Chapter 8
Z-Transform Models for the Analysis of Electromagnetic Transients in Transformers and Rotating Machines Windings

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ABSTRACT

High voltage power equipment with winding structures such as transformers, HV motors, and generators are important for the analysis of high frequency electromagnetic transients in electrical power systems. Conventional models of such equipment, for example the leakage inductance model, are only suitable for low frequency transients. A Z-transform model has been developed to simulate transformer, HV motor, and generator stator windings at higher frequencies. The new model covers a wide frequency range, which is more accurate and meaningful. It has many applications such as lightning protection and insulation coordination of substations and the circuit design of impulse voltage generator for transformer tests. The model can easily be implemented in EMTP programs.

INTRODUCTION

In the study of electromagnetic transients resulting from circuit switching in power systems, transformers are usually represented by their leakage impedances at power frequency. This simulation may not be correct in some conditions in which relatively high frequency transients are involved, for example, busbar switching in substations and clearing short-distance faults. For the study of lightning and switching surges in overvoltage protection, transformers, HV motors and generators are modelled by their surge capacitances. Also, these models may not be valid for the lightning and switching surges which have prolonged wavefronts when reaching the equipment.

Over the years, two main forms of distributed-parameter model for transformers and rotating machine windings have been developed. The first is where ladder networks with a finite number of

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sections represent the distributed characteristics of transformer winding systems. The second is based on the derivation of input-output frequency responses for winding pairs which are then used in time convolution forms of transient analysis. The technique presented in this chapter is an innovative development in this approach which gives more meaningful equivalent circuits for HV equipment with winding structures. The accuracy of the new models is superior to the existing models used in industry (Su et al 1990 – 93). A technique for the analysis of winding characteristics was also developed which is presented in Chapter 4 (Su et al 1991 – 92).

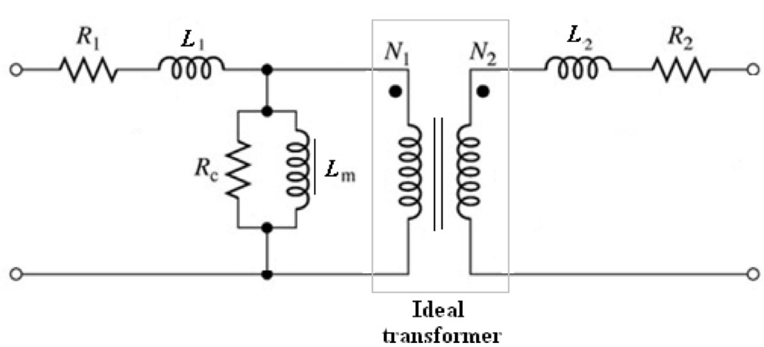
CONVENTIONAL TRANSFORMER AND ROTATING MACHINE MODELS FOR TERMINAL TRANSIENT ANALYSIS

Transformers, HV motors and generators have complicated winding structure. Under surge voltages at the terminal, their responses are very complicated and are dependent on the frequency of transient. At low frequencies, they can be simulated by their inductances and loss resistances. As shown in Figure 1, a two-winding transformer is represented by its leakage and magnetizing inductances (L1, L2 & Lm), winding and core losses (R1, R2 & Rc) and an ideal transformer with the turn ratio of N1 and N2. In order to consider the stray capacitances, Baccigalupi (1993) added three capacitances to the transformer equivalent circuit, as shown in Figure 2. However, it was found that these simple models could not accurately simulate the transient at transformer and rotating machine terminals.

Much work has been done on the models in which the distributed characteristics of the transformer and rotating machine windings are considered. In the early 1950's, Abetti (1953) introduced the electromagnetic model of the transformer core and windings to represent all of the self and mutual inductances, supplemented by an equivalent circuit of capacitances connected in the circuit at a multiplicity of points. The R, L and C ladder networks were also analysed by other researchers such as Lewis (1954). Based on the uniformed or almost uniformed equivalent circuit, detailed mathematic derivations were done and complicated close-form equations were derived. These equations are useful for the theoretical analysis of voltage distributions and electromagnetic transients in the winding. However, they are too complicated for the calculation of terminal transients.

The more convenient method of acquiring transient voltage data is to form a mathematical model of the winding and solved it using computer programs. In 1964, Lovass and Szendy developed an equivalent circuit built up of two

Figure 1. The general equivalent circuit for a two-winding transformer at low frequencies



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