An improved design of damped AC test system for partial discharge measurement in distribution power cables

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Abstract. This paper presents an improved technique to generate damped AC voltage for on-site PD detection on distribution power cables. The proposed technique is based on conventional frequency-tuned series resonant system and two additional high-speed switches. In order to reduce the size and weight of the proposed damped AC test system, electric simulation by Simulink and heat simulation by ANSYS are carried out to determine the system parameters. High-voltage test on two 10kV XLPE cable segments was conducted to validate the proposed technique.

1. Introduction

Power cables are of great importance in power distribution system[1]. However, cable insulation is deteriorated by various issues such as imperfections insulation with voids or bubbles formed in the process of manufacturing, protrusions in cable joints introduced in the process of joint fabrication[2]. These defects would not directly lead to insulation breakdown but cause partial discharge (PD) phenomenon. Therefore, partial discharge measurement is an effective method in cable insulation condition detection. Over the past decades, several techniques have been proposed and applied to on-site partial discharge measurement for estimating insulation condition of distribution power cables. According to the type of high voltage applied to the cable, DC voltage, AC voltage, very low frequency (VLF) voltage and damped AC (DAC) voltage are the common used technique. DC voltage is a technique for cable testing with a long application history. However, it is harmful to XLPE cable which is widely used at present[3]. For this reason, DC voltage has been removed from on-site testing on XLPE cable. Frequency-tuned series resonant technique has been proposed to meet the power requirement of capacitive load. However, the electronic devices used in the frequency-tuned system introduce severe noise, which is not suitable for PD measurement, into the testing circuit. VLF system generates a very low frequency square-wave or sine-wave voltage, which is usually 0.01~1 Hz, on the cable. Several researches have proved that PD behaviors under VLF voltage are quite different from those under 50 Hz AC voltage[4]. DAC test system has gained more and more interests in recent years for its effectiveness in on-site PD measurement. Conventional DAC test system contains high voltage switches which cost too much and introduce unstable issues. As a consequence, it is essential to design a cost-effective test system for PD detection of power cables.
This paper introduces an improved damped AC voltage test system which is based on the frequency-tuned series resonant technique. The proposed technique is suitable for on-site PD measurement of distribution cable due to its effectiveness and portability. The following chapters in the paper would demonstrate how to improve conventional frequency-tuned series resonant technique to conduct PD detection and how to reduce size and weight of the system to meet the on-site testing requirements. Besides, laboratory test on a 10 kV XLPE cable has been carried out to validate the proposed technique.

2. Technical theories
As mentioned above, for the convenience of on-site cable test, several test methods have been put forward and applied[5]. To achieve the aim to design a cost-effective system for on-site cable test, this paper has combined the advantages of two common techniques and the technical theories are presented as following.

2.1. Conventional DAC technique
DAC test technique has been brought out for decades and put into application all over the world in recent years[6][7]. The basic operation principle of conventional DAC system is to charge the cable to test voltage and discharge the cable via a high-voltage switch. A conventional DAC test system generally consists of a high-voltage DC supply, a PD-free inductor and a high-voltage switch, as shown in figure 1. When the cable is charged to test voltage, the high-voltage switch is closed and a DAC voltage is generated on the cable via the circuit consists of the cable, inductor and the high-voltage switch. During the DAC voltage stage, PD signals can be detected and analysed to evaluate the condition of the test cable insulation and locate the defects induce the PD signals. Unlike conventional DC voltage test, no ‘steady state’ DC conditions occur in the insulation of the test cable during the energizing stage under DAC voltage[8]. Besides, DAC test system is portable in test site for DC charge process reduces the power requirement.

During last few years, researches have demonstrated that the influence of different voltage shape and frequency applied on the cable is negligible in practice[9]. That is to say that the DAC voltage is suitable for on-site cable testing and behave well in PD detection and location.

![Figure 1. Schematic of conventional DAC test system.](image)

2.2. Frequency-tuned series resonant technique
Series resonant technique has been put into application for a long time and can be classified into two types, frequency-tune and inductance-tuned. The frequency-tuned type is used more frequently than the other type for the weight-power-ratio of frequency-tuned series resonant system is about 3–5 times than the inductance-tuned one[8]. Therefore, this paper only takes frequency-tuned series resonant technique into consideration.

The frequency-tuned series resonant system generally consist of the following parts and correspondingly shown in figure 2.

a. control and sample unit
b. variable frequency power source (frequency-tuned power source)
c. exciting transformer
d. resonant inductor
e. cable
f. high-voltage divider

Figure 2. Schematic of frequency-tuned resonant test system.

When the frequency of the variable frequency source is tuned to equal to the natural frequency (resonant frequency) of the cable-inductor circuit, it will generate a sine-wave voltage several tens of times than the output of the exciting transformer on the cable[10]. Under this resonant condition, only active power loss exists in the system so that the frequency-tuned resonant system is portable in test site. Usually, the frequency of the system ranges from 30~300Hz to meet the requirement of different cable lengths[11][12]. Besides, it has been verified and accepted that the frequency of the voltage stress in this range is similar to the operation frequency.

2.3. Improved system for DAC test
As described above, DAC system and frequency-tuned series resonant system are both suitable and effective for on-site cable test. Frequency-tuned series resonant system is widely used in the field of withstand test with the development of power electronic devices[13]. For on-site cable tests, frequency-tuned series resonant system is often used to conduct withstand test not diagnostic test. The general reason for this phenomenon is due to the power electronic devices introduce numerous switching noise which brings disadvantage to PD detection. As for DAC system, the solid-state high-voltage switch is relatively expensive. This paper proposes an improved technique which combines the advantages of both DAC technique and frequency-tuned series resonant system, i.e. the proposed system generate a DAC voltage based on frequency-tuned series resonant technique. Therefore, the proposed system can be denoted as AC-DAC system. The schematic of this technique is depicted in figure 3.

Figure 3. Schematic of AC-DAC system.

Comparing to conventional frequency-tuned series resonant system shown in figure 2, AC-DAC system mainly owns two more parts, switch K₁ and K₂ with the rated voltage of a few hundreds of volts. The basic operation principle of this AC-DAC test system is described as following.

a. When the system starts to work, K₁ is closed and K₂ is opened. Under this condition, the system could be regarded as a conventional frequency-tuned series resonant system.

b. Tune the frequency of the variable frequency source output to the natural frequency of the circuit. Generally, the natural frequency could be estimated by

\[ f = \frac{1}{2\pi\sqrt{LC_1}} \]  

(1)
c. Increase the output of the variable frequency source to boost the voltage on the cable to predetermined test level.

d. Open \( K_1 \) and close \( K_2 \) when the voltage on the cable reaches the peak value, the cable will discharge via the cable-inductor-transformer circuit. Due to the existence of the resistance in the inductor and the winding in transformer, the voltage generated on the cable will be in the form of damped AC voltage.

As the operation process shown above, the AC-DAC technique can be divided into two stages, resonant AC stage and DAC stage. During the resonant AC stage, the system contains a lot of switching noise from the variable frequency source. With the actions of \( K_1 \) and \( K_2 \), switching noise has been eliminated from the PD detection unit. Therefore, during the DAC stage, it is suitable for PD detection and data processing.

To validate the proposed technique, simulation of the AC-DAC system is carried out by Simulink software, as shown in figure 4. The variable frequency source is based on single-phase rectifier and corresponding inverter. The zoomed detail of the output voltage on the cable from the simulation result depicted in figure 4(b) has clearly demonstrate the resonant AC stage and DAC stage.

![Schematic diagram of the simulation.](image1)

![Output of the simulation.](image2)

**Figure 4.** Simulation of the AC-DAC system.

### 3. Power design of the proposed technique

For the portability of the system in test site, the AC-DAC system should be small in size and light in weight. Therefore, accurate power design of the system is of importance. The main parts that contribute to the total weight of the system are the exciting transformer and resonant inductor. Thus, special attention should be paid to the issues that could reduce the weight of the transformer and the inductor.

Firstly, set the maximum load capacitance as \( 0.5 \mu \text{F} \) which generally could represent a cable with the length of 2~2.5 km[14]. The inductor used in conventional frequency-tuned series resonant is usually in the range of several tens of \( \text{Henry} \) with iron core[15]. However, the inductor used in DAC test system is usually in the range of 0.7~1 H with air core. In order to improve the quality factor and reduce the weight of the proposed system, air-cored inductor with the value of 1H is a better
alternative in this paper. The current flows in the resonant circuit can be evaluated by the following equation,

$$I_s = \frac{C}{\sqrt{L}}U$$  \hspace{1cm} (2)

According to IEEE guide, the voltage applied on the cable when conducting diagnostic test should be twice as the operation voltage $U_0$ [12]. For the commonly used 8.7/10 kV XLPE distribution cable, the maximum current in the resonant circuit can be calculated as

$$I_{s,\text{max}} = \sqrt{\frac{0.5 \times 10^{-5}}{1}} \times 2 \times 8.7 \times 10^3 = 12.3 \text{ A}$$  \hspace{1cm} (3)

The voltage ratio of the exciting transformer can be chosen as 1:4 according to a simple simulation by Simulink software. Under this condition, the current flows in the primary winding of the exciting transformer can be approximately evaluated as 49.2 A.

Heat issues of the inductor and transformer are the key aspects that influence the power and weight of the system. Conventional frequency-tuned resonant system uses iron-core inductor for it maintains in the condition of maximum current for about 60 min. However, the proposed AC-DAC system employs an air-core inductor which leads to high current and low thermal capacity. The AC-DAC system works in discontinuous mode to solve this problem. Denote the process that the system generate a resonant AC voltage and transits to the DAC voltage as one DAC shot. One DAC shot totally takes about 1.5 seconds and then it takes about 1~2 seconds to conduct data transmission. During the data transmission time, the whole system gets natural cooling. Denote the sum of one DAC shot time and one natural cooling time as a heating cycle. The AC-DAC discontinuous heating mode is further explained in figure 5.

![Figure 5. The heating mode of the AC-DAC system.](image)

To evaluate the temperature condition of the AC-DAC system, a finite-element model was established by ANSYS software. A 3 kVA dry-type transformer was modelled with a double-E type iron core, depicted in figure 6(a). The air-core inductor was modelled as 4 winding layers with epoxy resin embedded. Apply the current obtained above to the simulation model and set the total operation time as 30 minutes, the results are shown in figure 6(b) and (c).

![Figure 6(a). Finite-element model of the transformer.](image)
The simulation results show that the maximum temperature of transformer rise from 25 ℃ (the pre-setting initial temperature) to 50.4 ℃ and the maximum temperature of inductor rise from 25 ℃ to 41.3 ℃. The simulation result of temperature rise is within the range of critical warning value of this kind of apparatus. The power parameters of the AC-DAC system designed in this paper is thus validated.

4. Laboratory test
An AC-DAC test system was manufactured on the basis of the proposed technique and validated parameters, shown in figure 7. The weight of the air-core inductor and the transformer are 35kg and 23kg, respectively. Therefore, it is suitable for transport and operate in the test site.

As shown in figure 7, a laboratory test on two 10 kV XLPE cable segments with the total length of 200m was carried out to further verify the proposed technique. An artificial insulation defect was made at the connection point of two cable segments.

The data detected at 16 kV (peak value) is shown in figure 8(a) and it is clear that PD data under the DAC stage can be used for PD source location. PD location can be identified according to time domain reflectometry technique and the result is drawn in figure 8(b). It is clear that the PD source is located at the position 101.8 m from the detection point. The result is consistent with the actual PD location in the layout of the experiment network.
5. Conclusion
The proposed system for PD detection using DAC voltage based on improved frequency-tuned series resonant technique has proven to be effective. The proposed technique shows economic benefit by adding two extra relatively low-voltage switches into conventional frequency-tuned resonant system rather than the high-voltage solid state switch in conventional DAC system. Through electric and heat simulation and design, the units employed in the proposed system also show advantages in on-site transportation and operation. A high-voltage experiment on two 10 kV XLPE cable segments was conducted and the results further validate the proposed technique.

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