number	Area	NUG capacity		
		1000 MW	1500 MW	2000 MW
203	C	245	299.76	273
178	N		—	174
172	N		399.03	114
174	N	413.03	64	64
218	S	110	110	110
219	S	110	110	110

(b) Off-peak load case

Generator number	Area	NUG capacity		
		1000 MW	1500 MW	2000 MW
203	C	218	253	280
213	S	—	—	355
182	C	—	396.3	165
183	C	—	165	165
184	C	141	120	120
185	C	120	120	120
178	N	99	99	99
172	N	114	114	114

—: the same as in Table 1

tive) when the NUG is added to the system. The NUG impact evaluation procedure is as follows

- Step 1: Run load flow program for the TPC system without the generator to get inter-area power flows and use the AESOPS program to obtain the eigenvalues and eigenvector for the inter-area mode without the NUG.
- Step 2: Add the non-utility generator to the TPC system. Since TPC must purchase the power generated by the NUG, redispatch the thermal units of TPC. For convenience, the power generated by the hydro units and nuclear units is assumed to remain unchanged.
- Step 3: Run load flow program and AESOPS program to get the inter-area power flows and the eigenvalues and eigenvector for the inter-area mode with NUG.
- Step 4: Compare the inter-area power flows and eigenvectors for the system with and without the NUG.
- Step 5: Compute the damping ratios of the inter-area modes for the system with and without the NUG.
- Step 6: Determine the oscillatory stability impact (OSI) by:

Table 5. Real power generations

NUG capacity (MW)	NUG site	Area	Surplus or deficit (–) power (MW)	
			Peak load case	Off-peak load case
1000	1(N)	N	–1553	1109.2
		C	–748	–4003
		S	2748	3108.4
1000	2(C)	N	–2553	109.2
		C	252	–3000.4
		S	2748	3108.4
1000	3(S)	N	–2553	109.2
		C	–748	3957
		S	3748	4108.4
1500	1(N)	N	–1553	1609.2
		C	–748	–4496
		S	2748	3108.4
1500	2(C)	N	–3035	109.2
		C	752	–2297.1
		S	2748	3108.4
1500	3(S)	N	–3035	109.2
		C	–748	–4421.1
		S	4248	4608.4
2000	1(N)	N	–1539	2109.2
		C	–762	–4722.5
		S	2748	2839.7
2000	2(C)	N	–3539	109.2
		C	1238	–2730.8
		S	2748	2839.7
2000	3(S)	N	–3539	109.2
		C	–762	–4625.5
		S	4748	4839.7

Table 6(a) Summary of oscillatory stability impact for the peak load case

NUG capacity (MW)	NUG site	Real part of eigenvalue	Frequency (Hz)	Damping ratio	OSI(%)
1000	original	-0.059	0.85	0.011	—
	1(N)	-0.1125	0.8797	0.0205	86.36
	2(C)	-0.1122	0.8855	0.02016	83.27
	3(S)	-0.099	0.8506	0.0185	68.18
1500	1(N)	-0.1212	0.8856	0.0217	97.27
	2(C)	-0.1212	0.8961	0.02166	96.9
	3(S)	-0.1093	0.8417	0.02028	84.36
2000	1(N)	-0.124	0.8865	0.0222	101.81
	2(C)	-0.1258	0.9011	0.0222	101.81
	3(S)	-0.1091	0.8252	0.021	90.9

(b) Summary of oscillatory stability impact for the off-peak case

NUG capacity (MW)	NUG site	Real part of eigenvalue	Frequency (Hz)	Damping ratio	OSI(%)
1000	original	-0.0413	0.858	0.0076	—
	1(N)	-0.0536	0.8614	0.0099	30.26
	2(C)	-0.0526	0.8717	0.0096	26.31
	3(S)	-0.017	0.824	0.00328	-56.84
1500	1(N)	-0.0548	0.856	0.01018	33.94
	2(C)	-0.0535	0.8727	0.00976	28.36
	3(S)	0.0036	0.7969	-0.00072	-109.4
2000	1(N)	-0.0576	0.8566	0.0107	40.78
	2(C)	-0.0565	0.88	0.0102	34.21
	3(S)	0.0179	0.7782	-0.00366	-148.16

$$\text{OSI}(\% \text{ impact}) = \frac{\text{damping ratio with NUG} - \text{damping ratio without NUG}}{\text{damping ratio without NUG}} \times 100\%$$

Step 7: Repeat Steps 2–6 for various NUG capacities.

V. Case studies

To demonstrate the effectiveness of the proposed NUG impact evaluation procedure and to examine which one of the three potential NUG sites in Figure 1 is the most desirable, several case studies were conducted on the study system described in Section II. Among them, only the results from two extreme cases are presented due to limited space.

Before the NUG is added, the real power generations and load demands for the three areas of Taiwan for the two cases under study are summarized in Table 2 for the peak load and off-peak load cases. The eigenvalues and damping ratios are listed in Table 3. The eigenvectors are depicted in Figure 3.

As we mentioned earlier, three possible NUG sites, Site 1 in the north, Site 2 in the center, and Site 3 in the south will be considered. For each NUG location, three different generator capacities, i.e. 1000, 1500 and 2000 MW, will be studied.

As pointed out in Step 2 of the evaluation procedure, the thermal units must be redispatched when the NUG is added to the system. Table 4 summarizes the generated powers of the units redispatched. Those units whose generated powers remain unchanged are not listed.

It is noted that the dispatch results are the same for the same NUG capacity regardless of the NUG site.

In order to estimate the area power balance for each case, the surplus (or deficit) powers in the three areas are listed in Table 5 for the peak load and off-peak load cases. Note that the results in Table 5 are summarized from the results in Tables 2 and 4. For example, when installing a 2000 MW NUG in the peak load case, units 172, 174, 178, 218 and 219 are redispatched (Table 4). If the NUG is located in the northern or central area, the power generation in the southern area will be reduced by 863 MW because the outputs of units 218 and 219 in the south are redispatched from 550 MW and 533 MW, respectively, to 110 MW. As a result, the surplus power in the south will be reduced from 3611 MW (Table 2) to 2748 MW (Table 5). Using the AESOPS program, we can obtain the eigenvalues for the inter-area modes. Then the damping

Figure 4. Oscillatory stability impact (OSI) as a function of NUG capacity (peak load case)

Figure 5. Oscillatory stability impact (OSI) as a function of NUG capacity (off-peak load case)

ratio and oscillatory stability impact (OSI) for each case can be figured out. Table 6a and b lists the results for the peak load and off-peak load case, respectively. The oscillatory stability impacts for each NUG site with different capacities are depicted in Figures 4 and 5 for the peak load and off-peak load case, respectively.

VI. Discussions

Based on the results in Tables 4–6 and Figures 4 and 5, the following observations can be made.

(1) In the case of peak load, oscillatory stability impacts for the three possible sites are all positive. In other words, the damping for the inter-area mode will be improved no matter where the NUG is installed. To see why the damping is improved by the NUG, let us examine the generator output powers redispatched by the NUG as shown in Table 4a and the area power balance in Table 5. It has been pointed out in Section II that heavy power flows over the trunk lines from the south to the center will cause undamped inter-area oscillations. The system without the NUG has a surplus power of 3611 MW in the south. When a 2000 MW NUG is installed in the northern or the central area, the surplus power in the south is reduced to 2748 MW, resulting in a decrease in the trunk line flow northward, which in turn, causes an improvement in the damping ratio as revealed by the positive OSI for the two cases. On the other hand, when a 2000 MW NUG is installed in the southern area, the surplus power in the south is increased to 4748 MW. The trunk line flow northward is increased but the OSI is also positive in this case. In fact, the damping ratio in this case is only slightly smaller than that for the case where the NUG is installed in the northern or central area. Why does an increase in trunk line flow cause an improvement in the damping ratio for inter-area oscillation? Recall that, in Reference 11, it was pointed out that, in addition to inter-area line flows, the output powers of some key generators would affect the damping for the inter-area mode. In the present study, units 218 and 219 in the south have been identified as the major key generators based on the results from numerous test runs. It is also observed that system damping will be increased when the output powers of units 218 and 219 are decreased. In the present case, the output powers of units 218 and 219 are decreased from 550 MW and 533 MW, respectively, to 110 MW for both units (Table 1 and Table 4a) when the NUG is added to the system. Thus the decrease in the output power of these major key generators helps to improve the damping for the inter-area mode. In summary, the oscillatory stability

impact seems to be the same no matter where the NUG is installed in the peak-load case.

(2) Consider the peak load case again. It seems that the OSI is somewhat improved when the NUG capacity is increased from 1000 to 2000 MW. This is due to the decrease in the output powers of the two minor key generators, units 172 and 174. When the output powers of these two generators are reduced, the damping for the inter-area oscillation will be somewhat improved, based on previous test results.

(3) In the case of off-peak load, most of the generators redispatched when the NUG is added to the system are located in the central area. The major key generators (units 218 and 219) are not redispatched. The damping for the inter-area mode is mainly determined by the trunk line flow from the south to the center and the power output of the minor key generator, unit 172.

(4) Consider again the case of off-peak load. When a 2000 MW NUG is installed in the northern or central area, the surplus power in the south is reduced from 3108 MW (Table 2) to 2839 MW (Table 5). Therefore, the damping ratio for the inter-area mode is improved from 0.0076 to 0.0107 and 0.0102 (Table 6b), respectively. The oscillatory stability impacts are 40.78 and 34.21 for the two cases, respectively. When the NUG is installed in the southern area, the surplus power in the south is increased from 3108 to 4839.7 MW. Since the surplus power increase will cause an increase in trunk line flow from the southern to the central area, it is reasonable to see a deterioration in the system damping ratio (from 0.0076 to -0.00336). The OSI is negative (-148.16) in this case, which means that the NUG will have a negative impact on the system stability. The general trend, that an NUG installed in the north or center has a positive OSI and that one installed in the south has a negative OSI, applies equally well when the NUG capacity is reduced from 2000 to 1500 or 1000 MW.

(5) As far as the eigenvectors for the inter-area mode for the system with an NUG are concerned, they are essentially similar to those for the system without NUG in both the peak-load and off-peak load case. In other words, the generators in the north and center form a group which oscillates with another group of generators in the south. These eigenvectors are not presented due to limited space.

VII. Conclusions

An NUG impact evaluation procedure has been developed to evaluate the impact of an NUG at a specific site, on the damping of the inter-area mode. Our primary concern is to determine whether an NUG at a specific site will cause undamped or poorly-damped inter-area oscillations, since such oscillations may cause severe damage to the whole transmission network. An oscillatory stability index is defined for the purpose of evaluating the NUG site impact.

Since the impact of an NUG on system damping is a function of system loading conditions, it is recommended that evaluations on several extreme cases, e.g., peak load condition and off-peak load conditions, be made first. If the damping ratio for a particular case is too small (e.g. less than 0.01) or even negative, the specific NUG site should be avoided and further analyses on other system conditions are not necessary. If the damping ratios for all cases are satisfactory, the average impact can be figured

out. The NUG site with a higher average oscillatory stability impact will give more contributions to system damping and can be regarded as a better NUG site as far as oscillatory stability is concerned.

The proposed oscillatory stability impact evaluation procedure can be applied to any utility with a potential oscillatory stability problem to determine if a specific NUG site is acceptable as far as the transfer capability of the utility is concerned. It is essential for the utility to conduct such evaluation since, as mentioned in Reference 14, the utility stockholders should not bear the adverse burden of the NUG generation connection.

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