PMSM SH Section

The PMSM SH model defines the Inductance Matrices Ld and Lq within a three-dimensional table stored in an RTT motor model file. Because the tables are three-dimensional rather than two-dimensional, the PMSM SH model can provide higher fidelity than the PMSM BLDC model. Please see **Permanent Magnet Synchronous Machine Models Comparison** for a comparison of the PMSM SH and PMSM BLDC models.

Configuration Page

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

This page includes the following components:

Name	Specifies the name of the machine model.
Description	Specifies a description for the machine model.
Model File	Specifies the path to the 3D Motor Model file on disk. Refer to **JMAG-RT RTT File Generation Recommendations** for details regarding the file format. The following standards are supported: • ANSYS (.txt) • JMAG (.rtt)
Enable	Enables the motor to execute. By default, the first PMSM SH instance is enabled, however, it is recommended to disable unused motors for an optimal timestep.
Initial Angle (Deg)	Initial Angle of the machine This may be useful when simulating two separate 3-phase machines that require a phase shift between them.
Enable Advanced Channels	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 the machine is enabled. Otherwise, the option is greyed out.
Solver Timestep (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.
Table Max Current (Amp)	Maximum current value that will be used to interpolate the model file. Use this feature to increase the resolution of the machine at lower Current operating points. This will reduce the machine operating range. Use -1 to use the full range available in model file.
DQ Angle Offset (Degrees)	Specifies the electrical angle offset $_{\mathbf{offset}}$ as described by the equation below $$\theta_e = pp * \theta_m + \theta_{offset}$$ By default, this parameter is set to **0 degrees**, which indicates the the D axis is aligned with Phase A when the rotor angle =0. Setting this parameter to **-90 Degrees** indicates that the Q axis is aligned with Phase A when the rotor angle =0.
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 Phase 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 Phase 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 159 Hz
Average Voltage Phase 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 159 Hz
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 **D-Q 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 **D-Q 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. For equations describing the electromagnetic torque of each type of machine, refer to their specific description pages under the **Machine Section**.

Advanced Channels

The following VeriStand channels are displayed under the **Advanced** section when the **Enable Advanced Channels** option is enabled on the PMSM SH configuration page.

Channel Name	Symbol	Type	Units	Default Value	Description
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 3D Motor Model File (JMAG .rtt or ANSYS .txt) Enabling these channels allows the user to reduce the machine signal error in high impedance conditions. Refer to the procedure on **How to Reduce PMSM SH Signal Error In High Impedance Conditions** for more information.
Resistance Phase A Override	R_a	Input	Ohm	0.12	Phase A resistance of the machine When **Enable Resistance Override** is True, this value overrides the Phase A resistance value defined in the 3D Motor Model File (JMAG .rtt or ANSYS .txt). 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	0.12	Phase B resistance of the machine When **Enable Resistance Override** is True, this value overrides the Phase B resistance value defined in the 3D Motor Model File (JMAG .rtt or ANSYS .txt). 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	0.12	Phase C resistance of the machine When **Enable Resistance Override** is True, this value overrides the Phase C resistance value defined in the 3D Motor Model File (JMAG .rtt or ANSYS .txt). When **Enable Resistance Override** is False, this channel is not used. This channel value can be modified while the simulation is running.

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 D-Q frame.

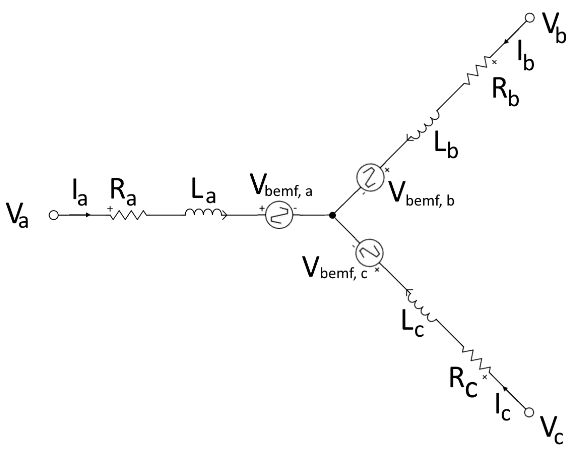

Figure 1. Electrical Model for PMSM

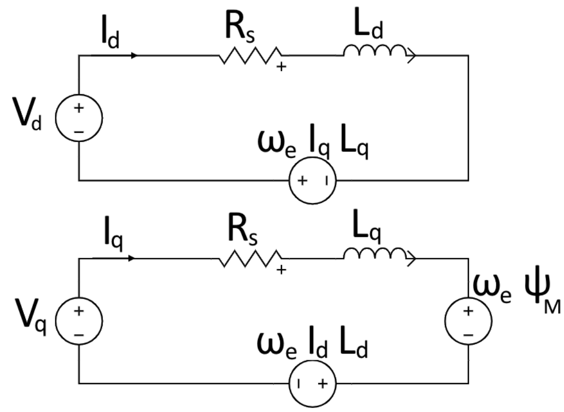

Figure 2. Electrical Model for PMSM in the D-Q frame

where $\mathbf{L_{abc}}$ are the phase inductances, $\mathbf{R_{abc}}$ are the stator resistances, $\mathbf{V_{abc}}$ are the instantaneous voltages across the stator windings, $\mathbf{V_{bemf,abc}}$ are the phase to neutral voltages induced by the electromotive forces, $\mathbf{V_{dq}}$ are the direct-axis and quadrature-axis stator voltages in the reference frame aligned with the rotor, $\mathbf{L_{dq}}$ are the direct-axis and quadrature-axis inductances of the machine, $_e$ is the electrical speed of the machine, and $_M$ is the permanent magnet flux linkage

General Equation

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

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

where $\mathbf{L_{abc}}$ is the time-varying inductance matrix (global inductance for Constant Ld/Lq and Variable Ld/Lq models), $\mathbf{I_{abc}}$ is the stator current inside the winding, $\mathbf{R_{abc}}$ are the stator resistances and $\mathbf{V_{abc}}$ 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)
$$\theta_e = pp * \theta_m + \theta_{offset}$$

D-Q Transform

In normal conditions, the ideal sinusoidal 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 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)

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

The D-Q Transform (also called Park-Clarke transform) reduces sinusoidal varying quantities of inductances, flux, current, and voltage to constant values in the D-Q 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 D-Q transforms and this often leads to confusion when interpreting the motor states inside the D-Q 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 D-Q orthonormal transform is power-invariant which means that the power computed in the D-Q 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**.

(7)

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

One may notice the absence of the 3/2 factor in (7), which is usually present in the PMSM torque equation when using non-orthonormal transforms. This is, again, because this model uses the orthonormal D-Q transform. Figure 3 explains the principle of the Park transform. Considering fixed ABC referential with all quantities ($\boldsymbol{V_{bemf}}$, *motor current **I***) rotating at the electric frequency , if we observe these quantities in a D-Q 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 $\boldsymbol{V_{bemf}}$ 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 $\boldsymbol{I_{amp}}$. In the figure below, is the rotor angle, aligned with the D-axis.

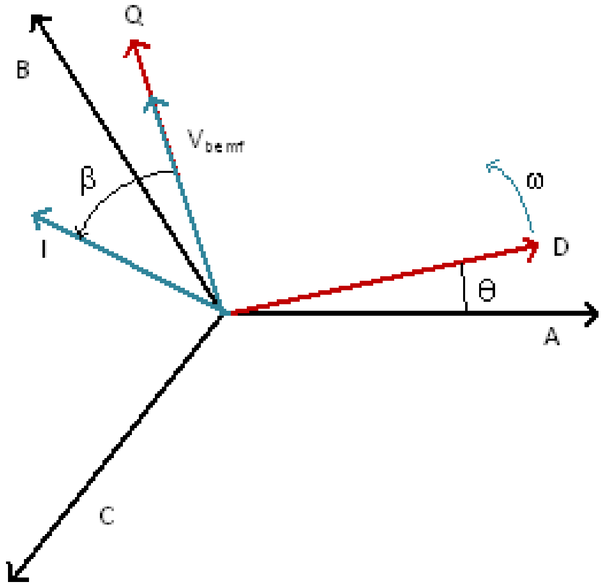

Figure 3. Park Transform with angle definitions for and

Power Equations

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

(8)
$$P = V_a I_a + V_b I_b + V_c I_c = V_d I_d + V_q I_q$$
$$Q = \frac{1}{\sqrt{3}}[(V_b - V_c)I_a + (V_c - V_a)I_b + (V_a - V_b)I_c] = V_q I_d - V_d I_q$$

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:

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