PMSM Current Controller with Pre-Control

Discrete-time permanent magnet synchronous machine current controller with pre-control

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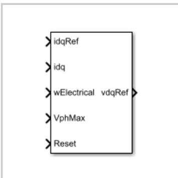


Description

The PMSM Current Controller with Pre-Control block implements a discrete-time PI-based permanent magnet synchronous machine (PMSM) current controller in the rotor d-q reference frame with internal feedforward pre-control.

You typically use this block in a series of blocks making up a control structure.

- You can generate a current reference in the d-q frame to be used as an input to this block with a PMSM Current Reference Generator.
- You can obtain a voltage reference in the abc domain by converting the output of this block using an Inverse Park Transform block.

You can see an example of a full control structure, from machine measurements to machine inputs, in the PMSM Field-Oriented Control block.

Equations

The block is discretized using the backward Euler method due to its first-order simplicity and its stability.

Two PI current controllers implemented in the rotor reference frame produce the reference voltage vector:

$$v_d^{ref} = \left(K_{p\_id} + K_{i\_id}\frac{T_s z}{z-1}\right)\left(i_d^{ref} - i_d\right) + v_{d\_FF},$$

and

$$v_q^{ref} = \left(K_{p\_iq} + K_{i\_iq}\frac{T_s z}{z-1}\right)\left(i_q^{ref} - i_q\right) + v_{q\_FF},$$

where:

- v_d^{ref} and v_q^{ref} are the *d*-axis and *q*-axis reference voltages, respectively.
- i_d^{ref} and i_q^{ref} are the *d*-axis and *q*-axis reference currents, respectively.
- i_d and i_q are the *d*-axis and *q*-axis currents, respectively.
- K_{p_id} and K_{p_iq} are the proportional gains for the *d*-axis and *q*-axis controllers, respectively.
- K_{i_id} and K_{i_iq} are the integral gains for the *d*-axis and *q*-axis controllers, respectively.

- T_s is the sample time of the discrete controller.
- v_{d_FF} and v_{q_FF} are the feedforward voltages for the *d*-axis and *q*-axis, respectively.

The feedforward voltages are obtained from the machine mathematical equations:

$$v_{d\_FF} = -\omega_e L_q i_q,$$

and

$$v_{q\_FF} = \omega_e (L_d i_d + \psi_m),$$

where:

- ω_e is the rotor electrical velocity.
- L_d and L_q are the *d*-axis and *q*-axis inductances, respectively.
- ψ_m is the permanent magnet flux linkage.

Zero Cancellation

Using PI control results in a zero in the closed-loop transfer function, which can result in undesired overshoot in the closed-loop response. This zero can be canceled by introducing a zero-cancelation block in the feedforward path. The zero cancellation transfer functions in discrete time are:

$$G_{ZC\_id}(z) = \frac{\frac{T_s K_{i\_id}}{K_{p\_id}}}{z + \left(\frac{T_s - \frac{K_{p\_id}}{K_{i\_id}}}{\frac{K_{p\_id}}{K_{i\_id}}}\right)},$$

and

$$G_{ZC\_iq}(z) = \frac{\frac{T_s K_{i\_iq}}{K_{p\_iq}}}{z + \left(\frac{T_s - \frac{K_{p\_iq}}{K_{i\_iq}}}{\frac{K_{p\_iq}}{K_{i\_iq}}}\right)}.$$

Voltage Saturation

Saturation must be imposed when the stator voltage vector exceeds the voltage phase limit V_{ph_max}:

$$\sqrt{v_d^2 + v_q^2} \le V_{ph\_max},$$

where v_d and v_q are the *d*-axis and *q*-axis voltages, respectively.

In the case of axis prioritization, the voltages v_1 and v_2 are introduced, where:

- $v_1 = v_d$ and $v_2 = v_q$ for *d*-axis prioritization.

- $v_1 = v_q$ and $v_2 = v_d$ for *q*-axis prioritization.

The constrained (saturated) voltages v_1^{sat} and v_2^{sat} are obtained as follows:

$$v_1^{sat} = \min\left(\max\left(v_1^{unsat}, -V_{ph\_max}\right), V_{ph\_max}\right)$$

and

$$v_2^{sat} = \min\left(\max\left(v_2^{unsat}, -V_{2\_max}\right), V_{2\_max}\right),$$

where:

- v_1^{unsat} and v_2^{unsat} are the unconstrained (unsaturated) voltages.
- v_{2_max} is the maximum value of v_2 that does not exceed the voltage phase limit, given by $v_{2\_max} = \sqrt{(V_{ph\_max})^2 - \left(v_1^{sat}\right)^2}$.

In the case that the direct and quadrature axes have the same priority (d-q equivalence), the constrained voltages are obtained as follows:

$$v_d^{sat} = \min\left(\max\left(v_d^{unsat}, -V_{d\_max}\right), V_{d\_max}\right)$$

and

$$v_q^{sat} = \min\left(\max\left(v_q^{unsat}, -V_{q\_max}\right), V_{q\_max}\right),$$

where:

$$V_{d\_max} = \frac{V_{ph\_max}\left|v_d^{unsat}\right|}{\sqrt{\left(v_d^{unsat}\right)^2 + \left(v_q^{unsat}\right)^2}}$$

and

$$V_{q\_max} = \frac{V_{ph\_max}\left|v_q^{unsat}\right|}{\sqrt{\left(v_d^{unsat}\right)^2 + \left(v_q^{unsat}\right)^2}}.$$

Integral Anti-Windup

An anti-windup mechanism is employed to avoid saturation of integrator output. In such a situation, the integrator gains become:

$$K_{i\_id} + K_{aw\_id}\left(v_d^{sat} - v_d^{unsat}\right)$$

and

$$K_{i\_iq} + K_{aw\_iq}\left(v_q^{sat} - v_q^{unsat}\right),$$

where K_{aw_id}, K_{aw_iq}, and K_{aw_if} are the anti-windup gains for the *d*-axis, *q*-axis, and field controllers, respectively.

Assumptions

- The plant model for direct and quadrature axis can be approximated with a first-order system.
- This control solution is used only for permanent magnet synchronous motors with sinusoidal flux distribution and field windings.

Ports

Input

collapse all

`idqRef` — Reference currents
vector

Desired *d*- and *q*-axis currents for control of a PMSM, in A.

Data Types: `single` | `double`

`idq` — Measured currents
vector

Actual *d*- and *q*-axis currents of the controlled PMSM, in A.

Data Types: `single` | `double`

`wElectrical` — Measured electrical velocity
vector

Rotor electrical velocity used for feedforward pre-control, in rad/s.

Data Types: `single` | `double`

`VphMax` — Maximum phase voltage
scalar

Maximum allowable voltage in each phase, in V.

Data Types: `single` | `double`

`Reset` — External reset
scalar

External reset signal (rising edge) for integrators.

Data Types: `single` | `double`

Output

expand all

`vdqRef` — **Reference voltages**
vector

Parameters

expand all

Control Parameters

`D-axis current proportional gain` — **D-axis proportional gain**
`1` (default) | positive number

`D-axis current integral gain` — **D-axis integral gain**
`100` (default) | positive number

`D-axis current anti-windup gain` — **D-axis anti-windup gain**
`1` (default) | positive number

`Q-axis current proportional gain` — **Q-axis proportional gain**
`1` (default) | positive number

`Q-axis current integral gain` — **Q-axis integral gain**
`100` (default) | positive number

`Q-axis current anti-windup gain` — **Q-axis anti-windup gain**
`1` (default) | positive number

`Sample time (-1 for inherited)` — **Block sample time**
`-1` (default) | `-1` or positive number

`Axis prioritization` — **Axis prioritization for voltage limiter**
`q-axis` (default) | `d-axis` | `d-q equivalence`

`Enable zero cancellation` — **Feedforward zero-cancellation**
`off` (default) | `on`

`Enable pre-control voltage` — **Pre-control voltage**
`on` (default) | `off`

Pre-Control Parameters

`D-axis current vector, id (A)` — **D-axis current breakpoint vector**
`[-200,0,200]A` (default) | monotonically increasing vector

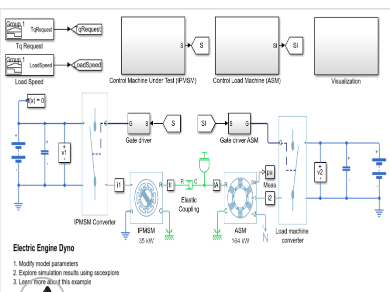
`Q-axis current vector, iq (A)` — **Q-axis current breakpoint vector**
`[-200,0,200]A` (default) | monotonically increasing vector

`Ld matrix, Ld(id,iq) (H)` — **D-axis inductance lookup data**
`0.0002 * ones(3, 3)H` (default) | positive matrix

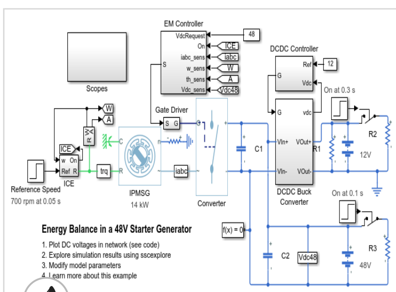
`Lq matrix, Lq(id,iq) (H)` — **Q-axis inductance lookup data**
`0.0002 * ones(3, 3)H` (default) | positive matrix

`Permanent magnet flux linkage matrix, PM(id,iq) (Wb)` — **Flux linkage lookup data**
`0.04 * ones(3, 3)Wb` (default) | real matrix

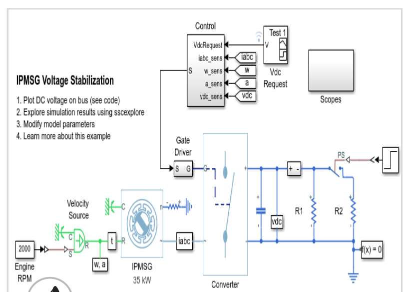
Model Examples



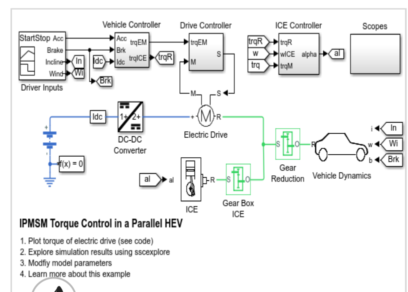
Electric Engine Dyno



Energy Balance in a 48V Starter Generator



IPMSG Voltage Stabilization



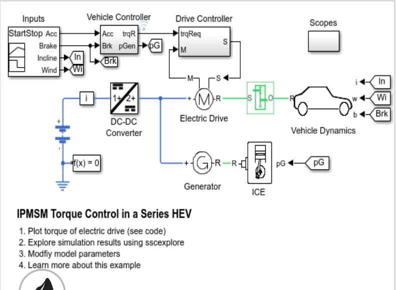
IPMSM Torque Control in a Parallel HEV

Model an electric vehicle dynamometer test. The test environment contains an asynchronous machine (ASM) and

An interior permanent magnet synchronous machine (IPMSM) used as a starter/generator in a simplified 48V automotive system.

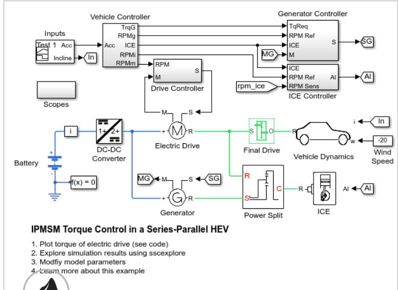
Control an Interior Permanent Magnet Synchronous Generator (IPMSG) based low voltage generator system for a hybrid

A simplified parallel hybrid electric vehicle (HEV). An interior permanent magnet synchronous machine (IPMSM) and an internal combustion



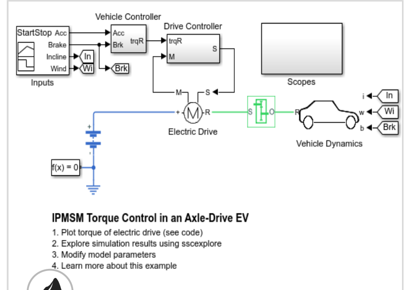
IPMSM Torque Control in a Series HEV

An interior permanent magnet synchronous machine (IPMSM) propelling a simplified series hybrid electric vehicle (HEV). An ideal



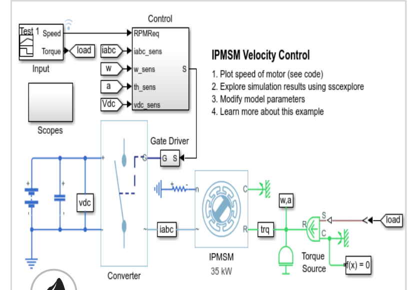
IPMSM Torque Control in a Series-Parallel HEV

A simplified series-parallel hybrid electric vehicle (HEV). An interior permanent magnet synchronous machine (IPMSM) and an internal



IPMSM Torque Control in an Axle-Drive HEV

An interior permanent magnet synchronous machine (IPMSM) propelling a simplified axle-drive electric vehicle. A high-voltage



IPMSM Velocity Control

Control the rotor angular velocity in an interior permanent magnet synchronous machine (IPMSM) based automotive electrical-traction

References

[1] Bernardes, T., V. F. Montagner, H. A. Gründling, and H. Pinheiro. "Discrete-time sliding mode observer for sensorless vector control of permanent magnet synchronous machine." *IEEE Transactions on Industrial Electronics.* Vol. 61, Number 4, 2014, pp. 1679–1691.

[2] Carpiuc, S., and C. Lazar. "Fast real-time constrained predictive current control in permanent magnet synchronous machine-based automotive traction drives." *IEEE Transactions on Transportation Electrification.* Vol.1, Number 4, 2015, pp. 326–335.

Extended Capabilities

C/C++ Code Generation
Generate C and C++ code using Simulink® Coder™.

See Also

Blocks

PMSM Current Controller | PMSM Current Reference Generator

Introduced in R2017b