RECTIFIER scope to observe the DC Fault protection action. Restart the simulation.
Figure 5-13: DC Line Fault on the Rectifier Side

At fault application (t = 0.7 s), the DC current increases to 2.2 p.u. and the DC voltage falls to zero at the rectifier. This DC voltage drop is seen by the Voltage Dependent Current Order Limiter (VDCOL) and the DC Fault protection. The VDCOL reduces the reference current to 0.3 p.u. at the rectifier. A DC current still continues to circulate in the fault. Then, at t = 0.77 s, the rectifier α firing angle is forced to 166 degrees by the DC Fault protection after detecting a low DC voltage. The rectifier now operates in inverter mode. The DC line voltage becomes negative and the energy stored in the line is returned to the AC system, causing rapid extinction of the fault current at its next zero crossing. Then α is released at t = 0.82 s and the normal DC voltage and current recover.
in approximately 0.5 s. Notice, the temporary mode change in the Rectifier controls between 1.18 s and 1.25 s.

**AC Line-to-Ground Fault at the Inverter**

Now modify the fault timings to apply a line-to-ground fault. In the DC Fault block, change the multiplication factor of 1 to 100, so that the DC fault is now eliminated. In the A-G Fault block, change the multiplication factor in the switching times to 1, so that a six-cycle line-to-ground fault is now applied at $t = 0.7$ s at the inverter. Restart the simulation.
Figure 5-14: Rectifier, Inverter Signals for an AC Line Fault on Inverter Side
Notice the 120 Hz oscillations in the DC voltage and currents during the fault. An unavoidable commutation failure occurs at the inverter at the very beginning of the fault and the DC current increases to 2 p.u. When the fault is cleared at \(t = 0.8\) s, the VDCOL operates and reduces the reference current to 0.3 p.u. The system recovers in approximately 0.35 s after fault clearing.
Look at the waveforms displayed on the PROTECTION INVERTER scope. The Low AC Voltage block detects the fault and locks the DC Fault protection that in this case should not detect a DC fault even if the DC line voltage dips. Look at the Commutation Failure Prevention Control (CFPREV) output (A_min_I) which decreases the maximum delay angle limit to increase the commutation margin during and after the fault.

Now open the dialog box of the CFPREV block located inside the Inverter Protections subsystem and deactivate the CFPREV protection by deselecting the “ON State.” Restart the simulation. Note that a second commutation failure now occurs during the fault (at t around 0.775 s). A commutation failure is the result of a failure of the incoming valve to take over the direct current before the commutation voltage reverses its polarity. The symptoms are a zero DC voltage across the affected bridge causing an increase of the DC current at a rate determined mainly by the DC circuit inductance.

References

VSC-Based HVDC Link

The increasing rating and improved performance of self-commutated semiconductor devices have made possible High Voltage DC (HVDC) transmission based on Voltage Sourced Converter (VSC). Two technologies offered by the manufacturers are the HVDC Light® [1] and the HVDCplus® [2].

The example described in this section illustrates modeling of a forced-commutated Voltage- Sourced Converter high-voltage direct current (VSC-HVDC) transmission link. The objectives of this example are to demonstrate the use of SimPowerSystems blocks in the simulation of a HVDC transmission link based on three-level Neutral Point Clamped (NPC) VSC converters with single-phase carrier based Sinusoidal Pulse Width Modulation (SPWM) switching. Perturbations are applied to examine the system dynamic performance.

Description of the HVDC Link

The principal characteristic of VSC-HVDC transmission is its ability to independently control the reactive and real power flow at each of the AC systems to which it is connected, at the Point of Common Coupling (PCC). In contrast to line-commutated HVDC transmission, the polarity of the DC link voltage remains the same with the DC current being reversed to change the direction of power flow.

The HVDC link described in this example is available in the power_hvdc_vsc model. Load this model and save it in your working directory as case5.mdl to allow further modifications to the original system. This model shown on Figure 5-16 represents a 200 MVA, +/- 100 kV VSC-HVDC transmission link.
The 230 kV, 2000 MVA AC systems (AC system1 and AC system2 subsystems) are modeled by damped L-R equivalents with an angle of 80 degrees at fundamental frequency (50 Hz) and at the third harmonic. The VSC converters are three-level bridge blocks using close to ideal switching device model of IGBT/diodes. The relative ease with which the IGBT can be controlled and its suitability for high-frequency switching, has made this device the better choice over GTO and thyristors. Open the Station 1 and Station 2 subsystems to see how they are built.

A converter transformer (Wye grounded /Delta) is used to permit the optimal voltage transformation. The present winding arrangement blocks triplen harmonics produced by the converter. The transformer tap changer or saturation are not simulated. The tap position is rather at a fixed position determined by a multiplication factor applied to the primary nominal voltage of the converter transformers. The multiplication factors are chosen to have a modulation index around 0.85 (transformer ratios of 0.915 on the rectifier side and 1.015 on the inverter side). The converter reactor and the transformer leakage reactance permit the VSC output voltage to shift in phase and amplitude with respect to the AC system, and allows control of converter active and reactive power output.
To meet AC system harmonic specifications, AC filters form an essential part of the scheme. They can be connected as shunt elements on the AC system side or the converter side of the converter transformer. Since there are only high frequency harmonics, shunt filtering is therefore relatively small compared to the converter rating. It is sufficient with a high pass-filter and no tuned filters are needed. The later arrangement is used in our model and a converter reactor, an air cored device, separates the fundamental frequency (filter bus) from the raw PWM waveform (converter bus). The AC harmonics generation [4] is mainly dependent on the:

- type of modulation (e.g. single-phase or three-phase carrier based, space vector, etc.)
- frequency index \( p = \text{carrier frequency} / \text{modulator frequency} \) (e.g. \( p = 1350/50 = 27 \))
- modulation index \( m = \text{fundamental output voltage of the converter} / \text{pole to pole DC voltage} \)

The principal harmonic voltages are generated at and around multiples of \( p \). The shunt AC filters are 27th and 54th high pass totaling 40 Mvar. To illustrate the AC filter action we did an FFT analysis in steady-state of the converter phase A voltage and the filter bus phase A voltage, using the Powergui block. The results are shown in Figure 5-17.
The reservoir DC capacitors are connected to the VSC terminals. They have an influence on the system dynamics and the voltage ripple on the DC side. The size of the capacitor is defined by the time constant $\tau$ corresponding to the time it takes to charge the capacitor to the base voltage (100 kV) if it is charged with the base current (1 kA). This yields

$$\tau = C \cdot Z_{\text{base}} = 70 \cdot 100 = 7 \text{ ms}$$

with $Z_{\text{base}} = 100 \text{kV/1 kA}$

The DC side filters blocking high-frequency are tuned to the 3rd harmonic, i.e. the main harmonic present in the positive and negative pole voltages. It is shown that a reactive converter current generate a relatively large third harmonic in both the positive and negative pole voltages [3] but not in the total DC voltage. The DC harmonics can also be zero-sequence harmonics (odd multiples of 3) transferred to the DC side (e.g. through the grounded AC filters). A smoothing reactor is connected in series at each pole terminal.
To keep the DC side balanced, the level of the difference between the pole voltages has to be controlled and kept to zero (see the DC Voltage Balance Control block in the VSC Controller block).

The rectifier and the inverter are interconnected through a 75 km cable (2 pi sections). The use of underground cable is typical for VSC-HVDC links. A circuit breaker is used to apply a three-phase to ground fault on the inverter AC side. A Three-Phase Programmable Voltage Source block is used in station 1 system to apply voltage sags.

**VSC Control System**

Figure 5-18 shows an overview diagram of the VSC control system and its interface with the main circuit [3].

![Figure 5-18: Overview of the Control System of a VSC Converter and Interface to the Main Circuit](image)
The converter 1 and converter 2 controller designs are identical. The two controllers are independent with no communication between them. Each converter has two degrees of freedom. In our case, these are used to control:

- P and Q in station 1 (rectifier)
- Udc and Q in station 2 (inverter).

The control of the AC voltage would be also possible as an alternative to Q. This requires an extra regulator which is not implemented in our model.

A high level block diagram of the Simulink discrete VSC controller model is shown in Figure 5-19.
Open the VSC Controller subsystem to see the details.

The sample time of the controller model (Ts_Control) is 74.06 µs, which is ten times the simulation sample time. The later is chosen to be one hundredth of the PWM carrier period (i.e. 0.01/1350 s) giving an acceptable simulation precision. The power elements, the anti-aliasing filters and the PWM generator block use the fundamental sample time (Ts_Power) of 7.406 µs. The unsynchronized PWM mode of operation is chosen for our model.

The normalized sampled voltages and currents (in p.u.) are provided to the controller.

The Clark Transformations block transforms the three-phase quantities to space vector components $\alpha$ and $\beta$ (real and imaginary part). The signal measurements (U and I) on the primary side are rotated by ±π/6 according to the transformer connection (YD11 or YD1) to have the same reference frame with the signal measured on the secondary side of the transformer (see block CLARK YD).

The dq transformations block computes the direct axis “d” and the quadratic axis “q” quantities (two axis rotating reference frame) from the $\alpha$ and $\beta$ quantities.

The Signal Calculations block calculates and filters quantities used by the controller (e.g. active and reactive power, modulation index, DC current and voltage, etc.).

**Phase Locked Loop (PLL)**

The Phase Locked Loop block measures the system frequency and provides the phase synchronous angle $\theta$ (more precisely [sin($\theta$), cos($\theta$)]) for the dq Transformations block. In steady-state, sin($\theta$) is in phase with the fundamental (positive sequence) of the $\alpha$ component and phase A of the PCC voltage (Uabc).

**Outer Active and Reactive Power and Voltage Loop**

The Active and reactive power and voltage loop contains the outer loop regulators that calculates the reference value of the converter current vector (Iref_dq) which is the input to the inner current loop. The control modes are: in the “d” axis, either the active power flow at the PCC or the pole-to-pole DC voltage; in the “q” axis, the reactive power flow at the PCC. Note that, it would be also possible to add an AC voltage control mode at the PCC in the “q” axis.
The main functions of the Active and reactive power and voltage loop are described below.

The Reactive Power Control regulator block combines a PI control with a feedforward control to increase the speed response. To avoid integrator wind-up the following actions are taken: the error is reset to zero, when the measured PCC voltage is less than a constant value (i.e. during an AC perturbation); when the regulator output is limited, the limitation error is fed back with the right sign, to the integrator input. The AC Voltage control override block, based on two PI regulators, will override the reactive power regulator to maintain the PCC AC voltage within a secure range, especially in steady-state.

The Active Power Control block is similar to the Reactive Power Control block. The extra Ramping block ramps the power order towards the desired value with an adjusted rate when the control is de-blocked. The ramped value is reset to zero when the converter is blocked. The DC Voltage control override block, based on two PI regulators, will override the active power regulator to maintain the DC voltage within a secure range, especially during a perturbation in the AC system of the station controlling the DC voltage.

The DC Voltage Control regulator block uses a PI regulator. The block is enabled when the Active Power Control block is disabled. The block output is a reference value, for the “d” component of converter current vector, for the Current Reference Limitation block.

The Current Reference Calculation block transforms the active and reactive power references, calculated by the P and Q controllers, to current references according to the measured (space vector) voltage at the filter bus. The current reference is estimated by dividing the power reference by the voltage (up to a minimum preset voltage value).

The current reference vector is limited to a maximum acceptable value (i.e. equipment dependent) by the Current Reference Limitation block. In power control mode, equal scaling is applied to the active and reactive power reference when a limit is imposed. In DC voltage control mode, higher priority is given to the active power when a limit is imposed for an efficient control of the voltage.

**Inner Current Loop**

The main functions of Inner Current Loop block are described below.
The AC Current Control block tracks the current reference vector ("d" and "q" components) with a feed forward scheme to achieve a fast control of the current at load changes and disturbances (e.g. so short-circuit faults do not exceed the references) [3] [5] [6]. In essence, it consist of knowing the \( U_{dq} \) vector voltages and computing what the converter voltages have to be, by adding the voltage drops due to the currents across the impedance between the U and the PWM-VSC voltages. The state equations representing the dynamics of the VSC currents are used (an approximation is made by neglecting the AC filters). The "d" and "q" components are decoupled to obtain two independent first-order plant models. A proportional integral (PI) feedback of the converter current is used to reduce the error to zero in steady state. The output of the AC Current Control block is the unlimited reference voltage vector \( V_{ref\_dq\_tmp} \).

The Reference Voltage Conditioning block takes into account the actual DC voltage and the theoretical maximum peak value of the fundamental bridge phase voltage in relation to the DC voltage to generate the new optimized reference voltage vector. In our model (i.e. a three-level NPC with carrier based PWM), the ratio between the maximum fundamental peak phase voltage and the DC total voltage (i.e. for a modulation index of 1) is \( \left( \sqrt{2} \right)/\left( \sqrt{3} \right) = 0.816 \). By choosing a nominal line voltage of 100 kV at the transformer secondary bus and a nominal total DC voltage of 200 kV the nominal modulation index would be 0.816. In theory, the converter should be able to generate up to \( 1/0.816 \) or 1.23 p.u. when the modulation index is equal to 1. This voltage margin is important for generating significant capacitive converter current (i.e. a reactive power flow to the AC system).

The Reference Voltage Limitation block limits the reference voltage vector amplitude to 1.0, since over modulation is not desired.

The Inverse dq and Inverse Clark transformation blocks are required to generate the three-phase voltage references to the PWM.

**DC Voltage Balance Control**

The DC Voltage Balance Control can be enabled or disabled. The difference between the DC side voltages (positive and negative) are controlled to keep the DC side of the three level bridge balanced (i.e. equal pole voltages) in steady-state. Small deviations between the pole voltages may occur at changes of active/reactive converter current or due to nonlinearity on lack of precision in the execution of the pulse width modulated bridge voltage. Furthermore, deviations between the pole voltages may be due to inherent unbalance in the circuit components impedance.
The DC midpoint current $I_{d0}$ determines the difference $U_{d0}$ between the upper and lower DC voltages (Figure 5-20).

\[ I_{d0} = -(I_{d1} + I_{d2}) = -C \cdot \frac{d}{dt}(U_{d1} - U_{d2}) = -C \cdot \frac{d}{dt}(U_{d0}) \]

**Figure 5-20: DC Voltages and Currents of the Three-Level Bridge**

By changing the conduction time of the switches in a pole it is possible to change the average of the DC midpoint current $I_{d0}$ and thereby control the difference voltage $U_{d0}$. For example, a positive difference ($U_{d0} \geq 0$) can be decreased to zero if the amplitude of the reference voltage which generates a positive midpoint current is increased at the same time as the amplitude of the reference voltage which generates a negative DC midpoint current is decreased. This is done by the addition of an offset component to the sinusoidal reference voltage. Consequently, the bridge voltage becomes distorted, and to limit the distortion effect, the control has to be slow. Finally, for better performance this function should be activated in the station controlling the DC voltage.

**Dynamic Performance**

In the next sections, the dynamic performance of the transmission system is verified by simulating and observing the

- Dynamic response to step changes applied to the principal regulator references, like active/reactive power and DC voltage
- Recovery from minor and severe perturbations in the AC system
For a comprehensive explanation of the procedure followed obtaining these results and more, refer to the Model Information block.

**System Startup - Steady State and Step Response**
The main waveforms from the scopes are reproduced below.

*Startup and P & Q Step Responses in Station 1*
Startup and Udc Step Response in Station 2

Station 2 converter controlling DC voltage is first deblocked at \( t=0.1 \) s. Then, station 1 controlling active power converter is deblocked at \( t=0.3 \) s and power is ramped up slowly to 1 p.u. Steady state is reached at approximately \( t=1.3 \) s with DC voltage and power at 1.0 p.u. (200 kV, 200 MW). Both converters control the reactive power flow to a null value in station 1 and to 20 Mvar (-0.1 p.u.) into station 2 system.

After steady state has been reached, a -0.1 p.u. step is applied to the reference active power in converter 1 (\( t=1.5 \) s) and later a -0.1 p.u. step is applied to the reference reactive power (\( t=2.0 \) s). In station 2, a -0.05 p.u. step is applied to the DC voltage reference. The dynamic response of the regulators are observed. Stabilizing time is approximately 0.3 s. The control design attempts to decouple the active and reactive power responses. Note how the regulators are more or less mutually affected.

AC Side Perturbations

From the steady state condition, a minor and a severe perturbation are executed at station 1 and 2 systems respectively. A three-phase voltage sag is first applied at station 1 bus. Then, following the system recovery, a
three-phase to ground fault is applied at station 2 bus. The system recovery from the perturbations should be prompt and stable. The main waveforms from the scopes are reproduced in the two figures below.

**Voltage Step on AC System 1**

The AC voltage step (-0.1 p.u.) is applied at \( t=1.5 \) s during 0.14 s (7 cycles) at station 1. The results show that the active and reactive power deviation from the pre-disturbance is less than 0.09 p.u. and 0.2 p.u. respectively. The recovery time is less than 0.3 s and the steady state is reached before next perturbation initiation.
The fault is applied at t=2.1 s during 0.12 s (6 cycles) at station 2.

Three-Phase to Ground Fault at Station 2 Bus

Note that during the three-phase fault the transmitted DC power is almost halted and the DC voltage tends to increase (1.2 p.u.) since the DC side capacitance is being excessively charged. A special function (DC Voltage Control Override) in the Active Power Control (in station 1) attempts to limit the DC voltage within a fixed range. The system recovers well after the fault, within 0.5 s. Note the damped oscillations (around 10 Hz) in the reactive power.

References.


Transient Stability of Power Systems Using Phasor Simulation

These case studies provide detailed, realistic examples of how to use the phasor simulation method of SimPowerSystems in typical power utility applications.

As explained in the section “Using the Phasor Solution Method for Stability Studies” on page 2-36, phasor simulation is the preferred method for simulating power grids when you are interested in the magnitude and phase of voltages and currents at fundamental frequency (50 Hz or 60 Hz). The phasor simulation is activated by means of the Powergui block. It supports all the elements of the `powerlib` library, including machines. In addition, two libraries of phasor models of power equipments found in utility grids (some of them including power electronics) have been introduced in version 4.0 of SimPowerSystems: the Flexible AC Transmission Systems (FACTS) library (factslib) and the Distributed Resources (DR) library (drlib). The case studies listed below show application examples of some of these phasor models.

- **Transient Stability of a Power System with SVC and PSS** (p. 6-2)
- **Control of Power Flow Using a UPFC and a PST** (p. 6-8)
- **Wind Farm Using Doubly-Fed Induction Generators** (p. 6-18)

Use of a static var compensator (SVC) and power system stabilizers (PSS) for improving stability of a two-machine transmission system

Control of power flow using a unified power flow controller (UPFC) and a phase shifting transformer (PST)

Study of a wind farm using doubly fed induction generators driven by wind turbines
Transient Stability of a Power System with SVC and PSS

The example described in this section illustrates modeling of a simple transmission system containing two hydraulic power plants. A static var compensator (SVC) and power system stabilizers (PSS) are used to improve transient stability and power oscillation damping of the system. The power system illustrated in this example is quite simple. However, the phasor simulation method allows you to simulate more complex power grids.

If you are not familiar with the SVC and PSS, please refer to the documentation of the following blocks: Static Var Compensator (Phasor Type), Generic Power System Stabilizer, and Multi-Band Power System Stabilizer.

Description of the Transmission System

The single line diagram shown below represents a simple 500 kV transmission system.

![Figure 6-1: 500 kV Transmission System](image)

A 1000 MW hydraulic generation plant (M1) is connected to a load center through a long 500 kV, 700 km transmission line. The load center is modeled by a 5000 MW resistive load. The load is fed by the remote 1000 MVA plant and a local generation of 5000 MVA (plant M2).

A load flow has been performed on this system with plant M1 generating 950 MW so that plant M2 produces 4046 MW. The line carries 944 MW which is close to its surge impedance loading (SIL = 977 MW). To maintain system stability after faults, the transmission line is shunt compensated at its center by a 200 Mvar static var compensator (SVC). The SVC does not have a power oscillation damping (POD) unit. The two machines are equipped with a
Hydraulic Turbine and Governor (HTG), Excitation system and Power System Stabilizer (PSS).

This system is available in the power_svc_pss model. Load this model and save it in your working directory as case1.mdl to allow further modifications to the original system. This model is shown in Figure 6-2.

**Figure 6-2: Model of the Transmission System (power_svc_pss)**

First, look inside the two Turbine and Regulators subsystems to see how the hydraulic turbine, and governor (HTG) and the excitation system are implemented. Two types of stabilizers can be connected on the excitation system: a generic model using the acceleration power ($P_a = \text{difference between mechanical power } P_m \text{ and output electrical power } P_e$) and a Multiband stabilizer using the speed deviation ($\Delta w$). These two stabilizers are standard models of the powerlib/Machines library. Manual Switch blocks surrounded by a blue zone allow you to select the type of stabilizer used for both machines or put the PSS out of service.
The SVC is the phasor model from the FACTS library. Open its dialog box and check in the Power data parameters that the SVC rating is +/- 200 Mvar. In the Control parameters, you can select either Voltage regulation or Var control (Fixed susceptance Bref) mode. Initially the SVC is set in Var control mode with a susceptance Bref=0, which is equivalent to having the SVC out of service.

A Fault Breaker block is connected at bus B1. You will use it to program different types of faults on the 500 kV system and observe the impact of the PSS and SVC on system stability.

To start the simulation in steady-state, the machines and the regulators have been previously initialized by means of the Load Flow and Machine Initialization of the Powergui block. Load flow has been performed with machine M1 defined as a PV generation bus (V=13800 V, P=950 MW) and machine M2 defined as a swing bus (V=13800 V, 0 degrees). After the load flow has been solved, the reference mechanical powers and reference voltages for the two machines have been automatically updated in the two constant blocks connected at the HTG and excitation system inputs: Pref1=0.95 p.u. (950 MW), Vref1=1.0 p.u.; Pref2=0.8091 p.u. (4046 MW), Vref2=1.0 p.u.

**Single-Phase Fault — Impact of PSS — No SVC**

Verify that the PSS (Generic Pa type) are in service and that a 6-cycle single-phase fault is programmed in the Fault Breaker block (Phase A checked, fault applied at t=0.1 s and cleared at t=0.2 s).

Start the simulation and observe signals on the Machines scope. For this type of fault the system is stable without SVC. After fault clearing, the 0.6 Hz oscillation is quickly damped. This oscillation mode is typical of interarea oscillations in a large power system. First trace on the Machines scope shows the rotor angle difference d_theta1_2 between the two machines. Power transfer is maximum when this angle reaches 90 degrees. This signal is a good indication of system stability. If d_theta1_2 exceeds 90 degrees for too long a period of time, the machines will lose synchronism and the system goes unstable. Second trace shows the machine speeds. Notice that machine 1 speed increases during the fault because during that period its electrical power is lower than its mechanical power. By simulating over a long period of time (50 seconds) you will also notice that the machine speeds oscillate together at a low frequency (0.025 Hz) after fault clearing. The two PSS (Pa type) succeed to damp the 0.6 Hz mode but they are not efficient for damping the 0.025 Hz
mode. If you select instead the Multi-Band PSS, you will notice that this stabilizer type succeeds to damp both the 0.6 Hz mode and the 0.025 Hz mode.

You will now repeat the test with the two PSS out of service. Restart simulation. Notice that the system is unstable without PSS. You can compare results with and without PSS by double clicking on the blue block on the right side identified «Show impact of PSS for 1-phase fault». The displayed waveforms are reproduced below.

**Impact of PSS for a Single-Phase Fault**

Note: This system is naturally unstable without PSS. If you remove the fault (by deselecting phase A in the Fault Breaker), you will see the instability slowly building up at approximately 1 Hz after a few seconds.
Three-Phase Fault — Impact of SVC — PSS in Service

You will now apply a 3-phase fault and observe the impact of the SVC for stabilizing the network during a severe contingency.

First put the two PSS (Generic Pa type) in service. Reprogram the Fault Breaker block to apply a 3-phase-to-ground fault. Verify that the SVC is in fixed susceptance mode with Bref = 0. Start the simulation. By looking at the d_theta1_2 signal, you should observe that the two machines quickly fall out of synchronism after fault clearing. In order not to pursue unnecessary simulation, the Simulink Stop block is used to stop the simulation when the angle difference reaches 3*360degrees.

Now open the SVC block menu and change the SVC mode of operation to Voltage regulation. The SVC will now try to support the voltage by injecting reactive power on the line when the voltage is lower than the reference voltage (1.009 pu). The chosen SVC reference voltage corresponds to the bus voltage with the SVC out of service. In steady state the SVC will therefore be floating and waiting for voltage compensation when voltage departs from its reference set point.

Restart simulation and observe that the system is now stable with a 3-phase fault. You can compare results with and without SVC by double clicking on the blue block identified «Show impact of SCV for 3-phase fault». The displayed waveforms are reproduced below.
Impact of the SVC for a Three-Phase Fault
Control of Power Flow Using a UPFC and a PST

The example described in this section illustrates application of SimPowerSystems to study the steady-state and dynamic performance of a Unified Power Flow Controller (UPFC) used to relieve power congestion in a transmission system.

If you are not familiar with the UPFC, please refer to the documentation of the Unified Power Flow Controller (Phasor Type) block.

Description of the Power System
The single-line diagram of the modeled power system is shown in Figure 6-3.

Figure 6-3: 500 kV / 230 kV Transmission System
A UPFC is used to control the power flow in a 500 kV/230 kV transmission system. The system, connected in a loop configuration, consists essentially of five buses (B1 to B5) interconnected through three transmission lines (L1, L2, L3) and two 500 kV/230 kV transformer banks Tr1 and Tr2. Two power plants located on the 230 kV system generate a total of 1500 MW which is transmitted to a 500 kV, 15000 MVA equivalent and to a 200 MW load connected at bus B3. Each plant model includes a speed regulator, an excitation system as well as a
power system stabilizer (PSS). In normal operation, most of the 1200 MW generation capacity of power plant #2 is exported to the 500 kV equivalent through two 400 MVA transformers connected between buses B4 and B5. For this demo we are considering a contingency case where only two transformers out of three are available (Tr2= 2*400 MVA = 800 MVA). The load flow shows that most of the power generated by plant #2 is transmitted through the 800 MVA transformer bank (899 MW out of 1000 MW) and that 96 MW is circulating in the loop. Transformer Tr2 is therefore overloaded by 99 MVA. The example illustrates how a UPFC can relief this power congestion. The UPFC located at the right end of line L2 is used to control the active and reactive powers at the 500 kV bus B3, as well as the voltage at bus B_UPFC. The UPFC consists of two 100 MVA, IGBT-based, converters (one shunt converter and one series converter interconnected through a DC bus). The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2.
This example is available in the `power_upfc` model. Load this model and save it in your working directory as `case2.mdl` to allow further modifications to the original system. This model is shown in Figure 6-4.

![Model of the UPFC Controlling Power on a 500 kV/230 kV Power System (power_upfc)](image)

Using the load flow option of the `powergui` block, the model has been initialized with plants #1 and #2 generating respectively 500 MW and 1000 MW and with the UPFC out of service (Bypass breaker closed). The resulting power flow obtained at buses B1 to B5 is indicated on the model by red numbers. This load flow corresponds to load flow shown in the single-line diagram, in Figure 6-3.
Power Flow Control with the UPFC

Parameters of the UPFC are given in the dialog box. Verify, in the Power data parameters, that the series converter is rated 100 MVA with a maximum voltage injection of 0.1 p.u. The shunt converter is also rated 100 MVA. Also verify, in the control parameters, that the shunt converter is in Voltage regulation mode and that the series converter is in Power flow control mode. The UPFC reference active and reactive powers are set in the magenta blocks labeled Pref(pu) and Qref(pu). Initially the Bypass breaker is closed and the resulting natural power flow at bus B3 is 587 MW and -27 Mvar. The Pref block is programmed with an initial active power of 5.87 p.u. corresponding to the natural power flow. Then, at t=10s, Pref is increased by 1 p.u. (100 MW), from 5.87 p.u. to 6.87 pu, while Qref is kept constant at -0.27 pu.

Run the simulation and look on the UPFC scope how P and Q measured at bus B3 follow the reference values. Waveforms are reproduced below.
At $t=5$ s, when the Bypass breaker is opened, the natural power is diverted from the Bypass breaker to the UPFC series branch without noticeable transient. At $t=10$ s, the power increases at a rate of 1 pu/s. It takes one second for the power to increase to 687 MW. This 100 MW increase of active power at bus B3 is achieved by injecting a series voltage of 0.089 p.u. with an angle of 94 degrees. This results in an approximate 100 MW decrease in the active power flowing through Tr2 (from 899 MW to 796 MW), which now carries an acceptable load. See the variations of active powers at buses B1 to B5 on the VPQ Lines scope.

**UPFC P-Q Controllable Region**

Now, open the UPFC dialog box and select Show Control parameters (series converter). Select Mode of operation = Manual Voltage injection. In this control mode the voltage generated by the series inverter is controlled by two external signals $V_d$, $V_q$ multiplexed at the $V_{dqref}$ input and generated in the $V_{dqref}$ magenta block. For the first five seconds the Bypass breaker stays closed, so that the PQ trajectory stays at the (-27Mvar, 587 MW) point. Then when the breaker opens, the magnitude of the injected series voltage is ramped, from 0.0094 to 0.1 p.u. At 10 s, the angle of the injected voltage starts varying at a rate of 45 deg./s.

Run the simulation and look on the UPFC scope the P and Q signals who vary according to the changing phase of the injected voltage. At the end of the simulation, double-click on the blue block identified «Double click to plot UPFC Controllable Region». The trajectory of the UPFC reactive power as function of
its active power, measured at bus B3, is reproduced below. The area located inside the ellipse represents the UPFC controllable region.

**UPFC Controllable Region**

**Power Flow Control Using a PST**

Although not as flexible as the UPFC, the Phase Shifting Transformer (PST) is nevertheless a very efficient means to control power flow because it acts directly on the phase angle $\delta$, as shown in Figure 6-5. The PST is the most commonly used device to control power flow on power grids.
Figure 6-5: Power Transfer Between Two Voltage Sources Without and With PST

You will now use a PST with a On Load Tap Changer (OLTC) to control the power flow on your power system. A phasor model of PST using the delta hexagonal connection is available in the facts/Transformers library. For details on this PST connection, please refer to the Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type) block documentation.

Delete the UPFC block in your model as well as the magenta blocks controlling the UPFC. Also delete the UPFC Measurements subsystem and the UPFC scope. Open the Transformer subsystem of the facts library and copy the Three-Phase OLTC Phase Shifting Transformer Delta-Hexagonal (Phasor Type) block in your model. Connect the ABC terminals to the B_UPFC bus and connect the abc terminals to the B3 bus. Now, open the PST dialog box and modify the following parameters:

1. Nominal parameters \([V_{nom}(V_{rms \ Ph \ Ph}) \ P_{nom}(VA) \ F_{nom} (Hz)]\): [500e3 800e6 60]

2. Number of taps per half tapped winding: 20

The nominal power is set to 800 MVA (maximum expected power transfer through the PST). The number of taps is set to 20, so that the phase shift resolution is approximately \(60/20 = 3\) degrees per step.

\[
P = \frac{V_1 V_2 \sin \delta}{X} \quad \text{(eq. 1)}
\]

\[
P = \frac{V_1 V_2 \sin(\delta + \psi)}{X + X_{pst}} \quad \text{(eq. 2)}
\]

where:
- \(P\) = Active power transmitted
- \(V_1\) = Line to line voltage of source \(V_1\)
- \(V_2\) = Line to line voltage \(V_2\)
- \(X\) = Reactance of interconnexion
- \(\delta\) = Angle of \(V_1\) with respect to \(V_2\)
- \(X_{pst}\) = PST leakage reactance
- \(\psi\) = PST phase shift
- \(\theta\) = angle of T2 voltages with respect to T1
In the power system, the natural power flow (without PST) from B_UPFC to B3 is \( P = +587 \text{ MW} \). If \( V_1 \) and \( V_2 \) in Figure 6-5 represent the internal voltages of systems connected respectively to B_UPFC and B3, it means that the angle \( \delta \) of equation 1 is positive. Therefore, according to equation 2, to increase power flow from B_UPFC to B3, the PST phase shift \( \Psi \) of abc terminals with respect to ABC terminals must also be positive. For this type of PST, the taps must be moved in the negative direction. This is achieved by sending pulses to the Down input of the PST tap changer.

The tap position is controlled by sending pulses to either the Up input or the Down input. In our case, as we need to increase phase shift from zero toward positive values, we have to send pulses to the Down input. Copy a Pulse Generator block from the Sources library of Simulink and connect it to the Down input of the PST. Open the block dialog box and modify the following parameters:

1. Period (secs): 5
2. Pulse Width (% of period): 10

Therefore, every 5 seconds the taps will be moved by one step in the negative direction and the phase shift will increase by approximately 3 degrees.

Finally, connect a Bus Selector block (from the Signal Routing library of Simulink) to the measurement output \( m \) of the PST. Open its dialog box and select the following two signals:

1. Tap
2. Psi (degrees)

Connect these two signals to a two input scope to observe the tap position and the phase shift during simulation. Set the simulation time to 25 s and start simulation.

On the VPQ lines scope, observe voltages at buses B1 to B5 and active and reactive power transfer through these buses. The variation of tap position, PST phase shift \( \Psi \) and active power transfer through bus B3 (power through PST) and B4 (power through transformer Tr2) are reproduced on the figure below.
Each tap change produces a phase angle variation of approximately 3 degrees, resulting in a 60 MW power increase through B3. At tap position -2, the power through transformer Tr2 as decreased from 900 MW to 775 MW, thus achieving the same goal as the UPFC for steady state control. You could get a better resolution in phase angle and power steps by increasing the number of taps in the OLTC.

You can notice that the discrete variation of phase angle produces overshoots and slight oscillations in active power. These power oscillations which are typical interarea electromechanical oscillations of machines in power plants 1 and 2 are quickly damped by the Power System Stabilizers (PSS) connected on the excitation systems.

If you disconnect the PSS from the vstab input of the excitation system (located in the Reg_M1 and Reg_M2 subsystems of the power plants) you will realize the impact of PSS on interarea oscillation damping. The active power through
B3 with and without PSS is reproduced below. Without PSS, the 1.2 Hz under damped power oscillations are clearly unacceptable.

Damping of Power Oscillations by PSS
Wind Farm Using Doubly-Fed Induction Generators

The example described in this section illustrates application of SimPowerSystems to study the steady-state and dynamic performance of a 9 MW wind farm connected to a distribution system.

The wind farm consists of six 1.5 MW wind turbines connected to a 25 kV distribution system exporting power to a 120 kV grid through a 30 km 25 kV feeder. A 2300 V, 2 MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200 kW resistive load is connected on the same feeder at bus B25. A 500 kW load is also connected on the 575 V bus of the wind farm. The single-line diagram of this system is illustrated in Figure 6-6.

![Figure 6-6: Single-Line Diagram of the Wind Farm Connected to a Distribution System](image)

Both the wind turbine and the motor load have a protection system monitoring voltage, current and machine speed. The DC link voltage of the DFIG is also monitored. Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed (see Wind Turbine Doubly-Fed Induction Generator (Phasor Type) block of the DRlib/Wind Generation library for more details). Another
advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generators.

This system is available in the `power_wind_dfig` model. Load this model and save it in your working directory as `case3.mdl` to allow further modifications to the original system. The SimPowerSystems diagram is shown in Figure 6-7 and Figure 6-8. In this case study, the rotor is running at subsynchronous speed for wind speeds lower than 10 m/s and it is running at a super-synchronous speed for higher wind speeds. The turbine mechanical power as function of turbine speed is displayed in Figure 6-9 for wind speeds ranging from 5 m/s to 16.2 m/s. These characteristics are obtained with the specified parameters of the Turbine data (Figure 6-9).
Figure 6-8: SimPowerSystems Diagram of the 2 MVA Plant with its Protection System
Wind Farm Using Doubly-Fed Induction Generators

Figure 6-9: Turbine Data Menu and the Turbine Power Characteristics

The DFIG is controlled to follow the ABCD curve in Figure 6-9. Turbine speed optimization is obtained between point B and point C on this curve.

The wind turbine model is a phasor model that allows transient stability type studies with long simulation times. In this case study, the system is observed during 50 s. The 6-wind-turbine farm is simulated by a single wind-turbine block by multiplying the following three parameters by six, as follows:

- The nominal wind turbine mechanical output power: $6 \times 1.5 \times 6$ watts, specified in the Turbine data menu
- The generator rated power: $6 \times 1.5 / 0.9$ MVA ($6 \times 1.5$ MW at 0.9 PF), specified in the Generator data menu
• The nominal DC bus capacitor: $6 \times 10000$ microfarads, specified in the Converters data menu.

The mode of operation is set to Voltage regulation in the Control Parameters dialog box. The terminal voltage will be controlled to a value imposed by the reference voltage ($V_{ref} = 1$ pu) and the voltage droop ($X_s = 0.02$ pu).

**Turbine Response to a Change in Wind Speed**

Observe the turbine response to a change in wind speed. Initially, wind speed is set at 8 m/s, and then at $t=5s$, wind speed increases suddenly at 14 m/s. Figure 6-10 illustrates the waveforms associated with this simulation. At $t=5s$, the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 9MW in approximately 15s. Over that time frame the turbine speed increases from 0.8 p.u. to 1.21 pu. Initially, the pitch angle of the turbine blades is zero degree and the turbine operating point follows the red curve of the turbine power characteristics up to point D. Then the pitch angle is increased from 0 deg to 0.76 deg to limit the mechanical power. Observe also the voltage and the generated reactive power. The reactive power is controlled to maintain a 1 p.u. voltage. At nominal power, the wind turbine absorbs 0.68 Mvar (generated $Q = -0.68$ Mvar) to control voltage at 1pu. If you change the mode of operation to Var regulation with the Generated reactive power $Q_{ref}$ set to zero, you will observe that the voltage increases to 1.021 p.u. when the wind turbine generates its nominal power at unity power factor (Figure 6-11).
Figure 6-10: Waveforms for a Gust of Wind (Wind Farm in Voltage Regulation Mode)
Simulation of a Voltage Sag on the 120-kV System

Now observe the impact of a voltage sag resulting from a remote fault on the 120 kV system. In this simulation the mode of operation is initially in Var regulation with $Q_{ref}=0$ and the wind speed is constant at 8 m/s. A 0.15 p.u. voltage drop lasting 0.5 s is programmed, in the 120 kV voltage source menu, to occur at $t=5$ s. The simulation results are illustrated in Figure 6-12. Observe the plant voltage and current as well as the motor speed. Note that the wind farm produces 1.87 MW. At $t=5$ s, the voltage falls below 0.9 p.u. and at $t=5.22$ s, the protection system trips the plant because an undervoltage lasting more than 0.2 s has been detected (exceeding protection settings for the Plant subsystem). The plant current falls to zero and motor speed decreases gradually, while the wind farm continues generating at a power level of 1.87 MW. After the plant has tripped, 1.25 MW of power ($P_{B25}$ measured at bus B25) is exported to the grid.
Now, the wind turbine control mode is changed to **Voltage regulation** and the simulation is repeated. You will notice that the plant does not trip anymore. This is because the voltage support provided by the 5 Mvar reactive power generated by the wind turbines during the voltage sag keeps the plant voltage above the 0.9 p.u. protection threshold. The plant voltage during the voltage sag is now 0.93 p.u. (Figure 6-13).

**Figure 6-12: Voltage Sag on the 120 kV System (Wind Farm in Var Regulation Mode)**
Finally, now observe the impact of a single phase-to-ground fault occurring on the 25kV line. At $t=5$ s a 9 cycle (0.15 s) phase-to-ground fault is applied on phase A at B25 bus. When the wind turbine is in Voltage regulation mode, the positive sequence voltage at wind turbine terminals ($V_{1,B575}$) drops to 0.8 p.u. during the fault, which is above the undervoltage protection threshold.
(0.75 p.u. for \( t > 0.1 \) s). The wind farm therefore stays in service (Figure 6-14). However, if the \textbf{Var regulation} mode is used with \( Q_{\text{ref}} = 0 \), the voltage drops under 0.7 p.u. and the undervoltage protection trips the wind farm. We can now observe that the turbine speed increases. At \( t = 40 \) s the pitch angle starts to increase to limit the speed (Figure 6-15).

![Wind Farm Waveforms During Fault at Bus B25 (Wind Farm in Voltage Regulation Mode)](image_url)

\textbf{Figure 6-14: Wind Farm Waveforms During Fault at Bus B25 (Wind Farm in Voltage Regulation Mode)}
Figure 6-15: Wind Farm Waveforms During Fault at Bus B25 (Wind Farm in Var Regulation Mode)
SimPowerSystems Block Reference

This chapter contains complete information on every block in SimPowerSystems. Refer to this chapter when you need to find detailed information on a particular block.

Blocks — Categorical List (p. 7-2)  The SimPowerSystems blocks summarized by block library

Blocks — Alphabetical List (p. 7-10)  The SimPowerSystems blocks listed alphabetically by name
Blocks — Categorical List

The SimPowerSystems main library, powerlib, organizes its blocks into libraries according to their behavior. The powerlib window displays the block library icons and names. This section lists all SimPowerSystems blocks arranged by library.

Use the Simulink Library Browser or the SimPowerSystems library to access the blocks directly, guided by this hierarchical library list.

The main SimPowerSystems powerlib library window contains the Powergui block that opens a graphical user interface for the steady-state analysis of electrical circuits.

**Electrical Sources Library**
Contains blocks that generate electric signals.

**Elements Library**
Contains linear and nonlinear circuit elements.

**Power Electronics Library**
Contains power electronics devices.

**Machines Library**
Contains power machinery models.

**Measurements Library**
Contains blocks for the current and voltage measurements.

The Applications Libraries icon in the powerlib library window lets you access the Electric Drives Library, the FACTS Library, and the DR Library, described below.

**Electric Drives Library**
Contains AC and DC electric drives models.

**Flexible AC Transmission Systems (FACTS) Library**
Contains the FACTS models.
Distributed Resources (DR) Library
Contains wind turbine models.

Extras Library
Contains three-phase blocks and specialized measurement and control blocks. You can also open this library by entering powerlib_extras at the command line.

Demos Library
Contains useful demos and case studies.

Obsolete Blocks
Contains obsolete blocks for backward compatibility.

Nonlinear Simulink Blocks for SimPowerSystems Models
The nonlinear Simulink blocks of the powerlib library are stored in a special block library named powerlib_models. These masked Simulink models are used by SimPowerSystems to build the equivalent Simulink model of your circuit. See Chapter 3, “Improving Simulation Performance” for a description of the powerlib_models library.
### Creating Electrical Sources

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Current Source</td>
<td>Implement a sinusoidal current source</td>
</tr>
<tr>
<td>AC Voltage Source</td>
<td>Implement a sinusoidal voltage source</td>
</tr>
<tr>
<td>Controlled Current Source</td>
<td>Implement a controlled current source</td>
</tr>
<tr>
<td>Controlled Voltage Source</td>
<td>Implement a controlled voltage source</td>
</tr>
<tr>
<td>DC Voltage Source</td>
<td>Implement a DC voltage source</td>
</tr>
<tr>
<td>Three-Phase Programmable</td>
<td>Implement a three-phase voltage source with programmable time variation of</td>
</tr>
<tr>
<td>Voltage Source</td>
<td>amplitude, phase, frequency, and harmonics</td>
</tr>
<tr>
<td>Three-Phase Source</td>
<td>Implement a three-phase source with internal R-L impedance</td>
</tr>
</tbody>
</table>

### Creating Circuit Elements

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaker</td>
<td>Implement a circuit breaker opening at current zero crossing</td>
</tr>
<tr>
<td>Connection Port</td>
<td>Create a terminal port for a subsystem</td>
</tr>
<tr>
<td>Distributed Parameter Line</td>
<td>Implement an N-phases distributed parameter line model with lumped losses</td>
</tr>
<tr>
<td>Ground</td>
<td>Provide a connection to the ground</td>
</tr>
<tr>
<td>Linear Transformer</td>
<td>Implement a two- or three-windings linear transformer</td>
</tr>
<tr>
<td>Multi-Winding Transformer</td>
<td>Implement a multi-winding transformer with taps</td>
</tr>
<tr>
<td>Mutual Inductance</td>
<td>Implement a magnetic coupling between two or three windings</td>
</tr>
<tr>
<td>Neutral</td>
<td>Implement a local common node in the circuit</td>
</tr>
<tr>
<td>Parallel RLC Branch</td>
<td>Implement a parallel RLC branch</td>
</tr>
<tr>
<td>Parallel RLC Load</td>
<td>Implement a linear parallel RLC load</td>
</tr>
<tr>
<td>PI Section Line</td>
<td>Implement a single-phase transmission line with lumped parameters</td>
</tr>
<tr>
<td>Saturable Transformer</td>
<td>Implement a two- or three-windings Saturable Transformer</td>
</tr>
<tr>
<td>Series RLC Branch</td>
<td>Implement a series RLC branch</td>
</tr>
<tr>
<td>Series RLC Load</td>
<td>Implement a linear series RLC load</td>
</tr>
<tr>
<td>Block Type</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Surge Arrester</td>
<td>Implement a metal-oxide surge arrester</td>
</tr>
<tr>
<td>Three-Phase Breaker</td>
<td>Implement a three-phase circuit breaker opening at current zero crossing</td>
</tr>
<tr>
<td>Three-Phase Dynamic Load</td>
<td>Implement a three-phase dynamic load with active power and reactive power as a function of voltage or controlled from an external input</td>
</tr>
<tr>
<td>Three-Phase Fault</td>
<td>Implement a programmable phase-to-phase and phase-to-ground fault breaker system</td>
</tr>
<tr>
<td>Three-Phase Harmonic Filter</td>
<td>Implement four types of three-phase harmonic filters using RLC components</td>
</tr>
<tr>
<td>Three-Phase Mutual Inductance Z1-Z0</td>
<td>Implement a three-phase RL impedance with mutual coupling between phases and allow specification in the form of positive- and zero-sequence parameters</td>
</tr>
<tr>
<td>Three-Phase Parallel RLC Branch</td>
<td>Implement a three-phase parallel RLC branch</td>
</tr>
<tr>
<td>Three-Phase Parallel RLC Load</td>
<td>Implement a three-phase parallel RLC load with selectable connection</td>
</tr>
<tr>
<td>Three-Phase PI Section Line</td>
<td>Implement a three-phase transmission line section with lumped parameters</td>
</tr>
<tr>
<td>Three-Phase Series RLC Branch</td>
<td>Implement a three-phase series RLC branch</td>
</tr>
<tr>
<td>Three-Phase Series RLC Load</td>
<td>Implement a three-phase series RLC load with selectable connection</td>
</tr>
<tr>
<td>Three-Phase Transformer 12 Terminals</td>
<td>Implement three single-phase, two-winding transformers where all terminals are accessible</td>
</tr>
<tr>
<td>Three-Phase Transformer (Two Windings)</td>
<td>Implement a three-phase transformer with two windings</td>
</tr>
<tr>
<td>Three-Phase Transformer (Three Windings)</td>
<td>Implement a three-phase transformer with three windings</td>
</tr>
<tr>
<td>Zigzag Phase-Shifting Transformer</td>
<td>Implement a zigzag phase-shifting transformer with secondary winding connection</td>
</tr>
</tbody>
</table>
### Modeling Power Electronics Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode</td>
<td>Implement a diode model</td>
</tr>
<tr>
<td>GTO</td>
<td>Implement a gate-turnoff (GTO) thyristor model</td>
</tr>
<tr>
<td>Ideal Switch</td>
<td>Implement an ideal switch model</td>
</tr>
<tr>
<td>IGBT</td>
<td>Implement an insulated-gate-bipolar-transformer (IGBT) model</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Implement a metal-oxide-semiconductor-field-effect-transistor (MOSFET) model</td>
</tr>
<tr>
<td>Three-Level Bridge</td>
<td>Implement a three-level neutral point clamped (NPC) power converter</td>
</tr>
<tr>
<td>Thyristor</td>
<td>Implement a thyristor model</td>
</tr>
<tr>
<td>Universal Bridge</td>
<td>Implement a universal three-phase bridge converter</td>
</tr>
</tbody>
</table>

### Modeling Electrical Machines

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asynchronous Machine</td>
<td>Model the dynamics of a three-phase asynchronous machine (induction machine)</td>
</tr>
<tr>
<td>DC Machine</td>
<td>Model a separately excited DC machine</td>
</tr>
<tr>
<td>Excitation System</td>
<td>Provide an excitation system for the synchronous machine and regulate its terminal voltage in generating mode</td>
</tr>
<tr>
<td>Generic Power System</td>
<td>Provide a generic power system stabilizer for the synchronous machine and regulate its electrical power</td>
</tr>
<tr>
<td>Stabilizer</td>
<td></td>
</tr>
<tr>
<td>Hydraulic Turbine and Governor</td>
<td>Model a hydraulic turbine and a proportional-integral-derivative governor system</td>
</tr>
<tr>
<td>Machine Measurement Demux</td>
<td>Split machine measurement signal into separate signals</td>
</tr>
<tr>
<td>Multiband Power System</td>
<td></td>
</tr>
<tr>
<td>Stabilizer</td>
<td></td>
</tr>
<tr>
<td>Permanent Magnet Synchronous Machine</td>
<td>Model the dynamics of a three-phase permanent magnet synchronous machine with sinusoidal flux distribution</td>
</tr>
<tr>
<td>Simplified Synchronous Machine</td>
<td>Model the dynamics of a simplified three-phase synchronous machine</td>
</tr>
<tr>
<td>Block</td>
<td>Function</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Steam Turbine and Governor</td>
<td>Implement a steam turbine and governor system</td>
</tr>
<tr>
<td>Synchronous Machine</td>
<td>Model the dynamics of a three-phase round-rotor or salient-pole synchronous machine</td>
</tr>
</tbody>
</table>

### Modeling Electric Drives

<table>
<thead>
<tr>
<th>Block</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Six-Step VSI Induction Motor Drive</td>
<td>Implement a six-step inverter fed Induction Motor Drive</td>
</tr>
<tr>
<td>Space Vector PWM VSI Induction Motor Drive</td>
<td>Implement a space vector PWM VSI induction motor drive</td>
</tr>
<tr>
<td>Field-Oriented Control Induction Motor Drive</td>
<td>Implement a field oriented control (F.O.C.) induction motor drive model</td>
</tr>
<tr>
<td>DTC Induction Motor Drive</td>
<td>Implement a direct torque and flux control (DTC) induction motor drive model</td>
</tr>
<tr>
<td>Self-Controlled Synchronous Motor Drive</td>
<td>Implement a Self-Controlled Synchronous Motor Drive</td>
</tr>
<tr>
<td>PM Synchronous Motor Drive</td>
<td>Implement a Permanent Magnet Synchronous Motor drive</td>
</tr>
<tr>
<td>Two-Quadrant Single-Phase Rectifier DC Drive</td>
<td>Implement a two-quadrant single-phase rectifier DC drive</td>
</tr>
<tr>
<td>Four-Quadrant Single-Phase Rectifier DC Drive</td>
<td>Implement a single-phase dual-converter DC drive with circulating current</td>
</tr>
<tr>
<td>Two-Quadrant Three-Phase Rectifier DC Drive</td>
<td>Implement a two-quadrant three-phase rectifier DC drive</td>
</tr>
<tr>
<td>Four-Quadrant Three-Phase Rectifier DC Drive</td>
<td>Implement a three-phase dual-converter DC drive with circulating current</td>
</tr>
<tr>
<td>One-Quadrant Chopper DC Drive</td>
<td>Implement a one-quadrant chopper (buck converter topology) DC drive</td>
</tr>
<tr>
<td>Two-Quadrant Chopper DC Drive</td>
<td>Implement a two-quadrant chopper (buck-boost converter topology) DC drive</td>
</tr>
<tr>
<td>Four-Quadrant Chopper DC Drive</td>
<td>Implement a four-quadrant chopper DC drive.</td>
</tr>
</tbody>
</table>
Mechanical Shaft  Implement a mechanical shaft
Speed Reducer  Implement a speed reducer

**Modeling FACTS Devices**

- Static Synchronous Compensator (Phasor Type)  Implement a phasor model of a three-phase static synchronous compensator (STATCOM)
- Static Synchronous Series Compensator (Phasor Type)  Implement a phasor model of a three-phase static synchronous series compensator (SSSC)
- Static Var Compensator (Phasor Type)  Implement a phasor model of a three-phase static var compensator
- Three-Phase OLTC Phase-Shifting Transformer Delta-Hexagonal (Phasor Type)  Implement a phasor model of a three-phase OLTC phase-shifting transformer using the delta hexagonal connection
- Three-Phase OLTC Regulating Transformer (Phasor Type)  Implement a phasor model of a three-phase OLTC regulating transformer
- Unified Power Flow Controller (Phasor Type)  Implement a phasor model of a three-phase unified power flow controller (UPFC)

**Modeling Distributed Resources Devices**

- Wind Turbine  Implement a model of a variable pitch wind turbine.
- Wind Turbine Doubly-Fed Induction Generator (Phasor Type)  Implement a phasor model of a variable speed doubly-fed induction generator driven by a wind turbine.
- Wind Turbine Induction Generator (Phasor Type)  Implement a phasor model of a squirrel-cage induction generator driven by a variable pitch wind turbine.

**Measuring Electrical Circuits**

- Current Measurement  Measure a current in a circuit
- Impedance Measurement  Measure the impedance in a circuit as a function of the frequency
- Multimeter  Measure voltage and current in SimPowerSystems blocks
Three-Phase V-I Measurement  Measure three-phase currents and voltages in a circuit
Voltage Measurement  Measure a voltage in a circuit

Analyzing Electrical Circuits

Powergui  Graphical user interface for the analysis of circuits and systems

Additional Useful Blocks

Signal Measurements

<table>
<thead>
<tr>
<th>Block</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>abc_to_dq0 Transformation</td>
<td>Perform a Park transformation from the three-phase (abc) reference frame to the dq0 reference frame</td>
</tr>
<tr>
<td>Active &amp; Reactive Power</td>
<td>Measure the active and reactive powers of a voltage-current pair</td>
</tr>
<tr>
<td>dq0_to_abc Transformation</td>
<td>Perform a Park transformation from the dq0 reference frame to the three-phase (abc) reference frame</td>
</tr>
<tr>
<td>Fourier</td>
<td>Fourier analyze a signal</td>
</tr>
<tr>
<td>RMS</td>
<td>Measure the root mean square (RMS) value of a signal</td>
</tr>
<tr>
<td>Three-Phase Sequence Analyzer</td>
<td>Measure the positive-, negative-, and zero-sequence components of a three-phase signal</td>
</tr>
<tr>
<td>Total Harmonic Distortion</td>
<td>Measure the total harmonic distortion of a voltage or current signal containing harmonics</td>
</tr>
</tbody>
</table>

Signal and Pulse Sources

<table>
<thead>
<tr>
<th>Block</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM Generator</td>
<td>Generate pulses for a carried-based Pulse Width Modulator (PWM)</td>
</tr>
<tr>
<td>Synchronized 6-Pulse Generator</td>
<td>Implement a synchronized pulse generator to fire the thyristors of a six-pulse converter</td>
</tr>
<tr>
<td>Synchronized 12-Pulse Generator</td>
<td>Implement a synchronized pulse generator to fire the thyristors of a twelve-pulse converter</td>
</tr>
<tr>
<td>Timer</td>
<td>Generate a signal changing at specified transition times</td>
</tr>
</tbody>
</table>
Blocks — Alphabetical List

The following pages describe the SimPowerSystems blocks.
abc_to_dq0 Transformation

**Purpose**
Perform a Park transformation from the three-phase (abc) reference frame to the dq0 reference frame.

**Library**
Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

**Description**

The abc_to_dq0 Transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. The following transformation is used:

\[
V_d = \frac{2}{3}(V_a \sin(\omega t) + V_b \sin(\omega t - 2\pi/3) + V_c \sin(\omega t + 2\pi/3))
\]

\[
V_q = \frac{2}{3}(V_a \cos(\omega t) + V_b \cos(\omega t - 2\pi/3) + V_c \cos(\omega t + 2\pi/3))
\]

\[
V_0 = \frac{1}{3}(V_a + V_b + V_c)
\]

where \( \omega \) = rotation speed (rad/s) of the rotating frame.

The transformation is the same for the case of a three-phase current; you simply replace the \( V_a, V_b, V_c, V_d, V_q, \) and \( V_0 \) variables with the \( I_a, I_b, I_c, I_d, I_q, \) and \( I_0 \) variables.

This transformation is commonly used in three-phase electric machine models, where it is known as a Park transformation. It allows you to eliminate time-varying inductances by referring the stator and rotor quantities to a fixed or rotating reference frame. In the case of a synchronous machine, the stator quantities are referred to the rotor. \( I_d \) and \( I_q \) represent the two DC currents flowing in the two equivalent rotor windings (d winding directly on the same axis as the field winding, and q winding on the quadratic axis), producing the same flux as the stator \( I_a, I_b, \) and \( I_c \) currents.

You can use this block in a control system to measure the positive-sequence component \( V_1 \) of a set of three-phase voltages or currents. The \( V_q \) and \( V_q \) (or \( I_d \) and \( I_q \)) then represent the rectangular coordinates of the positive-sequence component.
**abc_to_dq0 Transformation**

You can use the Math Function block and the Trigonometric Function block to obtain the modulus and angle of \( V_1 \):

\[
|V_1| = \sqrt{V_q^2 + V_d^2}
\]

\[
\angle V_1 = \text{atan2}(V_q/V_d)
\]

This measurement system does not introduce any delay, but, unlike the Fourier analysis done in the Sequence Analyzer block, it is sensitive to harmonics and imbalances.

**Dialog Box and Parameters**

**Inputs and Outputs**

**abc**

Connect to the first input the vectorized sinusoidal phase signal to be converted \([\text{phase A phase B phase C}]\).

**sin.Cos**

Connect to the second input a vectorized signal containing the \([\sin(\omega t) \cos(\omega t)]\) values, where \(\omega\) is the rotation speed of the reference frame.

**dq0**

The output is a vectorized signal containing the three sequence components \([d \ q \ o]\).
Example

The power_3phsignaldq demo uses a Discrete Three-Phase Programmable Source block to generate a 1 p.u., 15 degrees positive sequence voltage. At 0.05 second the positive sequence voltage is increased to 1.5 p.u. and at 0.1 second an imbalance is introduced by the addition of a 0.3 p.u. negative sequence component with a phase of −30 degrees. The magnitude and phase of the positive-sequence component are evaluated in two different ways:

- Sequence calculation of phasors using Fourier analysis
- abc-to-dq0 transformation
Start the simulation and observe the instantaneous signals $V_{abc}$ (Scope1), the signals returned by the Sequence Analyzer (Scope2), and the abc-to-dq0 transformation (Scope3).
Note that the Sequence Analyzer, which uses Fourier analysis, is immune to harmonics and imbalance. However, its response to a step is a one-cycle ramp. The abc-to-dqo transformation is instantaneous. However, an imbalance produces a ripple at the V1 and Phi1 outputs.
abc_to_dq0 Transformation

See Also dq0_to_abc Transformation reference section
AC Current Source

Purpose
Implement a sinusoidal current source

Library
Electrical Sources

Description
The AC Current Source block implements an ideal AC current source. The positive current direction is indicated by the arrow in the block icon. The generated current $I$ is described by the following relationship:

$$ I = A \sin(\omega t + \phi) \quad \omega = 2\pi f \quad \phi = \text{Phase in radians} $$

Negative values are allowed for amplitude and phase. A zero frequency specifies a DC current source. You cannot enter a negative frequency; Simulink returns an error in that case, and the block displays a question mark in the block icon. You can modify the first three block parameters at any time during the simulation.

Dialog Box and Parameters

Peak amplitude
The peak amplitude of the generated current, in amperes (A).
AC Current Source

**Phase**
The phase in degrees (deg).

**Frequency**
The source frequency in hertz (Hz).

**Sample time**
The sample period in seconds (s). The default is 0, corresponding to a continuous source.

**Measurements**
Select **Current** to measure the current flowing through the AC Current Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>Isrc:</td>
</tr>
</tbody>
</table>

**Example**
The `power_accurrent` demo uses two AC Current Source blocks in parallel to sum two sinusoidal currents in a resistor.

![Diagram](image)

**See Also**
Controlled Current Source reference section, Multimeter reference section
Active & Reactive Power

Purpose
Measure the active and reactive powers of a voltage-current pair

Library
Extras/Measurements
A discrete version of this block is available in the Extras/Discrete Measurements library.

Description
The Active & Reactive Power block measures the active power $P$ and reactive power $Q$ associated with a periodic voltage-current pair that can contain harmonics. $P$ and $Q$ are calculated by averaging the $VI$ product with a running average window over one cycle of the fundamental frequency, so that the powers are evaluated at fundamental frequency.

$$P = \frac{1}{T} \int_{(t-T)}^{t} \frac{1}{2\pi} \int (V(\omega t) \times I(\omega t)) \, dt$$

$$Q = \frac{1}{T} \int_{(t-T)}^{t} \frac{1}{2\pi} \int (V(\omega t) \times I(\omega t - \pi/2)) \, dt$$

where $T = 1/(\text{fundamental frequency})$.

A current flowing into an RL branch, for example, produces positive active and reactive powers.

As this block uses a running window, one cycle of simulation has to be completed before the output gives the correct active and reactive powers.

The discrete version of this block, available in the Extras/Discrete Measurements library, allows you to specify the initial input voltage and current (magnitude and phase). For the first cycle of simulation the outputs are held constant using the values specified by the initial input parameters.
Active & Reactive Power

Dialog Box and Parameters

![Block Parameters: Active & Reactive Power](image)

**Fundamental frequency (Hz)**

The fundamental frequency, in hertz, of the instantaneous voltage and current.

**Inputs and Outputs**

V  
The first input is the instantaneous voltage.

I  
The second input is the instantaneous current.

PQ  
The output is a vector \([P \ Q]\) of the active and reactive powers.

**Example**

The `power_transfo` demo simulates a three-winding distribution transformer rated at 75 kVA:14400/120/120 V. The transformer primary winding is connected to a high-voltage source of 14400 Vrms. Two identical inductive...
loads (20 kW-10 kvar) are connected to the two secondary windings. A third capacitive load (30 kW-20 kvar) is fed at 240 V.

Initially, the circuit breaker in series with Load 2 is closed, so that the system is balanced. When the circuit breaker opens, a current starts to flow in the neutral path as a result of the load imbalance.

The active power computed from the primary voltage and current is measured by an Active & Reactive Power block. When the breaker opens, the active power decreases from 70 kW to 50 kW.
Active & Reactive Power
**AC Voltage Source**

**Purpose**
Implement a sinusoidal voltage source

**Library**
Electrical Sources

**Description**
The AC Voltage Source block implements an ideal AC voltage source. The generated voltage $U$ is described by the following relationship:

$$U = A \sin(\omega t + \phi) \quad \omega = 2\pi f \quad \phi = \text{Phase in radians}$$

Negative values are allowed for amplitude and phase. A 0 frequency specifies a DC voltage source. Negative frequency is not allowed; otherwise Simulink signals an error, and the block displays a question mark in the block icon.

**Dialog Box and Parameters**

The AC Voltage Source block has the following parameters:

- **Peak amplitude (V)**: The peak amplitude of the generated voltage, in volts (V).
- **Phase (deg)**: The phase in degrees (deg).
- **Frequency (Hz)**: The frequency in hertz (Hz).
- **Sample time**: The sample time in seconds.
- **Measurements**: The measurements to be monitored.

**Peak amplitude**
The peak amplitude of the generated voltage, in volts (V).

**Phase**
The phase in degrees (deg).

**Frequency**
AC Voltage Source

The source frequency in hertz (Hz).

**Sample time**

The sample period in seconds (s). The default is 0, corresponding to a continuous source.

**Measurements**

Select **Voltage** to measure the voltage across the terminals of the AC Voltage Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Usrc:</td>
</tr>
</tbody>
</table>

**Example**

The `power_acvoltage` demo uses two AC Voltage Source blocks at different frequencies connected in series across a resistor. The sum of the two voltages is read by a Voltage Measurement block.

[Diagram of AC Voltage Source blocks connected in series]

**See Also**

Controlled Voltage Source reference section, DC Voltage Source reference section, Multimeter reference section
Asynchronous Machine

**Purpose**
Model the dynamics of a three-phase asynchronous machine, also known as an induction machine.

**Library**
Machines

**Description**
The Asynchronous Machine block operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque:

- If $T_m$ is positive, the machine acts as a motor.
- If $T_m$ is negative, the machine acts as a generator.

The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. All electrical variables and parameters are referred to the stator. This is indicated by the prime signs in the machine equations given below. All stator and rotor quantities are in the arbitrary two-axis reference frame (dq frame). The subscripts used are defined as follows:

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>d axis quantity</td>
</tr>
<tr>
<td>q</td>
<td>q axis quantity</td>
</tr>
<tr>
<td>r</td>
<td>Rotor quantity</td>
</tr>
<tr>
<td>s</td>
<td>Stator quantity</td>
</tr>
<tr>
<td>l</td>
<td>Leakage inductance</td>
</tr>
<tr>
<td>m</td>
<td>Magnetizing inductance</td>
</tr>
</tbody>
</table>

The mode of operation is dictated by the sign of the mechanical torque:

- If $T_m$ is positive, the machine acts as a motor.
- If $T_m$ is negative, the machine acts as a generator.
The Asynchronous Machine block parameters are defined as follows (all quantities are referred to the stator):

**Parameter** | **Definition**
---|---
$R_s$, $L_{ls}$ | Stator resistance and leakage inductance
$R'_r$, $L'_{lr}$ | Rotor resistance and leakage inductance
$L_m$ | Magnetizing inductance
$L_s$, $L'_r$ | Total stator and rotor inductances
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition (Continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{qs}$, $i_{qs}$</td>
<td>q axis stator voltage and current</td>
</tr>
<tr>
<td>$V'<em>{qr}$, $i'</em>{qr}$</td>
<td>q axis rotor voltage and current</td>
</tr>
<tr>
<td>$V_{ds}$, $i_{ds}$</td>
<td>d axis stator voltage and current</td>
</tr>
<tr>
<td>$V'<em>{dr}$, $i'</em>{dr}$</td>
<td>d axis rotor voltage and current</td>
</tr>
<tr>
<td>$\varphi_{qs}$, $\varphi_{ds}$</td>
<td>Stator q and d axis fluxes</td>
</tr>
<tr>
<td>$\varphi'<em>{qr}$, $\varphi'</em>{dr}$</td>
<td>Rotor q and d axis fluxes</td>
</tr>
<tr>
<td>$\omega_m$</td>
<td>Angular velocity of the rotor</td>
</tr>
<tr>
<td>$\theta_m$</td>
<td>Rotor angular position</td>
</tr>
<tr>
<td>$p$</td>
<td>Number of pole pairs</td>
</tr>
<tr>
<td>$\omega_r$</td>
<td>Electrical angular velocity ($\omega_m \times p$)</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>Electrical rotor angular position ($\theta_m \times p$)</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Electromagnetic torque</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Shaft mechanical torque</td>
</tr>
<tr>
<td>$J$</td>
<td>Combined rotor and load inertia coefficient. Set to infinite to simulate locked rotor.</td>
</tr>
<tr>
<td>$H$</td>
<td>Combined rotor and load inertia constant. Set to infinite to simulate locked rotor.</td>
</tr>
<tr>
<td>$F$</td>
<td>Combined rotor and load viscous friction coefficient</td>
</tr>
</tbody>
</table>
Asynchronous Machine

Dialog Boxes and Parameters

You can choose between two Asynchronous Machine blocks to specify the electrical and mechanical parameters of the model.

Preset model

Provides a set of predetermined electrical and mechanical parameters for various asynchronous machine ratings of power (HP), phase-to-phase voltage (V), frequency (Hz), and rated speed (rpm).

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select No if you don't want to use a preset model.
Select the **Show detailed parameters** parameter to view and edit the detailed parameters associated with the preset model.

**Show detailed parameters**

If selected, the mask displays the detailed parameters of the Asynchronous Machine block. The detailed parameters can be modified no matter the preset model you selected in the **Preset Model** list.

**Rotor type**

Specifies the branching for the rotor windings.

**Reference frame**

Specifies the reference frame that is used to convert input voltages (abc reference frame) to the dq reference frame, and output currents (dq reference frame) to the abc reference frame. You can choose among the following reference frame transformations:

- **Rotor** (Park transformation)
- **Stationary** (Clarke or \(\alpha\beta\) transformation)
- **Synchronous**

The following relationships describe the abc-to-dq reference frame transformations applied to the Asynchronous Machine phase-to-phase voltages.

\[
\begin{bmatrix}
V_{qs} \\
V_{ds}
\end{bmatrix} = \begin{bmatrix}
2\cos\theta & \cos\theta + \sqrt{3}\sin\theta \\
2\sin\theta & \sin\theta - \sqrt{3}\cos\theta
\end{bmatrix} \begin{bmatrix}
V_{abs} \\
V_{bcs}
\end{bmatrix}
\]

\[
\begin{bmatrix}
V'_{qr} \\
V'_{dr}
\end{bmatrix} = \begin{bmatrix}
2\cos\beta & \cos\beta + \sqrt{3}\sin\beta \\
2\sin\beta & \sin\beta - \sqrt{3}\cos\beta
\end{bmatrix} \begin{bmatrix}
V'_{abr} \\
V'_{bcr}
\end{bmatrix}
\]

In the preceding equations, \(\theta\) is the angular position of the reference frame, while \(\beta = \theta - \theta_r\) is the difference between the position of the reference frame and the position (electrical) of the rotor. Because the machine windings are connected in a three-wire Y configuration, there is no homopolar (0) component. This also justifies the fact that two line-to-line input voltages are used inside the model instead of three line-to-neutral voltages. The following relationships describe the dq-to-abc reference
Asynchronous Machine

frame transformations applied to the Asynchronous Machine phase currents.

\[
\begin{bmatrix}
  i_{as} \\
i_{bs}
\end{bmatrix} = \begin{bmatrix}
  \frac{\cos \theta}{2} & \frac{\sin \theta}{2} \\
  -\frac{\cos \theta + \sqrt{3}\sin \theta}{2} & -\frac{\sqrt{3}\cos \theta - \sin \theta}{2}
\end{bmatrix}\begin{bmatrix}
  i_{qs} \\
i_{ds}
\end{bmatrix}
\]

\[
\begin{bmatrix}
i'_{ar} \\
i'_{br}
\end{bmatrix} = \begin{bmatrix}
  \cos \beta & \sin \beta \\
  -\frac{\cos \beta + \sqrt{3}\sin \beta}{2} & -\frac{\sqrt{3}\cos \beta - \sin \beta}{2}
\end{bmatrix}\begin{bmatrix}
i'_{qr} \\
i'_{dr}
\end{bmatrix}
\]

\[
i_{cs} = -i_{as} - i_{bs}
\]

\[
i'_{cr} = -i'_{ar} - i'_{br}
\]

The following table shows the values taken by \( \theta \) and \( \beta \) in each reference frame (\( \theta_e \) is the position of the synchronously rotating reference frame).

<table>
<thead>
<tr>
<th>Reference Frame</th>
<th>( \theta )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>( \theta_r )</td>
<td>0</td>
</tr>
<tr>
<td>Stationary</td>
<td>0</td>
<td>-( \theta_r )</td>
</tr>
<tr>
<td>Synchronous</td>
<td>( \theta_e )</td>
<td>( \theta_e - \theta_r )</td>
</tr>
</tbody>
</table>

The choice of reference frame affects the waveforms of all dq variables. It also affects the simulation speed and in certain cases the accuracy of the results. The following guidelines are suggested in [1]:

- Use the stationary reference frame if the stator voltages are either unbalanced or discontinuous and the rotor voltages are balanced (or 0).
- Use the rotor reference frame if the rotor voltages are either unbalanced or discontinuous and the stator voltages are balanced.
- Use either the stationary or synchronous reference frames if all voltages are balanced and continuous.

**Nominal power, L-L volt, and freq.**

The nominal apparent power \( P_n \) (VA), RMS line-to-line voltage \( V_n \) (V), and frequency \( f_n \) (Hz).
Asynchronous Machine

**Stator**

The stator resistance $R_s$ (Ω or p.u.) and leakage inductance $L_{ls}$ (H or p.u.).

**Rotor**

The rotor resistance $R_r$ (Ω or p.u.) and leakage inductance $L_{lr}$ (H or p.u.), both referred to the stator.

**Mutual inductance**

The magnetizing inductance $L_m$ (H or p.u.).

**Inertia, friction factor, and pairs of poles**

For the **SI units** dialog box: the combined machine and load inertia coefficient $J$ (kg·m²), combined viscous friction coefficient $F$ (N·m·s), and pole pairs $p$. The friction torque $T_f$ is proportional to the rotor speed $\omega$ ($T_f = F \cdot \omega$).

For the **p.u. units** dialog box: the inertia constant $H$ (s), combined viscous friction coefficient $F$ (p.u.), and pole pairs $p$.

**Initial conditions**

Specifies the initial slip $s$, electrical angle $\theta_e$ (degrees), stator current magnitude (A or p.u.), and phase angles (degrees):

$$[\text{slip}, \, \text{th}, \, i_{as}, \, i_{bs}, \, i_{cs}, \, \text{phase}_{as}, \, \text{phase}_{bs}, \, \text{phase}_{cs}]$$

For the wound-rotor machine, you can also specify optional initial values for the rotor current magnitude (A or p.u.), and phase angles (degrees):

$$[\text{slip}, \, \text{th}, \, i_{as}, \, i_{bs}, \, i_{cs}, \, \text{phase}_{as}, \, \text{phase}_{bs}, \, \text{phase}_{cs}, \, i_{ar}, \, i_{br}, \, i_{cr}, \, \text{phase}_{ar}, \, \text{phase}_{br}, \, \text{phase}_{cr}]$$

For the squirrel cage machine, the initial conditions can be computed by the load flow utility in the Powergui block.

**Note**  Depending on the dialog box you choose to use, SimPowerSystems automatically converts the parameters you enter into per unit parameters. The Simulink model of the Asynchronous Machine block uses p.u. parameters.
Asynchronous Machine

Inputs and Outputs

The Simulink input of the block is the mechanical torque at the machine’s shaft. When the input is a positive Simulink signal, the asynchronous machine behaves as a motor. When the input is a negative signal, the asynchronous machine behaves as a generator.

The Simulink output of the block is a vector containing 21 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rotor current</td>
<td>A or p.u.</td>
<td>$i_{ra}'$</td>
</tr>
<tr>
<td>2</td>
<td>Rotor current</td>
<td>A or p.u.</td>
<td>$i_{rb}'$</td>
</tr>
<tr>
<td>3</td>
<td>Rotor current</td>
<td>A or p.u.</td>
<td>$i_{rc}'$</td>
</tr>
<tr>
<td>4</td>
<td>Rotor current</td>
<td>A or p.u.</td>
<td>$i_{qr}'$</td>
</tr>
<tr>
<td>5</td>
<td>Rotor current</td>
<td>A or p.u.</td>
<td>$i_{dr}'$</td>
</tr>
<tr>
<td>6</td>
<td>Rotor flux</td>
<td>V.s or p.u.</td>
<td>$\psi_{qr}'$</td>
</tr>
<tr>
<td>7</td>
<td>Rotor flux</td>
<td>V.s or p.u.</td>
<td>$\psi_{dr}'$</td>
</tr>
<tr>
<td>8</td>
<td>Rotor voltage</td>
<td>V or p.u.</td>
<td>$v_{qr}'$</td>
</tr>
<tr>
<td>9</td>
<td>Rotor voltage</td>
<td>V or p.u.</td>
<td>$v_{dr}'$</td>
</tr>
<tr>
<td>10</td>
<td>Stator current</td>
<td>A or p.u.</td>
<td>$i_{sa}$</td>
</tr>
<tr>
<td>11</td>
<td>Stator current</td>
<td>A or p.u.</td>
<td>$i_{sb}$</td>
</tr>
<tr>
<td>12</td>
<td>Stator current</td>
<td>A or p.u.</td>
<td>$i_{sc}$</td>
</tr>
<tr>
<td>13</td>
<td>Stator current</td>
<td>A or p.u.</td>
<td>$i_{qs}$</td>
</tr>
<tr>
<td>14</td>
<td>Stator current</td>
<td>A or p.u.</td>
<td>$i_{ds}$</td>
</tr>
<tr>
<td>15</td>
<td>Stator flux</td>
<td>V.s or p.u.</td>
<td>$\psi_{qs}$</td>
</tr>
<tr>
<td>16</td>
<td>Stator flux</td>
<td>V.s or p.u.</td>
<td>$\psi_{ds}$</td>
</tr>
</tbody>
</table>
Asynchronous Machine

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Stator voltage</td>
<td>V or p.u.</td>
<td>$v_{qs}$</td>
</tr>
<tr>
<td>18</td>
<td>Stator voltage</td>
<td>V or p.u.</td>
<td>$v_{ds}$</td>
</tr>
<tr>
<td>19</td>
<td>Rotor speed</td>
<td>rad/s</td>
<td>$\omega_m$</td>
</tr>
<tr>
<td>20</td>
<td>Electromagnetic</td>
<td>N.m or p.u.</td>
<td>$T_e$</td>
</tr>
<tr>
<td>21</td>
<td>Rotor angle</td>
<td>rad</td>
<td>$\theta_m$</td>
</tr>
</tbody>
</table>

The stator terminals of the Asynchronous Machine block are identified by the A, B, and C letters. The rotor terminals are identified by the a, b, and c letters. Note that the neutral connections of the stator and rotor windings are not available; three-wire Y connections are assumed.

Limitations

The Asynchronous Machine block does not include a representation of iron losses and saturation.

You must be careful when you connect ideal sources to the machine’s stator. If you choose to supply the stator via a three-phase Y-connected infinite voltage source, you must use three sources connected in Y. However, if you choose to simulate a delta source connection, you must use only two sources connected in series.

Example

The power_pwm demo illustrates the use of the Asynchronous Machine block in motor mode. It consists of an asynchronous machine in an open-loop speed control system.
Asynchronous Machine

The machine's rotor is short-circuited, and the stator is fed by a PWM inverter, built with Simulink blocks and interfaced to the Asynchronous Machine block through the Controlled Voltage Source block. The inverter uses sinusoidal pulse-width modulation, which is described in [2]. The base frequency of the sinusoidal reference wave is set at 60 Hz and the triangular carrier wave's frequency is set at 1980 Hz. This corresponds to a frequency modulation factor \( m_f \) of 33 (60 Hz \( \times \) 33 = 1980). It is recommended in [2] that \( m_f \) be an odd multiple of three and that the value be as high as possible.

The 3 HP machine is connected to a constant load of nominal value (11.9 N.m). It is started and reaches the set point speed of 1.0 p.u. at \( t = 0.9 \) second.

The parameters of the machine are those found in the **SI Units** dialog box above, except for the stator leakage inductance, which is set to twice its normal value. This is done to simulate a smoothing inductor placed between the inverter and the machine. Also, the stationary reference frame was used to obtain the results shown.
Open the `power_pwm` demo. Note in the simulation parameters that a small relative tolerance is required because of the high switching rate of the inverter.

Run the simulation and observe the machine’s speed and torque.

The first graph shows the machine’s speed going from 0 to 1725 rpm (1.0 p.u.). The second graph shows the electromagnetic torque developed by the machine. Because the stator is fed by a PWM inverter, a noisy torque is observed.

However, this noise is not visible in the speed because it is filtered out by the machine’s inertia, but it can also be seen in the stator and rotor currents, which are observed next.
Finally, look at the output of the PWM inverter. Because nothing of interest can be seen at the simulation time scale, the graph concentrates on the last moments of the simulation.
**References**


**See Also**

Machine Measurement Demux reference section, Powergui reference section
Purpose
Implement a circuit breaker opening at the current zero crossing

Library
Elements

Description
The Breaker block implements a circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode).

The arc extinction process is simulated by opening the breaker device when the current passes through 0 (first current zero crossing following the transition of the Simulink control input from 1 to 0).

When the breaker is closed it behaves as a resistive circuit. It is represented by a resistance Ron. The Ron value can be set as small as necessary in order to be negligible compared with external components (typical value is 10 mΩ). When the breaker is open it has an infinite resistance.

If the Breaker block is set in external control mode, a Simulink input appears on the block icon. The control signal connected to the Simulink input must be either 0 or 1: 0 to open the breaker, 1 to close it. If the Breaker block is set in internal control mode, the switching times are specified in the dialog box of the block.

If the breaker initial state is set to 1 (closed), SimPowerSystems automatically initializes all the states of the linear circuit and the Breaker block initial current so that the simulation starts in steady state.

A series Rs-Cs snubber circuit is included in the model. It can be connected to the circuit breaker. If the Breaker block happens to be in series with an inductive circuit, an open circuit or a current source, you must use a snubber.
Breaker

Dialog Box and Parameters

The internal breaker resistance, in ohms (Ω). The Breaker resistance $R_{on}$ parameter cannot be set to 0.

Initial state

The initial state of the breaker. A closed contact is displayed in the block icon when the Initial state parameter is set to 1, and an open contact is displayed when it is set to 0.

Snubber resistance $R_s$

The snubber resistance, in ohms (Ω). Set the Snubber resistance $R_s$ parameter to $\infty$ to eliminate the snubber from the model.

Snubber capacitance $C_s$
The snubber capacitance, in farads (F). Set the **Snubber capacitance Cs** parameter to 0 to eliminate the snubber, or to $\infty$ to get a resistive snubber.

**Switching times**

Specifies the vector of switching times when using the Breaker block in internal control mode. At each switching time the Breaker block opens or closes depending on its initial state. For example, if the **Initial state** parameter is 0 (open), the breaker closes at the first switching time, opens at the second switching time, and so on. The **Switching times** parameter is not visible in the dialog box if the **External control of switching times** parameter is selected.

**External control of switching times**

If selected, adds a Simulink input to the Breaker block for external control of the switching times of the breaker. The switching times are defined by a logical signal (0 or 1) connected to the Simulink input.

**Measurements**

Select **Branch voltage** to measure the voltage across the Breaker block terminals.

Select **Branch current** to measure the current flowing through the Breaker block. If the snubber device is connected to the breaker model, the measured current is the one flowing through the breaker contacts only.

Select **Branch voltage** and **current** to measure the breaker voltage and the breaker current.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch voltage</td>
<td>Ub:</td>
</tr>
<tr>
<td>Branch current</td>
<td>Ib:</td>
</tr>
</tbody>
</table>
Limitations

When the block is connected in series with an inductor or another current source, you must add the snubber circuit. In most applications you can use a resistive snubber (Snubber capacitance parameter set to $\infty$) with a large resistor value (Snubber resistance parameter set to 1e6 or so). Because of modeling constraints, the internal breaker inductance $R_{on}$ cannot be set to 0.

You must use a stiff integration algorithm to simulate circuits with the Breaker block. ode23tb or ode15s with default parameters usually gives the best simulation speed.

Example

The `power_breaker` demo illustrates a circuit breaker connected in series with a series RL circuit on a 60 Hz voltage source. The switching times of the Breaker block are controlled by a Simulink signal. The breaker device is initially closed and an opening order is given at $t = 1.5$ cycles, when current reaches a maximum. The current stops at the next zero crossing, then the breaker is reclosed at a zero crossing of voltage at $t = 3$ cycles.
Simulation produces the following results.

Note that the breaker device opens only when the load current has reached zero, after the opening order.

**See Also** Three-Phase Fault reference section
**Connection Port**

**Purpose**
Create a Physical Modeling connector port for a subsystem

**Library**
Elements

**Description**
The Connection Port block, placed inside a subsystem composed of SimPowerSystems blocks, creates a Physical Modeling open round connector port \(\circ\) on the boundary of the subsystem. Once connected to a connection line, the port becomes solid \(\bullet\). Once you begin the simulation, the solid port \(\bullet\) becomes an electrical terminal port, an open square \(\square\).

You connect individual SimPowerSystems blocks and subsystems made of SimPowerSystems blocks to one another with SimPowerSystems connection lines, instead of normal Simulink signal lines. These are anchored at the open, round connector ports \(\circ\). Subsystems constructed of SimPowerSystems blocks automatically have such open round connector ports. You can add additional connector ports by adding Connection Port blocks to your subsystem.

**Dialog Box and Parameters**

![Block Parameters: Connection Port](image)

**Port number**
This field labels the subsystem connector port created by the block. Multiple connector ports on the boundary of a single subsystem require different numbers as labels. The default value for the first port is 1.

**Port location on parent subsystem**
Choose which side of the parent subsystem boundary the port is placed on. The choices are Left or Right. The default is Left.
Connection Port

See Also

See “Creating Subsystems” in the Simulink documentation
Controlled Current Source

Purpose
Implement a controlled current source

Library
Electrical Sources

Description
The Controlled Current Source block provides a current source controlled by a Simulink signal. The positive current direction is as shown by the arrow in the block icon.

You can initialize the Controlled Current Source block with a specific AC or DC current. If you want to start the simulation in steady state, the block input must be connected to a signal starting as a sinusoidal or DC waveform corresponding to the initial values.

Dialog Box and Parameters

Initialize
If selected, initializes the Controlled Current Source block with the specified Initial current, Initial phase, and Initial frequency parameters.
Controlled Current Source

Source type
The Source type parameter is not visible if the Initialize parameter is not selected.

The type of current source. Select AC to initialize the Controlled Current Source Block as an AC current source. Select DC to initialize the Controlled Current Source block as a DC current.

Initial current
The Initial current parameter is not visible in the dialog box if the Initialize parameter is not selected. The initial peak current for the initialization of the source, in amperes (A).

Initial phase
The initial phase for the initialization of the source, in degrees. The Initial phase parameter is not visible in the dialog box if the Source type parameter is set to DC.

Initial frequency
The initial frequency for the initialization of the source, in hertz (Hz). The Initial frequency parameter is not visible in the dialog box if the Source type parameter is set to DC.

Measurements
Select Current to measure the current flowing through the Controlled Current Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the Available Measurements list box of the Multimeter block, the measurement is identified by a label followed by the block name:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>Isrc:</td>
</tr>
</tbody>
</table>

Example
The power_controlcurr demo uses a Controlled Current Source to generate a 60 Hz current modulated at 5 Hz.
Controlled Current Source

Simulation produces the following waveforms:

See Also

AC Current Source reference section, Controlled Voltage Source reference section, Multimeter reference section
Controlled Voltage Source

Purpose
Implement a controlled voltage source

Library
Electrical Sources

Description
The Controlled Voltage Source block provides a voltage source controlled by a Simulink signal.

You can initialize the Controlled Voltage Source block with a specific AC or DC voltage. If you want to start the simulation in steady state, the Simulink input must be connected to a signal starting as a sinusoidal or DC waveform corresponding to the initial values.

Dialog Box and Parameters

Initialize
If selected, initializes the Controlled Voltage Source block with the specified Initial voltage, Initial phase, and Initial frequency parameters.
Controlled Voltage Source

**Source type**

The **Source type** parameter is not available if the **Initialize** parameter is not selected.

The type of voltage source. Select **AC** to initialize the Controlled Voltage Source block with an AC voltage source. Select **DC** to initialize the Controlled Voltage Source Block with a DC voltage.

**Initial voltage**

The **Initial voltage** parameter is not available if the **Initialize** parameter is not selected. The initial voltage for the initialization of the source, in amperes (A).

**Initial phase**

The **Initial phase** parameter is not available if the **Source type** parameter is set to **DC**. The initial phase for the initialization of the source, in degrees.

**Initial frequency**

The initial frequency for the initialization of the source, in hertz (Hz). The **Initial frequency** parameter is not available in the dialog box if the **Source type** parameter is set to **DC**.

**Measurements**

Select **Voltage** to measure the voltage across the terminals of the Controlled Voltage Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the **Available Measurements** list box of the Multimeter block, the measurement is identified by a label followed by the block name:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Usrc:</td>
</tr>
</tbody>
</table>

**Example**

The `power_controlvolt` demo uses Controlled Voltage Source blocks to generate a 60 Hz sinusoidal voltage containing a third harmonic. One Controlled Voltage Source block is initialized as a 120 V AC voltage source with an initial frequency of 60 Hz and initial phase set to 0. The second Controlled Voltage Source block is not initialized.
At $t = 0.0333$ s a 100 V-180 Hz sinusoidal signal is added to the 120 V Simulink signal. The resulting capacitor voltages are compared on a Scope block.
The $V_c$ voltage starts in steady state, whereas the $V_{c1}$ voltage contains a DC offset.

**See Also**

AC Current Source reference section, Controlled Current Source reference section, Multimeter reference section
Current Measurement

**Purpose**
Measure a current in a circuit

**Library**
Measurements

**Description**
The Current Measurement block is used to measure the instantaneous current flowing in any electrical block or connection line. The Simulink output provides a Simulink signal that can be used by other Simulink blocks.

**Dialog Box and Parameters**

![Block Parameters: Current Measurement]

**Output signal**
Specifies the format of the output signal when the block is used in a phasor simulation. The *Output signal* parameter is disabled when the block is not used in a phasor simulation. The phasor simulation is activated by a Powgui block placed in the model.

Set to *Complex* to output the measured current as a complex value. The output is a complex signal.

Set to *Real-Imag* to output the real and imaginary parts of the measured current. The output is a vector of two elements.

Set to *Magnitude-Angle* to output the magnitude and angle of the measured current. The output is a vector of two elements.

Set to *Magnitude* to output the magnitude of the measured current. The output is a scalar value.
**Example**

The `power_currmeasure` demo uses four Current Measurement blocks to read currents in different branches of a circuit. The two scopes display the same current.

See Also

Powergui reference section, Three-Phase V-I Measurement reference section, Voltage Measurement reference section
### DC Machine

**Purpose**
Implement a separately excited DC machine

**Library**
Machines

**Description**
This block implements a separately excited DC machine. An access is provided to the field terminals (F+, F−) so that the machine model can be used as a shunt-connected or a series-connected DC machine. The torque applied to the shaft is provided at the Simulink input \( T_L \).

The armature circuit (A+, A−) consists of an inductor \( L_a \) and resistor \( R_a \) in series with a counter-electromotive force (CEMF) \( E \).

The CEMF is proportional to the machine speed.

\[
E = K_E \omega
\]

\( K_E \) is the voltage constant and \( \omega \) is the machine speed.

In a separately excited DC machine model, the voltage constant \( K_E \) is proportional to the field current \( I_f \).

\[
K_E = L_{af} I_f
\]

where \( L_{af} \) is the field-armature mutual inductance.

The electromechanical torque developed by the DC machine is proportional to the armature current \( I_a \).

\[
T_e = K_T I_a
\]

where \( K_T \) is the torque constant. The sign convention for \( T_e \) and \( T_L \) is

\[
T_e \ T_L > 0 \ : \text{Motor mode} \\
T_e \ T_L < 0 \ : \text{Generator mode}
\]

The torque constant is equal to the voltage constant.

\[
K_T = K_E
\]

The armature circuit is connected between the A+ and A− ports of the DC Machine block. It is represented by a series \( R_a \) \( L_a \) branch in series with a Controlled Voltage Source and a Current Measurement block.
Mechanical part:

The field circuit is represented by an RL circuit. It is connected between the F+ and F− ports of the DC Machine block.
The mechanical part computes the speed of the DC machine from the net torque applied to the rotor. The speed is used to implement the CEMF voltage $E$ of the armature circuit.

The mechanical part is represented by Simulink blocks that implement the equation

$$ J \frac{d\omega}{dt} = T_e - \text{sgn}(\omega)T_L - B_m \omega - T_f $$

where $J = \text{inertia}$, $B_m = \text{viscous friction coefficient}$, and $T_f = \text{Coulomb friction torque}$.

**Dialog Box and Parameters**

![Block Parameters: DC Machine](image)

- **DC machine (mask)**
  - This block implements a separately excited DC machine. Access is provided to the field connections so that the machine can be used as a shunt connected or a series connected DC machine.

- **Parameters**
  - Default model: $N_0$
  - **Show detailed parameters**
  - **Armature resistance and inductance** $\{R_a \text{ (ohm)} \ L_a \} \ [0.5 \ 0.01]$
  - **Field resistance and inductance** $\{R_f \text{ (ohm)} \ L_f \} \ [2 \ 0 \ 1.2 \ 0]$
  - **Field-armature mutual inductance** $L_{af} \text{ (H)} : 16$
  - **Total inertia** $J (kg \cdot m^2)$: $0.05$
  - **Viscous friction coefficient** $B_m (N \cdot m)$: $0.02$
  - **Coulomb friction torque** $T_f (N \cdot m)$: $0$
  - **Initial speed** $\omega_0 (rad/s)$: $0$

---

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Preset Model

Provides a set of predetermined electrical and mechanical parameters for various DC machine ratings of power (HP), DC voltage (V), rated speed (rpm), and field voltage (V).

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select No if you don’t want to use a preset model.

Select Show detailed parameters to view and edit the detailed parameters associated with the preset model.

Show detailed parameters

If selected, the mask displays the detailed parameters of the DC Machine block. The detailed parameters can be modified no matter the preset model you selected in the Preset Model list.

Armature resistance and inductance [Ra  La]

The armature resistance Ra, in ohms, and the armature inductance La, in henries.

Field resistance and inductance [Rf  Lf]

The field resistance Rf, in ohms, and the field inductance Lf, in henries.

Field armature mutual inductance Laf

The field armature mutual inductance, in henries.

Total inertia J

The total inertia of the DC machine, in kg.m².

Viscous friction coefficient Bm

The total friction coefficient of the DC machine, in N.m.s.

Coulomb friction torque Tf

The total Coulomb friction torque constant of the DC machine, in N.m.

Initial speed

Specifies an initial speed for the DC machine, in rad/s, in order to start the simulation with a specific initial speed. To start the simulation in steady state, the initial value of the input torque signal T_L must be proportional to the initial speed.
DC Machine

Inputs and Outputs

The Simulink output of the block is a vector containing four signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Speed ( w_m )</td>
<td>rad/s</td>
</tr>
<tr>
<td>2</td>
<td>Armature current ( i_a )</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>Field current ( i_f )</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>Electrical torque ( T_e )</td>
<td>N.m</td>
</tr>
</tbody>
</table>

Example

The power_dcmotor demo illustrates the starting of a 5 HP 240 V DC machine with a three-step resistance starter.

The Motor Starter subsystem is
DC Machine

References

Analysis of Electric Machinery, Krause et al., pp. 89-92.

See Also

Asynchronous Machine reference section, Synchronous Machine reference section
DC Voltage Source

Purpose

Implement a DC voltage source

Library

Electrical Sources

Description

The DC Voltage Source block implements an ideal DC voltage source. The positive terminal is represented by a plus sign on one port. You can modify the voltage at any time during the simulation.

Dialog Box and Parameters

Amplitude

The amplitude of the source, in volts (V).

Measurements

Select Voltage to measure the voltage across the terminals of the DC Voltage Source block.

Place a Multimeter block in your model to display the selected measurements during the simulation. In the Available Measurements list box of the Multimeter block, the measurement is identified by a label followed by the block name:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Usrc:</td>
</tr>
</tbody>
</table>
Example

The `power_dcvoltage` demo illustrates the simulation of the transient response of a first-order RC circuit.

See Also

AC Voltage Source reference section, Controlled Voltage Source reference section
Diode

**Purpose**
Implement a diode model

**Library**
Power Electronics

**Description**
The diode is a semiconductor device that is controlled by its own voltage $V_{ak}$ and current $I_{ak}$. When a diode is forward biased ($V_{ak} > 0$), it starts to conduct with a small forward voltage $V_f$ across it. It turns off when the current flow into the device becomes 0. When the diode is reverse biased ($V_{ak} < 0$), it stays in the off state.

![Diode symbol]

The Diode block is simulated by a resistor, an inductor, and a DC voltage source connected in series with a switch. The switch operation is controlled by the voltage $V_{ak}$ and the current $I_{ak}$.

![Diode block diagram]

The Diode block also contains a series $R_s-C_s$ snubber circuit that can be connected in parallel with the diode device (between nodes A and K).
Dialog Box and Parameters

Diode

Implements a diode in parallel with a series RC snubber circuit. In on state the Diode model has an internal resistance ($R_{on}$) and inductance ($L_{on}$). For most applications the internal inductance should be set to zero. The Diode impedance is infinite in off-state mode.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance $R_{on}$</td>
<td>0.001</td>
</tr>
<tr>
<td>Inductance $L_{on}$</td>
<td>0</td>
</tr>
<tr>
<td>Forward voltage $V_f$</td>
<td>0.8</td>
</tr>
<tr>
<td>Initial current $I_c$</td>
<td>0</td>
</tr>
<tr>
<td>Snubber resistance $R_s$</td>
<td>500</td>
</tr>
<tr>
<td>Snubber capacitance $C_s$</td>
<td>250nS</td>
</tr>
</tbody>
</table>

Show measurement port

OK     Cancel     Help     Apps

Resistance $R_{on}$

The diode internal resistance $R_{on}$, in ohms ($\Omega$). The **Resistance $R_{on}$** parameter cannot be set to 0 when the **Inductance $L_{on}$** parameter is set to 0.

Inductance $L_{on}$

The diode internal inductance $L_{on}$, in henries (H). The **Inductance $L_{on}$** parameter cannot be set to 0 when the **Resistance $R_{on}$** parameter is set to 0.

Forward voltage $V_f$

The forward voltage of the diode device, in volts (V).

Initial current $I_c$
Specifies an initial current flowing in the diode device. It is usually set to 0 in order to start the simulation with the diode device blocked. If the Initial Current IC parameter is set to a value greater than 0, the steady-state calculation of SimPowerSystems considers the initial status of the diode as closed.

Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

**Snubber resistance Rs**

The snubber resistance, in ohms (Ω). Set the Snubber resistance Rs parameter to `inf` to eliminate the snubber from the model.

**Snubber capacitance Cs**

The snubber capacitance in farads (F). Set the Snubber capacitance Cs parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

**Show measurement port**

If selected, adds a Simulink output to the block returning the diode current and voltage.

### Inputs and Outputs

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diode current</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>Diode voltage</td>
<td>V</td>
</tr>
</tbody>
</table>

### Assumptions and Limitations

The Diode block implements a macro model of a diode device. It does not take into account either the geometry of the device or the complex physical processes underlying the state change [1]. The leakage current in the blocking state and the reverse-recovery (negative) current are not considered. In most circuits, the reverse current does not affect converter or other device characteristics.
Depending on the value of the inductance \( L_{on} \), the diode is modeled either as a current source \((L_{on} > 0)\) or as a variable topology circuit \((L_{on} = 0)\). The Diode block cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See Chapter 3, "Improving Simulation Performance" for more details on this topic.

You must use a stiff integrator algorithm to simulate circuits containing diodes. \texttt{ode23tb} or \texttt{ode15s} with default parameters usually gives the best simulation speed.

The inductance \( L_{on} \) is forced to 0 if you choose to discretize your circuit.

**Example**

The \texttt{power_diode} demo illustrates a single pulse rectifier consisting of a Diode block, an RL load, and an AC Voltage source block.
Simulation produces the following results.

References


See Also
Thyristor reference section, Universal Bridge reference section
### Purpose
Discretize the state-space model of a circuit

### Library
powerlib

### Description
The Discrete System block, in previous versions of SimPowerSystems, served to discretize the state-space model of an electrical model. Discrete time models are used for the linear elements as well as for the nonlinear blocks of the Elements, Machines, and Power Electronics libraries of **powerlib**.

**Note** This block is now obsolete. Use the Powergui block to replace this block.

### See Also
Powergui reference section
Distributed Parameter Line

**Purpose**
Implement an N-phase distributed parameter transmission line model with lumped losses

**Library**
Elements

**Description**
The Distributed Parameter Line block implements an N-phase distributed parameter line model with lumped losses. The model is based on the Bergeron’s traveling wave method used by the Electromagnetic Transient Program (EMTP) [1]. In this model, the lossless distributed LC line is characterized by two values (for a single-phase line): the surge impedance $Z_c = \sqrt{L/C}$ and the phase velocity $v = 1/\sqrt{LC}$.

The model uses the fact that the quantity $e+Zi$ (where $e$ is line voltage and $i$ is line current) entering one end of the line must arrive unchanged at the other end after a transport delay of $\tau = d/v$, where $d$ is the line length. By lumping $R/4$ at both ends of the line and $R/2$ in the middle and using the current injection method of SimPowerSystems, the following two-port model is derived.

\[
\begin{align*}
Z_c & = \frac{1}{\tau} \\
L & = \frac{Z_c - R}{Z_c + R/4} \\
C & = \frac{\sqrt{L}}{Z_c} \\
\end{align*}
\]

where $Z = Z_c + \frac{R}{4}$, $h = \frac{Z_c - R}{Z_c + \frac{R}{4}}$, $Z_c = \frac{\sqrt{L}}{\sqrt{C}}$, and $\tau = d/\sqrt{LC}$. 

![Distributed Parameter Line Diagram](image)
For multiphase line models, modal transformation is used to convert line quantities from phase values (line currents and voltages) into modal values independent of each other. The previous calculations are made in the modal domain before being converted back to phase values.

In comparison to the PI section line model, the distributed line represents wave propagation phenomena and line end reflections with much better accuracy. See the comparison between the two models in the Example section.

### Dialog Box and Parameters

#### Number of phases N

Specifies the number of phases, N, of the model. The block icon dynamically changes according to the number of phases that you specify. When you
apply the parameters or close the dialog box, the number of inputs and outputs is updated.

**Frequency used for RLC specifications**
Specify the frequency used to compute the resistance $R$, inductance $L$, and capacitance $C$ matrices of the line model.

**Resistance per unit length**
The resistance $R$ per unit length, as an $N$-by-$N$ matrix in ohms/km ($\Omega$/km).

For a symmetrical line, you can either specify the $N$-by-$N$ matrix or the sequence parameters. For a two-phase or three-phase continuously transposed line, you can enter the positive and zero-sequence resistances $[R1 \ R0]$. For a symmetrical six-phase line you can enter the sequence parameters plus the zero-sequence mutual resistance $[R1 \ R0 \ R0m]$.

For asymmetrical lines, you must specify the complete $N$-by-$N$ resistance matrix.

**Inductance per unit length**
The inductance $L$ per unit length, as an $N$-by-$N$ matrix in henries/km (H/km).

For a symmetrical line, you can either specify the $N$-by-$N$ matrix or the sequence parameters. For a two-phase or three-phase continuously transposed line, you can enter the positive and zero-sequence inductances $[L1 \ L0]$. For a symmetrical six-phase line, you can enter the sequence parameters plus the zero-sequence mutual inductance $[L1 \ L0 \ L0m]$.

For asymmetrical lines, you must specify the complete $N$-by-$N$ inductance matrix.

**Capacitance per unit length**
The capacitance $C$ per unit length, as an $N$-by-$N$ matrix in farads/km ($F$/km).

For a symmetrical line, you can either specify the $N$-by-$N$ matrix or the sequence parameters. For a two-phase or three-phase continuously transposed line, you can enter the positive and zero-sequence capacitances $[C1 \ C0]$. For a symmetrical six-phase line you can enter the sequence parameters plus the zero-sequence mutual capacitance $[C1 \ C0 \ C0m]$. 
Distributed Parameter Line

For asymmetrical lines, you must specify the complete N-by-N capacitance matrix.

**Note** The Powergui block provide you a graphical tool for the calculation of the resistance, inductance, and capacitance per unit length based on the line geometry and the conductor characteristics.

**Line length**
The line length, in km.

**Measurements**
Select phase-to-ground voltages to measure the sending end and receiving end voltages for each phase of the line model.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the Available Measurements list box of the Multimeter block, the measurement is identified by a label followed by the block name:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-to-ground voltages, sending end</td>
<td>Us_ph1_gnd:, Us_ph2_gnd:,</td>
</tr>
<tr>
<td></td>
<td>Us_ph3_gnd:, etc.</td>
</tr>
<tr>
<td>Phase-to-ground voltages, receiving end</td>
<td>Ur_ph1_gnd:, Ur_ph2_gnd:,</td>
</tr>
<tr>
<td></td>
<td>Ur_ph3_gnd:, etc.</td>
</tr>
</tbody>
</table>

**Limitations**
This model does not represent accurately the frequency dependence of RLC parameters of real power lines. Indeed, because of the skin effects in the conductors and ground, the $R$ and $L$ matrices exhibit strong frequency dependence, causing an attenuation of the high frequencies.
Distributed Parameter Line

Example

The `power_monophase` demo illustrates a 200 km line connected on a 1 kV, 60 Hz infinite source. The line is de-energized and then reenergized after 2 cycles. The simulation is performed simultaneously with the Distributed Parameter Line block and with the PI Section Line block.
The receiving end voltage obtained with the Distributed Parameter Line block is compared with the one obtained with the PI Section Line block (two sections).
Distributed Parameter Line

Open the Powergui. Click the **Impedance vs Frequency Measurement** button. A new window appears, listing the two Impedance Measurement blocks connected to your circuit. Set the parameters of **Impedance vs Frequency Measurement** to compute impedance in the [0,2000] Hz frequency range, select the two measurements in the list, then click the **Update** button.

The distributed parameter line shows a succession of poles and zeros equally spaced, every 486 Hz. The first pole occurs at 243 Hz, corresponding to frequency \( f = \frac{1}{4 \cdot T} \), where

\[
T = \text{traveling time} = \frac{L}{\sqrt{LC}} = 1.028 \text{ ms}
\]

The PI section line only shows two poles because it consists of two PI sections. Impedance comparison shows that a two-section PI line gives a good approximation of the distributed line for the 0 to 350 Hz frequency range.
References


See Also

PI Section Line reference section
**Purpose**

Perform a Park transformation from the dq0 reference frame to the abc reference frame

**Library**

Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

**Description**

The dq0_to_abc Transformation block performs the reverse of the so-called Park transformation, which is commonly used in three-phase electric machine models. It transforms three quantities (direct axis, quadratic axis, and zero-sequence components) expressed in a two-axis reference frame back to phase quantities. The following transformation is used:

\[
\begin{align*}
V_a &= V_d \sin(\omega t) + V_q \cos(\omega t) + V_0 \\
V_b &= V_d \sin(\omega t - 2\pi/3) + V_q \cos(\omega t - 2\pi/3) + V_0 \\
V_c &= V_d \sin(\omega t + 2\pi/3) + V_q \cos(\omega t + 2\pi/3) + V_0
\end{align*}
\]

where

\[\omega = \text{rotation speed (rad/s) of the rotating frame}\]

The transformation is the same for the case of a three-phase current; you simply replace the \(V_a, V_b, V_c, V_d, V_q,\) and \(V_0\) variables with the \(I_a, I_b, I_c, I_d, I_q,\) and \(I_0\) variables.

The dq0_to_abc Transformation block is used in the model of the Synchronous Machine block where the stator quantities are referred to the rotor. The Park transformation then eliminates time-varying inductances by referring the stator and rotor quantities to a fixed or rotating reference frame. The \(I_q\) and \(I_d\) currents represent the two DC currents flowing in the two equivalent rotor windings (d winding on the same axis as the field winding, and q winding in quadratic) producing the same flux as the stator \(I_a, I_b,\) and \(I_c\) currents.
**dq0_to_abc Transformation**

**Dialog Box and Parameters**

The block transforms three quantities (direct axis, quadrature axis and zero-sequence components), expressed in a two-axis reference frame, back to phase quantities.

The following transformation is used:

\[
\begin{align*}
V_a &= V_d \sin(\omega t) + V_q \cos(\omega t) + V_0 \\
V_b &= V_d \sin(\omega t + 2\pi/3) + V_q \cos(\omega t + 2\pi/3) + V_0 \\
V_c &= V_d \sin(\omega t + 2\pi/3) + V_q \cos(\omega t + 2\pi/3) + V_0 
\end{align*}
\]

where \(\omega\) is the rotation speed \((\omega/2\pi)\) of the rotating frame.

**Inputs and Outputs**

- **dq0**
  - Connect to the first input a vectorized signal containing the sequence components \([d q 0]\) to be converted.

- **sin_cos**
  - Connect to the second input a vectorized signal containing the \([\sin(\omega t) \cos(\omega t)]\) values, where \(\omega\) is the rotation speed of the reference frame.

- **abc**
  - The output is a vectorized signal containing the three-phase sinusoidal quantities \([\text{phase A phase B phase C}]\).

**Example**

See the demo of the abc_to_dq0 Transformation block for an example using the dq0_to_abc Transformation block.

**See Also**

abc_to_dq0 Transformation reference section
DTC Induction Motor Drive

Purpose
Implement a direct torque and flux control (DTC) induction motor drive model

Library
Electric Drives/AC drives

Description
The high-level schematic shown below is built from six main blocks. The induction motor, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPowerSystems library. More details on these three blocks are available in the SimPowerSystems user guide. The speed controller, the braking chopper, and the DTC controller models are specific to the drive library.

AC4 Motor Drive High-level Schematic
The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the DTC controller block.

**Speed PI Regulator Schematic**

- Flux function
- Torque limiter
- Integral gain
- Limited integrator
- Proportional gain
- First-order low-pass filter
DTC Induction Motor Drive

DTC Controller  The DTC controller contains five main blocks, shown below. These blocks are described below.

DTC controller

Direct Torque and Flux Control (DTC) Schematic

The Torque & Flux calculator block is used to estimate the motor flux αβ components and the electromagnetic torque. This calculator is based on motor equation synthesis.

The αβ vector block is used to find the sector of the αβ plane in which the flux vector lies. The αβ plane is divided into six different sectors spaced by 60 degrees.

The Flux & Torque Hysteresis blocks contain a two-level hysteresis comparator for flux control and a three-level hysteresis comparator for the torque control. The description of the hysteresis comparators is available below.

The Switching table block contains two lookup tables that select a specific voltage vector in accordance with the output of the Flux & Torque Hysteresis comparators. This block also produces the initial flux in the machine.

The Switching control block is used to limit the inverter commutation frequency to a maximum value specified by the user.
Braking Chopper

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

Remarks

The model is discrete. Good simulation results have been obtained with a 1 μs time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The D.T.C. controller sampling time

The speed controller sampling time has to be a multiple of the D.T.C. sampling time. The latter sampling time has to be a multiple of the simulation time step.
The asynchronous machine tab displays the parameters of the asynchronous machine block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the asynchronous machine parameters.
Converters and DC Bus Tab

The rectifier section of the Converters and DC Bus tab displays the parameters of the rectifier block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the rectifier parameters.

Inverter Section

The inverter section of the Converters and DC Bus tab displays the parameters of the Inverter block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the inverter parameters.
**DC-Bus Capacitance**

The DC bus capacitance (F).

**Braking Chopper section**

**Resistance**

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor (Ω).

**Frequency**

The braking chopper frequency (Hz).

**Activation Voltage**

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band. The following figure illustrates the braking chopper hysteresis logic.

**Deactivation Voltage**

The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band.

---

**Chopper Hysteresis Logic**
Controller Tab

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

Regulation Type
This switch allows you to choose between speed and torque regulation.

Speed Controller section

Speed Sensor Cutoff Frequency
The speed measurement first-order low-pass filter cutoff frequency (Hz).

Speed Controller Sampling Time
The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.
DTC Induction Motor Drive

Acceleration
The maximum change of speed allowed during motor acceleration. An excessively large positive value can cause DC bus under-voltage (rpm/s).

Deceleration
The maximum change of speed allowed during motor deceleration. An excessively large negative value can cause DC bus over-voltage (rpm/s).

Proportional Gain
The speed controller proportional gain.

Integral Gain
The speed controller integral gain.

Torque Output Limits — Negative
The maximum negative demanded torque applied to the motor by the DTC controller (N.m).

Torque Output Limits — Positive
The maximum positive demanded torque applied to the motor by the DTC controller (N.m).

DTC Controller section

Maximum Switching Frequency
The maximum inverter switching frequency (Hz).

Initial Machine Flux
The desired initial stator flux established before the DTC drive module begins to produce an electromagnetic torque. This flux is produced by applying a constant voltage vector at the motor terminals (Wb).

DTC Sampling Time
The DTC controller sampling time (s). The sampling time must be a multiple of the simulation time step.

Hysteresis Bandwidth — Torque
The torque hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the torque set point (N.m). The following figure illustrates a case where the torque set point is $T_e^*$ and the torque hysteresis bandwidth is set to $dT_e$. 
The stator flux hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the flux set point (Wb). The following figure illustrates a case where the flux set point is $\psi^*$ and the torque hysteresis bandwidth is set to $d\psi$. 
**Inputs**
The block has five inputs: A, B, C, SP, and Mec_T.

The A, B, and C inputs are the three-phase incoming power.

The fourth input is the speed or torque set point, and the fifth input is the mechanical load torque.

Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

**Outputs**
The block has three output vectors: Motor, Conv., and Ctrl.

The first is the motor vector. This vector allows you to observe the motor’s variables using the SimPowerSystems motor demux.

The second output is the three-phase converters measurement vector. This vector includes:
- The DC bus voltage
- The rectifier output current
- The inverter input current

Note that all current and voltage values of the bridges can be visualized with the multimeter block (refer to the multimeter user note).

The third output is the controller vector. This vector contains the values of:
- The torque reference
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp or torque reference
Model Specifications

The library contains a 3 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 3 HP Drive Specifications

<table>
<thead>
<tr>
<th>Drive Input Voltage</th>
<th>3 HP Drive</th>
<th>200 HP Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>220 V</td>
<td>460 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
<td>60 Hz</td>
</tr>
</tbody>
</table>

### Motor Nominal Values

<table>
<thead>
<tr>
<th>Power</th>
<th>3 hp</th>
<th>200 hp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>1705 rpm</td>
<td>1785 rpm</td>
</tr>
<tr>
<td>Voltage</td>
<td>220 V</td>
<td>460 V</td>
</tr>
</tbody>
</table>

Example

The following figure illustrates an AC4 motor drive simulation with standard load condition. At time $t = 0$ s, the speed set point is 500 rpm.

AC4 Example Schematic

As shown in the following figure, the speed precisely follows the acceleration ramp. At $t = 0.5$ s, the nominal load torque is applied to the motor. At $t = 1$ s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At $t = 1.5$ s, the mechanical load passes from 792 N.m to -792 N.m.
DTC Induction Motor Drive

AC4 Example Waveforms

References


**Purpose**
Provide an excitation system for the synchronous machine and regulate its terminal voltage in generating mode.

**Library**
Machines

**Description**
The Excitation System block is a Simulink system implementing a DC exciter described in [1], without the exciter's saturation function. The basic elements that form the Excitation System block are the voltage regulator and the exciter.

The exciter is represented by the following transfer function between the exciter voltage $V_{fd}$ and the regulator's output $ef$:

$$\frac{V_{fd}}{ef} = \frac{1}{Ke + sTe}$$
Excitation System

Dialog Box and Parameters

![Dialog Box Image]

- **Low-pass filter time constant**
  The time constant $T_r$, in seconds (s), of the first-order system that represents the stator terminal voltage transducer.

- **Regulator gain and time constant**
  The gain $K_a$ and time constant $T_a$, in seconds (s), of the first-order system representing the main regulator.

- **Exciter**
  The gain $K_e$ and time constant $T_e$, in seconds (s), of the first-order system representing the exciter.
Transient gain reduction
The time constants \( T_b \) in seconds (s), and \( T_c \) in seconds (s), of the first-order system representing a lead-lag compensator.

Damping filter gain and time constant
The gain \( K_f \) and time constant \( T_f \) in seconds (s), of the first-order system representing a derivative feedback.

Regulator output limits and gain
Limits \( E_{fmin} \) and \( E_{fmax} \) are imposed on the output of the voltage regulator. The upper limit can be constant and equal to \( E_{fmax} \), or variable and equal to the rectified stator terminal voltage \( Vtf \) times a proportional gain \( K_p \). If \( K_p \) is set to 0, the former applies. If \( K_p \) is set to a positive value, the latter applies.

Initial values of terminal voltage and field voltage
The initial values of terminal voltage \( V_{t0} \) (p.u.) and field voltage \( V_{f0} \) (p.u.). When set correctly, they allow you to start the simulation in steady state. Initial terminal voltage should normally be set to 1 p.u. Both \( V_{t0} \) and \( V_{f0} \) values are automatically updated by the load flow utility of the Powergui block.

Example
See the Hydraulic Turbine and Governor block.

Inputs and Outputs

\( v_{ref} \)
The desired value, in p.u., of the stator terminal voltage.

\( v_d \)
\( v_d \) component, in p.u., of the terminal voltage.

\( v_q \)
\( v_q \) component, in p.u., of the terminal voltage.

\( v_{stab} \)
Connect this input to a power system stabilizer to provide additional stabilization of power system oscillations.

\( V_f \)
The field voltage, in p.u., for the Synchronous Machine block.
**Excitation System**

**References**


**See Also**

Generic Power System Stabilizer reference section, Hydraulic Turbine and Governor reference section, Multiband Power System Stabilizer reference section, Steam Turbine and Governor reference section, Synchronous Machine reference section
Field-Oriented Control Induction Motor Drive

**Purpose**
Implement a field oriented control (F.O.C.) induction motor drive model

**Library**
Electric Drives/AC drives

**Description**
The high-level schematic shown below is built from six main blocks. The induction motor, the three-phase inverter, and the three-phase diode rectifier models are from blocks provided in the SimPowerSystems library. The speed controller, the braking chopper, and the F.O.C. models are from blocks provided in the Electric Drives library.

**High-Level Schematic**

![AC3 Motor Drive High-Level Schematic](attachment:image.png)
Field-Oriented Control Induction Motor Drive

Simulink Schematic

AC3 Motor Drive Simulink Schematic

The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the FOC controller block.

Speed Controller

Speed controller

Speed PI Regulator Schematic
Field-Oriented Control Induction Motor Drive

Field Oriented Controller

The F.O.C. contains eleven main blocks, shown below. These blocks are described below.

Indirect Vector Control Simulink Schematic

The $\psi_r$ calculation block is used to estimate the motor’s rotor flux. This calculation is based on motor equation synthesis.

The $\theta_e$ calculation block is used to find the phase angle of the rotor flux rotating field.

The $abc$-$dq$ block performs the conversion of $abc$ phase variables into $dq$ components of the rotor flux rotating field reference frame.

The $dq$-$abc$ block performs the conversion of the $dq$ component of the rotor flux rotating field reference frame into $abc$ phase variables.
The \textit{iqs*calculation} block uses the calculated rotor flux and the torque reference to compute the stator current quadrature component required to produce the electromagnetic torque on the motor’s shaft.

The \textit{ids*calculation} block uses the rotor flux reference to compute the stator current direct component required to produce the rotor flux in the machine.

The \textit{current regulator} is a bang-bang current controller with adjustable hysteresis band width.

The \textit{switching control} block is used to limit the inverter commutation frequency to a maximum value specified by the user.

The \textit{flux controller} is used to control the flux dynamics and to reduce the steady-state flux error.

The \textit{magnetization vector} unit contains the vector used to create the motor initial flux.

The \textit{magnetization control} unit contains the logic used to switch between the magnetization and normal operation mode.

\textbf{Braking Chopper} The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

\textbf{Remarks} The model is discrete. Good simulation results have been obtained with a 1 $\mu$s time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The F.O.C. controller sampling time

The speed controller sampling time has to be a multiple of the F.O.C. sampling time. The latter sampling time has to be a multiple of the simulation time step.
The asynchronous machine tab displays the parameters of the asynchronous machine block of the powerlib library. Refer to the SimPowerSystem user guide for more information on the asynchronous machine parameters.
Converters and DC Bus Tab

Rectifier section
The rectifier section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the universal bridge parameters.

Inverter section
The inverter section of the Converters and DC bus tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the universal bridge parameters.
Field-Oriented Control Induction Motor Drive

**DC Bus Field — Capacitance**
The DC bus capacitance (F).

**Braking Chopper section**

**Resistance**
The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor (Ω).

**Frequency**
The braking chopper frequency (Hz).

**Activation Voltage**
The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band (V). The following figure illustrates the braking chopper hysteresis logic.

**Deactivation Voltage**
The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band (V).

![Chopper Hysteresis Logic](image)
Controller Tab

Field-Oriented Control Induction Motor Drive

The AC motor parameters are specified in the AC Machine tab. The braking chopper, the diode rectifier, and the inverter switching parameters are specified in the Converter and DC bus tab. F.O.C. and speed controller parameters are specified in the Controller tab.

<table>
<thead>
<tr>
<th>Regulation type</th>
<th>Speed regulator</th>
<th>Schematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asynchronous Machine</td>
<td>Converters and DC bus</td>
<td>Controller</td>
</tr>
</tbody>
</table>

**Speed controller**

<table>
<thead>
<tr>
<th>Speed range (rpm)</th>
<th>Acceleration</th>
<th>Deceleration</th>
<th>Speed cutoff frequency (Hz)</th>
<th>Speed controller sampling time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>0.03</td>
<td>0.007s</td>
</tr>
</tbody>
</table>

**PI regulator**

<table>
<thead>
<tr>
<th>Proportional gain</th>
<th>Integral gain</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
<td>-12.8</td>
<td>17.8</td>
</tr>
</tbody>
</table>

**Machine flux (We)**

<table>
<thead>
<tr>
<th>Initial</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Field-oriented control**

<table>
<thead>
<tr>
<th>Flux controller</th>
<th>Proportional gain</th>
<th>Integral gain</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
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<td>50</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current controller</th>
<th>Hysteresis band (A)</th>
<th>Maximum switching frequency (Hz)</th>
<th>Lowpass filter cutoff frequency (Hz)</th>
<th>Sampling time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>50</td>
<td>300</td>
<td>500</td>
<td>20</td>
</tr>
</tbody>
</table>

**Parameters file options**

[OK]  [Cancel]  [Help]  [Apply]
**Field-Oriented Control Induction Motor Drive**

**Regulation Type**
This pop-up menu allows you to choose between speed and torque regulation.

**Schematic Button**
When you press this button, a diagram illustrating the speed and current controllers schematics appears.

**Speed Controller section**

**Speed Sensor Cutoff Frequency**
The speed measurement first-order low-pass filter cutoff frequency (Hz).

**Sampling Time**
The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

**Speed Ramps — Acceleration**
The maximum change of speed allowed during motor acceleration. An excessively large positive value can cause DC bus under-voltage (rpm/s).

**Speed Ramps — Deceleration**
The maximum change of speed allowed during motor deceleration. An excessively large negative value can cause DC bus over-voltage (rpm/s).

**Proportional Gain**
The speed controller proportional gain.

**Integral Gain**
The speed controller integral gain.

**Output Limits — Negative**
The maximum negative demanded torque applied to the motor by the F.O.C. controller (Nm).

**Output Limits — Positive**
The maximum positive demanded torque applied to the motor by the F.O.C. controller (Nm).
Field-Oriented Control Induction Motor Drive

F.O.C. section

Maximum Switching Frequency
The maximum inverter switching frequency (Hz).

Initial Machine Flux
The desired initial rotor flux established before the F.O.C. module begins to produce an electromagnetic torque. Create this flux by applying a modulated voltage vector at the motor terminals (Wb).

Sampling Time
The F.O.C. controller sampling time (s). The sampling time must be a multiple of the simulation time step.

Hysteresis Bandwidth — Current
The current hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the current set point (A). The following figure illustrates a case where the current set point is Is and the current hysteresis bandwidth is set to dx.

Torque Hysteresis Bandwidth

Flux Controller Section
Proportional Gain
The flux controller proportional gain.

Integral Gain
The flux controller integral gain.

First-Order Low-Pass Cutoff Frequency
The flux estimation first-order filter cutoff frequency (Hz).

Output Limit — Positive
The flux controller maximum positive output (Wb).
Output Limit — Negative

The flux controller maximum negative output (Wb).

Block Inputs and Outputs

Inputs

The block has five inputs: A, B, C, SP, and Mec_T.

The A, B, and C inputs are the three-phase incoming power.

The fourth input is the speed or torque set point, and the fifth input is the mechanical load torque.

Note that the speed set point can be a step function, but the speed change rate will follow the acceleration / deceleration ramps. If the values of the load torque and speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

Outputs

The block has three output vectors: Motor, Conv., and Ctrl.

The first is the motor vector. This vector allows you to observe the motor's variables using the SimPowerSystems motor demux.

The second output is the three-phase converters measurement vector. This vector includes

- The DC bus voltage
- The rectifier output current
- The inverter input current

Note that all current and voltage values of the bridges can be visualized with the multimeter block (refer to the multimeter user note).

The third output is the controller vector. This vector contains the values of

- The torque reference
- The speed error (difference between the speed reference ramp and actual speed)
- The speed reference ramp or torque reference
Field-Oriented Control Induction Motor Drive

Model Specifications

The library contains a 3 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 3 HP and 200 HP Drive Specifications

<table>
<thead>
<tr>
<th>Drive Input Voltage</th>
<th>3 HP Drive</th>
<th>200 HP Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>220 V</td>
<td>460 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
<td>60 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motor Nominal Values</th>
<th>3 HP Drive</th>
<th>200 HP Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>3 hp</td>
<td>200 hp</td>
</tr>
<tr>
<td>Speed</td>
<td>1705 rpm</td>
<td>1785 rpm</td>
</tr>
<tr>
<td>Voltage</td>
<td>220 V</td>
<td>460 V</td>
</tr>
</tbody>
</table>

Example

The following figure illustrates an AC3 motor drive simulation with standard load conditions. At time t = 0 s, the speed set point is 500 rpm.

AC3 Example Schematic

As shown in the following figure, the speed precisely follows the acceleration ramp. At t = 0.5 s, the nominal load torque is applied to the motor. At t = 1 s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At t = 1.5 s, the mechanical load passes from 792 N.m to -792 N.m.
Field-Oriented Control Induction Motor Drive

AC3 Example Waveforms

References


Purpose
Perform a Fourier analysis of a signal

Library
Extras/Measurements

A discrete version of this block is available in the Extras/Discrete Measurements library.

Description
The Fourier block performs a Fourier analysis of the input signal over a running window of one cycle of the fundamental frequency of the signal. The Fourier block can be programmed to calculate the magnitude and phase of the DC component, the fundamental, or any harmonic component of the input signal.

Recall that a signal \( f(t) \) can be expressed by a Fourier series of the form

\[
f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n \omega t) + b_n \sin(n \omega t)
\]

where \( n \) represents the rank of the harmonics (\( n = 1 \) corresponds to the fundamental component). The magnitude and phase of the selected harmonic component are calculated by the following equations:

\[
|H_n| = \sqrt{\frac{a_n^2}{2} + \frac{b_n^2}{2}} \quad \angle H_n = \arctan\left(\frac{b_n}{a_n}\right)
\]

where

\[
a_n = \frac{2}{T} \int_{(t-T)}^{t} f(t)\cos(n \omega t)dt \\
b_n = \frac{2}{T} \int_{(t-T)}^{t} f(t)\sin(n \omega t)dt
\]

\[
T = \frac{1}{f_1}; \quad f_1: \text{Fundamental frequency}
\]

As this block uses a running average window, one cycle of simulation has to be completed before the outputs give the correct magnitude and angle. The discrete version of this block allows you to specify the initial magnitude and phase of the output signal. For the first cycle of simulation the outputs are held to the values specified by the initial input parameter.
**Fourier**

**Dialog Box and Parameters**

![Block Parameters: Fourier](image)

The Fourier block performs a Fourier analysis of the input signal over a running window of one cycle of the fundamental frequency. First and second outputs return respectively the magnitude and phase (degrees) of the harmonic component specified.

**Parameters**

- **Fundamental frequency f1** (Hz): Enter the fundamental frequency, in hertz, of the input signal.
- **Harmonic n (0 = DC; 1 = fundamental; 2 = 2nd harm; etc.)**: Specify the harmonic component you want to perform the Fourier analysis. Enter 0 if you want to analyze the DC component. Enter 1 if you want to analyze the fundamental frequency, or enter a number corresponding to the desired harmonic.

**Inputs and Outputs**

- **signal**: Connect to the signal to be analyzed. Typical input signals are voltages or currents measured by Current Measurement blocks or Voltage Measurement blocks.
- **magnitude**: The first output returns the magnitude of the harmonic component specified, in the same units as the input signal.
- **phase**: The second output returns the phase, in degrees, of the harmonic component specified.

**Example**

The `power_transformer` demo shows the energization of a 450 MVA three-phase transformer on a 500 kV network. The power system is simulated by an
equivalent circuit consisting of an inductive source having a short-circuit power of 3000 MVA and a parallel RC load.

The load capacitance is set to produce a resonance at 240 Hz (fourth harmonic). A Fourier block is used to measure the fourth harmonic content of phase A of the primary voltage.
The Fourier block measures a high level fourth harmonic in the voltage (on the second trace of Scope1) because of the fourth harmonic content of the current injected into the network resonating at that particular frequency (240 Hz).
Four-Quadrant Chopper DC Drive

**Purpose**
Implement a four-quadrant chopper DC drive

**Library**
Electric Drives/DC drives

**Description**
The high-level schematic shown below is built from four main blocks. The DC motor and the IGBT/Diode devices (within the Universal Bridge block) are provided with the SimPowerSystems library. More details on these two blocks are available in the SimPowerSystems user guide. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled.

**High-Level Schematic**

![DC Motor Drive High-Level Schematic](image-url)
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in p.u.) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system.

The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user.
The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate duty ratios of the fixed frequency pulses of the four IGBT devices (Pulse Width Modulation). This generates the average armature voltage needed to obtain the desired armature current and thus the desired electromagnetic torque. For proper system behavior, the instantaneous pulse values of IGBT devices 1 and 4 are the opposite of those of IGBT devices 2 and 3.

The controller takes the current reference (in p.u.) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block. The armature current input is filtered by a first-order low-pass filter.

The pulse width modulation is obtained by comparison of the PI output and a fixed frequency sawtooth carrier signal (as shown in the figure called “Pulse Width Modulation (PWM)” on page 7-116).
Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by an IGBT converter controlled by two PI regulators. The converter is fed by a constant DC voltage source. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The model is discrete. Good simulation results have been obtained with a 1 µs time step. In order to simulate a digital controller device, the control system has two different sampling times:

- The speed controller sampling time
- The current controller sampling time

The speed controller sampling time has to be a multiple of the current sampling time. The latter sampling time has to be a multiple of the simulation time step.
Four-Quadrant Chopper DC Drive

Pulse Width Modulation (PWM)
The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the DC machine block parameters.
**IGBT/Diode Devices section**

The IGBT/Diode section of the Converter tab displays the parameters of the Universal Bridge block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the Universal Bridge block parameters.

**Smoothing Inductance**

The smoothing inductance value (H).

**Field DC Source**

The DC motor field voltage value (V).
Controller Tab

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

Regulation Type
This pop-up menu allows you to choose between speed and torque regulation.

Controller - Speed Controller Subtab
Nominal Speed
The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to p.u. (per unit).

Initial Speed Reference
The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.
Four-Quadrant Chopper DC Drive

**Low-Pass Filter Cutoff Frequency**
Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

**Sampling Time**
The speed controller sampling time (s). This sampling time has to be a multiple of the current controller sampling time and of the simulation time step.

**Proportional Gain**
The proportional gain of the PI speed controller.

**Integral Gain**
The integral gain of the PI speed controller.

**Acceleration**
The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

**Deceleration**
The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.
Controller - Current Controller Subtab

Low-Pass Filter Cutoff Frequency
Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).

Symmetrical Reference Limit
Symmetrical current reference (p.u.) limit around 0 p.u. 1.5 p.u. is a common value.

PWM Switching Frequency
The switching frequency of the four IGBT devices (Hz).

Sampling Time
The current controller sampling time (s). This sampling time has to be a submultiple of the speed controller sampling time and a multiple of the simulation time step.
**Four-Quadrant Chopper DC Drive**

**Power and Voltage nominal values**

The DC motor nominal power (W) and voltage (V) values. These values are used to convert armature current from amperes to p.u. (per unit).

**Proportional Gain**

The proportional gain of the PI current controller.

**Integral Gain**

The integral gain of the PI current controller.

**Block Inputs and Outputs**

**Inputs**

The block has four inputs: SP, Mec_T, Vcc, and Gnd.

The first input is the speed (rpm) or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration/deceleration ramps.

The second input is the mechanical load torque. If the values of the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

The two last inputs, Vcc and Gnd, are the DC voltage source electric connections. The voltage must be adequate for the motor size.

**Outputs**

The block has three output vectors: Motor, Conv., and Ctrl.

The first output is the motor vector. This vector is composed of two elements:

- The armature voltage
- The DC motor “m” vector (containing the speed, armature current, field current, and electromagnetic torque values)

Note that the speed of the “m” vector is converted from rad/s to rpm before output.

The second output is the IGBT/Diode devices measurement vector. This vector includes the converter output voltage. The output current is not included since it is equal to the DC motor armature current. Note that all current and voltage values of the converter can be visualised with the multimeter block (refer to the multimeter user note).
The third output is the controller vector. This vector contains the values of

- The armature current reference
- The duty cycles of the four PWM pulses
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

The library contains a 5 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 5 HP and 200 HP Drive Specifications

<table>
<thead>
<tr>
<th></th>
<th>5 HP Drive</th>
<th>200 HP Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drive Input Voltage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude</td>
<td>280 V</td>
<td>500 V</td>
</tr>
<tr>
<td><strong>Motor Nominal Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>5 hp</td>
<td>200 hp</td>
</tr>
<tr>
<td>Speed</td>
<td>1750 rpm</td>
<td>1184 rpm</td>
</tr>
<tr>
<td>Voltage</td>
<td>240 V</td>
<td>440 V</td>
</tr>
</tbody>
</table>
Four-Quadrant Chopper DC Drive

Example

DC7 Example Schematic

This example illustrates the four-quadrant chopper drive used with the 200 hp drive parameter set during speed regulation. A 5 hp parameter set is also available in the library.

The converter is fed by a 515 V DC bus obtained by rectification of a 380 V AC 50 Hz voltage source. In order to limit the DC bus voltage during dynamic braking mode, a braking chopper has been added between the diode rectifier and the DC7 block. The IGBT switching frequency is 5 kHz.

The motor is coupled to a linear load, which means that the mechanical torque of the load is proportional to the speed.

The speed reference is set at 500 rpm at $t = 0\ s$. Observe that the motor speed follows the reference ramp accurately (+400 rpm/s) and reaches steady state around $t = 1.3\ s$.

The armature current follows the current reference very well, with fast response time and small ripples. Notice that the current ripple frequency is 5 kHz.

At $t = 2\ s$, speed reference drops to -1184 rpm. The current reference decreases to reduce the electromagnetic torque and causes the motor to decelerate with the help of the load torque.
At $t = 2.2$ s, the current reverses in order to produce a braking electromagnetic torque (dynamic braking mode). This causes the DC bus voltage to increase.

At $t = 3.25$ s, the motor reaches 0 rpm and the load torque reverses and becomes negative. The negative current now produces an accelerating electromagnetic torque to allow the motor to follow the negative speed ramp (-400 rpm/s). At $t = 6.3$ s, the speed reaches -1184 rpm and stabilizes around its reference.

The following figure shows the DC bus voltage, armature current, and speed waveforms.

**DC7 Example — DC Bus Voltage, Current, and Speed Waveforms**

The next figure shows the duty cycles of the chopper pulses and the corresponding armature voltage and current waveforms during a time interval of 2 ms.
Four-Quadrant Chopper DC Drive

DC7 Example — Duty Cycles, Armature Voltage, and Current Waveforms

References


Four-Quadrant Single-Phase Rectifier DC Drive

Purpose
Implement a single-phase dual-converter DC drive with circulating current

Library
Electric Drives/DC drives

Description
The high-level schematic shown below is built from six main blocks. The DC motor, the two single-phase full converters, and the bridge firing unit are provided with the SimPowerSystems library. More details on these blocks are available in the SimPowerSystems user guide. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled.

High-Level Schematic

DC2 Motor Drive High-Level Schematic
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in p.u.) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user.
The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angles of the two full converters. This generates the converter output voltages needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in p.u.) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block.

The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system. The firing angle can vary between 0 and 180 degrees. You can limit the lower and upper limits to intermediate values.

Both converters operate simultaneously, and the two firing angles are controlled so that the sum of their values stays equal to 180 degrees. This produces opposite average voltages at the converter DC output terminals and thus identical average voltages at the DC motor armature, the converters being connected in antiparallel. One converter is working in rectifier mode while the other is in inverter mode.
Bridge Firing Unit

The bridge firing unit converts the firing angles, provided by the current controller, to two series of four pulses applied respectively to the thyristor gates of each converter. The bridge firing unit block contains a band-pass filter on voltage measurement to remove voltage harmonics. Two discrete synchronized pulse generator blocks generate the pulses of each converter. Their architecture is based on the Discrete Synchronized 6-Pulse Generator block from SimPowerSystems. Refer to the SimPowerSystems user guide for more information on this block.

Remarks

The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by two single-phase antiparallel-connected converters controlled by two PI regulators. The circulating current produced by the instantaneous voltage difference at the terminal of both converters is limited by inductors connected between these terminals. Armature current oscillations are reduced by a smoothing inductance connected in series with the armature circuit.

The model is discrete. Good simulation results have been obtained with a 4 µs time step. The control system (speed and current controllers) samples data following a user-defined sample time in order to simulate a digital controller.
device. Keep in mind that this sampling time has to be a multiple of the simulation time step.
The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the DC machine block parameters.
**Four-Quadrant Single-Phase Rectifier DC Drive**

## Converter Tab

![Converter Tab Diagram](image)

### Smoothing Inductance
The smoothing inductance value (H).

### Field DC Source
The DC motor field voltage value (V).

### Circulating Current Inductors
The four circulating current inductors inductance value (H).

### Converter sections
The Converter 1 and Converter 2 sections of the Converter tab display the parameters of the Universal Bridge block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the Universal Bridge block parameters.
**Four-Quadrant Single-Phase Rectifier DC Drive**

**Controller Tab**

![Controller Tab Schematic](image)

Schematic Button
When you press this button, a diagram illustrating the speed and current controllers schematics appears.

Regulation Type
This pop-up menu allows you to choose between speed and torque regulation.

Sampling Time
The controller (speed and current) sampling time (s). The sampling time has to be a multiple of the simulation time step.

Controller - Speed Controller Subtab

Nominal Speed
The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to p.u. (per unit).
Four-Quadrant Single-Phase Rectifier DC Drive

Initial Speed Reference
The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

Low-Pass Filter Cutoff Frequency
Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

Proportional Gain
The proportional gain of the PI speed controller.

Integral Gain
The integral gain of the PI speed controller.

Acceleration
The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

Deceleration
The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.
Controller - Current Controller Subtab

![Current Controller Subtab](image)

**Power and Voltage nominal values**

The DC motor nominal power (W) and voltage (V) values.

The nominal power and voltage values are used to convert armature current from amperes to p.u. (per unit).

**Proportional Gain**

The proportional gain of the PI current controller.

**Integral Gain**

The integral gain of the PI current controller.

**Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).
Symmetrical Reference Limit
Symmetrical current reference (p.u.) limit around 0 p.u. 1.5 p.u. is a common value.

Controller - Bridge Firing Unit Subtab

Alpha Min
Minimum firing angle value (deg.). 20 degrees is a common value.

Alpha Max
Maximum firing angle value (deg.). 160 degrees is a common value.
Four-Quadrant Single-Phase Rectifier DC Drive

**Frequency of Synchronization Voltages**
Frequency of the synchronization voltages used by the discrete synchronized pulse generator block (Hz). This frequency is equal to the line frequency of the single-phase power line.

**Pulse Width**
The width of the pulses applied to the thyristor gates (deg.).

### Block Inputs and Outputs

#### Inputs
The block has four inputs: SP, Mec_T, A+, and A-.

The first input is the speed (rpm) or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration/deceleration ramps.

The second input is the mechanical load torque. If the values of the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

The last inputs, A+ and A-, are the single-phase electric connections. The voltage must be adequate for the motor size.

#### Outputs
The block has three output vectors: Motor, Conv., and Ctrl.

The first output is the motor vector. This vector is composed of two elements:

- The armature voltage
- The DC motor “m” vector (containing the speed, armature current, field current, and electromagnetic torque values)

Note that the speed of the “m” vector is converted from rad/s to rpm before output.

The second output is the single-phase converter measurement vector. This vector includes:

- The output voltage of converter 1
- The output voltage of converter 2
- The output current of converter 1
- The output current of converter 2
Four-Quadrant Single-Phase Rectifier DC Drive

Note that all current and voltage values of the bridges can be visualised with the mulimeter block (refer to the multimeter user note).

The third output is the controller vector. This vector contains the values of

- The armature current reference
- The firing angle computed by the current controller
- The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)
- The speed reference ramp or torque reference

Model Specifications

The library contains a 5 hp drive parameter set. The specifications of the 5 hp drive are shown in the following table.

5 HP Drive Specifications

<table>
<thead>
<tr>
<th>Drive Input Voltage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>320 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motor Nominal Values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>5 hp</td>
</tr>
<tr>
<td>Speed</td>
<td>1750 rpm</td>
</tr>
<tr>
<td>Voltage</td>
<td>240 V</td>
</tr>
</tbody>
</table>
Example

DC2 Example Schematic

This example illustrates the single-phase dual-converter drive used with the 5 hp drive parameter set during speed regulation.

The converters are fed by a 230 V AC 60 Hz voltage source followed by a linear transformer to boost the voltage to a sufficient value.

During this simulation, the motor is coupled to a linear load, which means that the mechanical torque produced by the load is proportional to the speed.

The speed reference is set at 1200 rpm at t = 0 s. Observe that the firing angles are symmetrical around 90 degrees and that the converter average output DC voltages are of opposite signs. The armature current is supplied by converter 1, and the total current in this converter is the sum of load current and circulating current. Converter 2 simply carries the circulating current.

Observe that the motor speed follows the reference ramp accurately (+250 rpm/s) and reaches steady state after 5.5 s. The armature current follows the current reference very well and stabilizes around 12 A.

At t = 6 s, speed reference drops to -600 rpm. The current reference decreases to reduce the electromagnetic torque, and the load torque causes the motor to decelerate. Around t = 8.5 s, the armature current becomes negative and the
electromagnetic torque reverses in order to brake the motor down to 0 rpm, the load torque being insufficient to decelerate the motor. The armature current is now provided by converter 2, converter 1 only handling the circulating current. At $t = 10.8$ s, the motor reaches 0 rpm and the load torque becomes negative. The electromagnetic torque now produces an accelerating torque to allow the motor to follow the negative speed ramp (-250 rpm/s). The armature current is now provided by converter 2, converter 1 only handling the circulating current. At $t = 14$ s, speed stabilizes at -600 rpm.
Four-Quadrant Single-Phase Rectifier DC Drive

DC2 Example Waveforms

References

Four-Quadrant Three-Phase Rectifier DC Drive

**Purpose**
Implement a three-phase dual-converter DC drive with circulating current

**Library**
Electric Drives/DC drives

**Description**
The high-level schematic shown below is built from six main blocks. The DC motor, the two three-phase full converters, and the bridge firing unit are provided with the SimPowerSystems library. More details on these blocks are available in the SimPowerSystems user guide. The two other blocks are specific to the Electric Drives library. These blocks are the speed controller and the current controller. They allow speed or torque regulation. A “regulation switch” block allows you to toggle from one type of regulation to the other. During torque regulation the speed controller is disabled.

![DC Motor Drive High-Level Schematic](image)
The speed regulator shown below uses a PI controller. The controller outputs the armature current reference (in p.u.) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

The current reference output is limited between symmetrical lower and upper limits defined by the user.
Four-Quadrant Three-Phase Rectifier DC Drive

### Speed Controller Schematic

The armature current regulator shown below is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angles of the two full converters. This generates the converter output voltages needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in p.u.) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the “regulation switch” block.

The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system. The firing angle can vary between 0 and 180 degrees. You can limit the lower and upper limits to intermediate values.

Both converters operate simultaneously, and the two firing angles are controlled so that the sum of their values stays equal to 180 degrees. This produces opposite average voltages at the converter DC output terminals and thus identical average voltages at the DC motor armature, the converters being connected in antiparallel. One converter is working in rectifier mode while the other is in inverter mode.
Four-Quadrant Three-Phase Rectifier DC Drive

Current Controller Schematics

Bridge Firing Unit
The bridge firing unit converts the firing angles, provided by the current controller, to two series of six pulses applied respectively to the thyristor gates of each converter. The bridge firing unit block contains a band-pass filter on voltage measurement to remove voltage harmonics. Two Discrete Synchronized 6-Pulse Generator blocks from SimPowerSystems generate the pulses. Refer to the SimPowerSystems user guide for more information on this block.

Remarks
The machine is separately excited with a constant DC field voltage source. There is thus no field voltage control. By default, the field current is set to its steady-state value when a simulation is started.

The armature voltage is provided by two three-phase antiparallel-connected converters controlled by two PI regulators. The circulating current produced by the instantaneous voltage difference at the terminal of both converters is limited by inductors connected between these terminals. No smoothing inductance is placed in series with the armature circuit, the armature current oscillations being quite small due to the three-phase voltage source.

The model is discrete. Good simulation results have been obtained with a 5 µs time step. The control system (speed and current controllers) samples data following a user-defined sample time in order to simulate a digital controller.
device. Keep in mind that this sampling time has to be a multiple of the simulation time step.
The DC Machine tab displays the parameters of the DC machine block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the DC machine block parameters.
### Four-Quadrant Three-Phase Rectifier DC Drive

**Converter Tab**

![Converter Tab Screenshot]

- **Field DC Source**
  - The DC motor field voltage value (V).

- **Circulating Current Inductors**
  - The four circulating current inductors inductance value (H).

- **Converter sections**
  - The Converter 1 and Converter 2 sections of the Converter tab display the parameters of the Universal Bridge block of the powerlib library. Refer to the SimPowerSystems user guide for more information on the Universal Bridge block parameters.
Four-Quadrant Three-Phase Rectifier DC Drive

Controller Tab

Schematic Button
When you press this button, a diagram illustrating the speed and current controllers schematics appears.

Regulation Type
This pop-up menu allows you to choose between speed and torque regulation.

Sampling Time
The controller (speed and current) sampling time (s). The sampling time has to be a multiple of the simulation time step.

Controller - Speed Controller Subtab
Nominal Speed
The nominal speed value of the DC motor (rpm). This value is used to convert motor speed from rpm to p.u. (per unit).
Four-Quadrant Three-Phase Rectifier DC Drive

Initial Speed Reference
The initial speed reference value (rpm). This value allows the user to start a simulation with a speed reference other than 0 rpm.

Low-Pass Filter Cutoff Frequency
Cutoff frequency of the low-pass filter used to filter the motor speed measurement (Hz).

Proportional Gain
The proportional gain of the PI speed controller.

Integral Gain
The integral gain of the PI speed controller.

Acceleration
The maximum change of speed allowed during motor acceleration (rpm/s). Too great a value can cause armature over-current.

Deceleration
The maximum change of speed allowed during motor deceleration (rpm/s). Too great a value can cause armature over-current.
Controller - Current Controller Subtab

**Power and Voltage nominal values**

The DC motor nominal power (VA) and voltage (V) values. The nominal power and voltage values are used to convert armature current from amperes to p.u. (per unit).

**Proportional Gain**

The proportional gain of the PI current controller.

**Integral Gain**

The integral gain of the PI current controller.

**Low-Pass Filter Cutoff Frequency**

Cutoff frequency of the low-pass filter used to filter the armature current measurement (Hz).
Four-Quadrant Three-Phase Rectifier DC Drive

Symmetrical Reference Limit
Symmetrical current reference (p.u.) limit around 0 p.u. 1.5 p.u. is a common value.

Controller - Bridge Firing Unit Subtab

Alpha Min
Minimum firing angle value (deg.). 20 degrees is a common value.

Alpha Max
Maximum firing angle value (deg.). 160 degrees is a common value.

Frequency of Synchronization Voltages
Frequency of the synchronization voltages used by the discrete synchronized 6-pulse generator block (Hz). This frequency is equal to the line frequency of the three-phase power line.

Pulse Width
The width of the pulses applied to the thyristor gates (deg.).
Four-Quadrant Three-Phase Rectifier DC Drive

Block Inputs and Outputs

Inputs
The block has five inputs: SP, Mec_T, A, B, and C.

The first input is the speed (rpm) or torque set point. Note that the speed set point can be a step function, but the speed change rate will follow the acceleration/deceleration ramps.

The second input is the mechanical load torque. If the values of the load torque and the speed have opposite signs, the accelerating torque will be the sum of the electromagnetic and load torques.

The last three inputs, A, B, and C, are the three-phase electric connections. The voltage must be adequate for the motor size.

Outputs
The block has three output vectors: Motor, Conv., and Ctrl.

The first output is the motor vector. This vector is composed of two elements:

- The armature voltage
- The DC motor “m” vector (containing the speed, armature current, field current, and electromagnetic torque values)

Note that the speed of the “m” vector is converted from rad/s to rpm before output.

The second output is the three-phase converter measurement vector. This vector includes:

- The output voltage of converter 1
- The output voltage of converter 2
- The output current of converter 1
- The output current of converter 2

Note that all current and voltage values of the bridges can be visualised with the multimeter block (refer to the multimeter user note).

The third output is the controller vector. This vector contains the values of:

- The armature current reference
- The firing angle computed by the current controller
The speed or torque error (difference between the speed reference ramp and actual speed or between the torque reference and actual torque)

- The speed reference ramp or torque reference

The library contains a 5 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

### 5 HP and 200 HP Drive Specifications

<table>
<thead>
<tr>
<th></th>
<th>5 HP Drive</th>
<th>200 HP Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drive Input Voltage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude</td>
<td>230 V</td>
<td>380 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td><strong>Motor Nominal Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>5 hp</td>
<td>200 hp</td>
</tr>
<tr>
<td>Speed</td>
<td>1750 rpm</td>
<td>1184 rpm</td>
</tr>
<tr>
<td>Voltage</td>
<td>240 V</td>
<td>440 V</td>
</tr>
</tbody>
</table>
**Example**

DC4 Example Schematic

This example illustrates the three-phase dual-converter drive used with the 200 hp drive parameter set during torque regulation. A 5 hp parameter set is also available in the library.

The converters are fed by a 380 V AC 50 Hz voltage source.

The motor is coupled to a linear load, which means that the mechanical torque of the load is proportional to the speed.

The initial torque reference is set to 0 N.m and the armature current is null. No electromagnetic torque is produced and the motor stays still.

At \( t = 0.2 \) s, the torque reference jumps to 600 N.m. This causes the armature current to rise to about 180 A. The armature current is supplied by converter 1, and the total current in this converter is the sum of load current and circulating current. Converter 2 simply carries the circulating current. Notice that the armature current follows the reference current quite accurately, with fast response time and small overshooting. Observe also that the firing angles are symmetrical around 90 degrees and that the converter average output DC voltages are equal but of opposite signs.
The electromagnetic torque produced by the armature current flow causes the motor to accelerate. The speed rises and starts to stabilize around $t = 4$ s at about 560 rpm, the sum of the load and viscous friction torques beginning to equalize the electromagnetic torque.

At $t = 4$ s, the torque reference is set to 0 N.m and the load torque causes the motor to decelerate. Notice that the four reactors keep the current oscillations quite small.

At $t = 8$ s, the torque reference is set to -300 N.m. The armature current jumps down to -90 A and is now delivered by converter 2 while converter 1 only handles the circulating current. Converter 2 is now working in rectifier mode and converter 1 in inverter mode.

The negative electromagnetic torque produced allows the motor to accelerate in the negative speed plane.

At $t = 12$ s, speed starts to stabilize around -290 rpm.
Four-Quadrant Three-Phase Rectifier DC Drive

DC4 Example Waveforms
Four-Quadrant Three-Phase Rectifier DC Drive

References


[2]
Generic Power System Stabilizer

Purpose

Implement a generic power system stabilizer for the synchronous machine

Library

Machines

Description

The Generic Power System Stabilizer (PSS) block can be used to add damping to the rotor oscillations of the synchronous machine by controlling its excitation. The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability. The output signal of the PSS is used as an additional input (vstab) to the Excitation System block. The PSS input signal can be either the machine speed deviation, dw, or its acceleration power, \( Pa = Pm - Peo \) (difference between the mechanical power and the electrical power).

The Generic Power System Stabilizer is modeled by the following nonlinear system:

\[
\text{To ensure a robust damping, the PSS should provide a moderate phase advance at frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced by the PSS action.}
\]

The model consists of a low-pass filter, a general gain, a washout high-pass filter, a phase-compensation system, and an output limiter. The general gain \( K \) determines the amount of damping produced by the stabilizer. The washout high-pass filter eliminates low frequencies that are present in the dw signal and allows the PSS to respond only to speed changes. The phase-compensation system is represented by a cascade of two first-order lead-lag transfer functions used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine.
Generic Power System Stabilizer

Dialog Box and Parameters

Sensor time constant
The time constant, in seconds (s), of the first-order low-pass filter used to filter the block's input signal.

Gain
The overall gain $K$ of the generic power system stabilizer.

Wash-out time constant
The time constant, in seconds (s), of the first-order high-pass filter used by the washout system of the model.
Generic Power System Stabilizer

Lead-lag #1 time constants: [Tnum Tden]
The numerator time constant T1n and denominator time constant T1d, in seconds (s), of the first lead-lag transfer function.

Lead-lag #2 time constants: [Tnum Tden]
The numerator time constant T2n and denominator time constant T2d, in seconds (s), of the second lead-lag transfer function.

Output limits: [Vsmin Vsmax]
The limits VSmin and VSmax, in p.u., imposed on the output of the stabilizer.

Initial input
The initial DC voltage, in p.u., of the block’s input signal. Specification of this parameter is required to initialize all states and start the simulation in steady state with vstab set to zero.

Plot frequency response
If selected, a plot of the frequency response of the stabilizer is displayed when you click the Apply button.

Magnitude in dB
The Magnitude in dB parameter is not visible if the Plot frequency response is not selected. If selected, the magnitude of the frequency response is plotted in dB.

Frequency range
The Frequency range parameter is not visible in the dialog box if the Plot frequency response is not selected. Specify the frequency range used to plot the frequency response of the stabilizer.

Inputs and Outputs

In
Two types of signals can be used at the input In:

- The synchronous machine speed deviation dw signal (in p.u.)
- The synchronous machine acceleration power Pa = Pm – Peo (difference between the machine mechanical power and output electrical power (in p.u.))

Vstab
Generic Power System Stabilizer

The output is the stabilization voltage (in p.u.) to connect to the Vstab input of the Excitation System block used to control the terminal voltage of the synchronous machine.

Example

See the help text of the power_PSS demo model.

References


See Also

Multiband Power System Stabilizer reference section
Ground

**Purpose**  Provide a connection to the ground

**Library**  Elements

**Description**  The Ground block implements a connection to the ground.

**Example**  The `power_ground` demo shows an application of the Ground block.

**See Also**  Neutral reference section
Purpose
Implement a gate turn off (GTO) thyristor model

Library
Power Electronics

Description
The gate turnoff (GTO) thyristor is a semiconductor device that can be turned on and off via a gate signal. Like a conventional thyristor, the GTO thyristor can be turned on by a positive gate signal \( (g > 0) \). However, unlike the thyristor, which can be turned off only at a zero crossing of current, the GTO can be turned off at any time by the application of a gate signal equal to 0.

The GTO thyristor is simulated as a resistor \( R_{on} \), an inductor \( L_{on} \), and a DC voltage source \( V_f \) connected in series with a switch. The switch is controlled by a logical signal depending on the voltage \( V_{ak} \), the current \( I_{ak} \), and the gate signal \( g \).

The \( V_f \), \( R_{on} \), and \( L_{on} \) parameters are the forward voltage drop while in conduction, the forward conducting resistance, and the inductance of the device. The GTO block also contains a series \( R_s-C_s \) snubber circuit that can be connected in parallel with the GTO device (between terminal ports A and K).

The GTO thyristor turns on when the anode-cathode voltage is greater than \( V_f \) and a positive pulse signal is present at the gate input \( (g > 0) \). When the gate signal is set to 0, the GTO thyristor starts to block but its current does not stop instantaneously.

Because the current extinction process of a GTO thyristor contributes significantly to the turnoff losses, the turnoff characteristic is built into the
model. The current decrease is approximated by two segments. When the gate signal becomes 0, the current Iak first decreases from the value Imax (value of Iak when the GTO thyristor starts to open) to Imax/10, during the fall time (Tf), and then from Imax/10 to 0 during the tail time (Tt). The GTO thyristor turns off when the current Iak becomes 0. The latching and holding currents are not considered.
**Dialog Box and Parameters**

The internal resistance $R_{on}$, in ohms ($\Omega$).

**Inductance $L_{on}$**

The internal inductance $L_{on}$, in henries (H). The **Inductance $L_{on}$** parameter cannot be set to 0.

**Forward voltage $V_f$**

The forward voltage of the GTO thyristor device, in volts (V).
Current 10% fall time
The current fall time $T_f$, in seconds (s).

Current tail time
The current tail time $T_t$, in seconds (s).

Initial current $I_c$
You can specify an initial current flowing in the GTO thyristor. It is usually set to 0 in order to start the simulation with the device blocked.

If the Initial Current IC parameter is set to a value greater than 0, the steady-state calculation of SimPowerSystems considers the initial status of the GTO as closed. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

Snubber resistance $R_s$
The snubber resistance, in ohms ($\Omega$). Set the Snubber resistance $R_s$ parameter to $\infty$ to eliminate the snubber from the model.

Snubber capacitance $C_s$
The snubber capacitance, in farads (F). Set the Snubber capacitance $C_s$ parameter to 0 to eliminate the snubber, or to $\infty$ to get a resistive snubber.

Show measurement port
If selected, add a Simulink output to the block returning the GTO current and voltage.

Inputs and Outputs

Simulink signal to control the gate of the GTO.

The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GTO current</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>GTO voltage</td>
<td>V</td>
</tr>
</tbody>
</table>
Assumptions and Limitations

The GTO block implements a macro model of a real GTO thyristor. It does not take into account either the geometry of the device or the underlying physical processes of the device [1].

The GTO block requires a continuous application of the gate signal ($g > 0$) in order to be in the on state (with $I_{ak} > 0$). The latching current and the holding current are not considered. The critical value of the derivative of the reapplied anode-cathode voltage is not considered.

The GTO block is modeled as a current source. It cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. In order to avoid an algebraic loop, you cannot set the inductance $L_{on}$ to 0.

Each GTO block adds an extra state to the electrical circuit model. Circuits containing GTO blocks cannot be discretized. In order to discretize circuits using GTO converters, use the Universal Bridge block or the Three-Level Bridge block. See Chapter 3, “Improving Simulation Performance” for more details on this topic.

You must use a stiff integrator algorithm to simulate circuits containing GTO blocks. $ode23tb$ or $ode15s$ with default parameters usually gives the best simulation speed.

Example

The power_buckconv demo illustrates the use of the GTO block in a buck converter topology. The basic polarized snubber circuit is connected across the GTO block. The snubber circuit consists of a capacitor $C_s$, a resistor $R_s$, and a diode $D_s$. The parasitic inductance $L_s$ of the snubber circuit is also taken into consideration.

The parameters of the GTO block are those found in the dialog box section, except for the internal snubber, which is not used ($R_s = \infty$; $C_s = 0$). The switching frequency is 1000 Hz and the pulse width is 216 degrees (duty cycle: 60%).
Run the simulation. Observe the GTO voltage and current as well as the load voltage and current.
References


See Also

IGBT reference section, MOSFET reference section, Three-Level Bridge reference section, Thyristor reference section, Universal Bridge reference section
Hydraulic Turbine and Governor

**Purpose**
Model a hydraulic turbine and a proportional-integral-derivative (PID) governor system

**Library**
Machines

**Description**
The Hydraulic Turbine and Governor block implements a nonlinear hydraulic turbine model, a PID governor system, and a servomotor [1].

The hydraulic turbine is modeled by the following nonlinear system.

The gate servomotor is modeled by a second-order system.
Hydraulic Turbine and Governor

Dialog Box and Parameters

Servo-motor
The gain $K_a$ and time constant $T_a$, in seconds (s), of the first-order system representing the servomotor.

Gate opening limits
The limits $g_{\text{min}}$ and $g_{\text{max}}$ (p.u.) imposed on the gate opening, and $v_{g_{\text{min}}}$ and $v_{g_{\text{max}}}$ (p.u./s) imposed on gate speed.

Permanent droop and regulator
The static gain of the governor is equal to the inverse of the permanent droop $R_p$ in the feedback loop. The PID regulator has a proportional gain $K_p$, an integral gain $K_i$, and a derivative gain $K_d$. The high-frequency gain of the PID is limited by a first-order low-pass filter with time constant $T_d$ (s).

Hydraulic turbine
The speed deviation damping coefficient $\beta$ and water starting time $T_w$ (s).
Hydraulic Turbine and Governor

Droop reference
Specifies the input of the feedback loop: gate position (set to 1) or electrical power deviation (set to 0).

Initial mechanical power
The initial mechanical power Pm0 (p.u.) at the machine’s shaft. This value is automatically updated by the load flow utility of the Powergui block.

Inputs and Outputs

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>wref</td>
<td>Reference speed, in p.u.</td>
</tr>
<tr>
<td>Pref</td>
<td>Reference mechanical power in p.u. This input can be left unconnected if you want to use the gate position as input to the feedback loop instead of the power deviation.</td>
</tr>
<tr>
<td>we</td>
<td>Machine actual speed, in p.u.</td>
</tr>
<tr>
<td>Pe0</td>
<td>Machine actual electrical power in p.u. This input can be left unconnected if you want to use the gate position as input to the feedback loop instead of the power deviation.</td>
</tr>
<tr>
<td>dw</td>
<td>Speed deviation, in p.u.</td>
</tr>
<tr>
<td>Pm</td>
<td>Mechanical power Pm for the Synchronous Machine block, in p.u.</td>
</tr>
<tr>
<td>gate</td>
<td>Gate opening, in p.u.</td>
</tr>
</tbody>
</table>

Example
This power_turbine demo illustrates the use of the Synchronous Machine associated with the Hydraulic Turbine and Governor (HTG) and Excitation System blocks. It also demonstrates the use of the load flow tool of the Powergui block to initialize machine currents and initial mechanical power of the HTG block. A three-phase generator rated 200 MVA, 13.8 kV, 112.5 rpm is connected to a 230 kV network through a Delta-Y 210 MVA transformer. The system starts in steady state with the generator supplying 150 MW of active...
power. At \( t = 0.1 \text{ s} \), a three-phase to ground fault occurs on the 230 kV bus of the transformer. The fault is cleared after six cycles (\( t = 0.2 \text{ s} \)).

In order to start the simulation in steady state, you must initialize the Synchronous Machine block for the desired load flow. Open the Powergui and select **Load flow and machine initialization**. The machine **Bus type** should be already initialized as \( \text{PV generator} \), indicating that the load flow is performed with the machine controlling the active power and its terminal voltage. Specify the desired values by entering the following parameters:

- Terminal voltage \( U_{AB} \) (Vrms) = 13800
- Active power (watts) = 150e6

Then click the **Update Load Flow** button. Once the load flow has been solved, the line-to-line machine voltages as well as the phase currents flowing out of the machine. The machine reactive power, mechanical power, and field voltage requested to supply the electrical power should also be displayed:

- \( Q = 3.4 \text{ Mvar} \)
Hydraulic Turbine and Governor

- \( P_{mec} = 150.32 \text{ MW (0.7516 p.u.)} \)
- Field voltage \( V_f = 1.291 \text{ p.u.} \)

The load flow also initializes the HTG and Excitation System blocks. Open the HTG block menu and notice that the initial mechanical power is set to 0.5007 p.u. (100.14 MW). Then open the Excitation System block menu and note that the initial terminal voltage and field voltage are set respectively to 1.0 and 1.291 p.u. Open the four scopes and start the simulation. The simulation starts in steady state.

Observe that the terminal voltage \( V_a \) is 1.0 p.u. at the beginning of the simulation. It falls to about 0.4 p.u. during the fault and returns to nominal quickly after the fault is cleared. This quick response in terminal voltage is due to the fact that the Excitation System output \( V_f \) can go as high as 11.5 p.u., which it does during the fault. The speed of the machine increases to 1.01 p.u. during the fault, then it oscillates around 1 p.u. as the governor system.
Hydraulic Turbine and Governor

regulates it. The speed takes much longer than the terminal voltage to stabilize, mainly because the rate of valve opening/closing in the governor system is limited to 0.1 p.u./s.

References


See Also

Excitation System reference section, Steam Turbine and Governor reference section, Synchronous Machine reference section
**Ideal Switch**

**Purpose**
Implement an ideal switch device

**Library**
Power Electronics

**Description**
The Ideal Switch block does not correspond to a particular physical device. When used with appropriate switching logic, it can be used to model simplified semiconductor devices such as a GTO or a MOSFET, or even a power circuit breaker with current chopping. The switch is simulated as a resistor $R_{on}$ in series with a switch controlled by a logical gate signal $g$.

The Ideal Switch block is fully controlled by the gate signal ($g > 0$ or $g = 0$). It has the following characteristics:

- Blocks any forward or reverse applied voltage with 0 current flow when $g = 0$
- Conducts any bidirectional current with quasi-zero voltage drop when $g > 0$
- Switches instantaneously between on and off states when triggered

The Ideal Switch block turns on when a positive signal is present at the gate input ($g > 0$). It turns off when the gate signal equals 0 ($g = 0$).

The Ideal Switch block also contains a series $R_s-C_s$ snubber circuit that can be connected in parallel with the ideal switch (between nodes 1 and 2).
**Ideal Switch**

![Diagram of Ideal Switch]

**Dialog Box and Parameters**

---

**Block Parameters: Ideal Switch**

- **Ideal Switch (mask):**
  - Switch controlled by a gate signal in parallel with a series R.C. snubber circuit. In on state the switch model has an internal resistance (Ron). In off state the internal resistance is infinite. The internal resistance must be greater than zero.
  - The switch model is on-state when the gate signal (\(g\)) is set to 1.

- **Parameters**:
  - Internal resistance Ron (Ohms):
    - 0.001
  - Initial state (0 for 'open', 1 for 'closed'):
    - 0
  - Snubber resistance Rs (Ohms):
    - 1e5
  - Snubber capacitance Cs (F):
    - 1
  - Show measurementport

---

7-179
**Ideal Switch**

**Internal resistance Ron**
The internal resistance of the switch device, in ohms (Ω). The **Internal resistance Ron** parameter cannot be set to 0.

**Initial state**
The initial state of the Ideal Switch block. The initial status of the Ideal Switch block is taken into account in the steady-state calculation of SimPowerSystems.

**Snubber resistance Rs**
The snubber resistance, in ohms (Ω). Set the **Snubber resistance Rs** parameter to `inf` to eliminate the snubber from the model.

**Snubber capacitance Cs**
The snubber capacitance in farads (F). Set the **Snubber capacitance Cs** parameter to 0 to eliminate the snubber, or to `inf` to get a resistive snubber.

**Show measurement port**
If selected, add a Simulink output to the block returning the ideal switch current and voltage.

**Inputs and Outputs**

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ideal switch current</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>Ideal switch voltage</td>
<td>V</td>
</tr>
</tbody>
</table>

**Assumptions and Limitations**
The Ideal Switch block is modeled as a current source. It cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. See Chapter 3, “Improving Simulation Performance” for more details on this topic.
You must use a stiff integrator algorithm to simulate circuits containing Ideal Switch blocks. ode23tb or ode15s with default parameters usually gives the best simulation speed.

**Example**

The `power_switch` demo uses the Ideal Switch block to switch an RLC circuit on an AC source (60 Hz). The switch, which is initially closed, is first opened at $t = 50$ ms (3 cycles) and then reclosed at $t = 138$ ms (8.25 cycles). The Ideal Switch block has 0.01 ohms resistance and no snubber is used.

Run the simulation and observe the inductor current, the switch current, and the capacitor voltage. Notice the high-frequency overvoltage produced by inductive current chopping. Note also the high switch current spike when the switch is reclosed on the capacitor at maximum source voltage.
Ideal Switch


See Also  Breaker reference section
Purpose
Implement an insulated gate bipolar transistor (IGBT)

Library
Power Electronics

Description
The IGBT block implements a semiconductor device controllable by the gate signal. The IGBT is simulated as a series combination of a resistor $R_{on}$, inductor $L_{on}$, and a DC voltage source $V_f$ in series with a switch controlled by a logical signal ($g > 0$ or $g = 0$).
The IGBT turns on when the collector-emitter voltage is positive and greater than $V_f$ and a positive signal is applied at the gate input ($g > 0$). It turns off when the collector-emitter voltage is positive and a 0 signal is applied at the gate input ($g = 0$).

The IGBT device is in the off state when the collector-emitter voltage is negative. Note that many commercial IGBTs do not have the reverse blocking capability. Therefore, they are usually used with an antiparallel diode.

The IGBT block contains a series $R_s$-$C_s$ snubber circuit, which is connected in parallel with the IGBT device (between terminals C and E).

The turnoff characteristic of the IGBT model is approximated by two segments. When the gate signal falls to 0, the collector current decreases from $I_{\text{max}}$ to 0.1 $I_{\text{max}}$ during the fall time ($T_f$), and then from 0.1 $I_{\text{max}}$ to 0 during the tail time ($T_t$).
IGBT

![IGBT Diagram](image-url)

- $G_t$
- $I_{C_t}$
- $I_{max}$
- $0.1I_{max}$
- $T_f$
- $T_l$
**IGBT**

**Dialog Box and Parameters**

**Resistance Ron**

The internal resistance Ron, in ohms (Ω).

**Inductance Lon**

The internal inductance Lon, in henries (H). The **Inductance Lon** parameter cannot be set to 0.

**Forward voltage Vf**

The forward voltage of the IGBT device, in volts (V).
**Current 10% fall time**

The current fall time \( T_f \), in seconds (s).

**Current tail time**

The current tail time \( T_t \), in seconds (s).

**Initial current \( I_c \)**

You can specify an initial current flowing in the IGBT. It is usually set to 0 in order to start the simulation with the device blocked.

If the **Initial Current IC** parameter is set to a value greater than 0, the steady-state calculation of SimPowerSystems considers the initial status of the IGBT as closed. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

**Snubber resistance \( R_s \)**

The snubber resistance, in ohms (\( \Omega \)). Set the **Snubber resistance Rs** parameter to \( \infty \) to eliminate the snubber from the model.

**Snubber capacitance \( C_s \)**

The snubber capacitance in farads (F). Set the **Snubber capacitance Cs** parameter to 0 to eliminate the snubber, or to \( \infty \) to get a resistive snubber.

**Show measurement port**

If selected, add a Simulink output to the block returning the diode IGBT current and voltage.

### Inputs and Outputs

- \( g \) Simulink signal to control the opening and closing of the IGBT.

- \( m \) The Simulink output of the block is a vector containing two signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IGBT current</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>IGBT voltage</td>
<td>V</td>
</tr>
</tbody>
</table>
Assumptions and Limitations

The IGBT block implements a macro model of the real IGBT device. It does not take into account either the geometry of the device or the complex physical processes [1].

The IGBT block is modeled as a current source. It cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. In order to avoid an algebraic loop, you cannot set the IGBT block inductance $L_{on}$ to 0. Each IGBT block adds an extra state to the electrical circuit model. See Chapter 3, “Improving Simulation Performance” for more details on this topic.

Circuits containing individual IGBT blocks cannot be discretized. However, discretization is permitted for IGBT/Diode bridges simulated with the Universal Bridge block or the Three-Level Bridge block.

You must use a stiff integrator algorithm to simulate circuits containing IGBTs. `ode23tb` or `ode15s` with default parameters usually gives the best simulation speed.

Example

The `power_igbtconv` demo illustrates the use of the IGBT block in a boost DC-DC converter. The IGBT is switched on and off at a frequency of 10 kHz to transfer energy from the DC source to the load (RC). The average output voltage ($V_R$) is a function of the duty cycle ($\alpha$) of the IGBT switch:

$$V_R = \frac{1}{1-\alpha} V_{dc}$$
In our example, $\alpha = 0.5$ so that the theoretical value of $V_R$ is 200 V, assuming no voltage drop across the diode and the IGBT.

Run the simulation and observe the inductor current ($I_L$), the IGBT collector current ($I_C$), the diode current ($I_D$), the IGBT device collector-emitter voltage ($V_{CE}$), and the load voltage ($V_R$).

The load voltage (197 V) is slightly lower than the theoretical value (200 V) mainly because of the forward voltage ($V_f$) of the diode (0.8 V) and of the IGBT ($V_f = 1$ V).
IGBT

References

See Also
GTO reference section, MOSFET reference section, Three-Level Bridge reference section, Thyristor reference section
Impedance Measurement

**Purpose**
Measure the impedance of a circuit as a function of frequency

**Library**
Measurements

**Description**
The Impedance Measurement block measures the impedance between two nodes of a linear circuit as a function of the frequency. It consists of a current source $I_z$, connected between inputs one and two of the Impedance Measurement block, and a voltage measurement $V_z$, connected across the terminals of the current source. The network impedance is calculated as the transfer function $H(s)$ from the current input to the voltage output of the state-space model.

$$H(s) = \frac{V_z(s)}{I_z(s)}$$

The impedance (magnitude and phase) as function of frequency is displayed by using the Impedance vs Frequency Measurement tool of the Powergui block.

The measurement takes into account the initial states of the Breaker and Ideal Switch blocks. It also allows impedance measurements with Distributed Parameter Line blocks in your circuit.

**Dialog Box and Parameter**

The Impedance Measurement block has a dialog box that allows you to set parameters. The dialog box includes a multiplication factor parameter, which you can use to rescale the measured impedance.

**Multiplication factor**
If you use the Impedance Measurement block in a three-phase circuit, you can use the Multiplication factor parameter to rescale the measured impedance.
Impedance Measurement

impedance. For example, measuring the impedance between two phases of a three-phase circuit gives two times the positive-sequence impedance. Therefore you must apply a multiplication factor of 1/2 to the impedance in order to obtain the correct positive-sequence impedance value.

Similarly, to measure the zero-sequence impedance of a balanced three-phase circuit, you can connect the Impedance Measurement block between ground or neutral and the three phases connected together.

In that case, you are measuring one third of the zero-sequence impedance and you must apply a multiplication factor of 3 to obtain the correct zero-sequence value.

Limitations

The only nonlinear blocks that are taken into account during the impedance measurement are the Breaker, Three-Phase Breaker, Three-Phase Fault, Ideal Switch, and Distributed Parameter Line blocks. All other nonlinear blocks, such as machines and power electronic devices, are not considered, and they are disconnected during the measurement.

If you plan to connect the Impedance Measurement block in series with an inductance, a current source, or any nonlinear element, you must add a large resistor across the terminals of the block, because the Impedance Measurement block is simulated as a current source block.

Example

See the Powergui block reference page for an example using the Impedance Measurement block.

See Also

Powergui reference section
Purpose
Implement a two-winding or three-winding linear transformer

Library
Elements

Description
The Linear Transformer block model shown consists of three coupled windings wound on the same core. The model takes into account the winding resistances (R1 R2 R3) and the leakage inductances (L1 L2 L3), as well as the magnetizing characteristics of the core, which is modeled by a linear (Rm Lm) branch.

The Per Unit Conversion
In order to comply with industry, you must specify the resistance and inductance of the windings in per unit (p.u.). The values are based on the transformer rated power $P_n$, in VA, nominal frequency $f_n$, in Hz, and nominal voltage $V_n$, in Vrms, of the corresponding winding. For each winding, the per unit resistance and inductance are defined as

$$R_{(p.u.)} = \frac{R(\Omega)}{R_{base}}$$

$$L_{(p.u.)} = \frac{L(H)}{L_{base}}$$
The base resistance and base inductance used for each winding are

\[ R_{\text{base}} = \frac{(Vn)^2}{Pn} \]
\[ L_{\text{base}} = \frac{R_{\text{base}}}{2 \pi f n} \]

For the magnetization resistance \( R_m \) and inductance \( L_m \), the p.u. values are based on the transformer rated power and on the nominal voltage of winding 1.

For example, the default parameters of winding 1 specified in the dialog box section give the following bases:

\[ R_{\text{base}} = \frac{(735 \cdot 3/\sqrt{3})^2}{250 \cdot 6} = 720.3 \Omega \quad L_{\text{base}} = \frac{720.3}{2 \pi \cdot 60} = 1.91 H \]

Suppose that the winding 1 parameters are \( R_1 = 1.44 \Omega \) and \( L_1 = 0.1528 \) H; the corresponding values to be entered in the dialog box are

\[ R_1 = \frac{1.44 \Omega}{720.3 \Omega} = 0.002 \text{ p.u.} \]
\[ L_1 = \frac{0.1528 H}{1.91 H} = 0.08 \text{ p.u.} \]

To specify a magnetizing current of 0.2% (resistive and inductive) based on nominal current, you must enter per unit values of \( 1/0.002 = 500 \) p.u. for the resistance and the inductance of the magnetizing branch. Using the base values calculated previously, these per unit values correspond to \( R_m = 3.6e5 \) ohms and \( L_m = 955 \) henries.

**Modeling an Ideal Transformer**

To implement a quasi-ideal transformer model, set the winding resistances to a very small value (e.g., 0.001 p.u.), inductances to 0, and the magnetization inductance \( L_m \) to \( \text{inf} \). The \( R_m \) value must have a finite value. Use a large value such as \( 1e4 \) (0.01% losses).
**Nominal power and frequency**

The nominal power rating $P_n$ in volt-amperes (VA) and frequency $f_n$, in hertz (Hz), of the transformer.

**Winding 1 parameters**

The nominal voltage $V_1$ in volts RMS, resistance, and leakage inductance in p.u. The p.u. values are based on the nominal power $P_n$ and on $V_1$.

**Winding 2 parameters**

The nominal voltage $V_2$ in volts RMS, resistance, and leakage inductance in p.u. The p.u. values are based on the nominal power $P_n$ and on $V_2$.

**Three windings transformer**

If selected, implements a linear transformer with three windings; otherwise, it implements a two-windings transformer.

**Winding 3 parameters**
Linear Transformer

The **Winding 3 parameters** parameter is not available if the **Three windings transformer** parameter is not selected.

The nominal voltage in volts RMS (Vrms), resistance, and leakage inductance in p.u. The p.u. values are based on the nominal power Pn and on V3.

**Magnetization resistance and reactance**

The resistance and inductance simulating the core active and reactive losses, both in p.u. The p.u. values are based on the nominal power Pn and on V1. For example, to specify 0.2% of active and reactive core losses, at nominal voltage, use $R_m = 500 \, \text{p.u.}$ and $L_m = 500 \, \text{p.u.}$

**Measurements**

- Select **Winding voltages** to measure the voltage across the winding terminals of the Linear Transformer block.
- Select **Winding currents** to measure the current flowing through the windings of the Linear Transformer block.
- Select **Magnetization current** to measure the magnetization current of the Linear Transformer block.
- Select **All voltages and currents** to measure the winding voltages and currents plus the magnetization current.

Place a Multimeter block in your model to display the selected measurements during the simulation.

In the **Available Measurements** list box of the Multimeter block, the measurements are identified by a label followed by the block name.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding voltages</td>
<td>Uw1:, Uw2:, Uw3:</td>
</tr>
<tr>
<td>Winding currents</td>
<td>Iw1:, Iw2:, Iw3:</td>
</tr>
<tr>
<td>Magnetization current</td>
<td>Imag:</td>
</tr>
</tbody>
</table>

**Limitations**

Windings can be left floating (that is, not connected to the rest of the circuit). However, an internal resistor is automatically added between the floating
winding and the main circuit. This internal connection does not affect voltage and current measurements.

**Example**

The `power_transformer` demo shows a typical residential distribution transformer network feeding line-to-neutral and line-to-line loads.

**See Also**

Mutual Inductance reference section, Saturable Transformer reference section, Three-Phase Transformer (Two Windings) reference section, Three-Phase Transformer (Three Windings) reference section
Machine Measurement Demux

**Purpose**
Split measurement signal of machine models into separate signals

**Library**
Machines

**Description**
The Machine Measurement Demux block is used to demux the measurement signals of the Simplified Synchronous Machine, the Synchronous Machine, the Asynchronous Machine, and the Permanent Magnet Synchronous Machine blocks.

The Machine Measurement Demux block is connected directly to the measurement output of the machine blocks. You select the type of machine connected to the block and you select the measurements you want to observe. An output is added to the block for each measurement in the list.

**Note** You can also use the Bus Selector block from Simulink library to demux the measurement signals of the machine blocks.

**Parameters**
**Machine type**
- Set to Simplified synchronous to display the measurement list for the Simplified Synchronous Machine block.
- Set to Synchronous to display the measurement list for the Synchronous Machine block.
- Set to Asynchronous to display the measurement list for the Asynchronous Machine block.
- Set to Permanent magnet synchronous to display the measurement list for the Permanent Magnet Synchronous Machine block.

**Measurement list**
Select the block parameters you want to output.

**See Also**
Bus Selector
Purpose
Implement a mechanical shaft

Library
Electric Drives/Shafts and Speed Reducers

Description
The model outputs the transmitted torque through the shaft regarding the speed difference between the driving side and the loaded side of the shaft.

The transmitted torque $T_I$ is given by the following equation:

$$ T_I = K \int (\omega_m - \omega_l) dt + B(\omega_m - \omega_l) $$

where $K$ (N.m) is the shaft stiffness, $B$ (N.m.s) is the internal damping, and $\omega_m$ and $\omega_l$ are the speeds (rad/s) of the driving side and the loaded side, respectively. The following figure shows the internal schematic of the model. In this model the speeds are converted from rpm to rad/s.

**Mechanical Shaft Model Schematic**

The stiffness is defined as

$$ K = \frac{T}{\theta} $$

where $T$ is the torsional torque applied to the shaft and $\theta$ the resulting angular deflection (rad).

The stiffness can also be determined by

$$ K = \frac{G \cdot J}{l} $$

where $G$ is the shear modulus, $J$ the polar moment of inertia, and $l$ the length of the shaft.
Mechanical Shaft

For steel, the shear modulus \( G \) is usually equal to about 80 GPa, and the polar moment of inertia \( J \) of a shaft with a circular section of diameter \( D \) is given by

\[
J = \frac{\pi \cdot D^4}{32}
\]

Mechanical shafts have very small angular deflections to avoid bearing problems. As an example, the following table gives the corresponding stiffnesses for angular deflections of 0.1 degrees at maximum torque with respect to the power and speed of electrical motors connected to the driving end of the shaft. The maximum torque is here assumed to be 1.5 times bigger than the nominal torque.

**Shaft Stiffness \( K \)**

<table>
<thead>
<tr>
<th>( P ) (HP)</th>
<th>( N ) (rpm)</th>
<th>( T ) (N.m)</th>
<th>( T_{\text{max}} ) (N.m) ((=1.5 , T))</th>
<th>( K ) (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1750</td>
<td>20</td>
<td>30</td>
<td>17190</td>
</tr>
<tr>
<td>200</td>
<td>1750</td>
<td>815</td>
<td>1223</td>
<td>700730</td>
</tr>
<tr>
<td>200</td>
<td>1200</td>
<td>1190</td>
<td>1785</td>
<td>1022730</td>
</tr>
</tbody>
</table>

The damping factor \( B \) represents internal friction. This factor increases with the shaft stiffness. As an example, the following table gives some values of \( B \) for the stiffnesses of the preceding table.

**Shaft Internal Damping \( B \)**

<table>
<thead>
<tr>
<th>( K ) (N.m)</th>
<th>( B ) (N.m.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17190</td>
<td>600</td>
</tr>
<tr>
<td>700730</td>
<td>24460</td>
</tr>
<tr>
<td>1022730</td>
<td>35700</td>
</tr>
</tbody>
</table>
**Mechanical Shaft**

**Simulink Schematic**

**Remarks**

The stiffness must be high enough to avoid large angular deflections that could cause misalignment inside the bearings and damage.

For proper simulation results, the internal damping must be high enough to avoid undesired transient speed and torque oscillations.

The model is discrete. Good simulation results have been obtained with a 10 $\mu$s time step.
Mechanical Shaft

Dialog Box

Mechanical Shaft Dialog Box

Preset Model
This pop-up menu allows you to choose preset model parameters.

Stiffness
The stiffness of the shaft (N.m).

Damping
The internal damping of the shaft (N.m.s).

Block Inputs and Outputs

Inputs
The block has two inputs: Nm and Nl.
The first input, Nm, is the speed (rpm) of the driving end of the shaft.
The second input, Nl, is the speed (rpm) of the load connected to the second end of the shaft.

Outputs
The block has one output: Tl.
The Tl output is the torque transmitted from the driving end of the shaft to the load.
The library contains three preset models. The nominal torques of these mechanical shaft models are shown in the following table:

<table>
<thead>
<tr>
<th>Preset Mechanical Shaft Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal torque (N.m)</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The preset models have been designed in order to present 0.1 degrees of angular deflection at maximum torque (supposed to be 1.5 times the nominal torque).

Example

This example illustrates the mechanical shaft model.

The shaft is driven by a variable speed source and is connected to a load. The load has an inertia of 0.35 kg.m² and a viscous friction term of 0.006 N.m.s.
The shaft has a stiffness of 17190 N.m and an internal damping factor of 600 N.m.s. This shaft is designed to have 0.1 degree of angular deflection for a 30 N.m load torque.

At $t = 0$ s, the driving speed starts climbing to 1750 rpm with a 500 rpm/s acceleration ramp. The angular deflection jumps to about 0.06 degree and the shaft transmits about 18.5 N.m to the load in order to accelerate it. At $t = 0.2$ s, the driving and load speeds tend to equalize. During the acceleration phase, the angular deflection increases slowly in order to transmit a higher torque to compensate the viscous friction increase.

At $t = 3.5$ s, the driving speed settles at 1750 rpm. This reduces the angular deflection and also the transmitted torque, which settles around 1.1 N.m to compensate the viscous friction of the load.

At $t = 5$ s, the driving speed lowers towards 0 rpm with a -500 rpm/s deceleration ramp. The angular deflection becomes negative and thus the transmitted torque in order to decelerate the load. During the deceleration phase, the angular deflection increases in order to transmit a higher deceleration torque to compensate the reduction of viscous friction.

At $t = 8.5$ s, the driving speed stabilizes at 0 rpm. This causes the angular deflection to decrease to 0 degree, the transmitted torque becomes null, and the load stops.

The following figure shows the speeds of the driving and loaded sides, the speed difference between both sides, the angular deflection, and the transmitted torque.
Mechanical Shaft Example Waveforms

References


**MOSFET**

**Purpose**
Implement a MOSFET model

**Library**
Power Electronics

**Description**

The metal-oxide semiconductor field-effect transistor (MOSFET) is a semiconductor device controllable by the gate signal \((g > 0)\) if its current \(I_d\) is positive \((I_d > 0)\). The MOSFET device is connected in parallel with an internal diode that turns on when the MOSFET device is reverse biased \((V_{ds} < 0)\). The model is simulated as a series combination of a variable resistor \((R_t)\) and inductor \((L_{on})\) in series with a switch controlled by a logical signal \((g > 0\) or \(g = 0)\).

The MOSFET device turns on when the drain-source voltage is positive and a positive signal is applied at the gate input \((g > 0)\).

With a positive current flowing through the device, the MOSFET turns off when the gate input becomes 0. If the current \(I_d\) is negative \((I_d\) flowing in the internal diode\) and without a gate signal \((g = 0)\), the MOSFET turns off when the current \(I_d\) becomes 0 \((I_d = 0)\).

Note that the on state resistance \(R_t\) depends on the drain current direction:

- \(R_t = R_{on}\) if \(I_d > 0\), where \(R_{on}\) represents the typical value of the forward conducting resistance of the MOSFET device.
- \(R_t = R_d\) if \(I_d < 0\), where \(R_d\) represents the internal diode resistance.
The MOSFET block also contains a series Rs-Cs snubber circuit that can be connected in parallel with the MOSFET (between nodes d and s).
Dialog Box and Parameters

Resistance Ron
The internal resistance Ron, in ohms (Ω).

Inductance Lon
The internal inductance Lon, in henries (H). The Inductance Lon parameter cannot be set to 0.

Internal diode resistance Rd
The internal resistance of the internal diode, in ohms (Ω).

Initial current Ic
You can specify an initial current flowing in the MOSFET device. It is usually set to 0 in order to start the simulation with the device blocked.
If the Initial current IC parameter is set to a value greater than 0, the steady-state calculation of SimPowerSystems considers the initial status of the MOSFET as closed. Initializing all states of a power electronic converter is a complex task. Therefore, this option is useful only with simple circuits.

**Snubber resistance Rs**
The snubber resistance, in ohms (Ω). Set the Snubber resistance Rs parameter to inf to eliminate the snubber from the model.

**Snubber capacitance Cs**
The snubber capacitance, in farads (F). Set the Snubber capacitance Cs parameter to 0 to eliminate the snubber, or to inf to get a resistive snubber.

**Show measurement port**
If selected, add a Simulink output to the block returning the MOSFET current and voltage.

### Inputs and Outputs

- **g** Simulink signal to control the opening and closing of the MOSFET.
- **m** The Simulink output of the block is a vector containing 2 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MOSFET current</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>MOSFET voltage</td>
<td>V</td>
</tr>
</tbody>
</table>

### Assumptions and Limitations

The MOSFET block implements a macro model of the real MOSFET device. It does not take into account either the geometry of the device or the complex physical processes [1].

The MOSFET block is modeled as a current source. It cannot be connected in series with an inductor, a current source, or an open circuit, unless its snubber circuit is in use. In order to avoid an algebraic loop, you cannot set the
MOSFET block inductance $L_{on}$ to 0. Each MOSFET block adds an extra state to the electrical circuit model. See Chapter 3, “Improving Simulation Performance” for more details on this topic.

Circuits containing individual MOSFET blocks cannot be discretized. However discretization is permitted for MOSFET/Diode bridges simulated with the Universal Bridge block or the Three-Level Bridge block.

You must use a stiff integrator algorithm to simulate circuits containing MOSFETs. `ode23tb` or `ode15s` with default parameters usually gives the best simulation speed.

**Example**

The `power_mosconv` demo illustrates the use of the MOSFET block in a zero-current quasi-resonant switch converter. In such a converter, the current produced by the $L_r-C_r$ resonant circuit flows through the MOSFET and internal diode. The negative current flows through the internal diode that turns off at 0 current [1]. The switching frequency is 2 MHz and the pulse width is 72 degrees (duty cycle: 20%).
Run the simulation and observe the gate pulse signal, the MOSFET current, the capacitor voltage, and the diode current on the four-trace Scope block.

References

See Also
Diode reference section, GTO reference section, Ideal Switch reference section, Three-Level Bridge reference section, Thyristor reference section, Universal Bridge reference section
Multiband Power System Stabilizer

Purpose
Implement a multiband power system stabilizer

Library
Machines

Description
The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system's stability. Electromechanical oscillations can be classified in four main categories:

• Local oscillations: between a unit and the rest of the generating station and between the latter and the rest of the power system. Their frequencies typically range from 0.8 to 4.0 Hz.

• Interplant oscillations: between two electrically close generation plants. Frequencies can vary from 1 to 2 Hz.

• Interarea oscillations: between two major groups of generation plants. Frequencies are typically in a range of 0.2 to 0.8 Hz.

• Global oscillation: characterized by a common in-phase oscillation of all generators as found on an isolated system. The frequency of such a global mode is typically under 0.2 Hz.

The need for effective damping of such a wide range, almost two decades, of electromechanical oscillations motivated the concept of the multiband power system stabilizer (MB-PSS).

As its name reveals, the MB-PSS structure is based on multiple working bands. Three separate bands are used, respectively dedicated to the low-, intermediate-, and high-frequency modes of oscillations: the low band is typically associated with the power system global mode, the intermediate with the interarea modes, and the high with the local modes.

Each of the three bands is made of a differential bandpass filter, a gain, and a limiter (see the figure called “Conceptual Representation” on page 7-213). The outputs of the three bands are summed and passed through a final limiter producing the stabilizer output $V_{stab}$. This signal then modulates the set point of the generator voltage regulator so as to improve the damping of the electromechanical oscillations.

To ensure robust damping, the MB-PSS should include a moderate phase advance at all frequencies of interest to compensate for the inherent lag.
between the field excitation and the electrical torque induced by the MB-PSS action.

Conceptual Representation

Internal Specifications
The MB-PSS is represented by the IEEE St. 421.5 PSS 4B type model [2], illustrated in the figure called “Internal Specifications” on page 7-213, with built-in speed transducers whose parameters are fixed according to manufacturer’s specifications.

Generally, only a few of the lead-lag blocks in this figure should be used in a given PSS application. Two different approaches are available to configure the settings in order to facilitate the tuning process:

1 Simplified settings:
   Only the first lead-lag block of each frequency band is used to tune the Multiband Power System Stabilizer block. The differential filters are assumed to be symmetrical bandpass filters respectively tuned at the center frequency $F_L$, $F_I$, and $F_H$. The peak magnitude of the frequency responses (see the figure called “Conceptual Representation” on page 7-213) can be adjusted independently through the three gains $K_L$, $K_I$, and $K_H$. Only six parameters are therefore required for a simplified tuning of the MB-PSS.

2 Detailed settings:
   The designer is free to use all the flexibility built into the MB-PSS structure to achieve nontrivial controller schemes and to tackle even the most constrained problem (for example, multi unit plant including an intermachine mode, in addition to a local mode and multiple interarea modes). In this case, all the time constants and gains appearing in the figure called “Internal Specifications” have to be specified in the dialog box.
Multiband Power System Stabilizer

**Dialog Box and Parameters**

**Simplified Settings Mode**

The block implements a Multiband Power System Stabilizer (MB-PSS). Two operation modes are available: Detailed setting and simplified setting (IEEE Std 421.5).

When "Detailed settings" is used, the low(L), intermediate(I), and high(H) frequency time constants must be given in the following order: Tref to Tref+2 followed by Tref+1 and Tref+2 (where sele = L, I, or H).

**Parameters**

- **Mode of operation**: Simplified settings
- **Global gain**: 1.0
- **Low frequency band**: [FL, KL]
  - [0.2 20]
- **Intermediate frequency band**: [FI, KI]
  - [0.5 20]
- **High frequency band**: [FH, KH]
  - [120, 145]
- **Signaling limits**: [Vlmax, Vlmax, Vhmax, Vhmax]
  - [0.75, 1.5, 1.5]
- **Plot frequency response**

### Global gain

The overall gain $K$ of the multiband power system stabilizer.

### Low frequency band: [FL, KL]

The center frequency, in hertz, and peak gain of the low-frequency bandpass filter.

### Intermediate frequency band: [FI, KI]

The center frequency, in hertz, and peak gain of the intermediate-frequency bandpass filter.

### High frequency band: [FH, KH]
Multiband Power System Stabilizer

The center frequency, in hertz, and peak gain of the high-frequency bandpass filter.

Signal limits [VLmax  VImax  VHmax  VSmax]
The limits imposed on the output of the low-, intermediate-, and high-frequency bands and the limit VSmax imposed on the output of the stabilizer, all in p.u.

Plot frequency response
If selected, a plot of the frequency response of the stabilizer is displayed when you click the Apply button.
Multiband Power System Stabilizer

Detailed Settings Mode

Low frequency gains: [KL1  KL2  KL]

The gains of the positive and negative branches of the differential filter in the low-frequency band and the overall gain $K_L$ of the low-frequency band, in p.u.

Low frequency time constants
Multiband Power System Stabilizer

The time constants, in seconds, of the lead-lag blocks in the positive and negative branches of the low-frequency filter. You need to specify the following twelve time constants and two gains:

\[ T_{B1} \ T_{B2} \ T_{B3} \ T_{B4} \ T_{B5} \ T_{B6} \ T_{B7} \ T_{B8} \ T_{B9} \ T_{B10} \ T_{B11} \ T_{B12} \ K_{B11} \ K_{B17} \]

Set \( K_{B11} \) to 0 in order to make the first block of the positive filter branch a washout block. Set \( K_{B11} \) to 1 in order to make the block a lead-lag block.

Set \( K_{B17} \) to 0 in order to make the first block of the negative filter branch a washout block. Set \( K_{B17} \) to 1 in order to make the block a lead-lag block.

**Intermediate frequency gains: \([K_{I1} \ K_{I2} \ K_{I}]\)**

The gains of the positive and negative branches of the differential filter in the intermediate-frequency band and the overall gain \( K_I \) of the intermediate-frequency band, in p.u.

**Intermediate frequency time constants**

The time constants, in seconds, of the lead-lag blocks in the positive and negative branches of the intermediate-frequency filter. You need to specify the following twelve time constants and two gains:

\[ T_{I1} \ T_{I2} \ T_{I3} \ T_{I4} \ T_{I5} \ T_{I6} \ T_{I7} \ T_{I8} \ T_{I9} \ T_{I10} \ T_{I11} \ T_{I12} \ K_{I11} \ K_{I17} \]

Set \( K_{I11} \) to 0 in order to make the first block of the positive filter branch a washout block. Set \( K_{I11} \) to 1 in order to make the block a lead-lag block.

Set \( K_{I17} \) to 0 in order to make the first block of the negative filter branch a washout block. Set \( K_{I17} \) to 1 in order to make the block a lead-lag block.

**High frequency gains: \([K_{H1} \ K_{H2} \ K_{H}]\)**

The gains of the positive and negative branches of the differential filter in the high-frequency band and the overall gain \( K_H \) of the high-frequency band, in p.u.

**High frequency time constants**

The time constants, in seconds, of the lead-lag blocks in the positive and negative branches of the high-frequency filter. You need to specify the following twelve time constants and two gains:

\[ T_{H1} \ T_{H2} \ T_{H3} \ T_{H4} \ T_{H5} \ T_{H6} \ T_{H7} \ T_{H8} \ T_{H9} \ T_{H10} \ T_{H11} \ T_{H12} \ K_{H11} \ K_{H17} \]
Multiband Power System Stabilizer

Set $K_{H11}$ to 0 in order to make the first block of the positive filter branch a washout block. Set $K_{H11}$ to 1 in order to make the block a lead-lag block.

Set $K_{H17}$ to 0 in order to make the first block of the negative filter branch a washout block. Set $K_{H17}$ to 1 in order to make the block a lead-lag block.

**Signal limits [VLmax VImax VHmax VSmax]**

The limits imposed on the output of the low-, intermediate-, and high-frequency bands and the limit VSmax imposed on the output of the stabilizer, all in p.u.

**Plot frequency response**

If selected, a plot of the frequency response of the stabilizer is displayed when you click the **Apply** button.

**Input and Output**

- **Input**
  - **dw**
    - Connect to the first input the synchronous machine speed deviation $dw$ signal (in p.u.).

- **Output**
  - **Vstab**
    - The output is the stabilization voltage, in p.u., to connect to the vstab input of the Excitation System block used to control the terminal voltage of the Synchronous Machine block.

**Example**

See the help text of the `power_PSS` demo model.

**References**


**See Also**

Generic Power System Stabilizer reference section
**Multimeter**

**Purpose**
Measure the voltages and currents specified in dialog boxes of SimPowerSystems blocks

**Library**
Measurements

**Description**
The Multimeter block is used to measure voltages and currents of the measurements described by the dialog boxes of SimPowerSystems blocks.

The `powerlib` blocks listed in the following table have a special parameter (Measurements) that allows you to measure voltages or currents related to the block. Choosing voltages or currents through this measurement parameter is equivalent to connecting an internal voltage or current measurement block inside your blocks. The measured signals can be observed through a Multimeter block placed in your circuit.

Drag the Multimeter block into the top-level system of your circuit and double-click the icon to open the dialog box.

<table>
<thead>
<tr>
<th>Block Name</th>
<th>Block Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Current Source</td>
<td>PI Section Line</td>
</tr>
<tr>
<td>AC Voltage Source</td>
<td>Saturable Transformer</td>
</tr>
<tr>
<td>Breaker</td>
<td>Series RLC Branch</td>
</tr>
<tr>
<td>Controlled Current Source</td>
<td>Series RLC Load</td>
</tr>
<tr>
<td>Controlled Voltage Source</td>
<td>Surge Arrester</td>
</tr>
<tr>
<td>DC Voltage Source</td>
<td>Three-Level Bridge</td>
</tr>
<tr>
<td>Distributed Parameter Line</td>
<td>Three-Phase Harmonic Filter</td>
</tr>
<tr>
<td>Linear Transformer</td>
<td>Three-Phase Load (Series and Parallel)</td>
</tr>
<tr>
<td>Multi-Winding Transformer</td>
<td>Three-Phase Branch (Series and Parallel)</td>
</tr>
</tbody>
</table>
Sign Conventions for Voltages and Currents

When you measure a current using a Current Measurement block, the positive direction of current is indicated on the block icon (positive current flowing from + terminal to – terminal). Similarly, when you measure a voltage using a Voltage Measurement block, the measured voltage is the voltage of the + terminal with respect to the – terminal. However, when voltages and currents of blocks from the Elements library are measured using the Multimeter block, the voltage and current polarities are not immediately obvious because blocks might have been rotated and there are no signs indicating polarities on the block icons.

Unlike Simulink signal lines and input and output ports, the Physical Modeling connection lines and terminal ports of SimPowerSystems lack intrinsic directionality. The voltage and current polarities are determined, not by line direction, but instead by block orientation. To find out a block orientation, first click the block to select it. Then enter the following command:

```
get_param(gcb,'Orientation')
```

The following table indicates the polarities of the currents and voltages measured with the Multimeter block for single-phase and three-phase RLC elements (branches or loads), surge arresters, and single-phase and
three-phase breakers. The table also indicates the polarities of their state variables (inductor currents and capacitor voltages).

<table>
<thead>
<tr>
<th>Block Orientation</th>
<th>Positive Current Direction</th>
<th>Measured Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>right</td>
<td>left —&gt; right</td>
<td>Vleft – Vright</td>
</tr>
<tr>
<td>left</td>
<td>right —&gt; left</td>
<td>Vright – Vleft</td>
</tr>
<tr>
<td>down</td>
<td>top —&gt; bottom</td>
<td>Vtop – Vbottom</td>
</tr>
<tr>
<td>up</td>
<td>bottom —&gt; top</td>
<td>Vbottom – Vtop</td>
</tr>
</tbody>
</table>

The natural orientation of the blocks (that is, their orientation in the Element library) is right for horizontal blocks and down for vertical blocks.

For single-phase transformers (linear or saturable), with the winding connectors appearing on the left and right sides, the winding voltages are the voltages of the top connector with respect to the bottom connector whatever the block orientation (right or left). The winding currents are the currents entering the top connector.

For three-phase transformers, the voltage polarities and positive current directions are indicated by the signal labels used in the Multimeter block. For example, Uan_w2 = phase A-to-neutral voltage of the Y connected winding #2, Iab_w1 = winding current flowing from A to B in the delta-connected winding #1.