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Three winding transformer *s*-domain model for modal analysis of electrical networks

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ABSTRACT

This paper describes an *s*-domain sequence model for three winding transformers to be used in modal analysis of ac networks. The model takes into account off-nominal tap positions and the phase shifts among the windings. The main contribution of this proposed model is to complete the set of *s*-domain models of electrical system components already developed (loads, transmission lines, generators, harmonic filters, shunt elements) suitable for modal analysis of complex electrical networks. Modal analysis provides an important set of system information that is hard to be obtained using the conventional time simulation and frequency response methods. This information may be effectively used to improve the harmonic performance of electrical networks, to build linear equivalents for harmonic and electromagnetic transient studies and to perform linear dynamic performance analysis.

1. Introduction

Power transformer modeling has been a subject of investigation and research for a long time. Several models have been developed for electromagnetic transients and harmonic analysis. Many approaches have been used resulting in models with various degrees of details and accuracy. In [1] measured frequency responses are approximated with rational functions using the vector fitting method [2] to produce a model for electromagnetic transient simulations. Several others papers are based on fitting approaches, such as [3]. In these fitting models, the frequency dependency of the transformer parameters is taken into account but the non-linearities are neglected. In [4] a detailed model is presented for investigation of terminal and internal voltage stresses that could be used for electromagnetic transient studies and transformer design. This model incorporates all frequency-dependent losses but also neglects the non-linearities. The models that do not consider non-linearities are suitable for high frequency electromagnetic transients.

Non-linearities are particularly important for analysis of large disturbances which cause low frequency electromagnetic transients such as transformer energization and ferroresonance. In these cases the frequency dependency of the transformer parameters can be neglected. Thus simpler models can be used where the saturation curve is fully represented [5].

In [6] a more complete transformer model for electromagnetic transient studies for a wider frequency range is presented considering frequency dependent parameters, losses and non-linearities. A bibliography review of several models is also presented.

In the analysis of harmonic power flows, the transformer is generally represented as a passive component. However, due to the magnetization non-linearity, the transformer constitutes a source of harmonic currents which in some cases can aggregate and cause substantial waveform distortion [7]. In [8] the magnetization of three-phase banks of transformers is modeled in harmonic domain. In [9] this modeling is generalized for three-phase transformers where the non-linear magnetization characteristic of each branch is taken into account.

Regardless of the extensive technical literature, none of the papers proposes an analytical model that could be used directly for modal analysis using *s*-domain modeling.

Modal analysis has been an important tool in electromechanical and subsynchronous resonances studies [10–12]. Besides, modal analysis has been applied to solve harmonic problems [13–18] and to build dynamic equivalents that can be used in electromagnetic transient and harmonic analysis [19]. In these areas, it is very important to fully represent the distributed nature of the electrical parameters of long transmission lines as well as their frequency dependence [20].

The most direct manner to develop models that take into account these electrical characteristics is to use an *s*-domain technique. The ac network can be modeled as a nodal admittance matrix in the *s*-domain, $\mathbf{Y}(s)$, as described in [21,22]. Robust and efficient algorithms for pole, zero, residue and sensitivity calculations for

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