Non-Linear Inductor SPICE Model

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Non-Ideal Inductor

Definition:
An inductive device which contain losses elements, such as core losses (hysteretic loss, eddy current loss), and copper losses (wiring losses) etc.

Non-Linear Inductor

Definition:
An inductive element which its inductance may vary due to core effect influenced by magnetic field.
Motives

- To determine the correct transfer function of circuits which both DC current and AC current flows through an inductor at the same time, such as DC-DC converters and APFC circuits.
- Simulating both large and small signal analysis for applications which consist on non-linear inductors.
- For iron powdered cores, which its inductance can be easily vary, this is the optimal solution.
- To provide to designers a useful tool for optimal core selection.
Previous work


- Non-Linear Saturable Kool Mu Core Model, Scott Frankel, Analytical Engineering Inc.

First reference:
Modeling Non-Ideal Inductors in SPICE

Offered model:

RP: Magnetic loss
CP: Self capacitance
RDC: Wire loss
LO: Nominal value
Second reference:
Non-Linear Saturable Kool Mu Core Model

• A capacitor is used to describe the inductance value
• Core parameters are described as voltage sources
• Parameters are calculated using data sheet characteristics
• Curves are found by non-linear fitting, with trial and error method.
• An excel spreadsheet is utilized in order to derive constants.
Third reference:
Beyond Designs – PSpice Non-Linear Magnetics Model

- A capacitor is used to describe the inductance value
- Geometric independent core model
- Initial inductor value has to be determined
- Treating the magnetic device as a “black box”
Previous work – disadvantages

• Complicated calculations has to be done to determine the constant losses.
• **Constant** losses are proper for a specific frequency, therefore small signal/AC analysis cannot be perform
• Models cannot be utilized in circuits which the DC current and the frequency are both varied, such as APFC circuits
Current work - goals

- Provide a well-behaved model for both transient and AC analysis.
- Model will be suited to analyze a specific inductor performance (which can be measured) as well as to analyze its performance by indicating its characteristics alone.
- Model will be easily manipulated to fit any type of magnetic element.
Permeability vs. Magnetizing force

77XXX 125 Kool Mu family

%μ VS. Magnetizing force
Model development

The inductor is described by two dependent sources, similar to an ideal transformer, however the conversion ratio is only indicated at one side.
Model development

The inductor impedance, reflected to the primary side is:

\[ X_L' = \frac{V_{pr}}{I_{pr}} = \frac{V_{pr}}{I_{sec}} \]

The inductance reflected to the primary side, expressed in terms of ‘k’ is:

\[ L' = \frac{L}{k} \]
ORCAD/SPICE implementation

- The dependent sources are described by two behavioral models of EVALUE and GVALUE.
- For the conversion ratio which describes the inductance changes due to the magnetic force, we use either a look-up table element of ETABLE, or an expression element such as ABM.

Note: Resistive elements are added in order to solve convergence problem.
ORCAD/SPICE implementation

Simulation with a lookup table

PARAMETERS:
- k = 1
- swp = 1
- n = 130
- length = 0.1
- area = 1.042
ORCAD/SPICE implementation

Simulation with an expression characteristics

PARAMETERS:

- k = 1
- swp = 1
- n = 130
- length = 0.1
- area = 1.042

\[
\text{func1} = \frac{(pwr(n,2) \times 3.14 \times pwr(10,-7) \times \text{area} \times pwr(10,-4) \times \text{length})}{\sqrt{((pwr(125,2) - 56.18u \times pwr(125,3) \times v(sw) + 104.3p \times pwr(125,4) \times pwr(v(sw),2)) / ((1+67.42u \times 125 \times v(sw) + 62.1n \times pwr(125,2) \times pwr(v(sw),2))))}}
\]
Experimental test

Test circuit:

The circuit was built in order to validate the model operation.
Experimental test

Core characteristics:

- 77254-A7 iron powder core
- Permeability (Kool Mu): 125
- Path length: 9.84 cm
- Window area: 4.27 cm²
- Area product: 4.58 cm⁴
- Inductance per 1000 twists: 168mH
Experimental test

Test conditions:

- Frequency: 31.5KHz using sine wave generator
- DC current varies from 0 to 6 amps
- Inductor current measured using a current probe
- Inductor voltage measured using a voltage probe
- Both current and voltage was measured with HP54600A digital oscilloscope
- Number of turns: 130 which provided initial inductance of 2.8mH
Experimental test

An excel spreadsheet was made with the measurements, a lookup table for the SPICE model was created.

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<th>IDC[A]</th>
<th>VL</th>
<th>IL[mA]</th>
<th>XL</th>
<th>L[mH]</th>
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</table>
Experimental test

A SPICE simulation took place, for the measured results and for an expression of permeability changes (from the MAGNETICS data sheet)

The results were almost identical (measurement error range)

Some important equations:

Kool Mu effective permeability

\[ \mu_{\text{eff}} = \sqrt{\frac{\mu_i^2 - 5.618 \times 10^{-5} \mu_i^3 H + 1.043 \times 10^{-10} \mu_i^4 H^2}{1 + 6.742 \times 10^{-5} \mu_i H + 6.21 \times 10^{-8} \mu_i^2 H^2}} \]

Inductance value

\[ L = \frac{\mu_0 \mu_{\text{eff}} n^2 A_e}{l_e} \]
Experimental test

Inductance VS. Force

The graph shows the relationship between inductance (L[H]) and H[öersteds]. The graph includes two lines:
- Red line: simulated with an expression
- Yellow line: expression values
- Blue line: simulated with measured values
- Light blue line: measured values

The y-axis represents the inductance values ranging from 3.0E-3 to 0.0E-6, while the x-axis represents the H[öersteds] values ranging from 1 to 1000.
Applications

• In order to demonstrate the qualities and versatility of this model, few examples (out of many) are presented.

• The examples show and emphasize the importance of simulating a Non-Linear inductor with a proper model.

Note: All simulations are based on the 77245 iron powder core characteristics.
Applications

The Non-Linear inductor model used in all simulations

Inductor model

Expression

Conversion unit
Applications

Determining the transfer function of a “buck” DC-DC converter.
Applications

Open loop gain for different output loads
Applications

closed loop gain and phase for two extreme cases

Po=0.5W, Ro=50Ω

Po=25W, Ro=1Ω

PM= 46

PM= -62 !!!
Applications

Transient analysis of a “boost” DC-DC converter (cycle by cycle).

The simulation with the linear inductor shows a moderate inrush current, compared to the non-linear inductor. However, the transient time until stabilization is much shorter.
Applications

Non-Linear inductor simulation

Max inrush = 10.37A

Linear inductor simulation

Max inrush = 6.4A

12A
Applications

Non-Linear inductor simulation

Ripple values in steady state

\[ \Delta I = 0.8\text{A} \]

Linear inductor simulation

\[ \Delta I = 0.32\text{A} \]

3.6A

3.2A
Applications

Parametric modulation:
Performing modulation on the input signal by changing the circuit parameters.
Applications

Parametric modulation:
Advantages

- Simple design.
- No initial inductance value need to be determined.
- The inductive element is represented by an inductor.
- The model can be simulated with any type of analysis.
- Designers don’t need to go through long, exhausting measurements and calculations to determine the inductor behavior,
  furthermore designers don’t need to have the inductor at all in order to simulate its behavior.
Improvements

• Eddy current losses and wire losses can be immediately be added to this model.
• Wire capacitance effect can be simply added if the resonance frequency is determined.
Conclusion

• The model for the non-linear inductor purposed in this work demonstrates very good the inductance changes caused by DC current changes.

• Simulating with the expression method meets the practical inductor characteristics with an exact match, while the measured method produce very close results, in the range of the measurement error.

• The model is well-behaved both in transient and AC analysis.
Thank You

THE END