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Technical Reference

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1 General Description

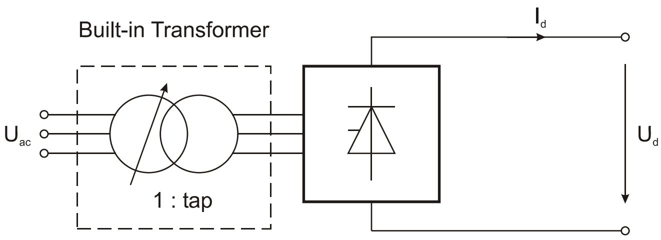

Figure 1.1: HVDC converter including built-in transformer

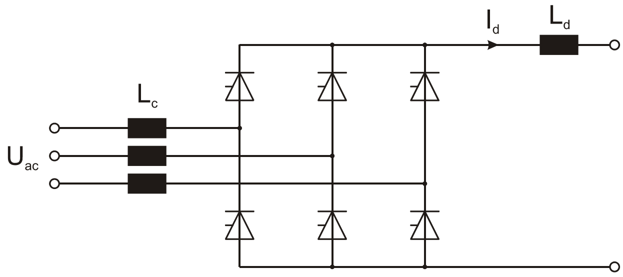

Figure 1.2: Detailed circuit with commutation reactance and DC reactance (not part of the model)

The model can be configured as:

- Three-phase diode rectifier
- Three-phase line-commutated rectifier/inverter

The orientation of the element has to be specified to allow representation of either a rectifier or an inverter.

The diode rectifier is a full-bridge diode rectifier, which is rectifying the three-phase AC voltage to a 6-pulse DC voltage. Due to the usage of diodes, which can neither be turned-on or turned-off externally, the DC voltage or DC current of the rectifier cannot be controlled.

The controlled converter model consists of six power thyristors, arranged as shown in Figure 1.2. These valves can be turned-on by an external control signal, but only turned-off when the current flowing through them becomes negative. This converter can operate as rectifier or as inverter, depending on the timing of the gate signal relative to the AC voltage wave.

A fundamental frequency model is used for load flow calculations and stability analysis, and is described in section 1.1. The detailed modelling of all six thyristors is only necessary for EMT simulations, where the converters are modelled as shown in Figure 1.2.

1.1 Fundamental Frequency Model

The models for load flow calculation and RMS-simulation are based on a fundamental frequency approach. The equations of the thyristor converter and the diode rectifier are identical if the diode rectifier is assumed as an uncontrolled thyristor converter (hence the firing angle α is set to zero).

During steady-state operation the converter can be modelled as a load with constant active and reactive power *P* and *Q*. The following equations describe the converter in a detailed way and give hints for the layout of an HVDC system.

The transmitted DC power of the high-voltage DC system is given by:

$$P_d = U_d \cdot I_d \tag{1}$$

The DC voltage of the ideal and uncontrolled converter, without load, is called the "ideal no-load direct voltage" U_{d0} , which is defined as follows:

$$U_{d0} = \frac{s_0 \cdot q}{\pi} \cdot \sin\left(\frac{\pi}{q}\right) \cdot \frac{\sqrt{2}}{\sqrt{3}} \cdot U_{LL} \tag{2}$$

where s_0 defines the number of commutation groups, q is the number of branches in a commutation group and U_{LL} is the AC voltage supplied to the converter station. For a 6-pulse converter there are two commutation groups ($s_0 = 2$) and q is equal to 3, hence the U_{d0} is

$$U_{d0} = \frac{3 \cdot \sqrt{2}}{\pi} U_{LL} \approx 1.35 \cdot U_{LL} \tag{3}$$

This equation is valid for the uncontrolled thyristor converter ($\alpha = 0$) as well as for the diode bridge. The gate control of the thyristors can be used to delay the ignition of the valves. The time delay due to the turn-on signal applied is defined to be $\omega t = \alpha$. Then the DC voltage depends on the ignition angle α

$$U_{d\alpha} = U_{d0} \cdot \cos(\alpha) \tag{4}$$

The effect of the ignition angle α is shown in Figure 1.3, where the AC voltage, the phase currents and the DC voltage can be seen for an idealized operation with the DC current I_d assumed to be constant. The ignition angle is also indicated in the figure. Here the time between the transfer of the current from one valve to the next is assumed to be zero, i.e the leakage reactance of the transformer is neglected and the commutation angle μ is zero.

To study more realistic converters the current commutation from one valve to the next must be considered. The commutation leads to a drop in the DC voltage ΔU_d:

$$U_d = U_{d0} \cdot \cos(\alpha) - \Delta U_d \tag{5}$$

ΔU_d is defined as a function of I_d and the commutation reactance X_c according to equation 6, where R_{cr} is the "equivalent commutating resistance". R_{cr} does not represent a real resistance and thus has no associated power losses. ΔU_d is defined as:

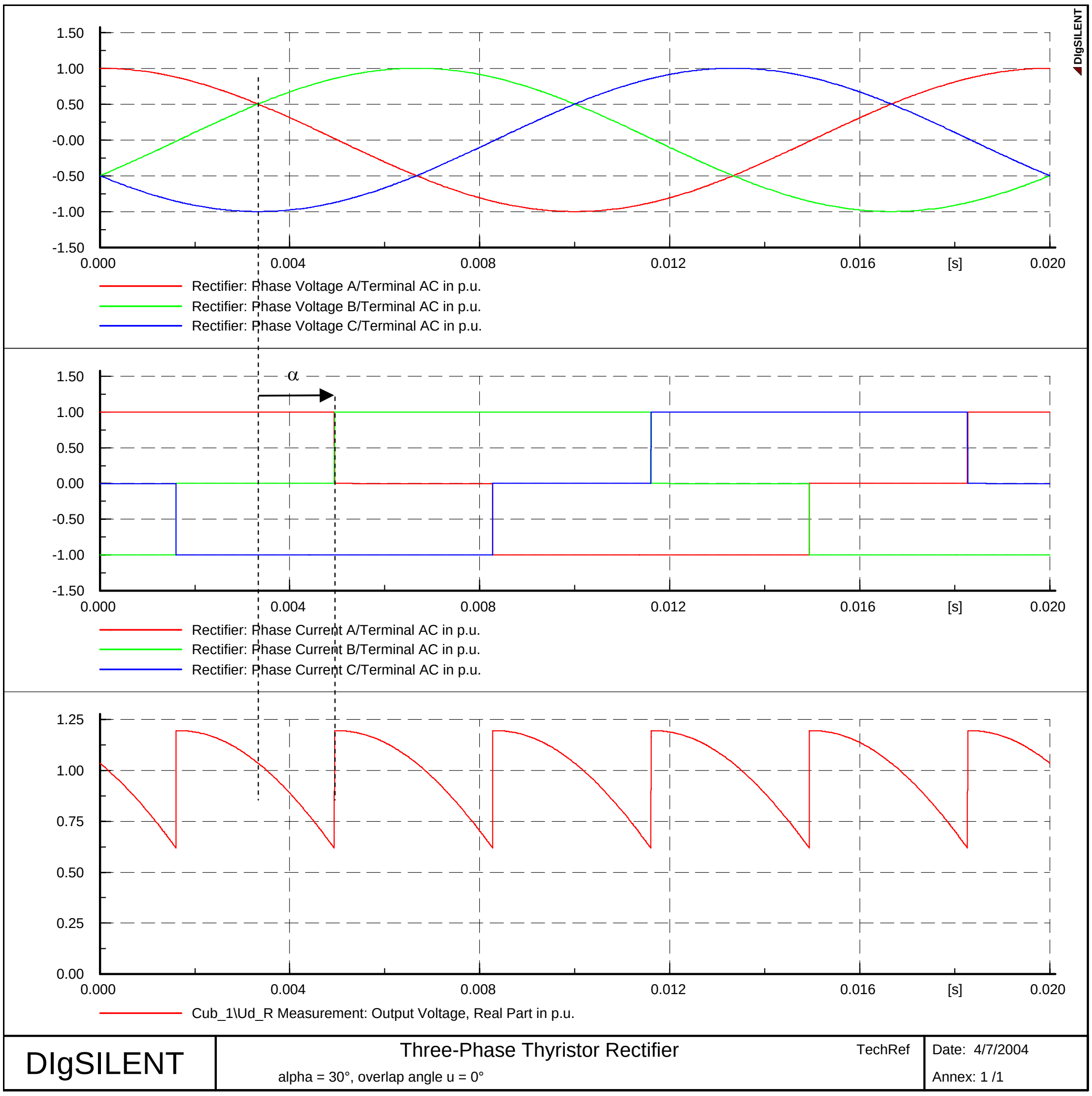

Figure 1.3: Phase voltages, phase currents and DC voltage of a three-phase rectifier operating with $\alpha = 30°$ and zero commutation angle μ

$$\Delta U_d = -R_{cr} \cdot I_d = -\frac{3}{\pi} \cdot \omega \cdot L_c \cdot I_d = -\frac{3}{\pi} \cdot X_c \cdot I_d \tag{6}$$

Combining equations 5 and 6, the DC voltage can be expressed as:

$$U_d = U_{d0} \cdot \cos(\alpha) + \frac{3}{\pi} \cdot X_c \cdot I_d \tag{7}$$

Figure 1.4 shows the equivalent circuit for the rectifier including the effects of commutation. Note in the figure and in the equations above, that the DC current is negative for the rectifier operation due to the representation with load-orientation.

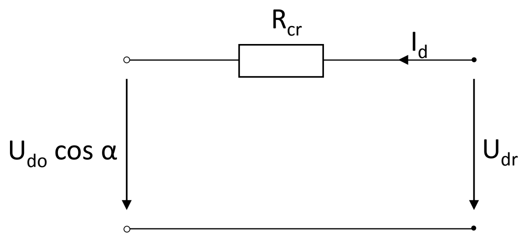

Figure 1.4: Rectifier equivalent circuit with equivalent commutating resistance R_{cr}

With the DC current being equal to its rated value I_d, the DC voltage can be written in a different form as:

$$U_d = U_{d0} \cdot (\cos(\alpha) - d_{xr}) \tag{8}$$

with

$$d_{xr} = \frac{1}{2} \cdot \frac{u_{kr}}{100} \tag{9}$$

The term d_{xr} has been calculated from the following relationship:

$$d_{xr} = \frac{3}{\pi} \cdot X_c \cdot \frac{|I_d|}{U_{d0}} \tag{10}$$

assuming the converter transformer rated current I_r is equal to $sqrt(2)/sqrt(3) \cdot I_d$ (see section 1.1.2) and expressing U_{do} according to equation 3.

The phase voltages and currents, as well as the DC voltage of a thyristor rectifier, including effects of commutation can be seen in Figure 1.5. The ignition angle α and the commutation angle μ are indicated in the figure.

Using these two angles two other angles can be defined. The extinction angle γ, which is normally used in the control on the inverter side of the HVDC, is defined as:

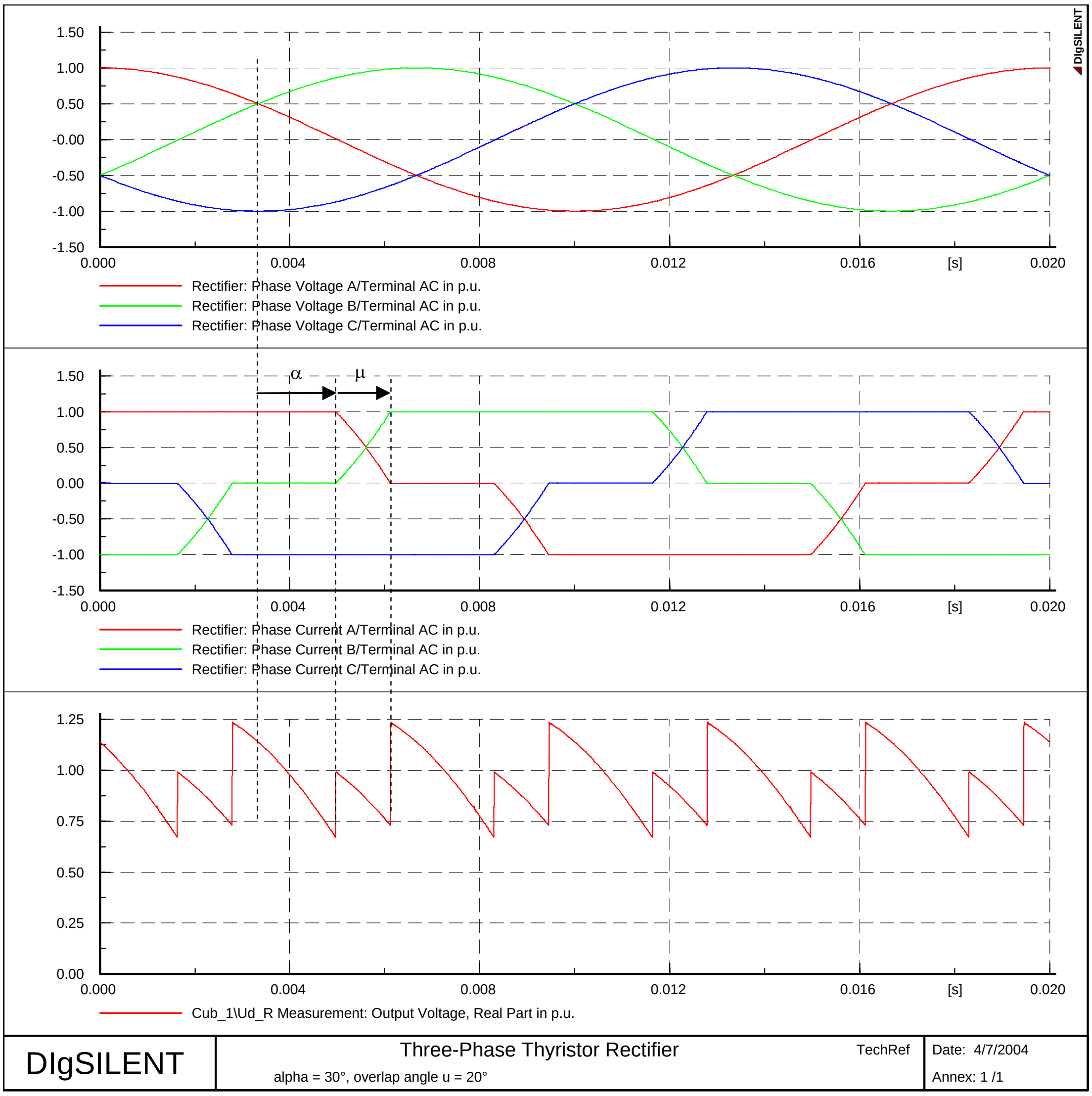

Figure 1.5: Phase voltages, phase currents and DC voltage of a three-phase rectifier operating with $\alpha = 30°$ and an overlap angle of $\mu = 20°$

$$\gamma = \pi - \alpha - \mu \tag{11}$$

The ignition advance angle β is defined as

$$\beta = \pi - \alpha \tag{12}$$

β is often used in the HVDC controllers for both the rectifier and inverter side.

Using these different angles the DC voltage can be calculated differently for the rectifier and for the inverter respectively:

$$U_{dr} = U_{d0} \cdot \frac{\cos(\alpha) + \cos(\alpha + \mu)}{2} \tag{13}$$

and

$$U_{di} = U_{d0} \cdot \frac{\cos(\beta) + \cos(\gamma)}{2} \tag{14}$$

The DC voltage for the inverter case is considered positive in equation 14. Using equations 13 and 8, the term d_{xr} can be expressed as:

$$d_{xr} = \frac{\cos(\alpha) - \cos(\alpha + \mu)}{2} \tag{15}$$

The phase currents of the 6-pulse bridge are shown in Figure 1.3 and Figure 1.5. In the literature the AC current is often calculated approximately from the ideal rectifier current with the commutation angle neglected. In *PowerFactory* the amplitude of the fundamental frequency current I_{L1} is calculated using the Fourier analysis of the phase current waveform, so the effect of the commutation is taken into account. This leads to the following relationship between the RMS value of the fundamental frequency component and the direct current:

$$I_{L1} = k \cdot \frac{\sqrt{6}}{\pi} \cdot I_d \tag{16}$$

where k is equal to

$$k = \frac{\sqrt{[\cos(2\alpha) - \cos 2(\alpha + \mu)]^2 + [2\mu + \sin(2\alpha) - \cos 2(\alpha + \mu)]^2}}{4 \cdot [\cos(\alpha) - \cos(\alpha + \mu)]} \tag{17}$$

This factor is close to unity for small values of μ, but if the angle becomes larger, the error increases up to 4% at $\mu = 60°$. For unsymmetrical operation the phase currents have to be calculated differently, which is described in section 1.1.4.

The power factor $cos(\varphi)$ can then be calculated, given the power equivalence on the AC and DC side and using equations 3, 14 and 17:

$$\sqrt{3} \cdot U_{LL} \cdot I_{L1} \cdot \cos(\varphi) = U_d \cdot \mathrm{I}_d = \frac{3\sqrt{2}}{\pi} \cdot U_{LL} \cdot \frac{\cos(\alpha) + \cos(\alpha + \mu)}{2} \cdot I_d \tag{18}$$

$$\cos(\varphi) = \frac{1}{2k} \cdot [\cos(\alpha) + \cos(\alpha + \mu)] \tag{19}$$

1.1.1 Commutation reactance

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 [1].

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

$$X_c = \frac{u_{kr}}{100} \cdot \frac{U_{r,conv}^2}{S_r} \qquad [\Omega] \tag{20}$$

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 $Unom$ and $tapnom$ 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):

  $$U_{r,conv} = Unom \cdot tapnom \tag{21}$$

  If the rated DC voltage of the converter is known, the rated voltage of the converter-side of the transformer can be calculated using the following equation:

  $$U_{r,conv} = \frac{\pi}{3 \cdot \sqrt{2}} \cdot \frac{U_d}{\cos(\alpha) - d_{xr}} \tag{22}$$

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 [1]. In [1], two practical examples for the calculation of the commutation reactances are presented. An external transformer needs to be modelled in this case.

1.1.2 Converter Transformer

The converter transformer can be modelled internally in the model or externally. 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:

  $$\underline{U}_{ac,conv} = \underline{U}_{term} \cdot tapnom \cdot nntap \cdot e^{j \cdot nt2ag \cdot \frac{\pi}{6}} \tag{23}$$

  where *nt2ag* is the built-in transformer phase shift and $\underline{U}_{term}$ is the voltage where the element is connected (grid terminal).

  The built-in transformer has a tap-changer on the LV side to control the converter-side voltage. The tap changer setting is specified with the actual winding ratio *nntap* parameter, which must be between the maximum and minimum turns-ratio specified in the type. The actual winding ratio *nntap* is given in per unit of the nominal turns-ratio *tapnom* of the converter transformer, also specified in the type.

  The built-in transformer can be configured as *Fixed Tap*, to control the firing (*alpha-control*) or extinction (*gamma-control*) angle of the converter. In the last two cases, the *Relaxation Factor* (*krelax*) parameter can be entered to speed up (set a factor of greater than 1.0) or slow down (set a factor of less than 1.0) the tap controller action.

- External transformer

  If an external transformer is used for the converter model, the AC voltage drop over the transformer is calculated using the commutation reactance specified in the converter dialogue window:

  $$\underline{U}_{ac,conv} = \underline{U}_{term} + \jmath \cdot X_c \cdot \underline{I} \tag{24}$$

  where $\underline{I}$ is the current flowing through the element,and X_c is the commutation reactance.

The rated AC current on the converter side of the transformer equals the RMS value of the total AC current which, neglecting commutation effects, consists of rectangular pulses with amplitude equal to the rated DC current I_d and duration of 120°. The rated AC current on the converter side of the transformer is found as:

$$I_{r,conv} = \sqrt{\frac{2}{3}} \cdot I_d \tag{25}$$

Note that this current is the RMS value of the total AC current, and not only of its fundamental frequency component, which is calculated instead as in equation 16. Hence the rated power can be calculated as

$$S_r = \sqrt{3} \cdot I_{r,conv} \cdot U_{r,conv} = \sqrt{2} \cdot I_d \cdot U_{r,conv} = \frac{\pi}{3} \cdot \frac{P_d}{cos(\alpha) - d_{xr}} \tag{26}$$

1.1.3 Losses

The model of the HVDC does not include the effects of losses so far. The losses in the converter bridge are caused due to the different components, i.e. the resistances of valves, transformers, smoothing reactances.

An exact representation of the losses associated with the converter station is very sophisticated, so it is common practice to model the losses in the Load Flow analysis as an equivalent series resistance on the DC side. Two more terms accounting respectively for the forward voltage drop in the thyristors and no-load losses depending on the DC voltage are also considered. In *PowerFactory*, rectifier/inverter losses are specified in fundamental frequency models as:

- No-load losses: specified with the input parameter $Pnold$ in [kW].
- Forward voltage drop losses: specified with the input parameter $swtLossFactor$ in [KW/A].
- Resistive losses: specified with the input parameter $resLossFactor$ in [Ohm].

The converter losses in [MW] are calculated as:

$$DCPoleLosses = G_{noload} \cdot U_d^2 + resLossFactor \cdot I_d^2 + V_{drop} \cdot I_d \tag{27}$$

with:

- $G_{noload} = \dfrac{P_{nold}}{1000 \cdot U_{nom,DC}^2}$ where U_{DCnom} is expressed in kV
- $V_{drop} = sign(I_d) \cdot swtLossFactor \cdot (1 - exp^{-200 \cdot |I_d|})$

To take into account the losses, equation 7 must be modified, both for rectifier and inverter, as:

$$U_d = U_{d0} \cdot \cos(\alpha) + \frac{3}{\pi} X_c \cdot I_d + resLossFactor \cdot I_d + V_{drop} \tag{28}$$

The representation of station losses of a rectifier for load flow calculations is shown in Figure 1.6. Note in the figure and in the equation above, that the DC current is negative for the rectifier operation due to the representation with load-orientation.

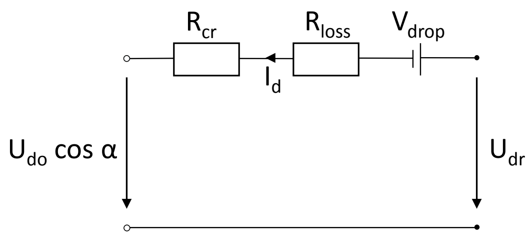

Figure 1.6: Simplified modelling of losses for a 6-pulse converter

The total losses for the element in MW and Mvar are obtained as:

$$\begin{aligned} &Ploss = P_{busac} + P_{busdc} = DCPoleLosses \\ &Qloss = 0 \end{aligned} \tag{29}$$

where P_{busac} and P_{busdc} are calculation parameters available for the element.

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

$$\begin{aligned} &Plossld = Ploss - Plossnld \\ &Qlossld = 0 \end{aligned} \tag{30}$$

where the no-load losses are $Plossnld = G_{noload} \cdot U_d^2$.

1.1.4 Unbalanced Operation

When the network voltages are unsymmetrical, the periods for natural conduction of the valves are not the same and the DC voltage will in general be made of six pulses with different duration and amplitude. The ideal no-load DC voltage can be calculated by taking the average of the pulses over half a period. As an example, with reference to Figure 1.7, at $\omega t = \theta_{ca} + \pi$ the DC current starts flowing in phase *a* and returns back through phase *b* until $\omega t = \theta_{bc}$.

For a thyristor converter, these angles can be delayed by α_a and α_c respectively. During this period, the DC voltage is equal to the line-line voltage U_{ab}. In *PowerFactory*, the thyristor converter implements the Equidistant Pulse Control, igniting the valves at equal time intervals [2].

The angles θ_{ab}, θ_{bc} and θ_{ca}, at which the corresponding line-line voltages cross zero and become positive, are calculated internally in the model, given the terminal voltage phasors. This holds only for load flow and RMS simulations.

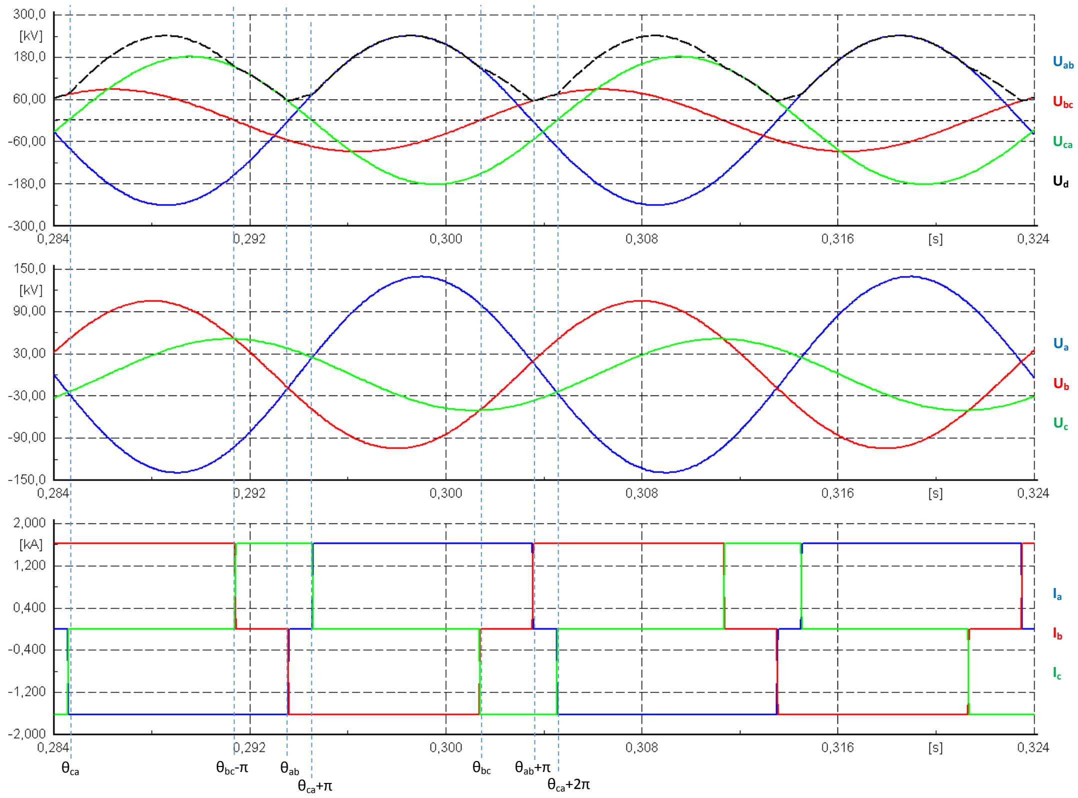

Figure 1.7: Currents and voltages for diode bridge rectifier with unbalanced network voltages and smoothing reactor on the DC side

By taking the average of the resulting three pulses over half a period, the ideal no-load DC voltage is calculated in load flow and RMS simulations as:

$$\begin{aligned} U_d = \frac{1}{\pi} \cdot \{ & U_{ab} \cdot [\cos(\theta_{ca} + \pi + \alpha_a - \theta_{ab}) - \cos(\theta_{bc} + \alpha_c - \theta_{ab})] + \\ & U_{bc} \cdot [\cos(\theta_{ab} + \pi + \alpha_b - \theta_{bc}) - \cos(\theta_{ca} + \alpha_a - \theta_{bc})] + \\ & U_{ca} \cdot [\cos(\theta_{bc} + \pi + \alpha_c - \theta_{ca}) - \cos(\theta_{ab} + \alpha_b - \theta_{ca})] \} \end{aligned} \tag{31}$$

In unsymmetrical load flow and RMS simulations, a PLL will measure the angle θ_1 of the positive zero-crossing of the positive sequence line-line voltage. The firing angles of the valves are then calculated in order to obtain an interval between the firing pulses of 60°. Therefore, the firing angles α_a, α_b and α_c will not be identical but differ according to the phase-shift of the phase voltages. The firing angles of the three phases are calculated internally in the model as (the negative sign is due to the fact that negative angles imply a lagging phase in equation 31):

$$\alpha_a = -[\alpha + (\theta_{ca} - (\theta_1 - 4\pi/3))] \tag{32}$$

$$\alpha_b = -[\alpha + (\theta_{ab} - \theta_1)] \tag{33}$$

$$\alpha_c = -[\alpha + (\theta_{bc} - (\theta_1 - 2\pi/3))] \tag{34}$$

In general it is not possible to obtain a 60° interval between the firing pulses, since this would require leading firing angles. As a consequence, for very large unbalances the pulses will still have different length even after applying different firing pulses for each phase.

The AC currents are affected by the different length of the pulses. Assuming a constant DC current, the amplitude of the fundamental frequency component of the phase currents is in general no longer equal because the conduction periods for each phase are different, as can be seen in Figure 1.7. Let θ_{Ii} represent the conducting time of phase *i*. The RMS value of the fundamental frequency component of each phase current is easily calculated by Fourier series expansion as:

$$I_{L1i} = k \cdot \frac{4}{\pi} \cdot \frac{I_d}{\sqrt{2}} \cdot \sin(\frac{\theta_{Ii}}{2}) \tag{35}$$

The DC power is then calculated as the sum of the real power of all phases on the secondary side of the transformer:

$$P_{dc} = P_a + P_b + P_c \tag{36}$$

2 Load Flow Analysis

In load flow analysis, it is common practice not to specify control variables directly but to define the controlled variables instead. The control variable (the firing angle α) is then resulting from the Load Flow calculation.

In the Load Flow command, several common control characteristics are supported by the HVDC converter model. Meaning and typical application of the various control modes are the following:

- Vdc: The firing angle is adjusted to obtain a predefined value for the DC voltage of the converter. This control mode is typically used at the inverter side of an HVDC transmission system.
- Vac: Specifies the magnitude of the AC voltage at the converter terminals, when the DC voltage is controlled externally. No typical application.
- P: The transmitted AC power is held constant. Typically used for rectifier side in HVDC systems.
- Q: Specifies the amount of reactive power absorbed by the converter. No typical application.
- I: The DC current of the converter is held constant. Typically used for rectifier control of an HVDC transmission system.
- Gamma: The extinction angle γ is specified. Normally the inverter side of an HVDC system is controlled to a minimum γ.
- EXT: The firing angle α is specified as an input to the model, provided by a *Controller* which must be specified with the parameter *pctrl*. The *Controller* is a line-commutated rectifier/inverter element (*ElmRec* or *ElmRecmono*) as well. The *EXT* control mode is useful in a 12-pulse arrangement with two converters: one converter is the *Controller* performing one of the other control modes, while the second converter is in *EXT* control mode.

These control modes are enabled if the flag *Automatic Firing Angle Control* is selected. Otherwise, the firing angle α is set equal to the *Actual Firing Angle*, specified with the parameter *alpha_set*.

Minimum and maximum firing angle limits can be specified. If the converter reaches one of these limits, the firing angle will remain constant at the limit and the converter cannot perform the chosen control function.

A minimum value of the extinction angle, *gammamin*, can also be entered. The angle *gammamin* represents a safe value of γ in order to avoid commutation failure in normal operating conditions; it does not represent the limiting value for commutation failure. If the inverter extinction angle γ reaches this limit, a warning is printed in the output window. For inverters in Vdc (EXT) control mode, the option *Consider minimum extinction angle (gammamin) for control* is available. If the option is selected, the inverter will no longer control the DC side voltage but will switch to a gamma-control mode with *gammamin* as setpoint if gammamin is reached.

In load flow calculations, commutation failure is assumed to take place only when the sum of the firing angle α and of the overlap angle μ would be higher than 180° (negative γ). A warning for commutation failure is printed in the output window. In this case, the load flow is still calculated assuming the overlap angle equal to zero. However, this may not represent a feasible operating point.

During load flow calculation, if the thyristor converter current is very low, the converter current is set to zero. The thyristor converter voltage is set to zero with the firing angle equal to 90°. A message is sent to the output window warning about zero current flowing in the converter.

Furthermore the control of the tap-changers of the converter transformer can be chosen between:

- Fixed Tap: The position of the tap-changers is fixed to a given winding ratio.
- alpha-control: The secondary voltage is adjusted by the tap-changers to obtain a specified setpoint of the firing angle. This is typically used at the rectifier station of the HVDC.
- gamma-control: The tap-changers are controlled to obtain a specified setpoint of the extinction angle. This is typically used at the inverter station of the HVDC.

Besides the firing angle control modes, the load flow page of the converter also comprises additional information for the converter transformer. Here the commutation reactance X_c is specified as the leakage reactance of the transformer, which is important for the calculation of the commutation angle. Also the phase-shift of the converter transformer can be entered here. This information is needed, when designing 12-pulse thyristor bridges with 30° phase-shift between two converters in series to reduce harmonic currents fed into the network.

Attention: This information is also needed, when no built-in transformer is selected in the converter type! The value of the commutation reactance is specified as the reactance of the converter transformer, modelled externally. The value of the commutation reactance is used to estimate the voltage on the transformer primary side, given the converter terminal voltage and current. The estimated voltage is used to calculate the ideal no-load DC voltage. Specifying the correct value of the commutation reactance is also important to get realistic values for the commutation angle.

2.1 P-setpoint Adaption

When the converter is in *P* control mode, usually the rectifier side in an HVDC system, the active power setpoint can be modified by the following controllers if selected:

- *Angle-difference dependent P-droop*
- *Active power participation*

When the ***Angle-difference dependent P-droop*** option is selected, the active power setpoint is modified. If the option *Consider active power setpoint* is selected, the new active power setpoint for the rectifier and inverter case is given according to:

$$P_r = P_{r,set} + Kpphi \cdot (phiu_{local} - phiu_{remote})$$
$$P_i = P_{i,set} - Kpphi \cdot (phiu_{local} - phiu_{remote})$$

If the option *Consider active power setpoint* is not selected, the new active power setpoint for the rectifier and inverter case is given according to:

$$P_r = +Kpphi \cdot (phiu_{local} - phiu_{remote})$$
$$P_i = -Kpphi \cdot (phiu_{local} - phiu_{remote})$$

When the ***Active power participation*** option is selected, the active power setpoint is modified. If the option *Consider active power setpoint* is selected, the new active power setpoint for the rectifier and inverter case is given according to:

$$P_r = P_{r,set} + K_{part} \cdot P_{meas}$$
$$P_i = P_{i,set} - K_{part} \cdot P_{meas}$$

If the option *Consider active power setpoint* is not selected, the new active power setpoint for the rectifier and inverter case is given according to:

$$P_r = +K_{part} \cdot P_{meas}$$
$$P_i = -K_{part} \cdot P_{meas}$$

where:

- $P_{r,set}$ is the active power setpoint, rectifier case.
- $P_{i,set}$ is the active power setpoint, inverter case.
- P_r is the modified active power setpoint, rectifier case.
- P_i is the modified active power setpoint, inverter case.
- $Kpphi$ is the specified factor for *Angle-difference dependent P-droop*.
- K_{part} is the specified factor for *Active power participation*.
- $phiu_{remote}$ is the positive-sequence voltage angle of the remote busbar.
- $phiu_{local}$ is the positive-sequence voltage angle of the local busbar.
- 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. Figure 2.1 shows how to correctly define the sign of *Kpart*. In the example, the converter INV is performing the active power control and has the *Active power participation* option selected.

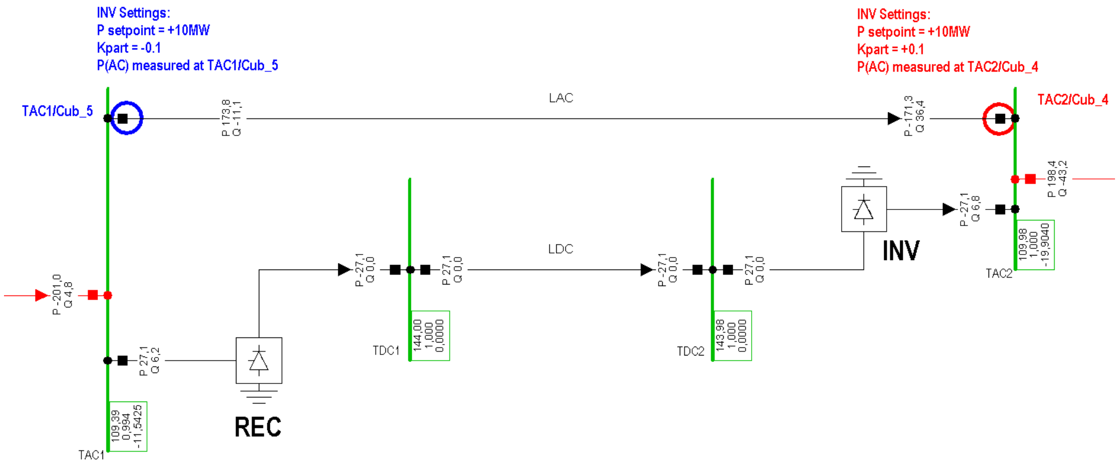

Figure 2.1: *Active power participation* example for converter INV. Active power setpoint is P=10MW.

2.2 HVDC LCC system

If a HVDC LCC system has been defined, the LoadFlow model is equivalent to the LoadFlow model used by the ElmHvdclcc element. Please refer to the Technical Reference of the ElmHvdclcc for more information.

3 Short-Circuit Calculations

Typically 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 do 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 being the rated AC current of the converter.

Enabling the option *Static converter-fed drive*, the element can be used to represent in short-circuit studies reversible static converter-fed drives, with the converter having then a different layout than a six-pulse bridge. In this case, the contribution of the converter to the short-circuit current is no longer neglected in the VDE 0102/0103 and IEC 60909 calculation method. According to these standards the converters are assumed to be asynchronous machines having a short-circuit current ratio of $I_{shc}/I_{rated} = 3$ and an R/X-ratio of $R/X = 0.1$. The short-circuit current contribution is only considered in symmetrical short-circuits. In case of asymmetrical short-circuits the current contribution of static converter drives is neglected. The contribution is only used to calculate the initial and the peak short-circuit current (*I"* and i_p).

The ANSI and the complete calculation method are not affected by this option.

Only the *ElmRecmono* is considered in the calculation of DC short-circuits according to IEC 61660 and ANSI/IEEE 946. Additional parameters required to perform DC short-circuit calculations according to the standards can be entered in the *DC Short-Circuit* page of the element *ElmRecmono* and of the type *TypRec*. In these pages, data about the commutation resistance, AC side impedance, DC side resistance and inductance, converter connection type and voltage factor are specified.

4 Harmonics

The currents of the 6-pulse thyristor-controlled converter, which are shown in Figure 1.3 with the commutation effect neglected and in Figure 1.5 including commutation, are characteristic waveforms. From these curves it can easily be seen, that the currents not only have a large 50-Hz-component but also cause a flow of harmonic currents of higher orders. Hence the most accurate harmonic model of the HVDC converter is a harmonic current source. The order of the harmonic currents is calculated as

$$h = 6 \cdot n \pm 1 \tag{37}$$

where $n = 1,2...$ is an integer value.

The injected harmonic current component can be calculated as:

$$I_h = \frac{I_{L1}}{h} \tag{38}$$

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:

- *Idealised 6-pulse-bridge*
  The typical spectrum of the converter is assumed up to a specified number (normally 31) using the above two equations with the commutation reactance neglected. This assumption usually causes the harmonic currents to be larger than in reality, but gives a good approximation.
- *Consider overlap angle*
  In this model the harmonic currents are obtained same as in the *Idealised 6-pulse-bridge* 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 6-pulse-bridge* model [2].
- *User defined*
  To represent the converter in a more realistic way, a harmonic current source can be defined and the amplitude and angle of the harmonic currents can be defined as shown in Figure 4.1. A balanced and unbalanced representation can be chosen. More information can be derived from the Technical Reference of the type “Harmonic Sources” (*TypHmccur*).

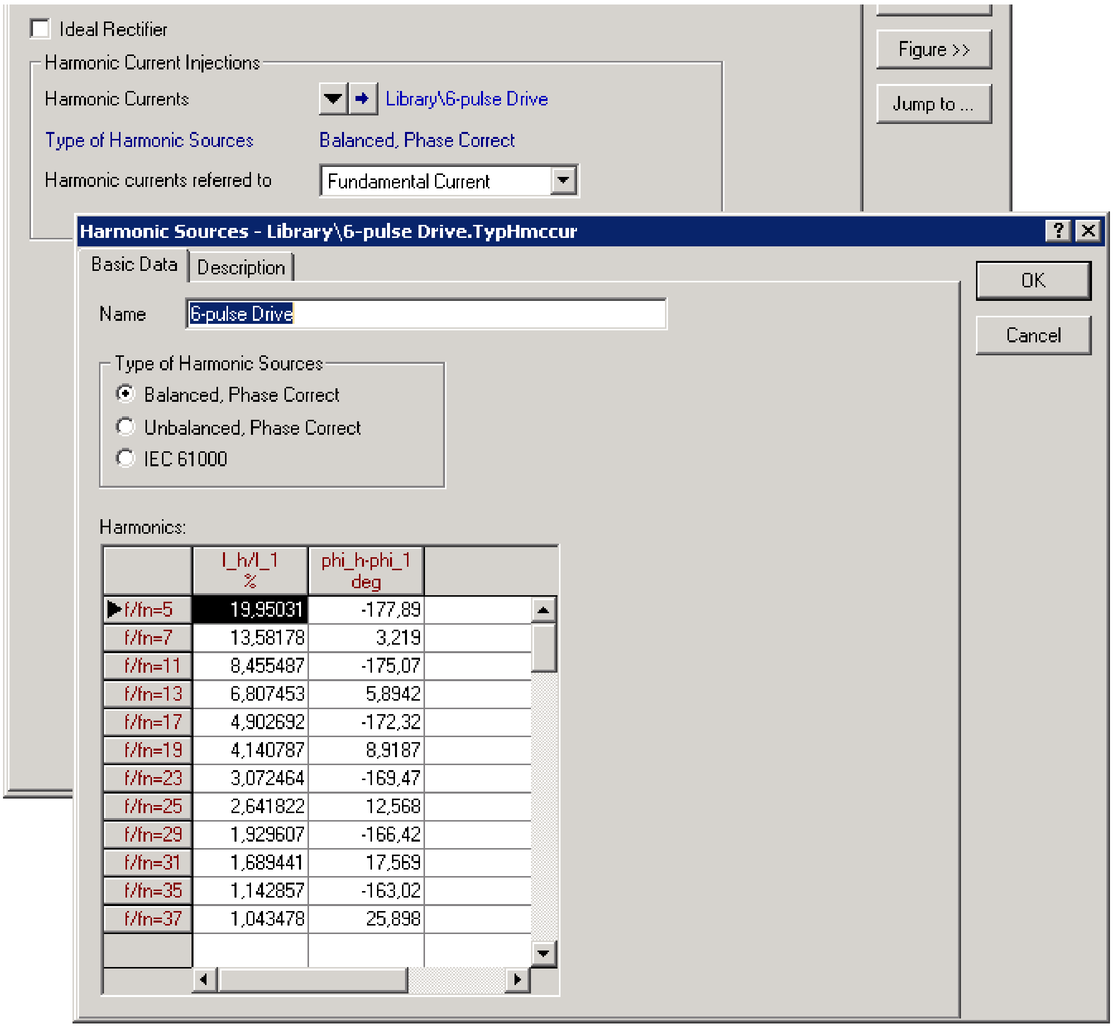

Figure 4.1: Example for a converter representation as harmonic current source

5 Dynamic Simulation

5.1 RMS Simulation

The stability model uses the same equations as described in section 2 (Load Flow analysis).

The converter transformer data, commutation reactance and phase shift, are identical with the values specified on the load flow page of the element.

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 γ reaches the specified *gammamindyn*, a message warning for commutation failure is printed in the output window, the DC side is short-circuited and the converter current is assumed equal to zero. Notice that the *gammamindyn* angle has a different meaning than the *gammamin* angle specified for control purposes in the load flow page.

With the signal *short_dc* is possible to short-circuit the DC side of the element, in order to bypass the valves. The DC voltage and the AC current go to zero during active *short_dc*. With the signal *block_all* all thyristors will be blocked. The AC and DC current are then both zero.

It is possible to select the way the extinction angle γ is handled when the converter is blocked through the parameter *gammaMode*: The angle can either be set to zero or kept constant. An additional output signal *gamma_state* is available. The value of *gamma_state* is 0 in normal operation, 1 if the converter is blocked (AC side), 2 if the converter is shorted (DC side) or if in commutation failure.

The zero sequence current is always zero in RMS simulations.

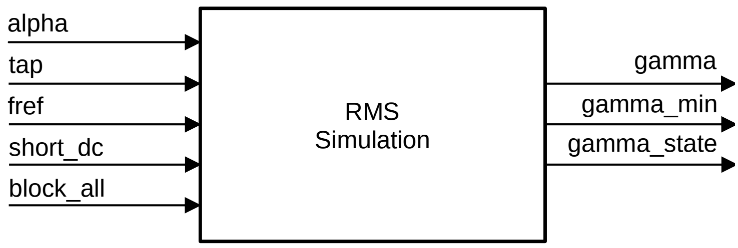

Figure 5.1: Input/Output definition of the HVDC converter model for stability analysis (RMS-simulation)

5.2 EMT Simulation

For the electro-magnetic transient simulation the detailed modelling of all six thyristors or diodes is necessary. Here the converters are modelled as shown in Figure 1.2. This detailed model represents the discrete valves including on- and off-resistances of the switches (R_{on}, G_{off}) and the elements of the snubber-circuits in parallel (shown in Figure 5.2). These values can be defined in the *EMT* page of the type *TypRec*.

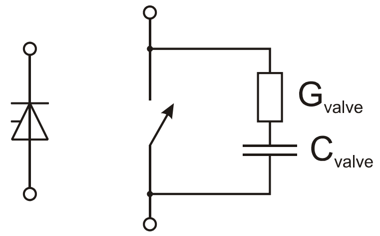

Figure 5.2: Detailed valve representation for EMT-simulations

For triggering the valves the built-in trigger-circuit can be used, which converts the firing angle supplied by the converter controller to the six correct firing signals of the discrete thyristors.

For an exact triggering of the valves, the times of zero-crossing of the AC voltages have to be measured. Since the 6-pulse converter does not have a built-in phase measurement, a PLL element (*ElmPhi__pll*) has to be provided. This means the output of a PLL *Fmeas* is required by the converter for accurate operation.

With the signal *short_dc* is possible to short-circuit the DC side of the element, through a valve with resistance equal to R_{on}. With the signal *block_all* all thyristors will be blocked. The AC and DC current are then both zero.

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

If the built in transformer is used the zero sequence current is always zero.

Attention: Modelling the converter transformer externally (i.e. the flag *Built-In Transformer* in *TypRec* is not selected) 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. Only small errors of this value affect the commutation angle and hence the EMT simulation can not calculate the right initial conditions. Here it is recommended to use the built-in transformer of the converter element instead to get correct results in the EMT-simulation!

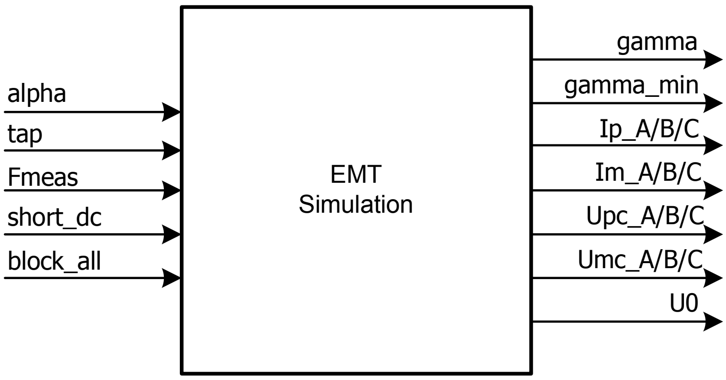

Figure 5.3: Input/Output definition of the HVDC converter model for stability analysis (EMT-simulation)

A Parameter Definitions

Table A.1: Parameters of the HVDC converter element

Parameter	Description	Unit
loc_name	Name	
typ_id	Type (*Typrec*)	
busac	Terminal AC (StaCubic)	
busac_bar	Terminal AC	
busdp	Terminal DC+ (StaCubic)	
busdm	Terminal DC- (StaCubic)	
busdc	Terminal DC (StaCubic)	
busdc_bar	Terminal DC	
outserv	Out of Service	
mode	Orientation (Rectifier/Inverter)	
bstp	Firing Angle (alpha-)Control: Control-Characteristic	
uset	Firing Angle (alpha-)Control: Voltage Setpoint	p.u.
Pset	Firing Angle (alpha-)Control: Power-Setpoint	MW
Qset	Firing Angle (alpha-)Control: Reactive Power-Setpoint	Mvar
Iset	Firing Angle (alpha-)Control: Current Setpoint	kA
gamma_set	Firing Angle (alpha-)Control: Extinction Angle (gamma) Setpoint	deg
pctrl	Firing Angle (alpha-)Control: Controller	
alphacn	Firing Angle (alpha-)Control: Automatic Firing Angle Control	
alpha_set	Firing Angle (alpha-)Control: Actual Firing-Angle	deg
alphamin	Firing Angle (alpha-)Control: Minimum Firing Angle	deg
alphamax	Firing Angle (alpha-)Control: Maximum Firing Angle	deg
gammamin	Firing Angle (alpha-)Control: Minimum Extinction Angle	deg
gammaminCtrl	Consider minimum extinction angle (gammamin) control	
ntrcn	Converter Transformer: Tap-Changer	
nntap	Converter Transformer: Actual Winding Ratio	p.u.
Xd [1]	Converter Transformer: Commutation Reactance	Ohm
nt2ag	Converter Transformer: Phase Shift	*30deg
iPphidrp	Angle difference dependent P-Droop	
Kpphi	Kpphi	MW/degree
p_b1phiu	Remote AC busbar (ElmTerm*)	
p_b2phiu	Local AC busbar (ElmTerm*)	
iPpart	Active power participation	
Kpart	Participation factor	
p_pmeas	P(AC) measured at (StaCubic*,ElmBoundary)	
iconfed	Static converter-fed drive	
i_int	Ideal Rectifier	
maxorder	Maximum Harmonic Order	
phmc	Harmonic Currents (TypHmccur)	
cTypHmc	Type of Harmonic Sources	
icurref	Harmonic Current Injections referred to	
Inom	Rated Harmonic Current Injection	kA
iAstabint	A-stable integration algorithm	
gammamindyn	Min. extinction angle for commutation failure	
gammaMode	Handling of extinction angle if rectifier is blocked	
comres	Commutation resistance (Only ElmRecmono)	Ohm
Racmax	Max. values: AC resistance (Only ElmRecmono)	Ohm
Xacmax	Max. values: AC reactance (Only ElmRecmono)	Ohm

[1] The parameter Xd corresponds to the commutation reactance Xc defined in equation 20

Racmin	Min. values: AC resistance (Only ElmRecmono)	Ohm
Xacmin	Min. values: AC reactance (Only ElmRecmono)	Ohm
volfac	IEC parameters: Voltage factor, c (Only ElmRecmono)	

Table A.2: Parameters of the HVDC Converter Type

Parameter	Description	Unit
loc_name	Name	
Unom	Rated AC Voltage	kV
Unomdc	Rated DC-Voltage (DC)	kV
Pnom	Rated Active Power	MW
Imax	Rated DC-Current	kA
tapnom	Nominal Turns-Ratio (t2/t1)	
alphanom	Nominal Firing Angle	deg
i_diode	Diode-/Thyristor Converter	
i_trf	Converter Transformer: Built-In Transformer	
tapmin	Converter Transformer: Minimum Turns-Ratio	p.u.
tapmax	Converter Transformer: Maximum Turns-Ratio	p.u.
Pnold	Losses: No-load losses	kW
swtLossFactor	Losses: Switching loss factor	kW/A
resLossFactor	Losses: Resistive loss factor	Ohm
Rthy	Thyristor-Resistance (at On)	Ohm
Goff	Thyristor-Conductance (at Off)	S
Gs	Snubber-Conductance	S
Cs	Snubber-Capacity	uF
rres	Rectifier resistance (DC-side)	mOhm
rind	Rectifier inductance (DC-side)	uH
fr_way	ANSI/IEEE Parameters	

B Signal Definitions

Table B.1: Input/Output signals

Name	Description	Unit	Type	Model
alpha	Firing Angle	rad	IN	RMS, EMT
tap	Tap-Position		IN	RMS, EMT
short_dc	DC Bypass		IN	RMS, EMT
block_all	AC Blocking		IN	RMS, EMT
fref	Reference Frequency	p.u.	IN	RMS
Fmeas	Frequency	Hz	IN	EMT
gamma	Extinction Angle	rad	OUT	RMS, EMT
gamma_min	Extinction Angle (Min. in one cycle)	rad	OUT	RMS, EMT
gamma_state	Gamma State		OUT	RMS
Ip_A	Thyristor Current (pos Thyristor, Phase A)	kA	OUT	EMT
Ip_B	Thyristor Current (pos Thyristor, Phase B)	kA	OUT	EMT
Ip_C	Thyristor Current (pos Thyristor, Phase C)	kA	OUT	EMT
Im_A	Thyristor Current (neg Thyristor, Phase A)	kA	OUT	EMT
Im_B	Thyristor Current (neg Thyristor, Phase B)	kA	OUT	EMT
Im_C	Thyristor Current (neg Thyristor, Phase C)	kA	OUT	EMT
Upc_A	Capacitive Voltage (pos Snubber Capacity, Phase A)	kV	OUT	EMT
Upc_B	Capacitive Voltage (pos Snubber Capacity, Phase B)	kV	OUT	EMT
Upc_C	Capacitive Voltage (pos Snubber Capacity, Phase C)	kV	OUT	EMT
Umc_A	Capacitive Voltage (neg Snubber Capacity, Phase A)	KV	OUT	EMT
Umc_B	Capacitive Voltage (neg Snubber Capacity, Phase B)	kV	OUT	EMT
Umc_C	Capacitive Voltage (neg Snubber Capacity, Phase C)	kV	OUT	EMT
U0	Zero Sequence Voltage	kV	OUT	EMT

C References

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

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

List of Figures

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