POWERFACTORY

PowerFactory 2021

Technical Reference

Four-Winding Transformer

ElmTr4,TypTr4

PF2021

POWER SYSTEM SOLUTIONS
MADE IN GERMANY

Publisher:
DIgSILENT GmbH
Heinrich-Hertz-Straße 9
72810 Gomaringen / Germany
Tel.: +49 (0) 7072-9168-0
Fax: +49 (0) 7072-9168-88
info@digsilent.de

Please visit our homepage at:
https://www.digsilent.de

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Contents

1 General Description

PowerFactory comes with a built-in model for four-winding transformers and the model is presented in this document.

A schematic representation of the four-winding transformer is shown in Figure 1.1.

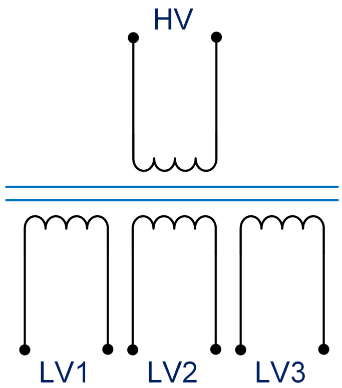

Figure 1.1: Schematic representation of a four-winding transformer

The four-winding transformer is a four-port element connecting four cubicles in the network. The transformer model in *PowerFactory* consists of the four-winding transformer element (*ElmTr4*), and the four-winding transformer type (*TypTr4*). The transformer element allows input of data relating to the control of the transformer under steady-state conditions, and the transformer type allows input of the physical properties of the transformer.

A neutral connection is not supported by the four-winding transformer model.

Saturation of the magnetizing reactance 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.

2 Model diagrams

2.1 Positive- and negative-sequence equivalent circuit

The detailed positive- and negative-sequence model with impedances in per-unit are shown in Figure 2.1. The user can select at which terminal the magnetizing impedance (comprising the magnetising reactance and iron losses) is connected. The transformer taps are always modelled at the terminals.

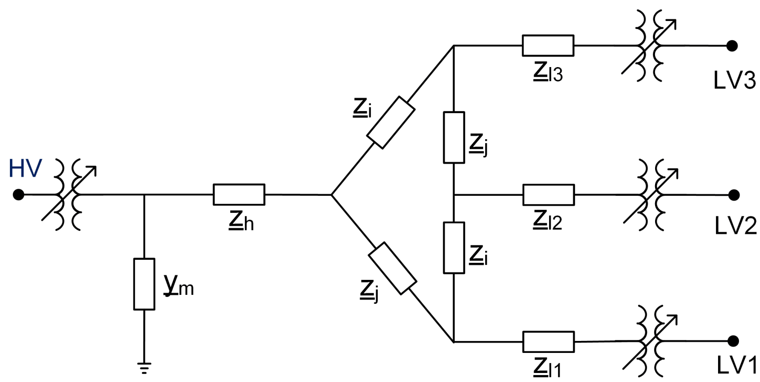

Figure 2.1: *PowerFactory* positive-sequence equivalent circuit of the four-winding transformer with magnetising impedance modelled at the HV-side

If the simplified input data option is used or if the resulting equivalent circuit parameters $\underline{z}_i$ and $\underline{z}_j$ are zero, the equivalent circuit has a simplified form as shown in Figure 2.2.

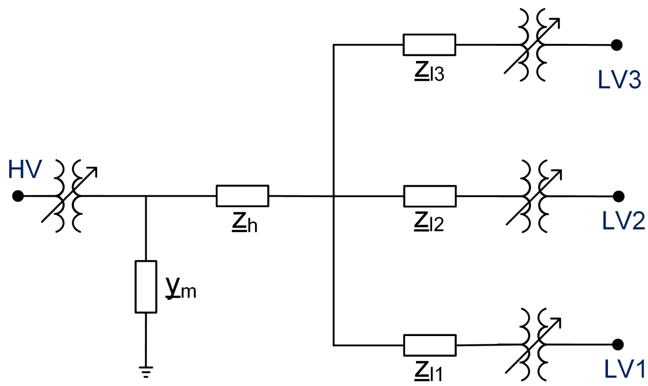

Figure 2.2: *PowerFactory* simplified form of the positive-sequence equivalent circuit of the four-winding transformer with magnetising impedance modelled at the HV-side

2.2 Zero-sequence equivalent circuit

In Figure 2.3, the zero-sequence equivalent circuits in per-unit are shown for several different combinations of connection groups.

Figure 2.3 does not show the location of the zero-sequence magnetising impedance and the taps. The zero-sequence magnetising impedance is calculated at the same terminal where the positive-sequence magnetising impedance is calculated. As in the case of the positive-sequence model, the taps are always modelled at the terminals.

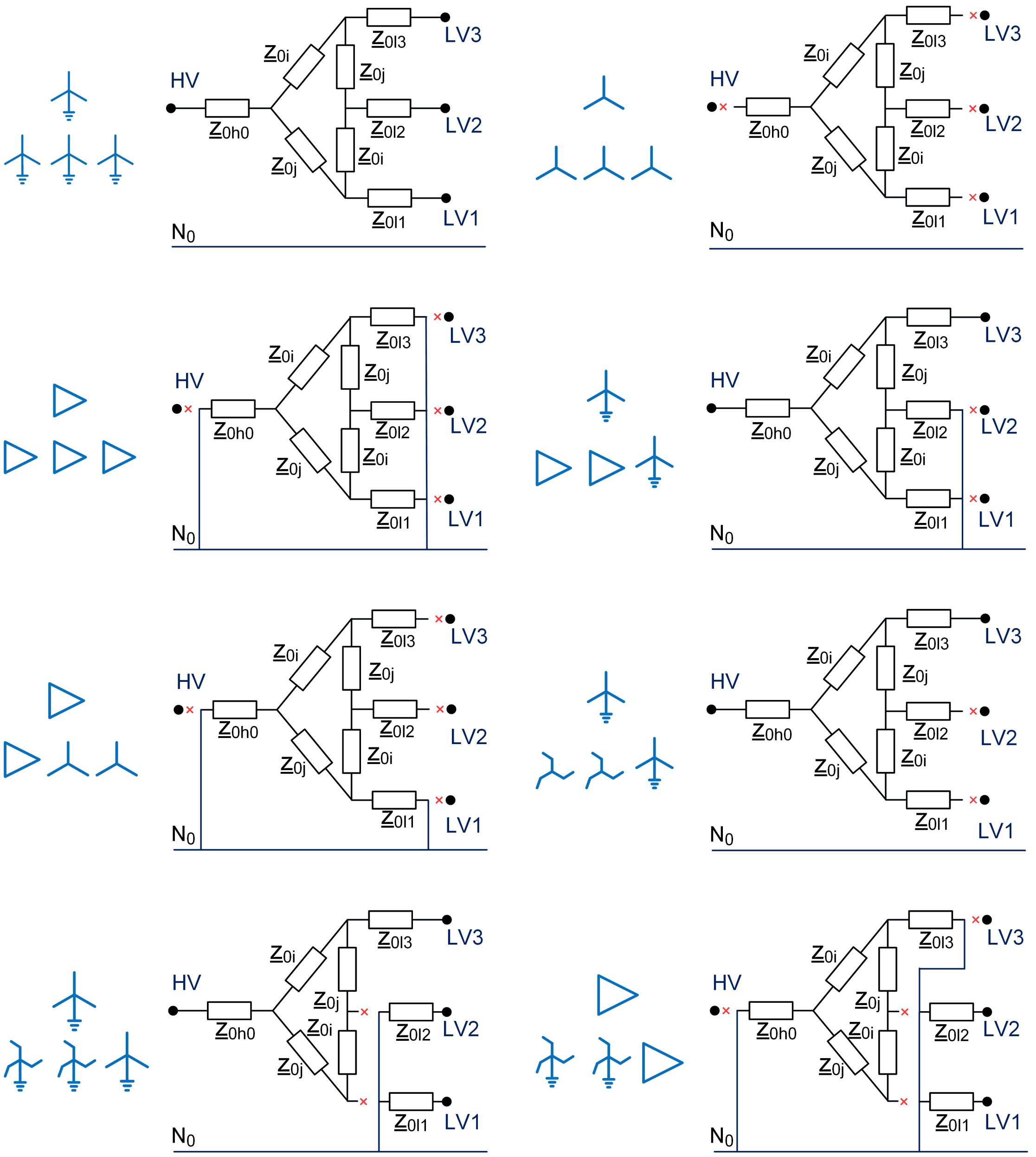

Figure 2.3: *PowerFactory* zero-sequence equivalent circuit for different combinations of connection groups (not showing zero-sequence magnetising impedance and taps)

As in the positive-sequence case, if the simplified input data option is used or if the resulting equivalent circuit parameters z_{0i} and z_{0j} are zero, the equivalent circuit has a simplified form.

An autotransformer can be defined if there are at least two YN or Y connections available.

3 Input and equivalent circuit parameters

The impedances for the four-winding transformer can be entered in two ways, using:

- Complete input data
- Simplified input data

Using these data, the impedances used by the four-winding transformer model are calculated.

In the following, the windings rated power and voltages are defined according to:

Table 3.1: Rated power and voltage parameters

Name	Symbol	Unit	Description
un_h0	U_{r_hv}	kV	HV-winding rated voltage
un_l1	U_{r_lv1}	kV	LV1-winding rated voltage
un_l2	U_{r_lv2}	kV	LV2-winding rated voltage
un_l3	U_{r_lv3}	kV	LV3-winding rated voltage
sn_h0	S_{r_hv}	MVA	HV-winding rated power
sn_l1	S_{r_lv1}	MVA	LV1-winding rated power
sn_l2	S_{r_lv2}	MVA	LV2-winding rated power
sn_l3	S_{r_lv3}	MVA	LV3-winding rated power

Rated currents

The rated currents (HV, LV1, LV2, LV3) are:

$$
\begin{aligned}
I_{r\_hv} &= \frac{S_{r\_hv}}{\sqrt{3} \cdot U_{r\_hv}} \\
I_{r\_lv1} &= \frac{S_{r\_lv1}}{\sqrt{3} \cdot U_{r\_lv1}} \\
I_{r\_lv2} &= \frac{S_{r\_lv2}}{\sqrt{3} \cdot U_{r\_lv2}} \\
I_{r\_lv3} &= \frac{S_{r\_lv3}}{\sqrt{3} \cdot U_{r\_lv3}}
\end{aligned}
\tag{1}
$$

3.1 Input parameters and calculation of equivalent circuit impedances

Using the entered input data, intermediate impedances based on the HV side are calculated internally in *PowerFactory*. From these intermediate impedances, the equivalent circuit parameters are obtained.

3.1.1 Complete input data

If the complete input data option is selected, the impedances measured between connection sides can be entered using the following combination of input data:

- Short-circuit voltages and copper losses (not available for the zero-sequence data)

- Short-circuit voltages and real part of short circuit voltages
- Short-circuit voltages and x/r ratios
- Reactances and resistances in p.u.

When entering positive and zero sequence voltages for a four-winding transformer, one must note that they are referred to the minimum rated apparent power of the two windings.

The short-circuit voltages (uk_h0l1, uk_h0l2, uk_h0l3, uk_l1l2, uk_l1l3, uk_l2l3) and copper losses (pcu_h0l1, pcu_h0l2, pcu_h0l3, pcu_l1l2, pcu_l1l3, pcu_l2l3) are the leading parameters for the positive and negative sequence impedances. The following conversions are used to convert to uk_l1l2 and pcu_l1l2 values depending on the available input parameters:

$$pcu\_l1l2 = r1pu\_l1l2 \cdot \min\{S_{r\_lv1}, S_{r\_lv2}\} \cdot 1000 \qquad kW \tag{2}$$

$$uk\_l1l2 = \sqrt{x1pu\_l1l2^2 + r1pu\_l1l2^2} \cdot 100 \qquad \% \tag{3}$$

where:

$$r1pu\_l1l2 = \frac{ukr\_l1l2}{100} \qquad p.u. \tag{4}$$

$$r1pu\_l1l2 = \frac{|uk\_l1l2|}{100} / \sqrt{1 + xtor\_l1l2^2} \qquad p.u. \tag{5}$$

In the above equations, ukr_l1l2 is the real part short circuit voltage between the LV1 and LV2 windings, $xt0r\_l1l2$ is the x to r ratio, $x1pu\_l1l2$ is the reactance, $r1pu\_l1l2$ is the resistance and $\min\{S_{r\_lv1}, S_{r\_lv2}\}$ is the smaller rated apparent power of the two windings. The conversions for the rest of the parameters are done in a similar manner.

The zero sequence short-circuit voltages ($uk0\_h0l1$, $uk0\_h0l2$, $uk0\_h0l3$, $uk0\_l1l2$, $uk0\_l1l3$, $uk0\_l2l3$) and the real part of the zero sequence short-circuit voltages ($ukr0\_h0l1$, $ukr0\_h0l2$, $ukr0\_h0l3$, $ukr0\_l1l2$, $ukr0\_l1l3$, $ukr0\_l2l3$) are the leading parameters for the zero sequence impedances. The following conversions are used to convert to $uk0\_l1l2$ and $ukr0\_l1l2$ values depending on the available input parameters:

$$r0pu\_l1l2 = \frac{|uk0\_l1l2|}{100} / \sqrt{1 + xtor0\_l1l2^2} \qquad p.u. \tag{6}$$

$$ukr0\_l1l2 = r0pu\_l1l2 \cdot 100 \qquad \% \tag{7}$$

$$uk0\_l1l2 = \sqrt{x0pu\_l1l2^2 + r0pu\_l1l2^2} \cdot 100 \qquad \% \tag{8}$$

where $xtor0\_l1l2$ is the zero sequence x to r ratio between the LV1 and LV2 two connection sides, $x0pu\_l1l2$ is the zero sequence reactance and $r0pu\_l1l2$ is the zero sequence resistance. The conversions for the rest of the parameters are done in a similar manner.

3.1.1.1 Calculating of the intermediate impedances

In an intermediate step, the measured impedances are calculated from these input data and then the equivalent circuit parameters are calculated.

Having the short-circuit voltages uk and copper losses pcu, the winding to winding impedances ($\underline{z\_h0l1}$, $\underline{z\_h0l2}$, $\underline{z\_h0l3}$, $\underline{z\_l1l2}$, $\underline{z\_l1l3}$, $\underline{z\_l2l3}$) are be calculated and re-based on the HV-winding apparent power. The following conversions apply for the LV1 to LV2 winding impedances:

$$z\_l1l2 = \frac{uk\_l1l2}{100} \cdot \frac{S_{r\_hv}}{\min\{S_{r\_lv1}, S_{r\_lv2}\}} \qquad p.u. \tag{9}$$

$$\underline{z\_l1l2}.r = \frac{pcu\_l1l2}{1000} \cdot \frac{S_{r\_hv}}{\min\{S_{r\_lv1}, S_{r\_lv2}\}^2} \qquad p.u. \tag{10}$$

$$\underline{z\_l1l2}.i = \sqrt{z\_l1l2^2 - \underline{z\_l1l2}.r^2} \qquad p.u. \tag{11}$$

where S_{r_hv} is the rated apparent power of the HV winding and $\min\{S_{r\_lv1}, S_{r\_lv2}\}$ is the smaller rated apparent power of the two respective windings. The apparent power ratio in Equation 9 is needed to re-base the short-circuit voltages which are based on the minimum apparent power of both windings to the apparent power of the HV winding. The conversions for the rest of the parameters are done in a similar manner.

Having the zero sequence short-circuit voltages $uk0$ and the zero sequence real part of the short-circuit voltages $ukr0$, the winding to winding intermediate impedances ($\underline{z0\_h0l1}$, $\underline{z0\_h0l2}$, $\underline{z0\_h0l3}$, $\underline{z0\_l1l2}$, $\underline{z0\_l1l3}$, $\underline{z0\_l2l3}$) can be calculated based on the HV winding apparent power. For the impedance between the LV1 and LV2 windings we have:

$$z0\_l1l2 = \frac{uk0\_l1l2}{100} \cdot \frac{S_{r\_hv}}{\min\{S_{r\_lv1}, S_{r\_lv2}\}} \qquad p.u. \tag{12}$$

$$\underline{z\_l1l2}.r = \frac{ukr0\_l1l2}{100} \cdot \frac{S_{r\_hv}}{\min\{S_{r\_lv1}, S_{r\_lv2}\}} \qquad p.u. \tag{13}$$

$$\underline{z\_l1l2}.i = \sqrt{z\_l1l2^2 - \underline{z\_l1l2}.r^2} \qquad p.u. \tag{14}$$

where S_{r_hv} is the rated apparent power of the HV winding and $\min\{S_{r\_lv1}, S_{r\_lv2}\}$ is the smaller rated apparent power of the two respective windings. The apparent power ratio in Equation 12 is needed to re-base the short-circuit voltages which are based on the minimum apparent power of both windings to the apparent power of the HV winding.The conversions for the rest of the impedances are done in a similar manner.

3.1.1.2 Calculating of the equivalent circuit impedances

The positive sequence equivalent circuit impedances are obtained from the impedances calculated above according to [1]:

$$\underline{k1} = \underline{z\_h0l2} + \underline{z\_l1l3} - \underline{z\_h0l1} - \underline{z\_l2l3} \tag{15}$$

$$\underline{k2} = \underline{z\_h0l2} + \underline{z\_l1l3} - \underline{z\_h0l3} - \underline{z\_l1l2} \tag{16}$$

$$\underline{k} = \sqrt{k1 \cdot k2} \tag{17}$$

$$\underline{z_i} = \underline{k1} + \underline{k} \tag{18}$$

$$\underline{z_j} = \underline{k2} + \underline{k} \tag{19}$$

$$\underline{z_h} = (\underline{z\_h0l1} + \underline{z\_h0l3} - \underline{z\_l1l3} - \underline{k})/2 \tag{20}$$

$$\underline{z_{l1}} = (\underline{z\_h0l1} + \underline{z\_l1l2} - \underline{z\_h0l2} - \underline{k})/2 \tag{21}$$

$$\underline{z_{l2}} = (\underline{z\_l1l2} + \underline{z\_l2l3} - \underline{z\_l1l3} - \underline{k})/2 \tag{22}$$

$$\underline{z_{l3}} = (\underline{z\_l2l3} + \underline{z\_h0l3} - \underline{z\_h0l2} - \underline{k})/2 \tag{23}$$

The zero sequence equivalent circuit impedances are obtained analogously to the positive sequence impedances.

With certain combination of the winding to winding impedances, the resulting value of the impedances $\underline{z_i}$ and $\underline{z_j}$ can be obtained as zero (equivalent circuit shown in Figure 2.2).

3.1.2 Simplified input data

If the simplified input data option is selected, the impedances of the transformer windings can be entered using the following combination of input data:

- Short-circuit voltages and copper losses (not available for the zero-sequence data)

- Short-circuit voltages and real part of short circuit voltages
- Short-circuit voltages and x/r ratios
- Reactances and resistances in p.u.

The short-circuit voltages (uk_h0, uk_l1, uk_l2, uk_l3) and copper losses (pcu_h0, pcu_l1, pcu_l2, pcu_l3) are the leading parameters for the positive and negative sequence impedances. The following conversions are used to convert to uk_l1 and pcu_l1 values depending on the available input parameters:

$$pcu\_l1 = r1p\_l1u \cdot S_{r\_lv1} \cdot 1000 \qquad kW \tag{24}$$

$$uk\_l1 = \sqrt{x1pu\_l1^2 + r1pu\_l1^2} \cdot 100 \qquad \% \tag{25}$$

where:

$$r1pu\_l1 = \frac{ukr\_l1}{100} \qquad p.u. \tag{26}$$

$$r1pu\_l1 = \frac{|uk\_l1|}{100} / \sqrt{1 + xtor\_l1^2} \qquad p.u. \tag{27}$$

In the above equations ukr_l1 is the real part short circuit voltage of the LV1 winding, $xt0r\_l1$ is the x to r ratio, $x1pu\_l1$ is the reactance, $r1pu\_l1$ is the resistance and S_{r_lv1} is the rated apparent power. The conversions for the rest of the parameters are done in a similar manner.

The zero sequence short-circuit voltages ($uk0\_h0$, $uk0\_l1$, $uk0\_l2$, $uk0\_l3$) and the real part of the zero sequence short-circuit voltages ($ukr0\_h0$, $ukr0\_l1$, $ukr0\_l2$, $ukr0\_l3$) are the leading parameters for the zero sequence impedances. The following conversions are used to convert to $uk0\_l1$ and $ukr0\_l1$ values depending on the available input parameters:

$$r0pu\_l1 = \frac{|uk0\_l1|}{100} / \sqrt{1 + xtor0\_l1^2} \qquad p.u. \tag{28}$$

$$ukr0\_l1 = r0pu\_l1 \cdot 100 \qquad \% \tag{29}$$

$$uk0\_l1 = \sqrt{x0pu\_l1^2 + r0pu\_l1^2} \cdot 100 \qquad \% \tag{30}$$

where $xtor0\_l1$ is the zero sequence x to r ratio of the LV1 winding, $x0pu\_l1$ is the zero sequence reactance and $r0pu\_l1$ is the zero sequence resistance. The conversions for the rest of the parameters are done in a similar manner.

3.1.2.1 Calculating of the equivalent circuit impedances

The intermediate step as in the case when the complete input data is selected, is here not needed and the equivalent circuit impedances can be calculated directly.

Having the short-circuit voltages uk and copper losses pcu of the windings, equivalent circuit impedances ($\underline{z_h}$, $\underline{z_{l1}}$, $\underline{z_{l2}}$, $\underline{z_{l3}}$) can be calculated and re-based on the HV-winding apparent power. For the LV1 winding the following is valid:

$$z_{l1} = \frac{uk\_l1}{100} \cdot \frac{S_{r\_hv}}{S_{r\_lv1}} \qquad p.u. \tag{31}$$

$$\underline{z_{l1}}.r = \frac{pcu}{1000} \cdot \frac{S_{r\_hv}}{S^2_{r\_lv1}} \qquad p.u. \tag{32}$$

$$\underline{z_{l1}}.i = \sqrt{z^2_{l1} - \underline{z_{l1}}.r^2} \qquad p.u. \tag{33}$$

where S_{r_hv} is the rated apparent power of the HV winding and S_{r_lv1} is the rated apparent power of the LV1 winding. The S_{r_hv}/S_{r_lv1} apparent power ratio is needed to rebase the short-circuit voltage which is based on the apparent power of the LV1 winding to the apparent power of the HV winding. The conversions for the rest of the impedances are done in a similar manner.

Having the zero sequence short-circuit voltages $uk0$ and the zero sequence real part of the short-circuit voltages $ukr0$ per winding, the impedances ($\underline{z_{0h}}$,$\underline{z_{0l1}}$, $\underline{z_{0l2}}$, $\underline{z_{0l3}}$) can be calculated and re-based on the HV winding apparent power. For the LV1 winding the following is valid:

$$z_{0l1} = \frac{uk0\_l1}{100} \cdot \frac{S_{r\_hv}}{S_{r\_lv1}} \qquad p.u. \tag{34}$$

$$\underline{z_{0l1}}.r = \frac{ukr0\_l1}{100} \cdot \frac{S_{r\_hv}}{S_{r\_lv1}} \qquad p.u. \tag{35}$$

$$\underline{z_{0l1}}.i = \sqrt{z_{0l1}^2 - \underline{z_{0l1}}.r^2} \qquad p.u. \tag{36}$$

where S_{r_hv} is the rated apparent power of the HV winding and S_{r_lv1} is the rated apparent power of the LV1 winding. The S_{r_hv}/S_{r_lv1} apparent power ratio is needed to rebase the short-circuit voltage which is based on the apparent power of the winding to the apparent power of the HV winding. The conversions for the rest of the impedances are done in a similar manner.

Using the simplified input mode, the impedances $\underline{z_i}$, $\underline{z_j}$, $\underline{z_{0i}}$ and $\underline{z_{0j}}$ are always set to zero (equivalent circuit shown in Figure 2.2).

3.2 Equivalent circuit parameters

The calculation model of the four-winding transformer uses the equivalent circuit parameters as presented in Table 3.2. For the EMT model, the parameters presented in Table 3.3 are used.

The magnetising admittance $\underline{y_m}$ (parallel representation of conductance and susceptance) is calculated as:

$$y_m = \frac{curmag}{100} \qquad p.u. \tag{37}$$

$$\underline{y_m}.r = \frac{pfe}{1000}/S_{r\_hv} \qquad p.u. \tag{38}$$

$$\underline{y_m}.i = -\sqrt{y_m^2 - \underline{y_m}.r^2} \qquad p.u. \tag{39}$$

where pfe are the measured no-load losses in kW and $curmag$ is the no-load current in $\%$.

The zero sequence magnetising admittance $\underline{y_{m0}}$ is calculated using the zero sequence no-load current $cur0mag$ and the zero sequence r to x magnitude $rtox0\_n$ as:

$$\underline{z_{m0}}.i = \frac{100}{cur0mag}/\sqrt{1 + rtox0\_n^2} \qquad p.u. \tag{40}$$

$$\underline{z_{m0}}.r = \underline{z_{m0}}.i \cdot rtox0\_n \qquad p.u. \tag{41}$$

$$\underline{y_{m0}} = 1/\underline{z_{m0}} \qquad p.u. \tag{42}$$

If one of the transformer windings is connected in delta, the zero sequence admittance is set to zero.

The earthing impedances are calculated using the internal grounding impedances and are all based on the HV-winding apparent power. They are calculated using the winding rated voltages

(U_{r_hv}, U_{r_lv1}, U_{r_lv2} and U_{r_lv3}) as:

$$\underline{z_{e0h}} = (re0hv0 + \jmath \cdot xe0hv0) \cdot \frac{S_{r\_hv}}{U_{r\_hv}^2} \tag{43}$$

$$\underline{z_{e0l1}} = (re0lv1 + \jmath \cdot xe0lv1) \cdot \frac{S_{r\_hv}}{U_{r\_lv1}^2} \tag{44}$$

$$\underline{z_{e0l2}} = (re0lv2 + \jmath \cdot xe0lv2) \cdot \frac{S_{r\_hv}}{U_{r\_lv2}^2} \tag{45}$$

$$\underline{z_{e0l3}} = (re0lv3 + \jmath \cdot xe0lv3) \cdot \frac{S_{r\_hv}}{U_{r\_lv3}^2} \tag{46}$$

The complex winding ratio of the HV-side is calculated according to Equation 47. The ratios of the other sides are calculated in similar manner.

$$\underline{t_h} = (1 + t_{dutap\_h} \cdot \underline{t_{phit\_h}}) \cdot \underline{t_{trangle\_h}} \tag{47}$$

where:

$$t_{dutap\_h} = (ntap\_h0 - ntapneu\_h0) \cdot \frac{dutap\_h0}{100} \tag{48}$$

$$\underline{t_{phitr\_h}} = \cos\left(\frac{phitr\_h0 \cdot \pi}{180}\right) + \jmath \cdot \sin\left(\frac{phitr\_h0 \cdot \pi}{180}\right) \tag{49}$$

$$\underline{t_{trangle\_h}} = \cos\left(\frac{trangle\_h0 \cdot \pi}{6}\right) - \jmath \cdot \sin\left(\frac{trangle\_h0 \cdot \pi}{6}\right) \tag{50}$$

The parameter $ntap\_h0$ is the actual tap position (element parameter), $ntapneu\_h0$ neutral tap position (type parameter), $dutap\_h0$ additional voltage per tap (type parameter), $phitr\_h0$ phase of du (type parameter) and $trangle\_h0$ is the phase shift (type parameter).

The resistances and inductances used for the EMT model are obtained from the complex impedance values calculated above as follows:

$$r = \underline{z}.r \tag{51}$$

$$l = \frac{\underline{z}.i}{2 \cdot \pi \cdot f_{nom}} \tag{52}$$

$$\tag{53}$$

The magnetising conductance and susceptance (in series for the EMT model) are calculated using the no-load current $curmag$ and no-load losses pfe as:

$$y_m = \frac{curmag}{100} \qquad p.u. \tag{54}$$

$$g_m = \frac{pfe}{1000}/S_{r\_hv} \qquad p.u. \tag{55}$$

$$b_m = \sqrt{y_m^2 - g_m^2} \cdot (2 \cdot \pi \cdot f_{nom}) \qquad p.u. \tag{56}$$

The zero sequence values are obtained as:

$$x_{m0} = \frac{100}{cur0mag}/\sqrt{1 + rtox0\_n^2} \tag{57}$$

$$r_{m0} = rtox0\_n \cdot x_{m0} \tag{58}$$

$$b_{m0} = \frac{2 \cdot \pi \cdot f_{nom}}{x_{m0}} \tag{59}$$

If one of the windings is connected in delta, r_{m0} is set to infinite so that no current flows in the magnetizing branch.

Table 3.2: Equivalent circuit parameters

Name in PF	Symbol	Unit	Description
z_h0	$\underline{z}_h$	$p.u.$	Short-circuit impedance HV-winding
z_l1	$\underline{z}_{l1}$	$p.u.$	Short-circuit impedance LV1-winding
z_l2	$\underline{z}_{l2}$	$p.u.$	Short-circuit impedance LV2-winding
z_l3	$\underline{z}_{l3}$	$p.u.$	Short-circuit impedance LV3-winding
z_i	$\underline{z}_i$	$p.u.$	Short-circuit impedance i
z_j	$\underline{z}_j$	$p.u.$	Short-circuit impedance j
ym	$\underline{y}_m$	$p.u.$	Magnetising admittance
$z0\_h0$	$\underline{z}_{0h}$	$p.u.$	Zero sequence short-circuit impedance HV-winding
$z0\_l1$	$\underline{z}_{0l1}$	$p.u.$	Zero sequence short-circuit impedance LV1-winding
$z0\_l2$	$\underline{z}_{0l2}$	$p.u.$	Zero sequence short-circuit impedance LV2-winding
$z0\_l3$	$\underline{z}_{0l3}$	$p.u.$	Zero sequence short-circuit impedance LV3-winding
$z0\_i$	$\underline{z}_{0i}$	$p.u.$	Zero sequence short-circuit impedance i
$z0\_j$	$\underline{z}_{0j}$	$p.u.$	Zero sequence short-circuit impedance j
$ym0$	$\underline{y}_{m0}$	$p.u.$	Zero sequence magnetising admittance
$ze0\_h0$	$\underline{z}_{e0h}$	$p.u.$	Earthing impedance HV-side
$ze0\_l1$	$\underline{z}_{e0l1}$	$p.u.$	Earthing impedance LV1-side
$ze0\_l2$	$\underline{z}_{e0l2}$	$p.u.$	Earthing impedance LV2-side
$ze0\_l3$	$\underline{z}_{e0l3}$	$p.u.$	Earthing impedance LV3-side
t_h0	$\underline{t}_h$	$p.u.$	Complex winding ratio (Tap) HV-side
t_l1	$\underline{t}_{l1}$	$p.u.$	Complex winding ratio (Tap) LV1-side
t_l2	$\underline{t}_{l2}$	$p.u.$	Complex winding ratio (Tap) LV2-side
t_l3	$\underline{t}_{l3}$	$p.u.$	Complex winding ratio (Tap) LV3-side

Table 3.3: Equivalent circuit parameters EMT

Name in PF	**Symbol**	**Unit**	**Description**
r_h0	l_h	$p.u.$	Short-circuit resistance HV-winding
r_l1	l_{l1}	$p.u.$	Short-circuit resistance LV1-winding
r_l2	l_{l2}	$p.u.$	Short-circuit resistance LV2-winding
r_l3	l_{l3}	$p.u.$	Short-circuit resistance LV3-winding
r_i	l_i	$p.u.$	Short-circuit resistance i
r_j	l_j	$p.u.$	Short-circuit resistance j
l_h0	l_h	$p.u.$	Short-circuit inductance HV-winding
l_l1	l_{l1}	$p.u.$	Short-circuit inductance LV1-winding
l_l2	l_{l2}	$p.u.$	Short-circuit inductance LV2-winding
l_l3	l_{l3}	$p.u.$	Short-circuit inductance LV3-winding
l_i	l_i	$p.u.$	Short-circuit inductance i
l_j	l_j	$p.u.$	Short-circuit inductance j
bm	b_m	$p.u.$	Magnetising inductance
gm	g_m	$p.u.$	Magnetising conductance
$r0\_h0$	l_{0h}	$p.u.$	Zero sequence short-circuit resistance HV-winding
$r0\_l1$	l_{0l1}	$p.u.$	Zero sequence short-circuit resistance LV1-winding
$r0\_l2$	l_{0l2}	$p.u.$	Zero sequence short-circuit resistance LV2-winding
$r0\_l3$	l_{0l3}	$p.u.$	Zero sequence short-circuit resistance LV3-winding
$r0\_i$	l_{0i}	$p.u.$	Zero sequence short-circuit resistance i
$r0\_j$	l_{0j}	$p.u.$	Zero sequence short-circuit resistance j
$l0\_h0$	l_{0h}	$p.u.$	Zero sequence short-circuit inductance HV-winding
$l0\_l1$	l_{0l1}	$p.u.$	Zero sequence short-circuit inductance LV1-winding
$l0\_l2$	l_{0l2}	$p.u.$	Zero sequence short-circuit inductance LV2-winding
$l0\_l3$	l_{0l3}	$p.u.$	Zero sequence short-circuit inductance LV3-winding
$l0\_i$	l_{0i}	$p.u.$	Zero sequence short-circuit inductance i
$l0\_j$	l_{0j}	$p.u.$	Zero sequence short-circuit inductance j
$bm0$	b_{m0}	$p.u.$	Zero sequence magnetising inductance
$gm0$	g_{m0}	$p.u.$	Zero sequence magnetising conductance
$re0\_h0$	r_{e0h}	$p.u.$	Earthing resistance HV-side
$re0\_l1$	r_{e0l1}	$p.u.$	Earthing resistance LV1-side
$re0\_l2$	r_{e0l2}	$p.u.$	Earthing resistance LV2-side
$re0\_l3$	r_{e0l3}	$p.u.$	Earthing resistance LV3-side
$le0\_h0$	l_{e0h}	$p.u.$	Earthing inductance HV-side
$le0\_l1$	l_{e0l1}	$p.u.$	Earthing inductance LV1-side
$le0\_l2$	l_{e0l2}	$p.u.$	Earthing inductance LV2-side
$le0\_l3$	l_{e0l3}	$p.u.$	Earthing inductance LV3-side
t_h0	$\underline{t}_h$	$p.u.$	Complex winding ratio (Tap) HV-side
t_l1	$\underline{t}_{l1}$	$p.u.$	Complex winding ratio (Tap) LV1-side
t_l2	$\underline{t}_{l2}$	$p.u.$	Complex winding ratio (Tap) LV2-side
t_l3	$\underline{t}_{l3}$	$p.u.$	Complex winding ratio (Tap) LV3-side

3.3 Relationship between per-unit and absolute values

3.3.1 Impedance between two connection sides

An impedance in Ω as seen from one of the connection sides, referred to the voltage of that connection side, needs to be divided by the reference impedance to get the $p.u.$ value and then multiplied with 100 to get the value in $\%$:

$$uk = \frac{Z_\Omega}{Z_r} \cdot 100 \qquad \% \tag{60}$$

The reference (rated) impedance is calculated as:

$$Z_r = \frac{U_r^2}{S_{r\_min}} \qquad \Omega \tag{61}$$

where U_r is the rated voltage of the connection side in kV and S_{r_min} is the minimum of the rated power of the connection sides. In the case of the simplified input, the rated apparent power of the referred winding is used.

For example, the following is valid for the Z_{HV-LV1} impedance given in Ω referred to the rated voltage of the HV side:

$$uk\_h0l1 = Z_{HV-LV1} \cdot \frac{min(S_{r\_hv}, S_{r\_lv1})}{U_{r\_hv}^2} \cdot 100 \qquad \% \tag{62}$$

3.3.2 No-load current

The no-load current $curmag$ in $\%$, based on the apparent power of the HV winding, is calculated from the measured no-load current I_0 in kA at the LV winding as:

$$curmag = \frac{I_0}{I_{r\_lv}} \cdot \frac{S_{r\_lv}}{S_{r\_hv}} \cdot 100 \qquad where \qquad I_{r\_lv} = \frac{S_{r\_lv}}{\sqrt{3} \cdot U_{r\_lv}} \tag{63}$$

where S_{r_lv} is the rated apparent power in MVA of the LV winding, S_{r_hv} is the rated apparent power in MVA of the HV winding and U_{r_lv} is the rated voltage in kV of the LV winding.

3.4 Nominal power and current

The nominal powers 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:

- $Inom\_h0$, $Inom\_l1$, $Inom\_l2$ and $Inom\_l3$ are the nominal currents in kA
- $Snom\_h0$, $Snom\_11$, $Snom\_12$ and $Snom\_l3$ are the nominal powers in MVA

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

- $Inom\_h0\_a$, $Inom\_l1\_a$, $Inom\_l2\_a$ and $Inom\_l3$ are the actual nominal currents
- $Snom\_h0\_a$, $Snom\_l1\_a$, $Snom\_l2\_a$ and $Snom\_l3\_a$ are the actual nominal powers

3.4.1 Nominal current

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

$$
\begin{aligned}
I_{nomhv} &= ratfac\_h0 \cdot I_{r\_hv} \cdot nt4nm \\
I_{nomlv1} &= ratfac\_l1 \cdot I_{r\_lv1} \cdot nt4nm \\
I_{nomlv2} &= ratfac\_l2 \cdot I_{r\_lv2} \cdot nt4nm \\
I_{nomlv3} &= ratfac\_l3 \cdot I_{r\_lv3} \cdot nt4nm
\end{aligned}
\tag{64}
$$

where the rated currents I_{r_hv}, I_{r_lv1}, I_{r_lv2} and I_{r_lv3} are defined in equation (1) at chapter 3

and

- $ratfac\_h0$, $ratfac\_lv1$, $ratfac\_lv2$ and $ratfac\_lv3$ are the rating factors for the transformer HV-, LV1-, LV2- and LV3-side, defined on the element *Basic Data* page
- $nt4nm$ is the number of parallel transformers, defined on the element *Basic Data* page
- S_{r_hv}, S_{r_lv1}, S_{r_lv2} and S_{r_lv3} are the transformer rated power in MVA for the HV-, LV1-, LV2- and LV3-side, see in table 3.1.
- U_{r_hv}, U_{r_lv1}, U_{r_lv2} and U_{r_lv3} are the transformer HV-, LV1-, LV2- and LV3-side rated voltages in kV, see in table 3.1.

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

- if the continuous rating is entered in MVA:

$$
\begin{aligned}
I_{nomhv} &= \frac{ContRating \cdot nt4nm}{\sqrt{3} \cdot U_{n(bush0)}} \\
I_{nomlv1} &= \frac{ContRating \cdot nt4nm}{\sqrt{3} \cdot U_{n(busl1)}} \\
I_{nomlv2} &= \frac{ContRating \cdot nt4nm}{\sqrt{3} \cdot U_{n(busl2)}} \\
I_{nomlv3} &= \frac{ContRating \cdot nt4nm}{\sqrt{3} \cdot U_{n(busl3)}}
\end{aligned}
$$

- if the continuous rating is entered in kA:

$$
\begin{aligned}
I_{nomhv} &= ContRating \cdot nt4nm \\
I_{nomlv1} &= ContRating \cdot nt4nm \\
I_{nomlv2} &= ContRating \cdot nt4nm \\
I_{nomlv3} &= ContRating \cdot nt4nm
\end{aligned}
$$

- if the continuous rating is entered in %:

$$
\begin{aligned}
I_{nomhv} &= ContRating/100 \cdot I_{r\_hv} \cdot nt4nm \\
I_{nomlv1} &= ContRating/100 \cdot I_{r\_lv1} \cdot nt4nm \\
I_{nomlv2} &= ContRating/100 \cdot I_{r\_lv2} \cdot nt4nm \\
I_{nomlv3} &= ContRating/100 \cdot I_{r\_lv3} \cdot nt4nm
\end{aligned}
$$

where $U_{n(bush0)}$, $U_{n(busl1)}$, $U_{n(busl2)}$ and $U_{n(busl3)}$ are the busbar line-line nominal voltages in kV at the HV-, LV1-, LV2- and LV3-side.

3.4.2 Nominal power

The nominal powers ($Snom\_h0$, $Snom\_l1$, $Snom\_l2$, $Snom\_l3$) and also the corresponding actual value ($Snom\_h0\_a$, $Snom\_l1\_a$, $Snom\_l2\_a$,, $Snom\_l3\_a$) are defined as follow:

When no thermal rating object is selected:

$$
\begin{aligned}
Snom\_h0 &= S_{r\_hv} \cdot nt4nm \cdot ratfac\_h0 \\
Snom\_l1 &= S_{r\_lv1} \cdot nt4nm \cdot ratfac\_l1 \\
Snom\_l2 &= S_{r\_lv2} \cdot nt4nm \cdot ratfac\_l2 \\
Snom\_l3 &= S_{r\_lv3} \cdot nt4nm \cdot ratfac\_l3
\end{aligned}
$$

and for the actual nominal powers:

$$
\begin{aligned}
Snom\_h0\_a &= S_{rT,HV} \cdot nt4nm \cdot ratfac\_h0\_a \\
Snom\_l1\_a &= S_{rT,MV} \cdot nt4nm \cdot ratfac\_l1\_a \\
Snom\_l2\_a &= S_{rT,LV} \cdot nt4nm \cdot ratfac\_l2\_a \\
Snom\_l3\_a &= S_{rT,LV} \cdot nt4nm \cdot ratfac\_l3\_a
\end{aligned}
$$

where:

- S_{r_hv}, S_{r_lv1}, S_{r_lv2} and S_{r_lv3} are the rated apparent powers in MVA, see in table 3.1
- $nt3nm$ is the number of parallel transformers, defined on the element *Basic Data* page
- $ratfac\_h0$, $ratfac\_lv1$, $ratfac\_lv2$ and $ratfac\_lv3$ are the rating factors for the transformer HV-, LV1-, LV2- and LV3-side, defined on the element *Basic Data* page
- $ratfac\_h0\_a$, $ratfac\_lv1\_a$, $ratfac\_lv2\_a$ and $ratfac\_lv3\_a$ are the actual rating factors incl. defined characterists.

In case of a thermal rating object is selected:

$$
\begin{aligned}
Snom\_h0 &= \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomhv} \\
Snom\_l1 &= \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomlv1} \\
Snom\_l2 &= \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomlv2} \\
Snom\_l3 &= \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomlv3}
\end{aligned}
$$

and for the actual nominal powers:

$$
\begin{aligned}
Snom\_h0\_a &= Snom\_h0 \\
Snom\_l1\_a &= Snom\_l1 \\
Snom\_l2\_a &= Snom\_l2 \\
Snom\_l3\_a &= Snom\_l3
\end{aligned}
$$

where:

- I_{nomhv}, I_{nomlv1}, I_{nomlv2} and I_{nomlv3} are the nominal currents at high, medium and low-voltage side, see section 3.4.1.
- $U_{n(bush0)}$, $U_{n(busl1)}$, $U_{n(busl2)}$ and $U_{n(busl3)}$ are the busbar line-line nominal voltages in kV at the HV-, LV1-, LV2- and LV3-side.

4 Load Flow Analysis

4.1 Calculation Quantities for AC Load Flow

4.1.1 Loading

The loading of the transformer is calculated as follows:

$$loading\_hv0 = \frac{I_{bush0}}{I_{nomhv}} \cdot 100 \qquad (\%)$$
$$loading\_lv1 = \frac{I_{busl1}}{I_{nomlv1}} \cdot 100 \qquad (\%)$$
$$loading\_lv2 = \frac{I_{busl2}}{I_{nomlv2}} \cdot 100 \qquad (\%)$$
$$loading\_lv3 = \frac{I_{busl3}}{I_{nomlv3}} \cdot 100 \qquad (\%)$$
$$loading = max(loading\_hv0, loading\_lv1, loading\_lv2, loading\_lv3) \qquad (\%)$$

- $loading$: Maximum loading in %
- $loading\_hv0$: Loading HV-side in %
- $loading\_lv1$: Loading LV1-side in %
- $loading\_lv2$: Loading LV2-side in %
- $loading\_lv3$: Loading LV3-side in %
- I_{nomhv} : Nominal current at HV-side in kA, see section 3.4.1.
- I_{nomlv1} : Nominal current at LV1-side in kA, see section 3.4.1.
- I_{nomlv2} : Nominal current at LV2-side in kA, see section 3.4.1.
- I_{nomlv3} : Nominal current at LV3-side in kA, see section 3.4.1.
- I_{bush0} : Magnitude of the current at h0 terminal
- I_{busl1} : Magnitude of the current at l1 terminal
- I_{busl2} : Magnitude of the current at l2 terminal
- I_{busl3} : Magnitude of the current at l3 terminal

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

4.1.2 Losses

The losses are calculated as follows:

Table 4.1: Losses Quantities

Quantity	Unit	Description	Value
$Ploss$	MW	Losses (total)	$= P_{bushv} + P_{busl1} + P_{busl2} + P_{busl3}$
$Qloss$	$Mvar$	Reactive-Losses (total)	$= Q_{bushv} + Q_{busl1} + Q_{busl2} + Q_{busl3}$
$Plossld$	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:

$$Gmload = Re(\underline{u_{mag}} \cdot \underline{i_{mag}}^*) \cdot S_{r\_hv} \cdot nt4nm \cdot 1000 \qquad (kW)$$
$$Xmload = Im(\underline{u_{mag}} \cdot \underline{i_{mag}}^*) \cdot S_{r\_hv} \cdot nt4nm \cdot 1000 \qquad (kvar)$$

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.

4.2 Calculation Quantities for linear DC Load Flow

4.2.1 Loading

The loading of the transformer is calculated as follows:

$$loading\_hv0 = \frac{|P_{bush0}|}{P_{nomhv}} \cdot 100 \qquad (\%)$$
$$loading\_lv1 = \frac{|P_{busl1}|}{P_{nomlv1}} \cdot 100 \qquad (\%)$$
$$loading\_lv2 = \frac{|P_{busl2}|}{P_{nomlv2}} \cdot 100 \qquad (\%)$$
$$loading\_lv3 = \frac{|P_{busl3}|}{P_{nomlv3}} \cdot 100 \qquad (\%)$$
$$loading = max(loading\_hv0, loading\_lv1, loading\_lv2, loading\_lv3) \qquad (\%)$$

where:

- P_{bush0} : Active power at h0 terminal
- P_{busl1} : Active power at l1 terminal
- P_{busl2} : Active power at l2 terminal
- P_{busl3} : Active power at l3 terminal

- P_{nomhv} : Nominal power at HV-side
- P_{nomlv1} : Nominal power at LV1-side
- P_{nomlv2} : Nominal power at LV2-side
- P_{nomlv3} : Nominal power at LV3-side

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

- $P_{nomhv} = \sqrt{3} \cdot U_{n(bush0)} \cdot I_{nomhv}$
- $P_{nomlv1} = \sqrt{3} \cdot U_{n(busl1)} \cdot I_{nomlv1}$
- $P_{nomlv2} = \sqrt{3} \cdot U_{n(busl2)} \cdot I_{nomlv2}$
- $P_{nomlv3} = \sqrt{3} \cdot U_{n(busl3)} \cdot I_{nomlv3}$

with the nominal currents of the transformer I_{nomhv}, I_{nomlv1}, I_{nomlv2} and I_{nomlv3} (see equation 64).
$U_{n(bush0)}$, $U_{n(busl1)}$, $U_{n(busl2)}$ and $U_{n(busl3)}$ are the busbar line-line nominal voltages in kV at the HV-, LV1-, LV2- and LV3- side.

If a thermal rating object is selected for the corresponding side, the nominal powers are determined as follows:

- if the continuous rating is entered in MVA:

$$\begin{aligned} P_{nomhv} &= ContRating \cdot nt4nm \qquad [MW] \\ P_{nomlv1} &= ContRating \cdot nt4nm \qquad [MW] \\ P_{nomlv2} &= ContRating \cdot nt4nm \qquad [MW] \\ P_{nomlv3} &= ContRating \cdot nt4nm \qquad [MW] \end{aligned}$$

- if the continuous rating is entered in kA:

$$\begin{aligned} P_{nomhv} &= \sqrt{3} \cdot U_{n(bush0)} \cdot ContRating \cdot nt4nm \qquad [MW] \\ P_{nomlv1} &= \sqrt{3} \cdot U_{n(busl1)} \cdot ContRating \cdot nt4nm \qquad [MW] \\ P_{nomlv2} &= \sqrt{3} \cdot U_{n(busl2)} \cdot ContRating \cdot nt4nm \qquad [MW] \\ P_{nomlv3} &= \sqrt{3} \cdot U_{n(busl3)} \cdot ContRating \cdot nt4nm \qquad [MW] \end{aligned}$$

- if the continuous rating is entered in %:

$$\begin{aligned} P_{nomhv} &= \sqrt{3} \cdot U_{n(bush0)} \cdot ContRating/100 \cdot I_{r\_hv} \cdot nt4nm \qquad [MW] \\ P_{nomlv1} &= \sqrt{3} \cdot U_{n(busl1)} \cdot ContRating/100 \cdot I_{r\_lv1} \cdot nt4nm \qquad [MW] \\ P_{nomlv2} &= \sqrt{3} \cdot U_{n(busl2)} \cdot ContRating/100 \cdot I_{r\_lv2} \cdot nt4nm \qquad [MW] \\ P_{nomlv3} &= \sqrt{3} \cdot U_{n(busl3)} \cdot ContRating/100 \cdot I_{r\_lv3} \cdot nt4nm \qquad [MW] \end{aligned}$$

where the rated currents I_{r_hv}, I_{r_lv1}, I_{r_lv2} and I_{r_lv3} are defined in equation (1) at chapter 3.

4.2.2 Losses

Losses are not calculated in the linear DC Load Flow.

5 Harmonics/Power Quality

On the *Harmonics* page of the transformer type, frequency-dependent positive and zero sequence (short-circuit) impedances can be defined. A frequency-dependent positive sequence magnetizing admittance can also be defined, by defining a characteristic for the imaginary and real part of the admittance. If the characteristic is defined through a *Frequency Polynomial Characteristic (ChaPol)* element, then it is automatically defined as relative to rated values. If the characteristic is defined through a *Parameter Characteristic - Vector (ChaVec)* element, then it can be defined as relative (in p.u. or %) or in absolute p.u. values.

6 Inputs/Outputs/State variables of the dynamic models

6.1 Stability Model (RMS)

Table 6.1: Input definition of the RMS-model

Input Signal	Symbol	Description	Unit
nntapin_h0		Tap position HV, controller input	
nntapin_l1		Tap position LV1, controller input	
nntapin_l2		Tap position LV2, controller input	
nntapin_l3		Tap position LV3, controller input	

Table 6.2: Output definition of the RMS-model

Parameter	Symbol	Description	Unit
I0rDelta_hv0		Circulating current in HV-Delta-Winding, Real Part	kA
I0rDelta_lv1		Circulating current in LV1-Delta-Winding, Real Part	kA
I0rDelta_lv2		Circulating current in LV2-Delta-Winding, Real Part	kA
I0rDelta_lv3		Circulating current in LV3-Delta-Winding, Real Part	kA
I0iDelta_hv0		Circulating current in HV-Delta-Winding, Imaginary Part	kA
I0iDelta_lv1		Circulating current in LV1-Delta-Winding, Imaginary Part	kA
I0iDelta_lv2		Circulating current in LV2-Delta-Winding, Imaginary Part	kA
I0iDelta_lv3		Circulating current in LV3-Delta-Winding, Imaginary Part	kA

6.2 EMT-Model

Table 6.3: Input definition of the EMT-model

Input Signal	Symbol	Description	Unit
nntapin_h0		Tap position HV, controller input	
nntapin_l1		Tap position LV1, controller input	
nntapin_l2		Tap position LV2, controller input	
nntapin_l3		Tap position LV3, controller input	

Table 6.4: State variables definition of the EMT-model

Parameter	Symbol	Description	Unit
i0_h0		Zero sequence current in Delta winding (HV)	p.u.
i0_l1		Zero sequence current in Delta winding (LV1)	p.u.
i0_l2		Zero sequence current in Delta winding (LV2)	p.u.
i0_l3		Zero sequence current in Delta winding (LV3)	p.u.
psim_r		Magnetising flux alpha-component	p.u.
psim_i		Magnetising flux beta-component	p.u.
psim_0		Magnetising flux gamma-component	p.u.

Table 6.5: Output definition of the EMT-model

Parameter	Symbol	Description	Unit
I0Delta_hv0		Circulating current in HV-Delta-Winding, Magnitude	kA
I0Delta_lv1		Circulating current in LV1-Delta-Winding, Magnitude	kA
I0Delta_lv2		Circulating current in LV2-Delta-Winding, Magnitude	kA
I0Delta_lv3		Circulating current in LV3-Delta-Winding, Magnitude	kA

7 References

[1] G. J. Wakileh, *Power System Harmonics: Fundamentals, Analysis and Filter Design*. Springer, 1 ed., 2001.

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