Research on measures suppressing high frequency transient overvoltage in offshore wind farms

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Abstract. A large number of different types of cables, wind turbines, transformers and vacuum circuit breakers (VCBs) are used in power collecting system of offshore wind farms (OWFs). Due to the phenomenon of traveling wave refraction and reflection in cable collector system, transient overvoltage with high amplitude and high steepness will be generated when reignition phenomenon occurs in frequent operation of vacuum circuit breakers on wind turbines, which will cause serious damage to transformers, the problem of overcurrent is also becoming more and more serious. Therefore, through the electromagnetic transient simulation software of ATP-EMTP, a single-phase model of VCB switching-off transformer in offshore wind farm is built to study the influence of the separation speed of contacts of vacuum circuit breaker, high-frequency arc quenching capability and arcing time on overvoltage. Then, the medium voltage cable collector system of OWF is built. Installing ferrite ring near the VCB or on the high-voltage side of transformer can suppress high frequency transient overvoltage. The results show that the high frequency transient overvoltage generated by offshore wind farm can be well suppressed after the installation of overvoltage protection device.

1. Introduction

With the increasing demand of contemporary energy and the worsening of living environment, renewable energy is developing at its largest growth rate and fastest speed. As a clean and renewable energy, wind power generation has attracted more and more attention in the world. However, during the operation of VCB in offshore wind farms, due to the harsh offshore environment, climatic conditions, and the intermittent nature of wind power, wind farms are often connected to or disconnected from the grid, and transformers are operated more and more frequently, which will lead to more serious overvoltage. In recent years, related reports indicate that the operating overvoltage caused by switching of VCB has become the main cause of transformer insulation failure. The results of another decade-long fault investigation showed that although the high-frequency transient overvoltage has a short duration, the probability of causing a transformer failure is as high as 33.9%, which may be the main cause of transformer insulation failure [1-8].

Reference [3] used the models module in ATP-EMTP to build a vacuum circuit breaker model; References [4] and [5] used PSCAD/EMTDC construct a model of offshore wind farms, and built a test platform of high-frequency transient overvoltage in power collecting system of offshore wind farms; Reference [6] studied the influence of feeder length and wind turbine operation mode on overvoltage in OWFs; Reference [7] used "lightning arrester + resistance-capacitance absorber" is adopted to suppress the high frequency transient overvoltage caused by the operation of VCB in offshore wind farm;
Reference [8] proposed three measures to suppress the overvoltage of VCB switching off shunt reactors, namely lightning arrester, resistance-capacitance absorber and extension cable. On the basis of these analyses, a VCB model suitable for overvoltage analysis is established, the electrical system of OWF is built. A method for suppressing overvoltage by installing ferrite ring is proposed, and simulation is performed to verify the suppression effect of overvoltage.

This paper is introduced from the following points. The first is to study the influence of contact separation speed, high-frequency arc quenching capability and arcing time of VCB on overvoltage.

Second, according to the actual wiring of offshore wind farms, building a simplified offshore wind farms medium-voltage cable collection system. Finally, Installing overvoltage protection device near the VCB.

2. The simplified model of offshore wind farm
The power collecting system of offshore wind farm is mainly composed of vacuum circuit breakers, submarine cables, wind turbines, transformers and other electrical equipment.

2.1. Model of vacuum circuit breaker
Vacuum circuit breakers are commonly used switchgears in modern times. They are used on a large scale due to their extremely high reliability, excellent arc quenching performance and high economy.

In ATP-EMTP, the circuit model is only a simple ideal switch, which is equivalent to infinite resistance when opened, and equivalent to infinitesimal resistance when closed. This ideal switch cannot simulate pre-strike and reignition. Therefore, the model module is selected and the C language programming is used to build a vacuum circuit breaker model with three electrical characteristic parameters: current chopping, dielectric strength, and high-frequency arc quenching capacity. The model is shown in Figure 1.

![Figure 1. Model of vacuum circuit breaker.](image)

In Figure 1, VCB is an ideal switch, \( R_S = 50 \Omega \), \( L_S = 50nH \) and \( C_S = 200pF \). The MODEL module includes 3 inputs and 3 outputs. The inputs include the voltages \( U_1 \) and \( U_2 \) on both sides of VCB, the current flowing through the switch. The outputs include dielectric strength DS, transient recovery voltage TRV, and the switch control signal SIGN. The MODEL module judges the current input and the conditions that are met, and obtains the output SIGN to control the status of VCB in real time. The written C language is added to build circuit breaker model, and the program judges that the system is in a disconnected or conductive state according to the input.

It can be obtained from the flow chart of Figure 2 that VCB opening conditions are as follows: the initial state of VCB is closed; power-frequency current is greater than current chopping \( I_{CH} \); \( \frac{dI}{dt} < HFQC \).

Opening conditions: the initial state of VCB is open; transient recovery voltage of VCB is greater than dielectric strength DS.
2.2. Current chopping
When vacuum circuit breaker receives opening signal, the contacts begin to separate. At this moment, the current flowing through VCB has only power-frequency components. When the instantaneous value near zero-crossing point of the line current is less than current chopping level, circuital current is forcibly cut off. The magnitude of interrupting current, frequency and contact material all affect the magnitude of current chopping. Current chopping can be described by the following formula:

\[ I_{ch} = \left( \omega \alpha \beta \right)^{\frac{1}{\alpha \beta}} \]  

(1)

In the formula: \( \alpha = 6.2 e^{-16} \) and \( \beta = 14.3 \) are constants associated with the size, material, strength, gap and circuit parameters of contact electrode. Current chopping level varies between 3A~8A. In this model, the current chopping is set to 5A.

2.3. Dielectric strength
When VCB is on, distance between the moving and static contacts begin to increase, the dielectric strength of contact gap also increases. Dielectric strength can be expressed as:

\[ DS = A(t - t_{open}) + B \]  

(2)

In the formula: \( A \) represents slope, or opening speed of vacuum circuit breaker, constant \( B \) represents dielectric constant of VCB at the moment of contact separation. In the opening process of VCB, when transient recovery voltage is greater than dielectric strength, VCB will reignite, high-frequency transient overvoltage will be generated. The reference values of parameters \( A \) and \( B \) are in Table 1.

| DS          | A(V/μs) | B(V) |
|-------------|---------|------|
| High Voltage| 17      | 3400 |
| Medium Voltage| 13  | 690  |
| Low Voltage | 0.47    | 690  |

2.4. High-frequency arc quenching capability
When the rate of change of current zero-crossing point is lower than a certain value, vacuum circuit breaker can successfully interrupt, but when it is greater than this value, vacuum circuit breaker just cannot be switched off. This value is the high-frequency arc quenching capability of vacuum circuit breaker. It can be expressed as follows, the reference values of parameters \( C \) and \( D \) are in Table 2.

\[ HFQC = C\left( t - t_{open} \right) + D \]  

(3)

| HFQC       | C(A/μs²) | D(A/μs²) |
|------------|----------|----------|
| High Voltage| -0.034   | 255      |
| Medium Voltage| 0.31   | 155      |
| Low Voltage | 1        | 190      |

2.5. Transformer model
Offshore wind farm transformer model uses BCTRAN model in ATP-EMTP. The parameters can be obtained from the nameplate of the S11-1600/35 transformer provided by Sichuan General Electric Power Co., Ltd. Its nameplate parameter data is shown in Table 3. Because the excitation branch in BCTRAN model is linear, the non-linear inductance Type-96 element is selected to simulate the non-
linear characteristics of wind turbine transformer. To establish the transformer BCTRAN model, it is necessary to call the subroutine BCTRAN. The required raw data is the transformer no-load and short-circuit test data. C_HL, C_HV, C_LV are used to simulate the high frequency characteristics of transformers. High frequency model of transformer is shown in Figure 3.

Table 3. The nameplate parameter data of transformer (3).

| Rated power (kVA) | Rated voltage (kV) | Short-circuit impedance (%) | No load losses (W) | Load losses (W) | Connections |
|-------------------|-------------------|----------------------------|--------------------|----------------|-------------|
| 1600              | 35/0.69           | 6.5                        | 1660               | 16500          | Dyn11       |

Figure 3. High frequency model of transformer.  Figure 4. Equivalent model of submarine cable.

2.6. Submarine cable

When building a submarine cable model in ATP-EMTP, it is necessary to consider the conductor, sheath, and insulator layer. In order to improve the accuracy of the simulation, the parameters of each layer are calculated according to the cable model provided by ABB and the cable model in ATP-EMTP, and the material characteristic parameters in the model are corrected according to the physical properties of the actual material and the geometric parameters of the hierarchical structure. The reference values of submarine cable come from the 33kV XLPE single-core cable provided by ABB. Figure 4 shows the equivalent model of the cable [5-11].

3. Simulation of switching-off transformer of VCB in single-phase system

3.1. The opening speed of contacts

By comparing transient recovery voltage TRV and dielectric strength DS, it’s determined whether vacuum circuit breaker will reignite and generate high-frequency transient overvoltage. while keeping other conditions unchanged, analysing the voltage waveform of VCB when A=1.3V/μs and A=26V/μs.

(a) Open VCB when $t_{open}=0.1015s$, $A=1.3V/\mu s$  
(b) Open VCB when $t_{open}=0.1015s$, $A=26V/\mu s$

Figure 5. Gap voltage waveform of contact of VCB.

It can be obtained from Figure 5 that when $A=1.3V/\mu s$, VCB failed to interrupt at the first zero-crossing of current, reignition appears. when $A=26V/\mu s$, as A increases, the contact separation speed of
VCB becomes faster, and dielectric strength DS also increases. At this time, TRV cannot no longer reach the DS withstand voltage, a successful interruption is achieved.

3.2. Arcing time
Arcing time refers to the time interval from the separation of static and dynamic contacts of VCB to the next zero-crossing point of power-frequency current. As current waveform shown in Figure 6, The next zero-crossing time of power frequency current is 0.135s. while keeping other conditions unchanged, setting breaker contact separation time $t_{open1}=0.126s$, the arcing time is 9ms, the arc is extinguished at the first zero-crossing point, VCB interrupts successfully. When $t_{open2}=0.129s$, the arcing time is 6ms, and VCB cannot successfully extinguish the arc at the first zero-crossing point. As the contact distance gradually increases, dielectric strength also continues to increase. VCB can successfully opened at the second zero-crossing point of current.

Figure 6. Current waveform of vacuum circuit breaker with different arcing time.

3.3. High-frequency arc quenching capability
By comparing HFQC and rate of change of current at crossing zero di/dt, it’s determined the number of reignitions of VCB. While keeping other conditions unchanged, analysing the current waveform of VCB when $C=0.31E8 A/s^2$ and $C=0.31E11 A/s^2$.

It can be obtained from Figure 7 that when $C=0.31E8 A/s^2$, the number of reignitions of VCB are less than when $C=0.31E11 A/s^2$. It can be concluded that as the value of $C$ increasing, the number of reignitions of VCB also increasing. This is because $C$ represents the rate of change of arc quenching ability of high-frequency current. The smaller the $C$ is, the easier the VCB is to be opened and the fewer the number of reignitions.

Figure 7. Current waveform of vacuum circuit breaker with different HFQC.

4. The effect of overvoltage protection device
The model of power collecting system of offshore wind farm is shown in Figure 8. The power supply voltage is 110kV, the transformer connected the power source changes the voltage to 35kV. The type of submarine cable is J. Marti in ATP-EMTP.

As shown in Figure 9, the ferrite ring protection device is installed to suppress the steepness and amplitude of high frequency transient overvoltage. Ferrite ring has different impedance characteristics at different frequencies. Generally Speaking, the impedance of ferrite ring is very small at low frequencies, when frequency increases, the impedance of ferrite ring increases sharply. When the load current passes, the saturation inductance of iron core decreases, most of current flows through the
inductance coil, and only a small amount of current flows through the resistance; The inductance coil has a large impedance at high frequencies, current mainly passes through resistance, and the damping effect is strengthened, so that the amplitude and steepness of multiple reignition overvoltage can be controlled in a relatively low range. The impedance characteristics are shown in Figure 10 [12-14].

![Figure 8. Power collecting system of offshore wind farm.](image)

**Figure 8.** Power collecting system of offshore wind farm.

![Figure 9. Ferrite ring equivalent circuit.](image)

**Figure 9.** Ferrite ring equivalent circuit.

![Figure 10. Impedance characteristic curve of ferrite ring.](image)

**Figure 10.** Impedance characteristic curve of ferrite ring.

The ferrite ring should be made of materials with high loss, high permeability and high frequency characteristics, because the core loss of ferrite ring at high frequency characteristics can consume the energy of transient overvoltage and accelerate the attenuation of waveform. As shown in Figure 10, in ATP-EMTP simulation, the device can be equivalent to a parallel connection of resistance and nonlinear inductance. The magnetization curve of nonlinear inductance can be calculated by Ansoft Maxwell according to the magnetization characteristics of ferrite ring material and the actual geometric size of the ferrite ring. After installing ferrite ring, as shown in Figure 11, the amplitude of overvoltage changed from 2.39p.u. to 1.01p.u., the number of reignitions was also significantly reduced, and the transient overvoltage phenomenon was basically eliminated.

![Figure 11. Comparison of single-phase voltage at termination of breaker with and without ferrite ring.](image)

**Figure 11.** Comparison of single-phase voltage at termination of breaker with and without ferrite ring.

5. Conclusions
The self-defined vacuum circuit model in this paper shows reignition phenomenon. The model of VCB switching-off transformer in OWF is built in ATP-EMTP and the inhibition of overvoltage by installing ferrite ring is proposed. Conclusions are as follows:
A single-phase model of VCB switching-off transformer is built to realize current chopping, reignition and high-frequency arc extinguishing. The contact separation speed has a great influence on overvoltage and reignition times. With the increase of HFQC, reignition times are also increasing. Reignition can be avoided by controlling the arcing time of VCB.

(2) The model of the internal electrical system of OWF is built. Installing ferrite ring protection device near the VCB can significantly reduce the number of reignitions and have a good suppression effect on the amplitude of overvoltage, the amplitude of overvoltage changed from 2.39p.u. to 1.01p.u.

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