KIEE International Transactions on PE, Vol. 3-A No. 3, pp. 161~167, 2003 ***161***

Steady-state Operational Strategies of UPFC in the KEPCO Transmission System

B. H. Chang*, J. B. Choo*, X. K. Xu and B. P. Lam****

Abstract - This paper presents a study performed to investigate the steady-state operational strategies of UPFCs in the Jeollanam-Do system in Korea. The objective of the study was to determine the UPFC operating points under normal and contingency conditions. The study consists of developing load flow models to simulate different load levels with and without UPFCs in the system, assessing the effectiveness of UPFCs by contingency analysis, and introducing optimal corrective actions for removing voltage problems caused by contingencies.

The paper describes analytical tools, models and approach. It also includes analysis and discussion of the study results. The paper contributes to the area of transmission operational studies with FACTS applications.

Keywords: FACTS (Flexible AC Transmission System), UPFC (Unified Power Flow Controller), STATCOM (Static Synchronous Compensator), SSSC (Static Synchronous Series Compensator), Optimal Power Flow (OPF), Contingency Analysis, Reactive-Voltage (Q-V) Analysis

1. Introduction

Fig. 1 shows a simplified power system of the Jeollanam-Do region in Korea. Jeollanam-Do is divided into three areas including Gwangju, Mokpo and Yeosu. In the Gwangju area, Gwangju City is the major load center and there are six nuclear plants in Youngkwang generating about 6000 MW. In the Yeosu area, the Honam and Yeosu thermal plants generate about 1000 MW in total, and the Yeocheon industry zone is the major load while other zones consist mainly of rural loads. In the Mokpo area, most of the loads are small urban or rural consumers, and the Haenam HVDC Converter Station (bus 7440) operates to supply electric power to Jeju Island (about 40% of the total island load) through submarine DC cable.

If the 345kV double-circuit line from GJU to WHS or from WHS to KJN is tripped, the Mokpo area would be electrically very remote from the generation sources in the Gwangju and Yeosu areas and would have to be supplied through 154kV lines. This would cause low bus voltages in the Mokpo area and some branch overloads in the Gwangju area.

To solve this problem, the KEPCO (Korea Electric Power Corporation) had considered construction of a 345kV line from KJN to GYG. However, the plan was delayed due to increasing difficulties in obtaining new rights-of-way (ROWs). In the meantime, loads continue to grow rapidly in the Mokpo area, aggravating the low voltage problems. This prompted KEPCO to look into alternatives other than line construction.

The KEPRI (Korea Electric Power Research Institute), as the research center of KEPCO, has conducted many feasibility studies on FACTS (Flexible AC Transmission System) applications to the Korean power system. One study concerned the application of FACTS as a method of resolving the aforementioned problem in the Jeollanam-Do region [1, 2]. The study results suggested the installa

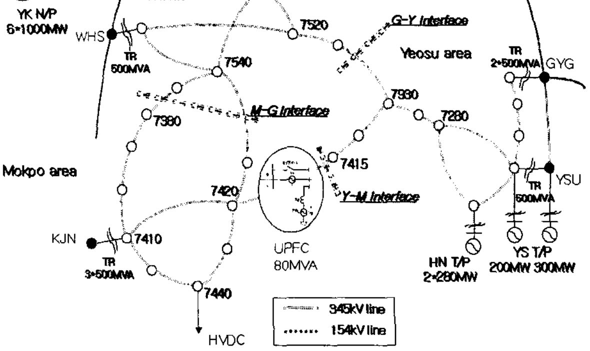


Fig. 1 Simplified Jeollanam-Do Power System

---

* Korea Electric Power Research Institute (KEPRI) of the Korea Electric Power Corporation (KEPCO), Teajeon, Korea (E-mail: jang7@kepri.re.kr).

** Power Technologies, Inc. (PTI), Schenectady, NY 12305 U.S.A. (E-mail: xiaokang.xu@shawgrp.com)

Received August 4, 2003 ; Accepted August 19, 2003

tion of a UPFC (Unified Power Flow Controller) with a rating of ±40MVA in each shunt and each series part at the 154kV Kangjin Substation for regulating the voltage on bus 7420 and controlling the power flow on the Y-M interface shown in Fig. 1.

This paper describes a study performed to investigate the steady-state operational strategies of a UPFC in the Jeollanam-Do region. The objective was to determine the UPFC operating points under normal and contingency conditions. The study consists of developing load flow models to simulate different load levels with and without a UPFC in the system, assessing the relative effectiveness of the UPFC under contingency conditions, and applying corrective actions to remove voltage problems caused by the contingencies.

This document further describes analytical tools, models and approach. It also includes analysis and discussion of the study results. The paper contributes to the area of transmission operational studies with FACTS applications.

2. Analytical Tools, Models And Approach

The analytical tools and models used in this study include:

- Contingency Analysis
- Optimal Power Flow
- Reactive-Voltage (Q-V) Curve Analysis
- UPFC, Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) Models

2.1 Contingency Analysis

Contingency analysis is based on an ac load flow model. This analysis identifies severe contingencies leading to thermal overloads, high or low voltages or voltage collapse under steady-state conditions. The contingency analysis is performed using a full AC Newton solution engine in the widely used commercial software package, PSS/E[1].

2.2 Optimal Power Flow (OPF)

The severe contingencies identified by contingency analysis are further analyzed using the OPF module in PSS/E [3]. This module uses an interior point algorithm based on the Newton and Kuhn-Tucker methods to solve a nonlinear problem consisting of an objective function and a combination of equality and inequality constraints [4]. In this application, the OPF is used to identify optimal locations and amount of reactive compensation required to eliminate the voltage limit violations.

2.3 Reactive-Voltage (Q-V) Curve Analysis

Fig. 2 is a typical Q-V that relates the reactive injection at a bus or a group of buses necessary to sustain a certain voltage. The minimum point ("Nose") on the curve (where dQ/dV=0) is the critical point, also referred to as the Voltage Collapse Point. The points on the curve to the left of the minimum represent unstable conditions, since lowering the voltage requires a more reactive power injection. The points to the right of the minimum are stable. The intersection of the V-Q curve with the horizontal axis is the voltage at the bus without reactive compensation. The vertical distance between the horizontal axis and the critical point is the reactive power margin. If the minimum point of the V-Q curve is above the horizontal axis, the system is deficient in reactive power, and additional supply of reactive power is required to prevent a voltage collapse. If the critical point is below the horizontal axis, the system has a positive reactive margin.

Q-V curve analysis can be performed using another feature of PSS/E known as IPLAN [5, 6], to find the minimum reactive compensation needed to maintain system voltages within the criteria. IPLAN is an environment independent programming language that can be used to control a host program, such as PSS/E. IPLAN can conduct two-way communication with the host. For example, IPLAN can provide instructions to PSS/E to sequentially decrease the controlled voltage, thereby developing Q-V curves. Upon detection of the critical "Nose" condition or an unconverged load flow condition, IPLAN automatically terminates the calculations.

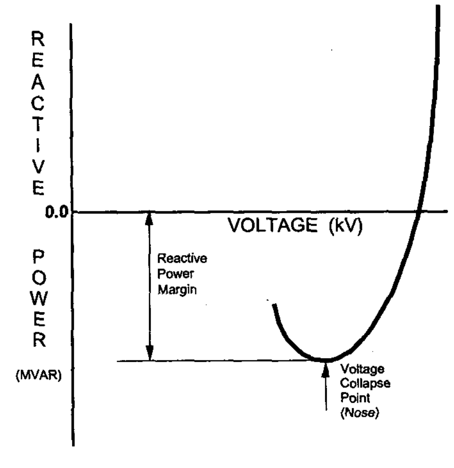


Fig. 2 Reactive Margin Measured by MVAr on Q-V Curve

---

[1] PSS/E (Power System Simulator for Engineering) is the commercial tradename for PTI's transmission planning and operation software.

2.4 UPFC, STATCOM and SSSC Models

Fig. 3 shows the block diagram of the steady state UPFC model implemented in PSS/E [7]. It has a series element, which is connected between two buses (*I*, *J*), and a shunt element, which is connected between the sending end bus (*I*) and the ground. One or both of these elements may be active, depending upon the type of device being represented. In typical operations, the series element maintains the desired active and reactive power flows (P_{DES} & Q_{DES} in the diagram) between the sending bus (*I*) and the terminal bus (*J*) while the shunt element maintains the desired sending end voltage magnitude (V_{SET}).

By properly selecting the data, different device types and control options can be represented. For example, a SSSC can be represented by setting the maximum bridge power transfer to zero and disabling the shunt component. A STATCOM can be represented by disabling the series component, while the reactive power output of the shunt element is varied to maintain the desired sending end bus voltage magnitude. In a UPFC, the current in the shunt connected bridge depends upon its variable output and the amount of power transferred to the series connected element.

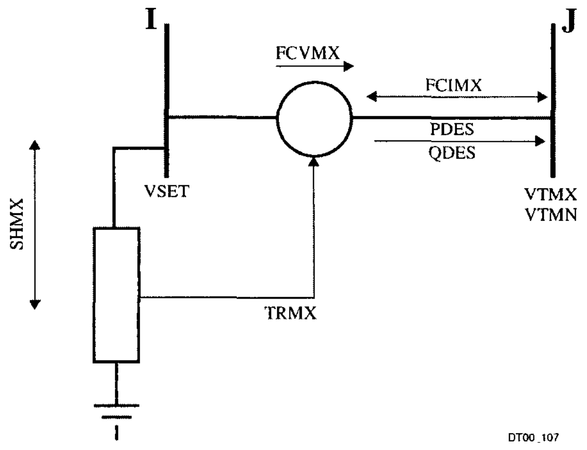


Fig. 3 UPFC Model in PSS/E

2.5 Study Approach

The following approach was adopted in this study:

1. Develop base power flow models representing peak, shoulder and light conditions, with and without UPFCs, for a given year. These base models are prepared using OPF to minimize active and reactive losses and optimize the UPFC operating points during normal conditions.

2. Perform contingency analysis to identify severe contingencies leading to thermal or voltage problems.

3. Find solutions to the above problems using OPF:

(a) In systems without UPFCs, adjust transformer OLTC's (On Load Tap Changers) and add shunts (existing & future) to resolve voltage problems. If necessary, use generation redispatch and load shed to settle overload problems.

(b) In systems with UPFCs, adjust OLTC's and add shunts. Adjust STATCOM to solve voltage problems. The OLTC's and shunt capacitor settings define preventive action (pre-contingency settings, if base case voltage criteria are not violated). STATCOM var output is set to be near zero (or slightly negative) in pre-contingency to allow for dynamic response during contingencies. The UPFC control will be corrective action (post-contingency adjustment).

(c) In systems with UPFCs, after solving problems in (b), if STATCOM output is at maximum in the post-contingency steady state, then consider the addition of more shunts to reserve STATCOM vars for dynamic response.

4. Based on (3), define pre-contingency and post-contingency settings of the STATCOM/UPFC for the three load levels as specified in (1).

5. Perform Q-V analysis on buses where voltages are observed to be lowest and/or shunt compensation is needed. Develop Q-V curves at these locations. Compare with and without STATCOM portion.

3. Case Studies and Results Analysis

The analytical tools, models and approach described in the previous section were applied to the KEPCO system with UPFCs. The subsequent sections present system background, case studies and results.

3.1 Brief Description of KEPCO System

Power generation complexes in Korea are concentrated in coastal areas and loads are concentrated in inland metropolitan areas considerably distanced from generation sources. System peak demand in 2003 is expected to be about 47 GW and total generation capacity is about 52 GW. The KEPCO transmission system consists mainly of 765 kV, 345 kV and 154 kV networks. Fig. 4 shows the surrounding power system near Kangjin where the UPFC is installed. The shunt connection of the UPFC is at the 154 kV Kangjin substation, and the series connection is on the double-circuit transmission line between the Kangjin and Jangheung substations. Under normal conditions, the UPFC is meant to increase transmission line capacity and reduce system losses through coordinated control of power flow and reactive power compensation. During contingencies, the UPFC is used to relieve undervoltage and overload problems in the surrounding system, if possible.

The KEPCO system is modeled as seven areas in PSS/E. Area 6, GWANGJU, where the UPFC is located, was defined as the Study Area. Other major voltage controlling equipment in the Study Area includes transformer on-load tap changers (OLTC's) and switchable shunts.

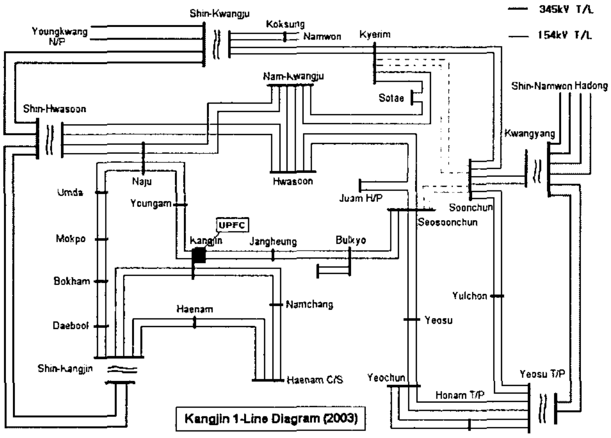


Fig. 4 Surrounding Power System near Kangjin

3.2 Power Flow Models Setup

The load flow scenarios were developed as follows:

- Peak case without a UPFC
- Peak case with a UPFC
- Shoulder case without a UPFC
- Shoulder case with a UPFC
- Light case without a UPFC
- Light case with a UPFC

In establishing these models, the OPF solution was used to minimize active and reactive losses by controlling power flow on the series element of the UPFC and by allowing existing shunt capacitors and reactors to be switched. The reactive output of the shunt element of the UPFC was set to be near zero during pre-contingency to allow for response during contingencies. The UPFC operating points in normal conditions are listed in Table 1. Positive power flow indicates that direction is from Kangjin to Jangheung. Other parameters of the UPFC model in PSS/E used in this study are included in the Appendix.

Table 1 UPFC Operating Setpoints In Normal Conditions

Loading	PDES (MW)	QDES (MVAr)	VSET (p.u.)	QSHUNT (MVAr)
Peak	-31.4	18.8	1.035	0.1
Shoulder	6.8	-9.2	1.016	0.0
Light	-6.8	-14.2	1.016	0.0

3.3 Contingency Analysis Results

In order to identify credible severe contingencies leading to thermal or voltage problems in the Study Area, a contingency analysis was performed on all the base cases to evaluate the steady-state response of the system to outages of 345 kV and 154 kV double-circuit lines in the area. The monitored elements included all 154 kV and above branches and buses in the Study Area.

The KEPCO Operating Criteria were applied to the contingency analysis. The Criteria require that, under normal conditions, the power flow in any branch of 154 kV or above should not exceed Normal Ratings (Rate A). Under contingencies (loss of any parallel 345kV or 154 kV circuits), the power flow in any branch of 154 kV or above should not exceed Emergency Ratings (Rate B).

System voltages in normal and contingency conditions are to be controlled in a range in accordance with the Criteria, as shown in Table 2.

Table 2 VOLTAGE Criteria

Voltage Limits (for Both Normal and Contingency Conditions)		High (p.u.)	Low (p.u.)
345 kV	For All Loading Conditions	1.0435	0.9739
154 kV	Peak	1.0649	1.0129
	Shoulder	1.0454	0.9935
	Light	1.0389	0.9870

All of the contingency cases were solved using the fixed sloped decoupled Newton-Raphson iterative algorithm with transformer taps, and switched shunts and DC tap controls were disabled.

Contingency analysis shows that outages of the parallel circuits result in only a few minor thermal overload problems but many voltage violations. Therefore, this study focused on the voltage performance of the Study Area. Table 3 shows statistics regarding the analysis results. There were about 60 double contingencies tested. Some of them resulted in multiple voltage violations. As expected, the system with the UPFC in operation shows fewer post-contingency voltage violations.

From the contingency results, five severe contingencies were selected for further study with corrective actions. These severe contingencies are:

1. Loss of the YKG-GJU 345 kV double-circuit line
2. Loss of the GJU-WHS 345 kV double-circuit line
3. Loss of the WHS-KJN 345 kV double-circuit line
4. Loss of a 154 kV double-circuit line(7610-7615/7616)
5. Loss of a 154 kV double-circuit line (7610-7215)

Table 3 Contingency Analysis Statistics

Case	No. of Voltage Violations		
	Peak	**Shoulder**	**Light**
W/ UPFC	113	105	47
W/O UPFC	184	133	61

3.4 Corrective Actions and OPF Results

For severe contingencies, the following corrective actions were applied:

(a) In the cases without UPFCs, existing OLTC's and switchable shunts were adjusted to relieve voltage problems.

(b) In the cases with UPFCs, existing OLTC's and switchable shunts were adjusted to relieve voltage problems. In addition, the var output of the UPFC shunt part (STATCOM) also responded automatically to provide voltage support. The var outputs of STATCOM under the severe contingencies are shown in Table 3. It can be seen from the table that the outputs vary by contingency and loading level.

Table 4 STATCOM Var Output During Contingency

Contingency	UPFC STATCOM Output (MVAr)		
	Peak	**Shoulder**	**Light**
Loss of the YKG-GJU 345 kV Double-Circuit Line	39.5	39.2	39.7
Loss of the GJU-WHS 345 kV Double-Circuit Line	34.5	39.2	40.1
Loss of the WHS-KJN 345 kV Double-Circuit Line	0.1	25.9	38.8
Loss of a 154 kV Double-Circuit Line (7610-7615/16)	40.5	40.0	19.4
Loss of a 154 kV Double-Circuit Line (7610-7215)	24.6	13.6	7.3

(c) The corrective actions in (a) and (b) would not completely remove the voltage violations caused by the severe contingencies. Therefore, OPF was used to find new corrective actions, including the location and amount of new switched shunts and the optimal control of existing OLTC's and switched shunts, summarized as below:

- In all base power flow cases, the voltage control ranges of the switched shunts at 154 kV buses were set at 1.02 to 1.05 p.u. during peak load. These limits are within the minimum and maximum voltage criteria of 154 kV buses. Using these limits allow the switchable shunts to respond to voltage violations during contingencies and initiate switching actions to correct the problems.
- The OLTC's of 345/154 kV transformers were set to control 154 kV voltages between 1.02 and 1.05 pu during peak load. Switchable shunts at the 154 kV buses of the transformers were set to control local voltage. This avoided control conflicts between the OLTC's and switchable shunts.
- Following the above actions, the remaining low voltage violations under the severe 345 kV contingencies were eliminated by adding new shunt capacitors at buses 7675 (5x5.0 MVAR), 7695 (5x5.0 MVAR) and 7945 (3x5.0 MVAR) as determined by OPF.
- Similarly, the low voltage violations under the severe 154 kV contingencies were eliminated by adding new shunts calculated by OPF.

3.5 Q-V Curve Analysis Results

In order to verify the suggested shunt additions determined by OPF, Q-V curve analysis was performed using an IPLAN program to discover the minimum reactive compensation needed to maintain system voltages within the Criteria.

In the study, Q-V curves were generated for the pre-contingency and post-contingency conditions for a set of selected severe contingencies and buses where voltages are worst and/or shunt compensation is needed. One case has been selected for illustration here. The selected bus and corresponding critical contingency are:

- Monitored bus is 7590
- Contingency is the loss of a 154 kV double-circuit line (7160-7615/7676)

Fig. 5 shows the Q-V curves at the monitored bus in the peak load case with a UPFC. The curve represents two conditions:

- Pre-Contingency (solid line in the figures)
- Post-Contingency (dashed line in the figures)

The curve also includes capacitor Q-V characteristics (10 MVAr, 50 MVAr and 100 MVAr) that represent the relationships between voltage and the reactive power produced by shunt capacitors.

It is observed from the figure that the minimum ("Nose") points under pre-contingency and post-contingency conditions are below the horizontal axis. This indicates that the reactive margins in these conditions are positive and voltage collapse would not occur on the system. This further verifies the previous contingency analysis in which no voltage collapse was found.

However, it is noted that the intersection of the V-Q curve with the horizontal axis under the post-contingency condition is below 1.0 p.u. voltage, which is lower than the Voltage Criteria (1.0129~1.0649 p.u. for 154 kV buses during peak load operation). This indicates that additional shunt compensation is needed. The intersection between the set of capacitor Q-V curves and the system post-contingency Q-V curve establish the steady-state operating point. From the figure, to operate the monitored bus at 1.0129 p.u. voltage under this contingency, approximately 30-40 MVAr of shunt capacitors are required at this bus. This is close to the value identified by OPF.

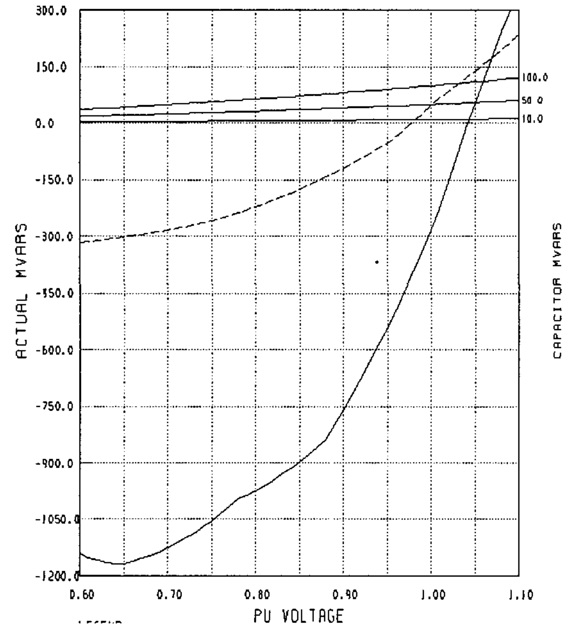


Fig. 5 Q-V Curve for Bus 7590 for Peak Case with UPFC

4. Conclusion

This study focused on the voltage issues in the Study Area. In general, the UPFC improved the voltage performance of the Study Area. The study can draw the following conclusions on the operation strategies of a UPFC with respect to the contingencies tested and the load flow scenarios studied:

1. The UPFC should be set such that the var output of its shunt part (STATCOM) is near zero under normal conditions for all three load levels, thus providing maximum reactive reserves for contingencies.

2. The series element of the UPFC should be set to control flow such that area losses are minimized.

3. To maximize the effectiveness of the UPFC, the voltage control ranges of OLTC's and switched shunts in the Study Area should be consistent with the Operating Criteria.

4. The control of 345/154 kV transformers and switchable shunts at 154 kV buses should be coordinated to avoid control conflicts.

5. Additional shunt compensation (approximately 100 MVAr determined by OPF) is needed to completely remove low voltages caused by the contingencies tested.

Appendix

Parameters of the UPFC model in PSS/E used in this study are set as follows:

- Maximum series voltage magnitude (VSMX)=0.0682
- Maximum series current magnitude (*IMX*)=586.8
- Maximum shunt current magnitude (*SHMX*)=40.0
- Maximum terminal voltage (*VTMX*)=1.05
- Minimum terminal voltage (*VTMN*)=0.95
- Maximum power transferable between the shunt and series connected bridges (*TRMX*)=40.0
- UPFC Rating: Series Part: ±40MVA; Shunt Part: ±40MVA

Acknowledgment

The authors wish to thank Mr. James W. Feltes and Dr. Yuriy Kazachkov for their assistance and helpful discussions during the study.

References

[1] Jin-Boo Choo and Byung-Hoon Chang, “Development of FACTS Operation Technology (Phase 1 : Decision of a Type and a Spec. Draft for the Installation of a Pilot Plant)”, *KEPRI Technical Report*, April, 1999

[2] In-Sup, Kim, “Long-term Forecast of KEPCO System Planning and Operation, in Korea”, in *Proceedings of 1998 Power System Engineering Symposium*, KIEE, May, 1998

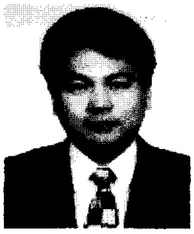
[3] “PSS/E Optimal Power Flow Manual – Version 29”, Power Technologies, Inc., December 2002

[4] H. W. Kuhn and A. W. Tucker, "Nonlinear Programming," in *Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability (J. Neyman, Editor)*, Berkeley, University of California Press, 1951

[5] J. V. Staron and A. R. Weekley “Expand Your Study Capability With IPLAN,” *PTI Newsletter, Power Technology*, Issue No. 53, April 1988

[6] R. J. Koessler “Voltage Collapse Analysis Using IPLAN,” *PTI Newsletter, Power Technology*, Issue No. 60, January 1990

[7] Xiaokang Xu, Baldwin P. Lam, Ricardo R. Austria, Wang Huaming, Fan Haihong, Yang Lin and Wang Xu, “Application of FACTS Technology for Increasing Power Transfers of Jiangsu Transmission System,” in *Proceedings of the CIGRE 2001 International Conference on Power Systems (CIGRE ICPS'2001)*, September 3-5, 2001, Wuhan, Hubei, China



Byunghoon Chang
He received B.S. and M.S. degrees from Korea University, Korea. He received his Ph. D. from Korea University in 1999. He has been working at the Korea Electric Power Research Institute as a Researcher for 9 years. He is presently a Senior Member of Technical Staff of the Power System Laboratory at the Korea Electric Power Research Institute. His research interests include FACTS, power system stability and power quality.

Jin-Boo Choo (M'1994)
He received B.S., M.S and Ph.D. degrees in Electrical Engineering from Seoul National University, Korea in 1977, 1987, and 1994 respectively. He worked at the Korea Electric Power Corporation as a Senior Engineer in the Power System Operation Center. Currently he is a Director and Group Leader of the Power system stabilization group and Power system analysis group at the Korea Electric Power Research Institute, and also the Real time power system analysis Team Leader of the National Research Lab. at Ministry of Science & Technology, Korea. His research interests include power system operation and control, FACTS, and Real time power system simulation.

Xiaokang Xu (M'92, SM'00)
He is a graduate of The Southeast University and The Electric Power Research Institute (EPRI) in China and The University of Western Ontario in Canada from which he holds his B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering. From 1984 to 1991 he was a Research Engineer for EPRI-China. During 1992 - 1993 he worked for Ontario Hydro of Canada as a Planning Engineer. From 1995 to 1998 he was with CAE Electronics Ltd., Canada as an EMS Engineer. He joined Power Technologies, Inc. (PTI), USA in March 1998 where he presently serves as an Executive Consultant. He is a Member of Sigma Xi.

Baldwin P. Lam
He is a B.S and M.E graduate of Rensselear Polytechnic Institute in Troy, New York. He has been with Power Technologies and its affliate since 1975. His main area of work includes load flow, stability and reliability studies of major power grids and industrial systems. He is presently an Associate Director of the Consulting Services Department. Mr. Lam is a Senior Member of IEEE.