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Korean Power System Security Analysis Using Benchmark Systems

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Abstract - This paper deals with the development of benchmark systems based on the Korea Electric Power Corporation (KEPCO) system. A novel procedure for constructing a dynamic equivalent system of the KEPCO system is proposed. By using such a system, various scenarios can be simulated and compared with the original system. The results of the simulation show the benefits of the proposed equivalent system and its validity is confirmed by applying it to the KEPCO system.

Keywords: Benchmark system, power system equivalent, transient and small-signal stability

1. Introduction

Because of deregulation and privatization in the power market and the increasing trend towards the interconnection of power grids, the dynamic characteristics of power systems are being significantly changed and it is of importance to improve their stability [1]. In recent years, the development of computationally-fast stability assessment methods for on-line and real-time applications has become important. In order to accomplish swift stability assessment, it is desirable to reduce the original power system to an equivalent power system, in order to match the size and capacity of the tool used with that of the original system, so that the results of the stability calculations are comparable. The objective of the equivalent power system is to simplify the network calculation and reduce the investigation time. The equivalent system is used to assess the efficacy and accuracy of the various analytical techniques used to examine the transient and small-signal stability [2, 3]. Nowadays, this objective seems to be declining in importance because of the increasingly high speed of the microprocessors that are employed, which are able to perform the simulations of large and complicated power systems in a reasonable amount of computational time. However, there still exists a limitation in the scale of the system to be simulated in the case of the on-line stability analysis and real-time power system simulators such as the Real-Time Digital Simulator (RTDS) or Electromagnetic Transients Program for DC application (EMTDC). Hence, it is necessary to develop reduced equivalent systems that preserve the desired properties of the original system. Dynamic equivalent systems are also necessary for performing small-signal stability studies using normal forms of vector fields. Moreover, these equivalent power systems can be used to develop and verify the protective relaying algorithm.

The purpose of this study is to develop a benchmark system for various scenarios and to assess its dynamic performance. At first, this study deals with the dynamic reduction of a large power system for the purpose of evaluating its transient and small-signal stability, and the proposed benchmark systems are compared with the original system. Based on the proposed system, the transient stability is assessed using a synthetic method. Finally, the effects of the inter-area oscillations according to the system structure and operating conditions are simulated in the proposed system, and the small-signal stability is assessed. The proposed benchmark systems are constructed based on the configuration of the KEPCO system in the year 2005, and the simulation results indicate the capabilities of the proposed method.

2. General characteristics of the study system

From a geographical point of view, the KEPCO system configuration has the following characteristics:

- The transmission system is a highly meshed network.
- Large base load generating plants are located in the southern coastal areas.
- Many combined-cycle gas turbine units are located in the vicinity of the load centers in the northern areas.
- The South-North connections are voltage stability constrained for certain contingencies.
- The West-East connections experience changes in power flow direction depending on the system's operating conditions.

More than 40% of the total load demand is in the metropolitan area, while the majority of the generation is carried out in non-metropolitan areas. For this reason, a large amount of active power flows through a set of

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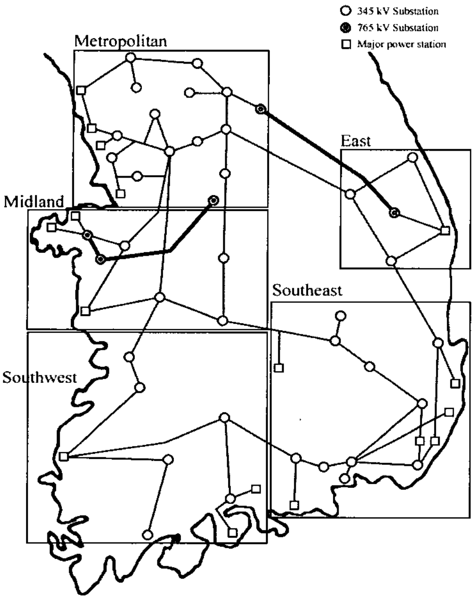

Fig. 1 Major part of the KEPCO system

interface lines connecting the metropolitan area with the other areas. Since its completion in 1998, the ±180kV 300MW HVDC system in the KEPCO conveys relatively cheap electric power from the Haenam substation on the mainland to the Jeju substation on Jeju Island by means of an undersea 101 km DC cable. Fig. 1 shows a map of the 765-kV and 345-kV transmission network and the major generating plants in the KEPCO system. As shown in Fig. 1, the system is composed of five areas, designated here as the Metropolitan (MP), Midland (ML), East (EA), Southwest (SW) and Southeast (SE) areas, which are separated by six boundaries.

3. The construction of a benchmark system

The various procedures for reducing the dynamic model of a power system have been presented in numerous papers [4, 5]. These procedures include coherency identification, generator aggregation and network reduction. In this paper, a novel procedure is proposed that produces a model whose dynamic characteristics are closer to those of the original system than is the case in the previous methods. The proposed procedure is as follows:

1. Data is acquired from the original system.
2. The generators with the same control model at the same bus are identified.
3. The gas-turbine and steam-turbine generators at combined cycle plants at the same bus are identified.
4. Detailed coherency identification is performed using a two-time scale method proposed by DYNRED. The regional characteristics should be taken into consideration, as shown in Fig. 1.
5. The machine in the coherent group that has the largest generating power is taken to be the reference machine. This means that the equivalent machine will be placed at this bus.
6. All the buses in the coherent group are joined to the reference machine bus and the shunt elements of the deleted buses are added to the reference machine bus.
7. After all machine bases have been aligned with the reference machine, the generation and load on each of the generator buses in the group are transferred to the reference machine bus. If the parameters are different, their average value is used, and a check is performed to determine if all the parameters are within the permitted limits.
8. Processing is returned to step 4 if the criteria, the condition of the power flow calculation and the characteristics associated with the dynamic simulation are not satisfied.
9. Once the equivalent generators are determined using generator aggregation, network reduction is performed by the PSS/E.

Table 1 Estimates of power supply and demand

	Original system	Benchmark system
Buses	1621	77
Branches	2714	302
Generators	258	20
Total generation	52212/11926	52205/11930
Total load*	51434/23768	51439/24868

MW/MVAR

The configuration of the KEPCO system in the year 2005 is used to apply and test the proposed procedure. Table 1 shows the sizes of the original and benchmark systems. The system includes the generators, buses, branches and load.

3.1 Benchmark tests

The focus of the benchmark system study was the transient stability performance of the MP area. Thus, the metropolitan system was kept intact, while the remaining parts of the KEPCO system were reduced, except for the high tension buses. To examine the validity of the benchmark system against the original system, a power flow calculation is performed. Tables 2 and 3 show the results of the power flow calculations for the original and benchmark systems, which demonstrate that the difference between the two systems is negligible.

The benchmark system is validated against the original system using time-domain simulations. The contingency simulated is a three-phase fault at bus #1800 (Joongbu) in the MP area. It is initiated at 1.0 s and cleared at 1.2 s. The simulation is performed for 5 s by the PSS/E. Fig. 2 shows the voltage magnitude at faulted bus #1800 and the amount of active power transfer in the transmission line between buses #1400 (Mikum) and #1800. The result presented in Fig. 2 indicates that there is good agreement between the original system and the benchmark system.

To examine the validity of the benchmark system over a wide range of system operating conditions, the loadings and generating powers in the original and benchmark systems were adjusted, so as to increase the amount of power transferred on the interface between the MP and ML areas. A three-phase fault at bus #4400 (Hwaseong) was applied for the dynamic simulation. It was initiated at 1.0 s and cleared at 1.1 s. The simulation was performed for 5 s by the PSS/E.

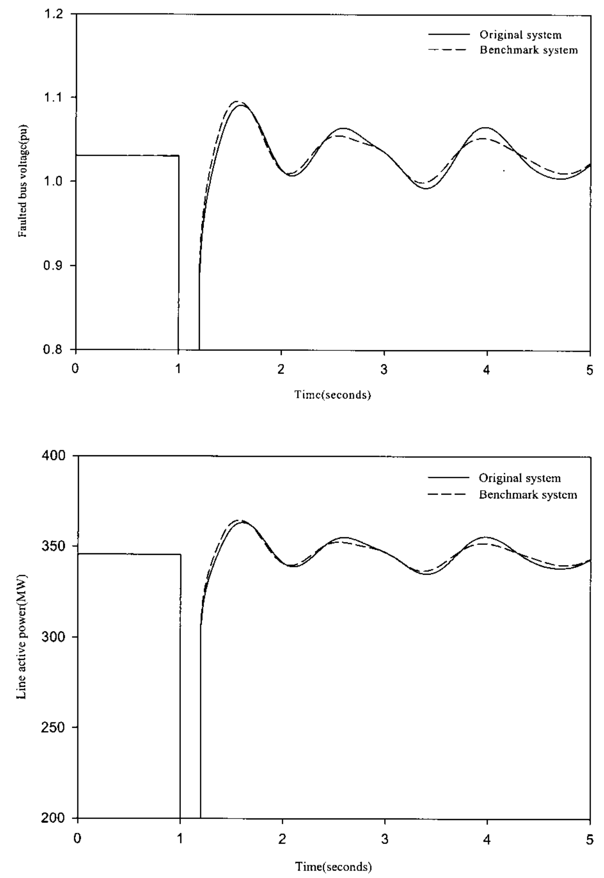

Fig. 2 Performance of the benchmark system

Table 2 Power-flow calculation results (bus voltage)

Bus	Voltage (pu/degree)	
	Original system	Benchmark system
1020	1.034∠-26.36	1.035∠-26.44
1400	1.035∠-36.78	1.035∠-36.85
3600	1.008∠-32.84	1.008∠-32.91
4010	1.031∠-24.62	1.031∠-24.70
4400	1.010∠-27.43	1.010∠-27.52
5700	1.027∠-23.30	1.027∠-23.37

Table 3 Power-flow calculation results (line flow)

Line	Line flows (MW/MVAR)	
	Original system	Benchmark system
1020-5010	2897.5/273.8	2898.0/272.4
4010-6030	2939.8/-275.2	2939.4/-272.2
4400-6950	2654.3/-362.0	2653.4/-361.0
4600-6800	1657.8/-224.6	1657.8/-224.8
4700-4800	0314.8/-217.6	0315.2/-219.0
4750-5700	1259.2/-147.2	1259.6/-148.2

Table 4 Modes in the benchmark system

Participating generator	Original system	Benchmark system
Dangjin	-0.3263±j8.9658	-0.3910±j9.2664
Boryung	-0.2636±j8.0358	-0.2745±j8.1307
Samchanpo	-0.3752±j8.7777	-0.3809±j9.5214
Wolsung	-0.3406±j7.8793	-0.3167±j7.8646
Youngkwang	-0.1056±j6.5341	-0.1560±j6.5894
Uljin	-0.1373±j4.4276	-0.1432±j4.4384

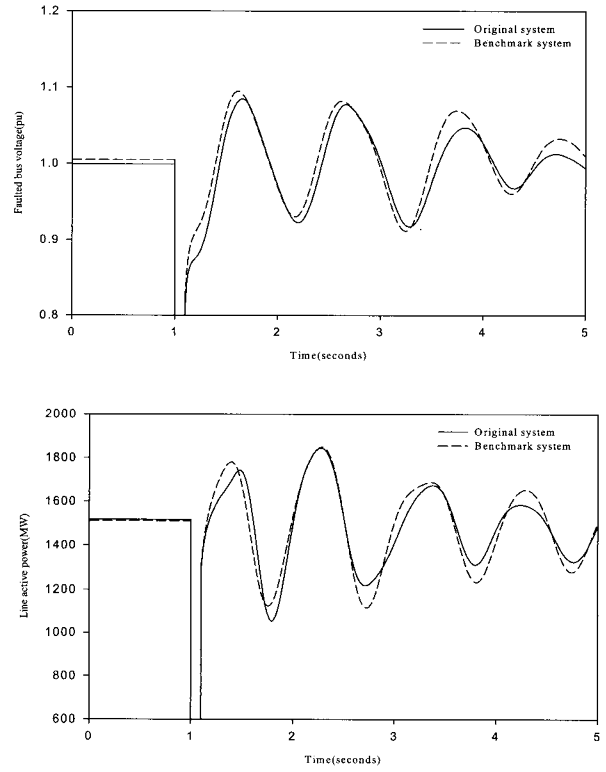

Fig. 3 Simulations at highly stressed conditions

Fig. 3 shows the voltage magnitude at faulted bus #4400 and the amount of active power transferred in the transmission line between buses # 4400 and #6950 (Asan). The results obtained from the original and equivalent systems are very similar, even under highly stressful conditions.

We also examined the characteristics of the low frequency modes in both systems, in order to evaluate the use of the benchmark system. As indicated in Table 4, the low frequency modes in the original and benchmark systems, which are selected in the range of 0.1 to 2.0 Hz, are shown along with their most dominant participating generator. Table 4 shows that the modal characteristics of the original system are well preserved in the benchmark system.

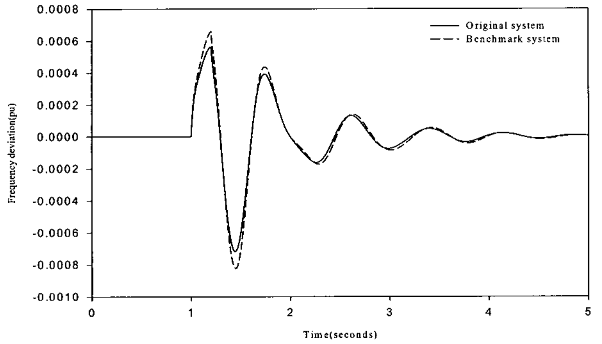

Fig. 4 Frequency response of the island system

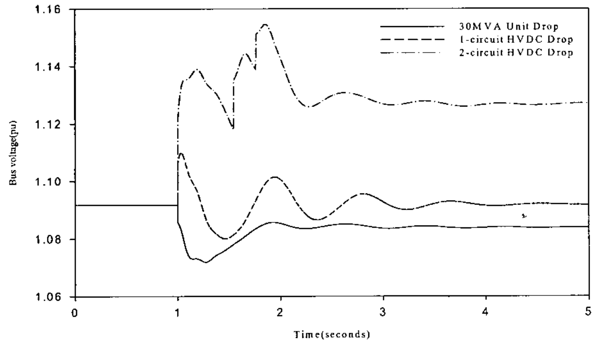

Fig. 5 Voltage response at the inverter

3.2 A benchmark test for HVDC system study

The benchmark system used to study the HVDC system consists of an extended 10-bus ac system at the inverter side. In order to demonstrate the validity of the benchmark used for the HVDC system study, a dynamic simulation is performed. Fig. 4 shows the sample frequency response of the original and benchmark systems during a three-phase fault at bus #166 (hanlim). It was initiated at 1.0 s and cleared at 1.2 s. The simulation was performed for 5 s by the PSS/E. As can be seen in Fig. 4, the response from the benchmark system is the closest to that of the original system. In this case, the total load demand of the island is 430 MW, and 150 MW is supplied by the HVDC system. The contingency is the dropping of a single unit. Under normal conditions, the voltage of the inverter terminal is simulated for 5 seconds by the PSS/E. Fig. 5 shows the voltage response at the inverter during the dropping of one unit. There is an active power shortage when the generator is dropped. Since the HVDC system is in frequency control mode, the output of the HVDC system is increased to 180 MW.

4. Study on the dynamic characteristics of the benchmark system for various scenarios

This section describes the dynamic characteristics of the benchmark system for various scenarios. This simple study demonstrates the ability to use the scenario system for analyzing the transient and small-signal stability. A description of the scenario systems is presented in Table 5. The procedure for designing the system with respect to the dynamic security analysis is shown in Fig. 6. The synthetic benchmark systems and their principal characteristics are summarized as follows:

- System A – a summer peaking system
- System B – a winter peaking system

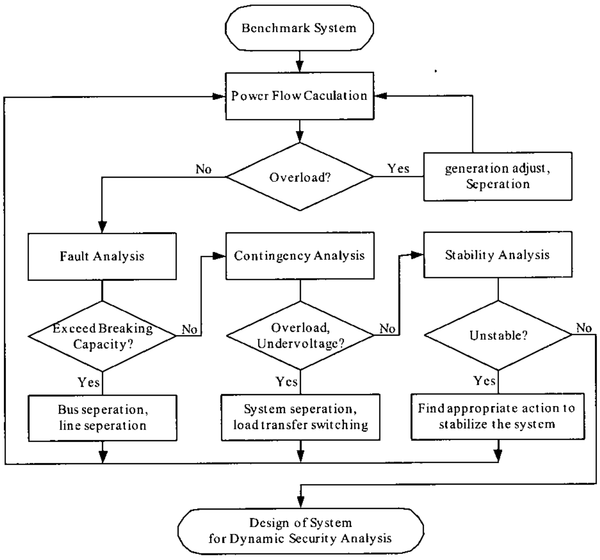

Fig. 6 The procedure for designing the system for dynamic security analysis

Table 5 Description of scenario systems

Scenario systems	Total generation (MW/MVAR)	Total load (MW/MVAR)	Metropolitan load (MW/MVAR)	Active power flow* (MW)
System A	52212.1/11926.0	51434.6/23768.4	21389.0/10184.3	11721.9
System B	48984.7/10183.0	48177.0/15676.5	17740.7/05353.0	10990.4
System C	43150.5/08930.8	42467.5/15213.4	15852.5/05340.4	11166.5
System D	32331.5/05308.5	31861.1/07207.1	10251.3/01894.9	08468.0

* Sum of active power flow on the interface lines between the metropolitan area and the neighboring areas in the KEPCO system.

- System C – an autumn peaking system
- System D – an off-peaking system

In these systems, the generation is performed remotely from the load, and the network mainly consists of a 345kV transmission network with some 765kV.

Table 6 Plant generation limit of a disturbance close to a generator

Sum of generation at bus #8150	Stability classification of scenario A (Fixed fault clearing time = 0.1250s)
2779 MW	Stable
2809 MW	Stable
2819 MW	Unstable

Table 7 Plant generation limit of a disturbance close to interface lines

Sum of generation at bus #26101 and bus #26201	Stability classification of scenario A (Fixed fault clearing time = 0.10s)
5943 MW	Stable
5953 MW	Stable
5963 MW	Unstable

5. Transient stability

The transient stability assessment of the plant generation limits and critical clearing time is performed using the proposed benchmark systems. Here, each assessment is also studied in the case of a disturbance situated close to a generator and the interface lines [6].

5.1 Plant generation limit

The contingency that occurs close to generator #28151 (wolsong1G) is a double line three-phase fault at 345 kV on the SE area, which is cleared at 0.1250 s. The stability limit is calculated in terms of the sum of the generated powers at the above generator. In obtaining new power flow solutions that are different from the base case, we change the generation at bus #8150 (wolsong), which can be absorbed in the slack bus. Table 6 shows the plant generation limits obtained using the PSS/E. The stability limits of the active power flow on the main transmission lines connecting the MP area and the neighboring areas in the KEPCO system are evaluated. The power flow problem is solved by increasing the generation in area 4 to 900 MW, with this power being absorbed in the slack bus. The contingency simulated is a double line three-phase fault at 765 kV on the MP–ML interface, which is cleared at 0.10 s. Table 7 shows the plant generation limits obtained using the PSS/E.

Table 8 CCT of a disturbance close to a generator

Clearing time (s)	System A	System B	System C	System D
0.0833	Stable	Stable	Stable	Stable
0.0917	Unstable	Stable	Stable	Stable
0.1000	Unstable	Stable	Stable	Stable
0.1083	Unstable	Unstable	Stable	Unstable
0.1167	Unstable	Unstable	Unstable	Unstable

Table 9 CCT of a disturbance close to interface lines

Line	System A	System B	System C	System D
1020-5010	*	*	*	0.1584
4010-6030	0.1263	1.1378	0.0991	0.1399

* CCT is not calculated because an unstable angle does not exist.

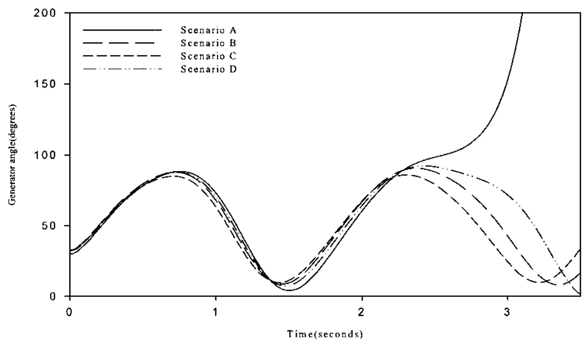

Fig. 7 Rotor angle response of the generator at bus #27151

5.2 Critical Clearing Time

The CCT is calculated using the proposed benchmark systems, in order to assess the transient stability. To obtain the CCT, the contingency of a double line three-phase fault in the 345 kV and 765 kV lines, which is cleared by tripping the faulted double line, is applied. The results obtained using the PSS/E for a double line three-phase fault, which occurs in the 345 kV transmission line close to generator #27151 (young-kwang1G) and which is cleared at 0.1 s, are shown in Table 8. Fig. 7 presents the rotor angle for the generator at bus #27151 with respect to the angle of the generator at slack bus for the four different scenarios. One of the three generators close to the fault is severely disturbed, and system A is particularly affected by the fault, as shown in Fig. 7. Table 9 indicates the results for the contingencies involving the main transmission lines connecting the MP area and the neighboring areas for the five scenarios. As shown in these results, the contingencies pertaining to scenarios A, B and C are definitely dangerous. As a consequence of these contingencies, the most important nuclear power plant close to the contingency loses synchronization, although the stability of the system is maintained in the contingency associated with scenario D. In the case of scenario A, the transmission line between buses #1020 (shingapyeong) and #5010 (shintaebaek) is an important one, which accounts for 13.5% of the load of the MP area. Thus, a contingency arising on this line has a significant influence on the stability of the MP area.

6. Small-signal stability

To identify the critical modes of inter-area oscillation, the eigenvalues of the system modes in the scenario systems were calculated with frequencies in the range of 0.1 to 1.0 Hz and a damping ratio less than 5% using the SSAT [7, 8]. The results of these works are summarized in Table 10. The two inter-area low frequency modes in scenarios A and B, and one inter-area mode in scenarios C and D are shown in Fig. 8. The two oscillating sides of a mode are denoted by positive and negative signs. In inter-area mode 1, the generating units in the MP and ML areas oscillate against the generating units in the SE area. Uljin, the nuclear power plant in the EA area, is associated with the generating group in the MP and ML areas, and Youngkwang, the nuclear power plant in the SW area, is associated with the generating group in the SE area. As a result, oscillation occurs between the northern and southern systems. On the other hand, in inter-area mode 2, the generating units in the MP and ML areas oscillate against the generating unit in the SE area. Uljin is associated with the generating group in the SE area, and Youngkwang is associated with the generating group in the MP and ML areas. As a result, oscillation occurs between the eastern and western systems. Since most generators in all of the areas are associated with the inter-area mode 2, the frequency of this mode of oscillation is very low. Scenarios C and D exist only in this mode.

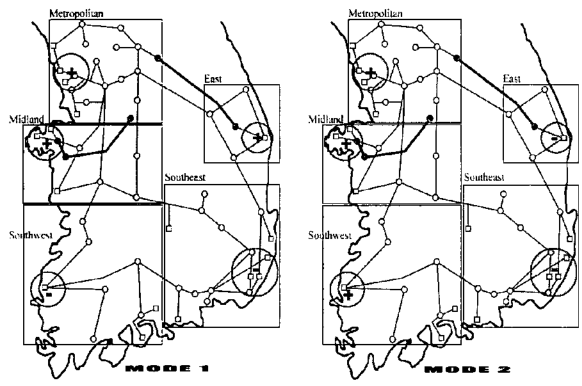

Fig. 8 Shapes of Modes 1 and 2

6.1 Effect of system structure on damping

The structure of the system influences the damping characteristics in the KEPCO. Several cases were developed to analyze this influence, representing various combinations of system configurations and amounts of power being transferred. Cases of particular interest included high power northward transfers and high power transfers from the EA to MP areas. Table 11 shows the simulation results in those cases where a number of operating conditions lead to low stability margins for inter-area mode 2.

6.2 Effect of power system stabilizers

The effect of line contingency on low frequency oscillation was investigated by calculating the eigenvalue in the case where the damping ratio is less than 4% when the line is tripped after a fault occurs. Following the analysis of the small signal stability under steady state and contingency situations, it was found that several unstable modes and stable modes lacking damping characteristics exist and, thus, that counterplans are required. In this paper, PSS is used to reduce the low frequency oscillation in the steady state and contingency situations. Under heavy northward power transfer conditions for System A, as simulated in the steady state and contingency situations, a PSS is needed at Youngkwang in the SW area. The damping ratio was improved by more than 4%, and the result is shown in Table 12.

Table 10 Oscillation modes between 0.1 and 1.0 Hz, with damping ratio less than 5%

Participating machines	System A		System B		System C		System D	
	Eigenvalue	f^{**}	Eigenvalue	f^{**}	Eigenvalue	f^{**}	Eigenvalue	f^{**}
North vs. south system	-0.143±j4.437	0.7062	-0.204±j4.513	0.7183	*		*	
East vs. west system	-0.169±j4.898	0.7796	-0.132±j4.495	0.7869	-0.125+j5.080	0.8084	-0.090+j5.288	0.8415

The mode is not found in the system. ** Frequency in Hz

Table 11 Effect of operating conditions on system damping

Network description	System B	System B	System C	System D
High northward power transfer	-0.147±j4.911	-0.108±j4.946	-0.099±j5.071	-0.056±j5.250
High eastward power transfer	-0.110±j4.845	-0.099±j4.936	-2.228±j5.701	-0.175±j4.748
Base case, 1 circuit MP-EA out	-0.153±j4.793	-0.115±j4.486	-0.127±j5.051	-0.072±j5.264

Table 12 Effect of a PSS at various outages for inter-area mode 2

State	Without PSS	With PSS
Line 4010-6030 out*	-0.133±j4.885	-0.192±j4.653
Line 4400-6950 out**	-0.035±j4.847	-0.207±j4.712
Line 4600-6800 out**	-0.118±j4.896	-0.266±j4.692

* Single circuit outage ** Double circuit outage

7. Conclusion

This paper presents the practical requirements for the development of a benchmark system, which is a smaller scale version of an actual large-scale power system that is used for transient and small-signal stability analysis. The validity of the benchmark system is evaluated in the case of the KEPCO system. Various scenarios are simulated and the stability is analyzed. The key conclusions, which can be drawn from this study are:

1) The results of the simulation showed that the developed KEPCO benchmark systems possess most of the characteristics of the original system and can be used to analyze the dynamic behaviors of the KEPCO system.
2) In the transient stability sense, the benchmark system is used to analyze the stability assessment of the plant generation limits and the critical clearing time. In addition, the results of the analysis of the stability limits of the active power flow in the main transmission lines connecting the neighboring areas in the KEPCO system are shown.
3) The benchmark system is simulated to analyze the small-signal stability, and the results indicate that the damping characteristics of the modes are related to the transfer level and network structure.

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