3-phase, 3 winding transformers, based on 1-phase units

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1   Description

These transformer models 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 available transformer versions are given in Figure 1. Some devices are available for convenience with two different symbols: winding symbol and round (O) symbol. The subnetworks of such devices are saved with a different type and different internal types for all levels, so in addition to the symbol, these devices must be considered as completely independent in a design.

All devices 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". This procedure must be applied top-down for all subnetworks to create a completely detached device. 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.
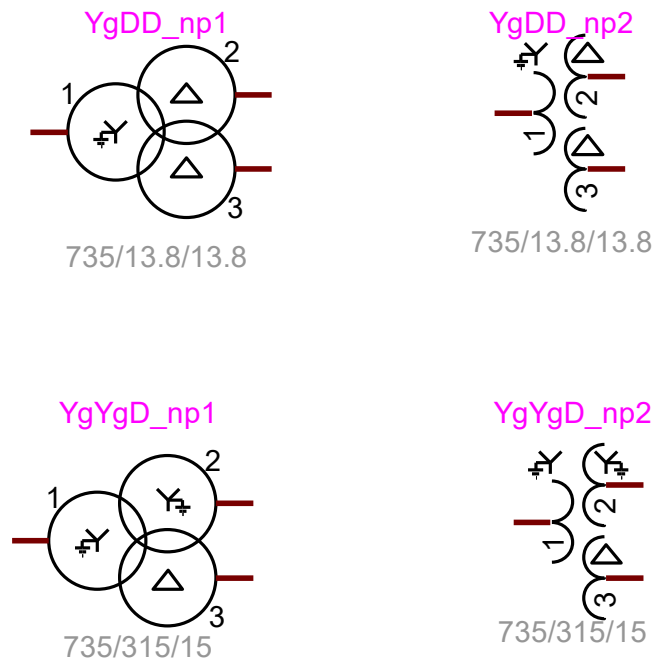
YgDD_np1

735/13.8/13.8

YgDD_np2

735/13.8/13.8

YgYgD_np1

735/315/15

YgYgD_np2

735/315/15

Figure 1 Available 3-phase, 3 windings transformers, library transformers.clf

RL1

#RW1#/#LW1#

W1_scope

#Rm#

Rmag

x_Rmag

Lmag_scope

Lmag

x_Lnonl

Tr0_1

#V1#

Tr0

#V2#

#V3#

W2_scope

RL2

#RW2#/#LW2#

RL3

#RW3#/#LW3#

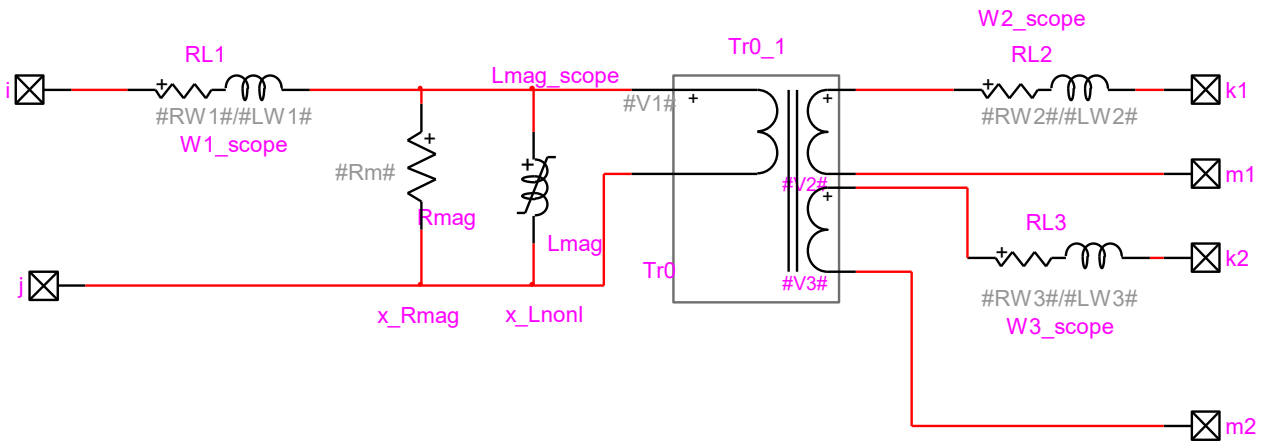W3_scope

i

j

k1

m1

k2

m2

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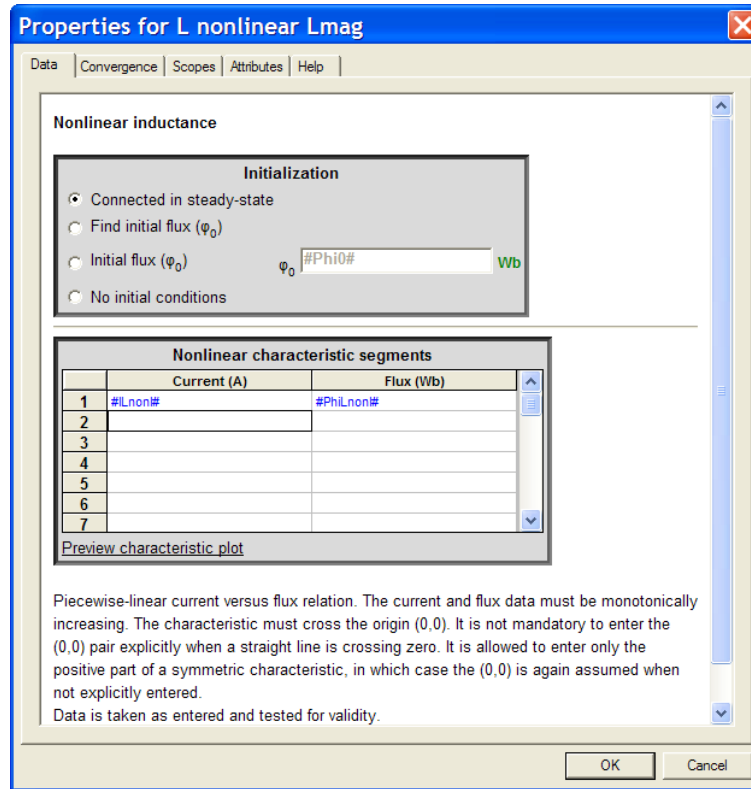
Figure 3 The nonlinear inductance programmable data forms

2   Parameters

The masks for all transformers 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 frequency: f
- Nominal power for winding 1:   base power S_{b_1} for winding 1
- Nominal power for winding 2:   base power S_{b_2} for winding 2
- Nominal power for winding 3:   base power S_{b_3} for winding 3
- 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 3 voltage: base voltage V_{b_3} of winding 3, RMS line-to-line voltage
- Winding 1 R: R_1 or R_{12} when pu is used
- Winding 2 R: R_2 or R_{13} when pu is used
- Winding 3 R: R_3 or R_{23} when pu is used

  Resistances Can be calculated by divided the load losses by the power base:
  R(pu) = Ploss (kW) / (Sbase (MVA) * 1000)

- Winding 1 X: X_1 or X_{12} when pu is used
- Winding 2 X: X_2 or X_{13} when pu is used
- Winding 3 X: X_3 or X_{23} when pu is used

  Admittances 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

- ❑ 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 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 MVA base is chosen as:

$$S_{common} = S_{b_1} \tag{1}$$

The common impedance base quantities are given by:

$$Z_{b_1} = \frac{V_{b_1}^2}{S_{common}} \tag{2}$$

$$Z_{b_2} = \frac{V_{b_2}^2}{S_{common}} \tag{3}$$

$$Z_{b_3} = \frac{V_{b_3}^2}{S_{common}} \tag{4}$$

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

$$i_{b_1} = \frac{1000\, S_b}{\sqrt{3}V_{b_1}} \tag{5}$$

2.1 "YgYgD": Wye-Wye-Delta with ground in Wye

The conversion from pu is given by:

$$R_1 = \frac{1}{2}\left[\frac{R_{12}}{S_{b_1}} + \frac{R_{13}}{S_{b_2}} - \frac{R_{23}}{S_{b_3}}\right]S_{common}Z_{b_1} \tag{6}$$

$$R_2 = \frac{1}{2}\left[\frac{R_{12}}{S_{b_1}} - \frac{R_{13}}{S_{b_2}} + \frac{R_{23}}{S_{b_3}}\right]S_{common}Z_{b_2} \tag{7}$$

$$R_3 = \frac{3}{2}\left[-\frac{R_{12}}{S_{b_1}} + \frac{R_{13}}{S_{b_2}} + \frac{R_{23}}{S_{b_3}}\right]S_{common}Z_{b_3} \tag{8}$$

$$L_1 = \frac{1}{2}\left[\frac{X_{12}}{S_{b_1}} + \frac{X_{13}}{S_{b_2}} - \frac{X_{23}}{S_{b_3}}\right]\frac{S_{common}Z_{b_1}}{2\pi f} \tag{9}$$

$$L_2 = \frac{1}{2}\left[\frac{X_{12}}{S_{b_1}} - \frac{X_{13}}{S_{b_2}} + \frac{X_{23}}{S_{b_3}}\right]\frac{S_{common}Z_{b_2}}{2\pi f} \tag{10}$$

$$L_3 = \frac{3}{2}\left[-\frac{X_{12}}{S_{b_1}} + \frac{X_{13}}{S_{b_2}} + \frac{X_{23}}{S_{b_3}}\right]\frac{S_{common}Z_{b_3}}{2\pi f} \tag{11}$$

R_1 is actually RW1 in Figure 2, this is also the case for the other R and L variables.
The magnetization branch is located on the winding 1 side:

$$Rm = R_{mag}Z_{b_1} \tag{12}$$

The nonlinear characteristic flux vector is converted using:

$$PhiLnonl = \frac{1000\sqrt{2}\ V_{b_1}}{2\pi f\sqrt{3}}\ \boldsymbol{\varphi} \tag{13}$$

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:

$$ILnonl = \sqrt{2}i_{b1}\ \boldsymbol{i_{mag}} \tag{14}$$

The ideal transformer winding voltages (V1, V2 and V3 in Figure 2) are given by:

$$V_1 = \frac{1000}{\sqrt{3}}V_{b_1} \tag{15}$$

$$V_2 = \frac{1000}{\sqrt{3}}V_{b_2} \tag{16}$$

$$V_3 = 1000V_{b_3} \tag{17}$$

2.2 "YgDD": Wye-Delta-Delta with ground in Wye

The conversion from pu is given by:

$$R_1 = \frac{1}{2}\left[\frac{R_{12}}{S_{b_1}} + \frac{R_{13}}{S_{b_2}} - \frac{R_{23}}{S_{b_3}}\right]S_{common}Z_{b_1} \tag{18}$$

$$R_2 = \frac{3}{2}\left[\frac{R_{12}}{S_{b_1}} - \frac{R_{13}}{S_{b_2}} + \frac{R_{23}}{S_{b_3}}\right]S_{common}Z_{b_2} \tag{19}$$

$$R_3 = \frac{3}{2}\left[-\frac{R_{12}}{S_{b_1}} + \frac{R_{13}}{S_{b_2}} + \frac{R_{23}}{S_{b_3}}\right]S_{common}Z_{b_3} \tag{20}$$

$$L_1 = \frac{1}{2}\left[\frac{X_{12}}{S_{b_1}} + \frac{X_{13}}{S_{b_2}} - \frac{X_{23}}{S_{b_3}}\right]\frac{S_{common}Z_{b_1}}{2\pi f} \tag{21}$$

$$L_2 = \frac{3}{2}\left[\frac{X_{12}}{S_{b_1}} - \frac{X_{13}}{S_{b_2}} + \frac{X_{23}}{S_{b_3}}\right]\frac{S_{common}Z_{b_2}}{2\pi f} \tag{22}$$

$$L_3 = \frac{3}{2}\left[-\frac{X_{12}}{S_{b_1}} + \frac{X_{13}}{S_{b_2}} + \frac{X_{23}}{S_{b_3}}\right]\frac{S_{common}Z_{b_3}}{2\pi f} \tag{23}$$

R_1 is actually RW1 in Figure 2, this is also the case for the other R and L variables.

The magnetization branch is located on the winding 1 side:

$$Rm = R_{mag}Z_{b_1} \tag{24}$$

The nonlinear characteristic flux vector is converted using:

$$PhiLnonl = \frac{1000\sqrt{2}\ V_{b_1}}{2\pi f\sqrt{3}}\boldsymbol{\varphi} \tag{25}$$

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:

$$ILnonl = \sqrt{2}i_{b1}\ \mathbf{i_{mag}} \tag{26}$$

The ideal transformer winding voltages (V1, V2 and V3 in Figure 2) are given by:

$$V_1 = \frac{1000}{\sqrt{3}}V_{b_1} \tag{27}$$

$$V_2 = 1000V_{b_2} \tag{28}$$

$$V_3 = 1000V_{b_3} \tag{29}$$

2.3 Rules

It is not allowed to enter 0 for primary and secondary winding impedances. In some conditions equations (6) to (11) or (18) to (23) can give negative impedances. Such conditions may become mathematically impossible and create numerical instabilities during the EMTP simulations.

It is not allowed to delete any 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.

3 Netlist format

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

@YgYgD_O_ce840ebb;YgYgD_np1;9;s4a,s4b,s4c,s5a,s5b,s5c,s6a,s6b,s6c,
RW1=2.5623157594213936;
LW1=0.2703791512689064;
Rm=243344.5945945946;
PhiLnonl=[1591.8809691854223 1711.272041874329 1830.6631145632357 1910.2571630225068
1958.0135920980694 2738.0352669989265];
ILnonl=[2.466152938312316 12.330764691561578 30.826911728903948 61.653823457807896
123.30764691561579 2466.1529383123156];
Lnonl='Lnonl';
Rmag='RLC';
RW2=-0.2560888846593072;
LW2=-0.0022376052072403062;
RW3=0.0063054815378759035;
LW3=0.0003178403578971664;
Phiss01=0;

```
Phiss02=0;
Phiss03=0;
V1=424352.44785437494;
V2=181865.33479473213;
V3=15000;
Lmag_scope='';
W1_scope ='';
W2_scope ='';
W3_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.