Transient Voltage Control of Sending-End Wind Farm Using a Synchronous Condenser Under Commutation Failure of HVDC Transmission System

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ABSTRACT When the large-scale wind power is sent out through the high voltage direct current (HVDC) transmission system and a DC commutation failure occurs, the voltage of AC bus at the sending end decreases first and then increases. Suppose the reactive power supported in the low voltage ride-through process by various reactive resources is not timely returned. In that case, it may aggravate the voltage rise caused by the commutation failure, and the off-grid risk of wind turbine under high-voltage will be aggravated. In order to reduce the off-grid risk of wind turbines caused by the DC commutation failure, a transient voltage control strategy of DC sending-end regulator based on the online sequential extreme learning machine (OS-ELM) voltage prediction model is proposed. Firstly, the influence factors of commutation failures are analyzed. Aiming at the key factors, the real-time voltage comprehensive prediction model based on OS-ELM is used to predict the voltage increase during the commutation failure process and uses the voltage prediction results to optimize the transient response of the synchronous condenser. A large-scale wind farm together with the HVDC system is established in PSCAD to verify the effectiveness of the proposed scheme. Simulation results show that the proposed scheme can reduce the risk of wind power off-grid risk under DC commutation failures and increase the speed of voltage recovery at the point of common coupling.

INDEX TERMS DC commutation failure, high voltage ride through, doubly-fed induction generator, synchronous condenser, transient voltage control.

I. INTRODUCTION

The environmental problems caused by fossil energy consumption have become increasingly serious, and wind power has been widely used worldwide. With the rapid development of wind power in China, the wind power consumption in regions with abundant wind power resources tends to be saturated. There is an urgent need for trans-regional transmission channels to improve the utilization efficiency of wind power resources [1], [2]. However, when wind turbines are connected to the grid via the high voltage direct current (HVDC) transmission system, they are easily affected by the failure of the DC system [3]. For example, when a commutation failure occurs in a DC system, the reactive power consumed by the DC system increases due to the increase of the direct current at the initial stage of the commutation failure, and the AC bus voltage of the sending-end converter station drops, and then the DC power drops sharply. All the reactive power surplus of the station flooded into the AC system, causing the AC bus voltage of the sending-end converter station to rise. Because the reactive power compensated by wind turbines and static var compensators (SVCs) are not returned in time, the voltage rise is aggravated. During this procedure, the wind farms face the process of low voltage ride through and high voltage ride.
through, respectively. If it is not controlled, it may lead to the high voltage ride-through failure of wind turbines and large-scale chain disconnection of wind farms, threatening the safe operation of the sending-end system. Therefore, it is studied that the transient voltage control of the sending-end wind farm under the commutation failure of the HVDC transmission system is of significance.

For the transient voltage control method, the researchers have also conducted certain work. Literature [4] proposes to increase the short-circuit capacity level of the DC transmission end system to reduce the voltage surge under the failure of DC commutation and to improve the voltage resistance level of the grid-connected wind turbines. It is difficult to reconstruct some projects which have been put into use. Literature [5]–[8] proposed the strategy of removing the AC filter of the DC sending-end bus during the fault and putting in a static, dynamic reactive power compensation device for reactive power compensation but did not consider the response time of the device and the impact of the moment of the fault on the wind farm. At present, the main dynamic reactive power compensation devices in the power grid are SVC, static var generator (SVG), and synchronous condenser. Compared with SVC, SVG and other dynamic reactive power compensation devices based on power electronics technology, the synchronous condenser, as a rotating equipment, not only provides short-circuit capacity for the system, but also has better reactive power output characteristics. It has unique advantages in reducing transient overvoltage at DC sending end, restraining commutation failure at DC receiving end, and improving system stability by using forced excitation [9]–[13].

State Grid Corporation of China has installed synchronous condensers in multiple high-voltage DC transmitters and receivers, and there will be more synchronous condensers installed in the future. In the existing research in terms of the application of the synchronous condenser, the literature [14] analyzed the reactive power-voltage coordinated control strategy of the excitation system of the large synchronous condenser. Literature [15] proposed a reactive power control strategy for power system voltage regulator (PSVR). However, there are few studies in controlling the synchronous condenser during the dynamic voltage process. The reactive power response of the synchronous condenser and the process of wind turbine fault ride-through and commutation failure also need to be closely coordinated. During the failure of DC commutation, if the excitation voltage retreads early, it can’t give enough support to the low voltage process, while if it retreads late, it will cause overvoltage problems. Literature [16] proposes a voltage prediction method based on convolutional neural networks. Literature [17] uses minimum mean squares estimation (MMSE) to predict voltage, but these articles rely on the accuracy of historical data and do not consider the effect of training model time. Online sequential extreme learning machine (OS-ELM) has the advantages of short training time and high prediction accuracy. When new data is input, OS-ELM can update quickly and avoid retraining historical data. It has applicability to transient voltage control scenarios.

To solve the over-voltage problems caused by the DC commutation failure, a new control idea for the synchronous condenser based on the OS-ELM voltage forecast model is proposed. Firstly, a simulation model of the wind power transmission via HVDC is established to study the method; Secondly, the formula of the voltage variation degree during the DC commutation failure is deduced, and the correlation analysis of its influencing factors is carried out; Subsequently, according to the key influencing factors, the real-time voltage during the commutation failure is predicted by OS-ELM method; Then, a reactive voltage control method of the synchronous condenser based on the voltage prediction is proposed. Finally, the effectiveness of this method is demonstrated by using examples.

II. ANALYSIS OF FAULT CHARACTERISTICS OF HVDC TRANSMISSION SYSTEM

A. ANALYSIS OF VOLTAGE CHANGE DEGREE OF WIND POWER GRID-CONNECTED POINT UNDER DC COMMUTATION FAILURE

DC commutation failure is one of the most common failures in AC/DC hybrid systems. In recent years, due to the rapid development of the large-scale new energy power generation, the problem of the change of the sending-end bus voltage caused by the failure of commutation has attracted the attention of scholars. Under normal operating conditions, the reactive power consumed by the converter station of the DC system is about 50% to 60% of the active power. When a DC commutation failure occurs, the reactive power will change significantly. As a result, the sending-end bus voltage fluctuates, which further affects the voltage of the wind farm at point of common coupling, causing the wind farm to face the problems of both low voltage ride through and high voltage ride through.

Based on the CIGRE HVDC standard model, this paper adds a wind farm model, which is equivalent to a doubly-fed wind turbine generator and a large synchronous condenser, at the end of the DC transmission. The overall structure is shown in Figure 1.

The voltage change at the grid-connected point of the wind turbine is mainly determined by the change in the AC reactive power of the converter station and the system and the short-circuit capacity of the AC system, which can usually be evaluated by the following formula:

$$\Delta U = \frac{Q_{exch}}{S_{com}}$$  \hspace{1cm} (1)

where,

- $\Delta U$ = transient voltage change rate at the grid connection point of the wind farm
- $Q_{exch}$ = reactive power difference between AC system and converter station
- $S_{com}$ = short-circuit capacity of the converter bus
It can be seen from Figure 1 that the short-circuit capacity of the converter bus is mainly provided by the wind farm, the synchronous condenser, the SVC, and AC grid, and the formula can be expressed as:

\[ S_{\text{com}} = S_{\text{windfarm}} + S_{sc} + S_{SVC} + S_{AC} \]  

(2)

where,

- \( S_{\text{windfarm}} \) = short-circuit capacity of the wind farm
- \( S_{sc} \) = short circuit capacity of synchronous condenser
- \( S_{SVC} \) = short circuit capacity of Static Var Compensator
- \( S_{AC} \) = short circuit capacity of other sending-end AC power supplies

The reactive power \( Q_{\text{exch}} \) exchanged between the wind farm station, and the converter station can be expressed as:

\[ Q_{\text{exch}} = (Q_{\text{conv}} + Q_t) - (Q_f + Q_{\text{windfarm}} + Q_{SVC} + Q_{sc}) \]  

(3)

where,

- \( Q_{\text{conv}} \) = reactive power consumed by the converter station on the rectifier side
- \( Q_t \) = reactive power consumed by the impedance of transmission line between the wind farm and commutating station
- \( Q_f \) = reactive power provided by AC filter and capacitor compensator of rectifier station
- \( Q_{\text{windfarm}} \) = reactive power provided by wind farm
- \( Q_{SVC} \) = reactive power provided by SVC
- \( Q_{sc} \) = reactive power provided by the synchronous condenser

In (3), the reactive power provided by the AC filter and capacitor compensator in the rectifier station can be further expressed as:

\[ Q_f = B_c U_r^2 \]  

(4)

where,

- \( B_c \) = equivalent susceptance of AC filter and compensator
- \( U_r \) = AC bus voltage on the rectifier side

It can be seen from formula (3) that \( Q_{\text{exch}} < 0 \) denotes the output of reactive power from the converter station to the wind farm and \( Q_{\text{exch}} > 0 \) represents the output of reactive power from the wind farm to the converter station.

In the CIGRE standard model, under normal operation mode, the inverter station adopts fixed extinction angle control, and the rectifier station adopts constant-current control.

\[ U_{dr} = U_{dor} \cos \alpha - R_{cr} I_d \]  

(5)

\[ I_d = \frac{U_{dor} \cos \alpha - U_{doi} \cos \beta}{R_{cr} + R_d - R_{ci}} \]  

(6)

where,

- \( U_{dor} \) = no-load DC voltage value of the rectifier station
- \( U_{doi} \) = no-load DC voltage value of inverter station
- \( U_{dr} \) = DC voltage on the rectifier side
- \( I_d \) = direct current
- \( R_d \) = DC line resistance
- \( \alpha \) = trigger angle on rectifier side
- \( \beta \) = inverter angle on the inverter side

In (6), the resistance value of the rectifier side and the inverter side can be replaced by the corresponding commutation transformer leakage reactance value:

\[ R_{cr} = 3/\pi X_{cr} \]  

(7)

\[ R_{ci} = 3/\pi X_{ci} \]  

(8)

where,

- \( X_{cr} \) = leakage reactance of commutation transformer on the rectifier side
- \( X_{ci} \) = leakage reactance of commutation transformer on the inverter side
When ignoring the harmonic components in the AC and DC sides, the formula can be expressed as:

\[
\cos \varphi = \frac{\cos \alpha + \cos(\alpha + \mu)}{2} = \cos \alpha - \frac{R_{AC}I_d}{U_{dor}} \tag{9}
\]

where,

\[
\varphi = \text{rectifier side power factor angle}
\]

\[
\mu = \text{commutation angle on the rectifier side.}
\]

At the same time, there is reactive power consumed by the converter station on the rectifier side:

\[
Q_{\text{conv}} = P_d \tan \varphi = U_{dor}I_d \sqrt{1 - (\cos \varphi)^2} \tag{10}
\]

where,

\[
P_d = \text{active power output by the rectifier station}
\]

In the AC/DC hybrid system, the short-circuit ratio of the AC system on the rectifier side \(K_{\text{SCR}}\) can be expressed as:

\[
K_{\text{SCR}} = \frac{S_{\text{AC}}}{P_{d\text{IN}}} \tag{11}
\]

where,

\[
P_{d\text{IN}} = \text{DC transmission power rating}
\]

From (1), (2), (5), (6), (11), we can see that (12), as shown at the bottom of the page.

Combining (12) and the field fault record of DC commutation failure [18], it can be seen that at the moment of commutation failure, the direct current rises sharply, the reactive power absorbed by the inverter increases, and the converter station is removed from the AC system. The converter station absorbs a large amount of reactive power, resulting in a decrease in voltage. However, with the start of the low-voltage current-limiting link on the inverter side of the converter station, the constant current control in the rectifier side begins to respond, the direct current is rapidly reduced, and the reactive power consumption required by the converter is also rapidly reduced. A large amount of reactive power surplus in the converter station flux to the AC system, causing the sending end AC bus voltage to rise.

### B. CORRELATION ANALYSIS BETWEEN THE DEGREE OF VOLTAGE CHANGE AND INFLUENCING FACTORS

It can be seen from (12) that the degree of voltage change \(\Delta U\) that the DC commutation failure is affected by the reactive power provided by the synchronous condenser \(Q_{\text{sc}}\), the short-circuit ratio of the AC system \(K_{\text{SCR}}\), and the equivalent susceptance of the AC filter and compensator \(B_c\). In order to further analyze the correlation between the degree of voltage change and its influencing factors, the method of Spearman correlation coefficient analysis is used for correlation analysis.

\[
\Delta U = \frac{B_cU_f^2 + Q_{\text{sc}} + Q_{\text{SVC}} + Q_{\text{windfarm}} - U_{dor}I_d \sqrt{1 - (\cos \alpha - \frac{R_{AC}I_d}{U_{dor}})^2}}{S_{\text{windfarm}} + S_{\text{SVC}} + K_{\text{SCR}}P_{d\text{IN}}} \tag{12}
\]

1) SPEARMAN CORRELATION COEFFICIENT

Spearman correlation coefficient is usually called Spearman rank correlation coefficient. Rank can be understood as an order or a sort. Therefore, the Spearman correlation coefficient is solved according to the sort position of the original data, thereby reducing the restriction on the linear correlation of the data itself. Assuming that there are \(n\) sets of data, namely \((x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\), the calculation formula of Spearman’s correlation coefficient is

\[
\rho_s = \frac{\sum_{i=1}^{n} (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n} (R_i - \bar{R})^2 \sum_{i=1}^{n} (S_i - \bar{S})^2}} \tag{13}
\]

where,

\[
\rho_s = \text{spareman correlation coefficient}
\]

\[
R_i, S_i = \text{the level corresponding to the i-th group of data}
\]

\[
\bar{R}, \bar{S} = \text{average rank of variables x and y}
\]

\[
n = \text{the number of data sets}
\]

It can be seen from (13) that the value range of \(\rho_s\) is \([-1, 1]\). When \(\rho_s\) is close to 0, it means that the variable \(x\) and \(y\) are not correlated. When \(\rho_s\) is close to 1 or -1, it means that the variable \(x\) and \(y\) are strongly correlated.

2) SPEARMAN CORRELATION COEFFICIENT ANALYSIS

By building a wind farm through a high-voltage direct-current model, multiple simulations were performed to obtain multiple sets of data corresponding to the influencing factors and the degree of voltage change. Spearman correlation analysis is performed on the obtained data, and Figure 2 is obtained.

It can be seen from Figure 2 that the two influencing factors related to the degree of voltage change are the short-circuit
ratio of the sending-end AC system and the equivalent susceptibility of the AC filter and compensator. At the same time, the degree of voltage change is related to the firing angle of the rectifier side and the DC resistance of the line is moderately correlated, and the DC transmission power rating is weakly correlated with the degree of voltage change. In the process of controlling the degree of voltage change caused by the failure of DC commutation, it is important to control the short-circuit ratio of the sending-end grid and the output reactive power of the synchronous condenser to reduce the degree of voltage change.

In actual engineering projects, the synchronous condenser uses the preset control logic in the hardware module to realize reactive power compensation and absorption of voltage fluctuations, but in the rapid process of voltage swells and drops, the response of the synchronous condenser cannot completely match the voltage change speed. By building a voltage prediction model, the voltage changes can be predicted in time. The synchronous condenser refers to the predicted voltage waveform and adjusts in advance to improve the matching degree of reactive power output with AC voltage changes, which has practical guiding significance for the actual reactive voltage control.

### III. COMPREHENSIVE VOLTAGE PREDICTION MODEL BASED ON OS-ELM

#### A. ELM ALGORITHM

The OS-ELM model is an algorithm that uses real-time data to learn and update output weights based on the extreme learning machine (ELM) algorithm. The standard ELM model is shown in Figure 3.

As shown in Figure 3, for a certain standard extreme learning machine network model, suppose there are N groups of arbitrary training samples \((X_i, Y_i)\), where \(X_i = [x_1, x_2, \ldots, x_n]^T\) are the inputs in the training samples and \(Y_i = [y_1, y_2, \ldots, y_m]^T\) are the outputs corresponding to the inputs in the training samples. The output function of the hidden layer has the following definitions:

\[
o_j = \sum_{i=1}^{L} \beta_i g(o_i \cdot x_j + b_i)
\]

where,

- \(j = 1, \ldots, N\)
- \(\beta_i = \) output weight
- \(g(x) = \) excitation function
- \(o_i = [o_{i,1}, o_{i,2}, \ldots, o_{i,n}]^T\), input weight
- \(b_i = \) Threshold of the i-th hidden layer unit

The goal of the ELM algorithm is to minimize the difference between the output of the model and the actual theoretical output:

\[
\sum_{i=1}^{N} ||o_i - y_i|| = 0
\]

Then \(\beta_i, o_i\) and \(b_i\) satisfies:

\[
\sum_{i=1}^{L} \beta_i g(o_i \cdot x_j + b_i) = y_j, \quad j = 1, 2, \ldots, N
\]

Expressing the formula through a matrix (16) gives

\[
H\beta = T
\]

where,

- \(H = \) hidden layer node output
- \(\beta = \) output weight

\[
H(o_1, \ldots, o_L, b_1, \ldots, b_L, X_1, \ldots, X_L) = \\
\begin{bmatrix}
g(o_1 \cdot X_1 + b_1) & \cdots & g(o_L \cdot X_1 + b_L) \\
\vdots & \ddots & \vdots \\
g(o_1 \cdot X_N + b_1) & \cdots & g(o_L \cdot X_N + b_L)
\end{bmatrix} 
\]

\[
\beta = \\
\begin{bmatrix}
\beta_1^T \\
\vdots \\
\beta_L^T
\end{bmatrix}, \quad T = \\
\begin{bmatrix}
T_1^T \\
\vdots \\
T_L^T
\end{bmatrix}
\]

In the ELM algorithm, the input weight and threshold are randomly given from the beginning. Moreover, the output weights between the hidden layer and the output layer do not need to be iterated repeatedly and can be determined at one time by solving the solution of the equation system, which greatly reduces the time of algorithm calculations. And literature [19] has proved that the global optimal output weight can be written as:

\[
\hat{\beta} = H^+T
\]

where,

\[H^+ = (H^T H)^{-1}H^T, \text{ it is the Moore-Penrose generalized inverse of the hidden layer output matrix } H.\]

#### B. OS-ELM MODEL

The Online Sequential ELM is an ELM algorithm that can use real-time data to learn and update output weights. It has the advantages of the speed and generalization ability and can continuously update the model with the arrival of new data instead of retraining the model. In the prediction process of various traditional models, the quality of the input sample
data will directly affect the prediction accuracy of the prediction model. In the actual production process, errors will occur during the collection and storage of various types of data, resulting in abnormal samples. At the same time, due to the uneven performance of the measurement equipment in real-time measurement, abnormal data samples often appear, and it is difficult to eliminate all abnormal samples. Therefore, these abnormal samples that deviate from the actual situation will affect the prediction results. In the process of new data input, OS-ELM can control the number of input samples within a reasonable range, and effectively screen training samples to ensure that there are no abnormal samples. With the continuous input of new data, the influence of abnormal samples in historical data on the prediction results will also be continuously weakened, thereby improving the robustness of the prediction model. OS-ELM is mainly divided into two stages in the specific implementation process.

1. Initialization section
   Given the initial training samples of the network, the number of hidden layer neurons, and the activation function, randomly generate input weights and thresholds to determine the hidden layer output weight $\beta_0$ and hidden layer output matrix $H_0$ in the initial network.

2. Online sequential learning section
   When a new batch of data arrives, the hidden layer output matrix and output weight vector can be updated according to the following expressions [18):

   $H_{t+1} = \begin{bmatrix} g(\omega^T_0 \cdot X^1_{t+1} + b_1) & \cdots & g(\omega^T_L \cdot X^L_{t+1} + b_L) \\ \vdots & \ddots & \vdots \\ g(\omega^T_0 \cdot X^1_{N_{t+1}} + b_1) & \cdots & g(\omega^T_L \cdot X^L_{N_{t+1}} + b_L) \end{bmatrix}_{N \times L}$ (21)

   $\beta_{t+1} = \beta_t + Q_{t+1}H_{t+1}(H_{t+1}^T - H_{t+1}^T \beta_t)$ (22)

   $Q_{t+1} = Q_t - \frac{Q_t H_{t+1}^T H_{t+1} Q_t}{I + H_{t+1}^T H_{t+1}}$ (23)

   $Q_0 = (H_0^T H_0)^{-1}$ (24)

OS-ELM will continuously update the parameters through the above formula combined with the newly added data $H$ and $\beta$.

### IV. COMBINED VOLTAGE PREDICTION MODEL BASED ON OS-ELM

#### A. COMBINED VOLTAGE PREDICTION MODEL BASED ON OS-ELM

The basic idea of the combined model is to reasonably integrate the model objects established from various angles to improve the model level and performance. This article combines voltage prediction with a combined model. An OS-ELM combined prediction model suitable for voltage prediction during a fault is proposed. Voltage prediction is essentially a problem of regression prediction of time series data. Prediction accuracy is closely related to multiple features and historical data. The combined model proposed in this paper combines the models based on feature components and historical data to improve the prediction accuracy and compatibility with noise data. The basic principles are as follows.

There is a training data set $X = \{X_1, X_2\}$, where the training set $X_1$ is used to train the OS-ELM single model, and the training set $X_2$ is used to train the power generation combined prediction model. The linear expression of the single model is as follows.

$$Y = \alpha Y_1 + \beta Y_2 + \gamma$$ (25)

where,

$\alpha, \beta = \text{weight parameters of the linear model}$

$\gamma = \text{bias of the combined model}$

$Y = \text{the output of combined prediction model}$

$Y_1 = \text{the output of feature variable prediction model}$

$Y_2 = \text{the output of real-time data prediction model}$

The voltage combined prediction model based on OS-ELM is shown in Figure 4. First, before the fault occurs, collect the four key characteristics of the short-circuit ratio of the sending-end power grid, the equivalent susceptance of the AC filter and the compensator, the trigger angle of the rectifier side, and the DC transmission power rates as the input of the offline OS-ELM model. An offline OS-ELM prediction model based on key features is established to predict the maximum voltage $v_{\text{max,1}}$. However, due to the action of electrical equipment in the power grid, the characteristic quantities are constantly changing. When a fault occurs, the actual voltage value during the voltage drop needs to be collected and input into the online OS-ELM to obtain the real-time predicted voltage value $v_{\text{max,2}}$. The output of the two models is linearly combined to obtain the final prediction result $v_{\text{max}}$, and finally, the value of the overvoltage is obtained with a certain time margin, which provides a reference for the actions of the synchronous condenser.

#### B. SYNCHRONOUS CONDENSER TRANSIENT VOLTAGE CONTROL STRATEGY BASED ON VOLTAGE PREDICTION

The synchronous condenser has unique advantages in providing reactive power support for the system. It provides reactive power compensation and voltage support in the full-time scale of sub-transient, transient and steady-state; in terms of sub-transient, the synchronous condenser has a smaller sub-transient reactance, which can release a large amount of reactive power instantly in the event of a fault, and quickly adapt to AC system voltage changes. In terms of transient conditions, the synchronous condenser excitation system can be strongly excited, providing reactive power support that exceeds the rated capacity of the synchronous condenser by two times or more in a short time. In terms of steady-state, the synchronous condenser can emit capacitive reactive power or inductive reactive power and can adjust the steady-state voltage level after an accident.
During the period of DC commutation failure, in the process of voltage change from low to high, it is necessary to collect the voltage data in real time and analyze the collected data to predict whether there will be overvoltage risk in the future. According to the prediction results, the synchronous condenser is controlled in advance to make full use of its time scale characteristics to realize reactive power control. The specific control flow chart is shown in Figure 5.

When there is no fault in the power system, the voltage prediction module will collect the information of the power grid, and extract the characteristic variables closely related to the transient overvoltage, so as to establish the offline OS-ELM voltage prediction model. When the DC commutation failure occurs in the system, the converter station absorbs a lot of reactive power, which leads to the decrease of AC bus voltage, and further leads to the sudden drop of the voltage at the grid point of wind turbine. By collecting real-time grid operation data, the real-time change of voltage is obtained, and the online OS-ELM voltage prediction model is established. The results of the two prediction models are combined to get the possible peak value of transient overvoltage, and the prediction results are used to judge whether there is overvoltage risk in the system. If there is over-voltage risk, the synchronous condenser will adopt the original control logic to maintain the safe and stable operation of the power grid.

V. CASE ANALYSIS
A. VALIDATION AND ANALYSIS OF VOLTAGE COMPREHENSIVE PREDICTION MODEL BASED ON OS-ELM
In order to verify the accuracy and effectiveness of the OS-ELM voltage combined prediction model proposed, a simulation model is built based on the actual operation architecture of the north-west power grid. Through the adjustment of power grid parameters, the power grid operation data under different conditions are collected and analyzed. The time resolution of each data is 0.01s.

For evaluating the accuracy and effectiveness of the model more accurately, this paper chooses Root Mean Squared Error (RMSE) and Mean Absolute Percent Error (MAPE). The calculation formulas of $e_{RMSE}$ and $e_{MAPE}$ are respectively:

$$e_{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2}$$  \hspace{1cm} (26)
In the process of model training, it is found that the number of hidden layers will have a great impact on the accuracy of the prediction results. Therefore, it is necessary to consider the accuracy of model prediction under different hidden layers. Through many experiments and attempts, the experimental results are shown in Table 1. When the number of hidden layers is less than 8 or greater than 16, the predicted result is quite different from the actual measured data. The MAPE value is generally greater than 30%, and the RMSE value is also greater, so it is not considered. When the number of hidden layers is in the range of 8 to 16, the values of MAPE and RMSE decrease with the increase of the number of hidden layers. When the number of hidden layers is 14 layers, the error reaches the minimum, MAPE and RMSE are 6.80113% and 0.0164kV, respectively, and the prediction effect is the best. As the number of hidden layers increases, the prediction error will also increase.

In the process of adjusting the excitation control of the synchronous condenser, from data acquisition to central control processing, and then to the order, the time required for the final adjustment of the synchronous condenser to achieve control is about 300ms. The DC commutation failure overvoltage generally occurs 500ms after the failure, so a

\[
e_{\text{MAPE}} = \frac{1}{n} \sum_{i=1}^{n} \left| y_i - y_{\hat{i}} \right| \times 100\% \quad (27)
\]

where,

\( n \) = number of test samples  
\( y_{\hat{i}} \) = predicted voltage output value  
\( y_i \) = actual voltage output value
TABLE 2. Short-circuit capacity and short-circuit ratio of the sending-end power grid under different schemes.

| Scheme   | Short circuit current/kA | Short circuit capacity/MW | Effective short circuit ratio |
|----------|--------------------------|---------------------------|-----------------------------|
| Without SC | 6.99                     | 3670                      | 2.45                        |
| With SC   | 9.14                     | 4799                      | 3.20                        |

combined voltage prediction model based on OS-ELM can fully predict the overvoltage in advance, and realize the reactive voltage optimization control during the DC commutation failure.

B. VERIFICATION AND ANALYSIS OF REACTIVE POWER AND VOLTAGE CONTROL OF SYNCHRONOUS CONDENSER BASED ON VOLTAGE PREDICTION

For the sake of verifying the effectiveness of the reactive voltage control strategy based on voltage prediction, the model of DFIG-HVDC is built by PSCAD/EMTDC software.

Considering that short-circuit faults near the receiving end converter station may cause DC commutation failures, the simulation simulates DC commutation failures by setting short-circuit faults on the AC bus connecting the converter station and the receiving-end grid. During the DC commutation failure, the voltage will drop suddenly due to the occurrence of the fault. Later, due to the release of a large amount of reactive power from the AC filter, the commutation bus voltage increases significantly, and the voltage of the wind turbine at the point of common coupling also increases.

In the new energy delivery system via HVDC, the grid structure is relatively weak, and the ability of AC to support DC is limited. Generally, the effectively short-circuit ratio is used to measure the ability of the AC system to support DC. The short-circuit ratio and short-circuit capacity of the sending-end system with or without the synchronous condenser is shown in Table 2. It can be seen from Figure 7 that the synchronous condenser working as a rotating device increases the short-circuit capacity and supports the capacity of the AC grid, which increases the short-circuit current by 2.15kA, and increased the effectively short-circuit ratio by 0.75.

The faults that cause DC commutation failure mainly include symmetrical and asymmetrical faults. In order to verify the improvement of the commutation failure by the reactive voltage control of the synchronous condenser based on voltage prediction, the simulation tests in this paper take single-phase and three-phase faults as typical examples. Different types of faults are set at the bus of the AC system on the inverter side, and the duration of the fault is selected from 0.05 to 0.2s.

1) SINGLE-PHASE FAULT

For different fault duration, the fault resistance of single-phase varies from $3 \sim 18 \Omega$ to study the influence of this method on commutation failure under different fault resistance at different times. The results are shown in Figure 8.

As can be seen from Figure 8, the white box indicates that under such fault conditions, the wind turbines operate normally and do not occur off-grid. The red box indicates that the original control mode will cause the wind turbine to trip off the grid, but the improved method proposed in this paper will not cause the wind turbine to trip off the grid. The dark red box indicates that the wind turbine will be off-grid under both control modes. When the control method proposed in this paper is adopted, the wind turbine can overcome some adverse faults. However, under some extreme faults, wind turbines will still be out of the grid.
Figure 9 shows that when the fault start time is 5.00s, the fault duration is 0.1s, and the fault resistance is 9 Ω, only the over-voltage occurs in the original control of the synchronous condenser. The figure shows the unit value of AC bus voltage (the base value is 220kV) and the unit value of reactive power compensated by the synchronous condenser during the fault period (the base value is 300MVar); Figure 10 shows the overvoltage that occurred in both the original control and the improved control of the condenser when the fault resistance is 6 Ω.

Compared with the control effect of the original control of the synchronous condenser, the improved control can timely predict the risk of overvoltage during the DC commutation failure, and then effectively excite the synchronous condenser in advance, and return the reactive power compensated in advance, to provide a certain reactive power margin for the overvoltage. When the system overvoltage is serious, it can also reduce the degree of overvoltage to a certain extent, and more effectively reduce the off-grid risk of wind turbines. Moreover, the proposed method can also improve the rapidity and effectiveness of system recovery after the fault.

2) THREE-PHASE FAULT
For different fault duration, the fault resistance of three-phase fault changes from 6 Ω to 23 Ω. The test results of the overvoltage in this method under different fault duration and fault resistance are shown in Figure 11. This method is similar to that of single-phase fault suppression. The method proposed in this paper can also help wind turbines overcome some of the more severe faults.

Figure 12 and Figure 13 show the waveform of voltage and reactive power in response to overvoltage (fault duration 0.1s, fault resistance 13 Ω) and overvoltage (fault duration 0.1s, fault resistance 7 Ω) of the original control respectively.

It can be seen from the waveform in the figure that the suppression effect of overvoltage under the most serious
three-phase fault of the AC system is as effective as the improvement of recovery after the fault.

VI. CONCLUSION

In this paper, the problem of HVDC commutation failure leading to the wind turbine facing high voltage ride through problems is studied, and the mechanism of its voltage change is analyzed by combining with the model. The correlation analysis is carried out for the factors affecting the voltage change, and the key influencing factors are studied. Finally, a transient voltage control strategy with the participation of the synchronous condenser is proposed based on the OS-ELM combined voltage prediction model. The research conclusions are as follows.

(1) In the wind power transmission system via HVDC, a large number of factors will affect the voltage change degree of DC commutation failure. Through the Spearman correlation coefficient analysis, it is clear that the equivalent susceptibilities of AC filter and compensator and the short-circuit ratio of the sending-end grid are the key factors affecting the voltage change degree.

(2) Based on the data of power grid parameters and voltage changes, this paper establishes OS-ELM combined prediction model to predict the degree of transient voltage changes during DC commutation failure, which provides a reference for the excitation control of the synchronous condenser, and realizes the fast response of the reactive power of the condenser according to the voltage at the point of common coupling.

(3) This paper studies the transient voltage control strategy of synchronous condenser based on voltage prediction during the DC commutation failure, which effectively reduces the degree of bus overvoltage during the failure, and thus plays a positive role in reducing the high-voltage disconnection of wind turbines. The reliability and effectiveness of this method are verified by an example.

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