DYNAMIC CHARACTERISTIC STUDY OF UPFC BASED ON A DETAILED SIMULATION MODEL

Sanbao Zheng and Yoke Lin Tan(SrMIEEE)
S2-B5c-02, School of Electrical &Electronic Engineering
Nanyang Technological University
Singapore 639798

Shijie Cheng (SrMIEEE) and Yifeng Zhu
Department of Electrical Engineering
Huazhong University of Science and Technology
Wuhan, China 430074

Abstract: The two converters are the basic parts of a Unified Power Flow Controller (UPFC). Based on the widely used MATLAB, a digital simulator for the UPFC with 12-pulse converters is developed. Simulation results show that the developed UPFC model is precise in reflecting the static and dynamic characteristics of the UPFC. The harmonics of the output of the model is also analyzed. Using a simple power system with the UPFC as an example, the dynamic characteristics of the UPFC is studied based on the model which has been developed. The simulation results show that the normal operating condition of UPFC could no longer be maintained following a severe disturbance. Furthermore, the fault status of the system could be aggravated by the UPFC if it is used only for power flow control.

Keywords: UPFC, dynamic characteristics, digital simulation, model, harmonics.

I. INTRODUCTION

With the rapid development of the techniques in the power electronics area, Flexible Alternating Current Transmission System (FACTS) devices are being used in power transmission systems all over the world. As a member of the FACTS family, UPFC [1] provides more controllable variables and thus is able to change various parameters of the controlled system and make the operation of the system more flexible. This is the reason why it is attractive to many researchers. At present, the first UPFC in the world is already in operation in a substation situated at the eastern part of Kentucky in the United States of America. Although some helpful experiences and analytical results from the design to operation stages of the practical device have been published [2, 3], detailed simulation models are still required by many researchers in order to further their investigation on the operational characteristic of the UPFC. It is still not practical to study the UPFC by physical simulation experiments because it is a comparatively new concept and its structure is more complicated than that of the other FACTS device. Therefore, a precise and convenient digital simulation method of the UPFC is in dire need.

At the present stage, the UPFC is simulated fundamentally based on the ideal double controllable power source model. In this ideal model, the power source produces controllable standard sinusoidal voltage (or current) because the harmonics and the dynamics caused by the switching behavior of the device are neglected; thus it cannot reflect precisely and thoroughly the operational characteristics of the UPFC and its influence on the power system. At the same time, the voltage of the DC link bus is often presumed to be invariant in a transient procedure, i.e., the dynamics of the device itself is ignored. In order to obtain a more accurate simulation results, these factors should be taken into consideration while modeling a UPFC device.

Based on a practical circuit, a detailed simulation model of the UPFC is developed in this paper. The effectiveness and preciseness of the simulation model is verified. Using a simple power system with the UPFC as an example, the dynamic characteristics of the UPFC are studied in-depth. Since the main objective of the UPFC in a practical system is to enhance the transmission capacity and damp the power oscillation on a transmission line, the simulation study in this paper is also based on this control objective.

II. THE UPFC MODEL AND ITS VERIFICATION

Figure 1 shows the schematic diagram of the UPFC. The two converters in the diagram have the same structure except for the difference in their rated values. The magnitude and phase angle of the AC side output voltages of the two converters can be regulated according to the operational requirements of the system. So there are four control inputs: V_{emc}, V_{bmc}, δ_{ec} and δ_{bc}, as shown in Figure 1. In a practical system, the power flow of the transmission line, the voltage of the controlled bus, and the voltage on the DC link capacitor of the device itself can be controlled by regulating these four control variables.

The modeling process of a 6-pulse converter using switching function is derived from reference [4]. Assuming

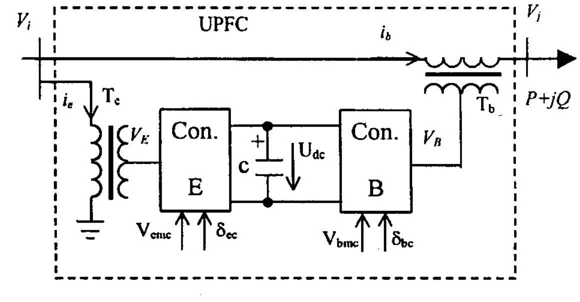

Fig. 1 Schematic Diagram of a UPFC

that the voltage on the capacitor is constant, it is known from the Fourier analysis that the AC side voltage output of the 6-pulse converter contains harmonics in the order of 6k±1(n=1,2,...), besides the fundamental wave. The lowest order of the harmonics is 5, and the magnitude of the harmonics is inverted to the order of the harmonics. This is not permitted in the practical system. In order to eliminate the low order harmonics, the Pulse Width Modulation (PWM) technique or Multi-pulse converter is often adopted in the practical systems. As an example, a 12-pulse converter is used in the UPFC model in this paper. The magnitude of the voltage output of the converter is regulated by means of vector synthesizing [5].

Based on a practical circuit of the 12 pulse converter, a detailed mathematical model of the UPFC is developed, and the mathematical model is realized by SIMULINK, a dynamic simulation tool in the MATLAB. In order to investigate the validity of the developed simulation model, a series of simulation experiments are designed as follows:

(i) Assuming U_{dc}=1, and the UPFC is not connected to the system (i.e., i_e=i_b=0), the simulation results are shown as Figure 2. From the AC side output voltages of converter E and the frequency spectrums, one can see that the simulation and theoretical results agree. The 12-pulse converter eliminates the 5^{th} and 7^{th} harmonics, but the magnitudes of the 11^{th} and the 13^{th} harmonics are still high. A higher pulse converter is required in the practical system.

(ii) To verify the magnitude and phase angle regulation characteristics of the converter, the control inputs, V_{emc} and δ_{ec}, are changed according to sinusoidal variation in the procedure of simulation. The simulation results in Figure 3 show that the outputs can track the control inputs with no time delay. As shown in Figure 3(a), when the control input is smaller than 0.5, the magnitude of the output is kept at 0.5. By so doing, the minimal output of the shunt converter is limited to 0.5.

(iii) By considering the shunt converter E, the variation of the voltage on the DC link capacitor is also studied by simulation. Controlling the output magnitude of the converter E to be 1 and the phase angle to be 0, at the same time setting the magnitude of AC side current i_e to 0.1, the variation trends of voltage U_{dc} are different when the angle between phasor i_e and V_E is different. Figure 4 shows the waveform of the charging current and the capacitor voltage for three different cases.

As shown in Figure 4, when the power factor angle φ=90°, the average charging current I_{dc} is 0, and the voltage on the capacitor remains unchanged. The larger the angle deviation from 90°, the greater the rate of change of voltage. The voltage changes to different directions with φ in different quadrants; this is consistent with the practical situation. Since the active power absorbed by the capacitor via converter E is in proportion to cosφ, when φ =90° and p=0, there is no active power exchange between the capacitor and the external system. As such, the voltage on the capacitor is constant. The active power p that is exchanged increases with the deviation of the power factor angle from 90°, thus the energy stored in the capacitor changes and the voltage on the capacitor changes accordingly. It follows that the voltage U_{dc} can be controlled by regulation of the power factor angle in the AC side of converter E.

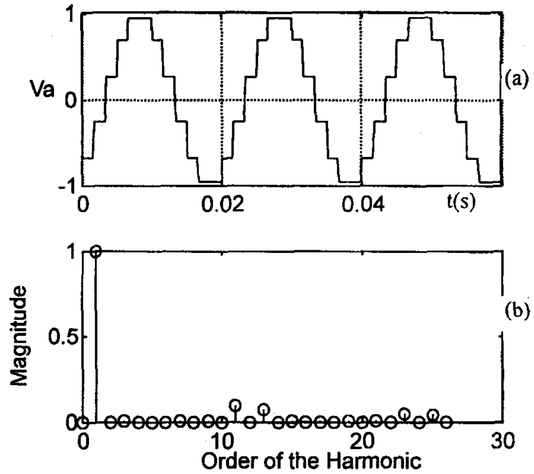

Fig. 2 Voltage Output of the 12-pulse Converter
(a) Output Waveform; (b) Frequency Spectrum

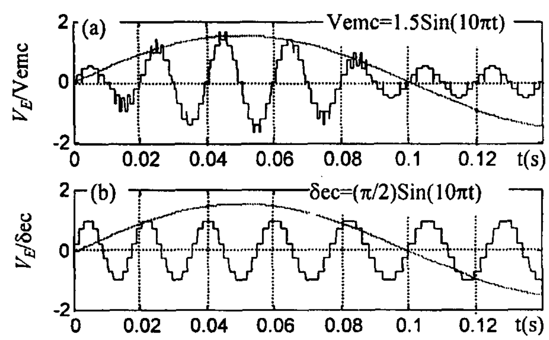

Fig. 3 Regulation of the Converter
(a) Magnitude Regulation; (b) Phase-angle Regulation

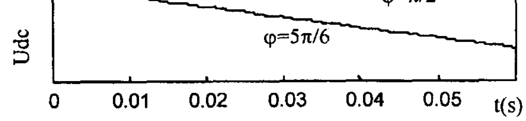

Fig. 4 Current and Voltage Waveforms of the Capacitor

III. A SIMPLE POWER SYSTEM WITH A UPFC

Consider a simple power system shown in Figure 5 with a double circuit transmission line. The UPFC is located at the mid-point and both sides of the transmission line are connected to the infinite bus systems.

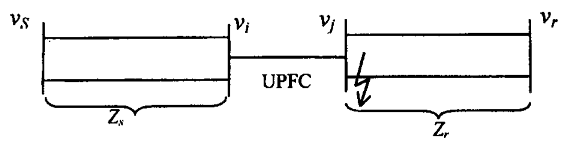

Fig. 5 A Simple Power System with UPFC

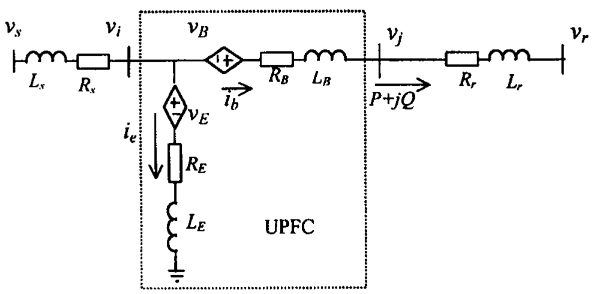

Fig. 6 The Equivalent Circuit of the Simple Power System with UPFC

In Figure 5, Zs and Zr represent the reactances of the transmission lines on both sides of the UPFC. Zs is equal to Zr in normal operating condition. A fault is simulated to study the dynamic behavior of the system. In order to investigate the operation of the UPFC under the most severe fault condition, consider a three-phase short-circuit on one of the transmission lines close to the right of the terminal bus of the UPFC.

To simplify the analysis, the susceptance of the transmission line is neglected. Under the normal operating condition, the equivalent circuit of the simple power system is shown in Figure 6. According to pertinent circuit laws, the circuit equation can be expressed as:

$$a\frac{di_e}{dt} = a_{11}i_e + a_{12}i_b - L_{rB}v_s - L_s v_r + L_{sr}v_E + L_s v_B \tag{1}$$

$$a\frac{di_b}{dt} = a_{21}i_e + a_{22}i_b - L_E v_s + L_{sE}v_r - L_s v_E - L_{sE}v_B \tag{2}$$

$$\begin{aligned} av_i = &(a_{11}L_E + aR_E)i_e + a_{12}L_E i_b \\ &- L_E L_{rB}v_s - L_E L_s v_r + (a + L_E L_{sr})v_E + L_E L_s v_B \end{aligned} \tag{3}$$

$$\begin{aligned} av_j = &a_{21}L_r i_e + (a_{22}L_r + aR_r)i_b \\ &- L_E L_r v_s + (a + L_r L_{sE})v_r - L_s L_r v_E - L_r L_{sE}v_B \end{aligned} \tag{4}$$

where $L_{rB}=L_r+L_B$; $L_{sE}=L_s+L_E$; $L_{sr}=L_s+L_B+L_r$; and

$a=L_s^2-L_{sr}L_{sE}$;

$a_{11}=L_{sr}(R_s+R_E)-L_sR_s$;

$a_{12}=L_{sr}R_s-L_s(R_s+R_r+R_B)$;

$a_{21}=L_{sE}R_s-L_s(R_s+R_E)$;

$a_{22}=L_{sE}(R_s+R_r+R_B)-L_sR_s$;

The parameters used in the simulation are given in the Appendix.

In Figure 6, the two controllable voltage sources, V_E and V_B, are the outputs of the UPFC model developed in section II, so they are not standard sinusoidal power sources. A PID control strategy is used to regulate the controllable parameters of the system. Due to space constraints, the structure of the model of the control circuit is not presented in this paper.

IV. SIMULATION STUDY ON THE NORMAL OPERATING CONDITION OF THE SYSTEM WITH UPFC

This section studies the static and dynamic characteristics of the system with the UPFC under normal operating condition (i.e., no disturbance), including the control effects of UPFC on various operational parameters and the dynamic response of the system when the reference values of the control input are being changed.

Case 1: It is assumed that there is no series control at the beginning of the simulation. The reference input of the shunt control is $V_{i\text{-ref}}=0.8$ and $U_{dc\text{-ref}}=1$, and the system is already in the steady-state. To investigate the control effects of the UPFC on the voltage of the controlled busbar, the reference input $V_{i\text{-ref}}$ is intentionally changed during simulation, i.e., $V_{i\text{-ref}}=1.1$ when t=0.1s~0.3s; $V_{i\text{-ref}}=1.0$ when t>0.3s. The simulation results are shown in Figure 7.

As shown in Figure 7, the voltage magnitude of the controlled busbar can track the variation of the reference input. The dynamic course of voltage regulation is fairly fast, and the influence of the regulator on the DC side voltage U_{dc} is slight and can be neglected.

Case 2: Keeping $V_{i\text{-ref}}=1.0$, and with the addition of the series control at t=0.1s with reference input $P_{ref}=1.0$ and $Q_{ref}=0.3$ to the system, the simulation results are shown in Figure 8.

As shown in Figure 8, the power flow is about 0.65+j0.1 when there is no series control; it is nearly up to the reference input of 1.0+j0.3 after the series control is added. This shows that the UPFC is able to regulate the power flow of a transmission line in a large range.

When series control is added to the system, the other two parameters controlled by the shunt converter, i.e., V_i and U_{dc}, are affected and fluctuate accordingly. Therefore, the control strategy to each system parameter should be uncoupled as fully as possible so as to reduce the mutual influence of the control effects.

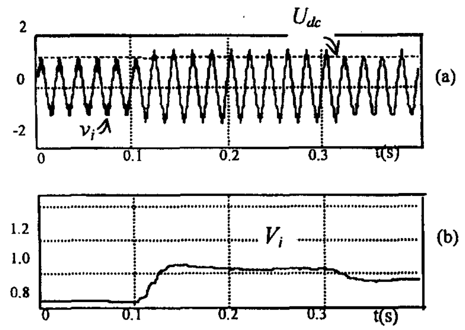

Fig. 7 The Simulation Result of the Bus Voltage Control
(a) The Waveforms of the Voltage of the Controlled Bus and the DC Side Bus
(b) The Magnitude of the Bus Voltage

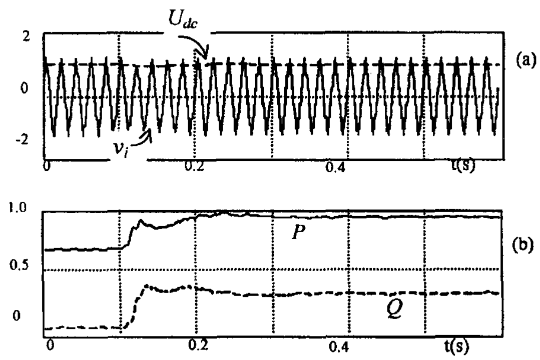

Fig. 8 The Simulation Result of the Power Flow Control
(a) The Waveforms of the Voltage of the Controlled Bus and he DC Side Bus
(b) The Power Flow of the Controlled Line

V. STUDY ON THE DYNAMIC CHARACTERISTICS OF THE SYSTEM WITH UPFC UNDER SEVERE DISTURBANCE

To investigate the dynamic characteristics of the power system with UPFC under a severe disturbance, a three-phase to ground short-circuit is simulated near the UPFC terminal bus at 0.1s, and the shorted line is removed at 0.2s

Assuming that the system is already in the steady-state before the disturbance occurs, and the reference inputs of the control circuit are $V_{i\text{-}ref}$=1.0, P_{ref}=1.0, Q_{ref}=0.3. The reference inputs are kept unchanged in the simulation procedure and the simulation results are shown in Figure 9.

Figure 9(a) shows the waveforms of the voltage of the controlled bus and the voltage of the DC link bus. Figure 9(b) shows the power flow on the transmission line. Figure 9(c) shows the current flowing through the series branch of the UPFC with and without UPFC control, respectively.

From the simulation results, one can draw the following conclusions:

(i) The DC link voltage can no longer be maintained constant when the system is disturbed severely. Thus the assumption that the DC link voltage is invariant in the transient procedure is no longer tenable. The range of fluctuation of the voltage is decided by the severity of the disturbance and the control strategy for the DC link voltage. In terms of the simple power system in this paper, the fluctuation will be reduced when the electrical distance between the UPFC and the fault point is increased. Figure 9(a) shows the most serious case of this simulation. In this case, the fluctuation of the voltage U_{dc} reaches as high as 1.5 times the rated value. This can give rise to failure of the system and the device itself. Certain measures should be adopted to avoid this while designing the control strategy for the system.

(ii) With the UPFC controller, the rest single line can still transmit the reactive power according to the reference input after the shorted line is removed, but the active power is slightly smaller than the reference input because that the regulating effect of the device has reached its rated limit.

(iii) From Figure 9(c), it is obvious that the current flowing across the series branch of the UPFC, when one of the lines is shorted, is much higher than the branch current during short-circuit without the UPFC controller. This is caused by the voltage and power flow control effects of the UPFC. In order to avoid the possible damage caused by the high short-circuit current, fast protective relays should be installed at the

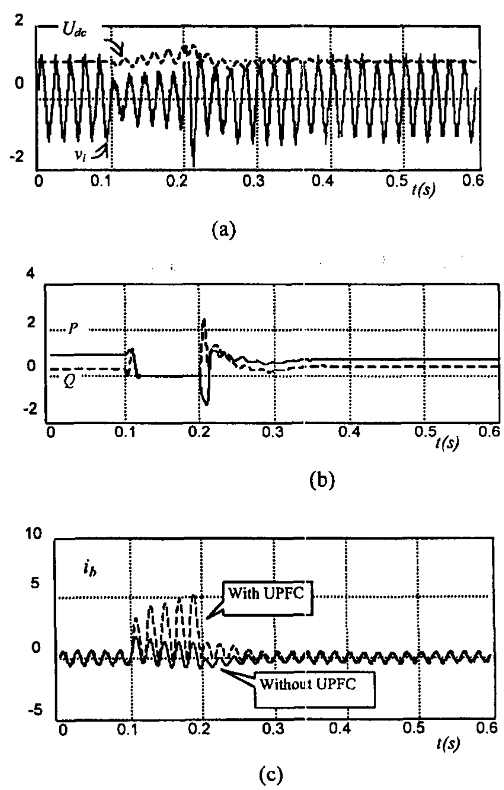

Fig. 9 The Simulation Results of the Simple Power System with UPFC Under Severe Disturbance

relevant location of the line in the practical system for rapid isolation of the faulty circuit. Another feasible way for this purpose is to design the control strategy of the UPFC so that the UPFC will change its control mode rapidly to limit the short-circuit current when a fault is detected.

VI. CONCLUSION

Based on MATLAB, a simple and effective digital simulator for the UPFC is developed. The UPFC simulator can be linked to the simulation program of an external power system conveniently so as to provide a necessary and effective method for future research work on the UPFC. The results from the simulation and analysis show that the UPFC simulator developed in this paper can reflect precisely the operational characteristics of the practical device.

The simulation results of the simple power system with the UPFC show that the UPFC can control the voltage and the power flow of the system effectively. The control strategy used in this paper is based on the need to maintain a desired power flow. Under this strategy, the DC link voltage will fluctuate severely and the fault current that flows through the UPFC series branch will increase remarkably when a short-circuit occurs on the line. All of these are likely to cause unfavorable effects on the power systems and should be taken into consideration in the operation of a practical system. The design of an overall control strategy to combine all of the desirable control objectives in one UPFC device is a prospective research project.

VII. ACKNOLEGEMENT

This research work was in part supported by Project Fund of PD9521907 and National Key Basic Research Special Fund (No. G1998020319) from China. Their financial assistance is gratefully acknowledged.

VIII. REFERENCES

[1] L. Gyugyi, C. D. Schauder, S. L. Williams, et al. The Unified Power Flow Controller: A New Approach to Power Transmission Control. IEEE Trans PWRD,10(2), April 1995.

[2] A. S. Mehraban, J. H. Provanzana, A. Edris, et al. Installation, Commissioning, and Operation of the word's First UPFC on the AEP System. Proceedings of 1998 International Conference on Power System Technology. Beijing, China. August 1998.

[3] M. Rahman, M. Ahmed, R. Gutman, et al. UPFC Application on the AEP System: Planning Considerations. IEEE Trans PWRS, 12(4), Nov 1997.

[4] A. Nabavi-Niaki, et al. Steady-state And Dynamic Models of Unified Power Flow Controller(UPFC) For Power System Studies. IEEE Trans on PS, 11(4), November 1996.

[5] Loren H. Walker. 10-MW GTO Converter for Battery Peaking Sevice. IEEE Trans. Industry Application, 26(1),Jan/Feb,1990.

IX. APPENDIX

System Parameters:

c	L_s	R_s	L_r	R_r	L_E	R_E	L_B	R_B
.01	.003	.05	.003	.05	.001	.02	.001	.02

Operating parameters:

Vs	Vr	Magnitude of V_E	Magnitude of V_B
$1\angle 60°$	$1\angle 0°$	0.5~1.5	0~0.5

X. BIOGRAPHIES

Sanbao Zheng received his B.Eng. and M. Eng. Degree in Electrical Engineering from Huazhong University of Science and Technology, China in 1992 and 1999, respectively. Now he is a research scholar in Nanyang Technological University, Singapore. His current research interests include power system control, FACTS, and power system simulation.

Yoke Lin Tan received the B.Eng. (Hons) degree in electrical engineering from the National University of Singapore in 1986. He received the D.I.C. and M.Sc. degree in control systems with a mark of distinction from the Imperial College of Science, Technology and Medicine, U.K. in 1992. He received the Ph.D. degree from the Nanyang Technological University of Singapore in 1999. Currently, he is an Associate Professor in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His current research interests include power system control and FACTS.

Shijie Cheng (M'1986, SM'1987) graduated from the Xi'an Jiaotong University, Xi'an, China in 1967 and received a Master of Engineering Degree from HUST, Wuhan, China in 1981 and a Ph.D. from the University of Calgary, Calgary, Canada in 1986 all in the Electrical Engineering. He is a full professor at HUST. His research interests are power system control, power system stability analysis and application of AI in power systems.

Yifeng Zhu was born in Nov., 1975. He received a Bachelor degrees and began his M.S. degree at the Huazhong University of Science & Technology (HUST), Wuhan, China, in 1997 and 1998 respectively, both in Electrical Engineering. His interest of research is power and control system, signal processing and power system stability.