3-phase transformers, 3 separate 1-phase units

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1   Description

Severable 3-phase transformer winding connections are available in the library transformers.clf. These transformers are based on a subnetwork design with masking for allowing to enter nameplate input data. The basic version in which the various connections can be selected is shown in Figure 1.

All connection types are using their own copy of the standard non-ideal unit shown in Figure 2. This subnetwork unit is fully parameterized to allow changing its data from the mask. In each transformer there are 3 identical (unique) 1-phase unit subnetworks, 1 for each phase. The subnetworks are masked to allow receiving and sending 3 possibly different initial flux conditions in the nonlinear inductance. The flux values are entered on the top level mask in the tab "IC". The nonlinear inductance device is also programmed using variables Phi0 for optional initial flux, ILnonl and PhiLnonl, as shown in Figure 3.

When several transformers of the same type are dragged into a design, only one internal subnetwork copy is available by default. If it is desired to make modifications in one of the transformers, it must be recalled that the changes will automatically propagate to all other transformers of the same type. If it is desired to modify one type without affecting the others, then the selected transformer subnetworks (all levels) must be first made into a unique type by using the menu "Options>Part Type>Make Unique Type". It is strongly recommended to maintain appropriate new type names and symbols to distinguish modified devices.

To view the subnetwork contents of a transformer dragged in from the library, it is first required to unlock the opening of the subnetwork. The subnetwork opening can be unlocked by selecting the transformer and then the menu "Options>Properties" or by using the shortcut key "CTRL-I" or by right-clicking on the device and selecting "Properties". The device info panel has a checkbox "Lock opening subcircuit". When the subnetwork becomes unclocked the "Push Into" ("Ctrl+Shift+I" keyboard shortcut) is used to open the subnetwork. The same procedure can be applied to all subnetwork levels.
The subnetwork transformer subnetwork contents allow visualizing its internal connectivity for various transformer types.

DY

315/120
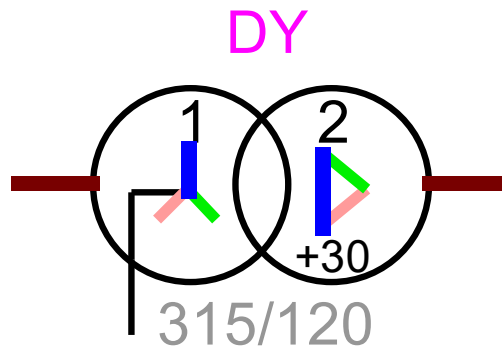
Figure 1 Available 3-phase transformers with 3 separate 1-phase units, library transformers.clf

RL1

Lmag_scope

Trans

RL2

#R1#/#L1#

W1_scope

#Rm#   Rmag

Lmag

#R2#/#L2#

W2_scope
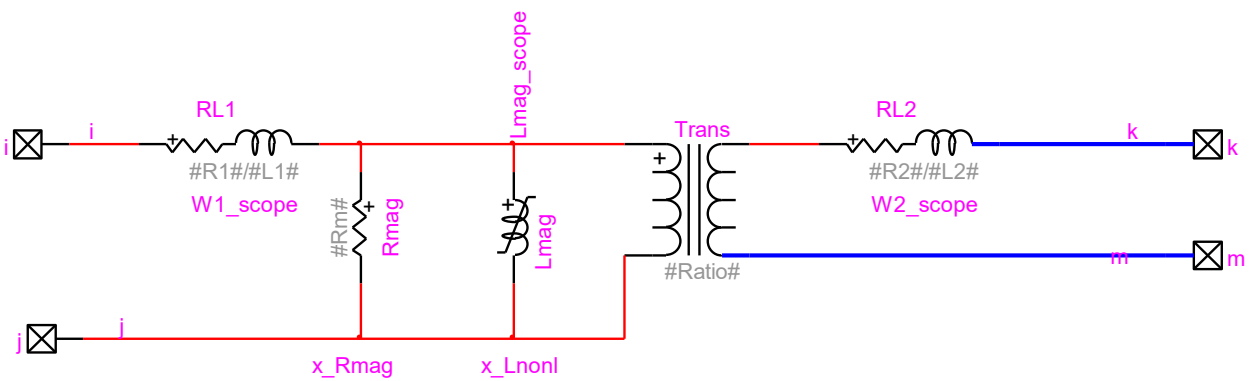
#Ratio#

x_Rmag

x_Lnonl

Figure 2 The basic building block device copied and used in all transformer devices of Figure 1
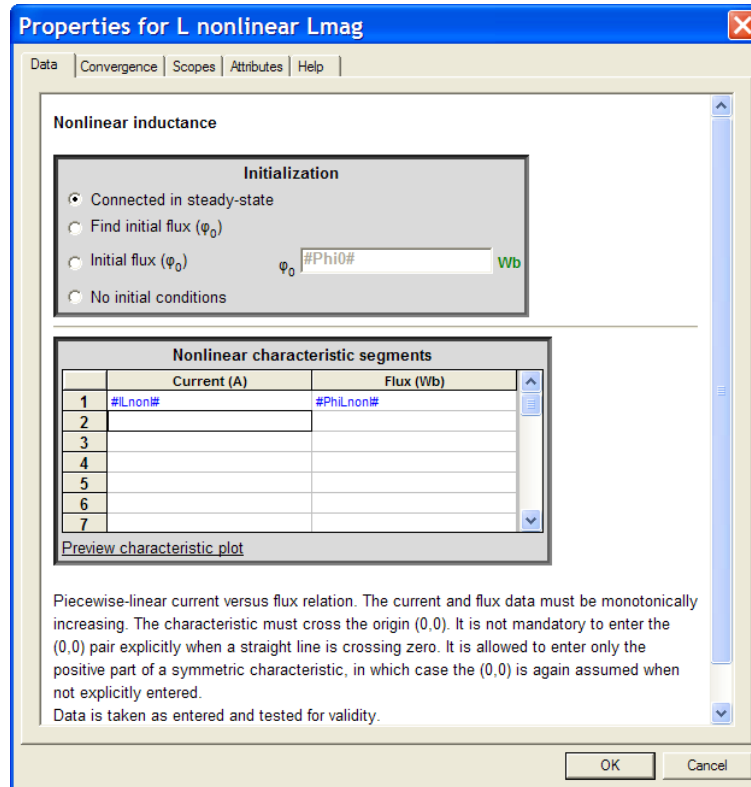
Figure 3 The nonlinear inductance programmable data forms

2   Parameters

The masks for all transformer connections of Figure 1 are the same, but the data conversion scripts are different. The device attribute Script.Open.Dev names the script used for each device. The common variables are:

- ❑   Nominal power: base power S_b
- ❑   Nominal frequency: f
- ❑   Winding 1 voltage: base voltage V_{b_1} of winding 1, RMS line-to-line voltage
- ❑   Winding 2 voltage: base voltage V_{b_2} of winding 2, RMS line-to-line voltage
- ❑   Winding R: R. Can be calculated by divided the load losses by the power base:
  R(pu) = Ploss (kW) / (Sbase (MVA) * 1000)
- ❑   Winding X: X. Can be calculated with the short-circuit impedance:
  Z_sc (%) = sqrt(X(pu)^2+R(pu)^2) * 100.
  A common approximation is to set X(pu) = Z_sc(%) since R << X
- ❑   Winding 1 R: R_1
- ❑   Winding 1 X: X_1
- ❑   Winding impedance on winding 1: Ratio D_w
- ❑   Use transformation ratio for R and X on winding 2: when this option is checked, the impedances on the secondary winding are calculated using the transformation ratio, see below
- ❑   Winding 2 R: R_2 , optional, when D_w is not used
- ❑   Winding 2 X: X_2 , optional, when D_w is not used
- ❑   Tap ratio: Tap ratio of the transformer. Increasing the tap ratio increases the voltage on the secondary side.
- ❑   Magnetization data: Definition options of the magnetization curve.
  - if Current-Voltage is selected, enter the excitation test current-voltage points (RMS measurements).

- if Current-Flux is selected, enter the current-flux curve of the magnetization inductance (instantaneous values).
When Current-Voltage is selected, the instantaneous current-flux point values are available in the PhiLnonl and ILnonl variable definitions in the ModelData attribute (right-click on the device/Attributes...)
- ❑ Current magnitude: Current $\mathbf{i_{mag}}$ (vector) in saturation characteristic, time-domain data
- ❑ Flux magnitude: Flux $\boldsymbol{\varphi}$ (vector) in saturation characteristic, time-domain data
- ❑ Add air-core inductance segment: Add a segment to the magnetization curve defined in the table. The air-core inductance is the winding inductance without the core. It dictates the behavior of the transformer when the core is fully saturated. Open-circuit tests are commonly carried up to 110% or 115% of nominal voltage which is enough to defined the saturation curve elbow, but not enough to determine the air-core reactance. The air-core reactance value has a significant impact on results for studies where the transformer saturates (i.e. transformer energizations, ferroresonance). This value is very often missing from transformer data sheet. When it is the case, data assimilation or sensitivity analysis must be carried. Its value is typically close to 0.3pu but can vary from 0.2pu to 0.9pu.
- ❑ Lsat: Air-core inductance value.
- ❑ Magnetization resistance: R_{mag}

The initial flux conditions are entered on the second data tab:
- ❑ Initial flux (φ_0) phase A: φ_{0_a}
- ❑ Initial flux (φ_0) phase B: φ_{0_b}
- ❑ Initial flux (φ_0) phase C: φ_{0_c}

When winding data is not given in pu and the D_w is not used, then the entered data is directly transmitted to the building block of Figure 2 using ohms and henrys:

$$R1 = R_1 \tag{1}$$
$$X1 = X_1 \tag{2}$$
$$R2 = R_2 \tag{3}$$
$$X2 = X_2 \tag{4}$$

When the D_w ratio is turned on:

$$R1 = D_w R \tag{5}$$
$$X1 = D_w X \tag{6}$$
$$R2 = (1 - D_w)R \tag{7}$$
$$X2 = (1 - D_w)X \tag{8}$$

When D_w is checked and the units of R are not in pu, then the conversion in (7) is given by:

$$R2 = m^2 (1 - D_w)R \tag{9}$$

The transformation ratio m is calculated from V_{b_1} and V_{b_2} and accounts for transformer connection type. The same treatment is used when X is not in pu.

When pu units are used then it is needed to convert back into default units for all quantities. The conversion method is related to the actual transformer connections. The common impedance base quantities are given by:

$$Z_{b_1} = \frac{V_{b_1}^2}{S_b} \tag{10}$$

$$Z_{b_2} = \frac{V_{b_2}^2}{S_b} \tag{11}$$

The common current base (line-to-neutral) on the primary side is given by:

$$i_{b_1} = \frac{1000\,S_b}{\sqrt{3}V_{b_1}} \tag{12}$$

2.1 "DD": Delta-Delta Connection Type

The conversion from pu is given by:

$$C_1 = 3 \tag{13}$$

$$C_2 = 3 \tag{14}$$

$$R1 = C_1 R Z_{b_1} D_w \tag{15}$$

$$R2 = C_2 R Z_{b_2} \left(1 - D_w\right) \tag{16}$$

$$X1 = C_1 X Z_{b_1} D_w \tag{17}$$

$$X2 = C_2 X Z_{b_2} \left(1 - D_w\right) \tag{18}$$

The magnetization branch is located on the winding 1 side:

$$Rm = C_1 R_{mag} Z_{b_1} \tag{19}$$

The nonlinear characteristic flux vector is converted using:

$$PhiLnonl = \frac{1000\sqrt{2}\ V_{b_1}}{2\pi f}\,\boldsymbol{\varphi} \tag{20}$$

A similar transformation is used for Phi0 when converting from φ_{0_a}, φ_{0_b} or φ_{0_c}.

The nonlinear characteristic current vector is converted using:

$$ILnonl = \frac{\sqrt{2}}{\sqrt{3}} i_{b1}\ \mathbf{i_{mag}} \tag{21}$$

The ratio parameter is given by:

$$Ratio = \frac{V_{b_2}}{V_{b_1}} \tag{22}$$

2.2 "DY +30", "DY -30", "DYg +30" and "DYg -30": Delta-Wye Connection Types

Winding 1 is Delta and winding 2 is Wye. The saturation branch is located in winding 1.
The equations (15) to (19) are repeated with $C_1 = 3$ and $C_2 = 1$.
The equations (20) and (21) remain unchanged.
The ratio parameter is given by:

$$Ratio = \frac{V_{b_2}}{V_{b_1}\sqrt{3}} \tag{23}$$

2.3 "YD +30", "YD -30", "YgD +30" and "YgD -30": Wye-Delta Connection Types

Winding 1 is Wye and winding 2 is Delta. The saturation branch is located in winding 1.
The equations (15) to (19) are repeated with $C_1 = 1$ and $C_2 = 3$.
Equation (20) is now given by:

$$PhiLnonl = \frac{1000\sqrt{2}\ V_{b_1}}{2\pi f\sqrt{3}}\,\boldsymbol{\varphi} \tag{24}$$

Equation (21) is replaced by:

$$ILnonl = \sqrt{2}i_{b_1}\ \mathbf{i_{mag}} \tag{25}$$

The ratio parameter is given by:

$$Ratio = \frac{V_{b_2}}{V_{b_1}}\sqrt{3} \tag{26}$$

2.4 "YY" and "YgYg": Wye-Wye Connection Types

Winding 1 is Wye and winding 2 is Wye. The saturation branch is located in winding 1.
The equations (15) to (19) are repeated with $C_1 = 1$ and $C_2 = 1$.
The flux and current conversion equations are given by equations (24) and (25).
The ratio parameter is given by:

$$Ratio = \frac{V_{b_2}}{V_{b_1}} \tag{27}$$

2.5 Rules

It is allowed to enter 0 for primary and secondary winding impedances, such conditions require however solving ideal networks and may result in mathematically impossible conditions and create numerical instability problems.
It is not allowed to delete pins.
Since entered data is not transmitted directly to the Netlist, but translated through a script, it is not possible to enter variables in data fields. Entering variables will result in error messages during the EMTP execution.
It is however, possible to program the mask of this device using scripting methods and mask exporting.

3 Netlist format

This device allows method-based scripting. The object data and methods are described in the script file referenced by the device Script.Open.Dev attribute.
The mask of this device is based on scripting.
Since entered data is not transmitted directly to the Netlist, but translated through a script, it is not possible to enter variables (named values) in data fields. It is however feasible to program the device mask from an upper circuit level using scripting methods.

The Netlist format for the "DY +30 nameplate input O" default data version is given by:

```
@DYp30_O_8f5d01c7;DY_2;7;s4a,s4b,s4c,s5a,s5b,s5c,s6,
R1=5.023265625;
L1=0.5329850364548994;
Rm=744187.5;
PhiLnonl=[1181.665164956202 1270.2900523279172 1358.9149396996322 1417.9981979474423
1453.4481528961284 2032.4640837246675];
ILnonl=[0.598608915290199 2.9930445764509947 7.482611441127488 14.965222882254975
29.93044576450995
598.608915290199];
Lnonl='Lnonl';
Rmag='RLC';
R2=0.026999999999999996;
L2=0.0028647889756541152;
Phiss01=0;
Phiss02=0;
Phiss03=0;
Ratio=0.219942959691286;
Lmag_scope=";
W1_scope =";
```

```
W2_scope ='';
```

The above Netlist is based on the EMTPWorks black-box device format. Programmable scopes are used to turn on scope requests from the lower level subnetwork circuit devices.

Device data is transmitted through the ModelData attribute.

4   Steady-state model

Steady-state representation based on subnetwork contents.

5   Initial conditions

Automatic initial conditions are found from the steady-state solution. Manual initial conditions can be provided for individual transformer phase unit fluxes.

6   Frequency Scan model

Steady-state representation based on subnetwork contents for each frequency.

7   Time-domain model

Time-domain representation based on subnetwork contents.