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POWERFACTORY

PowerFactory 2021

Technical Reference

AC Voltage Source

ElmVac, ElmVacbi

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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Contents

1 General Description

This document describes the models of the AC voltage Source *ElmVac* and the AC voltage Source with two terminals *ElmVacbi*.

The selection of the *Type* of voltage source is made on the *Basic Data* tab of the voltage source element. The following types are available:

- Voltage Source (Section 2);
- Voltage Source with two terminals (Section 3);
- Ideal RC Voltage Source (Section 7);
- Ward Equivalent (Section 8);
- Extended Ward Equivalent (Section 9).

2 Voltage Source

The AC voltage source model is represented in the positive-, negative-, and zero-sequence as illustrated in Figure 2.1.

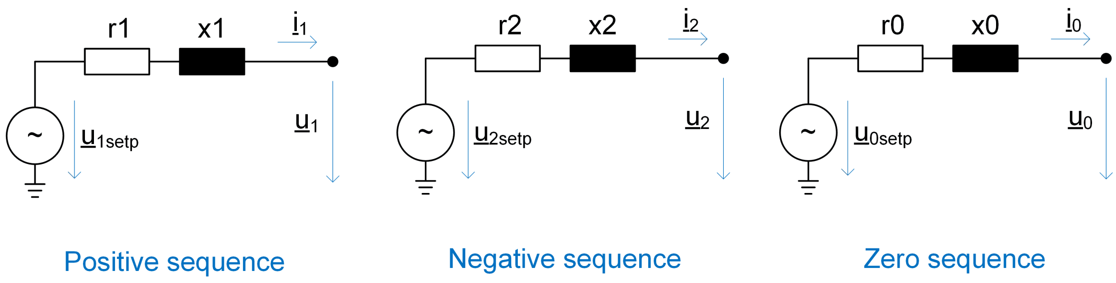

Figure 2.1: Sequence models of the voltage source

The resistance and reactance per unit values are obtained by dividing the input values by the base impedance $Z_{base} = \frac{U_{nom\_t}^2}{1}$ where U_{nom_t} is the nominal voltage square of the connected terminal an and the apparent power is $1MVA$.

Please note that the equations are given for all sequence components. For symmetrical calculations only the positive-sequence equations is taken into account.

2.1 Load Flow Model

Several models can be used for the Load Flow calculation. The standard model used in the Load Flow analysis is described in Section 2.1.1. The models when a remote node is controlled or an external controller is used are described in Sections 2.1.2 and 2.1.3. In cases when input signals are connected to the model through a composite frame (for example when *ElmFile* is used), the models are described in Sections 2.1.5.1 and 2.1.5.2.

Note: For a primary controlled load flow the voltage source forces the frequency deviation to 0. Hz ($dFin = 0.$).

2.1.1 Standard voltage source

In the voltage source, the voltage behind the internal impedance is controlled, and the resulting voltage depends on the impedance value and the current flowing through the element. If the internal impedance is zero, then the resulting busbar voltage is equal to the internal voltage setpoint. The main equations that need to be satisfied, are:

$$\begin{aligned} \underline{u}_1 &= \underline{u}_{1setp} - \underline{z}_1 \cdot \underline{i}_1 \\ \underline{u}_2 &= \underline{u}_{2setp} - \underline{z}_2 \cdot \underline{i}_2 \\ \underline{u}_0 &= \underline{u}_{0setp} - \underline{z}_0 \cdot \underline{i}_0 \end{aligned} \tag{1}$$

The p.u. values of the voltage setpoint input parameters (*usetp, usetp* and *usetp0*) refer to the nominal voltage of the voltage source. The voltage setpoints are calculated from the input parameters as follows:

$$\begin{aligned}
\underline{u}_{1setp} &= usetp \cdot \frac{U_{nom}}{U_{nom_t}} \cdot e^{i \cdot phiu} \\
\underline{u}_{2setp} &= usetp2 \cdot \frac{U_{nom}}{U_{nom_t}} \cdot e^{i \cdot phisetp2 \cdot \pi/180^\circ} \\
\underline{u}_{0setp} &= usetp0 \cdot \frac{U_{nom}}{U_{nom_t}} \cdot e^{i \cdot phisetp0 \cdot \pi/180^\circ}
\end{aligned} \tag{2}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal. The positive sequence voltage angle is calculated as follows:

$$phiu = (\varphi_{ini} - \varphi_{ini\_ref}) + phisetp \cdot \pi/180^\circ \tag{3}$$

φ_{ini} is the parameter $b : phiini$ (available for terminals) representing the initial voltage angle of the voltage source terminal and φ_{ini_ref} is the initial voltage angle of the reference machine terminal. The basic data parameter $b : phiini$ of the terminal takes into account only the initial dispatch angle of the reference machine and the vector group phase shift displacement of the transformers (e.g. if the initial dispatch angle of the reference machine is 0° and there is a Dyn5 transformer connected between the reference machine and the voltage source,the initial angle of the voltage source terminal will be $phiini = -210^\circ \cdot \pi/180 = 150^\circ \cdot \pi/180\ [rad]$);
If the voltage source is the reference machine than is $\varphi_{ini} = \varphi_{ini\_ref}$.

The absolute values of the voltage setpoints can be obtained by multiplying them with the nominal voltage of the connected terminal.

2.1.2 Voltage Magnitude and Angle Controlled at a Remote Node

The voltage source can be used to control the positive sequence voltage magnitude and angle at a user-specified remote node. To do this, it is necessary to select a node.

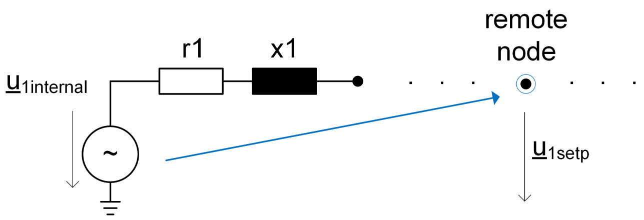

Figure 2.2: Control of remote node

When a remote node is controlled, the p.u. value of the voltage setpoint input parameter $usetp$ refers to the nominal voltage of the remote node. The internal positive sequence voltage $\underline{u}_{internal}$ is automatically calculated so that the target node voltage is controlled to:

$$\underline{u}_{1setp} = usetp \cdot e^{i \cdot phiu} \tag{4}$$

where:

$$phiu = (\varphi_{ini\_remote} - \varphi_{ini\_ref}) + phisetp \cdot \pi/180^\circ \tag{5}$$

φ_{ini_remote} is the parameter $b : phiini$ (available for terminals) representing the initial voltage angle of the remote node.

The resulting remote busbar voltage in absolute values $[V]$ is obtained by multiplying Equation 4 by the nominal voltage of the remote node (not of the voltage source as in the other cases):

$$\underline{U}_{1setp} = \underline{u}_{1setp} \cdot U_{nom\_rembus} \tag{6}$$

The negative and zero sequence voltages are controlled at the local bus and $usetp2$ and $usetp0$ refer to the nominal voltage of the voltage source.

In the case of the remote control being in a different area from the voltage source, the voltage source switches to standard control (see chapter 2.1.1).

2.1.3 Voltage Magnitude and Angle Controlled by an External Controller

The voltage source can be used to control the active power, reactive power or the voltage angle at a busbar. To do this, it is necessary to define a load flow controller model and select it as a voltage magnitude controller and/or a voltage angle controller.

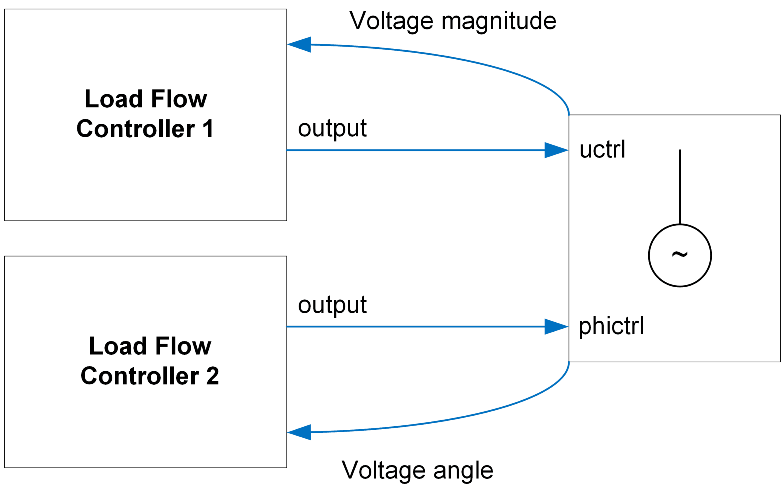

Figure 2.3: Voltage source controlled by external load flow controller

The output signal of the load flow controller is automatically connected to the voltage setpoint signal, $uctrl$, or to the voltage angle setpoint signal, $phictrl$. These two internal input signals are used to define the positive sequence voltage setpoint:

$$\underline{u}_{1setp} = uctrl \cdot e^{i \cdot (phictrl + dphiu)} \cdot U_{nom}/U_{nom\_t} \tag{7}$$

The zero- and negative sequence voltage setpoints are similarly calculated, as in Equation 2.

2.1.4 QDSL Interface

The following input signals are available to control the voltage source via QDSL model:

- $u0$ is the Voltage-Input signal in $p.u.$
- $Ul0$ is the Voltage-Input (Line-Line) in kV
- $dphiu$ is the Voltage Angle Input in rad

When one of the input signal is connected the voltage setpoint $\underline{u}_{1setp}$ is defined as follow (see equations (1)):

$$\underline{u}_{1setp} = \begin{cases} u0 \cdot \dfrac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot phiu1} & \text{if } u0 \text{ connected} \\ Ul0 \cdot \dfrac{1}{U_{nom\_t}} \cdot e^{i \cdot phiu1} & \text{if } Ul0 \text{ connected} \end{cases} \tag{8}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal.

The angle $phiu1$ can be modified by the additional input signal $dphiu$ in $[rad]$ (which is always initialised to 0).

$$phiu1 = (\varphi_{ini} - \varphi_{ini\_ref}) + phisetp \cdot \pi/180^{\circ} + dphiu \tag{9}$$

2.1.5 Measurement File Interface

In cases when input signals are connected to the model through a composite frame (for example when *ElmFile* is used) the voltage voltage setpoint $\underline{u}_{1setp}$ in equation (1)) is defined depending on the connected signal.

2.1.5.1 Input signal $u0$ or $Ul0$ is connected

The positive sequence voltage setpoint is calculated depending which of the input signals is connected:

$$\underline{u}_{1setp} = \begin{cases} u0 \cdot \dfrac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot phiu1} & \text{if u0 connected} \\ Ul0 \cdot \dfrac{1}{U_{nom\_t}} \cdot e^{i \cdot phiu1} & \text{if Ul0 connected} \end{cases} \tag{10}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal.

The angle $phiu1$ can be configured with the input parameter *Positive Sequence Voltage Angle* ($phisetp$) in $[deg]$, or with the input signal $dphiu$ in $[rad]$ (which is always initialised to 0).

$$phiu1 = (\varphi_{ini} - \varphi_{ini\_ref}) + phisetp \cdot \pi/180^{\circ} + dphiu \tag{11}$$

The model equations are the same as in Equation 1.

2.1.5.2 Input signals U_A, U_B and U_C are connected

If the input signals U_A, U_B and U_C are connected (and optionally $phiu_B$ and $phiu_C$), the complex voltages $\underline{u}_A$, $\underline{u}_B$ and $\underline{u}_C$ are calculated as follows:

$$\begin{aligned}
\underline{u}_A &= \sqrt{3} \cdot U_A \cdot \frac{1}{U_{nom_t}} \cdot e^{i \cdot phiu_A} \\
\underline{u}_B &= \sqrt{3} \cdot U_B \cdot \frac{1}{U_{nom_t}} \cdot e^{i \cdot phiu_B} \\
\underline{u}_C &= \sqrt{3} \cdot U_C \cdot \frac{1}{U_{nom_t}} \cdot e^{i \cdot phiu_C}
\end{aligned} \tag{12}$$

The complex voltages are then transformed to sequence components (Figure 2.4) by using the symmetrical component transformation. These voltages are the setpoint voltages that are used in Equation 1. Please note that these input signals are also available for the balanced calculation. In this case, only the positive sequence equation is used.

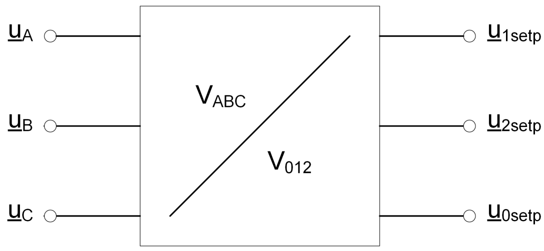

Figure 2.4: Phase to symmetrical components transformation

The angle for phase A ($phiA$) can be configured with the input parameter *Positive Sequence Voltage Angle* ($phisetp$) in $[deg]$, or with the input signal $dphiu$, in $[rad]$.

$$phiu_A = (\varphi_{ini} - \varphi_{ini\_ref}) + phisetp \cdot \pi/180^\circ + dphiu \tag{13}$$

For the angles of phases B and C, two additional signals are available. The angles are relative to the angle of phase A:

$$\begin{aligned}
phiu_B &= phiu_A + phiu_B \cdot \pi/180^\circ \\
phiu_C &= phiu_A + phiu_C \cdot \pi/180^\circ
\end{aligned} \tag{14}$$

If the two angle signals $phiu_B$ and $phiu_C$ are not connected, *PowerFactory* uses the standard 120° shift to calculate the two angles:

$$\begin{aligned}
phiu_B &= phiu_A - 120^\circ \cdot \pi/180^\circ \\
phiu_C &= phiu_A + 120^\circ \cdot \pi/180^\circ
\end{aligned} \tag{15}$$

2.2 Short-Circuit Model

2.2.1 IEC 60909 and VDE 102/103

The model used for the calculating short-circuit currents according to the IEC 60909 (which is equivalent to VDE 102/103) standard is presented in Figure 2.5.

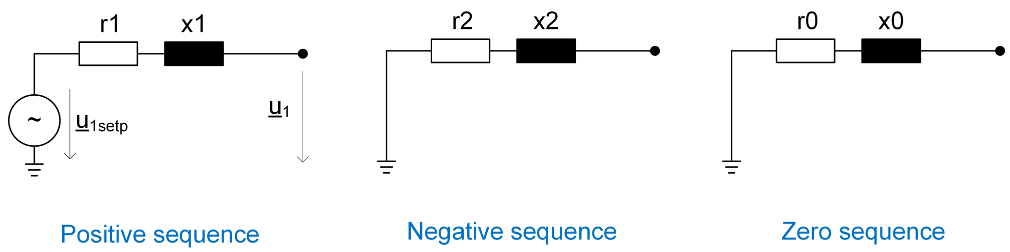

Figure 2.5: IEC 60909 and VDE 102/103 short-circuit model

IEC 60909 makes no provision of the pre-fault state. It always considers a voltage factor $cmax$ of $1{,}1$ (or $1{,}05$ in LV-networks).

In case of the voltage setpoint is zero (smaller than 1e-6 p.u.) the model is used as grounding element. When connected to a supplied area then:

1. unbalanced short-circuit calculation: the positive and negative sequence impedance ignored ($\underline{z1} = \infty$ and $\underline{z2} = \infty$). The zero sequence impedance $\underline{z0}$ is considered.
2. balanced short-circuit calculation: the model ignored ($\underline{z1} = \infty$)

When connected to an unsupplied area the voltage setpoint is forced to 0 p.u. and the model is considered as shown in 2.5.

2.2.2 Complete Short-Circuit Method

Using the complete short-circuit method, the internal voltage source is initialized by a preceding load flow calculation.

Based on the calculated subtransient and transient (AC) currents, *PowerFactory* derives other relevant short-circuit indices, such as peak short circuit current, peak-break current, AC-break current, equivalent thermal short-circuit current by applying the relevant methods according to IEC 60909.

The model used for the calculating short-circuits according to the complete method is equivalent to the model presented in Figure 2.1.

The complete short-circuit method calculates subtransient and transient fault currents using subtransient and transient voltage sources and impedances.

2.2.3 ANSI-C37 Short-Circuit

Besides IEC60909, *PowerFactory* supports short-circuit calculation according to ANSI C-37. Similar to short-circuit calculations according to IEC60909, only subtransient fault currents are actually calculated.

For further details related to ANSI C-37, please refer to the original ANSI C-37 standard and corresponding literature.

2.3 Harmonics and Frequency Sweep Analysis

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

$$x = \frac{\omega}{\omega_{base}} \cdot \frac{L}{L_{base}} \quad \left[\frac{\Omega}{\Omega}\right] = \frac{2 \cdot \pi \cdot f}{2 \cdot \pi \cdot f_n} \cdot \frac{L}{L_{base}} \quad \left[\frac{\Omega}{\Omega}\right] = \frac{f}{f_n} \cdot l = l \quad [p.u.] \tag{16}$$

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 $r(f)$:

$$z(f) = r(f) + \jmath \cdot x(f) = r(f) + \jmath \cdot \frac{f}{f_n} \cdot l(f) = r(f) + \jmath \cdot h \cdot l(f) \tag{17}$$

where $h = f/f_n$ 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:

$$\begin{aligned} r(f) &= r \cdot k(f) = r \cdot \left((1-a) + a \cdot (f/f_n)^b\right) \\ r(f) &= r \cdot k(f) = r \cdot \left(1 + a \cdot ((f/f_n) - 1)^b\right) \end{aligned} \tag{18}$$

2.3.1 Harmonic Load Flow

PowerFactory facilitates the modelling of background harmonics. This is done using either the AC voltage source element (*ElmVac*, *ElmVacbi*) or the external grid element (*ElmXnet*), on their respective *Harmonics/Power Quality* pages. If only the harmonic voltage amplitude is known (and not the angle), the *IEC 61000* option can be selected. Table 2.1 describes the consideration of the sequence components of the harmonic orders for the AC voltage source model.

Harmonic load flow	**Type of harm. voltages**	**Sequence Components of Harmonic Injections**
Balanced	*Phase Correct*	• Positive (i.e. 4, 7, 10, ...), negative (i.e. 2, 5, 8, ...); • Zero sequence orders (i.e. 3, 6, 9, ...) are ignored (with warning). • Non-integer harmonic orders (i.e. 5.5, 6.2, 8.35, ...) are considered in the positive sequence;
	IEC 61000	• Positive, negative; • Zero sequence orders and non-integer harmonics are in the positive sequence.
Unbalanced	*Phase Correct*	• Positive, negative, zero; • Non-integer harmonics are considered.
	IEC 61000	• As for balanced harmonic load flow.

Table 2.1: Sequence components of harmonic injections for AC voltage source

2.3.2 Frequency Sweep Analysis

In the frequency sweep calculation the internal voltage magnitude and angle of the voltage source are set to 0kV and 0° (short-circuited), respectively. An internal voltage can be defined on the *Harmonics* tab of the element dialog, via the use of parameters *Spectral Density of Voltage Magnitude/Angle* ($dudf$, $d\phi df$) in p.u./Hz (or deg/Hz), and the corresponding frequency dependent characteristic. This internal voltage is calculated according to:

$$u_i(\omega_h) = dudf \cdot u_{char}(\omega_h) \tag{19}$$

$$\phi_{Ui}(\omega_h) = d\phi df \cdot \phi_{U,char}(\omega_h) - \Delta\phi_{Ui} \tag{20}$$

where:

$$\Delta\phi_{Ui} = \phi_{Ui} - \phi_{Uref} \tag{21}$$

$dudf$ and $d\phi df$ are constant input parameters used to scale the frequency characteristics u_{char} and $\phi_{U,char}$ in Equation 19. The characteristics can be either polynomial (using the *PowerFactory ChaPol* object) or a vectorial characteristic (using the *ChaVec* object) with a frequency scale (using the *TriFreq* object). The angle $\Delta\phi_{Ui}$ accounts for the angle deviation between the internal voltage and the system reference voltage angle; that is, the angle of the reference machine or slack bus. It allows for the compensation of the voltage shift introduced due to components such as delta-wye connected transformers. Therefore, $\phi_{Ui}(\omega_h)$ is a relative angle - the voltage angle of the harmonic referred to the voltage angle of the source, as calculated by the load flow.

A typical application is the analysis of the transfer function of a part of the system or a particular piece of equipment, or the propagation of a voltage impulse in the frequency domain. For these kinds of applications, the user can assign the spectrum (amplitude and phase) of the excitation voltage to the voltage source and then execute a frequency sweep calculation to calculate the voltage at the remote end.

2.4 RMS-Simulation Model

Very similar as in the Load Flow calculation, the model used for the RMS simulation depends on the connected signals. The RMS model is initialised by using the results of a load flow calculation. The resulting voltages are also described by Equation 1. Please note in the case of a balanced simulation, only the positive sequence equation is used.

In the RMS simulation, the angle $phisetp$ used in Equation 11 and 13 is replaced by $phiu$ which is determined by the change of its derivative as (valid for all RMS models):

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot (f0 - f_{ref}) & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz - 2 \cdot \pi \cdot F_n \cdot f_{ref} & \text{if F0Hz is connected} \\ 0 & \text{if element is the reference} \end{cases} \tag{22}$$

If in the Load Flow calculation, a remote node was controlled, please refer to Section 2.4.3.

2.4.1 Input signal $u0$ or $Ul0$ is connected

In cases when one of the input signals $u0$ or $Ul0$ is connected, the model is equivalent to the model described in 2.1.5.1 (with the difference of how the angle is calculated).

2.4.2 Input signals U_A, U_B and U_C are connected

In cases when the input signals U_A, U_B and U_C (and optionally $phiu_B$ and $phiu_C$) are connected to the model, the models are described in Section 2.1.5.2 (with the difference of how the angle is calculated).

2.4.3 No signals connected

All the voltage and angle input signals of the RMS-simulation are initialised from the results provided by the Load Flow calculation. Also in the case when in the Load Flow calculation a remote node is controlled, $u0$, $Ul0$, U_A U_B U_C, ... are initialised.

Since all of the inputs are initialised, it is possible to use any of the models that require connected signals (Sections 2.4.1 and 2.4.2) and the result will be the same.

By using the parameter *Voltage input* (advanced page), the model can be switched to use $u0$, $Ul0$ or U_A U_B U_C. This is useful when a parameter event needs to be applied on one of the signals.

By using the *Frequency input* parameter, it can be selected if a parameter event can be applied on the signal $F0HZ$ or $f0$.

2.5 EMT-Simulation Model

Very similar as in the Load Flow calculation, the EMT model used depends on the connected signals. The EMT model is initialised by using the results of a load flow calculation. The EMT model transforms the phase voltages available from the EMT simulation to $\alpha\beta\gamma$.

In the EMT simulation, the angle $phisetp$ used in Equation 11 and 13 is replaced by the rotating angle $phiu$ which is determined by the change of its derivative as (valid for all EMT models):

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot f0 & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz & \text{if F0Hz is connected} \end{cases} \tag{23}$$

If in the Load Flow calculation, a remote node was controlled, please refer to Section 2.5.3.

All the voltage and angle input signals of the EMT-simulation are initialised from the results provided by the Load Flow calculation.

For the EMT model, the following equations are valid:

$$\begin{aligned} \underline{u}_{\alpha\beta} &= \underline{u}_{\alpha\beta setp} - r1 \cdot \underline{i}_{\alpha\beta} - \frac{x1}{2 \cdot \pi \cdot F_n} \cdot \frac{d\underline{i}_{\alpha\beta}}{dt} \\ u_\gamma &= u_{\gamma setp} - r0 \cdot i_\gamma - \frac{x0}{2 \cdot \pi \cdot F_n} \cdot \frac{d\underline{i}_\gamma}{dt} \end{aligned} \tag{24}$$

where $\underline{u}_{\alpha\beta} = u_\alpha + \jmath \cdot u_\beta$ and u_γ are the $\alpha\beta\gamma$ components of the terminal voltage.

The sepoint voltages are calculated dependent on the model that is being used.

2.5.1 Input signal $u0$ or $Ul0$ is connected

The α and β setpoint voltages are calculated as:

$$\underline{u}_{\alpha\beta setp} = \begin{cases} u0 \cdot e^{\jmath\cdot(phiu+dphiu)} + \left(uini2 \cdot e^{\jmath\cdot(phiu+phiini2)}\right)^* & \text{if u0 is connected} \\ \dfrac{Ul0 \cdot e^{\jmath\cdot(phiu+dphiu)}}{U_{nom\_t}} + \left(uini2 \cdot e^{\jmath\cdot(phiu+phiini2)}\right)^* & \text{if Ul0 is connected} \end{cases} \tag{25}$$

and the γ setpoint voltage is:

$$u_{\gamma setp} = uini0 \cdot cos(phiu + phiini0) \tag{26}$$

2.5.2 Input signals U_A, U_B and U_C are connected

This model is different to the model described in Section 2.5.1 only in how the setpoint voltages are calculated. First, the $\alpha\beta\gamma$ components are obtained from the input phase voltages U_A, U_B and U_C. Then the following equations are used to calculate the setpoint voltages:

$$\begin{aligned} u_{\alpha setp} &= \frac{\sqrt{3}}{\sqrt{2}} \cdot \frac{u_{\alpha input}}{U_{nom\_t}} \\ u_{\beta setp} &= \frac{\sqrt{3}}{\sqrt{2}} \cdot \frac{u_{\beta input}}{U_{nom\_t}} \\ u_{\gamma setp} &= \frac{\sqrt{3}}{\sqrt{2}} \cdot \frac{u_{\gamma input}}{U_{nom\_t}} \end{aligned} \tag{27}$$

2.5.3 No signals connected

All the voltage and angle input signals of the EMT-simulation are initialised from the results provided by the Load Flow calculation.

By using the parameter *Voltage input* (advanced page), the model can be switched to use equations utilising $u0$ or $Ul0$. This is useful when a parameter event needs to be applied on one of the signals.

By using the *Frequency input* parameter, it can be selected if a parameter event can be applied on the signal $F0HZ$ or $f0$.

The input signals used for U_A U_B U_C in the EMT model need to be sinusoidal. When no input signals are connected, the outputs are initialised from the load flow calculation and are not sinusoidal.

3 Voltage Source with two terminals

The model of the AC voltage source with two terminals does not have an internal impedance. The equivalent circuit is illustrated in Figure 3.1.

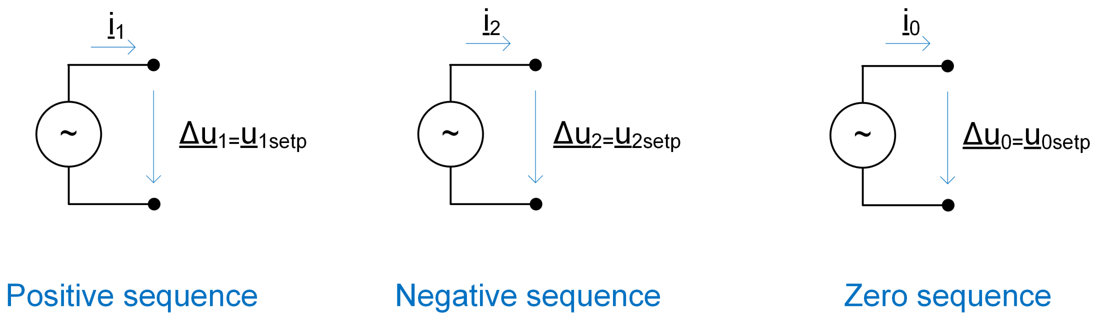

Figure 3.1: Sequence models of the voltage source with two terminals

3.1 Load Flow Model

In the voltage source with two terminals the voltage difference is controlled directly (no impedance is present as in the ElmVac model) to the setpoint voltages:

$$\begin{aligned}\Delta\underline{u}_1 &= \underline{u}_{1setp}\\ \Delta\underline{u}_2 &= \underline{u}_{2setp}\\ \Delta\underline{u}_0 &= \underline{u}_{0setp}\end{aligned} \tag{28}$$

The p.u. values of the voltage setpoint input parameters (*usetp, usetp* and *usetp0*) refer to the nominal voltage of the voltage source. The voltage setpoints are calculated from the input parameters as follows:

$$\begin{aligned}\underline{u}_{1setp} &= usetp\cdot\frac{U_{nom}}{U_{n,bus1}}\cdot e^{i\cdot phisetp\cdot\pi/180^\circ}\\ \underline{u}_{2setp} &= usetp2\cdot\frac{U_{nom}}{U_{n,bus1}}\cdot e^{i\cdot phisetp2\cdot\pi/180^\circ}\\ \underline{u}_{0setp} &= usetp0\cdot\frac{U_{nom}}{U_{n,bus1}}\cdot e^{i\cdot phisetp0\cdot\pi/180^\circ}\end{aligned} \tag{29}$$

where U_{nom} is the nominal voltage of the voltage source in kV and $U_{n,bus1}$ is the nominal voltage of the connected terminal at side 1 in kV.

In case when the voltage source is connected between different voltage level the Δ - voltages are re-based to the terminal 1 nominal voltage:

$$\begin{aligned}\Delta\underline{u}_1 &= \underline{u}_{1,bus1} - \underline{u}_{1,bus2}\cdot\frac{U_{n,bus2}}{U_{n,bus1}}\\ \Delta\underline{u}_2 &= \underline{u}_{2,bus1} - \underline{u}_{2,bus2}\cdot\frac{U_{n,bus2}}{U_{n,bus1}}\\ \Delta\underline{u}_0 &= \underline{u}_{0,bus1} - \underline{u}_{0,bus2}\cdot\frac{U_{n,bus2}}{U_{n,bus1}}\end{aligned} \tag{30}$$

where

- $U_{n,bus1}$ is the nominal voltage in kV of the terminal of connection 1 (bus1)
- $U_{n,bus2}$ is the nominal voltage in kV of the terminal of connection 2 (bus2)

In addition the following current equations are fulfilled:

$$\begin{aligned} \underline{I}_{a,bus1} + \underline{I}_{a,bus2} &= 0 \\ \underline{I}_{b,bus1} + \underline{I}_{b,bus2} &= 0 \\ \underline{I}_{c,bus1} + \underline{I}_{c,bus2} &= 0 \end{aligned} \tag{31}$$

with $\underline{I}_{a/b/c,bus1/2}$ in kA.

3.1.1 Standard voltage source (no signals connected)

The voltage setpoints for the standard model are calculated as in Section 2.1.1.

3.1.2 Input signal $u0$ or $Ul0$ is connected

The voltage setpoints for this model are obtained as the setpoints desribed in Section 2.1.5.1.

3.1.3 Input signals U_A, U_B and U_C are connected

The voltage setpoints for this model are obtained as the setpoints desribed in Section 2.1.5.2.

4 1-Phase Voltage Source

In the voltage source, the voltage behind the internal impedance is controlled, and the resulting voltage depends on the impedance value and the current flowing through the element. If the internal impedance is zero, then the resulting busbar voltage is equal to the internal voltage setpoint. The main equations that need to be satisfied, are:

$$\underline{u} = \underline{u}_{setp} - \underline{z}_1 \cdot \underline{i} \tag{32}$$

The per unit value of the impedance is obtained by dividing the input values by the base impedance $Z_{base} = \frac{U^2_{nom\_t}}{1}$ where U_{nom_t} is the nominal voltage square of the connected terminal an and the apparent power is $1MVA$.

4.1 Load Flow Model

The p.u. values of the voltage setpoint input parameters (*usetp*) refer to the nominal voltage of the voltage source. The voltage setpoints are calculated from the input parameters as follows:

$$\underline{u}_{setp} = usetp \cdot \frac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot phiu1} \tag{33}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal. The voltage angle is calculated as follows:

$$phiu1 = phisetp \cdot \pi/180^\circ \tag{34}$$

4.1.1 QDSL Interface

The following input signals are available to control the voltage source via QDSL model:

- $u0$ is the Voltage-Input signal in $p.u.$
- $Ul0$ is the Voltage-Input (Line-Line) in kV
- $dphiu$ is the Voltage Angle Input in rad

When one of the input signal is connected the voltage setpoint $\underline{u}_{setp}$ is defined as follows:

$$\underline{u}_{setp} = \begin{cases} u0 \cdot \frac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot phiu1} & \text{if } u0 \text{ connected} \\ Ul0 \cdot \frac{1}{U_{nom\_t}} \cdot e^{i \cdot phiu1} & \text{if } Ul0 \text{ connected} \end{cases} \tag{35}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal.

The angle $phiu1$ can be modified by the additional input signal $dphiu$ in $[rad]$ (which is always initialised to 0).

$$phiu1 = phisetp \cdot \pi/180^\circ + dphiu \tag{36}$$

4.2 RMS-Simulation Model

Very similar as in the Load Flow calculation, the model used for the RMS simulation depends on the connected signals. The RMS model is initialised by using the results of a load flow calculation.

In the RMS simulation, the angle $phiu$ is determined by the change of its derivative as:

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot (f0 - f_{ref}) & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz - 2 \cdot \pi \cdot F_n \cdot f_{ref} & \text{if F0Hz is connected} \\ 0 & \text{if element is the reference} \end{cases} \tag{37}$$

The following input signals are available to control the voltage source via the RMS model:

- $u0$ is the Voltage-Input signal in $p.u.$
- Ui is the Voltage-Input (Line-Earth) in kV
- $dphiu$ is the Voltage Angle Input in rad

When one of the input signal is connected the voltage setpoint $\underline{u}_{setp}$ is defined as follows:

$$\underline{u}_{setp} = \begin{cases} u0 \cdot \dfrac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot (phiu + dphiu)} & \text{if } u0 \text{ connected} \\ Ui \cdot \dfrac{\sqrt{3}}{U_{nom\_t}} \cdot e^{i \cdot (phiu + dphiu)} & \text{if } Ui \text{ connected} \end{cases} \tag{38}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal.

4.3 EMT-Simulation Model

In the EMT simulation, the angle $phiu$ is determined by the change of its derivative as:

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot f0 & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz & \text{if F0Hz is connected} \end{cases} \tag{39}$$

All the voltage and angle input signals of the EMT-simulation are initialised from the results provided by the Load Flow calculation.

For the EMT model, the following equation is valid:

$$U = U_{setp} - R \cdot I - L \cdot \frac{dI}{dt} \tag{40}$$

where:

$$U_{setp} = \begin{cases} u0 \cdot U_{nom} \cdot \dfrac{\sqrt{2}}{\sqrt{3}} \cdot \cos(phiu + dphiu) & \text{if } u0 \text{ connected} \\ Ui & \text{if } Ui \text{ connected} \end{cases} \tag{41}$$

In the above equation U_{nom} is the nominal voltage of the voltage source.

5 1-Phase Voltage Source with two terminals

In the single phase voltage source with two terminals the voltage difference is controlled directly (no impedance is present as in the ElmVac model) to the setpoint voltage:

$$\frac{\underline{u}_{bus1} - \underline{u}_{bus2} \cdot \frac{U_{nom\_t2}}{U_{nom\_t1}}}{\sqrt{3}} = \underline{u}_{setp} \tag{42}$$

where U_{nom} is the nominal voltage of the voltage source, U_{nom_t1} is the nominal voltage of the connected terminal at side 1 (bus1) in kV, U_{nom_t2} is the nominal voltage of the connected terminal at side 2 (bus2) in kV.

5.1 Load Flow Model

The voltage setpoint is calculated usign the $usetp$ input parameter as:

$$\underline{u}_{setp} = usetp \cdot \frac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot phiu1} \tag{43}$$

where the voltage angle is calculated as follows:

$$phiu1 = phisetp \cdot \pi/180° \tag{44}$$

5.1.1 QDSL Interface

Please refer to Section 4.1.1.

5.2 RMS-Simulation Model

Very similar as in the Load Flow calculation, the model used for the RMS simulation depends on the connected signals. The RMS model is initialised by using the results of a load flow calculation.

In the RMS simulation, the angle $phiu$ is determined by the change of its derivative as:

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot (f0 - f_{ref}) & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz - 2 \cdot \pi \cdot F_n \cdot f_{ref} & \text{if F0Hz is connected} \\ 0 & \text{if element is the reference} \end{cases} \tag{45}$$

The following input signals are available to control the voltage source via the RMS model:

- $u0$ is the Voltage-Input signal in $p.u.$
- $Ul0$ is the Voltage-Input (Line-Line) in kV
- $dphiu$ is the Voltage Angle Input in rad

When one of the input signal is connected the voltage setpoint $\underline{u}_{setp}$ is defined as follows:

$$\underline{u}_{setp} = \begin{cases} u0 \cdot \dfrac{U_{nom}}{U_{nom\_t1}} \cdot e^{i\cdot(phiu+dphiu)} & \text{if } u0 \text{ connected} \\ Ul0 \cdot \dfrac{1}{U_{nom\_t1}} \cdot e^{i\cdot(phiu+dphiu)} & \text{if } Ul0 \text{ connected} \end{cases} \tag{46}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t1} is the nominal voltage of the connected terminal from side 1.

5.3 EMT-Simulation Model

In the EMT simulation, the angle $phiu$ is determined by the change of its derivative as:

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot f0 & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz & \text{if F0Hz is connected} \end{cases} \tag{47}$$

All the voltage and angle input signals of the EMT-simulation are initialised from the results provided by the Load Flow calculation.

For the EMT model, the following equation is valid:

$$\frac{u_{bus1} \cdot U_{nom\_t1} - u_{bus2} \cdot U_{nom\_t2}}{\sqrt{3}} \cdot \sqrt{2} = U_{setp} \tag{48}$$

where:

$$U_{setp} = \begin{cases} Ul0 & \text{if } Ul0 \text{ connected} \\ u0 \cdot U_{nom} \cdot \sqrt{2} \cdot \cos(phiu + dphiu) & \text{if } u0 \text{ connected} \end{cases} \tag{49}$$

In the above equation U_{nom} is the nominal voltage of the voltage source.

6 2-Phase Voltage Source

The 2-Phase AC voltage source model is illustrated in Figure 6.1.

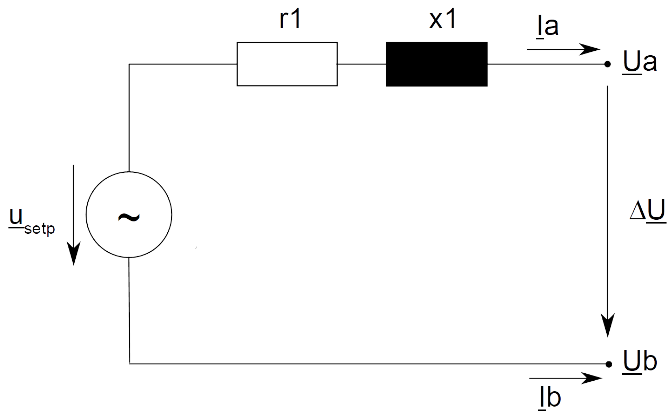

Figure 6.1: 2-phase models of the voltage source

In the voltage source, the voltage behind the internal impedance is controlled, and the resulting voltage depends on the impedance value and the current flowing through the element. If the internal impedance is zero, then the resulting busbar voltage is equal to the internal voltage setpoint. The main equations that need to be satisfied, are:

$$\begin{aligned} (\underline{u}_a - \underline{u}_b)/\sqrt{3} &= \underline{u}_{setp} - \underline{z}_1 \cdot \underline{i}_a \\ \underline{I}_a + \underline{I}_b &= 0 \end{aligned} \tag{50}$$

The p.u. values of the voltage setpoint input parameters (*usetp*) refer to the nominal voltage of the voltage source. The voltage setpoints are calculated from the input parameters as follows:

$$\underline{u}_{setp} = usetp \cdot \frac{U_{nom}}{U_{nom\_t}} \cdot e^{i \cdot phisetp \cdot \pi/180^\circ} \tag{51}$$

where U_{nom} is the nominal voltage of the voltage source and U_{nom_t} is the nominal voltage of the connected terminal.

The absolute values of the voltage setpoints can be obtained by multiplying them with the nominal voltage of the connected terminal.

The resistance and reactance per unit value are obtained by dividing the input values by the nominal voltage square of the connected terminal (U_{nom_t}).

6.1 Short-Circuit Model

The model does not contribute to the short-circuit when calculating according to the standards IEC 60909 (VDE 102/103) and ANSI-C37.

6.1.1 Complete Short-Circuit Method

The voltage difference introduced by the AC voltage source with two terminals element is taken into account when calculating according to the complete short-circuit method.

6.2 Harmonics and Frequency Sweep Analysis

6.2.1 Harmonic Load Flow

PowerFactory facilitates the modelling of background harmonics. This is done using either the AC voltage source element (*ElmVac*, *ElmVacbi*) or the external grid element (*ElmXnet*), on their respective *Harmonics/Power Quality* pages.

Table 6.1 describes the consideration of the phase correct sequence components of the harmonic orders for the AC voltage source with two terminals model.

Harmonic load flow	**Sequence Components of Harmonic Injections**
Balanced	• Positive (i.e. 4, 7, 10, ...), negative (i.e. 2, 5, 8, ...); • Zero sequence orders (i.e. 3, 6, 9, ...) are ignored (with warning). • Non-integer harmonic orders (i.e. 5.5, 6.2, 8.35, ...) are considered in the positive sequence.
Unbalanced	• Positive, negative, zero; • Non-integer harmonics are considered.

Table 6.1: Phase correct sequence components of harmonic injections for AC voltage source with two terminals

6.2.2 Frequency Sweep Analysis

Please refer to Section 2.3.2 for more information.

6.3 RMS-Simulation Model

Very similar as in the Load Flow calculation, the model used for the RMS simulation depends on the connected signals. The RMS model is initialised by using the results of a load flow calculation. The resulting voltages are also described by Equation 28.

In the RMS simulation, the angle $phisetp$ is replaced by $phiu$ which is determined by the change of its derivative as (valid for all RMS models):

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot (f0 - f_{ref}) & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz - 2 \cdot \pi \cdot F_n \cdot f_{ref} & \text{if F0Hz is connected} \\ 0 & \text{if element is the reference} \end{cases} \tag{52}$$

6.3.1 Input signal $u0$ or $Ul0$ is connected

In cases when one of the input signals $u0$ or $Ul0$ is connected, the model is equivalent to the model described in 3.1.2 (with the difference of how the angle is calculated).

6.3.2 Input signals U_A, U_B and U_C are connected

In cases when the input signals U_A U_B U_C are connected to the model, the models are described in Section 3.1.3 (with the difference of how the angle is calculated).

6.3.3 No signals connected

All the voltage and angle input signals of the RMS-simulation are initialised from the results provided by the Load Flow calculation. Also in the case when in the Load Flow calculation a remote node is controlled, $u0$, $Ul0$, U_A U_B U_C, ... are initialised.

Since all of the inputs are initialised, it is possible to use any of the models that require connected signals (Sections 6.3.1 and 6.3.2) and the result will be the same.

By using the parameter *Voltage input* (advanced page), the model can be switched to use $u0$, $Ul0$ or U_A U_B U_C. This is useful when a parameter event needs to be applied on one of the signals.

By using the *Frequency input* parameter, it can be selected if a parameter event can be applied on the signal $F0HZ$ or $f0$.

6.4 EMT-Simulation Model

Very similar as in the Load Flow calculation, the EMT model used depends on the connected signals. The EMT model is initialised by using the results of a load flow calculation. The EMT model transforms the phase voltages available from the EMT simulation to $\alpha\beta\gamma$.

In the EMT simulation, the angle $phisetp$ is replaced by the rotating angle $phiu$ which is determined by the change of its derivative as (valid for all EMT models):

$$\frac{d\,phiu}{dt} = \begin{cases} 2 \cdot \pi \cdot F_n \cdot f0 & \text{if f0 is connected} \\ 2 \cdot \pi \cdot F0Hz & \text{if F0Hz is connected} \end{cases} \tag{53}$$

All the voltage and angle input signals of the EMT-simulation are initialised from the results provided by the Load Flow calculation.

For the EMT model, the following equations are valid:

$$\begin{aligned} \Delta \underline{u}_{\alpha\beta} &= \underline{u}_{\alpha\beta setp} \\ \Delta u_{\gamma} &= u_{\gamma setp} \end{aligned} \tag{54}$$

where $\underline{u}_{\alpha\beta} = u_{\alpha} + \jmath \cdot u_{\beta}$ and u_{γ} are the $\alpha\beta\gamma$ components of the terminal voltage.

The sepoint voltages are calculated dependent on the model that is being used.

6.4.1 Input signal $u0$ or $Ul0$ is connected

The voltage setpoints for this model are obtained as the setpoints desribed in Section 2.5.1.

6.4.2 Input signals U_A, U_B and U_C are connected

The voltage setpoints for this model are obtained as the setpoints desribed in Section 2.5.2.

6.4.3 No signals connected

The same is valid as in Section 2.5.3.

7 Ideal RC Voltage Source

The ideal RC voltage source is not taken into account in load flow and short-circuit calculation and in the RMS and EMT simulations.

7.1 Harmonics Analysis Model

In the harmonic load flow, for all harmonic orders other than the fundamental frequency, the model is considered to be a normal voltage source (Section 2.3). At the fundamental frequency, the model is not considered and is therefore treated as having zero current.

The ideal RC voltage source is ignored for the frequency sweep analysis.

8 Ward Equivalent

A Ward Equivalent element is normally created as a result of the network reduction algorithm (depending on the settings).

8.1 Load Flow Model

The positive sequence model is comprised of the following elements:

- Source with constant active and reactive power;
- Load with constant active and reactive power;
- Constant impedance;
- Active power sources dependent on frequency.

The positive sequence load flow model of the Ward Equivalent is shown in Figure 8.1.

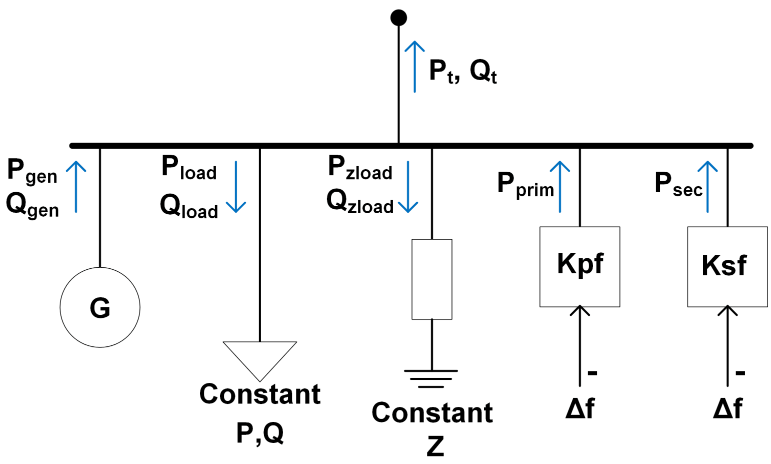

Figure 8.1: Ward equivalent model

The negative and zero sequence models are identical as in Figure 2.1.

The total active power injection is calculated according to:

$$P_t = (\underline{u}_1 \cdot \underline{i}_1^*).r = P_{gen} - P_{load} - P_{zload} \cdot |\underline{u}_1|^2 - (Kpf + Ksf) \cdot dF \tag{55}$$

where dF is the frequency deviation, $\underline{u}_1$ is the positive sequence terminal voltage and $\underline{u}_1^*$ is the complex conjugate of the positive sequence current. The total reactive power injection is calculated according to:

$$Q_t = (\underline{u}_1 \cdot \underline{i}_1^*).i = Q_{gen} - Q_{load} - Q_{zload} \cdot |\underline{u}_1|^2 \tag{56}$$

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

8.2 Short-Circuit Model

For the Short-Circuit calculation, the models described in Section 2.2 are valid. If the calculation method uses load flow initialisation, the resulting short-circuit results may be different depending on the load flow results.

8.3 RMS-Simulation Model

The RMS model is initialised by using the results of a load flow calculation. The models described in Section 2.4 are also valid for the Ward Equivalent model.

8.4 EMT-Simulation Model

The EMT model is initialised by using the results of a load flow calculation. The models described in Section 2.5 are also valid for the Ward Equivalent model.

8.5 Harmonics Analysis Model

In the harmonic load flow, the Ward Equivalent model is considered to be a normal voltage source (Section 2.3). The same is valid for the frequency sweep analysis.

9 Extended Ward Equivalent

An Extended Ward Equivalent element is normally created as a result of the network reduction algorithm (depending on the settings).

9.1 Load Flow Model

The model is essentially a Ward equivalent with the addition of a voltage controller. Two cases can be distinguished depending if the impedance $Z_{ext} = R_{ext} + \jmath\, X_{ext}$ is defined:

(i) If $\underline{Z}_{ext} = 0 + \jmath\, 0$:

If the impedance is zero, the reactive power needed to hold the voltage at the given setpoint is calculated as a result of the equation solution. The reactive powers of the other elements of the extended ward equivalent are neglected. The model is shown in Figure 9.1.

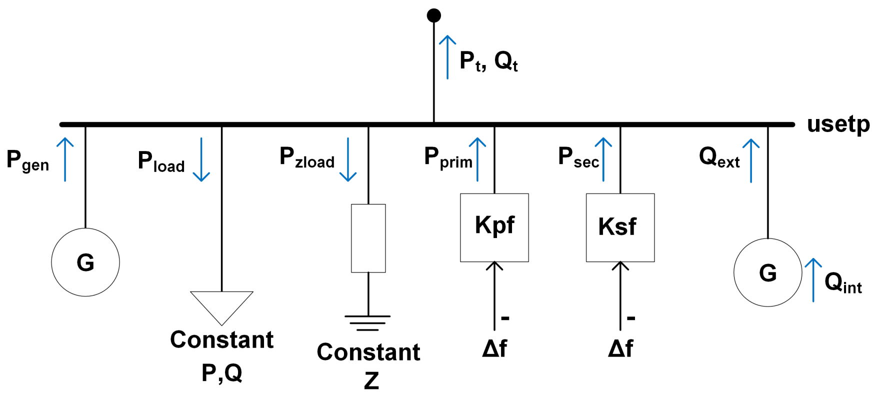

Figure 9.1: Extended Ward equivalent model with no impedance Z_{ext}

The amplitude of the positive sequence voltage of the busbar is controlled to the internal setpoint voltage u_{int} and the internal angle is set equal to the busbar positive sequence voltage angle:

$$|\underline{u}_1| = u_{int} \tag{57}$$
$$\phi_{uint} = \phi_u \tag{58}$$

where $u_{int} = usetp \cdot U_{nom}/U_{nom\_t}$.

The total active power injection is calculated according to (same as for the Ward Equivalent):

$$P_t = (\underline{u}_1 \cdot \underline{i}_1^*).r = P_{gen} - P_{load} - P_{zload} \cdot |\underline{u}_1|^2 - (Kpf + Ksf) \cdot dF \tag{59}$$

(ii) If $\underline{Z}_{ext} \neq 0 + \jmath\, 0$:

If the impedance is not zero, the voltage setpoint controls the positive sequence voltage magnitude before the impedance. The internal angle ϕ_{uint} is an unknown variable which is determined from the model equation solution for the given conditions. The model is shown in Figure 9.2.

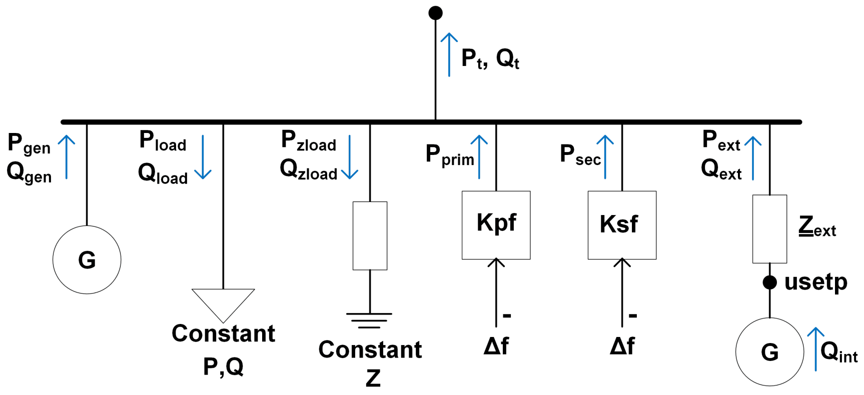

Figure 9.2: Extended Ward equivalent model

The equations that need to be solved for the total active and reactive power are:

$$\begin{aligned} P_t &= (\underline{u}_1 \cdot \underline{i}_1^*).r = P_{gen} - P_{load} - P_{zload} \cdot |\underline{u}_1|^2 - (Kpf + Ksf) \cdot dF + P_{ext} \\ Q_t &= (\underline{u}_1 \cdot \underline{i}_1^*).i = Q_{gen} - Q_{load} - Q_{zload} \cdot |\underline{u}_1|^2 + Q_{ext} \end{aligned} \tag{60}$$

The apparent power S_{ext} in Equation 60 is obtained as (defining u_{int} as $u_{int} = usetp \cdot U_{nom}/U_{nom\_t}$ and since $\underline{S} = \underline{U} \cdot \underline{U}^* \cdot \underline{Y}^* = |\underline{U}|^2 \cdot \underline{Y}^*$):

$$P_{ext} + \jmath\, Q_{ext} = \left(|\underline{u}_1| \cdot e^{\jmath\, \phi_u} \cdot u_{int} \cdot e^{-\jmath\, \phi_{uint}} - |\underline{u}_1|^2\right) \cdot \underline{y}_{ext}^* \tag{61}$$

where the internal angle ϕ_{uint} is an unknown variable and the admittance $\underline{y}_{ext}$ is calculated as:

$$\underline{y}_{ext} = \frac{1}{\frac{R_{ext}}{u_1^2} + \jmath\, \frac{X_{ext}}{u_1^2}} \tag{62}$$

The following additional equation needs to be solved for the active power (where P_{int} is set to 0) in order to obtaining the internal angle:

$$u_{int}^2 \cdot \underline{y}_{ext}.r = u_{int} \cdot |\underline{u}_1| \cdot \left(\underline{y}_{ext}.r \cdot cos(\phi_{uint} - \phi_u) - \underline{y}_{ext}.i \cdot sin(\phi_{uint} - \phi_u)\right) \tag{63}$$

The active power P_{ext} is produced only due to the resistance R_{ext} defined in the element $(P_{int} = 0)$.

9.2 Short-Circuit Model

For the Short-Circuit calculation, the models described in Section 2.2 are valid. If the calculation method uses load flow initialisation, the resulting short-circuit results may be different depending on the load flow results.

9.3 RMS-Simulation Model

The RMS model is initialised by using the results of a load flow calculation. The models described in Section 2.4 are also valid for the Extended Ward Equivalent model.

9.4 EMT-Simulation Model

The EMT model is initialised by using the results of a load flow calculation. The models described in Section 2.5 are also valid for the Extended Ward Equivalent model.

9.5 Harmonics Analysis Model

In the harmonic load flow, the Extended Ward Equivalent model is considered to be a normal voltage source (Section 2.3). The same is valid for the frequency sweep analysis.

A Signal Definitions

A.1 Internal Signals

Parameter	Unit	I/O	Description	Symbol
u0	p.u.	IN	Voltage-Input	$u0$
Ul0	kV	IN	Voltage-Input (Line-Line)	$Ul0$
U_A	kV	IN	Voltage, Magnitude, Phase a	U_A
U_B	kV	IN	Voltage, Magnitude, Phase b	U_B
U_C	kV	IN	Voltage, Magnitude, Phase c	U_C
phiu_B	deg	IN	Voltage, Angle, Phase b	$phiu_B$
phiu_C	deg	IN	Voltage, Angle, Phase c	$phiu_C$
dphiu	rad	IN	Voltage Angle Input	$dphiu$
uctrl	p.u.	IN	Voltage Input	$uctrl$
phictrl	rad	IN	Phase Input	$phictrl$
dF	Hz	IN	Frequency Deviation	dF

Table A.1: Internal signals (Load Flow)

Parameter	Unit	I/O	Description	Symbol
u0	p.u.	IN	Voltage-Input	$u0$
Ul0	kV	IN	Voltage-Input (Line-Line)	$Ul0$
U_A	kV	IN	Voltage, Magnitude, Phase a	U_A
U_B	kV	IN	Voltage, Magnitude, Phase b	U_B
U_C	kV	IN	Voltage, Magnitude, Phase c	U_C
phiu_B	deg	IN	Voltage, Angle, Phase b	$phiu_B$
phiu_C	deg	IN	Voltage, Angle, Phase c	$phiu_C$
dphiu	rad	IN	Voltage Angle Input	$dphiu$

Table A.2: Internal signals (Short-Circuit)

Parameter	Unit	I/O	Description	Symbol
u0	p.u.	IN	Voltage-Input	$u0$
Ul0	kV	IN	Voltage-Input (Line-Line)	$Ul0$
f0	p.u.	IN	Frequency-Input	$f0$
F0Hz	Hz	IN	Frequency-Input	$F0Hz$
U_A	kV	IN	Voltage, Magnitude, Phase a	U_A
U_B	kV	IN	Voltage, Magnitude, Phase b	U_B
U_C	kV	IN	Voltage, Magnitude, Phase c	U_C
phiu_B	deg	IN	Voltage, Angle, Phase b	$phiu_B$
phiu_C	deg	IN	Voltage, Angle, Phase c	$phiu_C$
dphiu	rad	IN	Additional Angle	$dphiu$
phiu	rad	STATE	Voltage Angle	$phiu$
fref	p.u.	IN	Reference Frequency	$fref$
xspeed	p.u.	OUT	Frequency	

Table A.3: Internal signals (RMS-Simulation)

Parameter	Unit	I/O	Description	Symbol
u0	p.u.	IN	Voltage-Input	$u0$
Ul0	kV	IN	Voltage-Input (Line-Line)	$Ul0$
f0	p.u.	IN	Frequency-Input	$f0$
F0Hz	Hz	IN	Frequency-Input	$F0Hz$
U_A	kV	IN	Voltage, Magnitude, Phase a	U_A
U_B	kV	IN	Voltage, Magnitude, Phase b	U_B
U_C	kV	IN	Voltage, Magnitude, Phase c	U_C
dphiu	rad	IN	Additional Angle	$dphiu$
phiu	rad	STATE	Voltage Angle	$phiu$

Table A.4: Internal signals (EMT-Simulation)

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