Research on Charge-Discharge Characteristics and Location of Cable Partial Discharge Detection System Based on Damped Oscillation Wave Voltage

Jin-ming GUO and Shu-jun TIAN

Electric Power Research Institute of Guangxi Power Grid Corporation, Nanning 530023, China

Keywords: Power cable, Partial discharge, Oscillation wave voltage, Positioning error, Damped characteristic.

Abstract. Traditional partial discharge detection methods of linked polyethylene (XLPE) cable have disadvantages about limited applicable conditions, low effectiveness and difficulty of field application. However, partial discharge detection method based on oscillation wave test system (OWTS) is a new type nondestructive testing technique for cable insulation with time short, Portable, flexible, and convenient operation. This paper researches on the charge-discharge principle and location error of cable partial discharge OWTS by using theoretical derivation method, reveals the damped characteristics of over-damped charge and under-damped discharge process, clarifies the influence mechanism of the abnormal insulation of the cable system on the charging failure, and indicates that the accurate value of the cable length and wave velocity can determine the precise location of the partial discharge defect. Therefore, the conclusion obtained from the research has a strong guiding significance for the detection and location of the cable partial discharge based on the damped oscillation wave voltage.

Introduction

With the development of electric power technology, power cables are widely used in the incoming or outlet line of power plant, power substation, industrial enterprise and mining[1]. Among them, XLPE insulated power cable obtained rapid development relying on its excellent electrical, thermal and mechanical properties, and the paper oil insulated power cables have been replaced below 220-kV cable systems[2].

According to bathtub curve theory of XLPE cable fault[3,4], influenced by the product and installation quality, the cable is prone to breakdown in initial stage (1~5 years). With basically entering a stable period of various properties in cable and its accessories, the cable’s fault rate is low in the medium term (5~25 years); however, there is still a risk of electric breakdown due to the cable insulation tree aging and affected with damp of its accessories; finally, because of the exacerbation of cable insulation tree aging, electric-heat aging and accessory materials aging in the later stage of cable operation (25 years later), the fault rate of the cable would increase sharply. Aiming at the detection and diagnosis of XLPE cable insulation, the partial discharge test is recommended as the best method for XLPE cable insulation evaluation by domestic and foreign experts, as well as IEC, IEEE, CIGRE and other international power authority, which can effectively detect latent defects in the cable insulation[5].

The traditional partial discharge detection methods of XLPE cable can be divided into two categories[6,7]: non-electrical method and electrical method. Among them, the non-electrical method mainly includes infrared imaging method and ultraviolet imaging method, and the electrical method includes capacitance coupling method, electromagnetic coupling method, difference method, ultrahigh frequency method and so on[8,9]. These methods solve the problem of partial discharge evaluation of XLPE cable insulation in a certain state, but most of them have disadvantages about limited applicable conditions, low effectiveness and difficulty of field application[10]. However, as a result of theoretical research and practical exploration, the method of cable partial discharge OWTS has been proved to be effective in detecting the partial discharge defects of cable insulation, and
obtained widely used as a new type nondestructive testing technique for cable insulation[11]. Then the related industry standard[12] has been released in 2016.

Principle Analysis of Cable OWTS

The illustrative diagram of cable partial discharge OWTS is shown in figure 1, whose working process of high voltage circuit is equivalent to second-order oscillating circuit of RLC series. Then the charging process is equivalent to the zero-state response and the discharging process is equivalent to the zero-input response. According to the design requirement of OWTS, the high voltage source shall charge to testing voltage of the tested cable in a few seconds to tens of seconds. And the values of equivalent components of OWTS should meet the requirements of the system response time. In order to facilitate the calculation and analysis, the high voltage circuit is separated from figure 1, and the equivalent circuit is shown in figure 2.

Theoretical Analysis of Charging Process

The charging process of the cable partial discharge OWTS is equivalent to the zero-state step response of the RLC series circuit, as shown in figure 2. During the charging process, the high voltage switch $S$ is in disconnected state, and the step excitation is generated by the direct-current high voltage source $u_s$, which charges the tested cable after charging protection resistance $R_f$, resonant inductance $L$ and discharge equivalent resistance $r$. The equivalent capacitance of the charging circuit is represented by $C$, which is the sum of the equivalent capacitance of tested cable, the equivalent capacitance of detection circuit and the stray capacitance of the high voltage circuit. $R = R_f + r$ is adopted to describe the equivalent resistance of the charging circuit, and the equation of the charging circuit can be obtained according to the Kirchhoff voltage law, as in

$$LC \frac{d^2u}{dt^2} + RC \frac{du}{dt} + u_s = u$$  \hspace{1cm} (1)
Equation (1) is second order nonhomogeneous linear differential equation with constant coefficients, and $u_c$ is the voltage of equivalent capacitance of the charging circuit $C$, whose expression is given in formula (2).

\[
\begin{align*}
\left\{ \begin{array}{l}
u_c = (\nu_c' + \nu_c^*) e(t) \\
\nu_c^* = \nu_c,
\end{array} \right. 
\end{align*}
\]

Where

- $\nu(t)$: unit step function
- $\nu_c'$: the general solution of second order homogeneous linear differential equation with constant coefficients corresponding to formula (1)
- $\nu_c^*$: special solution of formula (1)

The boundary conditions and characteristic equation of (1) are given in formula (3).

\[
\begin{align*}
\left[ \begin{array}{l}
u_c(0) = 0, i_L(0) = 0 \\
LCp^2 + RCp + 1 = 0
\end{array} \right.
\end{align*}
\]

Where $i_L$ is the charging current.

And the two roots of the characteristic equation are given in formula (4).

\[
\begin{align*}
p_1 &= \frac{R}{2L} + \sqrt{\left( \frac{R}{2L} \right)^2 - \frac{1}{\sqrt{LC}}} \\
p_2 &= \frac{R}{2L} - \sqrt{\left( \frac{R}{2L} \right)^2 - \frac{1}{\sqrt{LC}}}
\end{align*}
\]

The formula (5) can be obtained by using $\alpha$ and $\omega_0$ to replace the parameters in (4).

\[
\alpha = \frac{R}{2L}, \quad \omega_h = \frac{1}{\sqrt{LC}}, \quad \omega_d = \sqrt{\omega_0^2 - \alpha^2}
\]

Therefore, according to the relationship of $\alpha$ and $\omega_0$, the general solution of the (1) has three kinds of different forms, which correspond to the dynamic process of the zero-state response of the RLC series circuit. Within the range of $t \geq 0$, the unit step function $\nu(t) = 1$, and then the three kinds of zero-state step response functions can be obtained, which are shown in formula (6) to (8).

When $\alpha > \omega_0$, the expression of $u_c$ and $i_L$ are shown as follows:

\[
\begin{align*}
u_c &= \frac{1}{p_1 - p_2} \left( p_2 e^{p_2 t} - p_1 e^{p_1 t} \right) + 1 \\
i_L &= \frac{C}{L} \frac{du_c}{dt} = \frac{C u_c p_1 p_2}{p_1 - p_2} \left( e^{p_1 t} - e^{p_2 t} \right) \\
&\quad + \frac{u_c}{L(p_1 - p_2)} \left( e^{p_1 t} - e^{p_2 t} \right)
\end{align*}
\]

When $\alpha = \omega_0$, the expression of $u_c$ and $i_L$ are shown as follows:

\[
\begin{align*}
u_c &= \left( p_1 t - 1 \right) e^{p_1 t} + 1 \\
i_L &= \frac{C}{L} \frac{du_c}{dt} = C u_c p_1^2 e^{p_1 t} = \frac{u_c}{L} e^{p_1 t}
\end{align*}
\]

When $\alpha < \omega_0$, the expression of $u_c$ and $i_L$ are shown as follows:
Formula (6) shows that the equivalent capacitance of the charging circuit is charging all the time within the range of \( t > 0 \), constantly gets close to \( u_S \), as well as the loop current continues to decrease and gets close to zero. When the \( t \) approach infinity, the expressions of \( u_c = u_S \) and \( i_L = 0 \) are tenable. Therefore, when \( \alpha > \omega_0 \), the charging process of the high voltage circuit is unidirectional, which is called aperiodic charging or damping charging. And the condition of \( \alpha = \omega_0 \) is called critical-damped charging. Similarly, Formula (8) shows that the \( u_c \) and \( i_L \) keep damped oscillation all the time within the range of \( t > 0 \), that is, the \( u_c \) keeps damped oscillation in the vicinity of \( u_S \), but the maximum value is not more than double of \( u_S \), and the \( i_L \) keeps damped oscillation around zero. Evidently, the charging process is periodic, which is called periodic charging or oscillatory charging. According to the design requirements of the cable partial discharge OWTS, the charging process should be damping charging, than the values of the components of the charging circuit must meet the power and damping conditions of the system.

**Theoretical Analysis of Discharging Process**

The discharging process of the cable partial discharge OWTS is equivalent to the zero-input response of the RLC series circuit, as shown in figure 2. During the discharging process, the high voltage switch \( S \) is in closed state. The equivalent capacitance of the circuit discharges after discharge equivalent resistance \( r \) and resonant inductance \( L \), which has been charged to \( u_S \). Than the equation of the discharging circuit can be obtained according to the Kirchhoff voltage law, as in

\[
LC \frac{d^2u_c}{dt^2} + rC \frac{du_c}{dt} + u_c = 0
\]  

Equation (9) is second order homogeneous linear differential equation with constant coefficients, which boundary conditions and characteristic equation are given in formula (10). And the two roots of the (10) are given in formula (11). Then by using \( \alpha \) and \( \omega_0 \) to replace the parameters in (11), the formula (12) can be obtained.

\[
\begin{align*}
\alpha &= \frac{r}{2L} \\
\omega_0 &= \sqrt{\frac{1}{LC}} \\
\omega_d &= \sqrt{\omega_0^2 - \alpha^2}
\end{align*}
\]  

Similar to the charging process, according to the relationship of \( \alpha \) and \( \omega_0 \), the discharge process can be divided into three different situations, that is, over-damped discharge (\( \alpha > \omega_0 \)), critical-damped discharge (\( \alpha = \omega_0 \)) and under-damped discharge (\( \alpha < \omega_0 \)). Accordingly, the three kinds of zero-input response functions can be obtained, which are shown in formula (13) to (15).

\[
\begin{align*}
u_c &= \frac{u}{p_2 - p_1} \left( p_1 e^{p_1 t} - p_2 e^{p_2 t} \right) \\
i_L &= \frac{u}{L(p_2 - p_1)} \left( e^{p_1 t} - e^{p_2 t} \right)
\end{align*}
\]
\[
\begin{align*}
    u_c &= (1 - p_1 t) u_0 e^{\alpha t} \\
    i_c &= -C_u p_1^2 t e^{\alpha t} = -\frac{u_0}{L} t e^{\alpha t}
\end{align*}
\]  \( \text{(14)} \)

\[
\begin{align*}
    u_e &= \frac{\omega_0}{\omega_d} u e^{-\alpha t} \cos(\omega_d t - \theta) \\
    i_e &= \frac{u e^{-\alpha t} \sin \omega_d t}{L \omega_d}
\end{align*}
\]  \( \text{(15)} \)

Formula (13) to (15) show that the over-damped and critical-damped of discharging process are generated without oscillation, while the under-damped discharge is an exponential decaying oscillation of discharge process. And the \( \alpha, \omega_0 \) and \( \omega_d \) are adopted to represent attenuation coefficient, resonant angle frequency and attenuation resonant angle frequency correspondingly. According to the design requirements of the cable partial discharge OWTS, the process of generating damped oscillation voltage should be the under-damped discharge process.

In conclusion, the charging process of cable partial discharge OWTS is the over-damped charge, while the discharging process is under-damped discharge. To realize the conversion between the two states, the key lies in the matching values of equivalent components in the high voltage circuit. When \( \alpha > \omega_0 \), that is, \( R > 2\sqrt{L/C} \), the high voltage circuit is over-damped state, otherwise, \( \alpha < \omega_0 \), \( R < 2\sqrt{L/C} \), the high voltage circuit is under-damped state. Therefore, in the same test condition, the equivalent resistance of the circuit of over-damped state should be greater than the under-damped state. As shown in figure 2, the equivalent resistance of the high voltage circuit can be described by using \( R = R_f + r \) during the charging process; while it is described by using \( R = r \) during the discharging process. The method to meet the design requirements is to select the value of \( R_f \) and \( r \) reasonably.

**Cause Analysis of Charging Failure**

The equivalent inductance \( L \), charging protection resistance \( R_f \) and discharging equivalent resistance \( r \) of the cable partial discharge OWTS remain basically unchanged in the follow-up use procedure after produced, while the equivalent capacitance \( C \) of the circuit is significant different with the length and type of the tested cable. If the tested cable major insulation is too short or unhealthy where the value of \( C \) is too small and the inequality of \( R > 2\sqrt{L/C} \) is not established, the over-damped unidirectional charging state will be destroyed and convert to under-damped oscillatory charging, thus causing the charge to fail.

In practical applications, there have emerged two cases of charging failure. As a result of field investigation and analysis, the reason for the failure relates to the abnormal insulation of the tested cable system. The major insulation resistance of the tested cable has changed obviously before and after testing in the first case. When the charging failure occurs, the major insulation resistance has been reduced to several k\( \Omega \)'s, and then the charging process can be equivalent to parallel a several k\( \Omega \)'s resistor of the \( C \) in figure 2, that is, equivalent to short the points of tested cable. Thereby, the topology of the charging circuit is changed, and the equivalent capacitance of the circuit is minimal. In the second case, the tested cable is a returned cable. The appearance of charging failure is due to the imperfect treatment of the tested cable terminal part, where the outer semi conductive layer and the major insulation are in the same section whose distance from the cable core is too small. With the charging voltage reaching a certain value, the surface flashover discharge which destroyed the charging circuit structure occurred between the cable core and the outer semi conductive layer, thus causing the charge to fail. After the treatment of peeling off enough length of the outer semi conductive layer in tested cable terminal part, the problem of charging failure was solved successfully.
PD Location Error Analysis

Principle of Partial Discharge Location

The partial discharge pulse produced by the defect in cable insulation will propagate to the ends along the cable. By using the method of time domain reflectometry (TDR) and analyzing the time difference between direct and reflected pulses, the location and search of cable partial discharge can be achieved. The specific schematic diagram is shown in figure 3.

The related calculation formulas are given in (16).

\[
\begin{align*}
  t_1 &= \frac{x}{v} \\
  t_2 &= \frac{(l-x)+l}{v} \\
  x &= l - \frac{1}{2} v (t_2 - t_1)
\end{align*}
\]  

(16)

Where

- \( t_1 \): the propagation time of direct pulse
- \( t_2 \): the propagation time of reflected pulse
- \( x \): the distance of PD source location from test point
- \( v \): pulse propagation velocity in XLPE cable, abbreviated wave velocity
- \( l \): the length of tested cable

The location of partial discharge is to find out the specific value of \( x \) according to formula (16).

Location Error Analysis

Formula (16) shows that the PD source location is related to the length of tested cable \( l \), wave velocity \( v \) and time difference recorded by detection system. In the field testing, the value of \( l \) generally refers to the data provided by cable operation and maintenance department, and makes modifications based on TDR method. The time difference is automatically identified and recorded by the detection system, which the error is small to be ignored. The wave velocity \( v \) is only related to the material of the cable insulation, and generally speaking, the \( v \) is within the range of 170~172m/μs for XLPE cable, however, it can be affected by degree of cross-linking, impurity content and so on. As it is, the wave velocity has certain difference with the cables of different manufacturers, batches and aging degree. Therefore, the uncertainty of the length of tested cable and wave velocity is the main source of the PD localization error, which can be described by formula (17).

\[
\Delta x = (l - l_T) - \frac{1}{2} (t_2 - t_1) (v - v_T)
\]

(17)

Where

- \( l_T \): the actual length of tested cable
Formula (17) shows that the time difference is larger, the error caused by the uncertainty of the wave velocity is larger. Meanwhile, by adopting TDR method to calibrate the cable length and wave velocity, the process is coupled with each other. Therefore, it is very important to obtain accurate cable length and wave velocity, which can realize the precise location of cable partial discharge based on damped oscillation wave voltage. In addition, the application shows that the insulation defects discovered by testing technique based on damped oscillation wave voltage mostly located in cable joints or terminals. When the test results show that the PD data are abnormal, the cable joints or terminals around the locating point should be investigated firstly, if necessary, multiple detections and locations can be conducted.

Summary

As described above, this paper conducted the theoretical analysis of the charge-discharge principle and location error about the detection system of cable partial discharge based on damped oscillation wave voltage. As a result, the following conclusions are obtained.

a) The charging process of cable partial discharge OWTS is the over-damped charge, while the discharging process is under-damped discharge. To realize the conversion between the two states, the key lies in the matching values of equivalent components in the high voltage circuit.

b) When the tested cable is too short or its major insulation is unhealthy where the value of \( C \) is too small and the inequality of \( R > 2\sqrt{L/C} \) is not established, the over-damped unidirectional charging state will be destroyed and convert to under-damped oscillatory charging, thus causing the charge to fail. And the rationality of the analysis was proved by the case studied in engineering practice.

c) By adopting TDR method to calibrate the cable length and wave velocity, the process is coupled with each other. It is very important to obtain accurate cable length and wave velocity, which can make decisive effect in realizing the precise location of cable partial discharge based on damped oscillation wave voltage.

References


