POWERFACTORY

PowerFactory 2021

Technical Reference

Three-Winding Transformer

ElmTr3,TypTr3

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

January 28, 2021
PowerFactory 2021
Revision 2

Contents

1 General Description

The 3-winding transformer is a 3-port element connecting 3 cubicles in the network. *PowerFactory* comes with a built-in model for three-winding transformers explained in this document.

Section 1.1 presents the sequence equivalent models of the three-winding transformer including generalized tap-changers (for phase and magnitude). Section 4 discusses typical applications of three-winding transformers in power systems.

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 Model Diagrams

1.1.1 Positive and Negative sequence models

The detailed positive-sequence models with impedances in per unit are shown in Figure 1.1 and Figure 1.2. The negative-sequence models are identical to the positive-sequence models. 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 (default: star point, HV-Side, MV-Side or LV-Side). Also the position of the taps can be changed from the star point (Figure 1.1) to the terminal sides (Figure 1.2) with the default position being the star point.

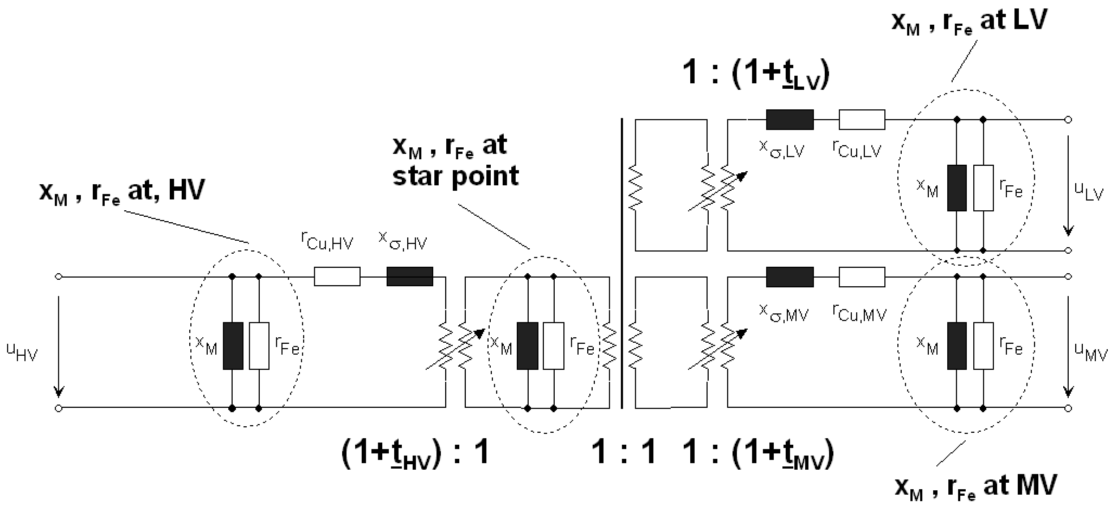

Figure 1.1: *PowerFactory* positive-sequence model of the 3-winding transformer, taps modelled at star point

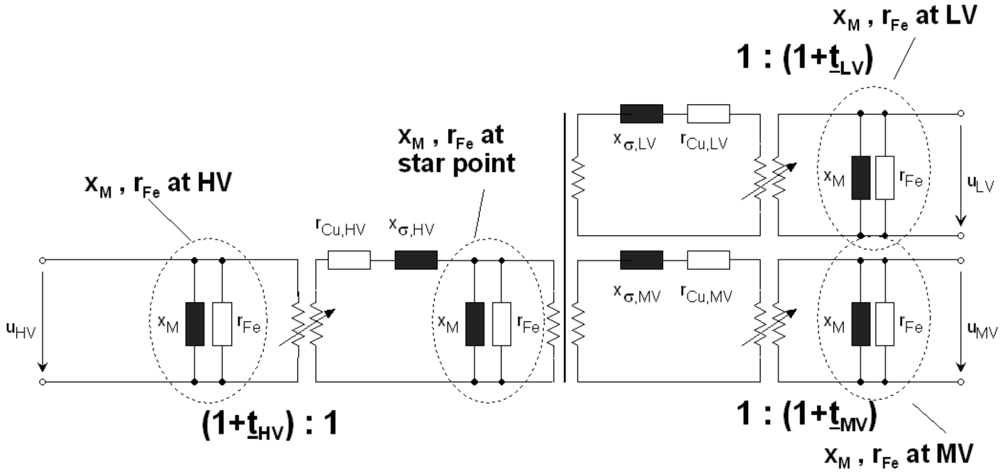

Figure 1.2: *PowerFactory* positive-sequence model of the 3-winding transformer, taps modelled at terminals

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:

$$
\begin{aligned}
I_{r,HV} &= \frac{S_{r,HV}}{\sqrt{3}\cdot U_{r,HV}} \qquad (kA)\\
I_{r,MV} &= \frac{S_{r,MV}}{\sqrt{3}\cdot U_{r,MV}} \qquad (kA)\\
I_{r,LV} &= \frac{S_{r,LV}}{\sqrt{3}\cdot U_{r,LV}} \qquad (kA)
\end{aligned}
\tag{1}
$$

The following sections briefly describe the measurements performed in order to determine the parameters of a three-winding transformer.

1.1.2.1 HV-MV Measurement

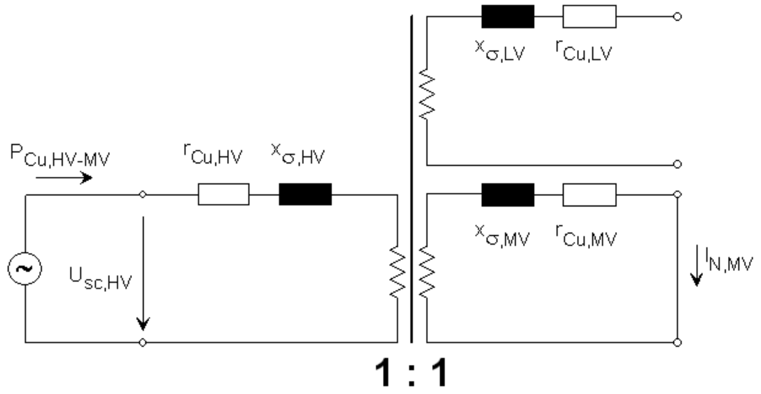

Figure 1.3: Short-circuit on MV-side, open-circuit on LV-side

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

$$I_{m,MV} = \frac{Min(S_{r,HV}, S_{r,MV})}{\sqrt{3} \cdot U_{r,MV}} \qquad (kA)$$

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.

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

1.1.2.2 MV-LV Measurement

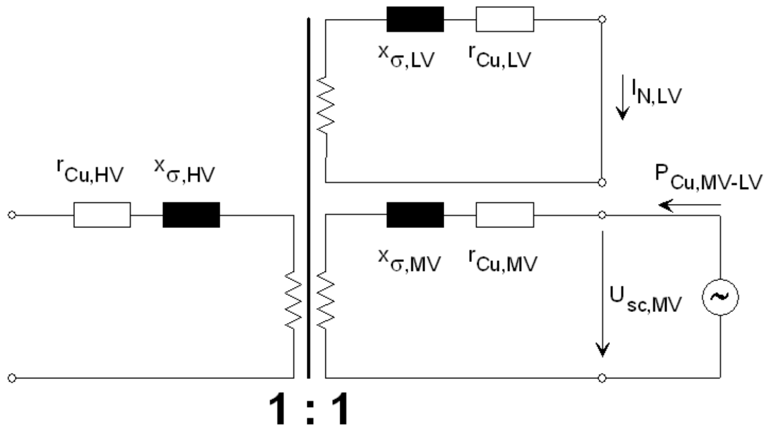

Figure 1.4: Short-circuit on LV-side, open-circuit on HV-side

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

$$I_{m,LV} = \frac{Min(S_{r,MV}, S_{r,LV})}{\sqrt{3} \cdot U_{r,LV}} \qquad (kA)$$

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

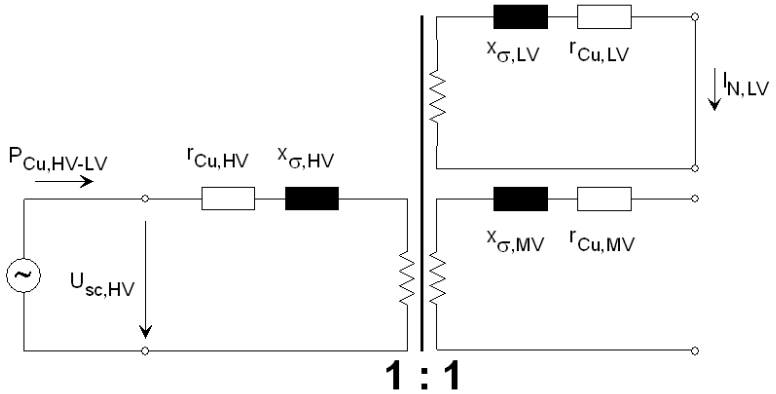

Figure 1.5: Short-circuit on LV-side, open-circuit on MV-side

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

$$I_{m,LV} = \frac{Min(S_{r,HV}, S_{r,LV})}{\sqrt{3} \cdot U_{r,LV}} \qquad (kA)$$

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:

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

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

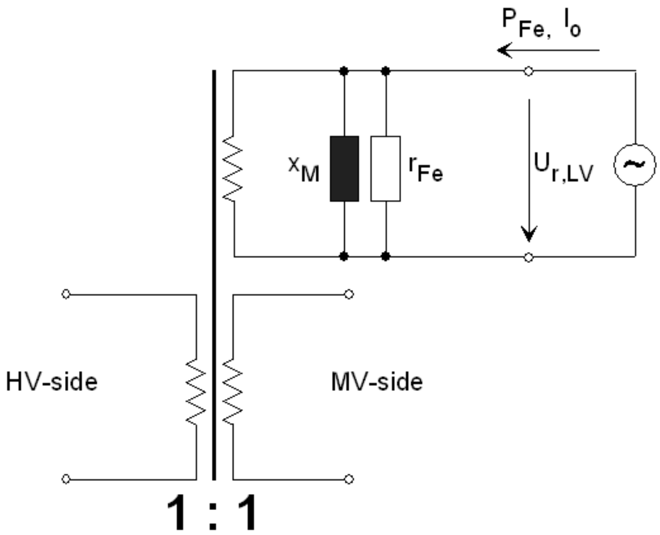

Figure 1.6: Measurement of iron losses and no load current on LV-side

The no-load current in % referred to the HV-side rated power is calculated according to the following equation:

$$i_0 = \frac{I_0}{I_{r,LV}} \cdot \frac{S_{r,LV}}{S_{ref}} \times 100\% \quad with \quad I_{r,LV} = \frac{S_{r,LV}}{\sqrt{3} \cdot U_{r,LV}} \quad in\, kA$$

I_0 measured no load current in kA

P_{Fe} measured iron losses in kW

$S_{ref} = S_{r,HV}$ *in MVA* $\rightarrow$ *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.

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

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

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

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

The zero-sequence model of a three-winding transformer depends on the vector group of each winding. The following sections describe the different vector groups, the measurement of the zero-sequence data and the input parameters. Please note that the dashed connections to the neutral terminals exist only if the option *External Star Point* is enabled (see transformer dialog). The option is only possible if one side (HV, MV or LV) is on grounded star (grounded wye) or grounded Z connection.

Note: If the transformer has a delta winding, the magnetising impedance is neglected since in reality it is effectively short circuited by the delta winding impedance (this impedance is much lower than the magnetising impedance).

1.1.3.1 Zero-sequence Input parameters

$u0_{sc,HV-MV}$, $u0_{sc,MV-LV}$, $u0_{sc,LV-HV}$	%	Relative zero-sequence short-circuit voltage of paths HV-MV, MV-LV, LV-HV
$u_{r,sc,HV-MV}$, $u_{r,sc,MV-LV}$, $u_{r,sc,LV-HV}$	%	Relative zero-sequence 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
$i30lc$	%	Zero-sequence magnetizing impedance, position
i_{0M}	%	Zero-sequence magnetizing impedance, no load current
R_{0M}/X_{0M}		R/X ratio of the zero sequence magnetising impedance

The zero sequence admittance $\underline{y}_{M0}$ is calculated using the zero sequence resistance and reactance as:

$$x_{M0} = \frac{100\%}{i_{0M}} \cdot \frac{1}{\sqrt{1+(R_{0M}/X_{0M})^2}}$$
$$r_{M0} = x_{M0} \cdot R_{0M}/X_{0M}$$
$$\underline{y}_{M0} = \frac{1}{r_{M0} + \jmath\, x_{M0}}$$

The zero sequence magnetisation reactance and iron loss resistance can be modelled at different positions (default: star point, HV-Side, MV-Side or LV-Side). For simplicity, in the following figures it is always shown at the star point.

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

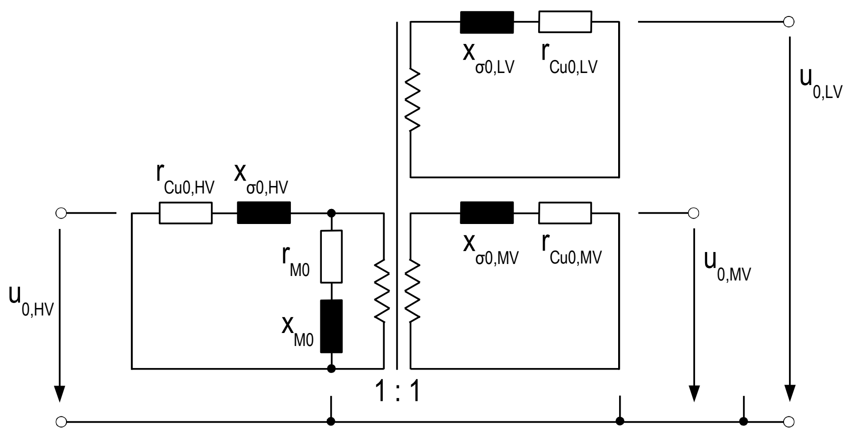

Figure 1.7: Zero-sequence model of D-d-d transformer

According to Figure 1.7 the zero-sequence impedances have no influence on the zero-sequence voltage. It is recommended for a D-d-d transformer to set the zero-sequence short-circuit voltage equal to the positive sequence short-circuit voltage.

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

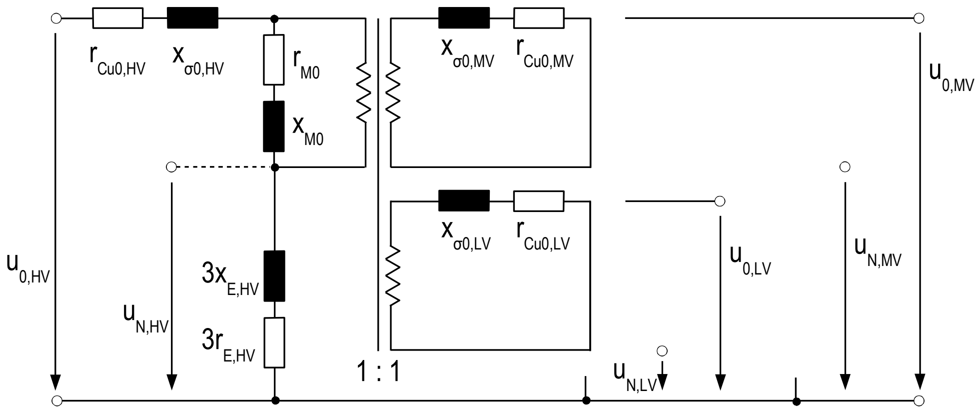

Figure 1.8: Zero-sequence model of YN-d-d transformer

Figure 1.8 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.

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

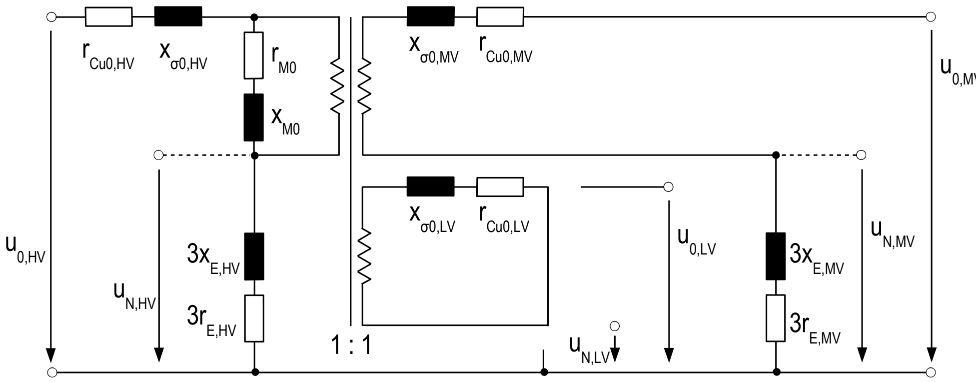

Figure 1.9: Zero-sequence model of YN-yn-d transformer

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

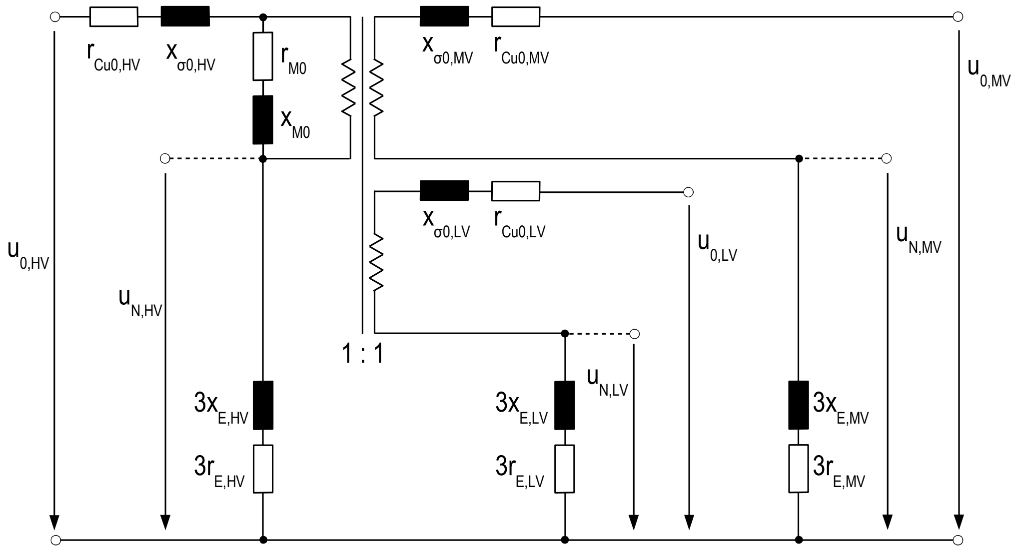

Figure 1.10: Zero-sequence model of YN-yn-yn transformer

1.1.3.6 YN-yn-d auto-transformer (Grounded wye-grounded wye-delta auto transformer)

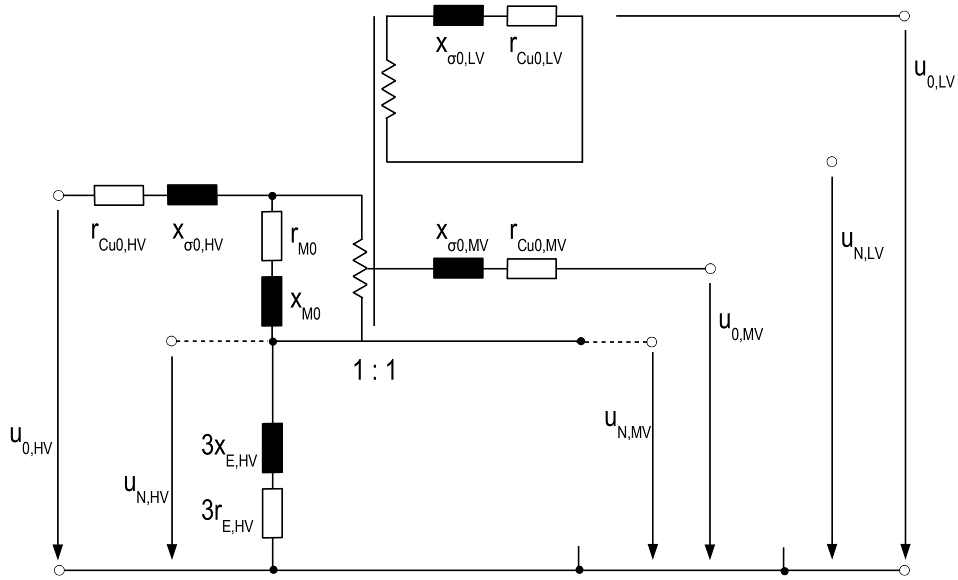

Figure 1.11: Zero-sequence model of YN-yn-d auto transformer

1.1.3.7 YN-d-zn (Grounded wye-delta-grounded Z)

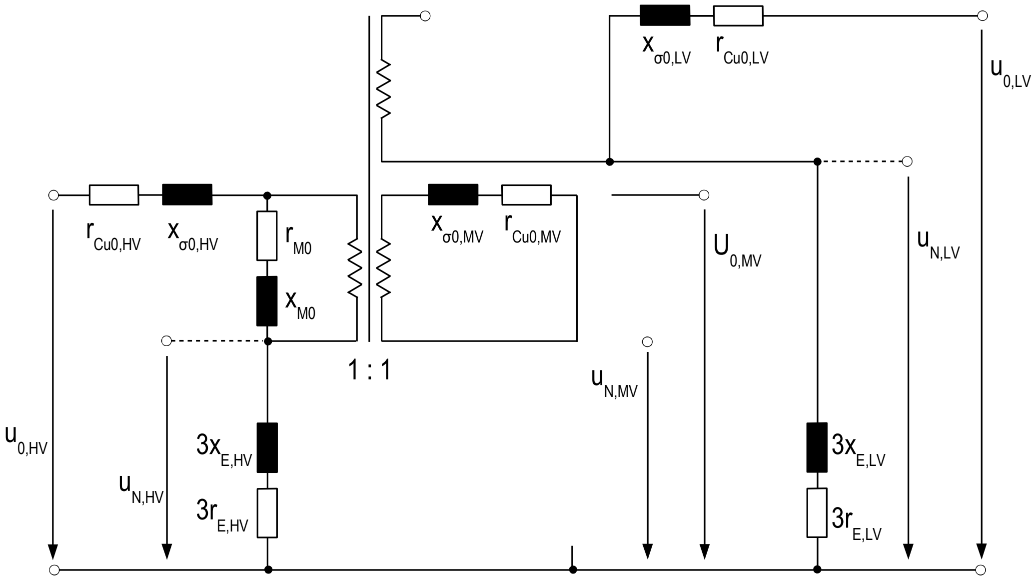

Figure 1.12: Zero-sequence model of YN-d-zn transformer

1.1.3.8 YN-d-y(Grounded wye-delta-wye)

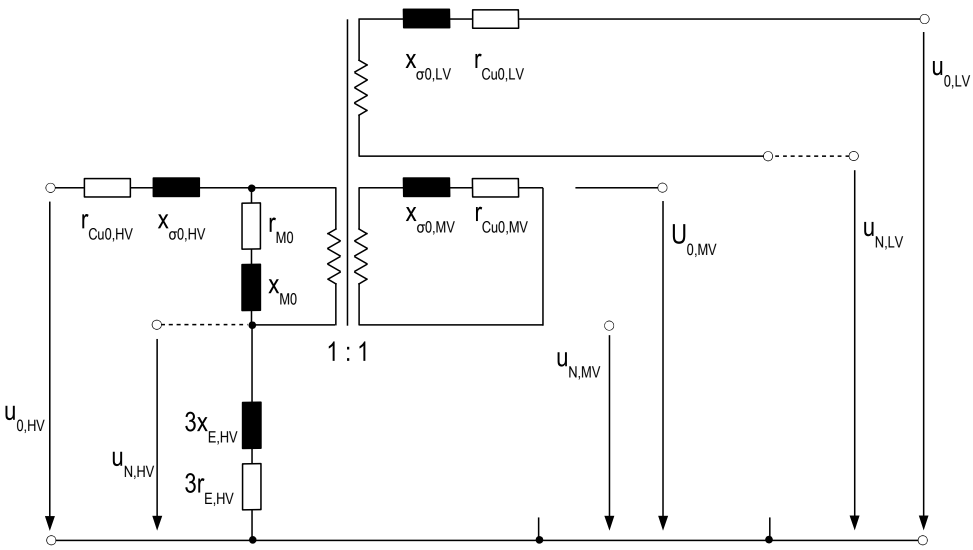

Figure 1.13: Zero-sequence model of YN-d-y transformer

1.1.4 Pocket Calculator

The pocket calculator is a tool, which transforms measured zero sequence impedance values (from test certificates with three measurements) into equivalent zero sequence impedances used by the *TypTr3* type of the three-winding transformer element. It can be used only for transformers having YN-yn-d, YN-d-yn or D-yn-yn connections.

For a YN-yn-d transformer, three impedance measurements are performed (Figure 1.14):

1. Zero sequence current is injected at the HV side with MV terminal kept open. The impedance $\underline{Z}_{0HV-LV}$ is measured.
2. Zero sequence current is injected at the MV side with HV terminal kept open. The impedance $\underline{Z}_{0MV-LV}$ is measured.
3. Zero sequence current is injected at the HV side with MV terminal short-circuited. The impedance $\underline{Z}_{0HV-MV||LV}$ is measured.

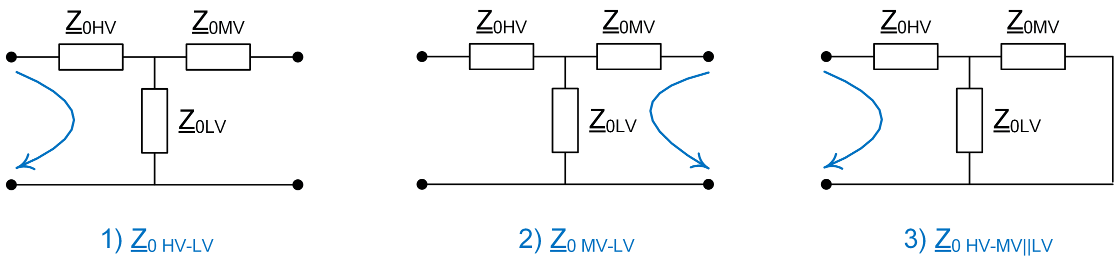

Figure 1.14: Measurement of zero sequence impedance for a YN-yn-d transformer

The measured data is entered in the pocket calculator in form of impedances (magnitude) and resistances. The measured complex impedance values are calculated using the entered data and are then referred to the rated power of the HV winding:

$$\underline{Z}_{a0} = \left(R_{a0} + \jmath\sqrt{Z_{a0}^2 - R_{a0}^2}\right) \cdot \frac{S_{HV}}{S_{meas.\ side}}$$
$$\underline{Z}_{b0} = (R_{b0} + \jmath\sqrt{Z_{b0}^2 - R_{b0}^2}) \cdot \frac{S_{HV}}{S_{meas.\ side}}$$
$$\underline{Z}_{c0} = (R_{c0} + \jmath\sqrt{Z_{c0}^2 - R_{c0}^2}) \cdot \frac{S_{HV}}{S_{meas.\ side}}$$

where $S_{meas.\ side}$ is the apparent power of the measured side (for YN-yn-d transformer, $S_{meas.\ side} = S_{HV}$ when calculating $\underline{Z}_{a0}$ and $\underline{Z}_{c0}$, and $S_{meas.\ side} = S_{MV}$ when calculating $\underline{Z}_{b0}$).

Note that for a YN-yn-d transformer, the entered data corresponds to the measured impedances as follows: $\underline{Z}_{a0} \equiv \underline{Z}_{0HV-LV}$, $\underline{Z}_{b0} \equiv \underline{Z}_{0MV-LV}$ and $\underline{Z}_{c0} \equiv \underline{Z}_{0HV-MV||LV}$. Similar is valid for the YN-d-yn and D-yn-yn transformers.

The zero sequence impedances for the HV, MV and LV side are calculated depending on the vector group of the transformer:

- YN-yn-d

$$\underline{Z}_{0LV_{1,2}} = \pm\sqrt{\underline{Z}_{b0} \cdot (\underline{Z}_{a0} - \underline{Z}_{c0})}$$
$$\underline{Z}_{0MV_{1,2}} = \underline{Z}_{b0} - \underline{Z}_{0LV_{1,2}}$$
$$\underline{Z}_{0HV_{1,2}} = \underline{Z}_{a0} - \underline{Z}_{0LV_{1,2}}$$

- YN-d-yn

$$\underline{Z}_{0MV_{1,2}} = \pm\sqrt{\underline{Z}_{b0} \cdot (\underline{Z}_{a0} - \underline{Z}_{c0})}$$
$$\underline{Z}_{0LV_{1,2}} = \underline{Z}_{b0} - \underline{Z}_{0MV_{1,2}}$$
$$\underline{Z}_{0HV_{1,2}} = \underline{Z}_{a0} - \underline{Z}_{0MV_{1,2}}$$

- D-yn-yn

$$\underline{Z}_{0HV_{1,2}} = \pm\sqrt{\underline{Z}_{b0} \cdot (\underline{Z}_{a0} - \underline{Z}_{c0})}$$
$$\underline{Z}_{0LV_{1,2}} = \underline{Z}_{b0} - \underline{Z}_{0HV_{1,2}}$$
$$\underline{Z}_{0MV_{1,2}} = \underline{Z}_{a0} - \underline{Z}_{0HV_{1,2}}$$

where there are two solutions for the impedances (subindex "$_1$" is used for the positive and subindex "$_2$" is used for the negative solution). Which solution is used depends on the sum of HV-MV, MV-LV and LV-HV reactances for both solutions ($\underline{X}_{0HV-MV_1} = \Im(\underline{Z}_{0HV_1} + \underline{Z}_{0MV_1})$, $\underline{X}_{0HV-MV_2} = \Im(\underline{Z}_{0HV_2} + \underline{Z}_{0MV_2})$, etc ...). Usually the first solution is used. The second solution is used when not all reactances of the first solution are positive and all reactances of the second solution are positive, and in some other specific cases.

The zero sequence impedances (magnitude) and resistances as result of the pocket calculator, used by the *TypTr3* type of the three-winding transformer element, are obtained as:

$$uk0hm = |\underline{Z}_{0HV} + \underline{Z}_{0MV}| \cdot \frac{min(S_{HV}, S_{MV})}{S_{HV}}$$
$$ur0hm = \Re(\underline{Z}_{0HV} + \underline{Z}_{0MV}) \cdot \frac{min(S_{HV}, S_{MV})}{S_{HV}}$$

$$uk0ml = |\underline{Z}_{0MV} + \underline{Z}_{0LV}| \cdot \frac{min(S_{MV}, S_{LV})}{S_{HV}}$$
$$ur0ml = \Re(\underline{Z}_{0MV} + \underline{Z}_{0LV}) \cdot \frac{min(S_{MV}, S_{LV})}{S_{HV}}$$

$$uk0hl = |\underline{Z}_{0LV} + \underline{Z}_{0HV}| \cdot \frac{min(S_{LV}, S_{HV})}{S_{HV}}$$
$$ur0hl = \Re(\underline{Z}_{0LV} + \underline{Z}_{0HV}) \cdot \frac{min(S_{LV}, S_{HV})}{S_{HV}}$$

1.1.5 Model with Stray capacitances

The stray capacitances of a transformer do not only depend on the physical characteristics of the transformer (i.e. the length of the windings, insulating material, core dimensions, etc) but also on the installation environment as well (indoor or outdoor transformer, proximity to other grounded components, walls, etc.).

The following capacitances can be defined after enabling the field *Consider Capacitances* option of the transformer element:

- C_{g_h} capacitance HV to ground: applies to the positive- and zero sequence
- C_{g_m} capacitance MV to ground: applies to the positive- and zero sequence
- C_{g_l} capacitance LV to ground: applies to the positive- and zero sequence
- C_{c1_hm} capacitance HV-MV, positive sequence
- C_{c1_ml} capacitance MV-LV, positive sequence
- C_{c1_lh} capacitance LV-HV, positive sequence
- C_{c0_hm} capacitance HV-MV, zero sequence
- C_{c0_ml} capacitance MV-LV, zero sequence

- C_{c0_lh} capacitance LV-HV, zero sequence

The model is valid only for transformers not having neutral connection (if *Consider Capacitances* is enabled the neutral wire connection of the element is disabled).

The positive sequence model of a three winding transformer with stray capacitances is shown in Figure 1.15.

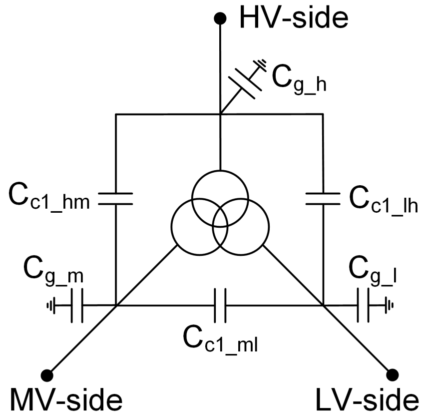

Figure 1.15: Positive-sequence model with stray capacitances

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 (in kA) are calculated as:

$$
\begin{aligned}
I_{nomhv} &= ratfac\_h \cdot I_{r,HV} \cdot nt3nm \\
I_{nommv} &= ratfac\_m \cdot I_{r,MV} \cdot nt3nm \\
I_{nomlv} &= ratfac\_l \cdot I_{r,LV} \cdot nt3nm
\end{aligned} \tag{2}
$$

where the rated currents $I_{r,HV}$, $I_{r,MV}$ and $I_{r,LV}$ are defined in equation (1) at section 1.1.2

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 Data* page
- $nt3nm$ is the number of parallel transformers, defined on the element *Basic Data* 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:

$$
\begin{aligned}
I_{nomhv} &= \frac{ContRating \cdot nt3num}{\sqrt{3} \cdot U_{n(bushv)}} \\
I_{nommv} &= \frac{ContRating \cdot nt3num}{\sqrt{3} \cdot U_{n(busmv)}} \\
I_{nomlv} &= \frac{ContRating \cdot nt3num}{\sqrt{3} \cdot U_{n(buslv)}}
\end{aligned}
$$

- if the continuous rating is entered in kA:

$$
\begin{aligned}
I_{nomhv} &= ContRating \cdot nt3nm \\
I_{nommv} &= ContRating \cdot nt3nm \\
I_{nomlv} &= ContRating \cdot nt3nm
\end{aligned}
$$

- if the continuous rating is entered in %:

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

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:

- $S_{r,HV}$, $S_{r,MV}$, and $S_{r,LV}$, 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:

$$Snom\_h = \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomhv}$$
$$Snom\_m = \sqrt{3} \cdot U_{n(busmv)} \cdot I_{nommv}$$
$$Snom\_l = \sqrt{3} \cdot U_{n(buslv)} \cdot I_{nomlv}$$

and for the actual nominal powers:

$$Snom\_h\_a = Snom\_h$$
$$Snom\_m\_a = Snom\_m$$
$$Snom\_l\_a = Snom\_l$$

where:

- I_{nomhv}, I_{nommv}, and I_{nomlv} are the nominal currents at high, medium and low- voltage side, see section 1.2.1.
- $U_{n(bushv)}$, $U_{n(busmv)}$, and $U_{n(buslv)}$ are the busbar line-line nominal voltages in kV at the high, medium and low-voltage side.

2 Load Flow Analysis

As the tap changer is of particular interest in load flow calculations, data relating to the tap changer is entered as follows:

- On the *Load Flow* page of the transformer element: control data and measurement report);
- On the *Load Flow* page of the transformer type: tap changer positions and tap-dependent impedance).

The following controls are included:

Tap Position For each tap controller, the actual tap position used during the load flow calculation. If *Automatic Tap Changing* is ticked, this value corresponds to the initial tap position.

According to Measurement Report If this option is enabled, then instead of using the type data for the tap-dependent transformer values, the *Measurement Report* defined in the element is used.

In addition, there are two tap changer controllers available, which can be set to control either the HV, the MV or the LV side. When both are active, they can be set to simultaneously control active power and voltage, or active power and reactive power (other combinations are not possible). Each controller has the option *Automatic Tap Changing*, which activates automatic tap adjustment (see Section 2.1).

2.1 Automatic tap changer control

This is activated by setting the corresponding option for *Controller 1* or *Controller 2* on the *Load Flow* page of the transformer element. Additionally, automatic tap adjustment can be globally enabled or disabled via the *Load Flow Calculation* command (*ComLdf*).

The following inputs are common for this option:

Tap Changer It has the two following options:

- *continuous*: An ideal, continuous tap changer is assumed. As a result, the tap controller can ideally comply with the specified control condition. This option is useful for voltage regulators in distribution systems having a very large number of tap steps or for thyristor-controlled tap changers. In this case, the corresponding voltage or power range settings are disregarded.
- *discrete*: Standard option. Only integer tap positions are considered, as well as the corresponding voltage or power range settings.

Controlled Node is at This control has the following options:

- *HV*: Tap controls the HV side.
- *MV*: Tap controls the MV side.
- *LV*: Tap controls the LV side.
- *EXT*: *Slave* mode. The tap changer follows the tap position of the selected *Master* transformer.

Control Mode The type of control for the tap. It has the following options, whose description can be seen in the Two-Winding Transformer Technical Reference.

- *V*: Voltage control. For unbalanced load flow analysis, the controlled phase needs to be additionally defined. The internal (LDC) line drop compensation is not supported.
- *Q*: Reactive power control.
- *P*: Active power control (only applicable to phase-shifters).

2.1.1 Voltage Control

The following inputs are valid for the voltage control:

Phase For unbalanced load flow analysis, the controlled phase needs to be additionally defined.

Setpoint Specifies how to enter the voltage setpoint and its range.

- *local*: The *Voltage Setpoint* and voltage range settings (*Lower Bound* and *Upper Bound*) must be entered in the transformer dialogue.
- *bus target voltage*: The voltage setpoint and voltage range settings (max./min. voltage) are taken from the controlled *busbar* (topological search).

Remote Control Allows for the selection of a busbar different to that at the transformer terminals.

Voltage Setpoint Voltage reference.

Lower/Upper Bound Lower and upper bound of the voltage. In the case of discrete tap changers, the tap control can drive the voltage into a permitted band. In the case of continuous tap changers, the tap controller ideally regulates to the reference point.

Compensation Different types of compensation are supported:

- *none*
- *external (LDC) line drop compensation*: Via a *Line Drop Compensation (StaLdc)* object.
- *current compounding*: See Section 2.1.1.1).

2.1.1.1 Current Compounding

Voltage control also includes an optional current compounding method, which controls the transformer voltage within acceptable limits, by increasing the voltage setpoint as the load current increases.

Table 2.1: Current compounding compensation (for voltage control)

Parameter	Description	Unit
Compounding	*apparent current*: Control is based on the magnitude of the measured apparent current (see Figure 2.1). Note: Disabled when the active component of the current feeds back. *active current*: Control is based on the active component of the measured current (see Figure 2.1). *reactive current*: Control is based on the reactive component of the measured current (see Figure 2.1). *apparent power*: Control is based on the magnitude of the measured apparent power. Note: Disabled when the active component of the current feeds back. *active power*: Control is based on the active component of the measured power (see Figure 2.2). *reactive power*: Control is based on the reactive component of the measured power.	-
V-Control-Curve	Pointer to voltage control curve (IntVctrlcurve).	-
Tolerance (+/-)	In the case of discrete tap changers, the tap control can drive the control variable into a permitted band. In the case of continuous tap changers, the tap controller ideally regulates to the reference point.	%

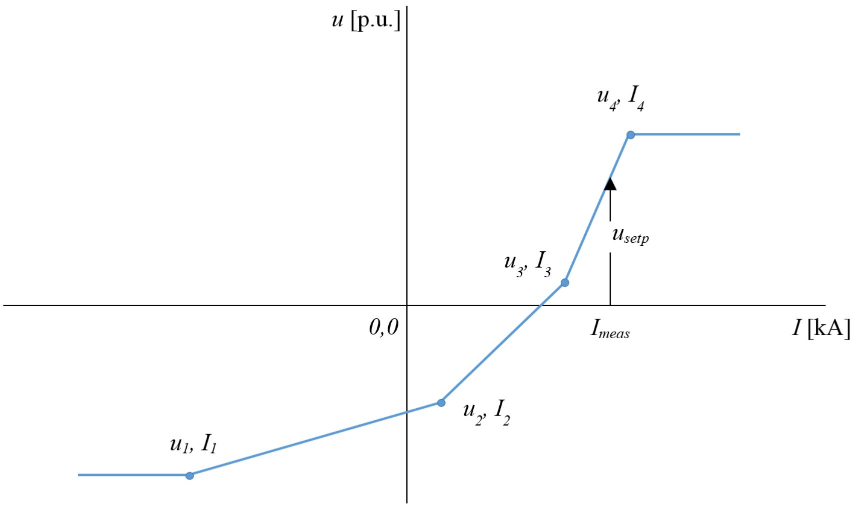

Figure 2.1: Current compounding based on apparent, active or reactive current

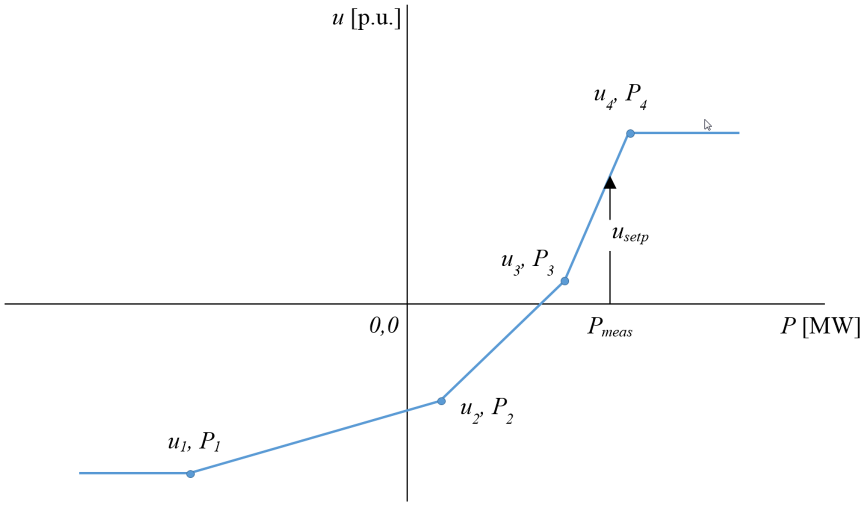

Figure 2.2: Current compounding based on active power

Note The control curve is the same whether the control node is at the HV side or at the LV side. However, the active and reactive power and current flows measured in *PowerFactory* depend on the measurement side, as it can be seen in Figure 2.3.

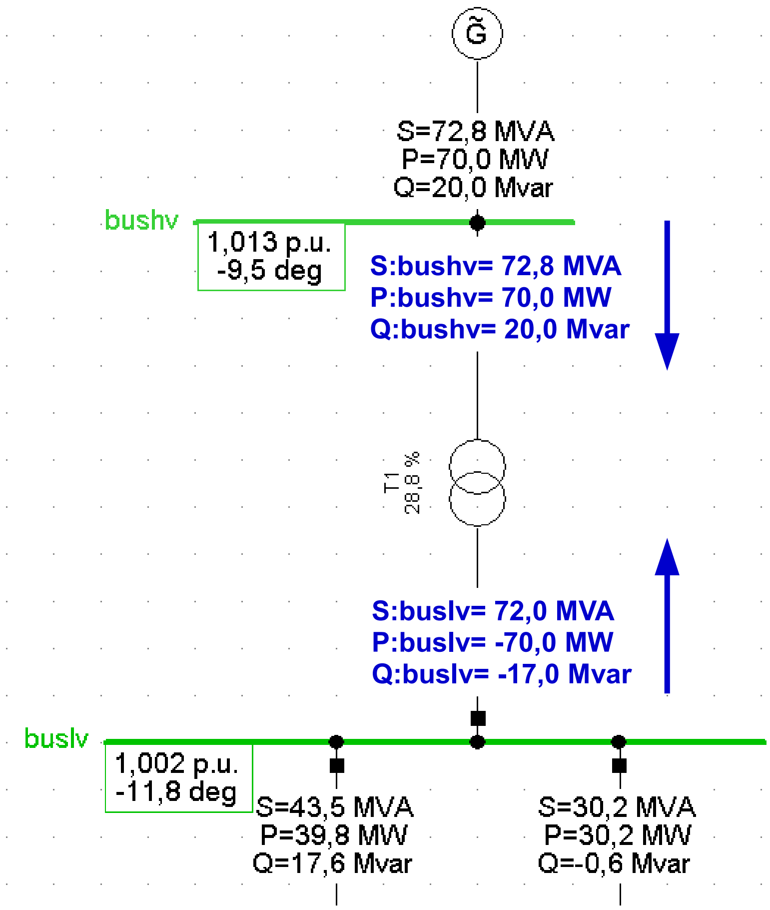

Figure 2.3: Power flow reported in *PowerFactory* at HV and LV sides

Therefore, the measured power flows and currents are always considered as the flows from HV to LV side (or HV to MV side in the case of three-winding transformers), as follows:

$$Pmeas = \begin{cases} P{:}bushv & \text{if Controlled Node at HV side} \\ -P{:}busmv & \text{if Controlled Node at MV side for 3-winding transformers} \\ -P{:}buslv & \text{if Controlled Node at LV side} \end{cases} \tag{3}$$

The same equation 3 applies for reactive power, and for active and reactive currents. For unbalanced load flow and RMS simulation the active and reactive power is always the total power of all phases (neutral wire is ignored).

$$P_{sum} = \sum_{i=1}^{nphase} P_i$$
$$Q_{sum} = \sum_{i=1}^{nphase} Q_i$$

For current compounding based on currents is dependent on the controlled note at phase setting:

- *a*, *b* or *c*: the corresponding phase current is used e.g. $I_{active} = |\underline{I}_a)| \cdot \cos(\phi_{U_a,I_a})$
- *a-b*, *b-c*, *c-a*:
  - for non-BI phase systems the phase-phase current/voltage is used e.g. $I_{active} = |\underline{I}_{a-b}| \cdot \cos(\phi_{U_{a-b},I_{a-b}})$ with $\underline{I}_{a-b} = (\underline{I}_a - \underline{I}_b)/\sqrt{3}$ and $\underline{U}_{a-b} = (\underline{U}_a - \underline{U}_b)/\sqrt{3}$
  - for BI phase systems the positive sequence current/voltage is used e.g. $I_{active} = |\underline{I}_1| \cdot \cos(\phi_{U_1,I_1})$ with $\underline{I}_1 = (\underline{I}_a - \underline{I}_b)/2.$ and $\underline{U}_1 = (\underline{U}_a - \underline{U}_b)/2.$
- *Pos.Seq* (positive sequence), only possible for 3-phase transformers: the positive sequence current/voltage is used e.g. $I_{active} = |\underline{I}_1| \cdot \cos(\phi_{U_1,I_1})$

2.1.2 Reactive Power Control

The following inputs are valid for the reactive power control:

Remote Control The flow through any selected cubicle can be controlled.

Reactive Power Setpoint Reactive power reference.

Lower/Upper Bound Lower and upper bound of the reactive power. In the case of discrete tap changers, the tap control can drive the reactive power into a permitted band. In the case of continuous tap changers, the tap controller ideally regulates to the reference point.

2.1.3 Active Power Control

The following inputs are valid for the active power control:

Remote Control The flow through any selected cubicle can be controlled.

Active Power Setpoint Active power reference.

Lower/Upper Bound Lower and upper bound of the active power. In the case of discrete tap changers, the tap control can drive the active power into a permitted band. In the case of continuous tap changers, the tap controller ideally regulates to the reference point.

Active Power Participation Allows the control of active power flow as a percentage of the power flow through a (parallel) user-defined boundary. See Section 2.1.3.1.

Participation factor The participation factor of the measured power flow of the selected boundary.

Tolerance In the case of discrete tap changers, the tap control can drive the active power into a permitted band. In the case of continuous tap changers, the tap controller ideally regulates to the reference point.

P measured at The user-defined boundary.

2.1.3.1 Active Power Participation

Below there is an example of the use of active power participation control. The first figure 2.4 shows the load flow solution without any control, and the set tap position at zero. In the second figure, 2.5, the transformer tap is set to carry 100% of the power measured at the Line on bus T0. The solution brings the tap position of the transformer to 0.49.

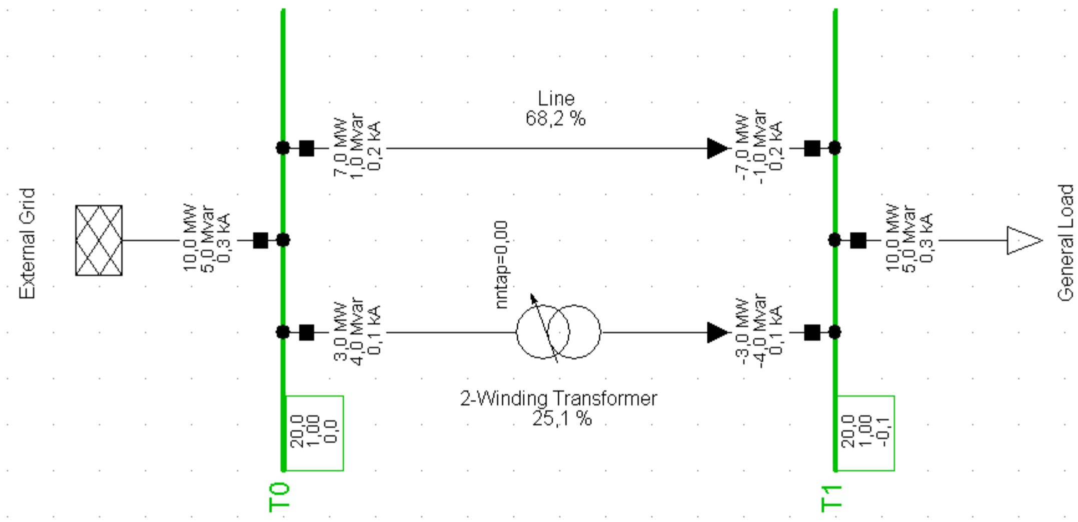

Figure 2.4: No Active Power Participation

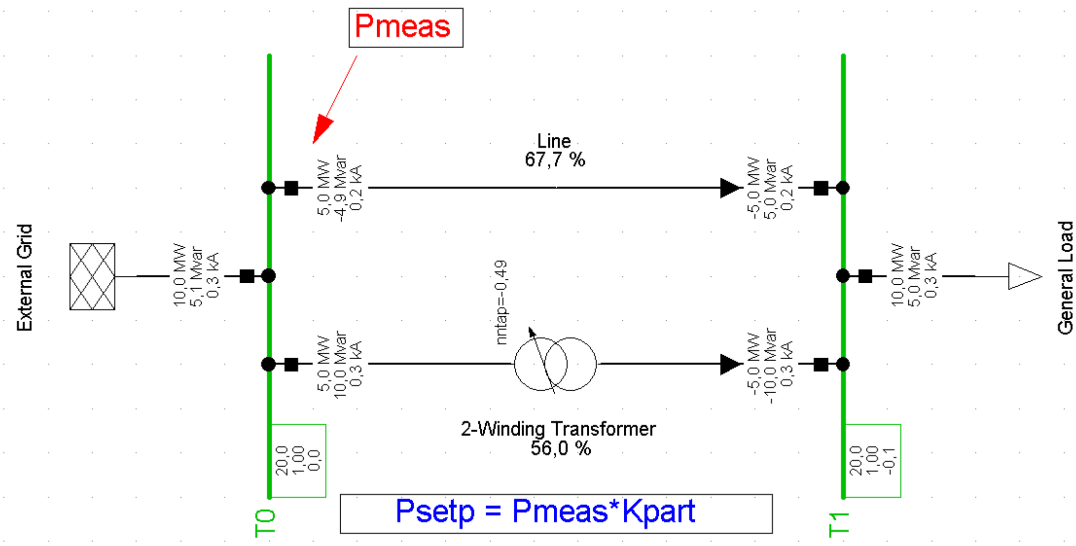

Figure 2.5: Tap control through active power participation

2.1.4 Controller Input Parameters

There is usually more than one possible solution to a load flow problem considering automatic tap changer control. In meshed networks in particular, several transformers can control the voltage in certain areas. In the case of parallel transformers, the problem can usually be solved by operating the two parallel transformers in master-slave mode.

In a general configuration however, especially when parallel transformers have different short-circuit impedances or different tap steps, the steady-state network solution cannot be easily obtained. *PowerFactory* addresses this problem by allowing the user to enter a controller time constant, specifying the speed of control actions and hence the participation of several transformers regulating the voltage at the same busbar.

The approach is based on controller block diagrams according to Figure 2.6. In the case of flow controllers (P-/Q-control), the *controller sensitivity* translating a power mismatch into an equivalent turns-ratio percentage can be entered additionally.

In the load flow algorithm, which only considers steady-state conditions, controller time constants and sensitivities are translated into equivalent participation factors.

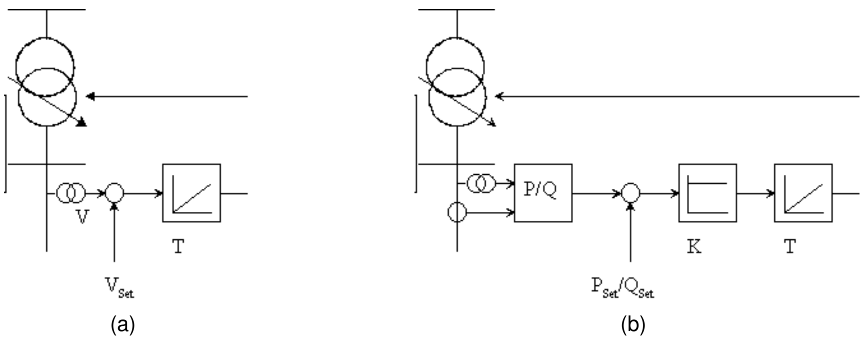

Figure 2.6: Principle of simulated dynamic control for V and P/Q

The controller input parameters for the transformer element are described in Table 2.2.

Table 2.2: Dynamic and static control parameters

Parameter	Description	Unit
Controller time constant	Time constant of the controller	s
Controller sensitivity dtap/dP	Estimated sensitivity of active power flow towards tap changer variations	tap/MW
Controller sensitivity dtap/dQ	Estimated sensitivity of reactive power flow towards tap changer variations	tap/Mvar

Hint: The controller sensitivities can be calculated directly from the *Load Flow Sensitivities* command (ComVstab). However, it must be noted, that the quantities calculated by this command are the inverse of the controller sensitivities. Thus,

$$\begin{aligned} Kpctrl &= \frac{1}{dPdtap} \\ Kqctrl &= \frac{1}{dQdtap} \end{aligned} \tag{4}$$

Where

- $Kpctrl$ is the *Controller sensitivity dtap/dP* in tap/MW
- $dPdtap$ is the *Branch Sensitivity dPbranch/dtap* in MW/tap calculated by the *Load Flow Sensitivities* command.
- $Kqctrl$ is the *Controller sensitivity dtap/dQ* in tap/Mvar
- $dQdtap$ is the *Branch Sensitivity dQbranch/dtap* in Mvar/tap calculated by the *Load Flow Sensitivities* command.

2.1.5 Tap Hunting Detection

To improve the outer loop convergence, automatic tap hunting detection is available in the transformer models. For a discrete transformer tap, *PowerFactory* checks whether the control condition can be fulfilled according to the setpoint (bounds). If for example, the upper and lower bounds are too close, the transformer will not be able to maintain the control condition within the bounds.

In the *Load Flow Calculation* command, Advanced Options page, the number of max. transitions can be entered (default = 3).

A transition is defined according to the following criteria:

- the voltage is above the upper bound of the setpoint and in the next iteration the voltage is below the lower bound (or vice versa)
- the delta tap change is one

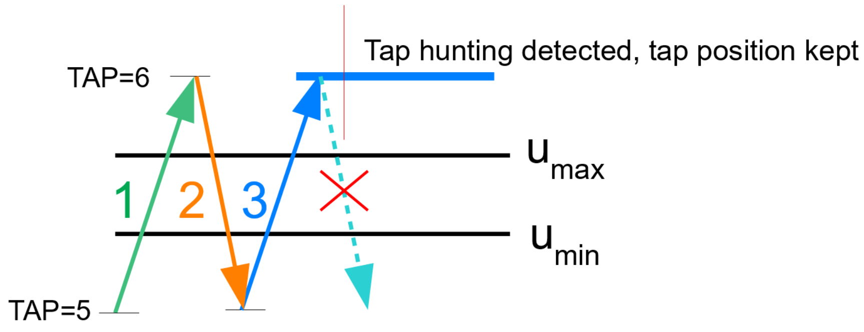

Figure 2.7: *PowerFactory* Tap hunting detection for no. of transitions = 3

In addition the delta tap per load flow outer loop will be limited (if the load flow tap adjustment method is set to *stepped*) e.g. in the case of large relaxation factors.

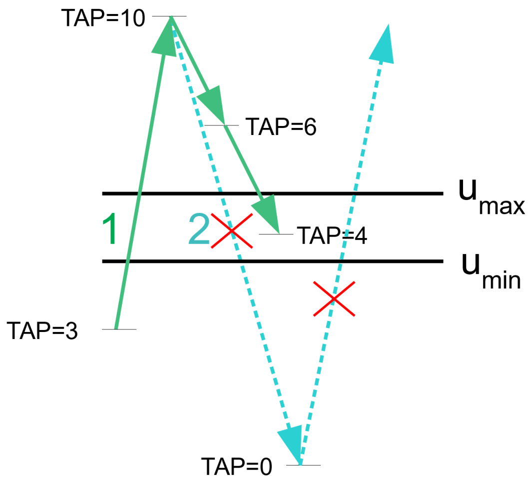

Figure 2.8: *PowerFactory* Delta tap limitation

The delta tap per outer loop will be limited after the first transition.

2.2 Calculation Quantities for AC Load Flow

2.2.1 Loading

The loading of the transformer is calculated as follows:

$$loading\_h = \frac{I_{bushv}}{I_{nomhv}} \cdot 100 \qquad (\%)$$

$$loading\_m = \frac{I_{busmv}}{I_{nommv}} \cdot 100 \qquad (\%)$$

$$loading\_l = \frac{I_{buslv}}{I_{nomlv}} \cdot 100 \qquad (\%)$$

$$loading = max(loading\_h, loading\_m, loading\_l) \qquad (\%)$$

- $loading$: 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.

2.2.2 Losses

The losses are calculated as follows:

Table 2.3: 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.

2.3 Calculation Quantities for linear DC Load Flow

2.3.1 Loading

The loading of the transformer is calculated as follows:

$$loading\_h = \frac{|P_{bushv}|}{P_{nomhv}} \cdot 100 \qquad (\%)$$
$$loading\_m = \frac{|P_{busmv}|}{P_{nommv}} \cdot 100 \qquad (\%)$$
$$loading\_l = \frac{|P_{buslv}|}{P_{nomlv}} \cdot 100 \qquad (\%)$$
$$loading = max(loading\_h, loading\_m, loading\_l) \qquad (\%)$$

where:

- P_{bushv} : Active power at high voltage side
- P_{busmv} : Active power at medium voltage side
- P_{buslv} : Active power at low voltage side
- P_{nomhv} : Nominal power at high voltage side
- P_{nommv} : Nominal power at medium voltage side
- P_{nomlv} : Nominal power at low voltage 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:

- $P_{nomhv} = \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomhv}$
- $P_{nommv} = \sqrt{3} \cdot U_{n(busmv)} \cdot I_{nommv}$
- $P_{nomlv} = \sqrt{3} \cdot U_{n(buslv)} \cdot I_{nomlv}$

with the nominal currents of the transformer I_{nomhv}, I_{nommv} and I_{nomlv} (see equation (2)). $U_{n(bushv)}$, $U_{n(busmv)}$ and $U_{n(buslv)}$ are the busbar line-line nominal voltages in kV at the high, medium and low voltage side.

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:

$$P_{nomhv} = ContRating \cdot nt3nm \qquad [MW]$$
$$P_{nommv} = ContRating \cdot nt3nm \qquad [MW]$$
$$P_{nomlv} = ContRating \cdot nt3nm \qquad [MW]$$

- if the continuous rating is entered in kA:

$$P_{nomhv} = \sqrt{3} \cdot U_{n(bushv)} \cdot ContRating \cdot nt3nm \qquad [MW]$$
$$P_{nommv} = \sqrt{3} \cdot U_{n(busmv)} \cdot ContRating \cdot nt3nm \qquad [MW]$$
$$P_{nomlv} = \sqrt{3} \cdot U_{n(buslv)} \cdot ContRating \cdot nt3nm \qquad [MW]$$

- if the continuous rating is entered in %:

$$P_{nomhv} = \sqrt{3} \cdot U_{n(bushv)} \cdot ContRating/100 \cdot I_{r,HV} \cdot nt3nm \qquad [MW]$$
$$P_{nommv} = \sqrt{3} \cdot U_{n(busmv)} \cdot ContRating/100 \cdot I_{r,MV} \cdot nt3nm \qquad [MW]$$
$$P_{nomlv} = \sqrt{3} \cdot U_{n(buslv)} \cdot ContRating/100 \cdot I_{r,LV} \cdot nt3nm \qquad [MW]$$

where the rated currents $I_{r,HV}$, $I_{r,MV}$ and $I_{r,LV}$ are defined in equation (1) at section 1.1.2.

2.3.2 Losses

Losses are not calculated in the linear DC Load Flow.

3 Harmonics/Power Quality

In order to accurately model the high frequency effects of transformers, additional capacitances need to be considered, as explained in Section 1.1.5.

3.1 Frequency-dependent impedances

On the *Harmonics* page of the transformer type, frequency-dependent positive and zero sequence (short-circuit) impedances can be defined. 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. If the positive and zero sequence (short-circuit) impedances are defined in the *Measurement Report*, the characteristic should be defined as *relative* otherwise the value in the *Measurement Report* will be overwritten. A frequency-dependent positive sequence magnetizing admittance can also be defined, by defining a characteristic for the imaginary and real part of the admittance.

4 Modelling Details and Application Tips

4.1 *PowerFactory* Handling

In *PowerFactory* each winding of a transformer can have taps, however only one of the tap changers can be controlled in the Load Flow calculation. The specification of the tap changers for each winding is done in the load flow page of the transformer type. Then, in the load flow page of the element a tap changer is specified for automatic control. Note that in order to have the load flow algorithm adjust the taps while trying to find a solution, in the *Load Flow* command *Basic Options* page, the option *Automatic Tap Adjust of Transformers* must be enabled.

In entering positive and zero sequence voltages for a three-winding transformer, one must note that they are referred to the minimum rated power of the two windings. For example, for a 60/60/10 MVA, 132/22/11 kV transformer, a value of 10% is specified both for the HV-MV and LV-HV positive-sequence short-circuit voltages. The impedance value (referred to HV-side) of the impedance between the HV and MV terminals is

$$0.1 \times \frac{(132kV)^2}{60MVA} = 29.04\, primary\, \Omega$$

while the impedance value (referred to HV-side) of the impedance between HV and LV terminals is

$$0.1 \times \frac{(132kV)^2}{10MVA} = 174.24\, primary\, \Omega$$

It is possible to use manufacturers or any other available measurement data for load flow calculation. By clicking on the right-arrow in the load flow specification page of a transformer element, the user goes to a new window where the option *According to Measurement Report* is displayed. Checking this option shows a table where data from measurements can be directly entered.

4.2 Third-harmonic Currents

The impact of third-harmonic currents from one star-connected side to the other star-connected side is reduced because these currents see the delta-connected side as a short-circuited winding. The effect can be explained using the zero-sequence diagrams in Figure 1.9 and Figure 1.11.

Let us assume a third-harmonic source at the HV side and a load at the MV side. For simplicity, the magnetizing and grounding impedances are ignored. If the MV and LV winding resistances and leakage reactances are referred to the HV side, the circuit in Figure 4.1 is obtained. The impedance of the middle leg is normally much less than that of the right leg which is why the third-harmonic current content of the load is reduced.

In this application the tertiary winding can be internal with no terminals provided for connection. However, if the terminals are brought out of the transformer tank, then the tertiary winding can also be used to connect shunt reactors, capacitors, or SVCs (Figure 4.2). In Figure 4.2, the star-connected windings are shown as separate windings; however, this application is common also in case of autotransformer.

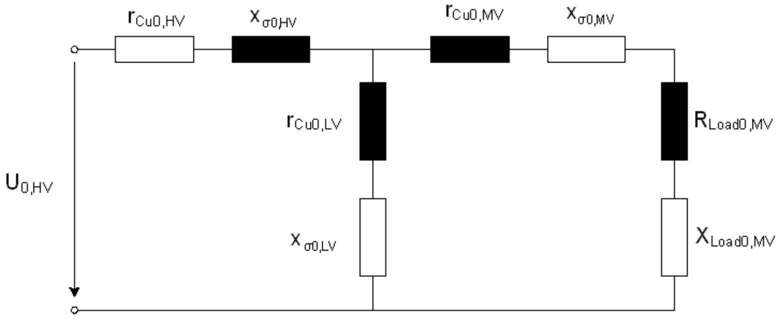

Figure 4.1: Zero-sequence load connected to the secondary of YN-yn-d transformer

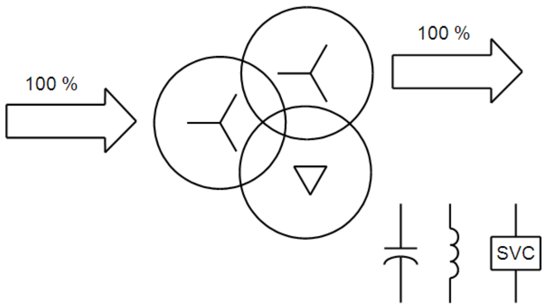

Figure 4.2: Small tertiary winding for zero-sequence and reactive compensation

Step-up transformers especially for hydro power plants can be three-winding transformers where there is one high-voltage side, and two low-voltage sides with the same voltage rating. This is cost-effective because then only one switchgear is needed for the high-voltage side (Figure 4.3). The same argument goes for network transformers for example in distribution networks.

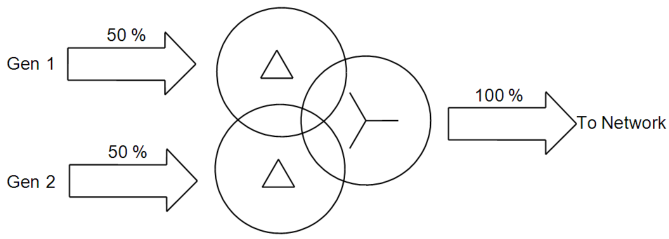

Figure 4.3: Tertiary winding to save on the high-voltage switchgear

Another application of three-winding transformers is when at some location in the network three different voltage levels for example 132kV, 22kV, and 11kV are to be connected together.

In HVDC systems, three winding transformers are used to combine two 6-pulse rectifiers into a 12-pulse one to give a smoother dc voltage. In this application, the 30° phase shift between a star-connected winding and a delta-connected winding is employed (Figure 4.4).

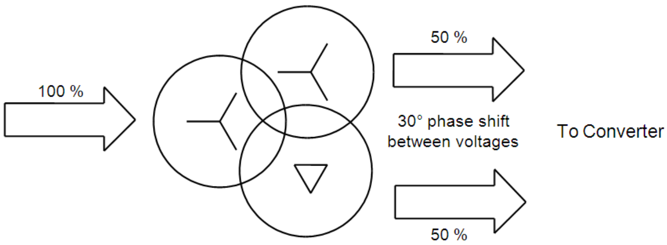

Figure 4.4: Tertiary winding for 30° phase shift

5 Input/Output Definitions of Dynamic Models

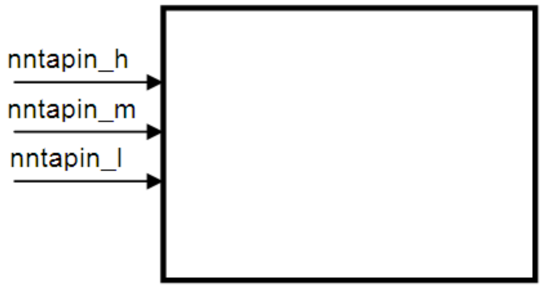

Figure 5.1: Input/Output Definition of 3-winding transformer model for RMS and EMT simulation

Table 5.1: Input Variables of RMS and EMT transformer model

Parameter	Description	Unit
nntapin	Tap position (HV), controller input	
nntapin	Tap position (MV), controller input	
nntapin	Tap position (LV), controller input	

Table 5.2: Signals of RMS transformer model

Parameter	Description	Unit
I0rDelta_h	Circulating Current in HV-Delta-Winding, Real Part	kA
I0rDelta_m	Circulating Current in MV-Delta-Winding, Real Part	kA
I0rDelta_l	Circulating Current in LV-Delta-Winding, Real Part	kA
I0iDelta_h	Circulating Current in HV-Delta-Winding, Imaginary Part	kA
I0iDelta_m	Circulating Current in MV-Delta-Winding, Imaginary Part	kA
I0iDelta_l	Circulating Current in LV-Delta-Winding, Imaginary Part	kA

Table 5.3: State Variables of transformer model for EMT-simulation

Parameter	Description	Unit
psim_r	Magnetizing flux (Real Part)	p.u.
psim_i	Magnetizing flux (Imaginary Part)	p.u.
psim_0	Magnetizing flux (Zero-Sequence)	p.u.

Table 5.4: Signals of EMT transformer model

Parameter	Description	Unit
I0Delta_h	Circulating Current in HV-Delta-Winding	kA
I0Delta_m	Circulating Current in MV-Delta-Winding	kA
I0Delta_l	Circulating Current in LV-Delta-Winding	kA
i0_h	Zero-Sequence Current in HV-Delta-Winding	p.u. (based on $S_{r,HV}$,$U_{r,HV}$)
i0_m	Zero-Sequence Current in MV-Delta-Winding	p.u. (based on $S_{r,HV}$,$U_{r,MV}$)
i0_l	Zero-Sequence Current in LV-Delta-Winding	p.u. (based on $S_{r,HV}$,$U_{r,LV}$)

List of Figures

List of Tables