Active Power Control of New Energy System of Large Power Grid With UPFC

Chao Yue 1,*, Donghui Wang 2
1 Qinghai Electric Power Design Institute Co., Ltd., Power China, Qinghai, Xining, 810008, China
2 School of Electric and Electronic Engineering, North China Electric Power University, Changping District, Beijing 102206, China
*a yuechao0516@126.com

Abstract. FACTS equipment based on power electronics and control technology has made great help to the optimization of power systems. The Unified Power Flow Controller (UPFC) is the most promising FACTS device due to its flexible regulation and complete functions. This paper analyzes the basic composition and working principle of UPFC, studies the idea of voltage injection control and current injection control, and presents the building of relevant control loops.

1. Introduction
The flexible AC transmission system FACTS equipment can react quickly and accurately under various controls of the power grid [1], take relevant measures according to the instructions to improve the power flow distribution in the system and power quality of the grid, and shorten the recovery time required after the fault, providing technical support for the development of smart grid. With Unified Power Flow Controller, the terminal voltage, line impedance angle and phase angle of the transmission line can be controlled selectively, and the active power flow and reactive power flow on the AC transmission line can be controlled independently.

2. Research Development and Current Status of UPFC
2.1. Application Status of UPFC Device
The anti-parallel thyristor control structure is adopted in the FACTS control technology initially, of which the main disadvantage is that large harmonic current is generated. After that, a new generation of devices based on voltage source converters was appeared later. It owns the advantage of relative smooth regulation characteristic, however such device cannot regulate the active and reactive power independently. In order to solve the problem, a device that can regulate and control the active and reactive power flow of the line independently has been developed [2]. It is UPFC. UPFC is the most complex and creative of many FACTS devices and is recognized as the most powerful FACTS component [3].

2.2. Research Status of UPFC Active Power Control Strategy
(1) Active power control with phase-shifting UPFC
At present, the traditional proportional integral (PI) control method is adopted in UPFC. The PI controller is used on the series circuits side of the UPFC to regulate the active power in the transmission
line[4], and it is also used on the parallel circuits side of the UPFC to control the access point voltage, in order to keep the voltage of the DC capacitor constant.

(2) Active power control with static synchronous series compensation UPFC
In order to change the situation that the control structure is only suitable for accurate mathematical models, foreign experts introduced fuzzy control theory for UPFC control, in which, the characteristics of the controlled system are described by linguistic variables, and the required control amount are inferred from the dynamic values of the system itself and the existing fuzzy control rules, according to the relevant theories in mathematical modeling.

(3) D-Q axis decoupling UPFC active power control
Professor Wang Haifeng mentioned in the literature[5] that the intelligent predictive control based on nonparametric model can decouple the coupling relationship between control variables. In the literature[6], Professor Chen Zhong proposed and designed a controller that combines proportional integral derivative control and intelligent decoupling process, which can improve the overall control capability of the UPFC and improve the dynamic response characteristics.

3. Basic Structure of UPFC System

3.1. Basic Structure and Principle of the UPFC System

3.1.1. Basic Structure of UPFC. The UPFC is composed of two voltage source converters, as shown in Figure 1. The main structure of the UPFC includes: voltage source converter; output filters C1, L1, C2, and L2; circuit breakers K1 and K2; bypass switch K3; parallel transformer Tshunt; series transformer Tseries; control section and protection unit. In steady state operation, K1 and K2 are in the closed state, K3 is disconnected, and the UPFC is put into operation. At this time, the current flowing through the series transformer is regarded as the current in the grid loop. In the event of a fault, K3 will be closed, and K1 and K2 will be disconnected, so that the UPFC is exited and protected.

3.1.2. Basic principle of UPFC. The parallel part keeps the active power balance inside the UPFC and provides reactive power compensation to the grid to keep the bus voltage; voltage is input by the series circuit section into the grid to change the voltage on the transmission line, thereby realizing the regulation of the power flow distribution, as shown in Figure 2.
3.2. Basic Functions of the UPFC System

With UPFC, the impedance of the line, the voltage amplitude and its phase angle of the transmission line node can be adjusted simultaneously, and it is also possible to implement FACTS component shunt compensation, series compensation, etc., and to combine these basic functions, as shown in Figure 3.

3.3. Basic Control Principle of UPFC System

3.3.1. Parallel Circuit Control. The parallel circuit section of the UPFC completes the active transmission and the reactive power compensation to the bus by exchanging power with the system through the transformer in parallel circuit mainly. The active part mainly provides the active power required for the converter of the series circuit section. Three cases shall be divided into on the reactive part:

(1) Reactive current direct injection method

Input $I_{q,SH}$ as a reference vector of reactive current, which is orthogonal to the delivery terminal voltage $V_1$. Use the closed loop feedback link to make the reactive current vector $I_{q,SH}$ in the actual line changing with its value, on the basis of injection of the vector. The sensitivity of actual system can be changed as preset by this type of control.

(2) Reactive power control mode

The purpose of inputting the reactive power required by the system is realized by inputting the reactive current, which is orthogonal to the voltage, to the delivery end of the actual line directly by the parallel circuit section using the control system. The solid line frame “Reactive/Current” convert the reactive power demand into the reactive current. The parallel circuit section exchanges active power with the actual system to keep the stability of the internal DC capacitor voltage of the UPFC.

(3) Voltage control method

The voltage control mode is similar to the above modes. The input reference value in the control system is the voltage value of the parallel circuit access point, and the feedback measurement value is the actual voltage of the access point. The two values are compared, and injected reactive current correction value is obtained by calculating the error signal with the closed-loop control algorithm.
3.3.2. Series Circuit Control

(1) Bus voltage adjusting method

The core idea is to input a voltage $U_{12}$ into the system loop that is in the same phase or inverted phase with the line delivery terminal voltage. The goal of the control is to keep the line delivery terminal voltage $V_{1\text{eff}}$ at the desired level after being compensated by the UPFC. In this method, it is required that an active power exchange path is provided by the parallel circuit section.

(2) Phase angle adjusting method

The voltage vector input in series circuit is controlled according to the bus voltage vector input by the system, and the amplitude thereof satisfies the following requirements: after the input, the output voltage is offset by a certain angle, but the voltage amplitude does not change.

(3) Flow control operation method

As the main operation method of UPFC, the adoption rate of flow control operation method is higher in the actual operating systems. In this mode of operation, the active power and reactive power on the transmission line is selected as the controlled amount to make the power flow on the line, that is, the active power and reactive power, stabilize at a given value. Measure the actual active power value and reactive power value on the transmission line of the UPFC series circuits, and compare the values with the corresponding given value to complete the overall operation of the closed-loop control system according to the corresponding control algorithm.

3.4. Control Strategy of UPFC System

(1) UPFC parallel circuit side control

The parallel circuit controller of UPFC is mainly used to ensure that the actual line bus voltage input by it is constant, and also provides the active power to the series circuit side to ensure the balance inside the UPFC, thus ensuring the constant of the internal capacitor voltage of the UPFC.

(2) UPFC series circuit side control

The series circuit side controller of the UPFC is mainly used to change the amplitude and phase angle of the access point voltage on the transmission line. By changing the line voltage amplitude and phase angle, the above several factors can be changed, thus realizing the adjustment of active and reactive power in the line.

(3) UPFC DC capacitor side control

The control is mainly achieved through a closed loop control link. Compare the given voltage with the actual voltage, and the subtracting value of them is regarded as the generated error signal. The compensation current value required is calculated by the PI controller, that is, the active current $I_a$.

4. Modeling of UPFC active power control and construction of large power grid system

4.1. Establishment of new energy grid system model

In a common double-ended transmission network, dual-loop transmission line, series converter and the parallel converter of the UPFC are connected to the grid through a transformer respectively, to maintain the current distribution of the entire system according to the previous operating mechanism.

The main system is a transmission line with double-end power supply and dual-circuit. The amplitude and phase angle of the supply voltage are given according to the actual grid to be simulated.

The next step is the introduction of the measuring components in the transmission line. The sensors includes mainly current sensor $I_a$, ground voltage sensor $E_a$ and power meter Power, which are monitoring the current, voltage, active power and reactive power on the transmission line in real time respectively and feed them back into the PLOT image.

Then for the core part of UPFC: the parallel control loop, series control loop, and the single-line three-phase loop of the transmission line passes through the parallel circuit section of the transformer, are connected to the UPFC core control part. The outlet end is divided into two parts, one part passes through the three-phase capacitor to stabilize the voltage of the line end; the other part is directly
connected to the rectification part of the parallel circuit section after going through the capacitive reactance.

The rectifying portion of the parallel circuit section is mainly composed of six IGBT tubes, and from left to right, from top to bottom, the order is 1, 3, 5, 4, 6, and 2. The trigger signal of the IGBT tube is provided by the corresponding control loop. The reactive compensation function of the parallel circuit section can be realized by its own capacitance, which can input (or absorb) reactive power to the grid line, thereby achieving stabilization of the line voltage. At the same time, since the power flow passed through the parallel circuit section needs to flow back to the power grid through the series circuit section, for the parallel capacitor between the series and parallel, the active power is still required to maintain the voltage of the capacitor terminal of shunt capacitors between series and parallel circuits.

For the next, it is the control loop of the UPFC series circuits. The biggest difference between the series circuit section and the parallel part is that the series circuit section transformer is connected in series in the line. Since the transformer is connected in series directly in the transmission line, direct control of the voltage in the line can be achieved.

In the structural analysis, the series circuit section also adopts six IGBT tubes in parallel circuits with the order from left to right and from top to bottom respectively, 5, 3, 1, 2, 6, and 4, which is related to the principle of signal generation. Through the 6-bit IGBT tube, the DC current flowing from the parallel part is inverted into the AC current flowing into the power grid. In the output end of series circuits, the parallel capacitor is still needed to keep the terminal voltage to ensure the reactive power compensation of its own part.

For the PLOT section, after the sensor is added to the system, the generated transmission signal is displayed on the waveform diagram through the data transmission channel. The overall process is shown in Figure 4:

![Figure 4. Structure diagram of the signal transmission system of the UPFC](image)

As we can see from the above diagrams, the electrical quantity in the line cannot be measured directly. A sensor is connected to the transformer on the secondary side, and the generated data signal is transmitted to the output channel through the data transmission channel, and then drawn by the PLOT of PSCAD/EMTDC to obtain the real-time image we need. The step length and simulation time of the simulation waveform can be set by yourself according to the requirements before the simulation.

4.2. Model Construction of UPFC Active Control Loop

4.2.1. IGBT Trigger Signal Generation Loop Construction. First, the generation loop of the sinusoidal signal, as shown in Figure 5, is introduced.
Figure 5. Generation loop of IGBT trigger signal sine wave

First, the integral gain and the differential gain of the PLL module are assigned through a PLL control template, and then the three-phase voltage generated by the parallel circuit section of the UPFC is input to the PLL module. The PLL module analyzes the input voltage signal, and obtains its amplitude and phase angle signals through algorithm analysis, and outputs them to the displacement module. The branching process mainly deals with the previous 6-bit signal. In one branch, the phase angle signal is directly converted into a sinusoidal signal, and then sinusoidal signal is put out through multiplier; the other branch is similar to it, but an inverter is added. The 6-bit signal is inverted and output to the subsequent sinusoidal conversion link and the multiplier to obtain an inverted sinusoidal signal. The two sinusoidal signals generated are transmitted to the comparison module. Prior to this, the triangle wave as a carrier has its loop shown in Figure6:

Figure 6. IGBT trigger signal triangle wave generation circuit

The PLL module analyzes the input voltage signal, and its amplitude and phase angle signals are obtained through algorithm analysis, and be output into the gain module. The resulted signal value is multiplied by a factor of 33 and entered into the angler by the gain module. The angle divider can convert the voltage phase angle radian into an angle system, and then process the previous 6-bit signals through two branches respectively. In one branch, the phase angle signal is directly linearly converted, and then the triangular wave signal is output; the other branch is similar, but the phase sequence of the triangular wave is inverted, and finally a triangular wave signal is output. The control signal can be obtained by comparing the resulting triangular wave signal with the sinusoidal signal.
Figure 7. UPFC signal comparison loop

The signal comparison loop compares the previously obtained triangular wave with the sine wave signal to generate the trigger pulse required to turn on the IGBT tube, and transmits it to the IGBT tube of the UPFC in the actual power grid. The time of generating the pulse signal is given by the clock module.

4.2.2. UPFC active power control loop analysis and model implementation. As shown in Figures 8 and 10, the two control quantities of the angle and gain of the parallel part are realized by the PI control loop, and the specific difference is mainly the difference of the PI control coefficient setting.

Figure 8. Parallel part gain control loop

Figure 9. Parallel part angle control loop

The voltage $V_{sh}$ phase angle input into the parallel circuit section of the system affects the magnitude and direction of the active power, while the voltage $V_{sh}$ amplitude affects the exchange of reactive power,
so the phase angle and amplitude of $V_{sh}$ are taken as the control amount. The control block diagram is shown in Figure 10:

![Figure 10. Parallel part control block diagram](image)

In the above control loop, $m_{sh}$ determines the modulation ratio of the parallel circuit section, and $\theta_{sh}$ determines the phase angle of the input voltage. $k_{T1}$, $k_{P1}$, $k_{T2}$, and $k_{P2}$ are the control coefficients of PI, and $T_m$ and $T_\theta$ are time inertia constants.

The phase angle difference of the series circuit section affects the active power, and the voltage amplitude affects the reactive power. Select the amplitude and phase angle of the voltage as the control amount, and the control block diagram of the series circuit section can be obtained, as shown in Figure 11.

![Figure 11. Series circuit control loop](image)

In where $k_{T3}$, $k_{P3}$, $k_{T4}$, and $k_{P4}$ are PI control coefficients, and $T_{msc}$ is a time inertia constant.

5. Conclusion

UPFC has the most advanced, most flexible and most powerful features among numerous FACTS devices. It can adjust the active and reactive power on the transmission line independently, and can also control various parameters on the line comprehensively, thus playing a huge role in making up for the lack of power flow control capability of the AC transmission network. This paper demonstrates the UPFC active control strategies and its specific implementation methods, and the specific control loop and simulation ideas are obtained. The effectiveness of the UPFC active control strategy is verified, by constructing a new energy grid model with UPFC based on the characteristics of new energy generation and using PSCAD/EMTDC power system simulation software.
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