POWERFACTORY

PowerFactory 2021

Technical Reference

Static Generator

ElmGenstat

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

PF2021

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Contents

1 General Description

The *ElmGenstat* is an easy-to-use model of any kind of three- or single-phase static generator. Applications are:

- Photovoltaic Generators
- Fuel Cells
- Storage devices
- HVDC Terminals
- Reactive Power Compensators
- Wind Generators

Wind generators, which are connected through a full-size converter to the grid, can also be modelled as static generators, because the behaviour of the plant (from the view of the grid side) is determined by the converter.

Note: There is a dedicated photovoltaic element (ElmPvsys) available in *PowerFactory*. This element can calculate its active power for the load flow via the geographic location, date, time and used technique (tracking, material..).

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2 Basic Data

The Basic Data page is split up into the General input tab and the tab for the Zero Sequence/Neutral Conductor data.

2.1 General

On the general tab the connection technology (3Ph, 3Ph-E, 1Ph Ph-E, 1Ph Ph-N) can be selected. The options shown on the second tab depend on the technology selection.

The number of parallel machines can be entered, as well as the MVA rating of a single generator. In general, the total MW and Mvar outputs of the static generator will be the dispatch of a single generator multiplied by the number of parallel machines. In the specific case of the **Wind Generator** category, the output will additionally be affected by the Wind Generation Scaling Factor of the zone to which it belongs.

2.2 Zero/Negative Sequence Model / Neutral Conductor

The input options for the neutral connection as well as for the zero sequence impedance are depending on the selected technology on the General tab.

For the technologies 3Ph-E, 1Ph Ph-E, 1Ph Ph-N it is possible to select how the neutral conductor should be connected. The options are:

- None
- At terminal (ABC-N)
- Separate terminal

The zero sequence is only considered for the technology 3Ph-E. For all other technology options the zero-sequence current is set to zero.

Input Parameter:

- $r0$: Zero-sequence Resistance in p.u.
- $x0$: Zero-sequence Reactance in p.u.

The negative sequence is only considered for technologies 3Ph and 3Ph-E. For all other technology options the negative-sequence current is set to zero. If the available input to control the negative sequence current are not connected, a constant impedance model is considered. The input parameters for the negative sequence impedance is located on the Load Flow/Advanced page. The default value is $99999\ p.u.$ (i.e. negative sequence current equal to 0). For further details on how to control the negative sequence currents, refer to section 3.9 for load flow calculation and to each model subsubsection in RMS calculation.

Input Parameter:

- $r2$: Negative-sequence Resistance in p.u.
- $x2$: Negative-sequence Reactance in p.u.

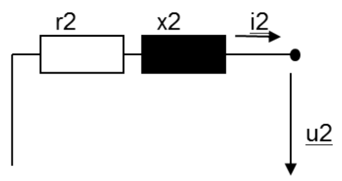

Figure 2.1: Negative-Sequence Model for 3Ph and 3Ph-E technology

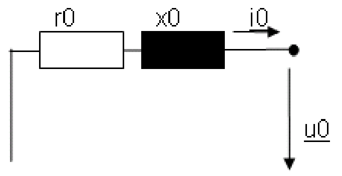

Figure 2.2: Zero-Sequence Model for technology 3Ph-E

3 Load Flow Analysis

The dispatch of the static generator can be entered directly as active and reactive power or by changing the input mode as combination of two parameters P, Q, S or cos(phi).

The active power can be limited as described in Section 3.7.

3.1 Local Controller Options

The local controller can be set to one of the following different modes (which are described in the following sub-chapters):

- Const. V
- Voltage Q-Droop
- Voltage Iq-Droop
- Const. Q
- Q(P)-Characteristic
- Q(V)-Characteristic
- Const. cosphi
- cosphi(P)-Characteristic

3.1.1 Const. V

This option corresponds to a PV bus type and its block diagram is shown in Figure 3.1 (second option P,U) where P and U are controlled.

Voltage control is done locally, i.e. the reactive power output of the generator is controlled to achieve the specified local voltage at its terminal. The dispatched active power output is kept constant. The reactive power will be increased or decreased till either the voltage set point or the reactive power limit (if the option *Consider Reactive Power Limits* in the Load Flow command is enabled) is reached.

When this option is selected, the voltage set-point box is enabled and its value must be entered.

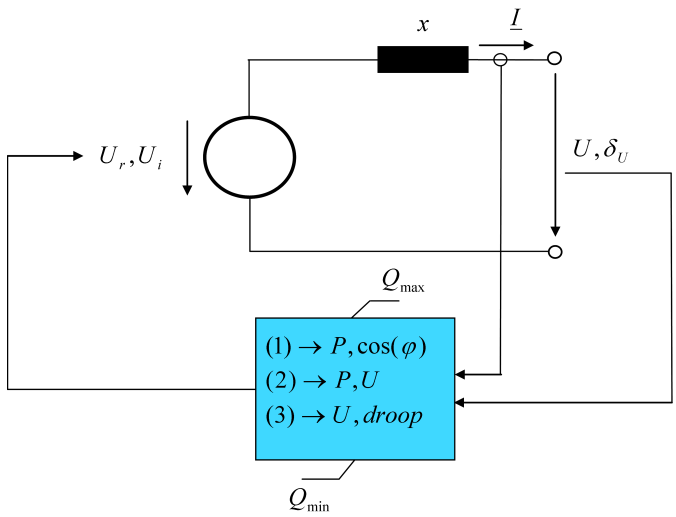

Figure 3.1: Local Controller - Options

3.1.2 Voltage Q-Droop control

Figures 3.1 and 3.2 describe the possibilities for this option. Figure 3.1 includes the alternative to control U and droop function.

The droop control corresponds to a proportional control. This means the amount of reactive power is calculated in proportion to the deviation from the voltage set-point entered in the element. The droop control can be used if several voltage controlling machines are placed close together.

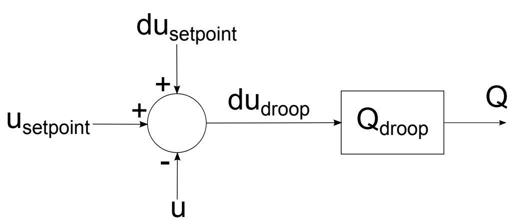

Figure 3.2: Voltage Q-Droop Control

When set to voltage q-droop control, a droop value can be entered. The voltage at the local busbar is then controlled according to the equations below. The equation is shown graphically in Figure 3.3. It can be inferred that a droop value of 1% and a voltage deviation of 0.01 p.u. result in an additional reactive power of 100% of the rated apparent power of the generator. Similarly, a droop value of 2% and the same voltage deviation of 0.01 p.u. result in an additional reactive power of 50% of the rated apparent power of the generator.

$$u = u_{setpoint} - \Delta u_{droop} \tag{1}$$

$$\Delta u_{droop} = \frac{Q - Q_{setpoint}}{Q_{droop}} \tag{2}$$

$$Q_{droop} = \frac{S_r \cdot 100}{ddroop} \tag{3}$$

where:

- u is the actual voltage value at the terminal
- $u_{setpoint}$ is the specified voltage setpoint of the static generator
- Δu_{droop} is the voltage deviation
- $du_{setpoint}$ is the voltage signal coming from the station controller, when the station controller is set to *Voltage Setpoint Adaptation* method, otherwise is zero by default. Please consult the Technical Reference of the Station Controller
- Q is the actual reactive power output of the static generator
- $Q_{setpoint}$ is the specified dispatch reactive power of the static generator
- Q_{droop} is the additional reactive power for the specified voltage droop
- S_r is the rated apparent power
- $ddroop$ is the voltage droop value specified in percentage

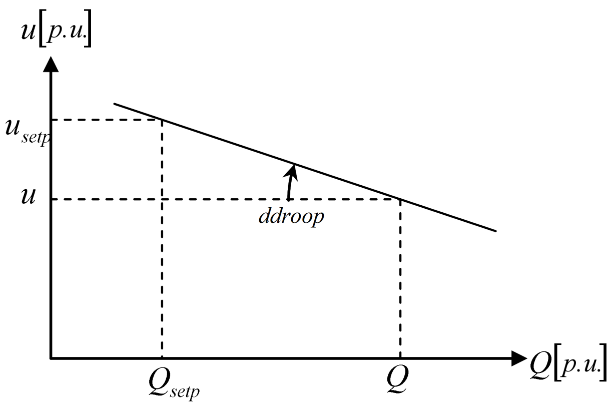

Figure 3.3: Voltage Q-Droop Control

3.1.3 Voltage Iq-Droop

The block diagram for this option is shown in Figure 3.4. The Voltage Iq-Droop control corresponds to a reactive current controller, in which the reactive current is calculated in proportion to the deviation from the voltage set point entered in the element.

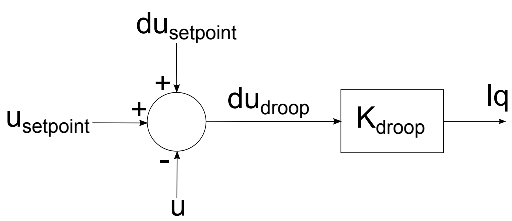

Figure 3.4: Voltage Iq-Droop Control

The voltage reactive current droop in p.u. is based on the rated active current of the machine and calculated as follows:

$$u = u_{setpoint} + du_{setpoint} - \Delta u_{droop} \tag{4}$$

$$\Delta u_{droop} = \frac{Iq - Iq_{setpoint}}{K_{droop} \cdot Ip_r} \tag{5}$$

$$K_{droop} = \frac{100}{ddroop} \tag{6}$$

with the reactive current setpoint:

$$Iq_{setpoint} = \frac{qgini \cdot ngnum}{\sqrt{3} \cdot U_{nom}} \tag{7}$$

and with the rated active current:

$$Ip_r = \frac{sgn \cdot ngnum \cdot cosn}{\sqrt{3} \cdot U_r} \tag{8}$$

Where:

- u is the actual voltage value at the terminal
- $u_{setpoint}$ is the specified voltage setpoint of the static generator
- Δu_{droop} is the voltage deviation
- $du_{setpoint}$ is the voltage signal coming from the station controller, when the station controller is set to *Voltage Setpoint Adaptation* method, otherwise is zero by default. Please consult the Technical Reference of the Station Controller
- Iq is the reactive current output of the machine in kA
- $Iq_{setpoint}$ is the reactive current setpoint of the machine in kA
- K_{droop} is the gain
- $ddroop$ is the voltage droop value specified in percentage
- $qgini$ is the reactive power setpoint in MVA
- $ngnum$ is the number of parallel machines
- U_{nom} is the nominal voltage of the corresponding connected busbar in kV
- U_r is the rated voltage of the machine in kV ($U_r = U_{nom}$)
- Ip_r is the rated active current in kA
- sgn is the rated apparent power in MVA
- $cosn$ is the rated power factor

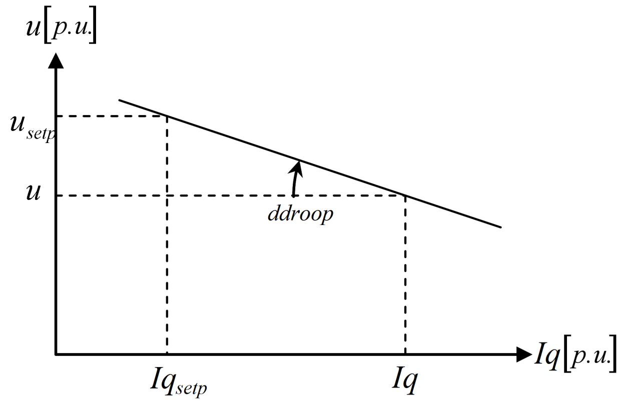

Figure 3.5: Voltage Iq-Droop Control

The dispatched reactive current is calculated by using the nominal voltage of the connected busbar instead of the rated voltage of the machine.

3.1.4 Const. Q

This option corresponds to a PQ bus type and its block diagram is shown in Figure 3.1 (first option P,cos(phi)) where P, cos(phi), U and droop are controlled.

With this type of control, the user can specify active and reactive power outputs at which the static generator will be operated. The way to specify these values will depend on the Input Mode selected for the dispatch.

The voltage and droop value boxes are disabled for the Power Factor control option. P_{sum} and Q_{sum} will be controlled in unbalanced load flow.

3.1.5 Q(P)-Characteristic

The Q(P) characteristic is a reactive power control and follows a user-specified characteristic as shown in Figure 3.6:

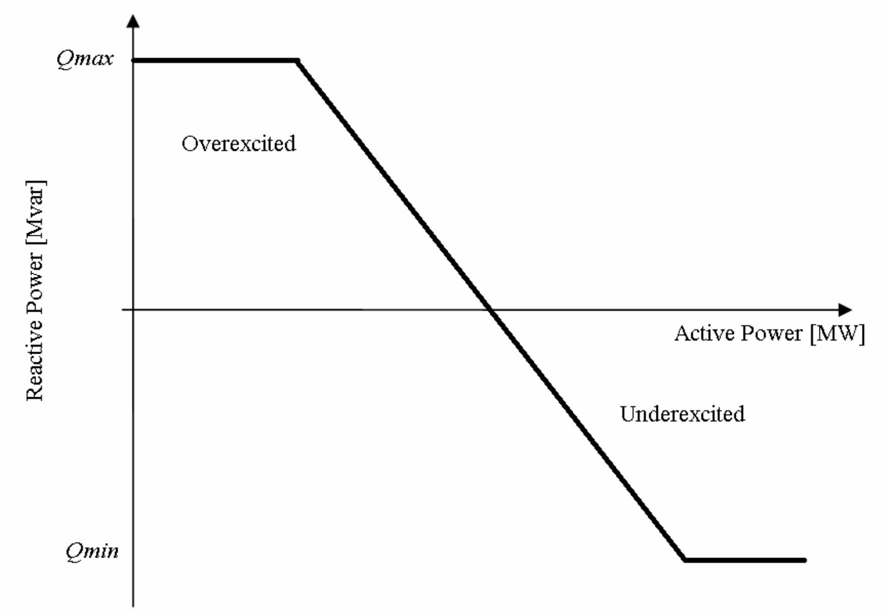

Figure 3.6: Q(P)-Characteristic

The local controller acts as a reactive power controller in which the reactive power setpoint is adapted according to the active power output of the machine.

The Q(P)-Curve is specified using the element “Q(P)-Curve” (*IntQpcurve*).

3.1.6 Q(V)-Characteristic

The Q(V) characteristic is a reactive power control and follows a specified characteristic as shown in Figure 3.7. *Umin* and *Umax* correspond to the lower and upper voltage deadband limit.

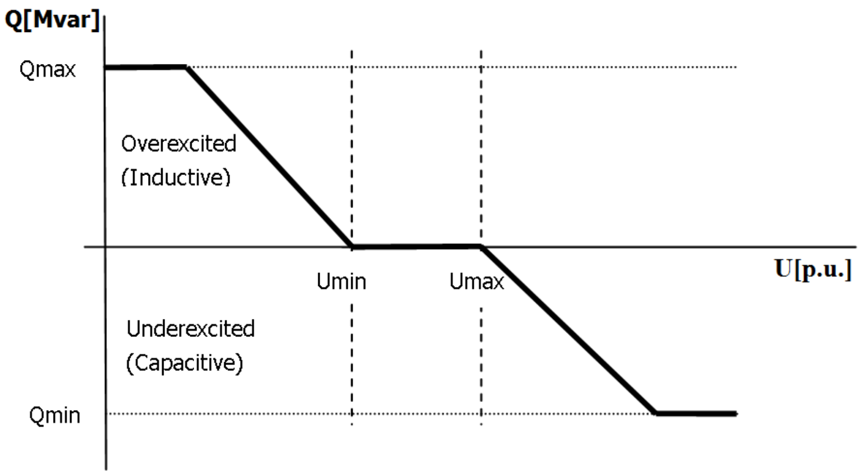

Figure 3.7: Q(V)-Characteristic

The local controller acts as a reactive power controller with a variable setpoint. While the reference voltage is within the deadband, the entered reactive power setpoint is kept. If the reference voltage leaves the deadband, the reactive power setpoint is adapted according to the droop entered by the user and the voltage deviation from the respective end of the deadband.

Additionally, the option *Different droop values* allows specifying two different droop values, one for the overexcited (inductive) side, and another for the underexcited (capacitive) side.

3.1.7 Const. cosphi

The local controller acts as a reactive power controller in which the reactive power setpoint is adapted according to the active power output of the machine, such that the specified power factor is kept constant.

For most cases, the active power setpoint does not vary during the solution, and therefore this mode acts as a constant reactive power control (see Section 3.1.4). However, for the cases where the generator is a slack, or a secondary controller is activated, or the load flow balancing is based on distributed slack by synchronous generators and static generators, then the active power output varies during the solution and this control mode is employed.

3.1.8 cosphi(P)-Characteristic

The cosphi(P) characteristic is a power factor control and follows a specified characteristic as shown in Figure 3.8 and Figure 3.9. The local controller acts as a power factor controller, where the power factor is determined from the characteristic for the input active power flow.

The user needs to define the characteristic with two limits. The overexcited limit is defined with the parameters *p_over* and *pf_over*, and the under-excited limit is defined with the parameters *p_under* and *pf_under*. *PowerFactory* detects which type of curve to use, according to the values *pf_over* and *pf_under*.

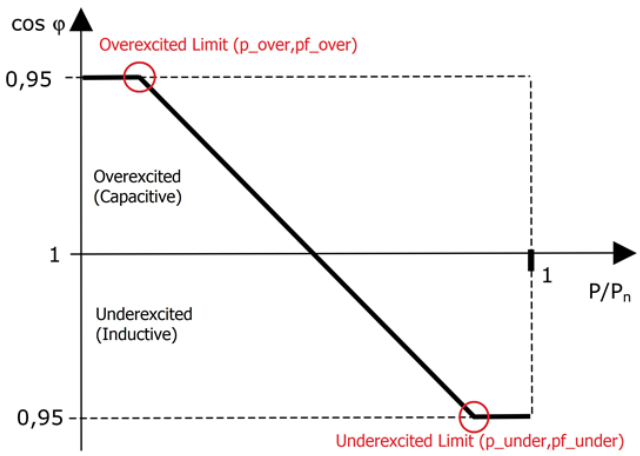

Figure 3.8: cosphi(P)-Characteristic: pf_over <pf_under

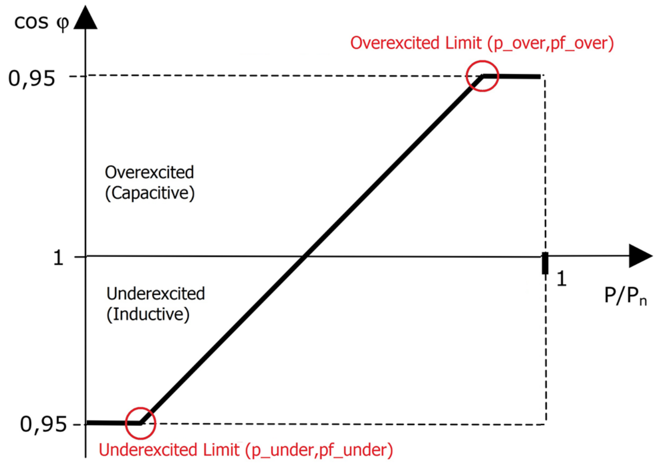

Figure 3.9: cosphi(P)-Characteristic: pf_over >pf_under

3.2 Static Generator as Slack

The static generator can be configured as a *Reference Machine*. This option is only available if a three phase technology (either 3Ph or 3Ph-E) is selected in the Basic Data page.

3.3 External Station Controller

The static generator can also be part of a station controller. In such a case, the external station controller has priority over the local voltage controller of the static generator. The reactive power set point of the single static generator will be considered as offset.

The way the station controller dispatches the static generators depends on the settings of the station controller. See Technical Reference of the Station Controller for more details.

3.4 Wind Speed Input for Wind Generators

When the static generator is a wind generator (Category = Wind) an additional option on the load flow page is available to either enter the active power directly (Active power input) or alternatively via wind speed (Wind speed input) and a corresponding wind power curve.

The active power in MW is then calculated as follow:

$$P = f(windspeed) \cdot scale0 \tag{9}$$

In case of the wind power curve is defined in p.u., the base value is the rated active power $P_r = sgn \cdot cosn$ in MW.

where:

- $windspeed$ is the wind speed in m/s
- $f(windspeed)$ is the corresponding calculated active power value from the wind power curve
- sgn is the rated apparent power

- $cosn$ is the rated power factor

The max. active power ($Pmax$) is automatically limited by the max. possible active power for the entered wind speed:

$$Pmax = Min(\ f(windspeed)\ or\ Pmax_{uc}) \tag{10}$$

where $Pmax_{uc}$ is the max. active power operational limit.

3.5 Primary frequency bias

Shortly following a disturbance, the governors of the units participating in primary control will increase/decrease their turbine power and drive the frequency close to its nominal value. The change in the generator power is proportional to the frequency deviation and is shared among participating units according to the gain (*Kpf*) of their primary controllers, this is depicted in Figure 3.10. If the *Active Power Control According to Primary Control* option is selected in *PowerFactory*'s Load Flow command, the power balance is established by all generators having a primary controller gain (parameter *Prim. Frequency Bias* from the Load Flow tab of the static generator), according to the corresponding frequency droop. This parameter is only available if a three phase technology (either 3Ph or 3Ph-E) static generator is selected.

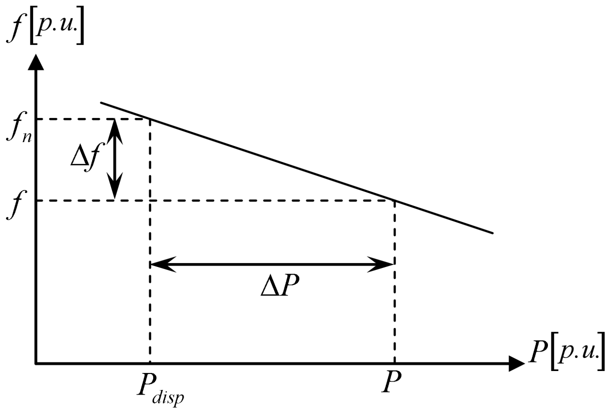

Figure 3.10: Primary Frequency Bias

The actual dispatched real power of the generator is calculated as:

$$P = P_{dispatch} + \Delta P \tag{11}$$

$$\Delta P = \Delta f \cdot Kpf \tag{12}$$

where:

- ΔP is the change in generator output
- Δf is the change in frequency
- Kpf is the primary frequency bias parameter of the generator

The corresponding calculation quantities (signal) for the frequency deviation can be found in the variable selection dialogue ($s : dFin$ in Hz).

3.6 Reactive Power Limits

The reactive power limits can be either specified as constant limits or via a *capability curve*. In both cases the reactive power output will be limited if the option *Consider Reactive Power Limits* on the Load Flow command is activated.

The given limits can be further scaled via the *Scaling Factor (min.)/(max.)* input parameters. These scaling values are used if the option *Consider Reactive Power Limits Scaling Factor* in the Basic Options of the Load Flow calculation dialog is activated.

Minimum/maximum constant limits
These values are used if no capability curve is selected. The input is available as absolute values *cQ_min* and *cQ_max* or as per unit values (*q_min*, *q_max*). In the case of the minimum/maximum limits, these are originally set equal to the minimum and maximum value of the rated apparent power.

Note: The reactive power limits are treated as operational data and will be saved to the operation scenario if active.

Capability Curve objects (IntQlim)
The capability curve allows the consideration of distinct voltage dependent minimum / maximum values of the reactive power at different levels of active power injection. Capability curves are stored inside the *Mvar Limits Curves* folder in the Operational Library.

How to create a new capability curve object is explained in the help of *PowerFactory*.

3.6.1 Applying Mvar Limits Curve from Operational Library

To apply an existing generator capability curve to a generator:

- Locate the “Reactive Power Limit” section in the Load Flow page of the static generator dialog.
- Press next to “Capability Curve”.
- Choose “Select...” to look for a suitable curve in the “Mvar Limit Curves” folder in the “Operational library” folder.

3.7 Active Power Limits

There are two ways to set a limit for the active power. If one of the two limits is exceeded during a Load Flow calculation a warning massage will be displayed in the output window. The active power will be limited if the option *Consider Active Power Limits* is activated in the Load Flow command on the *Active Power Control* page.

The *Active Power Operational Limits* are the minimum and maximum MW output limits of the generator from an operational perspective. The default value is 9999 MW.

The *Active Power: Rating* is the maximum active power output of the generator. The default value is calculated by multiplying the generator nameplate MVA rating by the power factor and the rating factor.

3.8 Automatic Dispatch

The three phase static generator can be part of a virtual power plant (*ElmBmu*) which can manage the active power dispatch. For this a virtual power plant (*ElmBmu*) has to be selected on the Automatic Dispatch tab and the *Generator Dispatch* has to be set to *Dispatchable*.

3.9 Negative Sequence

In load flow it is possible to control the injected negative sequence current through the input $i2r\_set$ and $i2i\_set$, using a Quasi-Dynamic Simulation Model (ElmQdsl).

If these input are not connected, a constant impedance model is considered.

4 Short-Circuit Calculation

4.1 VDE/IEC Short-Circuit

Static generators with three-phase technology can be configured as one of the following in any VDE/IEC short-circuit calculation:

- No short-circuit contribution
- Static converter-fed drive
- Equivalent synchronous machine

The following additional configurations are available for the short-circuit calculation according to IEC60909-2016:

- Doubly fed asynchronous generator
- Full size converter

The common equivalent circuit is shown in Figure 4.1.

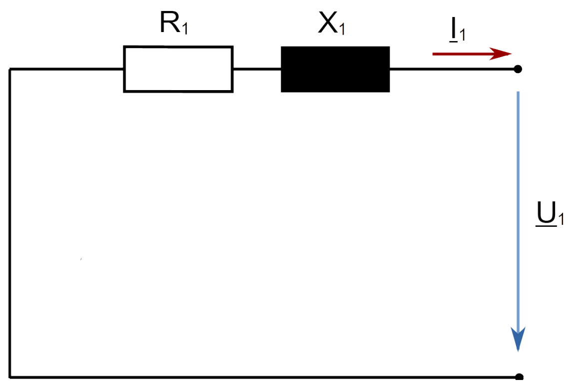

Figure 4.1: Equivalent positive sequence circuit for use in the VDE/IEC short-circuit calculation

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$X_1 = \frac{|Z_1|}{\sqrt{1 + (R/X)^2}} \tag{13}$$

$$R_1 = R/X \cdot X_1 \tag{14}$$

where:

- $|Z_1|$ is the magnitude of the impedance in $[\Omega]$
- R/X is the R/X ratio

Details of the different configurations and the calculation of the impedance are given in the sections below. Static generators are only considered for the calculation of maximum short-circuit currents in the VDE/IEC short-circuit calculation and are always neglected when calculating minimum short-circuit currents.

Note: Static generators with single-phase technology are not considered in any *PowerFactory* VDE/IEC short-circuit calculation.

4.1.1 No Short-Circuit Contribution

In this configuration, the static generator will not contribute to VDE/IEC short-circuit calculations.

4.1.2 Static Converter-Fed Drive

Static generators configured as a *Static Converter-Fed Drive* will only contribute to the subtransient and peak short-circuit currents.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 4.1, is calculated as follows:

$$|Z_1| = \frac{1}{3} \cdot \frac{{U_N}^2}{S_N} \tag{15}$$

$$R/X = 0.1 \tag{16}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- S_N is the nominal apparent power in [MVA] (*e:sgn*)

Steady-State and Breaking Current

As per IEC60909, static converter-fed drives do not contribute to breaking or steady-state currents.

Unbalanced Faults

As per IEC60909, static converter-fed drives are always neglected for unbalanced faults.

4.1.3 Equivalent Synchronous Machine

Static generators configured using the option *Equivalent Synchronous Machine* allow input of an individual contribution per generator.

Note: This model is not explicitly included in VDE/IEC standards and should be utilised at the user's discretion.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 4.1, is calculated as follows:

$$|Z_1| = c \cdot \frac{{U_N}^2}{S_k^{''}} \tag{17}$$

$$R/X = R/X^{''} \tag{18}$$

where:

- c is the VDE/IEC voltage factor
- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- $S_k^{''}$ is the subtransient short-circuit level in [MVA] (*e:Skss*)
- $R/X^{''}$ is the subtransient R/X ratio (*e:rtox*)

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the static generator will not contribute more than the specified subtransient short-circuit level, even with a fault at the terminals. This models the power electronic nature of the generator.

Alternative Input Modes

The subtransient short-circuit level can be entered as $S_k^{''}$ or $I_k^{''}$, where $S_k^{''} = \sqrt{3} \cdot U_N \cdot I_k^{''}$

The subtransient R/X ratio can be entered as $R/X^{''}$ or $X^{''}/R$, where $R/X^{''} = \left(X^{''}/R\right)^{-1}$

Breaking and Steady-State Current

For breaking and steady-state current calculations, the *Equivalent Synchronous Machine* is treated like an external grid, i.e.:

$$I_k = I_b = I_k^{''} \tag{19}$$

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, due to potentially different negative sequence control strategies during short-circuits, a dedicated set of parameters for the negative sequence impedance is used (*e:r2shc* and *e:x2shc*).

4.1.4 Doubly Fed Asynchronous Generator

Static generators configured using the option *Doubly Fed Asynchronous Generator* represent an asynchronous generator with converter controlled rotor voltage, also known as DFIG. This type is typically found in wind power plants. This model is only available for the short-circuit calculation according to IEC60909-2016.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 4.1, is calculated as follows:

$$|Z_1| = \frac{\sqrt{2} \cdot \kappa_{WD} \cdot U_N}{\sqrt{3} \cdot i_{WD,max}} \tag{20}$$

$$R/X = R/X_{WD} \tag{21}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- κ_{WD} is the factor for the calculation of the peak current contribution (*e:kWD*)
- $i_{max,WD}$ is the maximum instantaneous current contribution in [kA] (*e:iWDmax*)
- R/X_{WD} is the R/X ratio of the doubly fed asynchronous generator (*e:rxWD*)

Note: The factor κ_{WD} may contain effects of the converter protection system and should not be confused with κ used in the calculation of the peak short-circuit current.

If the *Externally Modelled Unit Transformer* option is used, $i_{max,WD}$ is referred to the HV side of the transformer. The resulting impedance, $\underline{Z}_1$, is distributed as described in Section 4.1.6.

Breaking and Steady-State Current

For breaking and steady-state calculations, the *Doubly Fed Asynchronous Generator* uses the input value for the maximum steady-state contribution *e:ikWDmax* in [kA].

If the *Externally Modelled Unit Transformer* option is used, $I_{k,WD}$ is referred to the HV side of the transformer.

$$I_k = I_b = I_{k,WD} \tag{22}$$

Note: Static generators will always be neglected for the calculation of minimum short-circuit currents, hence the input value for the minimum steady-state contribution will not be used.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, dedicated sets of parameters for the negative sequence impedance (*e:r2iec* and *e:x2iec*) and zero sequence impedance (*e:r0iec* and *e:x0iec*) are used.

If the *Externally Modelled Unit Transformer* option is used, $\underline{Z}_2$ is referred to the HV side of the transformer and distributed as described in Section 4.1.6. The zero sequence is not distributed.

Note: Even with the *Externally Modelled Unit Transformer* option enabled, the per-unit system used for the negative sequence impedance remains that of the static generator.

4.1.5 Full Size Converter

Static generators configured using the option *Full Size Converter* model a type of wind or photovoltaic generation which is connected to the network via power electronics. This model is only available for the short-circuit calculation according to IEC60909-2016.

Due to the unique characteristics of power electronics, *Full Size Converters* are treated as ideal current sources and do not use the equivalent impedance shown in Figure 4.1; i.e. $|Z1| = \infty$. Instead, they inject the specified currents based on the fault type:

- $I^{''}_{k3,PF}$ for 3-phase faults; in [kA] (*e:Ikss3PF*)
- $I^{''}_{k2,PF}$ for 2-phase or 2-phase-to-ground faults; in [kA] (*e:Ikss2PF*)
- $I^{''}_{k1,PF}$ for 1-phase-to-ground faults; in [kA] (*e:Ikss1PF*)

If the *Externally Modelled Unit Transformer* option is used, $I^{''}_{k3,PF}$, $I^{''}_{k2,PF}$ and $I^{''}_{k1,PF}$ are referred to the HV side of the transformer.

Breaking and Steady-State Current

For breaking and steady-state calculations, the *Full Size Converter* uses the input value for the maximum steady-state contribution *e:ikPFmax* in [kA].

If the *Externally Modelled Unit Transformer* option is used, $I_{k,PF}$ is referred to the HV side of the transformer.

$$I_k = I_b = I_{k,PF} \tag{23}$$

Note: Static generators will always be neglected for the calculation of minimum short-circuit currents, hence the input value for the minimum steady-state contribution will not be used.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, dedicated sets of parameters for the negative sequence impedance (*e:r2iec* and *e:x2iec*) and zero sequence (*e:r0iec* and *e:x0iec*) are used.

If the *Externally Modelled Unit Transformer* option is used, $\underline{Z}_2$ is referred to the HV side of the transformer and distributed as described in Section 4.1.6. The zero sequence is not distributed.

Note: Even with the *Externally Modelled Unit Transformer* option enabled, the per-unit system used for the negative sequence impedance remains that of the static generator.

4.1.6 Externally Modelled Unit Transformer

Input values obtained from manufacturers for *Doubly Fed Asynchronous Generators* or *Full Size Converters* are typically referred to the HV side of the generator unit transformer. In most cases, the static generator is assumed to model the whole unit; i.e. the nominal voltage of the model is equal to the HV side of the unit transformer. However, if the network model requires the unit transformer to be modelled separately, this option can be used to facilitate this approach.

The following conditions must be met for a transformer to be considered a unit transformer:

- there must be exactly one transformer connected to the static generator;
- it must be a 2-winding transformer (*ElmTr2*);
- it must be a 3-phase transformer; and
- it must be explicitly marked as a unit transformer (*iblock* on the Short-Circuit VDE/IEC page)

With the option enabled and a unit transformer present, relevant equations are referred to the HV side of the transformer and assumed to be in the following form:

$$\underline{Z} = \underline{Z}_T + \left(\frac{U_{r,HV}}{U_{r,LV}}\right)^2 \cdot \underline{Z}_{SG} \tag{24}$$

where:

- $\underline{Z}$ is the impedance of the whole unit seen from the HV side of the unit transformer in [Ω]
- $\underline{Z}_T$ is the impedance of the unit transformer referred to the HV side in [Ω]
- $U_{r,HV}$ is the rated voltage on the HV side of the unit transformer in [kV] (*t:utrn_h*)
- $U_{r,LV}$ is the rated voltage on the LV side of the unit transformer in [kV] (*t:utrn_l*)
- $\underline{Z}_{SG}$ is impedance of the static generator in [Ω]

Note: The impedance correction factor kT for unit transformers of *Doubly Fed Asynchronous Generators* or *Full Size Converters* is ignored, i.e. $kT = 1.0$

.

4.2 Complete Short-Circuit

Static generators with three-phase technology can be configured as one of the following in the complete short-circuit calculation:

- Equivalent synchronous machine
- Dynamic voltage support
- Doubly fed asynchronous generator
- Full size converter

Static generators with single-phase technology can be configured as one of the following in a complete short-circuit calculation for unbalanced faults:

- Equivalent synchronous machine
- Dynamic voltage support

The common equivalent circuit is shown in Figure 4.2.

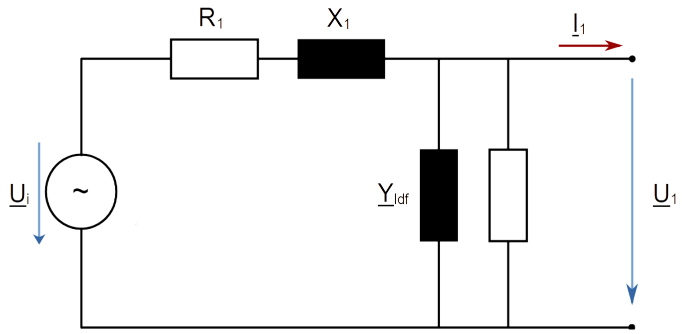

Figure 4.2: Equivalent positive sequence circuit for use in the complete short-circuit calculation

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$X_1 = \frac{|Z_1|}{\sqrt{1 + (R/X)^2}} \tag{25}$$

$$R_1 = R/X \cdot X_1 \tag{26}$$

where:

- $|Z_1|$ is the magnitude of the impedance in $[\Omega]$
- R/X is the R/X ratio

The load flow admittance $\underline{Y}_{ldf} = G_{ldf} + j \cdot B_{ldf}$ and the internal voltage $\underline{U}_i$ depend on the initialisation of the complete short-circuit.

- With load flow initialisation:

$$\underline{Y}_{ldf} = \frac{\underline{I}_{1,ldf}}{\underline{U}_{1,ldf}} \tag{27}$$

$$\underline{U}_i = \underline{U}_{1,ldf} \tag{28}$$

- Without load flow initialisation:

$$\underline{Y}_{ldf} = 0 \tag{29}$$

$$\underline{U}_i = c \cdot \frac{U_N}{\sqrt{3}} \tag{30}$$

where:

- $\underline{U}_{1,ldf}$ is the positive sequence pre-fault voltage in [kV]
- $\underline{I}_{1,ldf}$ is the positive sequence pre-fault current in [kA]
- c is the pre-fault voltage factor (Short-Circuit command input)
- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)

4.2.1 Equivalent Synchronous Machine

Static generators configured using the option *Equivalent Synchronous Machine* allow input of an individual subtransient and transient contribution per generator. Both contributions are considered as rotating contributions.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 4.2, is calculated as follows:

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{31}$$

$$|Z_1| = c \cdot \frac{{U_N}^2}{S_k^{''}} \tag{32}$$

$$R/X = R/X^{''} \tag{33}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- $S_k^{''}$ is the subtransient short-circuit level in [MVA] (*e:Skss*)
- $R/X^{''}$ is the subtransient R/X ratio (*e:rtox*)

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the static generator will not contribute more than the specified subtransient short-circuit level, even with a fault at the terminals. This models the power electronic nature of the generator.

Transient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 4.2, is calculated as follows (depending on whether a subtransient contribution has been specified):

- With $S_k^{''} > 0$

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{34}$$

$$|Z_k^{''}| = c \cdot \frac{{U_N}^2}{S_k^{''}} \tag{35}$$

$$|Z_k^{'}| = c \cdot \frac{{U_N}^2}{S_k^{'}} \tag{36}$$

$$R_1 = R/X^{''} \cdot \frac{|Z_k^{''}|}{\sqrt{1 + (R/X'')^2}} \tag{37}$$

$$X_1 = \sqrt{\left|Z_k^{'}\right|^2 - {R_1}^2} \tag{38}$$

- With $S_k^{''} = 0$

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{39}$$

$$|Z_1| = c \cdot \frac{{U_N}^2}{S_k^{'}} \tag{40}$$

$$R/X = R/X^{''} \tag{41}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- $S_k^{''}$ is the subtransient short-circuit level in [MVA] (*e:Skss*)
- $S_k^{'}$ is the transient short-circuit level in [MVA] (*e:Sks*)
- $R/X^{''}$ is the subtransient R/X ratio (*e:rtox*)

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the static generator will not contribute more than the specified transient short-circuit level, even with a fault at the terminals. This models the power electronic nature of the generator.

The additional dependence on the subtransient short-circuit level is used to keep the resistive part of the impedance constant, so that the change in short-circuit level is modelled as a time-dependent reactance.

Alternative Input Modes

The subtransient and transient short-circuit levels can be entered as $S_k^{''}$ and $S_k^{'}$ or $I_k^{''}$ and $I_k^{'}$, where $S_k^{''} = \sqrt{3} \cdot U_N \cdot I_k^{''}$ and $S_k^{'} = \sqrt{3} \cdot U_N \cdot I_k^{'}$

The subtransient R/X ratio can be entered as $R/X^{''}$ or $X^{''}/R$, where $R/X^{''} = \left(X^{''}/R\right)^{-1}$

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, due to potentially different negative sequence control strategies during short-circuits, a dedicated set of parameters for the negative sequence impedance is used (*e:r2shc* and *e:x2shc*).

4.2.2 Dynamic Voltage Support

Static generators configured using the option *Dynamic Voltage Support* are similar to an *Equivalent Synchronous Machine*, but the transient contribution is modelled as a constant current injection. The subtransient contribution is considered as a rotating contribution.

Note: This model is deprecated and will be removed in future versions. A suitable alternative is the *Doubly Fed Asynchronous Generator*.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ shown in Figure 4.2 is calculated as follows:

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{42}$$

$$|Z_1| = c \cdot \frac{{U_N}^2}{S_k^{''}} \tag{43}$$

$$R/X = R/X^{''} \tag{44}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- $S_k^{''}$ is the subtransient short-circuit level in [MVA] (*e:Skss*)
- $R/X^{''}$ is the subtransient R/X ratio (*e:rtox*)

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the static generator will not contribute more than the specified subtransient short-circuit level, even with a fault at the terminals. This models the power electronic nature of the generator.

Transient Contribution

For static generators with three-phase technology, the transient contribution is modelled as a constant current source, i.e. $|Z_1| = \infty$. For more information about the injection, see Section 4.2.5.

For static generators with single-phase technology, the following simplified rotating contribution is used:

$$|Z_1| = \begin{cases} \frac{1}{K} \cdot \frac{{U_N}^2}{S_N} & \text{if } K < i_{max} \\ \frac{1}{i_{max}} \cdot \frac{{U_N}^2}{S_N} & \text{if } K \geq i_{max} \end{cases} \tag{45}$$

$$R/X = 0 \tag{46}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- S_N is the nominal apparent power in [MVA] (*e:sgn*)
- K is a scaling factor (*e:K*)
- i_{max} is the maximum current in [p.u.] (*e:imax*)

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, due to potentially different negative sequence control strategies during short-circuits, a dedicated set of parameters for the negative sequence impedance is used (*e:r2shc* and *e:x2shc*).

4.2.3 Doubly Fed Asynchronous Generator

Static generators configured using the option *Doubly Fed Asynchronous Generator* represent an asynchronous generator with converter controlled rotor voltage, also known as DFIG. This type is typically found in wind power plants. The subtransient contribution is considered as rotating and the transient contribution is modelled as a constant current injection. This model is only available for static generators with three-phase technology.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ shown in Figure 4.2 is calculated as follows:

$$|Z_1| = \frac{\sqrt{2} \cdot \kappa_{WD} \cdot U_N}{\sqrt{3} \cdot i_{WD,max}} \tag{47}$$

$$R/X = R/X_{WD} \tag{48}$$

where:

- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- κ_{WD} is the factor for the calculation of the peak current contribution (*e:kWD*)
- $i_{max,WD}$ is the maximum instantaneous current contribution in [kA] (*e:iWDmax*)
- R/X_{WD} is the R/X ratio of the doubly fed asynchronous generator (*e:rxWD*)

Note: The factor κ_{WD} may contain effects of the converter protection system and should not be confused with κ used in the calculation of the peak short-circuit current.

If the *Externally Modelled Unit Transformer* option is used, $i_{max,WD}$ is referred to the HV side of the transformer. The resulting impedance $\underline{Z}_1$ is distributed as described in Section 4.1.6.

Transient Contribution

The transient contribution is modelled as a constant current injection, i.e. $|Z_1| = \infty$. For more information about the injection, see Section 4.2.5.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, dedicated sets of parameters for the negative sequence impedance (*e:r2iec* and *e:x2iec*) and zero sequence (*e:r0iec* and *e:x0iec*) are used.

If the *Externally Modelled Unit Transformer* option is used, $\underline{Z}_2$ is referred to the HV side of the transformer and distributed as described in Section 4.1.6. The zero sequence is not distributed.

Note: Even with the *Externally Modelled Unit Transformer* option enabled, the per-unit system used for the negative sequence impedance remains that of the static generator.

4.2.4 Full Size Converter

Static generators configured using the option *Full Size Converter* represent generation which is connected to the network via power electronics. This type is typically found in wind power or photovoltaic plants. Both contributions, subtransient and transient, are modelled as constant current injections. This model is only available for static generators with three-phase technology.

Subtransient Contribution

The transient contribution is modelled as a constant current injection; i.e. $|Z_1| = \infty$. For more information, see Section 4.2.5.

Transient Contribution

The transient contribution is modelled as a constant current injection; i.e. $|Z_1| = \infty$. For more information, see Section 4.2.5.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, dedicated sets of parameters for the negative sequence impedance (*e:r2iec* and *e:x2iec*) and zero sequence (*e:r0iec* and *e:x0iec*) are used.

If the *Externally Modelled Unit Transformer* option is used, $\underline{Z}_2$ is referred to the HV side of the transformer and distributed as described in Section 4.1.6. The zero sequence is not distributed.

Note: Even with the *Externally Modelled Unit Transformer* option enabled, the per-unit system used for the negative sequence impedance remains that of the static generator.

4.2.5 Constant Current Injection

Constant current injections inject a fixed positive sequence current at their terminals. The magnitude of the injected current depends on the voltage dip after the short-circuit calculation has been performed with only rotating machines participating. The angle of the injected current is chosen so that the additional voltage at the fault location, caused by the current injection, is in phase with the pre-fault voltage.

The magnitude of the injected current is calculated as follows:

$$
\begin{aligned}
I_{max} &= i_{max} \cdot I_N \\
\Delta u_1 &= \frac{|\underline{U}_{1,ldf}| - |\underline{U}_{1,rot}|}{U_N} \\
|I_1| &= \begin{cases} K \cdot \Delta u_1 \cdot I_{max} & \text{if } K \cdot \Delta u_1 < 1 \\ I_{max} & \text{if } K \cdot \Delta u_1 \geq 1 \end{cases}
\end{aligned} \tag{49}
$$

where:

- i_{max} is the maximum current injection in [p.u.] (*e:imax*)
- I_N is the nominal current in [kA] ($I_N = S_N/(\sqrt{3} \cdot U_N)$)
- S_N is the nominal apparent power in [MVA] (*e:sgn*)
- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- $\underline{U}_{1,ldf}$ is the positive sequence pre-fault voltage in [kV]
- $\underline{U}_{1,rot}$ is the positive sequence post-fault voltage from rotating machines in [kV]
- K is a scaling factor (*e:K*)

Note: The voltages are always measured at the generator terminal, including when the *Externally Modelled Unit Transformer* option is enabled.

Current Iteration

The magnitude of the injected current depends on the voltage dip from rotating machines. In most cases, the injected current will cause an increase in the terminal voltage. Hence, there will be a discrepancy between the final voltage at the terminal and the voltage used to calculate the injection. The *Current Iteration* option in the Short-Circuit command attempts to rectify this issue by re-calculating the voltage dip with the additional voltage caused by the converter injection. This is an iterative process, as the voltage increase at the terminal is also influenced by network topology and other injections.

The iterative process only adapts the magnitude of the injected current $|I_1|$, not the phase angle.

4.3 ANSI Short-Circuit

Static generators with three-phase technology can be configured as one of the following in the ANSI short-circuit calculation:

- No short-circuit contribution
- Equivalent synchronous machine

The common equivalent circuit is shown in Figure 4.3.

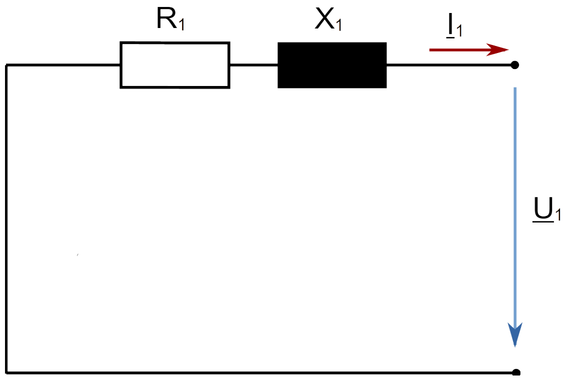

Figure 4.3: Equivalent positive sequence circuit for use in the ANSI short-circuit calculation

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$X_1 = \frac{|Z_1|}{\sqrt{1 + (R/X)^2}} \tag{50}$$

$$R_1 = R/X \cdot X_1 \tag{51}$$

where:

- $|Z_1|$ is the magnitude of the impedance in $[\Omega]$
- R/X is the R/X ratio

Details of the different configurations and the calculation of the impedance are given in the sections below.

Note: Static generators with single-phase technology are not considered in any *PowerFactory* ANSI short-circuit calculation.

4.3.1 No Short-Circuit Contribution

In this configuration, the static generator will not contribute to ANSI short-circuit calculations.

4.3.2 Equivalent Synchronous Machine

Static generators not configured using the option *No Short-Circuit Contribution* allow input of an individual contribution per generator.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$|Z_1| = u_{prefault} \cdot \frac{{U_N}^2}{S_k^{''}} \tag{52}$$

$$R/X = R/X^{''} \tag{53}$$

where:

- $u_{prefault}$ is the pre-fault voltage factor (short-circuit command input)
- U_N is the nominal voltage in [kV] (*e:uknom* of the connected bus)
- $S_k^{''}$ is the subtransient short-circuit level in [MVA] (*e:Skss*)
- $R/X^{''}$ is the subtransient R/X ratio (*e:rtox*)

The voltage factor, $u_{prefault}$, is used in the calculation of $|Z_1|$ to ensure that the static generator will not contribute more than the specified short-circuit level, even with a fault at the terminals. This models the power electronic nature of the generator.

Momentary Current Contribution

For the calculation of momentary currents, the model is considered as described above.

Interrupting Current Contribution

For the calculation of interrupting currents, the model is considered as described above and always considered as a “remote contribution”.

30-Cycle Current Contribution

For the calculation of 30-cycle currents, the model is neglected.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 2.2 are used. However, due to potentially different negative sequence control strategies during short-circuits, a dedicated set of parameters for the negative sequence impedance is used (*e:r2shc* and *e:x2shc*).

Alternative Input Modes

The subtransient short-circuit level can be entered as $S_k^{''}$ or $I_k^{''}$, where $S_k^{''} = \sqrt{3} \cdot U_N \cdot I_k^{''}$

The subtransient R/X ratio can be entered as $R/X^{''}$ or $X^{''}/R$, where $R/X^{''} = \left(X^{''}/R\right)^{-1}$

4.4 IEC 61363

Static generators with three-phase technology are considered as *Equivalent Generators* in the IEC61363 short-circuit calculation. Please refer to the standard for further information.

Note: Static generators with single-phase technology are not considered in any *PowerFactory* IEC61363 short-circuit calculation.

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5 Harmonics

The per unit values of the inductances and reactances are equivalent for frequency f equal to the base frequency $f_{base} = f_{nom}$:

$$x = \frac{\omega}{\omega_{base}} \cdot \frac{L}{L_{base}} \quad \left[\frac{\Omega}{\Omega}\right] = \frac{2 \cdot \pi \cdot f}{2 \cdot \pi \cdot f_{nom}} \cdot \frac{L}{L_{base}} \quad \left[\frac{\Omega}{\Omega}\right] = \frac{f}{f_{nom}} \cdot l = l \quad [p.u.] \tag{54}$$

The impedances in the harmonic analysis functions have frequency dependent reactances due to the change in frequency in the term $\omega_{nom} \cdot L$. It is additionally possible to consider the frequency dependency of the inductances $l(f)$ and resistances $r(f)$:

$$z(f) = r(f) + \jmath \cdot x(f) = r(f) + \jmath \cdot \frac{f}{f_{nom}} \cdot l(f) = r(f) + \jmath \cdot h \cdot l(f) \tag{55}$$

where $h = f/f_{nom}$ is the harmonic order.

This frequency dependency of the impedance can be considered by using characteristics. Several types of characteristics can be applied to the resistances and reactances shown in the Harmonic calculation tab of the static generator:

- Frequency Polynomial Characteristic (*ChaPol*)
- Vector Characteristic (*ChaVec*)
- Matrix Characteristic (*ChaMat*)

For example, when using the vector characteristic, values for the resistance can be entered for predefined frequencies (defined through a frequency scale). When using the frequency polynomial characteristic, the resistance can be made frequency dependent using the parameters a and b according to the functions:

$$\begin{aligned} r(f) &= r \cdot k(f) = r \cdot \left((1-a) + a \cdot (f/f_{nom})^b\right) \\ r(f) &= r \cdot k(f) = r \cdot \left(1 + a \cdot ((f/f_{nom}) - 1)^b\right) \end{aligned} \tag{56}$$

The static generator is represented by a Norton Equivalent current source model in the harmonic analysis. The equivalent circuits of the *Norton Equivalent* model for harmonics analysis are shown in Figure 5.1 (zero sequence model is available if the static generator *Technology* is set to $3PH - E$).

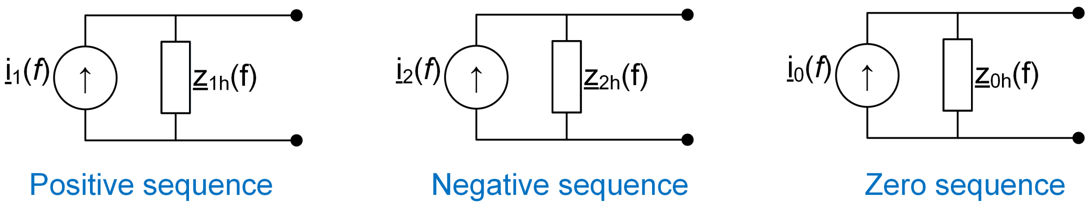

Figure 5.1: Norton Equivalent current source

The frequency dependent impedances are calculated from the input parameters as:

$$\begin{aligned} z_{1h}(f) &= r_{1h}(f) + h \cdot l_{1h}(f) \\ z_{2h}(f) &= r_{2h}(f) + h \cdot l_{2h}(f) \\ z_{0h}(f) &= r_{0h}(f) + h \cdot l_{0h}(f) \end{aligned} \tag{57}$$

The harmonic currents can be defined in an *Harmonic Sources TypHmccur* object. The spectrum of harmonic infeeds may be entered according to one of the options: $balanced$, $unbalanced$ or according to $IEC61000$. The harmonic currents given in the harmonic source object can be referred to the fundamental or rated current of the asynchronous machine. If *Rated Current* is selected then the phase angle is used from the initial bus voltage angle obtained from load flow. More information about the definition of harmonic current sources could be found in the corresponding chapter of the handbook.

The single phase static generator supports only unbalanced current sources.

5.1 Flicker Contribution

The model for flicker contribution is always a constant current source in the positive sequence system. For the negative and zero sequence system, the model of the Norton Equivalent is used, but without harmonic current injection.

6 RMS Simulation

The static generator supports several models which can be selected directly using *Model* parameter. If *According to connected input signals* is selected, it is checked which signals are connected and the corresponding model is being used. In case no signals are connected, the static generator behaves like a constant current source (load flow values are used). If the static generator is the reference machine, then it is automatically set to a constant voltage source model.

For all models except the constant impedance model, the user can specify a minimum operation voltage threshold.

If the negative sequence current is controlled in load flow as described in section 3.9, correct initialization in RMS simulations cannot be achieved with a constant impedance model. Instead, a controlled voltage source (input *u2r_in* and *u2i_in*) or current source model (input *i2d_ref* and *i2q_ref*) is needed in RMS for correct initialization.

6.1 Current source model

The current source model used in the RMS-simulation is shown in Figure 6.1

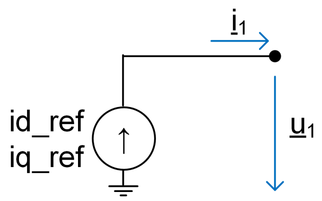

Figure 6.1: Current Source Model

Input Signals:

- id_ref: d-axis current reference in p.u.
- iq_ref: q-axis current reference in p.u.
- $cosref$: cos(dq-reference angle)
- $sinref$: sin(dq-reference angle)

If the input signals $cosref$ and $sinref$ are connected (from a PLL), then the following transformation for the current is used:

$$\underline{i}_1 = (id\_ref \cdot cosref - iq\_ref \cdot sinref) + \jmath \cdot (id\_ref \cdot sinref + iq\_ref \cdot cosref) \tag{58}$$

If the input signals $cosref$ and $sinref$ are not connected:

$$\underline{i}_1 = (id\_ref \cdot cosu - iq\_ref \cdot sinu) + \jmath \cdot (id\_ref \cdot sinu + iq\_ref \cdot cosu) \tag{59}$$

where $sinu$ and $cosu$ are internally calculated variables by using the positive sequence of the terminal voltage as follows:

$$cosu = \frac{Re(\underline{u}_1)}{|\underline{u}_1|} \tag{60}$$

$$sinu = \frac{Im(\underline{u}_1)}{|\underline{u}_1|} \tag{61}$$

If the option *dq-reference angle delay* is used, the internally calculated $sinu$ and $cosu$ are passed through a first order lag using the time constant $Tdelay$ and then used in equation 59.

6.1.1 Negative sequence

The negative sequence current source model used in the RMS-simulation is similar to the positive sequence model. Please note that the positive sequence reference angle is used in the transformation.

Input Signals:

- $i2d\_ref$: Negative sequence current, d-axis reference in p.u.
- $i2q\_ref$: Negative sequence current, q-axis reference in p.u.
- $cos2ref$: cos(negative sequence dq-reference angle)
- $sin2ref$: sin(negative sequence dq-reference angle)

If the negative sequence current input signals are not connected, the model used is described in 2.2.

In order to use a negative sequence angle for the transformation from dq to phasor values, the option *Use negative sequence angle for negative sequence current source* needs to be selected. If the input signals $cos2ref$ and $sin2ref$ are connected, then $\underline{i}_{2set}$ is calculated as:

$$\underline{i}_{2set} = i2d\_ref \cdot cos2ref + i2q\_ref \cdot sin2ref + \jmath \cdot (i2d\_ref \cdot sin2ref - i2q\_ref \cdot cos2ref) \tag{62}$$

If the input signals $cos2ref$ and $sin2ref$ are not connected, then $\underline{i}_{2set}$ is calculated as:

$$\underline{i}_{2set} = i2d\_ref \cdot cosu2 + i2q\_ref \cdot sinu2 + \jmath \cdot (i2d\_ref \cdot sinu2 - i2q\_ref \cdot cosu2) \tag{63}$$

where the quantities $cosu2$ and $sinu2$ are calculated by using the negative sequence of the terminal voltage:

$$cosu2 = \frac{Re(\underline{u}_2)}{|\underline{u}_2|} \tag{64}$$

$$sinu2 = \frac{Im(\underline{u}_2)}{|\underline{u}_2|} \tag{65}$$

If the option *Use negative sequence angle for negative sequence current source* is not selected, the positive sequence angle is used:

$$\underline{i}_2 = i2d\_ref \cdot cosref + i2q\_ref \cdot sinref + \jmath \cdot (i2d\_ref \cdot sinref - i2q\_ref \cdot cosref) \tag{66}$$

or if the input signals $cosref$ and $sinref$ are not connected:

$$\underline{i}_2 = i2d\_ref \cdot cosu + i2q\_ref \cdot sinu + \jmath \cdot (i2d\_ref \cdot sinu - i2q\_ref \cdot cosu) \tag{67}$$

If the option *dq-reference angle delay* is used, the internally calculated $sinu$ and $cosu$ and $sinu2$ and $cosu2$ are passed through a first order lag using the time constant $Tdelay$ and then used in equation 63 or 67.

6.2 Voltage source model

The voltage source model used in the RMS-simulation is shown in Figure 6.2.

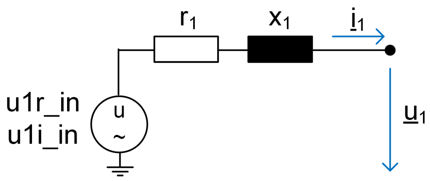

Figure 6.2: Voltage Source Model

Input Signals:

- $u1r\_in$: Voltage input, pos. sequence real part in p.u.
- $u1i\_in$: Voltage input, pos. sequence imaginary part in p.u.

Input Parameter:

- uk : Series reactor, short-circuit impedance in %
- Pcu : Series reactor, copper losses in kW

The following equations are used:

$$u1r\_in + \jmath \cdot u1i\_in = \underline{u}_1 + \underline{z}_1/sgn \cdot \underline{i}_1 \tag{68}$$

where $\underline{z}_1$ is calculated using the input parameters uk, Pcu and sgn:

$$z_1 = uk/100 \tag{69}$$

$$r_1 = Pcu/(1000 \cdot sgn) \tag{70}$$

$$x_1 = \sqrt{z_1^2 - r_1^2} \tag{71}$$

$$\underline{z}_1 = r_1 + \jmath \cdot x_1 \tag{72}$$

6.2.1 Negative sequence

Input Signals:

- $u2r\_in$: Negative sequence voltage input, real part in p.u.
- $u2i\_in$: Negative sequence voltage input, imaginary Part in p.u.

The following equation is used:

$$u2r\_in + \jmath \cdot u2i\_in = \underline{u}_2 + \underline{z}_2 \cdot \underline{i}_2 \tag{73}$$

The negative sequence impedance $\underline{z}_2$ can be defined as the series reactor impedance (by selecting the check box ”Use series reactor impedance, if negative sequence voltage signals are connected”) on the *Simulation RMS* page. In this case the negative sequence impedance is equal to the positive sequence impedance defined in section 6.2. Otherwise the negative sequence impedance described in section 2.2 is used.

Note: Generally the negative sequence impedance of the static generator is equal to the positive sequence impedance (the series reactor impedance is recommended to be used as negative sequence impedance).

6.2.2 Zero sequence

Input Signals:

- $u0r\_in$: Zero sequence voltage input, real part in p.u.
- $u0i\_in$: Zero sequence voltage input, imaginary Part in p.u.

The following equation is used:

$$u0r\_in + \jmath \cdot u0i\_in = \underline{u}_0 + \underline{z}_{sr0} \cdot \underline{i}_0 \tag{74}$$

where $\underline{u}_0$ is the zero sequence voltage at the terminal. The zero-sequence impedance $\underline{z}_{sr0}$ of the series reactor is defined as:

$$\underline{z}_{sr0} = Re(\underline{z}_1) \cdot R0toR1 + j \cdot Im(\underline{z}_1) \cdot X0toX1 \tag{75}$$

where $R0toR1$ and $X0toX1$ can be defined in the RMS and EMT data page (only for *3PH-E* technology).

6.2.3 Reference element model

If the static generator is the reference element in the system, it can be only used as a voltage source model.

If the voltage inputs are not connected when the static generator is the reference element in the system, then they are initialised from the load flow calculation.

The reference frequency of the system can be controlled by using the frequency input signals $f0$ or $F0Hz$.

6.3 Constant impedance model

The constant impedance model is shown in Figure 6.3.

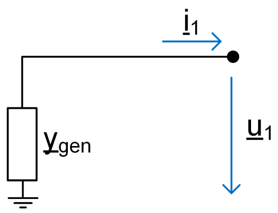

Figure 6.3: Constant impedance model

No input parameters and signals are required since the admittance used in the model is calculated from the load flow results as:

$$\underline{y}_{gen} = \frac{\underline{i}_{1\_ldf}}{\underline{u}_{1\_ldf}} \tag{76}$$

If the element is not connected then y_{gen} is calculated from the entered dispatch active and reactive power.

The equation that needs to be satisfied is:

$$\underline{i}_1 = \underline{y}_{gen} \cdot \underline{u}_1 \tag{77}$$

6.3.1 Negative sequence

The model is described in 2.2.

6.3.2 Zero sequence

The model is described in 2.2.

6.4 Constant power model

The constant power model is shown in Figure 6.4.

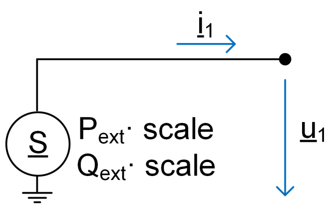

Figure 6.4: Constant power model

Input Signals:

- $Pext$: Active power input
- $Qext$: Reactive power input
- $scale$: Scale factor

The equation that needs to be satisfied is:

$$\underline{u}_1 \cdot \underline{i}_1^* = (Pext + \jmath \cdot Qext) \cdot scale \tag{78}$$

where it can be defined if the input signals are in absolute or per unit values.

6.4.1 Negative sequence

The model is described in 2.2.

7 EMT Simulation

Three different current source and one voltage source model are available for the EMT Simulation. The voltage source model is used if the static generator is the reference element in the system.

In EMT simulation the static generator is represented at the zero sequence either as a constant impedance, as described in section 2.2, or as a voltage source, see section 7.4.

The single phase static generator provides only one phase quantities. In the model implementation for the EMT-simulation, the imaginary voltage and current are generated using a PLL. Please refer to the PLL technical reference for more details.

7.1 Current controlled voltage source model

The current source model is shown in Figure 7.1.

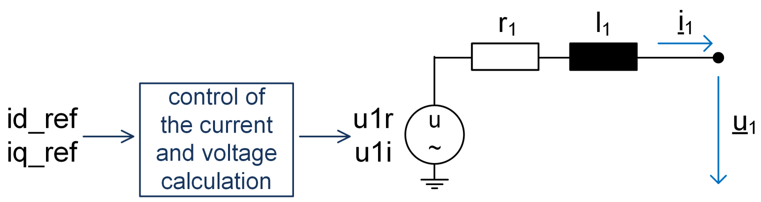

Figure 7.1: Model used for EMT-current source

Input Signals:

- id_ref : d-Axis Current Reference in p.u.
- iq_ref : q-Axis Current Reference in p.u.
- $cosref$: cos(dq-Reference Angle)
- $sinref$: sin(dq-Reference Angle)

The current source model is implemented as a voltage source with a controlled current. The current is controlled with a built-in current controller, which is defined as in Figure 7.2 where:

- K_d is the d-axis proportional gain
- T_d is the d-axis integration time constant in s
- K_q is the q-axis proportional gain
- T_q is the q-axis integration time constant in s

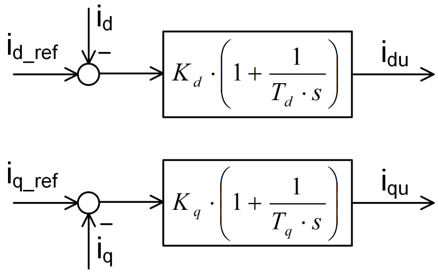

Figure 7.2: Built-in current controller

The voltage of the internal voltage source is calculated in the d-q-frame as follows:

$$u1d = i_{du} - 2 \cdot \pi \cdot f_{nom} \cdot l_1 \cdot i_q \tag{79}$$

$$u1q = i_{qu} - 2 \cdot \pi \cdot f_{nom} \cdot l_1 \cdot i_d \tag{80}$$

where the inductance l_1 in p.u. is calculated as:

$$l_1 = \frac{\sqrt{z_1^2 - r_1^2}}{2 \cdot \pi \cdot f_{nom}} \tag{81}$$

The voltage is transformed back to the system coordinates and applied to the voltage source using $cosu$ and $sinu$ (see Equations 60 and 61) as:

$$u1r = \text{cos}u \cdot u1d - \text{sin}u \cdot u1q \tag{82}$$

$$u1i = \text{sin}u \cdot u1d + \text{cos}u \cdot u1q \tag{83}$$

7.2 Current source model

By putting one of the time constants T_d and T_q equal to zero, the built-in current controller can be disabled and the input signals $i2d\_ref$ and $i2q\_ref$ can be used. The model represents an ideal current source where the positive and negative sequence current can be controlled (Figure 7.3).

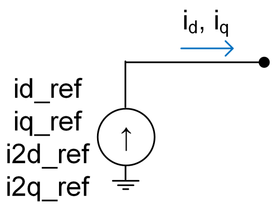

Figure 7.3: Current source model for positive and negative sequence

Input Signals:

- id_ref : d-Axis Current Reference in p.u.
- iq_ref : q-Axis Current Reference in p.u.
- $i2d\_ref$: Negative sequence d-Axis Current Reference in p.u.
- $i2q\_ref$: Negative sequence q-Axis Current Reference in p.u.

- $cosref$: cos(dq-Reference Angle)
- $sinref$: sin(dq-Reference Angle)

The resulting d-q current from the static generator are obtained as (based on $cosu$ and $sinu$ see Equations 60 and 61):

$$id = id\_ref + (i2d\_ref \cdot cos2u + i2q\_ref \cdot sin2u) \tag{84}$$
$$iq = iq\_ref + (-i2d\_ref \cdot sin2u + i2q\_ref \cdot cos2u) \tag{85}$$
$$cos2u = 2 \cdot (cosu)^2 - 1 \tag{86}$$
$$sin2u = 2 \cdot sinu \cdot cosu \tag{87}$$

where the following transformation between the d-q and positive sequence current is valid:

$$id = \mathrm{cos}u \cdot i1r + \mathrm{sin}u \cdot i1i \tag{88}$$
$$iq = -\mathrm{sin}u \cdot i1r + \mathrm{cos}u \cdot i1i \tag{89}$$

7.3 Phase current source model

Current source model when iin_a is connected If the input signal iin_a is connected, the model used is a pure current source as shown in Figure 7.4.

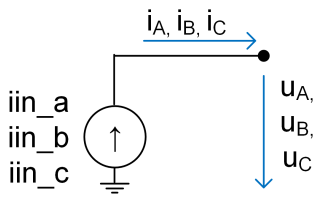

Figure 7.4: Current source model using phase voltages as inputs

This model is available only for the three phase static generator.

7.4 Voltage source model

The voltage source model of the EMT Simulation is using the input signals $u1r\_in$, $u1i\_in$ and $u0\_in$ and is shown in Figures 7.5 and 7.6.

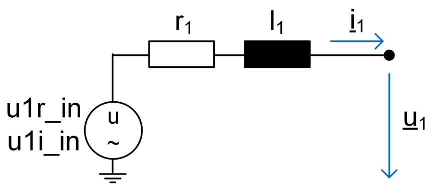

Figure 7.5: Voltage source model (alpha-beta)

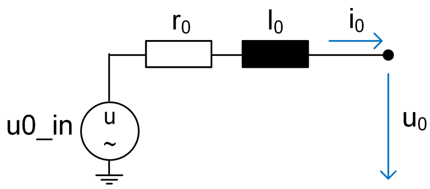

Figure 7.6: Voltage source model (zero sequence)

The zero sequence resistance and inductance are defined as:

$$r_0 = r_1 \cdot R0toR1 \tag{90}$$

$$l_0 = l_1 \cdot X0toX1 \tag{91}$$

where $R0toR1$ and $X0toX1$ can be defined in the RMS and EMT data page (only for *3PH-E* technology).

This model is equivalent as the voltage source model for the RMS-simulation.

7.4.1 Reference element model

If the static generator is the reference element in the system, it can be only used as a voltage source model. The static generator has then the full controllability of the voltage magnitude and frequency through the voltage inputs.

If the voltage inputs are not connected when the static generator is the reference element in the system, then only the frequency of the voltage outputs can be controlled. The voltage outputs are constructed by using the amplitude of the voltages (initialised from the load flow calculation) and a rotating angle with $2 \cdot \pi \cdot Fnom \cdot f0$ or $2 \cdot \pi \cdot F0Hz$. If one of the two frequency input signals are not connected, then the angle rotates constantly with $2 \cdot \pi \cdot Fnom$.

8 Minimum operation voltage in the RMS/EMT models

This feature can be used to block (switch-off) the static generator if the voltage drops under the given minimum voltage (*Switch-off threshold*). The static generator is unblocked (switched-on) if the voltage rises above the *Switch-on threshold*. This is done immediately or after a given delay *Switch-on delay*.

During the blocked state of the element the current is set to zero. The absolute value of the positive sequence voltage is used to detect if a threshold has been reached. In the single phase EMT model, the absolute voltage of the internal PLL is used.

This feature is not supported by the constant impedance RMS model.

9 Input/output definition of dynamic models

9.1 Stability model (RMS)

9.1.1 Current source model

Table 9.1: Input definition of the RMS model

Parameter	Description	Unit
id_ref	d-Axis Current Reference	p.u.
iq_ref	q-Axis Current Reference	p.u.
cosref	cos(dq-reference angle)	
sinref	sin(dq-reference angle)	
i2d_ref	Negative Sequence Current, d-Axis Current Reference	p.u.
i2q_ref	Negative Sequence Current, q-Axis Current Reference	p.u.

Table 9.2: Output definition of the RMS model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.1.2 Voltage source model

Table 9.3: Input definition of the RMS model

Parameter	Description	Unit
u1r_in	Voltage input, real part	p.u.
u1i_in	Voltage input, imaginary part	p.u.
u2r_in	Negative Sequence Voltage input, real part	p.u.
u2i_in	Negative Sequence Voltage input, imaginary part	p.u.
f0	Frequency-Input (only if reference element)	p.u.
F0Hz	Frequency-Input (only if reference element)	Hz

Table 9.4: Output definition of the RMS model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.1.3 Constant impedance model

Table 9.5: Output definition of the RMS model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.1.4 Constant power model

Table 9.6: Input definition of the RMS model

Parameter	Description	Unit
Pext	Active Power Input	p.u./MW
Qext	Reactive Power Input	p.u./Mvar
scale	Scale Factor	

Table 9.7: Output definition of the RMS model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.2 EMT model

9.2.1 Current source model - current controlled voltage source

Table 9.8: Input definition of the EMT model

Parameter	Description	Unit
id_ref	d-Axis Current Reference	p.u.
iq_ref	q-Axis Current Reference	p.u.
cosref	Cos(dq-Reference-Angle)	
sinref	Sin(dq-Reference-Angle)	

Table 9.9: Output definition of the EMT model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.2.2 Current source model for positive and negative sequence

Table 9.10: Input definition of the EMT model

Parameter	Description	Unit
id_ref	d-Axis Current Reference	p.u.
iq_ref	q-Axis Current Reference	p.u.
cosref	Cos(dq-Reference-Angle)	
sinref	Sin(dq-Reference-Angle)	
i2d_ref	Negative Sequence Current, d-Axis Current Reference (if internal current controller is disabled)	p.u.
i2q_ref	Negative Sequence Current, q-Axis Current Reference (if internal current controller is disabled)	p.u.

Table 9.11: Output definition of the EMT model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.2.3 Pure current source Model (when iin_a is connected)

Table 9.12: Input definition of the EMT model

Parameter	Description	Unit
iin_a	Current, Phase A	p.u.
iin_b	Current, Phase B	p.u.
iin_c	Current, Phase C	p.u.

Table 9.13: Output definition of the EMT model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

9.2.4 Voltage source model

Table 9.14: Input definition of the EMT model

Parameter	Description	Unit
u1r_in	Voltage Input, Real Part	p.u.
u1i_in	Voltage Input, Imaginary Part	p.u.
f0	Frequency-Input (only if reference element)	p.u.
F0Hz	Frequency-Input (only if reference element)	Hz

Table 9.15: Output definition of the EMT model

Parameter	Description	Unit
xspeed	Frequency	p.u.
id	Current, d-Axis	p.u.
iq	Current, q-Axis	p.u.

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