Adaptive VDCOL control strategy for the recovery of the UHVDC SPC system

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Abstract: The separating pole connection (SPC) mode of ultra-high-voltage direct current (UHVDC) can significantly improve the power stability, but when the AC bus of one pole is failed and two receiving systems are near, it may cause subsequent commutation failure. In order to restrain subsequent commutation failure and accelerate system’s recovery, an adaptive voltage-dependent current order limiter (VDCOL) control strategy based on granular computing is proposed. According to this VDCOL control strategy, VDCOL, which uses fuzzy rules to separate and granulate a different voltage level, can adjust DC current dynamically in a variety of environments. Also, some modifications on VDCOL characteristics are applied to reduce reactive power consumption during low-voltage situations. Then based on the MATLAB simulation platform, the simulation systems for 800 kV the UHVDC SPC system are built. Finally, the simulation example of the SPC mode with the adaptive VDCOL control strategy showed that this VDCOL control strategy can reduce the risk of subsequent commutation failure and improve the stability of the AC/DC interconnection system.

1 Introduction

In a multi-infeed high-voltage direct current (MIDC) system, if the receiving power system is disturbed by the disturbance, it may cause continuous commutation failures and voltage instability, and even cause the interruption of DC power transmission, posing a huge threat to the safe and stable operation of the power grid. Nowadays, in order to address the problem of MIDC from the aspect of the grid structure, a novel ultra-high-voltage direct current (UHVDC) separating pole connection (SPC) mode is proposed. However, when the electrical distance is short between the inverter stations and AC faults occur, the receiving system is extremely vulnerable to cause continuous commutation failures [1]. To improve the recovery performance of MIDC systems, it is significant to study the coordinated control of the UHVDC SPC mode.

In order to restrain subsequent commutation failure and speed up the system recovery, the control system introduces a voltage-dependent current order limiter (VDCOL) to improve the dynamic characteristics of the system under transient fault conditions. At present, VDCOL in the HVDC project is mostly linear static recovery characteristic. If a serious fault occurs, which is not conducive to the reconstruction of the voltage on the inverter side and the recovery of the DC transmission power, the power system is prone to continuous commutation failure. Some studies have shown that the optimisation of the VDCOL control strategy and parameters has a significant impact on the recovery characteristics of DC systems. Ke et al. and Juanjuan et al. [2,3] improve the HVDC system gradual recovery characteristics by adding delay elements and minimum selection units to the VDCOL module, but do not consider the dynamic characteristics of each electrical quantity. Chao et al. [4] present a dynamic self-adaptive VDCOL control strategy based on the AC bus voltage level of the inverter side, but this method has very high requirements on the setting of VDCOL parameters. Dachun et al. and Lei et al. [5,6] provide a design scheme of the variable slope VDCOL controller; however, the computational complexity of this scheme is not suitable for the modelling and simulation of large-scale power grids. Although the above methods have some limitations, they are still superior to the conventional VDCOL in terms of transient stability and the recovery rate of the HVDC system.

Based on the basic principle of VDCOL, this paper combines granular computing and fuzzy control, and proposes an adaptive VDCOL fuzzy control strategy based on granular computing. The optimal control strategy eliminates the fuzzification and defuzzification steps in the process of fuzzy control, effectively simplifies the fuzzy rules, and thus accelerates the response speed of the control system. The UHVDC SPC model is set up in MATLAB, and then the performance of the proposed strategy is verified. The results show that the proposed adaptive VDCOL control strategy is able to accelerate the recovery of the UHVDC SPC system after a fault and effectively restrain the system from consequential commutation failure. Section 2 of this paper introduces the UHVDC SPC mode, the characteristics of VDCOL, and the fundamental theory of granular computing and fuzzy control. Section 3 demonstrates the detailed design for the proposed adaptive VDCOL fuzzy control strategy based on granular computing optimisation. The effectiveness of the proposed VDCOL control strategy for the UHVDC SPC mode is analysed in Section 4. In the end, Section 5 concludes the paper.

2 Theoretical basis of VDCOL based on granular computing in the SPC model

2.1 Separating pole connection model of UHVDC

The definition of the UHVDC SPC model is that the positive pole and negative pole of DC transmission lines are, respectively, connected to different AC systems via converter buses. According to the electrical characteristics of two AC systems, the SPC model is divided into the separating pole monolayer connection model and the separating pole hierarchical connection (SPHC) model [7]. This paper sets up an SPHC model, which is available for two receiving systems with different voltage grades. The topology of an SPHC model is shown in Fig. 1. $E_a, E_b, Z_a, Z_b$ are, respectively, the equivalent voltage source and impedance of receiving AC systems, $k$ is the tap of the interconnecting transformer, and $Z_{ab}$ is the line interconnecting impedance. The value of $Z_{ab}$ is mainly related to the electrical distance of the AC systems, and $Z_{ab}$ is infinite if the electrical distance is remote.
In which, $S_{aci}$ is the short-circuit capacity of receiving systems $i$, $P_{di}$ is the rated DC power in monopole, $U_{Nq}$ is the nominal voltage of the converter bus, $Z_{eq}$ is the self-impedance element in the equivalent impedance matrix, and $Z_{eq}$ is the equivalent interacting impedance element in the equivalent impedance matrix which shows the coupling degree of the receiving systems $i$ and $j$.

Besides, taking the nominal voltage of the converter bus $U_{Nq}$ as the reference voltage, the SCR of the SPC mode is expressed as

$$R_{MSC} = \frac{S_{aci}}{P_{d}} = \frac{U_{Nq}/Z_{eq}}{P_{di} + \sum_{j \neq i} \frac{Z_{eq}/Z_{eqj}}{Z_{eqj}}}. \quad (1)$$

### 2.2 Characteristics of the conventional VDCOL

The function of the VDCOL controller is to limit the DC current when the DC voltage or AC voltage declines to a specified value because of fault, so as to reduce the reactive power demand of the AC system and help maintain and restore the voltage of power system. At present, most of the HVDC projects use the DC-VDCOL controller, whose characteristic curve is shown in Fig. 3. In Fig. 3, the characteristic curve manifests that the static recovery characteristics of the ordinary VDCOL are primarily determined by $I_{df}, I_{f}, U_{df}$, and $U_{df}$ and the relation between the voltage and current is linear.

### 2.3 Granular function and fuzzy control

The fuzzy mathematical model does not have a specific function expression, used to describe the matter whose boundary is obscure and concept is ambiguous. Meanwhile, the input and output of the granular function are all fuzzy concepts, expressed in fuzzy subsets. The membership functions indicate the degree of fuzzy extent, and there is a certain kind of mapping between the fuzzy input and output of the granular function, generally called fuzzy mapping and denoted by $f^*$ [9]. The statement of the $p$ granular function is given below.

$$X_i = \{x_{i1}; m_i = 1, 2, \ldots, M_i\};$$
$$X_p = \{x_{p1}; m_p = 1, 2, \ldots, M_p\};$$
$$Y = \{y_n; n = 1, 2, \ldots, N\};$$

are some given fuzzy sets, and the membership function of the fuzzy subset in these fuzzy sets is $\mu_i(a) \rightarrow [0, 1]$, where $i = 1, 2, \ldots, p$, and the membership function of the fuzzy subset in the fuzzy set $Y$ is $\mu_Y(a) \rightarrow [0, 1]$. If the mapping relation $x_{i1} \times x_{i2} \times \cdots \times x_{iM_i} \rightarrow y_n$ exists, we can obtain the expression of the $p$ granular function as (3), where ‘$\times$’ represents the Cartesian product:

$$y_n = f^*(x_{i1}, x_{i2}, \ldots, x_{ip}) \quad (3)$$

The independent variable and dependent variable of the granular function should be granulated, respectively, so that there is a one-to-one mapping relationship between the fuzzy granule in the independent variable and the fuzzy granule in the dependent variable. Let $X$ and $Y$ be the linguistic variables after fuzzy information granulation. $A_i$ and $B_i$ denote the fuzzy subset of $X$ and $Y$, whose fuzzy relation can be represented by the following fuzzy rules. If $Y = A_i$, then $Y = B_i$. The expression of the granule function acquired from the fuzzy mapping relation is shown in (4), where $^*$
and the DC voltage variation, but also the MISCR should be implemented function of the fuzzy controller relies on fuzzy rules, and the design of fuzzy rules is based on human experience [10]. Therefore, the response function of the fuzzy control system is called the granule response function. In fuzzy control, different fuzzification and defuzzification algorithms correspond to different granule response functions. According to the principle of fidelity in fuzzy quotient space theory, it is easy to find that the granular function obtained from the process of fuzzy control is coarse granularity, while the response function is fine granularity. If there is a solution in coarse granularity, there must be a solution in fine granularity; thus, a clear numerical response function can be accepted instead of the ordinary fuzzy controller.

3 Design of the adaptive VDCOL controller based on granular computing

3.1 Adaptive VDCOL controller based on granular computing

The recovery characteristics of the conventional VDCOL are a linear relationship between the DC current and DC voltage, which are unable to rationally restrict the growth of the current at a low voltage. In order to remove the drawback of the conventional VDCOL, a novel VDCOL fuzzy controller based on fuzzy theory is proposed, which adopts variable slope recovery characteristics [6]. Moreover, the characteristic curve is shown in Fig. 4. However, for the UHVDC SPC model, not only the DC voltage and the DC voltage variation, but also the MISCR should be considered. Under this condition, if the ordinary fuzzy controller is utilised, the dimension of the controller is too high and the control rules are too complex so that the response speed of the control system becomes slow, which hardly satisfies the requirements of engineering practice.

Based on the existing VDCOL fuzzy controller, this paper proposes an improved adaptive VDCOL control strategy. According to the value of the MISCR to optimise the sequencing of recovery for the DC voltage and power of each HDVC system; based on the DC voltage level to determine the DC current growth rate appropriately. More importantly, this strategy not only addresses the problem that the high-dimensional fuzzy controller is too difficult to be modelled, but also eliminates fuzzification and defuzzification steps in the fuzzy control process, which simplifies the process of fuzzy control to a great extent.

The core point of the optimisation algorithm is as follows: the fuzzy input and the fuzzy output are granulated, respectively, to acquire fuzzy information granule, and the mapping relation of granular sampling points is obtained through human experience, by which the granular function is fitted; a sort of mapping relation for the granular function is recorded by the tracing point method, and synthesise the normal fuzzy set of the finest granular layer into a fuzzy equivalent class of the coarsest granularity. Theoretically, only three fuzzy sets NS, ZO, and PS are contained in the coarsest granular layer. Based on the principle of fidelity in quotient space theory, if the issue is addressed in the original domain X with a fine granularity, the issue can be addressed in the domain [X]0 with a coarse granularity [11]. Therefore, it is feasible to simplify original fuzzy rules to achieve the same effect of original fuzzy control. The fuzzy language set and domain of each input variable and output variable in the finest granular layer are shown in Table 1.

### Table 1 Fuzzy language sets and domains of variables in the finest granular layer

| Variable | Language set | Domain |
|----------|--------------|--------|
| RDSC     | {VS, S, M, B, VB} | [0, 10] |
| Ud       | {NB, NM, NS, ZO, PS, PM, PB} | (-6, 6) |
| Id       | {NB, NM, NS, ZO, PS, PM, PB} | (-6, 6) |
| Io       | {NB, NM, NS, ZO, PS, PM, PB} | [0.3, 1] |

3.2 Granulation of the fuzzy Set

The domain X of the fuzzy set defined in fuzzy control is as clear as possible to the problem description; thus, the fuzzy information granule acquired from granulation should be the finest granular layer in the entire granular structure. In this article, a bottom-up granulation method is applied to synthesise the normal peak set NS, ZO, and PS of the finest granular layer into a fuzzy equivalent class ZO1, and synthesise the normal fuzzy set NB, NM of the finest granular layer into a fuzzy equivalent class NS1. Similarly, the fuzzy equivalent relation Rj also merges the other normal peak sets of the finest granular layer into the coarser granule. The coarsest granule is combined into a new granular layer [X]. Likewise, different fuzzy equivalent relations R1, R2, ..., Rn can be combined into different granular layers. After n times of operation, the granular layer [X]n is gained, which is corresponding to the coarsest granularity.

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3.3 Relation of the granular function and point response function

From Section 3.1, the crux of the control strategy proposed in this paper is to transform the granule response function into a point response function and replace the fuzzy controller with the point response function. According to the theory of the fuzzy information granule, each primitive is regarded as a fuzzy granule, and the granular function is acquired from the mapping relation of
granular sampling points, as shown in Fig. 6a. However, due to the fuzzy boundary of the granular function, which is unable to be applied to the control system directly, the control function used in project reality is similar to the point response function, as shown in Fig. 6b. The granular function can be considered as the fuzzification of a certain specific function, and the constraint of granular mapping relation is called as a fuzzy graph constraint. Furthermore, a fuzzy graph constraint can be expressed as a possible constraint on its approximation function.

The proposed adaptive VDCOL controller has three input variables: the DC voltage \( U_d \), DC voltage variation \( \Delta U_d \), MISCR \( R_{MSC} \), and one output \( I_o \) which is the target of the DC current. The input variables and output variable constitute a mapping, which means that the response function used to control the performance of VDCOL requires three independent variables and one dependent variable. The equation of the point response function can be expressed as

\[
I_o(R_{MSC}, U_d, \Delta U_d) = \sum_{i=0}^{n} \sum_{j=0}^{n-i} \sum_{p=0}^{n-i-j} M_{ijp} R_{MSC} U_d [U_d^{p}] \tag{5}
\]

In which, the order \( n \) can be defined according to the specific situation. Obviously, the higher the order, the more complex the function and more accurate the result.

When \( n = 2 \), the maximum number of (5) is 2. First, we granulate the three inputs, respectively, to obtain the three granular layers. Then the fuzzy granule of inputs is cyclically traversed via the MATLAB program so that a matrix of 1089 rows and 3 columns is obtained. According to the interpolation mechanism of the fuzzy controller, the value of this matrix is taken as the interpolated input, and an output is obtained, which is a new matrix of 1089 rows and 1 column. Apparently, it is simple to acquire the coefficients of the second-order function via the nonlinear least-squares method, and then the equation of the point response function is obtained as follows:

\[
I_o(R_{MSC}, U_d, U_d) = 0.0395R_{MSC} + 0.051U_d - 0.0254U_d^2 - 0.0228R_{MSC} U_d - 0.0491R_{MSC} U_d^2 + 0.0613U_d [U_d^{p}] \tag{6}
\]

Equation (6) is written into the Fcn module of Simulink in the form of a code, and then the three-dimensional fuzzy controller is replaced with the Fcn module, and the regulation coefficient is added for each input and output.

4 Simulation

According to the planning data of the Henan Power Grid in 2020, an example of the UHVDC SPC mode is constructed by using MATLAB/Simulink software. The basic parameters of the UVD C SPC system are the following: the rated DC voltage is ±1100 kV, the rated DC transmission power is 12,000 MW, the length of transmission is 280 km, the per unit impedance of the transmission line is \( Z_{line} = (0.08 + 0.4) \Omega/km \), the rated operating voltage of the sending-end system is 775 kV, and the voltage levels of the receiving AC systems are 550 and 1050 kV, respectively.

In this section, the models of the conventional VDCOL controller and the adaptive VDCOL controller based on granular computing are simulated, respectively, under various fault conditions, and the simulation results are compared and analysed. Moreover, in all simulation, it is assumed that the electrical distance between two receiving power systems is near, which means that the two receiving systems are connected by the interconnecting transformer and impedance.

4.1 Transient simulation of an A-phase ground fault

The positive pole is connected to the 550 kV receiving AC system and the negative pole is connected to the 1050 kV receiving AC system. The single-phase ground short-circuit fault has occurred at the inverter side of the positive pole. The fault starts at 3.0 s and lasts 100 ms. Under the two kinds of the VDCOL control strategies, the transient response of two receiving systems to the fault is shown in Figs. 7 and 8.

The simulation results manifest that when the single-phase ground fault occurs in the receiving AC system connected to the positive pole, the electrical coupling effect of two receiving power systems will give rise to the decline of voltage which belongs to the converter bus of the other receiving AC system, and then the commutation failure will occur in the negative pole. During the fault, the performance of the two control strategies is almost identical. After the fault is cleared, the DC current and DC voltage recovery of the UHVDC SPC mode, which utilise the adaptive VDCOL control strategy based on granular computing, is clearly faster than those using the conventional VDCOL control strategy. During the process of system recovery, there is no continued commutation failure between the positive and negative poles, which indicates that the adaptive VDCOL control strategy proposed in this paper can reduce the oscillation of the system electrical quantities and restrain the subsequent commutation failure effectively.

4.2 Transient simulation of the DC fault

The short-circuit fault has occur at the middle of the DC transmission line connected to the 550 kV receiving power system. The DC fault starts at 3.0 s and lasts 100 ms. Under the two kinds of VDCOL control strategies, the transient response of two receiving systems to the fault is shown in Figs. 9 and 10.

The simulation results indicate that the receiving system connected to the positive pole has a continuous fault after the DC
fault removal under the traditional VDCOL control method. However, utilising the adaptive VDCOL control method proposed in this paper, the receiving system can avoid the subsequent commutation failure and the DC current can be quickly restored to the rated value. Besides, when the DC fault occurs in the middle of the DC transmission line connected to the positive pole, even if the electrical distance of two receiving systems is near, the other pole is able to maintain normal operation despite minor fluctuation.

5 Conclusion
Firstly, the adaptive VDCOL control strategy proposed in this paper uses the point response function instead of the high-dimensional fuzzy controller to control the performance of VDCOL, which can avoid the ‘fuzzy rule explosion’ in a high-dimensional fuzzy controller. Meanwhile, this algorithm eliminates the fuzzification and defuzzification in the process of fuzzy control, which greatly simplifies the process of fuzzy control. Thus, the proposed adaptive VDCOL control strategy is of great practical value in optimal modelling and simulation of large-scale MIDC system.

Secondly, for the case that the electric distance between two receiving AC systems is near in the UHVDC SPC mode, the simulation results in Section 4 manifest that the proposed adaptive VDCOL control strategy based on granular computing has good control performance, which can quickly and efficiently make the power system recover from a fault and enhance the transient state stability of the UHVDC SPC system.

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Fig. 8 Negative transient response process of a phase short-circuit fault

Fig. 9 Positive transient response process of the DC fault

Fig. 10 Negative transient response process of the DC fault