POWERFACTORY

PowerFactory 2021

Technical Reference

Two-Winding Transformer (3-Phase)

ElmTr2,TypTr2

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

The two-winding transformer model is a highly-detailed model for various kinds of three-phase, two-winding transformers in power systems. It can be used to represent network transformers, block transformers, phase-shifters, auto transformers or MV-voltage regulators.

The 2-winding transformer model in *PowerFactory* is comprised of the 2-winding transformer element (*ElmTr2*), and the 2-winding transformer type (*TypTr2*). 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. For simplicity, these will simply be referred to hereafter as the *element* and the *type*, respectively.

The first section of this document describes the general model which is valid for all *PowerFactory* calculation functions. Other aspects such as saturation or capacitive effects, which are only relevant to specific calculation functions are described in later sections. Section 8 provides useful tips for special applications of the 2-winding transformer model.

1.1 Model diagrams

1.1.1 Positive and negative sequence models

The positive sequence (per-unit) equivalent circuit of the transformer is shown in Figure 1.1. The leakage reactances and winding resistances are included on the HV and LV sides, and the magnetising branch accounts for core losses. These losses are represented by the magnetising reactance and a parallel resistance. The ideal transformer has a complex winding ratio with a magnitude of 1:1 and models the phase shift representing the vector groups of the two windings.

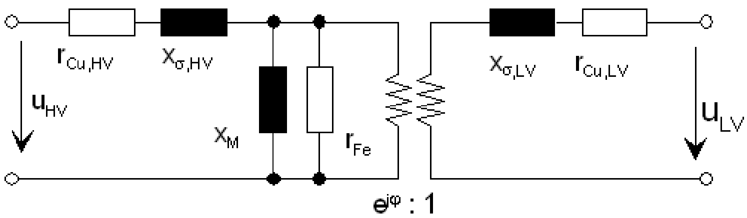


Figure 1.1: Positive sequence (per-unit) equivalent circuit of the 2-winding transformer

The relation between the mathematical parameters in the model and the parameters in the transformer type and element dialogues are described below, and the corresponding nomenclature is provided in Table 1.1.

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

The rated impedances are given by:

$$Z_{r,HV} = \frac{{U_{r,HV}}^2}{S_r} \qquad (\Omega) \tag{1}$$

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

Rated currents

The rated currents (HV, LV) are:

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

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

The short-circuit impedance (z_{sc}), short-circuit resistance (r_{sc}), and short-circuit reactance (x_{sc}) are calculated as follows:

$$z_{sc} = \frac{u_{sc}}{100} \qquad (\text{p.u.}) \tag{4}$$

$$r_{sc} = \frac{P_{Cu}/1000}{S_r} \qquad (\text{p.u.}) \tag{5}$$

$$x_{sc} = \sqrt{{z_{sc}}^2 - {r_{sc}}^2} \qquad (\text{p.u.}) \tag{6}$$

The leakage impedance (HV and LV sides, respectively) is:

$$zshv = (r_{sc} \cdot \gamma_{R,HV,1}) + (x_{sc} \cdot \gamma_{X,HV,1}) \qquad (\text{p.u.}) \tag{7}$$

$$zslv = (r_{sc} \cdot (1 - \gamma_{R,HV,1})) + (x_{sc} \cdot (1 - \gamma_{X,HV,1})) \qquad (\text{p.u.}) \tag{8}$$

The resistive losses in the windings (HV and LV sides, respectively) are represented by:

$$r_{Cu,HV} = r_{sc} \cdot \gamma_{R,HV,1} \qquad (\text{p.u.}) \tag{9}$$

$$r_{Cu,LV} = r_{sc} \cdot (1 - \gamma_{R,HV,1}) \qquad (\text{p.u.}) \tag{10}$$

The leakage reactance (HV and LV sides, respectively) is calculated as follows:

$$x_{\sigma,HV} = x_{sc} \cdot \gamma_{X,HV,1} \qquad (\text{p.u.}) \tag{11}$$

$$x_{\sigma,LV} = x_{sc} \cdot (1 - \gamma_{X,HV,1}) \qquad (\text{p.u.}) \tag{12}$$

The magnetising impedance is dependent on the no-load current, I_0, and is given by:

$$z_M = \frac{1}{I_0/100} \qquad (\text{p.u.}) \tag{13}$$

The resistive iron losses in the core are calculated as:

$$r_{Fe} = \frac{S_r}{P_{Fe}/1000} \qquad (\text{p.u.}) \tag{14}$$

and the magnetising reactance is calculated as follows:

$$x_M = \frac{1}{\sqrt{\frac{1}{{z_M}^2} - \frac{1}{{r_{Fe}}^2}}} \qquad (\text{p.u.}) \tag{15}$$

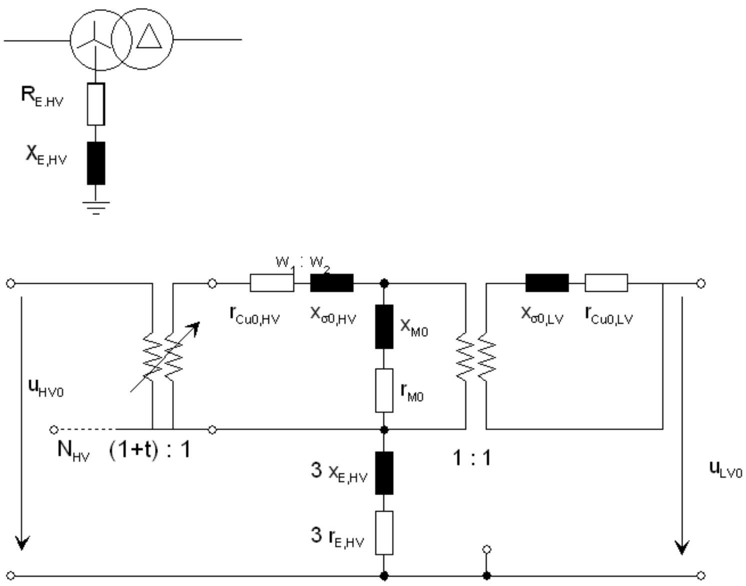
Table 1.1 provides a comprehensive list of the input- and calculation parameters described above, and their associated symbols and descriptions.

Table 1.1: Input- and calculation parameters

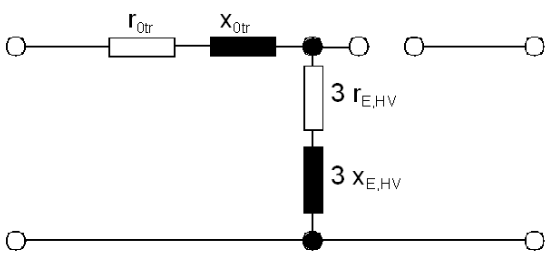
Name	Symbol	Unit	Description
$Z_{r,HV}$		Ω	Rated impedance, HV side
$Z_{r,LV}$		Ω	Rated impedance, LV side
$utrn_h$	$U_{r,HV}$	kV	Rated voltage on HV side
$utrn_l$	$U_{r,LV}$	kV	Rated voltage on LV side
$strn$	S_r	MVA	Rated apparent power
$pcutr$	P_{Cu}	kW	Copper losses
$uktr$	u_{sc}	%	Relative short-circuit voltage
z_s	z_{sc}	p.u.	Short-circuit impedance
r_s	r_{sc}	p.u.	Short-circuit resistance
x_s	x_{sc}	p.u.	Short-circuit reactance
$itrdl$	$\gamma_{X,HV,1}$	p.u.	Proportion of transformer short-circuit reactance on HV side in the positive sequence system
$itrdl\_lv$	$\gamma_{X,LV,1}$	p.u.	Proportion of transformer short-circuit reactance on LV side in the positive sequence system
$itrdr$	$\gamma_{R,HV,1}$	p.u.	Proportion of transformer short-circuit resistance on HV side in the positive sequence system
$itrdr\_lv$	$\gamma_{R,LV,1}$	p.u.	Proportion of transformer short-circuit resistance on LV side in the positive sequence system
$r_{Cu,HV}$		p.u.	Resistance on HV side
$r_{Cu,LV}$		p.u.	Resistance on LV side
$zshv$		p.u.	Leakage impedance on HV side
$zshl$		p.u.	Leakage impedance on LV side
$x_{\sigma,HV}$		p.u.	Leakage reactance on HV side
$x_{\sigma,LV}$		p.u.	Leakage reactance on LV side
$curmg$	I_0	%	No-load current
pfe	P_{Fe}	kW	No-load losses
z_M		p.u.	Magnetising impedance
x_M		p.u.	Magnetising reactance
r_{Fe}		p.u.	Shunt resistance

1.1.2 Zero sequence model

The zero sequence equivalent model of a Yd-transformer including a tap changer at the HV side is shown in Figure 1.2. Transformer models for a variety of configurations are provided in Section 8.2.



(a)



(b)

Figure 1.2: Zero sequence equivalent circuit of a Yd-transformer with HV side tap changer (a) detailed representation (b) simplified representation

1.2 YN-YN transformer with internal delta winding

The transformer type provides the option *Internal Delta Winding* for transformers defined as YN-YN. The internal zero sequence model of a YN-YN transformer is depicted in Figure 1.3.

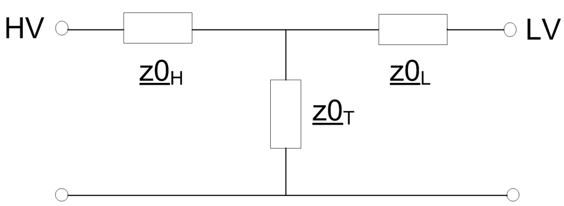


Figure 1.3: Internal zero sequence model of a YN-YN transformer

From the transformer type data, the quantities $\underline{z0}_H$, $\underline{z0}_L$ and $\underline{z0}_T$ are calculated. When the

Internal Delta Winding option is ticked, $uk0$ and $ur0$ between the HV and LV windings are:

$$uk0 = |\underline{z0}_H + \underline{z0}_L| \qquad \text{(p.u.)} \tag{16}$$

and

$$ur0 = |\operatorname{Re}(\underline{z0}_H) + \operatorname{Re}(\underline{z0}_L)| \qquad \text{(p.u.)} \tag{17}$$

The quantities $uk0$ and $ur0$ will be overwritten by the defined *Measurement Report*. The zero sequence impedance of the delta (tertiary) winding will be kept constant. The zero sequence contribution factor will also be kept constant and is calculated from the corresponding type data, *Distribution factor for the zero sequence reactance*:

$$x0dist = \frac{\operatorname{Im}(\underline{z0}_H)}{\operatorname{Im}(\underline{z0}_H) + \operatorname{Im}(\underline{z0}_L)} \qquad \text{(p.u.)} \tag{18}$$

and the distribution factor for the zero sequence resistance:

$$r0dist = \frac{\operatorname{Re}(\underline{z0}_H)}{\operatorname{Re}(\underline{z0}_H) + \operatorname{Re}(\underline{z0}_L)} \qquad \text{(p.u.)} \tag{19}$$

If the sum of the real parts equals zero, $r0dist$ will be set to $x0dist$. If the sum of the imaginary parts also equals zero, the distribution factor, $x0dist$, will be set to 0.5. The zero sequence impedance for the HV and LV winding (dependent on the tap position) is then calculated as follows:

$$x0hv = x0(tap) \cdot x0dist \qquad \text{(p.u.)} \tag{20}$$

$$x0lv = x0(tap) \cdot (1 - x0dist) \qquad \text{(p.u.)} \tag{21}$$

and

$$r0hv = r0(tap) \cdot r0dist \qquad \text{(p.u.)} \tag{22}$$

$$r0lv = r0(tap) \cdot (1 - r0dist) \qquad \text{(p.u.)} \tag{23}$$

with:

$$x0(tap) = \frac{\sqrt{uk0(tap)^2 - ur0(tap)^2}}{100} \qquad \text{(p.u.)} \tag{24}$$

$$r0(tap) = \frac{ur0(tap)}{100} \qquad \text{(p.u.)} \tag{25}$$

To determine the complex impedances in Figure 1.3, three measurements are required:

1. The zero sequence current injected at the HV terminal with the LV terminal short-circuited:

$$\underline{z0}_{HLs} = ur0_{hls} + j \cdot \sqrt{uk0_{hls}^2 - ur0_{hls}^2} \qquad \text{(p.u.)} \tag{26}$$

where $uk0_{hls}$ is the HV impedance (in p.u.) and $ur0_{hls}$ is the HV resistance (in p.u.), with the LV terminal short-circuited in both cases.

2. The zero sequence current injected at the HV terminal with the LV terminal open-circuited:

$$\underline{z0}_{HLo} = ur0_{hlo} + j \cdot \sqrt{uk0_{hlo}^2 - ur0_{hlo}^2} \qquad \text{(p.u.)} \tag{27}$$

where $uk0_{hlo}$ is the HV impedance (in p.u.) and $ur0_{hlo}$ is the HV resistance (in p.u.), with the LV terminal open-circuited in both cases.

3. The zero sequence current injected at the LV terminal with the HV terminal open-circuited:

$$\underline{z0}_{LHo} = ur0_{lho} + j \cdot \sqrt{uk0_{lho}^2 - ur0_{lho}^2} \qquad \text{(p.u.)} \tag{28}$$

where $uk0_{lho}$ is the LV impedance (in p.u.) and $ur0_{lho}$ is the LV resistance (in p.u.), with the HV terminal open-circuited in both cases.

For the first measurement:

$$\underline{z0}_{HLs} = \underline{z0}_H + \frac{\underline{z0}_L \cdot \underline{z0}_T}{\underline{z0}_L + \underline{z0}_T} \qquad \text{(p.u.)} \tag{29}$$

the second measurement:

$$\underline{z0}_{HLo} = \underline{z0}_H + \underline{z0}_T \qquad \text{(p.u.)} \tag{30}$$

and the third measurement:

$$\underline{z0}_{LHo} = \underline{z0}_L + \underline{z0}_T \qquad \text{(p.u.)} \tag{31}$$

Therefore, from (30) and (31):

$$\underline{z0}_H = \underline{z0}_{HLo} - \underline{z0}_T \qquad \text{(p.u.)} \tag{32}$$

$$\underline{z0}_L = \underline{z0}_{LHo} - \underline{z0}_T \qquad \text{(p.u.)} \tag{33}$$

Substituting (32) and (33) into (29), the tertiary impedances are obtained:

$$\underline{z0}_T = \pm\sqrt{\underline{z0}_{LHo} \cdot (\underline{z0}_{HLo} - \underline{z0}_{HLs})} \qquad \text{(p.u.)} \tag{34}$$

Equation (34) leads to two solutions:

$$\underline{z0}_T(1) = +\sqrt{\underline{z0}_{LHo} \cdot (\underline{z0}_{HLo} - \underline{z0}_{HLs})} \qquad \text{(p.u.)} \tag{35}$$

$$\underline{z0}_T(2) = -\sqrt{\underline{z0}_{LHo} \cdot (\underline{z0}_{HLo} - \underline{z0}_{HLs})} \qquad \text{(p.u.)} \tag{36}$$

The HV and LV zero sequence impedances are calculated for both solutions (35) and (36).

$$\underline{z0}_H(1) = \underline{z0}_{HLo} - \underline{z0}_T(1) \qquad \text{(p.u.)} \tag{37}$$

$$\underline{z0}_L(1) = \underline{z0}_{LHo} - \underline{z0}_T(1) \qquad \text{(p.u.)} \tag{38}$$

$$\underline{z0}_H(2) = \underline{z0}_{HLo} - \underline{z0}_T(2) \qquad \text{(p.u.)} \tag{39}$$

$$\underline{z0}_L(2) = \underline{z0}_{LHo} - \underline{z0}_T(2) \qquad \text{(p.u.)} \tag{40}$$

For the first (1) and second (2) solutions, the following series reactances are calculated:

$$x0_{HL}(1;2) = x0_H(1;2) + x0_L(1;2) \qquad \text{(p.u.)} \qquad (HV - LV) \tag{41}$$

$$x0_{HT}(1;2) = x0_H(1;2) + x0_T(1;2) \qquad \text{(p.u.)} \qquad (HV - T) \tag{42}$$

$$x0_{LT}(1;2) = x0_L(1;2) + x0_T(1;2) \qquad \text{(p.u.)} \qquad (LV - T) \tag{43}$$

The criteria used to determine the solution are as follows:

- If all reactances in solution (1) and solution (2) are positive, then the solution with the smallest HV-LV reactance is used;
- If all reactances in solution (1) are positive (but not in solution (2)), then solution (1) is used;
- If all reactances in solution (2) are positive (but not in solution (1)), then solution (2) is used;
- If all reactances in solution (1) and solution (2) are negative, the solution with the smallest HV-LV reactance (absolute value) is used.

1.2.1 Dependent parameters

When the *Internal Delta Winding* option in the transformer type is ticked, the six measured parameters are calculated from existing parameters:

The HV zero sequence impedance is:

$$\mathrm{Im}(\underline{z0}_H) = zx0hl_h \cdot \sqrt{uk0tr^2 - ur0tr^2} \qquad \text{(p.u.)} \tag{44}$$

$$\mathrm{Re}(\underline{z0}_H) = zx0hl_h \cdot ur0tr \qquad \text{(p.u.)} \tag{45}$$

The LV zero sequence impedance is:

$$\mathrm{Im}(\underline{z0}_L) = (1 - zx0hl_h) \cdot \sqrt{uk0tr^2 - ur0tr^2} \qquad \text{(p.u.)} \tag{46}$$

$$\mathrm{Re}(\underline{z0}_L) = (1 - zx0hl_h) \cdot ur0tr \qquad \text{(p.u.)} \tag{47}$$

The tertiary zero sequence impedance is:

$$\mathrm{Im}(\underline{z0}_T) = zx0hl_n \cdot \frac{uk0tr}{1 + rtox0_n{}^2} \qquad \text{(p.u.)} \tag{48}$$

$$\mathrm{Re}(\underline{z0}_T) = \mathrm{Im}(\underline{z0}_T) \cdot rtox0_n \qquad \text{(p.u.)} \tag{49}$$

The HV impedance (LV side short-circuited) is:

$$\underline{z0}_{HLs} = \underline{z0}_H + \frac{\underline{z0}_L \cdot \underline{z0}_T}{\underline{z0}_L + \underline{z0}_T} \qquad \text{(p.u.)} \tag{50}$$

$$uk0_{hls} = |\underline{z0}_{HLs}| \qquad \text{(p.u.)} \tag{51}$$

$$ur0_{hls} = \mathrm{Re}(\underline{z0}_{HLs}) \qquad \text{(p.u.)} \tag{52}$$

The HV impedance (LV side open-circuited) is:

$$\underline{z0}_{HLo} = \underline{z0}_H + \underline{z0}_T \qquad \text{(p.u.)} \tag{53}$$

$$uk0_{hlo} = |\underline{z0}_{HLo}| \qquad \text{(p.u.)} \tag{54}$$

$$ur0_{hlo} = \mathrm{Re}(\underline{z0}_{HLo}) \qquad \text{(p.u.)} \tag{55}$$

The LV impedance (HV side open-circuited) is:

$$\underline{z0}_{LHo} = \underline{z0}_L + \underline{z0}_T \qquad \text{(p.u.)} \tag{56}$$

$$uk0_{lho} = |\underline{z0}_{LHo}| \qquad \text{(p.u.)} \tag{57}$$

$$ur0_{lho} = \mathrm{Re}(\underline{z0}_{LHo}) \qquad \text{(p.u.)} \tag{58}$$

If the *Internal Delta Winding* option is ticked and one of the six impedances is changed, $\underline{z0}_H$, $\underline{z0}_L$ and $\underline{z0}_T$ are calculated according to Section 1.2.1, and the parameters below are calculated as follows:

Zero sequence impedance:

$$uk0tr = |\underline{z0}_H + \underline{z0}_L| \qquad \text{(p.u.)} \tag{59}$$

$$ur0tr = \mathrm{Re}(\underline{z0}_H + \underline{z0}_L) \qquad \text{(p.u.)} \tag{60}$$

The zero sequence magnetising impedance is:

$$zx0hl_n = \frac{|\underline{z0}_T|}{|\underline{z0}_H + \underline{z0}_L|} \quad \text{(p.u.)} \tag{61}$$

$$rtox0_n = \frac{\text{Re}(\underline{z0}_T)}{\text{Im}(\underline{z0}_T)} \quad \text{(p.u.)} \tag{62}$$

It should be noted that $rtox0_n$ is only set when $rtox0_n \geq 0$.

The distribution of zero sequence leakage impedances is given by:

$$zx0hl_h = \frac{|\underline{z0}_H|}{|\underline{z0}_H + \underline{z0}_L|} \quad \text{(p.u.)} \tag{63}$$

It should be noted that $zx0hl_h$ is only set when $0 \leq zx0hl_h \leq 1$.

1.3 Short-circuit impedance

The short-circuit impedance can be entered on the *Basic Data* page of the type, depending on the user-selected *Input* option. These *Input* options are described in Table 1.2, Table 1.3 and Table 1.4.

Table 1.2: Type *Basic Data*: Positive sequence impedance

Positive sequence impedance	**Input**	**Param.**	**Unit**
Short-Circuit Voltage uk and Copper Losses	*Short-Circuit Voltage uk*	$uktr$	%
	Copper Losses	$pcutr$	kW
Short-Circuit Voltage uk and SHC-Voltage Re(uk)	*Short-Circuit Voltage uk*	$uktr$	%
	SHC-Voltage Re(uk) ukr	$uktrr$	%
Short-Circuit Voltage uk and X/R Ratio	*Short-Circuit Voltage uk*	$uktr$	%
	Ratio X/R	$xtor$	-
Reactance in p.u. and Resistance in p.u.	*Reactance x1*	$x1pu$	p.u.
	Resistance r1	$r1pu$	p.u.

Table 1.3: Type *Basic Data*: Zero sequence impedance (no internal delta winding)

Zero sequence impedance	**Input**	**Param.**	**Unit**
Short-Circuit Voltage uk0 and SHC-Voltage Re(uk0)	*Short-Circuit Voltage uk0*	$uk0tr$	%
	SHC-Voltage Re(uk0) ukr0	$ur0tr$	%
Short-Circuit Voltage uk0 and X0/R0 Ratio	*Short-Circuit Voltage uk0*	$uk0tr$	%
	Ratio X0/R0	$x0tor0$	-
Reactance in p.u. and Resistance in p.u.	*Reactance x0*	$x0pu$	p.u.
	Resistance r0	$r0pu$	p.u.

Table 1.4: Type *Basic Data*: Zero sequence impedance: YN-YN; with internal delta winding

Zero sequence impedance	Input	Param.	Unit
Short-Circuit Voltage uk0 and SHC-Voltage Re(uk0)	*HV-SHC-Voltage uk0 (LV short-circuit)*	$uk0_{hls}$	%
	HV-SHC-Voltage Re(uk0) (LV short-circuit)	$ur0_{hls}$	%
	HV-SHC-Voltage uk0 (LV open)	$uk0_{hlo}$	%
	HV-SHC-Voltage Re(uk0) (LV open)	$ur0_{hlo}$	%
	LV-SHC-Voltage uk0 (HV open)	$uk0_{lho}$	%
	LV-SHC-Voltage Re(uk0) (HV open)	$ur0_{lho}$	%
Short-Circuit Voltage uk0 and X0/R0 Ratio	*HV-SHC-Voltage uk0 (LV short-circuit)*	$uk0_{hls}$	%
	HV-Ratio X0/R0 (LV short-circuit)	$xtr0_{hls}$	%
	HV-SHC-Voltage uk0 (LV open)	$uk0_{hlo}$	%
	HV-Ratio X0/R0 (LV open)	$xtr0_{hlo}$	%
	LV-SHC-Voltage uk0 (HV open)	$uk0_{lho}$	%
	LV-Ratio X0/R0 (HV open)	$xtr0_{lho}$	%
Reactance in p.u. and Resistance in p.u.	*HV-Reactance x0 (LV short-circuit)*	$x0pu_{hls}$	p.u.
	HV-Resistance r0 (LV short-circuit)	$r0pu_{hls}$	p.u.
	HV-Reactance x0 (LV open)	$x0pu_{hlo}$	p.u.
	HV-Resistance r0 (LV open)	$r0pu_{hlo}$	p.u.
	LV-Reactance x0 (HV open)	$x0pu_{lho}$	p.u.
	LV-Resistance r0 (HV open)	$r0pu_{lho}$	p.u.

1.3.1 Positive sequence impedance

If $r1pu$ and $x1pu$ are available as inputs on the *Basic Data* page of the transformer type:

$$uktr = \sqrt{r1pu^2 + x1pu^2} \cdot 100 \qquad (\%) \tag{64}$$

$$pcutr = r1pu \cdot 1000 \cdot S_r \tag{65}$$

Accordingly, if tap dependent, $r1putmn$, $r1putmx$ and $x1putmn$, $x1putmx$ are available as inputs on the *Load Flow* page, *Tap Changer* tab of the type.

For the minimum tap:

$$uktmn = \sqrt{r1putmn^2 + x1putmn^2} \cdot 100 \qquad (\%) \tag{66}$$

$$pcutmn = r1putmn \cdot 1000 \cdot strn \tag{67}$$

For the maximum tap:

$$uktmx = \sqrt{r1putmx^2 + x1putmx^2} \cdot 100 \qquad (\%) \tag{68}$$

$$pcutmx = r1putmx \cdot 1000 \cdot strn \tag{69}$$

1.3.2 Zero sequence impedance

The two additional input options for zero sequence impedance are available via the options page in the type: *Short-Circuit Voltage uk0 and X0/R0 Ratio* and *Reactance in p.u. and Resistance in p.u.* Based on the combination of selections of *Internal Delta Winding* and vector groups for the HV and LV sides, there are two situations:

1. If *Internal Delta Winding* is not ticked or vector group is not YN-YN:

If $uk0tr$ and $x0tor0$ are available as inputs on the *Basic Data* page of the transformer type:

$$r0pu = uk0tr/100/\sqrt{1 + x0tor0^2} \qquad \text{(p.u.)} \tag{70}$$

$$x0pu = \sqrt{\left(\frac{uk0tr}{100}\right)^2 - r0pu^2} \qquad \text{(p.u.)} \tag{71}$$

Accordingly, if tap dependent, $uk0tmn$, $uk0tmx$ and $x0tor0tmn$, $x0tor0tmx$ are available as inputs on the *Load Flow* page, *Tap Changer* tab of the type.

For minimum tap:

$$r0putmn = uk0tmn/100/\sqrt{1 + x0tor0tmn^2} \qquad \text{(p.u.)} \tag{72}$$

$$x0putmn = \sqrt{\left(\frac{uk0tmn}{100}\right)^2 - r0putmn^2} \qquad \text{(p.u.)} \tag{73}$$

For maximum tap:

$$r0putmx = uk0tmx/100/\sqrt{1 + x0tor0tmx^2} \qquad \text{(p.u.)} \tag{74}$$

$$x0putmx = \sqrt{\left(\frac{uk0tmx}{100}\right)^2 - r0putmx^2} \qquad \text{(p.u.)} \tag{75}$$

If $r0pu$ and $x0pu$ are available as inputs on the *Basic Data* page of the transformer type:

$$uk0tr = \sqrt{r0pu^2 + x0pu^2} \cdot 100 \qquad (\%) \tag{76}$$

$$ur0tr = r0pu \cdot 100 \qquad (\%) \tag{77}$$

$$x0tor0 = \frac{x0pu}{r0pu} \qquad \text{(p.u.)} \tag{78}$$

Accordingly, if tap dependent, $r0putmn$, $r0putmx$ and $x0putmn$, $x0putmx$ are available as inputs on the *Load Flow* page, *Tap Changer* tab of the type.

For minimum tap:

$$uk0tmn = \sqrt{r0putmn^2 + x0putmn^2} \cdot 100 \qquad (\%) \tag{79}$$

$$uk0rtmn = r0putmn \cdot 100 \qquad (\%) \tag{80}$$

$$x0tor0tmn = \frac{x0putmn}{r0putmn} \qquad (\text{p.u.}) \tag{81}$$

For maximum tap:

$$uk0tmx = \sqrt{r0putmx^2 + x0putmx^2} \cdot 100 \qquad (\%) \tag{82}$$

$$uk0rtmx = r0putmx \cdot 100 \qquad (\%) \tag{83}$$

$$x0tor0tmx = \frac{x0putmx}{r0putmx} \qquad (\text{p.u.}) \tag{84}$$

2. If *Internal Delta Winding* is ticked and vector group is YN-YN:

If $uk0_{(hls,hlo,lho)}$ and $xtr0_{(hls,hlo,lho)}$ are available as inputs on the *Basic Data* page of the transformer type:

$$r0pu_{hls} = ur0_{hls}/100/\sqrt{1 + xtr0_{hls}^2} \qquad (\text{p.u.}) \tag{85}$$

$$r0pu_{hlo} = ur0_{hlo}/100/\sqrt{1 + xtr0_{hlo}^2} \qquad (\text{p.u.}) \tag{86}$$

$$r0pu_{lho} = ur0_{lho}/100/\sqrt{1 + xtr0_{lho}^2} \qquad (\text{p.u.}) \tag{87}$$

$$x0pu_{hls} = \sqrt{(uk0_{hls}/100)^2 - (r0pu_{hls})^2} \qquad (\text{p.u.}) \tag{88}$$

$$x0pu_{hlo} = \sqrt{(uk0_{hlo}/100)^2 - (r0pu_{hlo})^2} \qquad (\text{p.u.}) \tag{89}$$

$$x0pu_{lho} = \sqrt{(uk0_{lho}/100)^2 - (r0pu_{lho})^2} \qquad (\text{p.u.}) \tag{90}$$

$$uk0_{hls} = \sqrt{r0pu_{hls}^2 + x0pu_{hls}^2} \cdot 100 \qquad (\%) \tag{91}$$

$$uk0_{hlo} = \sqrt{r0pu_{hlo}^2 + x0pu_{hlo}^2} \cdot 100 \qquad (\%) \tag{92}$$

$$uk0_{lho} = \sqrt{r0pu_{lho}^2 + x0pu_{lho}^2} \cdot 100 \qquad (\%) \tag{93}$$

$$uk0_{hls} = r0pu_{hls} \cdot 100 \qquad (\%) \tag{94}$$

$$uk0_{hlo} = r0pu_{hlo} \cdot 100 \qquad (\%) \tag{95}$$

$$uk0_{lho} = r0pu_{lho} \cdot 100 \qquad (\%) \tag{96}$$

$$xtr0_{hls} = \frac{x0pu_{hls}}{r0pu_{hls}} \qquad (\text{p.u.}) \tag{97}$$

$$xtr0_{hlo} = \frac{x0pu_{hlo}}{r0pu_{hlo}} \qquad (\text{p.u.}) \tag{98}$$

$$xtr0_{lho} = \frac{x0pu_{lho}}{r0pu_{lho}} \qquad (\text{p.u.}) \tag{99}$$

1.4 Nominal power and current

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

The following *DIgSILENT* parameter are available:

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

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

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

1.4.1 Nominal current

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

$$\begin{aligned} I_{nomhv} &= ratfac \cdot AddRatFactMeasTab \cdot I_{r,HV} \cdot ntnum \\ I_{nomlv} &= ratfac \cdot AddRatFactMeasTab \cdot I_{r,LV} \cdot ntnum \end{aligned} \tag{100}$$

where the rated currents $I_{r,HV}$ and $I_{r,LV}$ are defined in equation (3) at section 1.1

and

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

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

- if the continuous rating is entered in MVA:

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

- if the continuous rating is entered in %:

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

where $U_{n(bushv)}$ and $U_{n(buslv)}$ are the busbar line-line nominal voltages in kV at the high and low voltage side and the rated currents $I_{r,HV}$, $I_{r,LV}$ (see equation (3)).

1.4.2 Nominal power

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

When no thermal rating object is selected:

$$Snom = S_r \cdot ntnum \cdot ratfac_n$$
$$Snom\_a = S_r \cdot ntnum \cdot ratfac_{n}\_a$$

where:

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

In case of a thermal rating object is selected:

$$Snom = \sqrt{3} \cdot U_{n(bushv)} \cdot I_{nomhv}$$
$$Snom\_a = Snom$$

where:

- I_{nomhv} is the nominal current at high voltage side, see section 1.4.1.
- $U_{n(bushv)}$ is the busbar line-line nominal voltages in kV at the high voltage side.

2 Tap Changer Model

2.1 Description

The tap changer is represented by an additional, ideal transformer connected to either the HV or LV side (see Figure 2.1 and Figure 2.2). For most applications, the winding ratio of this transformer is real and is defined by the actual tap position (in number of steps) multiplied by the additional voltage per step.

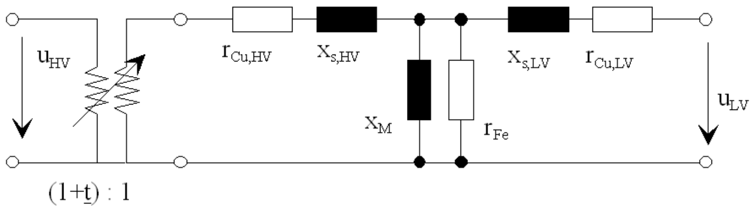


Figure 2.1: Transformer model with tap changer modelled at the HV side

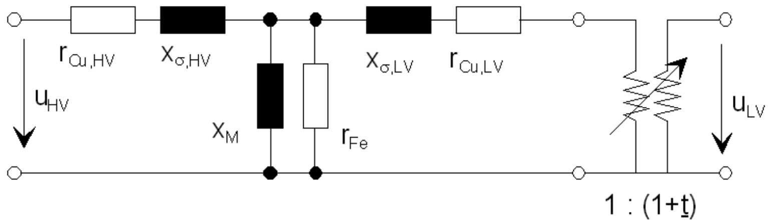


Figure 2.2: Transformer model with tap changer modelled at the LV side

Phase-shifting transformers are modelled by a complex ratio using a complex value, $\underline{du}$, which is expressed as:

$$\underline{du} = du_{tap}\,(cos(phitr) + j \cdot sin(phitr)) \tag{101}$$

This is illustrated for the asymmetrical tap changer model in Figure 2.3.

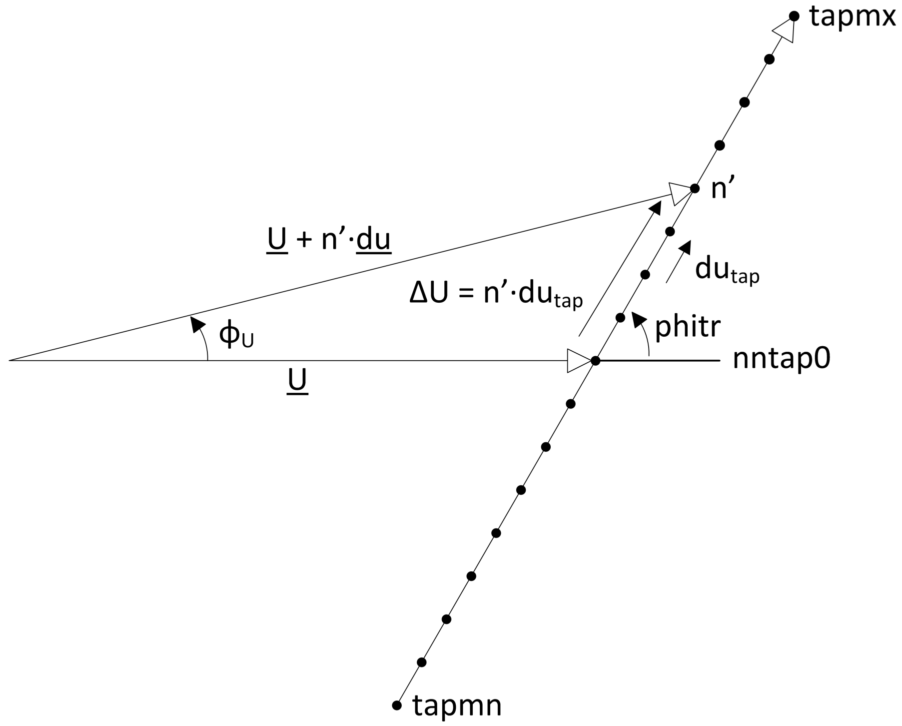


Figure 2.3: Complex tap changer model (asymmetrical) in *PowerFactory*

For the symmetrical phase shifter, as illustrated in Figure 2.4, $\underline{du}_1$ and $\underline{du}_2$ are expressed as:

$$\underline{du}_1 = j \cdot \frac{du_{tap}}{2} \tag{102}$$

$$\underline{du}_2 = -j \cdot \frac{du_{tap}}{2} \tag{103}$$

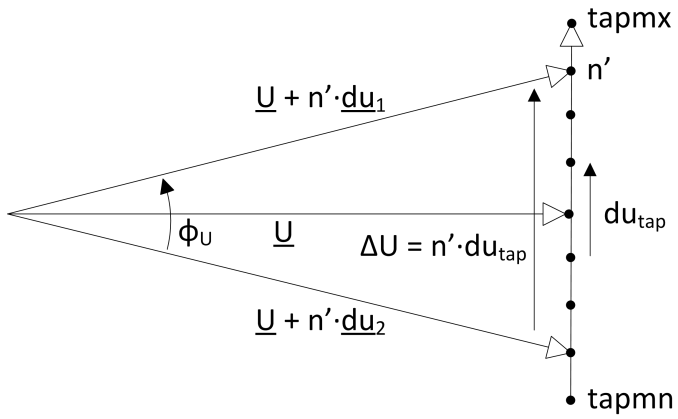


Figure 2.4: Complex tap changer model (symmetrical) in *PowerFactory*

PowerFactory provides two ways of defining a phase-shifting transformer:

1. In the type (*Basic Data* page): by entering the magnitude (du_{tap}) and angle ($phitr$) of the additional voltage per tap step; or
2. In the element (*Load Flow* page; option *According to Measurement Report* and associated table): by defining the magnitude ($U + du_{tap}$) and angle (Φ_U) at each individual tap step. Refer to Section 3.1 for further details.

2.2 Type data

The type data inputs available for the tap changer are listed in Table 2.1.

Table 2.1: *Load Flow* tap changer data

Parameter	Description	Unit
Type	Type of phase shifter	-
At side	Side at which the tap changer is modelled (not necessarily the side at which the tap changer is physically connected)	-
Additional voltage per tap	Additional voltage per tap	%
Phase of du	Constant phase between fixed voltage and additional voltage of the winding (parameter $phitr$ in Figure 2.3)	Degrees (°)
Neutral/min./max. position	Range of possible positions for the tap changer. At the neutral position, the winding ratio corresponds to the ratio of the rated voltages.	-

2.2.1 Tap changer with two taps

The transformer tap model supports the definition of two taps, which may have differing types:

- Ratio/Asym. Phase Shifter
- Ideal Phase Shifter
- Symmetrical Phase Shifter

2.2.1.1 Ideal phase shifter

If this option is selected for the tap changer type, the magnitude of the voltage will not be changed, only the angle. The parameter $dphitap$ or/and $dphitap2$ should not be set to $0°$, $180°$ or $-180°$. This model is illustrated in Figure 2.5.

If the tap is on the HV side, the complex transformer ratio is calculated as follows:

$$\underline{t}_{hv} = cos(nntap_{int} \cdot dphitap) + j \cdot sin(nntap_{int} \cdot dphitap) \tag{104}$$

If the tap is on the LV side:

$$\underline{t}_{lv} = cos(nntap_{int} \cdot dphitap) + j \cdot sin(nntap_{int} \cdot dphitap) \tag{105}$$

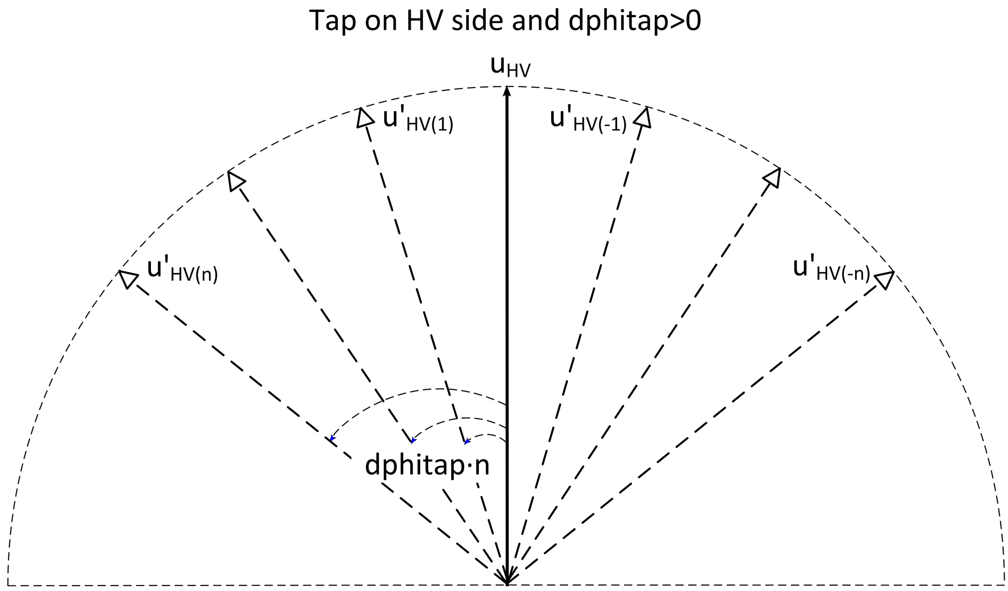


Figure 2.5: Ideal phase shifter

2.2.1.2 Symmetrical phase shifter

If this option is selected for the tap changer type, the parameter $dphitap$ will be automatically set to $90°$. A second tap definition is not available. The complex transformer ratio is calculated as shown for the following cases:

1. If tap changer 1 is modelled at the HV side:

$$\underline{t}_{hv} = 1 + nntap_{int} \cdot \frac{du}{2} \cdot (cos(phitr) + j \cdot sin(phitr)) \tag{106}$$

with $phitr = 90°$
and for the opposite tap at the LV side:

$$\underline{t}_{lv} = 1 - nntap_{int} \cdot \frac{du}{2} \cdot (cos(phitr) + j \cdot sin(phitr)) \tag{107}$$

2. If tap changer 1 is modelled at the LV side:

$$\underline{t}_{lv} = 1 + nntap_{int} \cdot \frac{du}{2} \cdot (cos(phitr) + j \cdot sin(phitr)) \tag{108}$$

with $phitr = 90°$
and for the opposite tap at the HV side:

$$\underline{t}_{hv} = 1 - nntap_{int} \cdot \frac{du}{2} \cdot (cos(phitr) + j \cdot sin(phitr)) \tag{109}$$

This model is illustrated in Figure 2.6.

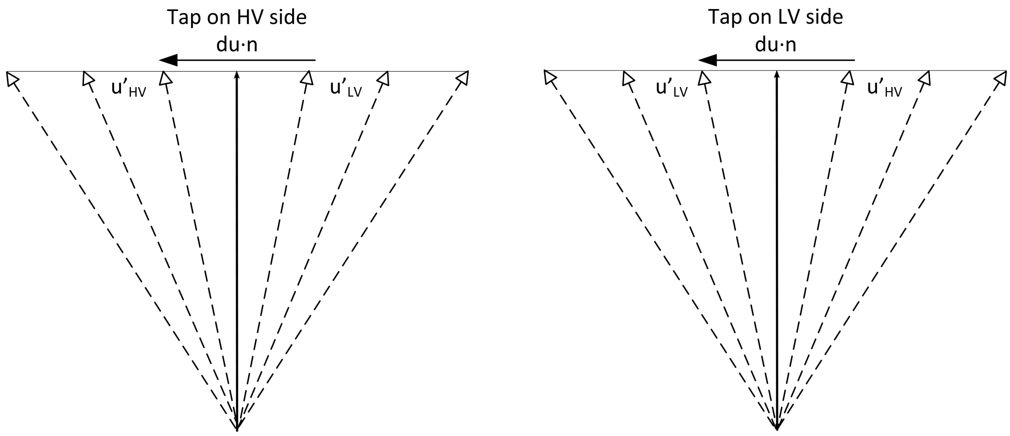


Figure 2.6: Symmetrical phase shifter

Example: symmetrical phase shifter

- Tap changer 1 modelled at HV side
- Type set to *Sym. Phase Shifter*
- $dutap > 0$ and tap position $>$ neutral position

The absolute angle change between the HV and LV sides is calculated as follows:

$$phi(u_{lv}) - phi(u_{hv}) = 2 \cdot \arctan\left(\frac{nntap_{int} \cdot dutap}{2}\right) \tag{110}$$

A positive tap position $(tap > neutral)$ leads to a negative voltage angle at the LV side.

2.2.1.3 Transformer with two tap changers

If two tap changers are defined, the complex transformer ratios are calculated as follows:

$$\underline{t}_{tap1} = 1 + nntap_{int} \cdot \frac{du}{2} \cdot (cos(phitr) + j \cdot sin(phitr)) \tag{111}$$

$$\underline{t}_{tap2} = 1 + nntap2_{int} \cdot \frac{du2}{2} \cdot (cos(phitr2) + j \cdot sin(phitr2))$$

If the second tap changer is an ideal phase shifter, the corresponding tap ($\underline{t}_{tap2}$) is calculated according to:

$$\underline{t}_{tap2} = cos(nntap2_{int} \cdot dphitap2) + j \cdot sin(nntap2_{int} \cdot dphitap2) \tag{112}$$

and with the relative tap positions:

$$\begin{aligned} nntap_{int} &= nntap0 - nntap \\ nntap2_{int} &= nntap02 - nntap2 \end{aligned} \tag{113}$$

The transformer ratios for the HV and LV sides are calculated as follows:

1. If both tap changers are modelled at the HV side:

$$\begin{aligned} \underline{t}_{hv} &= \underline{t}_{tap1} \cdot \underline{t}_{tap2} \\ \underline{t}_{lv} &= 1 \end{aligned} \tag{114}$$

2. If both tap changers are modelled at the LV side:

$$\begin{aligned} \underline{t}_{hv} &= 1 \\ \underline{t}_{lv} &= \underline{t}_{tap1} \cdot \underline{t}_{tap2} \end{aligned} \tag{115}$$

3. If tap changer 1 is at the HV side and tap changer 2 is at the LV side:

$$\begin{aligned} \underline{t}_{hv} &= \underline{t}_{tap1} \\ \underline{t}_{lv} &= \underline{t}_{tap2} \end{aligned} \tag{116}$$

4. If tap changer 1 is at the LV side and tap changer 2 is at the HV side:

$$\begin{aligned} \underline{t}_{hv} &= \underline{t}_{tap2} \\ \underline{t}_{lv} &= \underline{t}_{tap1} \end{aligned} \tag{117}$$

The internal voltages and currents are transferred accordingly:

$$\begin{aligned} \underline{u'}_{hv} &= \frac{\underline{u}_{hv}}{\underline{t}_{hv}} \\ \underline{i'}_{hv} &= \underline{i}_{hv} \cdot \underline{t}^{*}_{hv} \end{aligned} \tag{118}$$

and for the LV-side voltage:

$$\begin{aligned} \underline{u'}_{lv} &= \frac{\underline{u}_{lv}}{\underline{t}_{lv}} \\ \underline{i'}_{lv} &= \underline{i}_{lv} \cdot \underline{t}^{*}_{lv} \end{aligned} \tag{119}$$

2.2.1.4 Tap dependent impedance

Data relating to the tap dependent impedance can be entered when the *Tap dependent impedance* option in the type has been selected. Parameters that can be considered to be tap dependent are the short-circuit impedances and copper losses (short-circuit resistance) in the positive- and zero sequence systems. For tap positions between minimum and neutral, and between neutral and maximum, tap dependent parameters are interpolated using splines.

Transformer type *Load Flow* tap dependent impedance data is shown in Table 2.2.

Table 2.2: *Load Flow* Tap dependent impedance data

Parameter	Description	Unit
Reactance x1	Positive sequence reactance (at min. and max. tap positions)	p.u.
Resistance r1	Positive sequence resistance (at min. and max. tap positions)	p.u.
Reactance x0	Zero sequence reactance (at min. and max. tap positions)	p.u.
Resistance r0	Zero sequence resistance (at min. and max. tap positions)	p.u.
Ratio X0/R0	Ratio X0/R0 (at min. and max. tap positions)	p.u.

2.2.1.5 Zero sequence magnetising admittance calculation

The zero sequence magnetising admittance is always calculated from *uk0* at the neutral position of the transformer type (independent of the *Measurement Report* or whether the option *Tap dependent impedance* is enabled). For a transformer with the option *Internal Delta Winding* ticked, the zero sequence magnetising admittance is ignored. In such cases, the calculated zero sequence impedance for the internal delta winding (tertiary winding) is used instead.

3 Load Flow Analysis

The Load Flow Calculation in *PowerFactory* uses the detailed model of the transformer; i.e. all shunt and branch impedances are considered appropriately in the positive- and zero sequence systems.

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:

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 (see Section3.1) .

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

In addition, there are two tap changer controllers available (if they are also enabled in the type). 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 3.2).

3.1 Measurement report

This can be used for the precise definition of a tap changer. It allows all tap-dependent parameters to be entered per tap step. If the option *According to measurement report* is ticked, the corresponding type parameters are overwritten by their respective element parameters. The input parameters are described in Table 3.1.

Table 3.1: Measurement report data (transformer element)

Parameter	Description	Unit
Voltage	Voltage at tap position i	kV
Angle	Absolute tap angle (parameter Φ_U in Figure 2.3)	Degrees (°)
uk	Short-circuit voltage of the transformer	%
P_{Cu}	Copper losses	kW
Add. rating Factor	Rating factor for consideration of tap-dependent transformer rating. The additional rating factor is multiplied by the general rating factor (*Rating Factor* on the *Basic Data* page)	p.u.
uk0	Short-circuit voltage of the transformer, zero sequence (Only available if button *Include Zero-Sequence Impedance* has been pressed)	%
ur0	Short-circuit voltage of the transformer, zero sequence (real part) (Only available if button *Include Zero-Sequence Impedance* has been pressed)	%

The following points should be noted regarding the zero sequence impedance, *uk0* and *ur0*, in the *Measurement report*:

1. If the transformer type options *Internal Delta Winding* and *Tap dependent impedance* are disabled:
   - The column *uk0* is set to the value of *uk0tr* (absolute *uk0*) from the transformer type;
   - The column *ur0* is set to the value of *ur0tr* (resistive part *ukr0*) from the transformer type.
2. If the transformer type option *Internal Delta Winding* is disabled and *Tap dependent impedance* is enabled:
   - The column *uk0* is set to the corresponding spline-interpolated value of *uk0* (at tap) from the transformer type;
   - The column *ur0* is set to the corresponding spline-interpolated value of *ur0* (at tap) from the transformer type.
3. If the transformer type option *Internal Delta Winding* is enabled and the option *Tap dependent impedance* is disabled:
   - The column *uk0* is set to the value of the calculated *uk0* (absolute *uk0*) from the transformer type;
   - The column *uk0r* is set to the value of the calculated *ur0* (resistive part *ukr0*) from the transformer type.

3.2 Automatic tap changer control

This is activated by setting the corresponding option for both *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.
- *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:

- *V*: Voltage control. For unbalanced load flow analysis, the controlled phase needs to be additionally defined (see Section 3.2.1).
- *Q*: Reactive power control (see Section 3.2.2).
- *P*: Active power control (only applicable to phase-shifters) (see Section 3.2.3).

3.2.1 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*
- *internal (LDC) line drop compensation*: See Section 3.2.1.1).
- *external (LDC) line drop compensation*: Via a *Line Drop Compensation (StaLdc)* object.
- *current compounding*: See Section 3.2.1.2).

3.2.1.1 Line Drop Compensation

Voltage control includes optional line drop compensation (LDC). This function controls the voltage at a remote busbar without measuring the voltage at that busbar. Instead, the value is estimated by measuring the voltage at the HV or LV side of the transformer and simulating the voltage drop across the line.

The principle of line drop compensation is shown in Figure 3.1 and the corresponding transformer element input parameters are provided in Table 3.2.

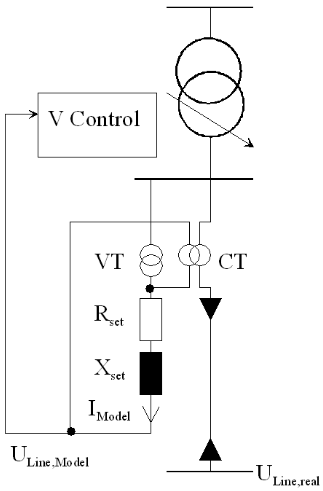


Figure 3.1: Line drop compensation

Table 3.2: Line drop compensation (for voltage control)

Parameter	**Description**	**Unit**
Current transformer rating	Primary CT current rating	A
Voltage transformer ratio	Ratio of the voltage transformer	-
RSet, XSet	LDC impedance, defined as the voltage drop at rated current. It corresponds to the LDC impedance (in Ω) multiplied by the secondary CT current rating.	V

3.2.1.2 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 3.3: 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 3.2). 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 3.2). *reactive current*: Control is based on the reactive component of the measured current (see Figure 3.2). *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 3.3). *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.	%

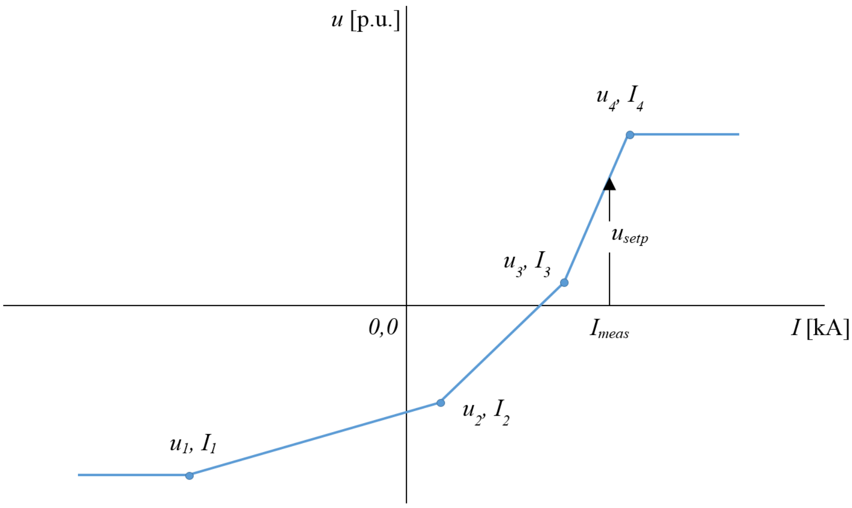


Figure 3.2: Current compounding based on apparent, active or reactive current

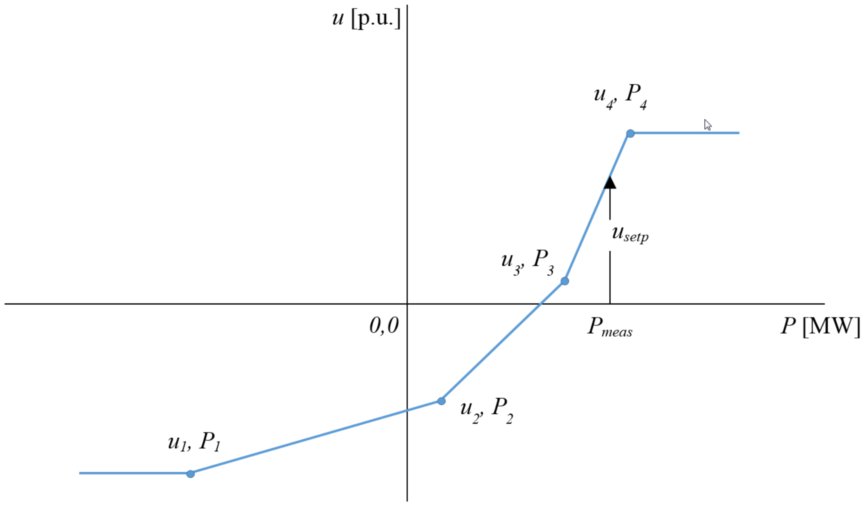


Figure 3.3: Current compounding based on active power

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 3.4.

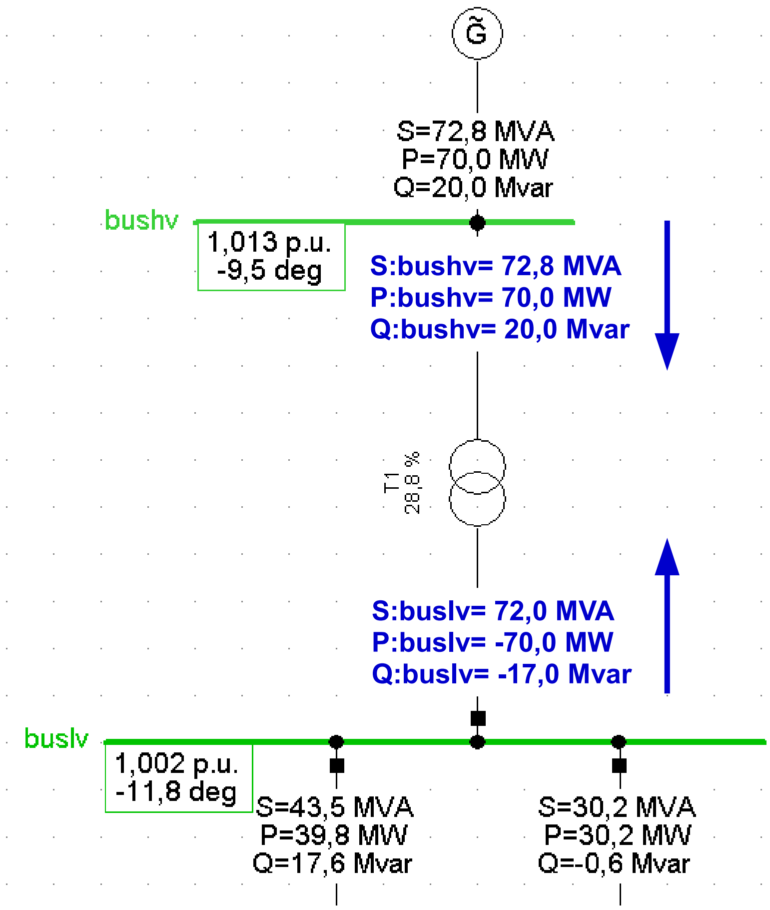


Figure 3.4: Power flow reported in *PowerFactory* at HV and LV sides

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:

$$Pmeas = \begin{cases} P{:}bushv & \text{if Controlled Node at HV side} \\ \\ -P{:}busmv & \text{if Controlled Node at MV side for 3-winding transformers} \\ \\ -P{:}buslv & \text{if Controlled Node at LV side} \end{cases} \tag{120}$$

The same equation 120 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. $I_{active} = |\underline{I}_1| \cdot \cos(\phi_{U_1,I_1})$

3.2.2 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.

3.2.3 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 3.2.3.1.

- **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.

3.2.3.1 Active Power Participation

Below there is an example of the use of active power participation control. The first figure 3.5 shows the load flow solution without any control, and the set tap position at zero. In the second figure, 3.6, 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.

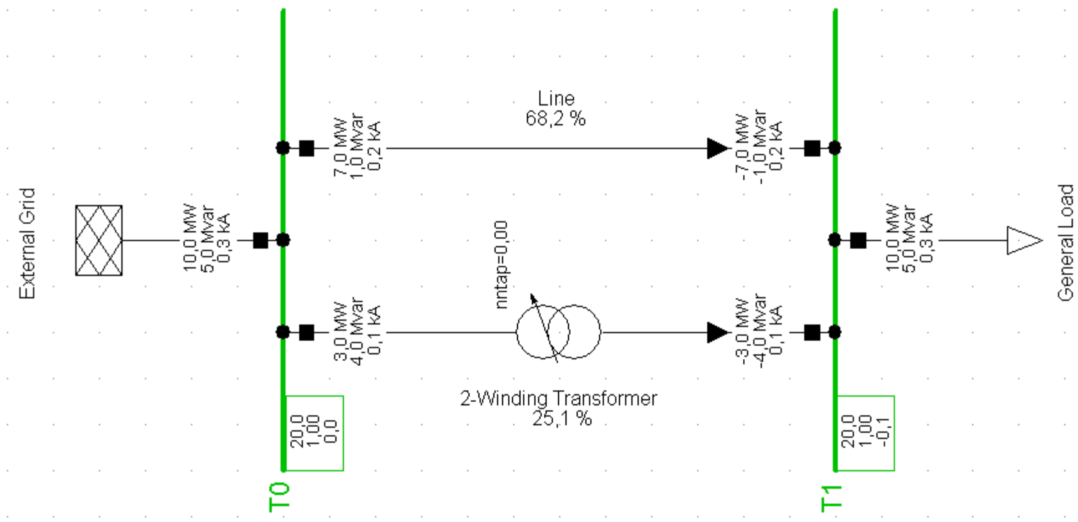


Figure 3.5: No Active Power Participation

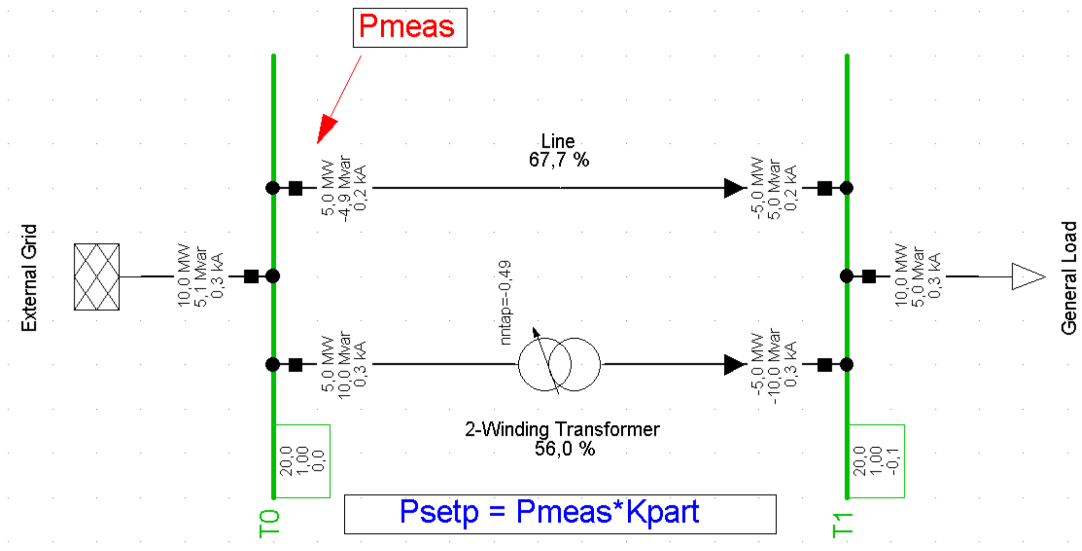


Figure 3.6: Tap control through active power participation

3.2.4 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 3.7. 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.

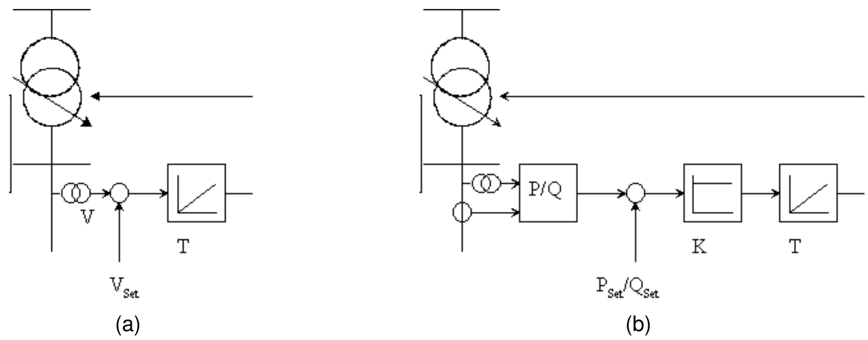


Figure 3.7: Principle of simulated dynamic control for V and P/Q

The controller input parameters for the transformer element are described in Table 3.4.

Table 3.4: 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,

$$
\begin{aligned}
Kpctrl &= \frac{1}{dPdtap} \\
Kqctrl &= \frac{1}{dQdtap}
\end{aligned}
\tag{121}
$$

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.

3.2.5 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

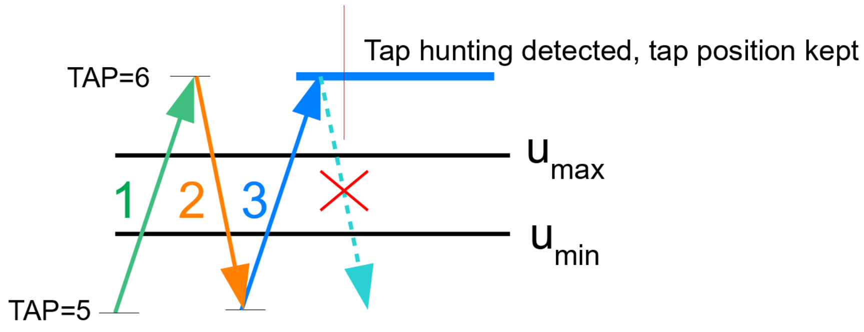


Figure 3.8: *PowerFactory* Tap hunting detection for no. of transitions = 3

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.

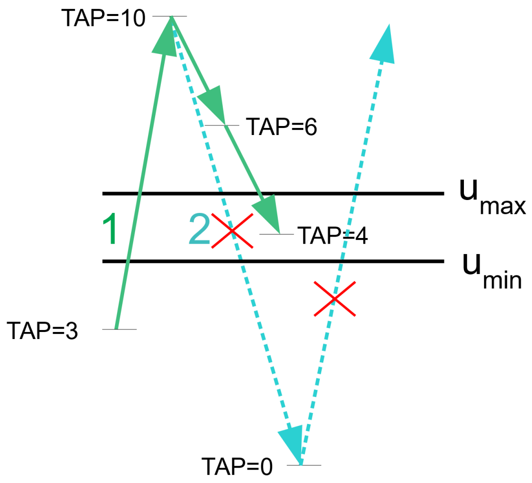


Figure 3.9: *PowerFactory* Delta tap limitation

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

3.3 Saturation characteristic

A saturation curve can be defined in the load flow page of the transformer type as current-voltage RMS values. This same curve is also used for RMS simulations. It can also be used for EMT simulations. This curve is often available from the manufacturer test report.

Note: Since the current waveform in saturated conditions is non-sinusoidal, the measured RMS current value contains also harmonics. Therefore, the use of this saturation characteristic in load flow and RMS simulations, which are based solely on fundamental frequency components, has to be seen as an approximation.

3.4 Calculation Quantities

3.4.1 Loading

The loading of the transformer is calculated as follows:

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

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

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

3.4.2 Losses

The losses are calculated as follows:

Table 3.5: Losses Quantities

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

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

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

and

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

3.4.3 Voltage Drop

Table 3.6: Voltage Drop Quantities, AC-model

Quantity	Unit	Description	Value
du	$p.u.$	Voltage Drop	$= u_{bushv} - u_{buslv}$
$dupc$	$\%$	Voltage Drop	$= du \cdot 100$
$dphiu$	deg	Voltage Drop Angle	$= \phi_{u,bushv} - \phi_{u,buslv}$
$du1$	$p.u.$	Positive Sequence Voltage Drop	$= u1_{bushv} - u1_{buslv}$
$du1pc$	$\%$	Positive Sequence Voltage Drop	$= du1 \cdot 100$
$dphiu1$	deg	Positive Sequence Voltage Drop Angle	$= \phi_{u1,bushv} - \phi_{u1,buslv}$

u_{bushv} and u_{buslv} are the corresponding terminal voltage in p.u. based on the rated voltage of the terminal. $\phi_{u,bushv}$ and $\phi_{u,buslv}$ the terminal voltage angle in deg. For an unbalanced load flow du, $dupc$, $dphiu$ is per phase available, e.g. $c : dupc : B$.

3.5 Calculation parameters for linear DC Load Flow

3.5.1 Loading

The loading of the transformer is calculated as follows:

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

where:

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

The nominal power is determined as follow when no thermal rating object is defined:

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

with the nominal currents of the transformer I_{nomhv} and I_{nomlv} (see equation (100)).
$U_{n(bushv)}$ and $U_{n(buslv)}$ are the busbar line-line nominal voltages in kV at the high and low voltage side.

If a thermal rating object is used, the nominal power is calculated using the parameter $ContRating$ and $U_{n(bushv)}$ and $U_{n(buslv)}$ as:

- if the continuous rating is entered in MVA:

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

- if the continuous rating is entered in %:

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

where the rated currents $I_{r,HV}$ and $I_{r,LV}$ are defined in equation (3) at section 1.1.

3.5.2 Losses

Losses are not calculated in the linear DC Load Flow.

4 Short-Circuit Analysis

4.1 IEC calculations

4.1.1 Element data

The *VDE/IEC Short-Circuit* page of the transformer element provides inputs which are used to calculate the impedance correction factor of the transformer. The first option, *Unit Transformer*, defines whether the transformer is a unit transformer or a network transformer. In the case of unit transformers, one common correction factor is applied to transformers and generators, independent of the actual operating conditions of a selected transformer. Network transformers are considered individually.

The second option, *Long-term operating conditions before short-circuit are known*, is more specific (requiring additional input data) and may lead to more precise calculation results.

If the following combination of options have been ticked:

- *Unit Transformer* (*VDE/IEC Short-Circuit* page of the transformer element); and
- *Long-term operating conditions before short-circuit are known* (*VDE/IEC Short-Circuit* page of the transformer element); and
- *On-load Tap Changer* (*VDE/IEC Short-Circuit* page of the transformer type),

then the parameter *Minimum Operating Voltage* can be entered on the *VDE/IEC Short-Circuit* page of the transformer element.

4.1.2 Type data

Short-circuit calculations according to IEC assume that the shunt impedances (i.e. magnetising reactances and iron losses) in the positive- and negative sequence are neglected. The shunt impedances in the zero sequence however, must be considered. These input parameters are available on the *VDE/IEC Short-Circuit* page of the type dialog.

The short-circuit calculation according to IEC distinguishes between no-load and on-load tap changers. Different impedance correction factors apply for each group. On-load variation of the tap changer can be ticked on the *VDE/IEC Short-Circuit* page of the type dialog.

5 RMS-Simulation

The model used by the RMS simulation is identical to the load flow model. However, tap controller definitions are not considered. For the simulation of tap controllers, a separate dynamic model must be defined that can be interfaced with the transformer using the input variable *nntapin* (tap-input).

6 EMT-Simulation

For simulating non-linear, electromagnetic transients such as transformer inrush currents or ferro-resonance, core saturation needs to be included in the model of the transformer. The saturation can be defined in the transformer type, as described in Section 6.2.1. In addition, depending on the frequencies involved in the transient simulation, the transformer model has to account for the stray capacitances between windings and winding to ground. These can be defined in the transformer element, as described in Section 6.1.1

6.1 Element data

6.1.1 Stray capacitances

In high frequency EMT applications, e.g. switching or lightning studies, transformer capacitances should be considered.

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 ticking the *Consider Capacitances* option on the *EMT-Simulation* page of the transformer element:

Capacitance HV to ground : applies to the positive- and zero sequence

Capacitance LV to ground : applies to the positive- and zero sequence

Capacitance HV-LV, positive sequence

Capacitance HV-LV, zero sequence

For typical values please refer to [6].

6.2 Type data

6.2.1 Saturation characteristic

Figure 6.1 shows the equivalent model of a 2-winding, 3-phase transformer for the positive sequence. For simplicity, the tap changer is not illustrated in the Figure, however it is considered in the model according to Figure 2.1, Figure 2.2 and Figure 2.3 as described in previous sections.

The excitation current of a transformer (no-load test) consists of an imaginary part, which is the magnetising current flowing through the non-linear reactance X_{M1} in Figure 6.1, and a smaller real part flowing through the resistance R_{Fe}, which accounts for the excitation losses.

The non-linear magnetising reactance X_{M1} represents the saturation characteristic of the transformer and is defined in the transformer type (*EMT-Simulation* page). The model supports the following options, which are explained in detail in the following sections:

Linear : no saturation considered.

Two slope : the saturation curve is approximated by two linear slopes.

Polynomial : the saturation curve is approximated by a polynomial of user-defined order. The polynomial fits asymptotically into the piecewise-linear definition.

Current/Flux peak values : the user inputs current-flux peak values as a sequence of points and selects either piecewise-linear or spline interpolation.

Current/Voltage RMS values : the user inputs current-voltage RMS values as a sequence of points and selects piecewise-linear interpolation, Frolich or Modified Frolich data fitting.

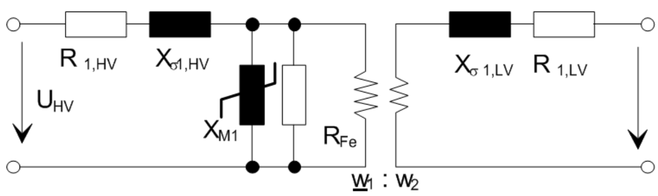


Figure 6.1: Positive sequence equivalent circuit of the 2-winding, 3-phase transformer

The position of the magnetising branch in the equivalent model of Figure 6.1 is defined in terms of the distribution of the leakage reactance and resistance (in the type, on the *EMT Simulation* page). The default value is 0.5, which means that the total leakage impedance of the transformer (short-circuit impedance) is equally distributed between the HV and LV windings. The user can change the position of the magnetising branch in the transformer model by modifying these factors accordingly.

Further, hysteresis modelling is also supported as described in section 6.2.3.

6.2.1.1 Two slope and polynomial characteristic

Figure 6.2 shows the magnetising current-flux plots for the two slope and polynomial characteristics. The input parameters of both plots are the same except for the saturation exponent, which only applies to the polynomial characteristic. The input parameters are listed in Table 6.1.

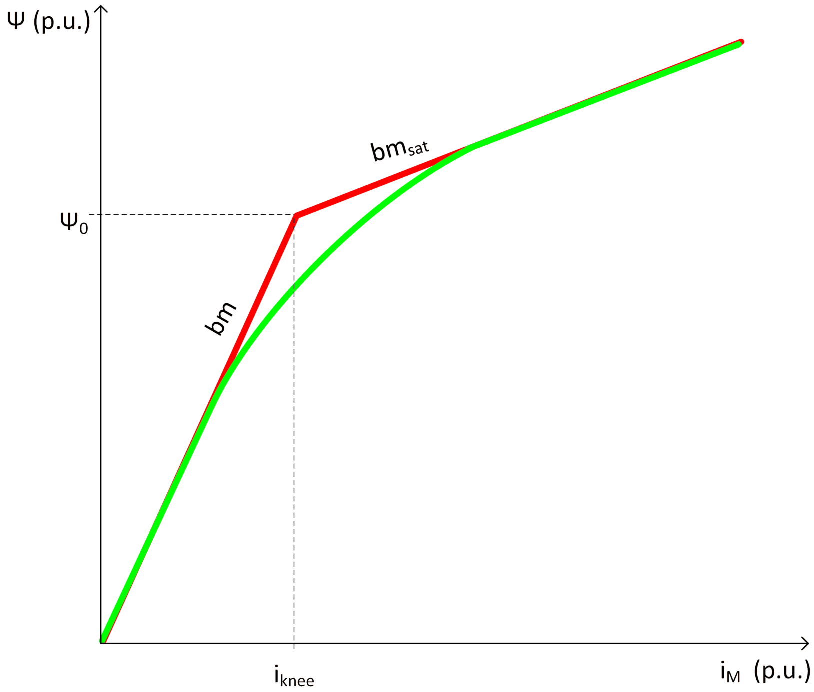


Figure 6.2: Two slope and polynomial saturation curves

Table 6.1: Two-slope and polynomial saturation characteristic input parameters

Parameter	Description	Unit
Knee Flux	Knee-point of asymptotic piecewise-linear characteristic. Typical value around 1.1 to 1.2 times the rated flux.	p.u.
Linear (unsaturated) reactance	Magnetising reactance for unsaturated conditions L_{unsat}. In p.u. values, the linear reactance is equal to the reciprocal of the magnetising current (reactive part of the exciting current).	p.u.
Saturated reactance	Magnetising reactance for saturated conditions L_{sat}.	p.u.
Saturation exponent	Exponent of polynomial representation (k_{sat}). Typical values are 9, 13, 15. The higher the exponent the sharper the saturation curve.	-

The reciprocal of the p.u. unsaturated reactance is equal to the p.u. magnetising current (i.e. the imaginary part of the exciting current). Therefore, *PowerFactory* automatically adjusts the unsaturated reactance based on the no-load current and no-load losses entered on the *Load Flow* page of the type, and vice-versa:

$$\frac{1}{X_M} = \sqrt{\left(\frac{I_M}{I_R}\right)^2 - \left(\frac{P_{exc}}{S_r}\right)^2} \tag{122}$$

where:

I_M : magnitude of the exciting current in the no-load test. This can be entered on the *Load Flow* page of the transformer type, under *Magnetising Impedance*; *No Load Current* (in %);

P_{exc} : excitation losses in the no-load test;

I_r, S_r : rated current and apparent power of the transformer, respectively.

The saturated reactance is also referred as the air-core reactance; it is fairly low compared to the unsaturated reactance. Typical values for two-winding transformers are 1 to 2 times the short-circuit inductance and 3 to 4 times for auto transformers [1].

The polynomial characteristic uses (123) to fit the curve asymptotically into the piecewise-linear definition. The higher the exponent, the sharper the saturation curve:

$$i_{MX} = \frac{\Psi_M}{l_M} \cdot \left(1 + \left|\frac{\Psi_M}{\Psi_0}\right|^{k_{sat}}\right) \qquad \text{(p.u.)} \tag{123}$$

where:

i_{MX} : Current (p.u.) through the magnetising reactance (as shown in Figure 6.3). This is the current (in p.u.) entered by the user in the transformer type; *EMT-Simulation* page, *Saturation* tab, *Saturation Table (EMT)*;

Ψ_M : Magnetising flux (p.u.);

l_M : Linear reactance (p.u.);

Ψ_0 : This parameter is automatically calculated so that the polynomial characteristic fits the saturated reactance in full saturation and transits steadily into the piecewise-linear characteristic at the knee flux point. (p.u.);

k_{sat} : Saturation exponent, i.e. polynomial degree.

This polynomial characteristic always lies underneath the corresponding linear representation. At full saturation the polynomial characteristic is extended linearly. Compared to the two-slope curve, it does not contain a singular point at the knee flux and therefore its derivative (magnetising voltage) is continuously defined.

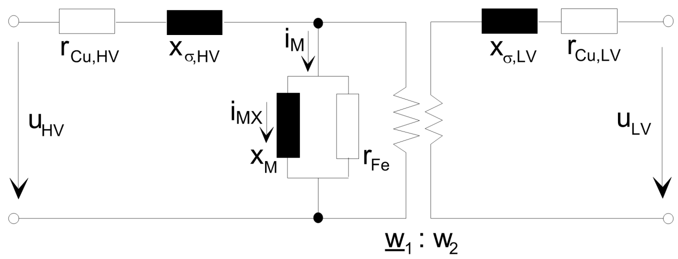


Figure 6.3: Equivalent (per-unit) circuit of the 2-winding, 3-phase transformer (magnetising current)

The per-unit values used for the definition of the saturation characteristic of the positive sequence model are referred to the following reference quantities:

- U_r in kV: rated voltage of the (energising) winding, i.e. the winding used for the no-load test;
- S_r in MVA: rated power of the (energising) winding;

- $I_r = \frac{S_r}{\sqrt{3} \cdot U_r} \cdot 1000$ (A)
- $\Psi_r = \frac{U_r/\sqrt{3}}{2\pi f_{nom}} \cdot 1000$ (Vs)
- $L_r = \left(\frac{U_r^2}{S_r}\right) \cdot \frac{1}{2\pi f_{nom}}$ (H)

$$\Psi_0 = \Psi_{Mknee} \cdot e^{\frac{-\ln\left(\frac{\left(\frac{bm_{sat}}{bm} - 1\right)}{(k_{sat}+1)}\right)}{k_{sat}}} \quad \text{(p.u.)} \tag{124}$$

$$i_{knee} = \frac{bm}{\omega_0} \cdot \Psi_{Mknee} \cdot \left(1 + \left(\frac{\Psi_{Mknee}}{\Psi_0}\right)^{k_{sat}}\right) \quad \text{(p.u.)} \tag{125}$$

For $\Psi(a, b, c) > \Psi_{Mknee}$:

$$i_{MX}(a,b,c) = i_{knee} + \frac{bm_{sat}}{\omega_0} \cdot (\Psi(a,b,c) - \Psi_{Mknee}) \quad \text{(p.u.)} \tag{126}$$

For $\Psi(a, b, c) < -\Psi_{Mknee}$:

$$i_{MX}(a,b,c) = -i_{knee} + \frac{bm_{sat}}{\omega_0} \cdot (\Psi(a,b,c) + \Psi_{Mknee}) \quad \text{(p.u.)} \tag{127}$$

otherwise:

$$i_{MX}(a,b,c) = \frac{bm}{\omega_0} \cdot \Psi(a,b,c) \cdot \left(1 + \left|\left(\frac{\Psi(a,b,c)}{\Psi_0}\right)^{k_{sat}}\right|\right) \quad \text{(p.u.)} \tag{128}$$

and:

$$i_M(a,b,c) = u_M(a,b,c) \cdot gm(a,b,c) + i_{MX}(a,b,c) \quad \text{(p.u.)} \tag{129}$$

where $gm(a,b,c)$ are available as input signals for EMT simulations and are initialised using gm, which is defined as:

$$gm = pfe/1000/strn \quad \text{(p.u.)} \tag{130}$$

and:

$$y_{mag} = \frac{curmg}{100} \quad \text{(p.u.)} \tag{131}$$

$$bm = \sqrt{{y_{mag}}^2 - gm^2} \cdot \omega_0 \quad \text{(p.u.)} \tag{132}$$

or

$$bm = \frac{\omega_0}{xmlin} \quad \text{(p.u.)} \tag{133}$$

$$\omega_0 = 2 \cdot \pi \cdot f_{nom} \quad \text{(rad/s)} \tag{134}$$

$$bm_{sat} = \frac{1}{xm_{air}} \cdot \omega_0 \qquad \text{(p.u.)} \tag{135}$$

$$\Psi_{Mknee} = \frac{k_{sat}+1}{k_{sat}} \cdot \Psi_0 \qquad \text{(p.u.)} \tag{136}$$

and xm_{air} is the saturated (air core) reactance (p.u.), Ψ_0 is the knee flux (p.u.) defined in the type, and k_{sat} is the saturation exponent.

6.2.1.2 Current-flux peak values

The saturation curve can also be defined in terms of measured current-flux values, and a choice of either *piecewise linear* or *spline* interpolation is available.

The current-flux values in the table are peak values in p.u. In a power transformer with impressed voltage, the magnetising flux in p.u. is equal to the magnetising voltage in p.u., thus flux and voltage are interchangeable and the p.u. current-flux curve also represents a p.u. current-voltage curve. Furthermore, it can be assumed that the applied voltage remains fairly linear during no-load tests, hence the ratio of RMS to peak values of the voltage is given by $\sqrt{2}$.

The magnetising current, on the other hand, is distorted (i.e. non-sinusoidal) because of the saturation curve. Consequently, the ratio of RMS to peak value of the magnetising current is no longer $\sqrt{2}$ and the user is required to enter true peak values in the table.

The reference quantities of the p.u. values in the current-flux table are also referred to the peak values of the corresponding nominal variables:

$$I_r = \sqrt{2} \cdot \frac{S_r}{\sqrt{3} \cdot U_r} \cdot 1000 \qquad \text{(A)}$$

$$\Psi_r = \sqrt{2} \cdot \frac{U_r/\sqrt{3}}{2\pi f_{nom}} \cdot 1000 \qquad \text{(Vs)}$$

6.2.1.3 Current-voltage RMS values

The saturation curve can also be defined in terms of measured current-voltage RMS values, often directly available from manufacturer test reports. With this option the user does not have to convert the available RMS current values to peak values, as required in the previous option. The conversion to peak current values is handled internally in *PowerFactory* and a current-voltage peak values table is generated. The user can choose to use a piecewise linear interpolation between the peak value points.

The user can also specify a value for the final slope of the converted current-voltage peak values used in the simulation, by defining the saturated reactance (air core reactance). If the final slope is not defined, this is assumed to be equal to the slope of the last segment of the curve when piecewise-linear interpolation is selected. Since the conversion between RMS and peak current values is non-linear, the slope of the last segment of the curve is generally not known. The final slope defined by the saturated reactance is not considered if higher than the slope of the last segment of the curve.

Alternatively to the piecewise-linear interpolation, a curve can be fitted to the converted flux-current peak value points according to the Frolich or Modified Frolich equation, defining the general relation between flux and current according to equations 137 and 138 respectively:

$$\Psi = \frac{i}{a + b \cdot |i|} \tag{137}$$

$$\Psi = \frac{i}{a + b \cdot |i| + c \cdot \left|\sqrt{i}\right|} \tag{138}$$

Note that the Frolich equation originally defines the relation between the flux density *B* and the magnetizing force *H* for a magnetic material, but parameters *a* and *b* can be scaled to represent the relationship between flux linkage and current, as in 137 and 138.

The Frolich equation implies that as the current increase toward infinite, the flux linkage tends to an asymptotic value. For fluxes above this value, the flux-current relationship is not defined and the Frolich equation cannot be used as it is. Instead, it is strongly recommended to define the saturated reactance. In this case, the Frolich and Modified Frolich equations are adapted as in 139 and 140 respectively:

$$\Psi = \frac{i}{a + b \cdot |i|} + xsat \cdot i \tag{139}$$

$$\Psi = \frac{i}{a + b \cdot |i| + c \cdot \left|\sqrt{i}\right|} + xsat \cdot i \tag{140}$$

where *xsat* is equal to the minimum between the specified saturated reactance parameter *xmair* and the slope of the last segment of the converted flux-current peak value curve.

At least two points of the magnetization curve are needed for fitting the Frolich equation and at least three points are needed for the modified Frolich equation. The modified Frolich equation allows a better fitting to the measured points around the knee flux [4]. Fitting of the Frolich equation is performed automatically, and the equation coefficients and mean square error can be observed in the Flexible data of the Type (c:aFrolich, c:bFrolich, c:cFrolich, c:xsatFrolich, c:mseFrolich).

The current-voltage RMS values are entered in p.u. of transformer nominal voltage and current.

The RMS current-voltage saturation curve is the same curve that can be independently defined also in load flow calculation and RMS simulation, see section 3.3.

6.2.2 Zero sequence magnetising reactance

The zero sequence magnetising current depends largely on the physical characteristics of the transformer core (three-legged, five-legged, shell-type, etc.) and its vector group. Figure 6.4 shows the zero sequence equivalent circuit for a YNyn transformer (grounding impedances are not shown). The magnetizing reactance X_{M0} is always linear if the transformer has a three-limb core. If the transformer has a five-limb core, the magnetizing reactance X_{M0} is considered equal to the positive sequence magnetizing reactance. 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).

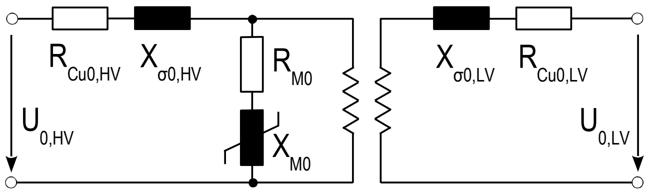


Figure 6.4: Zero sequence equivalent circuit of the 2-winding, 3-phase transformer

6.2.2.1 Transformer with delta-connected windings

If the transformer has delta-connected windings, then any zero sequence excitation approximates a zero sequence short-circuit, as the delta-connected winding short-circuits the zero sequence current. In such cases there is no need to represent zero sequence saturation.

For a Yd-transformer the zero sequence leakage impedance distribution factors are hidden when no saturation is defined. In this case, the zero sequence leakage impedance is attributed all to the Y-side and the magnetizing branch is then short-circuited by the delta winding. Transformer energization in the presence of saturation can give rise to a zero-sequence current, also with a pure positive-sequence magnetizing voltage. In reality part of this zero-sequence current can flow in the grid. To reproduce this behaviour, when modelling saturation it is possible to define the zero sequence leakage impedance distribution factors. When the zero sequence leakage impedance is attributed all to the Y-side, the zero sequence current originating from saturation circulates only in the delta winding. Attributing part of the zero sequence leakage impedance to the d-side will result in part of the zero sequence current flowing into the grid. It is recommended to define these factors so that the zero-sequence magnetizing branch is located at the terminals of the winding closest to the core.

6.2.2.2 Transformer without delta-connected windings

If the transformer does not have delta-connected windings, then the zero sequence excitation current is generally higher than the positive sequence excitation current and largely depends on the core type.

To account for the higher zero sequence linear exciting current when no delta-connected winding is available, *PowerFactory* allows for the definition of a linear (unsaturated) zero sequence magnetising impedance. This zero sequence magnetising impedance and its R/X ratio are defined in the type, on the *Load Flow* page. The input parameters are displayed in the dialog depending on the vector group (and are therefore hidden in cases where a delta-connected winding has been selected).

To account for the core type dependency of the zero sequence saturation characteristic, the transformer model supports the following two options on the *EMT-Simulation* page of the type:

3-Limb core: this option should be used for three-legged core designs. In this core type, the fluxes are roughly equal in the three legs and must therefore return outside the core through the air-gap and the tank. Because of the fact that the air-gap and the tanks are non-magnetic, the zero sequence magnetising current is almost linear and therefore the model uses the linear zero sequence magnetising impedance defined on the *Load Flow* page. In other words, zero sequence saturation effects are not considered.

5-Limb core: this option should be used for five-legged and shell-type cores. As the zero sequence fluxes return inside the core, the model uses the saturation characteristic (of the positive sequence) in the zero sequence magnetising reactance as well.

6.2.3 Hysteresis modelling

Including hysteresis in the transformer model can result in increased accuracy when performing some transient simulation studies, such as inrush current studies taking into account a residual flux in the transformer core or studies on ferroresonance phenomena [7]. In [5] it is mentioned that iron core laminations in modern transformers have much reduced losses compared to older constructions and the hysteresis loops are very narrow. As a result, a simple hysteresis model that can correctly reproduce the associated losses and damping contribution can be sufficient in most simulation studies.

Figure 6.5 shows the hysteresis major loop, minor loop and the saturation curve. The major loop is the limit loop obtained when the flux varies from a very high positive value to a very high negative value. All minor loops are constrained within the major loop. The width of the major loop is a parameter than can be defined in the transformer type, as percent of the nominal transformer current. All loops are traversed in counter-clockwise direction. For sufficiently high flux, the two halves of the major loop (the one valid when flux is increasing and the one valid when flux is decreasing) converge at a confluence point and are practically the same as the saturation curve. The ascending part of a loop is its lower half, valid when the flux is increasing.

PowerFactory supports a history independent hysteresis model. This means that the trajectory of a new minor loop calculated during the simulation when a flux turning point is detected does not depend on the past history, but only on the corresponding half of the major loop and the opposite confluence point. A similar approach has been used in [8].

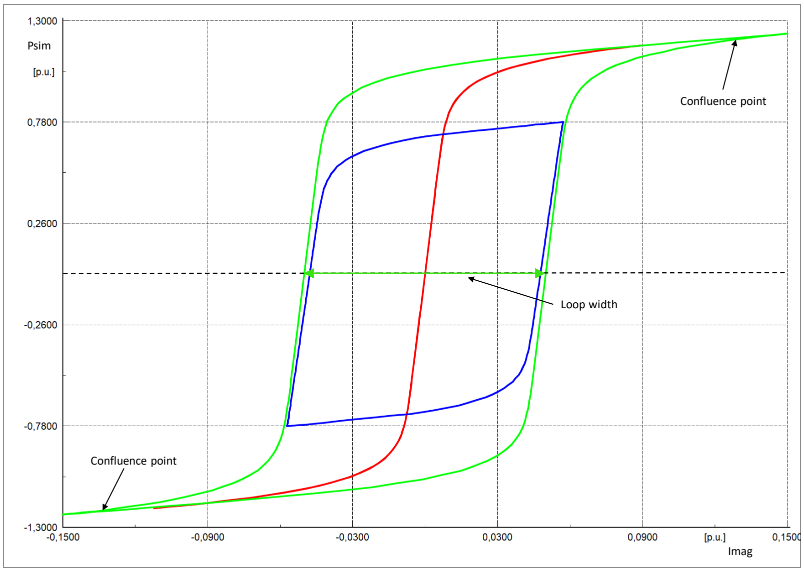


Figure 6.5: Hysteresis major loop (green), minor loop (blue) and saturation curve (red)

6.2.3.1 Generation of major loop

The ascending and descending half of the major loop are defined based on the saturation characteristic and the loop width entered by the user. The ascending curve is obtained by shifting horizontally by half the loop width the saturation curve. The descending curve is obtained by negating the ascending curve and by mirroring it around the flux axis. The curves are also shifted vertically so that they converge at high fluxes. In case of two-slope or polynomial saturation characteristic (*i_sat*=1 or 2) the curves of the major loop are built as a polynomial characteristic, with a default saturation exponent equal to 30 when *i_sat*=1 or with the user defined saturation exponent when *i_sat*=2.

6.2.3.2 Generation of minor loops

A minor loop trajectory (ascending or descending) is always generated when a flux turning point is detected and it will be followed in the simulation until the next flux turning point is detected. The minor loop trajectory is defined based on a few simple rules (given here for the ascending trajectory calculated when the flux starts increasing):

- The difference $Dmax$ between the actual flux value at the turning point and the flux value (for the actual current) on the ascending curve is calculated
- The difference $Dmin$ between the upper confluence point flux value and the flux value on the ascending curve at the confluence point current is calculated. This difference $Dmin$ is very small and close to zero
- The new ascending trajectory is generated (and saved in memory) by the adding to the ascending major loop curve a linear contribution which decreases from $Dmax$ to $Dmin$ as the flux increases from the actual turning point value to the value at the upper confluence point

The ascending trajectory is described by the following equations:

$$\psi_{min,asc}(i) = \psi_{maj,asc}(i) + f(\psi_{min,asc}(i)) \tag{141}$$

$$f(\psi_{min,asc}(i)) = a \cdot \psi_{min,asc}(i) + b \tag{142}$$

$$a = \frac{Dmin - Dmax}{\psi_{ucp} - \psi_{ltp}} \tag{143}$$

$$b = Dmax - \frac{Dmin - Dmax}{\psi_{ucp} - \psi_{ltp}} \cdot \psi_{ltp} \tag{144}$$

where

- ψ is the flux
- i is the current
- $\psi_{maj,asc}(i)$ is the ascending half of the major loop
- $\psi_{min,asc}(i)$ is the ascending half of the new minor loop
- ψ_{ucp} is the flux value at the upper confluence point
- ψ_{ltp} is the flux value at the last turning point (actual value of the flux when the curve is generated)

The ascending minor loop trajectory equation can be rearranged as

$$\psi_{min,asc}(i) = \frac{\psi_{maj,asc}(i) + b}{1 - a} \tag{145}$$

It may happen that the generated trajectory is beyond the major loops (above the descending curve or below the ascending curve). To avoid this, a check is performed and the actual trajectory is constrained to be within the major loop. A minor loop trajectory is generated as a piecewise linear curve with the smoothing factor entered by the used in the type saturation page.

6.2.3.3 Hysteresis losses

The area of a minor loop is associated with iron core losses. These losses are automatically considered in the EMT simulation.

No load losses are also specified in the load flow or simulation pages of the transformer type. These are compared with the iron core losses associated with the hysteresis loop calculated given the area of the minor loop corresponding to nominal voltage and frequency at the transformer terminals and at no-load. If these losses associated with the hysteresis loop are greater than the no load losses specified in the transformer type, then a warning message is printed in the output window and only the losses associated with the hysteresis loop are considered in the simulation. Otherwise a resistor in parallel with the magnetizing reactance is also considered, representing the difference between the specified no load losses and the losses associated with the hysteresis minor loop at nominal conditions. In this last case, the total iron core losses with nominal voltage, frequency and at no-load will be equal to the specified no load losses.

6.3 Residual flux

The residual flux is the magnetising flux that remains in the core after the transformer has been switched off.[1]

Without modelling hysteresis a residual flux implies the circulation of a magnetising current (Ψ_M = $L_M \cdot I_M$). Once the transformer has been switched off, this magnetising current circulates through the no-load losses resistance, R_m, and de-magnetises the core. The flux then decays exponentially with a time constant, L_m/R_m, where L_m is the linear magnetising inductance. To simulate the decaying magnetising current, and hence the decaying residual flux, it is necessary to define the no-load losses.

When modelling hysteresis a residual flux can exist in the core without the circulation of a magnetising current. Iron core losses associated with the hysteresis loop are automatically considered in EMT simulations.

The user has two options to define the residual flux in the EMT simulation:

- via a parameter event. The residual flux is entered in $\alpha\beta\gamma$-components using the following signals:

  psimd: residual flux (ψ_α), α-component in p.u.

  psimq: residual flux (ψ_β), β-component in p.u.

  psim0: residual flux (ψ_γ), γ-component in p.u.

- on the element EMT Advanced page whenever saturation has been modelled in the type. The residual flux is entered in abc-components and it is considered only when the transformer is initially non-supplied. If hysteresis is not modelled, the residual fluxes are considered from the instant of first energization only. If hysteresis is modelled the residual fluxes are considered from the start of simulation and a check is performed that they are

[1] The remnant flux is the flux at i=0 in the hysteresis major loop curve

within the major hysteresis loop (if not, they are scaled and forced to be within the major hysteresis loop).

The $\alpha\beta\gamma$-fluxes are transformed to abc-fluxes (phase or natural components) as follows:

$$\begin{bmatrix}\psi_\alpha\\ \psi_\beta\\ \psi_\gamma\end{bmatrix}=\begin{bmatrix}\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3}\\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}}\\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3}\end{bmatrix}\times\begin{bmatrix}\psi_a\\ \psi_b\\ \psi_c\end{bmatrix}$$

The inverse transformation is given by:

$$\begin{bmatrix}\psi_a\\ \psi_b\\ \psi_c\end{bmatrix}=\begin{bmatrix}1 & 0 & 1\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1\end{bmatrix}\times\begin{bmatrix}\psi_\alpha\\ \psi_\beta\\ \psi_\gamma\end{bmatrix}$$

The calculation parameters *c:psim_a, c:psim_b and c:psim_c* give the resulting flux (as a result of the simulation) in natural components for the phases a, b and c, respectively.

Generally speaking, it is difficult to reliably predict the residual flux of a transformer. However, as the residual flux strongly influences the amplitude of inrush currents, it should be considered in the model. If it is not known, typical maximum values between 0.8 and 0.9 p.u. can be assumed for worst-case conditions.

The magnetising voltage is related to the flux as follows:

$$\begin{bmatrix}u_{ma}\\ u_{mb}\\ u_{mc}\end{bmatrix}=\begin{bmatrix}1 & 0 & 1\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1\end{bmatrix}\times\frac{1}{2\cdot\pi\cdot f_{nom}}\cdot\begin{bmatrix}\frac{d\psi_\alpha}{dt}\\ \frac{d\psi_\beta}{dt}\\ \frac{d\psi_\gamma}{dt}\end{bmatrix}$$

where f_{nom} is the nominal frequency.

If the HV side is connected in delta, the flux, voltages and currents are calculated as follows:

$$
\begin{aligned}
\psi_{a'} &= \frac{(\psi_a - \psi_b)}{\sqrt{3}} \qquad \text{(p.u.)} \\
\psi_{b'} &= \frac{(\psi_b - \psi_c)}{\sqrt{3}} \qquad \text{(p.u.)} \\
\psi_{c'} &= \frac{(\psi_c - \psi_a)}{\sqrt{3}} \qquad \text{(p.u.)} \\
u_{ma'} &= \frac{(u_{ma} - u_{mb})}{\sqrt{3}} \qquad \text{(p.u.)} \\
u_{mb'} &= \frac{(u_{mb} - u_{mc})}{\sqrt{3}} \qquad \text{(p.u.)} \\
u_{mc'} &= \frac{(u_{mc} - u_{ma})}{\sqrt{3}} \qquad \text{(p.u.)} \\
i_{ma'} &= \frac{(i_{ma} - i_{mc})}{\sqrt{3}} \qquad \text{(p.u.)} \\
i_{mb'} &= \frac{(i_{mb} - i_{ma})}{\sqrt{3}} \qquad \text{(p.u.)} \\
i_{mc'} &= \frac{(i_{mc} - i_{mb})}{\sqrt{3}} \qquad \text{(p.u.)} \\
i_{m0} &= \frac{i_{ma} + i_{mb} + i_{mc}}{\frac{\sqrt{3}}{3}} + \frac{b_{m0}}{2 \cdot \pi \cdot f_{nom}} \cdot psim0 \qquad \text{(p.u.)}
\end{aligned}
$$

Otherwise, the currents are calculated according to:

$$
\begin{aligned}
i_{ma'} &= i_{ma} \qquad \text{(p.u.)} \\
i_{mb'} &= i_{mb} \qquad \text{(p.u.)} \\
i_{mc'} &= i_{mc} \qquad \text{(p.u.)} \\
i_{m0} &= \frac{i_{ma} + i_{mb} + i_{mc}}{3} + \frac{b_{m0}}{2 \cdot \pi \cdot f_{nom}} \cdot psim0 \qquad \text{(p.u.)}
\end{aligned}
$$

where $b_{m0} = 0$ for 5-limb transformers.

Note: the variable $psim0$ is not considered when calculating the saturation effect for 3-limb transformers. Instead, only the $\alpha\beta\gamma$-component parameters are used. However, for the calculation of the variables ψ_a, ψ_b and ψ_c, $psim0$ is considered for both 3- and 5-limb models.

7 Harmonics/Power Quality

In order to accurately model the high frequency effects of transformers, additional capacitances need to be considered, as shown in Figure 7.1. These capacitances are equivalent capacitances of the model and do not represent the actual winding capacitances. In order to obtain equivalent capacitances from winding capacitances, the winding connection (D/Y) must be additionally considered. The high frequency model according to Figure 7.1 provides an accurate frequency response with respect to voltages and currents at the transformer terminals. However, internal effects such as internal voltage stress cannot be simulated.

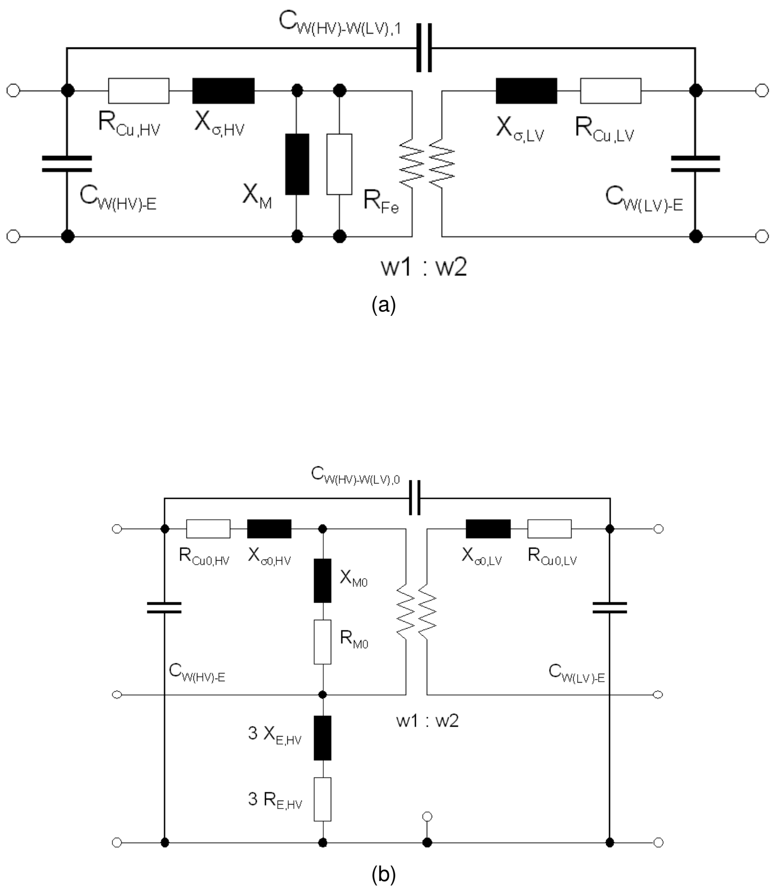


Figure 7.1: HF model for (a) external capacitances in the positive sequence system; and (b) zero sequence system

7.1 K-Factor, Factor-K and FHL

Transformers experience increased losses in the presence of power system harmonic currents. In the worst-case, excessive losses can lead to transformer overheating and subsequent failure. To assist in the selection of an appropriate transformer, various factors are available:

- K-factor (UL 1562); mainly used in the US
- Factor-K (BS 7821); mainly used in Europe
- Harmonic Loss Factor (FHL) (IEEE C.57.110-1998)

These factors are indicators of the ability of a transformer to handle harmonic loads. Non-linear loads in the power system produce harmonic currents which are capable of causing unwanted side-effects, including increased transformer losses. Transformer losses are comprised of:

- Stray magnetic losses in the transformer core; and
- Eddy current and ohmic losses in the transformer windings.

In the presence of harmonic currents, eddy current losses can become large because they increase with the square of the frequency. The winding eddy current losses (due to the skin effect) at harmonic order h are given by:

$$Pe\_h = Pe\_f1 \cdot {I_h}^2 \cdot h^2 \tag{146}$$

where Pe_f1 represents the rated eddy current losses (based solely on data from the transformer type (*TypTr2*)); Pe_h is the eddy current loss at harmonic order h; and I_h is the fraction of total rms load current at harmonic order h. The calculation variable *Po_f1* represents the rated ohmic losses (also based solely on data from the transformer type (*TypTr2*)).

In terms of *PowerFactory* transformer type (*TypTr2*) data, the rated eddy current losses, *Pe_f1*, are calculated in [kW] as follows:

$$Pe\_f1 = (zshv{:}r + zslv{:}r) \cdot strn \cdot 1000 \cdot eddypc \tag{147}$$

The total eddy current loss, Pe_tot, is given by the following summation:

$$Pe\_tot = Pe\_f1 \cdot \sum_{h=1}^{h_{max}} {I_h}^2 \cdot h^2 \tag{148}$$

7.1.1 K-Factor

The K-Factor accounts for the increased eddy current losses due to harmonic currents. Mathematically, it is the ratio of eddy current losses in the presence of non-linear and linear loads [3]:

$$K = \frac{Pe\_tot}{Pe\_f1} = \sum_{h=1}^{h_{max}} {I_h}^2 \cdot h^2 \tag{149}$$

Following the calculation of the K-Factor, an appropriate K-transformer can then be selected which has a higher K-rating.

7.1.2 Factor-K

The factor-K was introduced in [2] and is described mathematically by:

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^2 \cdot \sum_{h=2}^{h_{max}} \left(h^q \left(\frac{I_h}{I_1}\right)^2\right)\right]^{0.5} \tag{150}$$

where e is the eddy current loss at the fundamental frequency divided by the loss due to a dc current equal to the rms values of the sinusoidal current, both at reference temperature. The harmonic order is represented by h, and the exponential constant, q, depends on the type of winding and the frequency. Typical values are 1.7 for transformers utilising round/rectangular cross-section conductors in both windings, and 1.5 for transformers which use foil-type low voltage windings. This value should be available from the transformer manufacturer. I is the rms value of the sinusoidal current including all harmonics, and is given by:

$$I = \left(\sum_{h=1}^{h_{max}} (I_h)^2\right)^{0.5} = I_1 \left[\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2\right]^{0.5} \tag{151}$$

7.1.3 FHL

The FHL is described mathematically by [3]:

$$FHL = \frac{\sum_{h=1}^{h_{max}} \left[\frac{I_h}{I_1}\right]^2 \cdot h^2}{\sum_{h=1}^{h_{max}} \left[\frac{I_h}{I_1}\right]^2} \tag{152}$$

7.1.4 Input data

For the calculation of any of these factors, the ratio of winding eddy current losses to copper losses should be entered in the transformer type (*Harmonics/Power Quality* page) using input parameter *Ratio: winding eddy current-/copper losses*. By default, this value is set to 0.1 (i.e. 10%).

Additionally, for the calculation of Factor-K, the exponent q (from (150)) must be entered in the *Harmonic Load Flow* command (*ComHldf*) via input parameter *Calculation of Factor-K for Transformers (Exponent)*.

7.2 Frequency-dependent impedances

On the *Harmonics* page of the transformer type, a frequency-dependent positive and zero sequence (short-circuit) impedance 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) impedance 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.

The distribution factor for the positive sequence resistance and reactance will be kept constant and is obtained as follows:

- From the transformer type, *Distribution of Leakage Reactances* (itrdl) for the reactance;
- From the transformer type, *Distribution of Leakage Resistances* (itrdr) for the resistance.

The distribution factor for the zero sequence impedance will be kept constant and is obtained as follows:

- From the transformer type, *Distribution of Zero Sequ. Leakage-Impedances* (zx0hl_h) for a transformer with no *Internal Delta Winding*;
- For a transformer with an *Internal Delta Winding*, the distribution factors are calculated as in Section 1.2.

8 Modelling Details and Application Tips

8.1 Reference values

All transformer parameters entered in p.u. or % are referred to the transformer ratings. Transformer rated voltages different from nominal busbar voltages are correctly considered.

8.2 Zero sequence models for common vector groups

8.2.1 Yd-transformer

This model is described in detail in Section 1.1.2 as a general example for zero sequence system modelling.

If no accurate data is available from the manufacturer, the following estimations can be used for the zero sequence impedance voltages as seen from the grounded side:

Core-type transformer (3-limb) : $u_{sc,0} = 0.85 \cdot U_{sc,1}; \qquad u_{Rr,0} = 0$

Shell-type transformer (4/5-limb) : $u_{sc,0} = 1.0 \cdot U_{sc,1}; \qquad u_{Rr,0} = 0$

where $u_{sc,0}$ is the positive sequence impedance voltage.

It should be taken into account that when modelling magnetic flux saturation characteristics, transformer types with 3 or 4/5 limbs behave differently. In the 3-limb design, the zero sequence flux defined by (153) is not guided via the transformer limbs but uses parallel paths (e.g. through the transformer vessel, oil, ...) and can therefore be modelled linearly without saturation effects.

$$\Psi_0 = \frac{1}{3} \cdot (\Psi_A + \Psi_B + \Psi_C) \tag{153}$$

8.2.2 YNyn/YNy/Yyn-transformer

The zero sequence equivalent circuit diagram of the YNyn transformers is depicted in Figure 8.1. The equivalent circuit diagram of star connected transformers with isolated star point can be derived from this equivalent circuit by assuming infinite grounding impedances at the respective side.

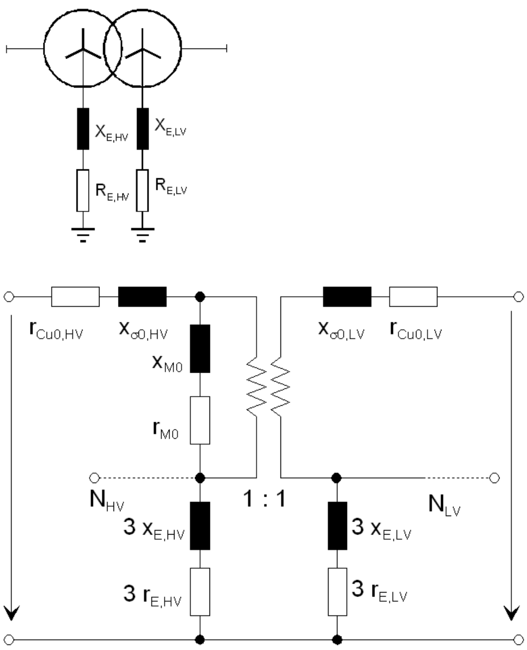


Figure 8.1: YNyn-transformer (zero sequence system)

Short-circuit impedance, HV-side $z_{sc,0,HV} = r_{Cu,0,HV} + x_{\sigma,0,HV}$

Short-circuit impedance, LV-side $z_{sc,0,LV} = r_{Cu,0,LV} + x_{\sigma,0,LV}$

Short-circuit impedance, both sides $z_{sc,0} = z_{sc,0,HV} + z_{sc,0,LV}$

The zero sequence magnetising impedance ratio heavily depends on the construction of the magnetic circuit of the transformer. Typical ranges are:

Core-type transformer (3-limb) : $\frac{z_{M0}}{z_{sc,0}} = 3 \dots 10$

Shell-type transformer (4/5-limb) : $\frac{z_{M0}}{z_{sc,0}} = 10 \dots 100$ (or bank of 3 single-phase units)

8.2.3 Model of YNyn/YNy/Yyn-transformer with closed tertiary delta winding

This transformer configuration can be modelled as described in section 1.2. An internal tertiary delta winding can also be considered by either using the *PowerFactory* three-winding model or, in a simplified way, by taking into account that the short-circuit impedance of the internal delta winding can be modelled by using a special case of the YNyn/YNy/Yyn transformer equivalent circuit shown in Figure 8.1. For this exception, an additional impedance representing the internal delta winding zero sequence short-circuit impedance is modelled parallel to the zero sequence magnetising impedance shown. Since the zero sequence short-circuit impedance of the delta winding is usually smaller than the zero sequence magnetising reactance, this last one can be neglected. Hence, if the option *Internal Delta Winding* is not used, an internal delta winding can be modelled by simply entering its zero sequence short-circuit impedance value in the field for the zero sequence magnetising impedance.

Typical values to be entered for the ratio between zero sequence magnetizing and short-circuit reactance are:

$$\frac{z_{M0}}{z_{sc,0}} = 1, \ldots, 2.4$$

The short-circuit resistance of the delta-tertiary winding can be entered as R/X ratio in the *Mag. R/X* field available on the *Load Flow* page of the transformer type.

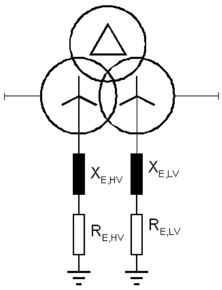


Figure 8.2: YNYnd-transformer

8.2.4 Model of YNzn/YNz/Zyn-transformer

A zig-zag winding completely decouples the primary and secondary sides of the zero sequence system, as shown in Figure 8.3.

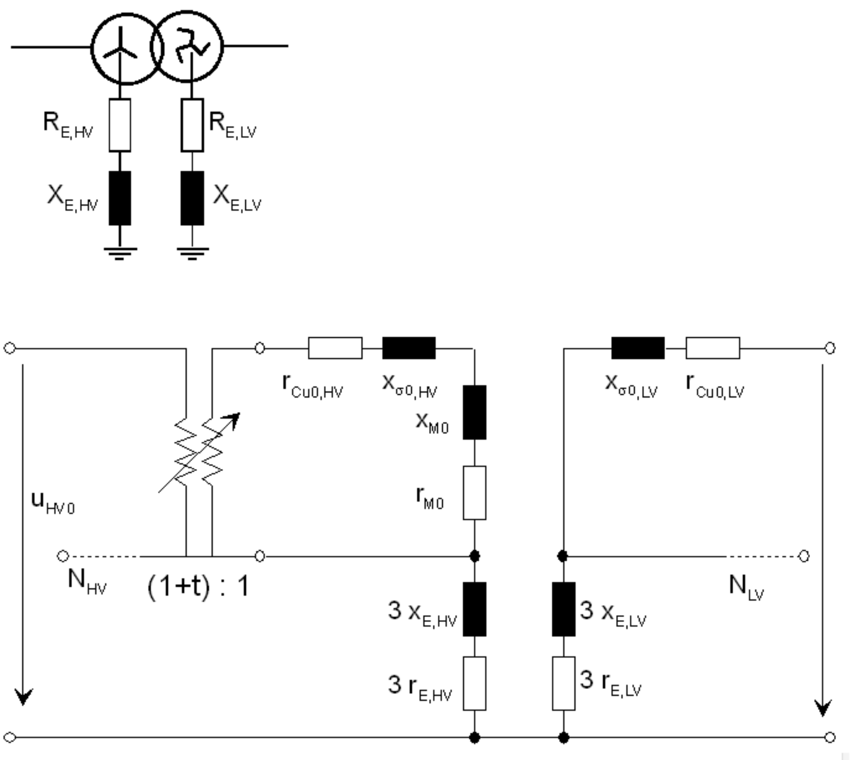


Figure 8.3: YNzn-transformer (zero sequence system) with HV side tap changer (detailed representation)

8.3 Auto transformer model

The *PowerFactory* model for the auto transformer is a special case of the 2-winding star/star (Yy)-transformer. The option *Auto Transformer* can be ticked on the *Basic Data* page of the element, however this option is only visible when the transformer has no assigned type, or when the assigned type has its vector group set to *YY*.

The effect of this connection can be seen in Figure 8.4. Besides the additional connection between the star points, only one grounding impedance can be entered.

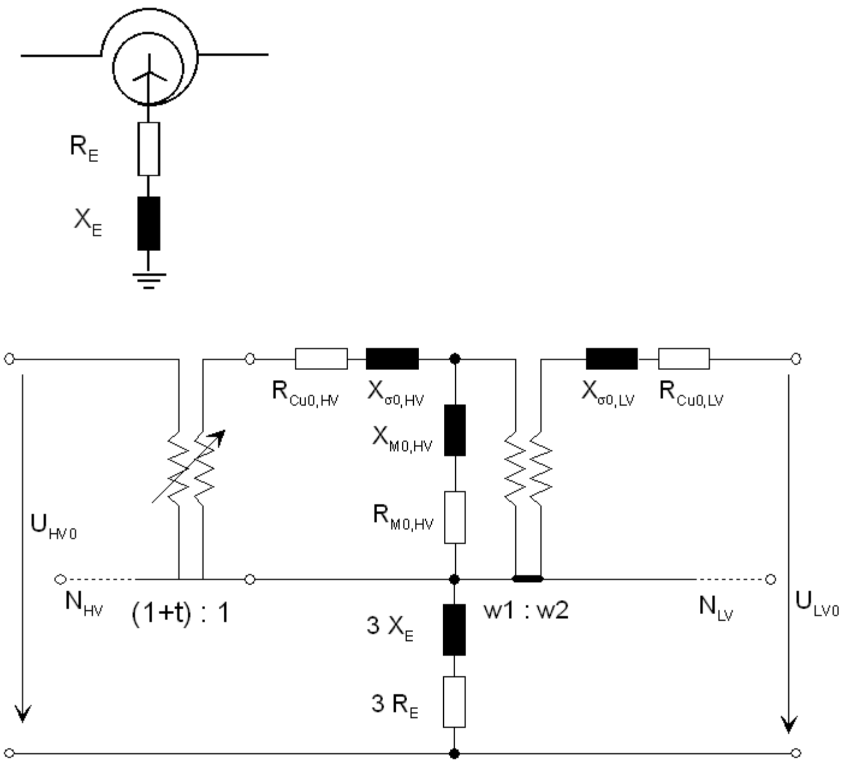


Figure 8.4: Yy-transformer (zero sequence system) in auto transformer configuration (incl. tap changer on the HV side)

For the Yy auto transformer the currents on the HV side and the LV side both flow through the same grounding impedance $Z_E = R_E + \mathrm{j}X_E$. The voltage over this grounding impedance, Z_E, therefore affects the zero sequence system voltages on both sides. This makes it necessary to consider the absolute values of the impedances, currents and voltages and not the p.u. values.

An additional delta tertiary winding is often used to reduce the zero sequence impedance of auto transformers. The approach for modelling this is equivalent to the internal delta tertiary winding modelling of Yy transformers.

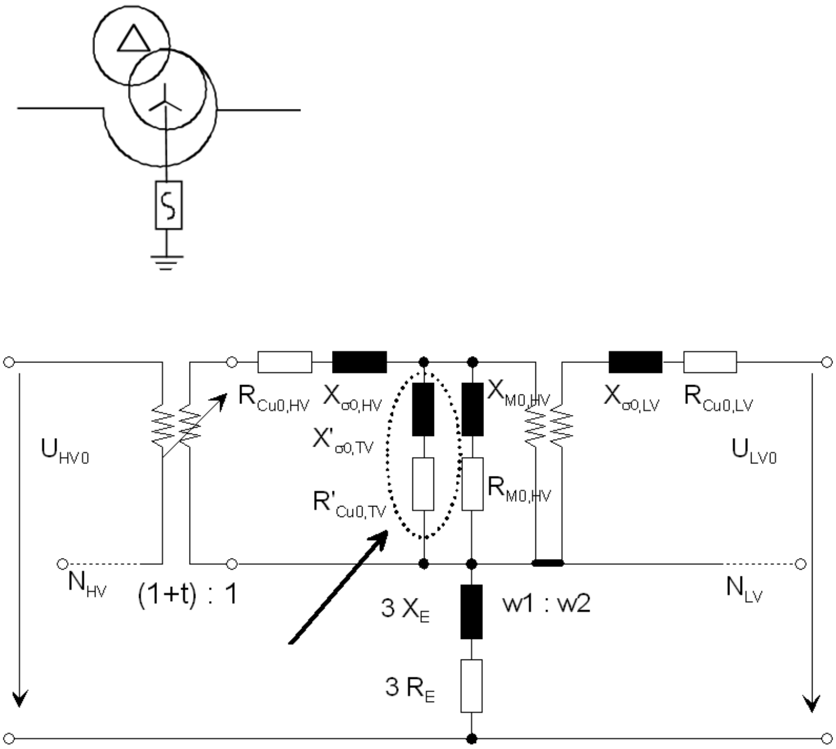


Figure 8.5: YYd-transformer (zero sequence system) in auto transformer configuration

9 Input/Output Definitions of Dynamic Models

Figure 9.1: Input/output definition of 2-winding transformer model for RMS- and EMT-simulation

Table 9.1: Input variables of RMS and EMT transformer model

Parameter	**Description**	**Unit**
nntapin	Tap position (input)	-

Table 9.2: State variables of transformer model for EMT-simulation

Parameter	**Description**	**Unit**
psimd	Magnetising flux, d-component	p.u.
psimq	Magnetising flux, q-component	p.u.
psim0	Magnetising flux, 0-component	p.u.

Table 9.3: Additional parameters and signals for EMT transformer model (calculation parameters)

Parameter	**Description**	**Unit**
psim_a	Magnetising flux, phase A	p.u.
psim_b	Magnetising flux, phase B	p.u.
psim_c	Magnetising flux, phase C	p.u.
im_a	Magnetising current, phase A	p.u.
im_b	Magnetising current, phase B	p.u.
im_c	Magnetising current, phase C	p.u.

10 Input Parameter Definitions

10.1 2-winding transformer type

Parameter	Description	Unit
loc_name	Name	
nt2ph	Technology	
strn	Rated Power	MVA
frnom	Nominal Frequency	Hz
utrn_h	Rated Voltage: HV-Side	kV
utrn_l	Rated Voltage: LV-Side	kV
uktr	Positive Sequence Impedance: Short-Circuit Voltage uk	%
pcutr	Positive Sequence Impedance: Copper Losses	kW
uktrr	Positive Sequence Impedance: SHC-Voltage (Re(uk)) ukr	%
xtor	Positive Sequence Impedance: Ratio X/R	
tr2cn_h	Vector Group: HV-Side	
tr2cn_l	Vector Group: LV-Side	
iIntDelta	Vector Group: Internal Delta Winding	
nt2ag	Vector Group: Phase Shift	*30deg
vecgrp	Vector Group: Name	
uk0tr	Zero Sequ. Impedance, Short-Circuit Voltage: Absolute uk0	%
ur0tr	Zero Sequ. Impedance, Short-Circuit Voltage: Resistive Part ukr0	%
tap_side	Tap Changer: at Side	
dutap	Tap Changer: Additional Voltage per Tap	%
phitr	Tap Changer: Phase of du	deg
nntap0	Tap Changer: Neutral Position	
ntpmn	Tap Changer: Minimum Position	
ntpmx	Tap Changer: Maximum Position	
curmg	Magnetising Impedance: No Load Current	%
pfe	Magnetising Impedance: No Load Losses	kW
zx0hl_n	Zero Sequence Magnetising Impedance: Mag. Impedance / uk0	
rtox0_n	Zero Sequence Magnetising R/X ratio: Mag. R/X	
zx0hl_h	Distribution of Zero Sequ. Leakage-Impedances: z, Zero Sequ. HV-Side	
zx0hl_l	Distribution of Zero Sequ. Leakage-Impedances: z, Zero Sequ. LV-Side	
x0tor0	Zero Sequence Impedance: Ratio X0/R0	
x0pu	Zero Sequence Impedance: Reactance x0	p.u.
r0pu	Zero Sequence Impedance: Resistance r0	p.u.
uk0_hls	Zero Sequence Impedance: HV-SHC-Voltage uk0 (LV short-circuit)	%
ur0_hls	Zero Sequence Impedance: HV-SHC-Voltage Re(uk0) (LV short-circuit)	%

Parameter	Description	Unit
uk0_hlo	Zero Sequence Impedance: HV-SHC-Voltage uk0 (LV open)	%
ur0_hlo	Zero Sequence Impedance: HV-SHC-Voltage Re(uk0) (LV open)	%
uk0_lho	Zero Sequence Impedance: LV-SHC-Voltage uk0 (HV open)	%
ur0_lho	Zero Sequence Impedance: LV-SHC-Voltage Re(uk0) (HV open)	%
x0pu_hls	Zero Sequence Impedance: HV-Reactance x0 (LV short-circuit)	p.u.
xtr0_hls	Zero Sequence Impedance: HV-Ratio X0/R0 (LV short-circuit)	
r0pu_hls	Zero Sequence Impedance: HV-Resistance r0 (LV short-circuit)	p.u.
x0pu_hlo	Zero Sequence Impedance: HV-Reactance x0 (LV open)	p.u.
xtr0_hlo	Zero Sequence Impedance: HV-Ratio X0/R0 (LV open)	
r0pu_hlo	Zero Sequence Impedance: HV-Resistance r0 (LV open)	p.u.
x0pu_lho	Zero Sequence Impedance: LV-Reactance x0 (HV open)	p.u.
xtr0_lho	Zero Sequence Impedance: LV-Ratio X0/R0 (HV open)	
r0pu_lho	Zero Sequence Impedance: LV-Resistance r0 (HV open)	p.u.
uk0delta	Delta Winding, uk0	%
ur0delta	Delta Winding, Re(uk0)	%
x0tor0delta	Delta Winding, X0/R0	
x0delta	Delta Winding, x0	p.u.
r0delta	Delta Winding, r0	p.u.
itapch	Tap Changer 1	
tapchtype	Tap Changer 1: Type	
tap_side	Tap Changer 1: at Side	
dutap	Tap Changer 1: Additional Voltage per Tap	%
dphitap	Tap Changer 1: Additional Angle per Tap	deg
itapch2	Tap Changer 2	
tapchtype2	Tap Changer 2: Type	
tap_side2	Tap Changer 2: at Side	
dutap2	Tap Changer 2: Additional Voltage per Tap	%
dphitap2	Tap Changer 2: Additional Angle per Tap	deg
phitr2	Tap Changer 2: Phase of du	deg
nntap02	Tap Changer 2: Neutral Position	
ntpmn2	Tap Changer 2: Minimum Position	
ntpmx2	Tap Changer 2: Maximum Position	
itapzdep	Tap dependent impedance	
uktr	Positive Sequence Impedance: Short-Circuit Voltage uk	%
x1pu	Positive Sequence Impedance: Reactance x1	p.u.
x1putmn	Tap dependent impedance: x1 (min. tap)	p.u.
x1putmx	Tap dependent impedance: x1 (max. tap)	p.u.
pcutr	Positive Sequence Impedance: Copper Losses	kW
uktrr	Positive Sequence Impedance: SHC-Voltage (Re(uk)) ukr	%
xtor	Positive Sequence Impedance: Ratio X/R	

Parameter	Description	Unit
r1pu	Positive Sequence Impedance: Resistance r1	p.u.
r1putmn	Tap dependent impedance: r1 (min. tap)	p.u.
r1putmx	Tap dependent impedance: r1 (max. tap)	p.u.
uk0tr	Zero Sequence Impedance: Short-Circuit Voltage uk0	%
x0pu	Zero Sequence Impedance: Reactance x0	p.u.
x0putmn	Tap dependent impedance: x0 (min. tap)	p.u.
x0putmx	Tap dependent impedance: x0 (max. tap)	p.u.
ur0tr	Zero Sequence Impedance: SHC-Voltage (Re(uk0)) uk0r	%
x0tor0	Zero Sequence Impedance: Ratio X0/R0	
r0pu	Zero Sequence Impedance: Resistance r0	p.u.
x0tor0tmn	Tap dependent impedance: X0/R0 (min. tap)	
r0putmn	Tap dependent impedance: r0 (min. tap)	p.u.
x0tor0tmx	Tap dependent impedance: X0/R0 (max. tap)	
r0putmx	Tap dependent impedance: r0 (max. tap)	p.u.
itapzdep	Tap dependent impedance	
uktmn	Tap dependent impedance: uk (min. tap)	%
uktmx	Tap dependent impedance: uk (max. tap)	%
pcutmn	Tap dependent impedance: Pcu (min. tap)	kW
ukrtmn	Tap dependent impedance: Re(uk) (min. tap)	%
xtortmn	Tap dependent impedance: X/R (min. tap)	
pcutmx	Tap dependent impedance: Pcu (max. tap)	kW
ukrtmx	Tap dependent impedance: Re(uk) (max. tap)	%
xtortmx	Tap dependent impedance: X/R (max. tap)	
uk0tmn	Tap dependent impedance: uk0 (min. tap)	%
uk0tmx	Tap dependent impedance: uk0 (max. tap)	%
uk0rtmn	Tap dependent impedance: Re(uk0) (min. tap)	%
uk0rtmx	Tap dependent impedance: Re(uk0) (max. tap)	%
itrdl	Distribution of Leakage Reactances (p.u.): x,Pos.Seq. HV-Side	
itrdl_lv	Distribution of Leakage Reactances (p.u.): x,Pos.Seq. LV-Side	
itrdr	Distribution of Leakage Resistances (p.u.): r,Pos.Seq. HV-Side	
itrdr_lv	Distribution of Leakage Resistances (p.u.): r,Pos.Seq. LV-Side	
itrldf	Magnetising Reactance: Type	
satcue	Magnetising Reactance: Current	%
satvol	Magnetising Reactance: Voltage	p.u.
satflux	Magnetising Reactance: Flux (peak)	p.u.
iInterPol	Magnetising Reactance: Interpolation	
smoothfac	Magnetising Reactance: Smoothing Factor	%
iLimb	Magnetising Reactance: Core	
iHyster	Hysteresis model	
Lwidth	Hysteresis: Loop width	%

Parameter	Description	Unit
itratioadpt	Transformer Ratio Adaptation	
pT	Tap Changer: Voltage Range	%
ansiclass	Class	
pict1	Inrush Peak Current: Ratio Ip/In (1)	p.u.
pitt1	Inrush Peak Current: Max. Time (1)	s
itrtype	Transformer Type	
pict2	Inrush Peak Current: Ratio Ip/In	p.u.
pitt2	Inrush Peak Current: Max. Time	s
itrmt	Magnetising Reactance: Type	
psi0	Magnetising Reactance: Knee Flux	p.u.
xmlin	Magnetising Reactance: Linear Reactance	p.u.
xmair	Magnetising Reactance: Saturated Reactance	p.u.
ksat	Saturation Exponent	
it0mt	Zero Sequence Magnetising Reactance: Type Zero Sequence	
pStoch	Stochastic model	StoTyptrf
eddypc	Ratio: eddy current-/copper losses	
fcharr1	Frequency Dependencies of Pos.-Sequence Impedance: r1(f)	
fcharl1	Frequency Dependencies of Pos.-Sequence Impedance: l1(f)	
fcharr0	Frequency Dependencies of Zero-Sequence Impedance: r0(f)	
fcharl0	Frequency Dependencies of Zero-Sequence Impedance: l0(f)	
strnfc	Rated Power (forced cooling)	MVA
oltc	On-load Tap Changer	
gnrl_modif	Object modified	
gnrl_modby	Object modified by	
manuf	Manufacturer	
chr_name	Characteristic Name	
dat_src	Data source	
for_name	Foreign Key	
doc_id	Additional Data ()	
desc	Description	
appr_status	Approval Information: Status	
appr_modif	Approval Information: Modified	
appr_modby	Approval Information: Modified by	

10.2 2-winding transformer element

Parameter	Description	Unit
loc_name	Name	
typ_id	Type (*TypTr2*)	
bushv	HV-Side (StaCubic)	

Parameter	Description	Unit
bushv_bar	HV-Side	
buslv	LV-Side (StaCubic)	
buslv_bar	LV-Side	
iZoneBus	Zone	
outserv	Out of Service	
ntnum	Number of: parallel Transformers	
ratfac	Rating Factor	
Snom	Nominal Power	MVA
i_auto	Connected Star Points (Auto Transformer)	
i_eahv	HV-side, phase 2 internally grounded	
ignd_h	Grounding Impedance, HV Side: Neutral Point	
re0tr_h	Grounding Impedance, HV Side: Re	Ohm
xe0tr_h	Grounding Impedance, HV Side: Xe	Ohm
i_ealv	LV-side, phase 2 internally grounded	
ignd_l	Grounding Impedance, LV Side: Neutral Point	
re0tr_l	Grounding Impedance, LV Side: Re	Ohm
xe0tr_l	Grounding Impedance, LV Side: Xe	Ohm
rSbasepu	r (Sbase)	p.u./Sbase
xSbasepu	x (Sbase)	p.u./Sbase
r0Sbasepu	r0 (Sbase)	p.u./Sbase
x0Sbasepu	x0 (Sbase)	p.u./Sbase
cpZone	Zone	
iAreaBus	Area	
cpArea	Area	
pRating	Thermal Rating (IntThrating)	
Snom_a	Nominal Power (act.)	MVA
cneutcon	Neutral Conductor: N-Connection	
bushvn	Neutral Conductor: HV-Neutral (StaCubic)	
bushvn_bar	Neutral Conductor: HV-Neutral	
buslvn	Neutral Conductor: LV-Neutral (StaCubic)	
buslvn_bar	Neutral Conductor: LV-Neutral	
iintgnd	Neutral Connection	
i_hvcon	HV-side, phase 2 connected	
cgnd_h	Internal Grounding Impedance, HV Side: Star Point	
cpeter_h	Internal Grounding Impedance, HV Side: Petersen Coil	
i_lvcon	LV-side, phase 2 connected	
cgnd_l	Internal Grounding Impedance, LV Side: Star	
cpeter_l	Internal Grounding Impedance, LV Side: Petersen Coil	
bSbasepu	b (Sbase)	p.u.
cpCtrlNode	Controller, Tap Changer 1: Target Node	
cpGrid	Grid	
cpOwner	Owner	

Parameter	Description	Unit
cpOperator	Operator	
cpBranch	Branch	
cpSubstat	Substation	
cpSite	Site	
cpMeteostat	Meteo Station	
cpHeadFold	Head Folder	
fold_id	In Folder ()	
ciOutaged	Planned Outage	
ciEnergized	Energized	
ciEarthed	Earthed	
cDisplayName	Display Name	
cpSupplyTransformer	Supplying Transformer	
cpSupplyTrfStation	Supplying Secondary Substation	
cpSupplySubstation	Supplying Substation	
Inom_h	HV-Side, Nominal Current	kA
Inom_l	LV-Side, Nominal Current	kA
iTaps	According to Measurement Report	
nntap	Tap: Tap Position	
ntrcn	Tap: Automatic Tap Changing	
i_cont	Tap: Tap Changer	
t2ldc	Tap: Controlled Node	
ilcph	Tap: Phase	
imldc	Tap: Control Mode	
uset_mode	Controller, Tap Changer 1: Setpoint	
dutap	Additional Voltage per Tap	%
dphitap	Additional Angle per Tap	deg
phitr	Phase of du	deg
nntap	Tap Changer 1: Tap Position	
iTaps	Tap Changer 1: According to Measurement Report	
dutap2	Additional Voltage per Tap	%
dphitap2	Additional Angle per Tap	deg
phitr2	Phase of du	deg
nntap2	Tap Changer 2: Tap Position	
c_ptapc	Controller, Tap Changer 1: External Tap Controller	
c_pstac	Controller, Tap Changer 1: External Station Controller	
i_rem	Tap: Remote Control	
p_rem	Tap: Controlled Node (StaBar,ElmTerm)	
p_cub	Tap: Controlled Branch (Cubicle) (StaCubic)	
usetp	Tap: Voltage Setpoint	p.u.
usp_low	Tap: Lower Voltage Bound	p.u.
usp_up	Tap: Upper Voltage Bound	p.u.
psetp	Tap: Active Power Setpoint	MW
psp_low	Tap: Lower Active Power Bound	MW
psp_up	Tap: Upper Active Power Bound	MW

Parameter	Description	Unit
qsetp	Tap: Reactive Power Setpoint	Mvar
qsp_low	Tap: Lower Reactive Power Bound	Mvar
qsp_up	Tap: Upper Reactive Power Bound	Mvar
Tctrl	Tap: Controller Time Constant	s
Kqctrl	Controller, Tap Changer 1: Controller Sensitivity dv/dQ	%/Mvar
ildc	Tap: Line Drop Compensation	
ldcct	Tap: Current Transformer Rating	A
ldcpt	Tap: Voltage Transformer Ratio	
ldcrs	Tap: Rset V	
ldcxs	Tap: Xset V	
tapctrl	Tap Controller (ElmTr2)	
iMeasLoc	Measured at	
mTaps	Measurement Report	
iblock	Unit Transformer	
ilt_op	Long-term operating condition before short-circuit are known	
Ub_lv	Values for LV-Side: Highest Operating Voltage	kV
Ib_lv	Values for LV-Side: Highest Operating Current	kA
cosphib_lv	Values for LV-Side: Power factor	
Ubqmin_hv	Values for HV-Side (only for Unit Transformer): Minimum Operating Voltage	kV
ifrqft	Frequent Fault ($>$10(5)/lifetime, Category II(III))	
iopt_hf	Consider HF-Parameter	
Cg_h	HF-Parameter: Capacitance HV-Ground	uF
Cg_l	HF-Parameter: Capacitance LV-Ground	uF
Cc1_hl	HF-Parameter: Capacitance HV-LV, 1-Sequence	uF
Cc0_hl	HF-Parameter: Capacitance HV-LV, 0-Sequence	uF
iOPFCload	Optimal Power Flow Constraints: Max. Loading	
i_uopt	Optimal Power Flow Controls: Tap Position	
ionlyPre	Optimal Power Flow Controls: Optimise	
i_uoptCont	Optimal Power Flow Controls: Control Mode	
cpFeed	Feeder	
ciDist	Distance from infeed in number of buses	
ciLater	Lateral Index	
ciDistRoot	Distance from first infeed in number of buses	
ciDistAll	Distance from infeed in number of buses including switches	
ciDistAllRoot	Distance from first infeed in number of buses including switches	
FOR1	Forced Outage Rate	1/a
FOE	Forced Outage Expectancy	h/a
FOD	Forced Outage Duration	h
iperfect	Ideal component	
pTypStoch	Type model	

Parameter	Description	Unit
pStoch	Element model	StoTyptrf
CCEarFr	Failures Double Earth Fault: Frequency of single earth faults	1/a
CCEarProb	Failures Double Earth Fault: Conditional probability of a second earth fault	%
CCEarRepMu	Failures Double Earth Fault: Repair duration	h
ifrqft	Time-Overcurrent Plot: Frequent Fault ($>$10(5)/lifetime, Category II(III))	
iansish	Time-Overcurrent Plot: ANSI Curve Shift	
drawInr	Time-Overcurrent Plot: Draw Inrush Current	
fr_coldload	Time-Overcurrent Plot: Cold load curve	
coldloadtab2	Values	
i_uopt	OPF-Controls: Tap Position	
maxload	OPF-Constraints: Max. Loading	%
gnrl_modif	Object modified	
gnrl_modby	Object modified by	
sernum	Serial Number	
constr	Year of Construction	
iComDate	Commissioning Date	
chr_name	Characteristic Name	
dat_src	Data source	
for_name	Foreign Key	
doc_id	Additional Data ()	
pOwner	Owner (ElmOwner)	
pOperator	Operator (ElmOperator)	
desc	Description	
appr_status	Approval Information: Status	
appr_modif	Approval Information: Modified	
appr_modby	Approval Information: Modified by	
ifc	Forced Cooling Enabled	
sOpComment	Operator Comment	
cimRdfId	RDF ID	
dpl1	dpl1	
dpl2	dpl2	
dpl3	dpl3	
dpl4	dpl4	
dpl5	dpl5	
iResFlux	Residual flux	
PsiresA	Residual flux, Phase A	p.u.
PsiresB	Residual flux, Phase B	p.u.
PsiresC	Residual flux, Phase C	p.u.

11 References

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