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Investigation on Overvoltage caused by Connecting Shunt Reactors with Vacuum Circuit Breakers in Offshore Wind Farms

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Abstract. Nowadays, the transient overvoltage occurs in offshore wind farms has aroused widespread concern. To improve the existing offshore wind farm model's accuracy in high frequency conditions, this paper proposes a high frequency model of the vacuum circuit breaker as well as a shunt reactor model considering the influence of stray capacitance. After that, a model of a typical offshore wind farm is constructed for the purpose to analyze the overvoltage occurring at bus bars and wind turbine transformers in the process of connecting a shunt reactor. Simulations show that connecting a shunt reactor in offshore wind farms cause overvoltage of high peak and high steepness compared than with those in onshore wind farms.

1. Introduction

Operational analysis of offshore wind farms is one of hotspots in China [1] for several reasons. First, the topology of offshore wind farms is different from onshore wind farms. Moreover, long and capacitive submarine cables are used more frequently in offshore wind farms. As a result, the charging power in offshore wind farms is greater. Therefore, it is necessary to employ shunt reactors and other devices to absorb the charging power in offshore wind farms. Because the submarine cable impedance is relatively small and the reactor inductance is relatively large, the amplitude and the steepness of overvoltage caused by VCB when switching shunt reactors in offshore wind farms are high [2]. These overvoltages may threaten the operation stability of offshore wind farms, so it is necessary to study the formation occurrence of such transients.

Vacuum circuit breaker is a widely used switching device in offshore wind farms for its advantages of strong arc extinguishing ability, high reliability, long service life, suitability for frequent operation and no fire hazard [3]. Reference [4] introduced the re-ignition and the prestrike phenomena of vacuum circuit breaker in the process of switching operation, and built a simplified model of this process by establishing formulas for dielectric recovery strength and high frequency quenching characteristics based on the experimental data of a 40.5 kV system in [5]. Reference [6] summarized the forming and developing mechanism for three-phase multiple re-ignition. Reference [7] established a simplified offshore wind farm model based on Power Systems Computer Aided Design (PSCAD), and reference [8] proposed a high frequency model of transformer considering terminal capacitances. Reference [8, 9] analyzed internal overvoltages occur in different operation conditions considering the position of transformers, the number of feeders and so on in offshore wind farms.

Overall, there have been abundant researches on the analysis of the overvoltage caused by VCB in the process of switching shunt reactors in traditional power system, while related researches are rare in scenarios for offshore wind farms. In this paper, the switching process of shunt reactors using a vacuum circuit breaker is simulated. In order to study the switching transient overvoltages in accordance with actual working conditions, the high frequency equipment models are built to replace power frequency models which usually used for the steady-state analysis of electric power system in offshore wind farms, namely, VCB and parallel reactors. To study the electromagnetic properties of these overvoltages, PSCAD, an electromagnetic transient simulation software widely used for solving differential equation in the time domain, is employed.

2. Model development for an offshore wind farm

Figure 1 shows a model of an offshore wind farm in Guangdong Province of China. In this model, a shunt reactor switched by a vacuum circuit breaker (VCB_2) is connected to the 35 kV bus. An ideal power supply of 110 kV is employed as the external power grid of the offshore wind farm and is connected to the offshore wind farm through a 35 kV/ 0.69 kV three-phase step-up transformer. The model of the overhead line between the ideal power supply and the step-up transformer is of the π type. Submarine cables are simulated using the frequency dependent phase model in PSCAD/EMTDC component library, because this model has a high accuracy in the wide band analysis considering the frequency dependence of component parameters and line losses. It is suitable for the simulation of the transient process during pre-strikes [7]. According to [9, 10], the duration of the transient process caused by switching a shunt reactor is short, during which the state of wind generators can be treated as unchanged. Therefore, in this study, inductances of 1.2 mH are used to represent the wind power generators. Transformers connected to the wind generators are simulated by the high-frequency transformer transient model considering the influence of stray capacitance in reference to [8].

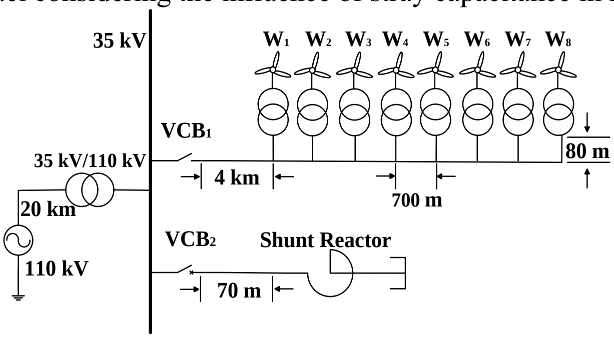


Figure 1. Layout of a typical offshore wind farm.

2.1. Vacuum circuit breaker model

Based on the vacuum switch model proposed in [11], a modified vacuum circuit breaker model considering basic characteristics of vacuum switching is employed in this study. This model, which is built in PSCAD/EMTDC, consists of an ideal circuit breaker and a parallel branch made up of a resistor, an inductor and an capacitor. Furthermore, the prestrike process is simulated by using a customized module to control switch opening and closing.

This model divides a closing transient process into four stages: first prestrike, repeated pretrikes, high frequency arc quenching and physical close, which are presetented by *fp, rp, ro* and *fc* respectively. The flowchart in Figure 2 shows the control logic of this vacuum circuit breaker model.

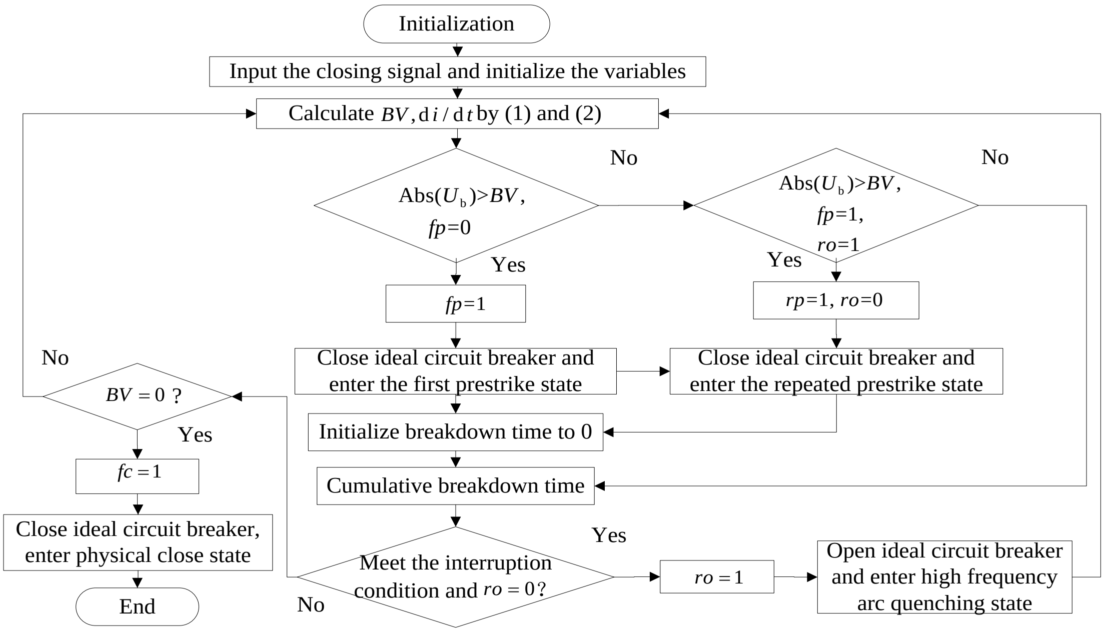


Figure 2. Control logic of the vacuum circuit breaker model.

2.1.1. The first prestrike stage. When the model receives a switch-in signal and the absolute value of voltage across the vacuum circuit breaker is more than the dielectric strength, the system gets into the first prestrike stage and the module sets *fp* to 1 to simulate the prestrike phenomenon. Before the prestrike happens, the frequency of the voltage across vacuum circuit breaker is 50 Hz and thus, the first prestrike also behaves as the frequency of 50 Hz. The dielectric strength in the vacuum circuit breaker is the key factor to determine whether the breaker enters the first prestrike. The prestrike frequency, duration of prestrike current and recovery voltage after prestrike interruption are regarded as constant, which actually decrease over time beause the dielectric strength of the vacuum circuit breaker decreases as the distance between contacts decreases [12]. Reference [13] proposed an approximate fitting method to calculate the dielectric strength based on test results of a specific type vacuum circuit breaker, which can't be used in other system. Different from the above mentioned method, general first order polynomial was employed for the calculation of the dielectric strength in [5]:

$$BV = BV_{\mathrm{limit}} - A(t - t_{\mathrm{close}}) - B \tag{1}$$

where BV denotes the dielectric strength, BV_{imit} represents the maximum dielectric strength, A denotes the closing speed, B is the dielectric constant constant, t is the current time and t_{close} is the time when the contacts starts to close.

2.1.2. High frequency quenching stage. After the first prestrike, the high frequency current which behaves in the form of high frequency arcs, appears between the contacts of the breaker. The interruption condition are:

- The duration of prestrike current is over the limit value or the absolute value of the high frequency arcs is less than the value of the high frequency chopping current;
- The high frequency arc across the vacuum circuit breaker is at the zero crossing point, whose changing rate is less than the high frequency quenching capability.

When the transient process gets to this stage, the custom control module sets *ro* to 1 and swiches-off the ideal circuit breaker, and then the voltage across the breaker restores gradually. The general formula for calculating the high frequency quenching capability is proposed in [5]:

$$\mathrm{d}i/\mathrm{d}t = C(t - t_{\mathrm{close}}) + D \tag{2}$$

where C is a constant in proportion to the arc extinguishing ability, D denotes restorability of the arc when the breaker begins to close.

2.1.3. The repeated prestrike stage. When the transient process enters the high frequency arc quenching recovery stage and the voltage across the vacuum circuit breaker is higher than the dielectric strength again, the custom module sets *rp* to 1 and the transient process turns into the repeated prestrike stage. Different from the first prestrike stage, in this stage, the voltage across the breaker has a relatively higher frequency rather than 50 Hz. The prestrike value is different from those mentioned in section 2.1.1, while the extinguishing conditions of the arc are the same as mentioned in section 2.1.2.

2.1.4. The physical close stage. During the transient process the high frequency quenching stage and the repeat prestrike stage repeat alternately. When in the prestrike stage, the dielectric strength is zero and the contacts of the breaker is closed, *fc* is set to 1 and the transient process enters the physical closing stage.

Figure 3 shows a comparison of the measured and simulation curves of the current and voltage across a vacuum circuit breaker during the closing transient prosess. In Figure 3, U_L is measured at the load side and I_L is the current across the vacuum circuit breaker, U_{L1} and I_{L1} are simulated results respect to U_L and I_L. In Figure 3, the first prestrikes occurs at point a and after that the frequency of prestrikes changes from 50 Hz to higher frequencies. At that time, the voltage across the breaker drops to 0 and the high frequency current and voltage at the load side increase rapidly. Then, at point b, the high frequency quenching stage begins. The voltage across the breaker gradually increases while the voltage at the load side decreases until the repeated prestrikes stage begins at point c. The position of points a_1, b_1, c_1 and points a, b, c, are similar and thus verifies that the proposed four-stages vacuum breaker model is accurate in the high frequency switching transient process.

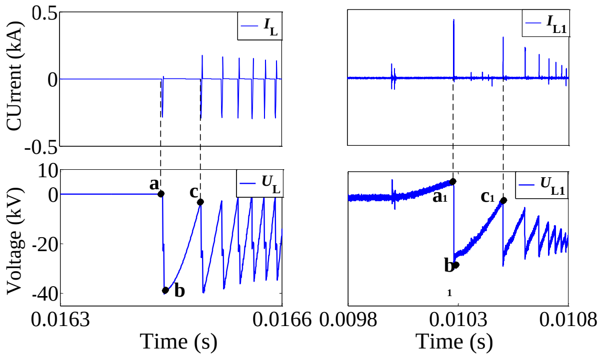
2.2. Shunt reactor model

The simulation system employs a shunt reactor with a rated voltage of 35 kV, the capacity of 3330 kVar and the reactance value of 106 mH. The neutral point of the shunt reator is float. When the vacuum circuit breaker is interrupted, the peak voltage between the contacts is calculated by:

$$U_m = \sqrt{\frac{L_S}{C_S} I_j^2 + U_j^2} \tag{3}$$

where U_m is the peak value of the overvoltage, U_j is the peak value of power supply phase voltage, I_j is the peak value of chopping current, L_s is the reactor inductance and C_s is the stray capacitance.

Because the stray capacitance of the shunt reactor is rather small, it has a great influence upon the amplitude of the interrupting overvoltage according to Equation (3). The traditional shunt reactor model in PSCAD only considers the three-phase inductance value and neutralpoint-to-ground capacitance, but does not take the stray capacitance such as interphase capacitance and phase-to-ground capacitance into account. In this study, a high frequency model of the reactor considering the stray capacitance is built based on the model proposed in [14]. A switching test circuit is used to compare the traditional reactor model with the high frequency model proposed in this study. In Figure 4, the simulated closing transient overvoltage amplitude obtained by using the high frequnecy model oscillates more significantly than that obtained by using the traditional model, which reflects the effect of the stray capacitance of the shunt reactor on the amplitudes of overvoltage. Therefore, the developed high frequency model is more accurate than the current model in transient simulations, and it has great significance for the study of transient overvoltage simulation in large systems.



(a) simulation results (b) measured results

Figure 3. A comparison of simulation and measured results of vacuum circuit breaker

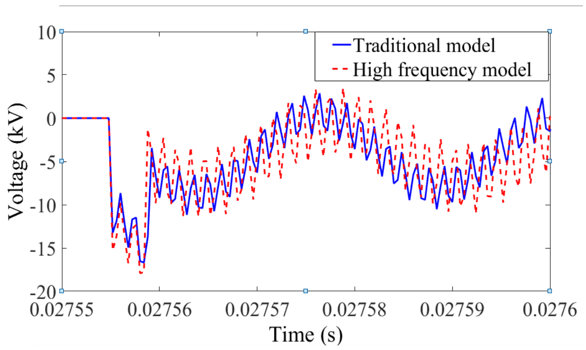


Figure 4. A comparison of simulations by the and high frequency model of shunt reactor.

3. Simulation results and discussion

Based on the offshore wind farm model mentioned above, the overvoltages is simulated in the process of closing VCB_2 when VCB_1 is already closed. The simulation results in comparison to the results of an onshore wind farm is listed in Table 1. In the model of the onshore wind farm the submarine cable model is replaced by the overhead lines of π type, and other conditions are the same as these in the offshore wind farm.

Table 1. Simultated overvoltages in offshore wind farms and onshore wind farms without protection

Equipment	Offshore wind farm		Onshore wind farm	
	Peak voltage (p.u.)	du/dt kV/μ s	Peak voltage (p.u.)	du/dt kV/μ s
Shunt reactor	6.100	116.30	1.160	27.30
35 kV bus	2.510	47.83	1.158	18.10
Transformer of W_1	2.130	20.32	1.155	17.89

Table 1. is the worst case of the closing overvoltage, which happens when the closing phase angle is near 90 degrees. Table 1 shows that overvoltage peak value and steepness of reactor terminal in an offshore wind farms are 5.2 times and 4.2 times larger than in the onshore wind farms. In addition, the overvoltage at the junction of the bus and transformer of W_1 in offshore wind farms is near 2 times greater than that in onshore wind farms. So the overvoltage of swiching-in shunt reactors in offshore wind farms is higher than that in onshore wind farm. The operation overvoltage appears not only at shunt reactors and VCB, but also at the bus and the transformers. The submarine cables are capacitive and the reactors are nonlinear inductive load. At the beginning, VCB_2 received a signal to switch on and the voltage exceeds the dielectric strength in as discussed in section 2.1.1. The energy stored in submarine cable capacitors flows rapidly to the reactor across the 35 kV bus and causes a large current and overvoltage in the system. And then, the quenching condition is satisfied and then VCB_2 opens and the 35 kV bus charges the submarine cable again. The reactor continues charging its stray capacitances as well as the submarine cable capacitors until the next breakdown occurs. As a result, the repeated prestrike of the vacuum circuit breaker causes high frequency oscillations in the system. In the process of repeated prestrike, the continuous energy exchange between inductances of the reactor and capacitances of the submarine cables leads to the increase of amplitude of high frequency oscillation. In onshore wind farms, transmission lines are usually inductive and the energy exchange in this system is mainly between inductances, and therefore the voltage amplitude and steepness are significantly smaller.

4. Conclusion

This paper investigates the overvoltage when connecting reactors in offshore wind farms. A vacuum circuit breaker model considering the arc characteristics, and a high-frequency shunt reactor model introducing stray capacitance are proposed and they are proved to be more accurate than the current models, which can be applied in the transient analysis of power systems. Long submarine cables with a large capacity in offshore wind farms store a lot of energy before they close, which cause overvoltages at the closing moment. The simulation results have shown that in offshore wind farms the connecting process of shunt reactor causes overvoltage with higher amplitude and steepness at shunt reactors, VCB, bus and wind turbine transformers than those of onshore wind farms.

Acknowledgments
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