Actuators

Actuator based on induction motor drive

Lab2

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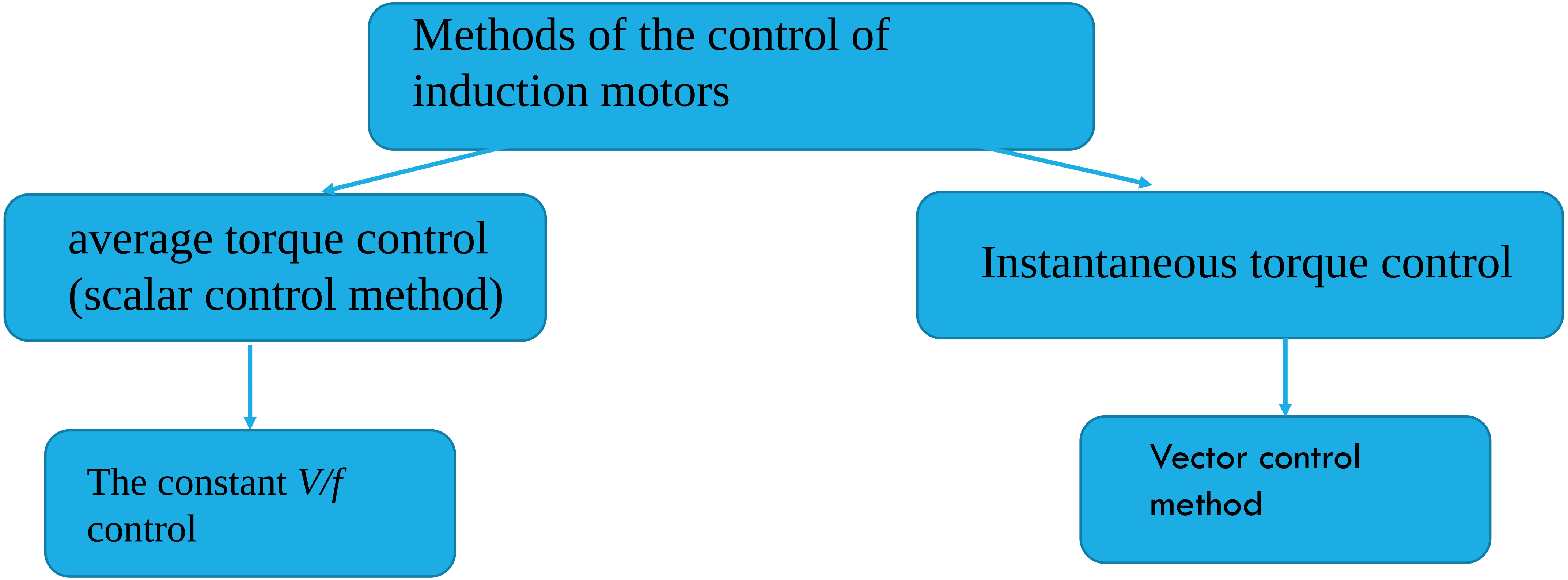
Open-loop control of an asynchronous (induction) motor

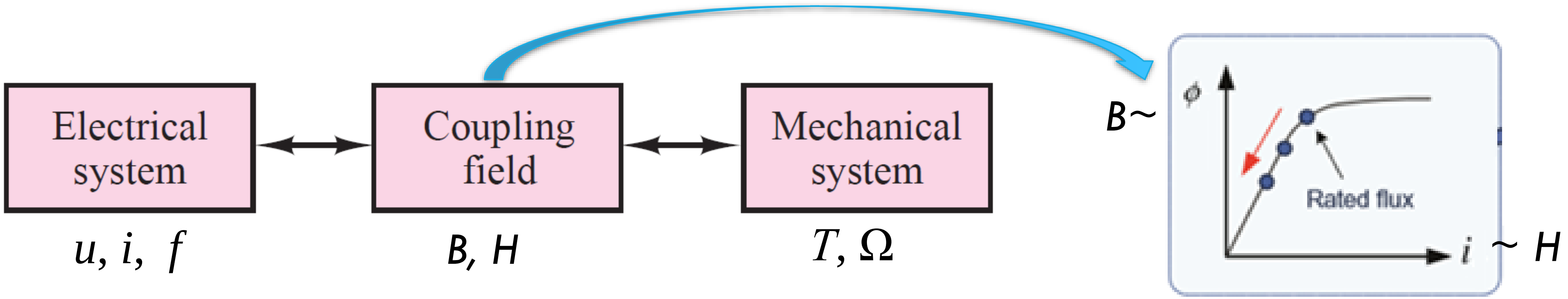
Two methods of the torque control

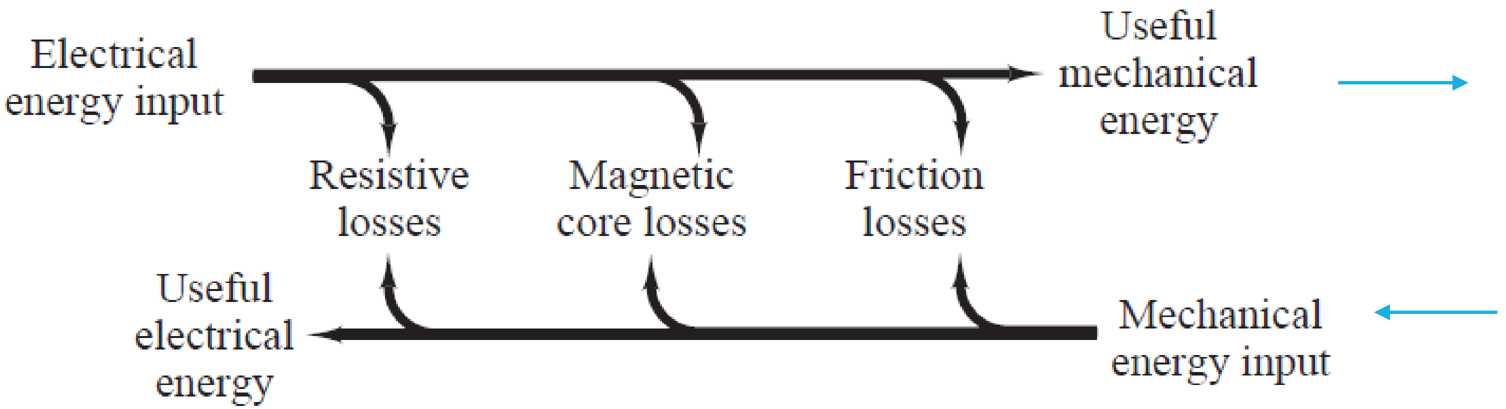


can control the motor torque only in the steady-state condition and thus cannot be used to control the dynamic behavior of the motor.

for high- performance applications such as robots, elevators, CNC machine tools, and automation line drives. In these applications a precise speed/torque control and a fast dynamic response are required

Energy conversion by electric machines

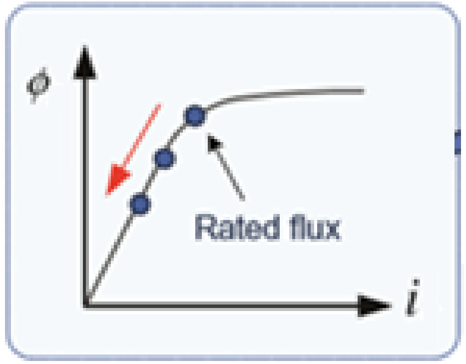




motor / actuator / energy transducer

generator / sensor

Average torque control (scalar control method)



$$E_s = 4.44 f_s N_s \phi K_{\omega s}$$

Drop of voltage of heat losses

Drop of voltage of leakage flux

$$v_s = \boxed{R_s i_s} + \boxed{L_{ls}\frac{di_s}{dt}} + L_m\frac{di_m}{dt} = \boxed{R_s i_s} + \boxed{L_{ls}\frac{di_s}{dt}} + e_s$$

$$\boxed{\phi \sim \frac{E_s}{f_s} \approx \frac{V_s}{f_s}}$$

Constant volts per Hertz (V/f) control

The *V/f* ratio may be adjusted according to the driven load.

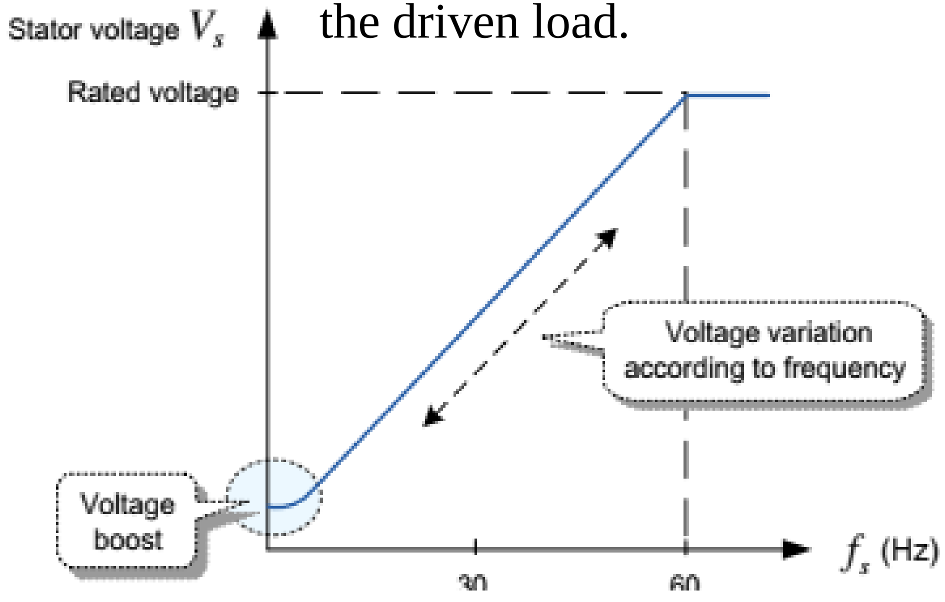
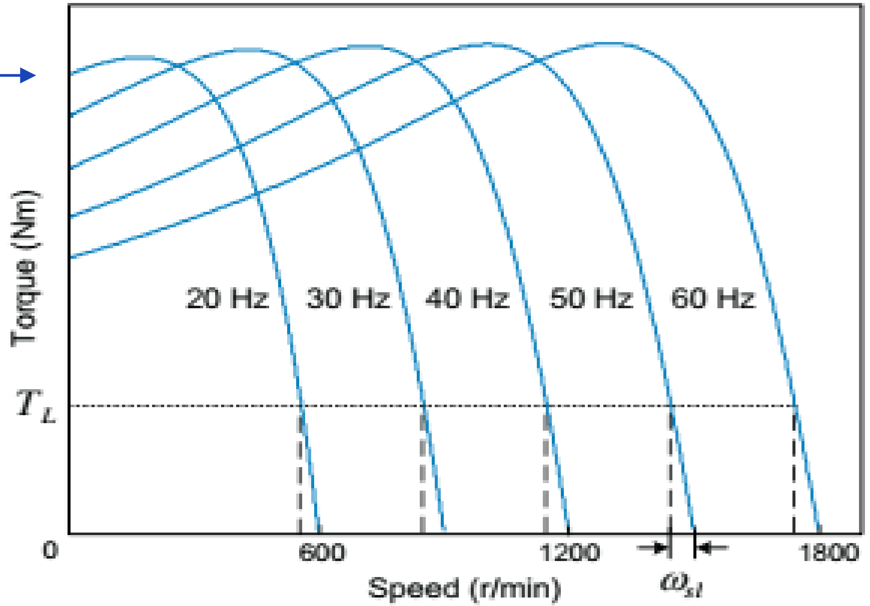


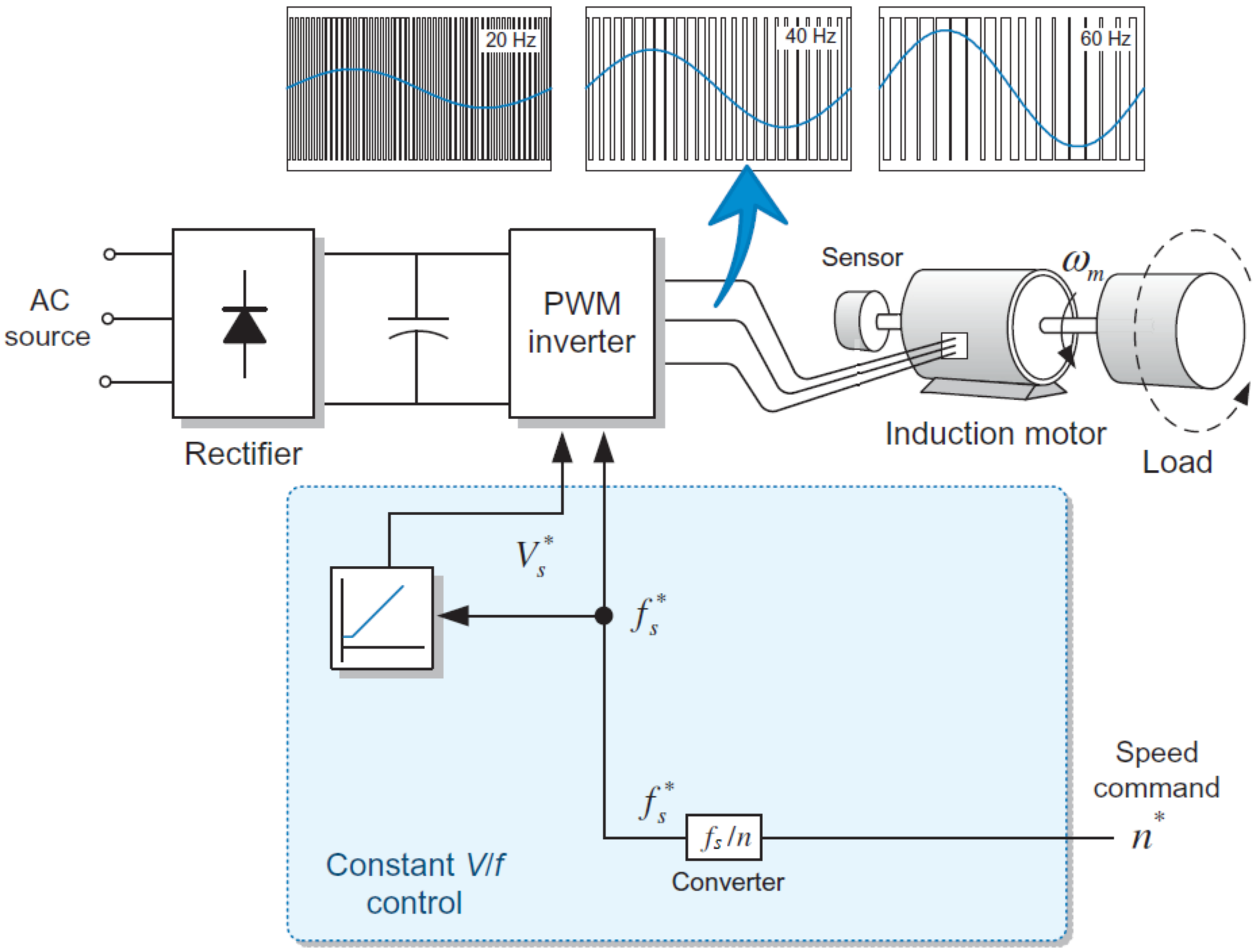
Figure Constant volts per Hertz (V/f) control

Large value of starting torque



Speed-torque curves with constant volts per Hertz control

Open-loop speed control by adjusting the slip frequency under constant V/ f control



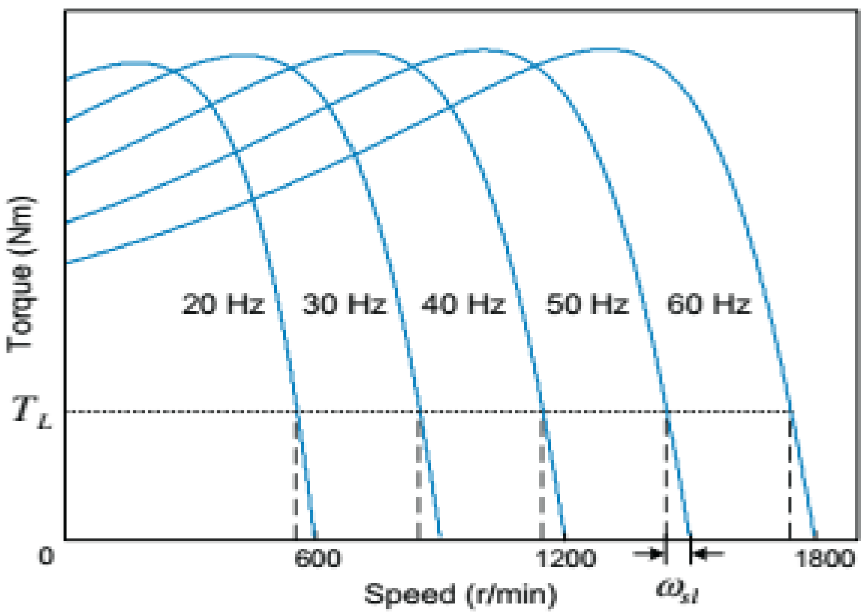
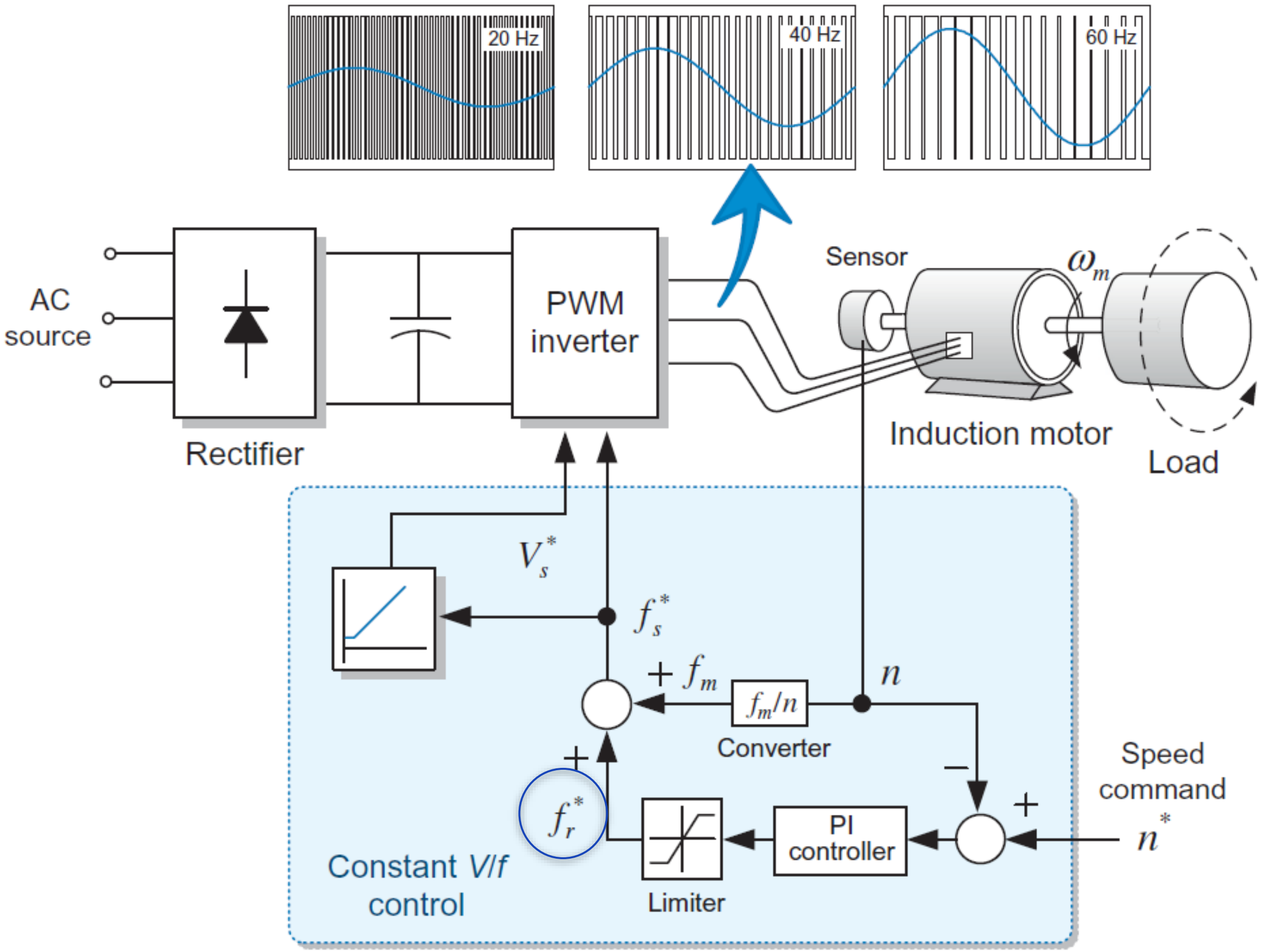


Figure - Speed control (open-loop system) by adjusting the slip frequency with constant *V/f* control

Closed-loop speed control by adjusting the slip frequency under constant V/ f control



$$T_{mech} = \left(\frac{V_s}{\omega_s}\right)^2 \frac{2\pi f_r R_r}{R_r^2 + (2\pi f_r L_{lr})^2} \qquad R_r >> 2\pi f_r L_{lr}$$

$$T_{mech} \cong \left(\frac{V_s}{\omega_s}\right)^2 \frac{2\pi}{R_r} f_r$$

$$f_s = f_r + f_m$$

f_s - stator frequency
f_r - slip frequency
f_m - motor frequency

Figure - Speed control (closed-loop system) by adjusting the slip frequency with constant *V/f* control

Content

LAB#2 Induction motor drive modelling

- ✓ LAB#2 is performed in MATLAB / Simulink
- ✓ LAB#2 consists three parts:

Task 1. Transformation between reference frames (Transformation of *abc* variables into *dq* (*Clarke transformation*) *and inverse* transformation, *Park's transformation*)

Task 2. Mathematical model of IM in stationary and synchronous reference frames

Task 3. Scalar control of IM: open-loop

Content

Task 1 Transformation between reference frames (Transformation of *abc* variables into *dq and inverse* transformation, *Park's transformation*)

Transformation between reference frames

Task 1.1 Transformation between reference frames: Transformation of *abc* variables into *dq and inverse* transformation)

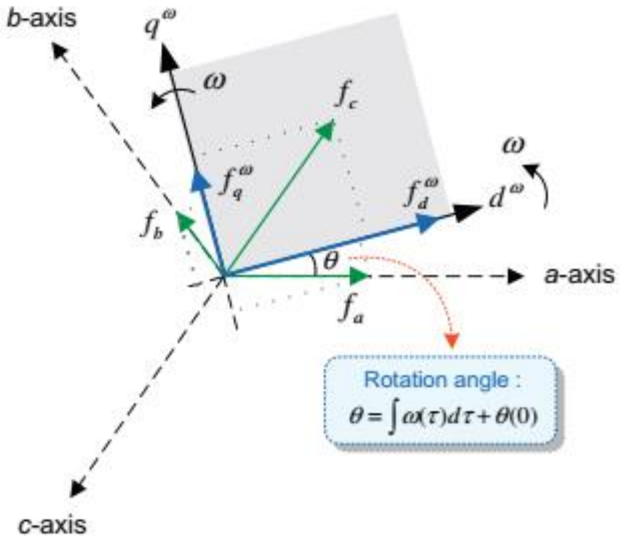


Figure Transformation into the arbitrary rotating reference frame.

- Transformation of *abc* variables into *dqn* variables in the stationary reference frame

$$f_d^s = \frac{2f_a - f_b - f_c}{3}$$

$$f_q^s = \frac{1}{\sqrt{3}}(f_b - f_c)$$

$$f_n^s = \frac{2(f_a + f_b + f_c)}{3}$$

- Inverse transformation ($f_n^s = 0$)

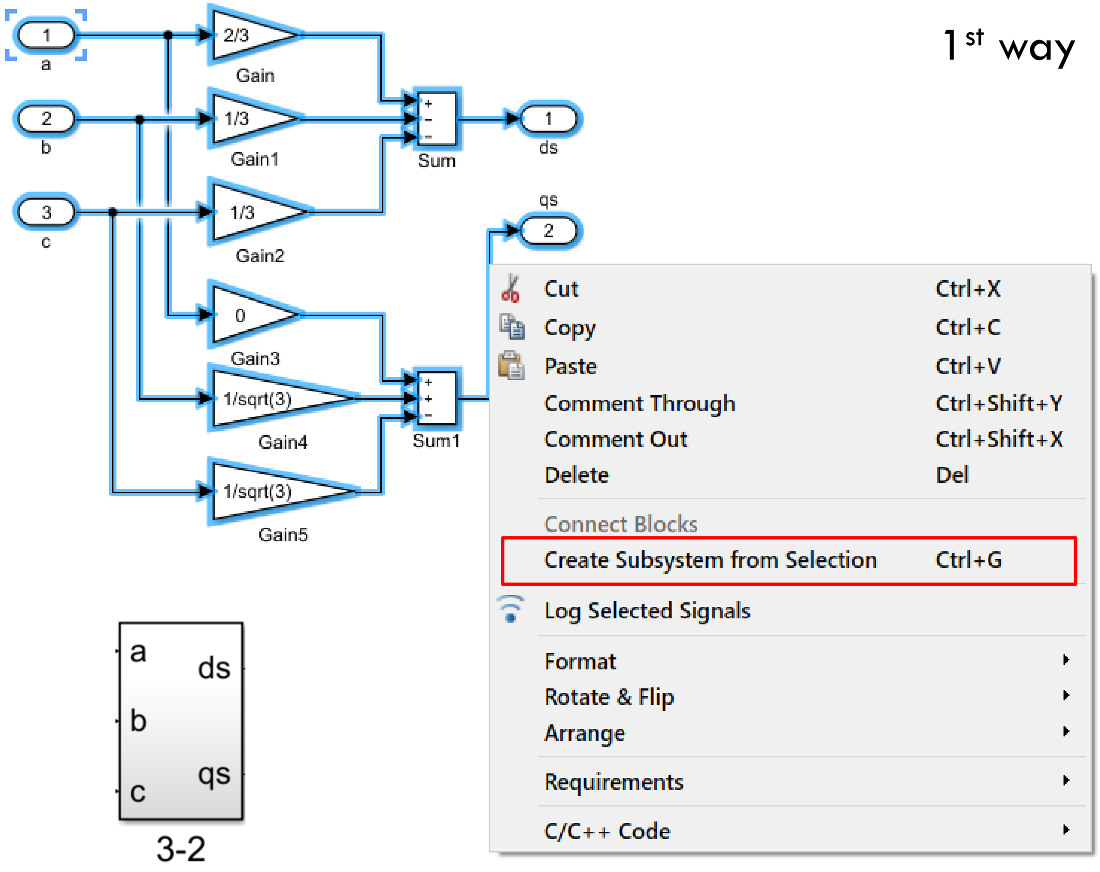
$$f_a = f_d^s$$

$$f_b = -\frac{1}{2} f_d^s + \frac{\sqrt{3}}{2} f_q^s$$

$$f_c = -\frac{1}{2} f_d^s - \frac{\sqrt{3}}{2} f_q^s$$

Task 1.1 Transformation between reference frames: Transformation of *abc* variables into *dq and inverse* transformation)

1 st way



- Transformation of abc variables into dqn variables in the stationary reference frame

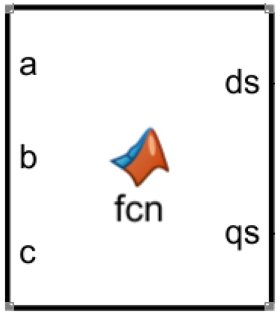
$$f_d^s = \frac{2f_a - f_b - f_c}{3}$$

$$f_q^s = \frac{1}{\sqrt{3}}(f_b - f_c)$$

$$f_n^s = \frac{2(f_a + f_b + f_c)}{3}$$

2nd way

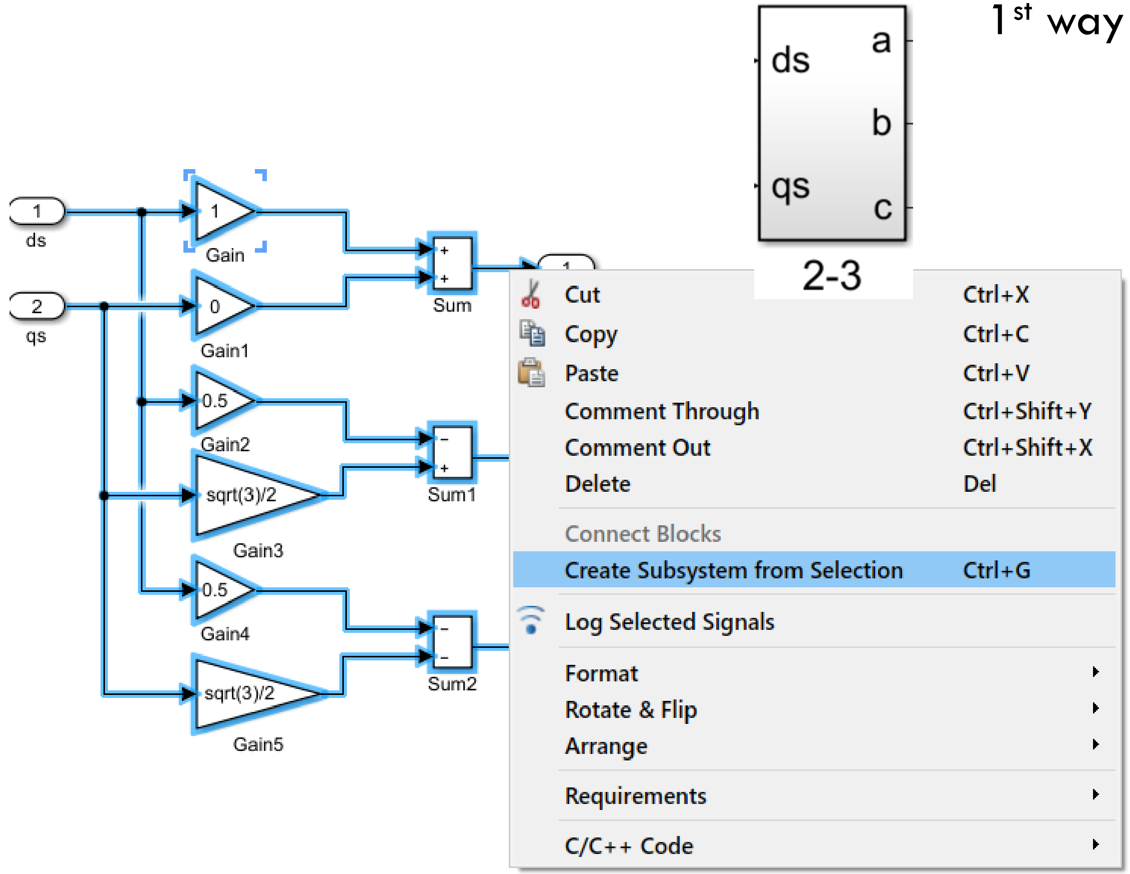
Simulink->User-Defined Functions->MATLAB Function




```
function [ds,qs] = fcn(a,b,c)
ds = (a*2/3) - (b/3) - (c/3);
qs = (b/(sqrt(3))) - (c/(sqrt(3)));
[ds; qs];
```

Task 1.1 Transformation between reference frames: Transformation of *abc* variables into *dq and inverse* transformation)

1st way

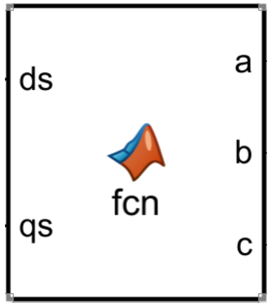


- Inverse transformation ($f_n^s = 0$)

$$f_a = f_d^s$$
$$f_b = -\frac{1}{2} f_d^s + \frac{\sqrt{3}}{2} f_q^s$$
$$f_c = -\frac{1}{2} f_d^s - \frac{\sqrt{3}}{2} f_q^s$$

2nd way

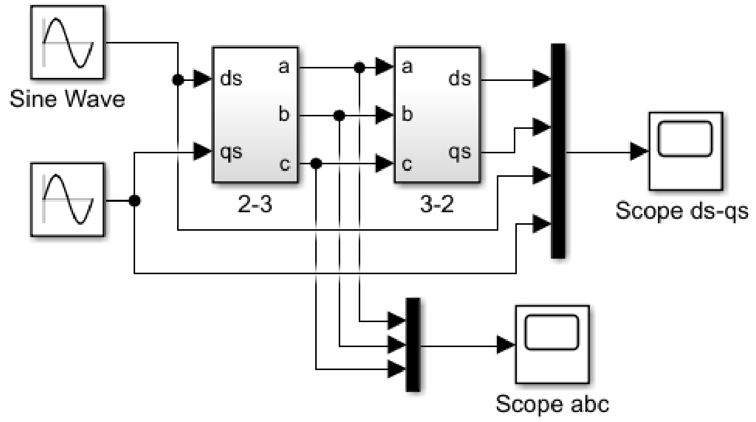
Simulink->User-Defined Functions->MATLAB Function



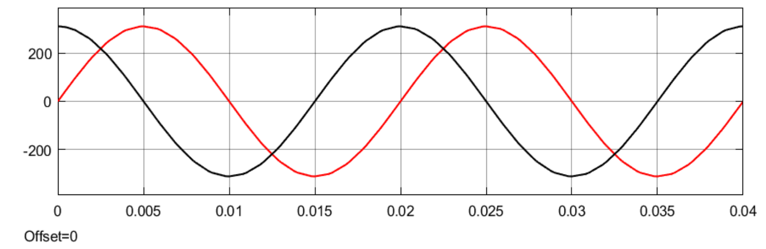

```
function [a,b,c] = fcn(ds,qs)
a = ds;
b = -0.5*ds + qs*sqrt(3)/2;
c = -0.5*ds - qs*sqrt(3)/2;
[a,b,c];
```

Task 1.1 Transformation between reference frames: Transformation of *abc* variables into *dq and inverse* transformation)

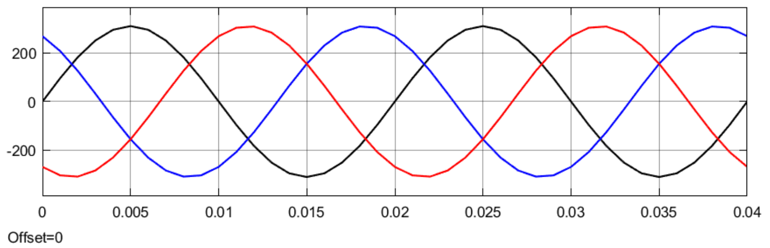
1 st way



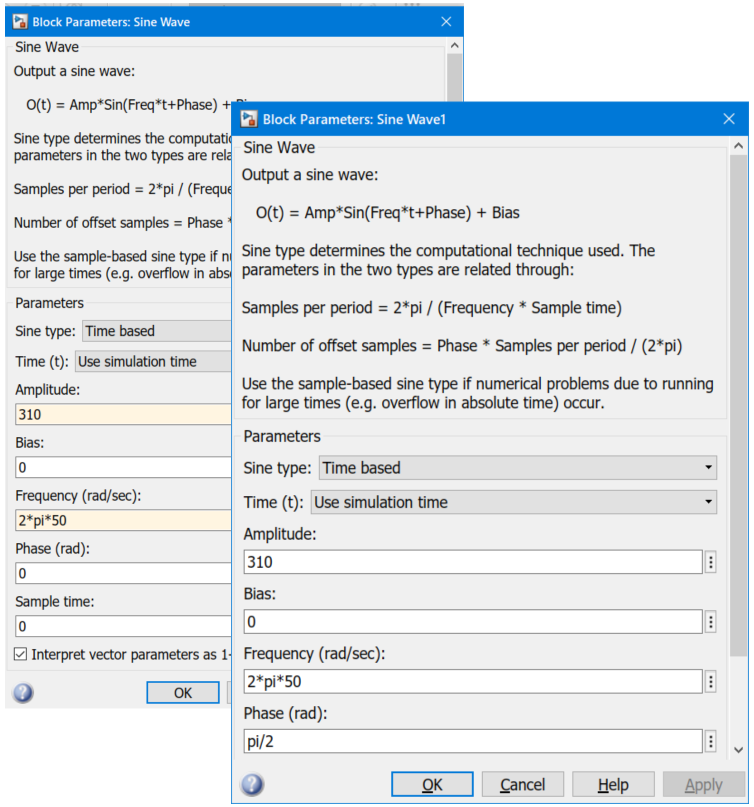
Scope_ds-qs



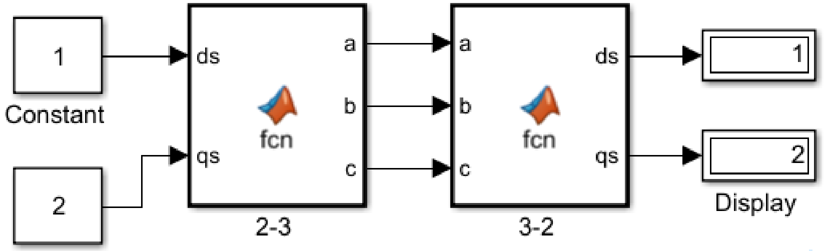
Scope_abc



CHECKING MODEL



2nd way



Task 1.2 Transformation between reference frames: *Park's transformation*

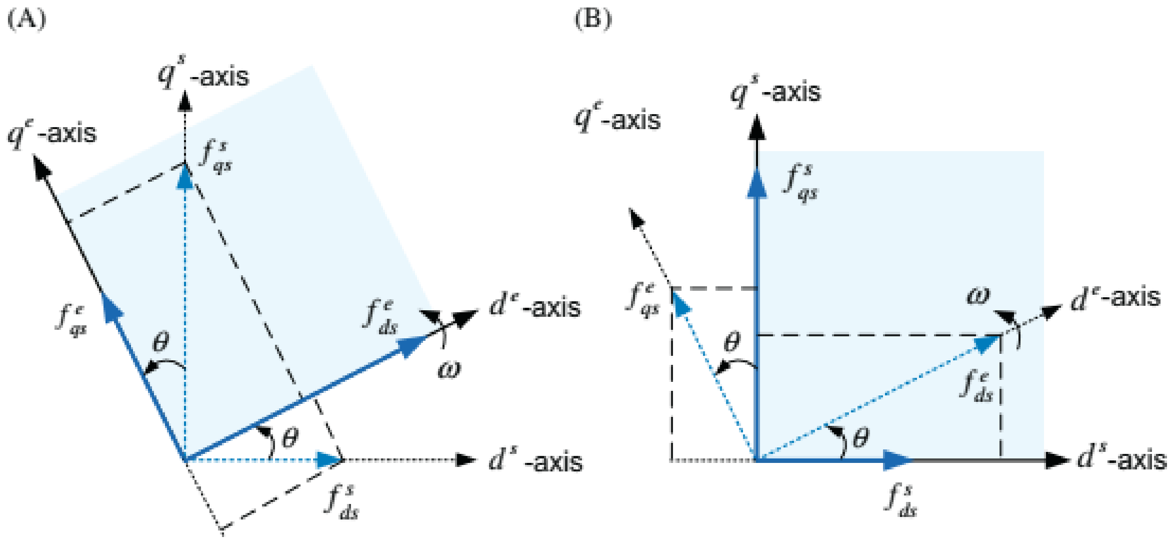


Figure Transformation between reference frames. (A) Stationary into rotating frame and (B) rotating into stationary frame

- Transformation of stationary reference frame into rotating reference frame

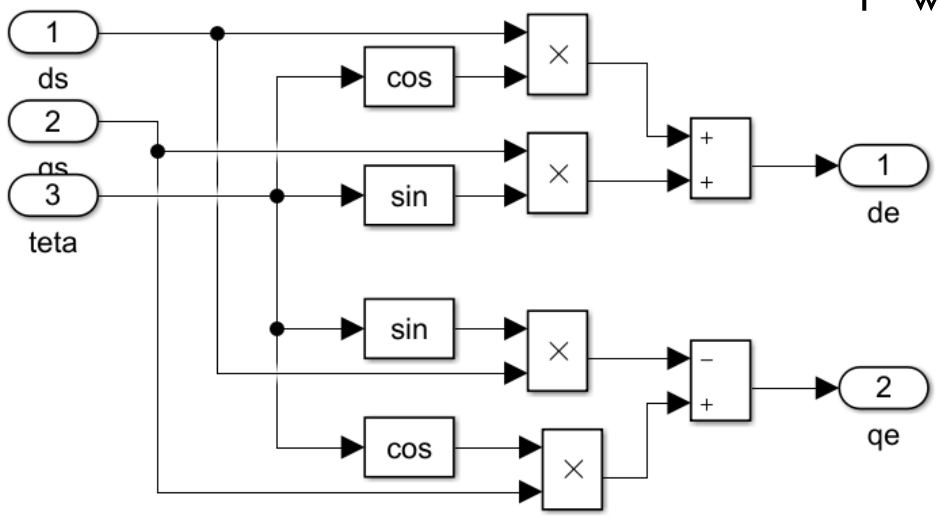
$$f_d^e = f_d^s \cos\theta + f_q^s \sin\theta$$
$$f_q^e = -f_d^s \sin\theta + f_q^s \cos\theta$$

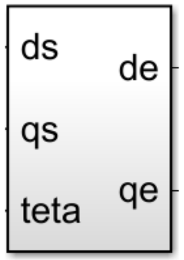
- Inverse transformation of stationary reference frame into rotating reference frame

$$f_d^s = f_d^e \cos\theta - f_q^e \sin\theta$$
$$f_q^s = f_d^e \sin\theta + f_q^e \cos\theta$$

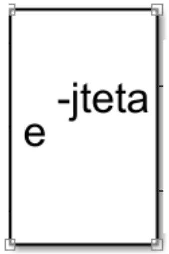
Task 1.2 Transformation between reference frames: *Park's transformation*

1st way





ds-qs -> de-qe



ds-qs -> de-qe

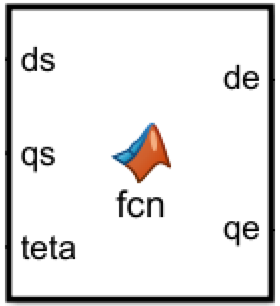
- Transformation of stationary reference frame into rotating reference frame

$$f_d^e = f_d^s \cos\theta + f_q^s \sin\theta$$
$$f_q^e = -f_d^s \sin\theta + f_q^s \cos\theta$$

$$f_{dq}^e = f_{abc} e^{-j\theta_e} = f_{dq}^s e^{-j\theta_e} \qquad \left(\theta_e = \int \omega_e(t)dt + \theta(0)\right)$$

2nd way

Simulink->User-Defined Functions->MATLAB Function

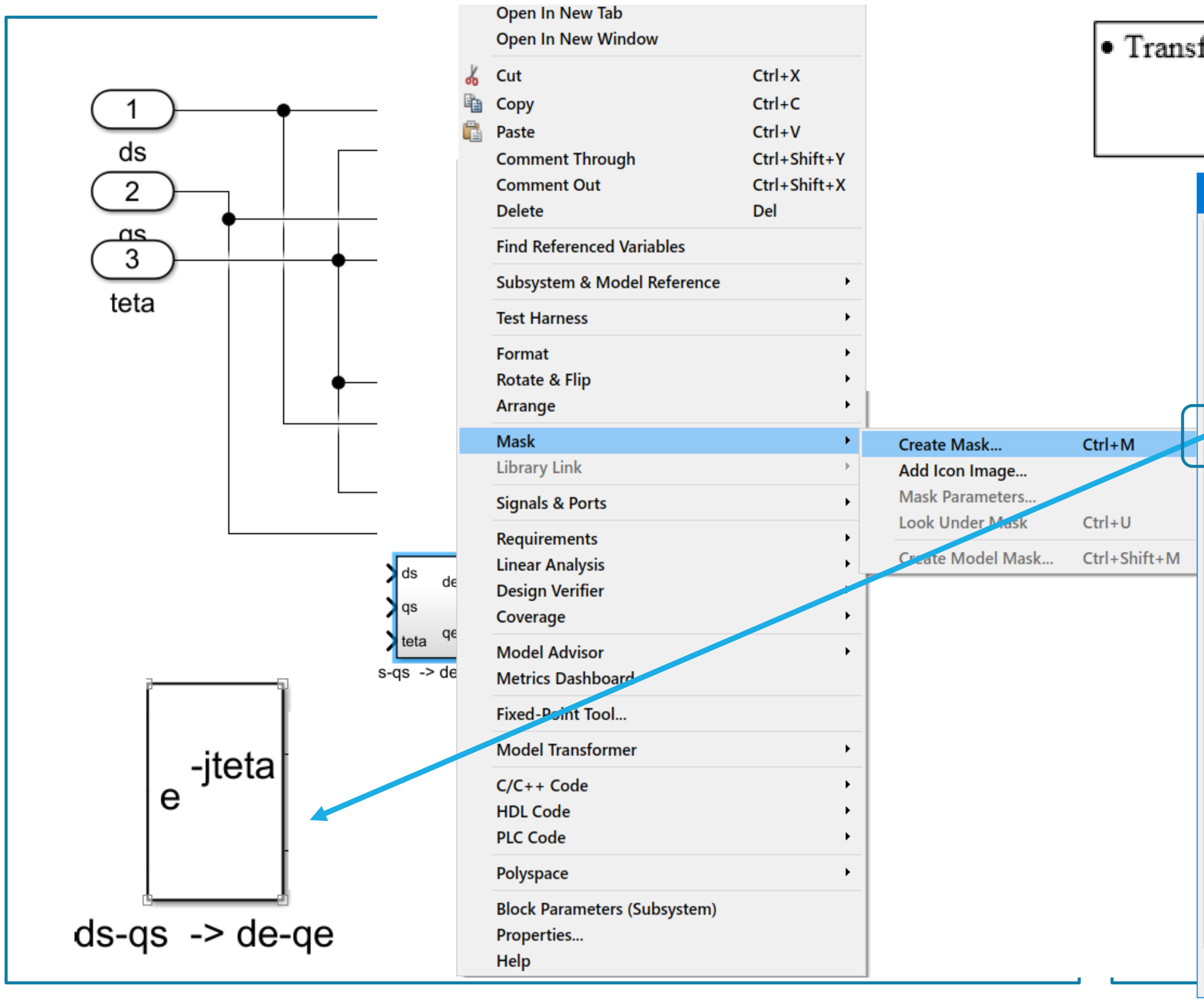



```
function [de, qe] = fcn(ds, qs, teta)

de = ds*cos(teta) + qs*sin(teta);
qe = - ds*sin(teta) + qs*cos(teta);
[de; qe];
```

Transformation between reference frames

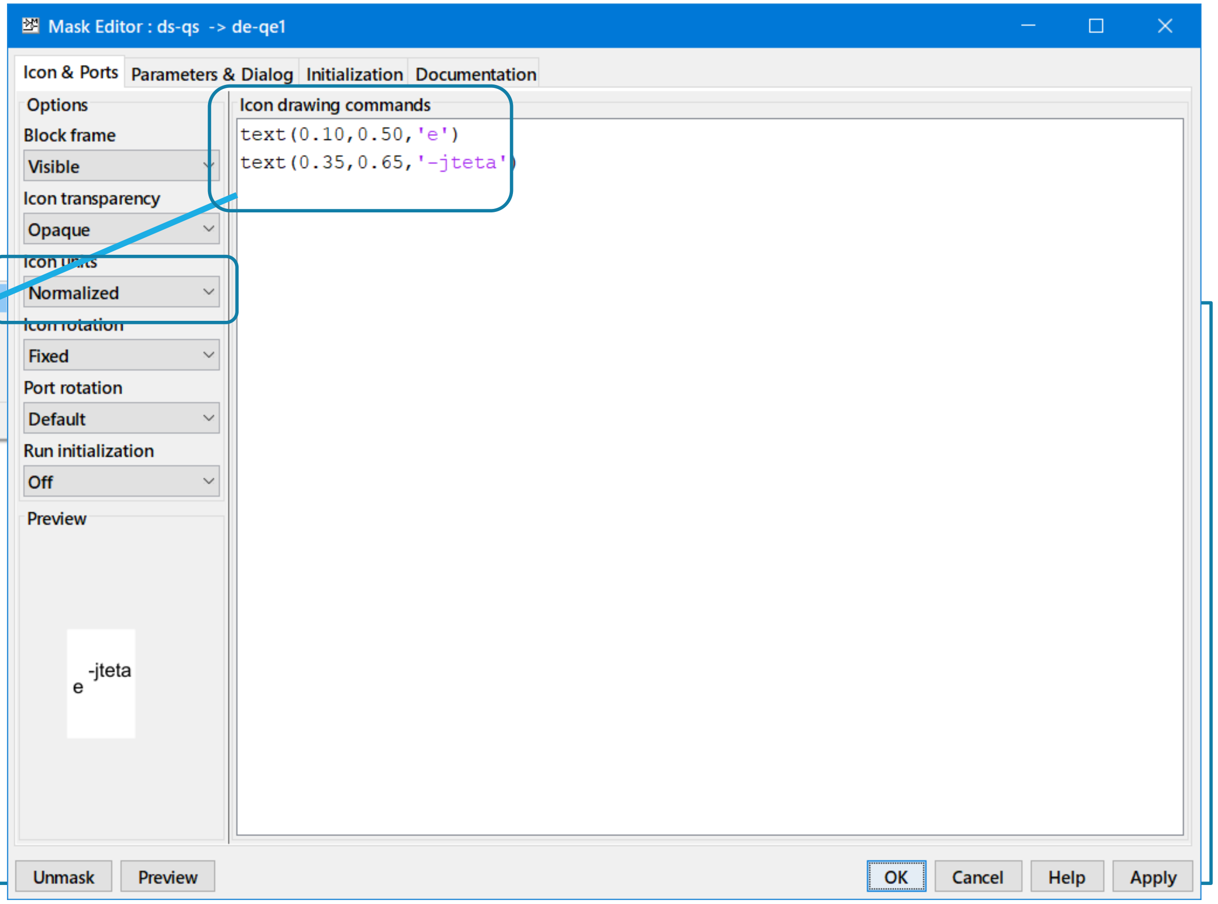
Task 1.2 Transformation between reference frames: *Park's transformation*



- Transformation of stationary reference frame into rotating reference frame

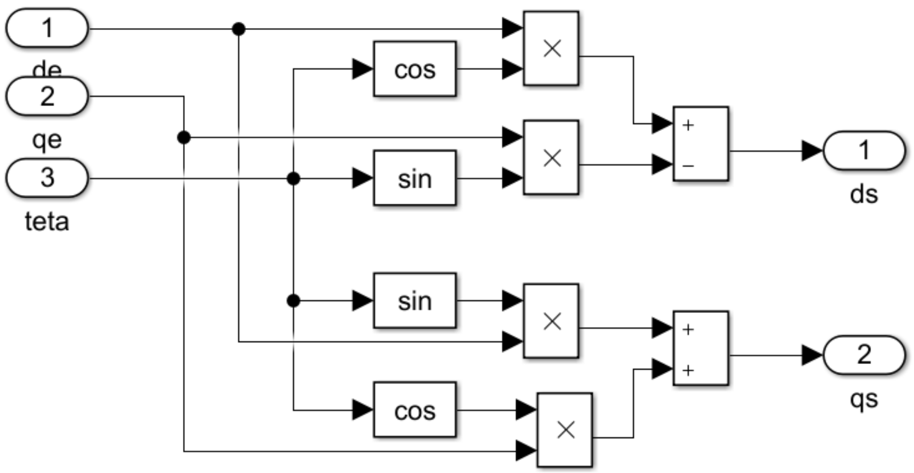
$$f_d^e = f_d^s \cos\theta + f_q^s \sin\theta$$

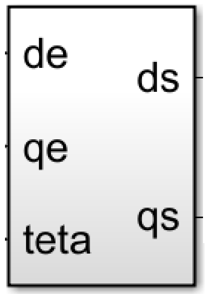
$$f_q^e = -f_d^s \sin\theta + f_q^s \cos\theta$$



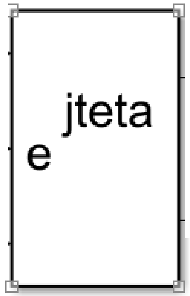
Task 1.2 Transformation between reference frames: *Park's transformation*

1st way





de-qe -> ds-qs



de-qe -> ds-qs

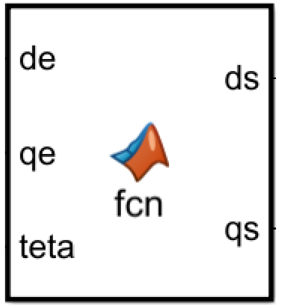
- Inverse transformation of stationary reference frame into rotating reference frame

$$f_d^s = f_d^e \cos\theta - f_q^e \sin\theta$$
$$f_q^s = f_d^e \sin\theta + f_q^e \cos\theta$$

$$f_{dq}^s = f_{dq}^e e^{j\theta_e} \qquad \left(\theta_e = \int \omega_e(t)dt + \theta(0)\right)$$

2nd way

Simulink->User-Defined Functions->MATLAB Function



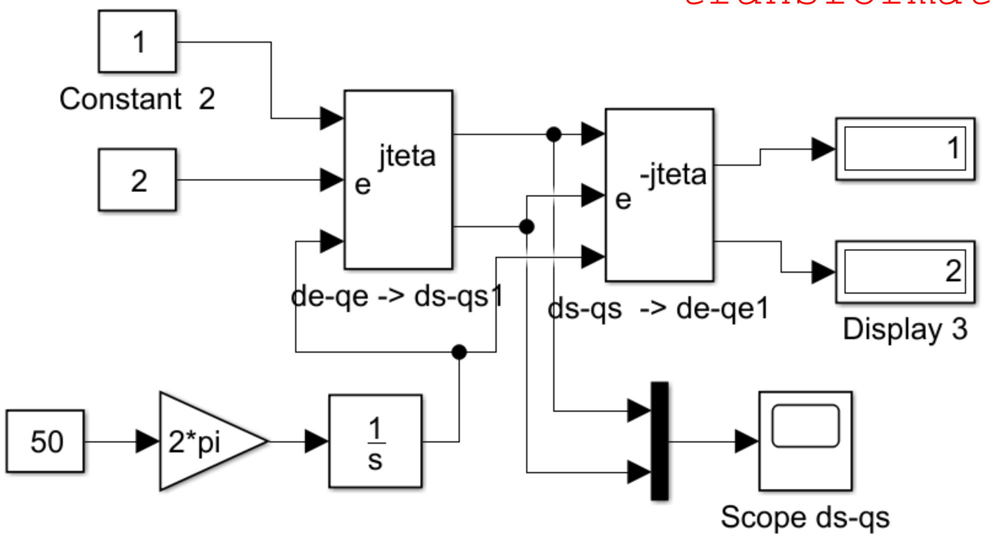

```
function [ds, qs] = fcn(de, qe, teta)

ds = de*cos(teta) - qe*sin(teta);
qs = de*sin(teta) + qe*cos(teta);
[ds; qs];
```

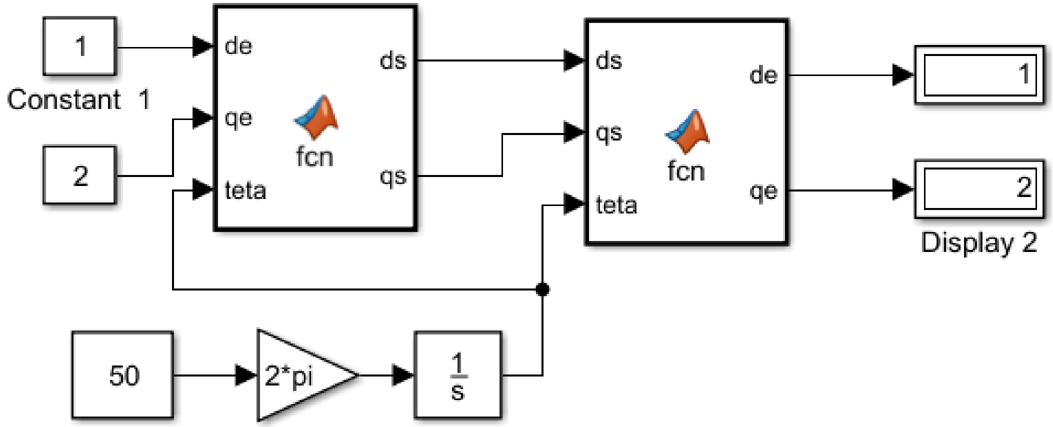
Task 1.2 Transformation between reference frames: *Park's transformation*

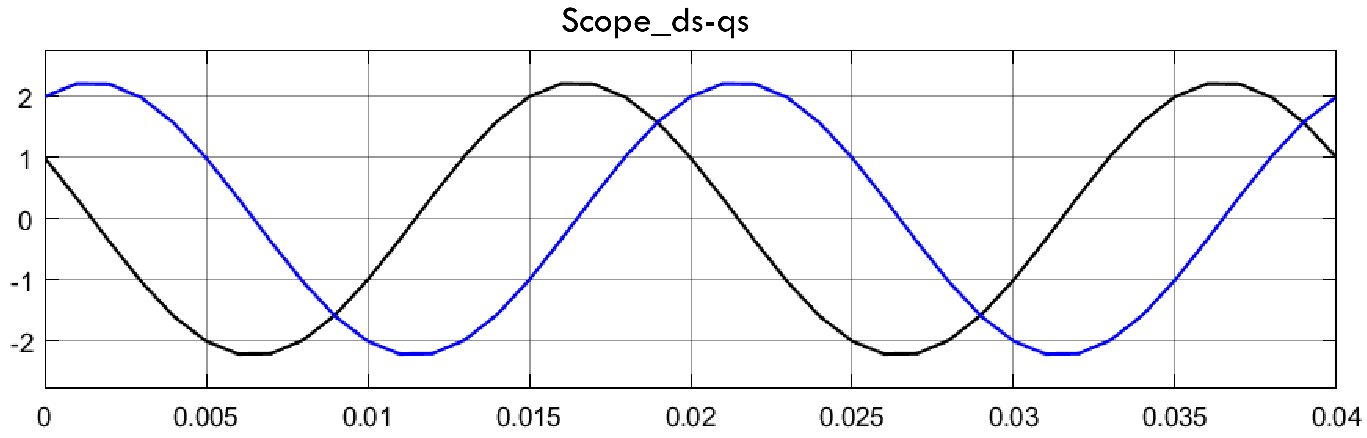
You need to check blocks of transformation in Simulink

1st way



2nd way





Transformation between reference frames

Task. Transformation between reference frames (*Park's transformation, Transformation of abc variables into dq and inverse* transformation)

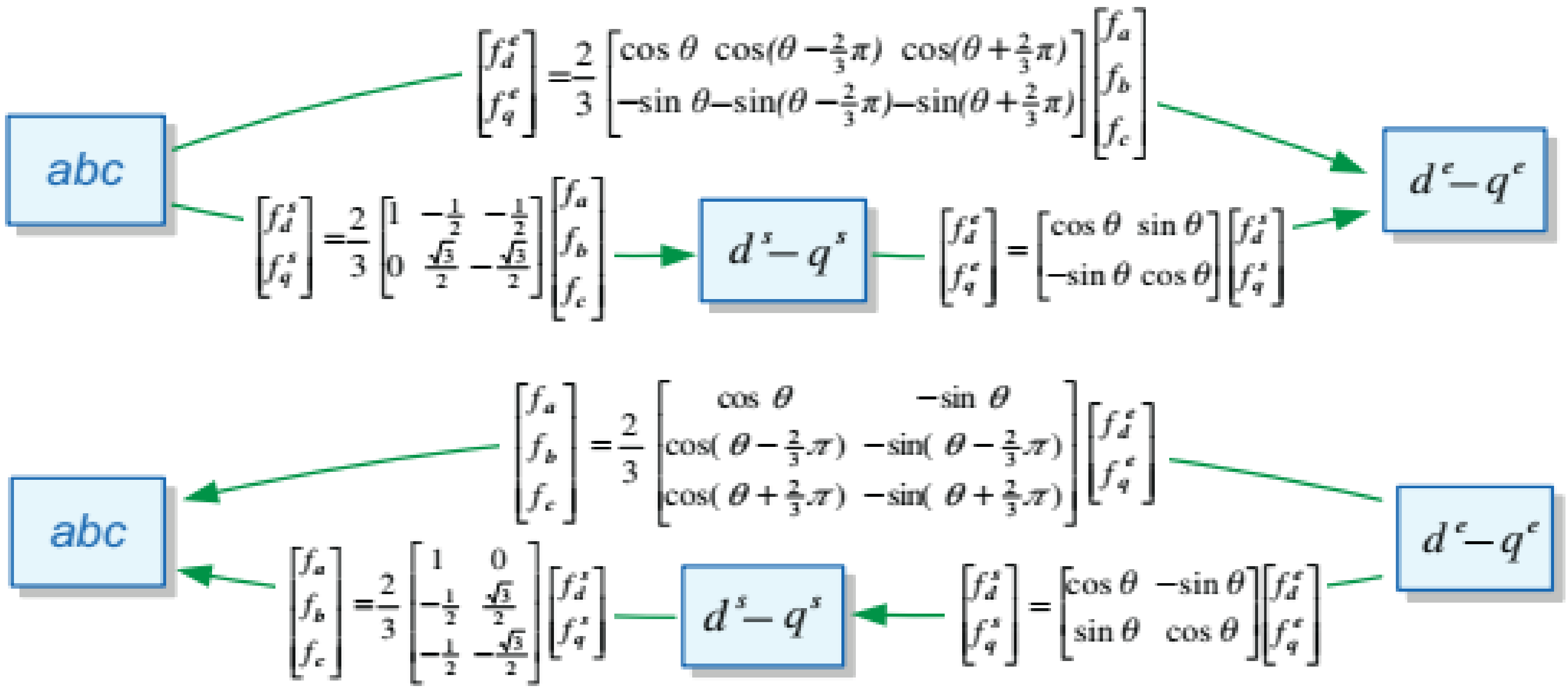
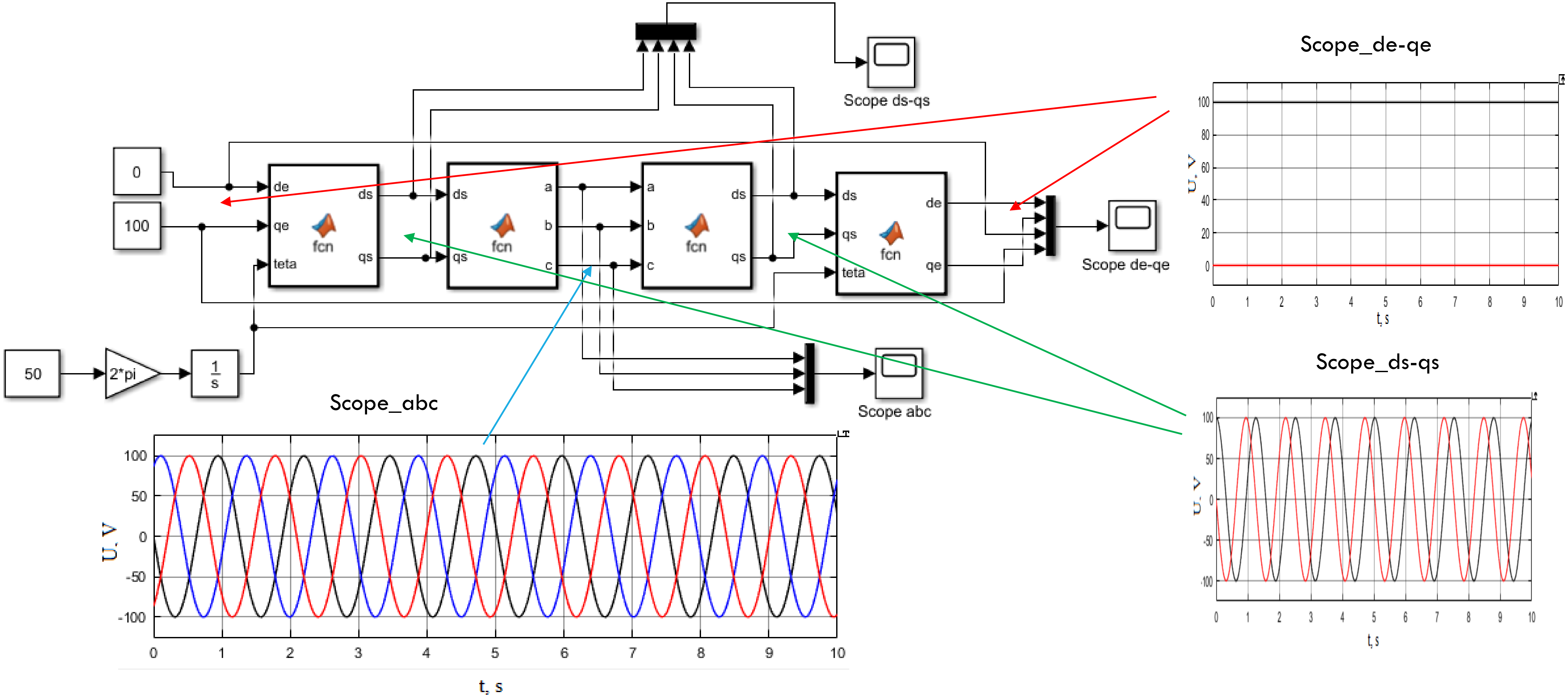


Figure Reference frame transformations

You need to include formulas of all transformation in your report before simulation

Transformation between reference frames

Task. Transformation between reference frames (*Park's transformation,* Transformation of *abc* variables into *dq and inverse* transformation)



Mathematical models of IM

Task 2.1 Model of IM in stationary reference frame

- Induction motor *d-q* equations in the stationary reference frame

$$
\begin{cases}
i^s{}_{ds} = \dfrac{1}{R_s'(1+sT_s')}\left(u^s{}_{ds} + \dfrac{K_2}{T_r}\lambda^s{}_{dr} + \omega K_2 \lambda^s{}_{qr}\right) \\
i^s{}_{qs} = \dfrac{1}{R_s'(1+sT_s')}\left(u^s{}_{qs} + \dfrac{K_2}{T_r}\lambda^s{}_{qr} - \omega K_2 \lambda^s{}_{dr}\right) \\
\lambda^s{}_{dr} = \dfrac{T_r}{1+sT_r}\left(R_r K_2 i^s{}_{ds} - \omega \lambda^s{}_{qr}\right) \\
\lambda^s{}_{qr} = \dfrac{T_r}{1+sT_r}\left(R_r K_2 i^s{}_{qs} + \omega \lambda^s{}_{dr}\right) \\
T = \dfrac{3}{2} z_p K_2 \left(\lambda^s{}_{dr} i^s{}_{qs} - \lambda^s{}_{qr} i^s{}_{ds}\right) \\
\Omega = \dfrac{T - T_l}{sJ} \qquad \omega = \dfrac{\Omega}{z_p}
\end{cases}
$$

Tr = Lr/Rr　　K1 = Lm/Ls　　K2 = Lm/Lr

Rss = (K2^2)*Rr+Rs　　Lss = Ls*(1-K1*K2)

Tss = Lss/Rss

?????

- Induction motor block diagram (Induction Motor Block) in stationary reference frame

Task 2.2 Model of IM in synchronous reference frame

- Induction motor *d-q* equations in the synchronous reference frame 1

$$i_{ds}^{e} = \frac{1}{R'_s(1+sT'_s)}\left(v_{ds}^{e} + \omega_e L'_s i_{qs}^{e} + \frac{k_2}{T_r}\lambda_{dr}^{e} + \omega_r k_2 \lambda_{qr}^{e}\right. \longrightarrow$$

$$i_{qs}^{e} = \frac{1}{R'_s(1+sT'_s)}\left(v_{qs}^{e} - \omega_e L'_s i_{ds}^{e} + \frac{k_2}{T_r}\lambda_{qr}^{e} - \omega_r k_2 \lambda_{dr}^{e}\right. \longrightarrow$$

$$\lambda_{dr}^{e} = \frac{T_r}{(1+sT_r)}\left(R_r k_2 i_{ds}^{e} + (\omega_e - \omega_r)\lambda_{qr}^{e}\right) \longrightarrow$$

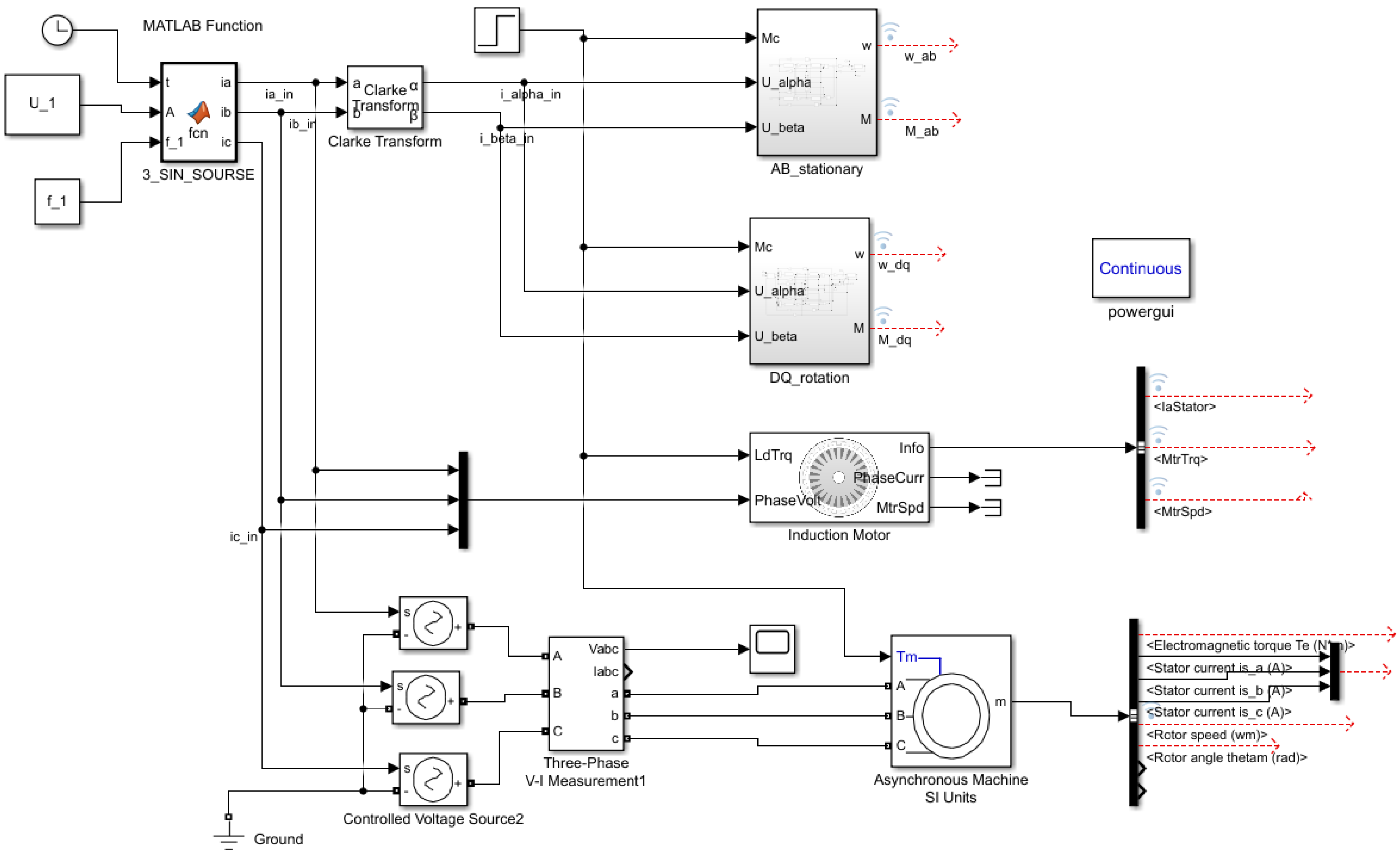
$$\lambda_{qr}^{e} = \frac{T_r}{(1+sT_r)}\left(R_r k_2 i_{qs}^{e} + (\omega_e - \omega_r)\lambda_{dr}^{e}\right) \longrightarrow$$

$$T = \frac{3}{2}\frac{P}{2}k_2\left(\lambda_{dr}^{e} i_{qs}^{e} - \lambda_{qr}^{e} i_{ds}^{e}\right) \longrightarrow$$

?????

- Induction motor block diagram (Induction Motor Block) in synchronous reference frame

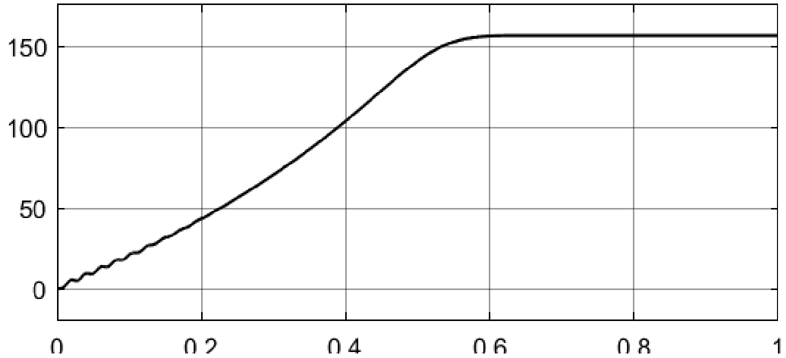
Task 2.3 Modelling results for different math.models of IM



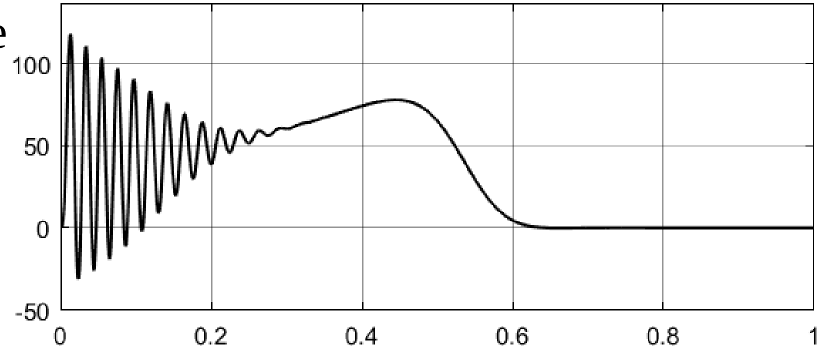
Task 2.3 Modelling results for different math.models of IM

The same results as in simulation of IM with stationary, synchronous reference frame and with Library Simulink Blocks «Asynchronous Machine SI Units» and « Induction Motor »

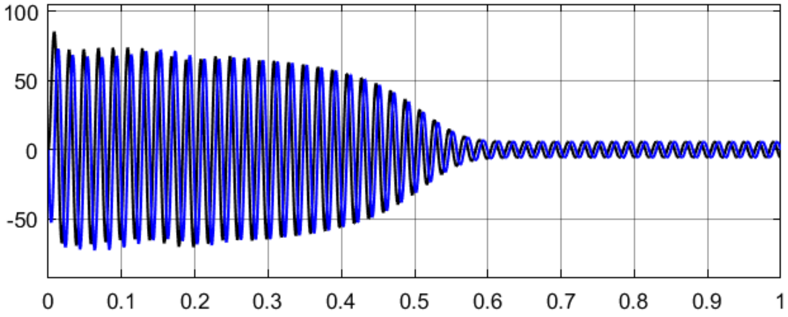
Speed [rad/s]



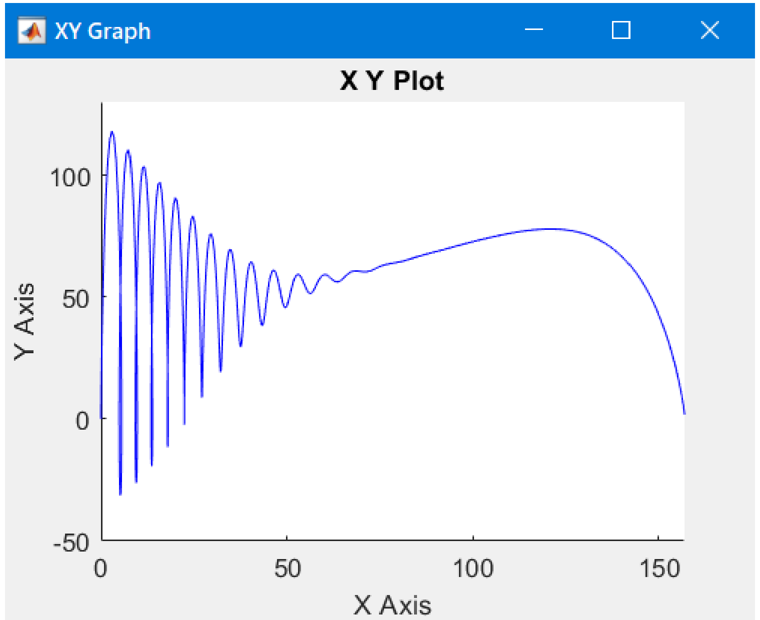
Torque [N*m]



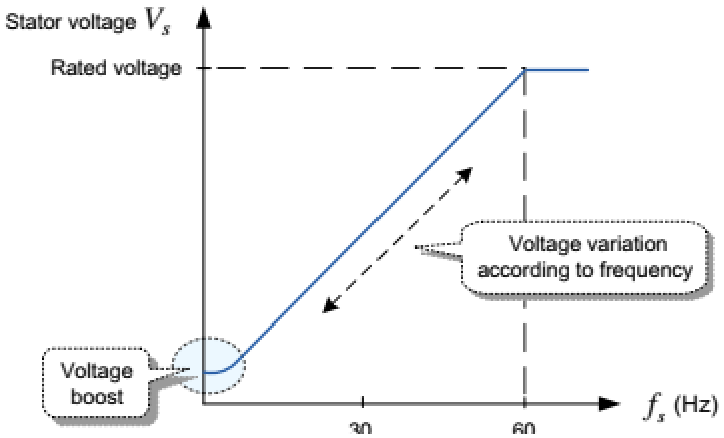
Currents [A]

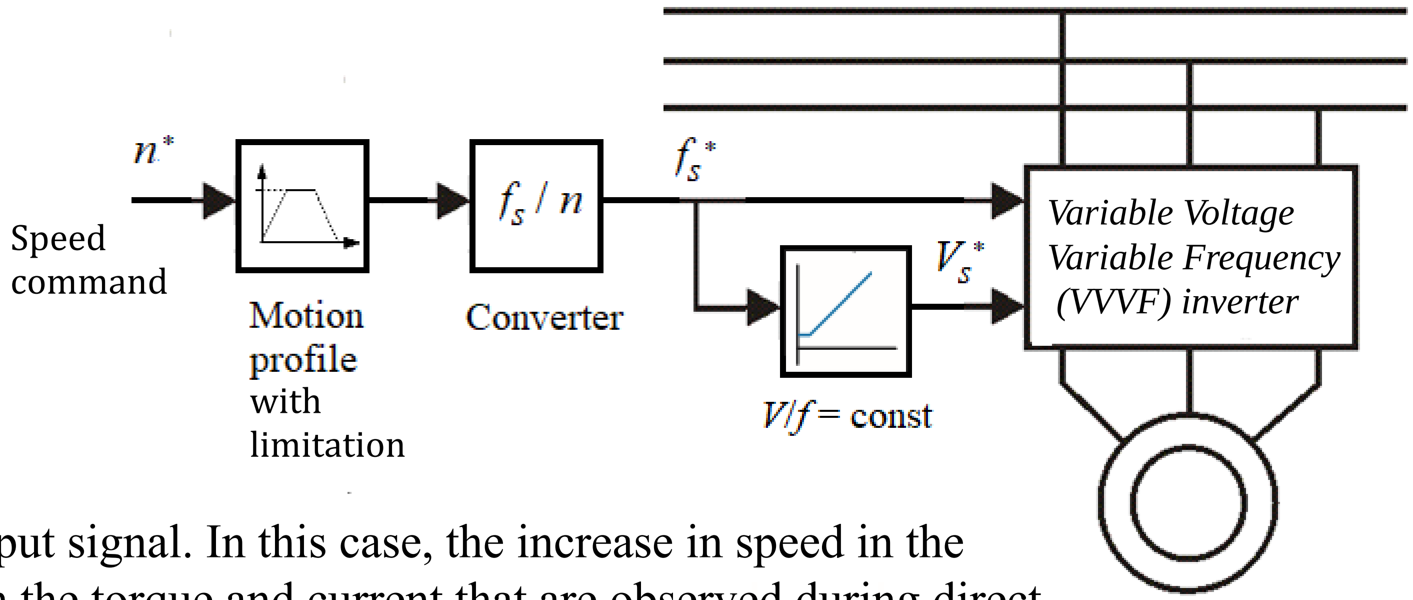


Torque-speed characteristic

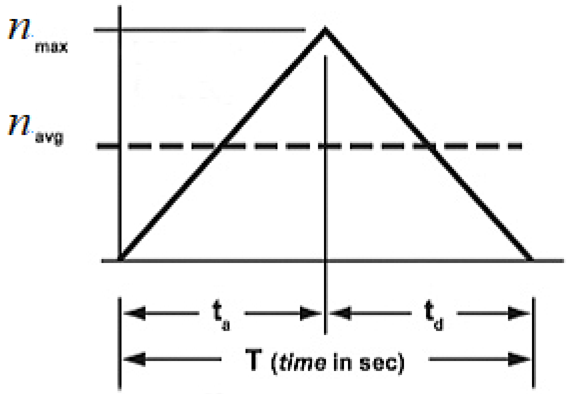


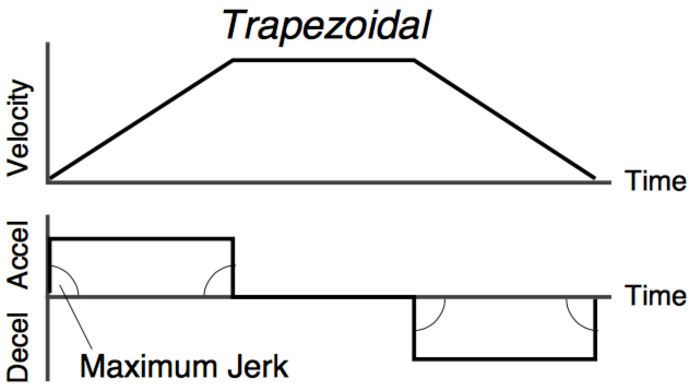
Task 3. Scalar control: open-loop system

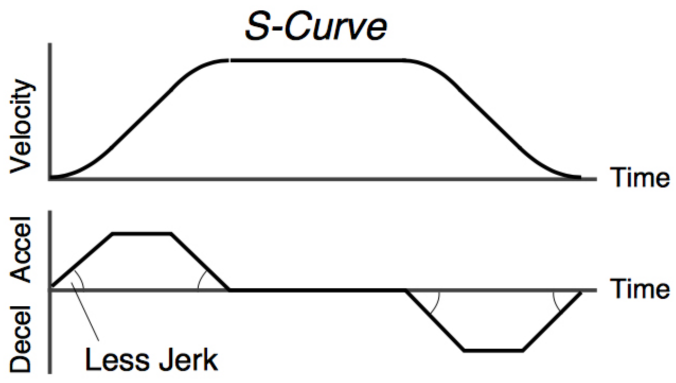




Motion profiles - forms a slowly increasing input signal. In this case, the increase in speed in the electric drive will not lead to large amplitude in the torque and current that are observed during direct start





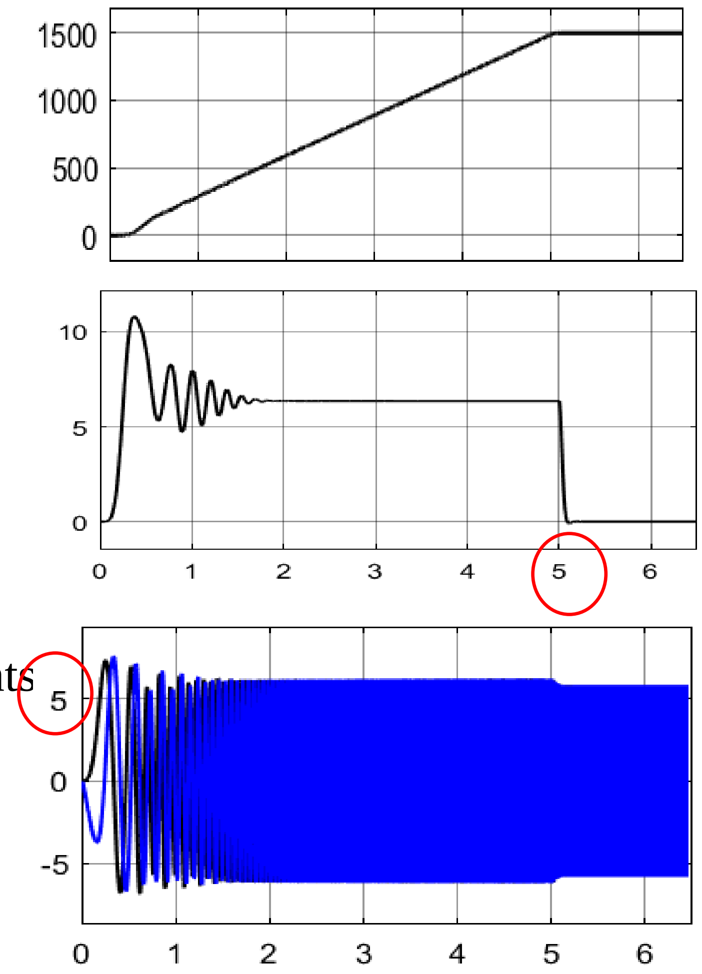


Task 3 Scalar control: open-loop system with/without motion profile

Speed [rpm]

Torque [N*m]

Currents [A]

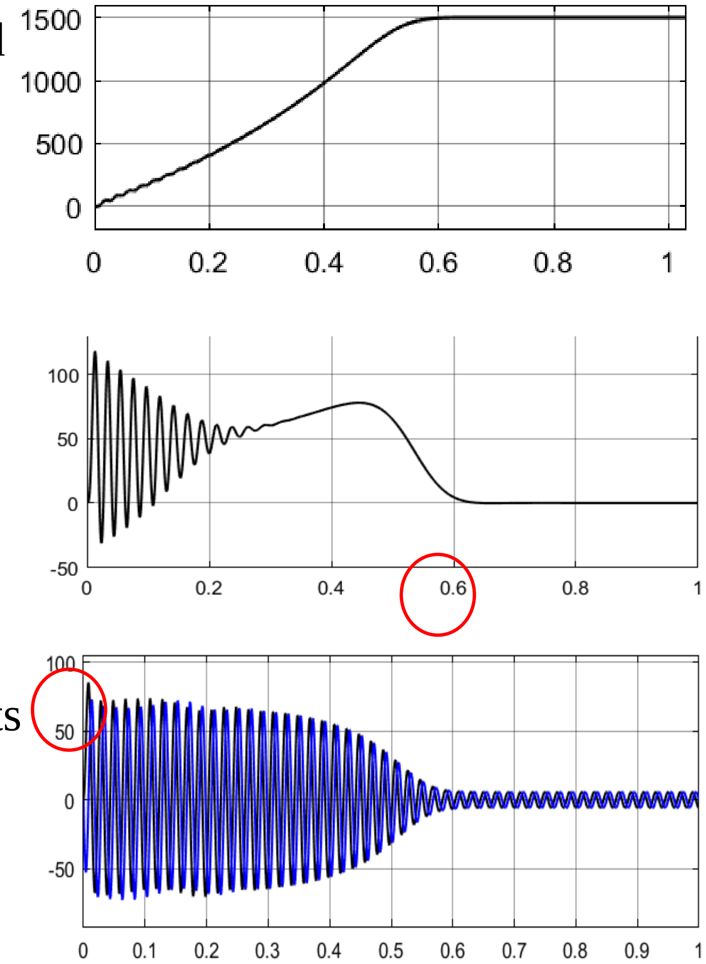


Open-loop drive system with motion profile and scalar control technique

Speed [rpm]

Torque [N*m]

Currents [A]



Open-loop drive system without motion profile profile and scalar control technique

Thank you for your attention