POWERFACTORY

PowerFactory 2021

Technical Reference

Phase Measurement Device

ElmPhi__pll

POWER SYSTEM SOLUTIONS

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Contents

1 General Description

PLLs are widely used for synchronization purposes, controller applications and can also be used to demodulate frequency-modulated signals. For more information about PLL definition and applications refer to [1] and [2].

The *Phase-Locked Loop* element (*ElmPhi__pll*) measures the frequency and phase of a voltage in the system. The PLL model is supported by the RMS and EMT simulations only.

In the following sections the working and behaviour of the PLL *Model Version* 2 and *Model Version* 3 (parameter $mversion$) are presented. The *Model Version* 2 supports blocking functionality and single-phase measurement. These features are not available in *Model Version* 1. Additional difference between the two versions is that in *Model Version* 1, a gain of $Ki \cdot Ki$ is used for the integrator part of the PI controller and in *Model Version* 2 the gain is, as typical, Ki. The *Model Version* 3 uses the tracking angle between the measured frequency and the nominal frequency to transform the in-quadrature input signals of the PLL. Then, this tracking angle is applied to get the corresponding output.

2 RMS-Simulation

The PLL uses as inputs, the voltage at the selected *Measurement Point* (reference node) in the input dialogue box of the PLL.

Depending on the selected *No. of Phases* option (parameter $nphase$), a three-phase or single-phase measurement is possible.

2.1 Three-phase measurement

The PLL structure is the same for both balanced and unbalanced RMS simulations. Internally, the input signals to the PLL ur and ui are the real and imaginary part of the positive sequence voltage (in-quadrature signals).

In the case of balanced network representation, the positive sequence voltage resulting from the simulation is fed directly to the input signals (uR, uI) of the PLL. In the case of unbalanced network representation, the positive sequence voltage is first being calculated using the symmetrical transformation on the input signals fed to the PLL ($uR\_A, uI\_A, uR\_B, uI\_B, uR\_C, uI\_C$).

The block diagram of the PLL version 2 is presented in Figure 2.1 where the following input parameters are used (connected automatically):

- ur and ui are the in-quadrature input signals of the PLL in $p.u.$;
- u is the magnitude of the input voltage in $p.u.$; and
- $fref$ is the frequency of the reference machine in $p.u.$.

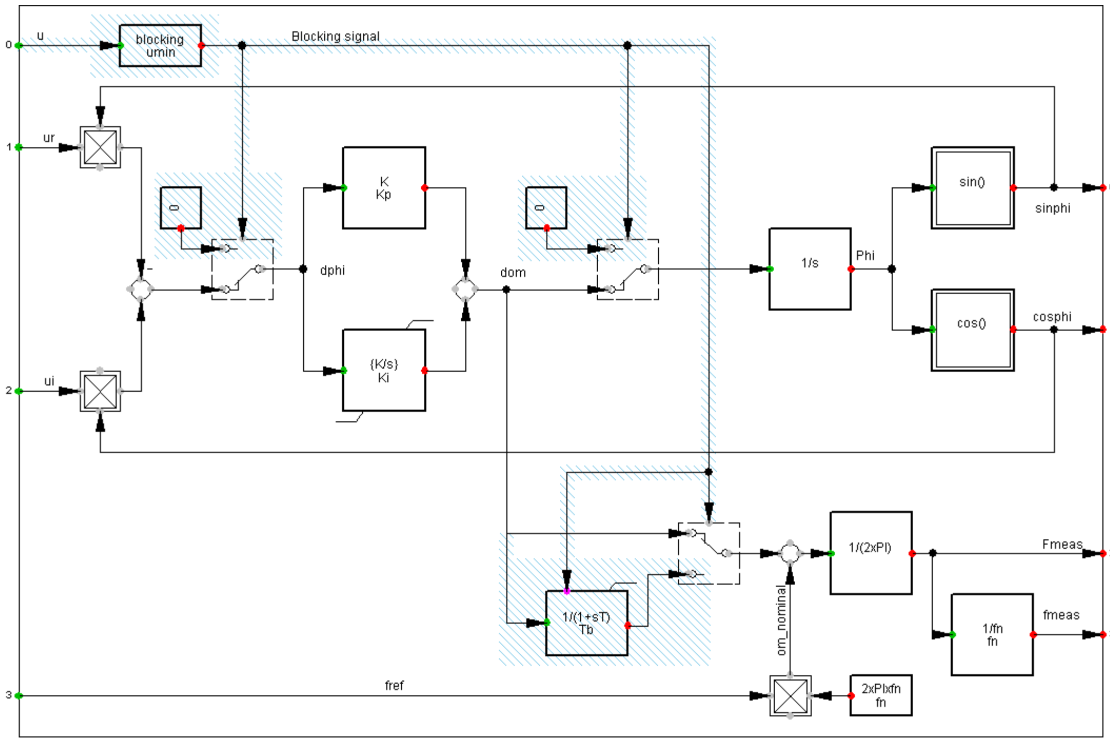

Figure 2.1: DIgSILENT PLL block diagram Version 2 (RMS simulation)

The blocks shaded in blue colour are enabled if the blocking functionality is being used. Please refer to Section 2.1.1.

The block diagram of the PLL Version 3 is presented in Figure 2.2 where the following input parameters are used (connected automatically):

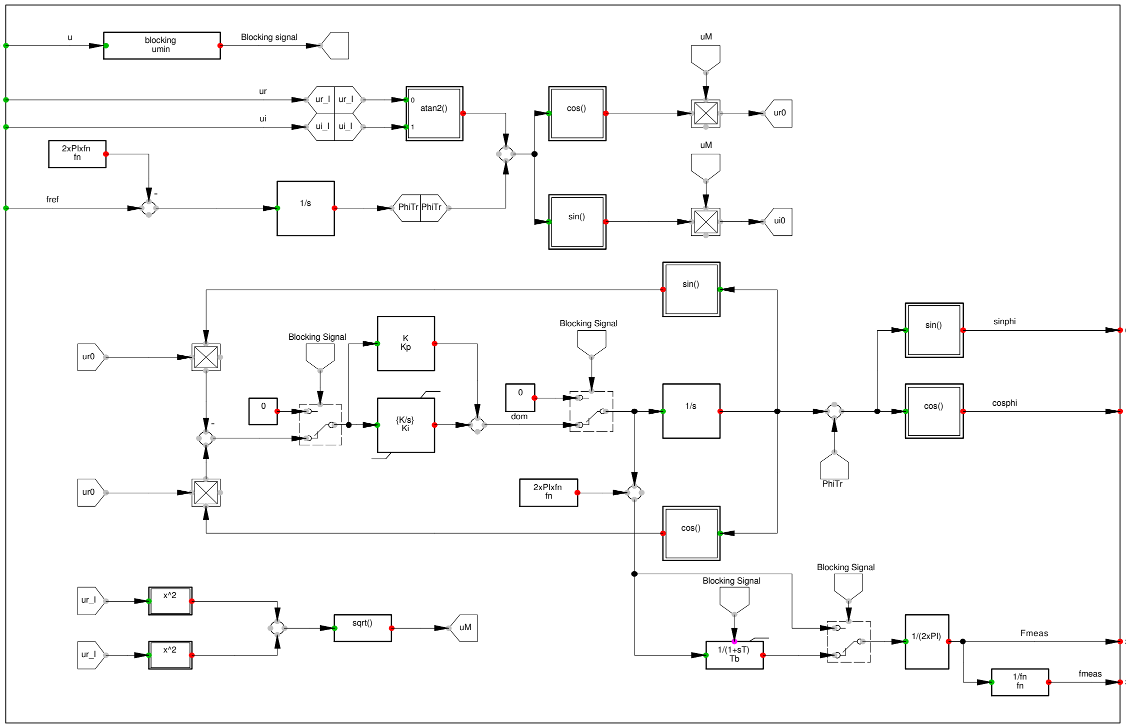

Figure 2.2: DIgSILENT PLL block diagram Version 3 (RMS simulation)

The limits on the integrator part of the PI controller for PLL Version 2 and Version 3 are calculated using the parameters $fmax$ and $fmin$ (*Upper frequency limit* and *Lower frequency limit*) as follows:

$$Lower\,limit = 2 \cdot \pi \cdot Fnom \cdot fmin - 2 \cdot \pi \cdot Fnom \cdot fref - Kp \cdot dphi \tag{1}$$

$$Upper\,limit = 2 \cdot \pi \cdot Fnom \cdot fmax - 2 \cdot \pi \cdot Fnom \cdot fref - Kp \cdot dphi \tag{2}$$

where:

- $fmin$ is the *Lower frequency limit* parameter in $p.u.$;
- $fmax$ is the *Upper frequency limit* parameter in $p.u.$;
- $Fnom$ is the nominal frequency in Hz;
- $fref$ is the frequency of the reference machine in $p.u.$;
- Kp is the proportional gain of the PI controller; and
- $dphi$ is the dphi signal (see Figure 2.1).

2.1.1 Blocking functionality

In real devices, the angle cannot be tracked if the voltage falls below a certain threshold. The option *Enable Blocking* can be used to simulate this. When this option is enabled, the blue colour shaded blocks in Figure 2.1 are considered in the calculation.

The blocking mode uses the parameters *Blocking voltage* $umin$ (in $p.u.$) and *Blocking filter time constant* Tb (in ms).

If the voltage magnitude drops below the user defined $umin$, the PLL goes into blocking mode and the signal $block$ is set to 1. If the magnitude of the voltage rises above $umin + 5\%$, the PLL switches to normal mode and the signal $block$ is set to 0.

The following changes are done when the PLL is in blocking mode:

- The outputs of the two integrators and of the tracking (first-order lag) block are kept constant;
- The frequency is calculated using the angular velocity difference input from the tracking block.

Blocking functionality is available in Version 2 and Version 3.

2.1.2 Signals

The signals used in the case of a balanced network representation are presented in Table 2.1. The input signals are automatically connected (internally in *PowerFactory*).

Table 2.1: Signals for Three-Phase Measurement (Balanced RMS-Simulation)

Name	Symbol	Unit	Type	Description
uR		$p.u.$	IN	Input Voltage, Real Part
uI		$p.u.$	IN	Input Voltage, Imaginary Part
$fref$		$p.u.$	IN	Reference Frequency
$Fmeas$		Hz	OUT	Measured Frequency
$fmeas$		$p.u.$	OUT	Measured Frequency
$x1$			STATE	State variable of the PI controller
$x2$		rad	STATE	State variable of the integrator (Phi)
$cosphi$			OUT	$\cos(Phi)$
$sinphi$			OUT	$\sin(Phi)$

The signals used in the case of an unbalanced network representation are presented in Table 2.2. The input signals are automatically connected (internally in *PowerFactory*).

2.1.3 Calculation parameters

The calculation parameters used in the three-phase RMS measurement are presented in Table 2.3.

Table 2.2: Signals for Three-Phase Measurement (Unbalanced RMS-Simulation)

Name	**Symbol**	**Unit**	**Type**	**Description**
uR_A		$p.u.$	IN	Input Voltage, Phase a, Real Part
uI_A		Hz	IN	Input Voltage, Phase a, Imaginary Part
uR_B		$p.u.$	IN	Input Voltage, Phase b, Real Part
uI_B		Hz	IN	Input Voltage, Phase b, Imaginary Part
uR_C		$p.u.$	IN	Input Voltage, Phase c, Real Part
uI_C		Hz	IN	Input Voltage, Phase c, Imaginary Part
$fref$		$p.u.$	IN	Reference Frequency
$Fmeas$		Hz	OUT	Measured Frequency
$fmeas$		$p.u.$	OUT	Measured Frequency
$x1$			STATE	State variable of the PI controller
$x2$		rad	STATE	State variable of the integrator (Phi)
$cosphi$			OUT	$\cos(Phi)$
$sinphi$			OUT	$\sin(Phi)$

Table 2.3: Calculation parameters for Three-Phase Measurement (RMS-Simulation)

Name	**Symbol**	**Unit**	**Description**
Kp			PI controller Proportional Gain
Ki			PI controller Integral Gain
$ommax$		rad/s	Upper Angular Frequency ($2 \cdot \pi \cdot frnom \cdot fmax$)
$ommin$		rad/s	Lower Angular Frequency ($2 \cdot \pi \cdot frnom \cdot fmin$)
$frnom$		Hz	Nominal Frequency
hpi		rad/s	Nominal Angular Frequency
Phi		deg	Voltage Angle
phi_AC		rad	Angle between Phase a and c
$umin$		$p.u.$	Blocking voltage limit
$block$			Blocking
Tb		s	Blocking Filter Time Constant

2.2 Single-phase measurement

Depending on the *Phase Technology* of the selected *Measurement Point*, the single-phase PLL can measure at phase a, b, c, $a-n$, $b-n$ or $c-n$. This can be selected by using the *Measured Phase* $it2p$ parameter.

The in-quadrature signals fed to the PLL algorithm are then automatically selected from the phase voltages depending on the *Measured Phase*.

The block diagram of the single-phase PLL is equal to the three-phase PLL diagram (presented in Figure 2.1).

2.2.1 Blocking functionality

Since the PLL structure of the three-phase PLL and single-phase PLL is the same, please refer to Section 2.1.1.

2.2.2 Signals

The signals used in the single-phase RMS model are the same as the signals used for the three-phase measurement in the balanced RMS simulation presented in Table 2.1.

2.2.3 Calculation parameters

The calculation parameters used for the single-phase measurement in the RMS model are presented in Table 2.4.

Table 2.4: Calculation parameters for Single-Phase Measurement (RMS-Simulation)

Name	Symbol	Unit	Description
Kp			PI controller Proportional Gain
Ki			PI controller Integral Gain
$ommax$		rad/s	Upper Angular Frequency ($2 \cdot \pi \cdot frnom \cdot fmax$)
$ommin$		rad/s	Lower Angular Frequency ($2 \cdot \pi \cdot frnom \cdot fmin$)
$frnom$		Hz	Nominal Frequency
hpi		rad/s	Nominal Angular Frequency
Phi		deg	Voltage Angle
$umin$		$p.u.$	Blocking voltage limit
$block$			Blocking
Tb		s	Blocking Filter Time Constant

3 EMT-Simulation

Depending on the selected *No. of Phases* option (parameter $nphase$), a three-phase or single-phase PLL measurement is possible. The *Model Version* 2 and The *Model Version* 3 are identical.

3.1 Three-phase measurement

The block diagram of the PLL is presented in Figure 3.1.

The phase voltages available from the EMT-simulation are set to the input values of the PLL u_a, u_b and u_c. The internally used voltages in the PLL, ur and ui (Figure 3.1), are calculated by using the $\alpha\beta$ transformation on the input voltages.

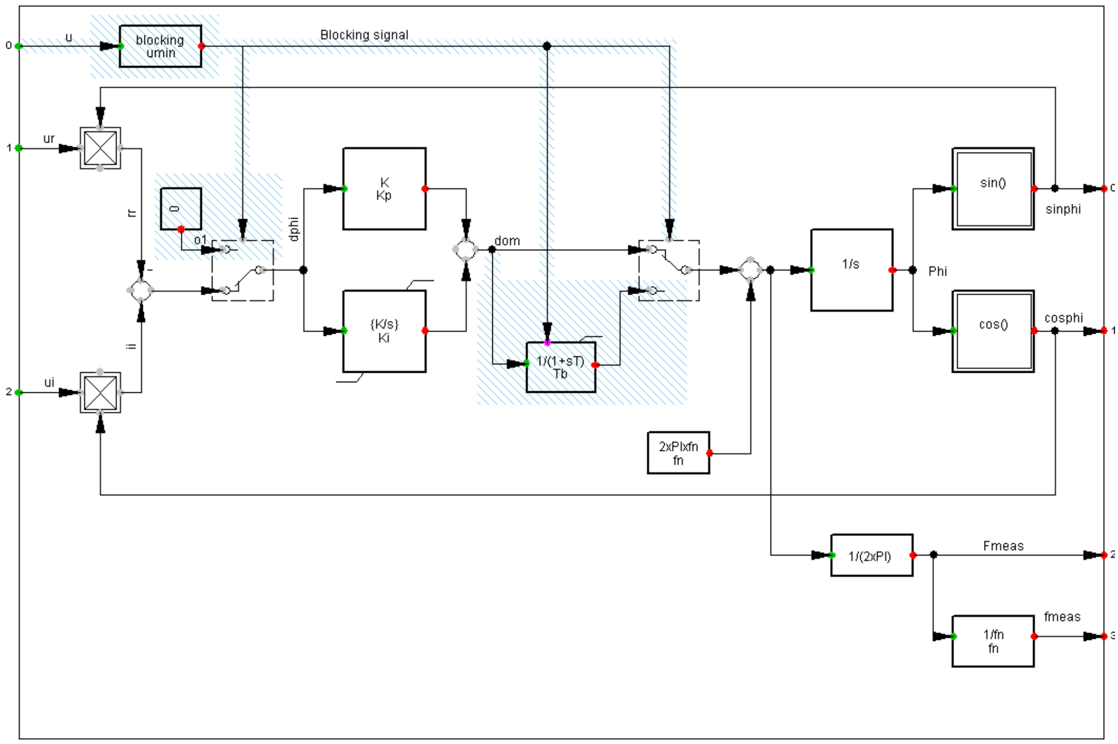

Figure 3.1: DIgSILENT PLL block diagram (EMT simulation)

The blocks shaded in blue colour are used when the blocking functionality is being used. Please refer to Section 3.1.1.

The limits of the integral part of the PI controller are back-calculated using the parameters $fmax$ and $fmin$ (*Upper frequency limit* and *Lower frequency limit*) as:

$$Lower\,limit = 2 \cdot \pi \cdot Fnom \cdot fmin - 2 \cdot \pi \cdot Fnom - Kp \cdot dphi \tag{3}$$

$$Upper\,limit = 2 \cdot \pi \cdot Fnom \cdot fmax - 2 \cdot \pi \cdot Fnom - Kp \cdot dphi \tag{4}$$

where:

- $fmin$ is the *Lower frequency limit* parameter in $p.u.$;
- $fmax$ is the *Upper frequency limit* parameter in $p.u.$;

- $Fnom$ is the nominal frequency in Hz;
- Kp is the proportional gain of the PI controller;
- $dphi$ is the dphi signal (see Figure 3.1).

3.1.1 Blocking functionality

The blocking functionality in the EMT model is very similar to the one in the RMS model. When this option is enabled, the blue colour shaded blocks in Figure 3.1 are enabled.

The following changes are done when the PLL is in blocking mode:

- The outputs of the integrator part of the PI controller of the tracking block are being kept constant;
- The frequency and the angle are calculated using the angular velocity difference input from the tracking block.

3.1.2 Signals

The signals used for the three-phase measurement in the EMT model are presented in Table 3.1. The input signals are automatically connected (internally in *PowerFactory*).

Table 3.1: Signals for Three-Phase Measurement (EMT-Simulation)

Name	Symbol	Unit	Type	Description
u_a		$p.u.$	IN	Input Voltage, Phase a
u_b		$p.u.$	IN	Input Voltage, Phase b
u_c		$p.u.$	IN	Input Voltage, Phase c
$Fmeas$		Hz	OUT	Measured Frequency
$fmeas$		$p.u.$	OUT	Measured Frequency
$x1$			STATE	State variable of the PI controller
$x2$		rad	STATE	State variable of the integrator (Phi)
$cosphi$			OUT	$\cos(Phi)$
$sinphi$			OUT	$\sin(Phi)$

3.1.3 Calculation parameters

The calculation parameters used for the three-phase measurement in the EMT model are presented in Table 3.2.

3.2 Single-phase measurement

As in the RMS model, the single-phase PLL can measure at phase a, b, c, $a - n$, $b - n$ or $c - n$.

Since the EMT simulation provides only one voltage and the PLL algorithm requires in-quadrature signals, the second signal has to be constructed. The in-quadrature image of the input single-phase signal is created using the Inverse Park Transform [3]. The image signal is constructed

Table 3.2: Calculation parameters for Three-Phase Measurement (EMT-Simulation)

Name	Symbol	Unit	Description
Kp			PI controller Proportional Gain
Ki			PI controller Integral Gain
$ommax$		rad/s	Upper Angular Frequency $(2 \cdot \pi \cdot frnom \cdot fmax)$
$ommin$		rad/s	Lower Angular Frequency $(2 \cdot \pi \cdot frnom \cdot fmin)$
$frnom$		Hz	Nominal Frequency
hpi		rad/s	Nominal Angular Frequency
Phi		deg	Voltage Angle
phi_AC		rad	Angle between Phase a and c
$umin$		$p.u.$	Blocking voltage limit
$block$			Blocking
Tb		s	Blocking Filter Time Constant
v_in_r		$p.u.$	Voltage fed to the PLL algorithm
v_in_i		$p.u.$	Voltage fed to the PLL algorithm

by introducing two low-pass filters in a loop consisting of the direct and inverse Park transformations. The filters use the *Low-Pass Filter Time Constant* $T1$ in ms. The default value of $T1$ is selected for a $50Hz$ system [3].

The single-phase signal from the EMT-simulation and the constructed image signal are fed to the PLL algorithm presented in Figure 3.1.

3.2.1 Blocking functionality

Since the PLL structure of the three-phase PLL and single-phase PLL is the same, please refer to Section 3.1.1.

3.2.2 Signals

The signals used for the single-phase measurement in the EMT model are presented in Table 3.3. The input signal is automatically connected (internally in *PowerFactory*).

Table 3.3: Signals for Single-Phase Measurement (EMT-Simulation)

Name	Symbol	Unit	Type	Description
uR		$p.u.$	IN	Input Voltage
$Fmeas$		Hz	OUT	Measured Frequency
$fmeas$		$p.u.$	OUT	Measured Frequency
$x1$			STATE	State variable of the PI controller
$x2$		rad	STATE	State variable of the integrator (Phi)
$cosphi$			OUT	$\cos(Phi)$
$sinphi$			OUT	$\sin(Phi)$
xd			STATE	State variable d Low-Pass Filter
xq			STATE	State variable q Low-Pass Filter

3.2.3 Calculation parameters

The calculation parameters used for the single-phase measurement in the EMT model are presented in Table 3.4.

Table 3.4: Calculation parameters for Single-Phase Measurement (EMT-Simulation)

Name	Symbol	Unit	Description
Kp			PI controller Proportional Gain
Ki			PI controller Integral Gain
$ommax$		rad/s	Upper Angular Frequency $(2 \cdot \pi \cdot frnom \cdot fmax)$
$ommin$		rad/s	Lower Angular Frequency $(2 \cdot \pi \cdot frnom \cdot fmin)$
$frnom$		Hz	Nominal Frequency
hpi		rad/s	Nominal Angular Frequency
Phi		deg	Voltage Angle
$umin$		$p.u.$	Blocking voltage limit
$block$			Blocking
Tb		s	Blocking Filter Time Constant
$T1$		s	Low-Pass Filter Time Constant (used for both Low-Pass Filters)
v_in_r		$p.u.$	Voltage fed to the PLL algorithm
v_in_i		$p.u.$	Voltage fed to the PLL algorithm
vd		$p.u.$	Voltage fed to the d Low-Pass Filter
vq		$p.u.$	Voltage fed to the q Low-Pass Filter

4 References

[1] R. E. Best. *Phase-Locked Loops: Design, Simulation and Applications*. McGraw Hill, 6 edition, 2007.

[2] B. K. Bose. *Modern Power Electronics and AC Drivers*. Prentice Hall of India, 1 edition, 2008.

[3] R. Teodorescu, M. Liserre, and P. Rodriguez. *Grid Converters for Photovoltaic and Wind Power Systems*. Wiley, 2011.

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