

An Approach to Embed Power Flow Control Model of UPFC into PSASP Based on User Program Interface Function

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Abstract—The unified power flow controller (UPFC) is one of the most promising flexible AC transmission systems (FACTS) devices for the power flow control. The main objective of power flow control for UPFC is to improve the power flow distribution and increase the transmission capacity over the existing transmission corridor or line. This paper presents a practical engineering methodology of embedding the power flow control model of UPFC into the commercial software -- power system analysis software package (PSASP) based on its user program interface (UPI) function. In the proposed methodology, the interface currents of UPFC series side and UPFC shunt side between the UPFC device and the network are used to control the transmission line power flow and UPFC bus voltage, respectively. In UPFC series side, the current of UPFC series branch is calculated from the target equation of the power flow in the controlled line. In UPFC shunt side, the decoupling control between the active power and reactive power is implemented and the reactive current of UPFC shunt side is used to control the bus voltage. In this study, simulations are performed on a typical two-area power system and a practical 496-bus power system and simulation results show that the proposed methodology can be efficiently applied to the engineering research and analysis of the real power grid with UPFC with good convergence and with only one control parameter needed to be prescribed.

Index Terms--interface current; power flow control; UPFC; PSASP; UPI

I. INTRODUCTION

The unified power flow controller (UPFC) is the most versatile FACTS device [1]. The world's first UPFC has been installed at the Inez Substation of American Electric Power (AEP) in eastern Kentucky [2]. UPFC is able to control the bus voltage and power flow in the

transmission line simultaneously. Determination of system steady state operating solution or load flow control, in the presence of UPFC, is essential in power system operation and planning studies [3, 4].

In recent years a number of investigations have been carried out on various capabilities of UPFC such as power flow control [5-7] and oscillation damping [8, 9]. Moreover some neural network-based intelligent controllers [10, 11] have been developed in the literature.

In recent years there has been increasing interest in modeling of the UPFC in power flow. The objective of UPFC power flow control is to adjust the power flow distribution along the transmission corridor and to increase the transmission capability through controlling power flows along the designated corridor or the transmission line. Hence, it is expected to upgrade the existing power flow analysis program to include the behavior of UPFC devices.

Ref. [12] represents the power flow model of UPFC as the series coupling transformer impedance together with a set of active and reactive nodal power injection at each end of the series impedance. UPFC is represented as the two-source power injection model [13-15]. Moreover, UPFC model is incorporated into the existing power flow programs through constructing the modified Jacobin matrix [16, 17].

In order to reduce the workload of writing the program, Ref. [18-20] construct the power flow modeling of UPFC by use of the user-defined models of power system analysis software package (PSASP). However the method of user-defined models is not flexible enough because of the limitations of basic function blocks provided by PSASP. Compared with user-defined models, it is more flexible for user program interface function (UPI) provided by PSASP and it can participate in the

calculation of PSASP by writing the user program codes. Ref. [21] constitutes the power flow model of UPFC based on injected power method using the UPI function provided by PSASP, however some simplifications are made such as neglecting the impedance of series transformer.

This paper pays attention to the interface between the power flow control model of UPFC and power system analysis software package (PSASP) without modifying the original load-flow codes. This paper proposes a novel interface-current-based method to insert the power flow control model of UPFC into PSASP based on its UPI function [22] without making any simplifications and assumptions. Control performance of UPFC in a typical two-area power system and a practical 496-bus power system in China validated the effectiveness and correctness of the proposed method.

II. INTERFACE POWER FLOW CONTROL MODEL OF UPFC WITH PSASP

A. Basic Concept of UPFC

Fig.1 and Fig.2 show the basic structure of UPFC and its equivalent circuit, respectively. The UPFC consists of series and shunt voltage source converters, which can be modeled as controllable voltage sources. The series branch of the UPFC injects a voltage of controllable magnitude and phase angle via an injecting transformer, it can control the power flow along the transmission line and hence improve the power flow capability of the line. The shunt branch of the UPFC can independently exchange reactive power with the system to control the voltage of the connected bus, and absorbs the real power demanded by the series converter to maintain the constant voltage across the dc capacitor connected between the two converters.

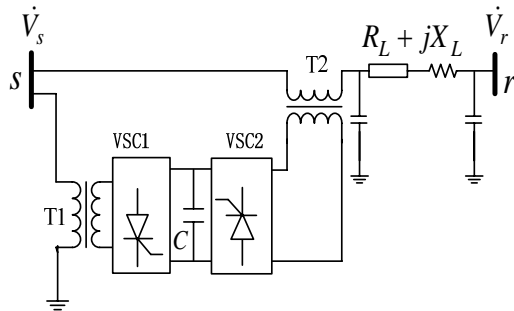


Figure 1. The basic structure of UPFC

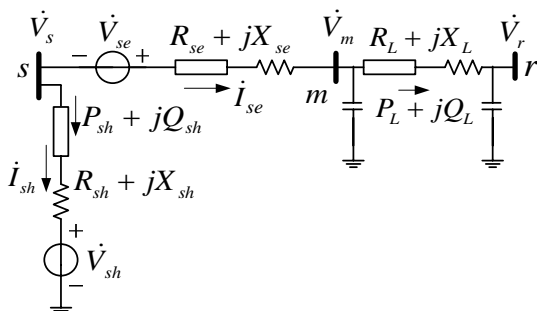


Figure 2. The equivalent circuit of UPFC

In Fig.2, the subscript sh and se denote the shunt side and series side of UPFC, respectively. \dot{V}_{sh} , \dot{I}_{sh} , \dot{V}_{se} and \dot{I}_{se} are the equivalent voltage and branch current of the shunt and series converters, respectively. R_{sh} , X_{sh} , R_{se} , X_{se} are the equivalent resistance and reactance of the coupling transformer T1 and T2, respectively.

B. Calculation of UPFC Series Side

UPFC series side can control the power flow of transmission line to the prescribed value through regulating the magnitude and phase of series injected voltage \dot{V}_{se} . As shown in Fig.2, when the voltage \dot{V}_s and \dot{V}_m are known, according to the reference value P_{Lref} and Q_{Lref} of the power flow of the controlled transmission line, the current of the UPFC series branch can be calculated by (1).

$$\dot{I}_{se} = \left(\frac{P_{Lref} + jQ_{Lref}}{\dot{V}_m} \right)^* \quad (1)$$

Then the series injected voltage \dot{V}_{se} can be obtained through (2).

$$\dot{V}_{se} = \dot{V}_m + \dot{I}_{se} (R_{se} + jX_{se}) - \dot{V}_s \quad (2)$$

The real power injected to the transmission line by the series converter can be calculated according to Eq. (3).

$$P_{se} = \text{Re} \left[\dot{V}_{se} \dot{I}_{se}^* \right] \quad (3)$$

C. Calculation of UPFC Shunt Side

The equivalent voltage \dot{V}_{sh} and current \dot{I}_{sh} of the UPFC shunt branch can be calculated by the following equations.

$$\begin{cases} \dot{V}_s = \dot{V}_{sh} + \dot{I}_{sh} (R_{sh} + jX_{sh}) \\ \text{Re} \left[\dot{V}_{sh} \dot{I}_{sh}^* \right] = \text{Re} \left[\dot{V}_{se} \dot{I}_{se}^* \right] = P_{se} \\ \dot{I}_{sh-q}^{(k+1)} = \dot{I}_{sh-q}^{(k)} + k_v (V_{s-ref} - V_s) \end{cases} \quad (4)$$

In (4), the first formula is the voltage equation of UPFC shunt branch, the second formula reflects the power balance relationship between the series and the shunt converters, which is a prerequisite to maintain the constant voltage across the dc capacitor. And the last formula employs the feedback control to the bus voltage through the reactive current component of the shunt current of the UPFC, where the superscript k+1 and k denote the iteration times, and k_v is the feedback coefficient of the voltage error.

The basic principle of the last formula in (4) is illustrated as follows. An important function of the shunt side of the UPFC is to maintain the voltage of the connected bus constant. Let \dot{V}_s be in phase with the d-axis, the phasor diagram of UPFC shunt branch is represented

as Fig.3, where I_{sh_d} and I_{sh_q} are the d-axis and q-axis components of UPFC shunt current, and θ_s is the angle of the bus voltage \dot{V}_s .

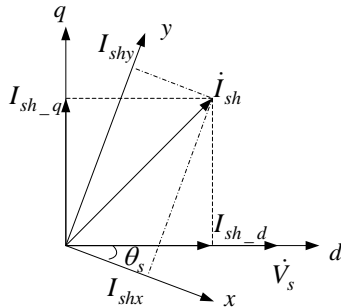


Figure 3. The phasor diagram of UPFC shunt branch

Based on the instantaneous power theory, the active power and reactive power absorbed by the UPFC shunt converter from the system can be expressed as:

$$\begin{cases} P_{sh} = \dot{V}_s \cdot \dot{I}_{sh} = V_{sd} I_{sh_d} + V_{sq} I_{sh_q} \\ Q_{sh} = \dot{V}_s \times \dot{I}_{sh} = V_{sq} I_{sh_d} - V_{sd} I_{sh_q} \end{cases} \quad (5)$$

As \dot{V}_s is in phase with the d-axis, so the d-axis component $V_{sd} = V_s$ and q-axis component $V_{sq} = 0$, therefore (1) can be simplified as:

$$\begin{cases} P_{sh} = V_s I_{sh_d} \\ Q_{sh} = -V_s I_{sh_q} \end{cases} \quad (6)$$

It can be seen from (6) that the decoupled control between the active power and reactive power is realized through the d-q transformation, and that the reactive power Q_{sh} can be controlled by the reactive current component I_{sh_q} .

When $I_{sh_q} > 0$, $Q_{sh} < 0$, the UPFC shunt converter supplies the reactive power to the system and then the bus voltage will be boosted; when $I_{sh_q} < 0$, $Q_{sh} > 0$, the UPFC shunt converter absorbs the reactive power from the system and the bus voltage will be reduced.

Hence, the reactive current of UPFC shunt branch can be calculated according to the error between reference voltage V_{s_ref} and actual bus voltage V_s as shown in the last formula in (4).

D. Inserting UPFC Model into PSASP Based on UPI Function

PSASP is powerful commercial software, which provides the electromechanical simulation environments as well as user program interface (UPI) function. The UPI function provided by PSASP makes PSASP significant difference from other commercial software, which allows incorporating new power system component into PSASP such as FACTS device with less workload of developing the new program through writing the user program (UP). The UP can be written in C++ language and converted into the dynamic link library, which is called by the load-

flow program (LP) or the transient stability program of PSASP in order to finish one calculation task.

In order to embed the power flow control model of UPFC into PSASP, the UPFC installed on the transmission line is removed from the grid with the interface currents \dot{I}_{s_inj} and \dot{I}_{m_inj} injected to the node-s and node-m as shown in Fig.4.

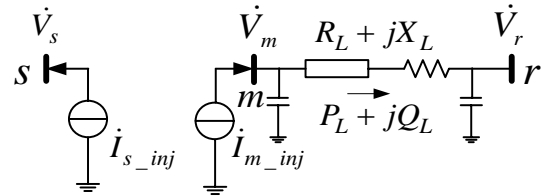


Figure 4. The current injection model of UPFC

According to Fig.2 and Fig.4, the interface currents \dot{I}_{s_inj} and \dot{I}_{m_inj} can be expressed as:

$$\begin{cases} \dot{I}_{s_inj} = -(\dot{I}_{se} + \dot{I}_{sh}) \\ \dot{I}_{m_inj} = \dot{I}_{se} \end{cases} \quad (7)$$

The power flow along the transmission line and the voltage of the connected bus can be controlled to the preset reference value through regulating the interface currents \dot{I}_{s_inj} and \dot{I}_{m_inj} , which are calculated based on \dot{I}_{se} and \dot{I}_{sh} as shown in (7). The calculation steps of the interface currents are illustrated in Fig. 5.

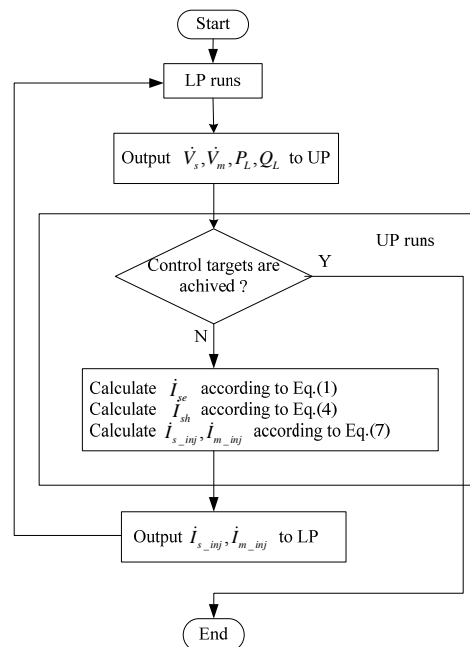


Figure 5. The flow chart of alternate solution between LP and UP

The load-flow program (LP) of PSASP and the user program (UP) developed by the user are solved alternately until the control objectives are achieved. The interface variables between LP and UP include: the complex voltage of node-s and node-m \dot{V}_s and \dot{V}_m , the power flow of the controlled transmission line P_L and Q_L , and the

injected currents of node-s and node-m \dot{I}_{s_inj} and \dot{I}_{m_inj} .

The LP transfers the data \dot{V}_s , \dot{V}_m , P_L and Q_L to the UP, \dot{I}_{s_inj} and \dot{I}_{m_inj} calculated from UP are transferred back to the LP. The flow chart of alternate solution between LP and UP is shown in Fig. 5.

III. CASE STUDY

A. Two-area Power System

A two-area power system as shown in Fig.6 is firstly used to verify the proposed approach of embedding the power flow control model of UPFC into the commercial software PSASP without modifying the original load flow codes. The parameters of the two-area system are the same as in [23] except that the impedances of line 8-9 and line 12-9 are modified, and the modified line parameters are shown in Table I.

Without UPFC, the voltage magnitude of bus 8 is 0.9894 p.u., while the power flows of line 8-9 and line 9-12 are 0.2558-j0.05953 p.u. and 0.1705-j0.03967 p.u. respectively. It can be seen that without UPFC the power flow distributions of the transmission lines are determined by the reciprocal value of the line impedance and line 8-9 has larger real power flow than line 12-9.

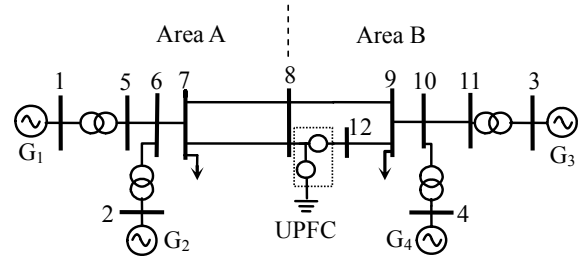


Figure 6. Two-area power system

TABLE I.
Modified parameters of double lines 8-9

	R(p.u.)	X(p.u.)	B/2(p.u.)
Line 8-9	0.0330	0.330	0.03210
Line 12-9	0.0495	0.495	0.02138

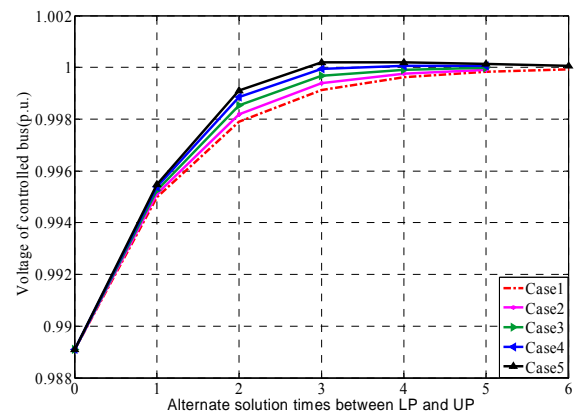
In order to balance the power flow of line 8-9 and line 12-9, one UPFC is installed on line 12-9 as shown in Fig.6. The reference voltage of bus 8 and the reference reactive power of line 12-9 are set as follows: $V_{8ref}=1.0$ and $Q_{Lref_line\ 12-9}=-0.03967$ p.u. (the reactive power is set to the original value without UPFC). Then the reference active power of line 12-9 is increased until the power flows along line 8-9 and line 12-9 are balanced. Here control precisions of the bus voltage and line power flow are both set at 0.0001, the voltage feedback coefficient k_v is set at 2.0. Control results are shown in Table II.

TABLE II.
Control results with UPFC installed on Line 12-9

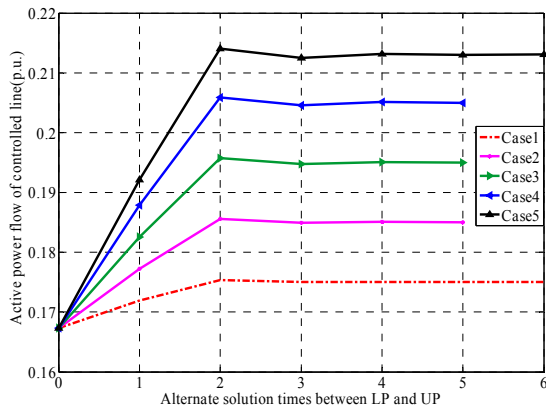
	Control references			Control results			Series voltage	Comparisons of active power		
	V_{sref} (p.u.)	P_{Lref} (p.u.)	Q_{Lref} (p.u.)	V_s (p.u.)	P_L (p.u.)	Q_L (p.u.)	\dot{V}_{se} (p.u. \angle°)	$P_{Line\ 8-9}$ (p.u.)	$P_{Line\ 12-9}$ (p.u.)	P_{Total} (p.u.)
Case 1	1.0	0.17500	-0.0397	0.99993	0.17501	-0.03969	0.0099 \angle 128.75	0.17501	0.25102	0.42603
Case 2	1.0	0.18500	-0.0397	0.99990	0.18500	-0.03968	0.0173 \angle 110.81	0.18500	0.24104	0.42604
Case 3	1.0	0.19500	-0.0397	0.99998	0.19500	-0.03970	0.0254 \angle 104.45	0.19500	0.23104	0.42604
Case 4	1.0	0.20500	-0.0397	1.00006	0.20498	-0.03972	0.0338 \angle 101.39	0.20498	0.22112	0.42610
Case 5	1.0	0.21307	-0.0397	1.00006	0.21308	-0.03971	0.0406 \angle 100.20	0.21308	0.21307	0.42615

It can be observed from TABLE II that UPFC can track the control targets very well. It can be seen from the column of comparisons of active power of Table II that the active power flow of line 12-9 will decrease when the active power flow of line 8-9 is controlled to increase. However the total power flow of line 8-9 plus line 12-9 almost keeps constant. When the active power flow of line 8-9 reaches 0.21308 p.u., the power flow of line 8-9 equals to that of line 12-9, which shows that UPFC can adjust the power flow distribution along the transmission corridor.

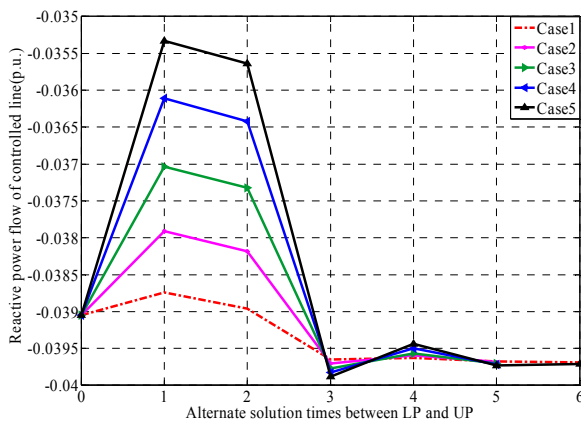
Variation curves of controlled bus voltage and power flow of controlled line of the two-area power system are illustrated in Fig.7. It can be seen that the proposed method has fast convergence speed with at most six alternate iterations between LP and UP.



(a) Variation of the voltage of bus 8 with alternate times



(b) Variation of the active power of line 12-9 with alternate times



(c) Variation of the reactive power of line 12-9 with alternate times

Figure 7. Variation curves of controlled bus voltage and power flow of controlled line of two-area power system

B. Real Power System in China

A real 496-bus power system in China is also studied. The local map of the real power system is shown in Fig.8. The double lines NINGDE-YANGZHONG have completely identical parameters, and the thermal current of single line NINGDE-YANGZHONG is 2700 A. Without UPFC, the voltage magnitude of bus NINGDE is 1.019 p.u., while the power flow of double lines NINGDE-YANGZHONG is $777.05+j13.35$ MVA, which is far less than the thermal capacity of the line.

Now two UPFCs are installed at the NINGDE side of double transmission lines NINGDE-YANGZHONG in order to increase the active power transmission capacity of the double lines. The maximum magnitude of the series injected voltage of UPFC is set to 0.1 p.u. Set the

reference voltage of bus NINGDE and the reference reactive power of the controlled double lines to the level before UPFCs are installed, that is, $V_{sref}=1.019$ p.u. and $Q_{Lref}=13.35$ Mvar, then increase the reference active power to the different level, the control results are shown in Table III. Here control precisions of the bus voltage and line power flow based on per-unit value are both set at 0.005, the voltage feedback coefficient k_v is set at 0.75.

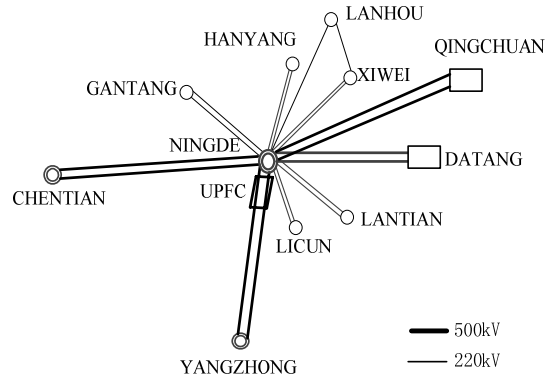


Figure 8. The local map of the real power grid in China

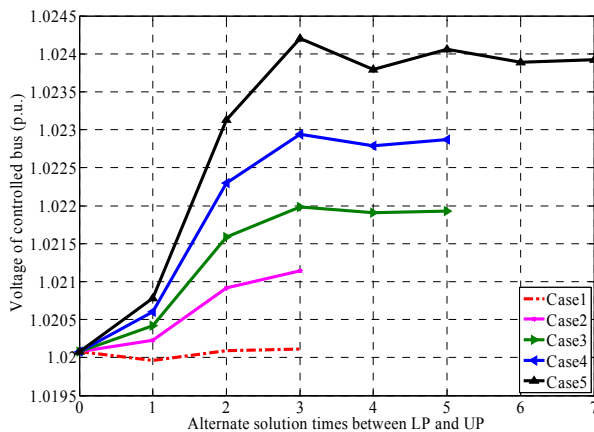
As shown in Table III, with the increase of active power of the controlled double line, the magnitude of series injected voltage increases and the voltage of bus NINGDE and the reactive power of the double line are controlled well at the preset reference values. When the control ability of UPFC reaches the limit with the magnitude of the series injected voltage at maximum 0.1, the active power of the double line is controlled at 1508MW. The results show the powerful control ability of UPFC compared to the original active power of 777MW of the double line NINGDE-YANGZHONG without UPFC, and verify the correctness and effectiveness of the power flow control method proposed for UPFC.

For Case 1–Case 5 shown in Table III, the variation curves of controlled bus voltage and the power flow of the controlled line with the alternate solution times between LP and UP are shown in Fig. 9. It can be seen from Fig. 9 that the power flow control method for UPFC proposed in this paper has good convergence, and that the bus voltage and the power flow can track the reference values quickly with at most seven iterations. Especially the active power flow reaches the reference value with only two iterations between LP and UP, which is because the power flow of the line is controlled directly based on the power flow target equation of the controlled line.

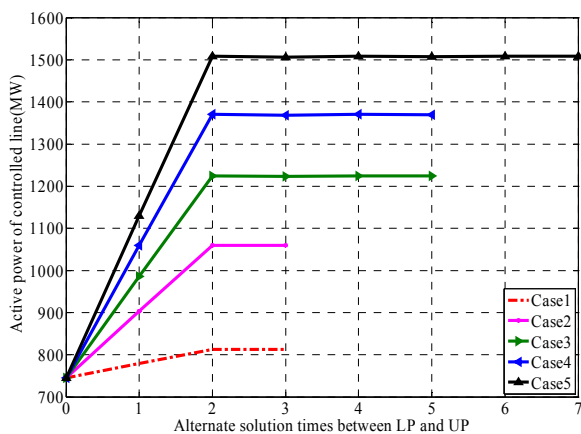
TABLE III.
Control result of UPFC installed on NINGDE—YANGZHONG double lines

	Control references			Control results			Control variables of each UPFC
	V_{sref} (p.u.)	P_{Lref} (MW)	Q_{Lref} (Mvar)	V_s (p.u.)	P_L (MW)	Q_L (MVar)	\dot{V}_{se} (p.u. \angle°)
Case 1	1.019	812	13.35	1.0201	812.00	13.35	0.0087 \angle 85.2
Case 2	1.019	1060	13.35	1.0211	1059.46	13.06	0.0411 \angle 89.6

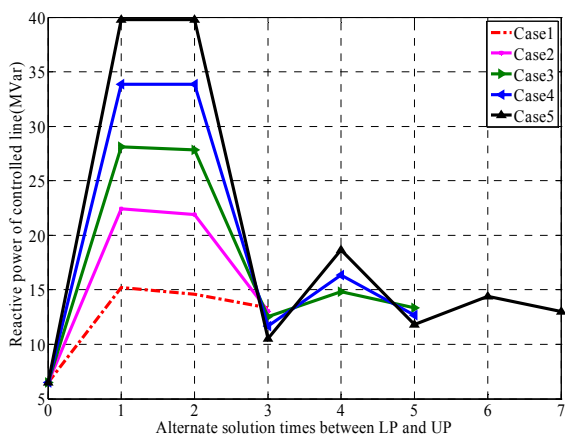
Case 3	1.019	1224	13.35	1.0222	1224.00	13.35	0.0626∠91.8
Case 4	1.019	1370	13.35	1.0232	1369.72	12.69	0.0818∠92.7
Case 5	1.019	1508	13.35	1.0244	1507.89	13.00	0.0999∠93.8



(a) Variation of the voltage of bus NINGDE with alternate times



(b) Variation of the active power along double line NINGDE—YANGZHONG with alternate times



(c) Variation of the reactive power along double line NINGDE—YANGZHONG with alternate times

Figure 9. Variation curves of controlled bus voltage and power flow of controlled line of the real power system in China

IV. CONCLUSION

Power flow control is the basic control function for UPFC. This paper proposes a novel interface-current-

based method of embedding UPFC power flow model into the commercial software –PSASP by using the user program interface function provided by PSASP. In the proposed method, the load-flow program (LP) of PSASP and the user program (UP) are solved alternately through regulating the interface currents between the UPFC device and the network until the control objectives of UPFC are achieved.

Case studies on a typical two-area power system and a real power system show that the proposed method of power flow control for UPFC has the good convergence characteristics without taking any assumptions and simplification, and that the proposed method is easy to implement in engineering application with only one preset control parameter.

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