AC Brushless Drive

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Electric Propulsion

A.Y. 2020/2021

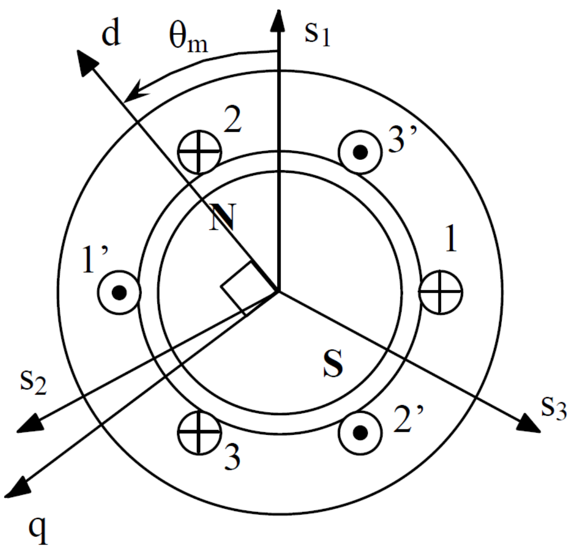
Modeling an AC Brushless Motor

AC Brushless machines are permanent magnet synchronous motors (PMSMs). Their model is derived similarly to that one for induction machines:

- identification of the differential equations in the three-phase system (please see professor Castelli Dezza's notes)
- transformation of the machine model in a new reference frame (dq axis, space vectors can be used)
- the model can be translated from SI units into normalized quantities (per unit, p.u.)

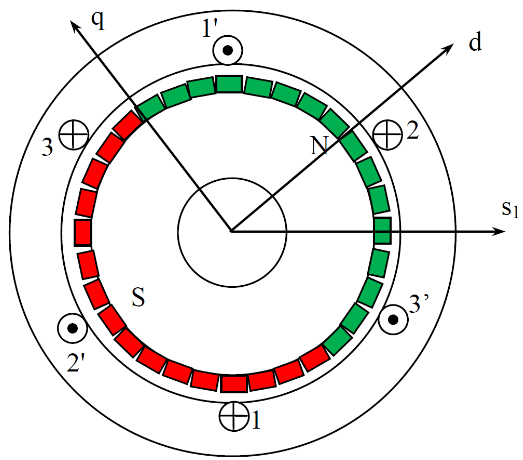
Modeling an AC Brushless Motor

stator

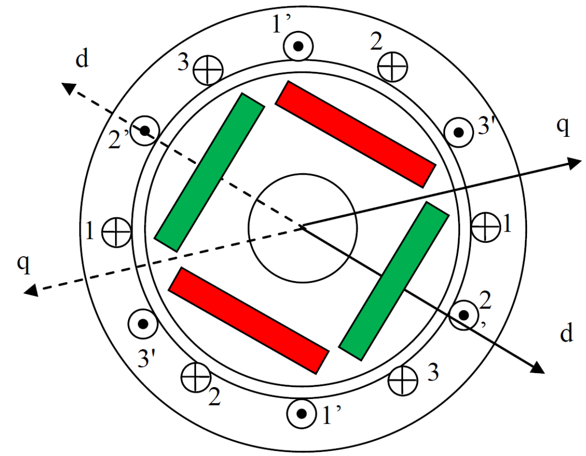


rotor

isotropic

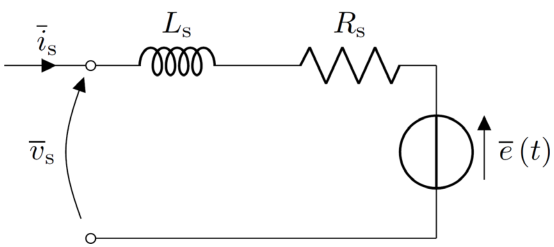


anisotropic



No simple equivalent circuit here

Simple model for isotropic rotor



$$\begin{cases} \overline{v}_s = R_s \bar{i}_s + p\overline{\psi}_s + j\omega_m \overline{\psi}_s \\ \overline{\psi}_s = L_s \bar{i}_s + \psi_{PM} \\ T_e = n_p \psi_{PM} i_{sq} \end{cases}$$

$$\begin{cases} \overline{v}_s = R_s \bar{i}_s + p\overline{\psi}_s + j\omega_m \overline{\psi}_s \\ \psi_{sd} = L_{sd} i_{sd} + \psi_{PM} \\ \psi_{sq} = L_{sq} i_{sq} \\ T_e = n_p \left[\left(L_{sd} - L_{sq} \right) i_{sd} i_{sq} + \psi_{PM} i_{sq} \right] \end{cases}$$

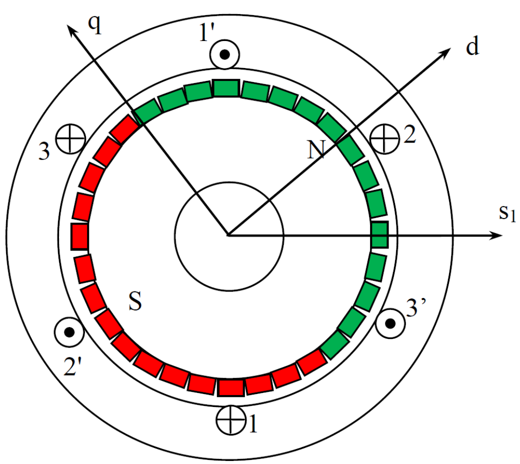
AC Brushless: Reference Frame

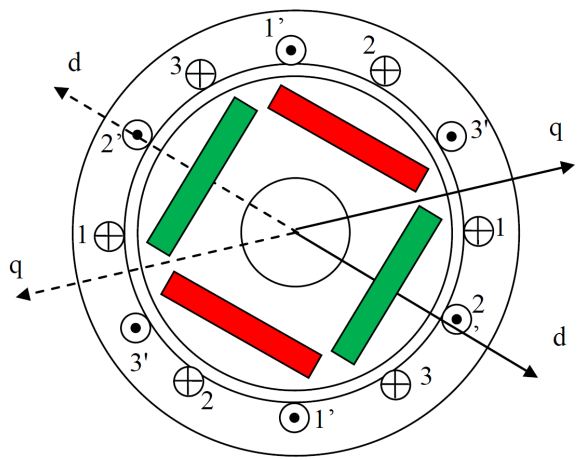
Rotating reference frame (Park transformation)

$\theta_\mathrm{s} = \int \omega_\mathrm{s} \mathrm{d}t$, $\omega_\mathrm{s} = \omega_\mathrm{m}$ **synchronous machine**

$$\overline{x}_\mathrm{dq} = \sqrt{\frac{2}{3}} \left(x_\mathrm{a} + \overline{\alpha} x_\mathrm{b} + \overline{\alpha}^2 x_\mathrm{c} \right) e^{j\theta_\mathrm{s}} = x_\mathrm{d} + j x_\mathrm{q}$$

$$\overline{x} = \overline{v}_\mathrm{s}, \, \overline{i}_\mathrm{s}, \, \overline{\psi}_\mathrm{s}$$





d-axis aligned with PM flux

AC Brushless: Simulink Model

$$
\begin{cases}
p\overline{\psi}_{\mathrm{s}} = \overline{v}_{\mathrm{s}} - R_{\mathrm{s}}\overline{i}_{\mathrm{s}} - j\omega_{\mathrm{m}}\overline{\psi}_{\mathrm{s}} \\
\overline{i}_{\mathrm{s}} = \dfrac{1}{L_{\mathrm{s}}}\left(\overline{\psi}_{\mathrm{s}} - \psi_{\mathrm{PM}}\right) \\
p\Omega_{\mathrm{m}} = \dfrac{1}{J}\left(T_{\mathrm{e}} - T_{\mathrm{l}} - \beta\Omega_{\mathrm{m}}\right) \\
T_{\mathrm{e}} = n_{\mathrm{p}}\psi_{\mathrm{PM}} i_{\mathrm{sq}}
\end{cases}
$$

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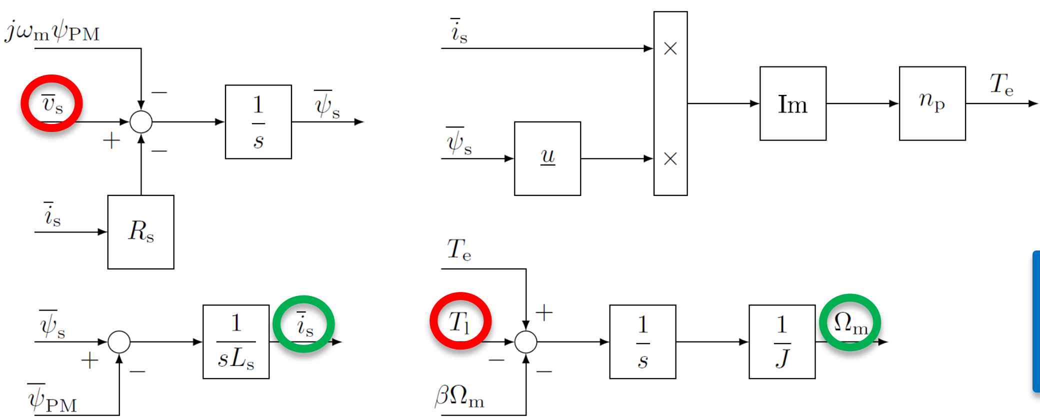
p\overline{\psi}_{\mathrm{s}} = \overline{v}_{\mathrm{s}} - R_{\mathrm{s}}\overline{i}_{\mathrm{s}} - j\omega_{\mathrm{m}}\overline{\psi}_{\mathrm{s}} \\
i_{\mathrm{sd}} = \dfrac{1}{L_{\mathrm{sd}}}\left(\psi_{\mathrm{sd}} - \psi_{\mathrm{PM}}\right) \\
i_{\mathrm{sq}} = \dfrac{1}{L_{\mathrm{sq}}}\psi_{\mathrm{sq}} \\
p\Omega_{\mathrm{m}} = \dfrac{1}{J}\left(T_{\mathrm{e}} - T_{\mathrm{l}} - \beta\Omega_{\mathrm{m}}\right) \\
T_{\mathrm{e}} = n_{\mathrm{p}}\left[\left(L_{\mathrm{sd}} - L_{\mathrm{sq}}\right) i_{\mathrm{sd}} i_{\mathrm{sq}} + \psi_{\mathrm{PM}} i_{\mathrm{sq}}\right]
\end{cases}
$$



Isotropic machine is considered for simplicity

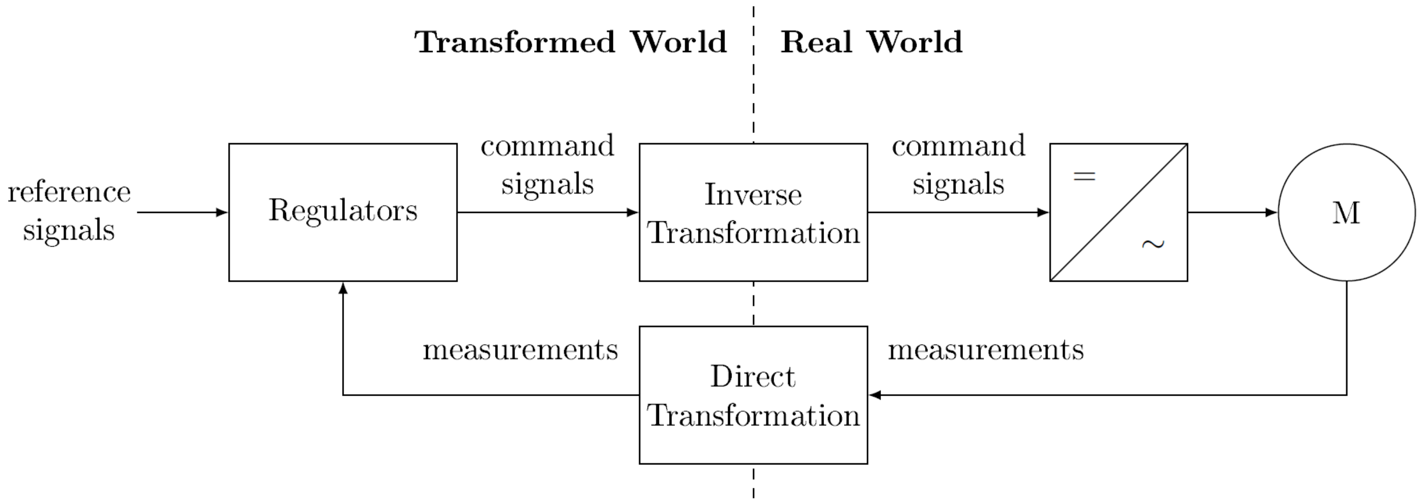
$$\boxed{j = \cos\left(\frac{\pi}{2}\right) + j\sin\left(\frac{\pi}{2}\right) = e^{j\frac{\pi}{2}}}$$

Vector Control

The control is based on an **equivalent transformed motor**

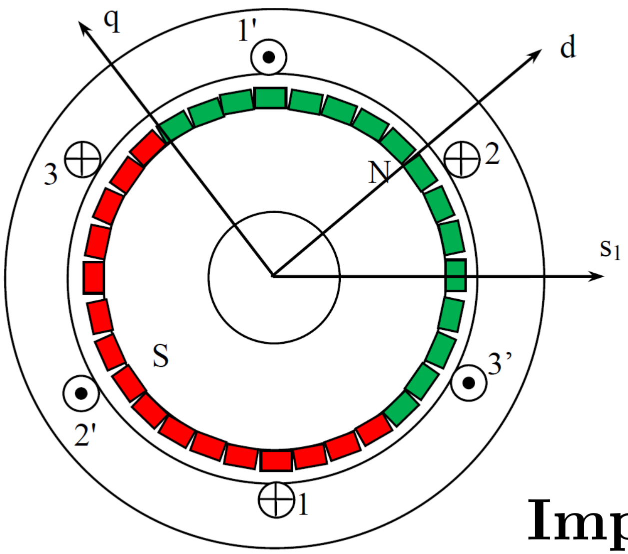
Both R-FOC and AC brushless drives allow to obtain two **decoupled** dynamics:

- slow transients (rotor flux, i_{sd})
- fast transients (torque, i_{sq})



AC Brushless Drive

The control is based on the same strategy adopted for DC and induction (R-FOC) motors. Namely, i_{sd} is used to perform flux weakening (the maximum value for the flux is set by PMs), whereas i_{sq} is exploited for varying the torque T_e.



- d-axis aligned with the PM flux

$$\begin{cases} \psi_{\mathrm{rd}} = \psi_{\mathrm{PM}} \\ \psi_{\mathrm{q}} = 0 \end{cases}$$

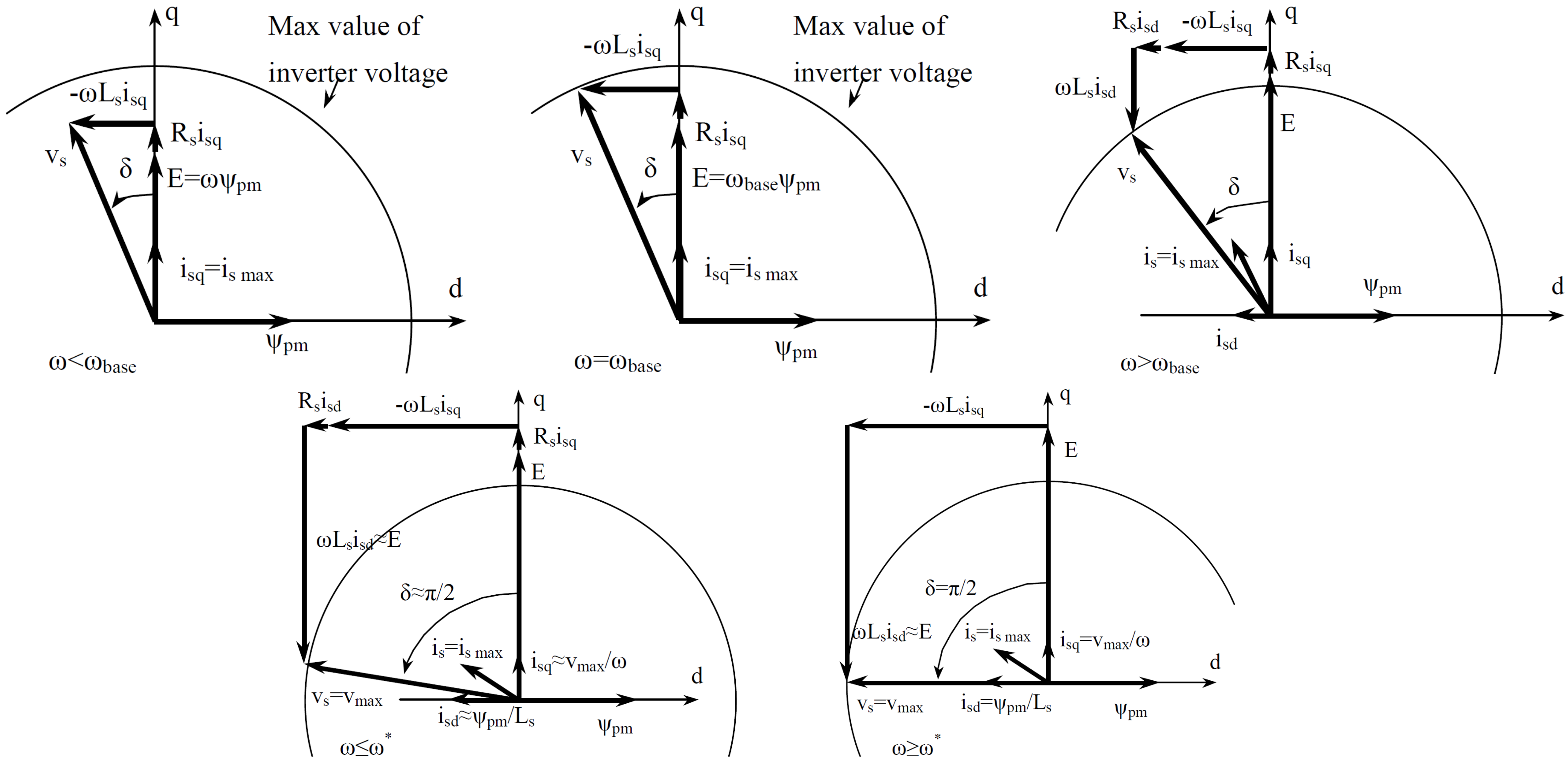
- the reference frame rotates synchronously with the rotor and all the electric variables

Important: i_{sd} and i_{sq} are components of the same transformed three-phase system (=IM)

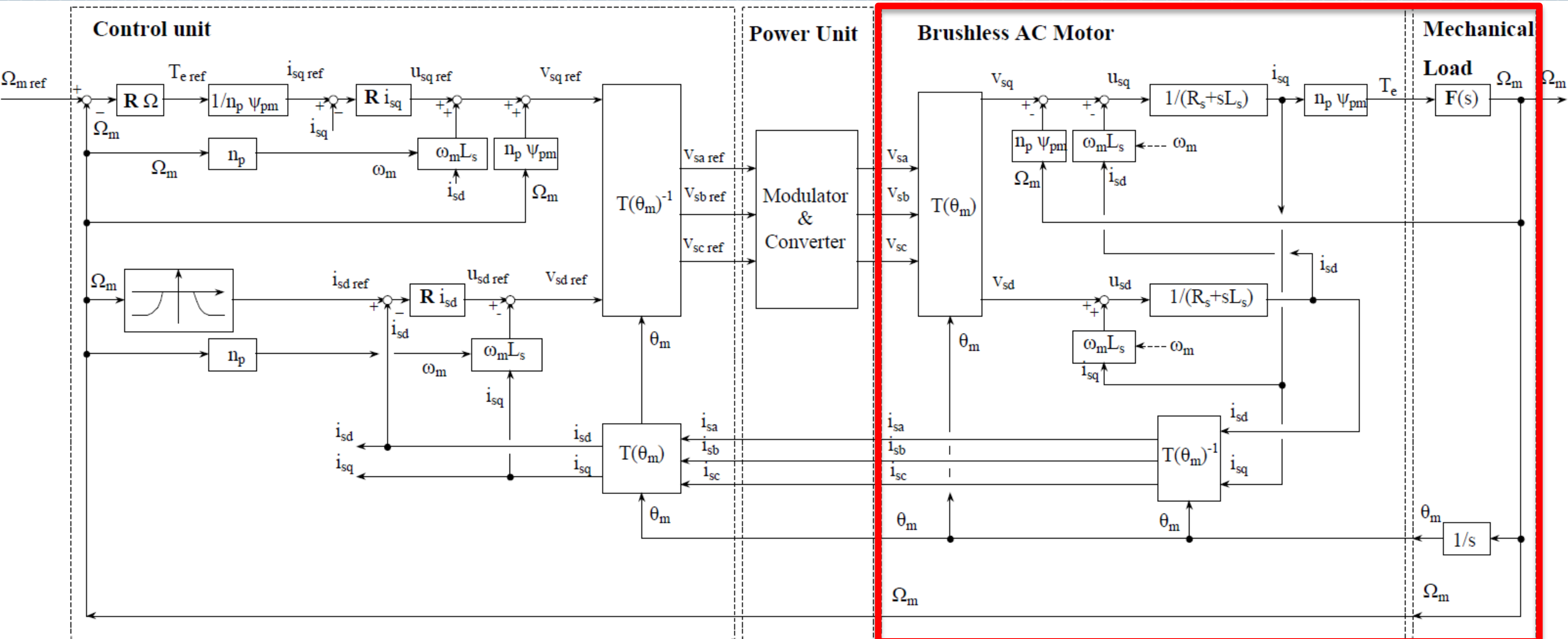
Working Principles

$$\begin{cases} \overline{v}_\mathrm{s} = R_\mathrm{s}\overline{i}_\mathrm{s} + p\overline{\psi}_\mathrm{s} + j\omega_\mathrm{m}\overline{\psi}_\mathrm{s} \\ \overline{\psi}_\mathrm{s} = L_\mathrm{s}\overline{i}_\mathrm{s} + \psi_\mathrm{PM} \end{cases} \qquad \begin{cases} v_\mathrm{sd} = R_\mathrm{s}i_\mathrm{sd} + L_\mathrm{s}pi_\mathrm{sd} - \omega_\mathrm{m}L_\mathrm{s}i_\mathrm{sq} \\ v_\mathrm{sq} = R_\mathrm{s}i_\mathrm{sq} + L_\mathrm{s}pi_\mathrm{sq} + \omega_\mathrm{m}L_\mathrm{s}i_\mathrm{sd} + \omega_\mathrm{m}\psi_\mathrm{PM} \end{cases}$$

a regime

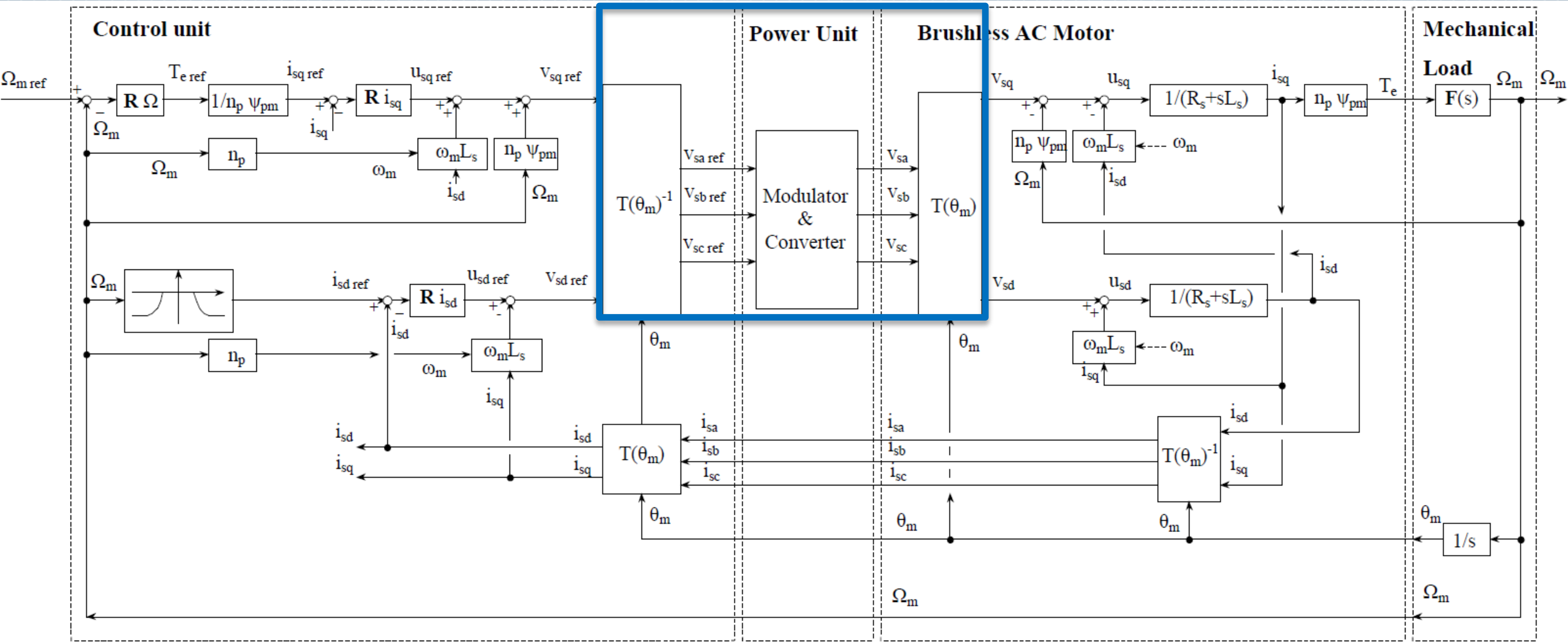


Control Scheme



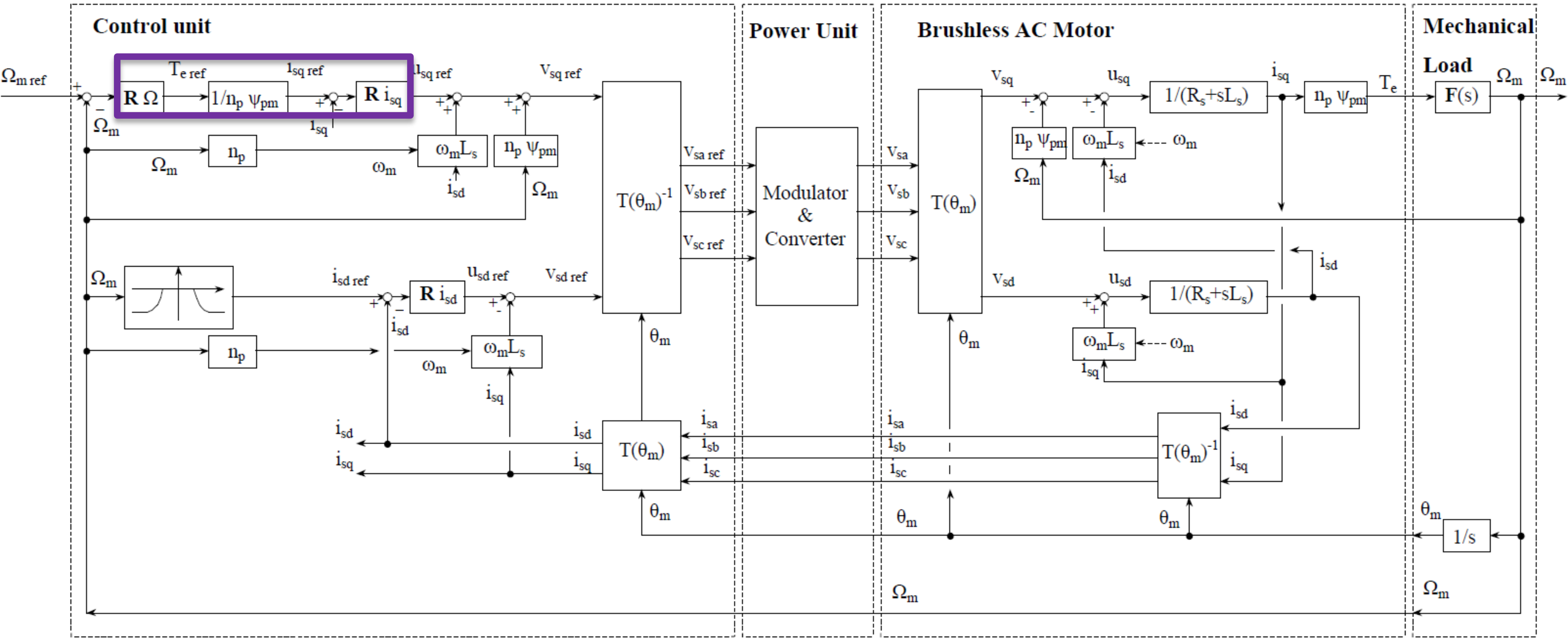
Motor model: dq reference frame. Use transfer function blocks to test each regulator, whereas the complete model should be exploited for the overall simulation

Control Scheme



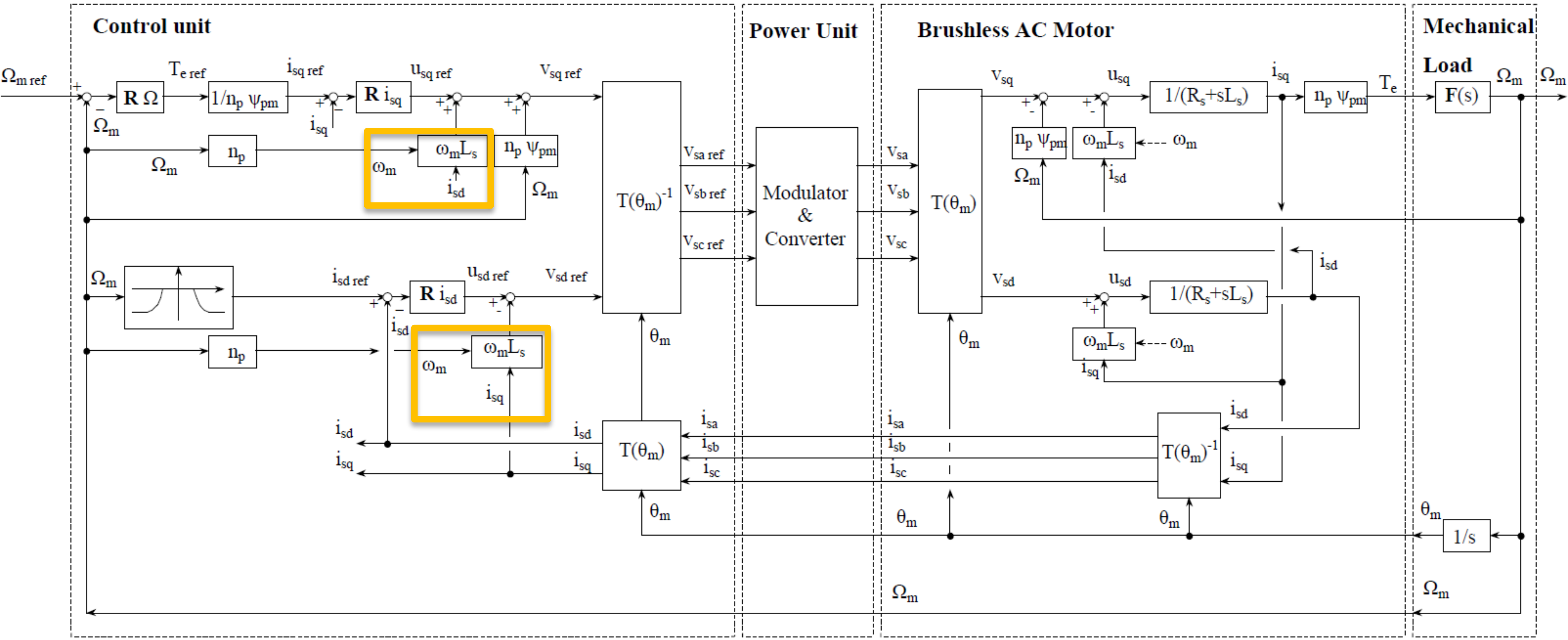
Inverter model: approximate it as a unitary gain. Do not consider the transformations and anti-transformations, since the model of the motor can be written on dq axis.

Control Scheme



Cascade control approach: inner loops must be much faster than the outer ones (at least 10 times). This constraint allows to design the PI independently. NO CASCADE for i_{sd}.

Control Scheme



Decoupling terms

Decoupling Terms

Considering the two voltage components

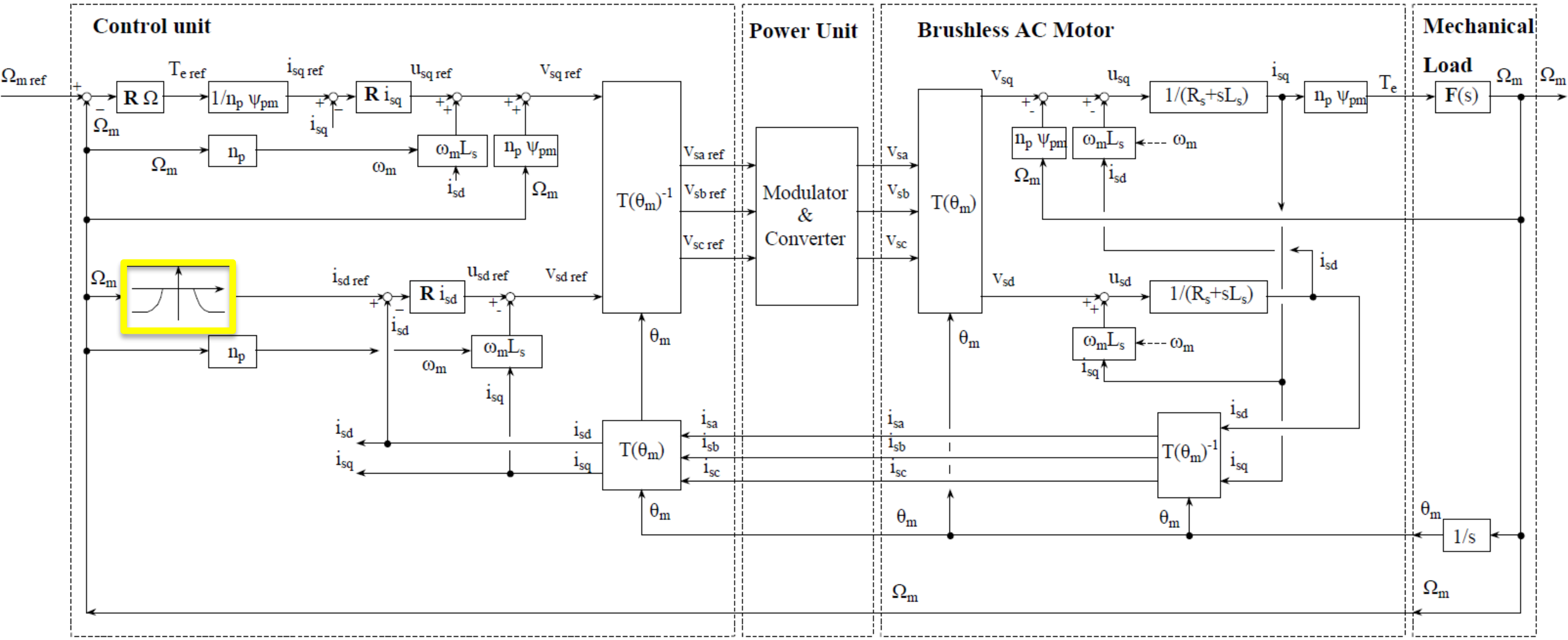
$$\begin{cases} v_{\mathrm{sd}} = R_{\mathrm{s}} i_{\mathrm{sd}} + L_{\mathrm{s}} p i_{\mathrm{sd}} \boxed{- \omega_{\mathrm{m}} L_{\mathrm{s}} i_{\mathrm{sq}}} \\ v_{\mathrm{sq}} = R_{\mathrm{s}} i_{\mathrm{sq}} + L_{\mathrm{s}} p i_{\mathrm{sq}} \boxed{+ \omega_{\mathrm{m}} L_{\mathrm{s}} i_{\mathrm{sd}}} \boxed{+ \omega_{\mathrm{m}} \psi_{\mathrm{PM}}} \end{cases}$$

The two controls for d and q axis are coupled.

Coupling terms must be compensated. Then, the two current loops can be designed separately considering the same transfer function.

$$G(s) = \frac{1}{R_{\mathrm{s}} + s L_{\mathrm{s}}}$$

Control Scheme

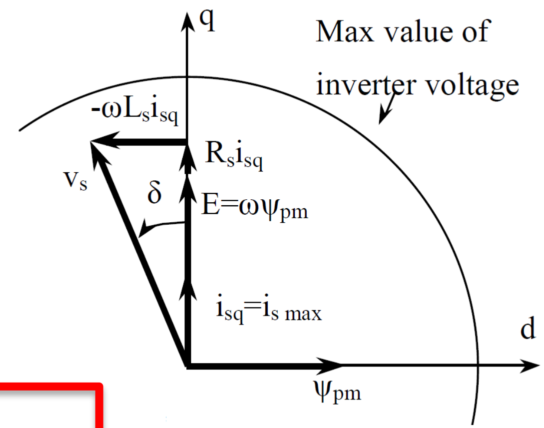


Operating regions and field weakening

Field Weakening

$$\Omega_m < \Omega_b$$

$$\omega_b = \sqrt{\frac{v_s^2}{\psi_{PM}^2 + L_s^2 i_{max}^2}} \qquad i_{sd} = 0$$



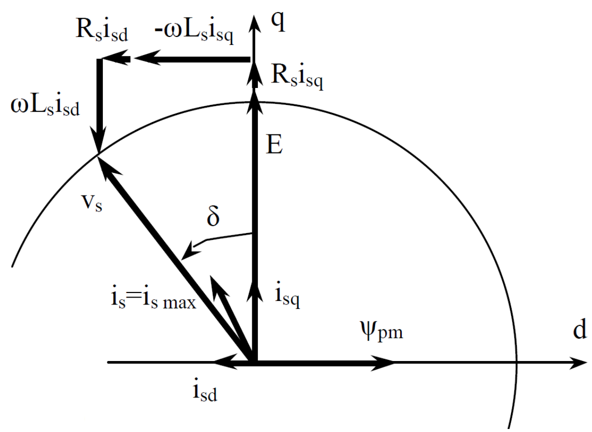
$$\Omega_m > \Omega_b$$

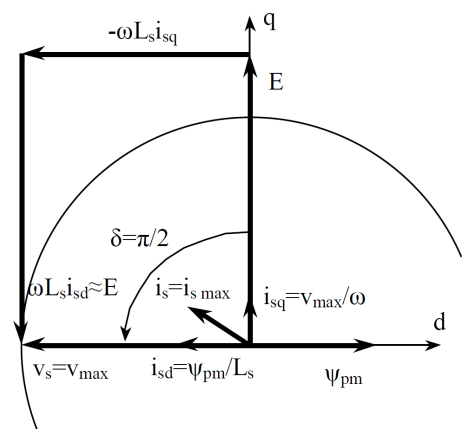
$$\boxed{i_s = \sqrt{i_{sd}^2 + i_{sq}^2} < i_{max}}$$

$$i_{sd} < 0$$

$$i_{sd_{max}} = -\frac{\psi_{PM}}{L_s}$$

$$\omega^* = \sqrt{\frac{v_s^2}{-\psi_{PM}^2 + L_s^2 i_{max}^2}}$$



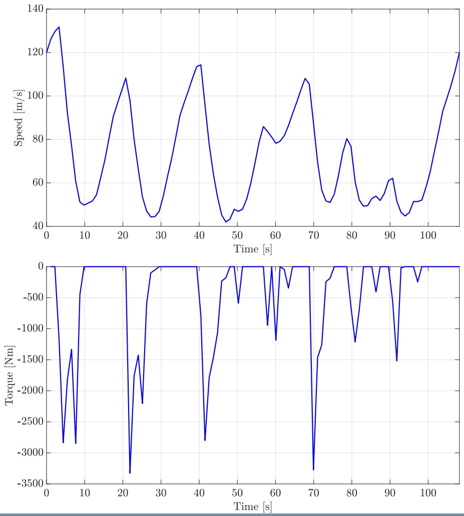


Exercise for Report

The Alfa Romeo Giulietta Quadrifoglio is an Italian sport car with 240 hp. It can reach a top speed of 240 km/h and it was produced with a turbo-diesel engine 1742 cm^3.

Exercise for Report

Let's assume that Alfa Romeo wants to start a production of a full-electric model of the Giulietta Quadrifoglio. You are the engineer in charge for the design of the electrical drive. Provided that an electric motor that allows to reach the same performances as for the combustion engine is chosen, use as reference signals the telemetry data coming from an hot lap in the Varano circuit.



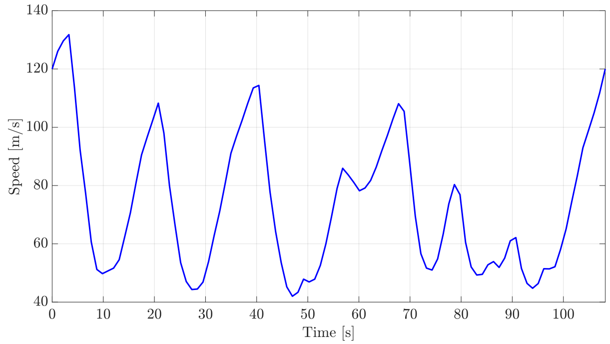
Exercise for Report

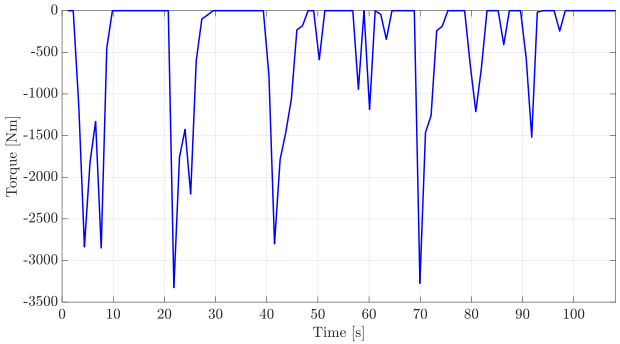
- Rated motor power: 180 kW
- Efficiency: 0.95
- Pole pairs: 2
- Power factor: $\cos\varphi = 1$
- Stator resistance: 0.1 Ω
- Stator inductance: 0.8 mH
- Rated speed: 400 rad/s
- PM flux: 0.5 Wb
- Car weight: 1500 kg (driver: 80 kg)
- Maximum acceleration: 4 m/s^2
- Friction coefficient: $\beta = 0.065$ Nm (T=$4\beta\Omega$)
- Tyre radius: 30 cm
- Gear ratio: 1/3

Exercise for Report

Based on this data:

- compute all the missing parameters of the system to control
- design a field weakening strategy for the onboard motor
- choose how much braking torque should be provided by the motor
- design and simulate a speed control loop for the car based on the telemetry at disposal





Exercise for Report: Hints

- The nominal power of an electrical machine refers to the power delivered to a load. Thus, P_{r} is a mechanical power for a motor. The corresponding absorbed electrical power is:

$$P_{\mathrm{el}} = \frac{P_{\mathrm{r}}}{\eta}$$

- The relationship between speed of the vehicle and rotational speed of the motor is:

$$v_{\mathrm{m/s}} = \Omega_{\mathrm{rad/s}} \rho \frac{d}{2}$$

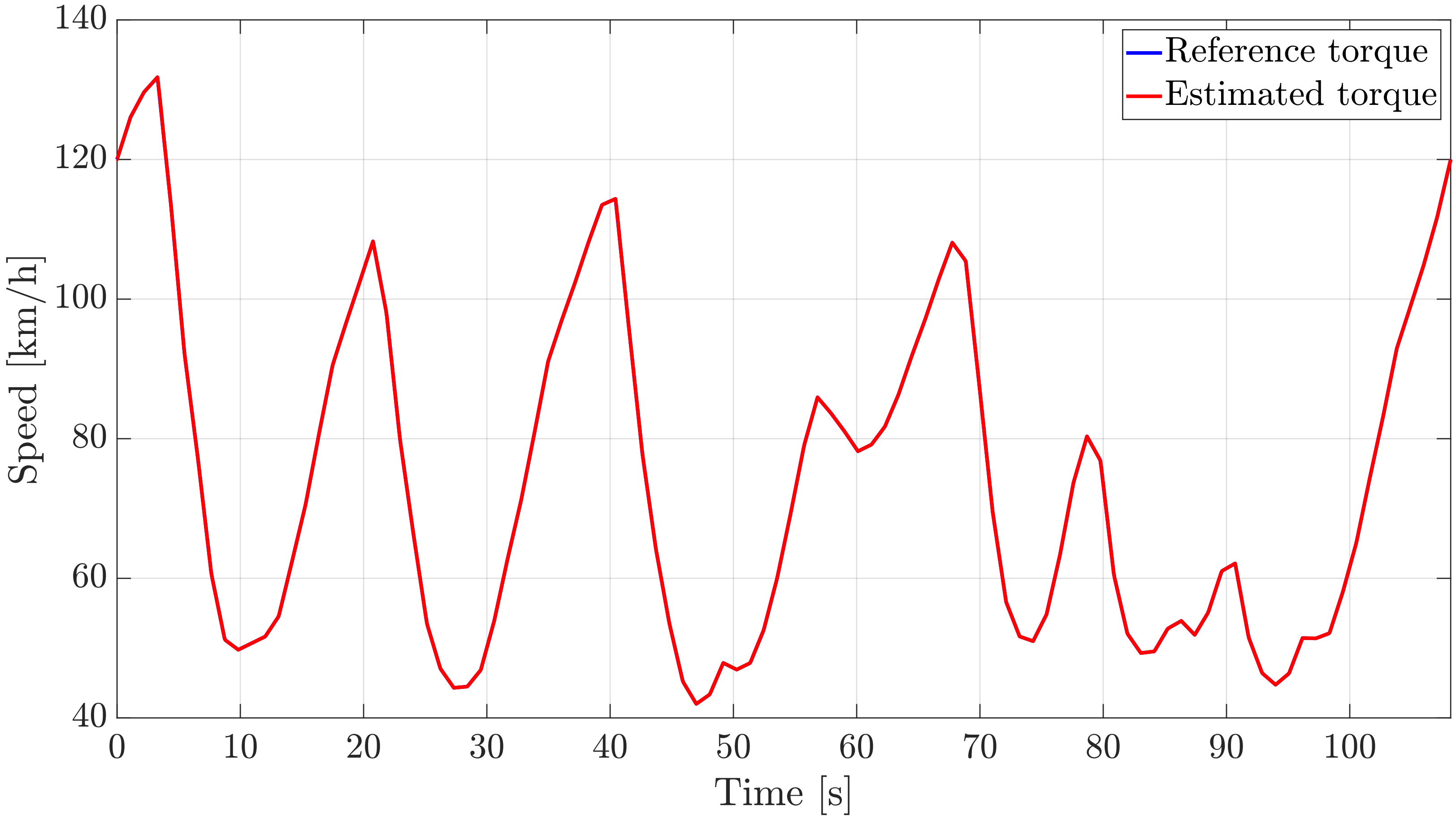
- The equivalent inertia seen from the motor shaft can be computed as:

$$J_{\mathrm{eq}} = m \frac{v_{\mathrm{m/s}}^2}{\Omega_{\mathrm{rad/s}}^2} = m \frac{\rho^2 d^2}{4}$$

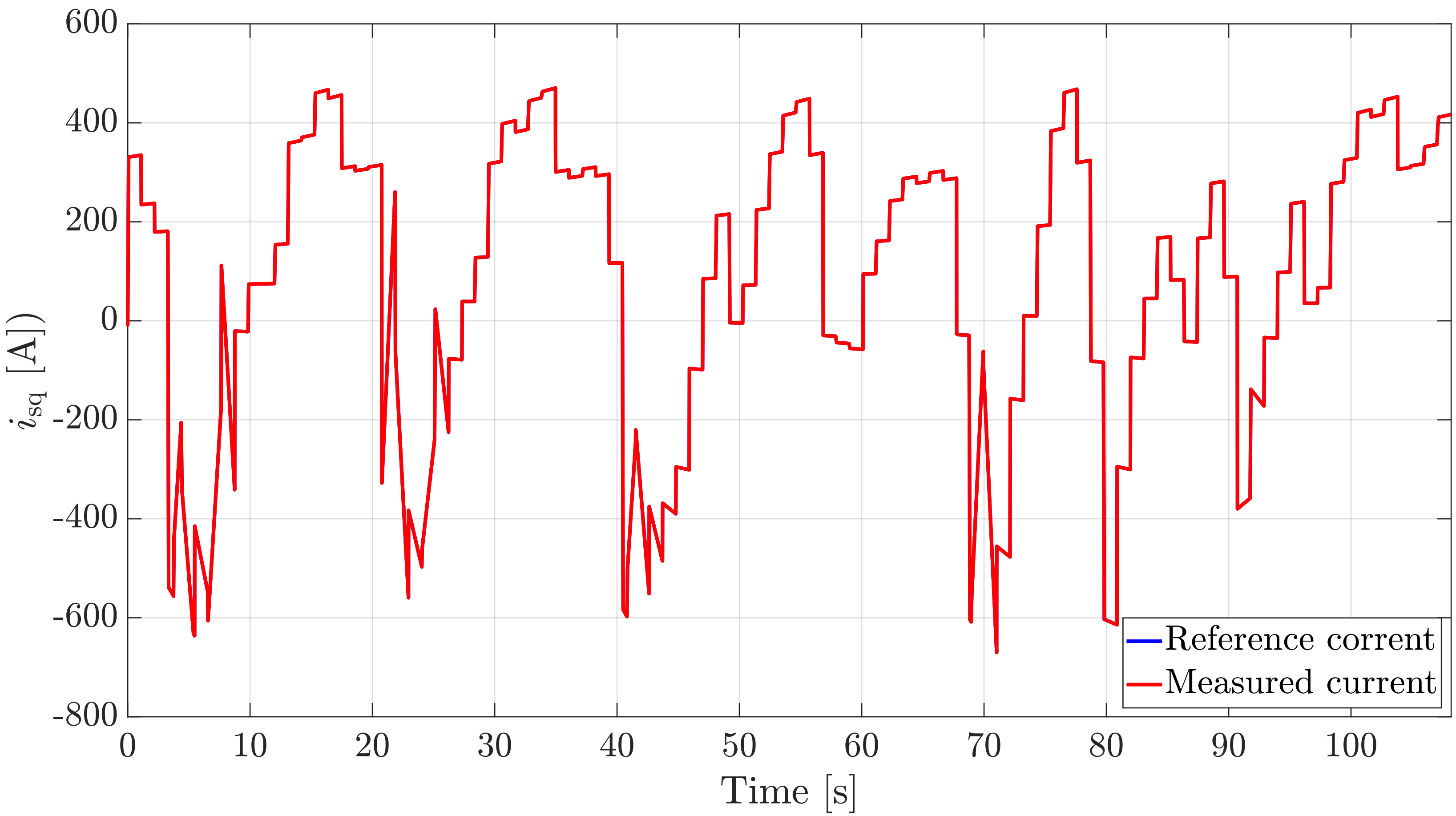
Exercise for Report: Hints

- Simulate the motor supplied at rated speed in no load conditions. Evaluate both the starting transients (look at the settling times) and the steady states for:
  - stator and rotor currents
  - stator and rotor flux
  - torque and speed
- Design and simulate all the regulators considering the cascade constraint. It is possible to test the behavior of each regulator through simplified simulations
- **Important**: you can both assume that the motor has been already started or you can add your own transition from 0 km/h

Exercise for Report: Results



Exercise for Report: Results



Exercise for Report: Results