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Simplified measurement-based black-box modeling of distribution transformers using transfer functions

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ABSTRACT

Modeling of power distribution transformers in the high-frequency range is of crucial importance in cases such as using power-line communication technology or investigating transient overvoltages at the transformer low-voltage side. This paper presents a simple black-box modeling methodology for distribution transformers using transfer functions defined by the recorded voltage ratios at the transformer terminals. The model parameters are estimated using an optimization method that minimizes the error between the measured and the calculated data. A significant advantage of the proposed methodology is the use of conventional instruments in conducting the measurements rather than high-precision and expensive equipment. The accuracy of the developed model is verified by its implementation in both frequency- and time-domain simulations.

1. Introduction

Accurate modeling of distribution transformers is essential for the investigation of transient overvoltages and the application of power-line communication (PLC) technology in distribution networks. Although the power transformer is one of the most common components in power systems, it is very difficult to obtain an accurate transformer model for a wide frequency range. This is mainly due to the frequency-dependent behavior of the transformer parameters, the different transformer configurations that exist, and the sensitivity of the transformer performance to the installation topology, especially at high frequencies (HFs).

Transformer modeling methods proposed in the literature can be generally classified into two categories [1]. In the first class detailed models are developed representing the transformer with an equivalent lumped circuit. The model parameters are determined using electromagnetic field approaches [2,3], analytical formulations [4], or measurements [1,5–8]. These models can be employed during the transformer design to predetermine internal overvoltages and electrical stresses along the transformer windings [9].

The second approach considers the transformer as a linear black-box seen from its terminals. In the black-box approach the transformer structure and parameters are not known a priori, overcoming the limitations of detailed modeling due to lack of information. The developed models are either based on an admittance matrix [10–12] or on equivalent lumped circuits [1,13]. Black-box transformer modeling is best suited for investigations of the transformer behavior in a given configuration, allowing the direct calculation of the interactions between grid and the transformer [12]. This is especially the case when considering HF phenomena, as the transformer behavior is mainly affected by the arbitrary stray winding inductances and capacitances [1]. However, the main drawback of this approach is that the developed models are usually formulated using measurements that require high-precision and expensive instrumentation, e.g. network analyzers, which are also not user-friendly and involve supplementary custom-made equipment [11]. Moreover, the admittance matrix based models are subjected to passivity enforcement procedures [11], increasing significantly the modeling complexity and computational effort [14], whereas additional dedicated measurements are necessary in configurations with ungrounded windings [15].

A major issue concerning the transformer behavior in the frequency range of 1 kHz–1 MHz is the transfer of overvoltages between windings [16]. Excessive overvoltages may occur at the

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unloaded transformer LV side due to resonance when the HV side is connected to a feeding cable [1,12,17]. Similarly, resonant overvoltages can also occur in cases when the voltages at the HV terminals are significantly polluted with harmonics [18]. Another interesting technical issue is the investigation of transmitting narrowband (NB) PLC signals in the frequency range of 3–500 kHz [19] through distribution transformers, instead of bypassing using additional bridging infrastructure [20]. In this way the additional required resources as well as the cost for couplers and for the modification of the substation switchgear can be significantly reduced. Taking advantage of this capability, the most known NB-PLC standards such as the Power line-Related Intelligent Metering Evolution (PRIME) [21], G3-PLC [22], ITU-T G.9955 (G.hnem) [23] and IEEE P1901.2 [24] have adopted this solution to broaden the applicability of NB-PLC technology in smart distribution grids [5,25,26], mainly in cases of transformer substations supplying a few LV customers.

The scope of this paper is to propose a comprehensive and simple black-box modeling methodology for distribution transformers in the frequency range of 1 kHz–1 MHz. The model parameters are identified by applying an optimization method on measurement datasets of voltage ratio transfer functions recorded at the transformer terminals with conventional instruments. The developed model can be used to investigate the transformer behavior on the transfer of steady-state (e.g. PLC signals) and transient HF voltages from the high-voltage (HV) terminals to the low-voltage (LV) side and vice versa.

The paper structure is the following: Section 2 describes the modeling fundamentals and the selected mathematical formulation, Section 3 describes the measurements conducted to investigate the transformer performance, Section 4 presents the proposed model parameter estimation methodology, Section 5 provides results from practical cases verifying the accuracy of the black-box model, and Section 6 summarizes this work highlighting the advantages of the proposed model and the most significant remarks of the analysis.

2. Black-box modeling approach

2.1. Model fundamentals

The proposed black-box model focuses on the investigation of HF voltage responses, especially regarding NB-PLC signal transmission as well as a wide range of transient overvoltages. Therefore the following assumptions are made in developing the model structure: (1) saturation and non-linear effects are ignored; (2) the applied frequency range varies from 1 kHz up to 1 MHz; (3) different types of signal injection are taken into account; and (4) different termination conditions at the transformer LV side are examined.

The mathematical structure of the model is based on measured transfer functions and the modeling procedure is summarized in the following steps:

Step 1: Conduct a set of preparatory measurements, record the voltages at the HV and LV terminals, and calculate the corresponding transfer functions.
Step 2: Define a mathematical formulation to represent the black-box transfer functions.
Step 3: Estimate and validate the transfer function parameters using non-linear least-square optimization.
Step 4: Integrate the developed black-box model into a calculation routine.

Similar modeling approaches have been used for dynamic load modeling [27] and power systems identification [28].

2.2. Formulation

The generic equation describing the black-box model in the frequency-domain is given in (1). The model handles individually the different transformer configurations, i.e. type of signal injection, LV loading conditions, etc., resulting in a modular structure of distinct computationally decoupled sub-systems.

$$\hat{\boldsymbol{V}}_{\mathrm{LV}} = \hat{\boldsymbol{H}} \cdot \boldsymbol{V}_{\mathrm{HV}} \tag{1}$$

where vector $\boldsymbol{V}_{\mathrm{HV}}$ is the model input, defined by the linearly independent voltages applied at the HV side, and $\hat{\boldsymbol{V}}_{\mathrm{LV}}$ is the output vector containing the estimated voltages at the LV side. In both sides line-to-ground voltages are considered and the secondary neutral at the LV side is earthed. The model transfer matrix $\hat{\boldsymbol{H}}$ in the generalized form is a 3×3 diagonal matrix as defined in (2).

$$\hat{\boldsymbol{H}} = diag[\, \hat{H}_s\angle\hat{\varphi}_s \quad \hat{H}_{m1}\angle\hat{\varphi}_{m1} \quad \hat{H}_{m2}\angle\hat{\varphi}_{m2}\,] \tag{2}$$

Matrix $\hat{\boldsymbol{H}}$ consists of the self-transfer function element $\hat{H}_s\angle\hat{\varphi}_s$ and the two mutual-transfer function elements $\hat{H}_{m1}\angle\hat{\varphi}_{m1}$ and $\hat{H}_{m2}\angle\hat{\varphi}_{m2}$, assuming cyclic symmetrical behavior of the transformer voltages. Self-transfer functions refer to voltage transfer between the same phases of the HV and the LV terminals. Mutual-transfer functions express the voltage transfer between the phase of the HV terminal where the voltage is applied and another phase of the LV terminal, e.g. the voltage transfer between phase *A* of the HV side to the LV phase *b*. The elements of the transfer matrix are functions of frequency *f*, and are identified using the corresponding dataset and measurement setup.

3. Preparatory measurements

In order to investigate the transformer performance in the HF range, several measurement setups are designed. Scope of these tests is to measure the HV to LV signal ratio for different operational cases. The examined cases include:

- Different types of voltage injection at the HV side: sequential single-phase injection at each HV terminal as well as zero-sequence injection is examined.
- Investigation of the influence of circuit elements connected to the non-excited HV terminals.
- Different loading conditions: measurements to investigate the influence of loading at the LV terminals.
- Sensitivity to the configuration: distribution transformers of the same type and construction installed at different locations are investigated.

3.1. Experimental setup

Two three-phase distribution transformers, namely DT1 and DT2, are installed at different positions in a laboratory site as shown in Fig. 1. Both transformers are 20-kV/400-V, with a rated power of 50-kVA, in wye/zigzag connection with a 330-degree lead and the neutral grounded at the LV side.

An AGILENT 33220A signal generator is connected to the transformer HV side and a TEKTRONIX TDS 3014B oscilloscope records the voltages at all terminals referenced to the ground. The active probes P6243 are used to ensure high accuracy on HF measurements. Active probes show high impedance, in the order of MΩ, at the transformer terminals to diminish loading effects, while they are connected with 1.3-m long coaxial measuring cables having characteristic impedance matched to the low input impedance of the oscilloscope. However, in the examined frequency range less expensive high-impedance passive probes can be also used, although some errors in the measurements might occur