idealCircuit

User's Manual

Rev. 1.0

06/01/2012

sidelinesoft

VERSION

This version of User's Manual is current for **idealCircuit** simulator version 1.0 (06/01/2012). The latest version of User's Manual can be found at ic.sidelinesoft.com.

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I. What is ideal Circuit

What is idealCircuit?

idealCircuit is an analog circuit simulator working with true ideal components. It uses exactly the same unique and robust algorithm as **NL5 Circuit Simulator** (nl5.sidelinesoft.com). However, it is simplified as much as possible: very simple and intuitive interface, less components and models, no fancy and powerful features.

What is "ideal" component?

The best example is an ideal switch, with zero resistance when closed, infinite resistance when open, and instantaneous switching. Another example: an ideal diode with similar properties. All other components might be not as "ideal" as switch or diode, however are also simplified to provide just a basic functionality required for component of that type.

Why use ideal components?

With ideal components, engineers can evaluate a general concept and prove the feasibility of the design very quickly, leaving thorough and detailed analysis to standard SPICE-based tools. Students can simulate exactly the same schematics they see in the textbooks: no need to select specific diode, transistor or amplifier from the list of thousands parts.

II. Schematic

Editing schematic

Schematic editing in **idealCircuit** is very simple and intuitive. Most of operations can be done using mouse, keyboard is used only for entering numbers. Please see Video Tutorial on YouTube for details.

Numbers format

Numbers format in **idealCircuit** is very flexible and complies with many commonly used styles and standards. A number can use exponential multipliers **E** or **e**, and **case-sensitive** letter multipliers:

Letter	Multiplier
T	10^{12}
G	10^{9}
M, mg	10^{6}
K, k	10^{3}

Letter	Multiplier
m	10^{-3}
u, mk	10^{-6}
n	10^{-9}
p	10^{-12}

For example:

```
1.3e+3   47E-9   100k   0.33mk   2.2M
```

Letter multiplier can be followed by any text, which is considered as units and will be ignored:

```
1.3kOhm   47nF   0.1mkH   333ps
```

Any text that does not begin with letter multiplier is considered as units and will be ignored:

```
1.3Ohm   0.001F   0.1H   333apples
```

Letter multiplier and units (with or without letter multiplier) can be used instead of a decimal point:

```
1k3   5n6   3nF3   47F0  2s2
```

Zero before decimal point or letter multiplier can be omitted. For example:

```
.47   n47   uF5
```

Being entered in a variety of formats available, a number is automatically converted and stored in the floating point (**double**) format. When number is displayed, an engineering notation, with exponential multiplier and power of ten to be multiple of three, is used:

Entered	Displayed
1k3	1.3e+3
47e-8	470e-9
5600000	5.6e+6

III. Transient Analysis

PWL simulation algorithm

idealCircuit is a piece-wise linear (PWL) simulator. All the components in the **idealCircuit** are either linear or piece-wise linear: consisting of a number of linear segments. For instance, a diode is either open or closed, so that its PWL representation consists of just two segments. As long as all of the components are staying within their current linear segment, the schematic is described by the same system of linear differential equations. The system is modified only at the moments when at least one component changes its linear segment. When this happens, the current linear range simulation ends, and another one starts. Typical **idealCircuit** simulation consists of DC operating point calculation (at t=0), followed by one or more linear range simulations.

DC operating point

Simulation always starts at t=0. First, Direct Current (DC) operating point is calculated. The calculation is performed considering Initial Condition (IC) of the components. For instance, capacitor is replaced by voltage source if IC voltage is specified, or ignored (open circuit) if IC is not specified (blank). Inductor is replaced by current source if IC current is specified, or by a short circuit if IC is not specified (blank). Diode is considered an open circuit if IC state is “Off”, and short circuit if IC state is “On”.

If schematic has more than one steady state, it can be set to a specific state by defining proper ICs. The result of DC operating point calculation is known voltages, currents, and states of all components. When DC operating point is found, a first linear range simulation starts.

Linear range simulation

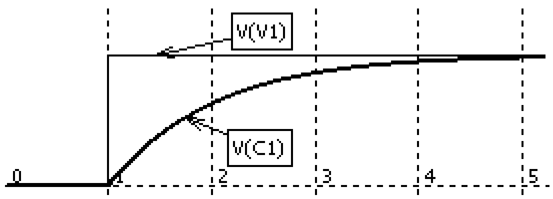
In the linear range, schematic is described by the system of linear differential equations, which is solved by Trapezoidal integration method. The method provides reasonable accuracy with good robustness and calculation speed. During linear range simulation, the algorithm is performing “switching point detection”: checking conditions on all components that may change their state (diodes, switches, logical components), or change the amplitude or slope (voltage and current sources). If any change occurred, the current linear range ends, and another one starts.

Calculation step

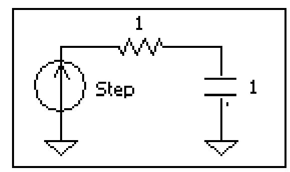
Unlike many analog simulators, **idealCircuit** does not perform automatic step control. Selecting calculation step is user's responsibility. This gives user full control on simulation, although requires certain experience and understanding of the process. The rule of thumb is keeping calculation step below smallest time constant in the schematic, otherwise the integration method may get unstable and produce "numerical" oscillations.

However, having calculation step to satisfy "smallest time constant" condition is not necessarily required. Sometimes even high enough calculation step provides good stability, while simulation speed can be significantly increased. To find out an optimal calculation step, run simulation several times with different step and compare simulation results. As a rule, reducing calculation step below some level does not have any visible effect on results. Selecting calculation step close to this level would give the best simulation performance.

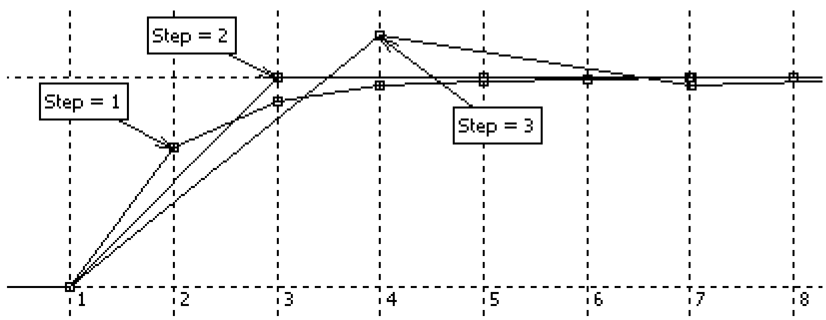
The following example shows how calculation step affects simulation of a simple schematic. The time constant of the RC chain is 1s, so that calculation step is supposed to be < 1s.



Ideal response

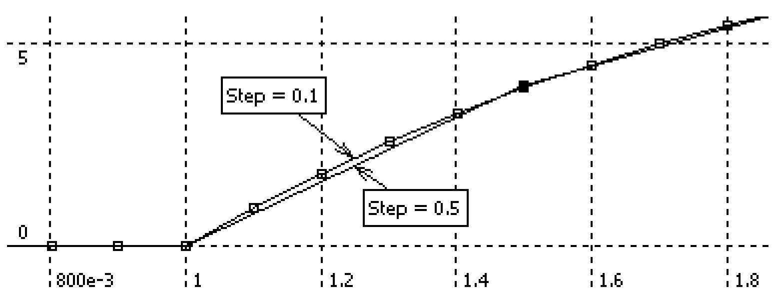


When 1s, 2s, or 3s step is selected, the transient waveform is wrong. The overshoot and further oscillations exist at 3s step. However, if exact waveform is not of interest, and if it does not affect functionality of the rest of the schematic, these steps could be used.



Simulation with large steps

Calculation steps below 1s produce very accurate waveforms. For instance, difference between traces with 0.5s and 0.1s steps can be noticed only at the very beginning of the transient, and it is extremely small.



Simulation with small steps

Automatic step reduction

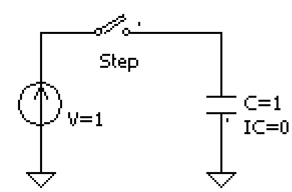
Although calculation step is specified by the user, **idealCircuit** still can automatically reduce the step to satisfy certain conditions, for instance:

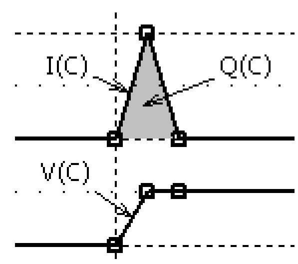
- Period of sine source contains at least 16 steps.
- Pulse or switch "On"/"Off" state contains at least 4 steps.
- Delay time of transmission line and "delay" component contains at least 2 steps.

Automatic step reduction is also used to provide better time resolution of switching point detection. If time constants of the circuit are large, and high calculation step can be used for linear range simulation, reducing the step only at switching points improves simulation performance significantly.

Handling infinite voltage and current pulses

Unlike standard Spice-based tools, **idealCircuit** is capable to simulate schematics with **true ideal components**. An example of such a component is an ideal switch, which has zero impedance when closed, infinite impedance when open, and instantaneous switching from one state to another. When an ideal switch is used for charging or discharging capacitors, an infinitely short current pulse with infinite amplitude may occur. Although amplitude of the pulse is infinite, the area (integral over time) is limited and is equal to the total charge coming to or out of the capacitor at the moment of switching. Similar situation may occur when current through the inductor is discontinued, which results in an infinite voltage pulse across the inductor. Integral of the voltage over time corresponds to a magnetic flux in the inductor.

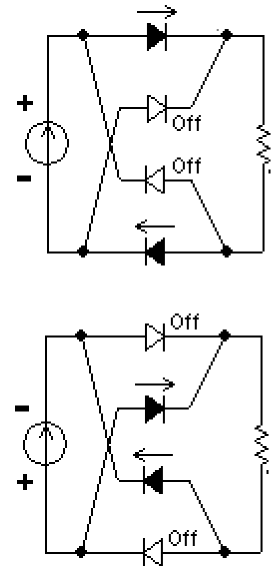




Such an infinitely short pulse with infinite amplitude and limited area is usually referred to as a Dirac pulse, or delta-function. Since showing true delta-function on the transient graph would be problematic, the following approach is implemented in **idealCircuit**. The current or voltage delta-function is shown as a triangle pulse with the duration of each slope equal to minimal calculation step used at that moment, and the area satisfies charge or magnetic flux conservation law. If calculation step is reasonably small, the displayed pulse will be short and will have high enough amplitude to be visually considered as a delta-function. At the same time, the integral of the pulse will give true value of the charge (for current pulse) or magnetic flux (voltage pulse). Changing calculation step will change duration and amplitude of the displayed pulse, however the integral of the pulse will stay the same.

Convergence

In Spice-based simulators convergence problem may occur any time: during DC analysis and transient analysis. Since **idealCircuit** is piece-wise linear simulator, most of the time it is dealing with linear systems, which do never experience convergence problem. The only time **idealCircuit** simulation may have some difficulties, is the moment when one or more components change their state or linear segment.



For systems with ideal piece-wise linear components, a typical situation is when several components have to change states exactly at the same moment, otherwise the system won't converge. For example, in a standard four-diodes bridge rectifier, diodes are always switching by pairs, or even all diodes at a time. With ideal diodes having zero resistance when closed, and infinite resistance when opened, a simple algorithm may have some trouble resolving switching process. Possible solution would be adding non-zero resistors in series and/or large resistors in parallel to the diodes. However, this may produce very small time constants, which results in very small calculation step, so that all the benefits of using ideal components vanish.

Since traditional iterative methods do not work reliable for such systems, **idealCircuit** uses robust proprietary algorithm. So far, the algorithm works perfect for all schematics tested, however nobody could prevent users from designing something special, which may have convergence difficulties.

Memory

Simulation data is stored in the operating memory. The memory is allocated as needed by relatively small blocks. If available operating memory is not enough for storing continuously increasing amount of simulation data, the operating system starts saving data to the disk, which may slow down simulation and display significantly. To prevent from this, the following mechanism is used: when amount of memory required for the trace exceeds the maximum value specified on **Transient** page of **Preferences** dialog box, the block of the memory currently storing the very beginning of the trace will be released and allocated again for the new data. Thus, the trace will be truncated at the beginning in order to keep the latest data.

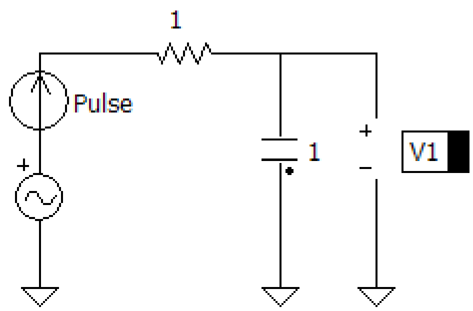
Please be aware that regardless of the size of operating memory on your computer, only 2GB can be used by **idealCircuit** due to restriction of 32-bit Windows application. If simulation data takes a large amount of memory, so that it is close to 2GB, the program operation may become extremely slow. **idealCircuit** continuously tracks amount of memory used, and automatically starts truncating traces data when needed in order to prevent from slowing operation down.

IV. AC Analysis

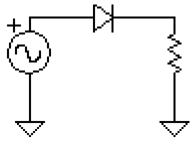
Low-signal AC simulation algorithm

idealCircuit performs standard low-signal AC analysis. First, all non-linear components are replaced with linear equivalents at their operating point. Second, a signal of specified frequency with unit amplitude and zero phase is applied to the **AC source** component, and signals at other nodes are found by solving a system of linear equations. The process is repeated for specified number of frequencies.

To perform AC analysis, one (and only one) **AC source** component should present in the circuit. During transient analysis AC source is ignored (short circuit). On the example below, voltage source "Pulse" is used for transient analysis (AC source is short circuit), and AC source is used for low signal AC analysis:



Linearization



The method always works for linear circuits. The method can be also used for circuits with non-linear components, but only if those components can be properly linearized at operating point: infinitely small amplitude of input AC signal should not change state of the components. For instance, the following circuit cannot be correctly analyzed by this method, as the ideal diode will change its state every time input AC signal changes polarity.

The method also cannot be used for switching-type circuits, since all the switches will be set to either open or closed state, and will not be switching as required.

In order to linearize schematic, state of all components should be known. It can be done manually by setting Initial Conditions (IC) for all non-linear components, diodes, and controlled switches. Initial conditions that are not specified manually will be calculated during DC operating point calculation. DC operating point is calculated exactly as in transient analysis.

V. Preferences

idealCircuit preferences are used to customize different features of the application, such as "look and feel" (fonts, colors, formats), default parameters, memory management, etc. Preferences apply to the whole application, not to the particular document (schematic). Changing preferences does not affect simulation results.

Preferences are stored in the same directory as `ic.exe`, in the file called `ic.icp`. Preferences are saved into the file every time **Apply** or **OK** button in the Preferences dialog box is clicked, and on exiting **idealCircuit**. At start-up, **idealCircuit** loads last saved preferences from the file.

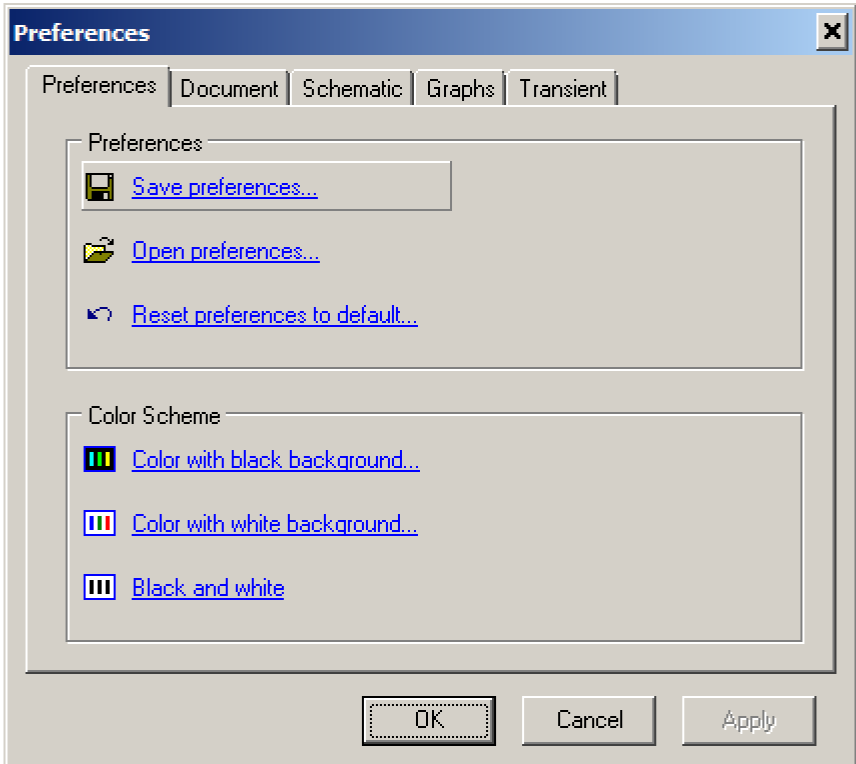
Preferences can also be saved in the custom preferences file (extension "`icp`"), and then opened back from the file. This feature allows having different profiles for different tasks and switch between them easily.

Open Preferences dialog box by Main menu command **Menu | Preferences**. The Preferences dialog box consists of several of pages. Select the page by clicking on the page name on the top of the dialog window. When any of parameters changed, **Apply** button is enabled. Click:

- **OK** – accept changes and close the dialog box.
- **Cancel –** cancel changes and close the dialog box.
- **Apply –** accept changes without closing the dialog box.

Preferences

Save/open preferences to/from a file and select color scheme.



Preferences

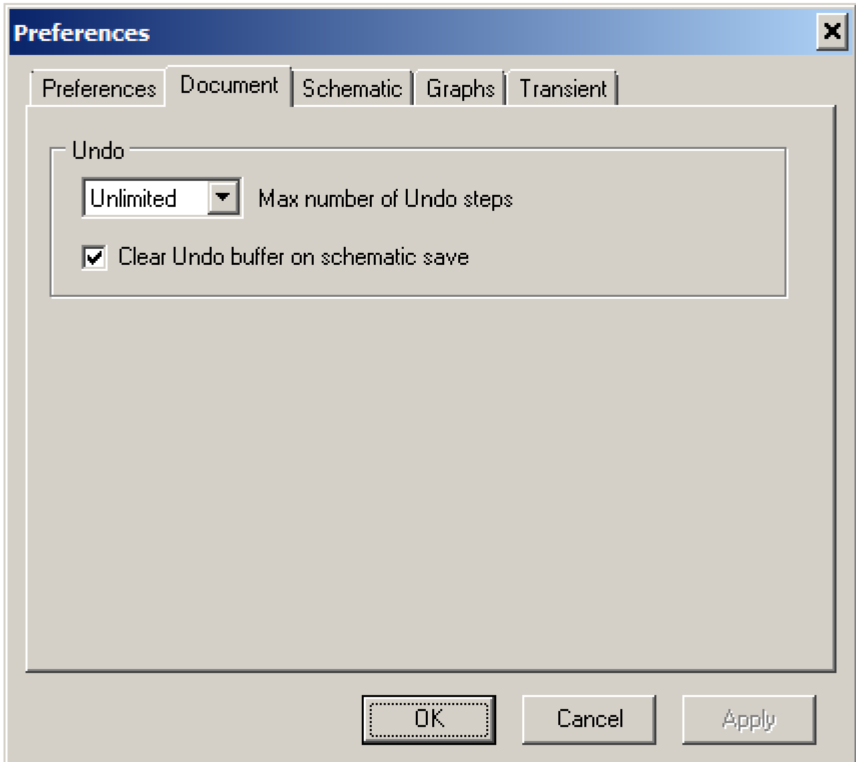
- **Save preferences**. Save preferences to a file.
- **Open preferences**. Open preferences from a file.
- **Reset preferences to default**.

Color scheme

- **Color with black background**.
- **Color with white background**.
- **Black and white**. This scheme can be temporary used to copy black and white schematic or graph image to the clipboard.

Document

Set up Undo options.

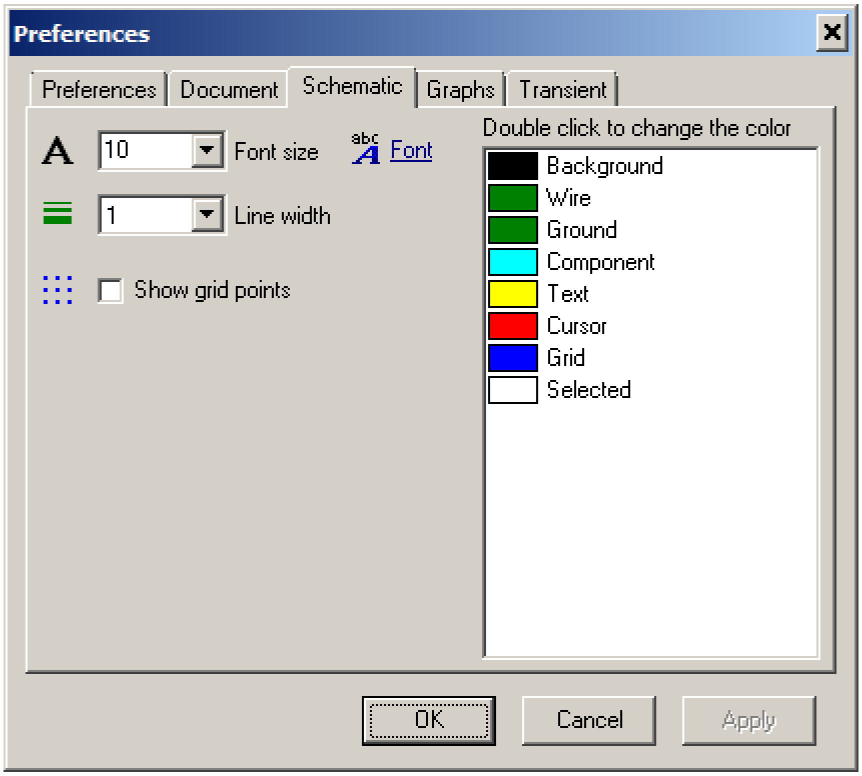


Undo

- **Max number of Undo steps.** Although Undo/Redo buffer can be unlimited, its maximum size may be specified as well. When new Undo information is being added and buffer size exceeds specified size, the earliest data will be removed from the buffer.
- **Clear Undo buffer on schematic save.** If selected, Undo buffer will be cleared when schematic is saved into file. Otherwise, all operations since opening or creating the schematic can be reversed.

Schematic

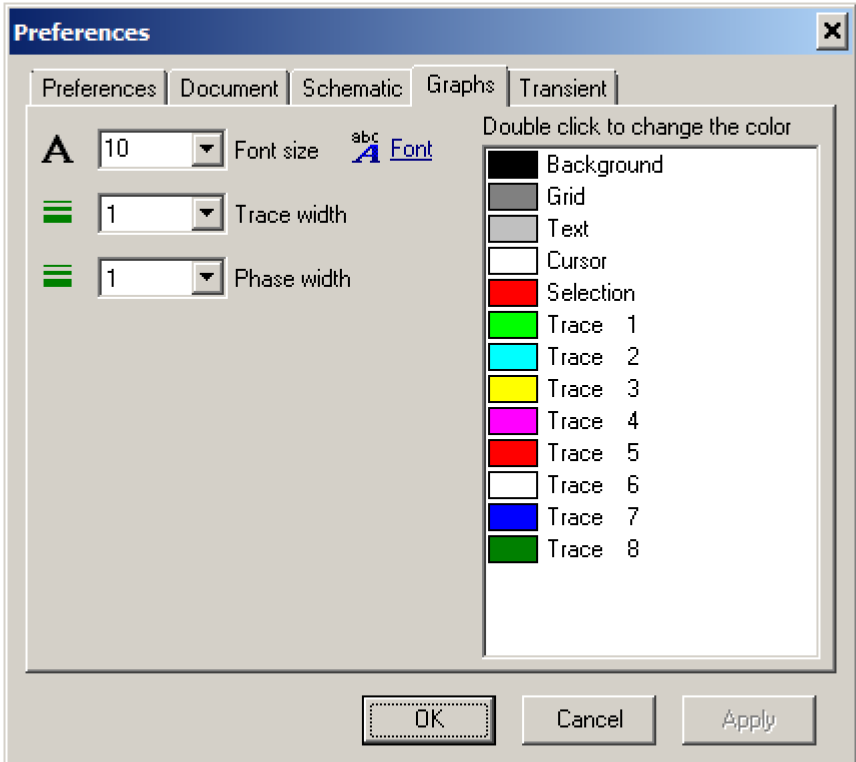
Set schematic properties.



- **Font size.** Set font size.
- **Font.** Select font.
- **Line width.** Set width of a line (wires and components).
- **Show grid points.** If selected, show schematic grid points.
- **Colors.** Double-click on the item in the list to change the color.

Graphs

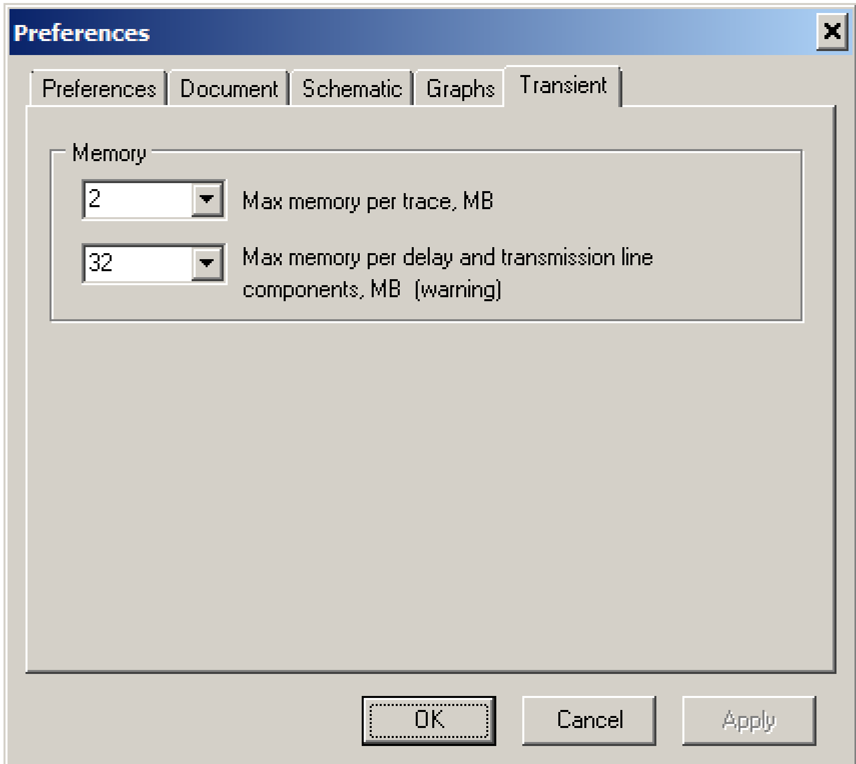
Set properties of Transient and AC graphs.



- **Font size.** Set font size of axes numbers.
- **Font.** Select font of axes numbers.
- **Default trace width.** Set width of a trace.
- **Default phase width.** Set width of a phase trace.
- **Colors.** Double-click on the item in the list to change the color.

Transient

Set transient memory options.



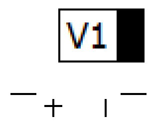
Memory.

- **Max memory per trace, MB.** Set maximum amount of memory allowed per one trace. If trace memory exceeds this limit, the beginning portion of the trace will be deleted.
- **Max memory per delay and transmission line components, MB (warning).** Set maximum amount of memory allowed for delay and transmission line components. If estimated required memory exceeds specified limit, a warning message will show up, with the option to continue or stop simulation**.**

VI. Components

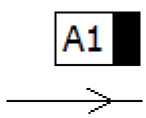
1. Probes, AC source

Voltmeter (voltage probe)

	Parameter	Units	Description
	No parameters		

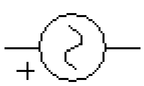
Voltmeter (voltage probe). Show measured voltage as a transient and AC trace.

Amperemeter (current probe)

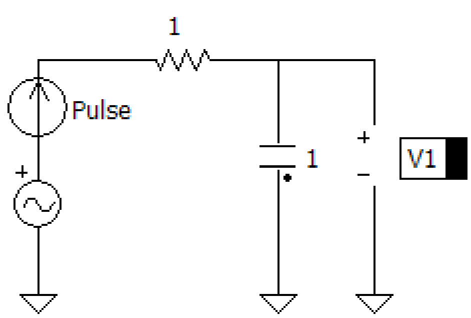
	Parameter	Units	Description
	No parameters		

Amperemeter (current probe). Show measured current as a transient and AC trace.

AC source

	Parameter	Units	Description
	No parameters		

AC source. Specifies AC source for low signal AC analysis. During transient analysis AC source is ignored (short circuit). On the example below, voltage source "Pulse" is used for transient analysis (AC source is short circuit), and AC source is used for low signal AC analysis:



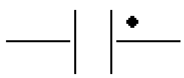
2. R, C, L

Resistor

Parameter	Units	Description
R	Ohm	Resistance

Linear resistor. V = R*I.

Capacitor



Parameter	Units	Description
C	F	Capacitance
IC	V	Initial condition: voltage. Leave blank if IC not defined.

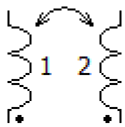
Linear capacitor. I = C*dV/dt. When calculating DC operating point, if initial voltage “IC” is defined, capacitor is replaced with voltage source equal to IC. Voltage is applied referenced to the pin with dot. If “IC” is not defined (blank), capacitor is temporarily removed (open circuit), DC operating point calculated, and then the voltage found across the capacitor is assigned to the capacitor as its initial voltage.

Inductor

Parameter	Units	Description
L	H	Inductance
IC	A	Initial condition: current. Leave blank if IC not defined.

Linear inductor. V = L*dI/dt. When calculating DC operating point, if initial current “IC” is defined, inductor is replaced with current source equal to IC. Current is flowing from the pin without dot to the pin with dot inside the inductor. If “IC” is not defined (blank), inductor is temporarily replaced by short circuit, DC operating point calculated, and then the current through short circuit is assigned to the inductor as its initial current.

Coupled inductors



Parameter	Units	Description
L1	H	L1 inductance
L2	H	L2 inductance
K		Coupling coefficient (-1…1)
IC1	A	L1 initial condition: current. Leave blank if IC1 not defined.
IC2	A	L2 initial condition: current. Leave blank if IC2 not defined.

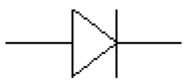
Coupled linear inductors.

V1 = L1*dI1/dt + M*dI2/dt
V2 = M*dI1/dt + L2*dI2/dt

where M = K*sqrt(L1*L2) is mutual inductance. When calculating DC operating point, initial conditions IC1 and IC2 are independently applied to corresponding inductors L1 and L2, similar to how it is done for the single inductor component.

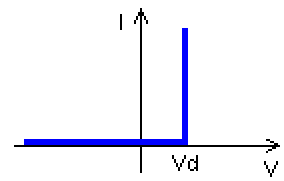
3. Diodes

Diode

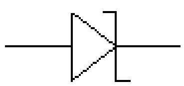


Parameter	Units	Description
Vd	V	Forward voltage drop.
IC		Initial condition: On/Off.

Ideal diode. If V >= "Vd", diode is On (short circuit, V=Vd). Otherwise diode is Off (open circuit, I=0). When calculating DC operating point diode is set to the state specified in "IC".

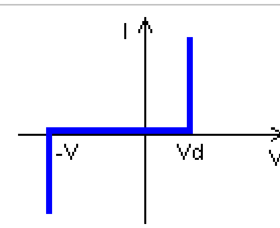


Zener

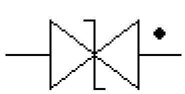


Parameter	Units	Description
V	V	Breakdown voltage drop.
Vd	V	Forward voltage drop.
IC		Initial condition: Minus/Off/Plus.

Ideal zener. If V <= -"V" or V >= "Vd", zener is On (short circuit). Otherwise zener is Off (open circuit, I=0). When calculating DC operating point zener is set to the state specified in "IC".

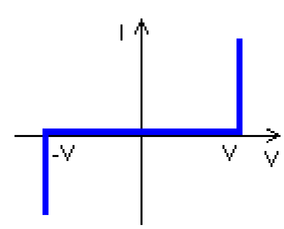


Bidirectional Zener

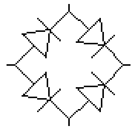


Parameter	Units	Description
V	V	Breakdown voltage drop.
IC		Initial condition: Minus/Off/Plus.

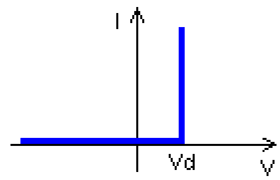
Ideal bidirectional zener. If V <= -"V" or V >= "V", zener is On (short circuit). Otherwise zener is Off (open circuit, I=0). When calculating DC operating point zener is set to the state specified in "IC".



Bridge rectifier

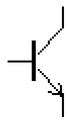
	Parameter	Units	Description
	V	V	Breakdown voltage drop.

Bridge rectifier with ideal diodes. For each diode, if V >= "Vd", the diode is On (short circuit, V=Vd). Otherwise the diode is Off (open circuit, I=0). When calculating DC operating point all diodes are Off

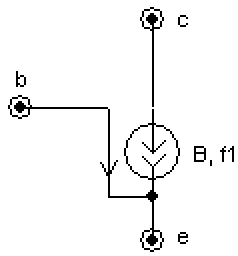


4. Transistors

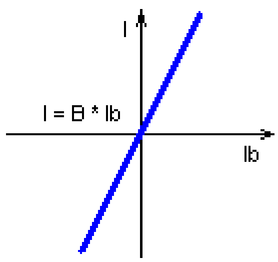
NPN transistor - Linear

	Parameter	Units	Description
	B	A/A	Gain (beta)
	f1	Hz	Unit gain frequency.
	IC	A	Initial condition: collector current.

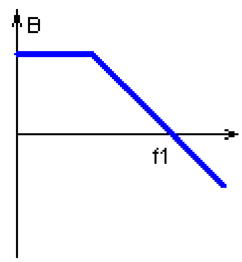
Linear BJT transistor. Current controlled current source with specified bandwidth. “B” is open loop gain (beta). Frequency response consists of one pole, “f1” is unit gain frequency. When calculating DC operating point, if “IC” is defined, collector current is set to specified output current “IC”. If “IC” is blank, static characteristic is used.



Equivalent schematic

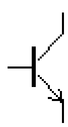


Static characteristic

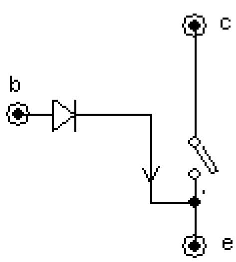


AC response (Bode plot)

NPN transistor - Switch

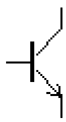
	Parameter	Units	Description
	Vbe	V	Forward voltage drop of base-emitter diode.
	IC		Initial condition of base-emitter diode: Off/On.

BJT transistor switch. Current controlled switch with a base-emitter diode. Switch is closed if diode current is non-zero. When calculating DC operating point the diode is set to the state specified in “IC”.



Equivalent schematic

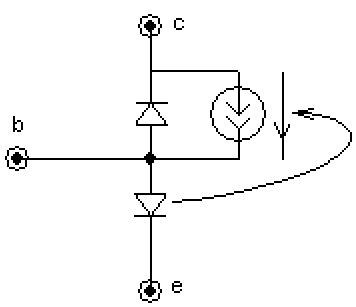
NPN transistor - Transistor



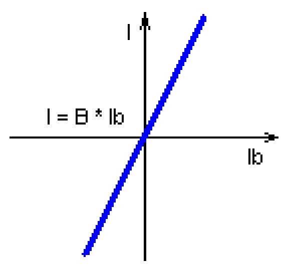
Parameter	Units	Description
B	A/A	Gain (beta)
f1	Hz	Unit gain frequency.
Vbe	V	Forward voltage drop of base-emitter diode.
Vsat	V	Collector-emitter saturation voltage drop.
IC	A	Initial condition: collector current.
ICbe		Initial condition of base-emitter diode: Off/On.
ICbc		Initial condition of base-collector diode: Off/On.

BJT transistor. Simplified Ebers-Moll BJT transistor model with saturation. It consists of two diodes (base-emitter and base-collector), and current source controlled by current through base-emitter diode with gain "alpha": $\alpha = \dfrac{\beta}{1+\beta}$

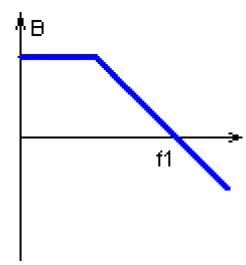
If collector-emitter voltage is higher than "Vsat", base-collector diode is open, transistor is not saturated, and behaves as "Linear" model (current controlled current source with specified bandwidth). "B" is open loop gain (beta). Low signal frequency response consists of one pole, "f1" is unit gain frequency.
If collector voltage drops below "Vsat", base-collector diode is closed, and transistor is saturated: collector-emitter voltage is equal to "Vsat".
When calculating DC operating point, if "IC" is defined, collector current is set to specified output current "IC". If "IC" is blank, static characteristic is used. Base-emitter diode is set to the state specified in "ICbe", Base-collector diode is set to the state specified in "ICbc".



Equivalent schematic

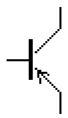


Non-saturated static characteristic

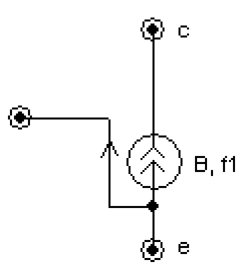


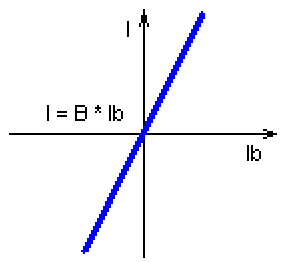
Low signal AC response) (Bode plot)

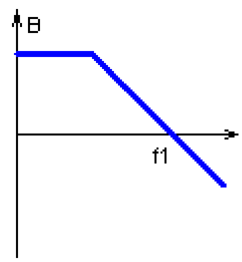
PNP transistor - Linear

	Parameter	Units	Description
	B	A/A	Gain (beta)
	f1	Hz	Unit gain frequency.
	IC	A	Initial condition: collector current.

Linear BJT transistor. Current controlled current source with specified bandwidth. “B” is open loop gain (beta). Frequency response consists of one pole, “f1” is unit gain frequency. When calculating DC operating point, if “IC” is defined, collector current is set to specified output current “IC”. If “IC” is blank, static characteristic is used.

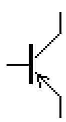




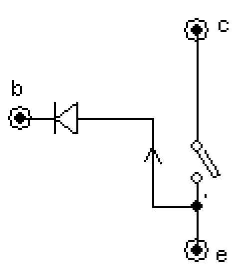


Equivalent schematic **Static characteristic** **AC response (Bode plot)**

PNP transistor - Switch

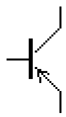
	Parameter	Units	Description
	Vbe	V	Forward voltage drop of base-emitter diode.
	IC		Initial condition of base-emitter diode: Off/On.

BJT transistor switch. Current controlled switch with a base-emitter diode. Switch is closed if diode current is non-zero. When calculating DC operating point the diode is set to the state specified in “IC”.



Equivalent schematic

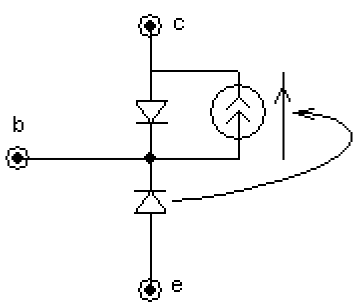
PNP transistor - Transistor



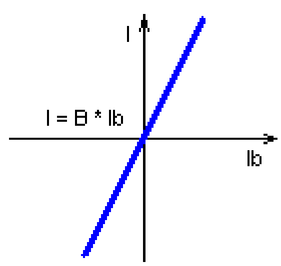
Parameter	Units	Description
B	A/A	Gain (beta)
f1	Hz	Unit gain frequency.
Vbe	V	Forward voltage drop of base-emitter diode.
Vsat	V	Collector-emitter saturation voltage drop.
IC	A	Initial condition: collector current.
ICbe		Initial condition of base-emitter diode: Off/On.
ICbc		Initial condition of base-collector diode: Off/On.

BJT transistor. Simplified Ebers-Moll BJT transistor model with saturation. It consists of two diodes (base-emitter and base-collector), and current source controlled by current through base-emitter diode with gain "alpha": $\alpha = \frac{\beta}{1+\beta}$

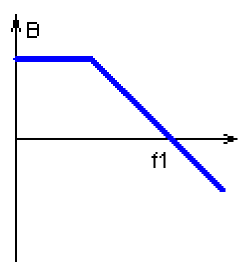
If collector-emitter voltage is negative and less than -"Vsat", base-collector diode is open, transistor is not saturated, and behaves as "Linear" model (current controlled current source with specified bandwidth). "B" is open loop gain (beta). Low signal frequency response consists of one pole, "f1" is unit gain frequency.
If collector voltage is higher than -"Vsat", base-collector diode is closed, and transistor is saturated: collector-emitter voltage is equal to -"Vsat".
When calculating DC operating point, if "IC" is defined, collector current is set to specified output current "IC". If "IC" is blank, static characteristic is used. Base-emitter diode is set to the state specified in "ICbe". Base-collector diode is set to the state specified in "ICbc".



Equivalent schematic

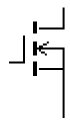


Non-saturated static characteristic



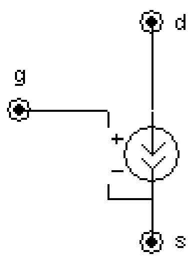
Low signal AC response)
(Bode plot)

N-FET transistor - Linear

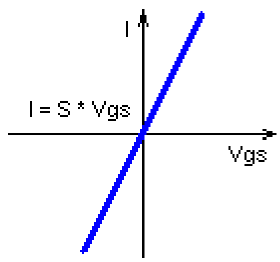


Parameter	Units	Description
S	A/V	Slope
f1	Hz	Unit gain frequency.
IC	A	Initial condition: drain current.

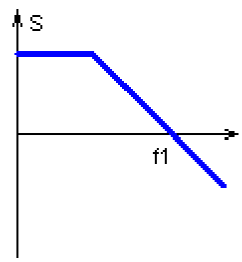
Linear FET transistor. Voltage controlled current source with specified bandwidth. "S" is open loop slope. Frequency response consists of one pole, "f1" is unit gain frequency.
When calculating DC operating point, if "IC" is defined, drain current is set to specified output current "IC". If "IC" is blank, static characteristic is used.



Equivalent schematic

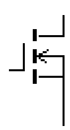


Static characteristic



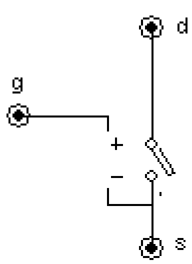
AC response (Bode plot)

N-FET transistor - Switch



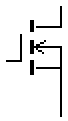
Parameter	Units	Description
Vth	V	Threshold.
IC		Initial condition of the switch: Off/On.

FET switch. Voltage controlled switch. Switch is closed if gate-source voltage exceeds threshold "Vth".
When calculating DC operating point switch is set to the state specified in "IC".



Equivalent schematic

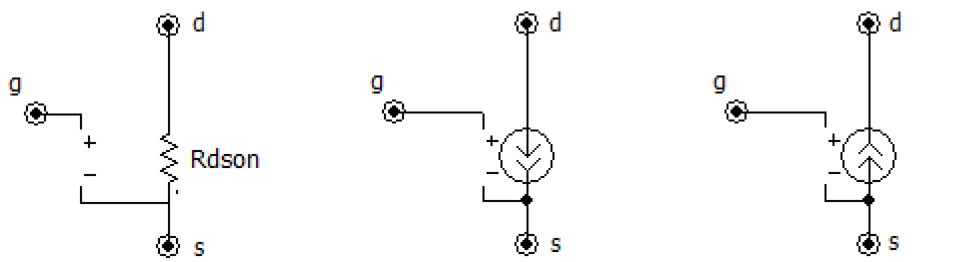
N-FET transistor - FET

	Parameter	Units	Description
	S	A/V	Slope.
	Vth	V	Threshold.
	Rdson	Ohm	Rdson resistance.
	IC		Initial condition: Off/R/Plus/Minus

FET transistor. The model has 3 modes of operation.

1. Vgs <= Vth . . . . : I = 0 (open)
2. Vgs > Vth, Vds <= (Vgs - Vth) * S * Rdson . . : V = I * Rdson (resistor)
3. Vgs > Vth, Vds > (Vgs - Vth) * S * Rdson . . : I = (Vgs - Vth) * S (current source)

FET works similar for positive and negative drain-source voltage, current direction changes accordingly.
Equivalent schematics (Vgs > Vth):



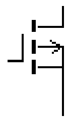
Vds <= (Vgs-Vth)*S*Rdson **Vds > (Vgs-Vth)*S*Rdson** **Vds > (Vgs-Vth)*S*Rdson**

Vds > 0 **Vds < 0**

When calculating DC operating point, transistor is set to an initial state specified by Initial Condition parameter “IC” as follows:

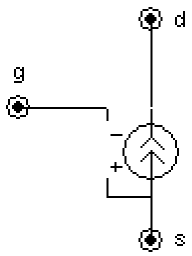
Off . . . : I = 0 (open)
R . . . . : V = I * Rdson (resistor)
Plus . . : Vds > 0, I = (Vgs - Vth) * S (“positive” current source)
Minus. : Vds < 0, I = (Vgs - Vth) * S (“negative” current source)

P-FET transistor - Linear

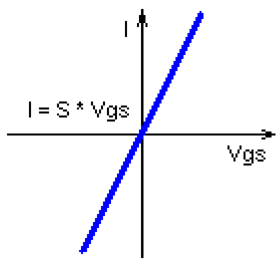


Parameter	Units	Description
S	A/V	Slope.
f1	Hz	Unit gain frequency.
IC	A	Initial condition: drain current.

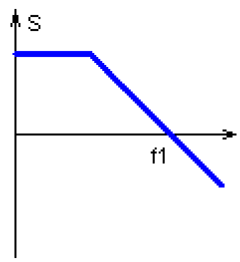
Linear FET transistor. Voltage controlled current source with specified bandwidth. "S" is open loop slope. Frequency response consists of one pole, "f1" is unit gain frequency.
When calculating DC operating point, if "IC" is defined, drain current is set to specified output current "IC". If "IC" is blank, static characteristic is used.



Equivalent schematic

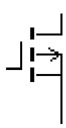


Static characteristic



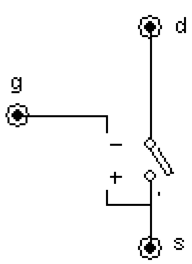
AC response (Bode plot)

P-FET transistor - Switch



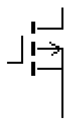
Parameter	Units	Description
Vth	V	Threshold.
IC		Initial condition of the switch: Off/On.

FET switch. Voltage controlled switch. Switch is closed if gate-source voltage is less than threshold "Vth".
When calculating DC operating point switch is set to the state specified in "IC".



Equivalent schematic

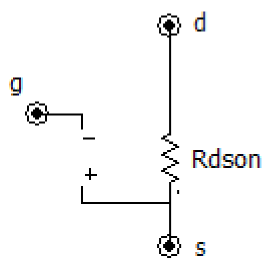
P-FET transistor - FET

	Parameter	Units	Description
	S	A/V	Slope.
	Vth	V	Threshold.
	Rdson	Ohm	Rdson resistance.
	IC		Initial condition: Off/R/Plus/Minus

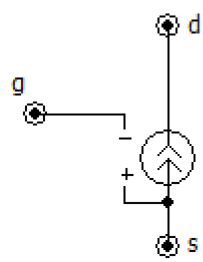
FET transistor. The model has 3 modes of operation.

1. Vgs >= Vth: . . . . : I = 0 (open)
2. Vgs < Vth, Vds >= (Vgs - Vth) * S * Rdson . . : V = I * Rdson (resistor)
3. Vgs < Vth, Vds < (Vgs - Vth) * S * Rdson . . . : I = (Vgs - Vth) * S (current source)

FET works similar for positive and negative drain-source voltage, current direction changes accordingly.
Equivalent schematics (Vgs < Vth):

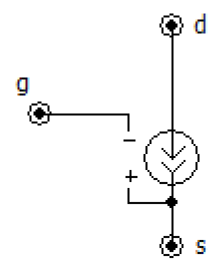


Vds >= (Vgs-Vth)*S*Rdson



Vds < (Vgs-Vth)*S*Rdson

Vds < 0



Vds < (Vgs-Vth)*S*Rdson

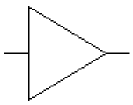
Vds > 0

When calculating DC operating point, transistor is set to an initial state specified by Initial Condition parameter "IC" as follows:

Off . . . : I = 0 (open)
R . . . . : V = I * Rdson (resistor)
Plus . . : Vds < 0, I = (Vgs - Vth) * S ("positive" current source)
Minus . : Vds > 0, I = (Vgs - Vth) * S ("negative" current source)

5. Amplifiers

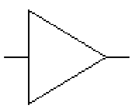
Buffer amplifier - Ideal



Parameter	Units	Description
K	V/V	Gain

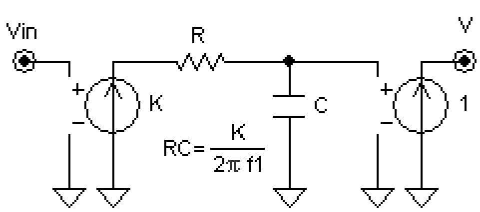
Ideal amplifier. “K” is the gain, frequency bandwidth is infinite

Buffer amplifier - Linear

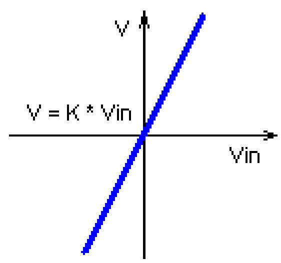


Parameter	Units	Description
K	V/V	Gain
f1	Hz	Unit gain frequency.
IC	V	Initial condition: output voltage.

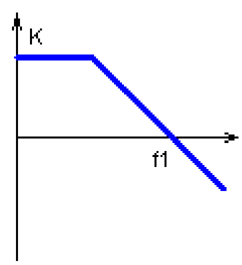
Linear amplifier. “K” is open loop gain. Frequency response consists of one pole, “f1” is unit gain frequency. When calculating DC operating point, if “IC” is defined, amplifier output is set to specified output voltage “IC”. If “IC” is blank, static characteristic is used.



Equivalent schematic

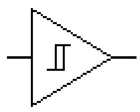


Static characteristic



AC response (Bode plot)

Comparator

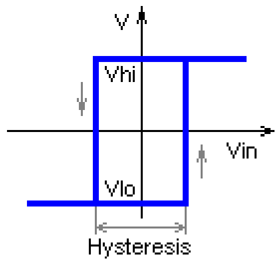


Parameter	Units	Description
Hysteresis	V/V	Hysteresis
Vhi		Max output voltage.
Vlo		Min output voltage.
IC		Initial condition: Low/High.

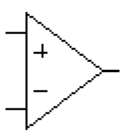
Comparator with hysteresis. Comparator output is set to “Vhi” or “Vlo” using the following rules:

Vin > Hysteresis/2 . . . : V = Vhi
Vin < - Hysteresis/2 . . : V = Vlo
Otherwise . . . .: V = previous state

When calculating DC operating point comparator output is set to “Vlo” or to “Vhi”, according to selected “IC”.



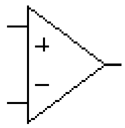
Differential amplifier - Ideal



Parameter	Units	Description
No parameters		

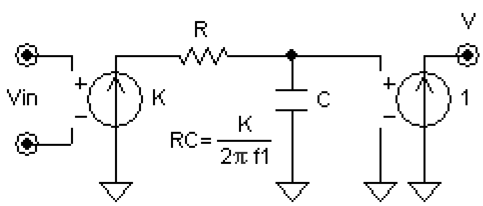
Ideal amplifier. “K” is infinite, frequency bandwidth is infinite.

Differential amplifier - Linear

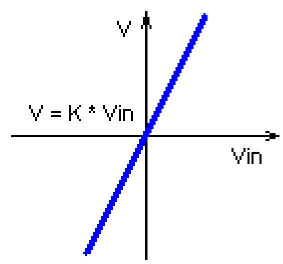


Parameter	Units	Description
K	V/V	Gain
f1	Hz	Unit gain frequency.
IC	V	Initial condition: output voltage.

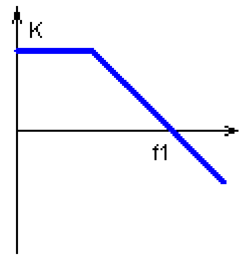
Linear differential amplifier. "K" is open loop gain. Frequency response consists of one pole, "f1" is unit gain frequency. When calculating DC operating point, if "IC" is defined, amplifier output is set to specified output voltage "IC". If "IC" is blank, static characteristic is used.



Equivalent schematic

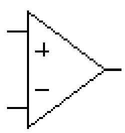


Static characteristic



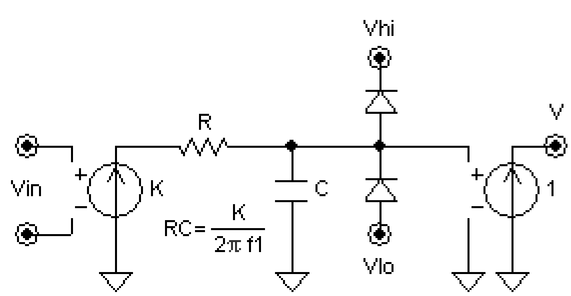
AC response (Bode plot)

Differential amplifier - OpAmp

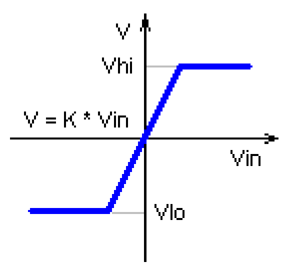


Parameter	Units	Description
K	V/V	Gain
f1	Hz	Unit gain frequency.
Vhi	V	Max output voltage.
Vlo	V	Min output voltage.
IC	V	Initial condition: output voltage.

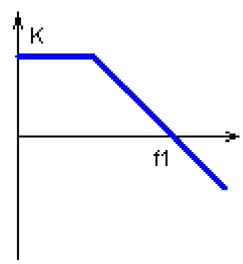
Linear differential amplifier with output limiter. "K" is open loop gain. Frequency response consists of one pole, "f1" is unit gain frequency. Output voltage is limiting between "Vlo" and "Vhi". When calculating DC operating point, if "IC" is defined, amplifier output is set to specified output voltage "IC". If "IC" is blank, static characteristic is used.



Equivalent schematic

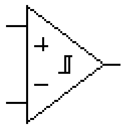


Static characteristic



AC response (Bode plot)

Differential comparator

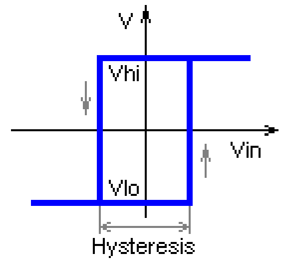


Parameter	Units	Description
Hysteresis	V/V	Hysteresis
Vhi		Max output voltage.
Vlo		Min output voltage.
IC		Initial condition: Low/High.

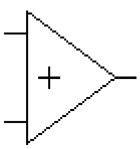
Differential comparator with hysteresis. Comparator output is set to "Vhi" or "Vlo" using the following rules:

Vin > Hysteresis/2 . . . : V = Vhi
Vin < - Hysteresis/2 . . : V = Vlo
Otherwise . . . .: V = previous state

When calculating DC operating point comparator output is set to "Vlo" or to "Vhi", according to selected "IC".



Summing amplifier

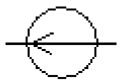


Parameter	Units	Description
K	V/V	Gain

Ideal summing amplifier. "K" is the gain, frequency bandwidth is infinite.

6. Sources

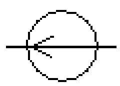
Voltage source - Voltage



Parameter	Units	Description
V	V	Voltage.

Constant voltage source. Voltage = "V".

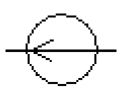
Voltage source - Pulse



Parameter	Units	Description
V1	V	Pulse On voltage.
V0	V	Pulse Off voltage.
Period	s	Period.
Width	s	Pulse width.
Delay	s	Delay before first pulse starts.

Pulse voltage source. Pulses start after "Delay" time.

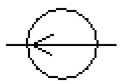
Voltage source - Step



Parameter	Units	Description
V1	V	Step On voltage.
V0	V	Step Off voltage.
Delay	s	Delay before step.

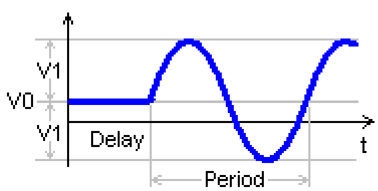
Step voltage source. Step starts after "Delay" time.

Voltage source - Sin

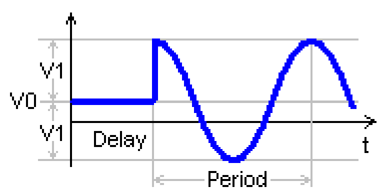


Parameter	Units	Description
V1	V	Voltage amplitude.
V0	V	Voltage baseline.
Period	s	Period.
Phase	deg	Phase.
Delay	s	Delay before sine signal starts.

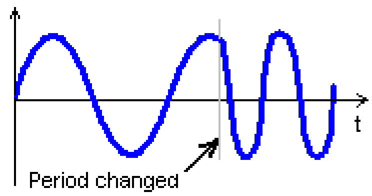
Sine voltage source. Sine signal starts after "Delay" time. "Phase" is sine phase in degrees at the moment when signal starts. If transient is paused, sine period changed, then transient is continued, the phase of the signal remains continuous, providing smooth sine signal of variable frequency.



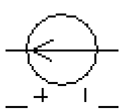
Phase = 0



Phase = 90



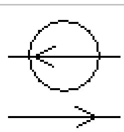
Voltage controlled voltage source



Parameter	Units	Description
K	V/V	Gain

Linear voltage controlled voltage source. V = K * Vin.

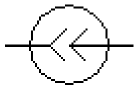
Current controlled voltage source



Parameter	Units	Description
K	V/A	Gain

Linear current controlled voltage source. V = K * Iin.

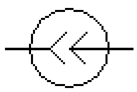
Current source - Current



Parameter	Units	Description
I	A	Current.

Constant current source. Current = "I".

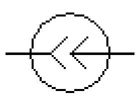
Current source - Pulse



Parameter	Units	Description
I0	A	Pulse Off current.
I1	A	Pulse On current.
Period	s	Period.
Width	s	Pulse width.
Delay	s	Delay before first pulse starts.

Pulse current source. Pulses start after "Delay" time.

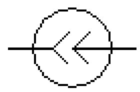
Current source - Step



Parameter	Units	Description
I0	A	Step Off current.
I1	A	Step On current.
Delay	s	Delay before step.

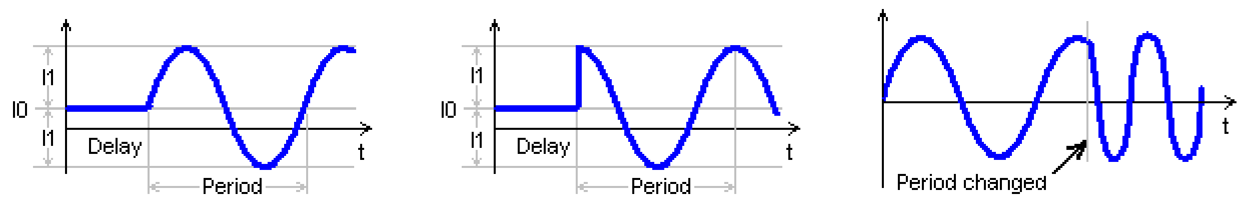
Step current source. Current changes from "I0" to "I1" after "Delay" time.

Current source - Sin



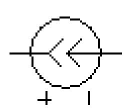
Parameter	Units	Description
I0	A	Current baseline.
I1	A	Current amplitude.
Period	s	Period.
Width	deg	Phase.
Delay	s	Delay before sine signal starts.

Sine current source. Sine signal starts after "Delay" time. "Phase" is sine phase in degrees at the moment when signal starts. If transient is paused, sine period changed, then transient is continued, the phase of the signal remains continuous, providing smooth sine signal of variable frequency.



Phase = 0 **Phase = 90**

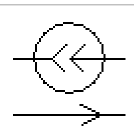
Voltage controlled current source



Parameter	Units	Description
K	A/V	Gain

Linear voltage controlled current source. I = K * Vin.

Current controlled current source

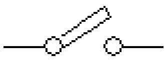


Parameter	Units	Description
K	A/A	Gain

Linear current controlled current source. I = K * Iin.

7. Switches

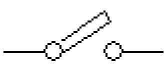
Switch - Switch



Parameter	Units	Description
Switch		Switch state: Off/On.

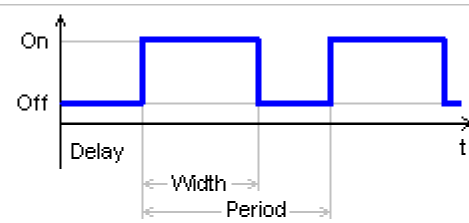
Switch. Off – open switch, infinite resistance. On – closed switch, zero resistance.

Switch - Pulse

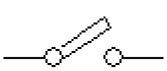


Parameter	Units	Description
Period	s	Period.
Width	s	Pulse width.
Delay	s	Delay before first pulse starts.
Active		Active switch state: Off/On.

Pulse switch. Switching starts after "Delay" time. Switch is in active state during "Width" time. The following switching diagram is shown for "Active" = On:

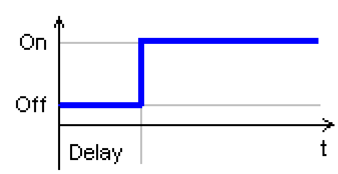


Switch - Step

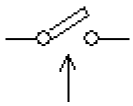


Parameter	Units	Description
Delay	s	Delay before active state.
Active		Active switch state: Off/On.

Step switch. Switch is in active state after "Delay" time. The following switching diagram is shown for "Active" = On:



Logic controlled switch



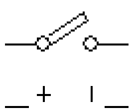
Parameter	Units	Description
Active		Active state: Off/On.
IC		Initial condition: Off/On.

Logic controlled switch. Switch is set to active or non-active state using following rules:

Vin > logical threshold . . . : active
Vin < logical threshold . . . : non-active

When calculating DC operating point switch is set to the state defined in "IC".

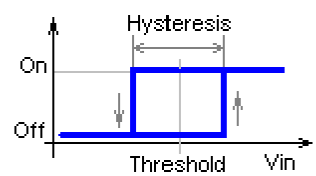
Voltage controlled switch



Parameter	Units	Description
Threshold	V	Voltage threshold.
Hysteresis	V	Hysteresis.
Active		Active state: Off/On.
IC		Initial condition: Off/On.

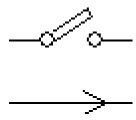
Voltage controlled switch. Switch is set to active or non-active state using following rules:

Vin > Threshold + Hysteresis/2. . . : active
Vin < Threshold - Hysteresis/2 . . . : non-active
Otherwise . . . . : previous state



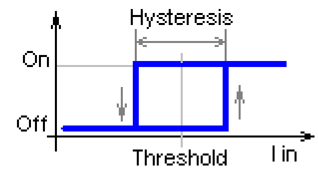
When calculating DC operating point switch is set to the state defined in "IC". The following is switching diagram for "Active" = On.

Current controlled switch



Parameter	Units	Description
Threshold	A	Current threshold.
Hysteresis	A	Hysteresis.
Active		Active state: Off/On.
IC		Initial condition: Off/On.

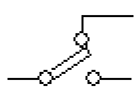
Current controlled switch. Switch is set to active or non-active state using following rules:



Iin > Threshold + Hysteresis/2. . . : active
Iin < Threshold - Hysteresis/2 . . . : non-active
Otherwise . . . . : previous state

When calculating DC operating point switch is set to the state defined in “IC”. The following is switching diagram for “Active” = On:

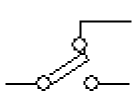
SPDT switch - Switch



Parameter	Units	Description
Switch		Switch state: Off/On.

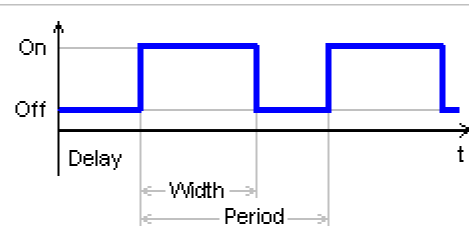
SPDT (single pole, double throw) switch. Open switch has infinite resistance, closed switch has zero resistance. Switch is shown in Off state.

SPDT switch - Pulse



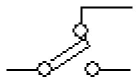
Parameter	Units	Description
Period	s	Period.
Width	s	Pulse width.
Delay	s	Delay before first pulse starts.
Active		Active switch state: Off/On.

SPDT (single pole, double throw) pulse switch. Switching starts after “Delay” time. Switch is in active state during “Width” time. Open switch has infinite resistance, closed switch has zero resistance. Switch is shown in Off state.



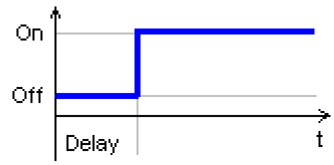
:

SPDT switch - Step

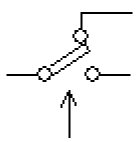


Parameter	Units	Description
Delay	s	Delay before active state.
Active	s	Active switch state: Off/On.

SPDT (single pole, double throw) step switch. Switch is in active state after “Delay” time. Open switch has infinite resistance, closed switch has zero resistance. Switch is shown in Off state



SPDT logic controlled switch



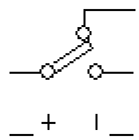
Parameter	Units	Description
Active		Active state: Off/On.
IC		Initial condition: Off/On.

Logic controlled switch. Switch is set to active or non-active state using following rules:

Vin > logical threshold . . . : active
Vin < logical threshold . . . : non-active

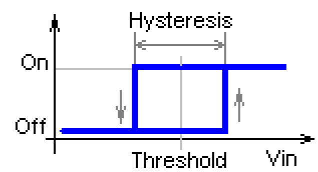
When calculating DC operating point switch is set to the state defined in “IC”. Open switch has infinite resistance, closed switch has zero resistance. Switch is shown in Off state.

SPDT voltage controlled switch



Parameter	Units	Description
Threshold	V	Voltage threshold.
Hysteresis	V	Hysteresis.
Active		Active state: Off/On.
IC		Initial condition: Off/On.

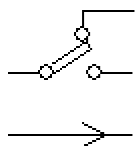
Voltage controlled switch. Switch is set to active or non-active state using following rules:



Vin > Threshold + Hysteresis/2. . . : active
Vin < Threshold - Hysteresis/2 . . . : non-active
Otherwise . . . . : previous state

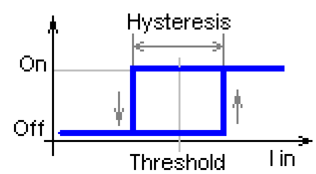
When calculating DC operating point switch is set to the state defined in "IC". Open switch has infinite resistance, closed switch has zero resistance. Switch is shown in Off state.

SPDT current controlled switch



Parameter	Units	Description
Threshold	A	Current threshold.
Hysteresis	A	Hysteresis.
Active		Active state: Off/On.
IC		Initial condition: Off/On.

Current controlled switch. Switch is set to active or non-active state using following rules:

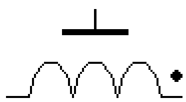


Iin > Threshold + Hysteresis/2. . . : active
Iin < Threshold - Hysteresis/2 . . . : non-active
Otherwise . . . . : previous state

When calculating DC operating point switch is set to the state defined in "IC". Open switch has infinite resistance, closed switch has zero resistance. Switch is shown in Off state.

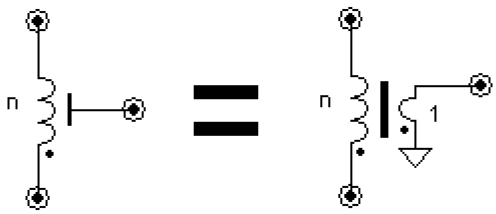
8. Transformers

Winding



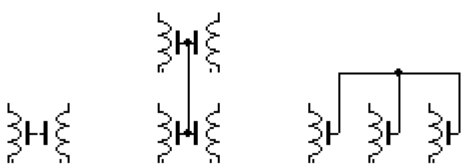
Parameter	Units	Description
n	turns	Number of turns.

Winding. The Winding is actually an ideal transformer, with 1 turn second winding, one end of each is grounded, and another end is shown as a “core” pin of the winding:

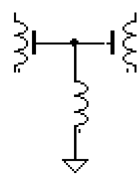


Equivalent schematic

To make an ideal transformer of arbitrary configuration, connect cores of two or more windings by wire. Core magnetizing can be modeled by setting linear or non-linear inductor from core to ground:

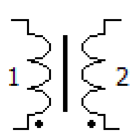


Ideal transformers



Transformer with magnetizing inductor

Transformer



Parameter	Units	Description
n1	turns	Number of turns in the first winding.
n2	turns	Number of turns in the second winding.

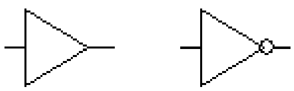
Ideal transformer with 2 windings. Coupling coefficient = 1.

9. Logical

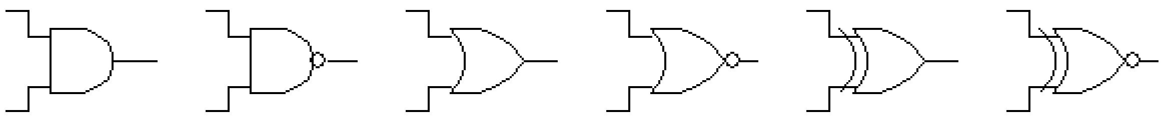
Logical

	Parameter	Units	Description
	IC		Initial condition: Low/High.

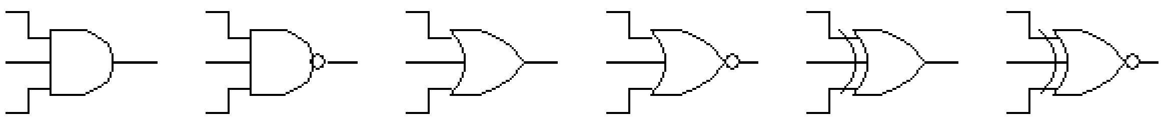
Logical component. Output voltage may have only logical levels (Low/High). Input voltage is considered Low if it is below logical threshold, or High if it is above logical threshold. When calculating DC operating point output is set to specified level "IC". When calculating transient, output voltage is always delayed by one calculation step.



Buffer Inverter

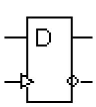


AND-2 NAND-2 OR-2 NOR-2 XOR-2 XNOR-2

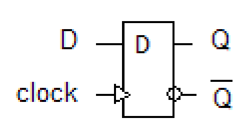


AND-3 NAND-3 OR-3 NOR-3 XOR-3 XNOR-3

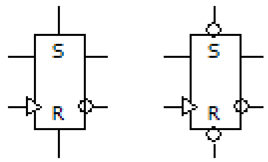
D flip-flop

	Parameter	Units	Description
	IC		Initial condition: Low/High.

D flip-flop. D-input is captured by rising edge of "clock" input. Output voltage may have only logical levels (Low/High). Input voltage is considered Low if it is below logical threshold, or High if it is above logical threshold. When calculating DC operating point output is set to specified level "IC". When calculating transient, output voltage is always delayed by one calculation step.

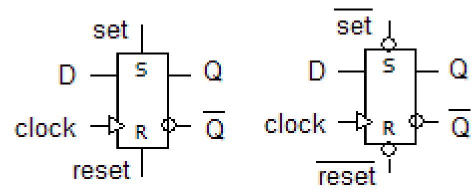


SR trigger

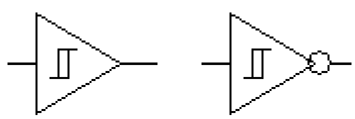


Parameter	Units	Description
IC		Initial condition: Low/High.

SR trigger. D-input is captured by rising edge of "clock" input. Output voltage may have only logical levels (Low/High). Input voltage is considered Low if it is below logical threshold, or High if it is above logical threshold. When calculating DC operating point output is set to specified level "IC". When calculating transient, output voltage is always delayed by one calculation step.



Schmitt trigger



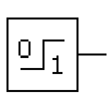
Parameter	Units	Description
Hysteresis	V	Hysteresis.
IC		Initial condition: Low/High.

Schmitt trigger. Output voltage may have only logical levels (Low/High). Output is set to Low or High level following rules (non-inverted output):

Vin > Threshold + Hysteresis/2 . . . : V = High
Vin < Threshold - Hysteresis/2 . . . .: V = Low
Otherwise . . . .: V = previous state

When calculating DC operating point output is set to specified level "IC". When calculating transient, output voltage is always delayed by one calculation step

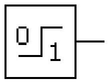
Logic generator - Logical



Parameter	Units	Description
Out		Logical output: Low/High.

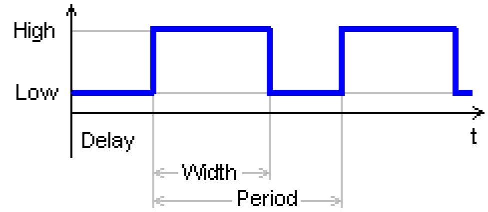
Logical output. Generates constant Low or High logical output.

Logic generator - Pulse

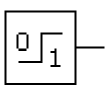


Parameter	Units	Description
Period	s	Period.
Width	s	Pulse width.
Delay	s	Delay before first pulse starts.
Active		Active output state: Low/High.

Logical pulses. Pulses start at “Delay” time. Output level is “Active” during “Width” time.



Logic generator - Step



Parameter	Units	Description
Delay	s	Delay before active state.
Active		Active output state: Low/High.

Logical step. Output level is non-“Active” before “Delay” time, turns to “Active” level after “Delay” time.

10. Miscellaneous

Function - Pwr

Parameter	Units	Description
power		Power.
K	V/V	Gain.
IC	V	Initial condition: output voltage.

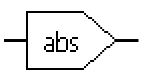
“Signed” power function. V = K * pwr(Vin, power). The function is calculated as follows:

if power = 0:
- if Vin < 0 . . . : V = -K
- if Vin = 0 . . . : V = 0
- if Vin > 0 . . . : V = K

if power ≠ 0:
- if Vin < 0 . . . : $V = - K * (-Vin)^{power}$
- if Vin = 0 . . . : V = 0
- if Vin > 0 . . . : $V = K * Vin^{power}$

When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

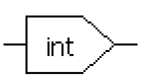
Function - Abs



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage.

Absolute value. V = K * abs(Vin). When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

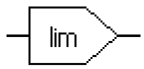
Function - Int



Parameter	Units	Description
resolution		Resolution.
K	V/V	Gain.
IC	V	Initial condition: output voltage.

Rounding function. V = K * round(Vin, resolution). Rounds to the nearest multiple of “resolution”. If resolution = 1, round to the nearest integer. When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Function - Lim



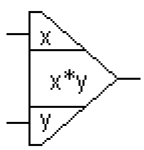
Parameter	Units	Description
Max	V	Maximum.
Min	V	Minimum.
IC	V	Initial condition: output voltage.

Limiting function. The function is calculated as follows:

if Vin < Min . . . : V = Min
if Vin > Max . . : V = Max
Otherwise . . . . : V = Vin

When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

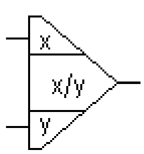
Function-2 - Mul



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Multiplication. V = K * Vx * Vy. When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

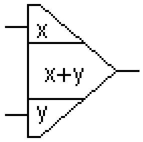
Function-2 - Div



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Division. V = K * Vx / Vy. If Vy = 0, V = 0. When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

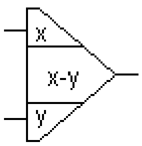
Function-2 - Sum



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Addition. V = K * (Vx + Vy). When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

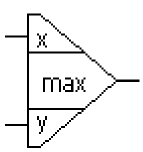
Function-2 - Sub



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Subtraction. V = K * (Vx - Vy). When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Function-2 - Max



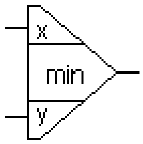
Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Maximum. V = K * max(Vx, Vy).

if Vx >= Vy . . : V = K * Vx
if Vx < Vy . . . : V = K * Vy

When calculating DC operating point output is set to specified output voltage “IC”. When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Function-2 - Min



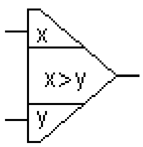
Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Minimum. V = K * min(Vx, Vy).

if Vx >= Vy . . : V = K * Vy
if Vx < Vy . . . : V = K * Vx

When calculating DC operating point output is set to specified output voltage "IC". When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Function-2 - GT



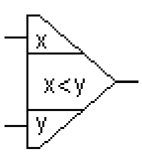
Parameter	Units	Description
IC	V	Initial condition: output voltage

Greater than. V = Vx > Vy ? High : Low.

if Vx <= Vy . . : V = Low
if Vx > Vy . . . : V = High

High and Low are logical levels. When calculating DC operating point output is set to specified output voltage "IC". When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Function-2 - LT



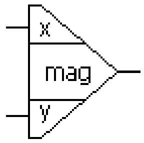
Parameter	Units	Description
IC	V	Initial condition: output voltage

Less than. V = Vx < Vy ? High : Low.

if Vx < Vy . . . . : V = High
if Vx >= Vy . . . : V = Low

High and Low are logical levels. When calculating DC operating point output is set to specified output voltage "IC". When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

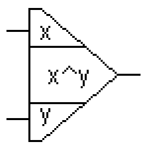
Function-2 - Mag



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Magnitude. V = K * sqrt(Vx^2 + Vy^2). When calculating DC operating point output is set to specified output voltage "IC". When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Function-2 - Pwr



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

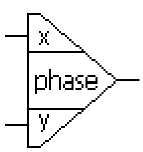
"Signed" power function. V = K * pwr(Vx, Vy). The function is calculated as follows:

if Vy = 0:
- if Vx < 0. . . : V = -K
- if Vx = 0. . . : V = 0
- if Vx > 0. . . : V = K

if Vy ≠ 0:
- if Vx < 0. . . : V = - K * $(-Vx)^{Vy}$
- if Vx = 0. . . : V = 0
- if Vx > 0. . . : V = K * Vx^{Vy}

When calculating DC operating point output is set to specified output voltage "IC". When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

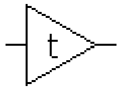
Function-2 - Phase



Parameter	Units	Description
K	V/V	Gain.
IC	V	Initial condition: output voltage

Phase. V = K * phase(Vx, Vy). V in Volts is equal to phase of a vector Vx + jVy in degrees.
If Vx = 0 and Vy = 0: V = 0. When calculating DC operating point output is set to specified output voltage "IC". When calculating transient, output voltage is always delayed by one calculation step. This may affect stability of the schematic with closed loop.

Delay



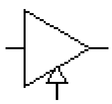
Parameter	Units	Description
t0	s	Delay.
IC	V	Initial condition: output voltage.

Delay. Output voltage is equal to input voltage, delayed by delay time "t0":

V(t) = Vin(t – t0), where t is current time.

When calculating DC operating point, output is set to specified output voltage "IC", or, if "IC" is blank, to input voltage. Then output voltage is not changing until delay time "t0". The model allocates memory for storing delayed data only when needed, and frees it immediately when possible. At transient start, an approximate amount of needed memory is estimated based on calculation step, and, if it exceeds a limit specified in Preferences (Transient page), the warning message is displayed.

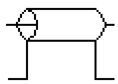
Sample/Hold



Parameter	Units	Description
IC	V	Initial condition: output voltage.

Sample/hold. Input voltage is sampled at rising edge of a logical clock signal.

Transmission line

	Parameter	Units	Description
	t0	s	Delay.
	z0	Ohm	Characteristic impedance.
	VIC	V	Initial condition: voltage.
	IIC	A	Initial condition: current.

Lossless transmission line. The voltage and current in the line are represented as a superposition of forward and reflected waves, with V/I ratio in each wave equal to line characteristic impedance "z0". V and I values of each wave are calculated based on boundary (input and output) conditions. The line functionality can also be described by the following equations:

$$Vin(t) = z0 * (Iin(t) - Iout(t - t0))$$
$$Vout(t) = z0 * (Iout(t) - Iin(t - t0))$$

where t is current time.

Input (left pins) and output (right pins) are galvanically isolated: no current is flowing between input and output, and any voltage difference between input and output may exist. When calculating DC operating point initial forward and reflected voltage and current are calculated based on the following conditions:

if "VIC" and "IIC" are blank . . . . : Vin = Vout, Iin = -Iout.
if "VIC" is specified and "IIC" is blank . . : Vin = Vout = "VIC".
if "VIC" is blank and "IIC" is specified . . : Iin = "IIC", Iout = -"IIC".
if "VIC" and "IIC" are specified . . . . : Vin = Vout = "VIC", Iin = "IIC", Iout = -"IIC".

The model allocates memory for storing forward and reflected wave data only when needed, and frees it immediately when possible. At transient start, an approximate amount of needed memory is estimated based on calculation step, and, if it exceeds a limit specified in Preferences (Transient page), the warning message is displayed. If real line characteristics are given in line capacitance and inductance per length, the following equations can be used to derive "t0" and "z0" parameters:

$$t0 = \sqrt{L*C} * D$$
$$z0 = \sqrt{L/C}$$

where:

C – line capacitance per length, F/m
L – line inductance per length, H/m
D – line length, m

The end