The Optimization of Distributed Power Flow Fuzzy Pi Controller

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Abstract: Distributed Power Flow Controller (DPFC) is one of the most powerful and economical devices in flexible AC transmission system. It has the ability to adjust the reactance, voltage, power and other structural parameters and operation parameters of power system simultaneously or independently. It can improve the transmission capacity of power grid and enhance the stability of power system. The network has broad application prospects. In this paper, based on the theory of fuzzy control, the fuzzy *PI* control is applied to optimize the design of distributed power flow controller. Firstly, the structure and principle of DPFC are analyzed; secondly, the fuzzy *PI* parameters are designed by using the fuzzy control theory; finally, the simulation results are verified by using Power System Analysis Software Package (PSASP). The results show that the fuzzy *PI* control can effectively improve the speed and scope of DPFC power flow control.

1. Introduction

With the continuous improvement of the voltage level of power system, the increasing scale of new energy and the development of HVDC transmission, the structure and operation mode of power system become more complex [1].

Flexible AC Transmission System (FACTS), proposed by Dr. N.G. Hingorani of the American Academy of Electric Power Sciences in 1986, is defined as improving the transmission capability and stability of AC transmission systems through power electronics or other types of controllers [2]. Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) are early FACTS devices. The capacitance and inductive output current of STATCOM are continuously adjustable and independent of the voltage amplitude at the injection point to realize reactive power compensation and stabilize bus voltage. SSSC is a passive reactive power compensation device, which controls the transmission power of the line by changing the voltage drop of reactive power on the line. UPFC is a series-parallel controller, which includes all functions of STATCOM and SSSC. It allows the two-way transmission of line power flow between parallel side and series side of UPFC [3]. DPFC is a new generation of FACTS equipment, which is improved by UPFC and has all the functions of UPFC.

2. DPFC Principle

DPFC parallel side and series side are distributed installed in the system. The third harmonic power is used to exchange energy between parallel side and series side. The harmonic channel of the line itself is used to replace the DC capacitor of UPFC parallel side and series side. DPFC consists of parallel-side converters installed on the bus at the head of the line and multiple series-side converters installed on the line. The structure diagram is shown in Fig. 1 [4].

DPFC converts fundamental wave power into harmonic power by parallel side converter, and adjusts line power flow by absorbing harmonic power in series side and outputting fundamental wave power. Each harmonic can exist independently in the system. The 3N harmonic forms a harmonic loop at the neutral grounding point of the triangle side, which is naturally blocked by the star side of the Y-Δ transformer. Because of the minimum network loss corresponding to the third harmonic, Y-Δ transformer is installed in the first and last section of DPFC line, and energy exchange between parallel side and series side is carried out through the third harmonic, thus effectively controlling the line power flow [5].

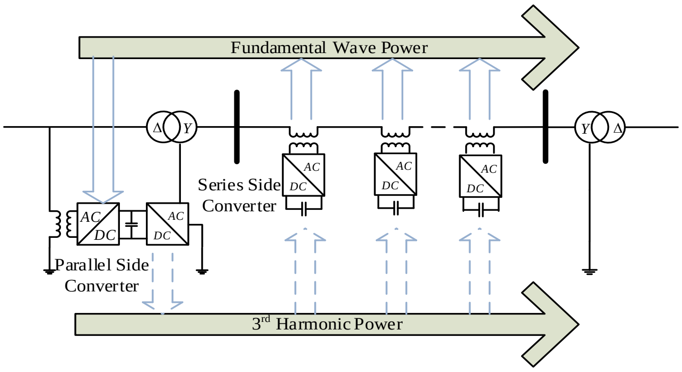

Fig. 1 DPFC structure diagram

3. Design of DPFC Fuzzy PI Controller

Fuzzy control differs greatly from traditional control. Traditional control is equivalent to piecewise function, and there are obvious steps at the specific boundary. Fuzzy control is much smoother from one section to the other. Therefore, the fuzzy control has a wider control range. Applying the fuzzy control theory to the traditional PI controller can not only show that the traditional PI is simple in structure, stable in control, but also enlarge the control range and improve the anti-disturbance ability.

The key parts of signal transmission of fuzzy control theory are: (1) Quantization factor; (2) fuzzification interface; (3) Fuzzy reasoning; (4) Fuzzification interface; (5) Proportion factor. By fuzzifying the input deviation, the fuzzy controller can obtain the corresponding output variables according to the dramatic fuzzy reasoning, and the PI control parameters can be controlled by the anti-fuzzy processing.

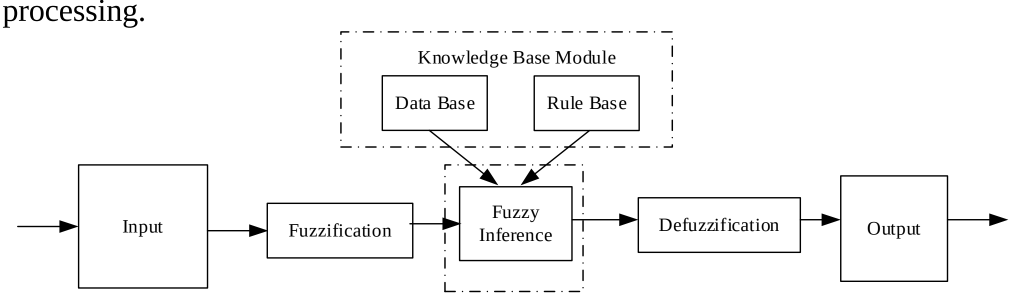

Fig. 2 Signal transmission block diagram of fuzzy control theory

At present, the most common one is the two-variable fuzzy controller, which takes the deviation signal e and the change rate of the deviation signal ec as the acquisition quantity of the fuzzy controller. The two-variable fuzzy controller can accurately reflect the dynamic process of the actual input signal [6].

Because DPFC's parallel bus voltage, active power and reactive power control at the end of series line are decoupled control, there is no decoupling problem in its fuzzy control. Moreover, the bus voltage control has a small adjusting range, and the robustness of the parallel voltage controller is enough to meet the voltage control. The input signal of the PI controller will fluctuate greatly when the power flow transfers in a large range. Therefore, this paper focuses on the active and reactive power control at the end of the series side line as an example to design the fuzzy controller. The parameters of active power PI control and reactive power PI control in series side are consistent. The following is an example of active power fuzzy control design. The structure diagram of adaptive PI control with fuzzy system is shown in Fig. 3.

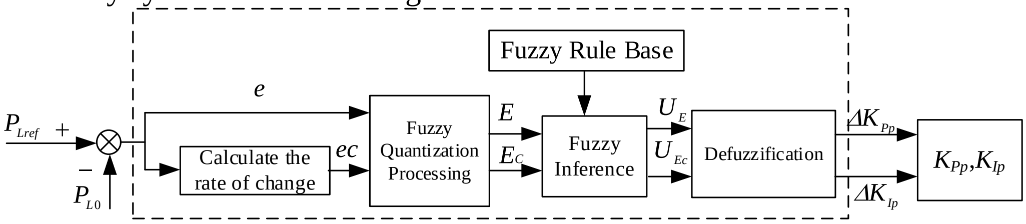

Fig. 3 Active power fuzzy control block diagram of DPFC series side

The difference between the active power instruction value and the actual active power at the end of the target line is the error e, and the change rate ec is the two-dimensional input of the fuzzy control link, which achieves the adaptive adjustment and distribution of parameters under different errors and change rates. The controller can get the current control parameter proportion coefficient correction ΔKPp and integral coefficient correction ΔKIP by fuzzy reasoning. When the 50% rated power of the line is taken as the given target value, the proportion coefficient KPp' and integral coefficient KIp' of the active power control on the series side are taken as the initial values, and the adaptive PI parameters of the fuzzy control are as follows.

$$\begin{cases} K_{Pp} = K'_{Pp} + \Delta K_{Pp} \\ K_{Ip} = K'_{Ip} + \Delta K_{Ip} \end{cases} \tag{1}$$

According to the characteristics of two-input and two-output of two-dimensional fuzzy controller, the set universe of input error *e*, its rate of change e_c, the correction of output proportional coefficient ΔK_{Pp} and the correction of integral coefficient ΔK_{IP} are defined.

$$\begin{cases} e \in \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\} \\ e_c \in \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\} \\ \Delta K_{Pp} \in \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\} \\ \Delta K_{Ip} \in \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\} \end{cases} \tag{2}$$

Quantitative factors and proportional factors are divided into seven grades according to the set universe: *NB* (negative big), *NM* (negative middle), *NS* (negative small), *ZE* (zero), *PS* (positive small), *PM* (positive middle), *PB* (positive big). If the actual universe of *e* is [-0.5P_{Lmax}, 0.5PLmax], the change rate is [-100%, 100%] and the corresponding fuzzy set universe is [-6, 6], then the error quantization factor G_e and the error change rate quantization factor G_{ec} can be defined.

$$G_e = \frac{P_{Lref}}{12} \tag{3}$$

$$G_{ec} = 16.67\% \tag{4}$$

The deviation *e (k)* measured at a certain time and the corresponding variation $e_c(k)$ are used as the input of the fuzzy controller according to the fuzzy factor.

$$E(k) = \frac{e(k)}{G_e} = \frac{12e(k)}{P_{Lref}} \tag{5}$$

$$E_C(k) = \frac{e_c(k)}{G_{ec}} = 6e_c(k) \tag{6}$$

The two input signals can be transformed into a fuzzy set by the following membership function. The membership function can be described by the simplest first-order function, as shown in Fig. 4.

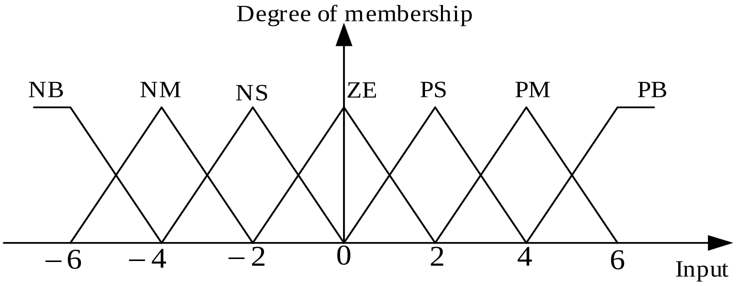

Fig. 4 Membership function diagram

According to the meaning of *PI* parameter and the design experience of *PI* parameters, the parameters control rules can be summarized.

(1) When the deviation is larger than $|E(k)|$, in order to make the controller track the target value quickly, the system needs larger proportion coefficient and smaller integral coefficient. (2) When the deviation is $|E(k)|$ moderate, in order to make the system stable quickly, the proportion coefficient is usually small and the integral coefficient is suitable. (3) When the deviation of $|E(k)|$ is small, in order to make the controller have good control effect, the proportional coefficient and integral coefficient are usually larger at the same time.

The input signals E and E_c are passed through the *Mamdani* fuzzy reasoning algorithm in the fuzzy reasoning link of the fuzzy controller, and the output is based on the table and the established fuzzy reasoning rules.

Table. 1 Proportional Coefficient Correction Adjustment Rules

ΔK_{Pp} \ E_c / E	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZE	ZE
NM	PB	PB	PM	PS	PS	ZE	NS
NS	PM	PM	PM	PS	ZE	NS	NS
ZE	PM	PM	PS	ZE	NS	NM	NM
PS	PS	PS	ZE	NS	NM	NM	NM
PM	PS	ZE	NS	NM	NM	NM	NB
PB	ZE	ZE	NM	NM	NM	NB	NB

Table. 2 Integral Coefficient Correction Adjustment Rules

ΔK_{Ip} \ E_c / E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZE	ZE
NM	NB	NB	NM	NS	NS	ZE	NS
NS	NB	NM	NS	NS	ZE	PS	PS
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PS	PM	PM
PM	ZE	ZE	PS	PS	PM	PB	PB
PB	ZE	ZE	PS	PM	PM	PB	PB

The output of the fuzzy reasoning module can be de-fuzzified by the method of gravity center. The exact calculation formulas of the scale coefficient correction ΔK_{Pp} and the integral coefficient correction ΔK_{IP} are shown in the formulas (7) and (8).

$$\Delta K_{Pp} = \frac{\int_{-6}^{6} U_E \cdot E dE}{\int_{-6}^{6} U_E dE} \quad (7)$$

$$\Delta K_{Ip} = \frac{\int_{-6}^{6} U_{Ec} \cdot E dEc}{\int_{-6}^{6} U_{Ec} dEc} \tag{8}$$

4. Simulation analysis

PSASP simulation software can be directly used in power flow calculation and transient stability analysis of power system. The following is the optimal DPFC configuration for a 500 kV power system in a certain area.

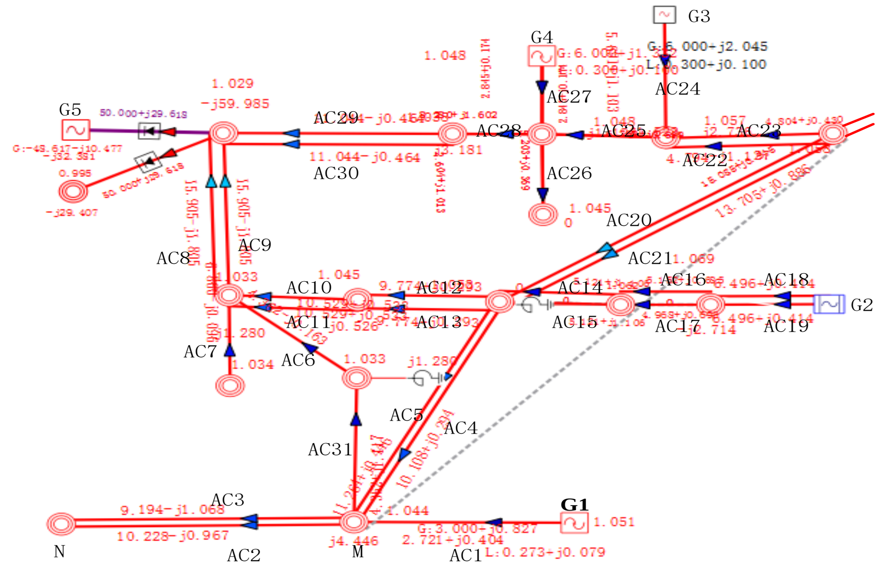

Fig. 5 Geographical connection map of 500 kV system in an area

As shown in Fig. 5, the geographic wiring diagram of the power flow transmission section of a 500kV system in a certain area is given. The overall flow of the current is from right to left. There are four zones in the power flow section area, five large-scale generating units, of which generator G1 belongs to region 1, generator G2 belongs to region 2, generator G 3 and G4 belong to region 3, and generator G5 belongs to region 4. There are 31 AC lines and 2 DC lines in the system. In the diagram, the power flow data is the standard unit, the reference capacity is 100 MVA, and the bus voltage is 500 kV.

DPFC is installed on line AC3. The parallel side of DPFC is connected to the M side of substation. The two series sides divide the line into two sections with equal impedance.The transmission power flow at the end of AC3 line and the voltage amplitude of M-side bus in substation are selected as the control objectives of DPFC. The initial power flow of line AC3 is 9.194-j1.068 (p.u.) and the rated active power of line AC3 is 18 (p.u.), so that the proportional and integral coefficients of PI control link when the transmission active power of line AC3 is 9 (p.u.) are taken as the initial PI parameters.The variation of power flow is shown in Fig. 6.

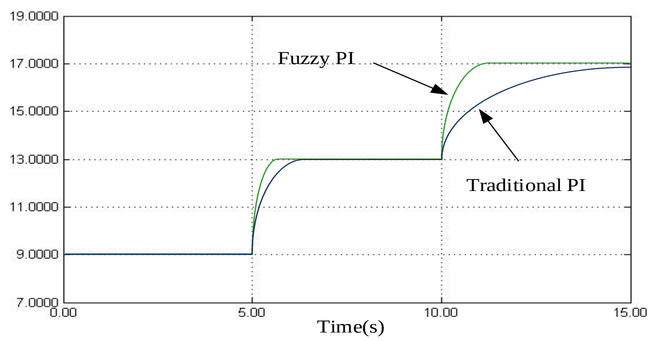

Fig. 6 Corresponding power curve of line AC3 under different control modes

By comparing the application of fuzzy PI control with traditional PI control, the power flow of transmission line can be increased from 9 (p.u.) to 13 (p.u.) at 5s and 17 (p.u.) at 10s. According to the variation of active power on line AC3 as shown in the figure, compared with the traditional *PI* control, the time of reaching the target value is shorter, and when the active power is increased from 13 (p.u.) to 17 (p.u.), the traditional *PI* control cannot reach the given value in 5s. Fuzzy *PI* control regulates the target value faster and has a wider adjustable range, which can better realize the control of DPFC system.

5. Summary

In this paper, fuzzy PI control theory is put forward to study the DPFC.The control function of DPFC in power system can be described by series voltage control and parallel current control.This analysis is accomplished on the PSASP software platform.The validity of the optimization is verified by simulation, and it has a good speed and range for power flow regulation and control of the system.

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