Modelling the pulse transformer in SPICE

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Abstract. The paper is devoted to modelling pulse transformers in SPICE. It shows the character of the selected models of this element, points out their advantages and disadvantages, and presents the results of experimental verification of the considered models. These models are characterized by varying degrees of complexity - from linearly coupled linear coils to nonlinear electrothermal models. The study was conducted for transformer with ring cores made of a variety of ferromagnetic materials, while exciting the sinusoidal signal of a frequency 100 kHz and different values of load resistance. The transformers operating conditions under which the considered models ensure the acceptable accuracy of calculations are indicated.

1. Introduction

Pulse transformers are widely used in switched-mode power supplies with galvanic isolation between the input and the output [1, 2]. In literature, there are a lot of papers concerning ferromagnetic material properties [3 – 10], as well as discussions concerning the impact of electromagnetic interactions occurring in transformers on their characteristics and operating parameters [11 - 16]. Few works in literature concern modeling pulse transformers, that take into account various physical phenomena [11, 12, 13, 16].

With a computer analysis of electronic circuits, the models of all the elements contained in these circuits are needed. These models should take into account all physical phenomena relevant to the circuits under consideration, while the character of these models should be simple enough to provide short duration calculations. These requirements are mutually contradictory. Therefore, it is important to choose the right model to solve every simulation problem.

Currently, a popular program for analyzing electronic circuits is SPICE [17], in which the basic models of electronic components are built-in [18]. However, it has no built-in model of the transformer in this program. Therefore, it is necessary to apply a macromodel of varying forms to describe the element.

An important physical phenomenon occurring in electronic components is self-heating, reflected by an increase in the internal component temperature due to conversion of electrical energy into heat by non-ideal cooling of the element [16, 19, 20]. Models which take into account the self-heating phenomenon are called electrothermal models and models which skip this phenomenon - isothermal models.

The paper describes the considered models and analyzes their suitability for modeling
characteristics of pulse transformers containing cores made of different materials. The results of calculation are compared with the measurement results.

2. Models descriptions
In the paper five arbitrary selected literature transformer models, implemented in SPICE, are considered. These models can be divided into two groups: isothermal and electrothermal. The first of the considered models of the transformer consists of linearly coupled linear coils, and the second - linearly coupled linear coils with series resistors, which model losses in the windings. In turn, the model from paper [11] describes non-linear properties of the core, but does not take into account losses. The next two models are electrothermal ones. The fourth model (electrothermal), described in [11] takes into account non-linearity of core characteristics and an increase of the internal temperature of the transformer windings and core as a result of self-heating. The last model (also electrothermal) – elaborated by the authors [12] allows calculating core temperature and winding temperature taking into account self-heating and mutual thermal coupling between the core and windings.

2.1. Linearly coupled linear coils
Figure 1 shows a circuit representation of a transformer model composed of linearly coupled linear coils. The primary winding represents a coil $L_1$, while the coil $L_2$ represents a secondary winding. This model describes the ideal transformer and transmission of the transformer is equal to

$$n = \sqrt{L_2/L_1}$$  \hspace{1cm} (1)

![Figure 1. Circuit representation of the linearly coupled linear coils model](image)

In this model we omit losses. It is impossible to include self-heating phenomena, either.

2.2 Linearly coupled linear coils with series resistances
Figure 2 shows a circuit representation of a transformer model composed of coupled linear coils and series resistors representing losses in the windings. The values of the resistance change depending on the parameters of the core used and the number of turns in the windings and their diameter.

![Figure 2. Circuit representation of the model with linearly coupled linear coils with series resistances.](image)

2.3 Isothermal model of the transformer from paper [11]
In paper [11] an isothermal model of the transformer consisting of the ferromagnetic core and windings is proposed. The circuit representation of the transformer model for SPICE based on the text description presented in [11] is shown in Figure 3.
In the model of windings there are two pairs of clamps - electric clamps (respectively p1, p2 and w1, w2), corresponding to transformer outputs, and magnetic clamps (respectively p3, p4, and w3, w4), the voltage of which corresponds to the magnetomotive force, and the current \( \text{–} \) to the magnetic flux. The magnetic clamps are connected to the core clamps (r1, r2) between which there is a controlled current source \( G_1 \) representing reluctance of the core. In the core model, the controlled voltage source \( E_1 \) is used to determine the effective magnetic force \( H_e \) and the controlled voltage source \( E_2 \) is used to determine the value of irreversible magnetization \( M_{an} \). The normalized reversible magnetization function \( M_{an} \) is approximated by the Langevin function \( L(H_e) \), of the form:

\[
M_{an} = \frac{1}{\tanh\left(\frac{H_e}{A}\right)} - \frac{A}{H_e}
\]

where \( A \) is the model parameter shaping a hysteresis loop.

Real reversible magnetization is obtained by multiplying the right side of equation (2) by saturation magnetization \( M_s \). The value of magnetization \( M \) can be determined by solving a differential equation of the form:

\[
\frac{dM}{dH} = \frac{1}{1 + \frac{\alpha}{\mu}} \left( \frac{M_{an} - M}{M_{an} - M_0} + \frac{c}{H_e} \frac{dM_{an}}{dH} \right)
\]

where \( \mu \) - magnetic permeability, \( \alpha \) - coefficient characterizing the magnetic field \( \delta \) - coefficient to determine the direction of a change of the magnetic field (\( \delta = 1 \) for \( \text{d}H/\text{d}t > 0 \), \( \delta = -1 \) for \( \text{d}H/\text{d}t < 0 \) ) \( k \) - coefficient of non-elastic deformation of domain walls \( c \) - coefficient of elastic deformation of domain walls.

The circuit consisting of the controlled voltage source \( E_1 \), the capacitor \( C_1 \), the resistor \( R_0 \) and the voltage source \( V_1 \) is used to determine the time derivative of the magnetic force \( \text{d}H/\text{d}t \). In turn, the circuit composed of the series connected controlled voltage source \( E_4 \), the resistor \( R_2 \) and the capacitor \( C_2 \) is responsible for the delay of the analyzed signal, slowing signal slopes or limiting the derivative \( \text{d}H/\text{d}t \). Next four circuits containing the controlled voltage source \( E_6 \) and the resistor \( R_4 \), the circuit including the controlled voltage source \( E_7 \), the resistor \( R_5 \) and the controlled voltage source \( E_5 \) connected in series with the diode \( D_1 \) and the resistor \( R_6 \), and the controlled current source \( G_1 \), are used.
to determine total magnetization M. The two branches consisting of the controlled voltage sources $E_{21}$ and $E_{22}$ are used to designate the magnetization curve $B(H)$ of the core.

The model of the windings contain the electromotive force corresponding to flux density (voltage source $E_1$), the winding resistance ($R_p$) and a circuit modeling the magnetomotive force generated by the current of each of the windings. The source voltage $V_1$ whose value is zero allows monitoring the output current of the winding. The voltage at the voltage sources $E_3$ and $E_5$ correspond to the magnetomotive force and magnetic flux. The circuit composed of the controlled current source $F_1$, the resistor $R_1$ and the coil $L_1$ allows determining the time derivative of the magnetic flux.

In the present ed model core losses are skipped, but energy losses in the winding are taken into account.

2.4 Electrothermal model from paper [11]

Figure 4 shows the electrothermal model of the transformer from paper [11]. Resembling the model described in section 2.3, this model contains blocks modeling the characteristics of the core and windings, but in the equations describing the components of the transformer the influence of temperature and self-heating phenomena are taken into account.

![Electrothermal model](image)

**Figure 4.** Circuit representation of the electrothermal model from paper [11]

In the models of the core and windings there are elements modeling energy losses. In the core model the voltage sources $E_8$, $E_9$, $E_{10}$ and the current source $G_{10}$ are used to determine power generated in the core. Similarly, in the models of windings the controlled current source $G_{TH}$ representing losses in the windings is included. Clamps of these sources are connected to the external RC network, representing transient thermal impedance of the transformer. Node $p_5$, $w_5$ and $r_3$ are connected, the voltage on these nodes corresponds to the excess of the transformer temperature above the ambient temperature.

Thus, in the considered model only one internal temperature of the whole transformer is used, i.e. in the considered model the temperature of the winding and the core are the same. In the model of the core circuits consisting of the series connected controlled voltage source $E$ and the resistor $R$ are used to determine the sequence of parameters of the core $M_S$, $M$, $C$, $A$, $ECRATE$ $ALPHA$ taking into account line influence on temperature. The temperature coefficients are designated $A_{TC}$, $C_{TC}$, $\alpha_{TC}$, $ECRATE_{TC}$.
The power loss in the windings is described by
\[ G_{\text{TH}} = I_w^2 \cdot R_w \]  
(4)
where \( I_w \) is the winding current, \( R_w \) is internal resistance of the windings.

In turn, core losses are described by the equation:
\[ P_{\text{LOSS}} = H \cdot \text{LEN} \cdot \mu_0 \cdot (M_s \cdot (1 + M_{\text{STC}} \cdot T) \cdot (M - M_{\text{an}}) + H) \]  
(5)
where \( \mu_0 \) – denotes magnetic permeability in free air, \( \text{LEN} \) – is the magnetic path length, \( \text{MSTC} \) – is the temperature coefficient of saturation magnetization, \( T \) – denotes the excess of core temperature over the ambient temperature determined from the thermal model.

In the formula (5) the ratio of the magnetic field strength \( H \) and the magnetic path length \( \text{LEN} \) is equal to the value of the magnetomotive force, observed between clamps of the core model (r1 and r2).

2.5. Model from paper [12]
Figure 5 is a circuit representation of the electrothermal model of a transformer for SPICE, presented by the authors in [12].

![Figure 5. Circuit representation of the model from paper [12]](image)

This model consists of three separate blocks: the core model, the windings model and the thermal model. The core model is based on a modified Jiles-Atherton model [3]. In this model the controlled voltage source \( E_H \) connected in series with the capacitor \( C_1 \) and the resistor \( R_1 \) is used to determine the magnetic force \( H \). The flux density corresponds to the voltage at the output node \( B \). Power losses in the core are equal to the voltage at the node \( P_{\text{loss}} \).

The thermal model allows calculating the core temperature \( T_R \) and the winding temperature \( T_U \), taking into account self-heating and mutual thermal coupling between the core and windings. This
model is in the form of the RC Foster network stimulated by the source representing power dissipated in the core \( P_{THR} \) and in the windings \( P_{THU} \). In order to take into account thermal coupling between the core and the windings the controlled current sources \( P_{thru1} \) and \( P_{thru2} \) are applied. The voltage source \( T_a \) is used to model the ambient temperature.

The detailed description of the core model contained in papers \([8, 21]\), and the description of the thermal model in \([22]\) show the performance of the controlled voltage sources included in the winding model. The voltage on the voltage source \( E_{V1} \) is given by

\[
E_{V1} = z_1 \cdot S_{Fe} \cdot \frac{dB}{dt}
\]  

(6)

where \( z_1 \) - the number of primary winding turns, \( S_{Fe} \) - cross-sectional area of the winding wire. Similarly, the voltage value is determined at the voltage source \( E_{V2} \) taking into account the number of turns of the secondary windings.

In the core model the controlled voltage source \( E_H \) representing the magnetic force \( H \) is added. This magnetic force is described by the following formula

\[
H = (z_1 \cdot i_1 + z_2 \cdot i_2) / l_{Fe}
\]  

(7)

where \( z_1 \) and \( z_2 \) are numbers of turns in primary and secondary windings, respectively, \( l_{Fe} \) is the magnetic path length, whereas \( i_1 \) and \( i_2 \) are currents of the windings.

Additionally, in order to improve the convergence of calculations in the differentiation networks used in this model the independent voltage sources are replaced by resistors, e.g. the network including the controlled voltage source \( E_H \), capacitor \( C_1 \) and resistor \( R_1 \) is used to calculate the derivative \( dH/dt \).

The flux density corresponds to the voltage on the terminal \( B \). The power losses in the core are equal to the voltage at the terminal \( P_{loss} \). The core losses \( P_{th} \) are described by the formula

\[
P_{loss} = V_E \cdot \left( \frac{B_{pp}}{2} \right)^{\beta - \alpha} \cdot \left( 1 + \alpha_p \cdot (T_R - T_m)^2 \right) \cdot \frac{P_{th}}{T_m} \int_0^T \left| \frac{dB}{dt} \right|^\alpha dt
\]  

(8)

In Eq. (8), \( \alpha_p \) denotes the square temperature coefficient of power losses, \( T_m \) – the temperature for minimum losses, \( T \) is a period of flux density and \( B_{pp} \) is the peak-to-peak value of flux density, \( V_E \) – the volume of the core, \( \beta \) and \( \alpha \) are the Steinmetz’s model parameters.

The windings model contains two networks representing primary winding, connected between the connectors 1a and 1b, and the secondary winding, connected between connectors 2a and 2b. In the model of the primary winding the resistor \( R_{S1} \) represents series resistance of this winding in the reference temperature \( T_0 \), the controlled voltage source \( E_{RMS1} \) models a change of this resistance during temperature changes of the windings \( T_U \) and the skin effect. The controlled voltage source \( E_V \) represents the voltage induced in the primary winding, the controlled current source \( G_{L1} \) represents the magnetizing current by the formula:

\[
G_{L1} = l_{Fe} \cdot \frac{\left( |H| + A \right)^2}{z_1^2 \cdot S_{Fe} \cdot B_{sat} \cdot A} \cdot \int_0^l U_p(x) \cdot dx
\]  

(9)

where \( U_p \) - voltage between clamps of the primary winding, \( l_{Fe} \) – magnetic path length, \( B_{sat} \) – core saturation flux density.

The controlled current source \( G_R \) models losses of energy in the core. The current of this source is given by the following equation

\[
G_R = P_{loss} \cdot \frac{V_i}{V_{RMS1}^2}
\]  

(10)

where \( V_{RMS1} \) denotes the rms value of the voltage on the source \( G_R \), while \( V_i \) is the actual value of this voltage. The voltage \( V_{RMS1} \) is calculated by means of the controlled voltage source \( E_{RMS1} \). Voltage
sources $V_{i1}$ and $V_{i11}$ have a zero-value of the output voltage and they are used to monitor the value of their currents. In turn, the model of the secondary winding contains only elements modelling voltage induced on the winding ($E_V$) and series resistance of this winding ($R_{S2}$ and $E_{RS2}$).

3 Results

In order to examine suitability of the transformer models described in section 2, calculations of the characteristics of the selected transformers containing cores made of different materials were carried out, while using them. Each test transformer had two windings of 20 turns of copper enamel wire having the diameter of 0.8 mm. The used toroidal cores respectively had the outer diameter of about 26 mm and were made of powdered iron (RTP), nanoperm (RTN) and ferrite (RTF).

Figure 6 shows a measuring circuit, where resistance of the resistor is $R_1 = 33 \, \Omega$ and $R_0$ is load resistance of the circuit. The voltage source $V_1$ generates a sine wave with the amplitude of 67 V and frequency of 100 kHz.

![Figure 6. Measuring circuit.](image)

The selected characteristics of this circuit are shown in the successive figures. In these figures the results of measurements are denoted by points, whereas the results of calculations – by lines.

For each of the considered models the values of the parameters corresponding to each of the tested transformers based on datasheets or additional measurements and estimation algorithms described in [23, 24] are used. Figures 7 - 9 show the calculated and measured characteristics of the transformer considered in the steady state. The results presented in Figure 7 concerns the transformer core RTP, Figure 8 - the transformer core RTF and Figure 9 - the transformer core RTN. The lines in purple represent calculations for the model described in section 2.1, the green colour - for the model from section 2.2. In turn, the isothermal model of paper [11] is presented by lines in black, and the electrothermal model of the same work – by blue lines. The results obtained with the authors’ model described in [12] are denoted by the red colour.

Figure 7 shows the results of the input voltage, output voltage, watt-hour efficiency and temperature on load resistance for the transformer with the RTP core. In this figure, solid lines represent the results of calculations obtained for the nominal values of parameters, and dotted lines - the results obtained with the adjusted parameter values, which better match of the results of calculations and measurements. To this end, value of MS parameter (for the models from [11]) was increased 3.2 times. In the case of the model from paper [12] $B_{S0}$ parameter was increased by 5%. After these changes the model of paper [12] best fit measurement results, and the difference in terms of measurement of the input voltage as a function of load resistance did not exceed 2.7%.

Figure 7a and 7b show that for all the considered models the increasing function describing the dependence of the input and output voltages on load resistance is obtained. One can see that all the models under consideration, except models from [11] (up to three times lower values obtained from calculations than values obtained from measurements) provide a satisfactory agreement between the calculations and measurements results, wherein the difference between these results is higher for the smaller values of resistance $R_0$. After the change of model parameters from [11] the maximum difference between the results of calculations and measurements does not exceed 15%. The authors’ model with the adjusted value of the $B_{S0}$ parameter provides the best accuracy of calculations, but also the models of the transformer in the form of coupled coils ensure the correct calculation results.
On the other hand, watt-hour efficiency is typically a decreasing function of load resistance. The authors’ model provides the most accurate description of the measured characteristics $\eta(R_0)$, and the used models from paper [11] obtained the understated values of watt-hour efficiency. Coupled coils have inflated the value of watt-hour efficiency, even several times. Changes in the core temperature as a function of load resistance were only possible to examine for model from paper [12] and the electrothermal model from paper [11]. For both these models the increasing function $T_R(R_0)$ was obtained. The model from paper [12] fits satisfactorily the measured characteristics and the model from [11] has no convergence between the results of calculations and measurements. This proves the incorrect modeling power loss in this model. It is worth noting that the core temperature reaches about 120°C at high load current, which shows high energy loss in the core associated with the high value of the amplitude of the flux density in the core.

![Figure 7](image_url)

**Figure 7.** Calculated and measured characteristics of the input voltage (a), output voltage (b) watt-hour efficiency (c) and the temperature of the core (d) on load resistance for the transformer with the RTP core.

Figure 8 shows the dependence of watt-hour efficiency and the core temperature on load resistance of the RTF core transformer.
The shape of the considered characteristics is similar to the shape of the characteristics shown in Figure 6. It is worth noting that the transformer with the RTF core is characterized by higher watt-hour efficiency and lower core temperature than the transformer with the RTP core. The best compliance of the calculated and measured characteristics was obtained for the authors’ model of the transformer. Unfortunately, significant deviation between the results of calculations and measurements in the range of small values of load resistance appeared.

Figure 9 shows the dependence of the output voltage and the core temperature on load resistance of the transformer with the RTN core.

The shape of the characteristics of the presented considered dependences is similar to the characteristics of the transformer with the RTP core. Big deviation between the calculated output voltage obtained using models from paper [11] is comprising. On the other hand, the simplest model of the transformer in the form of coupled coils ensures the achievement of similar correspondence between the calculated and measured values of the output voltage as the electrothermal model from [12]. The results of calculations realized by the model from [12], differ from measurements by not more than 6%.

In turn, each of the considered models underestimates the value of the core temperature in a range of small values of load resistance, and for the resistance $R_0 > 100 \, \Omega$ the authors’ model assures nearly perfect agreement with the results of measurements.
4 Conclusions
In the paper, five arbitrarily selected models of transformers for SPICE were described and their suitability for modeling the characteristics of this class of elements was tested. The considered models are characterized by varying degrees of complexity of the description of phenomena occurring in the transformer. Experimental tests were carried out for capacitors containing toroidal cores made of different ferromagnetic materials. The results confirmed that with wide range of load resistance in order to correctly determine the value of the amplitudes of the input and output voltage of the transformer it is necessary to apply sufficient models of this element in the form of linearly coupled linear coils. On the other hand, reliable determination of watt-hour efficiency of the tested transformers requires the use of non-linear models of the element, taking into account energy losses both in the core and in the windings.

Models from papers [11] and [12] based on the same Jiles-Atherton model describing properties of the core, nevertheless achieved by means of the calculation results significantly differ from each other. The better matching results of calculations and measurements are assured by the authors’ electrothermal transformer model from paper [12]. This model allows, in addition to the designation of voltage and current at transformer terminals and its watt-hour efficiency, calculation of the core and the windings temperature. The results described in the previous section show that this model provides the most accurate description of the characteristics of all transformers being considered. It should also be noted that under identical control and load conditions achieved significant differences in the values of parameters characterizing the considered transformers were obtained. For example, the greatest losses of energy and the highest core temperature values were obtained for the transformer with the RTP core. On the other hand, the highest watt-hour efficiency was obtained for the transformer with the RTF core.

The obtained results may be useful for designers of switched-mode power supplies. By using the presented models, the designers of this class of circuits will be able to make a realistic simulation of the designed equipment, which will reduce production costs of these circuits.

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