PMSM BLDC Section

The PMSM BLDC model implements three motor types which provide parametrization for different machine types (Permanent Magnet Synchronous Machine and Brushless DC Motor) and allow for different levels of model fidelity (Constant or Variable parametrization) : PMSM Constant Ld/Lq, PMSM Variable Ld/Lq, and BLDC Constant Ls. The **PMSM Constant Ld/Lq** and **BLDC Constant Ls** motor modes simulate a machine with constant inductance and magnetic flux parameters. The **PMSM Variable Ld/Lq** motor type simulates a PMSM whose inductance and magnetic flux parameters are variable based on the operating state of the simulation (in this case, based on I_d and I_q), which allows for greater model fidelity.

Configuration Page

In the **System Explorer** window configuration tree, expand the **Power Electronics Add-On** custom device and select **Circuit Model >> PMSM BLDC** to display this page. Use this page to configure the PMSM BLDC machine model.

This page includes the following components, configurable at edit-time only:

Name	Specifies the name of the machine model.
Description	Specifies a description for the machine model.
Motor Type	Choose from one of the following types. The motor configuration parameters automatically populate depending on the selected **Motor Type**. • PMSM Constant Ld/Lq • PMSM Variable Ld/Lq • BLDC Constant Ls

Use the Input Mapping Configuration to route signals to the **Voltage Phase A**, **Voltage Phase B**, and **Voltage Phase C** inputs of the machine model. Available routing options may vary depending on the selected **Hardware Configuration**.	
Group	Specifies the group that will be routed to the input voltages of the machine. The available routing options are defined by the selected Hardware Configuration, however it is typical to see the following options by default: • **Measurements** - eHS circuit model measurements
Element	Specifies the index of the measurement in the group that has been selected as the input voltage of the machine.

Section Channels

This section includes the following custom device channels:

Channel Name	Symbol	Type	Units	Default Value	Description
Current Phase A	I_a	Output	Ampere	0 A	Phase A current measured at the stator
Current Phase B	I_b	Output	Ampere	0 A	Phase B current measured at the stator
Current Phase C	I_c	Output	Ampere	0 A	Phase C current measured at the stator
Average Voltage A	$V_{a,avg}$	Output	Volts	0 V	Averaged Phase A voltage measured at the stator. The voltage is processed through a low-pass filter with a cutoff frequency of 159 Hz (1) $$f_c = \frac{1}{2\pi \times 1e-3} = 159 Hz$$
Average Voltage B	$V_{b,avg}$	Output	Volts	0 V	Averaged Phase B voltage measured at the stator. The voltage is processed through a low-pass filter with a cutoff frequency of 159Hz.
Average Voltage C	$V_{c,avg}$	Output	Volts	0 V	Averaged Phase C voltage measured at the stator. The voltage is processed through a low-pass filter with a cutoff frequency of 159Hz

Three-Phase Active Power	P	Output	Watts	0 W	Three-phase instantaneous active electrical power in Watts See **Power Equations** for more information on how this is calculated.
Three-Phase Reactive Power	Q	Output	Volt-ampere reactive	0 var	Three-phase instantaneous reactive electrical power in vars See **Power Equations** for more information on how this is calculated.
Direct Axis Stator Current	I_d	Output	Ampere	0 A	Direct-axis stator current in the reference frame aligned with the rotor For a description of the DQ-transform used to compute this value, see **DQ Transform**
Quadrature Axis Stator Current	I_q	Output	Ampere	0 A	Quadrature-axis stator current in the reference frame aligned with the rotor For a description of the DQ-transform used to compute this value, see **DQ Transform**
Back-EMF Phase A	$V_{bemf,a}$	Output	Volts	0 V	Phase A to neutral voltage induced by the electromotive force
Back-EMF Phase B	$V_{bemf,b}$	Output	Volts	0 V	Phase B to neutral voltage induced by the electromotive force
Back-EMF Phase C	$V_{bemf,c}$	Output	Volts	0 V	Phase C to neutral voltage induced by the electromotive force
Permanent Magnet Flux Linkage	M	Output	Weber	0 Wb	Latest-value measurement of the Permanent Magnet Flux Linkage used at the input of the electrical model In Constant mode, this will return the constant value input by the user in the Motor Configuration settings In Variable mode, this will be the value that is looked-up in the 2D Flux Linkage table.
Direct Axis Inductance	L_d	Output	Henry	0 H	Direct-axis inductance. This value is fed back from the input of the electrical model and describes only the latest value. In Constant mode, this will return the constant value input by the user in the Motor Configuration settings In Variable mode, this will be the value that is looked-up in the 2D L_d table.
Quadrature Axis Inductance	L_q	Output	Henry	0 H	Quadrature-axis inductance. This value is fed back from the input of the electrical model and describes only the latest value. In Constant mode, this will return the constant value input by the user in the Motor Configuration settings In Variable mode, this will be the value that is looked-up in the 2D L_q table.
Direct Axis Stator Voltage	V_d	Output	Volts	0 V	Direct-axis stator voltage in the reference frame aligned with the rotor For a description of the DQ-transform used to compute this value, see **DQ Transform**
Quadrature Axis Stator Voltage	V_q	Output	Volts	0 V	Quadrature-axis stator voltage in the reference frame aligned with the rotor For a description of the DQ-transform used to compute this value, see **DQ Transform**
Electrical Angle	$_e$	Output	Degrees	-90°	Position of the rotating magnetic field, defined by the **electrical angle equation** ⓘ If this signal is routed to a **Waveform Channel** or an **Analog Output Channel**, its value is expressed in Turns. The signal ranges in value from 0 to 1, with 1 representing a full rotation.
Electromagnetic Torque	T_e	Output	Nm	0 Nm	Torque generated through power at the stator. Refer to the **Torque Equation** of this model for more information.

Model Description

Permanent Magnet Synchronous Machines are common electrical machines in the the automotive and transportation industry. The PMSM is usually chosen because of its excellent power density (produced power over size or weight) or its capability to reach higher speed than others motor types. However, controlling a PMSM is usually more challenging when compared to other machine types. Since it is a synchronous machine, the controller must be aware of the rotor position at all times in order to properly control the torque. In addition, there is a chance of de-fluxing the magnet if the control is not stable, which would lead to a modification of the machine properties.

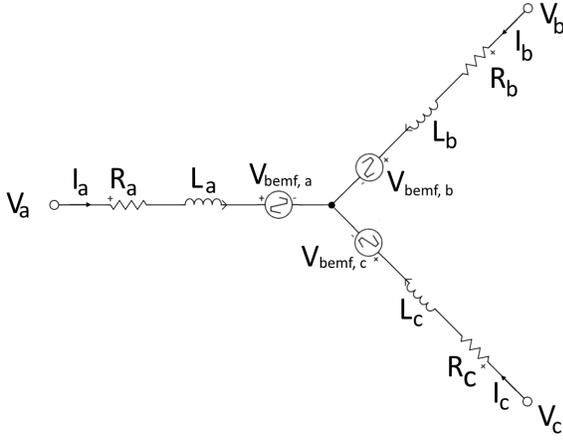The following figures illustrate the equivalent circuits of the PMSM motor model in the abc frame and in the DQ frame.
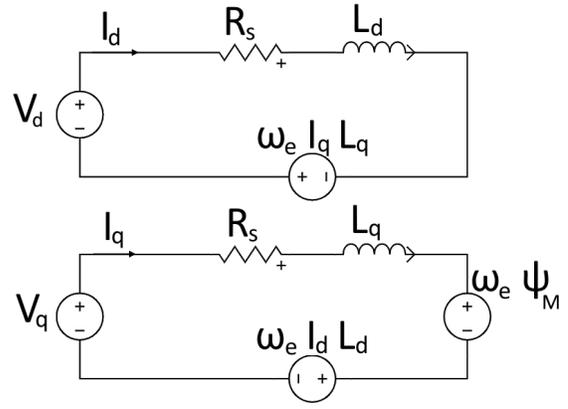
Figure 1. Electrical Model for PMSM

Figure 2. Electrical Model for PMSM in the DQ frame

General Equation

The equation of the PMSM model can be expressed as follows:

(2)
$$I_{abc} = [L_{abc}(\theta_e)]^{-1} \left\{ \int (V_{abc} - R_{abc} I_{abc}) dt - \psi_{abc} \right\}$$

where **L$_{abc}$** is the time-varying inductance matrix (global inductance for Constant Ld/Lq and Variable Ld/Lq models), **I$_{abc}$** is the stator current inside the winding, **R$_{abc}$** are the stator resistances and **V$_{abc}$** is the voltage across the stator windings. $_{abc}$ defines the magnet flux linked into the stator windings.

Electrical Angle

The electrical angle is expressed as follows:

(3)
$$\theta_e = pp * \theta_m + \theta_{offset}$$

DQ Transform

In normal conditions, the ideal stator voltages of the PMSM, back-EMFs, and inductances all have sinusoidal shapes. In the case of the BLDC, the back-EMFs are considered to be trapezoidal. One can transform the equation using the Park transformation with a referential locked on the rotor position $_r$ using (3) and (5).

(4)
$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \mathrm{T} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}$$

(5)
$$\mathrm{T} = \sqrt{2/3} \begin{bmatrix} \cos(\theta_r) & \sin(\theta_r) \\ -\sin(\theta_r) & \cos(\theta_r) \end{bmatrix} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$$

The DQ Transform (also called Park-Clarke transform) reduces sinusoidal varying quantities of inductances, flux, current, and voltage to constant values in the DQ frame thus greatly facilitating the analysis and control of the device under study.

It is important to note that there are many different types of DQ transforms and this often leads to confusion when interpreting the motor states inside the DQ frame. The one used here (which is typically standard in Japan) presents the advantage of being orthonormal (notice the sqrt(3/2) factor). This particular DQ orthonormal transform is power-invariant which means that the power computed in the DQ frame by performing a dot product of currents and voltages will be numerically equal to the one computed in the phase domain, namely:

(6)
$$V_{abc} I_{abc} = V_{dq} I_{dq}$$

Torque Equation

With this transform (and only this transform), the machine torque can be expressed by (7), where **pp** is the **number of pole pairs** and $\frac{\partial \psi_{abc}}{\partial \theta_r}$ is the partial derivative of the instantaneous permanent magnet flux.

$$(7) \qquad T_e = pp \left[I_{abc} \cdot \frac{\partial \psi_{abc}}{\partial \theta_r} + \left(L_d - L_q \right) i_d i_q \right]$$

In the case of the **PMSM Constant Ld/Lq** and **PMSM Variable Ld/Lq** motor types, the back EMF shape is sinusoidal and the torque can be further simplified into (8). Note that (8) does not apply to the **BLDC Constant Ls** motor type, whose back EMF shape is trapezoidal.

$$(8) \qquad T_e = pp \left[\sqrt{\frac{3}{2}}\, \psi_M\, i_q + \left(L_d - L_q \right) i_d i_q \right]$$

One may notice the absence of the 3/2 factor in (7) and (8), which is usually present in the PMSM torque equation when using non-orthonormal transforms. This is, again, because this model uses the orthonormal DQ transform. Figure 3 explains the principle of the Park transform. Considering fixed ABC referential with all quantities (V_{bemf}, motor current **I**) rotating at the electric frequency , if we observe these quantities in a DQ frame turning at the same speed we can see that the motor quantities will be constant.

This is easy to see for the Back-EMF voltage V_{bemf} that directly follows the Q-axis (because the magnet flux is on the D-axis by definition). In Figure 3, **I** leads and the Q-axis by an angle called (beta). The modulus of the vector **I** is called I_{amp}. In the figure below, is the rotor angle, aligned with the D-axis.
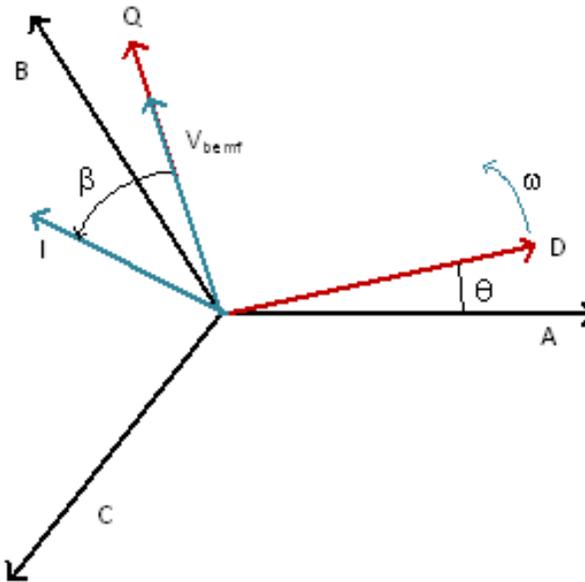

Figure 3. Park Transform with angle definitions for and

Power Equations

The instantaneous active and reactive power, P and Q are calculated as follows:

$$(9) \qquad \begin{aligned} P &= V_a I_a + V_b I_b + V_c I_c = V_d I_d + V_q I_q \\ Q &= \frac{1}{\sqrt{3}} \left[(V_b - V_c) I_a + (V_c - V_a) I_b + (V_a - V_b) I_c \right] = V_q I_d - V_d I_q \end{aligned}$$

where V_a, V_b, and V_c are the instantaneous stator voltages

The active and reactive power are processed through low-pass filters dependent on the timestep of the machine and are calculated as follows. When Ts is set to the minimum of 120ns, the cutoff frequencies are 133Hz:

(10)
$$f_c = \frac{1}{1 \times 10^4 \times Ts \times 2\pi} = \frac{1}{1 \times 10^4 \times 120 \times 10^{-9} \times 2\pi} = 133 Hz$$

Motor Type: PMSM Constant Ld/Lq

When set to the **PMSM Constant Ld/Lq** motor type, the machine model uses constant values for **Direct Inductance**, **Quadrature Inductance**, **Magnetic Flux**, **Phase [A, B, C] Resistance**, and **Pole Pairs**.

Configuration Parameters

The following parameters are available. They are modifiable at edit-time only:

	Symbol	Units	Default Value	Description
Direct Axis Inductance	L_d	Henry	0.002984 H	Direct-axis inductance of the machine
Quadrature Axis Inductance	L_q	Henry	0.004576 H	Quadrature-axis inductance of the machine
Permanent Magnet Flux Linkage	M	Weber	0.25366 Wb	Peak permanent magnet flux linkage
Phase A Resistance	R_a	Ohm	0.12	Phase A Resistance of the machine
Phase B Resistance	R_b	Ohm	0.12	Phase B Resistance of the machine
Phase C Resistance	R_c	Ohm	0.12	Phase C Resistance of the machine
Pole Pairs	pp		3	Number of pole pairs
Direct Quadrature Transform Angle Offset	offset		Aligned	Describes the electrical angle offset as described by the **Electrical Angle equation** • **Aligned** - Indicates that the D axis is aligned with Phase A when the rotor angle =0, which means that $_{offset}$ = -0 degrees. • **90 Degrees behind Phase A** - Indicates that the Q axis is aligned with Phase A when the rotor angle =0, which means that $_{offset}$ = -90 degrees
Initial Angle (Deg)	0	Degrees	0°	Initial Angle of the machine This may be useful when simulating two separate 3-phase machines that require a phase shift between them.
Solver Timestep	T_s	Second	1.2E-7 s	The timestep at which the machine model executes Every T_s, new outputs are computed by the FPGA machine model. By default, this is set to the minimum achievable timestep.

Motor Type: PMSM Variable Ld/Lq

When set to the **PMSM Variable Ld/Lq** motor type, the inductance and magnetic flux parameters are variable based on the operating state of the simulation, as defined in the **JSON Motor Model File**.

Configuration Parameters

The following parameters are available. They are modifiable at edit-time only:

	Symbol	Units	Default Value	Description
Model File				Specifies the path to the JSON Motor Model file on disk. Refer to **Motor Model File [JSON]** for details regarding the file format.

Channel Name	Symbol	Units	Default Value	Description
Enable Advanced Channels			False	Allows certain parameters to be exposed as tunable VeriStand Channels. See the **Advanced Channels** section below for more details. This checkbox is only available when a Motor Model File has been specified. Otherwise, the option is greyed out.
Initial Angle (Deg)	0	Degrees	0°	Initial Angle of the machine This may be useful when simulating two separate 3-phase machines that require a phase shift between them.
Solver Timestep	T_s	Second	1.2E-7 s	The timestep at which the machine model executes Every T_s, new outputs are computed by the FPGA machine model. By default, this is set to the minimum achievable timestep.

Advanced Channels

The following VeriStand channels are displayed under the **Advanced** section when the **Enable Advanced Channels** option is enabled on the PMSM Variable Ld/Lq configuration page. Channel values can be modified dynamically at execution time.

Channel Name	Symbol	Type	Units	Default Value	Description
Direct Axis Inductance Override	L_d	Input	Henry	0.002984 H	Direct-axis inductance of the machine When **Enable Inductance Override** is True, this value overrides the direct axis inductance value defined in the **JSON Motor Model File** table. When **Enable Inductance Override** is False, this channel is not used. This value can be modified while the simulation is running.
Enable Permanent Magnet Flux Linkage Override		Input		False	Enables the **Flux Linkage Override** channel, allowing the user to modify the permanent magnet flux linkage of the machine while the simulation is running. When True, the flux linkage of the machine is read from the **Flux Linkage Override** channel. When False, the flux linkage is read from the table in the **JSON Motor Model File**.
Enable Inductance Override		Input		False	Enables the **Direct Inductance Override** and **Quadrature Inductance Override** channels, allowing the user to modify the inductances of the machine while the simulation is running. When True, the inductances of the machine are read from the **Direct Inductance Override** and **Quadrature Inductance Override** channels. When False, the direct axis and quadrature axis inductances are read from the table in the **JSON Motor Model File**.
Enable Resistance Override		Input		False	Enables the **Resistance Phase A Override, Resistance Phase B Override,** and **Resistance Phase C Override** channels, allowing the user to modify the phase resistances of the machine while the simulation is running. When True, the phase resistances of the machine are read from the **Resistance Phase A Override, Resistance Phase B Override,** and **Resistance Phase C Override** channels. When False, the phase resistances are read from the table in the **JSON Motor Model File**.
Permanent Magnet Flux Linkage Override	M	Input	Weber	0.25366 Wb	Permanent magnet flux linkage of the machine When the **Enable Flux Linkage Override** channel is set to True, instead of reading the Flux Linkage from the 2D $_M$ lookup table defined in the Model File, the motor model will use the following scalar channel value as an input. When **Enable Flux Linkage Override** is True, this value overrides the flux linkage value defined in the **JSON Motor Model File** table. When **Enable Flux Linkage Override** is False, this channel is not used. This channel value can be modified while the simulation is running.
Quadrature Axis Inductance Override	L_q	Input	Henry	0.004576 H	Quadrature-axis inductance of the machine When **Enable Inductance Override** is True, this value overrides the direct axis inductance value defined in the **JSON Motor Model File** table. When **Enable Inductance Override** is False, this channel is not used. This value can be modified while the simulation is running.

Resistance Phase A Override	R_a	Input	Ohm	Read from JSON Model File when Advanced Channels are enabled	Phase A resistance of the machine When **Enable Resistance Override** is True, this value overrides the Phase A resistance value defined in the **JSON Motor Model File**. When **Enable Resistance Override** is False, this channel is not used. This channel value can be modified while the simulation is running.
Resistance Phase B Override	R_b	Input	Ohm	Read from JSON Model File when Advanced Channels are enabled	Phase B resistance of the machine When **Enable Resistance Override** is True, this value overrides the Phase B resistance value defined in the **JSON Motor Model File**. When **Enable Resistance Override** is False, this channel is not used. This channel value can be modified while the simulation is running.
Resistance Phase C Override	R_c	Input	Ohm	Read from JSON Model File when Advanced Channels are enabled	Phase C resistance of the machine When **Enable Resistance Override** is True, this value overrides the Phase C resistance value defined in the **JSON Motor Model File**. When **Enable Resistance Override** is False, this channel is not used. This channel value can be modified while the simulation is running.

Motor Type: BLDC Constant Ls

When set to the **BLDC Constant L$_S$** motor type, the machine model uses constant values for **Stator Inductance**, **Magnetic Flux**, **Phase [A, B, C] Resistance**, and **Pole Pairs**. The main difference between the PMSM and the BLDC motor types lies in the shape of the back EMF voltage, which is trapezoidal in the case of the BLDC.

Configuration Parameters

The following parameters are available. They are modifiable at edit-time only:

	Symbol	Units	Default Value	Description
Stator Inductance	L_s	Henry	0.002984 H	Stator inductance of the machine
Back EMF Flat Area	H	Degrees	0	Describes the length of the flat area in degrees of the trapezoidal back-EMF wave Please see **Trapezoidal Back-EMF Characteristics** for a description of the wave.
Initial Angle (Deg)	$_0$	Degrees	0°	Initial Angle of the machine This may be useful when simulating two separate 3-phase machines that require a phase shift between them.
Permanent Magnet Flux Linkage	M	Weber	0.25366 Wb	Peak permanent magnet flux linkage
Phase A Resistance	R_a	Ohm	0.12	Phase A Resistance of the machine
Phase B Resistance	R_b	Ohm	0.12	Phase B Resistance of the machine
Phase C Resistance	R_c	Ohm	0.12	Phase C Resistance of the machine
Pole Pairs	pp		3	Number of pole pairs
Direct Quadrature Transform Angle Offset	$_{offset}$		Aligned	Describes the electrical angle offset as described by the **Electrical Angle equation** • **Aligned** - Indicates that the D axis is aligned with Phase A when the rotor angle =0 • **90 Degrees behind Phase A** - Indicates that the Q axis is aligned with Phase A when the rotor angle =0, which means that $_{offset}$ = -90 degrees.
Solver Timestep	T_s	Second	1.2E-7 s	The timestep at which the machine model executes Every T_s, new outputs are computed by the FPGA machine model. By default, this is set to the minimum achievable timestep.

Trapezoidal Back-EMF Characteristics

The BLDC has a trapezoidal back EMF shape that is calculated using $_m$, the permanent magnet flux linkage, and **H**, the length of the flat portion of the trapezoid in degrees.
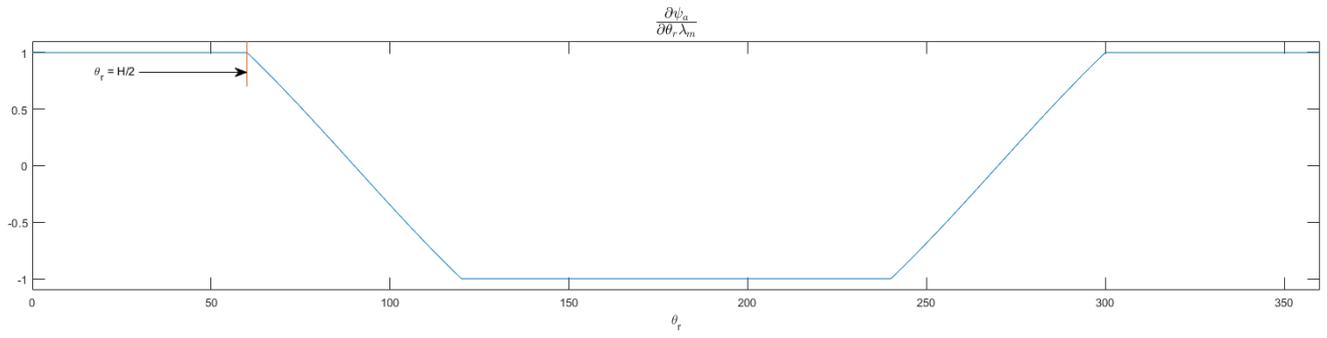
The electromotive force is constructed from a cosine table as described in the following equation:

(11)
$$\frac{\partial \psi_a}{\partial \theta_r \, \lambda_M} = max(min(\frac{cos(\theta_r)}{cos(\frac{H}{2})}, 1), -1)$$