Scalar control of AC machines

1. Basic considerations for motor control
2. A simple V/f controller
3. Compensation of voltage drop on stator resistance
4. Slip compensation
5. Demonstration of a scalar controller

Basic considerations for motor control

We will base our analysis on steady-state operation!

Steady-state operations

$$\bar{u}_s = r_s \bar{i}_s + j\omega_s \bar{\lambda}_s$$

$$\bar{u}_r = r_r \bar{i}_r + j\boxed{(\omega_s - \omega_m)}\bar{\lambda}_r = r_r \bar{i}_r + j\boxed{\omega_{se}}\bar{\lambda}_r$$

$$\bar{\lambda}_s = L_s \bar{i}_s + L_M \bar{i}_r$$

$$\bar{\lambda}_r = L_r \bar{i}_r + L_M \bar{i}_s$$

$$T_e = \frac{3}{2} p \operatorname{Im}\left(\bar{\lambda}_s^{\,*} \cdot \bar{i}_s\right)$$

$$\omega_s = \omega_\theta$$

Rotating speed of the reference frame

$$L_s = L_{ls} + L_m$$

$$L_r = L_{lr} + L_m$$

Choose the reference frame to be rotating at the stator side synchronous speed = $\omega_s = 2\pi f_s$

ω_{se} **is therefore the slip frequency in rad/s**

Basic considerations for motor control

In per-unit

$$\overline{u}_s = r_s \overline{i}_s + j\omega_s \overline{\lambda}_s$$

$$\overline{u}_r = r_r \overline{i}_r + j\omega_{se} \overline{\lambda}_r$$

$$\overline{\lambda}_s = X_s \overline{i}_s + X_M \overline{i}_r$$

$$\overline{\lambda}_r = X_r \overline{i}_r + X_M \overline{i}_s$$

$$T_e = \mathrm{Im}\left(\overline{\lambda}_s^{\,*} \cdot \overline{i}_s\right)$$

For example, note that all variables (including the speed) are per-unit value.

For example, per-unit speed,

$$\omega_s^* = \frac{\omega_s}{\omega_{sync,rated}} = \frac{\omega_s}{2\pi \cdot f_{s,rated}}$$

For simplicity, ω_s^* is just written as ω_s

Basic considerations for motor control

It is the torque ~ speed equation that we should pay attention to!

$$\bar{u}_s = r_s \bar{i}_s + j\omega_s \bar{\lambda}_s$$
$$\bar{u}_r = r_r \bar{i}_r + j\omega_{se} \boxed{\bar{\lambda}_r}$$
$$\bar{\lambda}_s = X_s \bar{i}_s + X_M \bar{i}_r$$
$$\boxed{\bar{\lambda}_r} = X_r \bar{i}_r + X_M \bar{i}_s$$
$$T_e = \mathrm{Im}\left(\bar{\lambda}_s^* \cdot \bar{i}_s\right)$$

$$\bar{u}_s = f_4\left(\bar{i}_s\right) \longrightarrow u_s^2 = f_5\left(i_s^2\right)$$

$$\xrightarrow{u_r = 0} \bar{i}_r = f_1\left(\bar{i}_s\right)$$

$$\bar{\lambda}_s = f_2\left(\bar{i}_s\right) \xrightarrow{T_e = \mathrm{Im}\left(\bar{\lambda}_s^* \cdot \bar{i}_s\right)} T_e = f_3\left(i_s^2\right)$$

$$T_e = \left(\frac{u_s}{\omega_s}\right)^2 \cdot \frac{\omega_{se}\left(x_M\right)^2 r_r}{\left(r_s r_r/\omega_s - \omega_{se}\sigma x_r x_s\right)^2 + \left(\omega_{se} r_s x_r/\omega_s + r_r x_s\right)^2}$$

$$\Big\Downarrow \ \omega_{se} \to 0 \ \& \ r_s = 0$$

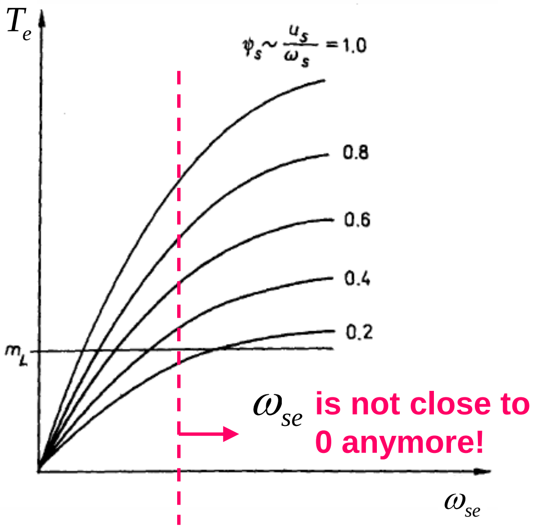
$$T_e = \left(\frac{u_s}{\omega_s}\right)^2 \cdot \frac{\left(x_M\right)^2}{\left(x_s\right)^2 r_r} \cdot \omega_{se}$$

$$T_m = \left(\frac{u_s}{\omega_s}\right)^2 \cdot \frac{\left(x_M\right)^2}{2\sigma\left(x_s\right)^2 x_r} \qquad \omega_{sm} = \frac{r_r}{\sigma x_r}$$

$$T_e = \frac{2T_m}{\omega_{sm}}\omega_{se} = K\left(\omega_s - \omega_m\right)$$

Basic considerations for motor control

Under a certain load condition



$$T_e = \frac{2T_m}{\omega_{sm}}\omega_{se} = K(\omega_s - \omega_m)$$

For load torque less than the rated torque

- A certain load torque can be achieved for different slip frequencies and flux levels.
- The slip increases while the flux reduces.
- The motor efficiency, power factor, etc., are different.
- At light load, the total loss may be reduced by 20-30% [Abrahamsen 2000].
- The max. (pull-out) torque is reduced with reduced flux level!

Notice that $\lambda_s \propto \frac{u_s}{\omega_s}$ (if $r_s = 0$)

Basic considerations for motor control

Our control target

For any load torque, the rotor speed is always kept as desired.

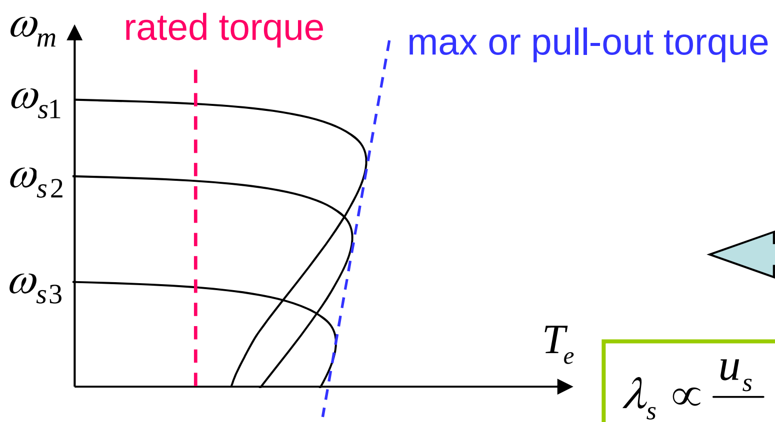
And …… , we set the following constrain

The stator flux is always kept at its rated value for any speed and any load torque!

- High torque production capability (max. torque / Ampere)
- (almost) linear torque-speed relationship
- low-slip operation (low rotor losses)
- High maximum (pull-out) torque
- (Not optimum efficiency operation)
- Please notice that $\longrightarrow$ $\dfrac{\lambda_s}{\lambda_r} = \dfrac{x_s}{x_M}\sqrt{1+\left(\dfrac{x_r}{r_r}\omega_{se}\right)} > 1$

Basic considerations for motor control

Understand more about the torque vs. speed characteristics



$$T_e = \frac{2T_m}{\omega_{sm}}\omega_{se} = K(\omega_s - \omega_m)$$

$$\omega_m = \omega_s - \left(\frac{\omega_{sm}}{2T_m}\right)T_e$$

$$\lambda_s \propto \frac{u_s}{\omega_s} \quad (\text{if } r_s = 0) \quad \text{constant}$$

Balanced by the load torque

- Because $\bar{u}_s = r_s \bar{i}_s + j\omega_s \bar{\lambda}_s$
  For low speed → low terminal voltage
  reduced stator flux and pull-out torque.

- Because linear torque-speed relationship, the absolute speed error (and the slip frequency) for the same load torque is constant.

- But the relative speed error (and the slip) increases with decreasing speed! (**Check this out in the Simulink model!**)

A simple V/f controller

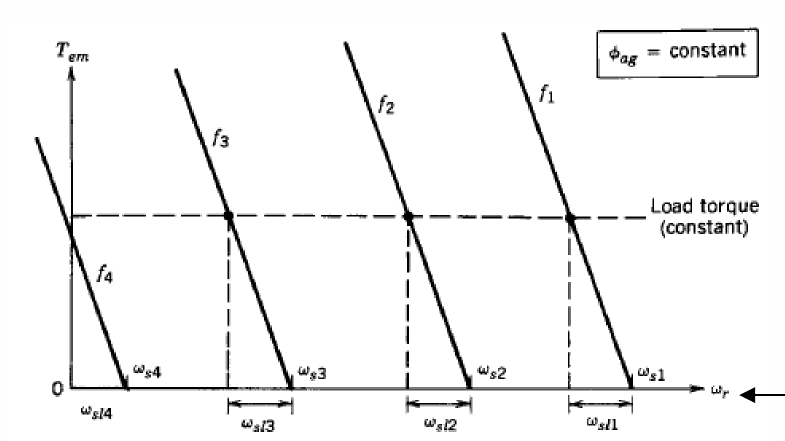
Conditions and ideas

- Under normal (what is 'normal'?) operation conditions, the slip is very small (less than 5%)
- So we can assume s = 0 (only for speed error consideration). Therefore the rotor speed = the synchronous speed / the number of pole pairs.
- We control the synchronous speed (stator frequency fs) to control the rotor speed.
- We need to keep the stator flux as rated, so

$$\boxed{U_{s,new} = f_{s,new} \cdot \frac{U_{s,rated}}{f_{s,rated}}}$$

RMS or peak value

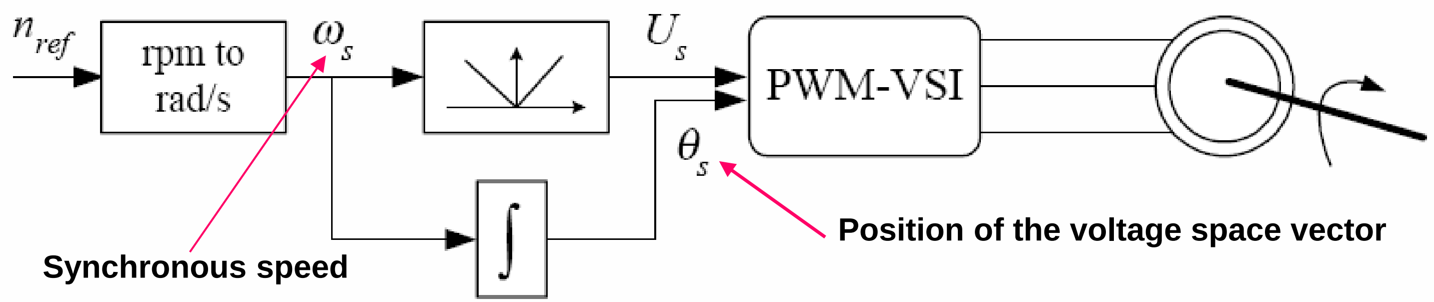
Calculate from the required rotor speed and the num. of pole pairs



means rotor speed!

A simple V/f controller

A schematic diagram of the controller



At time t = 0

a-axis

Vol. space vector

$$u_q = U_{pk} \qquad u_d = 0 \qquad u_0 = 0$$

$$qd0 \sim \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \sim abc$$

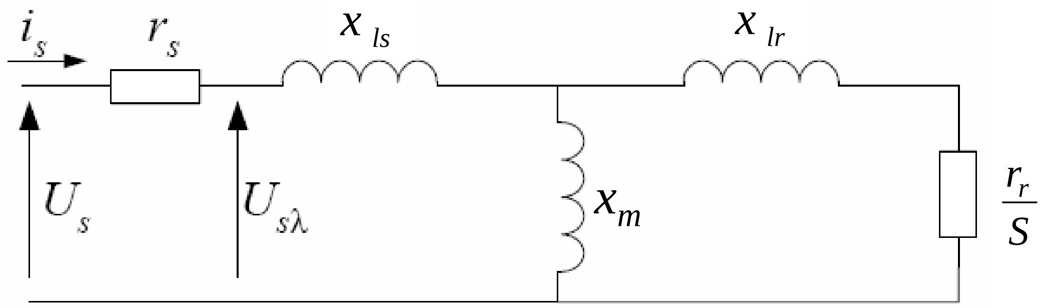
$$u_a = U_{pk}\cos\theta$$
$$u_b = U_{pk}\cos\left(\theta - \frac{2}{3}\pi\right)$$
$$u_c = U_{pk}\cos\left(\theta + \frac{2}{3}\pi\right)$$

- This voltage is impressed on the motor by means of the pulse-width modulated VSI
- Properties: 1. Very simple open-loop speed controller
  2. Limited performance (both stationary and dynamic)
  3. By introducing a few extra functions, acceptable performance may be obtained

Compensation of voltage drop on the stator resistance

A simple method

- The idea is to keep $\dfrac{U_{s\lambda}}{\omega_s}$ constant instead of $\dfrac{U_s}{\omega_s}$



- Simply assuming s = 0 (no-load condition)

$$\frac{\overline{U}_s}{r_s + j(x_{ls} + x_m)} = \frac{\overline{U}_{s\lambda}}{j(x_{ls} + x_m)}$$

$$\boxed{U_{s\lambda} = \frac{U_{s,rated}}{\omega_{s,rated}}\omega_{s,now}}$$

$$\Downarrow$$

$$U_s = \left|1 - j\frac{r_s}{(x_{ls} + x_m)}\right| U_{s\lambda} = U_{s\lambda} \cdot \sqrt{1 + \frac{r_s^{\,2}}{(x_{ls} + x_m)^2}} \Rightarrow U_s = \frac{U_{s,rated}}{\omega_{s,rated}} \cdot \omega_{s,now}\sqrt{1 + \frac{r_s^{\,2}}{x_m^{\,2}}}$$

Compensation of voltage drop on the stator resistance

Can we do better?

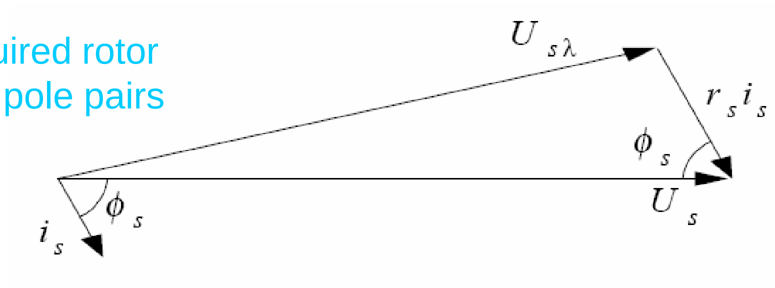
- We should design the controller by using as less as possible motor parameters!
- We can measure the instantaneous 3-phase currents (using two current sensors will be enough), to have some feedback signals.
- The output instantaneous voltage is controllable, but is the target value to be determined. If we use voltage space vector, its magnitude is unknown but its position is always known!

Compensation of voltage drop on the stator resistance

Method from Munoz-Garcia [1998]

$$U_{s\lambda} = \frac{U_{s,rated}}{f_{s,rated}} \boxed{f_{s,now}} \leftarrow$$

Calculate from the required rotor speed and the num. of pole pairs



$$U_s = r_s (I_s \cos\phi) + \sqrt{U^2{}_{s\lambda} - r_s{}^2 (I_s \sin\phi)^2} = r_s (I_s \cos\phi) + \sqrt{U^2{}_{s\lambda} - (r_s I_s)^2 + r_s{}^2 (I_s \cos\phi)^2}$$

measured and $i_c = -(i_a + i_b)$

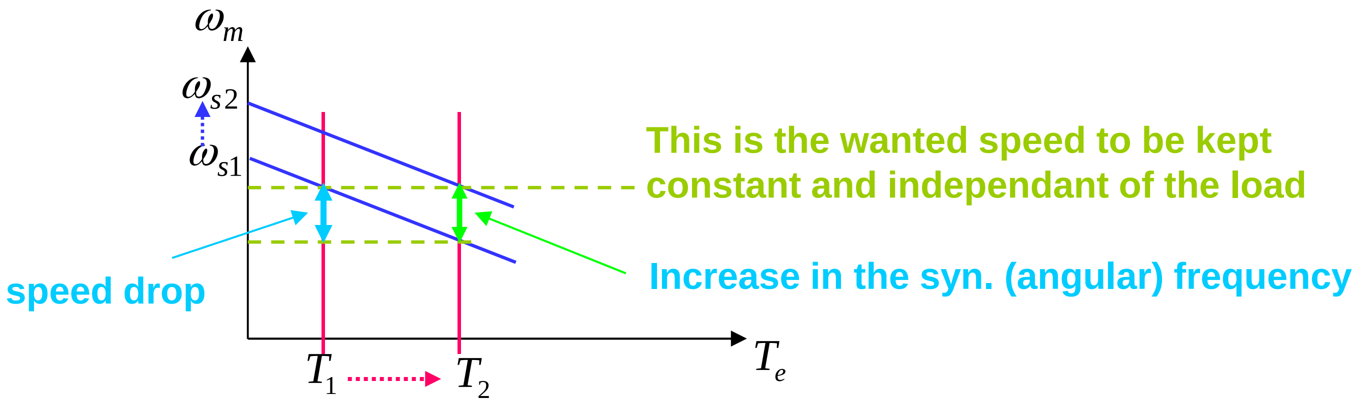
$$\bar{i}_s = \frac{2}{3}\left(i_a + e^{j\frac{2\pi}{3}} i_b + e^{-j\frac{2\pi}{3}} i_c \right)$$

$angle(\bar{u}_s)$ is known

$\Rightarrow$ The power factor angle can be calculated

Slip Compensation

- Slip compensation is very necessary for low-speed operations!
- If the slip frequency is known, then the basic idea is to



This is also applicable to non-linear situation!

Control of the syn. frequency is independant of the control of terminal volts for stator resistance compensation!

- So the only question left is

How can we electrically measure the slip (or rotor speed)?

Slip Compensation

- According to previous slides, the torque equation $T_e = \frac{2T_m}{\omega_{sm}}\omega_{se}$ is derived under the condition of zero stator resistance.
- The voltage drop on the resistance is compensated! So the above assumption is still true is we use $u_{s\lambda}$ instead of u_s as the terminal voltage.
- The stator resistance compensation algorithm assures

$$\frac{u_{s\lambda}}{\omega_s} = \lambda_s = const.$$

- So the maximum torque is always constant for any synchronous freq. Also notice that ω_{rk} is totally determined by the motor parameters.

Therefore $$\frac{T_e}{T_{rated}} = \frac{\omega_{se}}{\omega_{e,rated}} = \frac{f_{se}}{f_{se,rated}} = \frac{\boxed{f_{se}}}{S_{rated}\, f_{s,rated}}$$

Can be obtained if the torque is known

And the compensated stator frequency becomes $f_{s,new} = f_s + f_{se}$

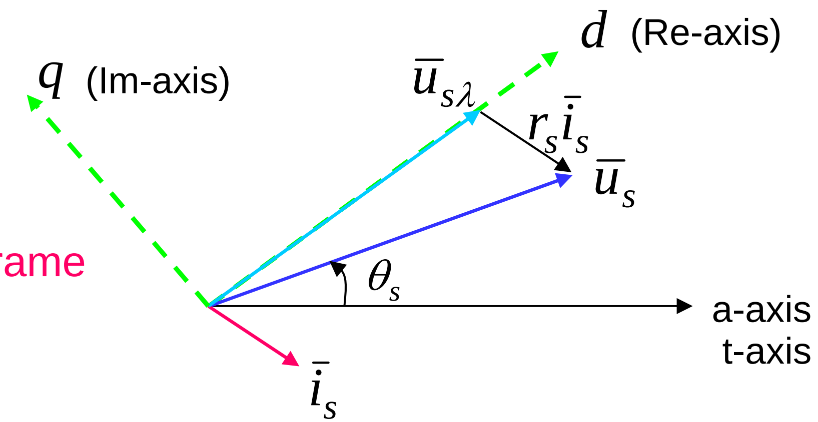
Slip Compensation

Now the problem becomes 'how to calculate the torque'?

In steady-states:

$$\bar{u}_{s\lambda} = j\omega_s \bar{\lambda}_s$$

$$T_e = \mathrm{Im}\left(\bar{\lambda}_s^{\,*} \cdot \bar{i}_s\right)$$



⇩ In the definded reference-frame

$$\bar{u}_{s\lambda} = u_{sd} = j\omega_s\left(\lambda_{sd} + j\lambda_{sq}\right)$$

⇩

$$\lambda_{sd} = 0 \qquad \lambda_{sq} = -\frac{u_{s\lambda}}{\omega_s}$$

Known!

$$\frac{M_{e,now}}{M_{e,rated}} = \frac{i_{sd}}{i_{sd,rated}}$$

⇩ Now use real value equations!

$$T_e = \mathrm{Im}\left(\bar{\lambda}_s^{\,*} \cdot \bar{i}_s\right) = \frac{3}{2} p \,\mathrm{Im}\left[j\frac{u_{s\lambda}}{\omega_s} \cdot \left(i_{sd} + j i_{sq}\right)\right] = \frac{3}{2} p \frac{u_{s\lambda}}{\omega_s} i_{sd}$$

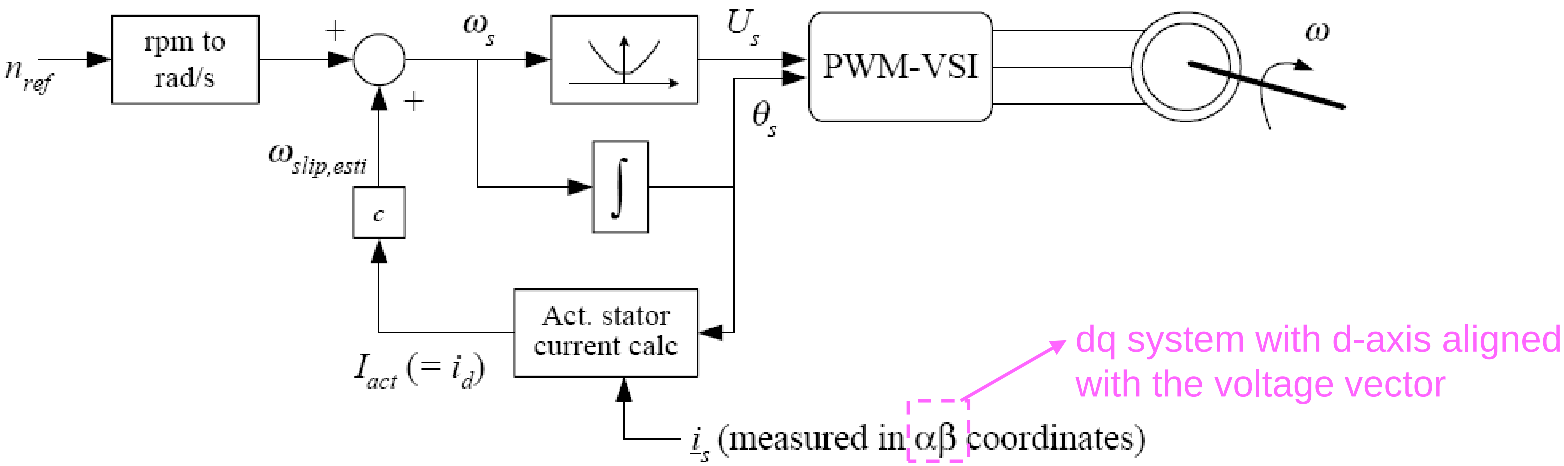
Slip Compensation

Finally, the slip frequency can be calculated by

$$\frac{M_{e,now}}{M_{e,rated}} = \frac{i_{sd}}{i_{sd,rated}}$$

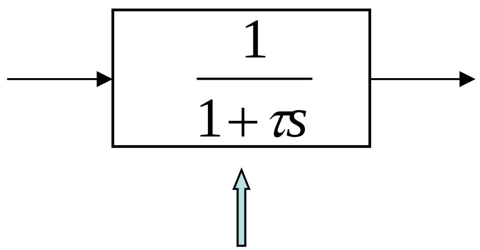
$$\frac{T_e}{T_{rated}} = \frac{\omega_{se}}{\omega_{se,rated}} = \frac{f_{se}}{S_{rated}\, f_{s,rated}}$$

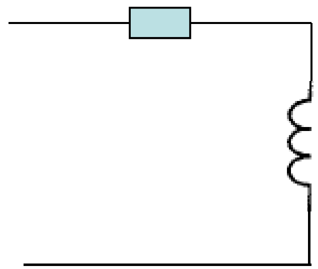
$$\Rightarrow \quad f_{se} = \frac{i_{sd}}{i_{sd,rated}} f_{se,rated}$$



Slip Compensation

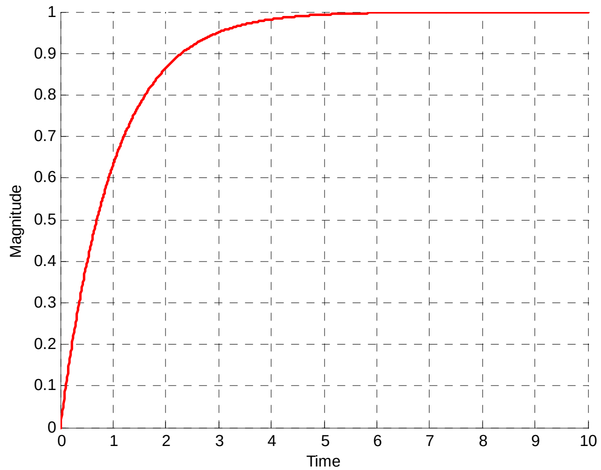
Use of a first-order lag to stabilize the controller!





A RL filter with a unit resistance

Transfer function $$i_L = \frac{u_{in}}{R+Ls}$$



$$i_L = \frac{U_{in,DC}}{R}\left(1-e^{-\frac{1}{L/R}t}\right)$$

Exercises

1. Finish the IM model.
2. Design a scalar controller running at min. Speed 150 rpm with a relative speed error less than 2%.