SPICE simulation of ferrite core losses and hot spot temperature estimation

Shmuel (Sam) Ben-Yaakov, *Life Fellow, IEEE*
Department of Electrical and Computer Engineering
Ben Gurion University of the Negev
Beer Sheva, Israel
sby@bgu.ac.il

***Abstract*—A simple, user-friendly model is proposed to estimate ferrite core losses and the hot spot temperature by SPICE simulation that are based on the Steinmetz equation. The model is capable to produce, on the fly, the estimates as the operating condition of the core are changing.**

Keywords—ferrite; core losses; Steinmetz; SPICE; simulation

I. INTRODUCTION

A limiting factor of ferrite core use in power electronics are the core losses. The main losses are eddy current losses and hysteresis losses. Of the two, the latter is more pronounced since the resistivity of the ferrite ceramic material is very high and thus conduction losses are negligibly small [1]. The hysteresis losses can be calculated if the parameters of the hysteresis loop, as well as the operating conditions of the magnetic element built around the core, are known. Unfortunately, the hysteresis parameters of cores under various operating conditions (such as flux density amplitude, temperature and frequency) have not been documented as yet for all commercial cores. Consequently, power loss estimation based on the hysteresis loop approach is not considered a viable engineering design tool.

An alternative approach to estimate ferrite core losses, which is used almost universally, is to apply the Steinmetz Equation (SE). This is an exponential-type experimental equation whose constants are obtained by measurements of core losses under various operating conditions. The SE constants (SC) are provided by all vendors of ferrite cores as part of their basic ferrite material data. The data is given as tables of the SC, as charts of losses versus flux density amplitude and as down loaded or on-line software calculators. It should be noted that the SE data is collected under sinusoidal signal excitation with no DC bias. It has been well documented though, that DC bias increases ferrite core losses. Furthermore, SE is formally valid for sinusoidal excitation, while in many power electronics systems, the magnetic flux excitation of the magnetic elements is triangular. A number of methods have been suggested to overcome the deficiencies of the basic SE ferrite core estimation [2-19]. Nevertheless, the basic SE based core loss estimation is still used by most workers in the field since the SC are the most comprehensive, reliable and readily available ferrite core loss data.

SPICE based simulators, and derivatives of thereof are very popular among workers in the power electronics area. Simulation is used in the design phase of power converters and to tune and optimize the design. A number of SPICE based simulators include ferrite core loss by add-on hysteresis models [20, 21]. However, as already pointed out above, the basic data needed for such estimation is not available for all cores. Furthermore, the accuracy of ferrite core loss estimation by these models was never been proven rigorously, at least not in the open literature.

The objective of this work is to implement the SE as a circuit model in SPICE based simulators such that it will produce, on the fly, the calculated ferrite core losses. The proposed model can be incorporated in any power electronic simulation circuit, as an-add, without interfering with the original simulation of the system. An extra benefit of the model is that it produces an estimate of the hot spot temperature of the magnetic element using the experimental equation offered by ferrite core vendors. Application of the proposed ferrite core loss simulation model can thus provide an estimate of the core losses under specific operating conditions in lieu of tedious manual calculations by the SE, or reading values off the charts that are offered by ferrite core manufacturers, or use one of the software calculators. The added advantage of the model is that it provides "real time" information in the sense that when, say, the input voltage of a switch mode converter is changing during a simulation, the core losses of the new operating condition are displayed – after some settling time.

II. THE STEINMETZ EQUATION (SE) AND HOT SPOT TEMPERATURE EQUATION

The SE equation is expressed as

$$P_v = kf^a\hat{B}^b \qquad (1)$$

Where P_v is core loss density in Power/Volume units, k, a, b are the SC, f is frequency and $\hat{B}$ is the peak value of the flux density. The constants of this fitted equation, (SC), are derived experimentally by sinusoidal excitation with no DC bias. It should be noted that the SC are temperature dependent and hence the SC values for each temperature need to be given. Some manufacturers have extended the fitting to include the temperature effect

$$P_v = kf^a\hat{B}^b(C_0 - C_1T + C_2T^2) \qquad (2)$$

where $C_{0,1,2}$ are the temperature coefficients and T is temperature rise in ^{0}C.

In (2) the SC are kept constant and the SE is now a function of temperature, aside from $\hat{B}$ and f. Considering the fact that the temperature coefficients are not available for all cores, the basic model presented here does not include this adjustment. It is, however, explained below how the model can be easily adjusted to include this modification.

Being an exponential function, the P_v versus $\hat{B}$ curve is straight lines when plotted in a log-log scale. Fig. 1 is a typical chart provided by just any ferrite core vendor. It should be emphasized again that these charts are strictly correct for sinusoidal excitation and at the specified temperature. Temperature dependence is then normally given by another chart, similar to Fig. 2.

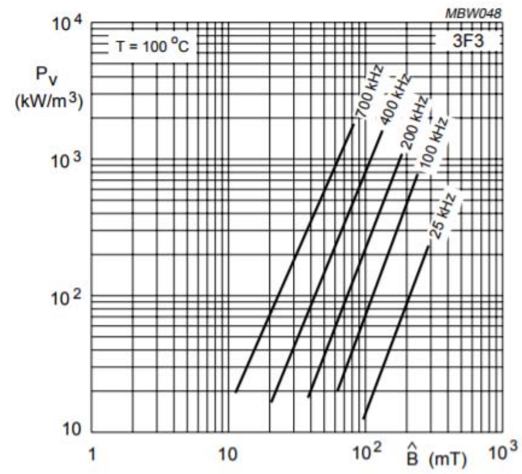

Fig. 1. Typical core loss data given by manufacturers. (Ferroxcube, no endorsement implied)

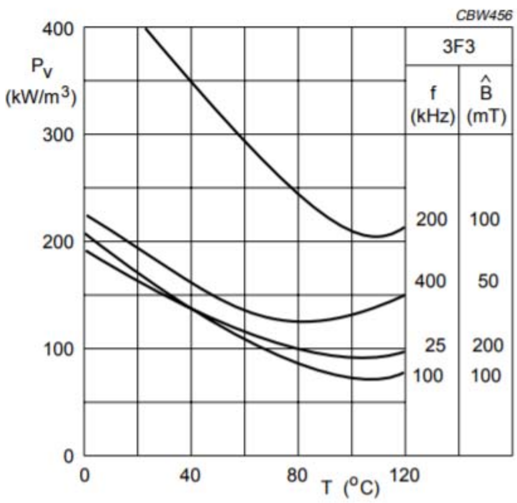

Fig. 2. Typical core loss temperature data given by manufacturers. (Ferroxcube, no endorsement implied)

An experimental equation for estimating the hot spot temperature of magnetic elements is cited by many ferrite core manufacturers as

$$T_{HS} = \left(\frac{P_t}{A_s}\right)^{0.833} \qquad (3)$$

where T_{HS} is the hot spot temperature above ambient (°C), P_t is total power loss, core loss plus wires ('copper') loss, in mW and A_s is the surface of the magnetic element (cm^2).

This experimental equation provides a coarse means to estimate the maximum temperature rise within the magnetic structure, presumably deep inside, where the thermal resistance to the outside is maximal. To calculate the hot spot temperature, one needs to know the core losses as well as the wire losses (or 'copper' losses as sometime referred to) of the magnetic element. The copper losses can be calculated from the currents through the windings and R_{ac}, that is, the resistance of the wires at the operating frequency and temperature. The R_{ac} is affected not only by the skin effect but also by the proximity effect and hence the accurate calculation of R_{ac} is rather complex. It the routine engineering work, the proximity effect is often neglected and R_{ac} is approximated by taking into account the skin effect only.

The SPICE model presented next calculates the total core loss by fixed SC SE (2) and estimates the hot spot temperature by (3), assuming that R_{ac} is given.

III. The Proposed Model

The PSPICE circuit diagram of proposed model is depicted in Fig. 3 in which an inductor (L1) is excited by a sinusoidal source V1. The voltage across L1, is used by the analog behavioral model (EVALUE) E1 to calculate the magnetic flux density by

$$B = \frac{\int V_L dt}{N * A_e} \qquad (4)$$

where N is the number of turns and A_e is the core cross section area. The integration is carried out by PSPICE operator SDT.

The calculated magnetic flux density is passed through a high pass filter (R_2 C_1) to remove any DC part. The peak of the filtered B, amplified by 1000 fold, is detected by D_1, R_3 , C_2. that produces the node voltage Bpk The purpose of the amplification is to reduce the error caused by the forward voltage drop of the diode. ABM1 calculates the core loss by (1) times the volume Ve, using the evaluated peak value of the flux density, Bpk, and the switching frequency, f, which is introduced in the PARAMETERS statement along with SC and other data. The instantaneous copper losses are calculated by ABM2: Rac times the current squares, which is then averaged by R_4 C_4 to obtain the average copper power loss. The hot spot temperature is calculated by ABM3 by (3). Care should be exercised to scale the different units in the various expressions.

The SPICE model in Fig. 3 applies the basic SE with temperature dependent SC. The temperature corrected SE can be easily set up by just changing the expression of ABM1 in Fig. 3 to the extended SE expression (2).

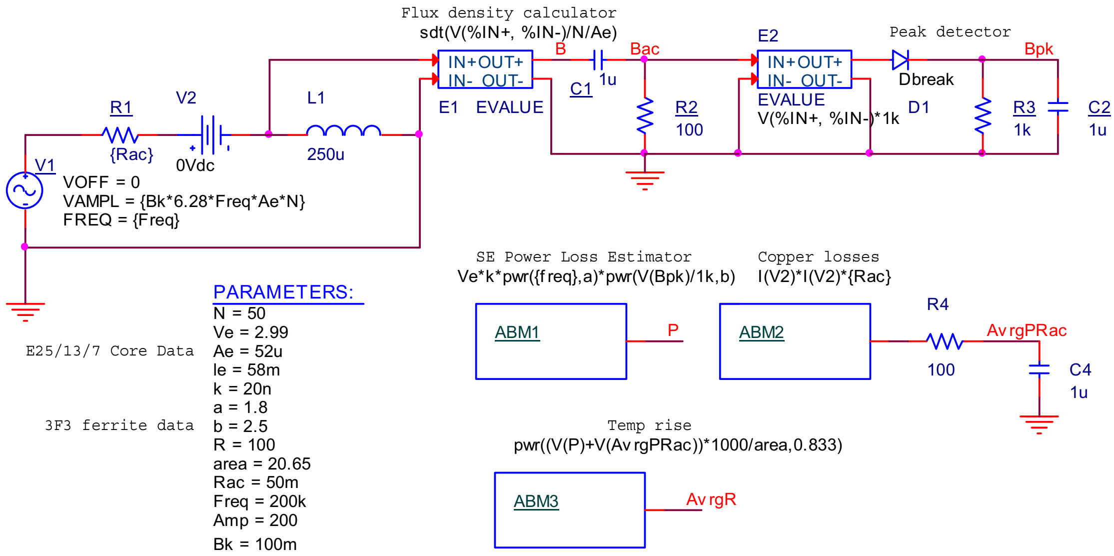

Fig. 3. Proposed model of ferrite core losses and hot spot temperature estimation.

IV. Examples

A. Sinusoidal excitation

Fig. 4 depicts simulation results of the circuit given in Fig. 3. The parameters values are as given in the PARAMETER statement. The plots clearly show the effectiveness of the DC filtering of B and that of the peak detector. Applying the PERFORMANCE ANNLYSIS capability, multiple runs can be used to construct charts similar to the ones published by ferrite core manufacturers (e.g. Fig. 1). Fig. 5 shows such a collection of data.

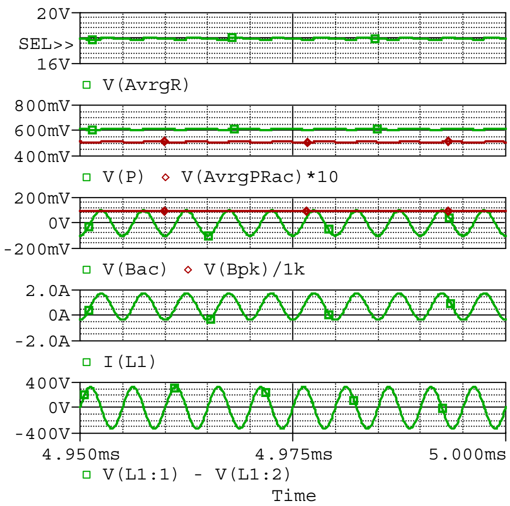

Fig. 4. Example of simulation output. See Fig. 3 for definition of curves, and PARAMETERS in that Fig. for operating conditions. Ferrite material: 3F3.

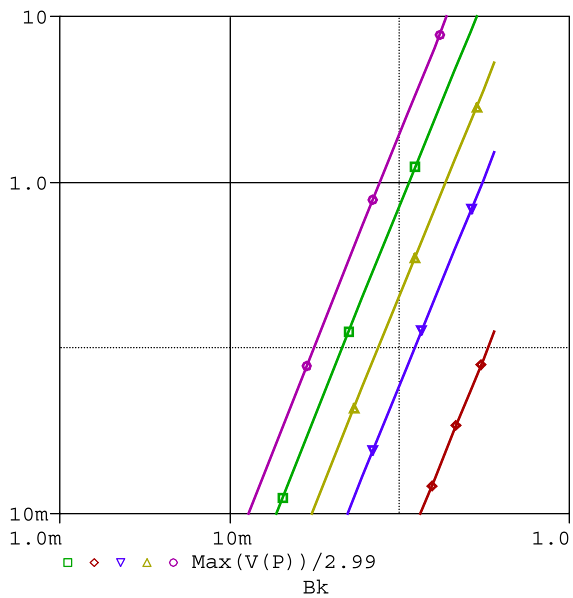

Fig. 5. Estimation of the average power loss of 3F3 E25/13/7 core by the simulation model of Fig. 3. (Compare to Fig. 1)

B. Buck converter

To further demonstrate the versatility of the proposed SPICE model, it is used to estimate the core losses and temperature rise in the inductor core of a 'Buck converter'-like circuit shown in Fig. 6, which is driven by a pulse generator with a duty cycle of 0.5. The simulation plots in Fig. 7 provide the estimated power loss and temperature rise.

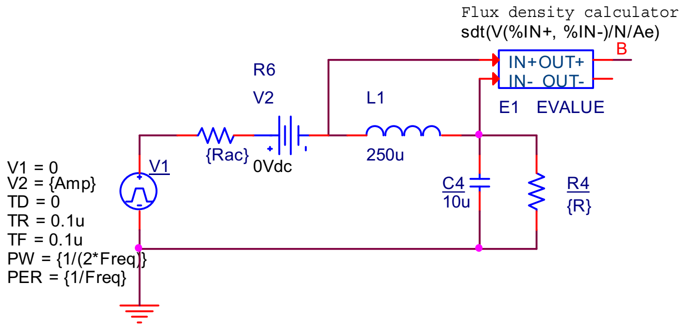

Fig. 5. Detail of Buck core loss simulation model. (The rest of the schematics is as in Fig. 3.)

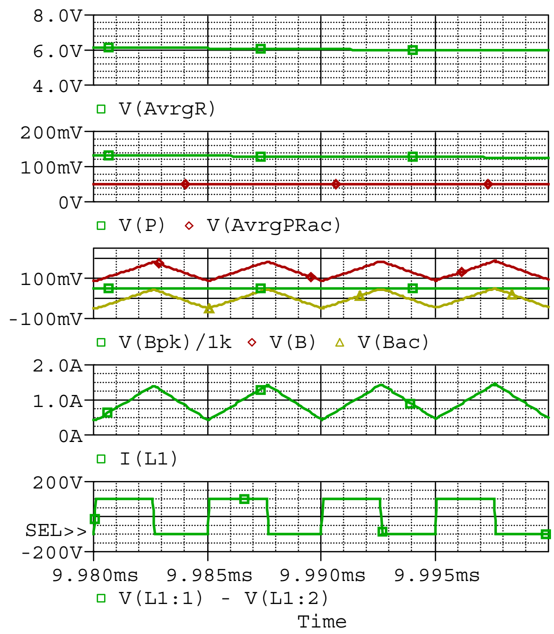

Fig. 4. Example of simulation output of Buck circuit. See Fig. 3 and Fig. 5 for definition of curves, and PARAMETERS in Fig. 3 for operating conditions. Ferrite material: 3F3.

V. Conclusion

A simple, user-friendly model is proposed to estimate ferrite core losses and the hot spot temperature by SPICE simulation. The model is based on the basic Steinmetz equation and is capable to produce, on the fly, the estimates as the operating condition of the core are changing. The SE used in this study to build the SPICE model has a limited accuracy since it does not take into account the DC bias effect and is strictly correct for sinusoidal excitation. Nonetheless, it is the most popular approach among designers since the SC are the readily available set of data.

Notwithstanding the shortcoming of the SE it is still an acceptable engineering tool and hence the proposed SPICE model could be useful to workers in the field in the design phase and when examining and tuning power conversion systems.

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