CONTROL ALGORITHM AND IMPLEMENTATION SCHEME OF UPFC IN LABORATORY

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ABSTRACT

This paper analyzes the work principle of UPFC and describes its control algorithm. On these fundamental, proposals a corresponding control scheme for the implementation of UPFC in laboratory.

Keywords: *UPFC, control, scheme design*

1. INTRODUCTION

Unified power flow controller (UPFC) can regulate the transmission line power flow and the bus voltage fast and continuously by means of controlling the impedance, terminal voltage magnitude and terminal voltage angle of the transmission line, so that, the unified power flow controller can served as series compensator, shunt compensator and phase shifter. Therefore, the UPFC is the milestone in flexibility AC transmission technology. Dr L.Gyugyi first proposed the UPFC in 1992, from then on, researchers worked very hard on it, and the first UPFC apparatus was installed at 138 kV transmission line in INEZ in 1998, and worked successfully. In china, the study of UPFC is on the researching and testing stage.

This paper analyzes the work principle, constructs the mathematical model of the UPFC, on the fundamental of these, and describes the voltage control/reactive current control model in shunt converter and automatic power flow control/voltage injection control model in series converter. At last, designs the corresponding control scheme of the implementation of UPFC in laboratory.

2. WORK PRINCIPLE OF UPFC

Figure 1 shows the UPFC connected into the single-machine infinite-bus system. The UPFC consists of two voltage-sourced converters-one injects an almost sinusoidal current at the point of connection and the other injects an almost sinusoidal voltage in series with the transmission line. One connected to the networked through a shunt coupling transformer and the other connected to the network by a series coupling transformer. The injected voltage in series with the line can be at any angle with the prevailing line current, thereby emulating an impedance in series with the line, and regulates power flow in the line within the range of 0-360°. The shunt-connected current source has two components. First, the real component, which is in phase with

the bus voltage, carries real power that is exchanged by the series-connected voltage source and losses in the UPFC. Second, the reactive component, which is in quadrature with the bus voltage, emulates an inductive reactance or a capacitive reactance at the point of connection. When the VSC1 and the VSC2 are independently operated, the dc link switch is open. The VSC1 regulates the bus voltage and, in turn, regulates the reactive current flow through it. The VSC2 injects a voltage in series with the transmission line and in quadrature with the line current.
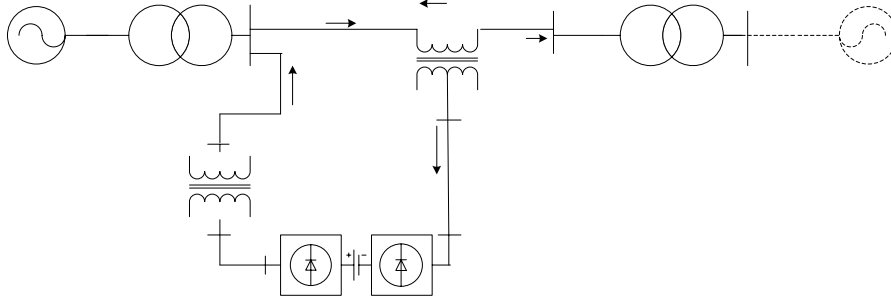

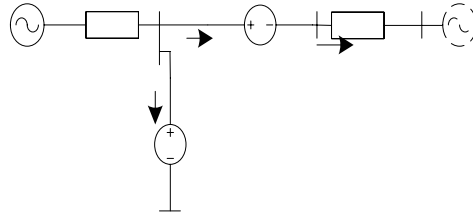*Fig.1 unified power flow controller in a simplified network*

Fig.2 equivalent circuit of UPFC

3. CONTROL ALGORITHM OF UPFC

The equivalent circuit of UPFC is shown in Figure 2, in which, the shunt and series converter are represented by a current source and a voltage source respectively. $V_i \angle \theta_i$ is the connected bus voltage and angle, V_s is the magnitude of the infinite terminal bus voltage, δ is the angle between the reference voltage $\dot{V}_S$ and the quadrature axis, X_{T1} and X_{T2} are the equivalent impedance of the transformer T1 and T2, $U_1 \angle \theta_1$ is the output voltage magnitude and angle of the shunt converter, $U_2 \angle \theta_2$ is the output voltage magnitude and angle of the series converter, $\dot{I}_1, \dot{I}_2$ is the shunt and series converter current respectively, P_{Lref} is the line real power and Q_{Lref} is the line reactive power.

From the equivalent circuit of UPFC in figure 2, the line power flow equations are deduced as following:

$$P_L = (V_{id} - U_{2d}) I_{2d} + (V_{iq} - U_{2q}) I_{2q} \quad (1)$$

$$Q_L (V_{iq} - U_{2q}) I_{2d} - (V_{id} - U_{2d}) I_{2q} \quad (2)$$

The voltage of nodal I is

$$V_i = \sqrt{V_{id}^2 + V_{iq}^2} \quad (3)$$

The constraint equation of UPFC is

$$P_1 + P_2 = 0 \quad (4)$$

If take the $\dot{E}_q$、X_d、X_q as the generator transient voltage, direct impedance and quadrature impedance respectively, then the network equations with UPFC are:

$$\dot{E}_q = V_{iq} + (X_d' + X_{T1}) (I_{1d} + I_{2d}) \quad (5)$$

$$0 = V_{id} - (X_q + X_{T1}) (I_{1q} + I_{2q}) \quad (6)$$

$$0 = V_{id} - U_{2d} + X_{T2} I_{2q} - V_S \sin \delta \quad (7)$$

$$0 = V_{id} - U_{2q} - X_{T2} I_{2d} - V_S \cos \delta \quad (8)$$

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Where,

I_{1d}、 I_{1q}、 I_{2d}、 I_{2q}、 U_{2d}、 U_{2q}、 V_{id}、 V_{iq}

are the direct and quadrature components of

$\dot{I}_1$、 $\dot{I}_2$、 $\dot{U}_2$、 $\dot{V}_i$.

When the system parameters $\dot{E}_q$、 V_S、 δ and

the control target P_L、 Q_L、 V_i are given, the

variable I_1、 θ_1、 U_2、 θ_2 can be calculated

from the equations shown above. And then the

magnitude and angle of I_2、 V_j can be

calculated.

According to the calculated results, take

v_i、 v_j、 i_1、 i_2 as the control variables, using

the control algorithm shown in figure 3 to control

the UPFC system. The control system can be

divided into two parts: the control of the VSC1

as a shunt compensator and the control of the VSC2 as a series compensator. An instantaneous 3-phase set of transmission line voltages, v_i , at BUS i is used to calculate the reference angle,θ , which is phase-locked to the phase of the bus voltage, v_{ia}, An instantaneous 3-phase set of measured VSC1 currents, i_1 , is decomposed into its real or direct component, I_{1d} , and reactive or quadrature component, I_{1q} , respectively. An instantaneous 3-phase set of measured line currents, i, is decomposed into its real or direct component, I_d , and reactive or quadrature component, I_q, respectively. An instantaneous 3-phase set of measured line voltages, v_i , at BUS i is decomposed into its direct component, V_{id} , and quadrature component, V_{iq} , respectively. The magnitude of the BUS i voltage, V_i , is calculated.
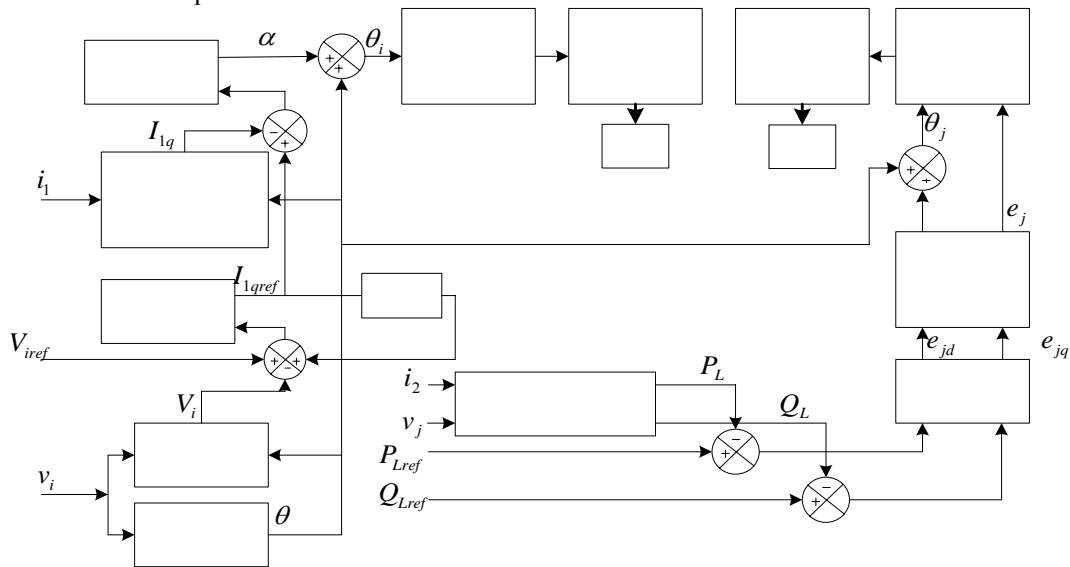

Fig.3 control principle diagram of UPFC

The control for the VSC1 works in such a way that the desired bus voltage magnitude reference, V_{iref} , (adjusted by the droop factor,) is compared with the BUS i voltage magnitude, V_i , using an outer voltage control loop and the error is passed through an error amplifier, which produces the reference quadrature component, I_{1qref} of the VSC1 current. The droop factor, K_{droop} , is defined as the allowable voltage error at the rated reactive current flow through the VSC1. The reference quadrature component, I_{1qref} , is compared with the measured quadrature component, I_{1q} , of the VSC1 current using an inner reactive current control loop and the error

is passed through an error amplifier, which produces a relative angle, α , of the VSC1 voltage with respect to the BUS i voltage. The phase angle,θ_j , of the VSC1 voltage is calculated by adding the relative angle, α, of the VSC1 voltage and the phase-locked-loop angle,θ . This is called "Voltage Control" mode of operation. The dc link capacitor voltage, v_{DC} , is dynamically adjusted in relationship with the VSC1's AC terminal voltage. Note that for a particular bus voltage magnitude demand, V_{iref} , if the reference quadrature component, I_{1qref} , exceeds the rated current of the VSC then $|I_{1qref}|$ is limited to 1 pu and the bus voltage is regulated

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to an intermediate value. The controllable range of the bus voltage can easily be determined by operating the VSC1 with the inner reactive current control loop and varying I_{1qref} from -1 pu to 1 pu. The reference quadrature component, I_{1qref} , of the converter current is defined to be either positive if the VSC1 is emulating an inductive reactance or negative if it is emulating a capacitive reactance. This is called "Reactive Current Control" mode of operation. In this case, there is no need for the use of the outer voltage control loop.

The control for the VSC2 works in such a way that the desired real and reactive power, P_{Lref} and, Q_{Lref} are compared with the measured real and reactive power P_L, and Q_L , using an automatic power flow control algorithm and the errors are passed through an error amplifier, which produces, with respect to the bus voltage, the direct and the quadrature components of the series injection voltage e_{jd}, and e_{jq} , respectively. Next, the magnitude of the voltage, e_j , at the output of the VSC2 and its relative angle, β , with respect to the reference phase-locked-loop angle are calculated. The phase angle,θ_2 , of the VSC2 voltage is calculated by adding the relative angle,β , of the VSC2 voltage and the phase-locked-loop angle,θ . This is called "Automatic Power Flow Control" mode of operation. Note that for a particular real and reactive power P_{Lref}, and Q_{Lref}, demand, if the magnitude of the voltage, e_j , exceeds the rated voltage of the VSC then e_j is limited to 1 pu and the real and reactive power flow are regulated to an intermediate value. The controllable range of the real and reactive power flow can easily be determined with the open loop voltage injection by injecting the rated e_j within its entire 360° range. This is called "Voltage Injection" mode of operation. In this case, there is no need for the use of the automatic power flow control algorithm.

4. CONTROL SCHEME OF UPFC IMPLEMENTED IN LABORATORY

Using the control algorithm stated above, designs a UPFC facility, applying in the system shown in Figure 1, the connection is shown in Figure 4.

Where, LBR is the line breaker, SHNBRK is the shunt breaker, SRSBRK is the series breaker, BYPBRK is the bypass breaker.

Because the shunt converter should exchange the real power with the system and should keep the v_{DC} constant, so the sampled variables are system voltage v_i , output voltage of VSC1, u_1 , current i_1, and dc link capacitor voltage u_{dc} . The series converter injects voltage, the magnitude and angle can be regulated to control the line impedance, terminal bus voltage and shift the angle, so the sampled variables are: system voltage v_j , output voltage of VSC2, v_2 , and the line current i. in addition to that, the reference value P_{Lref} , Q_{Lref} , V_{iref} , i_{1qref} , U_{2ref}, together with the breaker status should also be processed.

There are so many variables should be sampled and processed, the corresponding calculating task is very hard, for the dynamic response of the control system, the digital signal processor is used as the core of the control system in the facility implementation of UPFC.

The design conditions are stated as: when the VSC2 used as series compensator, the compensate range is 0%-30%, used as angle shifter, the angle shifting range is 0°-10°, served as terminal voltage regulator, the injected voltage range, with respect to the system voltage is 0%-20%.
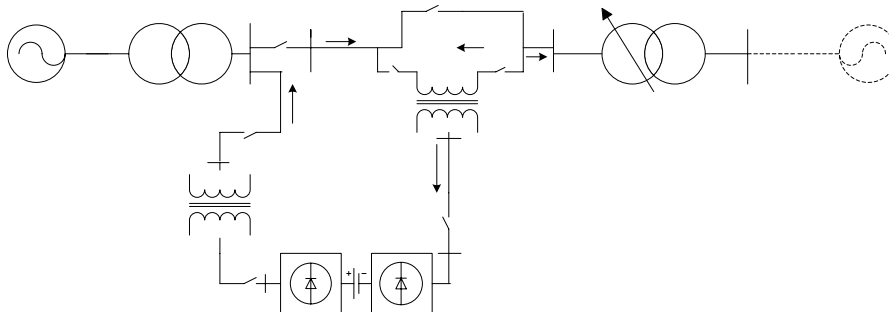

Fig.4 UPFC connected to the network in laboratory

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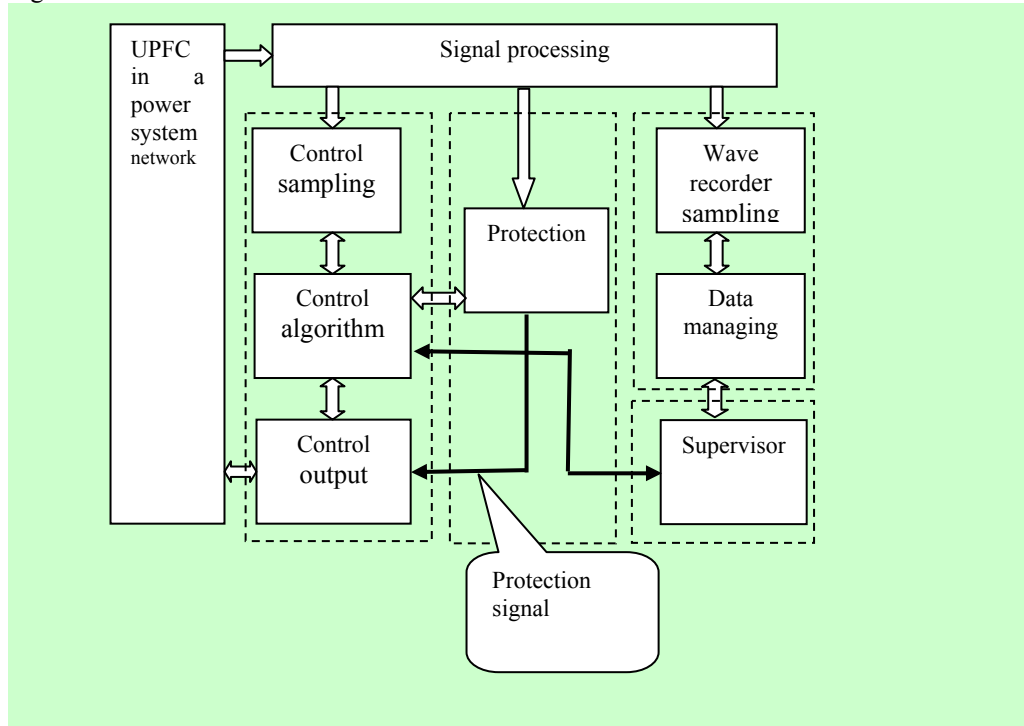
Fig.5 shows the control scheme

Fig.5 control scheme of UPFC

5. CONCLUSION

On the fundamental of calculated the shunt current, connection nodal voltage, series current and output voltage of series converter through the work principle, using shunt current, system bus voltage to implement the voltage/reactive current control in shunt converter using series current, output voltage of vsc2 voltage to implement the automatic power flow control/voltage injection control. Using this control algorithm, designed the control scheme in the implementation of UPFC in laboratory. This control scheme is very useful for the implementation of UPFC in practice.

REFERENCES

[1] Yan Wei, etal, "Enhancement of Power System Stability Using Linear Optimal Control Strategy of UPFC", *Proceedings of the CSEE*, Vol: 20, No:1, pp. 45-49, 2000.

[2] Tan Weipu, etal, "Application of Digital Signal Processor on UPFC Experimentation Device", *Power System Technology*, Vol: 23, No: 8, pp. 17-20, 1999.

[3] Kalyan K. Sen, Albert J. F. Keri, "Comparison of Field Results and Digital Simulation Results of Voltage-Sourced Converter-Based FACTS Controllers", *IEEE Transactions on Power Delivery*, Vol: 18, No:1, pp. 300-306, 2003.

[4] K. K. Sen and E. J. Stacey, "UPFC—Unified Power Flow Controller: Theory, Modeling, And Applications", *IEEE Trans. Power Delivery*, Vol: 13, No: 4, pp. 1453-1460, 1998.

[5] K. R. Padiyar, A. M. Kulkarni, "Control Design and Simulation of Unified Power Flow Controller", *IEEE Transactions on Power Delivery*, Vol: 13, No: 4, pp. 1348-1354, 1998.