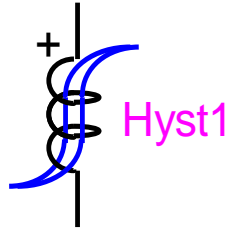


Hysteretic reactor device



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1 Available versions

The Hysteretic reactor device accepts both 1-phase and 3-phase signals. The 3-phase version is the equivalent of 3 decoupled branches (one for each phase). The only difference is that in the 3-phase version it is allowed to request scope data for the extra phases.

1.1 When changing phases

It is allowed to switch from 1-phase to 3-phase or from 3-phase to 1-phase. The user must only verify the scope requests according to requirements.

2 Description

The Hysteretic reactor is a nonlinear device designed to simulate saturation and hysteresis in the steel core of a power transformer. The theoretical background to this model is given in [1] which is also referring to [2]-[8].

2.1 Introduction

The Hysteretic reactor is modeled by a closed-form function that relates instantaneous flux to current in two steps. An intermediate flux, named unsaturated flux, is used to link these two steps. Two different equations are defined:

- A hysteresis function relating “unsaturated” flux λ_{unsat} to current. This function models the pure hysteresis effect: present state depends on

previous state. Saturation is not taken into account: the more the current increases the more the intermediate flux increases.

- A saturation function relating instantaneous flux, named “saturated” flux λ_{sat} , to “unsaturated” flux λ_{unsat} . This function is to model the saturation effect between input flux and output flux.

Hysteresis and saturation functions are based on quadratic equations and represented by hyperbolic branches. Only some parts of these branches are taken to obtain the final saturation curve.

2.2 Saturation modeling

First instantaneous flux (or saturated flux) is linked with unsaturated flux. The saturation equation introduces saturation effect in this model:

$$C_{\text{sat}} = \left[\lambda_{\text{unsat}} - \frac{\lambda_{\text{sat}}}{S_{\text{sv}}} - X_{\text{sv}} \right] \left[S_{\text{sh}} \lambda_{\text{unsat}} - \lambda_{\text{sat}} + Y_{\text{sh}} \right] \quad (1)$$

The first two parts of this quadratic equation define 2 asymptotes. It is a hyperbolic function with 2 asymptotes: vertical and horizontal. The vertical asymptote is given by:

$$\lambda_{\text{unsat}} - \frac{\lambda_{\text{sat}}}{S_{\text{sv}}} - X_{\text{sv}} = 0 \quad (2)$$

which is equivalent to:

$$\lambda_{\text{sat}} = S_{\text{sv}} (\lambda_{\text{unsat}} - X_{\text{sv}}) \quad (3)$$

It is a straight line with slope S_{sv} and x-axis intercept X_{sv} .

The horizontal asymptote is defined by:

$$S_{\text{sh}} \lambda_{\text{unsat}} - \lambda_{\text{sat}} + Y_{\text{sh}} = 0 \quad (4)$$

which is equivalent to:

$$\lambda_{\text{sat}} = S_{\text{sh}} \lambda_{\text{unsat}} + Y_{\text{sh}} \quad (5)$$

It is a straight line with slope S_{sh} and y-axis intercept Y_{sh} .

C_{sat} is the curvature of the curve. The smaller is C_{sat} the closer is the curve to its asymptotes.

The asymptotes are defined with their slopes and axis intercepts. S_{sh} is the slope of high saturation. It is related to the permeability μ_0 .

When the main shape of the saturation curve is defined, one branch will be chosen to be the final saturation curve. The concave branch will be taken for positive values of saturated and unsaturated flux. For negative values of flux, symmetry on the saturated branch is performed. As a consequence the final saturation curve passes through the origin (see Figure 1). No remnant flux is taken into account; it will be modeled with the hysteresis effect.

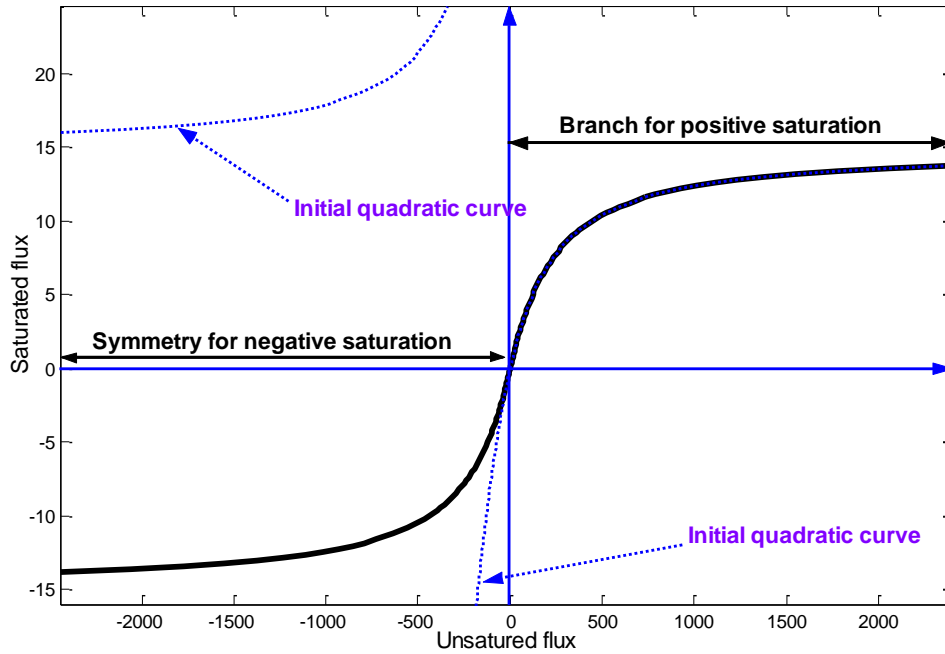


Figure 1 Saturation function

2.3 Hysteresis modeling

The hysteresis modeling is to find a relation between the instantaneous flux and the current in the transformer. In this model saturation and hysteresis are decoupled. The saturation curve is represented by pieces of quadratic branches. It links the instantaneous flux, named saturated flux, and an intermediate flux, named unsaturated flux.

In the same way pure hysteresis is modeled with a quadratic equation giving the unsaturated flux as a function of current:

$$C_{\text{hyst}} = \left[i - \frac{\lambda_{\text{unsat}}}{S_{\text{hv}}} - X_{\text{hv}} \right] \left[S_{\text{hh}}i - \lambda_{\text{unsat}} + Y_{\text{hh}} \right] \quad (6)$$

This equation is of the same shape as the saturation equation.

The first two parts of this quadratic equation define 2 asymptotes. The vertical asymptote is defined by:

$$i - \frac{\lambda_{\text{unsat}}}{S_{\text{hv}}} - X_{\text{hv}} = 0 \quad (7)$$

which is equivalent to:

$$\lambda_{\text{unsat}} = S_{\text{hv}}(i - X_{\text{hv}}) \quad (8)$$

It is a straight line with slope S_{hv} and x-axis intercept X_{hv} . The horizontal asymptote is defined by:

$$S_{\text{hh}}i - \lambda_{\text{unsat}} + Y_{\text{hh}} = 0 \quad (9)$$

which is equivalent to:

$$\lambda_{\text{unsat}} = S_{\text{hh}}i + Y_{\text{hh}} \quad (10)$$

It is a straight line with slope S_{hh} and y-axis intercept Y_{hh} .

C_{hyst} is the curvature of the curve. The smaller is C_{hyst} the closer is the curve to its asymptotes.

When the main shape of the hysteresis curve is defined, the convex branch will be chosen for upward trajectory and the concave branch for downward trajectory. But these two branches cannot define a closed shape. A translation of this hysteresis curve will give the width of the loop. To translate the curve it is needed to translate the asymptotes. The slopes of the asymptotes do not change, but the axis intercepts will change their sign. As a consequence the translated curve is defined by:

$$C_{\text{hyst}} = \left[i - \frac{\lambda_{\text{unsat}}}{S_{\text{hv}}} + X_{\text{hv}} \right] [S_{\text{hh}}i - \lambda_{\text{unsat}} + Y_{\text{hh}}] \quad (11)$$

Figure 2 shows the initial curve (solid blue lines) and the translated curves (red lines). The upward and downward trajectories form the hysteresis loop.

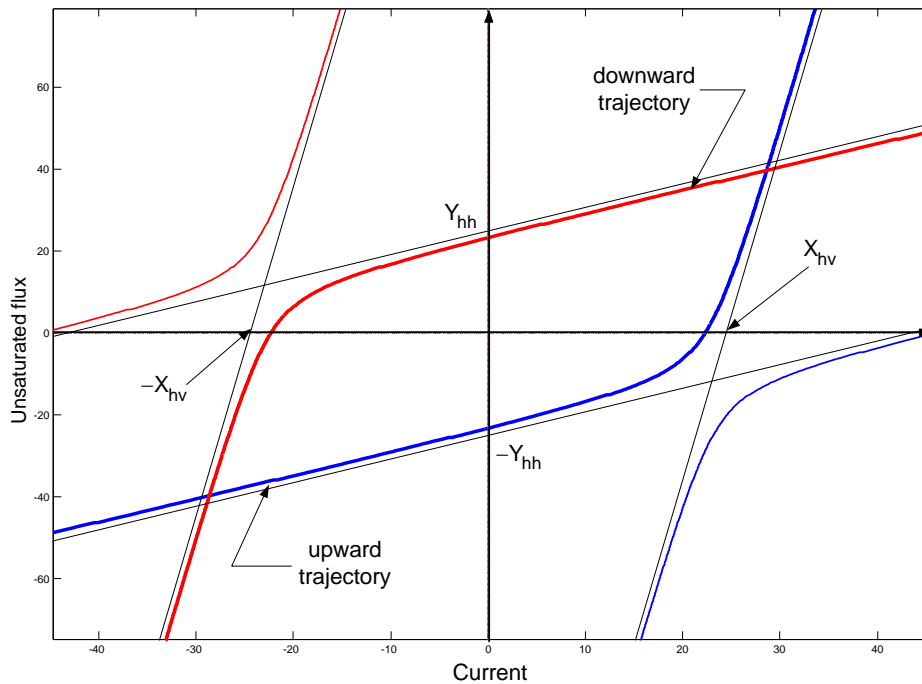


Figure 2 Hysteresis function

3 Parameters and Rules

The first data tab allows selecting initialization options and entering the model parameters.

□ The initialization options are:

- If **Connected in steady-state** is selected, it means that a **Steady-state inductance** L_{ss} is used for the linear harmonic steady-state solution. The Hysteretic reactor is automatically replaced by a linear inductance for the steady-state solution. If L_{ss} is zero, then the reactor is disconnected in the steady-solution. If L_{ss} is positive, then its value will be used for steady-state initialization. If L_{ss} is any negative number, then EMTF will select the linear inductance value automatically. The mean slope of the major hysteresis loop will be taken. If a parameter (undetermined value) is used then this option is activated when the parameter takes a non-zero value.

- **Initial flux** (φ_0): this option allows to select manually the initial flux φ_0 at $t=0$ and for zero current. If this value is greater than the remnant flux defined by the major hysteresis loop, EMTP will take the remnant flux. The initial direction of the flux trajectory will depend on the initial conditions of the rest of the network connected to this device. If zero is specified then there are no initial conditions. If a parameter is entered instead of a fixed value, then this option is activated (overrides the other selections) when the parameter is given a non-zero value.
 - **No initial conditions**: means that this device is disconnected in the steady-state solution and the initial flux is zero.
- The Model Data section is used to enter the model parameters. The following data fields can be obtained from the Hysteresis Fitter device (See Hysteresis Fitter Help and equations above) :
- S_{hv} : slope of hysteresis vertical asymptote, must be strictly positive
 - S_{hh} : slope of hysteresis horizontal asymptote
 - C_{hyst} : Curvature of the hysteresis curve, must be strictly positive
 - Coer : Half width of major loop, must be strictly positive
 - S_{sv} : slope of saturation vertical asymptote, must be strictly positive
 - S_{sh} : slope of saturation horizontal asymptote, must be strictly positive
 - C_{sat} : Curvature of the saturation curve, must be strictly positive
 - Y_{hh} : X-axis intercept of saturation horizontal asymptote

The “Load data from file” option allows loading data from the data files generated by the Hysteresis Fitter. These files have the extension “.hys”. Only data for the first Data tab can be loaded and only for the “Model data” section.

It is not allowed to delete any pins.

4 Netlist format

Example of data:

```
_Hyst;Hyst1;2;2;s1,s2,
1,-1,0,1e-06,?v,?i,?p,?f,
75 10 856 8
561 6 315870. 340
```

Field	Description
<u>Hyst</u>	Part name
Hyst1	Instance name, any name.
2	Total number of pins
2	Number of pins given in this data section
S1	Signal name connected to k-pin, any name
S2	Signal name connected to m-pin, any name
Initialization option	1 is for “Connected in steady-state” 2 is for “Initial flux (φ_0)” 3 is for “No initial conditions”
Steady-state inductance	Entered L_{ss} data
Initial flux	Entered φ_0 data.
tolerance	Relative tolerance, from the “Convergence” data tab
?v	Request for voltage scope, sent to scope group vb (branch voltages), optional
?i	Request for current scope, sent to scope group ib (branch

	currents), optional
?p	Request for power scope, sent to scope group p (branch power), optional
?f	Request for flux scope, sent to scope group flux (phi), optional
Model data	The model data. On the first line : S_{hv} , S_{hh} , C_{hyst} , $Coer$ On the second line : S_{sv} , S_{sh} , C_{sat} , Y_{hh}

In the 3-phase case EMTPWorks automatically appends the phase characters to device names and signal names and creates 3 separate devices sharing the same data. The extra phase lines are used to carry scope and observe requests in addition to connectivity.

The comma separated data fields are saved into ParamsA, ParamsB and ParamsC attributes of this device. The model parameters are saved in the ModelData attribute.

5 Steady-state model

The steady-state model is given by a linear reactance $j\omega L_{ss}$ calculated as explained above and for the “Connected in steady-state” option. The frequency ω may take more than one value in the linear steady-state harmonic superposition option.

6 Initial conditions

The initialization options are available in the “Initialization” data section described above.

7 Frequency Scan model

When the “Connected in steady-state” option is selected, the reactance $j\omega L_{ss}$ is calculated at each frequency imposed by the frequency scan option.

8 Time domain representation

In the time-domain solution this device is a nonlinear function. It is solved through the iterative process of EMTP until convergence according to the relative tolerance option for the given device.

9 References

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