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Simulation of oscillation wave test system for partial discharge detection of three-core cables in wind power plants

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Abstract. Wind power plants include wind power generation systems, which contain machinery, electrical appliances and their control equipment. Each equipment requires a corresponding cable to connect. In the current application of power cables, the cables used are three single-core conductors or one three-core conductor. Moreover, the wind energy cable must be able to rotate in the forward and reverse directions with the wind turbine. Therefore, the cable must have a soft structure, sufficient tensile strength and bending resistance, and oil and low temperature resistance for the insulating sheath. Due to the harsh environment of wind power generation, the fan has a long service life, and the cable rotates with the fan, which requires high performance of the cable. At this time, the insulation detection of the cable is particularly important. For the current power cable oscillation wave test system, most of the literature only introduces the simple principle of the detection system, and studies based on single-core cable. Based on the three-core cable, this paper performs oscillating wave detection on the three-core cable, and designs the simulation system and studies the influence of insulation defects in different parts. From the experiment results, the proposed system is able to successfully simulate the working procedure of the oscillation wave test system, and to collect the effective partial discharge signals, which validates the effectiveness of the simulation system.

1. Introduction

Wind energy is inexhaustible, environment-friendly and ecology-protective. In recent years, more and more wind power plants have been built, and the demand for cables has also increased. [1] Cables in wind power plants are used in underground circumstance to connect all wind turbine outputs to the low voltage transformers for long distance supply. Most of the wind power plants are built in sparsely populated areas, and the surrounding environment of the wind power plants is so complicated that the cables are more susceptible to aging and damage. This requires timely detection and replacement of faulty cables to ensure the reliability and safety of wind power plants operation. [2] Early detection of cable faults and replacement of aging cables can solve this problem and reduce unnecessary losses, which makes partial discharge (PD) a hot-topic in recent studies on the operation and maintenance of wind power plants.

The oscillation wave test system (OWTS) is a convenient partial discharge (PD) detection method, which cannot only help to find partial discharge in the cable, but also locate the defect position. At present, most scholars analyze the partial discharge phenomenon and focus on single-core cables, and there is little research on three-core cables. Kreuger and Shihab [3] proposed a partial discharge model



of a three-core cable. Harkink et al [4] conducted a more detailed analysis on this basis. After that, Wagenaars [5] analyzed the propagation of the three-core cable PD signal. At present, there are few simulations of OWTS of a three-core cable.

In this paper, a simulation system of OWTS for a typical three-core cable partial discharge is provided, which provides a way to study the signal processing of partial discharge of three-core cables. The remains of this paper are organized as follows. Section 2 establishes a capacitance model of three-core cables. Section 3 proposes the simulation model of OWTS. Section 4 uses the proposed simulation model for PD detection tests and Section 5 presents the test results and discussions. Finally, Section 6 concludes the whole paper.

2. Capacitance model of three-core cables

It is structure difference that makes three-core cable discharge characteristics distinguish from single-core cables[6]. It is not feasible to use the original single-core oscillation wave test method directly for the three-core cables. Therefore, it is necessary to analyze the internal equivalent capacitance distribution of the three-core cable before performing the oscillation wave test of the three-core cables [7].

A cross-sectional view of a three-core Cross-linked polyethylene(XLPE) cable is shown in Figure 1. There are three insulated conductors inside the three-core XLPE cable, which is mainly composed of polyvinyl chloride(PVC) lining, copper conductor, XLPE insulation and PVC sheath.

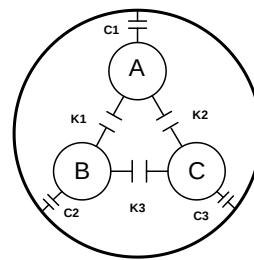
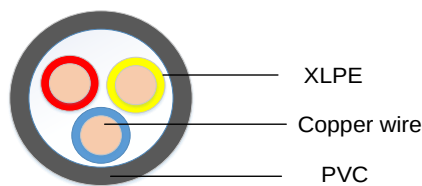


Figure 1. Three-core cable profile. **Figure 2.** Three-core cable equivalent capacitance model.

According to the literature [3] [8], there is a complex capacitive coupling relationship inside the three-core cable. From the structural analysis, there are six equivalent capacitors inside the three-core cable, which are the capacitances K1, K2, and K3 between the three conductors, and the equivalent capacitances C1, C2, and C3 between the three conductors and the outermost insulating layer, as shown in Figure 2.

In practice, PD may occur on one or more of these capacitors, or in the air or fill material space, which is not explicitly shown in the equivalent circuit [3]. This paper will discuss the partial discharge of a capacitor between a conductor and ground and the partial discharge of the capacitor between the two conductors.

3. Simulation model of oscillation wave test for three-core cable

3.1. Oscillation loop model

Cable oscillation wave partial discharge detection circuit is mainly divided into two parts: detection oscillation wave generation circuit and signal detection circuit. The oscillation wave generating circuit is the main circuit of the whole test system, and includes high-voltage DC power supply, semiconductor switch, current limiting resistor, resonant inductor, and cable to be tested, and is a main circuit through which a high voltage oscillation wave and a high frequency partial discharge signal flow through. The signal detection circuit comprises a high voltage dividing circuit and a signal conditioning circuit, which is responsible for monitoring the cable voltage and the acquisition, analysis and storage of the PD signal [9]. The structure diagram is shown in Figure 3.

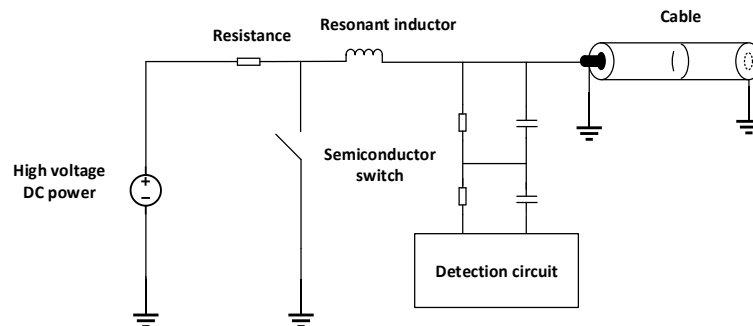


Figure 3. OWTS circuit.

The function of the main circuit of the cable oscillation wave partial discharge detection is to generate LC attenuation oscillation. The high-voltage DC power provides energy to the entire circuit through short-time access. When the resonant inductance and the cable equivalent capacitance are charged completely, the high-voltage DC power supply is immediately disconnected from the main circuit. The energy of the resonant inductor and the resonant capacitor is released by the equivalent resistance of the cable in the form of attenuating oscillations, producing an amplitude-damped oscillatory wave.

3.2. Simulated defect model

The discharge phenomenon at the simulated defect of the cable can be described by a three-capacitance model of partial discharge. Figure 4 shows this simulated model, where R_v and C_v stand for cavity resistance and capacitance, R_s and C_{se} are the elements of the model for the safe insulation in the same column. R_a corresponds to the discharge model. When the voltage across the cavity exceeds the breakdown voltage, the switch closes, which simulates the discharge phenomenon. When the voltage becomes lower than the residual voltage, the switch turns on [10] [11]. As shown in Figure 4, the simulation model is built in Matlab.

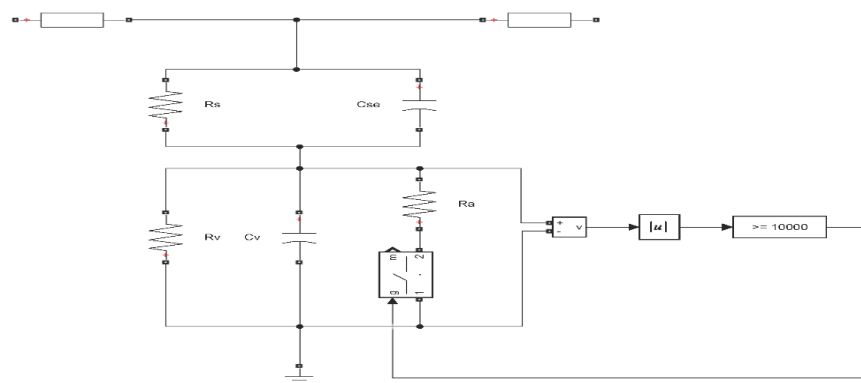


Figure 4. Defect simulation.

The voltage and current transitions in the air gap at the time of partial discharge are shown in Figure 5: U_g discharges as the external voltage rises, and C_v discharges when the discharge capacitor voltage rises to the initial discharge voltage. In the meanwhile, the C_v voltage quickly drops from U_g to U_r . Then the discharge process ends. If the voltage of C_v can reach the discharge voltage, it will discharge again [12]. According to the query data, the capacitance of the cable defect is about 10^{-13} F, where C_{se} is 5×10^{-13} F and C_v is 10^{-13} F.

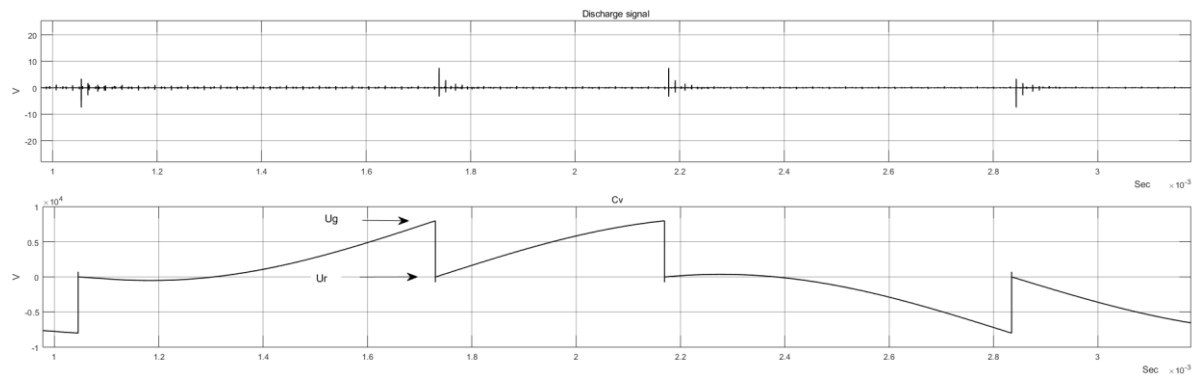


Figure 5. Voltage change during discharge.

4. Three core cable oscillation wave test

Based on relevant design data and model, a simulation model of oscillation test of three-core cable is established under Matlab Simulink platform. According to the query data[6], the equivalent capacitance per unit length of XKLPE cable is $0.24\mu\text{F}/\text{km}$.

In the practical application of the three-core cable, the insulation defect will not only occur in the insulation of the core and the insulating skin, but may also occur in the insulation between the two cores. The designed model can detect the insulation defect between the two cores and the defect between the core and the insulating skin.

4.1. Partial discharge detection between two cores

In the three-core cable capacitance model, the capacitors represent Insulating medium and air gap capacitors. In the process of simulation, the three-capacitance model is used to replace the capacitance between the two cores. The oscillation wave test simulation of the two-core cable is shown in Figure 6.

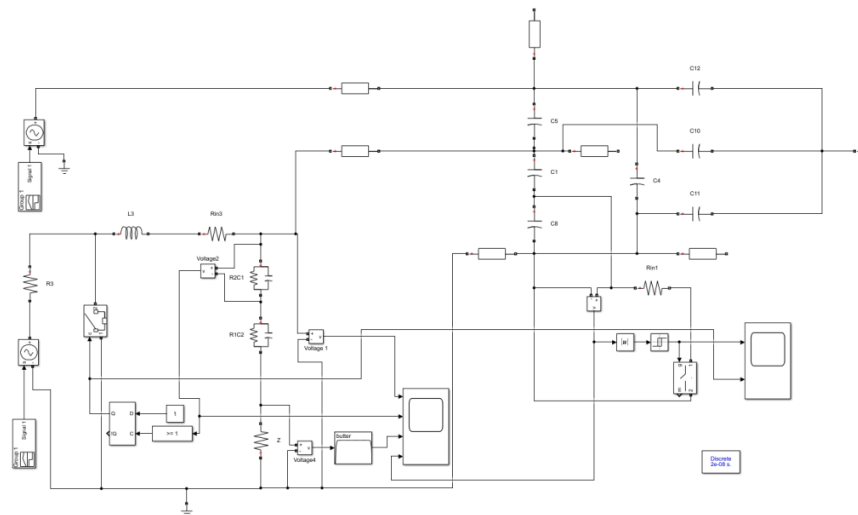


Figure 6. Partial discharge detection model between two core cables.

Single-core cable is powered by DC source alone, and the supply voltage is 18 kV. The other two cores are connected to the other DC power supply at both ends. At the same time, the voltage of the cable is tested with the voltage divider, which makes partial voltage ratio to be 1:1000. When a cable voltage of 10 kV is detected, the two cores are disconnected from power and the oscillator loop is connected. The Oscillation frequency $f = \frac{1}{2\pi\sqrt{LC}} = 458.4\text{Hz}$ [13]. Then the two cores start oscillation,

producing an attenuated oscillation voltage. When the voltage of air gap capacitance reaches the

discharge voltage of 8kV, the air gap capacitance begins to discharge, generating partial discharge signals. Partial discharge signal turns to partial discharge voltage on coupled unit Z. Then, the partial discharge signals can be observed by voltmeter and oscilloscope.

4.2. Partial discharge detection between a core and the insulating skin

The simulation of the partial discharge detection system for the insulation defect between a core and the insulating skin is shown in figure 7.

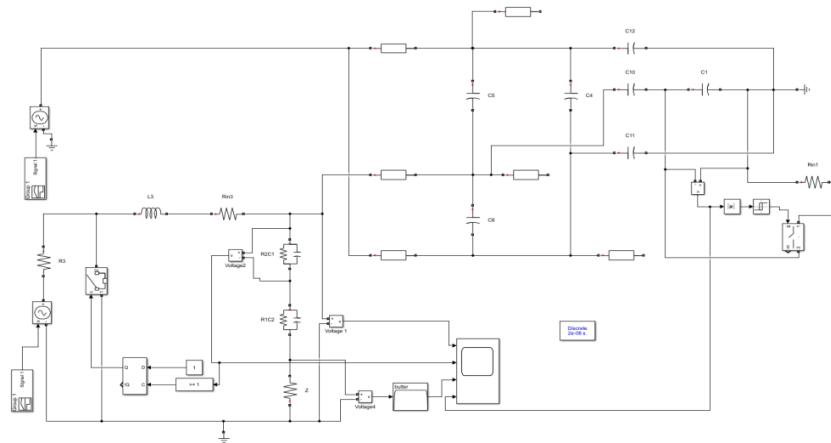


Figure 7. Partial discharge detection model between a core and the insulating skin.

The insulation defect between the core and the insulation can also be explained by the principle of three capacitors. The two-core cable is powered by DC, and the power supply voltage is 18 kV. The oscillation wave is detected separately for the middle core. The parameter setting is the same as the detection between the two cores, and the voltage across the cable is detected by a voltage divider. When the voltage across the cable reaches 10 kV, power supply is disconnected, causing the

oscillation circuit to start to oscillate. The Oscillation frequency $f = \frac{1}{2\pi\sqrt{LC}} = 458.4\text{Hz}$. Then it exits the defect to emit the voltage signal, the generation of the partial discharge signal can be detected by the coupling element [14].

5. Discussions

The above model is simulated, the simulation duration is set to 0.01s, and the step size is set to discrete 2e-8s. The oscillation voltage across the cable, the voltage after division, and the partial discharge voltage on the coupling unit is tested by an oscilloscope. The results obtained are as shown Figure 8.

The oscillation starts when the voltage across the cable reaches about 10kv. The Oscillation frequency is 457.201Hz, which is not much different from the calculated frequency. The charge of the air gap between the two cores begins to discharge after air gap charge is completed. When the discharged power reaches the residual voltage, the oscillation voltage continues to charge the air gap capacitor. This process repeats several times, and periodic partial discharge signals can be observed from the figure. The magnitude of the partial discharge voltage can show the severity of the insulation defect between the two core cables. The larger amplitude it can be observed, the more serious insulation defects there may be. From the results obtained, the designed oscillation wave test system can detect insulation defects between the two core cables. The simulation result of the insulation defect model between one cable and the insulating skin is shown in figure 9.

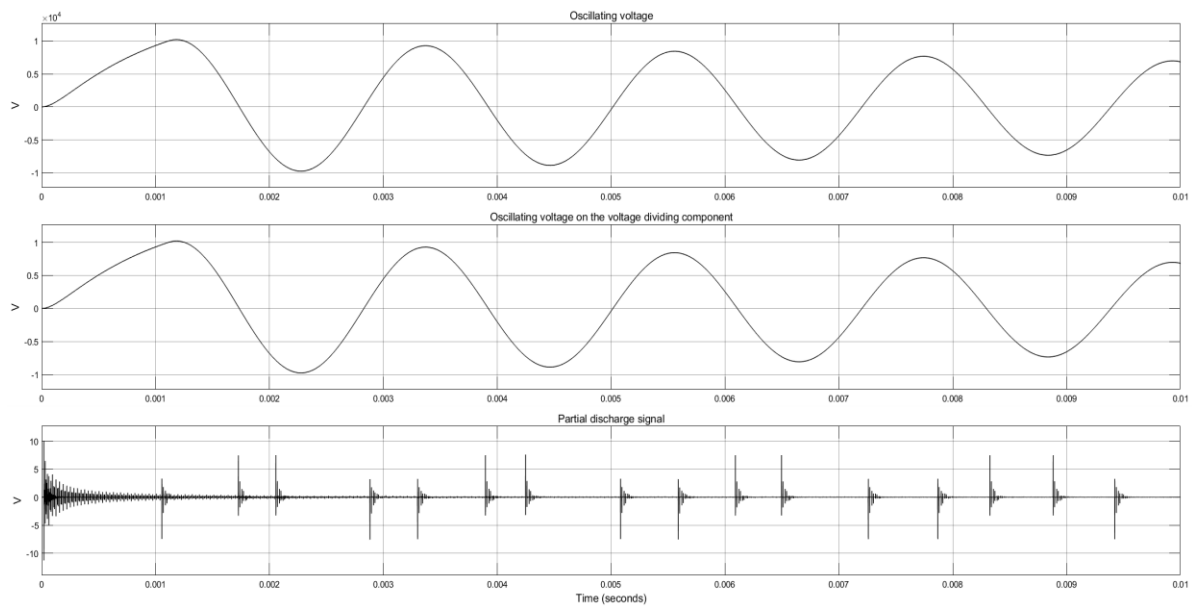


Figure 8. Simulation results of oscillation wave test of two-core cable.

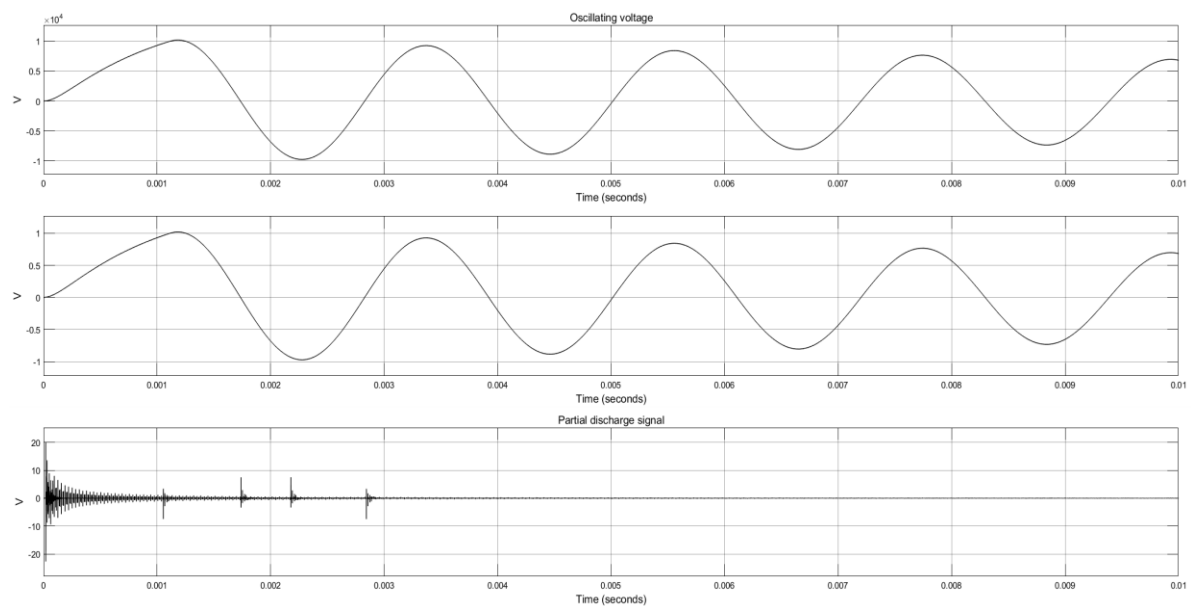


Figure 9. Simulation result of oscillation wave test of one core and insulating skin.

As with the two-core cable test simulation, the oscillation begins when the voltage of the core cable reaches 10kV. The Oscillation frequency is 457.203Hz, which is not much different from the calculated frequency. The air gap capacitor begins to charge periodically and discharge. A partial discharge signal can be detected by the coupling unit[15]. Figure 9 shows: The partial discharge voltage caused by the insulation defect between the core and the insulation skin is slightly larger than the partial discharge voltage caused by the insulation defect between the two core cables. The influence of insulation defects between one core and the insulation is greater than the influence of insulation defects between the two cores. Compare Figure 8 with Figure 9, the amplitude of the partial discharge voltage between the two cores is relatively small, but the effects caused by the defects are cumulative, and the cable will be fatal over time.

6. Conclusions

The surrounding environment of wind power plants are harsh, complex and changeable, and there are strict requirements for the insulation performance and detection of cable. This paper analyzes the structure of the three-core cables, the principle and structure of the partial discharge detection circuit and the three-capacitance discharge model for the oscillation wave test system. This paper also optimizes the former three-capacitance discharge model, and better simulates the whole process of three-core cable partial discharge. The model of three-core cable oscillation wave test system is established in Matlab. Partial discharge simulation is conducted for the defects of different parts of the cable, and the signals can be successfully detected. This simulation can also provide an idea for signal processing of partial discharge. The effectiveness of the designed system is verified, which provides ideas and basis for the application of cable insulation detection between the wind power plants and distribution network.

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