Development of a compact very low frequency cosine-rectangular and damped alternating current voltage generator for insulation testing of medium-voltage power cables

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Abstract: This study describes the research and design of a novel and compact very low frequency cosine-rectangular (VLF-CR) and damped alternating current (DAC) voltage generator that can be used to test the insulation condition of the medium-voltage power cables. Further, a complete system based on a voltage multiplier (VM), which can be cascaded to increase the output voltage, is proposed to simultaneously realise VLF-CR and DAC voltages for the withstand voltage and offline partial discharge (PD) tests, enabling the test system to be lightweight and efficient. The system principle and operating characteristics associated with the generation of two different voltages are analysed in detail according to the new circuit topology of the proposed generator. Furthermore, oscillation suppression and multiple output units are considered to improve the voltage waveform and provide power supply to the VM module, respectively. A laboratory prototype is also developed and tested. Finally, the integrated generator is used for the PD testing on cables with artificial defects, verifying the practicability of the proposed system.

1 Introduction

Power distribution with respect to critical processes is usually achieved in modern commercial and industrial facilities via power cable systems. Therefore, the safe operation of the cable is crucial from the viewpoint of subscribers. Detecting of the insulation status is a vital preventive measure to ensure reliable power supply. Over the last a few decades, various detection methods, such as withstand voltage, partial discharge (PD), and dielectric characteristic testing, have been developed. All these methods exhibit advantages as well as disadvantages [1–5]. The offline PD testing is widely recognised as an effective tool to assess the insulation quality of the power cable system. Based on different voltage waveforms, some scholars have summarised four types of excitation voltages for the PD testing, i.e. DC, AC, very low frequency (VLF), and damped alternating current (DAC) voltages [6–11]. Generally, power cable insulation testing is conducted using different methods to obtain comprehensive test results and accurate evaluation criteria for the insulation status [12–14]. However, performing field testing simultaneously is considerably inconvenient because various test systems are independent.

The VLF testing offers unique advantages for detecting dielectric losses and eliminating insulation defects [6, 15]. In particular, in case of VLF cosine-rectangular (VLF-CR) voltage testing, dangerous space charges are unlikely to develop in the insulation owing to continuous polarity changes, which are similar to those observed at the power frequency when performing the PD testing [16]. Regardless, compared to the VLF test system with a sinusoidal waveform, a complete VLF-CR voltage test system is rarely mentioned. Previously [17], a VLF-CR voltage generator comprising a bipolar high-voltage DC (HVDC) power supply and a HV polarity transfer switch has been proposed. However, this generator was not widely accepted due to its complex structure and higher costs.

The DAC testing is an alternative method for AC voltage testing and is applicable to a broad range of medium voltages (MVs). The structure and experimental method of a DAC detection system were introduced previously [11]. Further, He et al. [18] implement a novel damped AC system based on frequency-tuned resonant technique. In a previous study [19], a generator with a rated voltage of 20 kV was designed. However, this system could not be applied because of its complicated circuit topology, high cost, and large size, which are impediments for the on-site detection of the insulation status of the power cable systems.

To address the aforementioned issues, this study presents a new type of compact generator using VLF-CR and DAC voltages for insulation testing of MV power cables. A generator that uses the principle of voltage multipliers (VMs) [20–22] is developed, which can simultaneously generate VLF-CR and DAC voltages. The key to achieving this objective is to use the buck-boost insulated-gate bipolar translator (IGBT) cells, which are bidirectional. The generation process for the VLF-CR and DAC voltages is achieved by controlling the switching of IGBTs using the trigger module. Finally, the proposed apparatus is used for a PD testing on cables with artificial defects. The results prove that the generator offers a promising advantage in improving the field testing efficiency.

2 System overview

A novel circuit topology capable of achieving bipolar HV, as shown in Fig. 1, is proposed instead of an HVDC module by considering the conventional VLF-CR and DAC voltage test systems. This topology can simultaneously provide power supply for the test systems [17, 19]. This topology enables the device to achieve miniaturisation and high efficiency.

2.1 Schematic overview of the VLF-CR and DAC voltage test systems

The standard VLF-CR voltage and its test system are presented in a previous study [12, 17]. This test system can be simplified as that depicted in Fig. 1a. First, an HVDC source with positive and negative voltages is necessary to obtain VLF-CR voltage. Second, a polarity reversal unit is used to generate voltages with different polarities. Finally, a resonant circuit comprising an inductor and a capacitor is established to generate a cosine wave during the
discharge process. The bipolar HV power supply and polarity reversal process are essential for generating the VLF-CR voltage. However, the DAC test system requires a unipolar HV power supply, as shown in Fig. 1b. Upon the completion of charging using the unipolar HVDC source, the resonant circuit comprising the inductor and capacitor is discharged to generate an oscillating-wave voltage by turning off the power and turning on the grounding switch. The key difference in the system principle of these two detection methods lies in the power supply requirements. Several researchers proposed a bipolar HVDC generator in [23], but this is not applicable. Consequently, this study proposed a novel topology which is capable of generating bipolar HVDC and providing a discharging path for resonant processes to generate VLF-CR and DAC voltage simultaneously. It allows the use of the system to test the insulation state of MV cables in the field with various methods.

2.2 Circuit topology of the integrated VLF-CR and DAC voltage generator

Based on the aforementioned discussion, the novel topology of the proposed generator and its test system are shown in Fig. 2. This circuit mainly aims to achieve bipolar HV with a compact topology based on VM as shown in Fig. 3. The main components of the circuit include the power module, VM module, reactor, and capacitive specimens, such as power cables. The power module comprises a rectifier and an inverter unit connected in series to achieve frequency conversion for the VM module that consists of several bidirectional HV switches, charging capacitors, and blocking resistors. The output voltage can be increased by cascading the VM modules. Furthermore, a special discharge HV switch, S1 comprising IGBTs is designed to prevent the blocking effect of the transformer winding on the discharge circuit, as shown in Fig. 2.

The high-frequency AC voltage source is provided by applying the pulse-width modulation (PWM) technology to the inverter bridge, facilitating power supply to the VM. The output voltage can be adjusted in a smooth manner using the PWM technology, which is helpful to develop field tests. Furthermore, the adjustable frequency helps in obtaining a smaller ripple coefficient and voltage drop. Finally, the high frequency allows the acceleration of the charging process. All these advantages provide the necessary conditions for obtaining a waveform in accordance with the requirements of IEEE Standard 400.2. In addition, to suppress switching noise, a low-pass filter is considered in the power module to suppress the switching noise.

The VM module is constructed based on the voltage-doubler rectifier circuit, as shown in Figs. 2 and 3. The capacitors, which are stage-by-stage charged, use a high-frequency AC voltage to generate HVDC. Quraan et al. [24] provide a detailed description.
in terms of the configuration and operating principles of VM circuits. The traditional VM uses diodes to realise the charging and discharging process of the capacitors [21]. Currently, numerous controllable semiconductor switches have emerged with the advancement of semiconductor technology. Consequently, several pairs of back-to-back connected IGBTs are connected in series to construct bidirectional HV switches instead of the diodes in the VM circuit, as shown in Fig. 3. Furthermore, the resistors are considered as an oscillation suppression unit is connected to the charging capacitors to prevent negative influences of the surge current and oscillating voltage when the polarity is reversed, which is particularly explained in the next section.

3 Generation process of the VLF-CR and DAC voltages

The proposed topology can be used to simultaneously generate the VLF-CR and DAC voltages. Their formation mainly includes the charging and discharging processes, as shown in Fig. 1. The proposed generator can implement these processes with a compact topology instead of requiring a dedicated discharge branch. The two-stage element is considered as an example to simplify the analysis process.

3.1 Operating principles of the VLF-CR voltage

The structure of the proposed generator is presented in Fig. 2. When the generator runs in the VLF mode, the process can be generalised in four steps. Fig. 4 shows the equivalent circuits of each step, which can be further described as follows:

(a) Positive charging: At the start, the specimen is positively charged. The switches $T_{ia}$ and $T_{ic}$ are turned on, whereas the switches $T_{ib}$ and $T_{id}$ are turned off, as shown in Fig. 4a. The high-frequency AC voltage source provides power support for the system when S1 is turned off. The duration of this process depends on the required VLF-CR voltage frequency. Furthermore, the output voltage of the VM module can become approximately four times the peak voltage of the AC source if the leakage current of IGBTs and capacitors is neglected [24].

(b) Positive polarity reversal: The polarity reversal process occurs when the specimen is charged for a specific interval. During this process, the electrons in the charging capacitors are discharged through the adjacent HV switches, which do not affect the polarity reversal process, and the specimen capacitor discharges through the inductor and HV switches to generate $L-C$ series resonance. According to the presented operating strategy, Fig. 4b presents the details when the polarity is reversed from positive to negative. The switches $T_{ia}$ and $T_{ic}$ are turned off, whereas the switches $T_{ib}$ and $T_{id}$ are turned on. If the voltage drops in IGBTs are neglected, a cosine voltage wave can be observed on the specimen, which can be expressed as follows:

$$U_{Cx}(t) = \frac{U_0}{A}e^{-\alpha t} \cos\left[\omega(t - t_0) + \beta\right]$$  \hspace{1cm} (1)

where

$$A = \sqrt{\frac{1 - R_L^2}{L^2 C_x^2}}$$  \hspace{1cm} (2)

$$\alpha = \frac{R_L}{2L}$$  \hspace{1cm} (3)

$$\omega = \sqrt{\frac{1}{LC_x} - \frac{R_L^2}{4L^2}}$$  \hspace{1cm} (4)

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

where $U_0$ and $t_0$ are the initial voltage and initial time, respectively, when the voltage reverses, $L$ is the inductance of the reactor, $R_L$ is the internal resistance of the reactor, and $C_x$ is the capacitance of the specimen.

When the polarity reversal is completed, the voltage amplitude cannot reach the positive peak $U_0$ because of the presence of the damping resistor $R_L$, which is expressed as

$$U_{Cx}(t) = -KU_0$$  \hspace{1cm} (6)
After the polarity reversal is completed, the voltage on the sample is imposed on $T_{dc}$ and $T_{de}$, which is very unfavourable for the selection of IGBT when producing the laboratory prototype. Therefore, the measures that can be implemented include turning on $T_{da}, T_{db}, T_{dc}, T_{dd},$ and $S1$ instead of turning on only $T_{db}$ and $T_{dd}$ during the polarity reversal so that $C_{1A}, C_{1B}, C_{2A},$ and $C_{2B}$ are simultaneously charged after the end of the polarity reversal, as shown in Fig. 5b. Thus, the peak voltage on each HV switch during system operation is twice that of the input AC voltage.

(c) Negative charging: After polarity reversal from positive to negative, the absolute peak voltage is observed to decrease slightly because of energy loss due to the internal resistance of $L$ and the recharging process of the charging capacitors. Therefore, in this step, the specimen $C_{s}$ is negatively charged until the absolute peak voltage is the same as that under the condition before polarity reversal. In contrast to step $a$, the switches $T_{iu}$ and $T_{ic}$ are turned off, whereas the switches $T_{ib}$ and $T_{id}$ are turned on, as shown in Fig. 4c.

(d) Negative polarity reversal: Similar to step $b$, the polarity reverses from negative to positive in this step. The switches $T_{ia}, T_{ib}, T_{ic}, T_{id},$ and $S1$ are turned on, which is similar to that shown in Fig. 5b.

Subsequently, the process returns to step $a$; thus, a periodic VLF-CR voltage is achieved. VLF-CR voltages with different frequencies can be realised as required by controlling the positive and negative polarity charging processes.

### 3.2 Operating principles of DAC voltage

The working principle of the DAC voltage is simpler when compared with that of the VLF-CR voltage. The key to the generation of the oscillating wave is that the specimen, such as a power cable, is charged to a predetermined voltage level; subsequently, the specimen is discharged through the $L-C$ series resonance circuit.

In particular, the specimen is initially charged with a positive or negative voltage using the proposed generator shown in Fig. 1. Its equivalent circuits are shown in Figs. 4a and c. Subsequently, it can be discharged through the circuit shown in Fig. 6 to generate an oscillating-wave voltage. This process is identical to the VLF-CR voltage polarity reversal. Using (1)–(4), the frequency can be simplified as

$$f \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC_s}}$$

because of the negligible reactor resistance.

### 4 Design and implementation

A laboratory prototype is developed according to the aforementioned system principles using a two-stage VM module by comprehensively considering the proposed generator weight and
control complexity. Considerable attention is devoted to the hardware design process in this study, as presented in the following subsections, to ensure that the proposed generator can achieve improved application performance.

4.1 HV switch comprising IGBTs

Irrespective of the charging or discharging process, the HV switch plays an important role in ensuring that the proposed generator can achieve reliable operation, thereby satisfying the voltage-blocking requirement and achieving fast response speed. Fig. 7 shows the proposed HV switch module comprising an IGBT stack and auxiliary circuit. Fig. 3 shows that the IGBT stack comprises two sets of back-to-back IGBT cells, and each IGBT cell is formed using several series-connected IGBTs. Furthermore, a voltage balancing strategy is applied, wherein parallel static voltage-sharing resistors and transient voltage suppressors are used, to ensure that the voltage on each IGBT is balanced. The maximum test voltage for the withstand voltage and PD tests was identified previously as $2-2.5U_0$ [11, 12], where $U_0$ is the rated phase root-mean-square voltage of the cable sample. Hence, a voltage amplitude of up to 20 kV is considered sufficient for an insulation test of 6-10 kV power cables. Based on this voltage, the rated voltage of each HV switch must become 10 kV for the generator proposed in this study with respect to the conditions associated with each HV switch during operation. After investigation and testing, five couples of IGBT chips, the rated voltage of which is 3.6 kV, are selected as the cell for the HV switches. Thus, the withstand voltage of each HV switch can reach 18 kV, completely satisfying the voltage requirements associated with 6/10 kV power cable detection.

4.2 Power supply system for the IGBT drive circuit

As mentioned above, the usage of multiple IGBTs in series to increase the rated voltage of the HV switch must consider multiple output capabilities of the power supply system. The voltage to ground of each IGBT is different, and HV isolation measures are required between them, necessitating for the construction of a power supply system. Thus, a power supply system with the aforementioned characteristics is designed, as shown in Fig. 8. Power supply isolation can be achieved by considering a flyback circuit as the main structure of this topology.

The proposed power supply system includes a buck rectifier circuit, a flyback circuit, and multiple output units, as shown in Fig. 8. The major factor associated with operation of this system is the usage of a power factor correction module to control the working state of the semiconductor switch. Furthermore, an RCD absorption circuit, which can limit the current spikes caused by the loosely coupled coils, is considered. An expandable magnetic coupling structure is employed for this circuit to improve the efficiency of the voltage output. After the test, the output voltage of this circuit can become 17 V, which is sufficient to drive the IGBTs.

4.3 Control system

In case of the generator topology proposed herein, the control of the HV switch is a prerequisite to generate standard VLF-CR and DAC voltages. However, the HV switches comprising IGBTs require multiple trigger signals for control, necessitating considerably high signal synchronisation, otherwise, the generator will not work properly. Therefore, a field programmable gate array chip capable of simultaneously outputting multiple signals is considered to be the control system. Moreover, a photoelectric...
conversion technology is required to ensure isolation between the control circuit and HV host system and achieve communication between them, realising reliable and efficient operation of the control system.

5 Experimental result

Fig. 9a shows the assembled complete test system used in the proposed compact VLF-CR and DAC voltage generator. The parameters of the experimental setup are given in Table 1. Moreover, an air-core inductor integrated in the system is used to eliminate the effects of magnetic saturation on the operating characteristics of the generator. The system is used to perform insulation testing on a capacitive load and a power cable sample with an artificial defect to evaluate the system performance.

First, the proposed generator is tested under a capacitive load to verify its output capability. The VLF-CR and DAC voltages become 25 kV, satisfying the voltage requirement provided in IEEE Standard 400.2 for the insulation state test of 6/10 kV power cables.

In order to evaluate the performance of the proposed voltage generator in the field, the application-oriented tests aim to PD diagnostics. The specimen under test is a 310 m 6/10 kV single-phase cross-linked polyethylene cable with artificial defects in the joint as shown in Fig. 10a. The PD testing is conducted using the proposed generator in the VLF-CR and DAC modes, as depicted in Fig. 10b and 10c.

| Table 1 | Specific parameters of the proposed circuit |
|---------|--------------------------------------------|
| Parameter | Value   |
| inverter (input source) voltage | 7.5 kV   |
| inverter (input source) frequency | 10 kHz   |
| stage number of VM2 | 2 |
| charging capacitors | 10 nF   |
| suppression resistors | 10 kΩ   |
| inductor | 0.7 H   |
| inductor resistance | 23 Ω   |

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Figs. 10b and c, respectively. The testing results indicate the considerable field application potential of the generator. Fig. 10b shows that PD mainly occurs during the polarity reversal process of the VLF-CR voltage instead of under a positive or negative voltage, indicating that the PD inception voltage of the AC voltage is considerably lower than the DC voltage. Thus, the AC voltage is more suitable for the detection of PD. Similarly, a promising result is obtained using the DAC voltage, as shown in Fig. 10c. PD is successfully excited under $1.5U_0$, where $U_0$ is the rated voltage of the cable. The aforementioned object-oriented application results prove the effectiveness of the generator in PD tests.

6 Conclusion

This study proposes a novel type of compact generator of VLF-CR and DAC voltages for insulation testing of the MV power cables, thereby providing an opportunity to apply various detection methods simultaneously for improving the field testing efficiency. Thus, withstand voltage testing and offline PD testing can be conducted at two different voltages simultaneously. In addition, the proposed generator exhibits a compact topology, making the equipment compact and lightweight. The experimental and field testing results indicate that the proposed generator is an alternative and reliable technology for MV power cable insulation testing.

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8 References

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