Electrical Machines

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Permanent magnet synchronous motors

Laboratory task (10 points max)

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Laboratory task «Surface mounted permanent magnet synchronous motor modelling»

Initial data

$L_s = L_d = L_q$	inductance of the stator phase [H]
R_s	resistance of the stator phase [Ohm]
ϕ_f	rotor flux [Wb]
z_p	number of pole pairs
J	inertia of the motor's shaft and mechanical load [kg * m^2]
n_{rated}	rated speed [rev/min]
$t_{startup}$	time of the PMSM startup from zero to rated speed

Laboratory task «Surface mounted permanent magnet synchronous motor modelling»

Task 1. Building the SPMSM model based on differential equations

1.1 Build the SPMSM model in d/q axes using following equations

$$v_{ds}^r = R_s i_{ds}^r + \frac{d\lambda_{ds}^r}{dt} - \omega\lambda_{qs}^r$$

$$v_{qs}^r = R_s i_{qs}^r + \frac{d\lambda_{qs}^r}{dt} + \omega\lambda_{ds}^r$$

$$\lambda_{ds}^r = L_{ds} i_{ds}^r + \phi_f$$

$$\lambda_{qs}^r = L_{qs} i_{qs}^r$$

$$T_e = \frac{p}{2}\frac{3}{2}\left[\phi_f i_{qs}^r + \left(L_{ds} - L_{qs}\right) i_{ds}^r i_{qs}^r\right]$$

$$\boxed{\begin{aligned}\phi_f &= const \\ \frac{d\phi_f}{dt} &= 0\end{aligned}} \Rightarrow$$

$$\frac{di_{ds}^r}{dt} = \frac{v_{ds}^r}{L_{ds}} - \frac{R_s i_{ds}^r}{L_{ds}} + \frac{\omega L_{qs} i_{qs}^r}{L_{ds}}$$

$$\frac{di_{qs}^r}{dt} = \frac{v_{qs}^r}{L_{qs}} - \frac{R_s i_{qs}^r}{L_{qs}} - \frac{\omega L_{ds} i_{ds}^r}{L_{qs}} - \frac{\omega\phi_f}{L_{qs}}$$

$$T_e = \frac{p}{2}\frac{3}{2}\left[\phi_f i_{qs}^r + \left(L_{ds} - L_{qs}\right) i_{ds}^r i_{qs}^r\right]$$

Laboratory task «Surface mounted permanent magnet synchronous motor modelling»

Inputs of PMSM model

u_a, u_b, u_c abc voltages

ω_m, θ_m velocity and angle of the PMSM shaft

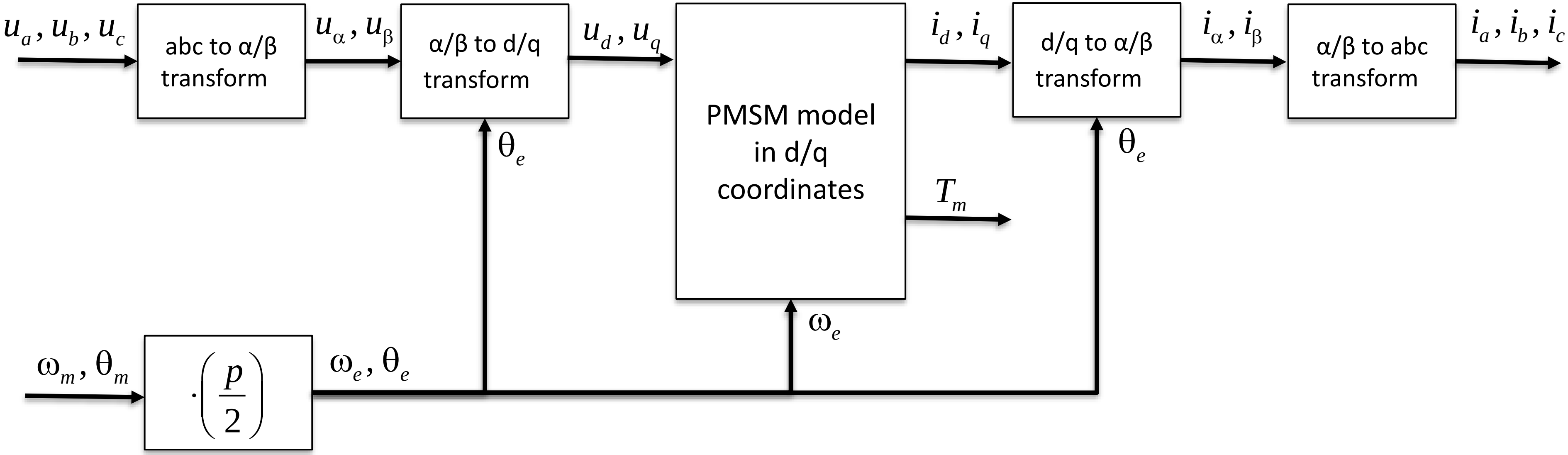
Use magnitude invariance reference frame transformation!

Outputs of PMSM model

i_a, i_b, i_c abc currents

T_m torque of the PMSM

Laboratory task «Surface mounted permanent magnet synchronous motor modelling»



Laboratory task «Surface mounted permanent magnet synchronous motor modelling»

1.2 Build the mechanical part of the model based on follows equations:

$$J\frac{d\omega_m}{dt} = T_m - T_{load}$$

$$\frac{d\theta_m}{dt} = \omega_m$$

Task 2. Build the SPMSM model based on Simscape model of PMSM

MATLAB implementation of Task 1 and Task 2

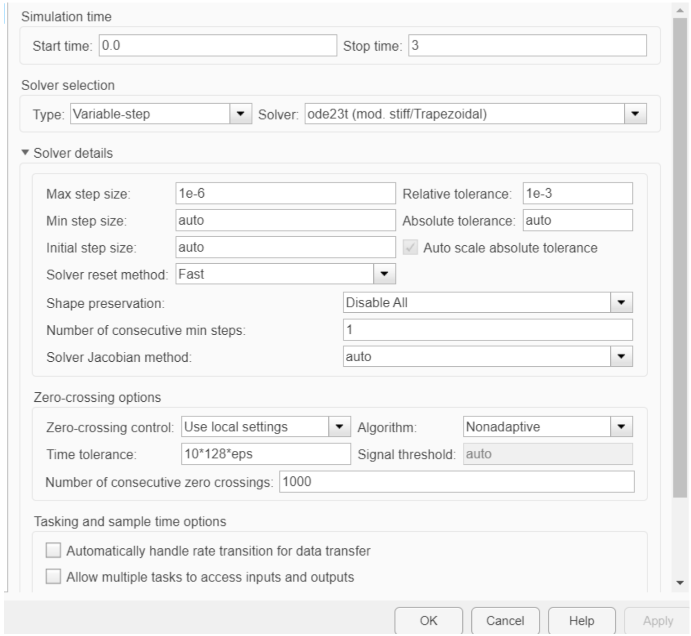
m-script with initial data:

```
Rs = 2.2; % resistance
Ls = 0.012; % inductance
zp = 15; % number of pole pairs
psi = 0.1815; % flux
J = 0.14; %inertia
n_rated = 35; % rated speed rev/min
t_startup = 10; % sec
```

MATLAB implementation of Task 1 and Task 2

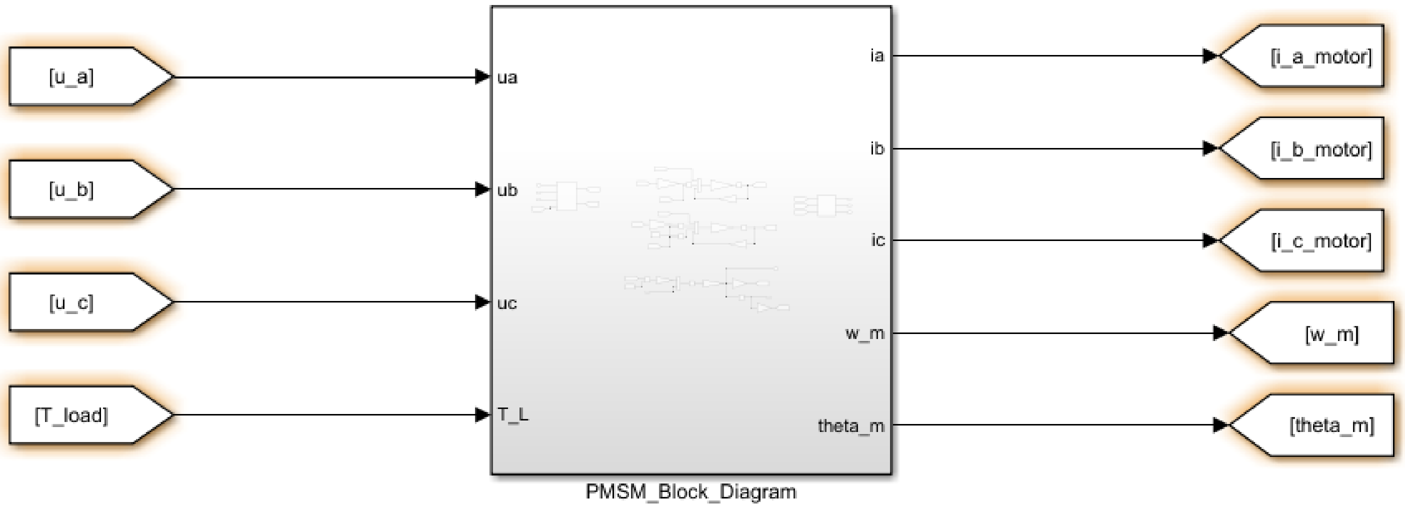
Open Matlab/Simulink and create new model.

Tune the model configuration.



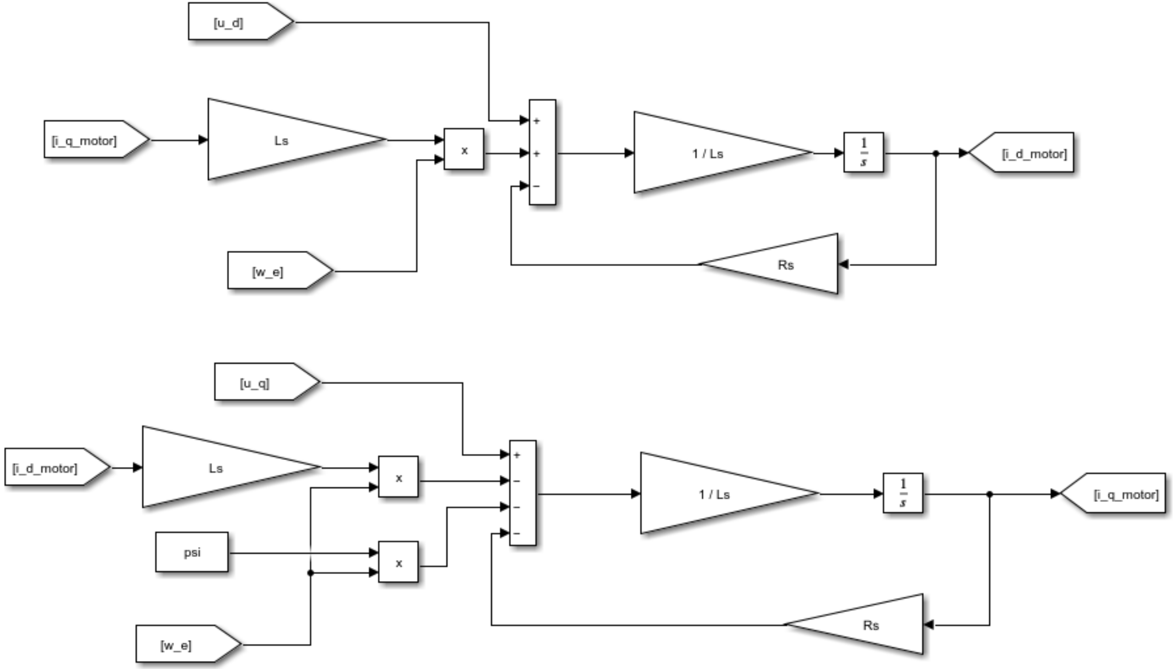
MATLAB implementation of Task 1 and Task 2

The model of SPMSM based on differential equations



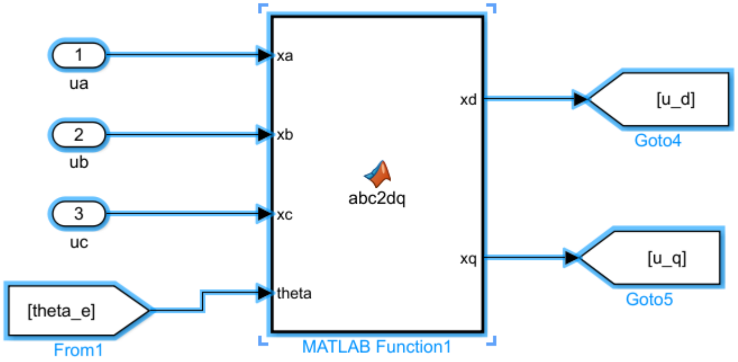
MATLAB implementation of Task 1 and Task 2

Block diagram of dq equations



MATLAB implementation of Task 1 and Task 2

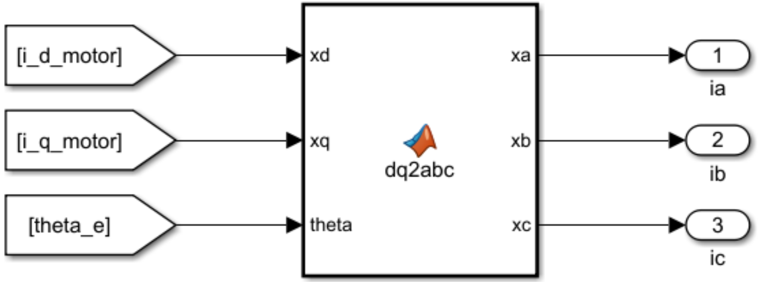
Input Clark & Park transformation:




```matlab
function [xd, xq] = abc2dq(xa, xb, xc, theta)
    sin_t = sin(theta);
    cos_t = cos(theta);
    x2 = [2/3 -(1/3) -(1/3); 0 1/sqrt(3) -1/sqrt(3)] * [xa xb xc]';
    x_alpha = x2(1);
    x_beta = x2(2);
    xd = x_alpha * cos_t + x_beta * sin_t;
    xq = -x_alpha * sin_t + x_beta * cos_t;
end
```

MATLAB implementation of Task 1 and Task 2

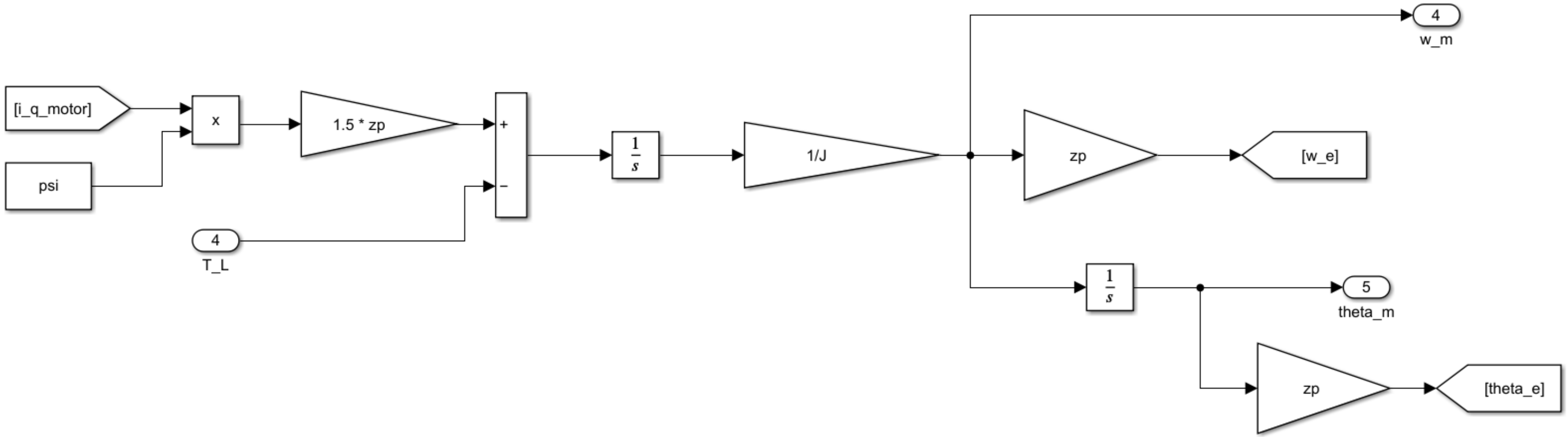
Output inverse Park & Clark transformation:




```
function [xa, xb, xc] = dq2abc(xd, xq, theta)
    sin_t = sin(theta);
    cos_t = cos(theta);
    x_alpha = xd * cos_t - xq * sin_t;
    x_beta = xd * sin_t + xq * cos_t;
    xa = x_alpha;
    xb = (-0.5) * x_alpha + sqrt(3) / 2 * x_beta;
    xc = (-0.5) * x_alpha - sqrt(3) / 2 * x_beta;
end
```

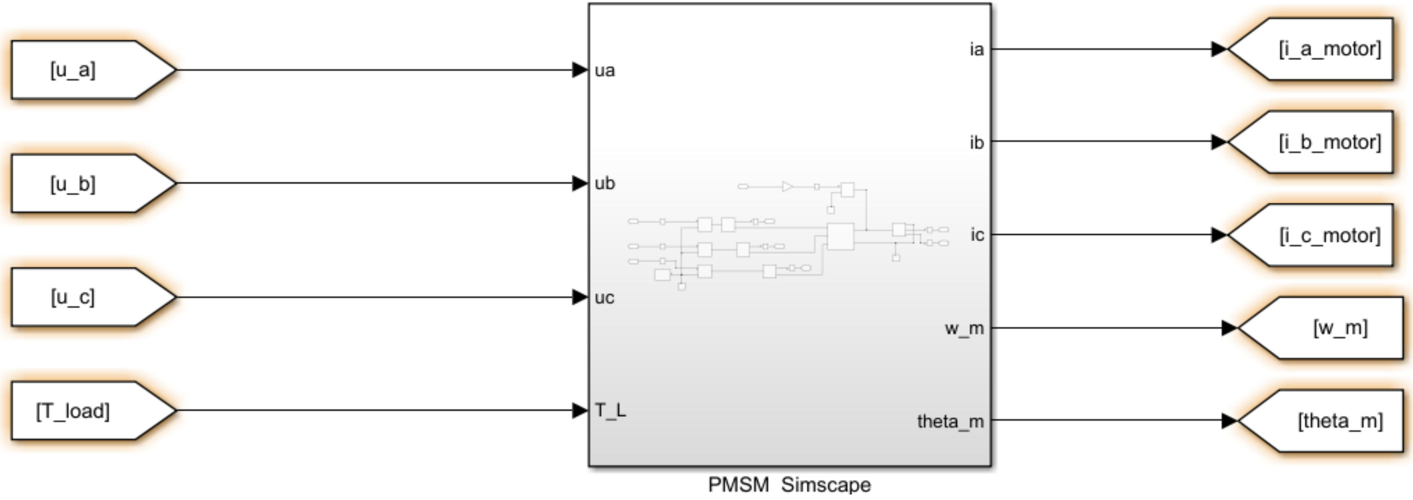
MATLAB implementation of Task 1 and Task 2

Mechanical part:



MATLAB implementation of Task 1 and Task 2

The model of SPMSM based on Simscape model



MATLAB implementation of Task 1 and Task 2

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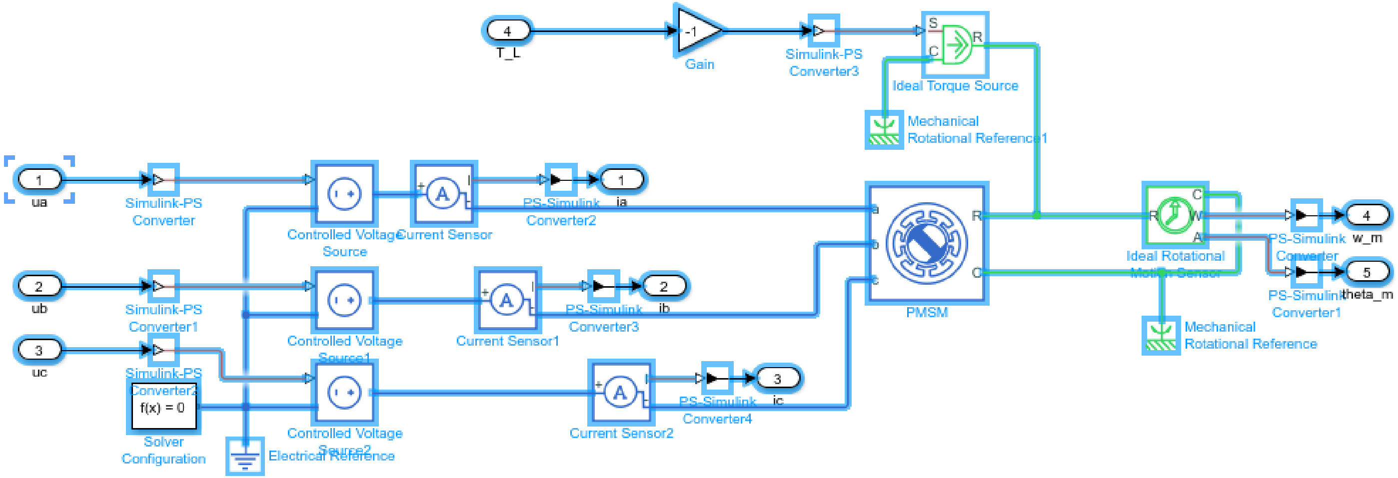
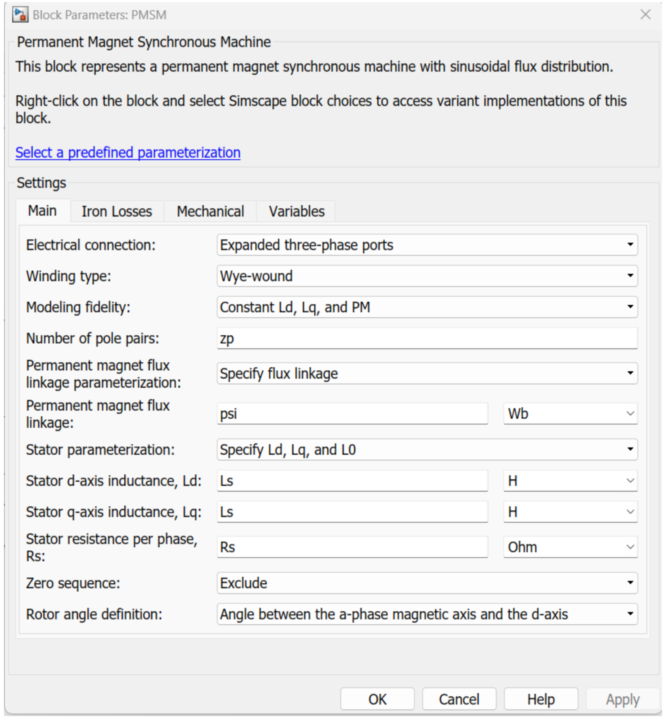
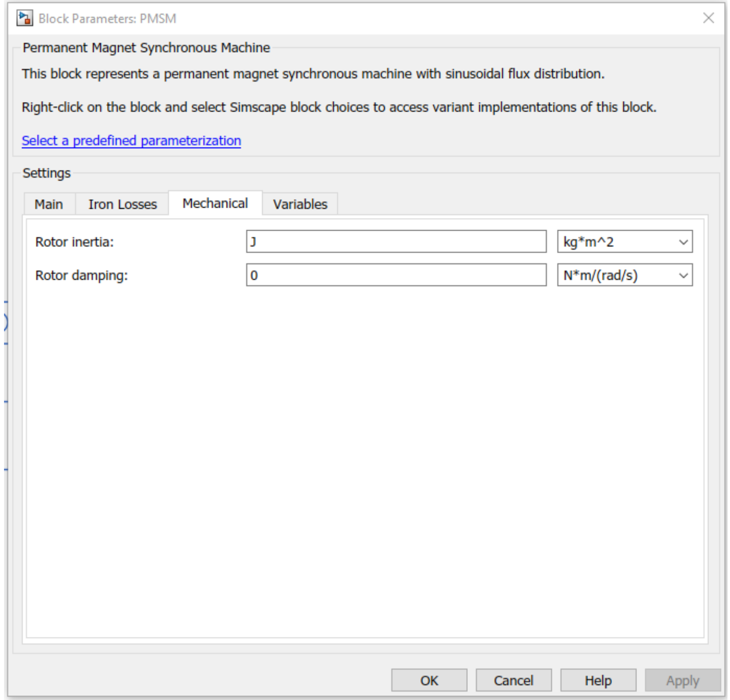


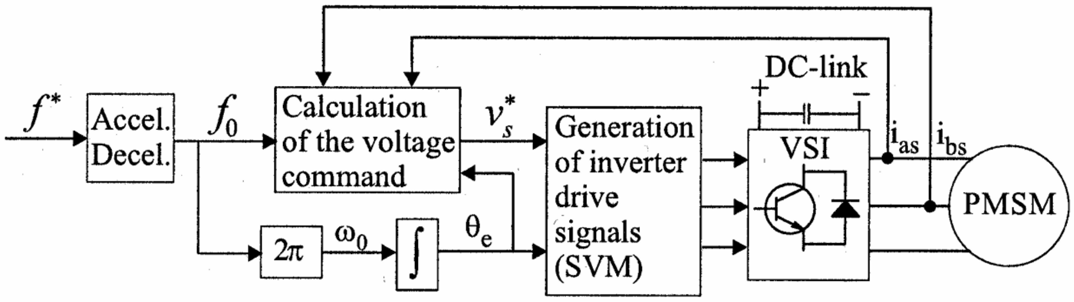
MATLAB implementation of Task 1 and Task 2

The model of SPMSM based on Simscape model

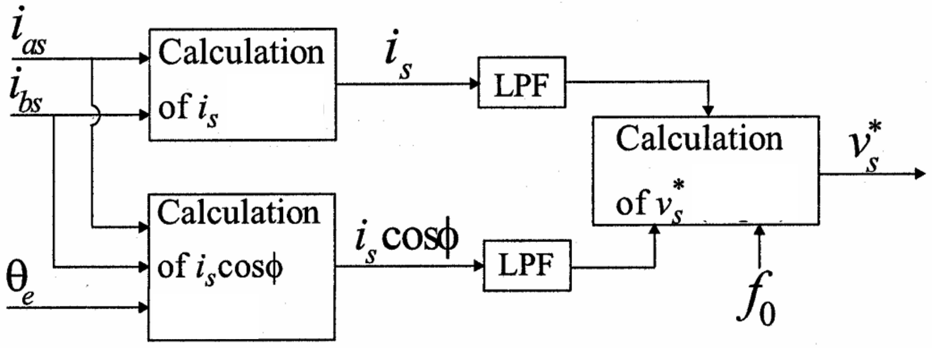




Task 3. Implement the V/f startup strategy for SPMSM

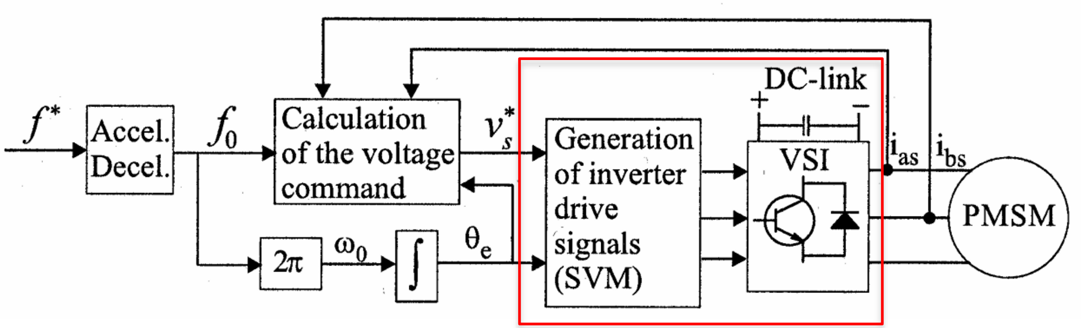


Preliminary drive configuration with voltage control method.



Calculation of the voltage command

3.1 Simplified linear model of the VSI inverter

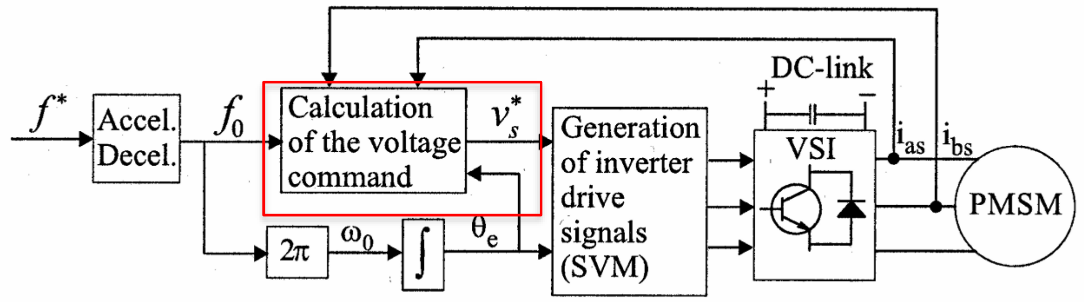


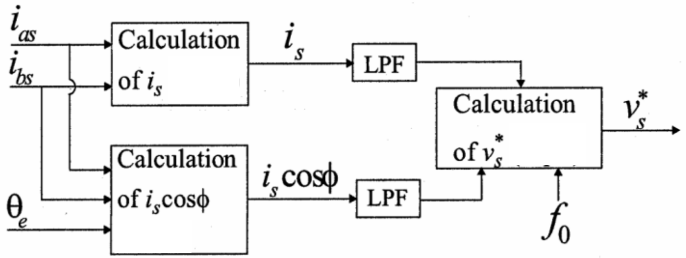
$$u_a = v_s^* \sin(\theta_e)$$

$$u_b = v_s^* \sin\left(\theta_e - \frac{2\pi}{3}\right)$$

$$u_c = v_s^* \sin\left(\theta_e + \frac{2\pi}{3}\right)$$

3.2 Calculation of the voltage command



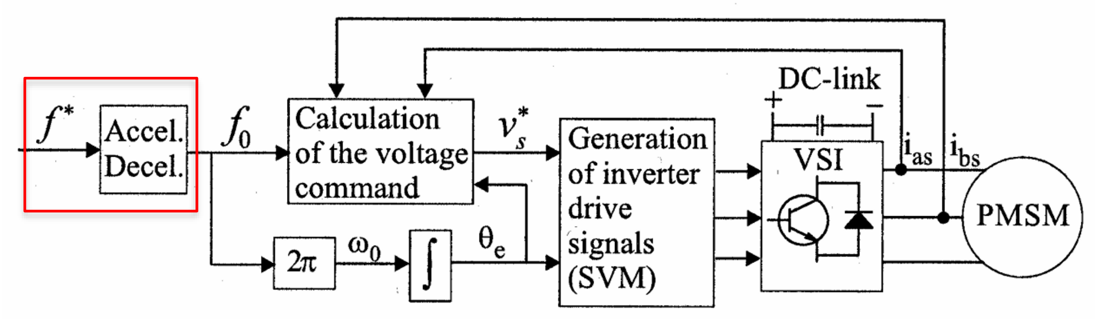


$$i_s\cos\varphi = \frac{2}{3}\left[i_{as}\cos\theta_e + i_{bs}\cos\left(\theta_e - \frac{2\pi}{3}\right) - \left(i_{as} + i_{bs}\right)\cos\left(\theta_e + \frac{2\pi}{3}\right)\right]$$

$$i_s = \sqrt{\frac{1}{3}\left(i_{as} + 2i_{bs}\right)^2 + \left(i_{as}\right)^2}$$

$$v_s^* = R_s i_s \cos\varphi + \sqrt{\left(2\pi f_0 \phi_f\right)^2 + \left(R_s i_s\cos\varphi\right)^2 - \left(R_s i_s\right)^2}$$

3.3 Generation of the frequency command



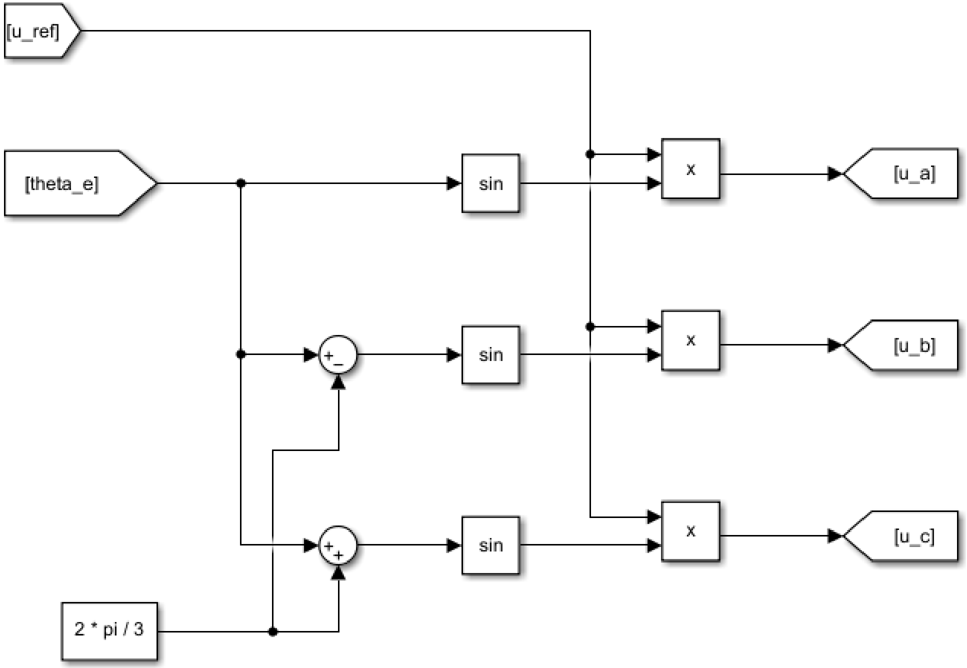
$$f^* = \frac{n_{rated}}{60} z_p$$

$$\varepsilon_{startup} = \frac{f^*}{t_{startup}}$$

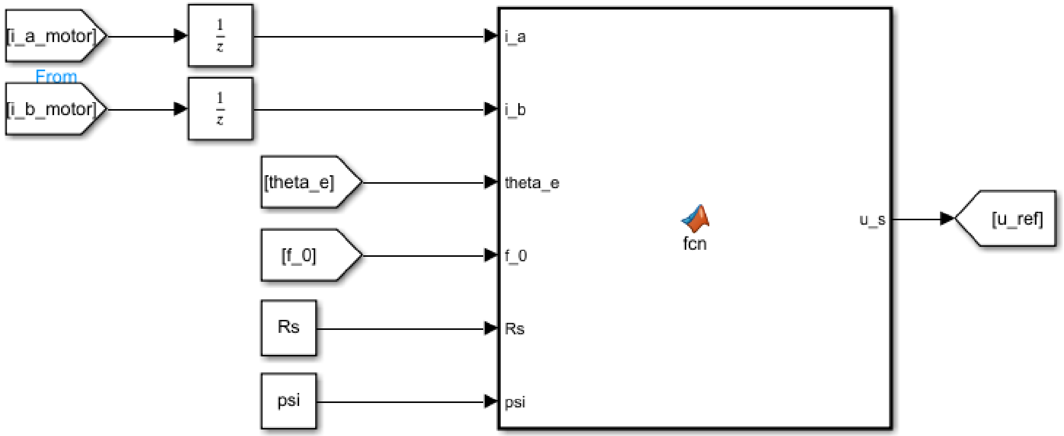
$$\begin{cases} \varepsilon(t) = \varepsilon_{startup}, & t \le t_{startup} \\ \varepsilon(t) = 0, & t > t_{startup} \end{cases}$$

$$f_0 = \int \varepsilon(t) dt$$

Matlab implementation

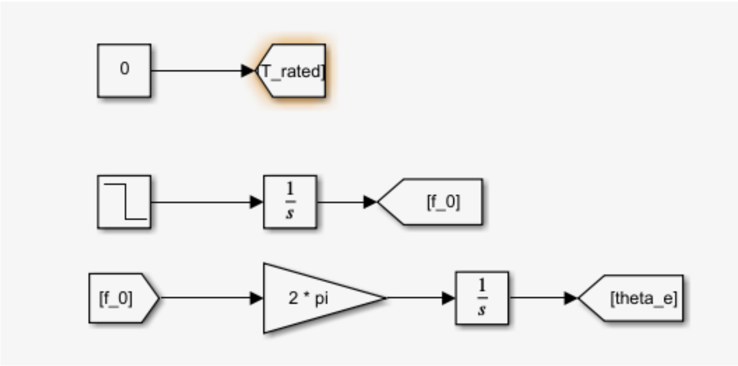


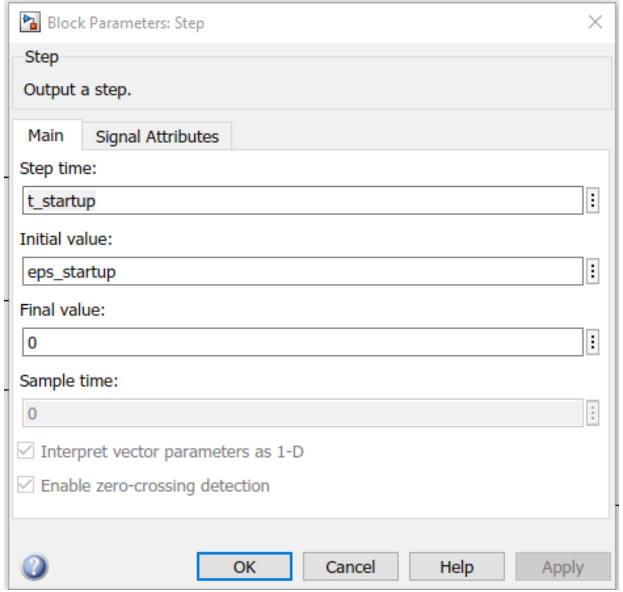
Matlab implementation




```matlab
function u_s = fcn(i_a, i_b, theta_e, f_0, Rs, psi)

i_s_cos = 2 / 3 * (i_a * cos(theta_e) + i_a * cos(theta_e - 2 * pi / 3) - (i_a + i_b) * cos(theta_e + 2 * pi / 3));

i_s = sqrt(1 / 3 * (i_a + 2 * i_b)^2 + i_a^2);

u_s = Rs * i_s_cos + sqrt((2 * pi * f_0 * psi)^2 + (Rs * i_s_cos)^2 - (Rs * i_s)^2);


end
```

Matlab implementation





3.4 Simulations

Simulate the startup process for both of SPMSM models under no load condition.

Simulation time: 11 sec.

Make sure that both models work the same way.

Plot the follows graphs for both models:

- reference frequency and motor velocity in rev/min
- phase currents i_a, i_b, i_c, A
- reference voltage v_s^*, V
- phase voltages v_a, v_b, v_c, V
- *dq*-voltages, V
- *dq*-currents, A

Report requirements

Report must contain:

- your name in English, your HDU and ITMO numbers, your photo.
- good resolution screenshots of your models of SPMSM
- good resolution screenshots of your startup scheme
- good resolution figures from simulations (white background, legend, unit of measurements).
- listing of your m-file with calculations.
- conclusion.

Reports should be uploaded to the folder in DingTalk chat.

[HDU-AT3-24] Electrical Machines/Student_works/PMSM_Reports

Report requirements

Deadline for report: 2024/10/22

Penalties:

- inaccurate figures: - 2 points
- skipping the deadline: - 4 points
- no conclusions or inadequate conclusion: - 2 points

IN THE CASE OF PLAGIARISM IN ANY PART OF THE LAB, ALL PARTS OF DC LAB WILL BE EVALUATED BY ZERO POINTS. THE FACT OF PLAGIARISM WILL BE REPORTED TO THE FACULTY.

Thank you!

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