BLDC

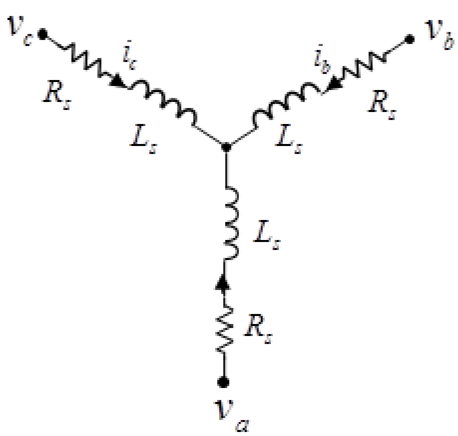
Three-winding brushless DC motor with trapezoidal flux distribution

Library: Simscape / Electrical / Electromechanical / Permanent Magnet

Description

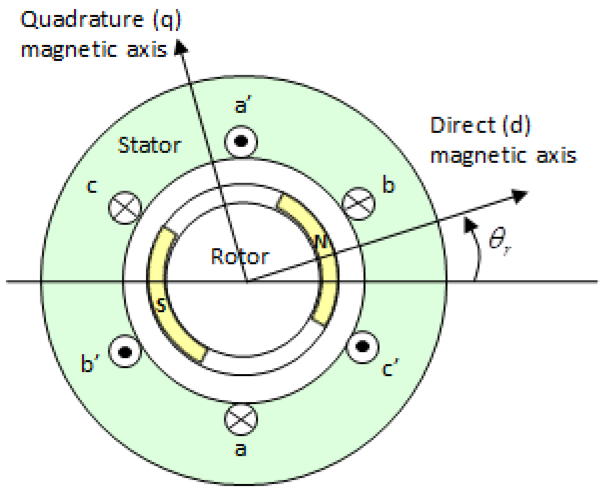
The BLDC block models a permanent magnet synchronous machine with a three-phase wye-wound stator. The block has four options for defining the permanent magnet flux distribution as a function of rotor angle. Two options allow for simple parameterization by assuming a perfect trapezoid for the back emf. For simple parameterization, you specify either the flux linkage or the rotor-induced back emf. The other two options give more accurate results using tabulated data that you specify. For more accurate results, you specify either the flux linkage partial derivative or the measured back emf constant for a given rotor speed.

The figure shows the equivalent electrical circuit for the stator windings.



Motor Construction

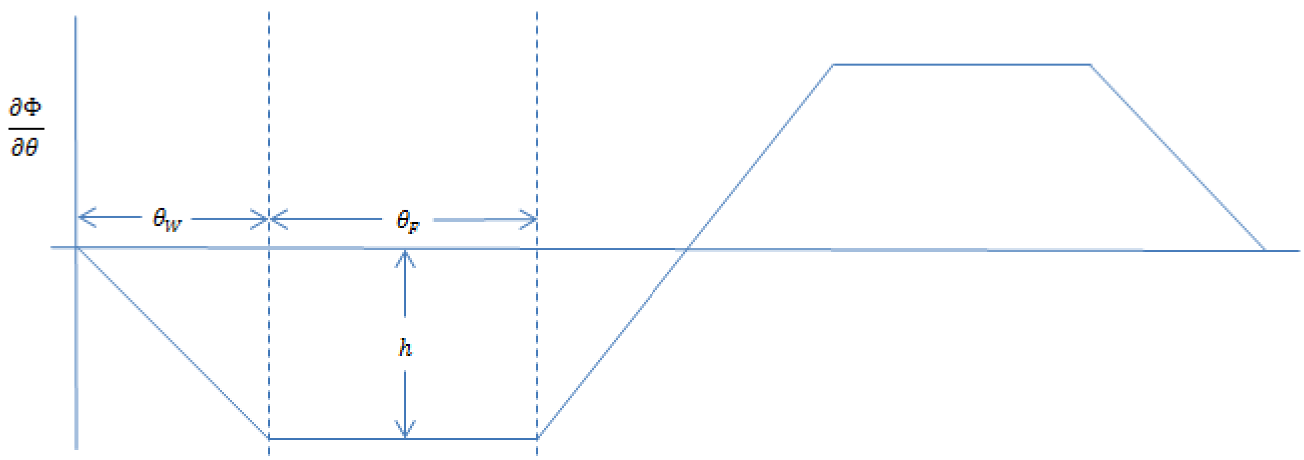
This figure shows the motor construction with a single pole-pair on the rotor.



For the axes convention in the preceding figure, the a-phase and permanent magnet fluxes are aligned when rotor angle θ_r is zero. The block supports a second rotor-axis definition. For the second definition, the rotor angle is the angle between the a-phase magnetic axis and the rotor q-axis.

Trapezoidal Rate of Change of Flux

The rotor magnetic field due to the permanent magnets create a trapezoidal rate of change of flux with rotor angle. The figure shows this rate of change of flux.



Back emf is the rate of change of flux, defined by

$$\frac{d\Phi}{dt} = \frac{\partial \Phi}{\partial \theta}\frac{d\theta}{dt} = \frac{\partial \Phi}{\partial \theta}\omega,$$

where:

- Φ is the permanent magnet flux linkage.
- θ is the rotor angle.
- ω is the mechanical rotational speed.

The height h of the trapezoidal rate of change of flux profile is derived from the permanent magnet peak flux.

Integrating $\frac{\partial \Phi}{\partial \theta}$ over the range 0 to π/2,

$$\Phi_{max} = \frac{h}{2}(\theta_F + \theta_W),$$

where:

- Φ_{max} is the permanent magnet flux linkage.

- h is the rate of change of flux profile height.
- θ_F is the rotor angle range over which the back emf that the permanent magnet flux induces in the stator is constant.
- θ_W is the rotor angle range over which back emf increases or decreases linearly when the rotor moves at constant speed.

Rearranging the preceding equation,

$$h = 2\Phi_{max}/(\theta_F + \theta_W).$$

Electrical Defining Equations

Voltages across the stator windings are defined by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \frac{d\psi_a}{dt} \\ \frac{d\psi_b}{dt} \\ \frac{d\psi_c}{dt} \end{bmatrix},$$

where:

- v_a, v_b, and v_c are the external voltages applied to the three motor electrical connections.
- R_s is the equivalent resistance of each stator winding.
- i_a, i_b, and i_c are the currents flowing in the stator windings.
- $\frac{d\psi_a}{dt}, \frac{d\psi_b}{dt}$, and $\frac{d\psi_c}{dt}$

  are the rates of change of magnetic flux in each stator winding.

The permanent magnet and the three windings contribute to the total flux linking each winding. The total flux is defined by

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \psi_{am} \\ \psi_{bm} \\ \psi_{cm} \end{bmatrix},$$

where:

- ψ_a, ψ_b, and ψ_c are the total fluxes linking each stator winding.
- L_{aa}, L_{bb}, and L_{cc} are the self-inductances of the stator windings.
- L_{ab}, L_{ac}, L_{ba}, etc. are the mutual inductances of the stator windings.
- ψ_{am}, ψ_{bm}, and ψ_{cm} are the permanent magnet fluxes linking the stator windings.

The inductances in the stator windings are functions of rotor angle, defined by

$$L_{aa} = L_s + L_m \cos(2\theta_r),$$

$$L_{bb} = L_s + L_m \cos(2(\theta_r - 2\pi/3)),$$

$$L_{cc} = L_s + L_m \cos(2(\theta_r + 2\pi/3)),$$

$$L_{ab} = L_{ba} = -M_s - L_m \cos(2(\theta_r + \pi/6)),$$

$$L_{bc} = L_{cb} = -M_s - L_m \cos(2(\theta_r + \pi/6 - 2\pi/3)),$$

and

$$L_{ca} = L_{ac} = -M_s - L_m \cos(2(\theta_r + \pi/6 + 2\pi/3)),$$

where:

- L_s is the stator self-inductance per phase — The average self-inductance of each of the stator windings.
- L_m is the stator inductance fluctuation — The amplitude of the fluctuation in self-inductance and mutual inductance with changing rotor angle.
- M_s is the stator mutual inductance — The average mutual inductance between the stator windings.

The permanent magnet flux linking each stator winding follows the trapezoidal profile shown in the figure. The block implements the trapezoidal profile using lookup tables to calculate permanent magnet flux values.

Simplified Equations

The defining voltage and torque equations for the block are

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = P\left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - N\omega \begin{bmatrix} \dfrac{\partial\psi_{am}}{\partial\theta_r} \\ \dfrac{\partial\psi_{bm}}{\partial\theta_r} \\ \dfrac{\partial\psi_{cm}}{\partial\theta_r} \end{bmatrix} \right),$$

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - N\omega i_q L_q,$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + N\omega i_d L_d,$$

$$v_0 = R_s i_0 + L_0 \frac{di_0}{dt},$$

and

$$T = \frac{3}{2}N(i_q i_d L_d - i_d i_q L_q) + \begin{bmatrix} i_a & i_b & i_c \end{bmatrix} \begin{bmatrix} \dfrac{\partial\psi_{am}}{\partial\theta_r} \\ \dfrac{\partial\psi_{bm}}{\partial\theta_r} \\ \dfrac{\partial\psi_{cm}}{\partial\theta_r} \end{bmatrix},$$

where:

- v_d, v_q, and v_0 are the d-axis, q-axis, and zero-sequence voltages.
- P is Park's Transformation, defined by

$$P = 2/3 \begin{bmatrix} \cos\theta_e & \cos(\theta_e - 2\pi/3) & \cos(\theta_e + 2\pi/3) \\ -\sin\theta_e & -\sin(\theta_e - 2\pi/3) & -\sin(\theta_e + 2\pi/3) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}.$$

- N is the number of rotor permanent magnet pole pairs.
- ω is the rotor mechanical rotational speed.
- $\dfrac{\partial\psi_{am}}{\partial\theta_r}$, $\dfrac{\partial\psi_{bm}}{\partial\theta_r}$, and $\dfrac{\partial\psi_{cm}}{\partial\theta_r}$

  are the partial derivatives of instantaneous permanent magnet flux linking each phase winding.
- i_d, i_q, and i_0 are the d-axis, q-axis, and zero-sequence currents, defined by

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}.$$

- $L_d = L_s + M_s + 3/2\ L_m$. L_d is the stator d-axis inductance.
- $L_q = L_s + M_s - 3/2\ L_m$. L_q is the stator q-axis inductance.
- $L_0 = L_s - 2M_s$. L_0 is the stator zero-sequence inductance.
- T is the rotor torque. Torque flows from the motor case (block physical port C) to the motor rotor (block physical port R).

Variables

Use the **Variables** settings to specify the priority and initial target values for the block variables before simulation. For more information, see Set Priority and Initial Target for Block Variables (Simscape).

Ports

Conserving

expand all

~ — Three-phase port
electrical

n — Neutral phase
electrical

R — Motor rotor
mechanical

C — Motor case
mechanical

Parameters

expand all

Rotor

`Winding type` — Windings configuration
`Wye-wound` (default) | `Delta-wound`

`Back EMF profile` — Back EMF profile
`Perfect trapezoid - specify maximum flux linkage` (default) | `Perfect trapezoid - specify maximum rotor-induced back emf` | `Tabulated - specify flux partial derivative with respect to rotor angle` | `Tabulated - specify rotor-induced back emf as a function of rotor angle`

`Maximum permanent magnet flux linkage` — Maximuym permanent magnet flux linkage
`0.03 Wb` (default)

Rotor angle over which back emf is constant — **Rotor angle over which back emf is constant**
pi / 12 rad (default)

Maximum rotor-induced back emf — **Maximum rotor-induced back emf**
9.6 V (default)

Rotor-induced back emf — **Rotor-induced back emf**
[0, -9.6, -9.6, 9.6, 9.6, 0] V (default)

Flux linkage partial derivative with respect to rotor angle — **Flux linkage partial derivative with respect to rotor angle**
[0, -.1528, -.1528, .1528, .1528, 0] Wb/rad (default)

Corresponding rotor angles — **Corresponding rotor angles**
[0, 7.5, 22.5, 37.5, 52.5, 60] deg (default)

Rotor speed used for back emf measurement — **Rotor speed used for back emf measurement**
600 rpm (default)

Number of pole pairs — **Number of pole pairs**
6 (default)

Zero sequence — **Zero sequence option**
Include (default) | Exclude

Rotor angle definition — **Reference point for the rotor angle measurement**
Angle between the a-phase magnetic axis and the d-axis (default) | Angle between the a-phase magnetic axis and the q-axis

Stator

Stator parameterization — **Stator parameterization**
Specify Ld, Lq, and L0 (default) | Specify Ls, Lm, and Ms

Stator d-axis inductance, Ld — **Stator d-axis inductance**
0.00022 H (default)

Stator q-axis inductance, Lq — **Stator q-axis inductance**
0.00022 H (default)

`Stator zero-sequence inductance, L0` — **Stator zero-sequence inductance**
`0.00016 H` (default)

`Stator self-inductance per phase, Ls` — **Stator self-inductance per phase**
`0.0002 H` (default)

`Stator inductance fluctuation, Lm` — **Stator inductance fluctuation**
`0 H` (default)

`Stator mutual inductance, Ms` — **Stator mutual inductance**
`0.00002 H` (default)

`Stator resistance per phase, Rs` — **Stator resistance per phase**
`0.013 Ohm` (default)

Mechanical

`Rotor inertia` — **Rotor inertia**
`0.01 kg*m^2` (default)

`Rotor damping` — **Rotor damping**
`0 N*m/(rad/s)` (default)

Model Examples

BLDC Speed Control

Control the rotor speed in a BLDC based electrical drive. An ideal torque source provides the load. The Control subsystem uses a PI-

Open Model

References

[1] Kundur, P. *Power System Stability and Control.* New York, NY: McGraw Hill, 1993.

[2] Anderson, P. M. *Analysis of Faulted Power Systems*. Hoboken, NJ: Wiley-IEEE Press, 1995.

Extended Capabilities

C/C++ Code Generation

Generate C and C++ code using Simulink® Coder™.

See Also

Simscape Blocks

Hybrid Excitation Synchronous Machine | Permanent Magnet Synchronous Motor

Blocks

BLDC Commutation Logic | BLDC Current Controller | BLDC Current Controller with PWM Generation

Topics

Expand and Collapse Three-Phase Ports on a Block

Introduced in R2013b