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Simulative and experimental investigation of transfer function of inter-turn faults in transformer windings

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ABSTRACT

The transfer function (TF) method is a powerful tool to detect inter-turn faults. Correct interpretation of the TF variations is significant to distinguish the inter-turn faults from less urgency defects. This paper investigates transfer functions of inter-turn faults in transformer windings using simulative and experimental approach. An improved lumped circuit (ILC) model was developed to investigate the detailed energy transmission mode between adjacent turns. Actual experiments of inter-turn faults in different levels were carried out on a purpose-made winding by shorting the adjacent turns with different value resistors to verify the simulative results. Simulative and experimental results show the same characteristics of TF variations. The resonance frequency increases with rising transmission energy in shorting resistance. The amplitudes of resonance frequency vary in a U-shaped trend, which is determined by the energy consumed in the shorting resistance.

1. Introduction

Inter-turn fault is one of the leading root causes of failures in transformers [1]. It originates in deterioration of longitudinal insulation between adjacent turns, develops to a high current fault in layer or disc level, and finally leads to a catastrophic damage to the transformer. A series of detection approaches have been proposed in the past years. Given the advantages of on-line monitoring technology, differential protection scheme [2,3] is widely applied by electric power companies. However, it is difficult to indicate faults in the incipient stage due to the low sensitivity [4]. Dissolved gas analysis (DGA) is an effective diagnosis technique for the detection of power transformer faults, especially for the insulation failure in the preliminary stages. It identifies the inter-turn faults in an indirect way. Localized overheating caused by the circulating current can be confirmed based on the analysis of the composition of typical gas [5,6]. Since other faults may have the same effect, DGA is prone to wrong diagnoses [7]. New approaches proposed in [8,9] have improved the detection sensitivity. However, inter-turn faults of the early stage, in which a single turn is shorted, are still hard to detect in a power transformer.

TF method has been proved able to detect the insulation integrity of transformer windings [10,11], yet further studies on the detection of inter-turn faults are rather limited due to the disadvantage of the offline measurement. In recent years, online monitoring techniques of TFs have been developed [12–15], providing a versatile tool for further research. Experiment studies of inter-turn faults were carried out in [15,16]. Although the two test windings have different construction and size, similar features are shown by the variations of TF curves; and the results indicate comparatively high sensitivity. Efforts were made to analyze the causes of TF variations in terms of electromagnetic field [15]. However, detailed simulation corresponding to the experiments results is not available. Winding mechanical defects, including deformation, loosing, and displacement, also affect the TF curves [17–19]. It is essential to identify the insulation fault out of less urgency defects. Faults classification methods based on experiments data have been reported in [20,21], which indicated that different faults of the experimental windings were distinguished accurately. However, the application is limited because the feature of TF of different transformer windings. Therefore, it is meaningful to propose a reasonable interpretation of TF variations caused by inter-turn fault.

Theoretical interpretation of TFs of transformer windings based on simulation models is widely researched. Lumped circuits models show good performance on the simulation of mechanical defects [22,23]. In [11], a fault location method based on lumped circuits model is proposed. Insulation fault between adjacent discs are simulated by reducing the corresponding inductance. However, since each layer or disc is simplified to a unit circuit, inter-turn fault is not simulated accurately. Multiconductor transmission line (MTL) models consider each turn as a transmission line [24]. Analyzing the TF of transformers at high frequencies is realizable because lumped circuit parameters are replaced by distribution parameters [25]. In contrast, the energy transmission mode among turns is impossible

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to examine. Hence, the root cause of TF variations and detection sensitivity cannot be obtained. These challenges lead to discovery of a new approach to investigate the TF variations caused by inter-turn faults.

In this paper, an improved lumped circuits (ILC) model was established to interpret the TF variations caused by the inter-turn fault of the early stage. Each turn of the winding is divided into several sections. The correctness of the ILC model is verified by comparing with the MTL model. Experiments were carried out on a continuous winding specially made for this research. The variations of TF curves obtained from the simulative and experimental results exhibit same characteristics. The energy transmission mode between adjacent turns is analyzed and the variations resulted from the inter-turn faults are interpreted. Besides, sensitivity of the TF method to inter-turn fault also investigated.

This paper is organized as follows. In Section 2, the measurement method of the TF is presented. The ILC model is proposed and the simulative results are analyzed in Section 3. Section 4 presents the experiments carried out on a purpose-made winding. In Section 5, the TF variations resulted from inter-turn faults is interpreted and the sensitivity is discussed. The conclusion is given in Section 6.

2. Measurement of transfer function

Obtaining the TF either in the time or frequency domain is possible [26]. Low voltage impulse (LVI) method is applied in this study to obtain the TFs in the time domain. Trans-admittance is selected as the TF because of its high sensitivity. Fig. 1 illustrates the measurement setup applied in general practice by industrial and power utilities. The measurements were performed offline. The tested winding is grounded via a resistor to measure output current. The value of the resistor should be carefully selected to match the cable impedance. The non-tested windings should be kept open at the line end and grounded at the neutral end. Repeated low voltage impulses are injected into the tested winding at the line end. The HV terminal voltage and neutral current are recorded in the time domain. Trans-admittance is calculated through fast Fourier transform (FFT):

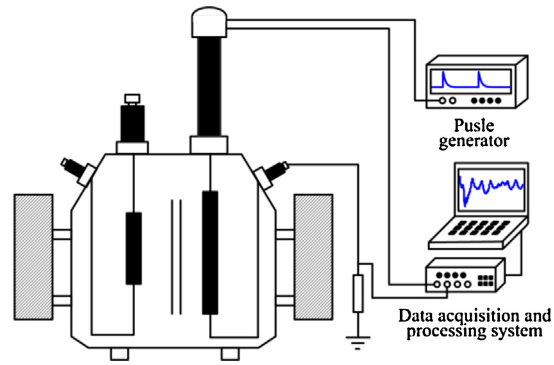

Fig. 1. Experiment setup of the LVI method.

$$TF_{\text{admittance}} = \frac{I_o(f)}{V_i(f)} \qquad (1)$$

where V_i is the voltage at the HV terminal and I_o is the response current at the earth-end.

Generally, the impulse parameters applied in the LVI method are front-times of 200 ns to 1 μs and times to half-value of 40–200 μs. The highest analyzable frequency is approximately 1 MHz because of the low signal-to-noise ratio (SNR) at high frequencies. Averaging multiple measurements is a simple way to increase bandwidth at the cost of measurement time. The other approach aims at improving the impulse spectrum characteristics. Previous research [27] has proven that impulses with short front-times and long times to half-value have large bandwidth. Nanosecond impulse can be utilized to improve the LVI method because the former has a wide spectrum.

The measurement circuit will be significant changed when on-line monitoring is performed. Consequently, a visible difference exists in the measurement results of TF between offline and online tests. However, all information on the tested winding is still

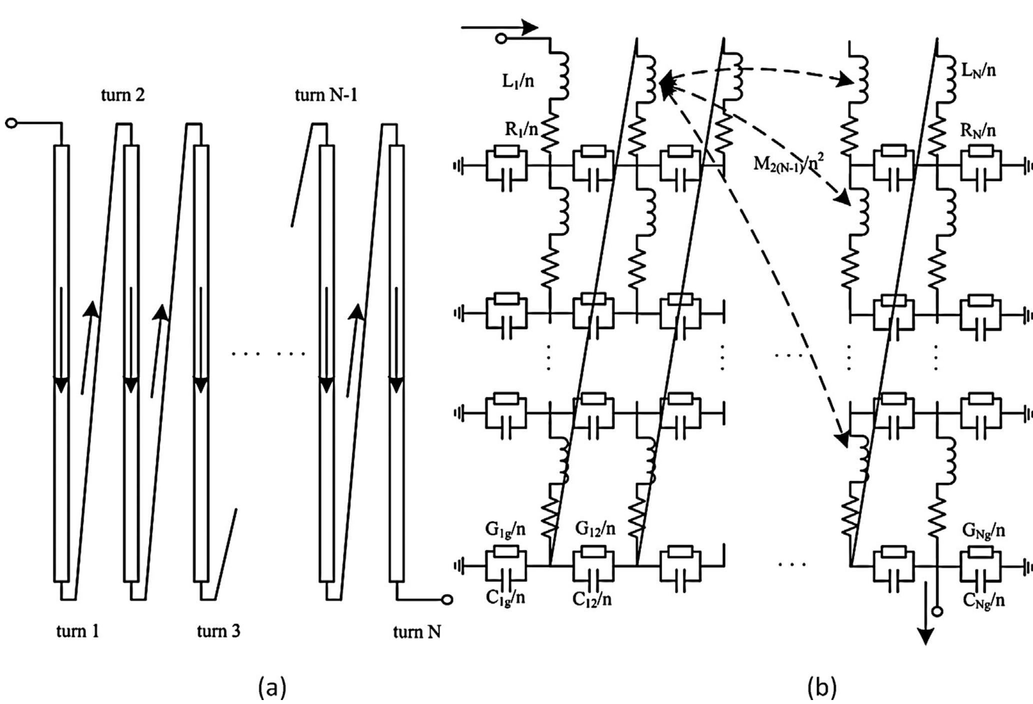

Fig. 2. (a) Electrical connection in the transformer winding. (b) The improved lumped circuits (ILC) model.