Direct Torque Control

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Electric Propulsion

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DTC vs FOC

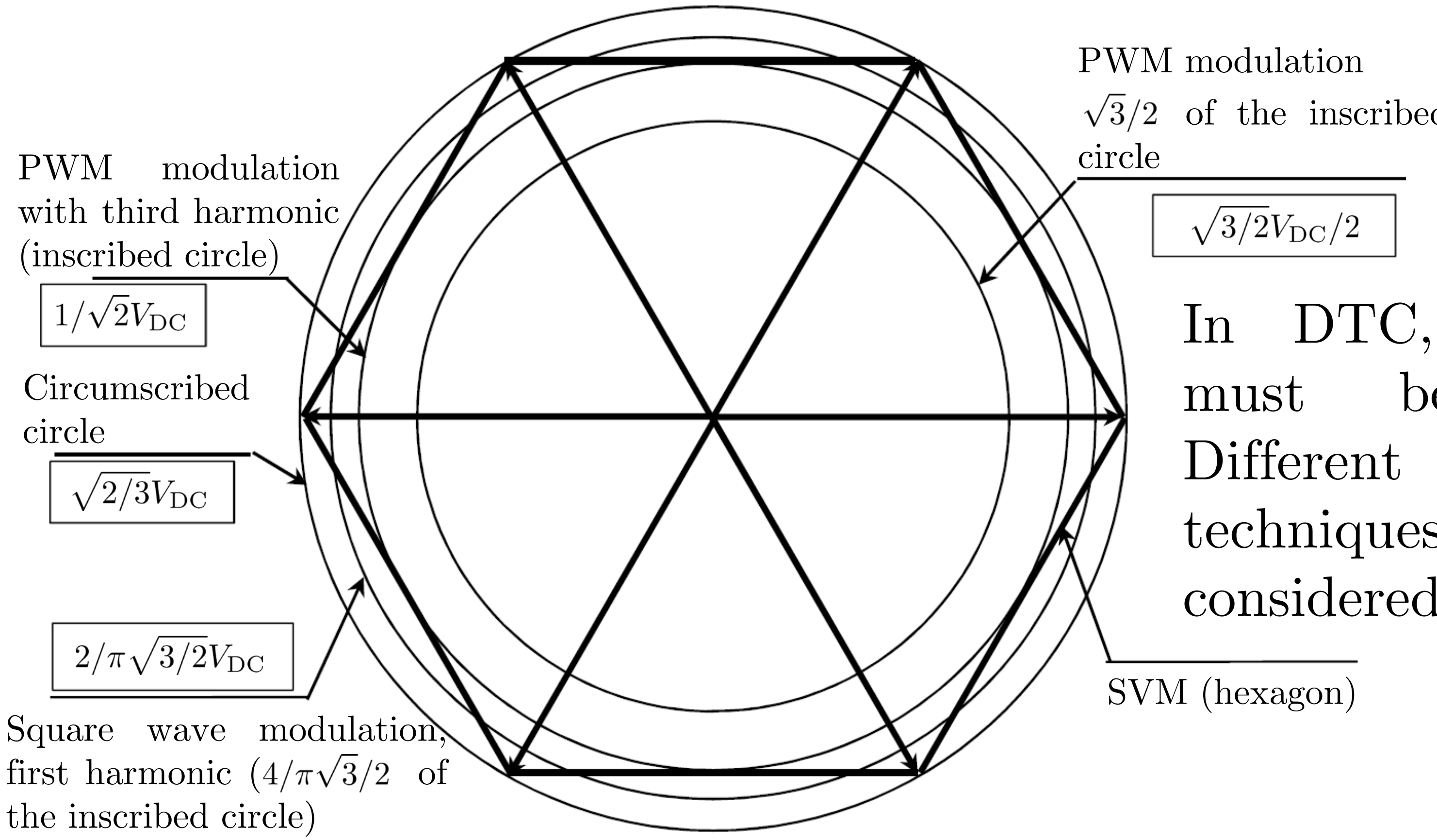
Pros:

- higher dynamics (based on hysteresis control, non linear)
- ripple management through bandwidths
- no cross-coupling terms and non need for compensation

Cons:

- variable switching frequency due to the hysteresis control, thus, difficult design of the power electronics
- powerful hardware required due to the possible high switching frequency and low sample time
- estimators needed

Modulation Techniques



In DTC, the inverter must be considered. Different modulation techniques can be considered in principle

Best trajectory: circle (1^{st} harmonic only). It provides the best harmonic content to the torque

DTC: Working Pinciple

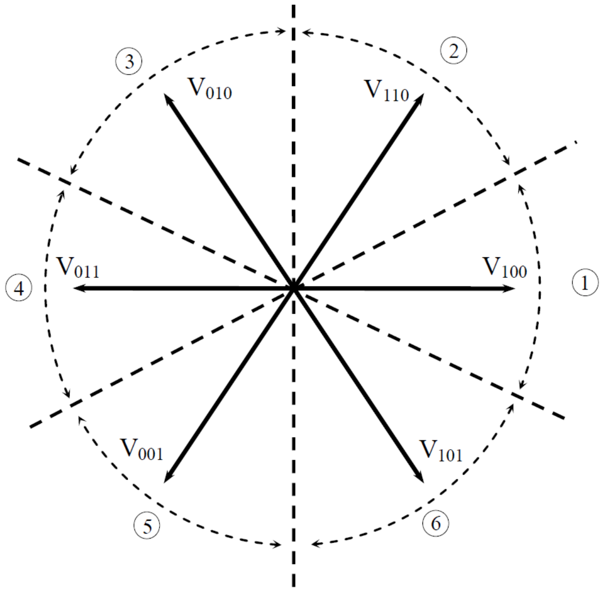
- No need for nested loops
- No need for current loops
- The voltage is computed as the "most suitable" inverter configuration

For a two-level converter, 8 configurations are possible (6 active and 2 zero)

These inverter configurations are chosen to satisfy two requirements:

- keep the flux inside a tolerance bandwidth
- keep the torque inside a tolerance bandwidth

DTC: Working Pinciple



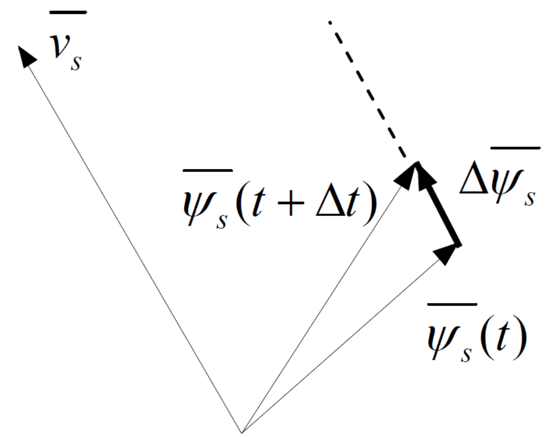
configuration	S_{ah}	S_{bh}	S_{ch}
$1 = v_{100}$	1	0	0
$2 = v_{110}$	1	1	0
$3 = v_{010}$	0	1	0
$4 = v_{011}$	0	1	1
$5 = v_{001}$	0	0	1
$6 = v_{101}$	1	0	1
$7 = v_{111}$	1	1	1
$8 = v_{000}$	0	0	0

6 active voltage configurations

2 zero voltage configurations

Sectors can be defined depending on the flux position.

The voltage can be interpreted as the speed of the flux



DTC: Working Pinciple

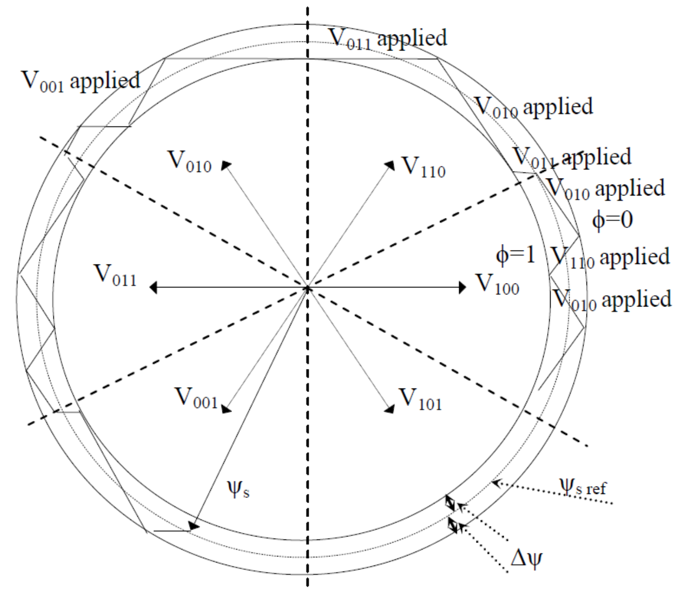
Indeed:

$$\overline{v}_{\mathrm{s}} = R_{\mathrm{s}}\overline{i}_{\mathrm{s}} + \frac{\mathrm{d}\overline{\psi}_{\mathrm{s}}}{\mathrm{d}t} \rightarrow \overline{\psi}_{\mathrm{s}} = \int_0^t \overline{v}_{\mathrm{s}} - R_{\mathrm{s}}\overline{i}_{\mathrm{s}}\mathrm{d}t$$

Assuming that the stator resistance is negligible:

$$\overline{v}_{\mathrm{s}} = \frac{\mathrm{d}\overline{\psi}_{\mathrm{s}}}{\mathrm{d}t} \rightarrow \overline{\psi}_{\mathrm{s}} = \int_0^t \overline{v}_{\mathrm{s}}\mathrm{d}t$$

In addition, the trajectory of the flux changes depending on the applied voltage configuration. A narrow bandwidth is chosen to approximate a circle

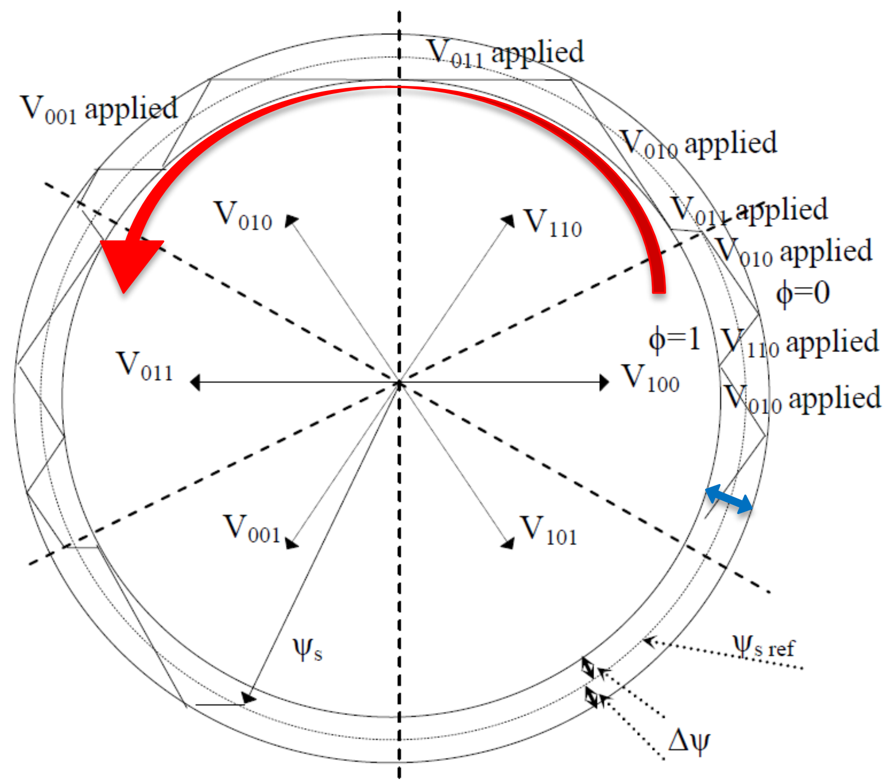


DTC: Working Pinciple

Thus, the voltage can:

- regulate the abs value of the flux
- rotate the flux vector

Two active voltage states in a flux vector regulates the abs value and the direction of rotation. The succession of active and zero voltages regulates the speed of rotation

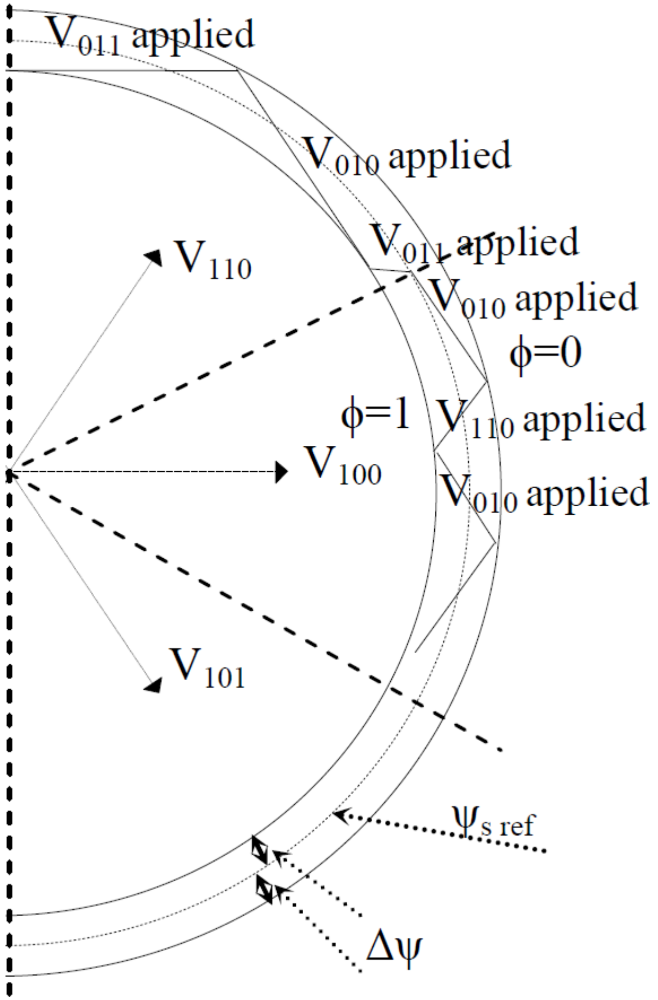


Flux Regulation

The abs value of the flux can be:

- increased (counterclockwise rotation) applying the first consecutive voltage configuration
- decreased (counterclockwise rotation) applying the second consecutive voltage configuration

A torque control is required to regulate the speed of the flux vector



Torque Regulation

The slip can be interpreted as an angle difference between the stator and rotor flux

This angle can be varied by stopping the stator flux or by supplying the machine

$$T_{\mathrm{e}} = \frac{n_{\mathrm{p}}}{L_{\mathrm{ks}}} \mathrm{Im}\left\{\overline{\psi}_{\mathrm{s}} \overline{\psi}_{\mathrm{r}}\right\} = \frac{n_{\mathrm{p}}}{L_{\mathrm{ks}}} \left|\overline{\psi}_{\mathrm{s}}\right| \left|\overline{\psi}_{\mathrm{r}}\right| \sin\left(\delta\right)$$

The rotor flux has slower dynamics compared to the stator one. It lags the stator flux

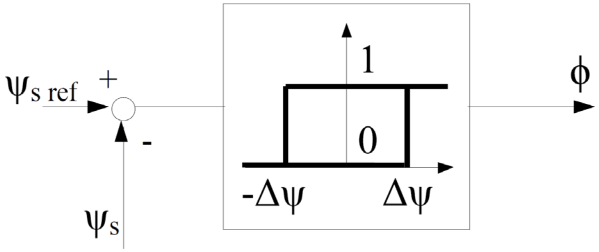
Variation in δ are approximated as variations in the angle of the stator flux: its trajectory can be controlled through the input voltage

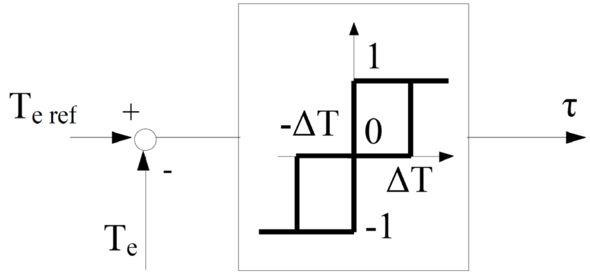
Switching Table and Comparators

Both stator flux and the torque are controlled through the input voltage

		torque error τ		
		-1	0	1
flux error ϕ	1	v_{s-1}	0	v_{s+1}
	0	v_{s-2}	0	v_{s+2}

$\phi = 1 \;\rightarrow$ flux increase
$\phi = 0 \;\rightarrow$ flux decrease
$\tau = \pm 1 \;\rightarrow$ torque increase (clockwise or counterclockwise)
$\tau = 0 \;\rightarrow$ torque decrese





Relay block in Simulink

Switching Table and Comparators

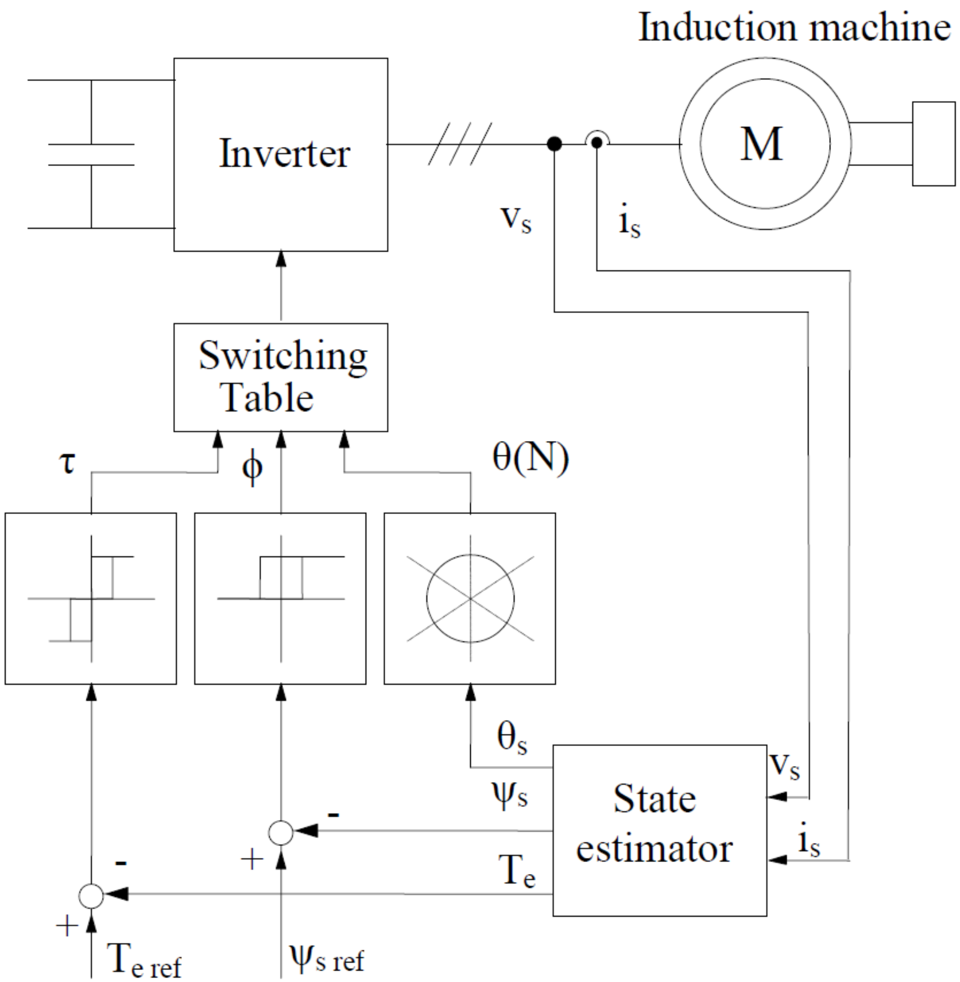
Informations on the flux sector is needed to build the switching table

		$\theta\,(1)$	$\theta\,(2)$	$\theta\,(3)$	$\theta\,(4)$	$\theta\,(5)$	$\theta\,(6)$
$\phi = 0$	$\tau = 1$	v_{010}	v_{011}	v_{001}	v_{101}	v_{100}	v_{110}
	$\tau = 0$	v_{000}	v_{111}	v_{000}	v_{111}	v_{000}	v_{111}
	$\tau = -1$	v_{001}	v_{101}	v_{100}	v_{110}	v_{010}	v_{011}
$\phi = 1$	$\tau = 1$	v_{110}	v_{010}	v_{011}	v_{001}	v_{101}	v_{100}
	$\tau = 0$	v_{111}	v_{000}	v_{111}	v_{000}	v_{111}	v_{000}
	$\tau = -1$	v_{101}	v_{100}	v_{110}	v_{010}	v_{011}	v_{001}

In Simulink: 3D Lookup table

Breakpoints: θ, ϕ, τ

Switching Table and Comparators



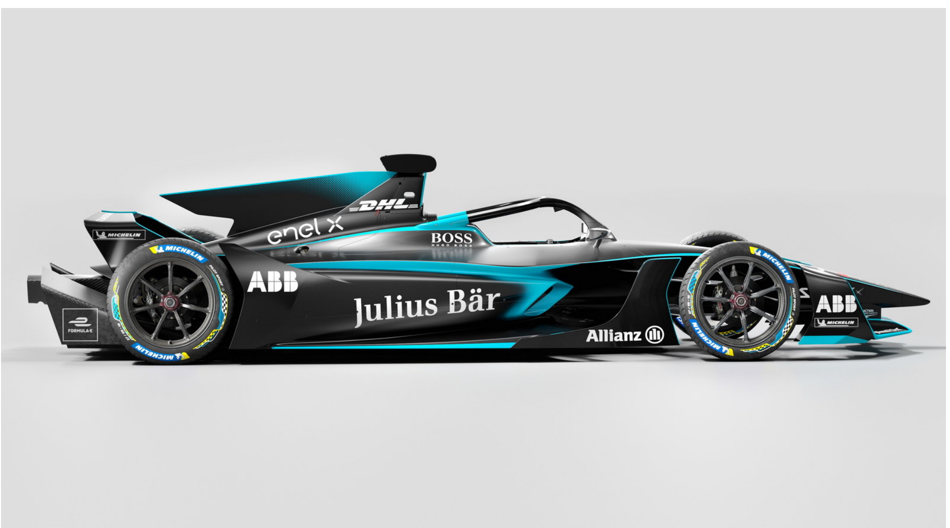
		$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
$\phi = 0$	$\tau = 1$	v_{010}	v_{011}	v_{001}	v_{101}	v_{100}	v_{110}
	$\tau = 0$	v_{000}	v_{111}	v_{000}	v_{111}	v_{000}	v_{111}
	$\tau = -1$	v_{001}	v_{101}	v_{100}	v_{110}	v_{010}	v_{011}
$\phi = 1$	$\tau = 1$	v_{110}	v_{010}	v_{011}	v_{001}	v_{101}	v_{100}
	$\tau = 0$	v_{111}	v_{000}	v_{111}	v_{000}	v_{111}	v_{000}
	$\tau = -1$	v_{101}	v_{100}	v_{110}	v_{010}	v_{011}	v_{001}

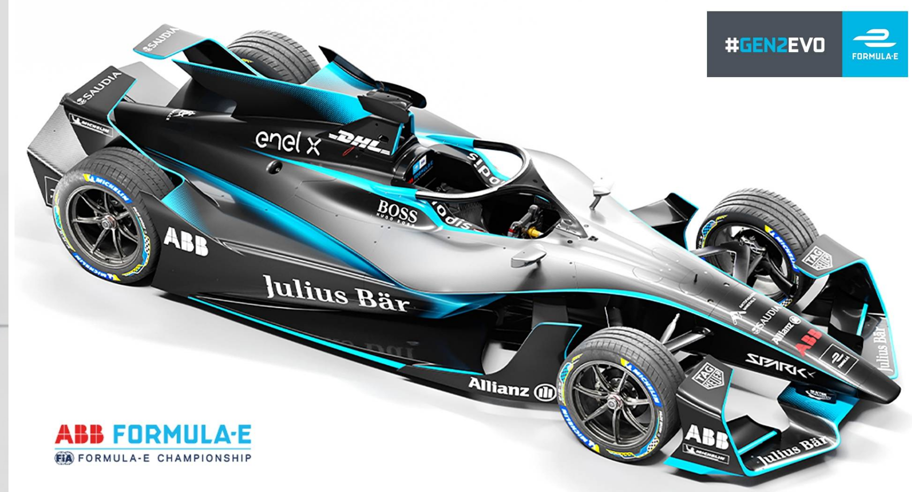
3D matrix: these two 3x6 matrices are arranged along the third dimension.

A 3x6x2 matrix is obtained

Exercise for Report

Formula E cars are equipped with a 800 V battery (54 kWh) and an AC brushless drive with PM. They have an accelleration which allows to reach 100 km/h in 2.8 s. The maximum speed of such a car is 280 km/h.



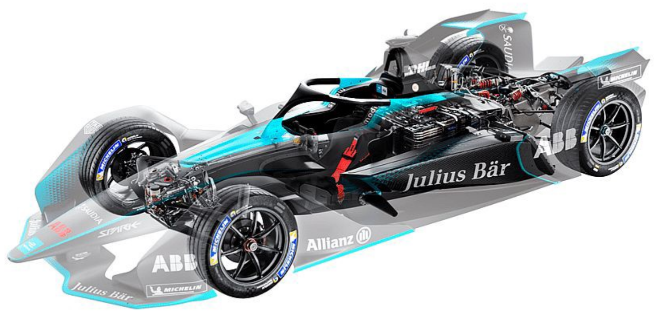


Exercise for Report

Let's assume that you are asked to design a car with similar performances of that one racing in the Formula E championship.

Consider:

- the same 800 V, 54 kWh battery
- an induction motor in spite of a PM synchronous motor
- a DTC drive



Exercise for Report: Data

efficiency of the motor: 0.9

rated power of the motor: 200 kW

pole pairs: 4

power factor: 0.9

stator resistance: 0.01 p.u.

rotor resistance: 0.01 p.u.

locked-rotor inductance: 0.15 p.u.

magnetizing inductance: 2.5 p.u.

diameter of the wheel: 457 mm

mass of the vehicle (driver included): 800 kg

friction coefficient: 0.6

Exercise for Report

Do not overcome the base speed, which is 65 km/h

Further informations can be found in:

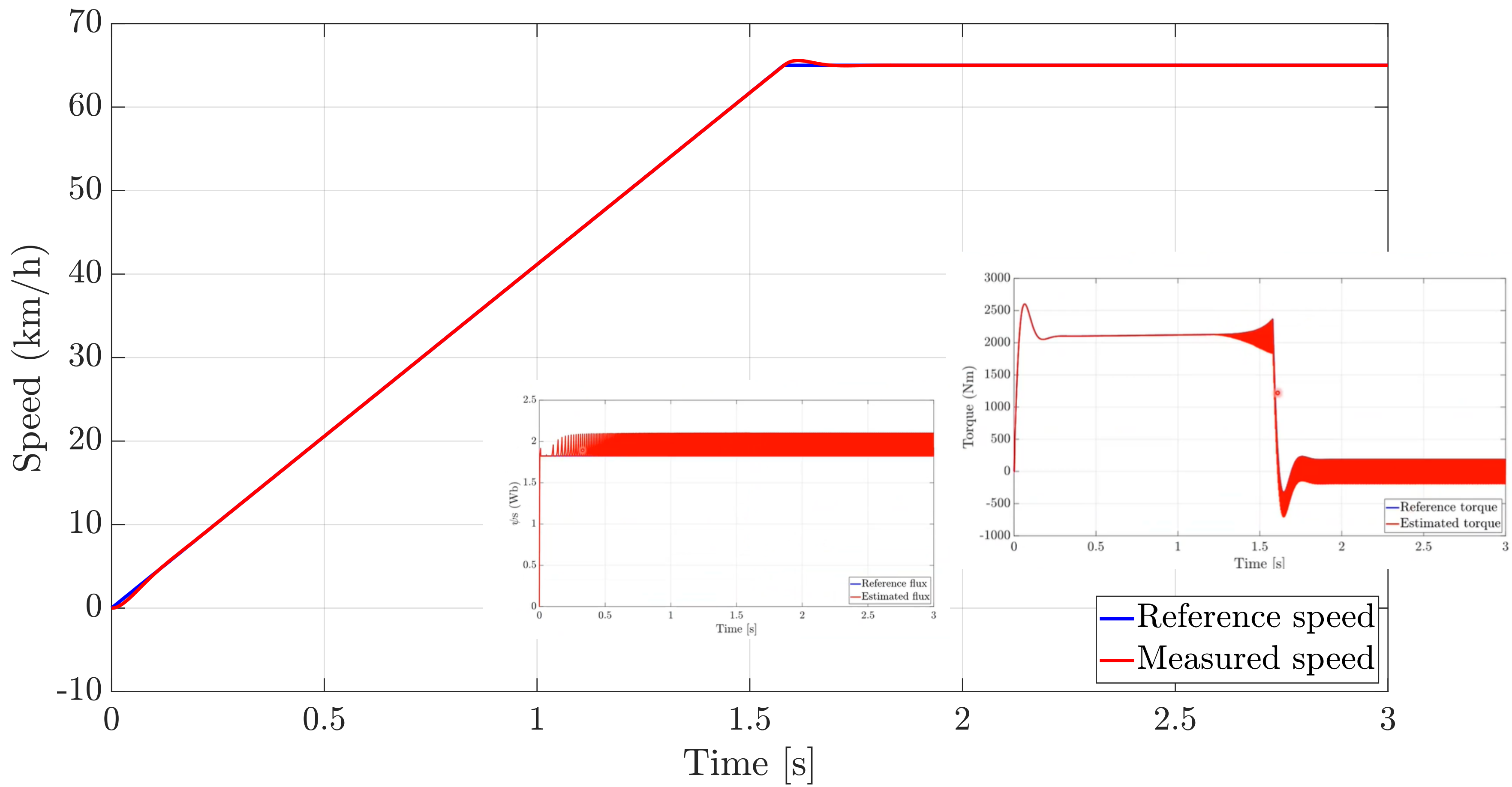
I. Takahashi and T. Noguchi, "A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor," in IEEE Transactions on Industry Applications, vol. IA-22, no. 5, pp. 820-827, Sept. 1986, doi: 10.1109/TIA.1986.4504799.

II. Sang-Hoon Kim and Seung-Ki Sul, "Voltage control strategy for maximum torque operation of an induction machine in the field-weakening region," in IEEE Transactions on Industrial Electronics, vol. 44, no. 4, pp. 512-518, Aug. 1997, doi: 10.1109/41.605628.

III. D. Casadei, G. Serra, A. Tani and L. Zarri, "A robust method for flux weakening operation of DTC induction motor drive with on-line estimation of the break-down torque," 2005 European Conference on Power Electronics and Applications, Dresden, 2005, pp. 10 pp.-P.10, doi: 10.1109/EPE.2005.219305.

IV. T. G. Habetler, F. Profumo, M. Pastorelli and L. M. Tolbert, "Direct torque control of induction machines using space vector modulation," in IEEE Transactions on Industry Applications, vol. 28, no. 5, pp. 1045-1053, Sept.-Oct. 1992, doi: 10.1109/28.158828.

Result



Speed (km/h)
Time [s]
Reference speed
Measured speed
ψs (Wb)
Time [s]
Reference flux
Estimated flux
Torque (Nm)
Time [s]
Reference torque
Estimated torque