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A comparison of transformer HF models and their application to PQ analysis

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Abstract. This research work is devoted to the comparison of some proposed high-frequency (HF) models of transformers and their application to power quality (PQ) studies. The models are classified according their structure, physical description and experimental methodology and set-up facilities needed to obtain the parameters.

1. Introduction

High-frequency modeling is essential during the design stage of power transformers in order to study the impulse voltage response, the winding integrity, power quality problems and also for insulation diagnosis. In some cases, high-fidelity models in a bandwidth up to 10 MHz are required for condition monitoring purposes.

From an experimental point of view the study of the high-frequency part of the spectra have to be done in order to obtain the stray capacitances that shunt the series inductances and dominating the response.

2. HF models

A. Physics-based models

This type of model is close to the real behavior of the real transformer [1–3]. The main drawback of this approach is the neccessity of information about the physical structure of the machine, including dimensions, materials and geometry. The needed data is raraley provided by the transformer manufacturer. Fig 1 shows a finite elements model using the physical description of the machine.

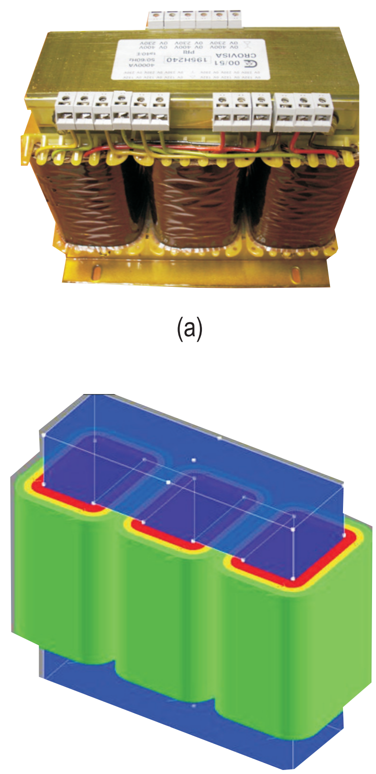

Figure 1. Finite elements description of a laboratory transformer. (a) Image of the real transformer; (b) Finite Elements model.

B. Black-box models

Black-box models are suitable to obtain the HF behavior of the transformer when it is difficult to obtain information about the machine. The basic idea is to obtain the transfer function using transient information about voltage and current [4]. The admittance matrix is defined in the frequency domain in ranges that goes from 50 Hz to 1 MHz. Numerical models are introduced based on two-port network theory [5–8] where its parameters are computed at different resonance frequencies which are experimentally measured.

The advantage of this approach regarding physical models is their ability to work with commercial grade transformers. Fig. 2 shows a two-port description of a single fase transformer for HF modeling.

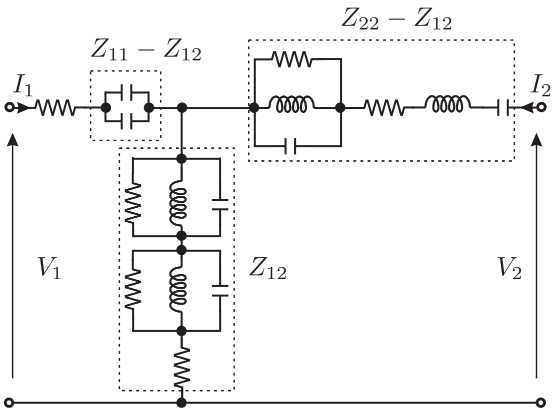

Figure 2. HF two-port description of a laboratory transformer [5].

3. MODEL COMPARISON

Model comparative has been made by introducing a set of basic parameters related with three key points:

- **Model** The type of model from the point of view of their physical meaning. There are two main sets: i) Physical. The parameters of the model have a physical equivalent and ii) Black-box. The parameters are computed using a mathematical approach without considering their physical meaning.
- **Frequency** The range of frequency in which the model is accurate enough. The frequency spectrum is partitioned in three bands: i) dc - 2.5 kHz; ii) 2.5 kHz - 1 MHz and iii) 1 MHz to ∞.
- **Data** The theoretical or experimental approach followed to obtain the parameters: i) Nameplate data; ii) Experimental high-frequency (HF) data; iii) Experimental low-frequency (LF) data and iv) Finite elements software.

Table I summarizes a comparison between models according to different criteria. The comparison includes information about the data source, the type of model used and the experimental approach needed for parameter extraction.

4. PQ REQUIREMENTS

The standard IEEE Std. 1159 [9] provides a detailed description of each disturbance in terms of their typical spectral content, duration and magnitude. The summary provided by table II can be used as a reference point in order to define the models in terms of frequency spectrum and amplitude. The amplitude is also important because the saturation problem. At low frequencies (between 50-60 Hz and 3 kHz) it is expected that classic models could be extended to consider harmonic losses and additional saturation.

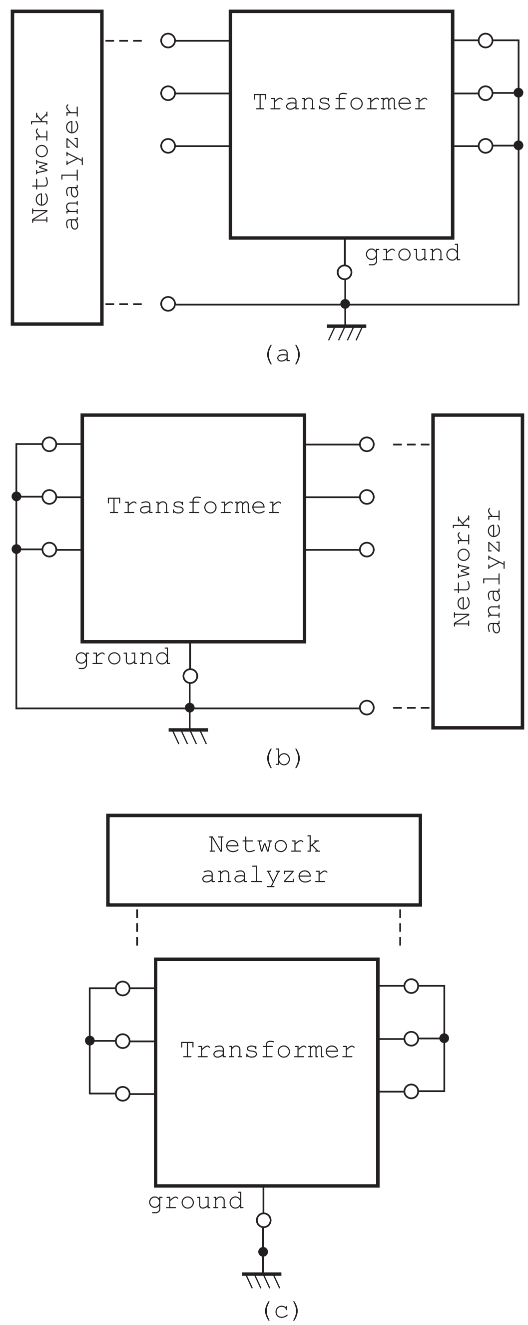

Figure 3. Transformer connection for the capacitance measurement.

TABLE I

COMPARISON BETWEEN DIFFERENT TRANSFORMER HF MODELS.

		Model				
		Abed [1]	Sabiha [5]	Gustavsen [4]	Zhongyuan [7]	Abeywickrama [3]
Model	Physical	✓				✓
	Black-box		✓	✓	✓	
Frequency	$f \leq 2.5$ kHz					
	2.5 kHz $< f \leq 1$ MHz	✓		✓		✓
	$f > 1$ MHz		✓		✓	
Data	Nameplate					
	Experimental HF		✓	✓	✓	
	Experimental LF					
	Finite elements	✓				✓

TABLE II

CATEGORIES AND TYPICAL CHARACTERISTICS OF POWER SYSTEM ELECTROMAGNETIC PHENOMENA AS DEFINED IN IEEE STD. 1159 [9] VS SIMULATION MODEL.

Categories	Typical spectral content	Typical duration	Typical voltage magnitude	model
1.0 Transients	5 ns rise 0.55 MHz	$<$ 50 ns	0 8 pu	Sabiha [5] and Zhongyuan [7]
2.0 Short-duration root-mean-square (rms) variations		Between 0.5 cycles and 1 min	0.1 - 1.8 pu	Classic models
3.0 Long duration rms variations		$>$ 1 min	0 - 1.2 pu	Classic models
4.0 Imbalance		steady state	0.5 - 30 %	Classic models
5.0 Waveform distortion	09 kHz and broadband	steady state	0 - 20 %	Abed [1], Gustavsen [4] and Abeywickrama [3]
6.0 Voltage fluctuations	$<$ 25 Hz	intermittent	0.1 - 7 %	Classic models
7.0 Power frequency variations		$<$ 10 s	$\pm$ 0.10 Hz	Classic models

5. SET-UP

The set-up facility allows us to obtain the parameters of the model. It is necessary to carry out three different sets of measurements:

1) open-circuit.
2) short-circuit.
3) capacitance measurement.

The connections used for open-circuit and short-circuit follow the classical approach that is used at nominal frequency (50 or 60 Hz). For the measurement of capacitances it has been proposed three configurations [10]. Fig. 3 summarizes the three configuration needed for the capacitance measurements:

- Input capacitance. Fig. 3.a shows the configuration for the measurement of the input capacitance.
- Output capacitance. Fig. 3.b shows the configuration for the measurement of the output capacitance.
- I-O capacitance. Fig. 3.c shows the configuration for the measurement of the input to output capacitance.

6. CONCLUSIONS

This research work establishes a comparison between different models that can be used for high-frequency modeling. The comparison includes different criteria like the type of model and the experimental methodology and set-up. In a future work the models will be evaluated in a experimental way in order to compare their accuracy.

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