PSPICE Modeling and Experimental Results of the Magnetic Behavior of a Primary Side Phase Controlled Transformer

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Abstract - **This work compares measurements made on a phase controlled power transformer with PSPICE simulations. In sinusoidal operation the similarity between measurements and simulation is very good. Also in case of phase control leading to non-sinusoidal primary side voltages, the simulations give very accurate results.**

In case of heavy saturation, obtained by creating a DC voltage on primary side of the transformer the PSPICE model gives inaccurate current magnitudes, while the simulated current shapes are correct.

The main conclusion of this paper is that the transformer model is accurate apart from situations with a heavily saturated core.

Keywords: power transformer, PSPICE transformer model, primary side phase control, experiment, modeling, saturation

I. INTRODUCTION

Modeling the magnetic circuit of power transformer has been a point of discussion for many years now. Several models have been proposed, most of which have been non-satisfactory.

In the 80s, two physicists, Jiles and Atherton, proposed a semi-empirical model of the hysteresis and saturation effects of ferro-magnetic materials [1].

The Jiles-Atherton model is part of the PSPICE package. Although PSPICE was originally intended for the simulation of electronic circuits, the inclusion of this model makes it now also suitable for the study of saturation effects in power transformers [2].

A spot resistance welding power transformer with primary side phase control has been used in an experimental setup. Current and voltage were measured during normal operation and during saturation of the transformer. The transformer was driven into saturation by suppressing the firing pulses to one of the thyristors leading to a DC magnetizing current.

The experimental results have been compared with the results from PSPICE modeling.

In this paper a selection of the results from the comparison of the PSPICE model of a primary side phase controlled power transformer with the experiments will be presented. Some suggestions on how to improve the simulation model are included.

II. TRANSFORMER MODELLING

A. GENERAL TRANSFORMER MODEL

Since a long time there has been a search for a general transformer model, i.e. a model capable of predicting the transformer's behavior over a wide frequency range and for all possible load situations. Such a model could be incorporated as a black box in a power system analysis package like EMTP or SPICE. The user of the program would then no longer have to worry about the validity of the model.

Different models can be used for different frequency ranges and different loading situations of the transformer. An overview of models is given in [3]. As long as the transformer is loaded and the frequency of interest is low, fairly simple models can be used: leakage reactance, copper losses, winding capacitances.

For non-loaded transformers the non-linear behavior of the transformer core has to be taken into account. As long as the magnetizing currents is more or less sinusoidal, including hysteresis and saturation will lead to acceptable results. But for cases with non-sinusoidal currents or voltages no satisfactory model has been proposed yet. Examples are the inrush current in non-loaded transformers, ferro-resonant overvoltages, and the main subject of this paper: thyristor control of welding transformers. What makes this especially arduous is the combination of non-linear and frequency dependent effects, Where the former calls for a time-domain model the latter requires a more frequency-domain oriented approach as e.g. used in transmission line modeling. The more non-sinusoidal the voltage or current, the more high frequencies are present and the more the frequency dependent effects have to be taken into account. Note that because of the non-linearity a sinusoidal excitation no longer guarantees a sinusoidal response. The frequency range of interest can thus only be determined after an initial study.

A very comprehensive list of references on models for the transformer core and their application is given in [4]. Recently non-linear and frequency-dependent models have been merged by Vakilian et al. [5,6]. They concentrate on transformer winding resonance due to switching transients. At those resonant frequencies (several kHz) the influence of the transformer core is rather small. The influence of non-linear varistors is of course significant. A comparison between measured and calculated inrush currents shows that their model still has some shortcomings.

B. MODELS OF THE MAGNETIC BEHAVIOUR

One of the main difficulties encountered when modeling a transformer is the complicated relationship between the magnetic flux density B and the magnetic field strength H. The hysteresis curve is well known and a correct way of modeling as long as the flux varies relatively slowly from close to saturation in one direction to close to saturation in the other direction and back, as is the case in normal transformer operation. When the field changes direction somewhere in between, the B-H path will not follow the same curve back but starts to describe so-called "minor loops". In [7] a description is introduced of the "reversal points" and minor loops that can be incorporated in a network model. This proposal has been further developed in [8] and [9]. These models are based on the assumption that there is only one shape of the magnetization curve; this one corresponds to the so-called "virgin curve" obtained when slowly magnetizing a ferromagnetic material. After every reversal point a new virgin curve starts from the last reversal point.

These models are strictly speaking only valid for quasi-DC phenomena. For 50 Hz the models are still reasonably accurate. But for higher frequencies other effects start to play important roles. One of them is the apparent reduction of the permeability due to eddy current effects, together with an increase in iron losses.

C. THE JILES-ATHERTON MODEL

The magnetic core model used in the simulation package SPICE is based on the semi-empirical description of ferromagnetic effects by Jiles and Atherton [1,10]. This description is based on physical properties of the magnetic material.

The model distinguishes between irreversible domain wall movement and reversible domain wall movement.

Reversible domain wall movement takes place for small values of the field (i.e. shortly after a reversal point). If the field decreases again the material gets back to its initial state. There is thus no hysteresis. Reversible domain wall movement is quantified in the Jiles-Atherton model through the "flexing constant" determined by the initial permeability of the virgin curve.

Irreversible domain wall movement is what causes the large increase of flux density with magnetic field strength for ferromagnetic materials. According to the Jiles-Atherton model there are two effects. The anhysteric magnetization determines the flux density as a function of field strength in case there were no impurities in the material, i.e. if the domain walls could move freely. The "pinning energy density" represents impurities preventing domain wall movement. The shape of the anhysteric depends on the material. Although it is physically defined it cannot be obtained by measurements. SPICE uses a fixed function for the anhysteric.

The Jiles-Atherton model in SPICE requires the following input parameters:
- magnetization saturation
- thermal energy parameter
- domain flexing constant
- domain anisotropy constant
- interdomain coupling parameter

The main limitation of the SPICE model is that these are not the parameters that transformer manufacturers or manufacturers of transformer steel can provide. In fact they cannot even be determined directly through measurements. The model parameters have to be determined from a measured hysteresis curve through an iterative trial-and-error process [11]. A parameter that is ill-defined by the 50 Hz curve could have a big influence on e.g. the magnitude of the inrush current. Another limitation is that the Jiles-Atherton model is basically still a quasi-DC model, despite the incorporation of some domain wall damping. Recent improvements of the model include frequency dependent losses [12,15], but are not yet implemented in SPICE.

III.EXPERIMENTAL SETUP

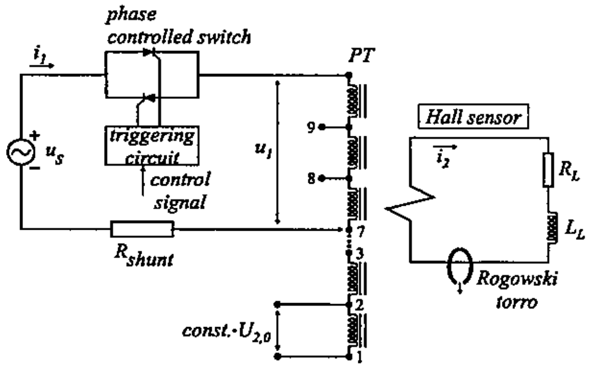

Fig. 1. Experimental setup

The experimental setup from Fig. 1 represents the equivalent electrical model of a transformer circuit with primary-side thyristor control. A pair of thyristors in inverse-parallel connection can perform the function of an electronic switch. If suitable gating pulses are applied to the thyristors while their anode voltage is positive, conduction is initiated. The conduction angle depends on the triggering (firing) angle α, and the load phase angle φ. With the arrangement of Fig. 1, the effective load voltage can be varied from zero, corresponding to extinction of both thyristors, to almost full supply voltage, corresponding to full conduction of both thyristors [13].

The tested transformer is used for spot resistance welding. It has the following characteristics:
Primary voltage : 380 V
Secondary voltage: 1,5 - 4,8 V
full rated power : 20.4 kVA
"half" rated power : 28 kVA
The load phase angle is: $41,40^0$

Measurements were performed for position five of the transformer, with a secondary voltage of 2,6 Volts (turns ratio = 146).

The primary current and voltage wave shapes are described by the relationships:

$$i(t) = i_{\sin}(t) + i_t(t) =$$
$$i_{\sin,m}\sin(\omega \cdot t + \alpha - \varphi) - i_{\sin,m}\sin(\alpha - \varphi)e^{(-\omega \cdot t \cdot ctg\varphi)}$$

$$u(t) = U_m \sin(\omega \cdot t + \alpha)\begin{cases} -\alpha \le \omega \cdot t \le -(\pi - \lambda) \\ 0 \le \omega \cdot t \le \lambda \end{cases}$$

Measurements were made for 8 different transformer ratios, 5 different firing angles of the phase controlled switch (PCS) varying from $\alpha = \varphi$ up to deep phase control ($\alpha > \varphi$), as well as cases when asymmetrical firing takes place $\alpha < \varphi$ (the firing angle is smaller then the load phase angle).

For the purposes of this investigation measurements were also made with saturated transformer. This regime was performed by suppressing the firing pulse to one of the thyristors which leads to DC magnetizing current and thus fast saturation of the transformers core. As a result of this regime, the primary current increases considerably (up to 8 times its normal value) while the secondary current decreases. We will refer to this situation as an "extremely asymmetrical regime" (EAR). This is an interesting phenomenon to assess the behavior of the PSPICE transformer model.

IV. PSPICE MODEL

Recent versions of PSPICE have the capability of simulating the hysteresis loop of magnetic materials. The transformer model is based on the Jiles-Atherton theory of ferromagnetic hysteresis [1].

For this investigation the experimental setup from Fig.1 was simulated with the plant shown in Fig. 2.

In Fig.2 the welding transformer is simulated by the nonlinear magnetic core device. The resistances R_1 and R_2 correspond to the measured resistances of the primary and secondary circuit. Resistance R_2 includes the resistance of the welding electrodes. The inductance L_3 represents the leakage inductance plus the inductance of the secondary circuit of the welding transformer. The two thyristors in inverse parallel connection perform the phase controlled switch.

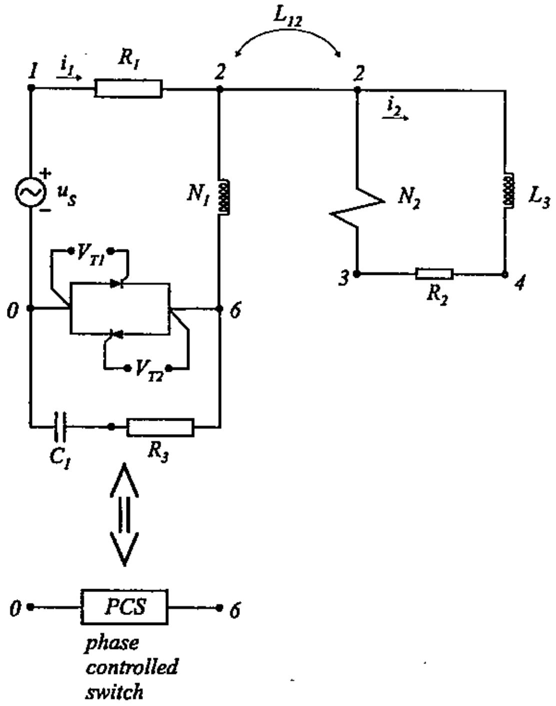

Fig. 2. Simulation model

All data could be easily obtained apart from the values for the Jiles-Atherton model. These have to be obtained in an iterative process, by matching the simulated hysteresis loop to the one obtained experimentally [2,14,1,11].

The default values of the parameters in SPICE have been used as initial values in the iteration process. For each of the parameters its influence on the shape of the hysteresis loop has been determined. Via a number of iterations a good representation of the measured curve was obtained. These parameters obtained this way were used in the subsequent simulations.

From our measurements, manufacturers data, and the iteration process, the following parameters were found:

Magnetization saturation : 1.8×10^6A/m
Interdomain coupling parameter : 25 900
Thermal energy parameter : 228 A/m
Domain anisotropy parameter : 240 A/m
Domain flexing parameter : 0.4
Cross section of core : $60 cm^2$
Magnetic path length : 40 cm
Turns ratio : 146

The model parameters used for the simulation plant were tested for an unloaded transformer and then compared with the measured data for the magnetic properties. The relative error does not exceed 9% (see tab. 1). The shape of the corresponding simulated hysteresis is shown in Fig. 3

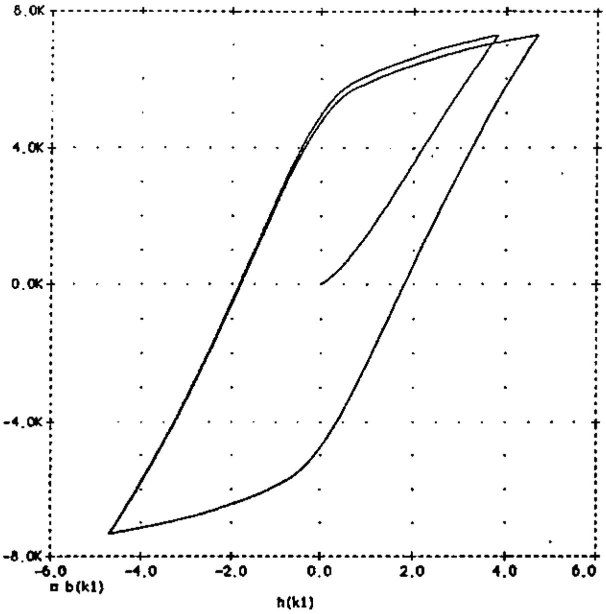

Fig. 3. Simulated hysteresis
(1 Gauss = 10^{-4}T, 1 Oersted=79,6A/m)

Table 1.Comparison of Measured and Modeled Magnetic Properties

	experiment	simulation	relative error
magnetiz. current	1,037 A	1,021 A	-1,54 %
remanence	0,524 T	0,476 T	-9,16 %
coercivity	145,3 A/m	143,2 A/m	-1,44 %
saturation induction	0,77 T	0,731 T	-5,06 %
field at loop tip	377,3 A/m	372,9 A/m	-1,16 %

V. COMPARISON BETWEEN MEASUREMENTS AND SIMULATION

A. *Sinusoidal currents*

The first simulations were made for the case of sinusoidal currents which is considered as the most frequent regime for the power transformers. This mode of operation was obtained by making both firing angles the same. A selection of the comparison between measurements and simulation is given in table 2.

Table 2. Comparison of the Simulated and Measured Current Values for Sinusoidal Operation of the Switch

	current	simulation	experiment	relative error
primary current	$\hat{I}_1$	40,68 A	41,3 A	-1,5 %
	I_{1rms}	28,7 A	28,44 A	0,9 %
secondary current	$\hat{I}_2$	5842 A	4049 A	-3,4 %
	I_{2rms}	4049 A	4279 A	-5,3 %

The simulations are in good agreement with the measurements. That indicates that the steady-state parameters of the model were selected correctly. Also these results show that the model calculates accurately values for inductances and flux for the transformer windings and obtains the correct hysteresis in case of sinusoidal operation.

B. *Non-sinusoidal currents*

The transformer model was tested for different firing angles of the PCS. When the firing angle of the PCS is greater then the load phase angle the currents become discontinuous and nonsinusoidal. The increase of the firing angle results into decrease of the RMS values of the primary and secondary currents. This mode of operation is common for welding transformers with primary side thyristor control. An example of simulated and measured results is shown in fig. 4 and fig. 5. This shows that the simulation are qualitatively and quantitatively accurate. A selection of measured and simulated results is given in table 3.

Table 3: Comparison of the Simulated and Measured RMS Current Values

extinction period for each of the thyristors [ms]	current	simulation	measurements	relative error
1,36	primary secondary	22,2 A 3164 A	23,92 A 3711 A	-7,3 % -14,7 %
2,16	primary secondary	21,53 A 3080A	20,01 A 3134 A	7,6 % -1,7 %
3,05	primary secondary	16,9 A 2424 A	15,75 A 2470 A	7,3 % -1,8 %
3,86	primary secondary	13,67 A 1923A	12,79 A 1993 A	6,8% -3,5 %

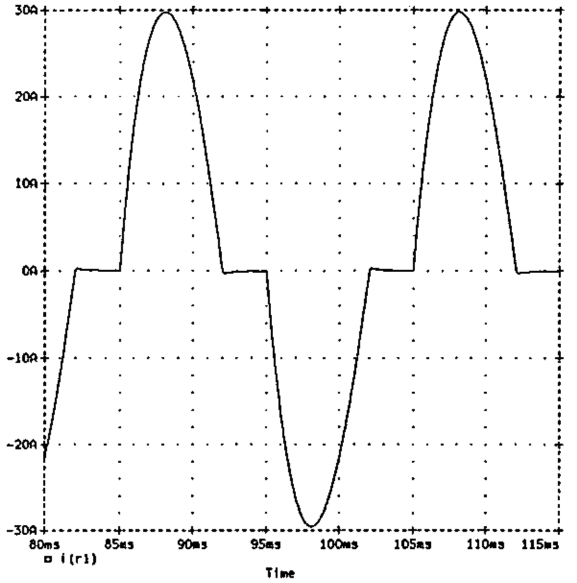

Fig. 4. Simulated primary current shape in case of primary circuit phase control

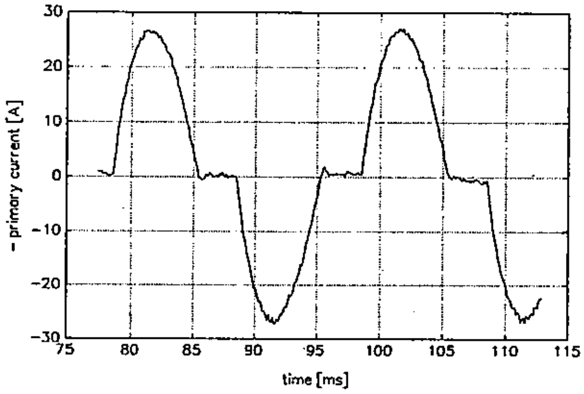

Fig. 5. Measured primary current shape in case of primary circuit phase control

The results show that the PSPICE transformer model is accurate and suitable for simulating cases with symmetrical and discontinues current shapes.

C. *Saturation*

The transformer model has been tested for the case of saturation, too. This mode was defined before as an extremely asymmetrical mode of operation of the PCS, when only one of the thyristors conducts. However this is not a common or preferable regime but it is a good way to asses the transformer model.. The transformer model was tested for the case when the existing halfperiod is continuous.

Examples of measurements and simulation are shown in fig. 6 and fig. 7. Fig. 6 shows the simulated primary and secondary currents in case of saturation. Fig. 7 shows the corresponding measured current shapes.

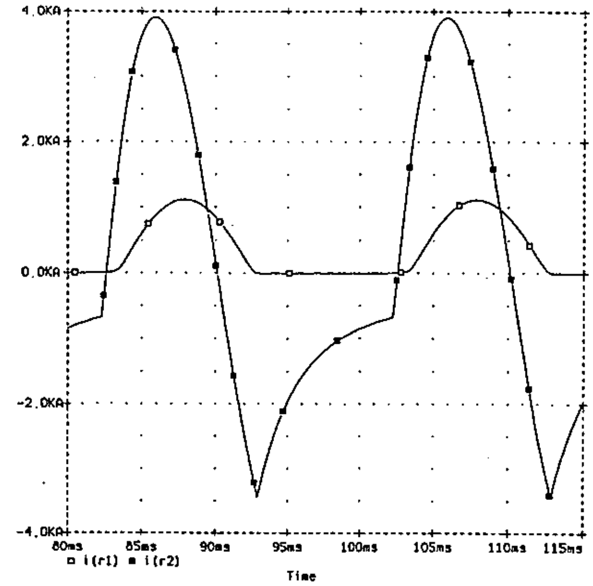

Fig. 6. Simulated current shapes for case of EAR

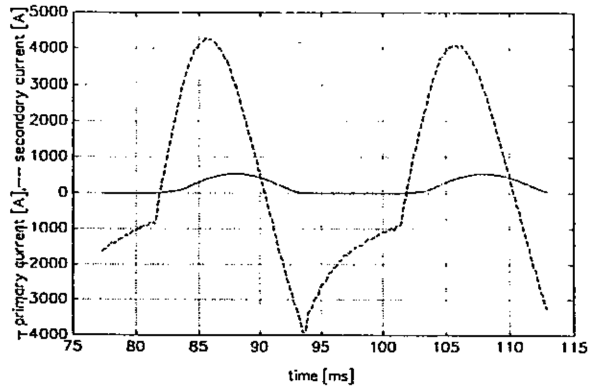

Fig. 7. Measured current shapes for case of EAR

Like in the previous section one can conclude that simulation does result in the accurate shape of the currents, but that the magnitude of the primary currents is overestimated. A summary of the overall results is given in table 4.

Table 4. Comparison of the Simulated and Measured RMS Current Values in case of EAR

extinction period of the thyristor which conducts	current	measurements	simulations
0 ms	primary	263 A	580 A
	secondary	2467A	2278 A

The results show that for the case when the transformer is driven into saturation the PSPICE transformer model overestimates the primary current even more then 100% while the secondary current is only slightly less than measured.

D. *Model improvements*

The comparison between measurements and simulations shows that the PSPICE transformer model is accurate as long as the core is not driven into saturation. For extremely asymmetrical regime the latter is the case, and the model overestimates the primary current by a factor of two.

The fairly simple transformer model used (one leakage reactance plus one magnetizing reactance) can explain some of the error but not a factor of two. The Jiles-Atherton model, despite its physical detail, remains a quasi-DC model, valid for slow variations only. The highly non-sinusoidal current in case of saturation contains a significant amount of higher harmonics. The damping of these is not incorporated correctly.

Adding resistances at strategic places in the model, with proper values, might give the correct result for one situation. But this can hardly be called a "general transformer model".

When interpreting these results one has to keep in mind that the measurements were performed on 28kVA welding transformer. The core losses are probably (relatively speaking) much larger than those of multi-MVA power transformers.

VI. CONCLUSIONS

The PSPICE transformer model has been assessed for different modes of operation. The comparison of the simulated results with those from the measurements showed that:

- in the case of sinusoidal operation, the model calculates accurately values for inductances and flux for the transformer windings and obtains the correct hysteresis. The simulated values of the current and voltage agree completely with those from the measurements;
- in the case when the currents are non-sinusoidal and discontinuous the simulation results are accurate.
- in the case of saturation due to DC magnetization of the core, the simulated results are qualitatively correct. Quantitatively the simulation results show overestimation of the primary current up to 100%, while the secondary current is comparable with the measured.

These results show that the PSPICE transformer model is suitable and accurate for symmetrical, continuos as well as discontinuous magnetizing currents.

The quantitative disagreement of the simulated results in saturation shows that the magnetic material in the model can not follow the fast changes happening when high-frequency components are present in the transformer core.

A better frequency dependent model is needed, one suitable for more general modes of operation of the power transformers.

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