POWERFACTORY

# PowerFactory 2021

## Technical Reference

### HVDC LCC

ElmHvdclcc, TypHvdclcc

PF2021

POWER SYSTEM SOLUTIONS
MADE IN GERMANY

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# Contents

# 1 General Description

This document describes the HVDC Line Commutated Converter model in *PowerFactory*. The *ElmHvdclcc* uses the type *TypHvdclcc*.

The HVDC LCC model has several pre-defined configurations (Figure 1.1):

- 6-pulse (single bridge) rectifier and inverter without internal transformer
- 6-pulse (single bridge) rectifier and inverter with $YY$ internal transformer
- 12-pulse (two bridges) rectifier and inverter with one $YY$ and one $Y\Delta$ internal transformers having a phase shift of $0$ and $30$ degrees.
- 24-pulse (four bridges) rectifier and inverter with one $YY$ and three $Y\Delta$ internal transformers having a phase shift of $0$, $15$, $30$ and $45$ degrees.

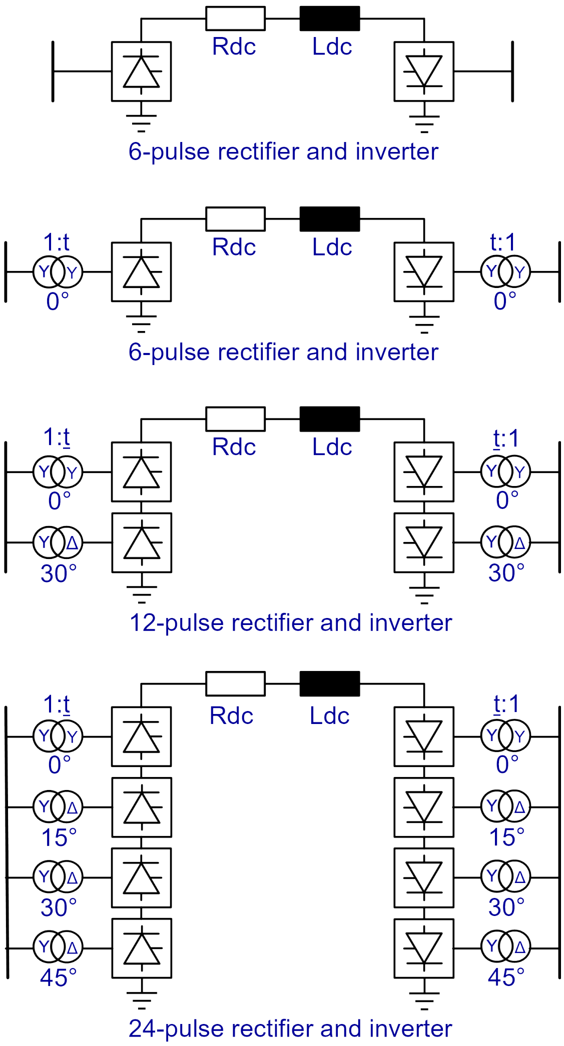


Figure 1.1: HVDC LCC configurations

The inductance *Ldc* (type parameter) shown in Figure 1.1 is used only in the dynamic simulation models. It represents the combined DC line and DC reactor inductance of the HVDC unit. This parameter has a direct influence on the speed by which the current decays to zero.

The controlled 6-pulse converter bridge consists of six power thyristors, arranged as shown in Figure 1.2.

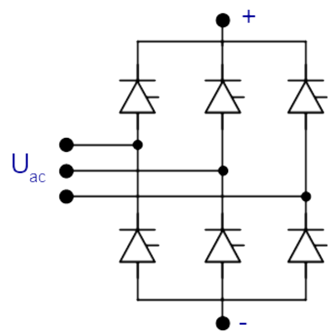


Figure 1.2: Detailed thyristor bridge representation

A fundamental frequency (averaged) model is used for load flow calculations and stability analysis. For balanced analysis, the monopolar configurations shown in Figure 1.1 can be used to also analyse bipolar configurations [1].

The detailed modelling of all six thyristors is only necessary for EMT simulations. For systems with strong unbalance, the EMT model is the most appropriate model.

# 2 Load Flow analysis

There are two different models for Load Flow analysis in *PowerFactory*, one for balanced and another for unbalanced analysis.

## 2.1 Commutation reactance

The commutation resistances and reactances are entered per converter bridge. Specifying the correct values of the commutation reactances is important to get realistic values for the commutation (overlap) angles. The commutation reactances should be referred to the converter-side voltage of the transformer.

The commutation reactance is the reactance between the commutating voltage and the converter valves. The voltage where its waveform is reasonably sinusoidal (under normal operating conditions) can be taken as the commutating voltage. This is normally the case where filtering and phase-shifting is provided at the converter stations [2].

Typically, it is sufficient to take the voltage at the grid-side of the converter transformer as commutation voltage. Therefore, as commutation reactances, the leakage reactances of the transformers can be assumed (the transformer leakage reactance is usually the biggest part of the total reactance from the Grid side). The commutation reactances $X_{c1}$ and $X_{c2}$ can be calculated as:

$$X_c = \frac{u_{kr}}{100} \cdot \frac{U_{r,conv}^2}{S_r} \qquad [\Omega] \tag{1}$$

where:

- $u_{kr}$ is the converter transformer short-circuit voltage in $\%$,
- $S_r$ is the rated power,
- $U_{r,conv}$ is the rated voltage on the converter side of the transformer. If a built-in transformer is used, the converter-side transformer voltage can be calculated using the parameters $Unom1$ and $turnsratio1$ or $Unom2$ and $turnsratio2$ defined in the type (it is here assumed that the nominal rated AC voltage $Unom$ is the same as the built-in transformer rated voltage on the grid side):

$$U_{r,conv} = Unom \cdot turnsratio \tag{2}$$

For more detailed studies, the presence of local plant (e.g. synchronous compensators and generators) needs to be taken into account for the commutation reactances since it has influence on the commutation process [2].In [2], two practical examples for the calculation of the commutation reactances are presented. An external transformer needs to be modelled in this case.

## 2.2 Converter Transformer

For the 6-pulse configuration for rectifier and inverter, an external or internal transformer can be defined. If a configuration with 12-or 24-pulse bridges is selected, only internal transformers are available in the model and the transformers are modelled as being identical.

The commutation reactance needs to be included in the voltage which is being considered for calculating the ideal no-load dc voltages of the converters. Depending if the transformer is modelled internally or externally, the voltage is calculated as follows:

- Internal (built-in) transformer

  The AC voltage drop due to the leakage (commutating) reactance is already considered in the model and only the tap position, nominal ratio and phase shift need to be taken into account:

$$\begin{aligned} \underline{U}_{ac1} &= \underline{U}_{term1} \cdot turnsratio_1 \cdot ntap_1 \cdot e^{j \cdot phaseshift} \\ \underline{U}_{ac2} &= \underline{U}_{term2} \cdot turnsratio_2 \cdot ntap_2 \cdot e^{j \cdot phaseshift} \end{aligned} \tag{3}$$

  where:

  - $\underline{U}_{term1}$ and $\underline{U}_{term2}$ are the voltages where the element is connected (grid terminals),
  - $turnsratio_1$ and $turnsratio_2$ are the nominal turns ratio of the internal transformers (type parameters),
  - $ntap_1$ and $ntap_2$ are the tap positions of the internal transformers,
  - $phaseshift$ is the pre-defined phase shift of the internal transformers and depends on the number of bridges per converter (Figure 1.1).

  The built-in transformer tap-changer is located on the LV side and controls the converter-side voltage. The tap changer setting is specified with the actual tap position parameter, which must be between the maximum and minimum tap positions specified in the type.

- External tranformer

  The AC voltage drop over the transformer is estimated using the commutation impedance entered in the model:

$$\begin{aligned} \underline{U}_{ac1} &= \underline{U}_{term1} + (R_{c1} + \jmath \cdot X_{c1}) \cdot \underline{I}_1 / Bnum \\ \underline{U}_{ac2} &= \underline{U}_{term2} + (R_{c2} + \jmath \cdot X_{c2}) \cdot \underline{I}_2 / Bnum \end{aligned} \tag{4}$$

  where:

  - $\underline{I}_1$ and $\underline{I}_2$ are the currents flowing through the element,
  - $Bnum$ is the number of bridges in series per converter (it is assumed that the rectifier and inverter have the same number of bridges),
  - $X_{c1}$ and $X_{c2}$ are the commutation reactances,
  - $R_{c1}$ and $R_{c2}$ are the commutation resistances.

## 2.3 Calculation of converter parameters

The ideal no-load DC-voltages per bridge on connection side 1 (rectifier) and side 2 (inverter) are calculated using the line to line voltage as [1] [3]:

$$\begin{aligned} U_{dci1} &= \frac{\sqrt{2} \cdot 3}{\pi} \cdot |\underline{U}_{ac1}| \\ U_{dci2} &= \frac{\sqrt{2} \cdot 3}{\pi} \cdot |\underline{U}_{ac2}| \end{aligned} \tag{5}$$

where:

- $\underline{U}_{ac1}$ is side 1 AC voltage,
- $\underline{U}_{ac2}$ is side 2 AC voltage.

The DC voltages are calculated as the sum of the DC voltages per converter bridge:

$$\begin{aligned} U_{dc1} &= Bnum \cdot \left( Udci1 \cdot \cos(\alpha_1) - \frac{3}{\pi} \cdot X_{c1} \cdot I_{dc} - 2 \cdot R_{c1} \cdot I_{dc} - Losses_1 \right) \\ U_{dc2} &= Bnum \cdot \left( Udci2 \cdot \cos(\gamma_2) - \frac{3}{\pi} \cdot X_{c2} \cdot I_{dc} + 2 \cdot R_{c2} \cdot I_{dc} + Losses_2 \right) \end{aligned} \tag{6}$$

where:

- $Bnum$ is the number of bridges in series per converter (it is assumed that the rectifier and inverter have the same number of bridges),
- $\alpha_1$ and $\gamma_2$ are the firing angle of the rectifier and extinction angle of the inverter (assumed equal for all bridges),
- $X_{c1}$ and $X_{c2}$ are the commutation reactances,
- $R_{c1}$ and $R_{c2}$ are the commutation resistances,
- $Losses_1$ and $Losses_2$ are the losses per converter bridge and are calculated as follows:

$$\begin{aligned} Losses_1 &= resLossFactor \cdot I_{dc} + V_{drop1} \\ Losses_2 &= resLossFactor \cdot I_{dc} + V_{drop2} \end{aligned} \tag{7}$$

  where:
  - the first term represents the resistive losses where the parameter $resLossFactor$ in $\Omega$ is used,
  - the second term represents the voltage drop losses in the thyristors where the parameter $swtLossFactor$ in $KW/A$ and the nominal DC-currents are used:

$$V_{drop1} = swtLossFactor \cdot \left(1 - e^{-200 \cdot \frac{I_{dc}}{I_{dcnom1}}}\right) \tag{8}$$

$$V_{drop2} = swtLossFactor \cdot \left(1 - e^{-200 \cdot \frac{I_{dc}}{I_{dcnom2}}}\right) \tag{9}$$

The overlap (commutation) angles are calculated as:

$$\begin{aligned} \mu_1 &= \arccos\left(\cos\delta_1\right) - \alpha_1 \\ \mu_2 &= \arccos\left(\cos\delta_2\right) - \gamma_2 \end{aligned} \tag{10}$$

where the cosinus of the extinction delay angles are calculated as:

$$\begin{aligned} \cos\delta_1 &= \cos\alpha_1 - Bnum \cdot \frac{6 \cdot X_{c1}}{\pi} \cdot \frac{I_{dc}}{U_{dci1}} \\ \cos\delta_2 &= \cos\gamma_2 - Bnum \cdot \frac{6 \cdot X_{c2}}{\pi} \cdot \frac{I_{dc}}{U_{dci2}} \end{aligned} \tag{11}$$

The active powers of the rectifier and inverter are calculated as:

$$\begin{aligned} P_1 &= U_{dc1} \cdot I_{dc} + DCPoleLosses_1 \\ P_2 &= -U_{dc2} \cdot I_{dc} + DCPoleLosses_2 \end{aligned} \tag{12}$$

The DC pole losses are calculated as the sum of the no-load losses, the forward voltage drop losses (specified with the input parameter $swtLossFactor$) and the resistive losses (specified with the input parameter $resLossFactor$) as:

$$\begin{aligned} DCPoleLosses_1 &= Plossnld_1 + Bnum \cdot I_{dc} \cdot V_{drop1} + Bnum \cdot I_{dc}^2 \cdot resLossFactor \\ DCPoleLosses_2 &= Plossnld_2 + Bnum \cdot I_{dc} \cdot V_{drop2} + Bnum \cdot I_{dc}^2 \cdot resLossFactor \end{aligned} \tag{13}$$

where the no-load losses are calculated using the no-load losses parameter $Pnold$ in $kW$ and the nominal DC voltages:

$$\begin{aligned} Plossnld_1 &= Bnum \cdot \frac{P_{nold}}{1000} \cdot \frac{U_{dc1}^2}{U_{dcnom1}^2} \\ Plossnld_2 &= Bnum \cdot \frac{P_{nold}}{1000} \cdot \frac{U_{dc2}^2}{U_{dcnom2}^2} \end{aligned} \tag{14}$$

If an internal transformer is defined, the losses due to the commutation resistances are considered into Equation 12 and are calculated using the fundamental current.

The reactive powers are obtained as:

$$\begin{aligned}
Q_1 &= U_{dci1} \cdot I_{dc} \cdot \frac{\sin(2 \cdot \alpha_1) - \sin(2 \cdot (\alpha_1 + \mu_1)) + 2 \cdot \mu_1}{4 \cdot (cos(\alpha_1) - cos(\alpha_1 + \mu_1))} \\
Q_2 &= U_{dci2} \cdot I_{dc} \cdot \frac{\sin(2 \cdot \gamma_2) - \sin(2 \cdot (\gamma_2 + \mu_2)) + 2 \cdot \mu_2}{4 \cdot (cos(\gamma_2) - cos(\gamma_2 + \mu_2))}
\end{aligned} \tag{15}$$

The resistance of the DC-line is taken into account using the following equation:

$$U_{dc1} = U_{dc2} + R_{dc} \cdot I_{dc} \tag{16}$$

**Total losses**

The total losses in $MW$ and $Mvar$ are obtained as:

$$\begin{aligned}
&Ploss = P_{busi} + P_{busj} \\
&Qloss = 0
\end{aligned} \tag{17}$$

where $P_{busi}$ and $P_{busj}$ are calculation parameters available for the branch element.

The load losses are calculated as the difference between the total losses and the no-load losses:

$$\begin{aligned}
&Plossld = Ploss - Plossnld \\
&Qlossld = 0
\end{aligned} \tag{18}$$

where the no-load losses are the sum of the no-load losses: $Plossnld = Plossnld_1 + Plossnld_2$.

## 2.4 Model for unbalanced analysis

When the network voltages are unsymmetrical, the periods for natural conduction of the valves are not the same and the DC voltage will be made of six pulses with different duration and amplitude.

This model in *PowerFactory* calculates the ideal DC-voltages based on the equidistant phase control where the conduction periods per phase are determined. This calculation is made per bridge and at the end the sum of the variables for all bridges is calculated.

In addition to the active and reactive power equations, for the unbalanced Load Flow, also equations for the zero and negative sequence currents must be satisfied. The zero sequence current is set to zero and the negative sequence current is calculated from the currents flowing in the converter [3].

## 2.5 Control and operating modes

The firing angle control in the rectifier enables two different control modes of DC variables:

- $I$ current
  The current is controlled to the setpoint value.
- $P$ active power
  In this control mode, the current is controlled to a different setpoint calculated from the active power setpoint.

The active power can be controlled either on rectifier or inverter side if the inverter voltage is higher or equal to the minimum inverter voltage for power control (parameter $Uminp$):

$$Iset = \begin{cases} \dfrac{Pset}{Udc1} & \text{at rectifier} \\ \dfrac{Pset}{Udc2} & \text{at inverter} \end{cases} \tag{19}$$

If the option P-setpoint adaption is being used, the setpoint is modified for a value $P_{offset}$:

$$Iset = \begin{cases} \dfrac{Pset - P_{offset}}{Udc1} & \text{at rectifier} \\ \dfrac{Pset - P_{offset}}{Udc2} & \text{at inverter} \end{cases} \tag{20}$$

The active power setpoint can be adapted using one of the following options:

– *Angle-difference dependent P-droop*

$$P_{offset} = Kpphi \cdot (\varphi_{u\_remote} - \varphi_{u\_local}) \tag{21}$$

where $Kpphi$ is the specified factor for the droop, $\varphi_{u_remote}$and $\varphi_{u\_local}$ are the positive-sequence voltage angles of the selected remote and local busbars.

– *Active power participation*

$$P_{offset} = -Kpart \cdot P_{measured} \tag{22}$$

where $Kpart$ is the participation factor and $P_{meas}$ is the active power measured (assumed positive with load orientation) at a specified cubicle/boundary.

The *Angle-difference dependent P-droop* and *Active power participation* options can be used to adapt the active power of the converter depending on the active power flow on a parallel AC line. When the *Active power participation* option is selected, the sign of the parameter *Kpart* depends on the orientation of the power flow at the point where the parameter *Pmeas* is measured.

If the inverter voltage is lower then the minimum inverter voltage for power control (parameter $Uminp$), the active power will be controlled to:

$$Iset = \begin{cases} \dfrac{Pset}{Uset} & \text{if inverter is in voltage control mode} \\ \dfrac{Pset}{U_\gamma} & \text{if inverter is in gamma control mode} \end{cases} \tag{23}$$

where $U_\gamma$ is calculated using the gamma setpoint.

The extinction angle control in the inverter enables two different control modes:

- $U$ voltage
  The voltage is controlled to the setpoint value.
- $gamma$ extinction angle setpoint
  The extinction angle is controlled to the setpoint value.

The voltage control droop (parameter $Rdroop$) can be used to control the voltage along the DC line or even at the rectifier side if the value is set equal to the resistance of the DC line.

### Steady-state control characteristic

Under normal conditions, the rectifier controls the current and the inverter controls the voltage to the setpoint values. If the inverter side voltage cannot be controlled up to the setpoint value, the inverter goes into $\gamma_{min}$-control mode (the extinction angle has reached the minimum allowed value $gammamin$). This avoids commutation failure in normal operating conditions (it does not represent the limiting value for commutation failure). Figure 2.1 shows the steady state characteristic of the converters with rectifier in $Idc$ and inverter in $Udc$ control mode (mode 1).

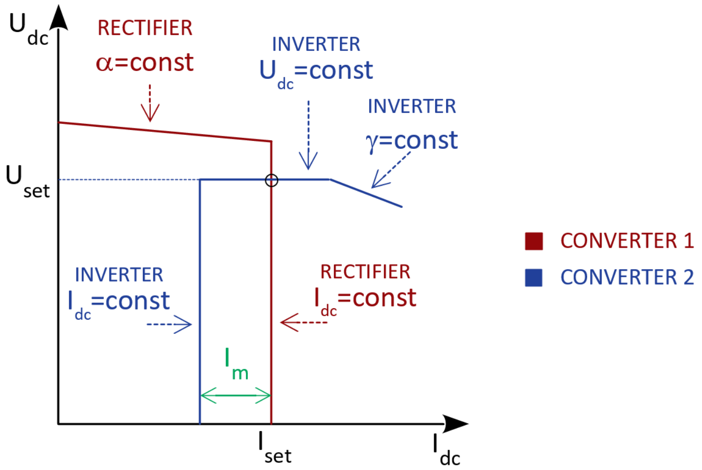


Figure 2.1: Converter steady-state control characteristics

If the rectifier cannot control the current to the setpoint value, the rectifier goes into $\alpha_{min}$-control mode (the firing angle has reached the minimum allowed value $alphamin$). In this case the HVDC LCC will go to another mode of operation (mode 2) where the rectifier controls the voltage and the inverter controls the current. In this mode of operation, the firing angle of the rectifier has the minimum value and the extinction angle of the inverter is used to control the current to a new reduced setpoint. The new setpoint is reduced for the value of the current margin $Im$ in $\%$. Figure 2.2 shows the the characteristic of the converters for reduced AC voltage with rectifier in $\alpha$ and inverter in $Idc$ control mode (mode 2).

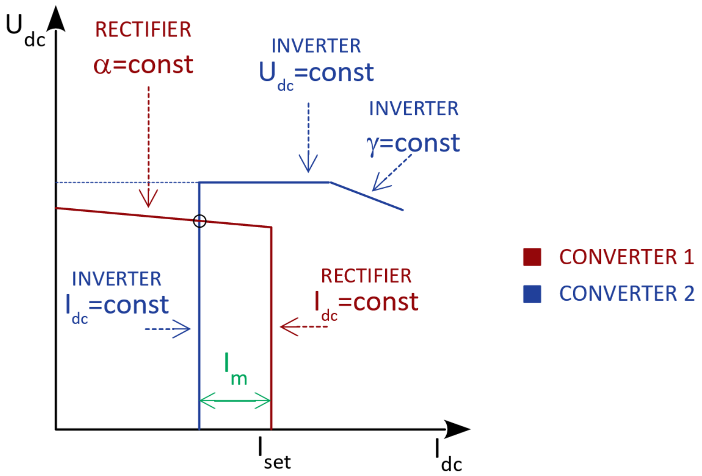


Figure 2.2: Converter steady-state control characteristics (mode 2)

### 2.5.1 Reverse power flow

Each converter can function as a rectifier and as an inverter. In order to define reverse power flow in the *PowerFactory* model one of the following needs to be satisfied: $Iset > 0$ and $Uset < 0$ or $Pset < 0$ and $Uset < 0$ or $Pset < 0$ in gamma control mode. Please note that $Idc$ is always positive and that a negative power flow cannot be defined by using a current $Iset$ and gamma control mode. Figure 2.3 shows the complete steady state characteristic of the converters for positive and negative power flow. With positive power flow the rectifier settings apply to converter 1 and the inverter settings to converter 2. With negative power flow the rectifier settings apply to converter 2 and the inverter settings to converter 1.

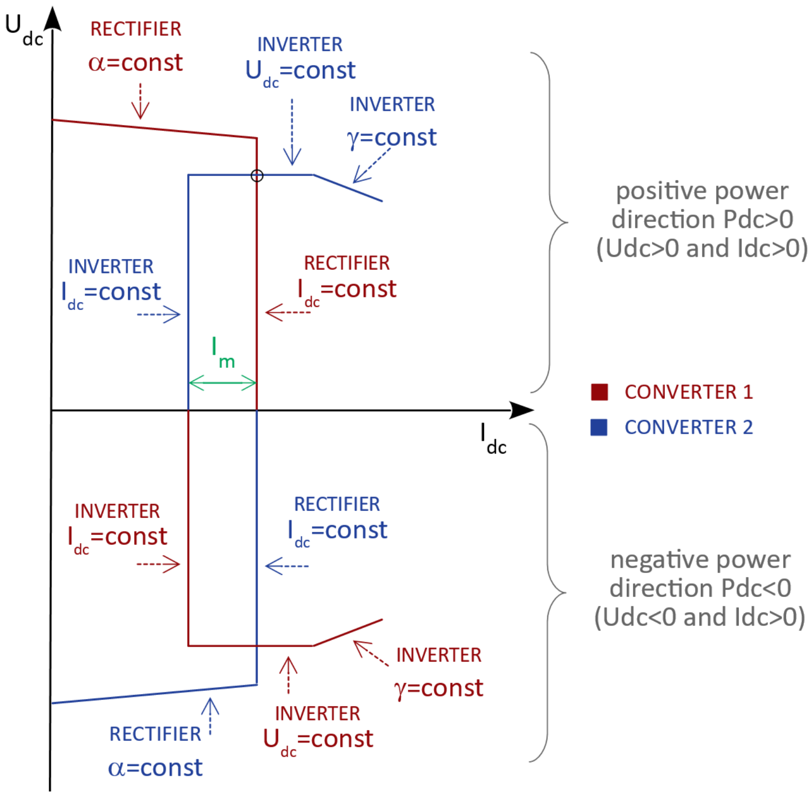


Figure 2.3: Complete steady-state control characteristics

### 2.5.2 Automatic tap changing

If the automatic tap changing is enabled, the transformer automatically taps during the Load Flow iterations if the firing/extinction angle hits the minimum or maximum allowed value and brings the angle into the defined bounds:

- If the firing angle hits its maximum allowed limit, the transformer from the rectifier side will tap down automatically.
- If the extinction angle hits its maximum allowed limit, the transformer from the inverter side will tap down automatically.
- If the firing angle hits its minimum allowed limit, the transformer from the rectifier side will tap up automatically.

- If the extinction angle hits its minimum allowed limit, the transformer from the inverter side will tap up automatically.

# 3 Short-Circuit Calculations

The line-commutated converters are neglected during short-circuit calculations due to the effect, that the thyristors are automatically blocking during very low voltages at the AC side. This results in low short-circuit currents supplied by the converter. The calculation methods using the VDE, IEC or ANSI standards neglect the contribution of the converters.

If a *complete* method short-circuit calculation is executed, the short-circuit current of the converter will not be neglected but defined as the load flow AC current of the converter.

# 4 Harmonics

The currents of a thyristor-controlled converter not only have a large fundamental component but also cause a flow of harmonic currents of higher orders. Hence, the harmonic model used for the HVDC LCC is a harmonic current source. The order of the harmonic currents is calculated as:

$$h = 6 \cdot n \pm 1 \tag{24}$$

where $n = 1{,}2...$ is an integer value.
The polarity of the harmonics (angle) is $180°$ for the $5^{th}$, $11^{th}$, etc. harmonics (represented in the negative sequence) and $0°$ for the $7^{th}$, $13^{th}$, etc. harmonics (represented in the positive sequence).

The harmonic spectrum can be defined using three different models:

- *User defined*
  This model can be used to represent the converter in a more realistic way where a harmonic current source *TypHmccur* can be defined. In the harmonic current source the amplitude and angle of the harmonic currents can be defined (more information for the harmonic sources is available in the Technical Reference).
- *Idealised converter*
  A typical spectrum of the converter is assumed up to a specified maximum harmonic order [1].
- *Consider overlap angle*
  In this model the harmonic currents are obtained same as in the *Idealised converter* model and then are multiplied with a reduction factor calculated using the overlap angle. In this case, under typical loading conditions the $11^{th}$ and $13^{th}$ harmonics are $30\%$ to $40\%$ of the harmonics calculated using the *Idealised converter* model [1].

# 5 RMS Simulation

The stability model uses the same equations as described for the Load Flow calculations in sections 2.2 to 2.4.

A separate minimum extinction angle for commutation failure *gammamindyn* can be specified in the *RMS* page. This angle specifies the minimum extinction angle below which commutation failure is assumed to take place. When the extinction angle reaches the specified *gammamindyn*, a message warning for commutation failure is printed in the output window (*gammamindyn* has a different meaning than the *gammamin* angle specified in the load flow page).

With the signals *short_dc1* and *short_dc2* is possible to short-circuit the DC sides of the rectifier or inverter, in order to bypass the valves. With the signals *block_all1* and *block_all2* all thyristors (rectifier and inverter) will be blocked.

The converter also blocks (without signals block_all1 or block_all2 being active) if the DC current tries to change direction (i.e. crosses zero). An output window message is printed saying that the converter is in blocking mode. The converter will switch back to normal operation if the prospective DC voltage on the rectifier side is greater than the prospective DC voltage on the inverter side (an output message will be printed in the output window that the converter is back in operation).

It is possible to select the way the extinction angle is handled during commutation failure. The extinction angle can either be set to zero or set to minimum (constant value).

The additional output signals *gamma_state1* and *gamma_state2* have the value $0$ in normal operation, $1$ if the converter is blocked (AC side), $2$ if the converter is in commutation failure or shorted (DC side).

# 6 EMT Simulation

For the electro-magnetic transient simulation the detailed modelling of all six thyristors per bridge is necessary. The detailed discrete valve model is represented in Figure 6.1. It includes the switch resistance in on-state $R_{thy}$, the switch conductance in off-state $G_{off}$, the snubber conductance $G_s$ and the snubber capacitance $C_s$. These values can be defined on the *EMT* page of the type *TypHvdclcc*.

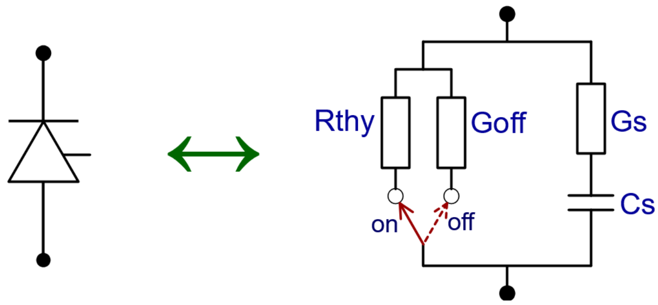


Figure 6.1: Detailed valve representation for EMT-simulations

The valves are triggered by the built-in trigger-logic, which converts the firing angle supplied by the converter controller to the firing signals of the discrete thyristors. For an exact triggering of the valves, the times of zero-crossing of the AC voltages is internally measured. Since the converter does not have a built-in phase measurement, a PLL element (*ElmPhi__pll*) needs to be provided for the rectifier and for the inverter side. This means that the output *Fmeas* of two PLL elements is required by the converter for accurate operation.

With the signal *short_dc1* or *short_dc2* is possible to short-circuit the DC side of the rectifier or the inverter, through a valve with resistance equal to $R_{thy}$. With the signal *block_all1* or *block_all2* all thyristors from the converter will be blocked. The AC and DC current are then both zero.

The converter transformer data and commutation reactance, are identical with the values specified on the load flow page of the element. The minimum extinction angle *gammamindyn* is not used in EMT simulations.

Opposite to the RMS model, no messages are given for commutation failure and similar.

**Note:** Modelling the converter transformer externally can cause problems due to the exact value of commutation reactance specified on the load flow page and the additional reactance inserted by the transformer element. Small errors of this value affect the commutation angle and hence the EMT simulation cannot calculate the right initial conditions. Here it is recommended to use the built-in transformer of the converter element instead in order to get correct results in the EMT-simulation.

# 7 Inputs/Outputs/State Variables of the Dynamic Model

## 7.1 RMS Model

Table 7.1: Inputs to the RMS-Model

| Input Signal | Symbol | Description | Unit |
|---|---|---|---|
| alpha1 | $\alpha_1$ | Firing angle 1 | rad |
| alpha2 | $\alpha_2$ | Firing angle 2 | rad |
| ntap1 | $ntap_1$ | Tap Position 1 | p.u. |
| ntap2 | $ntap_2$ | Tap Position 2 | p.u. |
| fref1 | $f_{ref1}$ | Reference frequency 1 (automatically assigned) | p.u. |
| fref2 | $f_{ref2}$ | Reference frequency 2 (automatically assigned) | p.u. |
| dc_bypass1 | $dc\_bypass_1$ | DC bypass 1 | |
| dc_bypass2 | $dc\_bypass_2$ | DC bypass 1 | |
| block_all1 | $block\_all_1$ | AC blocking 1 | |
| block_all2 | $block\_all_2$ | AC blocking 2 | |

Table 7.2: State Variables used by the RMS-Model

| Parameter | Symbol | Description | Unit |
|---|---|---|---|
| Idc | $I_{dc}$ | DC current | kA |

Table 7.3: Outputs from the RMS-Model

| Parameter | Symbol | Description | Unit |
|---|---|---|---|
| Idcout | | DC Current (equal to Idc) | kA |
| Udc1 | $U_{dc1}$ | DC voltage 1 | kV |
| Udc2 | $U_{dc2}$ | DC voltage 2 | kV |
| gamma1 | $\gamma_1$ | Extinction angle 1 | rad |
| gamma2 | $\gamma_2$ | Extinction angle 2 | rad |
| gamma_min1 | $\gamma_{min1}$ | Extinction angle gamma 1 (min. in one cycle) | rad |
| gamma_min2 | $\gamma_{min2}$ | Extinction angle gamma 1 (min. in one cycle) | rad |
| gamma_state1 | $\gamma_{state1}$ | Gamma state 1 | |
| gamma_state2 | $\gamma_{state2}$ | Gamma state 2 | |

## 7.2 EMT-Model

Table 7.4: Inputs to the EMT-Model

| **Input Signal** | **Symbol** | **Description** | **Unit** |
|---|---|---|---|
| alpha1 | $\alpha_1$ | Firing angle 1 | rad |
| alpha2 | $\alpha_2$ | Firing angle 2 | rad |
| ntap1 | $ntap_1$ | Tap Position 1 | p.u. |
| ntap2 | $ntap_2$ | Tap Position 2 | p.u. |
| Fmeas1 | $F_{meas1}$ | Frequency 1 | Hz |
| Fmeas2 | $F_{meas2}$ | Frequency 2 | Hz |
| dc_bypass1 | $dc\_bypass_1$ | DC bypass 1 | |
| dc_bypass2 | $dc\_bypass_2$ | DC bypass 1 | |
| block_all1 | $block\_all_1$ | AC blocking 1 | |
| block_all2 | $block\_all_2$ | AC blocking 2 | |

Table 7.5: State Variables used by the EMT-Model

| **Parameter** | **Symbol** | **Description** | **Unit** |
|---|---|---|---|
| Idc | $I_{dc}$ | DC current | kA |
| phiref1 | | Reference angle 1 | rad |
| phiref2 | | Reference angle 2 | rad |

In addition to the state variables listed in Table 7.5, additional three state variables per bridge for the phase currents are defined.

Table 7.6: Outputs from the EMT-Model

| **Parameter** | **Symbol** | **Description** | **Unit** |
|---|---|---|---|
| Idcout | | DC Current (equal to Idc) | kA |
| Udc1 | $U_{dc1}$ | DC voltage 1 | kV |
| Udc2 | $U_{dc2}$ | DC voltage 2 | kV |
| U1b1_0 | $U_{1b1\_0}$ | Zero sequence voltage side 1 bridge 1 | kV |
| U2b1_0 | $U_{2b1\_0}$ | Zero sequence voltage side 2 bridge 1 | kV |
| gamma_min1 | $\gamma_{min1}$ | Extinction angle gamma 1 (min. in one cycle) | rad |
| gamma_min2 | $\gamma_{min2}$ | Extinction angle gamma 1 (min. in one cycle) | rad |
| I1p_A | | Thyristor current side 1 bridge 1, positive, phase A | kA |
| I1m_C | | Thyristor current side 1 bridge 1, minus, phase C | kA |
| I1p_B | | Thyristor current side 1 bridge 1, positive, phase B | kA |
| I1m_A | | Thyristor current side 1 bridge 1, minus, phase A | kA |
| I1p_C | | Thyristor current side 1 bridge 1, positive, phase C | kA |
| I1m_B | | Thyristor current side 1 bridge 1, minus, phase B | kA |
| I2p_A | | Thyristor current side 2 bridge 1, positive, phase A | kA |
| I2m_C | | Thyristor current side 2 bridge 1, minus, phase C | kA |
| I2p_B | | Thyristor current side 2 bridge 1, positive, phase B | kA |
| I2m_A | | Thyristor current side 2 bridge 1, minus, phase A | kA |
| I2p_C | | Thyristor current side 2 bridge 1, positive, phase C | kA |
| I2m_B | | Thyristor current side 2 bridge 1, minus, phase B | kA |
| U1pc_A | | Capacitive voltage side 1 bridge 1, positive, phase A | kV |
| U1mc_C | | Capacitive voltage side 1 bridge 1, positive, phase C | kV |
| U1pc_B | | Capacitive voltage side 1 bridge 1, positive, phase B | kV |
| U1mc_A | | Capacitive voltage side 1 bridge 1, positive, phase A | kV |
| U1pc_C | | Capacitive voltage side 1 bridge 1, positive, phase C | kV |
| U1mc_B | | Capacitive voltage side 1 bridge 1, positive, phase B | kV |
| U2pc_A | | Capacitive voltage side 2 bridge 1, positive, phase A | kV |
| U2mc_C | | Capacitive voltage side 2 bridge 1, positive, phase C | kV |
| U2pc_B | | Capacitive voltage side 2 bridge 1, positive, phase B | kV |
| U2mc_A | | Capacitive voltage side 2 bridge 1, positive, phase A | kV |
| U2pc_C | | Capacitive voltage side 2 bridge 1, positive, phase C | kV |
| U2mc_B | | Capacitive voltage side 2 bridge 1, positive, phase B | kV |

The thyristor currents and capacitive voltages listed in Table 7.5 are only for the first bridge of both connection sides. If configuration with more then one bridge per converter is selected, the needed currents and voltages are dynamically allocated internally in *PowerFactory*.

# 8 References

[1] P. Kundur, *Power System Stability and Control*. McGraw-Hill, Inc, 1994.

[2] J. Arrillaga, *High Voltage Direct Current Transmission*. IEE, second ed., 1998.

[3] E. Wilson Kimbark, *Direct Current Transmission*. Wiley-Interscience, 1971.

# List of Figures

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