

## Chapter 3

# Frequency Characteristics of Transformer Windings

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### ABSTRACT

*Transformers are subjected to voltages and currents of various waveforms while in service or during insulation tests. They could be system voltages, ferroresonance, and harmonics at low frequencies, lightning or switching impulses at high frequencies, and corona/partial discharges at ultra-high frequencies (a brief explanation is given at the end of the chapter). It is of great importance to understand the frequency characteristics of transformer windings, so that technical problems such as impulse distribution, resonance, and partial discharge attenuation can be more readily solved. The frequency characteristics of a transformer winding depend on its layout, core structure, and insulation materials.*

### INTRODUCTION

For transformers subjected to impulse voltages at the terminals or within the windings, an equivalent circuit consisting of a capacitive ladder network is usually adopted in order to analyze the voltage distribution along the windings. This method has been widely used to study windings subjected to lightning impulse voltages. However, it has been found that the sharp voltage pulses occur-

ring in partial discharge (PD) measurements lead to significant errors when a capacitive ladder network equivalent circuit is used for analysis. This problem was investigated by the author on different types of transformer windings (Su et al, 1989-1992). It was found that for some windings, especially interleaved windings, there exists a range of frequencies within which the signal does not change phase when travelling through the winding. This observation suggests that the winding behaves as a capacitive network within that particular frequency range. Such behavior can

DOI: 10.4018/978-1-4666-1921-0.ch003

be explained using a coil equivalent circuit, and a simple method based on terminal calibrations can be used to determine the frequency range. The development of this method is described in detail below. Within the relevant frequency range, the capacitively transferred voltage components along the windings were extracted with the aid of digital filtering techniques, and good agreement between the measured and calculated components was obtained. For ordinary disk windings, the capacitive ladder network simulation may not be valid for the frequency under 2 MHz. However, at frequencies below approximately 200 kHz, the windings behave like transmission lines, as shown by travelling wave delay and terminal reflection measurements on several transformers.

High frequency electromagnetic transients in transformers can be produced by circuit switching in power systems, or by lightning strikes on nearby transmission lines. Due to the complicated winding structure, sharp impulse voltages of large amplitude can appear at various positions along a winding, causing insulation breakdown. It has long been known that the  $1.2/50\mu\text{s}$  impulse voltage distribution along interleaved windings is much more uniform than that along continuous ordinary disk windings (Bewley 1951). It was recognized that the larger capacitance between disks in interleaved windings contributed to the more uniform voltage distribution improvement. However it was not known why the lightning impulse distribution was improved for conventional interleaved windings, but not for pulses with rise times shorter than about  $0.5\mu\text{s}$  generated by vacuum switches and partial discharges. In 1990, the impulse voltage distribution along different windings was measured, and compared with the calculated voltage distribution using a simplified model (Su et al, 1992). It was proved that an interleaved winding can be simulated as a capacitive ladder circuit within the approximate frequency range 100-500 kHz. Since the equivalent frequency of the lightning impulse (200 kHz) falls in this range for most interleaved windings, the

impulse voltage distribution may be determined using the capacitive ladder network. However, if the impulse rise time is shorter than  $0.5\mu\text{s}$ , the equivalent frequency will be higher than 500 kHz, and the measured voltage distribution will deviate significantly from the calculated distribution.

In order to investigate further the effect of interleaved windings on the voltage distribution, a more accurate model developed by Electricity De France (EDF) was used to analyse the data for two windings of the same size but with different coil connections. One was interleaved and the other was continuously wound (Moreau 2000). The calculated transfer functions proved the existence of a capacitive frequency range for any interleaved winding.

### **ANALYSIS METHODS OF WINDING FREQUENCY CHARACTERISTICS**

The frequency characteristics of a transformer winding may be analysed from its terminal transfer function. Sinusoidal low voltages with different frequencies are applied at one end of the winding, and the response is measured at the other end. If the winding can be accessed at several points, the sinusoidal voltage distribution along the winding can also be analysed. Although the detailed equivalent circuit of a winding consists of distributed inductance, capacitance and resistance, within a certain frequency range it may perform approximately as a transmission line or a capacitive ladder network. These frequency ranges are important in impulse voltage distribution analysis and partial discharge location.

### **Transfer Functions of Transmission Line and Capacitive Ladder Network**

Figure 1 (a) and (b) show respectively the equivalent circuits of a transmission line and a simple capacitive ladder network.

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