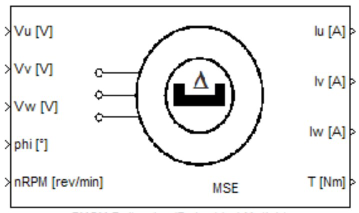
Permanent Magnet Synchronous Machine in *delta abc* (EMPSMD3E01MSEREF) Documentation

July 30, 2021



PMSM Delta abc (Embedded Matlab)
<EMPSMD3E01MSEREF>

Description

In the following $\omega = n_{\mathrm{RPM}} \cdot \frac{\pi}{30}$ is used.

This is a model of a permanent magnet synchronous machine in delta connection. The electric part of the machine is described by the linear state space model of the background documentation. The mechanical port (torque output, phase angular input) can be used to model the mechanical part (eg. inertia).
The EMPSMY301MSEREF model can handle salient poles which are represented by Fourier series describing inductances and permanent magnet flux. Magnetic conditions are assumed to be linear (i.e. no magnetic saturation, no hysteresis) and no eddy currents are considered. The machine is configured symmetrically w.r.t. inductances and resistances.

Features

- Uses Embedded MATLAB

Application area

For more information about the application area, please consult the overview documentation.

Model assumptions and limits

- Linear magnetic conditions: these are normally fulfilled when the motor operates in the vicinity of the idle speed.
- Symmetric configuration wrt inductances and resistances: please consult the background documentation. With this assumption, it is not possible to simulate unbalanced phases, but the model parametrization is simplified.
- Generating mode on open-circuit only (*Simulink* restriction): in generating mode, a machine connected to an electrical load is equivalent to a voltage source: it delivers three voltage waveforms and inputs three current waveforms. This signal flow definition is not compatible with the motoring mode, where the input signals are three voltage waveforms and the output signals three current waveforms. In generating mode and on open-circuit, the voltage waveforms delivered by the machine are equal to the emf voltage waveforms computed by this model. That is the reason why this last case can be considered in this model.
- Robust implementation for $l_0 >> 2 \cdot m_0$ only: to solve the electrical equations given by (1), the inductance matrix is currently inversed numerically. This inversion is not robust when the value of l_0 is close to the value of $2 \times m_0$ (the determinant of this matrix is close to zero and the matrix is bad conditioned).

Model equations

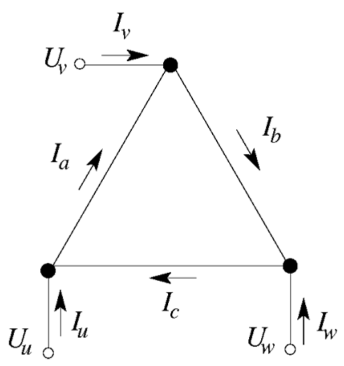


Figure 1: Currents and Votages in delta connection

The system has three states $[I_a, I_b, I_c]$, which are computed by:

$$\boxed{\frac{dI_{abc}}{dt} = \mathcal{L}^{-1}(\varphi)\left(-\frac{d\lambda(\varphi)}{d\varphi}\omega - \mathcal{R}I + V_{diff}\right)} \tag{1}$$

where

$$\boxed{V_{diff} = \begin{pmatrix} V_u - V_v \\ V_v - V_w \\ V_w - V_u \end{pmatrix}} \tag{2}$$

The outputs equations are

$$\boxed{\begin{pmatrix} I_u \\ I_v \\ I_w \end{pmatrix} = \begin{pmatrix} I_a - I_c \\ I_b - I_a \\ I_c - I_b \end{pmatrix}} \tag{3}$$

$$\boxed{T = \sum_{i=a,b,c} \underbrace{\left(\frac{d\lambda_{\mathrm{pm},i}}{d\varphi} I_{\mathrm{i}}\right.}_{T_{\mathrm{pm}}} + \underbrace{\left.\frac{1}{2}\frac{dL_i}{d\varphi} I_{\mathrm{i}}^2\right) - \left(\frac{dM_{\mathrm{ab}}}{d\varphi} I_{\mathrm{a}} I_{\mathrm{b}} + \frac{dM_{\mathrm{ac}}}{d\varphi} I_{\mathrm{a}} I_{\mathrm{c}} + \frac{dM_{\mathrm{bc}}}{d\varphi} I_{\mathrm{b}} I_{\mathrm{c}}\right)}_{T_{\mathrm{reluc}}}} \tag{4}$$

Moreover

$$\mathcal{L}(\varphi) = \begin{pmatrix} L_{\mathrm{a}}(\varphi) & -M_{\mathrm{ab}}(\varphi) & -M_{\mathrm{ac}}(\varphi) \\ -M_{\mathrm{ab}}(\varphi) & L_{\mathrm{b}}(\varphi) & -M_{\mathrm{bc}}(\varphi) \\ -M_{\mathrm{ac}}(\varphi) & -M_{\mathrm{bc}}(\varphi) & L_{\mathrm{c}}(\varphi) \end{pmatrix}. \tag{5}$$

with

$$L_{\mathrm{a}}(\varphi) = \sum_{k=0}^{4}(l_k \cos(kN\varphi)),\ L_{\mathrm{b}}(\varphi) = L_{\mathrm{a}}\left(\varphi - \frac{1}{N}\frac{2\pi}{3}\right),\ L_{\mathrm{c}}(\varphi) = L_{\mathrm{a}}\left(\varphi - \frac{1}{N}\frac{4\pi}{3}\right) \tag{6}$$

$$M_{\mathrm{bc}}(\varphi) = \sum_{k=0}^{4}(m_k \cos(kN\varphi)),\ M_{\mathrm{ac}}(\varphi) = M_{\mathrm{bc}}\left(\varphi - \frac{1}{N}\frac{2\pi}{3}\right),\ M_{\mathrm{ab}}(\varphi) = M_{\mathrm{bc}}\left(\varphi - \frac{1}{N}\frac{4\pi}{3}\right), \tag{7}$$

and flux is given by

$$\lambda_{\mathrm{a}} = L_{\mathrm{a}}(\varphi)I_{\mathrm{a}} - M_{\mathrm{ab}}(\varphi)I_{\mathrm{b}} - M_{\mathrm{ac}}(\varphi)I_{\mathrm{c}} + \lambda_{\mathrm{pm},a}(\varphi) \tag{8a}$$
$$\lambda_{\mathrm{b}} = L_{\mathrm{b}}(\varphi)I_{\mathrm{b}} - M_{\mathrm{ab}}(\varphi)I_{\mathrm{a}} - M_{\mathrm{bc}}(\varphi)I_{\mathrm{c}} + \lambda_{\mathrm{pm},b}(\varphi) \tag{8b}$$
$$\lambda_{\mathrm{c}} = L_{\mathrm{c}}(\varphi)I_{\mathrm{c}} - M_{\mathrm{ac}}(\varphi)I_{\mathrm{a}} - M_{\mathrm{bc}}(\varphi)I_{\mathrm{b}} + \lambda_{\mathrm{pm},c}(\varphi) \tag{8c}$$

where

$$\lambda_{\mathrm{pm},a}(\varphi) = K_m \cos(N\varphi) + a_3 \cos(3N\varphi) + a_5 \cos(5N\varphi) + a_7 \cos(7N\varphi) \tag{9a}$$

$$\lambda_{\mathrm{pm},b}(\varphi) = \lambda_{\mathrm{pm},a}\left(\varphi - \frac{1}{N}\frac{2\pi}{3}\right), \quad \lambda_{\mathrm{pm},c}(\varphi) = \lambda_{\mathrm{pm},a}\left(\varphi - \frac{1}{N}\frac{4\pi}{3}\right). \tag{9b}$$

See the background documentation for further information.

Advices about how to connect this block to three sine/cosine voltage sources

When the PMSM is connected to three balanced potential sources V_u, V_v and V_w (directly using three sine voltages or indirectly using a B6-bridge), it is necessary to configure them correctly with respect to phase offsets and amplitude to get correct phase current waveforms and mechanical torque.

To simply and quickly connect this PMSM block to three balanced cosine respectively sine voltage sources (representing a pure D respectively Q voltage in the DQ coordinate system), it is recommended to use the dq to abc transformation block from the MSERef emachines library, see Figure 2. This block combination can then be extended to consider more effects in the PMSM's control strategy (e.g., advance angle for turn-on[1]).

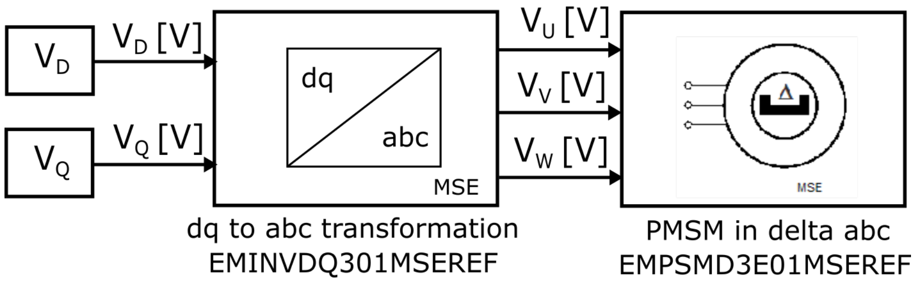


Figure 2: PMSM block connected to three balanced potential sources.

As illustration, the Figure 3 documents the potentials V_U, V_V and V_W at the PMSM terminals, the line currents I_U, I_V and I_W, the motor torque T and the rotor position φ that are expected with following parametrization[2]:

- $V_Q = 17\ [V]$
- $n_{RPM} = 20000\ [rev/min]$
- $N = 8\ [-]$

[1] Also called *Vorkommutierungswinkel*.
[2] Only the parameters with a value different from zero are documented here.

- $R = 95\ [m\Omega]$
- $L = 50\ [\mu H]$
- $K_m = 2.5\ [mVs]$

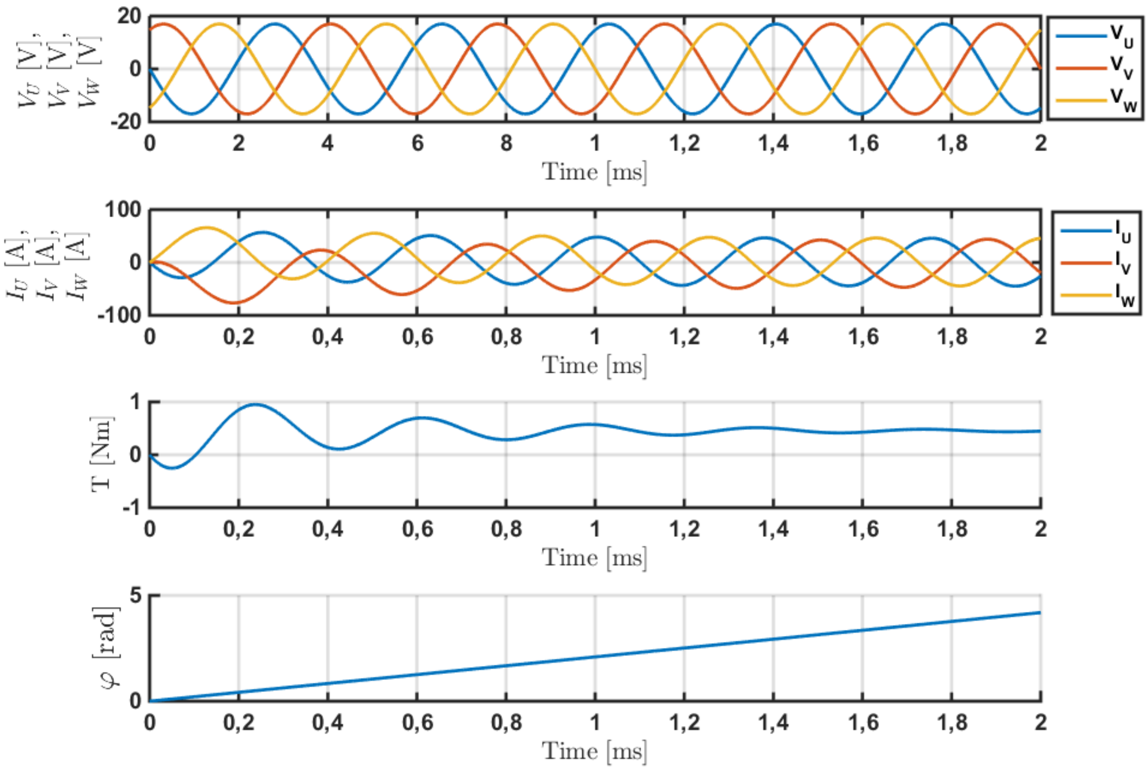


Figure 3: Potentials at the PMSM terminals (V_U, V_V and V_W), line currents (I_U, I_V and I_W), motor torque T and rotor position φ.

Model validation

This model was validated for a brushless DC motor designed for customer goods applications (impact wrench). For more information about the model validation, please consult [1].

Code Generation

To inquire if it is principally possible to generate code from this block, please consult the related *Code generation* section in the overview documentation.

Parameters

Type[3]	Name	Description	Symbol	Unit	Default	Values
Initial values						
F	`xIainit`	Initial Stator current, phase a	I_{a0}	A	0.0	$[-10^9, 10^9]$
F	`xIbinit`	Initial Stator current, phase b	I_{b0}	A	0.0	$[-10^9, 10^9]$
F	`xIcinit`	Initial Stator current, phase c	I_{c0}	A	0.0	$[-10^9, 10^9]$
Parameters						
I	`N`	Number of pole pairs N	N		2	$[1, 1000]$
F	`r_m`	Winding resistance R	R	Ω	0.1	$[0, 10^9]$
FV	`l` [size=5]	Self inductance [l0 l1 l2 l3...]	L	H	[1e-4 0 0.1e-4 0 0]	$[-10^9, 10^9]$
FV	`m` [size=5]	Mutal inductance [m0 m1 m2 m3...]	M	H	[1e-5 0 0.1e-5 0 0]	$[-10^9, 10^9]$
F	`Km`	Fundamental of flux Km	K_m	V s	0.005	$[0, 10^9]$
FV	`a357` [size=3]	Flux harmonic [a3 a5 a7...]	$a357$	V s	[1/9 1/25 1/49]*5e-3	$[-10^9, 10^9]$

Ports

Inputs

Direction	Type	Name	Symbol	Description	Unit
input	Float	`Vu`	V_u	Stator voltage line u	V
input	Float	`Vv`	V_v	Stator voltage line v	V
input	Float	`Vw`	V_w	Stator voltage line w	V
input	Float	`phi`	φ	Rotor position	deg
input	Float	`nRPM`	n_{RPM}	Rotor speed	rev min^{-1}

[3] I: Integer parameter, FV: Float parameter vector, F: Float parameter

Outputs

Direction	Type	Name	Symbol	Description	Unit
output	Float	`Iu`	I_u	Stator current line u	A
output	Float	`Iv`	I_v	Stator current line v	A
output	Float	`Iw`	I_w	Stator current line w	A
output	Float	`T`	T	Motor torque	N m
output	Float	`Vstar`	V_{star}	Star point voltage	V

States

Type[4]	Name	Symbol	Description	Unit	Initial Value
CS	`xIa`	I_{a}	Stator current, phase a	A	xIainit
CS	`xIb`	I_{b}	Stator current, phase b	A	xIbinit
CS	`xIc`	I_{c}	Stator current, phase c	A	xIcinit

References

[1] A. Vandamme S. Laber. Functional modelling of a brushless DC motor, implementation in SimScape using MSE methods, parameterization using SPEED PC-BDC, validation with measurements. Report 2664, CR/AEH1, 2012.

[4] CS: Continuous state

