Development of A Resonant Frequency Converter for Partial Discharge Tests on Potential Transformers

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Abstract—In this paper, the development of a partial discharge testing system based on a resonant frequency converter for potential transformers (PTs) is presented. The system is composed of a power low-voltage variable frequency converter connected with a frequency tuning circuit, a high-voltage testing transformer, and a conventional partial discharge detection system. The performances of the developed system in comparison with the conventional PWM frequency converter were investigated terms of the quality of the output voltage from the high-voltage testing transformer, i.e. the voltage difference (peak voltage/square root of 2 and rms voltage), total harmonic distortion of the output high voltages (THDv), and background noises in the partial discharge test. It is found that the developed system based on the resonant frequency converter provides the better performances (in terms of the output voltage from a testing transformer, the voltage difference, THDv, and background noise) than those of the PWM converter. The voltage difference and THDv are lower than 2%, and the background noise is less than 2.5 pC. In addition, the developed system has been used for the real partial test on a potential transformer in the distribution system successfully. The developed inverter is an attractive choice in the PD tests of potential transformers.

Index Terms—high-voltage tests; partial discharge; potential transformer; power variable frequency converter; resonant circuit

I. INTRODUCTION

Partial discharge (PD) is a localized electrical discharge that only partially bridges the insulation between conductors. PD may not occur next to the conductor. Generally, PD is a consequence of local stress concentration in the insulation or on the insulation surface. PD can be classified as an external discharge and an internal discharge. The external discharge is referred to PD which occurs in ambient air while the internal discharge is due to the imperfections in insulating liquids, in compressed gas and in solid dielectrics. PD phenomena in the high voltage equipment can be examined with various techniques. For example PD charge can be detected by the circuit as recommended in IEC 60270[1]. The high partial discharge level on the high-voltage equipment often leads to complete insulation breakdown. Therefore, the partial discharge level is a crucial parameter used in evaluation of insulation performance and life time of high-voltage equipment.

In the industrial potential transformer (PT) production, partial discharge (PD) test is a routine test that all PTs in the line production must be passed. In the PD test, high voltage (HV) is applied to the high-voltage winding of the PT under test. This HV level is always higher than the rated voltage of the PT. For example, a PT with the rating voltage of 12 kV shall be tested at 22.4 kV for prestress voltage condition, and at 14.4 kV for recording PD activity. Therefore, saturation on the PT is avoided by applying the voltage with the frequency which is higher than the rated frequency of the PT. Normally, the frequency of from 100 Hz to 400 Hz is suitable for all PTs with the rating frequencies of 50 Hz and 60 Hz. In the past, motor generator set was employed in the PD test. However, now the motor generator set is quite hard to find in the real industrial market and is made by order. It leads the price of the motor generator set is quite high. For example, the price of a 30-kVA and 200-Hz or 400-Hz motor generator set is around 100,000 USD.

Now a day power electronics device and control topology have a lot of innovation progress [2]. Therefore, it is very useful, if we apply the power electronic frequency converter to use in HV test. However, the problem for using the frequency converter in the PD test is that the generated testing voltage shall be closed to pure sinusoidal waveform with the requirements, i.e. (1) the difference between peak voltage divided by square root of 2 and rms voltage shall be less than 5%, (2) the total harmonic distortion of voltage defined by eq. (1) shall be below 5%;

$$THD = \frac{1}{V_{1peak}} \sqrt{\sum_{n=2}^{50} V_{npeak}^2} \quad (1)$$

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where, \( V_{1,\text{peak}} \) is peak voltage of the fundamental frequency voltage, and \( V_{n,\text{peak}} \) is peak voltage of the \( n \)th harmonic frequency voltage.

Also, the converter also produce the high level of noise signal due to switching operation. It leads the very high background noise level in the PD test. In [3], the frequency converter was applied for transformer test. It found that the background noise is around 50 pC. With this background noise condition, the background noise is acceptable for testing power transformer, since the acceptable background noise is higher than a few hundred picocoulomb. However, it is still to high in the PD test of potential transformers. The acceptable background noise for the PD test of PTs shall be lower than 2.5 pC, because the acceptable PD level for the PT in some specific type is only 5 pC [4], [5]. However, in [6] the background noise in the PD test with the PWM converter was reduced to the level which is acceptable as the standard requirement, but additional measures for the pure sinusoidal generated waveform are still required.

In this paper, a developed power resonant frequency converter is proposed to employ in high-voltage and partial discharge tests. The H-bridge inverter was constructed for the PD test. The additional tuning circuit was applied to reduce the waveform distortion and the background noise, and it magnifies the voltage at the resonant frequency in the PD test. The performances of the developed variable frequency converter are investigated in terms of the output voltage from the HV testing transformer, the voltage difference (peak voltage divided by square root of 2 and rms voltage), total harmonic distortion of the generated voltage, and background noise level in the partial discharge test in comparison with the conventional PWM converter. From the experimental results, the developed system with the resonant converter provides the better performances in terms of the voltage difference, the total harmonic distortion, and background noise level in the PD test, when it is compared with those of the conventional PWM converter [6].

II. PARTIAL DISCHARGE TESTING SYSTEM FOR PTs

The developed partial discharge testing system is separated into two parts. The first part is high voltage source, and the second one is the partial discharge detection system in accordance with IEC 60270 standard as shown in Fig. 1. The detail of those parts are given as follows.

A. High-voltage source

In the PD test of a potential transformer, low-voltage power supply being normally from a low-voltage grid, a motor generator set, or power converter is connected with a voltage regulator and then connected to a high-voltage testing transformer. Also, a low-pass filter or a frequency tuning circuit is possibly connected to the system to control the voltage distortion and background noise in the PD test.

For the problems in the partial discharge tests in the real situation, the total harmonic distortion of the high voltage from the HV transformer supplied from the low-voltage grid is quite hard to control to be lower than 5%, and the noise signal from the grid often hard to control to be the acceptable level of the partial discharge test. Therefore, the grounding system in the high-voltage testing room shall be designed and constructed in an appropriate way, and the additional low-pass filter is necessary connected to the system. From those reasons, the efficient frequency converter is an attractive choice in the PD tests.

B. Partial discharge detection system

The partial discharge detection system according to IEC 60270 [1] as shown in Fig. 1 is composed of a coupling capacitor (\( C_k \)) connected in series with a coupling device (CD) or a measuring impedance and a measuring instrument (MI). The measuring impedance (CD) is the main part which converts the input PD current pulses into pulse voltage. The voltage signal is routed via a measuring cable (CC) to the PD measuring instrument (MI). Additionally, the coupling device is composed with supplementary elements for signal filtering in order to eliminate disturbing harmonics caused by the AC test voltage supply. Moreover, a fast over-voltage protection unit is required for suppressing over-voltages which may result from unexpected breakdowns of the test object. To ensure an optimum PD signal transmission, the coupling device should be located physically as close as possible to the coupling capacitor (\( C_k \)) and, for safety reasons, always inside the high voltage test area. The series connection of the coupling capacitor (\( C_k \)) with the measuring impedance is acted as a high-pass filter circuit. Normally, the frequency range used in the conventional PD tests is from 100 kHz to 400 kHz. The PD current having high frequency component will go to the part of the coupling capacitor, because the blocking impedance (\( Z_d \)) will be very high in a case of high frequency range. The calibration of the PD detection system with the known charge is required in the real PD test.
III. POWER RESONANT FREQUENCY CONVERTERS

As mentioned on the limitation of the low voltage supply in Section II, the PWM converters [4] for the PD tested has been developed. The developed PWM converter has promising performances in terms of quality of the generated output voltage from a HV testing transformer and low background noise accepted for the real PD tests. The THDv is less than 5% and background noise is less than 2.5 pC.

In this paper, the resonant frequency converter is proposed to use as a low-voltage power supply in the PD tests. As shown in Fig. 2, the developed converter starts from using full bridge rectifier for converting the AC voltage with the frequency of 50 Hz from the low voltage grid to DC voltage. Then, the DC voltage is converted to AC voltage with the required frequency (from 100 to Hz 400 Hz). In this part, insulated-gate bipolar transistors (IGBTs) are connected in H-bridge configuration. The control signals generated by a digital to analog circuit are employed to control the IGBTs’ switching to obtain the required output voltages. The square wave is generated at the output of the IGBT set which is connected with the frequency tuning circuit. The frequency tuning circuit in Figs. 1 and 2 is composed of an inductor and a capacitor connected in series. The inductance (L) and capacitance (C) are designed to the resonant at the specified frequency (f_r) about 170 Hz as eq. (2).

\[ f_r = \frac{1}{2\pi \sqrt{LC}} \]  

IV. EXPERIMENTS

In this section, some experiments were carried out to investigate the performance of the developed system in the partial discharge tests. The developed inverters was connected the HV testing transformer which was connected to the PD detection system in cases of no load and with a PT. The transformer ratings are 460 V/70 kV and 40 kVA. The output voltage from the HV testing transformer, the voltage difference (peak voltage/square root of 2 and rms voltage), THDv, and background noise in the PD tests were examined and measured by the commercial PD detection system (Omicron MPD 600).
Fig. 3 shows experimental set up for the PD test. In the PD test, the standard PD current with the charge of 10 pC was utilized in the calibration process. The background noise of the HV testing laboratory without application of the developed inverter is less than 0.5 pC.

A. The performance of the converter without a test object

The developed power converter was employed to generate voltage from the HV testing transformer. In this case, the frequency was varied from 100 Hz to 250 Hz. The DC charging voltage was set be about 20 V in all experiments in this section. The output voltages form the HV testing transformer and partial discharge level were recorded. There was no test object connected to the system. The experimental results are shown in Figs. 4 to 6.

Fig. 4. Output voltages from the HV testing transformer and the frequency varied from 100 Hz to 250 Hz.

Fig. 5. Background noise level from the HV testing transformer and the frequency varied from 100 Hz to 250 Hz.

The measured resonant frequency of about 170 Hz is agreed well with the design value. At the resonant frequency, the highest gain of the output voltage is found. The background noise at the resonant frequency is lower than 2 pC. The voltage difference is less than 2% and the THDv is also less than 2%. It is confirmed that the developed resonant converter is applicable in the PD tests according to the standard. However, the background noise is still depended the applied DC charging voltage at the specific frequency application. The PD signal from IGBTs’ switching is found in the experimental results in Fig. 6.

B. Experiment with a potential transformer

For confirmation of performance in the PD test of the developed resonant converter and the tuning circuit in comparison with the unipolar PWM converter with an additional filter, the convertors were employed to generate voltage of 22.4 kV for pre-stress condition and about 14.4 kV for recording PD activity.

The PWM converter generates the pulse width modulation waveform with the switching frequency of 2 kHz as shown in Fig. 7. The filter in the case of the PWM converter application is composed of an inductor connected in series with a capacitor (the same configuration as the tuning circuit in Fig. 1). The inductance and capacitance are 1 mH and 22 μF, respectively. The calculated cut off frequency is about 1 kHz. The standard PD current with the charge of 5 pC is used for calibration in the PD test.
The experimental results in the case of the applied voltage of 14.4 kV at the potential transformer (PT) are shown in Fig. 8 for the resonant converter and Fig. 9 for the PWM one. In the case of the test with the PT, the resonant frequency is bit changed to 160 Hz due the capacitance of the PT. The voltage differences of the converters were less than 2%. The THDv was also less than 2% for the resonant converter, and it is 3% for the PWM one. The background noises were 2.3 pC for the resonant converter and 2.0 pC for the PWM one. Due to the resonant condition, the DC charging voltage of the resonant converter was only 18 V, while the DC charging voltage of the PWM one was 102 V. It is confirmed that the developed system can be employed in the PD test with a potential transformer successfully. Again, the background noise is still depended the applied DC charging voltage at the specific frequency application. If the higher testing voltage is required in the experiment, additional filter shall be applied in the testing system.

V. CONCLUSION

The developed partial discharge testing system based on the resonant frequency converter has been presented. The resonant frequency converter with the appropriate tuning circuit provides the promising performances in terms of the output voltage gain, the voltage difference, the THDv, and the background noise in the partial discharge test. The voltage difference is less than 2%, the THDv is less than 2%, and the background noise is also less than 2.5 pC. In addition, the developed system has been used for the real partial test on a potential transformer in the distribution system successfully. The developed resonant power frequency converter is an attractive choice in the PD tests due to high performances and low cost when it is compared with the motor generator system.

REFERENCES