Dynamic Operational Strategies of UPFC in the KEPCO Transmission System

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Abstract - The Korea Electric Power Corporation (KEPCO) has installed an 80 MVA Unified Power Flow Controller (UPFC) at its 154kV `Kang-Jin Substation in South Korea. The device, manufactured by Siemens & Hyusung, has been operational since October 2002. The Korea Electric Power Research Institute (KEPRI), a division of KEPCO was tasked to study operational strategies that could be employed for the UPFC and surrounding reactive support devices concerning problems of low voltages and overloads in the Mokpo & Gwangju areas. Particular apprehension surrounded the possibility of delay in the installation of a new 345kV transmission line from 2005 to beyond 2010. The studies were to specifically determine whether these problems could be eliminated by application of a UPFC. The analysis included determining the UPFC operating point under various conditions, investigations of the coordination between the UPFC and a HVDC line terminating in this area, and the design of a supplementary damping controller for the UFPC. This paper summarizes the results of those studies, demonstrating the dynamic characteristics of the operation of this UPFC operation in the Korean power system.

Keywords: Power system dynamic stability, Power electronics, Power system control.

1. Introduction

Fig. 1 shows the local simplified power system of Jeollanam-Do in Korea. Jeollanam-Do is divided into three sub-areas including Gwangju, Mokpo and Yeosu. In the Gwangju area, Gwangju City is categorized as large load and the six Youngkwang nuclear plants generate about 6000MW. In the Yeosu area, the Honam thermal plant and the Yeosu thermal plant generate a total of approximately 1000MW. The Yeocheon industry area is classified as major load while other areas are considered rural loads. In the Mokpo area, most loads are categorized as small city or rural. The 7440 bus (Haenam converter Station of the HVDC) operates to supply electric power (about 40% of the total load in Jeju Island) to Jeju Island through underwater DC cable.

If the 345kV line from GJU to WHS or from WHS to KJN were opened, the Mokpo area would be distant from any power source and would only be supplied by power through the 154kV line in the Kangju area and Yeosu area. That would lead to low voltage buses in the Mokpo area and overload in the Kangju area. Voltage oscillation of the 7440 bus, HVDC C/S would occur.

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Received August 4, 2003 ; Accepted August 19, 2003

In order to solve these issues, KEPCO previously had the construction plan of the 345kV line running from KJN to GYG. But KEPCO had to delay the plan due to increasing difficulties in obtaining new right-of-ways (ROWs). However, the more loads increase in the Mokpo area, the more detrimental are the problems that can transpire. Therefore, KEPCO needed to seek for alternatives to line construction.

This paper investigates the dynamic problems and the operational effects of the KEPCO UPFC under the following disturbances.

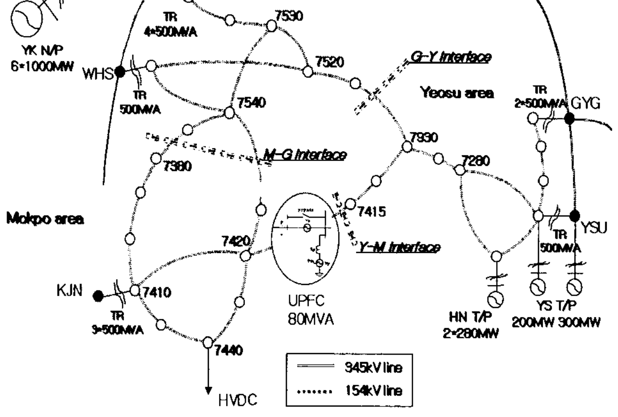

Fig. 1 Simplified one-line of the Jeollanam-Do system

Jeollanam-Do, Mainland
- Severe contingency, 345kV WHS-KJN line 3-phase fault
- Large disturbance, 1 unit outage in YK N/P
- Small disturbance, 154kV Heanam bus (7440) 2000[Mvar] on/off

Jeju-Do, Island
- Severe contingency, 154kV JJU-DJJ line 3-phase fault
- Large disturbance, 1 unit outage in Jeju T/P
- Small disturbance, 154kV DJJ bus (130) -600[Mvar] on/off

The major dynamic problems under these circumstances are the oscillation of the ac bus voltage, the active power and dc voltage and the dc current of HVDC.

On behalf of KEPCO, KEPRI had implemented numerous feasibility studies for FACTS application to the Korea power system. Therefore, KEPRI was requested by KEPCO to apply the results of the FACTS study to solving the problem in Jeollanam-Do, Korea. Through the results of the study, KEPRI suggested the site, the capability and the type of FACTS. The KEPCO UPFC, which has a ±40MVA inverter, was installed at the 154kV Kangjin Substation for regulating the voltage of the 7420 bus and for controlling the power flow of the Y-M interface as shown in Fig. 1.

2. Modeling

2.1 HVDC

The HVDC connected between the mainland and Jeju Island in Korea has the following dynamic characteristics.

- Blocking: If the ac voltage of the rectifier terminal in the HVDC goes below 0.6[pu], the HVDC system blocks the current from the rectifier terminal bus.
- Unblocking: If the ac voltage of the rectifier terminal in the HVDC recovers more than 0.65[pu], the HVDC system unblocks the current from the rectifier terminal bus.
- Bypass: If the dc voltage of the inverter terminal in the HVDC goes below 108[kV], the HVDC system bypasses the current from the inverter terminal bus.
- Unbypass: If the ac voltage of the inverter terminal in the HVDC recovers more than 0.65[pu], the HVDC system unbypasses the current from the inverter terminal bus.
- Recovering Ramp: The recovering ramp of the dc voltage and the dc current in the HVDC rectifier has the rate of 0.2[pu/sec]. The ramp in the inverter has the same rate.
- The HVDC has the modulation control to maintain the frequency in Jeju Island.

The CDC4 and SQBAUX in PSS/E models of PTI are used in Korea to represent the general dynamic characteristics and the modulation control of the HVDC.

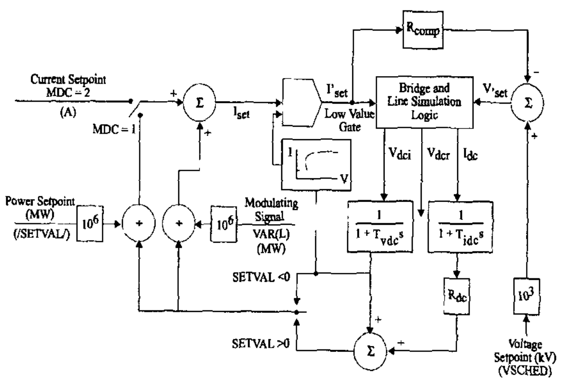

Fig. 2 Block Diagram of CDC4

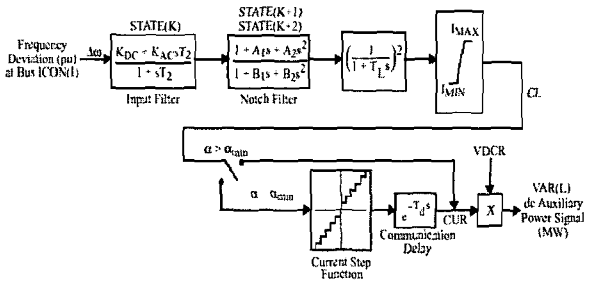

Fig. 3 Block Diagram of SQBAUX

2.2 UPFC

The dynamic response of the UPFC to a disturbance is very rapid. Due to this fact no integrator is needed to model the UPFC and an algebraic model is sufficient for dynamics studies. An algebraic model in the PSS/E is a model that is called through CONET subroutine and contains no STATE. PQ control and Voltage insertion for series elements are the two modes of operation that are implemented in this dynamics model.

A theoretical model for the UPFC consists of two voltage sources, one in series, corresponding to the series inverter and one in shunt, corresponding to the shunt inverter, as shown in Fig. 4. The two voltage sources are coupled by the real power flow Pdc, which is drawn from the power system by the shunt inverter and injected into the power system by the series inverter. XP is the leakage reactance of the shunt transformer.

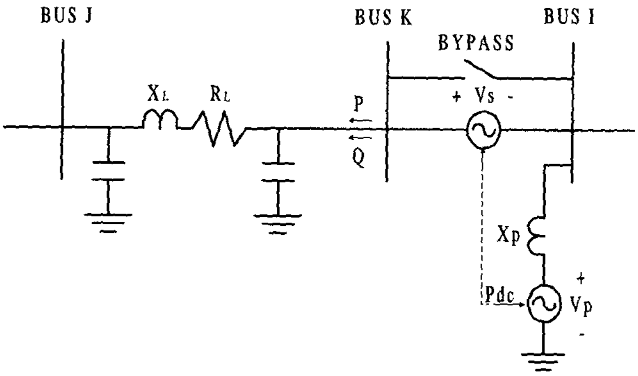

Fig. 4 UPFC Dynamic Model

3. Operation Effects of UPFC

The interactions between the HVDC and UPFC in Jeollanam-Do are investigated using the PSS/E models. The dynamic problems under the disturbances are also investigated. The following disturbances are simulated for investigation of the dynamic problems.

Table 1 Contingency Cases

Disturbance Type	Main Land	Island
Severe Line Fault	345kV Line Fault	154kV Line Fault
Large Disturbance	1000MVA Unit Off	70MVA Unit Off
Small Disturbance	-2000 MVar On/Off	-600 MVar On/Off

3.1 Jeolllanam-Do, Mainland system

Three types of disturbances are simulated in the local system of Jeollanam-Do in which both the UPFC and HVDC were installed. The first type is the 3-phase fault of the 345kV non-looped line. The second is the #3 unit outage of the YK Nuclear Plant. The third is the -2000 [Mvar] reactors on/off rather than various disturbances such as line-ground fault.

The operational effects of UPFC with respect to the dynamic problems taking place at the disturbances are analyzed.

If the dynamic problems are transferred into Jeju Island through the HVDC, the UPFC effects relating to the dynamics of the HVDC are also analyzed.

3.1.1 Severe Line Fault

This is considered to be a severe contingency since it causes the voltage source in the Kwangju area to load in the Mokpo area. This results in significant weakening of the transmission line crossing the M-G interface.

a) Voltage dynamics

Fig. 5 shows the voltage dynamics at the ac terminal bus of the HVDC (7440) and UPFC (7420) with/without UPFC. Almost all ac buses in the Mokpo area experience voltage oscillations without UPFC operation, but the oscillations are almost entirely eliminated by UPFC operation. Fig. six shows the damping effect of the oscillations at the HVDC and UPFC terminal buses during UPFC operation.

When the fault occurs at 1.0[sec], the HVDC reacts to block the rectifier since the terminal bus has a low voltage of less than 0.6[pu], blocking the reference voltage. The terminal bus of the HVDC reaches the unblocking voltage of 0.65[pu] at 5.1[sec] once the fault is cleared at 1.1[sec]. But the rectifier dc voltage of the HVDC oscillates under the influence of the ac terminal bus of the rectifier. Fig. 6 shows the dynamic relationship between the ac and dc voltage of the HVDC rectifier.

Fig. 7 shows the damping effects of the dc voltage oscillations at the rectifier of the HVDC ***after the during*** the UPFC operation.

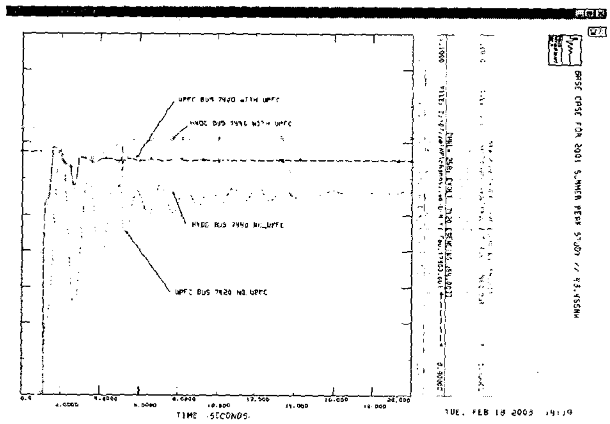

Fig. 5 Effects of Voltage Control at the Severe Line Fault on the Mainland

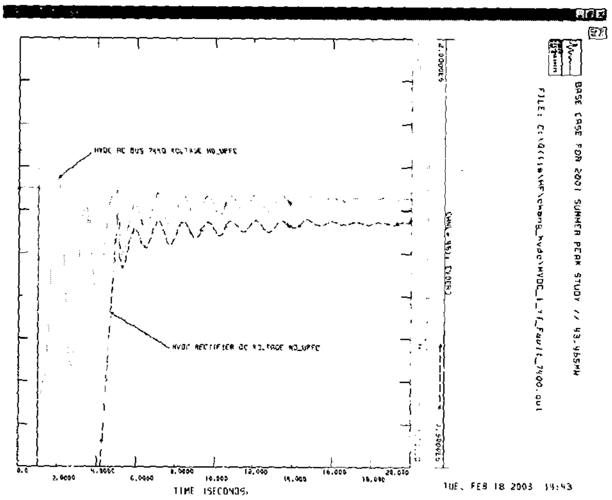

Fig. 6 DC Voltage Characteristics of the HVDC bus at the Severe Line Fault on the Mainland

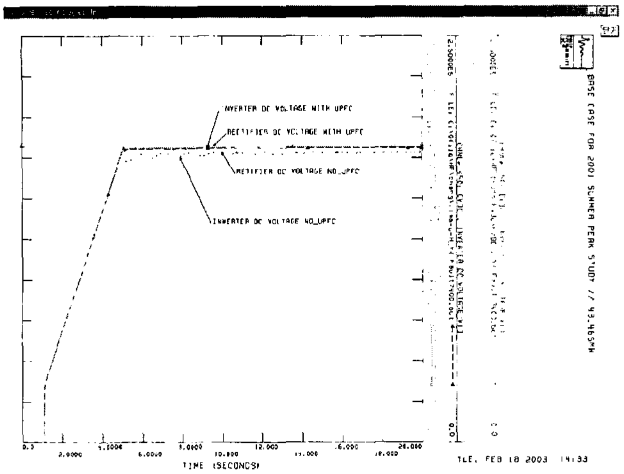

Fig. 7 Effects of DC Voltage Control of HVDC bus at Severe Line Fault on the Mainland

b) Power flow dynamics

Fig. 8 shows the active power flow dynamics into the HVDC at the 345kV line 3-phase fault. UPFC is operated for maintaining the desired P and Q of the line, but UPFC doesn't have the damping effect of oscillation since it is post contingency. The reason for not damping the power oscillation near the HVDC in the Mokpo area is that the recovering action of the HVDC following blocking of the rectifier is more dominant than the constant power flow control action of UPFC. Another reason for not damping the power oscillation crossing the M-Y interface is that the capability of UPFC is too small to handle the oscillation occurring throughout the entire system in Korea.

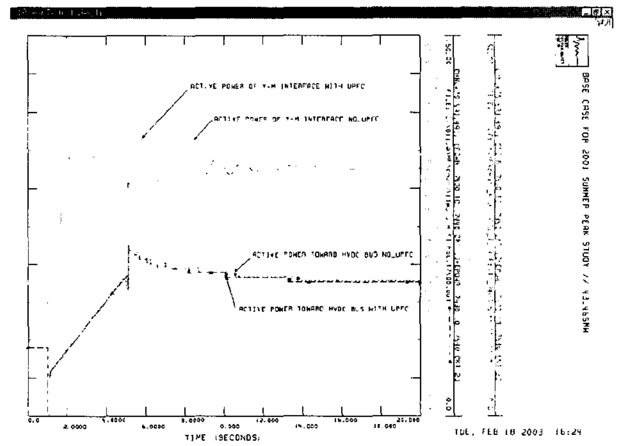

Fig. 8 Effects of Power Flow Control at the Severe Line Fault on the Mainland

3.1.2 Large Disturbance

The large disturbance, #3 unit outage has a significant impact on the YK nuclear plant complex. This results in significant dynamic problems like sustained oscillations in the entire KEPCO system including the Mokpo area.

a) Voltage dynamics

Fig. 9 shows that the oscillations at the ac terminal buses of the HVDC (7440) and UPFC (7420) are dramatically damped by UPFC operation.

Fig. 10 displays the damping effects of dc voltage oscillation in the HVDC during UPFC operation.

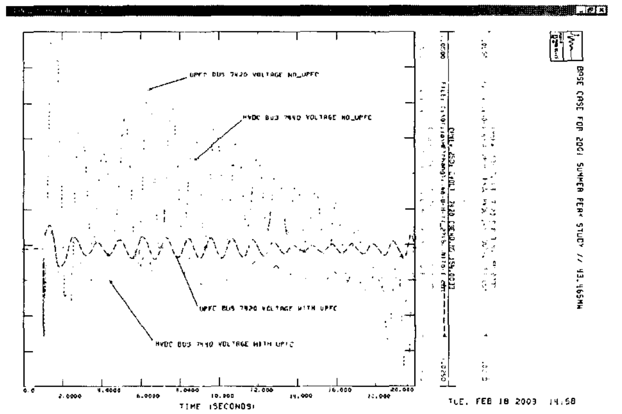

Fig. 9 Effects of Voltage Control at the Large Disturbance on the Mainland

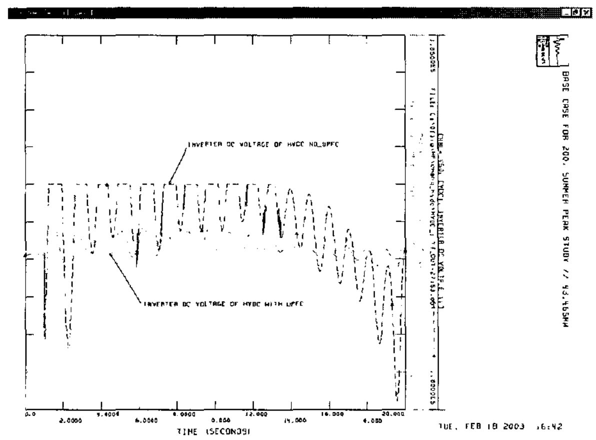

Fig. 10 DC Voltage Characteristics of the HVDC bus at the Large Disturbance on the Mainland

b) Power flow dynamics

Fig. 11 shows that UPFC is controlling the constant power flow of the line at the large disturbance.

Fig. 12 indicates that the power flowing into the ac terminal bus of the HVDC is oscillating owing to the large disturbance. The power oscillation is damped by UPFC operation as shown in the same Fig..

Fig. 13 shows that the DC current and the firing angel of the HVDC are oscillating under the influence of the large disturbance. The oscillations in the HVDC are eliminated since the power oscillation flowing toward the HVDC is damped by the constant PQ control of UPFC.

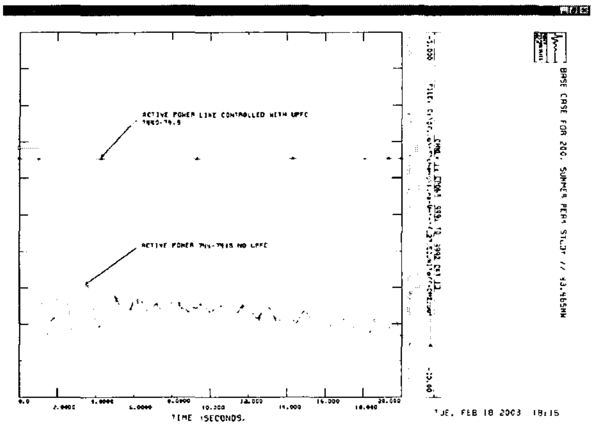

Fig. 11 Effects of Power Flow Control at the Large Disturbance on the Mainland

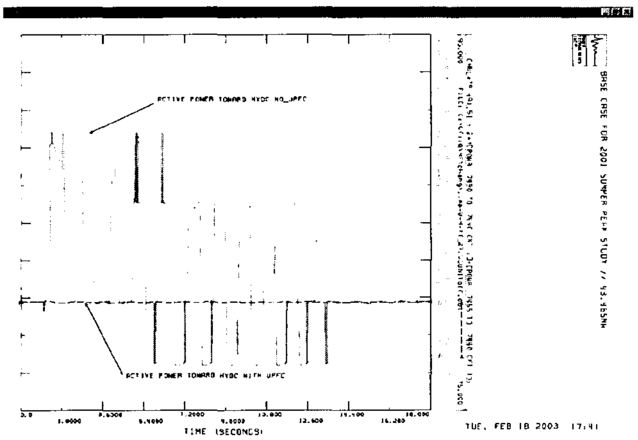

Fig. 12 Effects of DC Power Flow Control of the HVDC at the Large Disturbance on the Mainland

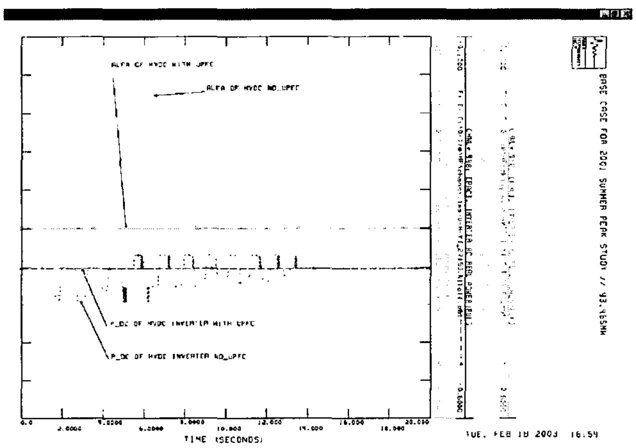

Fig. 13 Effects of DC Current Control of HVDC at the Large Disturbance on the Mainland

Active power dynamic problems happen in Jeju Island because the HVDC, which is connected with the mainland, causes active power oscillation. Fig. 14 shows the power oscillation between the HVDC and Jeju Island. The oscillation is damped by the effect of UPFC operation.

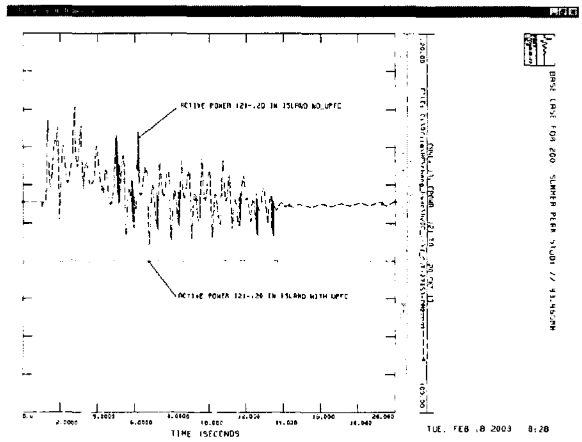

Fig. 14 Effects of Power Flow Control of the Island at Large Disturbance on the Mainland

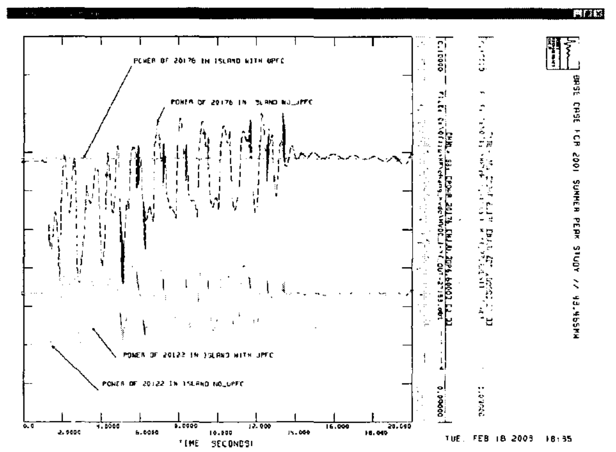

Fig. 15 Power Oscillation Damping of Island Plant at the Large Disturbance on the Mainland

Fig. 15 shows the electric power oscillation of the generators in Jeju Island. The oscillation is damped by the effect of UPFC operation.

3.1.3 Small Disturbance

For the small disturbance, the -2000[Mvar] reactor is connected instantly to the 154kV bus nearby the rectifier ac bus of the HVDC. This results in limited oscillation of voltage and power in the Mokpo area.

a) Voltage dynamics

Fig. 16 shows that the oscillations at the ac terminal buses of the HVDC (7440) and UPFC (7420) are well damped by UPFC operation.

The voltage oscillation of the terminal ac bus influences the dc voltage of the HVDC as shown in Fig.16.

b) Power flow dynamics

Fig. 17 shows that the small oscillation happens at the power flow to the HVDC. The oscillation is damped by UPFC operation, but the oscillation has no influence over the dynamic actions of the HVDC like as seen in Fig. 18.

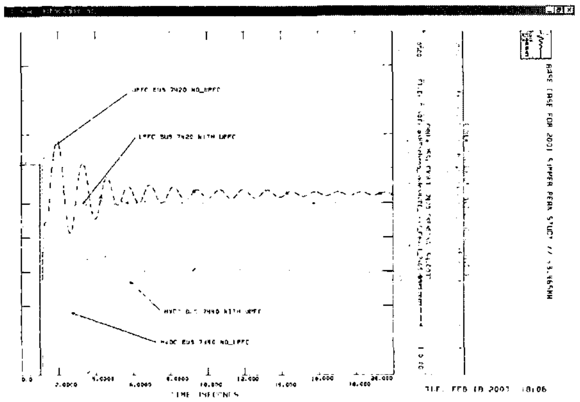

Fig. 16 Effects of Voltage Control at the Small Disturbance on the Mainland

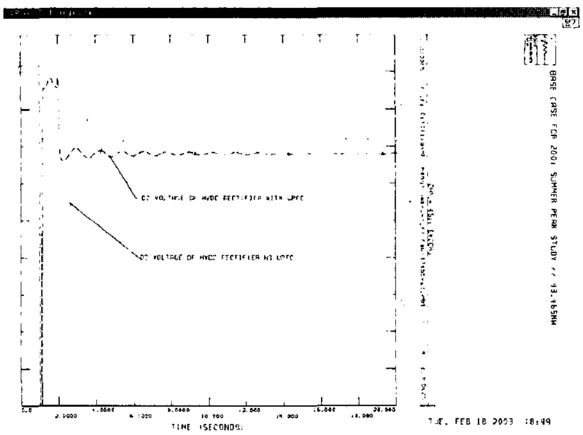

Fig. 17 Effects of Power Flow Control at the Small Disturbance on the Mainland

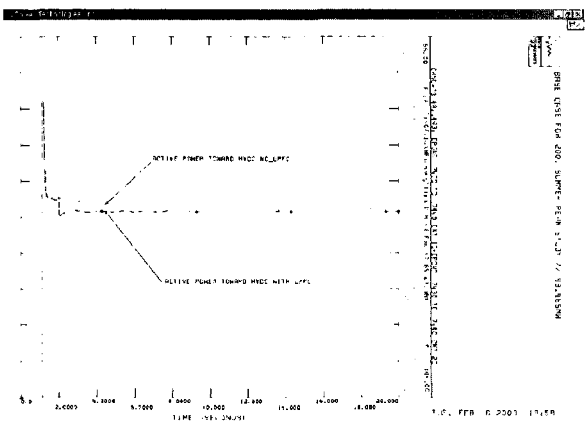

Fig. 18 Effects of DC Power Flow Control of the HVDC at the Small Disturbance on the Mainland

3.2 Jeju-Do, Island system

Three types of disturbances are simulated in Jeju-Do connected with the mainland through the HVDC. The first type is the 3-phase fault of the 154kV line, which is one of two lines distributing power from the inverter terminal of the HVDC to the load area in Jeju-Do. The second is the #2 unit outage of the Jeju Thermal Plant. The third is the -600[Mvar] reactor on/off rather than other various disturbances such as ground-line fault.

The operational effects of UPFC with respect to the dynamic problems at the disturbances are analyzed when these situations are transferred from Jeju Island to the mainland through the HVDC.

3.2.1 Severe Line Fault

When a fault occurs at 1.0[sec], the HVDC acts to bypass the inverter since the terminal bus has a low voltage of less than 108[dc V], bypassing the reference voltage. The terminal inverter bus of the HVDC reaches the unbypassing voltage of 0.65[pu] at 5.1[sec] once the fault is cleared at 1.1[sec].

a) Voltage dynamics

Fig. 19 illustrates the voltage dynamics at the dc current and ac & dc voltage of the HVDC rectifier with/without UPFC. This shows the damping effects of the ac voltage oscillations at the rectifier bus of the HVDC after dc voltage recovers to the nominal value by UPFC operation.

b) Power flow dynamics

Fig. 20 shows the active power flowing into the rectifier terminal bus of the HVDC and also shows the electric power of Jeju TP at the 154kV line 3-phase fault in Jeju Island. This results in power oscillation in the Jeju TP. However, there is no oscillation of active power flowing into the rectifier terminal bus of the HVDC because the HVDC has a dc voltage recovery mechanism that activates during Jeju TP power oscillation.

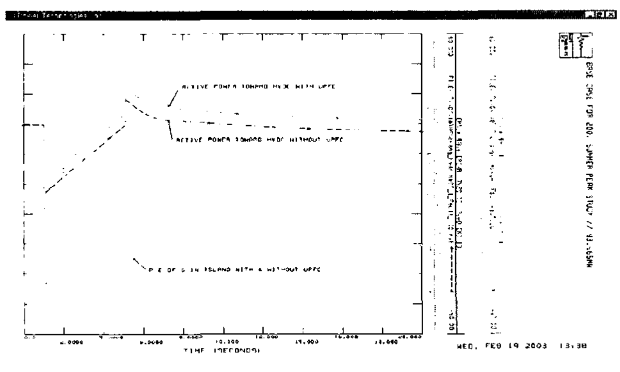

Fig. 19 Effects of Voltage Control at the Severe Line Fault on the Island

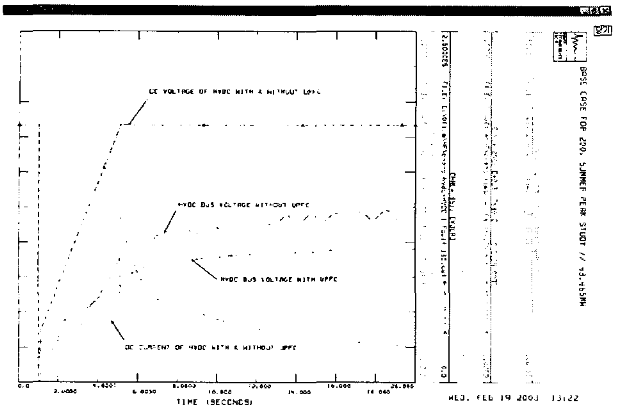

Fig. 20 Effects of Power Flow Control at the Severe Line Fault on the Island

3.2.2 Large Disturbance

a) Dynamics of voltage and power flow

Fig. 21 illustrates the voltage at the ac terminal bus of the HVDC (7440) and the power flow into the rectifier bus of the HVDC. The HVDC increases the power gradually since it contains the SQABAUX modulation controller, which responds slowly. As such, there are no dynamic oscillations.

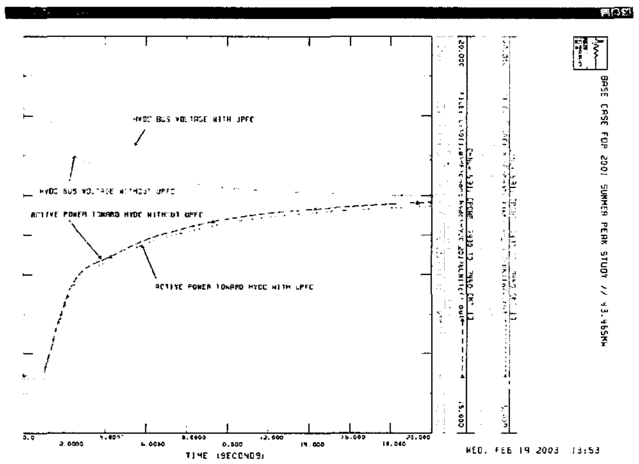

Fig. 21 Effects of Voltage & Power Flow Control at the Large Disturbance on the Island

3.2.3 Small Disturbance

a) Dynamics of voltage and power flow

Fig. 22 specifies the voltage at the ac terminal bus of the HVDC (7440) as well as the power flow into the rectifier bus of the HVDC. Because of low voltage during the disturbance, the voltage at the terminal bus oscillates slightly. However, the oscillation is damped by UPFC operation. The oscillation of power flow doesn't occur in Jeollanam-Do.

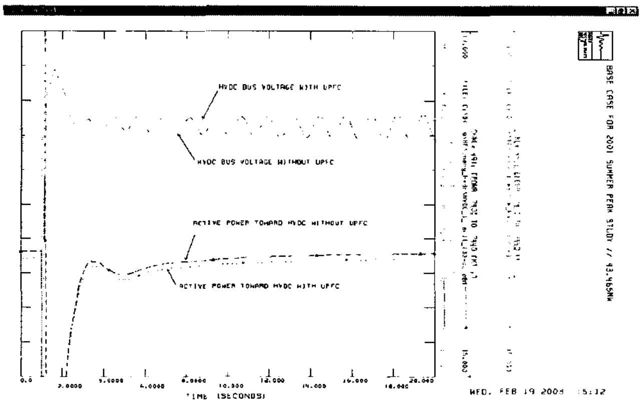

Fig. 22 Effects of Voltage & Power Flow Control at the Small Disturbance on the Island

4. Control Strategy

4.1 Voltage Control

It is well known that shunt reactive power infection can be used to control bus voltage. The voltage compensation by the 80MVA KEPCO UPFC influences the voltage dynamics in the nearby UPFC in the Jeollanam-Do system of KOREA. Analyzing the results of the dynamic simulations to investigate the operational effects of UPFC to damp out the voltage oscillation that occurs at the various disturbances is shown in Table 2.

Table 2 Effects of Dynamic Voltage Control by UPFC Operation

voltage dynamics / Types of Disturbance		Effects of UPFC operation					
		Oscillation			Damping		
		Main	HVDC	Island	Main	HVDC	Island
Main	345kV Line Fault	O	X	X	O	-	-
	1000MVA Unit Off	O	O	O	O	O	O
	-2000 MVar On/Off	O	X	X	O	-	-
Island	154kV Line Fault	O	O	O	O	O	O
	70MVA Unit Off	X	X	O	-	-	O
	-600 MVar On/Off	X	X	O	-	-	O

4.2 Power Flow Control

The real and reactive power flow in the line can be controlled independently using series injected voltage. The series component of KEPCO UPFC has two control modes. One is the PQ control mode that maintains the constant active and reactive power desired by the operator. The other is the V control mode that maintains the constant series injected voltage desired by the operator. The V control mode is most commonly used when the operator wants the maximum series compensation of UPFC.

The series compensation by the 80MVA KEPCO UPFC influences the power flow dynamics of the KEPCO UPFC. The UPFC can damp out the power flow oscillation except in the case of severe contingency such as the 345kV line fault in the mainland as shown in Table 3. When a severe emergency takes place, the control mode is best changed from PQ control mode to V control mode for maximum series compensation.

Table 3 Effects of Dynamic Power flow Control by UPFC Operation

Types of Dynamic Disturbances \ Power		Effects of UPFC Operation					
		Oscillation			Damping		
		Main	HVDC	Island	Main	HVDC	Island
Main	345kV Line Fault	O	X	X	X	-	-
	1000MVA Unit Off	O	O	O	O	O	O
	-2000MVar On/Off	O	X	X	O	-	-
Island	154kV Line Fault	X	X	O	-	-	-
	70MVA Unit Off	X	X	O	-	-	-
	-600 MVar On/Off	X	X	O	-	-	-

Fig. 23 illustrates the simulated results of series operation examples of KEPCO's UPFC. The UPFC is operated on the PQ control mode until 1[sec] as the steady state. Once the system experiences a large disturbance, such as YK NP 1 unit outage at 1[sec], the dynamics of UPFC are simulated until 10[sec]. Finally the dynamics of UPFC are simulated until 20[sec] after a severe 345kV line fault occurs at 10[sec] during 0.1[sec] and then the fault clears at 10.1[sec].

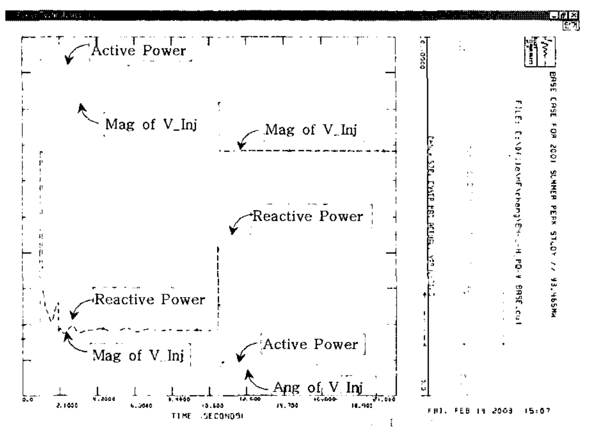

Fig. 23 Dynamic Characteristics of UPFC though the changes of operation mode

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] High Voltage Direct Current Handbook, EPRI TR?104166S, 1994.

[4] Schauder, C., et al, "AEP Unified Power Flow Controller Performance", IEEE Transactions on Power Delivery, March, 1999.

[5] Gyugyi, et al. "The Unified Power Flow Controller: A New Approach to Power Transmission Control", IEEE Transactions on Power Delivery, April, 1995,

[6] Gyugyi, L., Hingorani, N. "Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems", IEEE press, 2000.

[7] Jin-Boo, Choo, et al, "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.

[8] O. B. Nayak, A. M. Gole, D. G. Chapman, J. B. Davies, "Dynamic Performance of Static and Synchronous Compensators at HVDC Inverter Bus a very Weak AC System", *IEEE Transactions on Power Systems*, Vol. .9, No. 3, pp. 1350 - 1358, 1994.

[9] P. Kunder, *Power system stability anOd control*, Mcgraw Hill, 1996.

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