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PAPERS

Application and verification of partial discharge measurement system for power cable based on oscillating wave voltage

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Compared with conventional methods for insulation performance evaluation of power cables, the oscillating wave test system used in partial discharge measurement for power cables has advantages of high integrity, easy operation, low power consumption, and compact size in addition, partial discharge, defect localization, and dielectric loss can be measured simultaneously without any damage to cable insulation. Therefore, the oscillating wave test system has been widely applied for insulation performance evaluation of newly installed as well as fault power cables. However, there is no study so far on the verification method of oscillating wave test system. This paper dealt with the application and verification for cable partial discharge measurement devices based on oscillating wave voltage, which is aimed to verify performances of oscillating wave voltage generator, partial discharge measurement, and partial discharge localization. The proposed verification system is expected to be applied in the admittance testing and regular verification of oscillating wave test system, for the purpose of improving the its accuracy and standardization in partial discharge measurement of power cable.

K e y w o r d s: power cable oscillating wave voltage; partial discharge; measurement; verification system

1 Introduction

In recent years, power cables have been widely used in the urban power grid and their proportion in the transmission network of the whole power system has increased gradually. Power cables has advantages of excellent insulation performance, easy installation, save in land space, and high reliability. However, as results of the raw materials, design or degradation, insulation defects may exist in the manufacturing, assembly, transportation, and operation processes of power cables. Typical defects of cables include cavity or impurity in the insulation layer, delamination of conductor and insulation layer, protrusion on the conductor, and electrical tree, all of which may locate in the cable body, joint, and terminal [1-5]. Under the testing voltage or rated voltage, partial discharge (PD) may occur when the applied electric filed excesses the dielectric strength of cable insulation. PD is the main reason of cable deterioration and is an early indicator of insulation breakdown. Therefore, detection of PD is regarded as one of the most effective methods to ensure the reliable operation of power cables [6-9].

Conventional methods for cable insulation performance evaluation include DC withstand test, AC withstand test, and very low frequency test, however, each method has its respective limitations in the field application. In the DC withstand test, space charges may remain adjacent to the defect, which may lead to insulation breakdown after the cable is put into operation. Although the AC withstand test is similar to the actual operational environment of power cables, the insulation may be damaged owing to the long test time. In addition, since power cables usually have high value of capacitance, the experimental power supply must be designed with abundant capacity, leading to its huge size and weight. The very low frequency method uses 0.1Hz test voltage to solve problem in capacity of power supply, the long test time may also result in insulation damage of power cable.

The oscillating wave test system has been widely used for insulation performance evaluation of newly installed and fault power cables owing to its advantages of high integrity, easy operation, low power consumption, and compact size. In addition, partial discharge, defect localization, and dielectric loss can be measured simultaneously without any damage to cable insulation [10-13]. However, there is no study so far on the verification method of oscillating wave test system. In this paper, the application and verification methods for cable partial discharge measurement system based on oscillating wave voltage are proposed, with the aim to improve the accuracy and validity of device.

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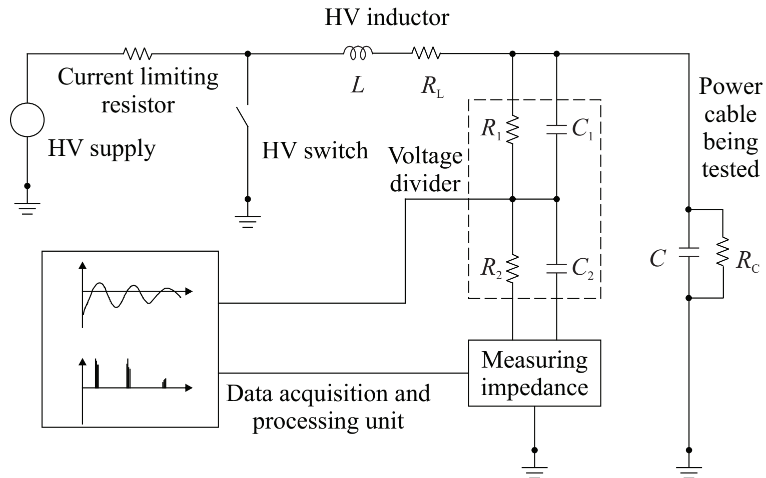

Fig. 1. Configuration of partial discharge measurement system based on oscillating wave voltage

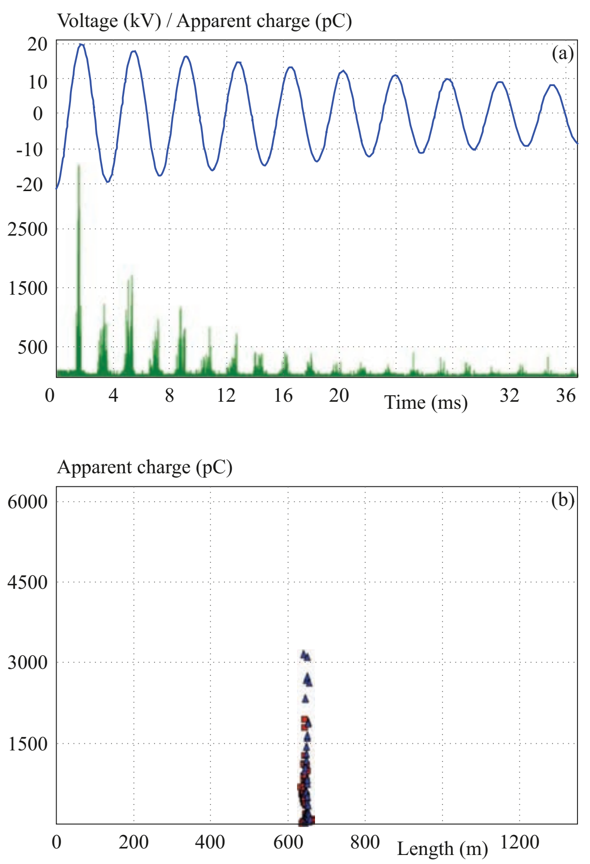

Fig. 2. Configuration of partial discharge measurement system based on oscillating wave voltage

2 Partial discharge measurement based on oscillating wave voltage

The configuration of partial discharge measurement system for cables based on oscillating wave voltage is shown in Fig. 1, which mainly consists of HV power supply, current limiting resistor, solid switch, HV inductor, voltage divider, partial discharge measuring impedance, and power cable being tested. During the test, the HV power supply charges the power cable through the current limiting resistor and HV inductor. When the charging voltage reaches the setting value, the solid switch is closed immediately to disconnect the power supply from the circuit and to generate an oscillating wave voltage in the LC circuit that is composed by the HV inductor and the cable being tested. The frequency of oscillating wave voltage is in rang of 30 Hz≈500 Hz depending on the capacitance of power cable. PD may occur from the insulation defect in power cable and be detected by the measuring impedance of oscillating wave voltage system. The defect can be localized by the time-domain reflectometry method, which is based on the cable length, propagation velocity of impulse in power cable, and time interval between the incident wave and the reflected wave. In addition, the dielectric loss of power cable can be estimated using the attenuation characteristic of oscillating wave voltage [12,14].

The measurement items of oscillating wave voltage system include magnitude and frequency of the oscillating voltage, PD parameters, capacitance and dielectric loss of cable being tested, as well as defect position in cable. The oscillation frequency f can be calculated based on the time interval between two crests of the oscillating voltage, and the capacitance C of cable can be calculated by

$$C = \frac{1}{\omega^2 L}, \tag{1}$$

where $\omega = 2\pi f$ and L is the inductance of the HV inductor. The dielectric loss $\tan\delta$ of power cable can be estimated using the attenuation characteristic of oscillatintang wave voltage, and is given by

$$\tan\delta = \frac{R_C}{\omega L}, \tag{2}$$

$$R_C = \frac{L}{2\beta_{\mathrm{DAC}} LC - R_L C}, \tag{3}$$

$$\beta_{DAC} = -\frac{\ln(U_5/U_1)}{t_5 - t_1}, \tag{4}$$

where R_C is the equivalent resistance of power cable and R_L is the equivalent resistance of inductor. U_1 and U_5 are the magnitudes of the first and the fifth crest of the oscillating wave voltage, and T_1 and T_5 are the corresponding times.

Figure 2 shows the application of oscillating wave voltage system in PD measurement and defect localization for power cable. The test object was a 10 kV cross-linked polyethylene (XLPE) cable with a length of 1350 m. When the magnitude of oscillating wave voltage reached 20.9 kV, discharge with maximum apparent charge of 3100 pC occurred, and the defect was localized at 648 m away from the measuring end. After disassembly and inspection of the cable, it was verified that the outer sheath at 1.3 m from the cable joint was damaged and water drops can be seen clearly. Photographs of disassemble and inspection of the fault cable are shown in Fig. 3.

Fig. 3. Disassemble and inspection of the fault cable

3 Verification system and methods

The configuration of verification system for oscillating wave test system is demonstrated in Fig. 4, which is composed of the oscillating wave test system being verified, standard voltage divider, load capacitor, standard calibrator, data acquisition unit, standard double pulse generator, and power cable. The cable partial discharge measurement device based on oscillating wave voltage is the test object, and the verification system can verify functions in terms of oscillating voltage generator, PD measurement, and PD localization [14-16]. In this paper, the measurement error is defined as the measured quantity value by the oscillating wave test system minus a reference quantity value that measured using the standard components, namely the standard voltage divider, standard calibrator, and standard double pulse generator[17-18].

3.1 Verification of oscillating voltage generator

The oscillating voltage generator is the power supply of cable partial discharge measurement devices based on oscillating wave voltage, whose voltage magnitude, voltage error, and voltage frequency influence the generation and measurement of PD. Therefore, verification of the oscillating voltage generator is necessary for improving the reliability of partial discharge measurement based on oscillating wave voltage.

As shown in Fig. 4, for verifying the oscillating voltage generator, the load capacitor and standard voltage divider are connected in parallel with the oscillating wave voltage system being verified, and the data acquisition unit is used to obtain the waveform of charging voltage and oscillating wave voltage. The load capacitor has a capacitance of 150 nF and its PD level at maximum operating voltage is lower than 5 pC. The rated voltage and ratio of standard voltage divider are 60 kV and 10000:1, respectively. The data acquisition unit has a sampling rate of 1GS/s and a bandwidth of 250 MHz. The verification items for oscillating voltage generator include oscillating frequency, attenuation in voltage magnitude, voltage error, maximum output voltage, charging time, and charging current.

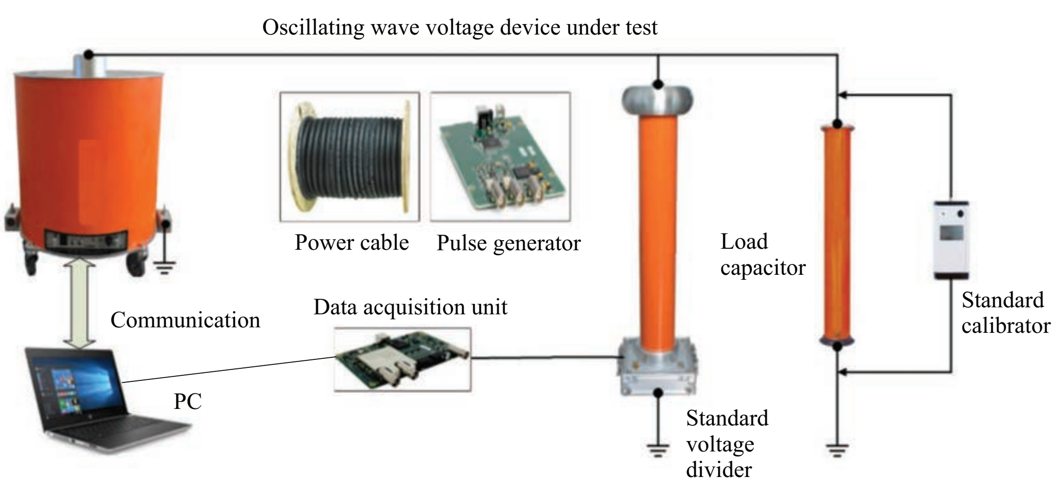

Fig. 4. Configuration of verification system

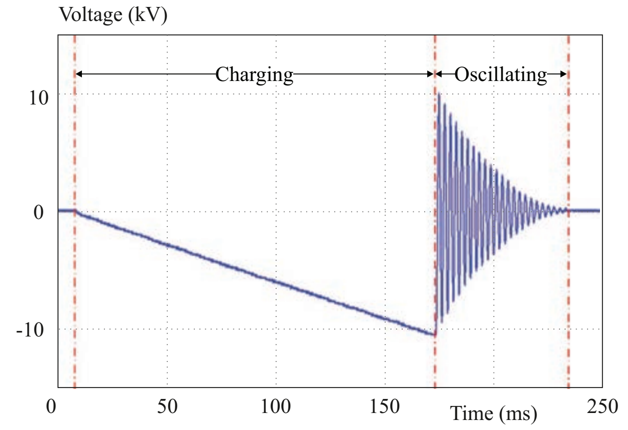

Fig. 5. Charing voltage and oscillating wave voltage

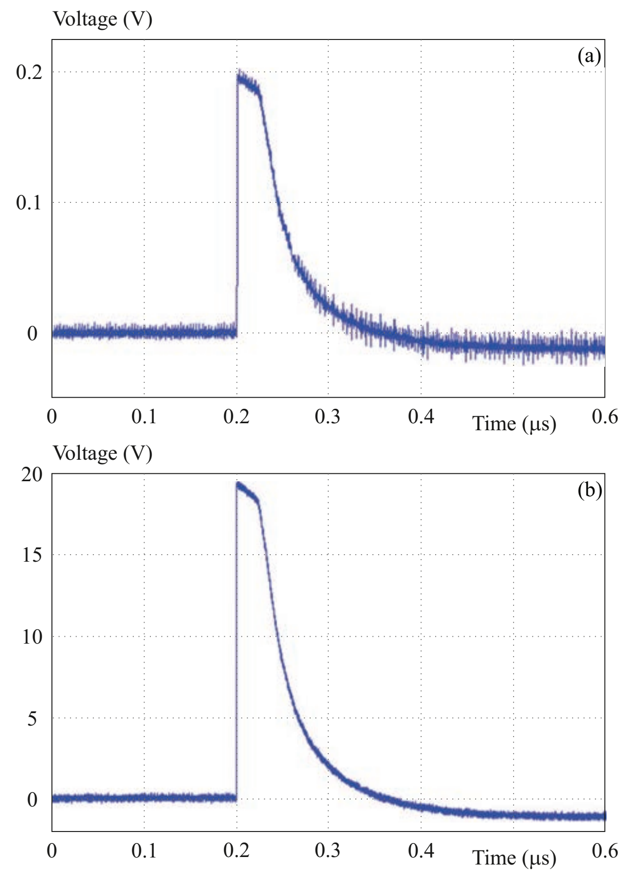

Fig. 6. Waveform of calibration pulses

Figure 5 shows the typical waveform of charging voltage and oscillating wave voltage measured by the standard voltage divider. The oscillating frequency is defined as number of crests in a continuous oscillating wave voltage per second, whose values should be in range of 30 Hz 500 Hz. At 80% of the maximum applied voltage, the attenuation in voltage magnitude should be lower than 50% in the first 8 cycles. The voltage error is calculated from 5 measurement points on the oscillating wave voltages that are detected by the oscillating wave voltage system itself and by the standard voltage divider, and the value should be lower than 3%. The maximum output voltage can be verified by adjusting the oscillating wave voltage system to its maximum rated voltage and reading the peak value on the waveform of oscillating wave voltage. For DC-supplied and AC-supplied device, the maximum output voltage should be higher than $2\sqrt{2}$ and 2 times of the rated voltage of cable, respectively. The charging time is defined as 2.5 times of the time period from 30% to 70% of the maximum rated voltage during the charging process, whose unit is in second. Its value should be lower than 40 times of the maximum output voltage that is expressed in kilovolt. During the charging process, the charging current at the maximum rated voltage should be higher than 8 mA.

In the voltage waveform shown in Fig. 5, the oscillating frequency is 208Hz and the attenuation in voltage magnitude in the first 8 cycles is 47.6%. The voltage error is 1.2% and the maximum output voltage is 10 kV. The charging time and charging current are 78 ms and 14 mA, respectively.

3.2 Verification of partial discharge measurement

The verification items of PD measurement include measurement stability, measurement error, and measurement sensitivity, which are carried out by injecting pulse with known apparent charge to the load capacitor using the standard calibrator. The standard calibrator is designed with output of 1 pC ≈ 20 pC, 20≈100 pC, 500 pC, 1 nC, 5 nC, 1 nC, 10 nC as well as 20 nC, and has a resolution of 1 pC from 1 pC to 20 pC and of 5 pC from 20 pC 100 pC. Figure 6 illustrates the waveform of calibration pulses with apparent charge of 100 pC and 10 nC. The apparent charge q can be calculated by

$$q = \int_{t_1}^{t_2} i(t)\mathrm{d}t = \int_{t_1}^{t_2} u(t)/R_m \mathrm{d}t, \tag{5}$$

where $i(t)$ and $u(t)$ are the current and voltage of the calibration pulse, and R_m is the value of measuring impedance.

For verifying PD measurement stability, the standard calibrator is firstly used to inject pulses with apparent charge Q_s to the load capacitor, by which the oscillating wave voltage system being verified is calibrated. And then, by measuring the apparent charge for 5 times at each output of the standard calibrator, the measurement stability ES (in %) can be calculated by

$$E_S = |(Q_m ax - Q_m in)/Q_s| \times 100, \tag{6}$$

where $Q_{\max}$ and $Q_{\min}$ are the maximum and minimum value in 5 times of measurement. The PD measurement stability should be lower than 5%. For verifying PD measurement error, the calibrator of oscillating wave voltage system is firstly used to inject pulses with apparent charge Q_s to the load capacitor, by which the system being verified is calibrated. And then, the standard calibrator is used to inject pulses with apparent charge Q_m

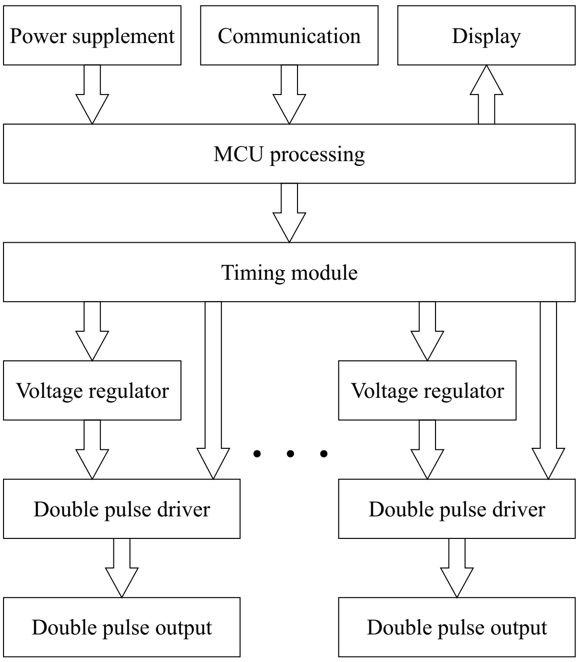

Fig. 7. Double pulse generator

to the capacitor. At each corresponding apparent charge, the measurement error E_m is given by

$$E_m = |(Q_m - Q_s)/Q_s| \times 100, \tag{7}$$

this value should be lower than 10%. During the verification of PD measurement sensitivity, the calibrator of oscillating wave voltage system being verified is firstly used to inject pulse with apparent charge of 20 pC to calibrate the system being verified. And then, pulse with apparent charge of 20 pC that is generated by the standard calibrator is injected to the capacitor, and the output apparent charge is reduced gradually. The minimum output apparent charge that can be detected by the oscillating wave voltage system is defined as PD measurement sensitivity, whose value should be higher than 10 pC.

3.3 Verification of partial discharge localization

The accurate localization of insulation defects in power cable is meaningful for equipment managers to inspect potential faults and to make proper maintenance plan, which significantly improve the cable maintenance efficiency. The verification items of PD localization include localization sensitivity, localization error, and multiple PD source localization performance.

The PD localization sensitivity is defined as the minimum detectable apparent charge of reflected pulse by the oscillating wave voltage system in 100 m XPLE cable. The localization sensitivity should be higher than 10 pC. For verifying the localization sensitivity, the standard calibrator is used to inject pulse with apparent charge of 100 pC to the cable at the measuring end and the opposite end. Two pulses are detected by the data acquisition unit and their magnitudes are obtained as V_1 and V_2. The attenuation factor F of tested cable is given by

$$F = -\ln \frac{V_2}{V_1}, \tag{8}$$

After calculating the attenuation factor, the XLPE cable is connected to the oscillating wave voltage system. And then, pulse with apparent charge of 100pC that is generated by the standard calibrator is injected to the cable at the opposite end, and the output apparent charge is reduced gradually. PD localization sensitivity S can be calculated by

$$S = Q_{\min} e^{F_s - F}, \tag{9}$$

where $Q_{\min}$ is the minimum injected apparent charge of detectable pulse, and F_s is the typical attenuation factor of cable.

Figure 7 demonstrates the schematic diagram and prototype of double pulse generator, which is used for verifying PD localization error and multiple PD source localization performance. The double pulse generator is connected to the verification system by wireless communication. The timing module is used to control the time interval of double pulse in one group and the time intervals of different pulse groups. To be specific, the double pulse in one group is used to verify the PD localization error and the pulse groups are used to verify the performance of multiple PD source localization. The voltage regulator is used to determine the pulse magnitude, and the double pulse is finally generated by the pulse driver and pulse output module. The voltage regulator, double pulse driver, and double pulse output module are extensible, by which different requirements for verification of multiple PD source localization performance can be met.

For verifying PD localization error, the pulse generator is used to inject double pulse in one group to the data acquisition unit and to the oscillating wave voltage system. When the double pulse is injected to the data acquisition unit, the standard localization result X_s is calculated based on the time-domain reflectometry method, which is given by

$$X_s = l - 170 \frac{\Delta T}{2}, \tag{10}$$

where l is the cable length and ΔT is the time interval of double pulse in one group. The double pulse can be regarded as the time interval between the incident wave and the reflected wave of PD pulse. When the double pulse is injected to the oscillating wave voltage system, localization result is obtained as X_m from the system being verified. PD localization error El is calculated by,

$$E_l = \frac{X_m - X_s}{l} 100. \tag{11}$$

Multiple PD source localization means that the oscillating wave voltage device can distinguish the number

Table 1. Verification items and criterions

Content	Item	Criterion
Oscillating voltage generator	Oscillating frequency	$20 \sim 500\,\text{Hz}$
	Voltage attenuation	less than 50% in the first 8 cycles
	Voltage error	$\leq 3\%$
	Maximum output voltage	$\geq 2\sqrt{2}$ times of cable rated voltage (DC-supplied)
		≥ 2 times of the cable rated voltage (AC-supplied)
	Charging time	≤ 40 times of the maximum output voltage
	Charging current	≥ 8 mA
Partial discharge measurement	Stability	$\leq 5\%$
	Error	$\leq 10\%$
	Sensitivity	≥ 10 pC
Partial discharge localization	Sensitivity	≥ 50 pC
	Error	$\leq 1\%$
	Multiple PD source	$\leq 1\%$

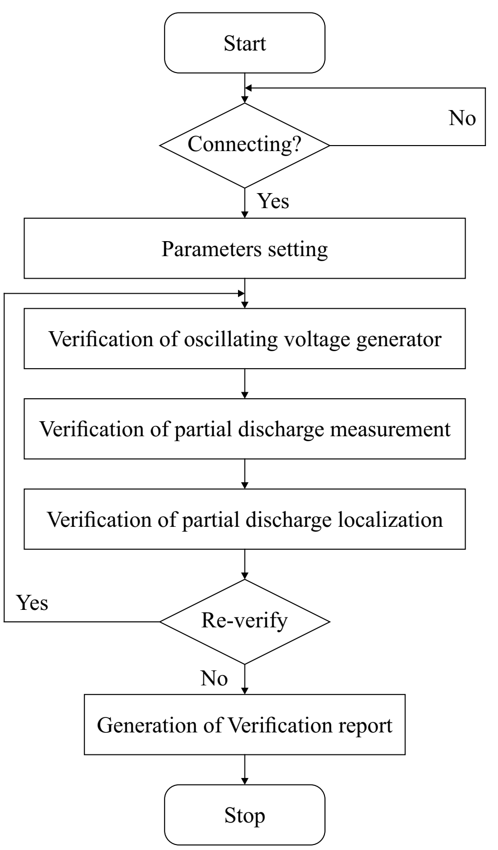

Fig. 8. Flowchart of software for verification system

of discharge sources and locate their positions accurately when there are more than one insulation defects in power cable. For calibrating the multiple PD source localization, four groups of double pulse are used. The localization results are obtained by the data acquisition unit and the oscillating wave voltage device, respectively. The multiple PD source localization error can be calculated by (11), which should be less than 1%.

3.4 Software development

The flowchart of software for verification system is shown in Fig. 8, which has functions of parameters setting, verification of oscillating voltage generator, verification of partial discharge measurement, verification of partial discharge localization, and generation of calibration report. The software can compare the results obtained from the oscillating wave voltage system and the verification system, and calculate the verification items automatically. Each function is designed in modular and the report can be generated after all the items are calibrated. Table 1 shows the verification items and criterions for oscillating wave voltage system.

4 Conclusion

Although the PD measurement device based on oscillating wave voltage has been widely used for insulation performance evaluation of power cable, few studies has been carried out to investigate its verification methods. In this paper, the application of cable partial discharge measurement devices based on oscillating wave voltage is introduced, and the verification methods as well as the verification system are proposed. The system consists of oscillating wave voltage device being verified, standard voltage divider, load capacitor, standard calibrator, data acquisition unit, double pulse generator, and power cable, which can verify the performance of oscillating wave voltage generator, PD measurement, and PD localization. The calibration items for oscillating voltage generator include oscillating frequency, attenuation in voltage magnitude, voltage error, maximum output voltage, charging time, and charging current. The PD measurement is calibrated in terms of measurement stability, measurement error, and measurement sensitivity. The calibration of PD localization includes localization sensitivity, localization error, and multiple PD source localization performance. The proposed methods and system are expected to be applied in the admittance testing and regular calibration of oscillating wave test device, by which the oscillating wave voltage system can be effectively regulated and the accuracy of partial discharge measurement can be improved.

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