POWERFACTORY

PowerFactory 2021

Technical Reference

Single Phase Three Winding Transformer

ElmTr3,TypTr3

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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January 28, 2021
PowerFactory 2021
Revision 2

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1 General Description

PowerFactory single-phase 3-winding transformer supports two types of windings. For a *D* winding, the two endings are connected between two different phases. The *D* winding is assumed to short-circuit the zero sequence through its impedance, i.e. it acts at the zero sequence as a stabilizing winding (equivalent to a delta winding in a three-phase transformer). Additionally it can be grounded through an impedance at one end, which may or may not be connected to a phase/neutral. A *YN* winding represents a centre-tapped winding, can have neutral and can be grounded (both at centre-tap).

The *PowerFactory* *YN* and *D* naming for the single-phase 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 *"YNdyn"* vector group is also referred to as *"INi0in0"*. The *"0"* for the MV and 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 *"INi6in6"* (180 degrees phase-shift) is not explicitly supported, but can be achieved by swapping the phases at the terminals at which the MV and LV side are connected.

The rated voltage of the transformer for the HV-, MV- and the LV-side is always the rated voltage between phase 1 and phase 2. If one phase is connected to neutral (ground) the rated phase-neutral (ground) voltage should be entered.

The single-phase three-winding transformer supports the automatic tap changer control with the same features and options as for the three-phase 3-winding transformer. Please refer to the three-phase 3-winding transformer technical reference for further details.

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.

1.1 Basic winding configurations

Some of the basic winding configurations are reported in the following figures. Autotransformer connection is only possible between two *D* windings. In this case, the third winding can be both *D* or *YN*.

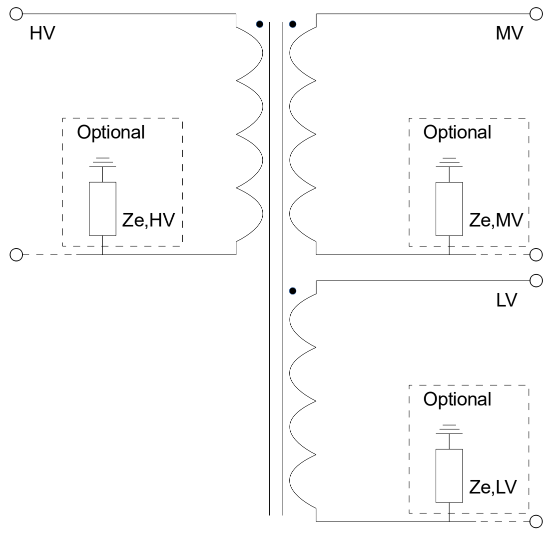

Figure 1.1: D-D-D vector group. For each winding, phase 2 can be connected, grounded or both connected and grounded

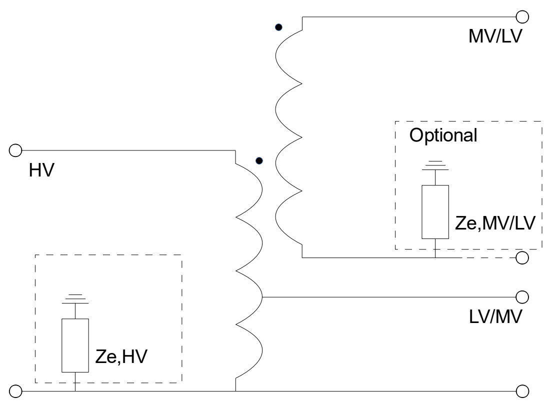

Figure 1.2: D-D-D vector group (autotransformer between any two windings). For the two windings of the autotransformer, phase 2 is always connected; the common grounding is defined in the dialog only for the higher voltage winding (if grounded, phase 2 should normally be connected to neutral)

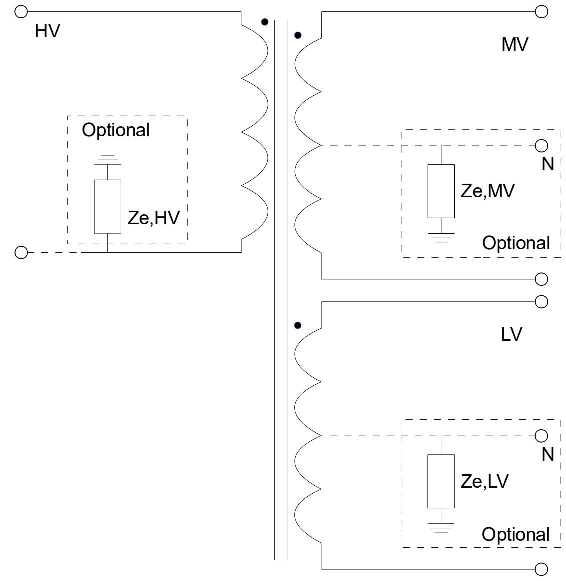

Figure 1.3: D-YN-YN vector group. For the D winding, phase 2 can be connected, grounded or both connected and grounded. For the YN windings, the tapped midpoint can be connected to neutral, grounded or both connected and grounded

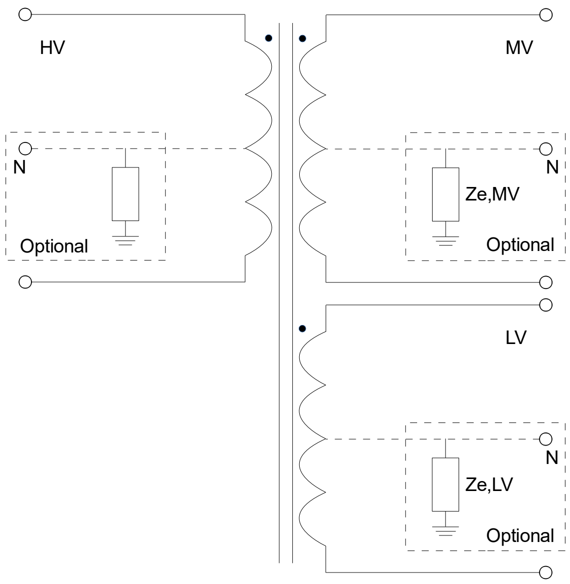

Figure 1.4: YN-YN-YN vector group. For each winding, the tapped midpoint can be connected to neutral, grounded or both connected and grounded

1.1.1 Positive sequence models

For single-phase elements the positive sequence voltage in p.u. is defined in *PowerFactory* as:

$$\underline{u}_1 = \frac{\underline{u}_{L1} - \underline{u}_{L2}}{k} \tag{1}$$

where $\underline{u}_{L1}$ and $\underline{u}_{L2}$ are the phasor voltages of the first and second phase, $k = 2$ if connected to a BI-phase terminal or $k = \sqrt{3}$ if connected to a three-phase terminal. Hence the positive sequence voltage is closely linked to the voltage difference between the two phases of a winding. A similar equation holds for the definition of the positive sequence current.

The positive sequence equivalent circuits for the single-phase 3-winding transformer is similar to that of the three-phase 3-winding transformer and they are reported below. The voltage at the terminals are the positive sequence voltages calculated according to 1. The detailed positive-sequence models with impedances in per unit are shown in Figure 1.5 and Figure 1.6. The positive sequence equivalent is the same for a single-phase *YN* winding or a *D* winding without internal grounding (hence with phase 2 connected). Each of the HV, MV, and LV windings has a resistance and a leakage reactance designated by r_{Cu} and X_σ together with the corresponding winding initials. An ideal transformer with a 1:1 turns ratio links the three windings at the magnetic *star point*. The models also include a magnetisation reactance and an iron loss resistance designated respectively by x_M and r_{Fe}. The magnetisation reactance and the iron loss resistance can be modelled at different positions (star point, HV-Side, MV-Side or LV-Side). Also the position of the taps can be changed from the star point (Figure 1.5) to the terminal sides (Figure 1.6) with the default position being the star point.

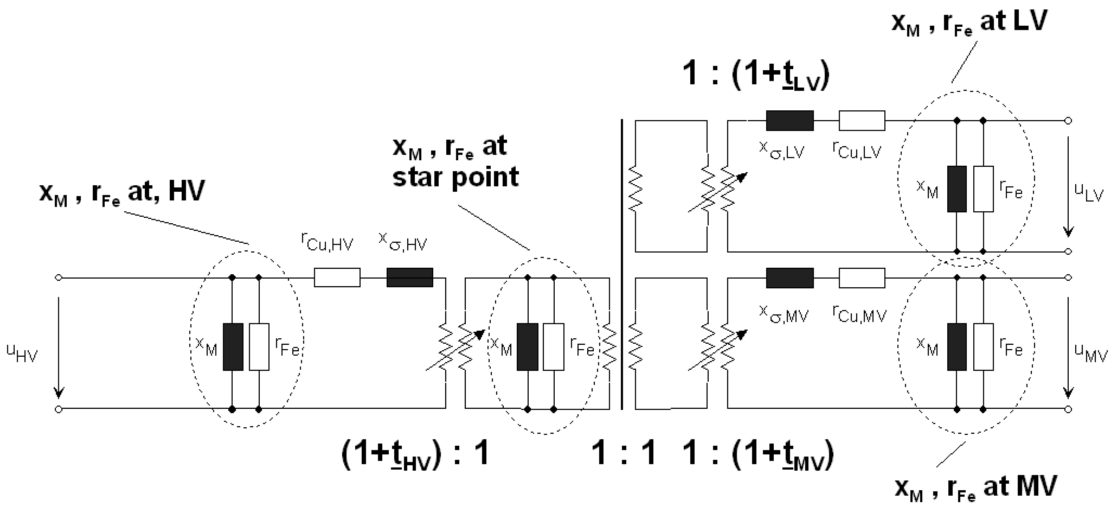

Figure 1.5: *PowerFactory* positive-sequence model of the single-phase 3-winding transformer, taps modelled at star point

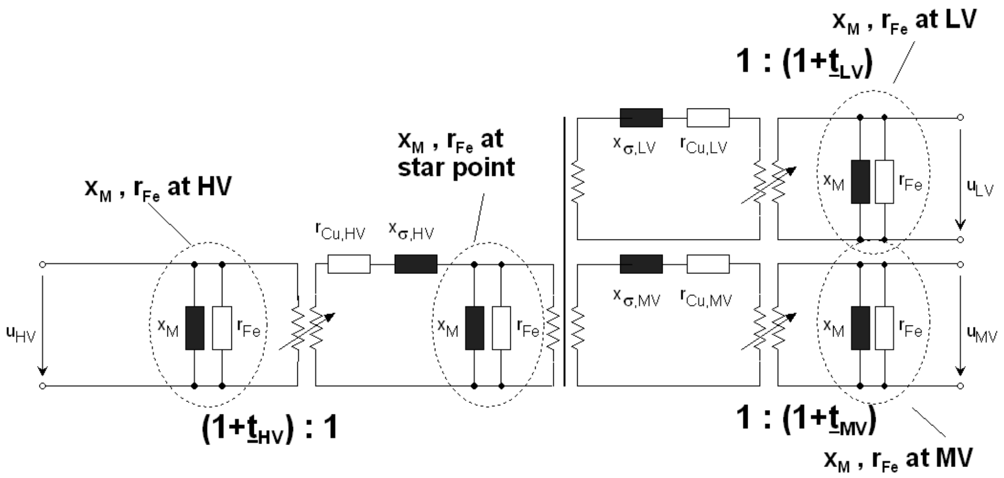

Figure 1.6: *PowerFactory* positive-sequence model of the single-phase 3-winding transformer, taps modelled at terminals

If a *D* winding is grounded and its phase 2 is not connected, the above positive sequence equivalent circuits are still valid, but the positive sequence voltage and current must be intended as the voltage across the winding and the current through the winding. If re and xe are the internal grounding resistance and reactance connected between winding ending 2 and ground, then in p.u.:

$$\underline{i}_1 = \underline{i}_{L1} \tag{2}$$

$$\underline{u}_1 = \underline{u}_{L1} - (re + jxe) \cdot \underline{i}_1 \tag{3}$$

1.1.2 Positive sequence input parameters

$U_{r,HV}$, $U_{r,MV}$, $U_{r,LV}$	kV	Rated voltages on HV/MV/LV side
$S_{r,HV}$, $S_{r,MV}$, $S_{r,LV}$	MVA	Rated power for the windings on HV/MV/LV side
$u_{sc,HV-MV}$, $u_{sc,MV-LV}$, $u_{sc,LV-HV}$	%	Relative short-circuit voltage of paths HV-MV, MV-LV, LV-HV
$P_{Cu,HV-MV}$, $P_{Cu,MV-LV}$, $P_{Cu,LV-HV}$	kW	Copper losses of path HV-MV, MV-LV, LV-HV
$u_{r,sc,HV-MV}$, $u_{r,sc,MV-LV}$, $u_{r,sc,LV-HV}$	%	Relative short-circuit voltage, resistive part of paths HV-MV, MV-LV, LV-HV
X/R_{HV-MV}, X/R_{MV-LV}, X/R_{LV-HV}		Relative short-circuit voltage, X/R ratio of path HV-MV, MV-LV, LV-HV
$i0$	%	No-load current, related to rated current at HV side
P_{Fe}	kW	No-load losses

Rated currents

The rated currents (HV, MV, LV) are:

$$
\begin{aligned}
I_{r,HV} &= \frac{S_{r,HV}}{U_{r,HV}} \qquad (kA) \\
I_{r,MV} &= \frac{S_{r,MV}}{U_{r,MV}} \qquad (kA) \\
I_{r,LV} &= \frac{S_{r,LV}}{U_{r,LV}} \qquad (kA)
\end{aligned} \tag{4}
$$

The following sections briefly describe the measurements performed in order to determine the parameters of a single-phase three-winding transformer. The equivalent circuits describing the test measurements are conceptually similar to the ones for a three-phase three-winding transformer. In order to perform the positive sequence short-circuit tests for a single-phase transformer, a single-phase voltage source is connected between phase 1 and 2 of the supplied side, while phase 1 and 2 are shorted on the relevant shorted winding.

1.1.2.1 HV-MV Measurement

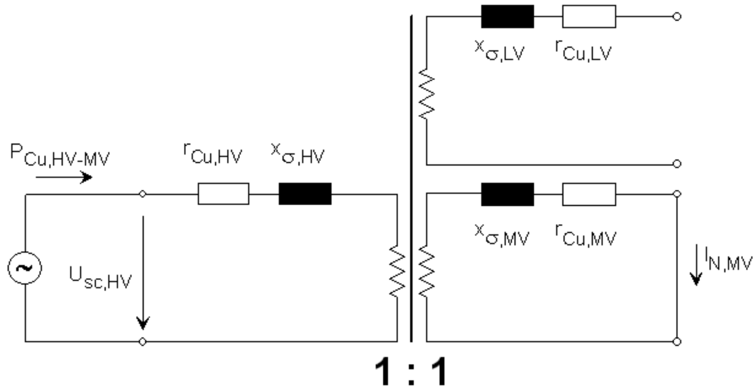

Figure 1.7: Short-circuit on MV-side, open-circuit on LV-side

The short-circuited winding (MV-side) should carry the current according to:

$$I_{m,MV} = \frac{Min(S_{r,HV}, S_{r,MV})}{U_{r,MV}} \qquad (kA)$$

The positive-sequence short-circuit voltage HV-MV can be calculated from the measured voltage on the HV-side:

$$u_{sc,HV-MV} = \frac{U_{sc,HV}}{U_{r,HV}} \cdot 100\%$$

The real part of the short-circuit voltage can be specified in different ways:

- Copper Losses in kW:
  The measured active power flow in kW can be directly entered into the corresponding input field

- Real part of short-circuit voltage in %:

$$u_{r,sc,HV-MV} = \frac{P_{Cu,HV-MV}}{Min(S_{r,HV},S_{r,MV}) \cdot 1000} \cdot 100\%$$

  with P_{Cu} in kW.

- X/R ratio:
  Imaginary part of the short-circuit voltage HV-MV:

$$u_{i,HV-MV} = \sqrt{U^2_{sc,HV-MV} - U^2_{r,sc,HV-MV}}$$

  X/R ratio for HV-MV:

$$X/R_{HV-MV} = \frac{U_{i,HV-MV}}{U_{r,HV-MV}}$$

The short-circuit voltage and impedance are referred to the minimum of the HV-side and MV-side rated powers.

$$r_{Cu,HV-MV} = \frac{u_{r,sc,HV-MV}}{100\%} = r_{Cu,HV} + r_{Cu,MV}$$
$$x_{\sigma,HV-MV} = \frac{u_{i,sc,HV-MV}}{100\%} = x_{\sigma,HV} + x_{\sigma,MV}$$

1.1.2.2 MV-LV Measurement

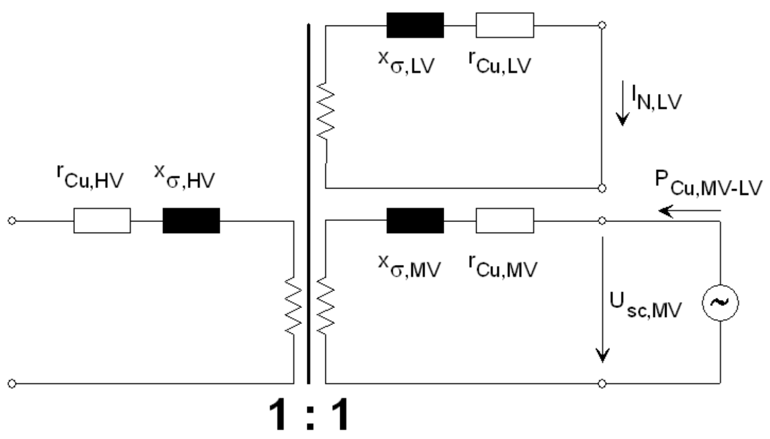

Figure 1.8: Short-circuit on LV-side, open-circuit on HV-side

The short-circuited winding (LV-side) should carry the current calculated as:

$$I_{m,LV} = \frac{Min(S_{r,MV},S_{r,LV})}{U_{r,LV}} \quad (kA)$$

The positive-sequence short-circuit voltage MV-LV can be calculated from the measured voltage on the MV-side as:

$$u_{sc,MV-LV} = \frac{U_{sc,MV}}{U_{r,MV}} \cdot 100\%$$

The real part of the short-circuit voltage can be specified in different ways:

- Copper Losses in kW:
  The measured active power flow in kW can be directly entered into the corresponding input field
- Real part of short-circuit voltage in %:

$$u_{r,sc,MV-LV} = \frac{P_{Cu,MV-LV}}{Min(S_{r,MV}, S_{r,LV}) \cdot 1000} \cdot 100\%$$

  with P_{Cu} in kW.

- X/R ratio:
  Imaginary part of the short-circuit voltage HV-MV:

$$u_{i,MV-LV} = \sqrt{U_{sc,MV-LV}^2 - U_{r,sc,MV-LV}^2}$$

  X/R ratio for HV-MV:

$$X/R_{MV-LV} = \frac{U_{i,MV-LV}}{U_{r,MV-LV}}$$

The short-circuit voltage and impedance are referred to the minimum of the MV-side and LV-side rated powers.

$$r_{Cu,MV-LV} = \frac{u_{r,sc,MV-LV}}{100\%} = r_{Cu,MV} + r_{Cu,LV}$$
$$x_{\sigma,MV-LV} = \frac{u_{i,sc,MV-LV}}{100\%} = x_{\sigma,MV} + x_{\sigma,LV}$$

1.1.2.3 LV-HV Measurement

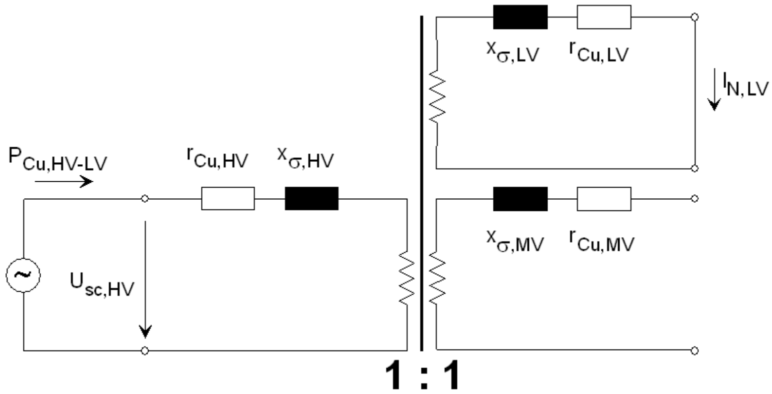

Figure 1.9: Short-circuit on LV-side, open-circuit on MV-side

The short-circuited winding (LV-side) should carry the current calculated as:

$$I_{m,LV} = \frac{Min(S_{r,HV}, S_{r,LV})}{U_{r,LV}} \quad (kA)$$

The positive-sequence short-circuit voltage LV-HV can be calculated from the measured voltage on the HV-side as:

$$u_{sc,LV-HV} = \frac{U_{sc,HV}}{U_{r,HV}} \cdot 100\%$$

The real part of the short-circuit voltage can be specified in different ways:

- Copper Losses in kW:
  The measured active power flow in kW can be directly entered into the corresponding input field
- Real part of short-circuit voltage in %:

  $$u_{r,sc,LV-HV} = \frac{P_{Cu,LV-HV}}{Min(S_{r,HV}, S_{r,LV}) \cdot 1000} \cdot 100\%$$

  with P_{Cu} in kW.
- X/R ratio:
  Imaginary part of the short-circuit voltage LV-HV:

  $$u_{i,LV-HV} = \sqrt{U^2_{sc,LV-HV} - U^2_{r,sc,LV-HV}}$$

  X/R ratio for LV-HV:

  $$X/R_{LV-HV} = \frac{U_{i,LV-HV}}{U_{r,LV-HV}}$$

The short-circuit voltage and impedance are referred to the minimum of the LV-side and HV-side rated powers.

$$r_{Cu,LV-HV} = \frac{u_{r,sc,LV-HV}}{100\%} = r_{Cu,LV} + r_{Cu,HV}$$
$$x_{\sigma,LV-HV} = \frac{u_{i,sc,LV-HV}}{100\%} = x_{\sigma,LV} + x_{\sigma,HV}$$

1.1.2.4 Magnetizing impedance measurement

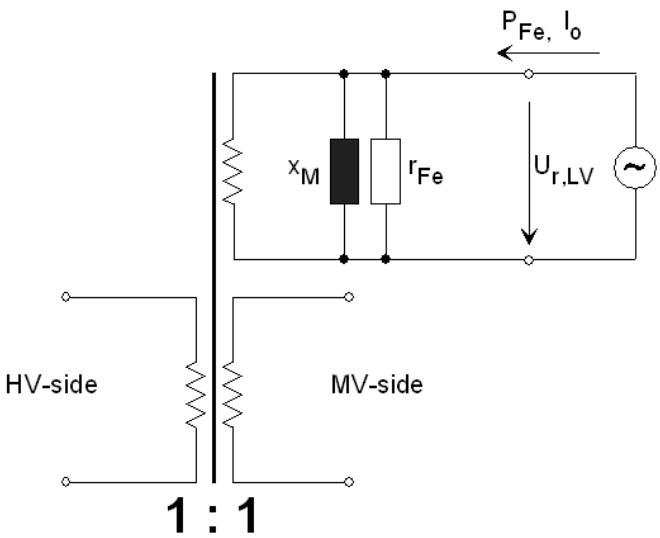

Figure 1.10: Measurement of iron losses and no load current on LV-side

The no-load current in % referred to the HV-side rated power (type parameter *curm3*) is calculated according to the following equation::

$$i_0 = \frac{I_0}{I_{r,LV}} \cdot \frac{S_{r,LV}}{S_{ref}} \times 100\% \quad with \quad I_{r,LV} = \frac{S_{r,LV}}{U_{r,LV}} \quad in\, kA$$

I_0 measured no load current in kA

P_{Fe} measured iron losses in kW (type parameter *pfe*)

$S_{ref} = S_{r,HV}$ *in MVA → reference power in* PowerFactory *is equal to HV-side rated power*

The measured active power P_{Fe} in kW is entered directly into the corresponding *PowerFactory* input field. The p.u. magnetizing impedance, reactance and iron loss resistance are related to the measured no-load current and iron losses according to:

$$y_M = \frac{i_0}{100\%}$$

$$r_{Fe} = \frac{S_{ref}}{P_{Fe} \cdot 1000} \qquad P_{Fe}\, in\, kW\, and\, S_{ref}\, in\, MVA$$

$$x_M = \frac{1}{\sqrt{(y_M^2 - (1/r_{Fe})^2)}}$$

1.1.2.5 Relation between input parameters and absolute impedances

The relation between the input parameters in the type and element dialogues and the absolute impedances are described in the following:

Impedance Z_{HV-MV} seen from the HV-side:

$$u_{sc,HV-MV} = Z_{HV,MV} \cdot \frac{Min(S_{r,HV}, S_{r,MV})}{U_{r,HV}^2} \times 100\% \quad \text{with } Z_{HV-MV} \text{ in Ohm referred to } U_{r,HV}$$

Impedance Z_{MV-LV} seen from the MV-side:

$$u_{sc,MV-LV} = Z_{MV,LV} \cdot \frac{Min(S_{r,MV}, S_{r,LV})}{U_{r,MV}^2} \times 100\% \quad \text{with } Z_{MV-LV} \text{ in Ohm referred to } U_{r,MV}$$

Impedance Z_{LV-HV} seen from the LV-side:

$$u_{sc,LV-HV} = Z_{LV,HV} \cdot \frac{Min(S_{r,LV}, S_{r,HV})}{U_{r,LV}^2} \times 100\% \quad \text{with } Z_{LV-HV} \text{ in Ohm referred to } U_{r,LV}$$

1.1.3 Zero sequence models

For single-phase elements the zero sequence voltage in p.u. is defined in *PowerFactory* as:

$$\underline{u}_0 = \frac{\underline{u}_{L1} + \underline{u}_{L2}}{k} \tag{5}$$

where $\underline{u}_{L1}$ and $\underline{u}_{L2}$ are the phasor voltages of the first and second phase, $k = 2$ if connected to a BI-phase terminal or $k = \sqrt{3}$ if connected to a three-phase terminal. A similar equation holds for the definition of the zero sequence current.

The zero sequence short-circuit impedances are assumed to be equal to the positive sequence ones (usually zero sequence short-circuit tests are not available).

An ungrounded *D* winding (hence, with phase 2 connected) is seen from its terminals as an open circuit at the zero sequence. For a grounded *D* winding with phase 2 connected a zero sequence current can flow at its terminals. For a grounded *D* winding without connection of phase 2 there is no need to treat the zero sequence (treating solely the positive sequence is enough to determine its behaviour). In all cases, a *D* winding, when not part of an autotransformer, is assumed to be winded in such a way to act as a stabilizing winding, thus providing a short-circuiting path for the zero sequence (analogously to a delta winding for a three-phase transformer).

The zero-sequence model of a single-phase three-winding transformer depends on the vector group of each winding. The following sections describe the different vector groups.

Note: If the transformer has a delta winding, the zero sequence magnetising impedance is neglected since in reality it is effectively short circuited by the delta (stabilizing) winding impedance (this impedance is lower than the magnetising impedance). If the transformer vector group is *YNynyn*, the zero sequence magnetising impedance is assumed equal to the positive sequence magnetising impedance.

In the following figures, $k = 2$ if the corresponding transformer side is connected to a BI-phase terminal or $k = \sqrt{3}$ if connected to a three-phase terminal.

1.1.3.1 Ungrounded D-d-d connection (Delta-delta-delta)

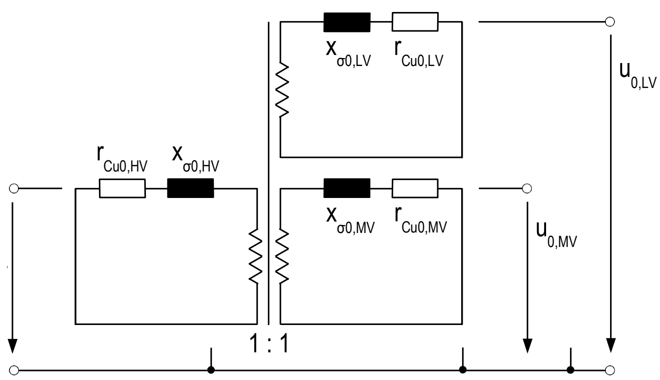

Figure 1.11: Zero-sequence model of single-phase D-d-d transformer. All d windings are ungrounded

According to Figure 1.11 the zero-sequence impedances have no influence on the zero-sequence voltage. An ungrounded *D* winding with phase 2 connected is seen from its terminals as an open circuit at the zero sequence.

1.1.3.2 Grounded D-d-d connection (Delta-delta-delta)

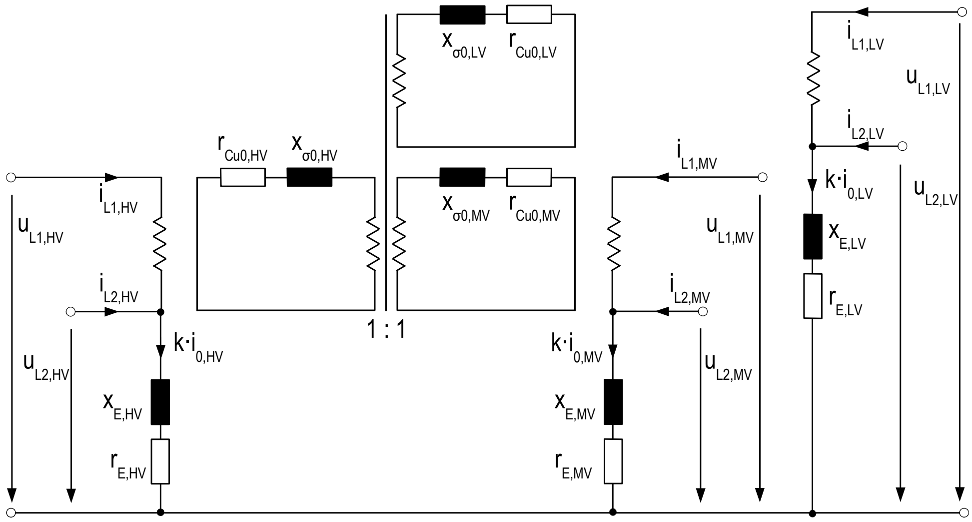

Figure 1.12: Zero-sequence model of single-phase D-d-d transformer. All d windings are internally grounded and phase 2 is connected

According to Figure 1.12 a zero-sequence current can flow to ground from the *d* winding terminals but no zero sequence voltage can be transformed from a *d* winding to another winding.

$$\underline{i}_0 = \frac{\underline{i}_{L1} + \underline{i}_{L2}}{k} \tag{6}$$

$$\underline{u}_{L2} = k \cdot (re + jxe) \cdot \underline{i}_0 = (re + jxe) \cdot (\underline{i}_{L1} + \underline{i}_{L2}) \tag{7}$$

1.1.3.3 YN-d-d connection (Grounded wye-delta-delta)

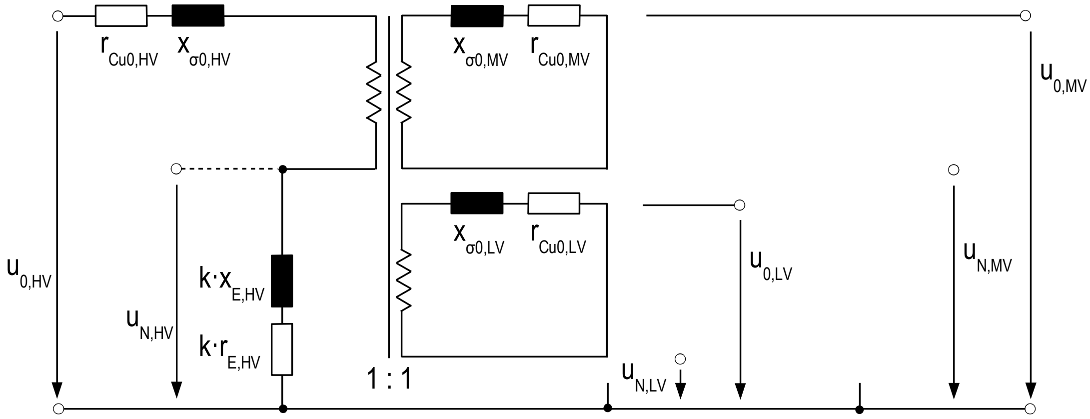

Figure 1.13: Zero-sequence model of single-phase YN-d-d transformer

Figure 1.13 shows that the LV-side and the MV-side have no zero-sequence connection to the terminals. Both delta windings are short-circuited in the zero-sequence system (they act as a stabilizing winding). The zero-sequence magnetizing impedance is neglected.

1.1.3.4 YN-yn-d connection (Grounded wye-grounded wye-delta)

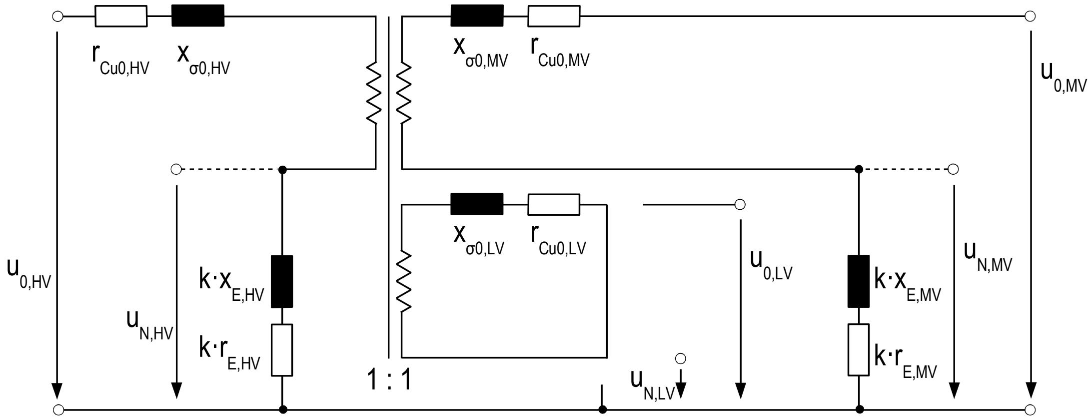

Figure 1.14: Zero-sequence model of YN-yn-d transformer

1.1.3.5 YN-yn-yn connection (Grounded wye-grounded wye-grounded wye)

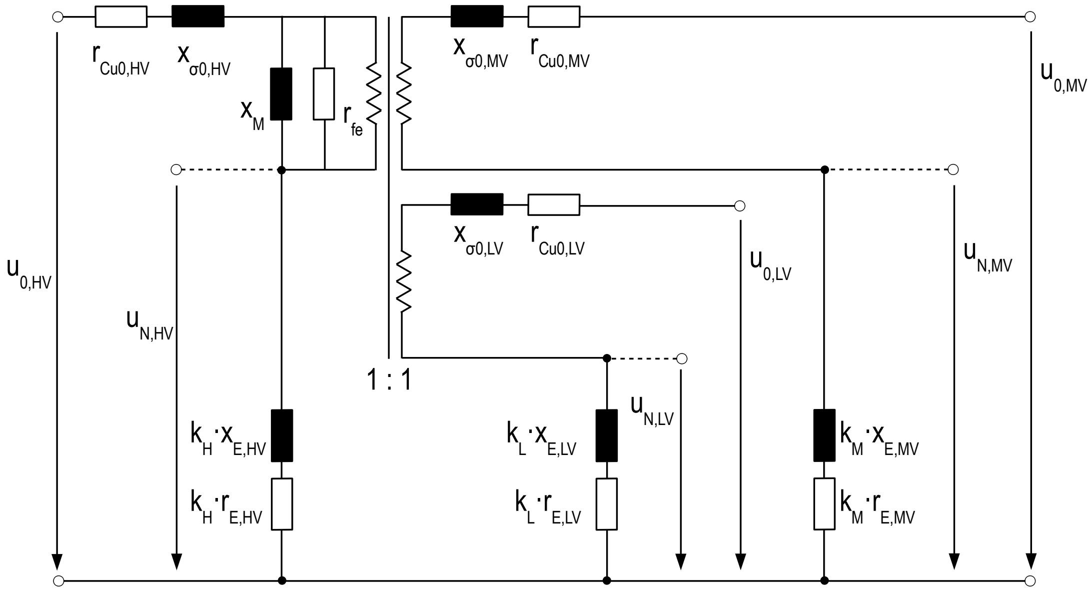

Figure 1.15: Zero-sequence model of YN-yn-yn transformer

1.1.3.6 D-d-d auto-transformer (Delta-Delta-delta auto transformer)

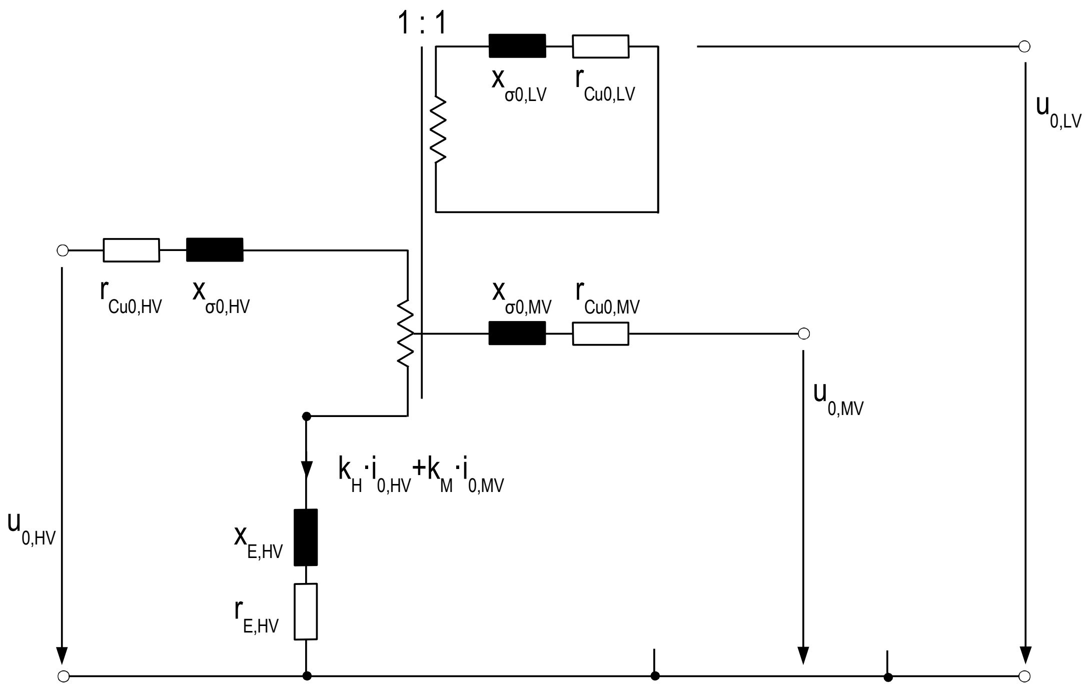

Figure 1.16: Zero-sequence model of single-phase D-d-d auto transformer

For the two *d* windings of the autotransformer (HV and MV side in the shown case), the following holds (all currents are in kA, all voltages in kV and all impedances in Ohm):

$$k_H \cdot \underline{I}_{0,HV} + k_M \cdot \underline{I}_{0,MV} = \frac{\underline{U}_{L2,HV}}{r_{e,HV} + jx_{e,HV}} \tag{8}$$

$$\underline{I}_{L1,HV} + \underline{I}_{L2,HV} + \underline{I}_{L1,MV} + \underline{I}_{L2,MV} = \frac{\underline{U}_{L2,HV}}{r_{e,HV} + jx_{e,HV}} \tag{9}$$

$$\underline{U}_{L2,HV} = \underline{U}_{L2,MV} \tag{10}$$

where $k_H = 2$ if the HV side is connected to a BI-phase terminal or $k_H = \sqrt{3}$ if the HV side is connected to a three-phase terminal, $k_M = 2$ if the MV side is connected to a BI-phase terminal or $k_M = \sqrt{3}$ if the MV side is connected to a three-phase terminal. In case of an ungrounded autotransformer, the equation 8 simplifies to:

$$k_H \cdot \underline{I}_{0,HV} + k_M \cdot \underline{I}_{0,MV} = 0 \tag{11}$$

$$\underline{I}_{L1,HV} + \underline{I}_{L2,HV} + \underline{I}_{L1,MV} + \underline{I}_{L2,MV} = 0 \tag{12}$$

1.1.3.7 D-d-yn auto-transformer (Delta-Delta-grounded wye auto transformer)

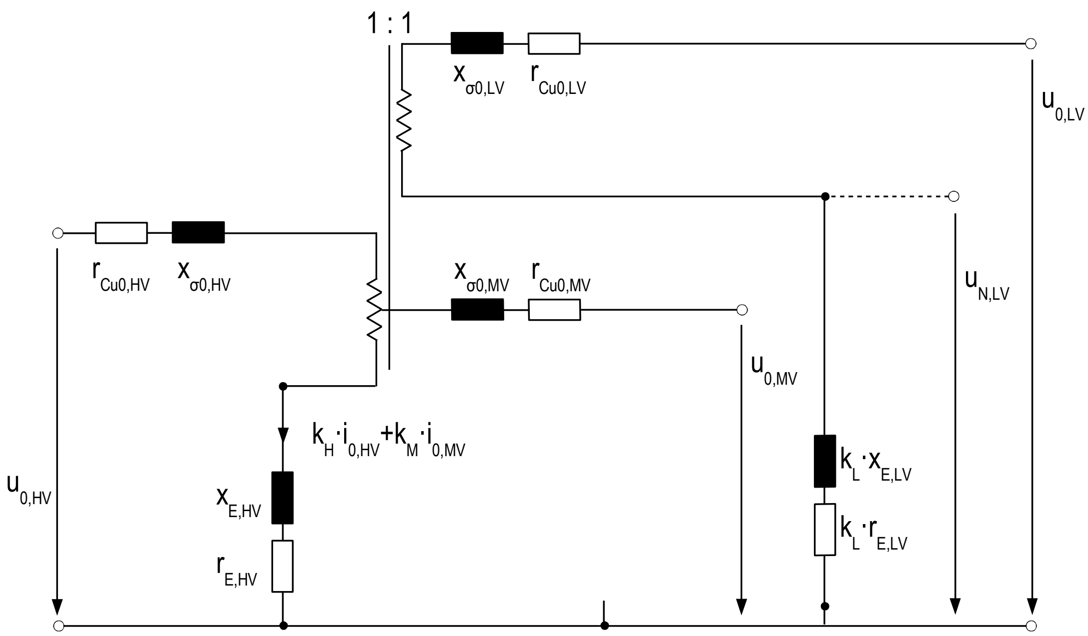

Figure 1.17: Zero-sequence model of D-d-yn auto transformer

For the autotransformer, equations 8, 11 and 10 are still valid.

1.2 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:

- $Inom\_h$, $Inom\_m$ and $Inom\_l$ are the nominal currents in kA
- $Snom\_h$, $Snom\_m$ and $Snom\_l$ 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:

- $Inom\_h\_a$, $Inom\_m\_a$ and $Inom\_lv$ are the actual nominal currents
- $Snom\_h\_a$, $Snom\_m\_a$ and $Snom\_l\_a$ are the actual nominal powers

1.2.1 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:

$$
\begin{aligned}
I_{nomhv} &= ratfac\_h \cdot I_{r,HV} \cdot nt3nm \\
I_{nommv} &= ratfac\_m \cdot I_{r,MV} \cdot nt3nm \\
I_{nomlv} &= ratfac\_l \cdot I_{r,LV} \cdot nt3nm
\end{aligned}
\tag{13}
$$

where the rated currents $I_{r,HV}$, $I_{r,MV}$ and $I_{r,LV}$ are defined in equation (4) at section 1.1.1

and

- $ratfac\_h$, $ratfac\_m$ and $ratfac\_l$ are the rating factors for the transformer HV-, MV- and LV-side, defined on the element Basic page
- $nt3nm$ is the number of parallel transformers, defined on the element Basic page
- $S_{r,HV}$, $S_{r,MV}$, $S_{r,LV}$, $U_{r,HV}$, $U_{r,MV}$, $U_{r,LV}$ are defined in section 1.1.2

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:

$$
\begin{aligned}
I_{nomhv} &= \frac{ContRating \cdot nt3num}{U_{bushv}} \\
I_{nommv} &= \frac{ContRating \cdot nt3num}{U_{busmv}} \\
I_{nomlv} &= \frac{ContRating \cdot nt3num}{U_{buslv}}
\end{aligned}
$$

where U_{bushv}, U_{busmv} 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.

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

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

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

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

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

- if the continuous rating is entered in kA:

$$I_{nomhv} = ContRating \cdot nt3nm$$
$$I_{nommv} = ContRating \cdot nt3nm$$
$$I_{nomlv} = ContRating \cdot nt3nm$$

- if the continuous rating is entered in %:

$$I_{nomhv} = ContRating/100 \cdot I_{r,HV} \cdot nt3nm$$
$$I_{nommv} = ContRating/100 \cdot I_{r,MV} \cdot nt3nm$$
$$I_{nomlv} = ContRating/100 \cdot I_{r,LV} \cdot nt3nm$$

where $U_{n(bushv)}$, $U_{n(busmv)}$ and $U_{n(buslv)}$ are the busbar line-line nominal voltages in kV at the high, medium and low-voltage side.

1.2.2 Nominal power

The nominal powers ($Snom\_h$, $Snom\_m$, $Snom\_l$) and also the corresponding actual value ($Snom\_h\_a$, $Snom\_m\_a$, $Snom\_l\_a$) are defined as follow:

When no thermal rating object is selected:

$$Snom\_h = S_{r,HV} \cdot nt3nm \cdot ratfac\_h$$
$$Snom\_m = S_{r,MV} \cdot nt3nm \cdot ratfac\_m$$
$$Snom\_l = S_{r,LV} \cdot nt3nm \cdot ratfac\_l$$

and for the actual nominal powers:

$$Snom\_h\_a = S_{r,HV} \cdot nt3nm \cdot ratfac\_h\_a$$
$$Snom\_m\_a = S_{r,MV} \cdot nt3nm \cdot ratfac\_m\_a$$
$$Snom\_l\_a = S_{r,LV} \cdot nt3nm \cdot ratfac\_l\_a$$

where:

- $S_{r,HV}$, $S_{r,MV}$, $S_{r,LV}$, are the rated apparent powers, see also in section 1.1.2
- $nt3nm$ is the number of parallel transformers, defined on the element *Basic Data* page
- $ratfac\_h$, $ratfac\_m$ and $ratfac\_l$ are the rating factors for the transformer HV-, MV- and LV-side, defined on the element *Basic Data* page
- $ratfac\_h\_a$, $ratfac\_m\_a$ and $ratfac\_l\_a$ are the actual rating factors incl. defined characteristics.

In case of a thermal rating object is selected:

$$
\begin{aligned}
Snom\_h &= U_{bushv} \cdot I_{nomhv} \\
Snom\_m &= U_{busmv} \cdot I_{nommv} \\
Snom\_l &= U_{buslv} \cdot I_{nomlv}
\end{aligned}
$$

and for the actual nominal powers:

$$
\begin{aligned}
Snom\_h\_a &= Snom\_h \\
Snom\_m\_a &= Snom\_m \\
Snom\_l\_a &= Snom\_l
\end{aligned}
$$

where:

- I_{nomhv}, I_{nommv}, I_{nomlv} are the nominal currents at high, medium and low- voltage side, see section 1.2.1.
- U_{bushv}, U_{busmv} 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.

$$
\begin{aligned}
U_{bushv} &= U_{n(bushv)} \\
U_{busmv} &= U_{n(busmv)} \\
U_{buslv} &= U_{n(buslv)}
\end{aligned}
$$

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

$$
\begin{aligned}
U_{bushv} &= U_{n(bushv)}/\sqrt{3} \\
U_{busmv} &= U_{n(busmv)}/\sqrt{3} \\
U_{buslv} &= U_{n(buslv)}/\sqrt{3}
\end{aligned}
$$

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

$$
\begin{aligned}
U_{bushv} &= U_{n(bushv)}/2 \\
U_{busmv} &= U_{n(busmv)}/2 \\
U_{buslv} &= U_{n(buslv)}/2
\end{aligned}
$$

2 Load Flow Analysis

The tap changer control is implemented as for the three-phase three-winding transformer, please refer to *ElmTr3* technical reference for further details.

2.1 Calculation Quantities for AC Load Flow

2.1.1 Loading

The loading of the transformer is calculated as follows:

$$
\begin{aligned}
loading\_h &= \frac{I_{bushv}}{I_{nomhv}} \cdot 100 \qquad (\%) \\
loading\_m &= \frac{I_{busmv}}{I_{nommv}} \cdot 100 \qquad (\%) \\
loading\_l &= \frac{I_{buslv}}{I_{nomlv}} \cdot 100 \qquad (\%) \\
loading &= max(loading\_h, loading\_m, loading\_l) \qquad (\%)
\end{aligned}
$$

- $loading$: Maximum loading in %
- $loading\_h$: Loading high voltage side in %
- $loading\_m$: Loading medium voltage side in %
- $loading\_l$: Loading low voltage side in %
- I_{nomhv} : Nominal current at the high voltage side in kA, see section 1.2.1.
- I_{nommv} : Nominal current at the medium voltage side in kA, see section 1.2.1.
- I_{nomlv} : Nominal current at the low voltage side in kA, see section 1.2.1.
- I_{bushv} : Magnitude of the current at high voltage terminal
- I_{busmv} : Magnitude of the current at medium 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)	$= P_{bushv} + P_{busmv} + P_{buslv}$
$Qloss$	$Mvar$	Reactive-Losses (total)	$= Q_{bushv} + Q_{busmv} + Q_{buslv}$
$Plossld$	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:

$$Gmload = Re(\underline{u}_{mag} \cdot \underline{i}^*_{mag}) \cdot S_{r,HV} \cdot nt3nm \cdot 1000 \qquad (kW)$$
$$Xmload = Im(\underline{u}_{mag} \cdot \underline{i}^*_{mag}) \cdot S_{r,HV} \cdot nt3nm \cdot 1000 \qquad (kvar)$$

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.

3 Input/Output Definitions of Dynamic Models

Table 3.1: Input Variables of RMS and EMT transformer model

Parameter	Description	Unit
nntapin_h	Tap position (HV), controller input	
nntapin_m	Tap position (MV), controller input	
nntapin_l	Tap position (LV), controller input	

Table 3.2: State Variables of transformer model for EMT-simulation

Parameter	Description	Unit
psim	Magnetizing flux	p.u.
psim_0	Magnetizing flux (Zero-Sequence)	p.u.

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