Electric Power Systems Research 142 (2017) 47–57

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Wideband modeling of a 45-MVA generator step-up transformer for network interaction studies

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ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 3 August 2016
Accepted 30 August 2016

Keywords:
Transformer
Black-box model
Frequency dependency
Simulation
Transients
Transient recovery voltage

ABSTRACT

A stable and passive six-terminal model is developed for a 45-MVA generator step-up transformer based on frequency sweep measurements in the range 5 Hz–10 MHz and curve fitting with rational functions. The modeling employs separate treatment of the zero sequence system in combination with a new variant of the fast residue perturbation method for passivity enforcement. For use in system level simulations, the model can be employed in PSCAD, EMTP-RV and ATP. With ATP, the representation with an equivalent electrical circuit requires some care to prevent the occurrence of near zero circuit elements. Comparison with measured time domain responses at reduced voltage shows that the model can accurately reproduce transient voltage transfer between the windings while taking into account the loading effect of the connected system. The model also reproduces the transient recovery voltage (TRV) when interrupting short-circuit currents. As an application example, the model is demonstrated for simulation of resonant voltage transfer from the high-voltage side to the low-voltage side. In this setting, it is shown that the transformer input impedance can at high frequencies greatly influence the shape of the impinging overvoltages, thereby giving a self-protective effect against incoming overvoltages.

1. Introduction

The simulation of high-frequency transformer-network interactions [1] requires transformer models that are sufficiently accurate within the considered frequency band in terms of voltage ratios and impedance characteristics. Relevant simulation studies include voltage transfer between windings, resonant overvoltage buildup, and circuit breaker transient recovery voltage.

A number of works have been presented that demonstrate successful application of measurement-based black-box modeling of distribution transformers [2–8] and power transformers [9–14], using low-amplitude measurements. These works assume linearity for the transformer behavior, which is usually considered a valid assumption at higher frequencies. Despite the many positive reports, the successful modeling of a transformer is non-trivial and still requires improvements [15].

This work presents exhaustive results from the measurement-based modeling of a 45-MVA three-phase generator step-up transformer. Its modeling is challenging because of its high voltage ratio (137 kV/8.5 kV) which leads to an undesirable scaling of the four sub-blocks of the terminal admittance matrix, and because its low-voltage winding is connected in delta. The latter results in the terminal admittance matrix having one very small eigenvalue at low frequencies which can lead to large error magnifications in applications if not handled properly.

The measurement procedure is first described, emphasizing procedures for retaining the accuracy at low frequencies and noise removal. Following the procedure in Ref. [4], the zero sequence system is measured separately in order to capture the very small eigenvalue at low frequencies that pertains to the delta winding. A passive pole-residue model is extracted for the zero sequence system alone, and for the remaining admittance matrix with the zero sequence system excluded. The two models are finally combined into a single model. Special challenges are addressed and resolved for the passivity correction step which were not considered in Ref. [4].

The accuracy of the model is validated against measured voltage transfer functions in the frequency domain. Using convolution, the model is also validated in the time domain for voltage transfer between windings, with alternative loading conditions. Finally,

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http://dx.doi.org/10.1016/j.epsr.2016.08.035

Table 1
Transformer main data.

S_n	U_{pn}	U_{sn}	e_r	e_k
45 MVA	8.5 kV	137 kV	0.21%	11.2%

Table 2
List of Instruments.

Current sensor	Ion Physics, model CM-100-6L
Vector network analyzer	Agilent E5061B-3L5

the model is also validated when applied in calculation of breaker transient recovery voltage (TRV). The accuracy at 50 Hz is also discussed.

For use with general simulations, EMTP-type circuit simulators should be used. The export to the programs PSCAD, EMTP-RV and ATP is reviewed, and special challenges related to generation of ATP circuit netlist are described and resolved. The model is applied in EMTP-RV for simulation of resonant voltage transfer from the high-voltage side to the low-voltage side.

2. Transformer main data

The unit is a three-phase two-winding YNd11 transformer of rated power $S_n = 45$ MV that is used for connecting a hydro power generator to the grid. The primary voltage has two settings: 8.5 kV or 7.5 kV while the secondary voltage is 137 kV. In this work, a model is developed with the secondary winding neutral point solidly grounded and with the 8.5 kV setting on the primary, leading to a component with six external terminals. The main electrical data for the transformer are given in Table 1, referenced to 20 °C. Parameters e_r and e_k denote respectively the real and imaginary part of the short-circuit impedance.

3. Problem statement

The transformer behavior is to be characterized (measured) in the frequency domain with respect to its external terminals. Since linearity is assumed, the characterization will be based on the admittance matrix $\mathbf{Y}$ (6×6) which relates the terminal voltages $\mathbf{v}$ (6×1) with the terminal currents $\mathbf{i}$ (6×1),

$$\boldsymbol{i}(\omega) = \boldsymbol{Y}_{\text{meas}}(\omega)\,\boldsymbol{v}(\omega) \tag{1}$$

The (measured) admittance matrix $\mathbf{Y}_{\text{meas}}$ is to be approximated (fitted) by a pole-residue type rational model (2) which is stable, passive, and symmetrical. The modeling is to be performed in such way that the model can be utilized with different terminal conditions, i.e. without excessive error magnifications.

$$\mathbf{Y}_{\text{meas}}(\omega) \cong \mathbf{Y}(\omega) = \mathbf{R}_0 + \sum_{k=1}^{N} \frac{\mathbf{R}_k}{j\omega - a_k} \tag{2}$$

The model is to be utilized in an EMTP-type simulation environment and be validated against measurements.

4. Measurement setup and processing

4.1. Measurement setup

The admittance matrix $\mathbf{Y}$ was measured in the frequency range 5 Hz–10 MHz using a setup similar to the one described in Ref. [3]. The setup utilizes the gain-phase measurement capability of a Vector Network Analyzer (VNA) in combination with a wide-band current monitor (Table 2) that is integrated within a connection box, see Fig. 1. Manual reconnections on the connection box allows to measure the elements of $\mathbf{Y}$ one-by-one, and to perform voltage transfer measurements using voltage probes. The six transformer terminals were connected to the box using shielded coaxial cables which ranged from about five to six meters in length. The use of such long lengths was necessary as the measurement equipment had to be placed on a platform since the space on top of the transformer was too small to allow a suitable work environment. A braided wire flat was placed on top of the transformer and connected to the neutral point ("N") and to the tank at several local points, see Fig. 2. The braided wire served as a local earth to which the cable screens were connected. Calibration was performed to account for the non-ideal frequency response and insertion impedance effect of the current monitor [16].

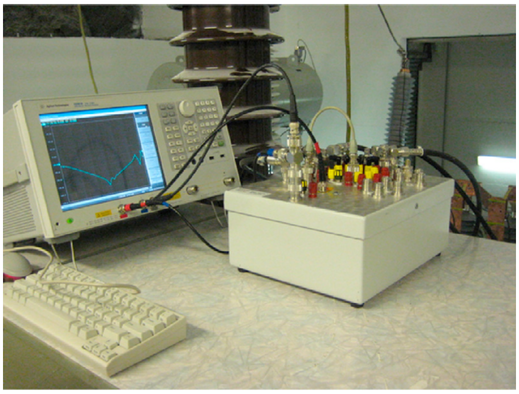

Fig. 1. VNA and connection box with built-in current monitor.

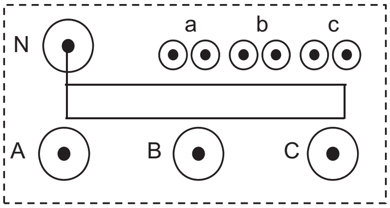

Fig. 2. Grounding plane (solid line) on top of transformer.

The setup gives the admittance matrix seen from the connection box, i.e. of the transformer with the measurement cables in series. The measurement cables do noticeably influence the measurements and thus the model that is extracted, and their effect should therefore be eliminated. However, in order to validate the accuracy of the measurement and model extraction procedure against additional measurements on the connection box, the results after cable elimination will not be shown. The connection points on the box are therefore referred to as transformer terminals, in both frequency domain and time domain measurements. The effect of cable elimination is presented in detail in Ref. [17] for this 45 MVA transformer where a new cable elimination method based on a transmission line equivalent is applied.

4.2. Series resistors on LV side

At low frequencies, the admittance matrix elements are large in magnitude with a small real part. As a result, the insertion impedance from measurements cables and connections may affect the measured admittance elements significantly, thereby corrupting the behavioral information such as voltage ratio and passivity characteristics. Also, since the output impedance of the VNA is 50 Ω, the voltage at the VNA reference input can become too low to be measured with sufficient accuracy. As a precaution, small resistors (0.1 Ω) were placed in series with the LV terminals. Their effect are discussed in Section 11.