Simulation Bits: A SPICE Behavioral Model of Non-Linear Inductors©

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SPICE simulation is already recognized as a viable tool in Power Electronics. Simulation is particularly useful when dealing with a non-linear behavior that cannot be easily handled analytically. Such a case is the analysis of a switching power converter that includes a non-linear inductor that might affect the inrush current, magnitude of the current ripple, small signal transfer functions and others. Modern SPICE simulation packages, such as ORCAD (Cadence, CA, USA) include a non-linear magnetic core model that is based on the Jiles and Atherton model [1]. However, unless the vendor already provides a model for a given core, developing your own model for your specific application may prove to be very frustrating if not practically impossible.

Here we demonstrate how a SPICE compatible behavioral model of a non-linear inductor can be developed easily using core manufacturer's data or simple laboratory measurements. The resulting model is by no means perfect. It does not include core losses, temperature effects, or frequency dependence of the permeability, and it does not show the hysteresis effect. Nonetheless, one may still find it useful in many applications such as the examination of the current ripple of iron powder core inductors under various operating conditions or in small signal analysis based an behavioral average modeling [2].

The basic idea of the proposed inductor model is to reflect the behavior of a linear inductor via a non-linear 'transformer' that is realized by (E1, G1) dependent sources (Fig. 1) defined by:

$$E1 \equiv V_{pr}\frac{1}{K} = V_{sec} \qquad (1)$$

$$G1 \equiv I_{sec} = I_{pr} \qquad (2)$$

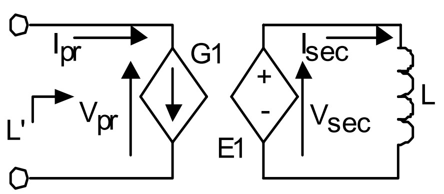

Figure 1. A non-linear inductor model built by reflecting a linear inductor via a non-linear 'transformer.'

The impedance X_L of the original inductor L is defined as:

$$X_L = \frac{V_{sec}}{I_{sec}} \qquad (3)$$

Based on Eqs (1) – (3), the inductor impedance X'_L reflected to the primary side is:

$$X'_L = \frac{V_{pr}}{I_{pr}} = \frac{K\,V_{sec}}{I_{sec}} = K\,X_L \qquad (4)$$

Consequently, the inductance L' reflected to the primary side, expressed in terms of K, is:

$$L' = L \times K \qquad (5)$$

If K is made dependent on the current through the inductor (or through a bias winding [3]), then the model will emulate the non-linearity of the device. In the modern SPICE environment, one could use behavioral dependent sources in which the dependence of K on the current can be defined as an expression ('EVALUE' or Analog Behavioral Model 'ABM' dependent sources in ORCAD) or a table ('ETABLE' element in ORCAD). The two approaches are demonstrated by considering two cases: one based on simple laboratory measurements that map the non-linearity of the device, and the other using manufacturer's data.

Method A – Experimental Fitting. In this case, one has first to carry out (incremental) inductance measurements on the physical inductor, over the expected range of inductor current. Subjecting the inductor to a dc current (I_{DC}) via an auxiliary inductor (L_{AUX}), and applying a signal generator (V_{AC}) to measure the small-signal impedance of the tested inductor (V_L/I_L) could easily accomplish this (Fig. 2).

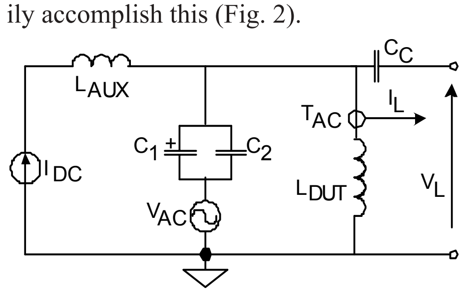

Figure 2. Experimental setup for measuring the small signal impedance of a dc biased inductor.

The results of the inductance measurements are then inserted in the ETABLE element to form the model of the non-linear inductor (Fig. 3). Notice that for simplicity L is made equal to 1 H and the values listed in ETABLE correspond to the measured inductances.

Method B – Fitting to Manufacturer's Data. In this case and for L = 1 H, K is defined by the inductance equation:

$$K = \frac{\mu_0 n^2 A_e}{L_{eng}}\mu_r(H) \qquad (6)$$

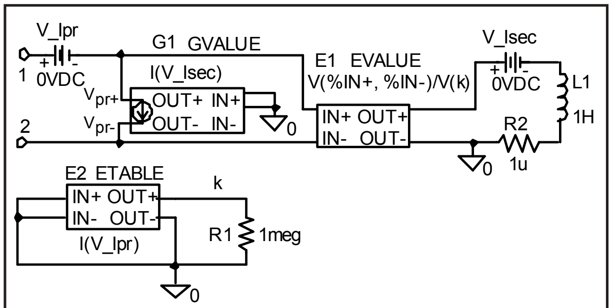

Figure 3. A non-linear inductor SPICE model based on measured inductance values. The table of the ETABLE dependent source lists the measured inductance as a function of dc current.

where μ_0 is the air permeability, A_e is the effective magnetic area of the core, L_{eng} is the effective magnetic length of the core , n is the number of turns, and $\mu_r(H)$ is the relative permeability as a function of the magnetic field H.

Core manufacturers provide the $\mu_r(H)$ information as graphs or experimental equations. If an equation is not given then the graph data could be fitted to an experimental equation or described as a table. In the latter case one can use again the ETABLE element. If the equation is available then it can be used as an expression in an EVALUE or ABM element. For example, the experimental equation given by Magnetics [4, 5] for Kool Mu cores is (after some streamlining):

$$\mu_r(H) = \mu_i\sqrt{\frac{1-5.618\times10^{-5}\beta+1.043\times10^{-10}\beta^2}{1+6.742\times10^{-5}\beta+6.21\times10^{-8}\beta^2}} \qquad (7)$$

where μ_i is the initial relative permeability, $\beta = \mu_i H$, and H is the magnetic force in Oersted units (1 Oe ≈ 80 Amp-turn/m).

The magnetic force H is in turn a function of the magnetizing current I:

$$H = \frac{nI}{L_{eng}} \qquad (8)$$

Using this experimental equation (7) along with Eqs (6) and (8) one can easily construct a SPICE model for an inductor that is built around this core (Fig. 4).

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Non-linear Inductor *from page 9*

The proposed model of a non-linear inductor is compatible with all basic SPICE analyses (DC, AC, TRAN). We have found it to reproduce faithfully the behavior of the physical core in practical applications. The method can be easily extended to cores with separate dc bias windings [3] and to represent the non-linearity of the magnetization inductance of transformers.

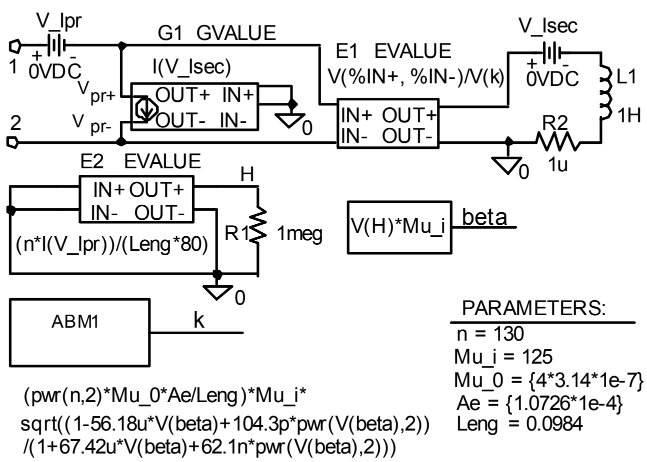

Figure 4. A non-linear inductor SPICE model based on manufacturer's data (Eq. 7) for a 77254-A7 Kool Mu iron powder core. H is calculated in MKS units and then divided by 80 to get it in Oe units as required for Eqs (7) & (8).

SPICE/ORCAD files (Evaluation Version 9.2) that include examples of the proposed inductor model can be downloaded from <u>*http://www.ee.bgu.ac.il/~pel/download.htm*</u>.

References

[1] D. C. Jiles and D. L. Atherton, "Theory of ferromagnetic hysteresis," *Journal of Magnetism and Magnetic Materials*, vol. 61, pp. 48-60, 1986.

[2] I. Zafrani, S. Ben-Yaakov, "Generalized switched inductor model (GSIM): accounting for conduction losses," *IEEE Trans. Aerospace and Electronic Systems*, vol. 38, pp. 681-687, 2002.

[3] D. Medini and S. Ben-Yaakov, "A current controlled variable inductor for high frequency resonant power circuits," in *IEEE Applied Power Electronics Conference*, APEC'94, pp. 219-225, Orlando, 1994.

[4] Powder Core Technical Data, Magnetics, PA, USA Available: <u>*http://www.mag-inc.com/pdf/MAGNETICS_Powder_Core_Technical_Data.pdf*</u>

[5] Powder Core Data, Magnetics, PA, USA <u>*http://www.mag-inc.com/pdf/MAGNETICS_Powder_Core_Data.pdf*</u>

Biographies

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Distributed Inverters *from page 8*

Stricter and better-defined specifications for small, distributed power inverters in relation with the background voltage distortion and harmonic levels in networks are required. For more information and technical results as well as some practical guidelines, see the reference below.

[1] J.H.R. Enslin and P.J.M. Heskes, "Harmonic Interaction between a Large Number of Distributed Power Inverters and the Distribution Network," in *Proceedings 34th IEEE Power Electronics Specialists Conference*, Acapulco, Mexico, June 15 – 19, 2003.

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President's Message *from page 3*

In order to provide for this kind of granularity, my predecessor Tom Habetler decided to develop our technical committees, something which I soon saw was of great value in supporting our members, and something which I also should pursue. Thus within the short space of 2 years we have gone from 6 committees to 11, and we are busily working to get them all set up with "effectiveness for our members" as the primary criterion.

So what goes on in a technical committee? We have deliberately left that without a lot of fine detail—no rules, regulations, briefs, or terms of reference—leaning rather to guidelines, with an overarching goal that they provide easy and productive ways for interaction between our members in each of these subspecialties.

To put all that in perspective, here is a list of our current technical committees including two very new ones approved by our ADCOM at the IAS annual meeting in Salt Lake City in October 2003.

PELS Technical Committees

- Automotive Power Electronics, John Shen <johnshen@umich.edu>
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- Electronic Transformers, Bill Goethe <opswest@msn.com>
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