Experimental Study on the Unified Power Flow Controller

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SUMMARY

This paper presents the results of experimental study on the performance of a Unified Power Flow Controller (UPFC), one of the FACTS (Flexible AC Transmission Systems) controllers. A laboratory-scale UPFC was manufactured and installed on a laboratory electric power system to investigate its multifunctional capabilities as a power flow controller. The UPFC consists of two 4.5-kVA, 200-V back-to-back voltage-sourced converters, labeled "Converter 1" and "Converter 2," operated from a common DC link provided by a DC storage capacitor of 380 V. It can provide independent control of both the real and reactive power flow in the line. Tests were performed to examine the capabilities of the UPFC, under one-machine connected to an infinite-bus system. Steady-state responses under various kinds of operating conditions were measured and analyzed.

Key words: UPFC; FACTS; electric power system; DC link; power flow control; steady-state stability.

1. Introduction

In recent years, devices that use power electronics technology are being used in a wide variety of fields. In electric power systems, a representative example of equipment that uses power electronics technology is the FACTS equipment proposed in the United States in the late 1980s. Of these, the Unified Power Flow Controller (UPFC) is expected to improve system stability and power flow control performance through control of power flow when used in an electric power system. At present, the majority of reports about UPFC are based on computer simulations, and there are few reports of research using real equipment. However, accurately simulating an entire electric power system, including the UPFC, is difficult because of the presence of uncertain elements such as changes in the internal parameters of a generator resulting from system control.

In this paper, using experimental equipment for a simulated power system and a UPFC prototype, the authors report on the results of analysis using real equipment of the effects on the basic characteristics of the UPFC and the electric power system. Reactive power compensation and voltage control, the main functions of the UPFC prototype, were analyzed through experiments when using a load device and commercial three-phase power source in the UPFC prototype, and when using a simulated power system experimental setup in a single-machine infinite-bus system. Moreover, the authors analyzed the system stability when setting up a UPFC in a single-machine infinite-bus system.

2. Configuration of the UPFC Test Device

The UPFC consists of two self-exciting AC converters (inverters) connected via a DC capacitor, with one connected in parallel to the power system, and the other connected in series to the power system. They are referred to as the shunt compensator (Converter 1) and the series compensator (Converter 2). Figure 1 shows the basic configuration of the UPFC.

Here, $\dot{I}_{sh}$ represents the current flowing into the UPFC; $\dot{V}_s$, the UPFC input edge voltage; $\dot{V}_i$, the output voltage from the parallel compensator; $\mathbf{X}_t$, the reactance of the parallel compensator; $\dot{I}$, the system current; $\dot{V}_{pq}$, the UPFC compensation voltage; and V_{DC}, the DC voltage.

The UPFC can control the effective power and reactive power in an electric power system at high speed and continuously by controlling the phase with a high voltage

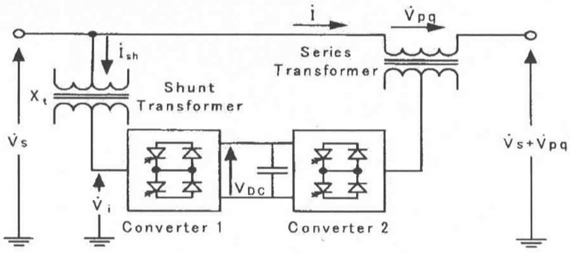

Fig. 1. Configuration of UPFC.

using the series compensator, and the absorption and input of reactive power using the parallel compensator.

Figure 2 shows the control structure for the prototype UPFC. The parallel and series compensators have a measuring component and a computational component (CPU). The series compensator and shunt compensator are set up to be able to operate independently as a STATCOM and SSSC, respectively.

Fundamentally, the UPFC performs processing, from receiving input from the operator to performing calculations, as a single control device. In the prototype, emphasis is placed on performing instructions precisely for each of the series and shunt compensators, and specifications are given to perform command value calculations separately in each converter.

The ratings for the prototype were determined with consideration for the connection with the experimental setup for the simulated electric power system. Moreover, a single-phase AC 100-V power source is supplied separately from the input as a control power source.

To prevent damage to the equipment, protection using a breaker and software protection using an inverter control board were set up. The latter is performing by opening or closing an electromagnetic switch using commands from the inverter control board. The protected operating values can be changed as needed.

Table 1 lists the specifications for the prototype UPFC used in this research.

Table 1. Specification of prototype UPFC

Input		3phase AC200±10%
DC Link Voltage		380V
Series Converter	Range of Voltage Regulation	0~±35Vrms
	Maximum Load Capacity	4.5kVA
	Maximum Load Current	20A
	Compensation Method	Voltage Regulation
Shunt Converter	Maximum Reactive Power Input	±4.5kvar
	Range of Reactive Power Compensation	0~±4.5kvar
	Compensation Voltage	Δ V=10% (Zs=10%)
	Compensation Method	Current Control
Inverter	Rated Capacity	4.5kVA
	Rated Output Voltage	0~220V
	Rated Output Current	11A
	Switching Module	PM30RSF60
	Switching Frequency	10.2kHz

3. Functionality and Performance of the UPFC Prototype

The authors confirmed the basic characteristics of the compensation while evaluating the power system with the UPFC. The authors measured the compensation function of the device (reactive power compensation using the shunt compensator and voltage compensation using the series compensator) using a commercial three-phase power source and load. Figure 3 shows a diagram of the measurement circuit.

The following measurements were performed to confirm the operation of the UPFC.

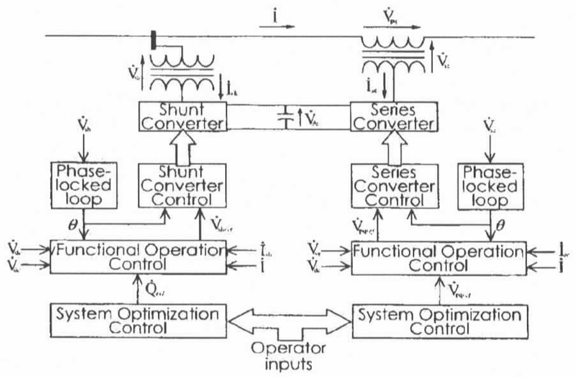

Fig. 2. Control structure of prototype UPFC.

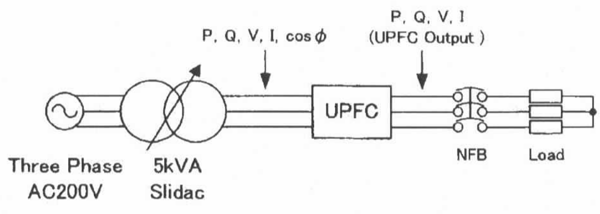

Fig. 3. Measurement circuit.

3.1 Automatic operation of reactive power compensation using the shunt compensator

An operational state in which the reactive power flowing to the UPFC from a commercial three-phase power source is detected, and the reactive power going into the UPFC is canceled. Figure 4 is a block diagram of the control structure of the shunt compensator.

For the load connected to the UPFC, a reactor with a power factor of 0.999 and a capacity of 2.58 kVA was used as an inductive load, and a capacitor with a power factor of 0.626 and a capacity of 1.26 kVA was used as the capacitive load. Table 2 lists the results of compensation for the reactive power.

Based on Table 2, the authors were able to confirm that the reactive power flowing into the UPFC from the commercial three-phase power source was canceled before and after operation.

3.2 Compensation operation for output-side voltage using the series compensator

An operational state in which the output voltage in the UPFC (load-side voltage) is regulated to a rated value (200 V) using the series compensator. Figure 5 is a block diagram for the control structure of the series compensator.

The control method used in the series compensator in the prototype performs control by creating a separation in a static orthogonal coordinate system using the three-phase–two-phase conversion and rotational axis conversion with only the three-phase voltage value at the device output point as input, and deriving the control bias from the d-axis component.

Control methods such as system voltage control, phase control, and impedance control are representative for the series compensator [4]. However, because the current is not controlled in the prototype in this paper, parameters

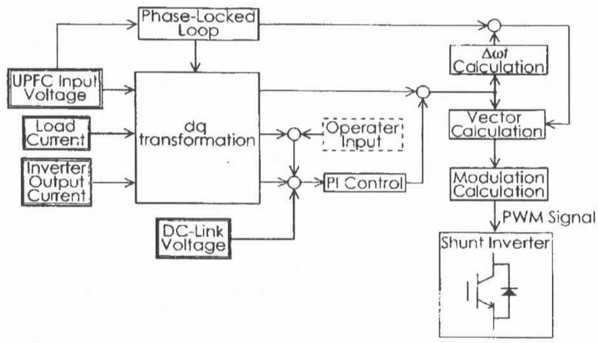

Fig. 4. Control structure of shunt compensator.

Table 2. Compensation operation results of reactive power

Case		Reactive power [kvar] (From three phase source to UPFC)	Reactive power [kvar] (From UPFC to load)
Before compensation	Inductive load	0.14	0.1107
	Capacitive load	-1.103	-0.9849
After compensation	Inductive load	0.0024	0.1108
	Capacitive load	0.0707	-0.9595

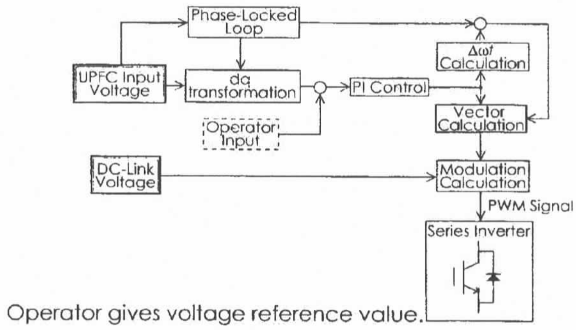

Fig. 5. Control structure of series compensator.

Table 3. Change in output voltage of UPFC

Case	Line voltage	Input voltage [V]	Output voltage [V]	Compensated voltage [V]
1	V_{RS}	140.81	200.1	59.29
	V_{TS}	138.82	199.12	60.3
2	V_{RS}	251.53	199.92	-51.61
	V_{TS}	250.12	199.01	-51.11

Table 4. Equivalent impedance value with compensation

Compensation mode	Equivalent impedance [ohm]
Inoperation	0
Series only (reference value 200V)	C-Load 5.31, L-Load 5.76
Shunt only	65.83
Simultaneously (reference value 200V)	48.96

other than the power system voltage vary along with changes in the voltage.

The authors performed measurements for when the input voltage was "higher" and "lower" than the rated voltage using a slidax connected to the input side of the UPFC. Table 3 lists the results.

V_{RS} and V_{TS} represent the R-S phase line voltage and the T-S phase line voltage for the input and output voltage. Based on Table 3, the authors were able to confirm that when the input voltage was lower (case 1) and higher (case 2) than the rated voltage (200 V), it was regulated to near the set control value of 200 V.

Based on these experimental results, the authors were able to find the equivalent impedance value for when the device was performing compensation. Table 4 lists the equivalent impedance values in various operating states.

4. Experiments Using a One-Machine Infinite-Bus Power System with the UPFC

The UPFC prototype was connected to the experimental equipment for the simulated electric power system, and measurements were taken for the compensation performance (reactive power compensation using the shunt compensator and output voltage compensation using the series compensator) in the UPFC prototype when using a one-machine infinite-bus power system. Figure 6 illustrates the one-machine infinite-bus power system used in this experiment.

4.1 Reactive power compensation (shunt compensator)

For the UPFC prototype settings, the reactive power was set to 0 kvar (reactive power output from the generator was 0 kvar) as seen from the device's input side. Figure 7 shows the changes in the reactive power that appear in the generator. Based on the figure, when the shunt compensator was running ("Shunt only" and "Simultaneous") the reactive power value was kept close to 0 kvar.

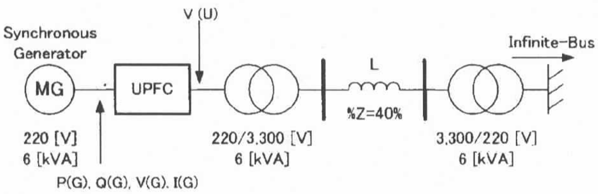

Fig. 6. One-machine infinite-bus power system 1.

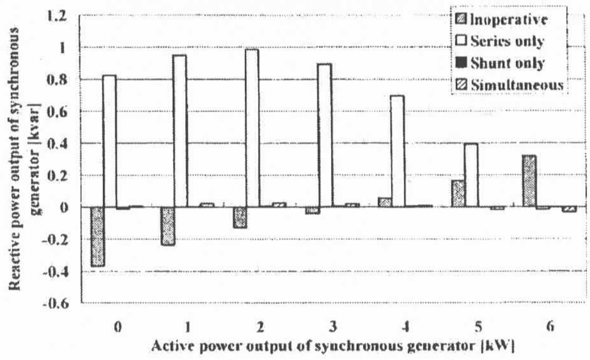

Fig. 7. Change in the reactive power.

4.2 Confirming the voltage suppression function (series compensator)

For the UPFC prototype settings, the device's output terminal voltage was set to 200 V. Figure 8 shows the changes in the voltage at the input and output edge of the UPFC prototype. Here, the input and output voltage represent the three-phase average voltage for each line voltage. Because the generator's output terminal is connected directly to the input terminal of the UPFC prototype, the voltage on the UPFC input side is the generator terminal voltage. When the series compensator is running in the various generator output states ("Series only" and "Simultaneous"), the UPFC output edge voltage is clearly kept around 200 V.

Based on the above, the authors were able to confirm the two compensation functions, reactive power regulation using the shunt compensator and voltage regulation using the series compensator.

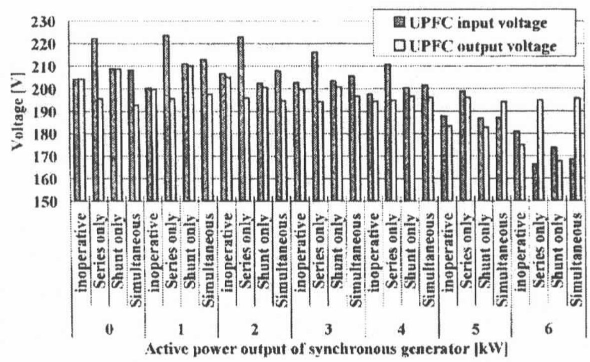

Fig. 8. Change in the input output voltage of UPFC.

5. Experiments on Generator Stability

Improvements in system stability represent one of the advantages of using a UPFC in an electric power system. In discussions about system stability, finding the maximum power (steady-state stability limit power) that can be transmitted is important. Thus, the authors measured the steady-state stability limit power using the one-machine infinite-bus power system shown in Fig. 9. Based on these measurements, the power–angle curve (P–δ curve) and the noise curve (P–V curve) were drawn, and the mutual relationship with the generator's operating state (AVR operation or steady magnetic field current operation) was examined with and without the UPFC.

The process of increasing output until rated levels after synchronous input of the generator, and then raising the generator output gently until loss of synchronism was reached was examined. The operating conditions for the generator and the UPFC prototype are given in Fig. 10. Table 5 lists the measured values for the steady-state stability limit power P_{max}.

Based on Table 5, it is clear that P_{max} is highest when the output edge voltage is regulated to 200 V and the synchronous generator is in AVR (compared to when AVR alone is used, P_{max} is 13% higher). On the other hand, when the synchronous generator is operated with the field magnetic current constant, P_{max} due to compensation using the UPFC falls (9% when performing compensation using the shunt compensator).

Figure 11 shows the power angle curve (P–δ curve) for each operational state. The curves are shown up to P_{max}.

Based on Fig. 11, it is evident that using the AVR at the same time as the UPFC results in greater stability than performing system control with the UPFC alone, and that the difference is substantial between the two.

When control is performed using only the UPFC and without AVR, there are substantial fluctuations before P_{max} is reached, and as can be seen in Fig. 11, the device stops. As a result, in all cases, the fluctuations calm down due to tracking the curve for when no control was used. For P_{max} as well, Table 5 clearly shows that in most cases a value close to P_{max} without control results.

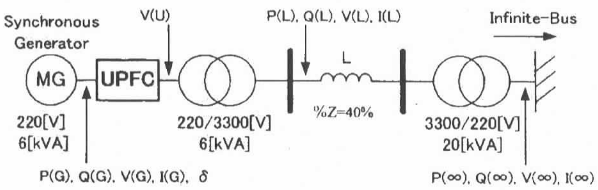

Fig. 9. One-machine infinite-bus power system 2.

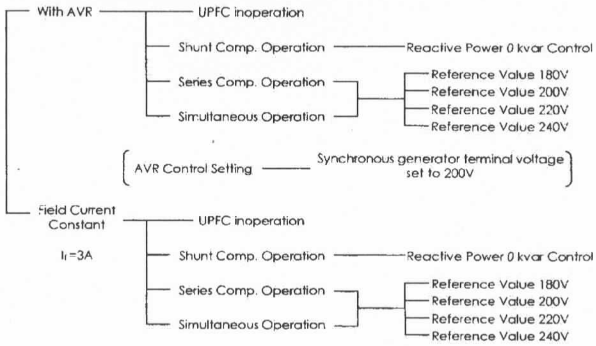

Fig. 10. Experiment conditions for the steady-state stability.

Table 5. Measurement data of steady-state stability limit power

Operation condition		Steady state stability limit power [kw]
Without AVR	Inoperative	6.91
	Series ref. 180V	6.72
	Series ref. 200V	6.84
	Series ref 220V	6.89
	Shunt only	6.29
	Simultaneous ref. 180V	6.71
	Simultaneous ref. 200V	6.81
	Simultaneous ref. 220V	6.94
With AVR	AVR only	10.71
	Series ref. 180V	11.10
	Series ref. 200V	11.21
	Series ref 220V	11.18
	Shunt only	11.90
	Simultaneous ref. 180V	11.87
	Simultaneous ref. 200V	12.11
	Simultaneous ref. 220V	10.67

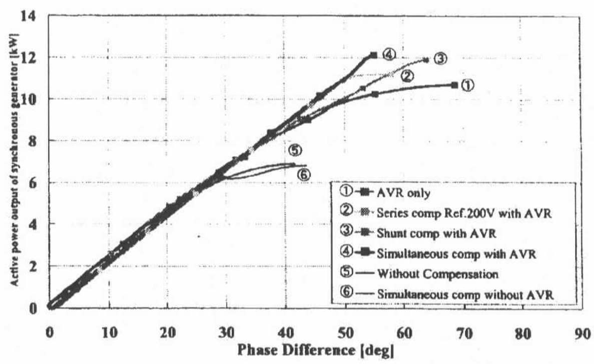

Fig. 11. Power–angle curve.

When AVR is used, greater stability is achieved by using the UPFC at the same time as compared to using AVR alone. Moreover, in Table 5, greater stability is achieved when control is performed simultaneously using AVR and the shunt compensator as compared to when control is performed using AVR and the series compensator. In Fig. 11, it is clear that in the latter case, the fluctuations in the effective power at the point in time for P_{max} are small, and the stability limit for the generator is reached, but in the former case, the effective power at the point in time for P_{max} tends to increase, and at that point, the generator seems to be stable. Based on these results, the authors believe that using AVR and the shunt compensator at the same time creates more stability.

Figure 12 shows the noise curve (P–V curve) for the various operating states so as to evaluate the stability on the load side.

Based on Fig. 12, it is clear that when the UPFC is running, the voltage on the load side is more stable. In particular, when the series compensator is running, the voltage is kept to its set value of 200 V as a result of voltage compensation, and compensation is performed until the device is stopped by the protection function.

Here, the drop in the input terminal voltage in the device occurring along with UPFC operation when AVR is not used is discussed.

In general, the UPFC is represented by a leak reactance in the series converter, one equivalent voltage source, and two equivalent current sources.

Figure 13 shows a UPFC equivalent model.

In the series compensator, the voltage of the system is regulated via the series converter so that the detected system voltage value and the compensation command value are the same. At this point, the effective power that is generated or absorbed is supplied from the DC capacitor. The shunt compensator regulates the current between it and the system via the shunt converter so that the voltage maintained in the DC capacitor is steady. The drop in the

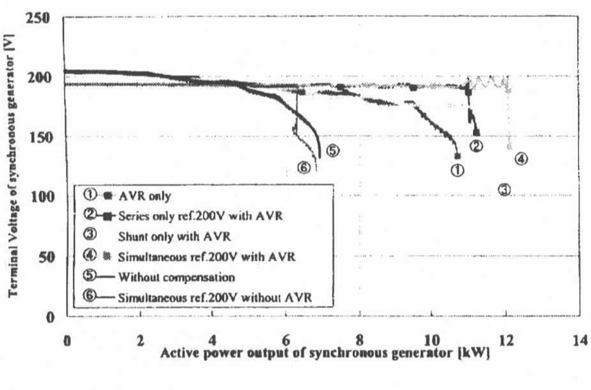

Fig. 12. Power–voltage curve.

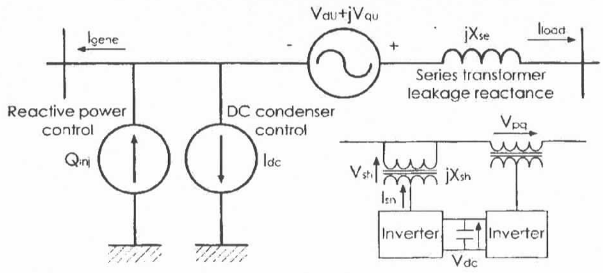

Fig. 13. UPFC equivalent model.

UPFC input terminal voltage that occurs when the UPFC is operating is a result of the drop in the generator terminal voltage due to the demagnetization that occurs in the generator and the changes in the current in the system due to the current I_{sh} involved at this point. If the generator output increases along with a decrease in the generator terminal voltage, the compensation voltage resulting from the series compensator will rise more, and the effective power supplied from the DC capacitor will also increase. As a result, during operation without current control and only the series compensator, the UPFC input terminal voltage drops as a result of the drop in the terminal voltage accompanying an increase in the output of the generator and the demagnetization effect.

When AVR is used, the drop in the generator terminal voltage can be compensated. As a result, the UPFC operates more stably as compared to when AVR is not used. Moreover, because the AVR regulates the generator terminal voltage to 200 V, when the series compensator is set to 200 V, the load with respect to the device is at its lowest. Consequently, using the AVR along with both compensators at the same time, controlling the current using the shunt compensator and keeping the series compensator set to 200 V, results in the greatest stability.

6. Conclusion

In this paper the authors experimentally explored the basic characteristics of a UPFC, a subject with examples of studies, and evaluated the improvements in stability in an electric power system. The following conclusions were reached.

(1) The authors confirmed that each compensation function (reactive power compensation and voltage regulation) was performed as per design in the UPFC prototype.

When a load device and a commercial three-phase power source were used with the UPFC prototype, and when the UPFC was placed in a simulated electric power system experimental setup in a one-machine infinite-bus system, values for the control settings of 0 kvar for the reactive power compensation and 200 V for the voltage compensation were obtained in both cases. Moreover, the authors confirmed that even when the series compensator and shunt compensator were both operating at the same time, compensation was performed correctly.

(2) The authors confirmed that system stability could be improved by placing the UPFC prototype in a one-machine infinite-bus system and performing voltage control in AVR and the UPFC series compensator.

Good compensation performance for the UPFC as a result of using AVR and the UPFC prototype was demonstrated. As a result, the authors were able to confirm that the steady-state stability limit power and the phase difference could be raised, and stability could be improved. In particular, compared to using AVR alone, using AVR and the UPFC series compensator at the same time resulted in a greater increase in the steady-state stability limit power and the phase difference. For the voltage stability as well, using the UPFC prototype at the same time yielded better voltage maintenance as compared to when only AVR was used, and more stable power could clearly be supplied to the connected load.

Therefore, when setting up a UPFC in an electric power system, using the UPFC and AVR at the same time yields the greatest operating stability.

The authors next plan to evaluate suppression of system fluctuations in the UPFC when transient changes due to transmission line faults occur.

REFERENCES

1. Hingorani NG, Gyugyi L. Understanding FACTS. IEEE Press; 2000.
2. Komukai T, Irokawa S, Kato M. Electrical power systems engineering. Maruzen Press; 1999.
3. Gyugyi L. Dynamic compensation of AC transmission lines by solid-state synchronous voltage source. IEEE 93SM434-1 PWRD, 1993.
4. Takehara T, Sugihara H. Control system design and instantaneous value analysis for UPFC. PE-00-137, PSE-00-142, 2000.
5. Choo J-B, Chang B-H, Yoon J-S, Kim S-Y, Lim S-J, Koh K-K. The first introduction of UPFC to the KEPCO power network. Proc ICEE 2002, p 2103–2108.
6. Serizawa Y. Electrical power systems engineering. Maruzen Press; 1996.
7. Institute of Electrical Engineers of Japan, Semiconductor Power Conversion Systems Exploratory Committee. Power electronics circuits. Ohm Publishing; 2000.
8. Yamamura A, Ono S. Introduction to power electronics. Ohm Publishing; 1997.
9. Aratame K. Applications for electric power systems technology computation. Denkishoten Press; 1993.