Compact 30kV 0.1 Hz cosine square wave testing system for PD detection on XLPE cables

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Abstract. To provide a more convenient and efficient method for detecting partial discharge (PD) on XLPE cables, this paper describes a 0.1 Hz cosine-square wave testing system, which can output peak voltage up to 30 kV. Due to L-C series resonance principle, the wave of discharge process is in cosine form which can be equivalent to AC voltage. Therefore, PD detection can be conducted under the rising and falling edges. The vital component of the proposed system is high-voltage semiconductor switch which consists of several series connected IGBTs. Based on the idea of compactness, a prototype system is integrated in the lab. Withstand test and PD detection test are also carried out to validate the proposed system. The experiment result shows that the system is effective to detect PD signal in power cables and has certain development prospects on insulation condition assessment of XLPE cables.

1. Introduction

The applied quantity of power cables increases year by year, as power demand is rising, which proposes high standard for safe operation of cables. XLPE cables have superiority in fine heat-resistance, mechanical behaviour, installation and preventive maintenance. However, XLPE cables usually get damaged during production progress and cable laying [1-2]. There are two main methods for power cable insulation testing, namely, online test and offline test [3]. Offline test has the features of high precision and easy operation, and thus it’s widely used in engineering. Depending on the difference of excitation source, offline test mainly includes power frequency AC voltage test, DC voltage test, oscillating wave test and VLF (very low frequency) voltage test etc [4-9]. Power cables often have large equivalent capacitance due to the long laying distance, and it is not convenient to engineer while using AC voltage test, because they have to adopt high capacity and massive transformer. Furthermore, it’ll develop additional electric field after DC voltage withstand test [10-12]. Therefore, VLF voltage test and oscillating wave test are mainly used in the cable insulation test.

Over the years, VLF cosine square wave is the develop priority in the power industry. It can conduct DC voltage withstand test for cable by using the part of square wave, and lastly we can obtain leakage current and dielectric loss reflecting the whole insulation status of cables. In addition, the rising and falling edges similar to AC voltage can carry out partial discharge detection [13-14]. This paper presents compact 0.1 Hz cosine square wave testing system designed for on-site cable insulation test, and it can output 30 kV peak voltage and has the advantage of compactness and portability. Several XLPE cables have been tested by using the system, and experiments results show that this system have excellent performance in the field of cable insulation test.
2. Basic principle of system

2.1. Component f system

As depicted in the Figure 1, the main components are described as follows:

a. Positive high-voltage source, namely, voltage doubling rectifier circuit.
b. Discharge unit consisted of bipolar high voltage semiconductor switch.
c. Detection unit including high voltage divider and PD detection unit.
d. Capacitive load.

In the Figure 1, $S_r$ is the relay controlling on-off of electric supply, and $T_1$ is step-up transformer, and $R_1$ is limiting resistor. $S_p$, $S_1$ and $S_2$ are high-voltage switch, and $L_1$ is air-core reactor. $C_x$ is equivalent capacitance, and $C$ is auxiliary capacitance.

High-voltage semiconductor switch is the vital component of system, and switch has to meet the demand of high speed and high withstand voltage. High-voltage switch proposed consists of several series-connected IGBTs.

![Figure 1. Topology model of 0.1Hz testing system](image)

2.2. Working process of system

In working condition, cable as capacitive load is charged to a default voltage through positive DC source firstly, and it’s in the part of square wave. Thus, load begins to discharge via inductance and load capacitor, and voltage polarity of load reverses. It’s worth mentioning that energy of load is recycled under the discharge process. The typical waveform is shown in Figure 2. Specific process is depicted as follows:

![Figure 2. Typical waveform of 0.1Hz cosine square wave](image)

A. Phase $[t_0,t_1]$:

Before $t_0$, cable is charged to a positive level, and at $t_0$, $S_r$ and $S_p$ are turned off making DC source stop power supply. Then, $S_1$ is turned on and $S_2$ is still in off mode. Load capacitor begins to
discharge via reactor $L_1$, forming into a L-C resonance loop. Voltage polarity of load turns to reverse, and the waveform of $V_o$ shows cosine wave form. Mathematical expression is depicted as below:

$$V_o = \frac{U_o}{A} e^{-\delta(t-t_0)} \cos [\omega(t-t_0) + \beta]$$  \hspace{1cm} (1)

Where,

$$A = \left(1 - \frac{R_l^2(C_x + C)}{4L_1}\right)^{1/2}$$ \hspace{1cm} (2)

$$\delta = \frac{R_l}{2L_1}$$ \hspace{1cm} (3)

$$\omega = \left(\frac{1}{L_4(C_x + C)} - \left(\frac{R_l}{2L_4}\right)^2\right)^{1/2}$$ \hspace{1cm} (4)

$$\beta = \arccos (A)$$ \hspace{1cm} (5)

Where $U_o$ is the default voltage, and $R_l$ is equivalent resistance of the air-core reactor. Value of $\Delta T$ is related to $L_1$, $C$ and $C_x$, and mathematical expression is depicted as below:

$$\Delta T = \frac{\pi}{\omega} = \pi \left(\frac{1}{L_4(C_x + C)} - \left(\frac{R_l}{2L_4}\right)^2\right)^{1/2}$$ \hspace{1cm} (6)

Usually, $R_l$ is so small that it can be neglected, and then expression can be simplified as below:

$$\Delta T \approx \pi \left(\frac{1}{L_4(C_x + C)}\right)^{1/2} = \pi \left(L_4(C_x + C)\right)^{1/2}$$ \hspace{1cm} (7)

B. Phase $[t_1,t_2]$

In fact, a small energy loss occurs in the cable when cable is in the process of discharge, therefore peak voltage at $t_1$ of cable is smaller than voltage at $t_0$. From $t_1$ to $t_2$, switches $S_1$ and $S_2$ are both turned off, and $S_p$ and $S_r$ are still in off mode. Time period of this process is 5 seconds.

C. Phase $[t_2,t_3]$

Similar to first step, at $t_2$, $S_p$ and $S_r$ are still in off mode. And $S_2$ is turned on, but $S_1$ is still in off mode. At the moment, cable begins to discharge via reactor $L_1$, forming into a L-C resonance loop. Finally voltage polarity of load turns to reverse, and the waveform of $V_o$ shows cosine wave form. Mathematical expression is depicted as below:

$$V_o = \frac{KU_o}{A} e^{-\delta(t-t_2)} \cos [\omega(t-t_2) + \beta], \hspace{1cm} 0 < K < 1$$ \hspace{1cm} (8)

Where, $K$ is loss coefficient due to energy loss.

D. Phase $[t_3,t_4]$

At $t_3$, voltage polarity of $V_o$ is positive. In order to replenish energy loss, $S_r$ and $S_p$ are turned on, but $S_1$ and $S_2$ are turned off. Therefore, DC source works following that cable begins to be charged. And time period of this process is also 5 seconds.

3. System design

3.1. High-voltage switch

According to explanation above, the testing system need three high-voltage switches, and switches require higher operating speed, higher withstand voltage and smaller size. There is comparison of characteristics among three electronic power switches as depicted in Table 1.

Table 1 shows that IGBT and MOSFET both have low driving power and high operating speed, but MOSFET has higher saturation voltage. Therefore, IGBT is chosen as vital component of high-voltage switch. Taking various factors into consideration, high-voltage semiconductor switch designed is
based on several series connected IGBTs. The whole switch unit consists of IGBT, drive circuit, isolation power supply system and signal control system.

**Table 1.** Comparison of characteristics among three electronic power.

|                  | IGBT    | MOSFET  | BJT     |
|------------------|---------|---------|---------|
| **Driving mode** | Voltage | Voltage | Current |
| **Operating speed** | ns      | ns      | µs      |
| **Driving power** | Low     | Low     | High    |
| **Saturation voltage** | Low    | High    | Low     |

When several IGBTs are connected in series, question about series even-voltage on different IGBTs has to be taken into account. Respective IGBTs have different static parameter and dynamic parameter. Besides, delay of trigger signal and exist of stray capacitance will have effect on even-voltage on IGBTs. To solve the problem, each IGBT is in parallel with high-voltage resistor calculated to be 25 MΩ. When IGBT operates, there is transient pulse voltage, which will affect normal operation of IGBT, therefore each IGBT is also in parallel with transient voltage suppressors (TVS). TVS has fast response time that is less than 1.0 ps from 0 volts to breakdown voltage, and can completely satisfy the requirement. For integration of system, high-voltage switch is designed in circle outline as shown in Figure 3. A high-voltage switch board consists of eight IGBT modules, which are connected in series.

![Figure 3. Physical map of high voltage switch](image)

Reference potential difference of respective drive circuit is up to a few thousand volts, therefore supply power of drive circuit must be isolated respectively. Flyback switching power supply has advantage of stable operation and good isolation. Besides, it is easily realizable to have multiplexed output. A multi-output signal flyback switching power supply is proposed in this paper. High-frequency transformer is placed on the centre of switch board. And there are eight outputs in the secondary side of transformer. As shown in Figure 4, the primary side of transformer is controlled by MOSFET, forming into main circuit of power supply with relevant driving circuit.
3.2. Control unit
From Figure 1, we can see that system has $S_p$, $S_1$ and $S_2$ totaling three high-voltage switches, and one relay. In order to ensure electrical isolation, control unit needs three ways of optical signal to control on-off of high-voltage switches and two ways of optical signal to control on-off of isolation power supply system. For switches, control signal is firstly generated by FPGA control board, and thus it’s transferred to multichannel control board by optical fiber, and multichannel control signal are also transferred to corresponding IGBT modules by optical fiber at last.

For power supply system, it will generate much noise interference. In order to detect accurately partial discharge in cable, power supply system must be shut up in the process of polarity reversal. Similarly, two ways of optical signal are generated by FPGA control board, and thus they will be transferred to power supply system by optical fiber. Besides, for relay, control signal is generated by FPGA control board in the mode of electrical signal, and it can drive the relay corresponding with audion.

3.3. Physical design
In the final design, the diameter of high-voltage switch is 520 mm, each weighed 3kg. The charge unit consists of two high-voltage switches, and sixteen IGBTs rated for 4 kV are chosen in these switches. The discharge unit consists of four high-voltage switches, and thirty-two IGBTs rated for 3 kV are chosen in these ones. The vertical distance between each switch board is about 80 mm, assuming safe enough insulation distance.

Finally, HV source, charge unit, detection unit and air-core reactor are put together in one epoxy cylinder, and the inductance of reactor is 1 H. And discharge unit and control unit are integrated in another epoxy cylinder, which is connected with the former cylinder by flexible cable.

4. High voltage test
After system integration, PD detection test for cable was conducted in the laboratory. Before the experiment, for system’s reliability and security, withstand voltage test was carried out using oil filled capacitor instead of XLPE cable as load. As can be seen in Figure 5, the peak value of output voltage is up to 30 kV. In the test, the value of capacitor is 0.1 μf, and according to expression (7), the time of rising edge and falling edge can be calculated.
For PD detection test, a 200 m single core 10 kV XLPE cable was chosen as test object, which was connected by two 100 m XLPE cables. Besides, a defect was made artificially in the intermediate joint of this cable, which could cause partial discharge under high voltage. As depicted in Figure 6, a needle was stuck into insulating layer of intermediate joint, and the depth was about 2.5 mm.

Using 0.1Hz cosine square wave testing system, PD detection on the XLPE proposed was conducted in the laboratory. Experiment results are shown in Figure 7 and Figure 8. From results, we can clearly see that PD signal was accurately detected by the testing system.

**Figure 5.** Output waveform of system

![Output waveform of system](image)

**Figure 6.** Defect in the intermediate joint of this cable

![Defect in the intermediate joint](image)

**Figure 7.** PD detection on cable under the rising edge

![PD detection on cable](image)
5. Conclusion
A compact testing system for PD detection on power cable is presented in this paper. Benefiting from high-voltage semiconductor switch proposed, it can output 0.1 Hz cosine square voltage rated for 30 kV. Through lab tests, system has been proven to be effective on PD detection. Because energy loss is much small under the process of polarity reverse, DC source has low power and small size. The system proposed is more suitable for on-site cable test than conventional AC system. In fact, this system also can locate defect point by using TDR and it will be discussed in the future.

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