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A STUDY OF INTERLINE POWER FLOW ANALYSIS BASED ON A NEW MATHEMATICAL MODEL OF INTERCONNECTED POWER SYSTEM WITH IPC

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ABSTRACT: At present, a large parts of power networks are connected by AC tie-lines. Yet, there are some problems in the operation of AC interconnected power systems, such as fault spreading and the power fluctuation on tie-line. As a new FACTS device, IPC has several advantages such as fault current restriction and the robust control of tie-line power flow. After taking action to enhance the synchronous ability, IPC can play well effects to control tie-line power flow of interconnect power systems.

Based on IPC network analytic equation, tracking estimation technology of Thevenin equivalent parameters for area network and the short-time-step dynamic power flow considering the frequency difference of area network, a mathematical model of frequency decoupling is established in this paper. Wholly considering the facts such as tie-line transmission capacity, port voltages of sending and receiving networks, the voltages of IPC capacitor and reactor, the parameter preferences are given. And the strategy of changing IPC parameters is used to control the tie-line power. The simulation of North China and Northeast interconnected power system is emulated to validate the proposed methods and to analyze the relative slippage between the two subsystems.

Key Words: Flexible AC Transmission Systems, Interphase power controller (IPC), Interconnected power systems, Power flow control

I. Introduction

As general trends of many countries in the world, building a nationwide interconnected power system is a strategic target of China for competition and co-operation in international deregulatory electric power market in the new century [1,2]. The advantages and disadvantages of AC or DC scheme have been studied in detail by domestic groups. DC link can isolate disturbances, and DC link power flow control and power exchanges are relatively easy than that of AC. However, a large AC interconnected systems is more robust, lower cost and can share fluctuations caused by load variation or disturbances, as well as share power reserve [3,4]. A common view is that some big region networks can be connected with infirm ones by FACTS devices with AC circuit during the early stage of interconnecting in China.

As a new FACTS instrument, IPC is based on the series connection of impedances between different phases of the two networks to be interconnected. By adjusting the value of IPC parameters, the current in each network can be forced and thus enables the power carried by the IPC to be set. Furthermore, IPC has several advantages in power flow control such as robustness, fault current restriction and tie-line power flow control. After taking action to enhance the synchronous ability, IPC can play well effect to control tie-line flow of interconnect power systems [5~7].

In order to meet future demands, the interconnection between North China and Northeast power system is in operation since the electric loads in North China increase rapidly and Northeast power system is abundant in energy generation. In this paper, a mathematical model is firstly established by the nonlinear Thevenin equivalent method in Section II. Secondly, the relationship between the network and IPC parameters is provided by circuit analysis in Section Ⅲ. Thirdly, the control strategy of IPC parameters is analyzed in Section Ⅳ. Fourthly, the control strategy and some faults are simulated, such as short-circuit of low-level voltage node, units out of operation and branch line breaks in North China network in Section V. Finally, conclusions are discussed in Section VI.

II. Nonlinear Thevenin Equivalence

As shown in Fig.1, the interconnected power system is composed of two subsystems and one tie-line with IPC. Sometimes the weak interconnection might be preferable for some interconnection projects. Studies show that weak interconnection between regional systems may cause stability problems, especially in the edge area of subsystems. In this section, a new nonlinear Thevenin equivalent methodology is presented to analyze the above questions.

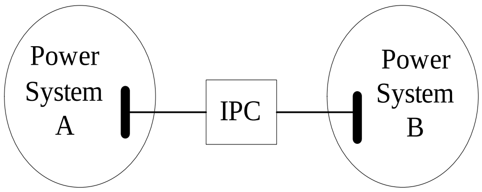

Fig.1 Power system interconnect with IPC

The output port of sending subsystem and the input port of receiving side can be denoted as two equivalent nodes, respectively [8]. Between the equivalent node and the geoelectric node, Thevenin equivalence represents the power system with an electric resource and impedance as in Fig.2.

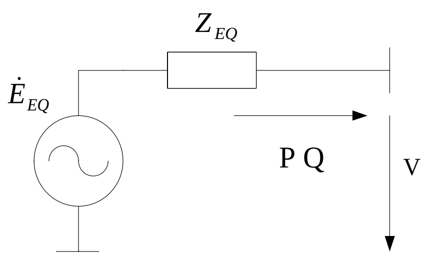

Fig.2 Thevenin equivalent circuit

In this paper, the export active power and the reactive power are regarded as positive. With the changing of tie-line power flow, P and Q may be positive or negative. In the Fig.3, the solid line represents that P and Q have the same sign, and P and Q have the different signs for the dot line.

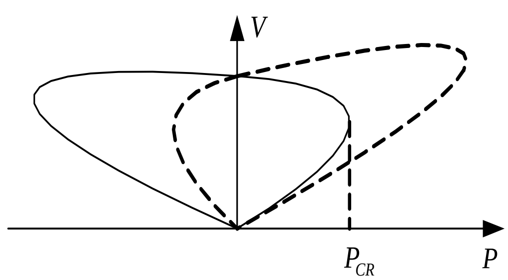

Fig. 3 Extended P-V curves of equivalent circuit

The expression (1) corresponds to the extended P-V curves of the equivalent circuit above. The solid line in the first quadrant is the normal P-V curve in circuit theory.

$$V = E_{eq}\sqrt{\frac{S(P) \pm \sqrt{S^2(P)-1}}{2\frac{P_{cr}}{P}(1+u)}} \tag{1}$$

Where:

$$\begin{aligned} S(P) &= \frac{P_{cr}(1+\cos(\phi_{eq}-\phi))}{P} - \cos(\phi_{eq}-\phi) \\ &= (\frac{P_{cr}}{P}-1)u + \frac{P_{cr}}{P} = Au + B \end{aligned} \tag{2}$$

$$P_{cr} = \frac{E_{eq}^2 \cos\phi}{2Z_{eq}(1+\cos(\phi_{eq}-\phi))} \tag{3}$$

$$u = \cos(\phi_{eq}-\phi) \tag{4}$$

Where E_{eq} is the equivalent electrical voltage, Z_{eq} is the value and ϕ_{eq} is the angle of the equivalent impedance. P_{cr} is the critical power and ϕ is defined as $\arctan(\frac{P}{Q})$.

Around the operating node A, two neighboring nodes are selected as short segment of P-V characteristics curve in Fig.4.

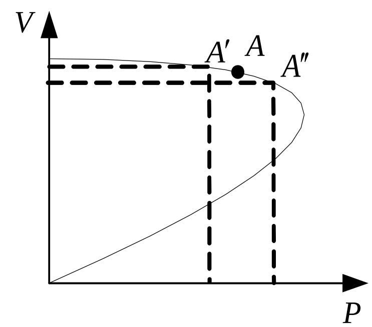

Fig. 4 Operating node selection

The parameters of the three nodes can be obtained by power flow calculation. And the ratio function between the operation and neighboring nodes is given by the following expressions.

$$Y_m' = \frac{[S(P) \pm \sqrt{S^2(P)-1}]}{[S(P') \pm \sqrt{S^2(P')-1}]} - \frac{V^2 P'}{V'^2 P} = 0 \tag{5}$$

$$Y_m'' = \frac{[S(P) \pm \sqrt{S^2(P)-1}]}{[S(P'') \pm \sqrt{S^2(P'')-1}]} - \frac{V^2 P''}{V''^2 P} = 0 \tag{6}$$

In order to evaluate the Thevenin equivalent parameters, Jacobian matrix (see expression 7) is established and the respective differential coefficients (ΔP_{CR}, $\Delta\mu$) satisfy the expression (8).

$$[J] = \begin{bmatrix} \frac{\partial Y_m'}{\partial\mu} & \frac{\partial Y_m'}{\partial P_{CR}} \\ \frac{\partial Y_m''}{\partial\mu} & \frac{\partial Y_m''}{\partial P_{CR}} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} \Delta\mu \\ \Delta P_{CR} \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta Y_m' \\ \Delta Y_m'' \end{bmatrix} \tag{8}$$

Selecting the proper initial value, we cannot revise the intermediate parameters (P_{CR} and μ) by solving Jacobian matrix of working variables in an iterative manner until Y'_m and Y''_m are close to zero. And then, the Thevenin equivalent parameters can be deduced from expressions (1), (3) and (4).

This method can track and estimate the system equivalent parameters more accurately, and the influence of the nonlinearity of the power system is also considered. The method possesses a good numerical stability, and can be applied to the equivalence of any side of interconnected networks connected by a tie-line with IPC.

III. Simplified Mathematical Model

The two complex subsystems in Fig.1 can be simplified by the method in section Ⅱ. And the equivalent system is presented in Fig.5.

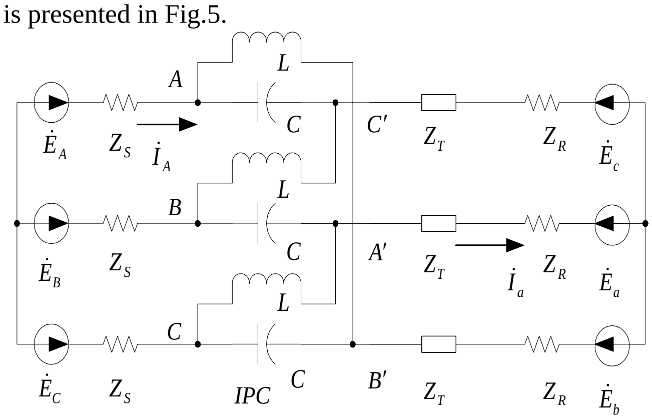

Fig.5 Structural diagram of power system with IPC

Generic circuit of IPC is established and the vector relation is analyzed based on the simple circuit [9,10]. After some mathematical transformation, the following expressions are obtained.

$$Z_M = X_L X_C + X_L Z_S + X_C Z_S + (Z_T + Z_R)(3Z_S + X_L + X_C) \quad (9)$$

$$\dot I_a = [(X_L e^{-j\frac{2\pi}{3}} + X_C e^{-j\frac{4\pi}{3}})\dot E_A - (3Z_S + X_L + X_C)\dot E_a]/Z_M \quad (10)$$

$$\dot V_a = \dot E_a + \dot I_a Z_R \quad (11)$$

$$S_a = \dot V_a \hat{\dot I}_a \quad (12)$$

$$\dot I_A = [(3Z_T + 3Z_R + X_L + X_C)\dot E_A - (X_L e^{-j\frac{\pi}{3}} + X_C e^{j\frac{\pi}{3}})\dot E_a]/Z_M \quad (13)$$

$$\dot V_A = \dot E_A - \dot I_A \dot Z_S \quad (14)$$

$$S_A = \dot V_A \hat{\dot I}_A \quad (15)$$

$$\dot V_L = \{[\sqrt{3}X_L(Z_T + Z_R)e^{-j\frac{\pi}{2}} - X_L X_C e^{j\frac{2}{3}\pi}]\dot E_A + [\sqrt{3}X_L Z_S e^{j\frac{\pi}{6}} + X_L X_C]\dot E_a\}/Z_M \quad (16)$$

$$\dot V_C = \{[\sqrt{3}X_C(Z_T + Z_R)e^{j\frac{\pi}{2}} - X_L X_C e^{-j\frac{2}{3}\pi}]\dot E_A + [\sqrt{3}X_C Z_S e^{j\frac{\pi}{6}} + X_L X_C]\dot E_a\}/Z_M \quad (17)$$

Where

$\dot V_a$: Voltage of input port in receiving subsystem

$\dot I_a$: Current of tie-line on receiving side

S_a : Receiving Power of subsystem B

$\dot V_A$: Voltage of output port in sending subsystem

$\dot I_A$: Current of sending subsystem

S_A : Sending Power of subsystem A

$\dot V_L$: Voltage on the reactor of IPC

$\dot V_C$: Voltage on the capacitor of IPC

$\dot E_A$: Equivalent electrical source of sending subsystem

Z_S : Equivalent impedance of sending subsystem

$\dot E_a$: Equivalent electrical source of receiving subsystem

Z_R : Equivalent impedance of receiving subsystem

X_L : Impedance of reactor

X_C : Impedance of capacitor

Z_T : Impedance of tie-line

The relation of the IPC parameters to the interconnected power system is given in expressions (9)-(17), which can be applied to the tie-line power flow control.

IV. Control Strategy

During the normal disturbance, the relative phase slippage varies with the change of the load frequency between the power systems on both sides of the tie-line. While the loads of the two sides vary abnormally, the phase deviation turns larger because of the difference of the frequency variable step. The fluctuations of the tie-line power may work in the adaptable area (the left area of y-axis in Fig.6, $dP_{AR}/d\delta > 0$), which is in favor of the synchronous operation. On the other hand, in the right inadaptable area ($dP_{AR}/d\delta < 0$), perhaps, the two networks operate in the asynchronous state. To avoid the above situation, a control strategy of adjusting IPC parameters is proposed in Fig.6 to keep the tie-line power flow in the right scope. The strategy is based on the complex power system Thevenin equivalence, simplified mathematical circuit with IPC and the short-time- step dynamic power flow considering the frequency difference between the two subsystems.

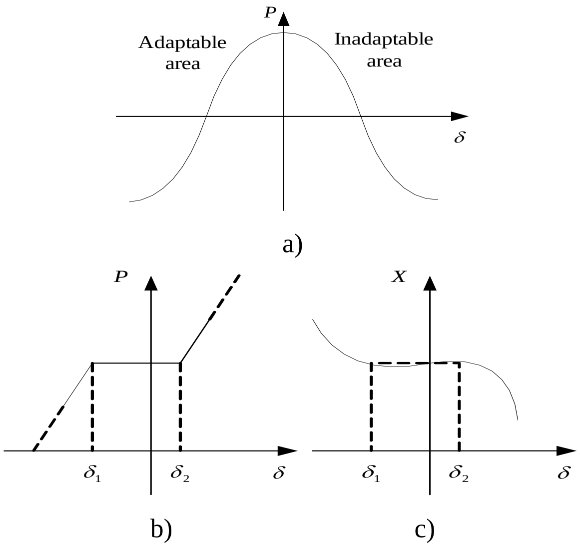

Fig.6 Control strategy of IPC parameter

According to the difference of phase angle, the $P-\delta$ curve of IPC is shown in Fig.6 (a), and the control curve of IPC parameters can be obtained as Fig.6 (b) because of the robust power control advantage of IPC. In the (δ_1, δ_2) region, the tie-line power remains constant and the generators operate on the state of each side. In the other region, the tie-line power is enhanced to guarantee the synchronization of both subsystems by adjusting the IPC parameters. The corresponding control equation is as follows:

$$P(x)=\begin{cases} P+k_1(\delta-\delta_2) & (\delta>\delta_2) \\ P & (\delta_1 \le \delta \le \delta_2) \\ P-k_2(\delta+\delta_1) & (\delta<-\delta_2) \end{cases} \quad (18)$$

Where k_1 and k_2 are the control coefficients. In theory, the region is $-25° < \delta_1 < \delta_2 < 25°$. To ensure that IPC operates in the adaptable area δ_2 is selected nearby zero. In the Fig.6(c), the reactance curve of IPC parameters is given based on the fuzzy control technology.

V. Simulation results of the interconnected system between North China and Northeast China with IPC

Founded on the IPC circuit model, it assumes that IPC is equipped on SuiZhong port of the tie-line of the northeast and north network with the former as sending network while the latter as receiving one. SuiZhong node is selected as the equivalent node in the Northeast network and Jiangjiaying node as the equivalent node of the North, and the two sides are equaled by the Thevenin equivalent method as section Ⅱ. The primary control goal is to ensure tie-line interchanges from the given area around the scheduled values. The regulation is executed by changing the IPC parameters. Detailed simulations are studied based on the proposed interconnection schemes, taking applications of IPC into account. And the effect of variety faults at two ends of the line is discussed.

In this paper, reactors and capacitors of IPC are always considered to be ideal without reactance and any losses. To analyze the influence of tie-line power flow by changing IPC parameters, we consider the value of IPC parameters could be varied continuously. The unitage of S_B is 500KV and V_B is 100MVA. Based on the expressions in section Ⅲ, the initial reactance of capacitors and reactors are selected for 0.34 p.u [11]. All the relevant data satisfy the operation conditions as follows, sending port voltage (1.09424), receiving port voltage (0.913793), reactor voltage of IPC (1.050064), capacitor voltage of IPC (0.290358).

In Table 1, the equivalent parameters (E_{EQ}, Z_{EQ}, ψ_{EQ}) and the tie-line power flow (P_T, Q_T) in four states are listed to compare the difference from each other by the method proposed in section Ⅱ and the formula in section Ⅲ.

The four simulated states are as follows:

A: Normal operation state

B: State after short current at Wangfujing node in North China subsystem

C: State after generators suspend at Yangliuqing node in North China subsystem

D: State after open circuit at branch from Hangu to Beijiao in North China subsystem

TABLE.1 EQUIVALENT PARAMETERS AND TIE-LINE POWER FLOW UNDER DIFFERENT STATES

	E_{EQ}	Z_{EQ}	ψ_{EQ}	P_T	Q_T
A	1.05380	0.034969	78.52036°	6.02053	0.90247
B	1.05398	0.034973	78.53497°	6.07501	0.87133
C	1.05372	0.034981	78.47664°	6.15005	0.83917
D	1.05367	0.034972	78.52439°	6.15045	0.87334

In Fig.7, three faulty states (B, C and D) are compared with the normal state (A) respectively. And the thin columns are the values of the branch flow nearby the faulty node and the thick one (TL) is the tie-line power flow. To show the variety of the power more effectively, the ratio of actual power to limit value is calculated as the y-axis of Fig.7.

During the normal disturbance, the relative phase slippage varies with the change of the load frequency between the power systems on both sides of the tie-line. While the loads of the two sides vary abnormally, the state of the relative phase slippage may be turned into asynchronous state because of the difference of the frequency variable step.

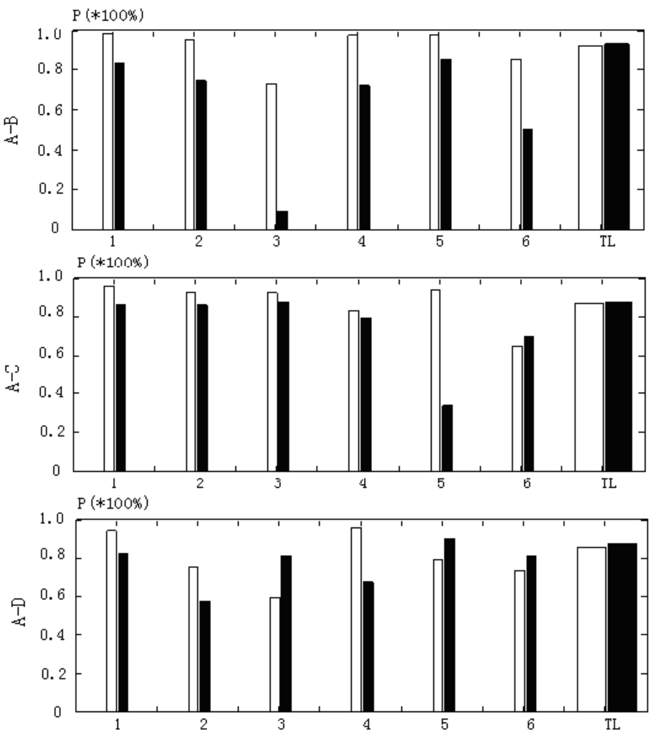

Fig.7 Comparative column of different faulty state with normal state

It can be seen from Table 1 and Fig.7, during the external faults, the tie-lie transmitting power remains close to the normal state while the branch flow nearby the fault node varies observably. The decoupling effect and the advantage to limit the short current of IPC are illustrated.

The control strategy in section Ⅳ is used to adjust the IPC parameters to remain the tie-line power in the scheduled scope. To simulate the situation of load variety, the load of North subsystem vary randomly in a little scope all the time and the Northeast one decreases 2 percent of the whole load from 10 to 70 seconds to make IPC operate in the inadaptable area (which is shown in Fig.8). In the course of simulation, the control coefficients satisfy the condition:

$$k_1 = k_2 = 0.1, \delta_1 = -18°, \delta_2 = 3°$$

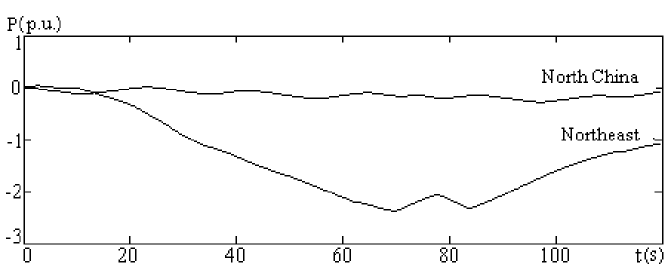

Fig.8 Load variety of both sides power systems

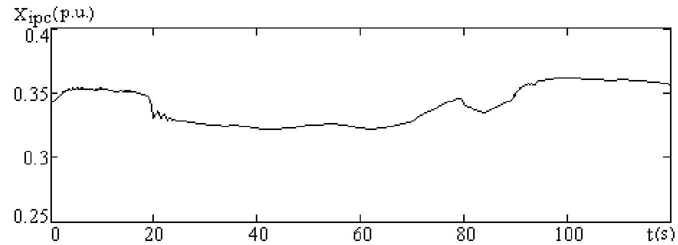

Fig.9 Variety of tuned IPC parameter

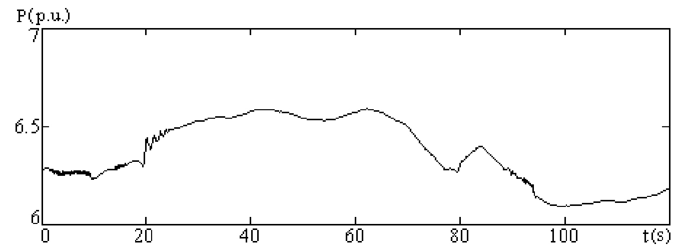

Fig.10 Tie-line power with tuned IPC

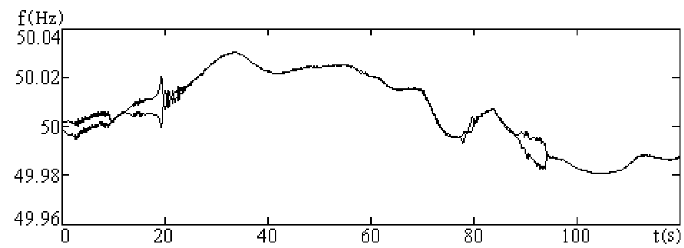

Fig.11 Frequency variety of both power systems with tuned IPC

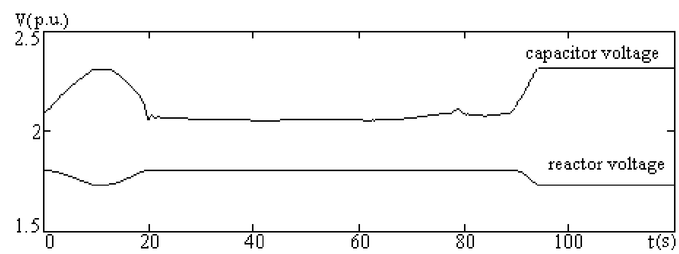

Fig.12 Capacitor and reactance voltage of tuned IPC

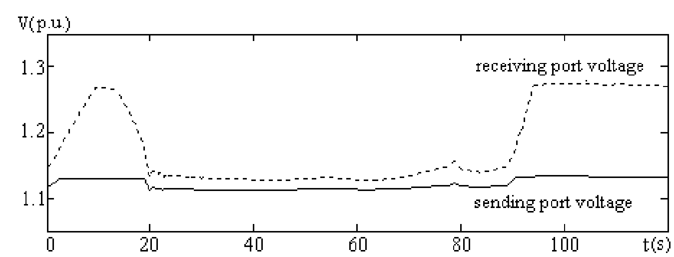

Fig.13 Send port and receive port voltage of tuned IPC

It could be observed from Figs.9 and 10 that the tie-line power is controlled in the region between 6p.u. and 6.5p.u by adjusting IPC reactance nearby 3.5p.u. Although there is little difference between the two subsystems, the interconnected power systems still run in the synchronal state which is shown in Fig.11. The voltage of IPC capacitors varies larger than the reactor voltage while the IPC parameters are changed, and this phenomenon is illustrated in Fig.12. As shown in Fig.13, with the load changing on the receiving side, the sending port voltage varies little because of the decoupling advantage of IPC.

VI. Conclusions

A nonlinear Thevenin equivalent mathematical method is proposed to simplify the complex power systems. The method could be applied to analyze the relative slippage between the two subsystems of interconnected networks connected by a tie line with IPC.

The relations between the parameters of IPC and the simplified power systems are proposed in the paper, which are in favor of the selection of IPC parameters, the analysis of IPC operation and controllable character, and the over voltage protection etc.

Simulation results show that the decoupling advantage of IPC can insulate the faulty in the other network and the power flow robust characters of IPC can control the tie-line power by adjusting the IPC parameters effectively.

VII. References

[1] J.Brochu, P.pelletier et al. The Interphase Power Controller A new Concept for Managing Power Flow Within AC Networks. IEEE Trans. On Power Delivery. 1994, 9(2): 833~841

[2] Zhaoxu Liu; Yongzhuang Li. Challenges for developing nationwide interconnected power systems in China, Power Engineering Society Summer Meeting, 2000. IEEE 2000(4): 1975 - 1980

[3] Pierre Pelletier, Jacques Lemay, et al. The Interphase Power Controller-A Robust Solution for Synchronous Interconnections and Management of Power Flows. AC and DC Power Transmission, Sixth International Conference. 1996, 23(4): 291~296

[4] Brochu, J. Beauregard, F. Morin, G. The IPC technology-a new approach for substation updating with passive short-circuit limitation. Power Delivery, IEEE Transactions. 1998, 13(1): 233~240

[5] Habashi K, Lombard J J, Mourad S, et al. The design of a 200 MW interphase power controller prototype. IEEE Trans. on Power Delivery. 1994, 9(2): 1041~1048

[6] Bruohu J et al. Application of the interphase power controller technology for transmission line power flow control. IEEE/PES SM453-1 PWRD ,1996.

[7] J.Lemay, M.Gvozdanovic, et al. The Plattsburgh Interphase Power Controller. Transmission and Distribution Conference. 1999, 2(4): 648~653

[8] Juan Li; Xiukuan Liu; Guochen Cao. A tracking estimation method for network equivalent parameters of facing the node. Proceedings of the CSEE. 2003, 23(3): 30-33.

[9] Zuyi Qu; Jilai Yu; Zhuo Liu. Circuit analysis for the mechanism of interphase power controller. Proceedings of the CSEE. 2001, 21(3): 37-40.

[10] Zuyi Qu; Juan Li; Xiukuan Liu. Analysis one interphase power controller considering the phase slippage between the power systems on both sides. Automation of electric power systems. 2002,26(17): 27-30

[11] Xiukuan Liu; Yan Liu; Juan Li. IPC parameter selection based on power system interconnection. Proceedings of the CSEE. 2003, 21(12): 64-67