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Benchmarking of hysteretic elements in topological transformer model

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ABSTRACT

Transformer core modeling is of importance for some transient studies like inrush currents, ferroresonance and geomagnetically induced current. This paper compares a transformer model with different magnetization representations to actual measurements. Piecewise nonlinear (Type 98) or hysteretic inductors (Type 96) both in parallel to a constant resistance, Jiles–Atherton hysteretic inductance and a newly developed inverse dynamic hysteresis model (DHM) are tested for open circuit response, residual flux after switching out, and inrush currents when energizing the transformer. The models have all problems of reproducing the magnetization current details and there are substantial differences between the models in residual flux estimation resulting in quite different inrush patterns. The DHM model is the easiest to use as few parameters are required and the model gives fairly well agreement with measurements.

1. Introduction

Topological transformer models are important to accurately predict steady-state regimes and transient behaviors, from steady-state losses to inrush currents [1,2]. Shortcomings of available models are primarily in the imperfection of the core model and in particular in the estimation of frequency dependency, nonlinear losses and residual flux. This is important for ferroresonance, inrush current calculations, and geomagnetically induced currents.

Previously, the Hybrid Transformer model was presented at IPST [3,4] and this model extends the classical BCTRAN model [5] with a topological core with fitting to open circuit test report data. The core equivalent in this model is represented by nonlinear inductances (type 98) in parallel to constant core-loss resistances. The model has also an option to use a hysteretic inductance (type 96) representing a part of the total core loss [6,7]. In attempts to better reproduce residual flux, the model was extended with a Jiles–Atherton (JA) hysteresis model [8–10]. The Jiles–Atherton model is not publicly available and the parameter determination procedure is complicated. A review of hysteresis models is found in Ref. [13].

Recently, a new dynamic hysteresis model (DHM) has been implemented in the ATP-EMTP. This three-component DHM consists of a static hysteresis model (SHM) [11] implemented as a rate-independent hysteretic inductor, and two resistive elements, linear and nonlinear, reproducing classical eddy-current and excess losses respectively. This model is based on steel manufacturer's data including static hysteresis loops, catalog losses and the DC magnetization curve reaching high induction levels. When the DHM is incorporated into a transformer model, the presupposed or manufacturer provided core geometry and turn numbers are employed to recalculate magnetic variables (the magnetic field H and induction B) into flux-current curves of the legs and yokes. Although the DHM itself has shown performance in agreement with Epstein frame measurements [12], the model should always be fitted to the no-load test of a specific transformer. This is due to uncertainties in the stacking factor and joint air gaps as well as increased losses in real designs compared to catalog data.

Section 2 gives the transformer test report and design data, Section 3 outlines the transformer model used, and Section 4 compares simulations and measurements.

2. Transformer data

A 300 kVA Yyn-connected distribution transformer is used as test object for the benchmarking. The test report is given in Table 1,

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Table 1
Transformer test report.

OC test	V (rms, %)	V (ARV, %)	I_0 (%)	P_0 (kW)
Voltage on LV side	80.803	80.550	0.2749	0.3531
	90.033	89.580	0.4047	0.4548
	94.255	93.620	0.5006	0.5118
	97.518	96.670	0.6000	0.5625
	101.540	100.240	0.7800	0.6352
	108.910	105.990	1.4927	0.7936
	113.090	108.830	2.3205	0.8917
	116.456	111.030	3.4029	0.9786
	118.409	112.280	4.2701	1.0359
	120.595	113.600	5.5446	1.1094
	127.731	116.790	15.2612	1.5562
SC test	(kV)	(kVA)	V_{SC} (%)	P_{SC} (kW)
HS/LS	11.43/0.235	300	4.1	3.187

both for open and short circuit tests. Both true rms and average rectified voltage scaled to rms are reported in the table. There are significant differences between the two voltages above 100% excitation indicating high waveform distortions. The V_{ARV} is used in the rest of this paper as it gives a better representation of the peak flux.

Transformer core dimensions are given in Table 2 where the cross sections of the legs and yokes were determined from geometrical dimensions of their packs (the stacking factor (SF) of 1.0 was supposed). The 3-legged core is stacked with the Armco 0.3-mm thick steel M5 with resistivity of 0.48 μΩ m. A stacking factor of 0.965 is later assumed for the DHM model. The number of turns in the star-connected LV windings is 21.

3. Transformer model

A simple, but topologically correct transformer model is used to benchmark the influence of various magnetization branch representations. Fig. 1 shows the basic structure of the transformer model for a 3-legged core. The model is somewhat modified compared to the Hybrid Transformer model [3,4] as the magnetization branch of the legs more correctly is connected to the opposite side of the leakage inductance. This difference in leg connection is found to have little influence [9]. The leakage model is based on only two inductances L_{LC} and L_{HL}, plus the zero-sequence inductance. The inductances and resistance are split in two halves to obtain symmetry. In addition to the core and winding parts shown in Fig. 1, capacitances are added to the terminals of the high and low voltage winding.

3.1. Transformer model quantities

Based on the test report in Table 1, the parameters of the model in Fig. 1 are calculated. The leakage inductance is

$$L_{HL} = \sqrt{\left(\frac{e_k}{100}\right)^2 - \left(\frac{P_k}{S}\right)^2} \cdot \frac{V_L^2}{S} \cdot \frac{1}{2\pi f} = 23.2 \quad \mu\text{H} \tag{1}$$

The off-core inductance between the LV winding and the core, L_{LC} is assumed to be 0.33 of the leakage inductance. This can be estimated from the winding design information and is approximately the ratio between the distance from the LV winding to the core and the distance between the LV and HV winding. A factor of 0.5 is used in the Hybrid Transformer model [3]. The frequency is 50 Hz.

Table 2
Core dimensions.

Core part	Area (mm²)	Length (mm)
Leg	17,528	670
Yoke	19,812	580

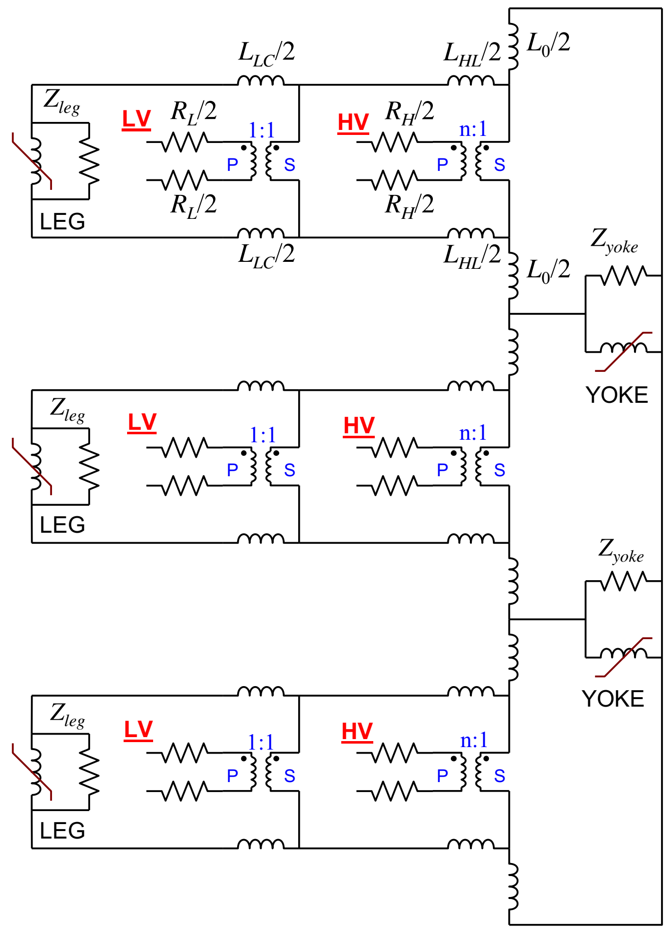

Fig. 1. Electric model of the transformer [4], 2-windings (*H* and *L*), 3-phases, 3-legged core.

The final slope of the magnetization inductance of the leg is estimated from the design information:

$$L_\infty = \mu_0 \cdot N^2 \cdot \frac{A_L}{l_L} = 14.5\,\mu\text{H} \tag{2}$$

The winding resistance is

$$R_{LH} = \frac{P_k}{S} \cdot \frac{V_L^2}{S} = 1.9556\,\text{m}\Omega \tag{3}$$

This is split between the LV and HV side based on the measures DC resistance ratio (61.6% on the LV side) so that

$$R_L = R_{LH} \cdot 0.616 = 1.2054\,\text{m}\Omega \tag{4}$$

$$R_L = R_{LH} \cdot 0.384 \cdot \frac{V_H^2}{V_L^2} = 1.7747\,\Omega \tag{5}$$

The zero-sequence impedance is measured separately as L_0 = 0.42 mH. This value is of little significance in the no-load from the LV terminals, but has some influence on the inrush currents calculated for HV excitations.

The capacitances are also measured as C_L = 1.115 nF, C_{HL} = 0.495 nF, C_{Hac} = 0.236 nF, C_{Hb} = 0.163 nF. In addition, there is a 0.2 nF added to the HV side to represent the voltage divider. These capacitances have some relevance for the ring-down transients only, but are kept to ease numerical complications due to the isolated neutral of the transformer.