DIgSILENT

POWERFACTORY

PowerFactory 2021

Technical Reference

Single Phase Two Winding Transformer

ElmTr2, TypTr2

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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Contents

1 General Description

PowerFactory supports the following types of windings for the single-phase 2-winding transformer, *YN* (centre-tapped) and *D* (or *Y*) windings. These windings are often also referred to as *"IN"* and *"I"* windings respectively. The name of the single-phase transformer vector group according to this nomenclature is displayed as a comment in the vector group frame on the Type basic data page. For ex. a YNd (or YNy) vector group is also referred to as INi0. The "0" for the LV windings indicate that the voltage measured between first and second phases are in phase with the voltage measured between first and second phases on the HV side (zero phase shift). The vector group INi6 (180 degrees phase-shift) is not explicitly supported, but can be achieved by swapping the phases at the terminal at which the LV side is connected.

For the single phase transformer models saturation is represented in the same way as for the three-phase 2-winding transformer model. Please refer to the three-phase 2-winding transformer technical reference for further details.

1.1 Single Phase Transformer Models

The following chapter described the models which can be setup dependent on the vector group of both windings. The second phase of the delta winding can be optional grounded or not. The rated voltage of the transformer for the HV - side and the LV - side is always the rated voltage between *phase 1* and *phase 2*. So if one phase is connected to neutral (ground) you should add the rated phase - neutral (ground) voltage instead of the phase - phase voltage. The following basic models are used for the single phase transformer:

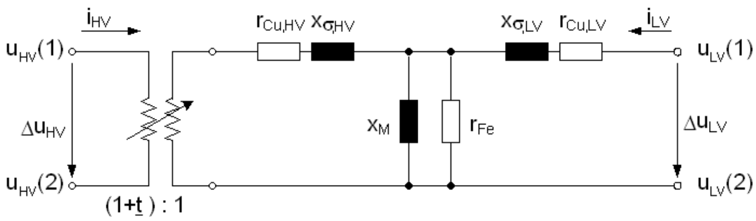

Figure 1.1: Transformer model with tap changer modelled at HV - side

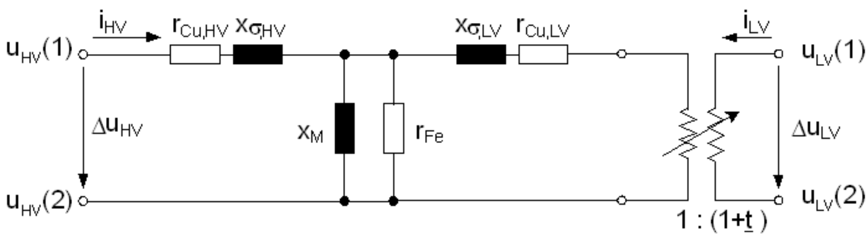

Figure 1.2: Transformer model with tap changer modelled at LV - side

Rated impedances ($Z_{r,HV}$, $Z_{r,LV}$)

The rated impedances are defined as follow:

$$Z_{r,HV} = \frac{U_{r,HV}^2}{S_r} \qquad (\Omega)$$
$$Z_{r,LV} = \frac{U_{r,LV}^2}{S_r} \qquad (\Omega)$$

where:

- $U_{r,HV}$: Rated HV side voltage in kV
- $U_{r,LV}$: Rated LV-side voltage in kV
- S_r : Rated Power in MVA

Rated currents

The rated currents (HV, LV) are:

$$I_{r,HV} = \frac{S_r}{U_{r,HV}} \qquad (kA)$$
$$I_{r,LV} = \frac{S_r}{U_{r,LV}} \qquad (kA)$$

The relation between the mathematical parameters in the model and the parameters in the type and element dialogs are described as follows:

The short-circuit impedances:

$$z_{sc} = u_{sc}/100$$
$$r_{sc} = \frac{P_{sc}/1000}{S_r}$$
$$x_{sc} = \sqrt{z_{sc}^2 - r_{sc}^2}$$
$$r_{cu,HV} = \gamma_{R,HV,1} \cdot r_{sc}$$
$$r_{cu,LV} = (1 - \gamma_{R,HV,1}) \cdot r_{sc}$$
$$x_{\sigma,HV} = \gamma_{X,HV,1} \cdot x_{sc}$$
$$x_{\sigma,LV} = (1 - \gamma_{X,HV,1}) \cdot x_{sc}$$

and the magnetizing impedance:

$$z_M = \frac{1}{i_0/100}$$
$$r_{Fe} = \frac{S_r}{P_{Fe}/1000}$$
$$x_M = \frac{1}{\sqrt{\frac{1}{z_M^2} - \frac{1}{r_{Fe}^2}}}$$

and:

$$\Delta u_{HV} = u_{HV}(1) - u_{HV}(2)$$
$$\Delta u_{LV} = u_{LV}(1) - u_{LV}(2)$$

where,

Table 1.1: Input- and calculation parameters

$Z_{r,HV}$	Ω	Rated impedance, HV side
$Z_{r,LV}$	Ω	Rated impedance, LV side
$U_{r,HV}$, $U_{r,LV}$	kV	Rated voltages on HV/LV side
S_r	MVA	Rated power
P_{Cu}	kW	Copper losses
u_{SC}	%	Relative short-circuit voltage
z_{SC}	p.u.	Short-circuit impedance
r_{SC}	p.u.	Short-circuit resistance
x_{SC}	p.u.	Short-circuit reactance
$\gamma_{X,HV,1}$	p.u.	Share of transformer short-circuit reactance on HV side in the positive-sequence system
$\gamma_{R,HV,1}$	p.u.	Share of transformer short-circuit resistance on HV side in the positive-sequence system
$r_{Cu,HV}$, $r_{Cu,LV}$	p.u.	Resistances on HV/LV sides
$x_{\sigma,HV}$, $x_{\sigma,LV}$	p.u.	Leakage reactances on HV/LV side
i_0	%	no-load current
P_{Fe}	kW	No-load losses
x_M	p.u.	Magnetizing impedance
r_{Fe}	p.u.	Shunt resistance

For the zero-sequence model are the following relation used:

$$r0_{Cu} = r_{sc}$$
$$x0_{\sigma} = x_{sc}$$
$$r0_{Cu,HV} = r_{Cu,HV}$$
$$r0_{Cu,LV} = r_{Cu,LV}$$
$$x0_{\sigma,HV} = x_{\sigma,HV}$$
$$x0_{\sigma,LV} = x_{\sigma,LV}$$
$$r0_{Fe} = r_{Fe}$$
$$x0_{M} = x_{M}$$

The equation used for transformer the phase voltages and current to the zero-sequence are the following:

$$u0_{HV} = \frac{u_{HV}(1) + u_{HV}(2)}{2}$$
$$i0_{HV} = \frac{i_{HV}(1) + i_{HV}(2)}{2}$$

$$u0_{LV} = \frac{u_{LV}(1) + u_{LV}(2)}{2}$$
$$i0_{LV} = \frac{i_{LV}(1) + i_{LV}(2)}{2}$$

1.1.1 D-D Connection (non - auto transformer)

The connection D - D is for example used to create from a 3 - phase or 2 - phase system, a single phase with neutral system or a two phase system. It can also be used for a single wire earth return connection (the second phase of both sides must be set to not connected).
The grounding impedance can be insert with the option *LV - side or/and HV - side phase 2 internally grounded* in the element dialog. If the second phase is grounded it's recommended to connect the second phase to the neutral phase (N). Further is it possible if the second phase is grounded to disconnect the second phase (HV-side or/and LV-side). For that the corresponding option *HV-side, phase 2 connected* or/and *LV-side, phase 2 connected* must be disabled.

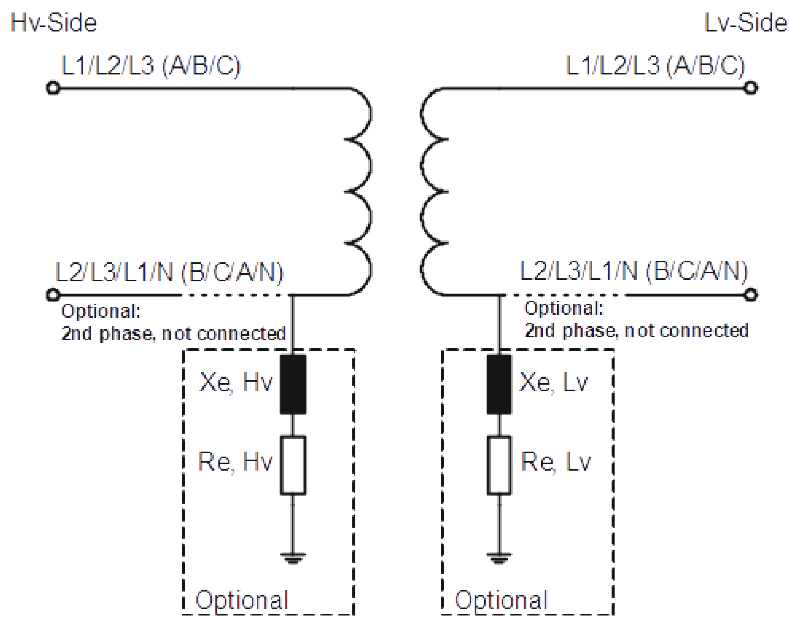

Figure 1.3: D - D Transformer

$$i_{HV} = i_{HV}(1) \quad and \quad i_{LV} = i_{LV}(1)$$

The following conditions for the zero-sequence system of the HV - and LV - side are used if the second phase is grounded:

$$\underline{U}_{HV}(2) = 2 \cdot (Re_{HV} + jXe_{HV}) \cdot \underline{I}0_{HV})$$
$$\underline{U}_{HV}(2) = 2 \cdot (Re_{LV} + jXe_{LV}) \cdot \underline{I}0_{LV}$$

For ungrounded second phase are the following equations used:

$$\underline{I}0_{HV} = 0 \qquad (no\, zero - sequence\, current\, is\, flowing)$$
$$\underline{I}0_{LV} = 0 \qquad (no\, zero - sequence\, current\, is\, flowing)$$

1.1.2 D-D Connection (auto transformer)

For a single phase auto transformer it's necessary to setup in the transformer type, the vector group to D - D, and to enable the option in the element dialog: *Auto Transformer*.
Further is it possible to disconnect the second phase of the LV-side (disable option *LV-side, phase 2 connected*.

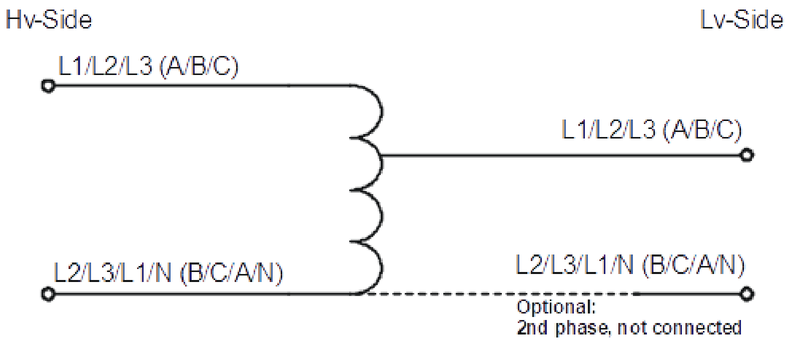

Figure 1.4: Auto Transformer

$$I_{HV} = I_{HV}(1) \qquad and \qquad I_{LV} = I_{LV}(1)$$

The following equations are used for the auto transformer:

$$\underline{U}_{HV}(2) = \underline{U}_{HV}(2) \qquad (the\, secondphase\, voltages\, must\, be\, equal)$$
$$\underline{I}0_{HV} + \underline{I}0_{LV} = 0 \qquad (the\, sum\, of the\, zero - sequence\, currents\, must\, be\, equal\, zero)$$

1.1.3 YN - YN Connection

The connection YN - YN is used to couple or to transformer two BI - phase systems.
When the option *External Star Point* is enabled, the LV - side *star point* must be connected to the neutral phase.

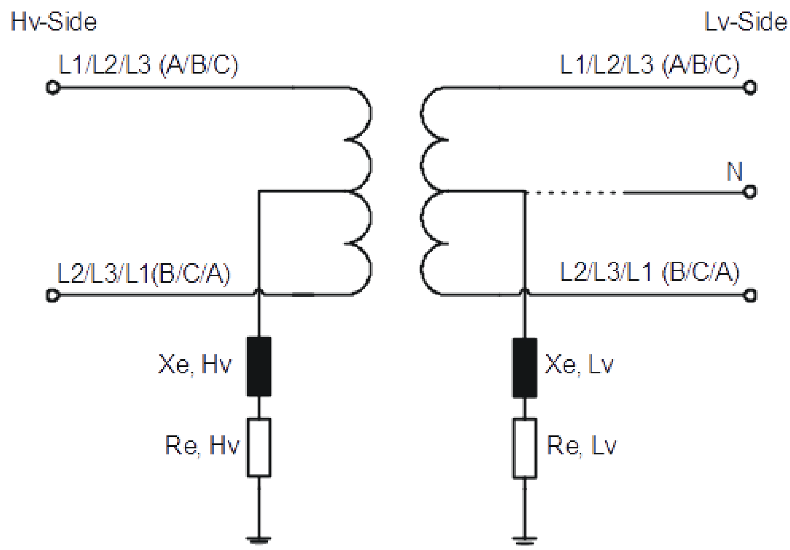

Figure 1.5: YN - YN Transformer

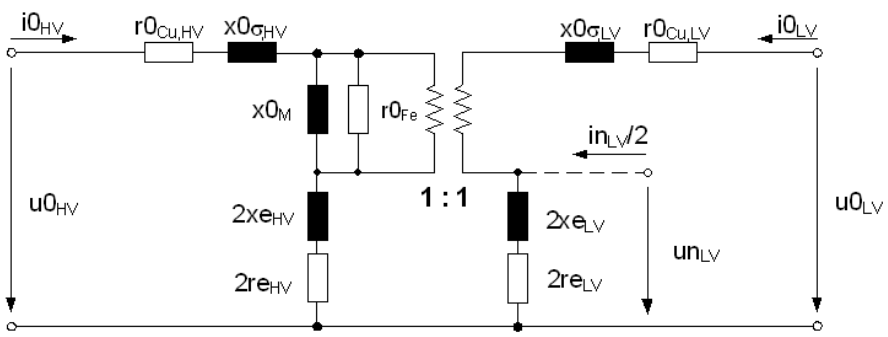

Figure 1.6: Zero-sequence model for YN - YN connection

If the tap is modelled on the HV - side only the voltage $u0^{'}_{HV} - un_{HV}$ is transfer by the transformer ratio (1 + t). If the tap is modelled on the LV - side the voltage $u0^{'}_{LV} - un_{LV}$ is transfer by the transformer ratio (1 + t).

1.1.4 D - YN Connection

The connection D - YN is for example used to create a BI - phase system from a e.g. 3 - phase system or a 2 - phase system.
When the option *External Star Point* is enabled, the LV - side *star point* must be connected to the neutral phase. The option *HV-side, phase 2 internally grounded* can be enabled to ground the second phase. If the star-point of the HV-side is grounded it is possible to disconnect the second phase with the disabled option: *HV-side, phase 2 connected*.

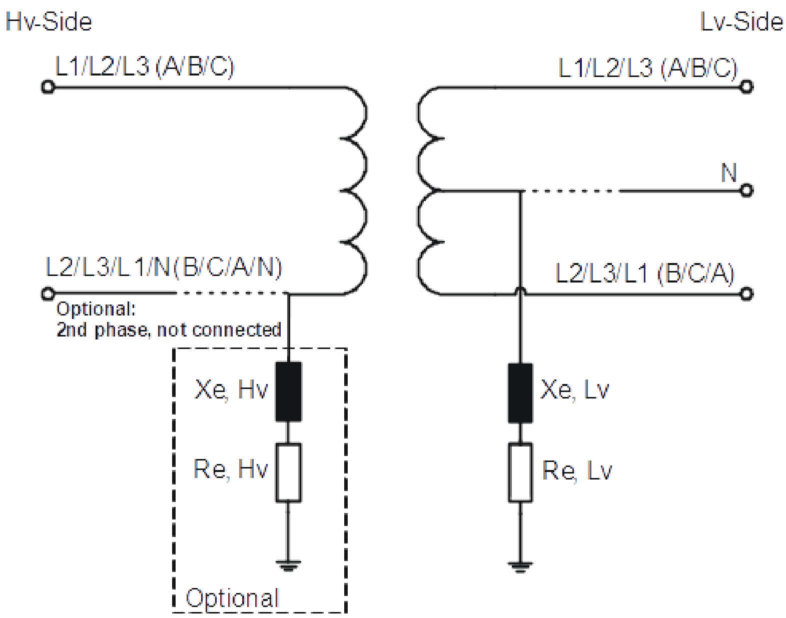

Figure 1.7: D - YN Transformer

$$i_{HV} = i_{HV}(1) \qquad and \qquad i_{LV} = (i_{LV}(1) - i_{LV}(2))/2$$

The following conditions are used if the second phase of the HV - Side winding is grounded:

$$\underline{U}_{HV}(2) = 2 \cdot (Re_{HV} + jXe_{HV}) \cdot \underline{I}0_{HV})$$

If the second phase of the HV - side winding is not grounded the following equation is used:

$$\underline{I}0_{HV} = 0$$

The zero-sequence model for the LV - side winding shows the following picture:

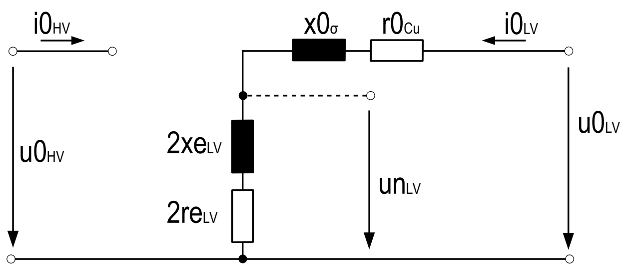

Figure 1.8: LV - side zero-sequence model for D - YN connection

1.1.5 YN - D Connection

The connection YN - D is for example used to create from a BI - phase system a two phase system.
When the option *External Star Point* is enabled, the HV - side *star point* must be connected to the neutral phase. The option *LV-side, phase 2 internally grounded* can be enabled to ground the second phase. If the star-point of the LV-side is grounded it is possible to disconnected the second phase with the disabled option: *LV-side, phase 2 connected*.

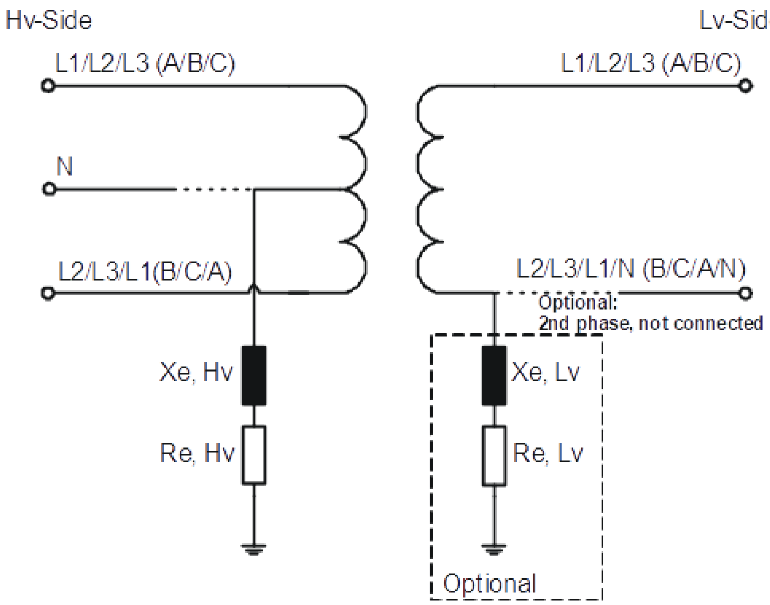

Figure 1.9: YN - D Transformer

$$i_{HV} = (i_{HV}(1) - i_{HV}(2))/2 \qquad and \qquad i_{LV} = i_{LV}(1)$$

The following conditions are used if the second phase of the LV - side winding is grounded:

$$\underline{U}_{LV}(2) = 2 \cdot (Re_{LV} + jXe_{LV}) \cdot \underline{I}0_{LV})$$

If the second phase of the HV - side winding is not grounded the following equation is used:

$$\underline{I}0_{LV} = 0$$

The zero-sequence model for the HV - side winding shows the following picture:

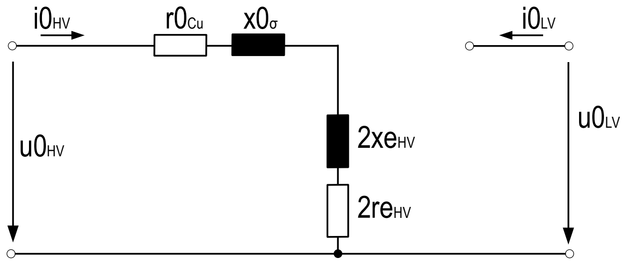

Figure 1.10: HV - side zero-sequence model for YN - D connection

1.2 Single Wire Earth Return Model

The following chapter described the models for a single wire earth return transformer. The rated voltage of the transformer for the HV - side and the LV - side is **always** the rated line-line voltage.

The following basic models are used for the single wire earth return model:

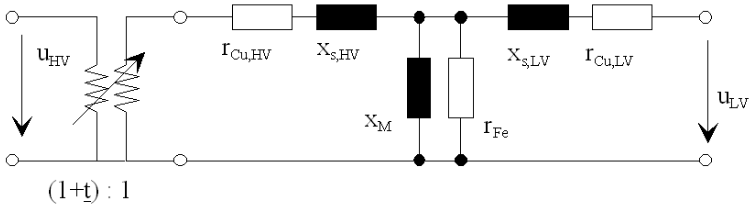

Figure 1.11: Transformer model with tap changer modelled at HV - side

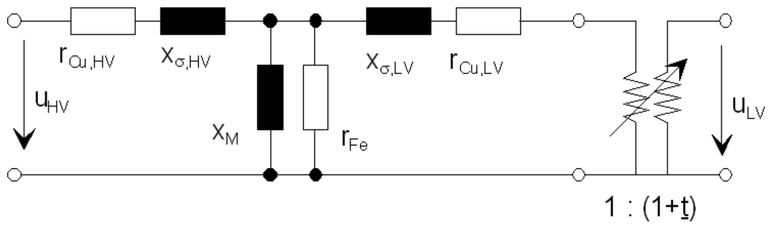

Figure 1.12: Transformer model with tap changer modelled at LV - side

Rated impedances ($Z_{r,HV}$, $Z_{r,LV}$)

The rated impedances are depending on the corresponding connected busbars of the transformer.

When connected to a three, two or single phase systems (no AC/BI):

$$Z_{r,HV} = \frac{(U_{r,HV}/\sqrt{3})^2}{S_r} \qquad (\Omega)$$

$$Z_{r,LV} = \frac{(U_{r,LV}/\sqrt{3})^2}{S_r} \qquad (\Omega)$$

When connected to AC/BI phase system:

$$Z_{r,HV} = \frac{(U_{r,HV}/2)^2}{S_r} \qquad (\Omega)$$

$$Z_{r,LV} = \frac{(U_{r,LV}/2)^2}{S_r} \qquad (\Omega)$$

where:

- $U_{r,HV}$: Rated HV-side voltage (line-line) in kV
- $U_{r,LV}$: Rated LV-side voltage (line-line) in kV
- S_r : Rated Power in MVA

Rated currents

The rated currents (HV, LV) also depends on the corresponding connected busbars of the transformer.

When connected to a three, two or single phase systems (no AC/BI):

$$I_{r,HV} = \frac{S_r}{U_{r,HV}/\sqrt{3}} \qquad (kA)$$
$$I_{r,LV} = \frac{S_r}{U_{r,LV}/\sqrt{3}} \qquad (kA)$$

When connected to AC/BI phase system:

$$I_{r,HV} = \frac{S_r}{U_{r,HV}/2} \qquad (kA)$$
$$I_{r,LV} = \frac{S_r}{U_{r,LV}/2} \qquad (kA)$$

The relation between the mathematical parameters in the model and the parameters in the type and element dialogs are described as follows:

The short-circuit impedances:

$$\begin{aligned}
z_{sc} &= u_{sc}/100 \\
r_{sc} &= \frac{P_{sc}/1000}{S_r} \\
x_{sc} &= \sqrt{z_{sc}^2 - r_{sc}^2} \\
r_{cu,HV} &= \gamma_{R,HV,1} \cdot r_{sc} \\
r_{cu,LV} &= (1 - \gamma_{R,HV,1}) \cdot r_{sc} \\
x_{\sigma,HV} &= \gamma_{X,HV,1} \cdot x_{sc} \\
x_{\sigma,LV} &= (1 - \gamma_{X,HV,1}) \cdot x_{sc}
\end{aligned}$$

and the magnetizing impedance:

$$\begin{aligned}
z_M &= \frac{1}{i_0/100} \\
r_{Fe} &= \frac{S_r}{P_{Fe}/1000} \\
x_M &= \frac{1}{\sqrt{\frac{1}{z_M^2} - \frac{1}{r_{Fe}^2}}}
\end{aligned}$$

where,

$Z_{r,HV}$	Ω	Rated impedance, HV side
$Z_{r,LV}$	Ω	Rated impedance, LV side
$U_{r,HV}$, $U_{r,LV}$	kV	Rated voltages **(line-line)** on HV/LV side
S_r	MVA	Rated power
P_{Cu}	kW	Copper losses
u_{SC}	%	Relative short-circuit voltage
z_{SC}	p.u.	Short-circuit impedance
r_{SC}	p.u.	Short-circuit resistance
x_{SC}	p.u.	Short-circuit reactance
$\gamma_{X,HV,1}$	p.u.	Share of transformer short-circuit reactance on HV side in the positive-sequence system
$\gamma_{R,HV,1}$	p.u.	Share of transformer short-circuit resistance on HV side in the positive-sequence system
$r_{Cu,HV}$, $r_{Cu,LV}$	p.u.	Resistances on HV/LV sides
$x_{\sigma,HV}$, $x_{\sigma,LV}$	p.u.	Leakage reactances on HV/LV side
i_0	%	no-load current
P_{Fe}	kW	No-load losses
x_M	p.u.	Magnetizing impedance
r_{Fe}	p.u.	Shunt resistance

1.3 Connection

The single phase earth return transformer model is similar the single phase transformer in D-D connection where the second phases of the HV side or LV side are grounded.

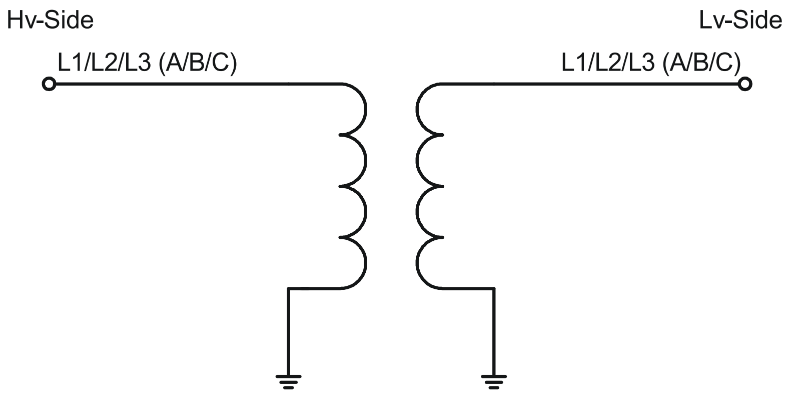

Figure 1.13: SWER Transformer Model

1.4 Nominal power and current

The nominal power and currents for the corresponding windings are used e.g. to calculate the loading of the transformer. They are also displayed in the transformer dialogue and can also be used in scripts or on the flexible data page.

The following *DIgSILENT* parameter are available:

- $Inom\_h$, $Inom\_l$ are the nominal currents in kA
- $Snom$ is the nominal power in MVA

When e.g. a characteristic is defined for the rating factor, the actual values (considers characteristics) can be accessed as follow:

- $Inom\_h\_a$ and $Inom\_l$ are the actual nominal currents in kA
- $Snom_a$ is the actual nominal power in MVA

1.4.1 Nominal current

The calculation of the nominal currents depends whether a thermal rating object is selected or not. If it is not selected, the nominal currents are calculated as:

$$\begin{aligned} I_{nomhv} &= ratfac \cdot AddRatFactMeasTab \cdot I_{r,HV} \cdot ntnum \\ I_{nomlv} &= ratfac \cdot AddRatFactMeasTab \cdot I_{r,LV} \cdot ntnum \end{aligned} \tag{1}$$

where

- $ratfac$ is the rating factor of the transformer, defined on the element *Basic Data* page
- $AddRatFactMeasTab$ is the additional rating factor (only if a measurement table for the tap changer is defined in the element Load flow advanced page, otherwise = 1)
- $ntnum$ is the number of parallel transformers, defined on the element *Basic Data* page
- $I_{r,HV}$ and $I_{r,LV}$ are the rated currents of the corresponding transformer models, see paragraph (1.1 and 1.2).

If a thermal rating object is selected, the nominal currents are determined as follows:

- if the continuous rating is entered in MVA:

  $$I_{nomhv} = \frac{ContRating \cdot ntnum}{U_{bushv}}$$
  $$I_{nomlv} = \frac{ContRating \cdot ntnum}{U_{buslv}}$$

  where U_{bushv} and U_{buslv} are based on the following nominal busbar voltages:

  – for phase-phase connections (A-B, B-C, C-A) the corresponding busbar line-line nominal voltages in kV are used.

  $$U_{bushv} = U_{n(bushv)}$$
  $$U_{buslv} = U_{n(buslv)}$$

– for phase-neutral (A-N,B-N,C-N) or phase-earth connections (single wire earth return models) and not connected to AC/BI system:

$$U_{bushv} = U_{n(bushv)}/\sqrt{3}$$
$$U_{buslv} = U_{n(buslv)}/\sqrt{3}$$

– for phase-neutral (A-N,B-N,C-N) or phase-earth connections (single wire earth return models) and connected to AC/BI system:

$$U_{bushv} = U_{n(bushv)}/2$$
$$U_{buslv} = U_{n(buslv)}/2$$

- if the continuous rating is entered in %:

$$I_{nomhv} = ContRating/100 \cdot I_{r,HV} \cdot ntnum$$
$$I_{nomlv} = ContRating/100 \cdot I_{r,LV} \cdot ntnum$$

where $U_{n(bushv)}$ and $U_{n(buslv)}$ are the busbar line-line nominal voltages in kV at the high and low-voltage side and $I_{r,HV}$ and $I_{r,LV}$ are the rated currents of the corresponding transformer models, see Rated currents (1.1 and 1.2).

1.4.2 Nominal power

The nominal power ($Snon$) and also the corresponding actual value ($Snon\_a$) are defined as follow:

When no thermal rating object is selected:

$$Snom = S_r \cdot ntnum \cdot ratfac_n$$
$$Snom\_a = S_r \cdot ntnum \cdot ratfac_n\_a$$

where:

- S_r is the rated apparent power, see also table 1.1.
- $ntnum$ is the number of parallel transformers, defined on the element *Basic Data* page.
- $ratfac_n$ is the rating factor at neutral tap position without consideration of possible defined characteristics.
- $ratfac_n\_a$ is the actual rating factor incl. defined characteristics.

In case of a thermal rating object is selected:

$$Snom = U_{bushv} \cdot I_{nomhv}$$
$$Snom\_a = Snom$$

where:

- I_{nomhv} is the nominal current at high voltage side, see section 1.4.1.

- U_{bushv} is based on the nominal busbar voltages in kV at the high voltage side.
  - for phase-phase connections (A-B, B-C, C-A) the corresponding busbar line-line nominal voltages in kV are used.

$$U_{bushv} = U_{n(bushv)}$$

  - for phase-neutral (A-N,B-N,C-N) or phase-earth connections (single wire earth return models) and not connected to AC/BI system:

$$U_{bushv} = U_{n(bushv)}/\sqrt{3}$$

  - for phase-neutral (A-N,B-N,C-N) or phase-earth connections (single wire earth return models) and connected to AC/BI system:

$$U_{bushv} = U_{n(bushv)}/2$$

- $U_{n(bushv)}$ is the busbar line-line nominal voltages in kV at the high voltage side.

2 Load Flow Analysis

2.1 Calculation Quantities

2.1.1 Loading

The loading of the transformer is calculated as follows:

$$loading\_h = \frac{I_{bushv}}{I_{nomhv}} \cdot 100 \qquad (\%)$$
$$loading\_l = \frac{I_{buslv}}{I_{nomlv}} \cdot 100 \qquad (\%)$$
$$loading = max(loading\_h, loading\_l) \qquad (\%)$$

- $loading$: Loading in %
- $loading\_h$: Loading high voltage side in %
- $loading\_l$: Loading low voltage side in %
- I_{nomhv} : Nominal current at the high voltage side in kA, see section 1.4.1.
- I_{nomlv} : Nominal current at the low voltage side in kA, see section 1.4.1.
- I_{bushv} : Magnitude of the current at high voltage terminal
- I_{buslv} : Magnitude of the current at low voltage terminal

For an unbalanced load flow calculation the highest current of all phases/neutral is used.

2.1.2 Losses

The losses are calculated as follows:

Table 2.1: Losses Quantities

Quantity	Unit	Description	Value
$Ploss$	MW	Losses (total)	$= P_{bushv} + P_{buslv}$
$Qloss$	$Mvar$	Reactive-Losses (total)	$= Q_{bushv} + Q_{buslv}$
$Plossld$	MW	Losses (load)	$= Ploss - Plossnld$
$Qlossld$	$Mvar$	Reactive-Losses (load)	$= Qloss - Qlossnld$
$Plossnld$	MW	Losses (no load)	$Gmload/1000$
$Qlossnld$	$Mvar$	Reactive-Losses (no load)	$Xmload/1000$

where $Gmload$ and $Xmload$ are calculated as:

$$Gmload = Re(\underline{u_{mag}} \cdot \underline{i_{mag}}^{*}) \cdot S_r \cdot ntnum \cdot 1000 \qquad (kW)$$
$$Xmload = Im(\underline{u_{mag}} \cdot \underline{i_{mag}}^{*}) \cdot S_r \cdot ntnum \cdot 1000 \qquad (kvar)$$

and

- $\underline{u_{mag}}$ is the actual phasor voltage over the transformer magnetising branch in p.u.
- $\underline{i_{mag}}$ is the actual phasor current over the transformer magnetising branch in p.u.

List of Figures