Optimal Design of Excitation Systems of Synchronous Condensers for HVDC Systems in Power Grid Environment Based on Variable Universe Fuzzy Adaptive PID Controller

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Abstract. In a gesture to optimize the reactive power properties of synchronous condensers and improve capabilities of condensers to support the voltages of AC systems, the outer loop control of the reactive power of condensers and the outer loop control of the voltages of AC systems are introduced into the conventional design of the main excitation systems of condensers in high voltage direct current (HVDC) systems in this study. Moreover, variable universe fuzzy adaptive PID controller is proposed to serve excitation systems of condensers to improve the response ability of condensers in power grid faults and the recovery speed of condensers after power grid faults, and to reduce overvoltage of power grids generated by condensers in the process of fault recovery. To verify its experimental validation, the model of ±100 kV HVDC system containing a condenser is set up in MATLAB/Simulink. The verified results reveal that the optimal design strategy of excitation systems of synchronous condensers in the proposal can ensure rapid regulation of the voltages of AC systems arising from condensers, and reduce overcompensation of the voltages and reactive power of AC systems arising from condensers when faults recover.

Keywords: Synchronous condenser; HVDC; Fuzzy control; PID control; Optimal design.

1. Introduction
The insufficient dynamic reactive power is the major cause of the voltage stability problem of high voltage direct current (HVDC) systems during system fault [1]. Synchronous condensers have the characteristics of large capacity of reactive power output, high forced excitation multiple and strong capability of high and low voltage crossing [2], which may precisely satisfy the requirement of dynamic reactive power in power grids at the moment of the fault. Reference [3] verified that the new high-capacity condensers are more suitable for the existing UHVDC hybrid grids than SVC, STATCOM and other reactive power compensation equipment from the perspective of operation principle and practical engineering. The strong capabilities of dynamic reactive power response and power grid support of the condensers can greatly improve the insufficient short-circuit capacity at the sending ends and voltage support at the receiving ends in the process of large-scale construction of HVDC transmission projects. Furthermore, the excitation systems is the important part of synchronous condensers. The establishment of the excitation systems and their control systems, formulation of appropriate control strategies and tuning of parameters of excitation systems have an important impact on optimizing the operation performance of condensers and enhancing operation security of the power systems [4]. The excitation control and reactive power output of synchronous condensers under different disturbances were investigated in [5], and it has been found that the parameters of the excitation regulator have great influence on the characteristics of the reactive power output of condensers under low-
frequency disturbances. The control strategy of the excitation system of the new type of condenser was introduced in detail in reference [6]. The excitation controller was optimized for large voltage overshoot and long recovery time of the power grid during fault recovery in [7]. In regard to double closed loop control of the main excitation system, an optimization method of introducing grid voltage as reference was proposed, which provided a reference for further optimization of excitation control. In [8], a control strategy of the voltage of the excitation system was proposed from the perspective of the characteristics of the condenser, which improved the fast response ability of the condenser in the converter station, and provided a reference for the research on the excitation control strategy of the condenser.

The existing automatic voltage regulator of excitation systems of condensers generally adopts the voltage closed-loop control mode, and its control goal is to maintain the voltage stability of the condensers [9], which can not accurately reflect the degree of voltage drop of the AC systems and can not maintain the voltage stability of the AC systems. In addition, the continuous adjustment of the reactive power of condensers can not change suddenly. After the fault recovery of the AC systems, the condensers will still transmit some reactive power to AC systems, which will cause overvoltage to AC systems [10]. Hence, traditional excitation control systems have some deficiencies as mentioned before. In the study, an optimal design technique of excitation systems of synchronous condensers utilizing variable universe fuzzy adaptive PID controller is proposed. Firstly, outer loop control of reactive power of condensers and the outer loop control of the voltages of AC systems are both introduced into the design of the main excitation systems of condensers in HVDC systems, in a gesture to optimize reactive power properties of condensers, improve capabilities of condensers to support voltages of AC systems and solve the problem that the input voltages of the excitation systems can not accurately reflect the degree of voltage drop of the AC systems; Secondly, the variable universe fuzzy adaptive PID controller is proposed to optimize excitation systems of condensers to improve the response ability of condensers in power grid faults and the recovery speed of condensers after power grid faults, and to address the overvoltage problem in power grids caused by condensers in the process of fault recovery of the power grids. Finally, the simulation model of ±100 kV HVDC system containing a condenser is set up in MATLAB/Simulink. The verified results reveal that the optimal design strategy of excitation systems of synchronous condensers in the proposal can ensure rapid regulation of the voltages of AC systems arising from condensers, and reduce overcompensation of the voltages and reactive power of AC systems arising from condensers when faults recover.

2. Preliminary Design of Excitation Systems for Synchronous Condensers in HVDC Systems

With respect to the traditional main excitation control systems of synchronous condensers that employ the voltage closed loop control, the outer loop control of reactive power of condensers is introduced to bring about the reactive power optimization regulation of the condensers. The outer loop control of the voltages of AC systems is introduced into the voltage loop to cope with the problem that the input voltages of conventional excitation systems can not accurately reflect the voltage drop degree of AC systems in case of faults. Therefore, the preliminary design structure of the excitation system for a condenser is built, see Fig. 1, where \( U_{\text{pref}} \) and \( U_{s} \) are separately the reference and practical value of the terminal voltage of the condenser; \( U_{\text{pref}} \) and \( U_{s} \) are separately the reference and practical value of the voltage of the AC system; \( Q_{\text{pref}} \) and \( Q \) are separately the reference and practical value of the reactive power of the condenser; \( U_{f} \) is the excitation voltage; \( k_{s} \) is the proportional adjustment coefficient of the voltage deviation of the AC system; \( k_{g1} \) and \( k_{g2} \) are respectively the proportional adjustment coefficients of the terminal voltage deviation of the condenser in outer loop control of the voltage of the AC system and outer loop control of the reactive power of the condenser; \( k_{q} \) is the proportional adjustment coefficient of the reactive power deviation of the condenser; \( PA \) is a power amplifier.
3. Optimization Design of Excitation Systems of Synchronous Condensers Based upon Variable Universe Fuzzy Adaptive PID Controller

In a gesture to ameliorate the response ability of condensers in power grid faults and the recovery speed of condensers after power grid faults and further reduce the overvoltage of power grids generated by condensers in the process of fault recovery, the variable universe fuzzy adaptive PID controller is introduced into excitation systems of condensers, in which the variable universe fuzzy controller is used to dynamically optimize proportion, integral and differential adjustment coefficients of the PID controller. Hence, the optimal design structure of the excitation system for a condenser is displayed in Fig. 2.

Figure 1. Structural diagram of the excitation system of a condenser.

Figure 2. Optimal structural diagram of the excitation system for a synchronous condenser.

The design form of the variable universe fuzzy controller is described by (1) [11]:

\[ y = \beta \theta (x) \]

(1)

in which \( x \) and \( y \) are separately the input and output of the fuzzy controller; \( \alpha \) and \( \beta \) are respectively the expandable & shrinkable factors of universes of the input and output variables; \( \theta \) is a parameter vector of rule consequent; \( \zeta (x) \) is the fuzzy basis function.

The variable universe fuzzy adaptive PID controller of the excitation system of a condenser is designed as follows.

Step 1) The input variables of the variable universe fuzzy controller are designed as the sum of deviations of the voltage and reactive power and its change rate while the output variables of that are designed as the increment of the proportional regulation coefficient, the increment of the integral regulation coefficient and the increment of the differential regulation coefficient of the PID controller.

Step 2) The fuzzy sets of variables of the variable universe fuzzy controller are both designed as \{NL, NM, NS, ZE, PS, PM, PL\}.

Step 3) Let initial universes of input variables \( x \) and \( x_c \) be respectively \([-X, X] \) and \([-X_c, X_c] \) and the initial universes of output variables \( y_p, y_i \) and \( y_d \) be respectively \([-Y_p, Y_p], [-Y_i, Y_i] \) and \([-Y_d, Y_d] \). The peak points of fuzzy sets are designed based on fuzzy sets and initial universes. To mention a few, the peak points of the fuzzy set of the input variable \( x \) are designed as \(-X, -2X/3, -X/3, 0, X/3, 2X/3 \) and \( X \).
Step 4) The exponential expandable & shrinkable factors are introduced into the design of universes, and the fuzzy rules, control precision and control speed are adjusted by changing the universes. When the deviations are large, the universes will be extended, fuzzy rules will be added and the control speed will be increased; when the deviations are small, the universes will be narrowed, fuzzy rules will be reduced and the control precision will be improved.

The expandable & shrinkable factors of the universes of input variables $x$ and $x_c$ are respectively designed as

$$\alpha(x) = 1 - \lambda \exp(-k x^2), \quad \lambda \in (0,1), \; k > 0$$

(2)

$$\alpha_c(x_c) = 1 - \lambda_c \exp(-k_c x_c^2), \quad \lambda_c \in (0,1), \; k_c > 0$$

(3)

Hence, the universes of input variables $x$ and $x_c$ are $[-\alpha(x)x, \alpha(x)x]$ and $[-\alpha_c(x_c)X_c, \alpha_c(x_c)X_c]$, respectively.

The expandable & shrinkable factors of the universes of output variables $y_p$, $y_i$ and $y_d$ are respectively designed as

$$\beta_p(t) = n_p \int_{-\beta_p}^{\beta_p} |x(s)| \, ds + \beta_p, \quad n_p > 0, \; \beta_p > 0$$

(4)

$$\beta_i(t) = n_i \int_{-\beta_i}^{\beta_i} |x(s)| \, ds + \beta_i, \quad n_i > 0, \; \beta_i > 0$$

(5)

$$\beta_d(t) = n_d \int_{-\beta_d}^{\beta_d} |x(s)| \, ds + \beta_d, \quad n_d > 0, \; \beta_d > 0$$

(6)

Thus, the universes of output variables $y_p$, $y_i$ and $y_d$ are respectively $[-\beta_p Y_p, \beta_p Y_p]$, $[-\beta_i Y_i, \beta_i Y_i]$ and $[-\beta_d Y_d, \beta_d Y_d]$.

Step 5) The membership function is designed as triangular wave.

Step 6) The fuzzy rules are devised as following:

**Table 1. Fuzzy rules (Output 1).**

| Output 1 | Input 2 |
|---|---|
| NL  | NM  | NS  | ZE  | PS  | PM  | PL  |
| NL  | PL  | PL  | PM  | PM  | PS  | ZE  | ZE  |
| NM  | PL  | PL  | PM  | PS  | PS  | ZE  | NS  |
| NS  | PM  | PM  | PM  | PS  | ZE  | NS  | NS  |
| ZE  | PM  | PM  | PS  | ZE  | NS  | NS  | NM  | NM  |
| PS  | PS  | PS  | ZE  | NS  | NS  | NM  | NM  | NM  |
| PM  | PS  | ZE  | NS  | NM  | NM  | NM  | NL  | NL  |
| PL  | ZE  | ZE  | NM  | NM  | NM  | NL  | NL  | NL  |

**Table 2. Fuzzy rules (Output 2).**

| Output 2 | Input 2 |
|---|---|
| NL  | NM  | NS  | ZE  | PS  | PM  | PL  |
| NL  | NL  | NL  | NM  | NM  | NS  | ZE  | ZE  |
| NM  | NL  | NL  | NM  | NS  | NS  | ZE  | ZE  |
| NS  | NM  | NM  | NM  | ZE  | PS  | PS  |
Table 3. Fuzzy rules (Output 3).

| Output 3 | Input2 |
|----------|--------|
| NL       | NL     |
| NM       | NM     |
| NS       | NS     |
| ZE       | ZE     |
| PS       | PS     |
| PM       | PM     |
| PL       | PL     |

Step 7) Mamdani method is used for fuzzy reasoning, and centroid method is employed for inverse fuzzy operation.

Step 8) If the initial values of the proportion, integral and differential adjustment coefficients of the PID controller are designed as $K_{p0}$, $K_{i0}$ and $K_{d0}$ respectively, then their final values after optimized by variable universe fuzzy control are as following:

$$K_p = K_{p0} + y_p$$

$$K_i = K_{i0} + y_i$$

$$K_d = K_{d0} + y_d$$

4. Simulation Analysis

A HVDC project is utilized to verify the experimental validation of this study [12]. The nominal values of DC voltage, DC current and capacity of the project are respectively ±100kV, 2kA and 200MW. The model of the HVDC system with a condenser is built in MATLAB/Simulink in view of basic data of the project, see Fig. 3, on which the excitation system of the condenser is optimized and devised. The model primarily consists of three-phase voltage sources, three-phase parallel RL branches, converter stations, converter station control systems, a data acquisition module, DC lines, a condenser and its excitation system, where the converter stations consist of three-phase two-winding transformers, AC filters, three-phase series RL branches, voltage source converters, grounded wye shunt capacitors, DC filters and flat wave reactors; in the converter station control modules, SPWM modulation method is adopted for voltage source converters, besides, active and reactive power control strategies are utilized with the rectifier, and reactive power and DC voltage control strategies are employed with the inverter; the excitation system of the condenser adopts the optimization design strategy conceived in this study, and its internal structure is displayed in Fig. 2.
Based upon the simulation model in Fig. 3, a single-phase grounding fault is set in a fault module with the occurrence time and duration of the fault are 0.25 s and 0.15 s respectively and the grounding resistance is set as 20Ω; besides, the simulation time of the model is 3 s. Two optimal design schemes of the excitation system of the condenser are devised as follows.

Scheme 1: The outer loop control of the reactive power of the condenser and outer loop control of the voltage of the AC system are introduced into the excitation system, but which is not optimized;

Scheme 2: Based on Scheme 1, the variable universe fuzzy adaptive PID controller is introduced into optimal design of the excitation system.

Under the two optimal design schemes of the excitation system, the various indexes of the voltage of the receiving-end grid are displayed in Table 4. Additionally, the reactive power outputs of the condenser and the voltages of the receiving-end grid are respectively shown in Fig. 4 and Fig. 5.

| Optimized results                        | Optimal design schemes |
|------------------------------------------|------------------------|
| The integral value of voltage deviations (p.u.) | 0.0567                  |
| The peak value of voltage deviations (p.u.)     | 0.1216                  |
| The steady-state value of voltage deviations (p.u.) | 0.0075                  |

With respect to Scheme 1, the feedback links of the reactive power of the condenser and the voltage of the AC system are added on the basis of the conventional voltage closed-loop control of the excitation system, so both the response speed and output capacity of the reactive power of the condenser are improved when the receiving-end grid fault occurs. As a result, the support capability of the condenser to the grid voltage is enhanced, and the steady-state voltage of the grid is close to the reference value (the steady-state deviation is 0.0075 p.u.). However, the reactive power output by the condenser is too much and cannot be reduced rapidly after fault recovery, which brings about serious overvoltage (the peak deviation is 0.1216 p.u.).

Compared with Scheme 1, Scheme 2 introduces the variable universe fuzzy adaptive PID controller into optimal design of the excitation system, which improves the response ability of condensers in power grid faults and the recovery speed of condensers after power grid faults, reduces the overvoltage brought by the condenser to the power grid during fault recovery (the peak deviation is reduced from 0.1216 p.u. to 0.0504 p.u.), and ensures better support ability brought by the condenser to the grid voltage, resulting in the steady-state voltage of the grid being closer to the reference value (the steady-state deviation is reduced from 0.0075 p.u. to 0.0071 p.u.).

Besides automatic reactive power response of the condenser, its excitation system will as well act to adjust the excitation voltage after changes of the grid voltage, which makes the condenser enter forced
excitation state. Therefore, see Fig. 4, the reactive power output of the condenser reaches the maximum value at 0.4 s. Under the action of Scheme 1, the overshoot of the reactive power output is larger. After optimizing the excitation system in Scheme 2, the overshoot is reduced.

![Figure 4. Reactive power outputs of the condenser under two optimal design schemes of the excitation system.](image1)

![Figure 5. Voltages of the receiving-end grid under two optimal design schemes of the excitation system.](image2)

5. Conclusion
In this study, the outer loop control of reactive power of condensers and the outer loop control of the voltages of AC systems have been added on the basis of the conventional design of the main excitation systems of synchronous condensers in HVDC systems. Moreover, the variable universe fuzzy adaptive PID controller has been proposed to serve the excitation systems of condensers, for the sake of improving the response ability of condensers in power grid faults and the recovery speed of condensers after power grid faults, and addressing the overvoltage problem in power grids caused by condensers in the process of fault recovery of the power grids. The verified results indicate that the optimal design method of excitation systems of synchronous condensers in the proposal compared to the other method can not only ensure rapid regulation of the voltages of AC systems arising from condensers, but also reduce overcompensation of the voltages and reactive power of AC systems arising from condensers.
when faults recover.

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