Modeling and Analysis of the KEPCO UPFC System by EMTDC/PSCAD

Jong Su Yoon*, Soo Yeol Kim*, Byung Hoon Chang*, Seong Joo Lim* and Jin Boo Choo*

Abstract - This paper describes the development of KEPCO's 80MVA UPFC electromagnetic transient model and the analysis of its performance in the actual Korean power system. KEPCO's 80MVA UPFC is currently undergoing installation and will be ready for commercial operation from the year 2003. In order to apply a new FACTS device such as the UPFC to the actual power system, the utility needs, in advance, both load flow stability studies and transient studies. Therefore, KEPRI, the research institute of KEPCO, developed a detailed transient analysis model that is based on the actual UPFC S/W algorithm and H/W specifications. This simulation model is implemented by an EMTDC/PSCAD package. The results of the simulation show the effectiveness of UPFC operation in the KEPCO power system.

Keywords: FACTS (Flexible AC Transmission System), STATCOM (Static Synchronous Compensator), SSSC (Static Synchronous Series Compensator), GTO (Gate Turn-Off Thyristor), UPFC (Unified Power Flow Controller)

1. Introduction

During the last decade, a number of FACTS devices based on static Voltage Source Inverter (VSI) technology have been developed in order to provide a solution for variant problems of the operation aspects in the power system, such as DVR, SSSC, STATCOM and UPFC. The configuration of UPFC is slightly different from that of other devices. The UPFC consists of two VSIs, which are connected through a common DC link capacitor. Each inverter has a coupling transformer with the transmission line interface. The VSI 1, known as STATCOM, injects an almost sinusoidal current at the point of connection. The VSI 2, known as SSSC, injects an almost sinusoidal voltage of variable magnitude in series with the transmission line. When both VSIs are operating together as a unified system, the injected voltage in series with the transmission line can be at any angle with respect to the line current; therefore, the exchanged power at the terminals of each inverter can be reactive as well as real. The result is that the real and reactive power flow in the line can be regulated independently. The exchanged real power at the terminals of one VSI with the power flows bi-directionally to the terminals of the other VSI through the common DC link capacitor [1].

KEPCO's UPFC consists of ±40MVA parallel VSI and ±40MVA serial VSI connected with a 154kV transmission line. Each ±40MVA VSI is composed of two ±20MVA inverter modules, which are coupled with an auxiliary transformer as illustrated in Fig. 1. The output voltage of the UPFC has a 24-pulse wave pattern that is caused by a 3-level and multi-pulse inverter.

KEPCO's ±80MVA UPFC is now under installation to the Kangjin-Jangheung transmission line at a 154kV Kangjin power substation. The results of the load flow and stability study completed in advance show that the UPFC can reduce a line overload and voltage drop problem under a 345kV line fault. Under normal conditions, KEPCO's UPFC is expected to increase transmission line capacity and reduce system losses through coordinated control of power flow and reactive power compensation [2]. In addition to the studies regarding large scaled systems such as load flow and stability, KEPRI completed the transient study to verify its performance and dynamic response under transient states using the detailed EMTDC/PSCAD model. In order for the developed simulation model to achieve the same results as the actual system, the same 3-level GTO inverter pole structure and transformer characteristics were used in the models. An equivalent network model of the KEPCO power system was also connected to the UPFC system model.

2. 80MVA UPFC

This section presents an overview of the 80MVA UPFC

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device addressed in this paper.

System Configuration

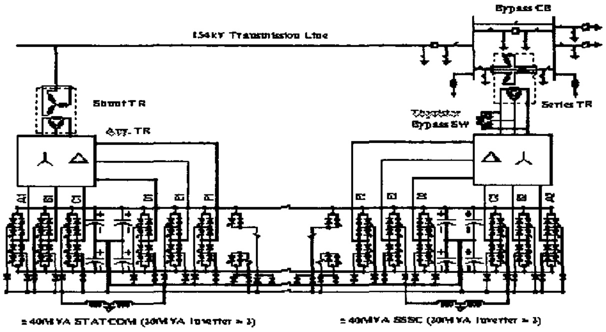


Fig. 1 80MVA UPFC Configuration Diagram(Magnetic Circuit, Inverters, Bypass)

2.1 Inverter stack

As illustrated in Fig. 1, KEPCO's UPFC employs two voltage source inverters (STATCOM, SSSC), and each is capable of full four quadrant operation. The AC current rating of each GTO inverter pole is 1500A rms. Each pole consists of four GTO valves, each of which is composed of a string of five series-connected GTO modules. Table 1 shows the number of poles, modules per valve, dc bus voltage, and ac inverter output terminal voltage.

Table 1 Specifications of a 3-level GTO inverter stack

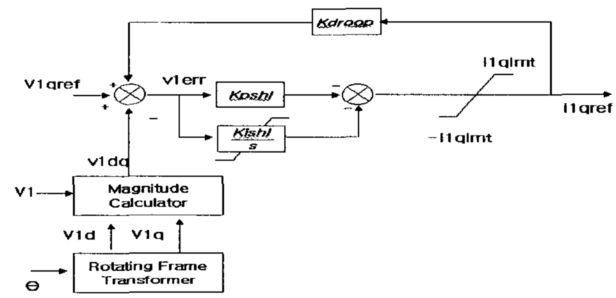
VSI rating	Pulse number	No. of poles	No. of modules	Nominal DC	Nominal output(p-n)
40MVA	24	6	5	4.8kV	4.285kV (rms)

2.2 Power transformer

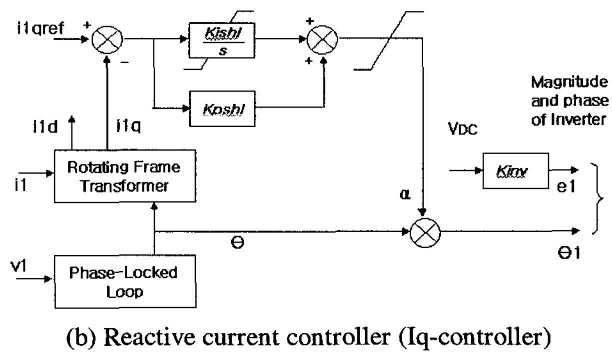
Each inverter is connected to the grid through a transformer. There are a total of four transformers used in the grid connection. The shunt and parallel transformers are ±40MVA each and the two auxiliary transformers are each rated at ±22.2MVA. As shown in Fig. 1, two identical twelve pulse, three level inverters connected to a common DC capacitor bank combining the output through an auxiliary transformer, 24-pulse harmonic neutralized inverter can be configured. By combining the output waveforms of the two inverters with this configuration, harmonic components can be reduced. The combined output is connected to the grid through the serial and shunt transformers.

2.2.1 System Control

In the whole operation aspect, three control modes are provided; STATCOM, SSSC, and UPFC. The function of the UPFC control mode is to independently control the flow of real and reactive power on the transmission line while maintaining the bus voltage at specified levels. To implement this function, the shunt inverter generates an AC voltage from DC voltage that is synchronous with that of the network. The amplitude difference between these voltages defines the reactive power absorbed or supplied by the inverter. The phase difference causes an exchange of real power, which charges or discharges the DC capacitor. The controller for the shunt inverter has to calculate and regulate the magnitude and angle of the output voltage in order to exchange reactive power with the network and compensate DC voltage simultaneously. The controller for the shunt inverter is broken down into two parts as illustrated in Fig. 2; the reactive power flow controller (so called Iq-controller) and the voltage controller. The voltage controller has more upper function than that of the Iq-controller. In the case of the series inverter, both the dc-to-ac ratio of the inverter and the phase angle (ρ) of the inverter output voltage are controlled. The dc bus voltage stays substantially constant (with some variation due to STATCOM operation) while the inverter output voltage (e2) may be varied, with its duty cycle, from zero to the maximum available. The control objective for the UPFC series inverter control is to inject a voltage in series with the line so that the flow of real and reactive power can be independently influenced. One basic control loop is provided in that the controller has to regulate the voltage magnitude and phase injected by the series part. In order to increase the convenience of the user operation, a P-Q power flow controller is also connected to the Vdq-controller.



(a) Voltage controller



(b) Reactive current controller (Iq-controller)

Fig. 2 Control block diagram for the shunt inverter

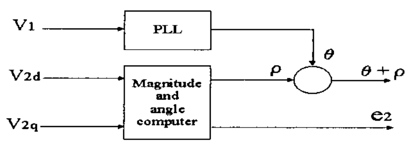


Fig. 3 Control block diagram (Vdq-controller) for the injection voltage control of the series inverter

2.2.2 System Protection

During power system faults, which result in excessive through-flow current or inadequate system voltage, KEPCO's UPFC has bypass functions that remove the inverter assembly (series inverter) from service without damage. The bypass function is implemented by the operation of the thyristor switch and mechanical circuit breaker. Because thyristor switching operation is very fast (90μsec), line overcurrent can be bypassed instantaneously. Upon restoration of normal system conditions, the UPFC can be capable of placing itself back into service within 2 seconds and maintaining the appropriate setpoint to the capability of its ratings. However, if severe over-voltage conditions continue in spite of the thyristor switching, the protection controller operates all the circuit breakers additionally (i.e, opening the shunt CB and closing the series CB).

3. EMTDC/PSCAD Model

Fig. 4 shows the main circuit module of the developed EMTDC/PSCAD model. Network 1 and 2 in Fig. 4 represent the equivalent power system connected with KEPCO's UPFC.

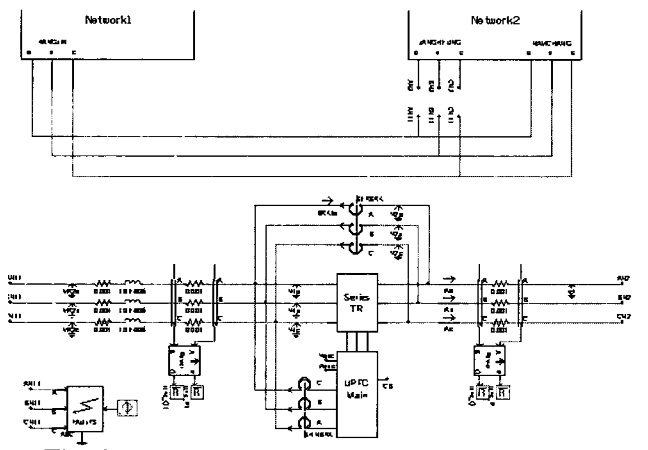
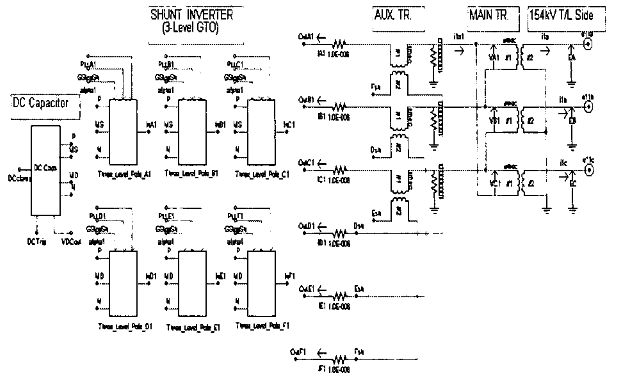
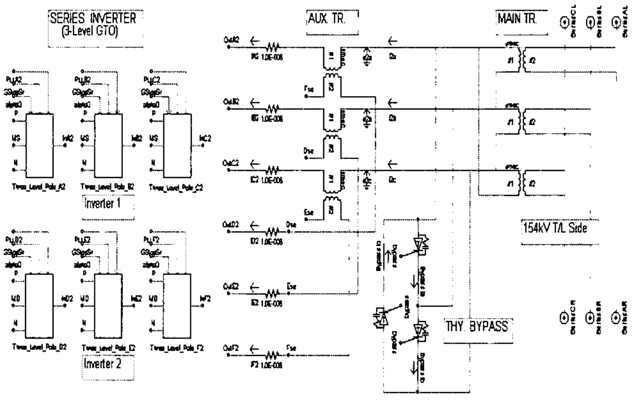


Fig. 4 The main module of the UPFC circuit model

Fig. 5 shows the electric circuit parts of the UPFC model such as GTO inverter stacks, transformers and bypass switch.



(b) The shunt part of the UPFC circuit model



(c) The series part of the UPFC circuit model

Fig. 5 The inverter model of KEPCO's UPFC system

4. EMTDC/PSCAD Simulation

The following simulations were carried out to assess the effectiveness of the operation of KEPCO's UPFC in the actual Korean power system. Fig. 6 shows the test system used to carry out the simulation. The test system is an equivalent network based on the power system planing data of the year 2003. The test system comprises many bus loads, RLC line impedances, and equivalent voltage source models to represent the connection with external network.

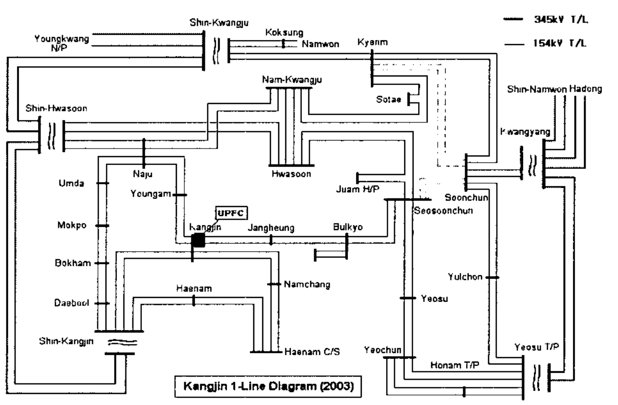


Fig. 6 Surrounding power system near UPFC site

Table 2 shows the results of the UPFC inverter operation such as firing angle variation α and output voltage phase shift δ caused by several UPFC control cases. In this case, the controllers for the shunt and series inverter are the reactive power (Iq) and voltage controller (Vdq), respectively. In case of the shunt inverter, firing angle α for the variation of the midpoint (zero-level) intervals of a 3-level inverter is always the constant value 7.5° , as illustrated in Table 2. It is caused by the design of the shunt controller to generate the 24-pulse wave pattern and reduce harmonic components (especially, 5^{th} and 7^{th}). Because all the controllers are basically designed per unit system, the shunt control command Iq 1 and –1 means 40Mvar capacitive and 40Mvar inductive operation of the shunt inverter, respectively. The control command of the series inverter means the setpoint of the Vdq controller in Fig. 3. Therefore, case 2 in Table 2 is the same as a power system state without UPFC in steady state.

Table 2 KEPCO's UPFC simulation cases

Case	Control Command			Sh – Inverter Control state		Sr – Inverter Control state	
	Sh	Sr					
	Iq	Vd	Vq	α angle	δ angle	α angle	δ angle
1	-1	0	0	7.5°	0.30°	180°	57.3°
2	0	0	0	7.5°	-0.75°	57.3°	180°
3	1	0	0	7.5°	-0.60°	57.3°	-180°
4	-1	0	1	7.5°	0.04°	0.0°	-270°
5	-1	1	0	7.5°	0.04°	0.0°	0.0°
6	1	0	1	7.5°	-0.74°	0.06°	90.7°
7	1	1	0	7.5°	0.74°	0.0°	-0.37°

Tables 3 and 4 show the response of the inverter and power system with reference to the UPFC operation cases in Table 2.

The following are simulation results for dynamic performance analysis of the UPFC Shunt Inverter (STATCOM). Table 5 is a simulation condition for voltage control mode of STATCOM. Fig. 7 shows the difference between bus voltage and output voltage of STATCOM. As this figure shows, capacitive control mode of STATCOM means the state that inverter output voltage is higher than bus voltage.

Table 3 Shunt inverter and controlled power system states

Case	Vdc – voltage	Sh – Inv output	Bus voltage	Line current	Line power flow P & Q	
	(kV)	(Mvar)	(kV)	(kA)	(MW)	(Mvar)
1	8.23	40.0(L)	153.5	0.25	13.2	4.0
2	9.77	0	158.0	0.20	9.12	20.6
3	11.34	40.6(C)	162.6	0.18	9.10	28.1
4	8.30	40.3(L)	156.6	0.16	-2.28	-36.6
5	8.13	40.3(L)	158.0	0.38	60.2	5.40
6	11.44	41.5(C)	162.7	0.30	-6.30	-40.0
7	11.28	41.0(C)	160.0	0.41	79.8	19.0

Table 4 Control voltage and output power by series inverter

Case	Injected voltage By Sr-Inverter		Power output (P + jQ) By Sr-Inverter	
	Mag. (kV)	Angle (deg)	(MW)	(Mvar)
1	0.032	-31.0°	-0.00126	-0.0003
2	0.038	150.0°	-0.0006	-0.0025
3	0.047	164.0°	-0.001	-0.004
4	5.230	181.5°	2.57	0.14
5	5.150	262.0°	-0.096	3.77
6	7.210	181.0°	4.07	0.54
7	7.050	-86.0°	6.80	-0.90

Table 5 STATCOM simulation (voltage control mode)

	Control command change		
V	1.013pu(156kV)	1.0pu(154kV)	1.026pu(158kV)
(ref)	Normal State	Inductive Mode	Capacitive Mode

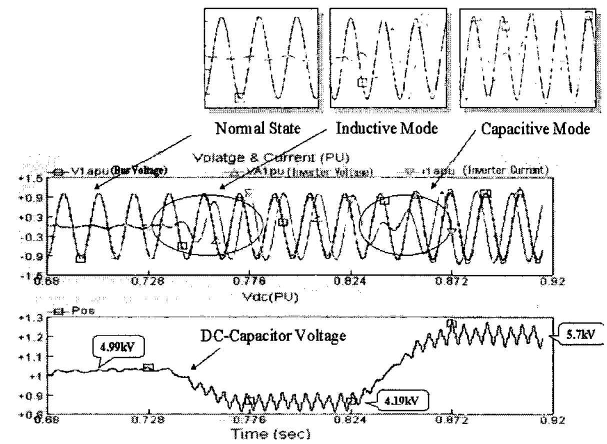


Fig. 7 STATCOM output voltage & Vdc (pu)

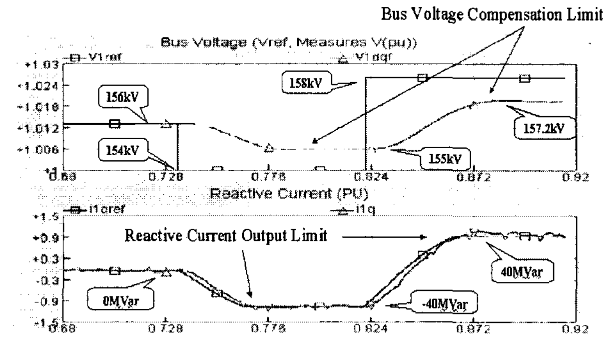


Fig. 8 Control command & response (pu)

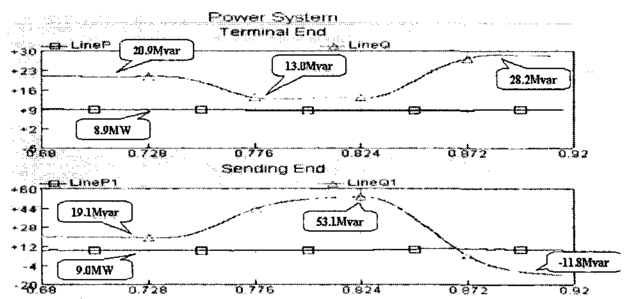


Fig. 9 Power Flow (Sending & Receiving Side)

Fig. 8 shows the reactive power output according to variant control command (Vref). Because reactive current (Iq) controller, sub-controller of voltage controller, already reach the output limit (+40MVA or –40MVA), bus voltage 154kV and 158kV can not achieve in this STATCOM rating. Fig. 9 illustrates the variation result of the reactive power flow in the transmission line. Table 6 is a simulation condition of the reactive current control mode. In this case, only the reactive current controller (Iq-controller) is used in the Fig. 2.

Table 6 STATCOM simulation (current control mode)

	Control command change		
Iq (ref)	0.0pu(0Mvar)	-1.0pu(-40Mvar)	1.0pu(+40Mvar)
	Normal State	Inductive Mode	Capacitive Mode

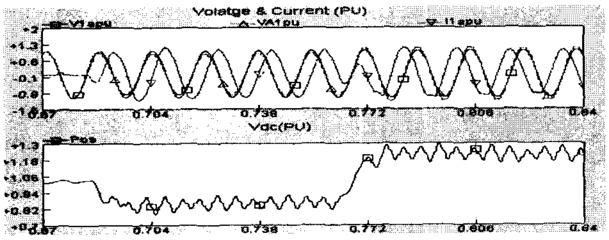


Fig. 10 STATCOM output voltage & Vdc (pu)

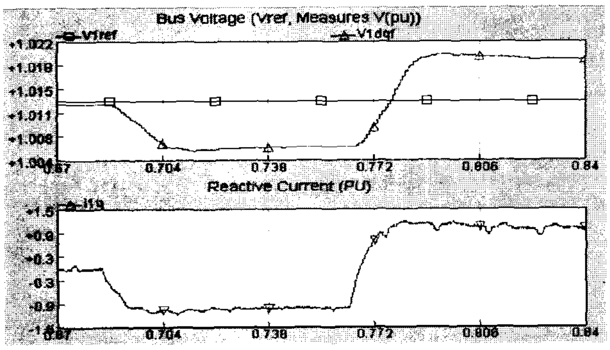


Fig. 11 Control command & response (pu)

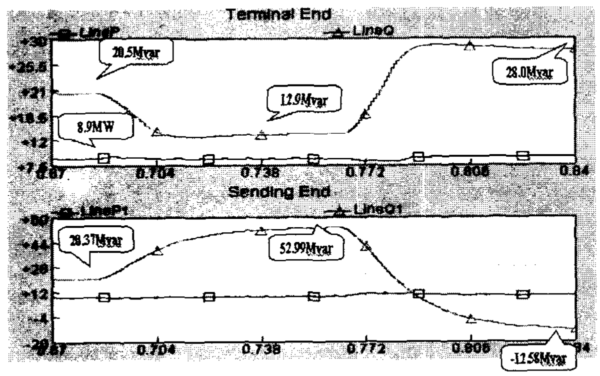


Fig. 12 Power flow (sending & receiving side)

The following are simulation results for dynamic performance analysis of KEPCO's UPFC.

Table 7 UPFC simulation (power flow control mode)

		Inverter Command Change		
STATCOM	V(ref)	1.013pu	1.013pu	1.013pu
SSSC	P(ref)	0MW	20MW	-20MW
	Q(ref)	0MVar	0MVar	0MVar

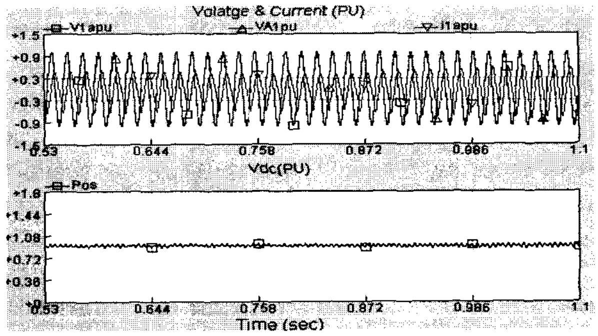


Fig. 13 Sh-inverter output voltage & DC voltage (pu)

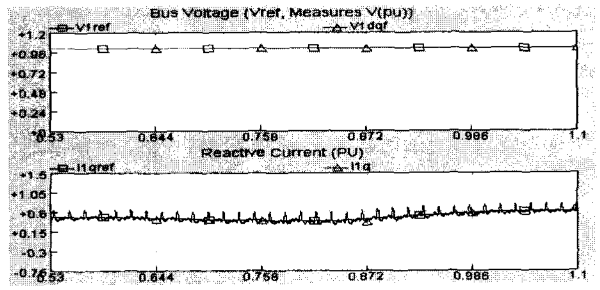


Fig. 14 Sh-inverter control command & response

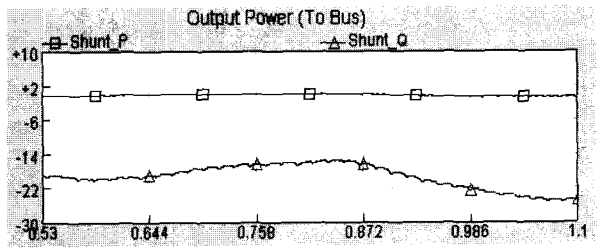


Fig. 15 Sh-inverter output power (to bus)

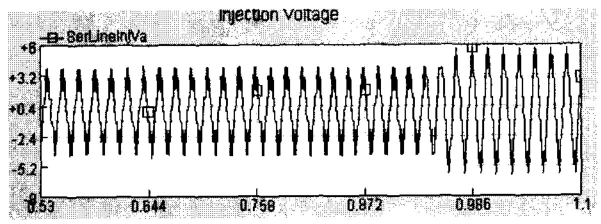


Fig. 16 Sr-Inverter Injection Voltage

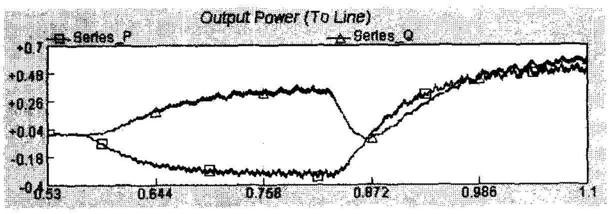


Fig. 17 Sr-inverter output power (to line)

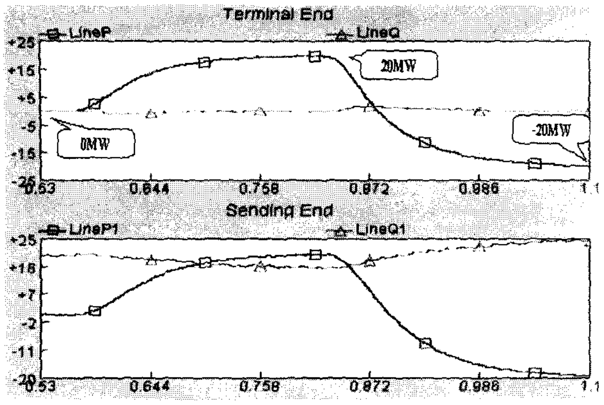


Fig. 18 Power flow (sending & receiving side)

Fig. 13 shows the output power of a shunt inverter and a phase voltage (p-n) of shunt bus during control input transition. Bus voltage is almost constant as illustrated in this figure. Figs. 16 and 17 show inverter injection voltage and output power from the series inverter. Fig. 18 shows variations of the active and reactive power flow (P + jQ) at the receiving end in the transmission line. These figures illustrate that the UPFC can independently control the flow of real and reactive power on the series line by maintaining the bus voltage at the specified reference value.

5. Conclusion

This paper has presented an electromagnetic transient simulation model of KEPCO's 80MVA UPFC, and applied this model to analyze the effectiveness of its operation in the actual Korean power system. The developed UPFC EMTDC/PSCAD model consists of the same control algorithms, 3-level GTO inverter stacks and electromagnetic circuits as that of the actual system so as to achieve the same simulation results as the actual response. Therefore, this model can be used to simulate almost all aspects of UPFC operation such as control, protection, harmonic and transient analysis.

The simulation carried out shows that KEPCO's UPFC provides excellent control capability. It was observed that its power flow control and voltage regulation can be operated independently without a coupling effect.

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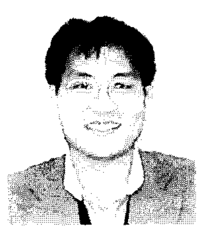

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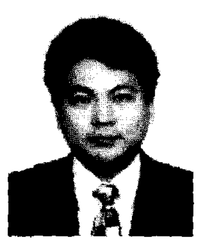

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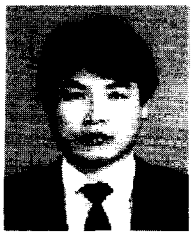

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