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Future template numerical interpretation techniques for PD pulse location in transformer windings

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ABSTRACT

Identification and location of partial discharge (PD) source is an important diagnostic tool for reliable operation of transformer. In this paper, future template numerical interpretation techniques are proposed for location of PD pulse duration from 0.1 μs to 5 μs in transformer windings using sweep frequency response analysis (SFRA) principle. To analyze the efficacy of the proposed techniques due to different PD pulses, experimental studies are performed on 22 kV transformer windings by injecting a voltage source of PD pulse across each winding section (tapping). According to Parseval's theorem, energy distributions of the winding responses are calculated to decide on time period/frequency range to be considered for analysis. The measured winding responses obtained due to injection of 1 μs reference pulse across the winding are considered as reference responses. If the PD has occurred any where within the winding, numerical interpretation coefficient has to observe real PD response and make a 'best estimate/best matches' with reference responses through appropriate mathematical formulation. The best matches will give the originating source of PD. To predict the confidence limits and significances of numerical interpretation coefficients output for PD pulse location, hypothesis test and probable error methods are utilized.

1. Introduction

The transformer is one of the most expensive and important component of any power systems. Most of the transformer failures are due to the insulation which is mainly due to partial discharge (PD). PD signal detection and location is one of the main challenges for power utilities and equipment manufacturers. Generally, electrical methods are more sensitive and preferable for PD detection and location [1]. Electrical methods are standardized by International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE).

To represent the discharge source across the winding section during excitation of transformer, PD pulse is injected through conventional 'abc' model/pulse injection for validating the already proposed techniques [2]. Hence, to analyze the sensitivity of the future template numerical interpretation techniques, a fingerprint PD pulse (reference pulse) is injected across a winding section. As a result, there are different characters in the measurement including resonant frequencies, phase shift and magnitude of the winding response [3,4]. Based on variations in the resonant frequencies and magnitude of the winding response at each section within the winding, it is possible to detect the location of PD pulse. The work presented in this study has therefore concentrated on location of PD due to effect of different PD pulse durations within transformer winding which are implemented by injecting a PD pulse across the winding.

2. Principles of PD location for proposed techniques

The future template numerical interpretation techniques can be theoretically and experimentally adopted to general cases as follows:

- The reference responses of the windings are estimated theoretically by using an accurate equivalent winding circuit model [5] and injecting a reference pulse across the different sections of the transformer windings. The measured winding responses can be used as reference responses to identify the PD pulse location.
- In general, sweep frequency response analysis (SFRA) is a comparative method, in which one measures the frequency responses of the winding and compares the results with reference responses (in frequency domain) of the investigated transformer winding or another phase of the same transformer winding or with reference

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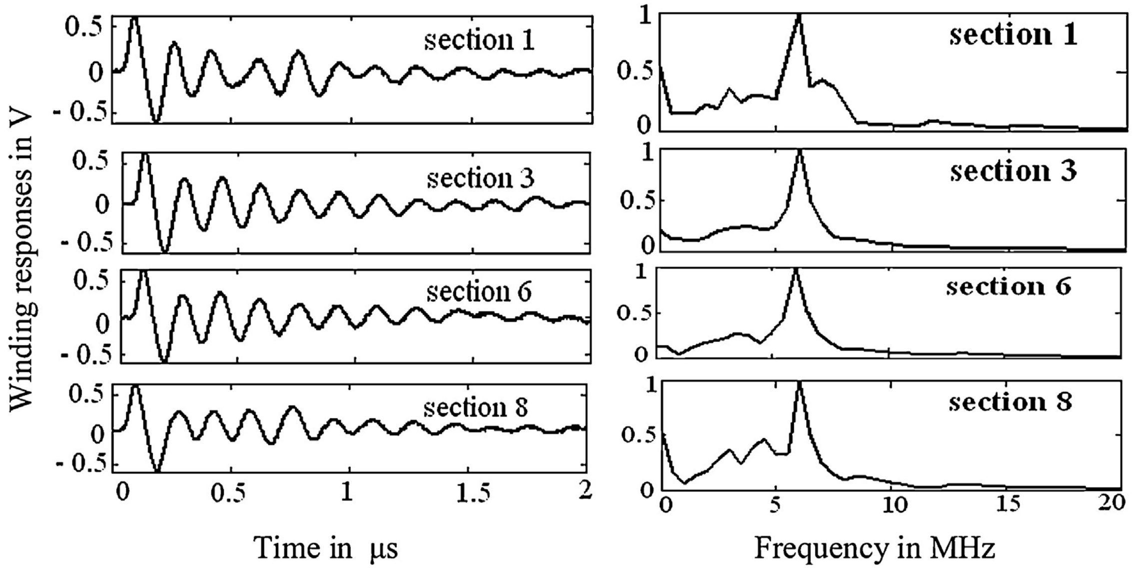

Fig. 1. Reference responses of continuous disc winding for $t_{ref} = 1\ \mu s$.

responses from a sister unit transformer to identify the PD pulse location.

- The current standard for testing of transformer winding treats it as a single-input and single-output (SISO) system (IEC 60076). The applied voltage is an input and the winding response is an output. In practice, occurrence of PD across a section or section to ground along the winding is also input to the windings. If the effect of PD pulse is considered during an input excitation, the transformer winding is treated as a multiple-input and single-output (MISO) system and it is discussed in reference [6,7]. In the effect, transformer winding is no longer a SISO system, but a MISO system. This follows from the principle of superposition theorem and it is adopted to identify the PD pulse location. To study the response of the winding due to PD pulse, experimental analyses are performed only by exciting the winding using a voltage pulse of impulse waveshape and they are based on the superposition theorem.

3. Measurement of winding responses for PD

In the present study to validate the proposed techniques, 22 kV layer, continuous disc and interleaved windings are considered. The continuous disc winding and interleaved winding are designed in such a way to have the same resistance, inductance and ground capacitance by having equal number of turns, conductor dimension and height of the windings [8]. The layer winding has 500 turns and tapping is taken across every 50 turns (10% of the winding). The continuous disc winding and interleaved winding (with the order of interleaving as two) have 40 discs with 12 turns per disc. Tapping is brought out uniformly at every four discs (10% of the winding) other than 4th and 36th discs. Hence, eight tappings (sections) are provided to inject the different PD pulse across the transformer windings. Earthed galvanized iron shields are placed inside the transformer windings to represent the core.

A set of reference responses are necessary for location of PD pulse across a section of the winding. To simulate PD with different pulse durations at different sections within the winding, a PD model in terms of a voltage pulse source is suggested [8] and a PD pulse is modelled as impulse waveshape [9,10]. Hence, the reference pulse of duration $t_{ref} = 1\ \mu s$ (impulse waveshape) is applied across a tapping section 'i' [8,11] (where $i = 1$ to number of tapping section N, 8). The corresponding time domain responses of the winding (reference responses, $s_i(t)$) are measured up to 3 µs using a Tektronix make digital storage oscilloscope TDS 3054B. Generally, one can consider any reference pulse (V_{pulse}) of duration t_{ref} for reference responses. The measured winding responses $s_i(t)$ are converted into frequency domain responses $s_i(f)$ using MATLAB functions utilizing the data obtained from experimental study. In this case, Fast Fourier transform (FFT) of time domain response at the measuring terminal indicates the frequency content of the PD pulse and its location [8]. Hence, the frequency domain responses of the winding are considered for further analysis. For example, Fig. 1 shows the reference responses of the continuous disc winding (enlarged view up to 2 µs) for injection of $t_{ref} = 1\ \mu s$ across the tapping section of 1, 3, 6 and 8. The experimentally measured eight templates responses ($s_i(t)$ and $s_i(f)$, Fig. 1) due to injection of 1 µs pulse across continuous disc winding contain the features to locate the PD.

PD occurs always in the region of high electrical field and in case of transformers, it occurs mostly in the winding insulation. In practice, the location of PD occurrence, shape and pulse duration within the winding are random in nature. A number of attempts have been performed on solid, liquid and gaseous insulating structures during lightning impulse excitations at laboratory conditions using different electrode configurations and do not exhibit a behaviour that can be modelled as a simple circuit element [12]. When a discharge is initiated, high frequency transient pulses appear at particular section within the winding insulation and persist for wide range of durations. Generally, PDs are of very short pulses of durations from tens of ns to 5 µs [12]. Hence, the task of PD pulse location with different duration is considered from 0.1 µs to 5 µs in this study.

To avoid any circuit interpretation and analysis the precise effect of PD pulse duration with controllable manner across different sections of the winding, a PD pulse is injected at each tapping section. Hence, a test PD pulse (V_{test}) of duration (t_{test}) (any duration from 0.1 µs to 5 µs with impulse shape of pulse) across any section 'x', where 'x' can be anything between sections 1 and 8 is injected and the corresponding test PD response $r_x(t)$ is measured. For example, Fig. 2 shows the time and frequency domain responses of the continuous disc winding responses (enlarged view up to 2 µs) due to injection of test PD pulse duration of 5 µs. In practice, if a real or test PD response $r_x(t)$ is measured (for any PD pulse duration from 0.1 µs