PSIM Software

Tutorial on
How to Define the Saturable Core Element

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The magnetic elements in PSIM (windings, leakage paths, air gaps, and magnetic cores) provide a powerful way of modelling magnetic devices. The objective of this tutorial is to show how to define the saturable core element.

The saturable core element has the following parameters:

Inductance Factor A_L	Inductance factor A_L of the core, in H, defined as the inductance per turn squared.
Resistance for Losses	Resistance R, in Ohm, that represents the core losses
Coefficient phi_sat	Coefficient phi_sat for the core B-H curve, in Weber
Coefficient K_1	Coefficient K_1 for the core B-H curve
Coefficient K_{exp1}	Coefficient K_{exp1} for the core B-H curve
Coefficient K_2	Coefficient K_2 for the core B-H curve
Coefficient K_{exp2}	Coefficient K_{exp2} for the core B-H curve
Current Flag	Flag of the electric current that flows through the resistor R for the core losses. If the rms value of the current is Irms, the core losses can be calculated as: Pcore_loss = Irms*Irms*R.

The simulated B-H curve of the saturable core depends on the combined effect of all the parameters above. The diagram below shows how the parameters are related to the B-H curve.

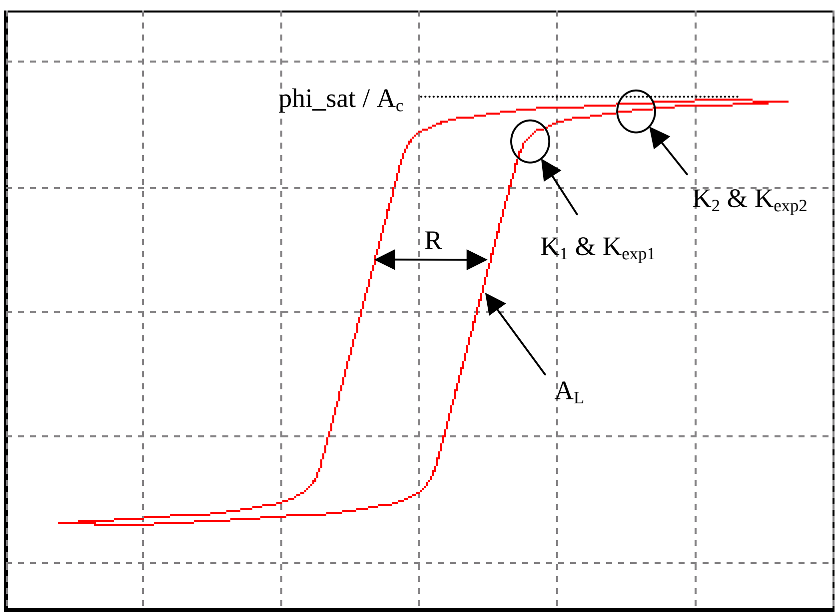

Fig. 1: The B-H curve of a saturable core

The inductance factor A_L mainly affects the slope of the B-H curve in the linear region. A larger value of A_L will result in a steeper slope.

The resistance R determines the width of the hysteresis loop. The larger the resistance, the wider the hysteresis loop.

The coefficient phi_sat is roughly equal to the core flux at the deep saturation. It can be calculated as the flux density B at the deep saturation multiplied by the core cross section area A_c.

The coefficients K_1 and K_{exp1} determine when the B-H curve starts to saturate (the first knee point), and how sharp the transition of the curve is. A good guess of K_1 is the ratio of the flux density at this point versus the flux density at the deep saturation. For example, if the flux density at this point is 0.245, and the flux density at the deep saturation is 0.35 T, the ratio will be 0.7. The initial guess of K_1 will then be 0.7.

The coefficient K_{exp1} determines how sharp the transition of the curve is around this point. The larger the value of K_{exp1}, the sharper the transition. A normal range of K_{exp1} is from 10 for low permeability ferrite to 200 for metglas.

The coefficients K_2 and K_{exp2} are associated with the second knee point in the saturation region, and are used mainly to better fit the curve in the saturation region. A good guess of K_2 is again the ratio of the flux density at this point versus the flux density at the deep saturation. The coefficients K_2 and K_{exp2} are used in rare occasions such as for ferroresonant regulators. They are normally set as $K_2 > 2$ and $K_{exp2} > 20$ to keep them from affecting the B-H curve.

To illustrate the effect of the coefficients K_2 and K_{exp2}, two B-H curves without and with the effect of K_2 and K_{exp2} are shown below. The flux density on the Y-axis is normalized so that the saturation flux density is 1.

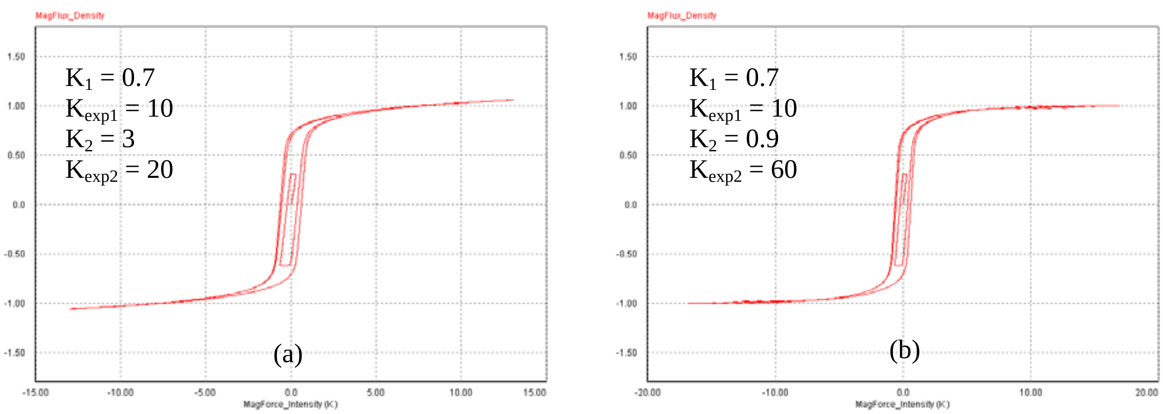

Fig. 2: The B-H curve with: (a) the effect of only K_1 and K_{exp1}; and (b) the effect of both K_1, K_{exp1}, and K_2, and K_{exp2}

Fig. 2(a) shows the B-H curve without the effect of K_2 and K_{exp2}. Notice how the curve continues to increase beyond the saturation flux density of 1. Fig. 2(b) shows the B-H curve with the effect of K_2 and K_{exp2}. In comparison, the curve in the saturation region is flatter than the previous case.

The following example is used to illustrate how to obtain the core parameters from the manufacturer datasheet.

Inductor and the Operating Conditions:

The desired inductor and the design information is as follows:

Inductance:	4.2 uH
Core:	EFD-25
	Core effective cross section area A_c = 58 mm^2
	Core effective length Length = 57 mm
	Approximate air gap inductance factor = 0.1167 uH (or gap length l_g = 0.62 mm)
Core Material:	3F3 ferrite
Number of Turns:	6
Operating Conditions:	
	Maximum current = 25 A
	Peak-to-peak current ripple = 4 A
	Switching frequency = 200 kHz

Creating the Test Circuit:

The first step is to obtain the B-H curve of the core material from manufacturers. In this example, the B-H curve from Ferroxcube (www.ferroxcube.com) for the 3F3 ferrite material is shown below.

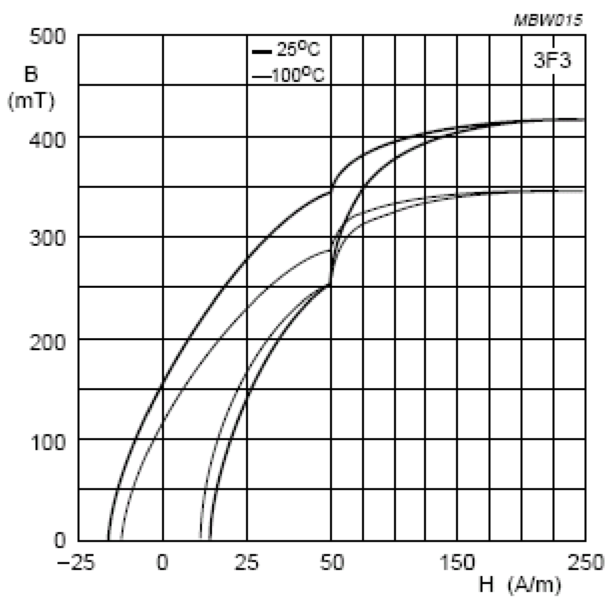

Fig. 3: The B-H curve of the 3F3 ferrite material from Ferroxcube

The next step is to create a test circuit in PSIM to simulate the core and match the simulated B-H curve with the manufacturer's B-H curve in Fig. 3. The circuit below is created to test and measure the B-H curve of the saturable core element.

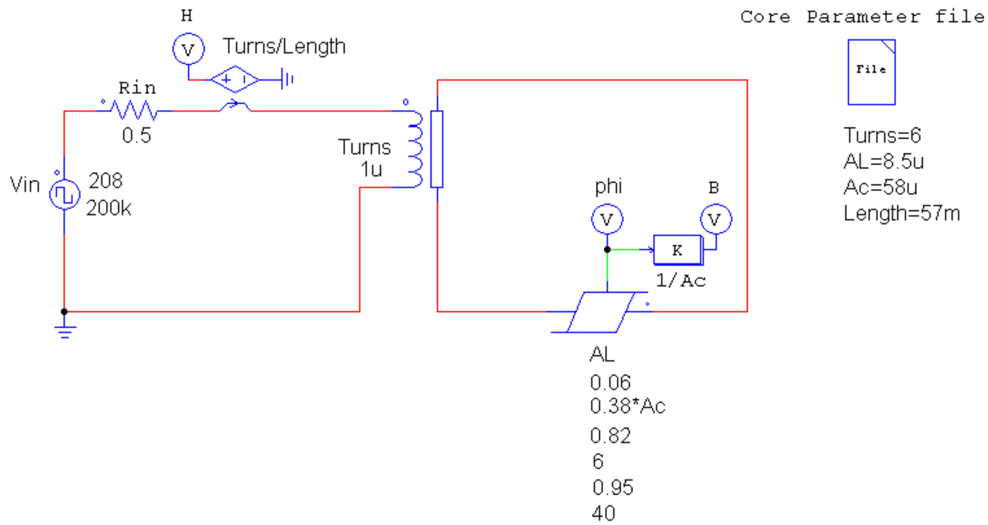

Fig. 4: Test circuit to measure the B-H curve of saturable core model

In the circuit, the values of the core parameters are from the inductor design. A square-wave voltage source is used as the test source. The peak voltage and the dc offset of the source are adjusted so that the simulated B-H curve gives the same range of the magnetizing force H as the datasheet. In this example, the range of H is from –250 to 250 A/m. The source frequency is set to be the same as the operating frequency of 200 kHz.

The resistor Rin is used to provide damping so that the circuit can quickly reach the steady state.

The extra node of the saturable core element gives the flux phi flowing through the core. By dividing the flux by the core cross section area A_c, we have the flux density B.

By multiplying the current with the number of turns and then dividing by the core length, we have the magnetizing force H.

After the circuit is simulated, we first show the flux density B in the Y axis in Simview. Then go to **Axis -> Choose X-Axis variables**, and choose H as the variable to plot the B-H curve.

Determining the Core Coefficients:

Determining the core eofficients is an iterative process. One would start with an initial guess. Then run the simulation, and compare the two B-H curves. Then go back to changes the coefficients and run the simulation again. It may take many iterations to come with a good match.

A good initial guess of the coefficients will help speed up the process. The sections below describe how the initial values are set for this example.

Inductance Factor A_L

From the EFD-25 core datasheet, we have the core area of 58 mm^2, the core length of 57 mm, and from the 3F3 ferrite datesheet, we have the relative permeability μ_r of 4000 (at 100^{o}C). Based on the information, we can calculate the core inductance factor as:

$$A_L = \frac{\mu_o \cdot \mu_r \cdot A_c}{Length}$$

which gives a value of 5.1uH. This value is used as the initial value for A_L. As it turns out, in order to better fit the B-H curve, this value needs to be increased. The final value of A_L used is 8.5 uH.

Resistance R

The resistance R determines the width of the hysteresis loop. We started with an initial value of 1 mOhm, but found that the loop area to be too small. The resistance was eventually increased to 0.06 Ohm.

Coefficient phi_sat

The coefficient phi_sat is relatively easy to determine. The flux density B at deep saturation is around 0.35 Tesla. The initial value for phi_sat was set to 0.35*A_c (where A_c is the core cross section area). After some iterations, the final value of phi_sat was set at 0.38*A_c.

Coefficient K_1, K_{exp1}, K_2, and K_{exp2}

The B-H curve from the datasheet, in Fig. 1, shows no clear transition from the linear region to the saturation region. It means that the coefficient K_{exp1} should be relatively small. By examining the B-H curve, we started with the initial guess as: $K_1 = 0.3$; $K_{exp1} = 10.$; $K_2 = 2$; and $K_{exp2} = 20$.

In this example, adjusting K_1 and K_{exp1} alone will not result in a good fit, and K_2 and K_{exp2} also need to be adjusted to obtain a better fit. After numerous iterations and trial-and-error, the set of parameters below was obtained as: $K_1 = 0.82$; $K_{exp1} = 6.$; $K_2 = 0.95$; and $K_{exp2} = 40$.

The simulated B-H curve is shown as below:

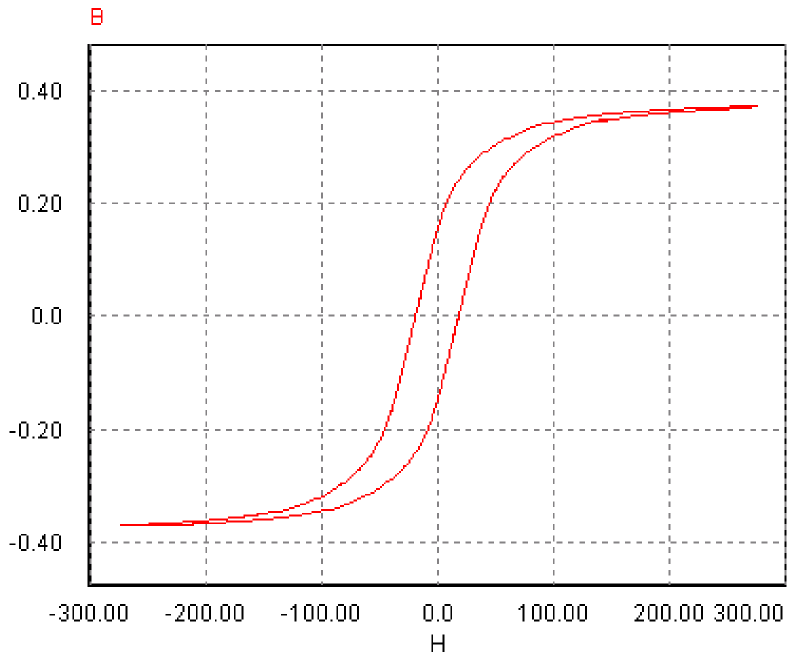

Fig. 5: The simulated B-H curve from the saturable core model

Creating the Inductor Model:

By connecting the air gap element in series with the core, we have the model for the inductor. The circuit below shows the 4.2-uH inductor in a buck converter.

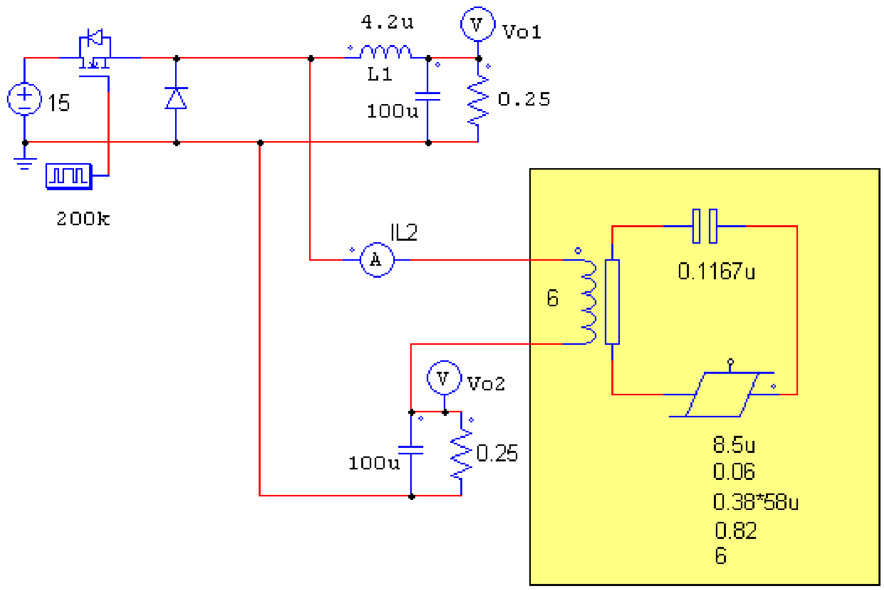

Fig. 6: The modelled inductor in a buck converter

The result of the circuit using the modelled inductor is found to be very close to the result using the ideal inductor.