Basics of Permanent Magnet Motors and Field Oriented Control

Ondrej HOLY
Tomas DRESLER

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Physics lecture

- Now we'll take a look at basic physics happening in the motor
- It's no rocket science and we will discuss only few equations describing why the motor turns and what's the relation between the current, voltage, momentum, torque and speed
- No more than 10 slides!

Glossary

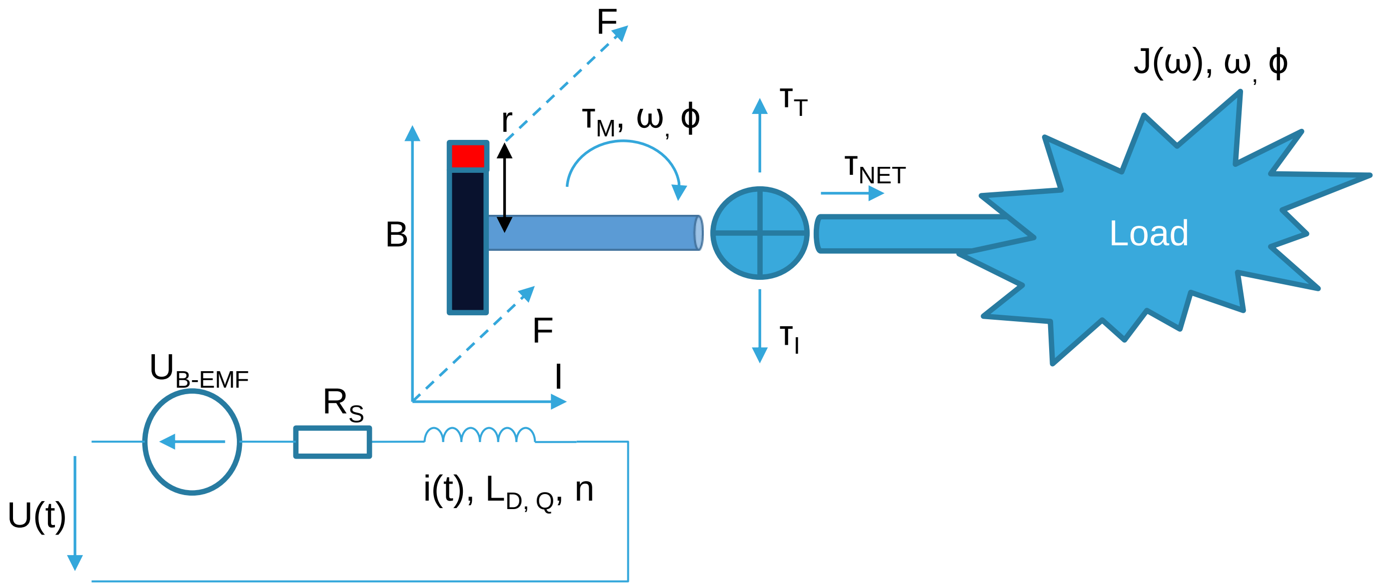
Mechanics

r	radius	[m]
F	force	[N]
T	torque	[Nm]
τ_M	motor torque	[Nm]
τ_T	break away (stiction) torque	[Nm]
τ_I	damping and windage torque	[Nm]
τ_{SH}	shaft instant passive torque	[Nm]
τ_{NET}	torque on the load	[Nm]
ω	mechanical or electrical speed	[$rad \cdot s^{-1}$]
ϕ	mechanical or electrical angle	[rad]
J	moment of inertia	[$kg \cdot m^2$]
D	damping	[Nms]
K	spring constant	[Nm]
L	angular momentum	[$kg \cdot m^2 \cdot s^{-1}$]
t	time	[s]

Electrics & magnetics

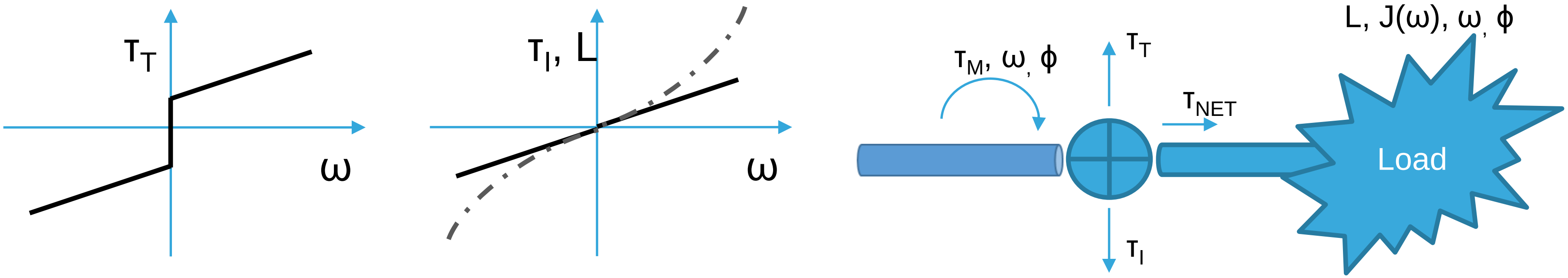
U, $u(t)$	voltage	[V]
I, $i(t)$	el. current	[A]
R	el. resistance	[Ω]
L	el. inductance	[H]
n, Z	number of turns	[-]
B	mag. induction	[T]
Φm	mag. flux	[Wb]
l	loop length	[m]

What causes rotation & speed? (1/10)
Our physical system



What causes rotation & speed? (2/10) Mechanics

- The stable torque equation: $\tau_M + \tau_T + \tau_I + \tau_{NET} = 0$
- τ_M is motor torque
- $\tau_{T,\,I}$ are mechanical system "resistances", non-linear

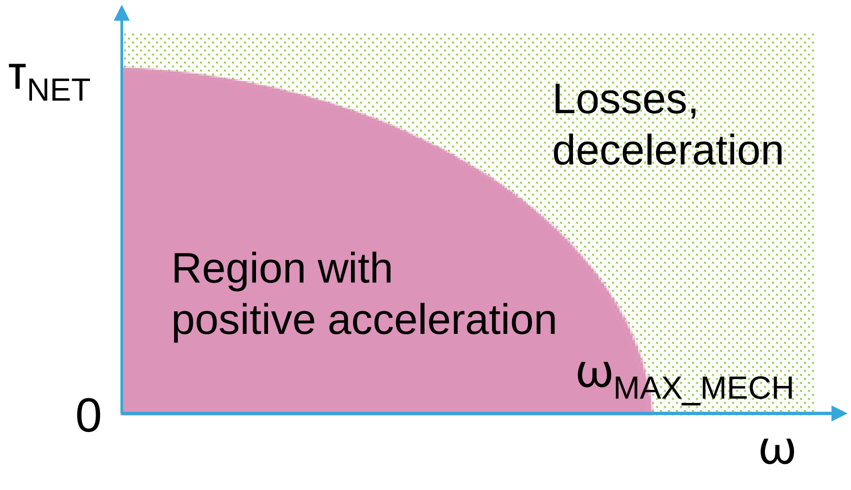


- $\tau_{NET} = J(\omega)\frac{d\omega}{dt}$ is load torque, typically non-linear
- Thus $\omega(t) = \int_{\tau_0}^{t} \frac{\tau_{NET}(t)}{J(t)}dt + \omega_0$

What causes rotation & speed? (3/10) Mechanics – wrap up

- Change of speed is equal to available torque:
  - Positive torque remains → motor accelerates
  - Negative torque remains → motor slows down and even reverses

- The bigger the speed, the bigger losses and less torque → acceleration is smaller, down to zero, where we reach maximum speed ω_{MAX_MECH}:



What causes rotation & speed? (4/10) Mechanics

- Dynamic torque equation (for reference):

$$J\frac{d\varphi^2}{dt^2} + D\frac{d\varphi}{dt} + K\varphi = \pm\tau_M \mp \tau_{SH}$$

J	-	moment of inertia
D	-	damping
K	-	spring constant
τ_M	-	motor torque
τ_{SH}	-	shaft instant passive torque
φ	-	shaft angle

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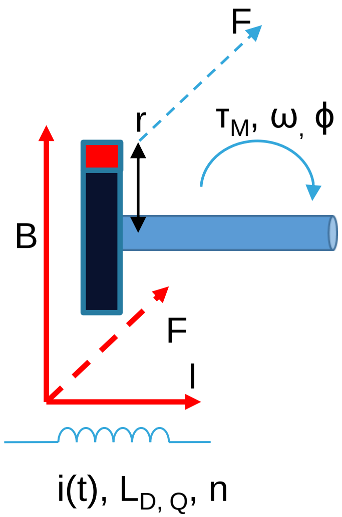
What causes rotation & speed? (5/10) Mechanics

- Mechanical power on load

$$P_{MECH.} = \tau_M \omega - D_M \omega^2 - \tau_T \omega$$

D_M	-	damping
τ_M	-	motor torque
τ_T	-	resistive torque
ω	-	mechanical speed

What causes rotation & speed? (6/10) Magnetics



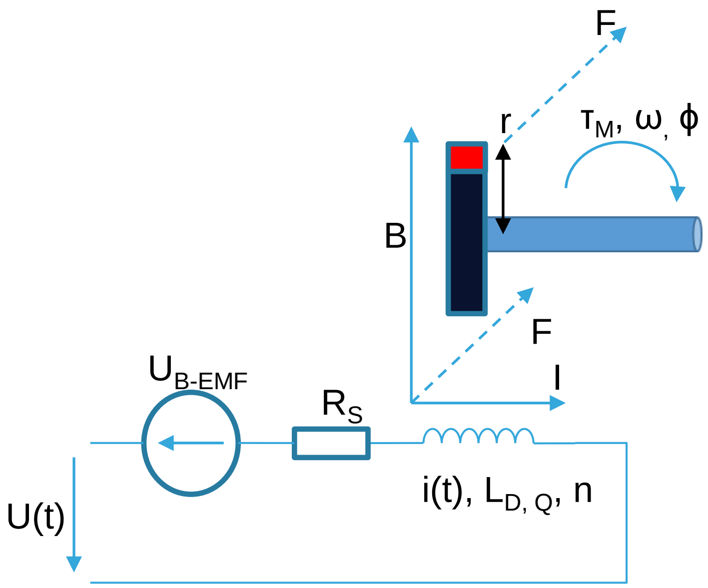
- Lorentz law:
  $\vec{F} = I\vec{l} \times \vec{B}$, $F = IlB \sin\varphi$
  [N; A, m, T]

- $\tau_M = F \cdot r = IlBrn$
  [Nm; N, m, -]

➢ We control current I and phase φ

➢ Biggest force (torque) is applied when φ is 90° (i.e. sin(φ)=1)

What causes rotation & speed? (7/10) Electrics



- $U = L_{D,Q}\frac{dI}{dt} + R_S I + K_e\omega$

U - supply voltage

$K_e\omega$ - b-emf voltage

$K_e = Brln$
- electric constant

$R_S I$ - winding losses

$L_{D,Q}\frac{dI}{dt}$ - the useful part

What causes rotation & speed? (8/10) Electrics – wrap up

- Speed is proportional to the voltage
- Torque is proportional to the current

➢ Torque constant [Nm/A] is proportional to electrical constant [V/krpm]

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What causes rotation & speed? (9/10) Electrics – b-emf voltage

- B-emf voltage is induced by rotor turning in the stator winding, with opposite direction of supply current

➢ For constant supply voltage, the higher the speed, the lower current we can achieve and thus the lower the available torque

$$U = L_{D,Q}\frac{dI}{dt} + R_S I + K_e\omega, \text{ or}$$

$$U = K \cdot torque + losses + b\_emf$$

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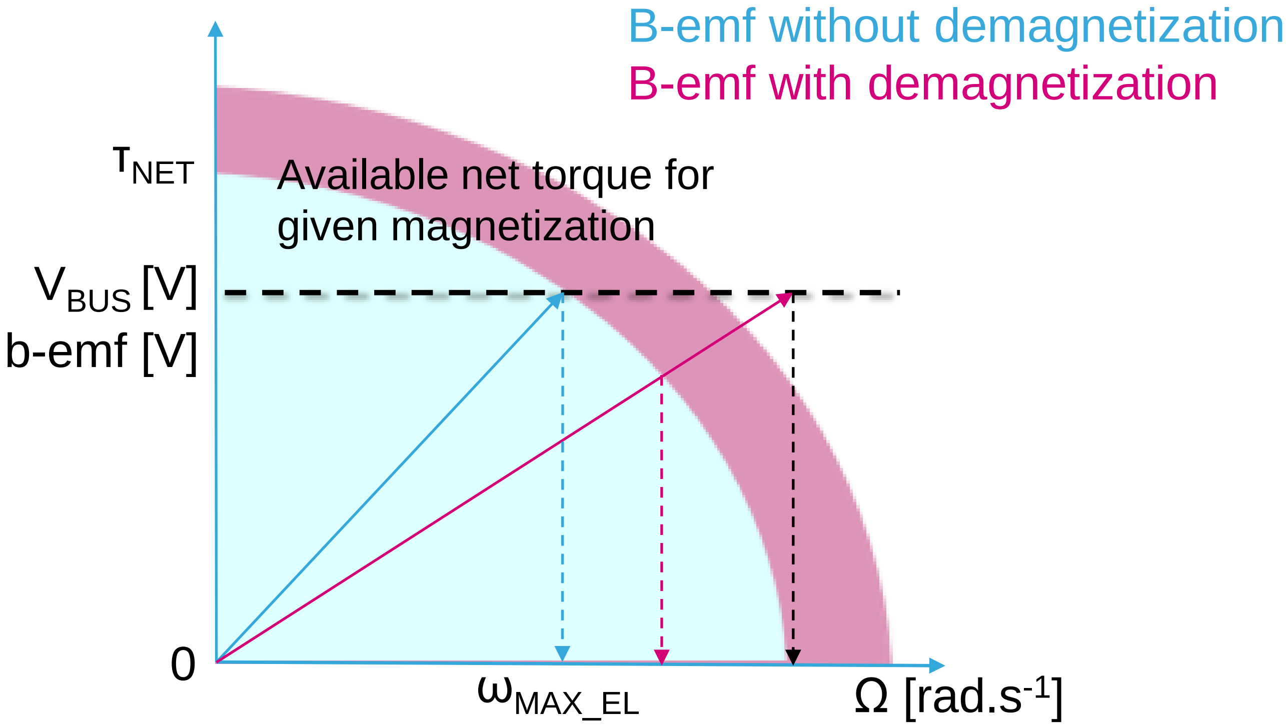
Effects of B-emf and demagnetization

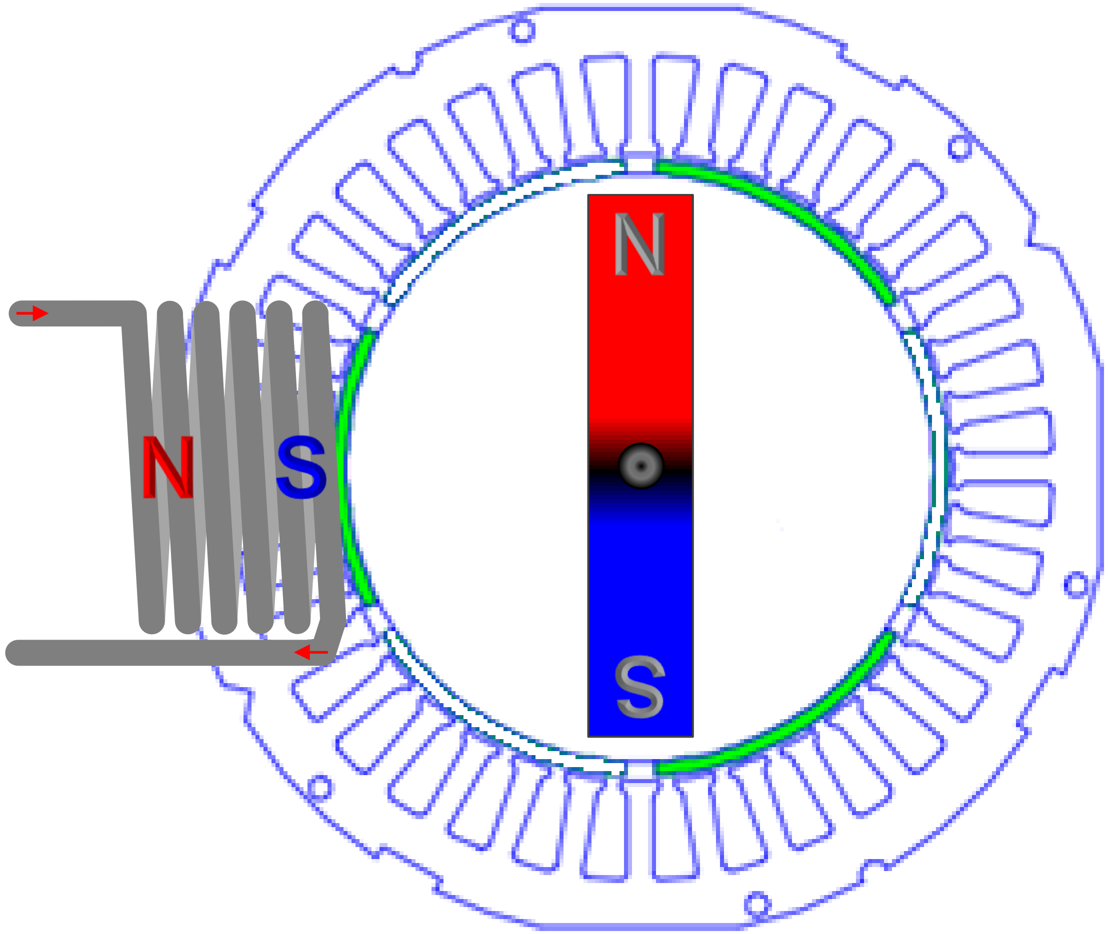
Application of part of coil electromagnetic vector against magnetic field of the permanent magnet in the rotor, which reduces the effective electrical constant $K'=K-B_D$ and b-emf size

Benefits:
- higher achievable speed
- Smooth speed control

Drawbacks:
- Reduced torque
- Need for overvoltage protection



PMSM principle – coil & magnetic rotor



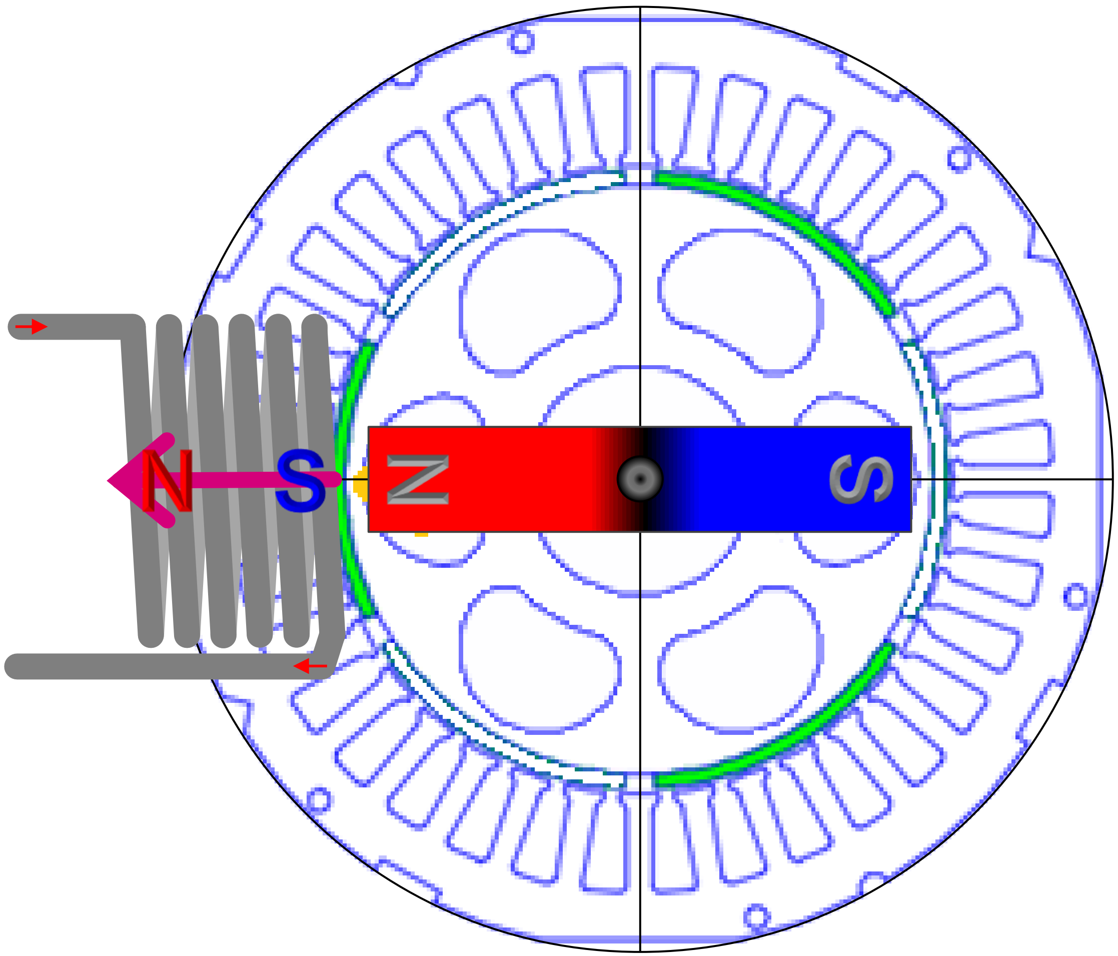
Stator

Rotor (permanent magnet) fixed on applicate axis

Stator coil

Current running in the coil causes rotor to **move** and **align**

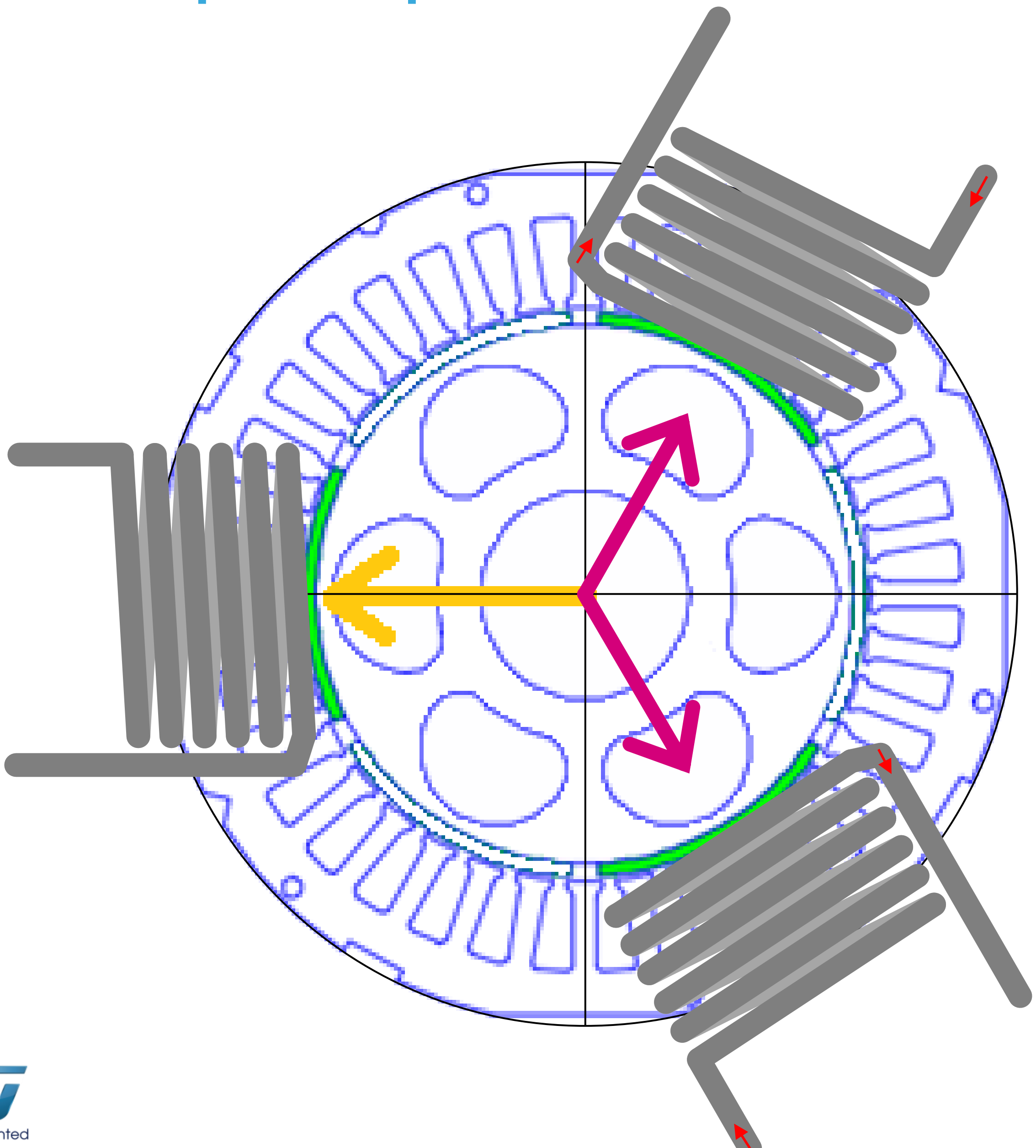
PMSM principle – vector representation



Magnetic fields of the rotor and coil can be described by **vectors** (with their size and direction, or x-y coordinates)

Their **common point** is placed in the **rotor axis**

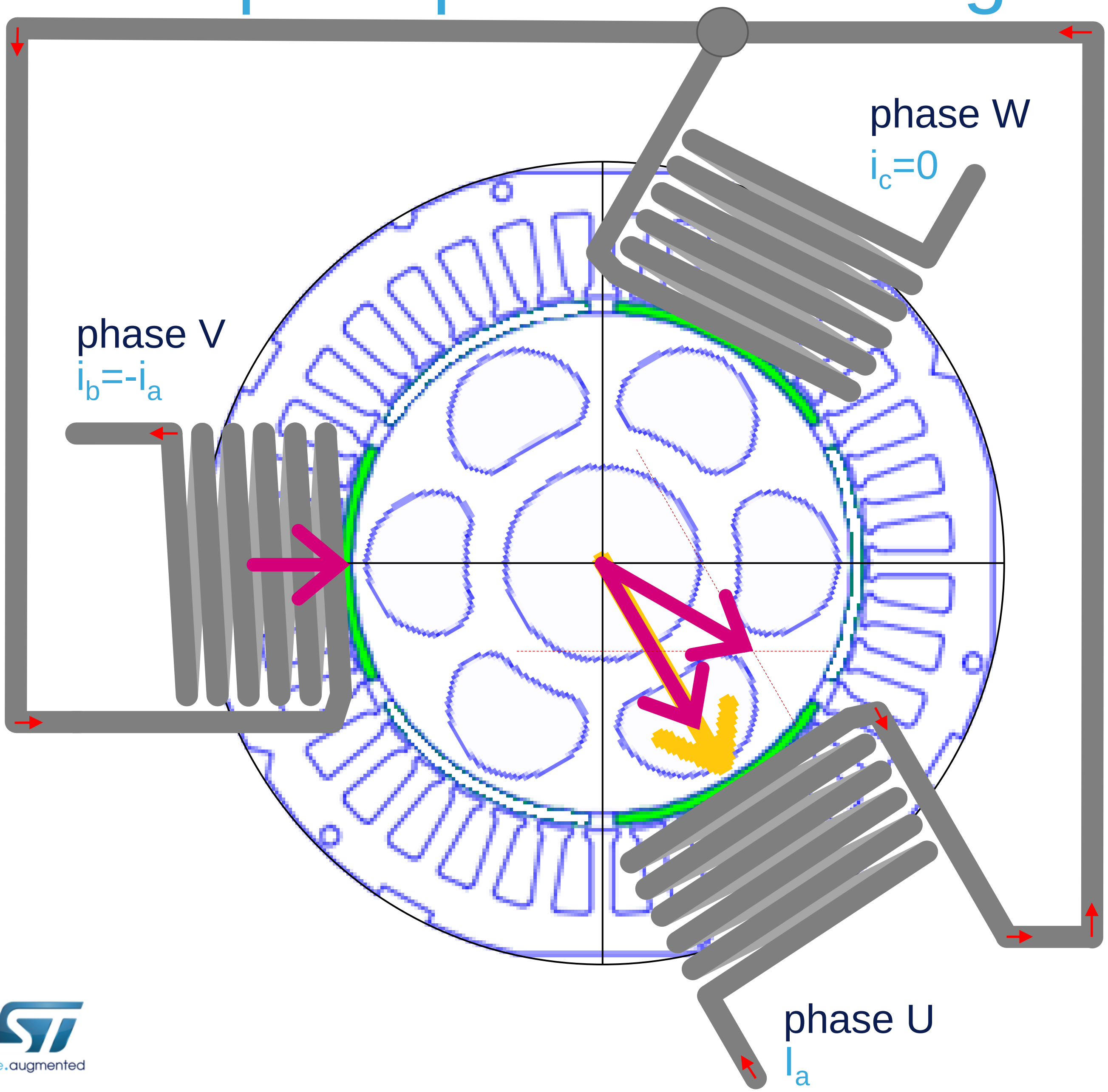
PMSM principle – 3 coils – 3 phases



Second coil
Current applied to this coil causes **rotor** to **move** again

Third coil
Current applied to this coil causes **rotor** to **move** yet again

PMSM principle – star configuration

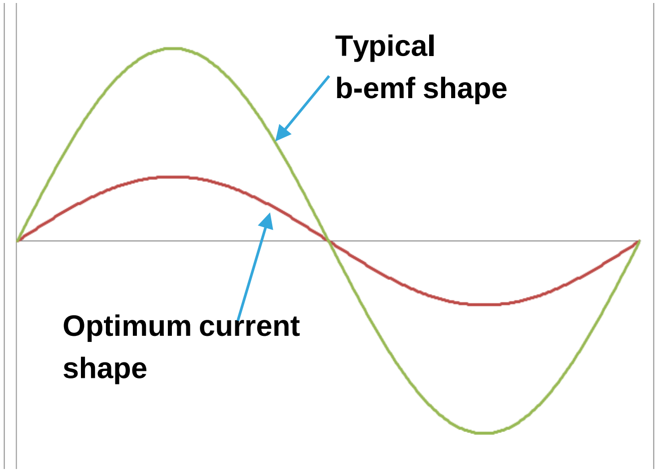


Stator coils are connected in the neutral point, only 3 terminals U, V, W are needed

The final stator electromagne-tic vector is a sum of those generated by each coil current

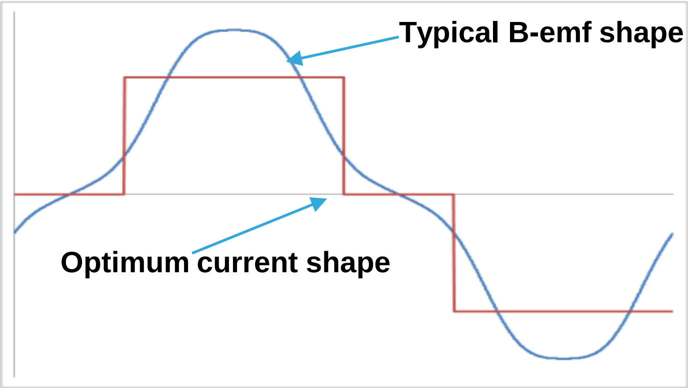
PMSM and BLDC motors

- **Permanent Magnet Synchronous Motor (PMSM)**
  - Stator consists of three phase windings
  - Rotor houses permanent magnets
    - on the surface → Surface Mounted (SM) PMSM
    - Buried within the rotor →Internal (I) PMSM
  - Stator excitation frequency must be synchronous with rotor electrical speed
  - Rotation induces sinusoidal Back Electro-Motive Force (B-EMF) in motor phases
  - Gives best performances (torque steadiness) when driven by sinusoidal phase current



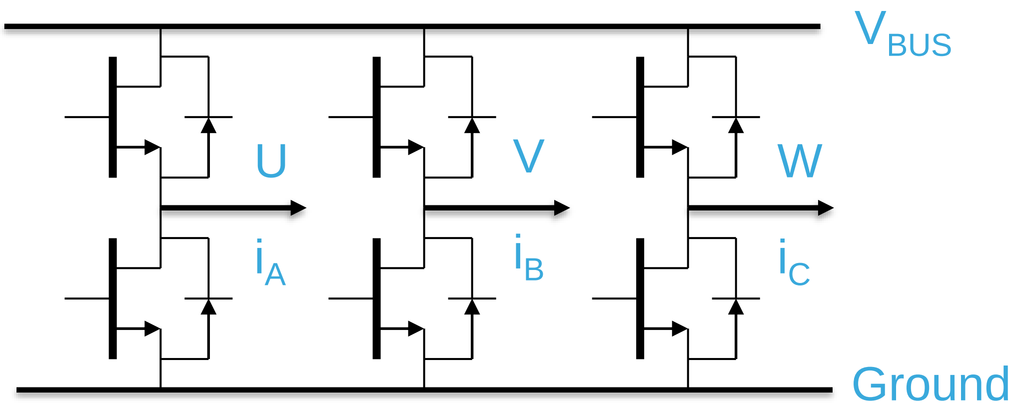
PMSM and BLDC motors

- **Permanent Magnet Brushless DC motors (BLDC)**
  - Like PMSM - and despite of their name - require alternating stator current
  - Like in PMSM, rotor houses permanent magnets, usually glued on its surface
  - Like PMSM, stator excitation frequency matches rotor electrical speed
  - Unlike PMSM, rotor spinning induced trapezoidal shaped Back Electro-Motive Force (B-EMF)
  - Gives best performances (torque steadiness) when driven by rectangular-shaped currents



PMSM control principles

- Voltages on phases U, V, W are controlled independently



- 3 currents flow in – or not?

$$i_a + i_b + i_c = 0$$

is equivalent to

$$i_a = -i_b - i_c$$
$$i_b = -i_a - i_c$$
$$i_c = -i_a - i_b$$

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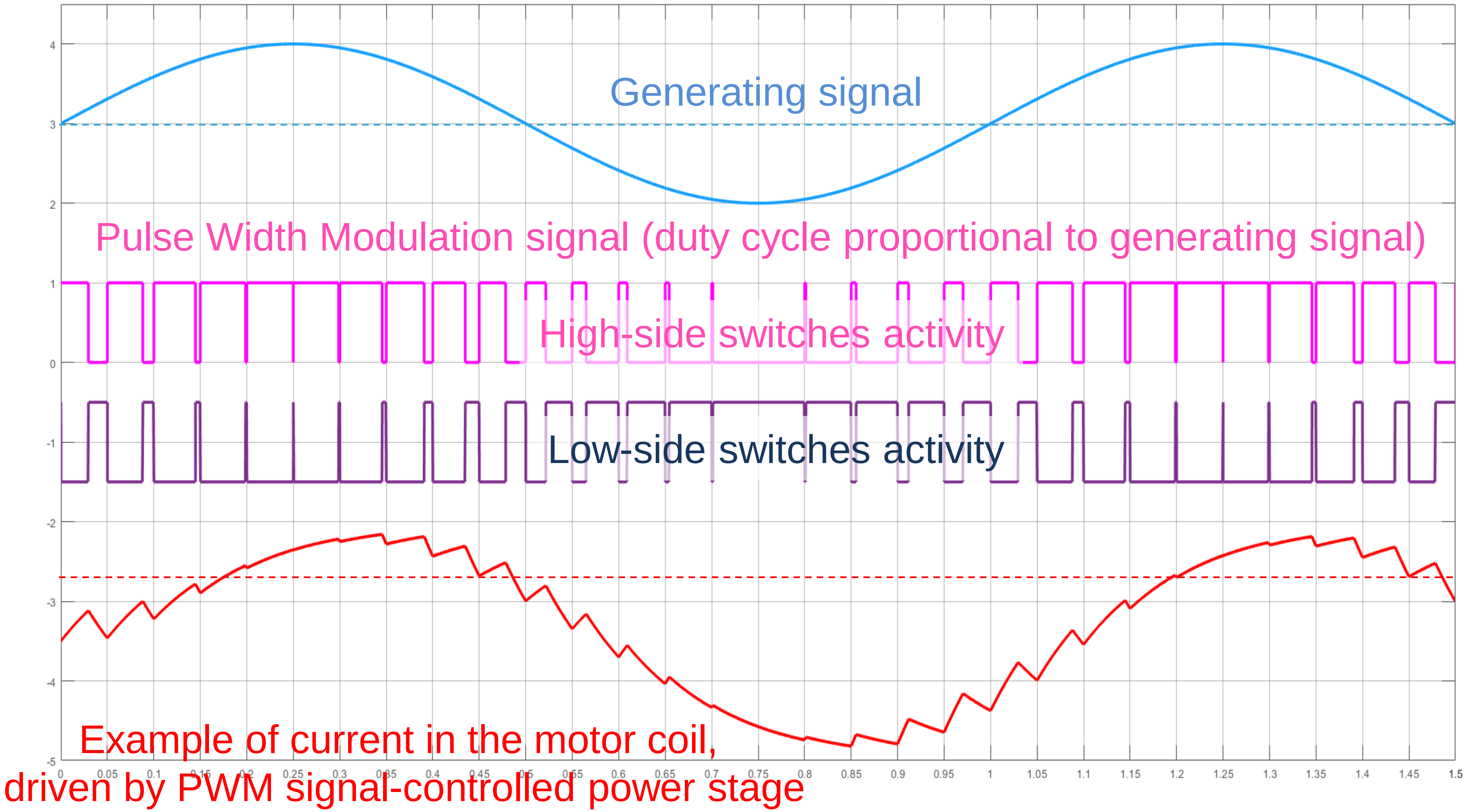
PMSM control principles

- All mentioned methods use Pulse Width Modulation with fixed frequency and variable pulse length to control effective voltage on the phases

- Block commutation
  - Historically used
  - Simple to implement
  - Drawbacks in control: higher torque ripple, slow reaction on load change

- Sinusoidal Field Oriented Control (FOC)
  - More complicated and more expensive
  - More difficult to implement, requires DSP-like functionality
  - Rapid reaction on torque/load change, low torque ripple, full 4-quadrant operation

PWM generation (single phase)



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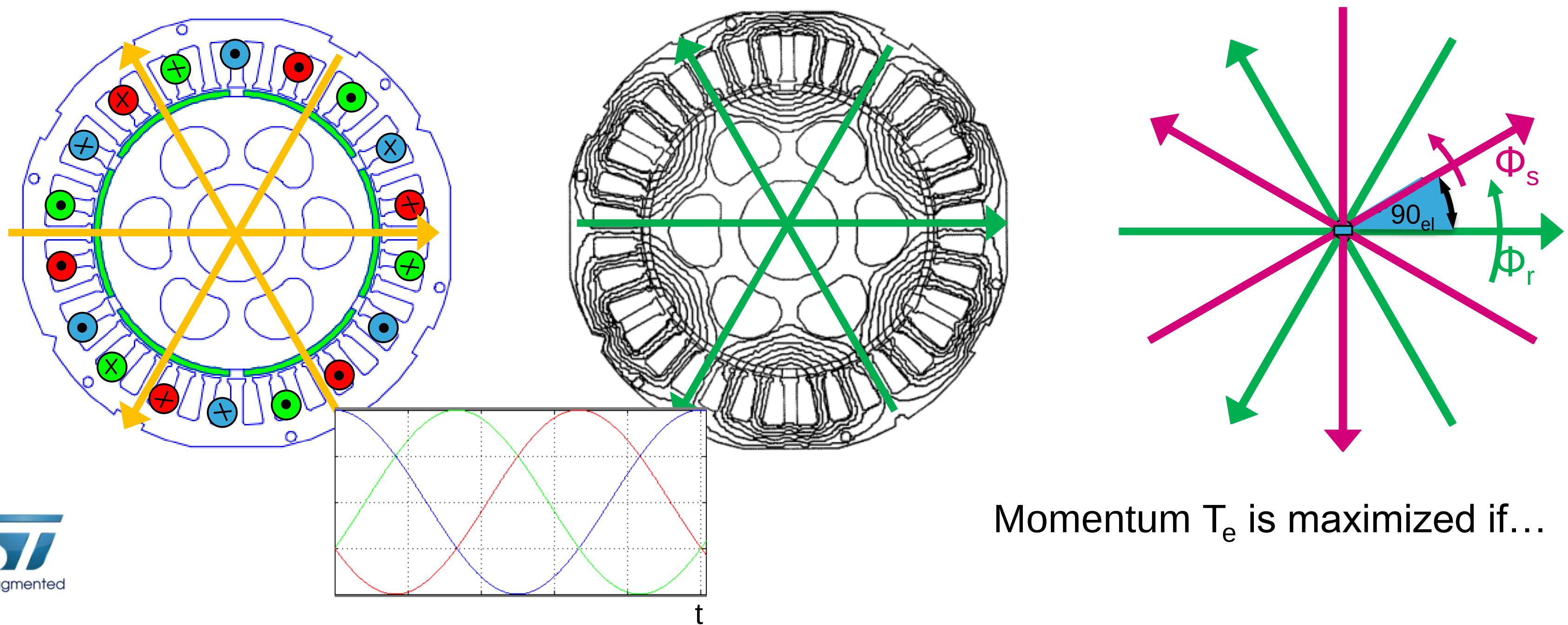
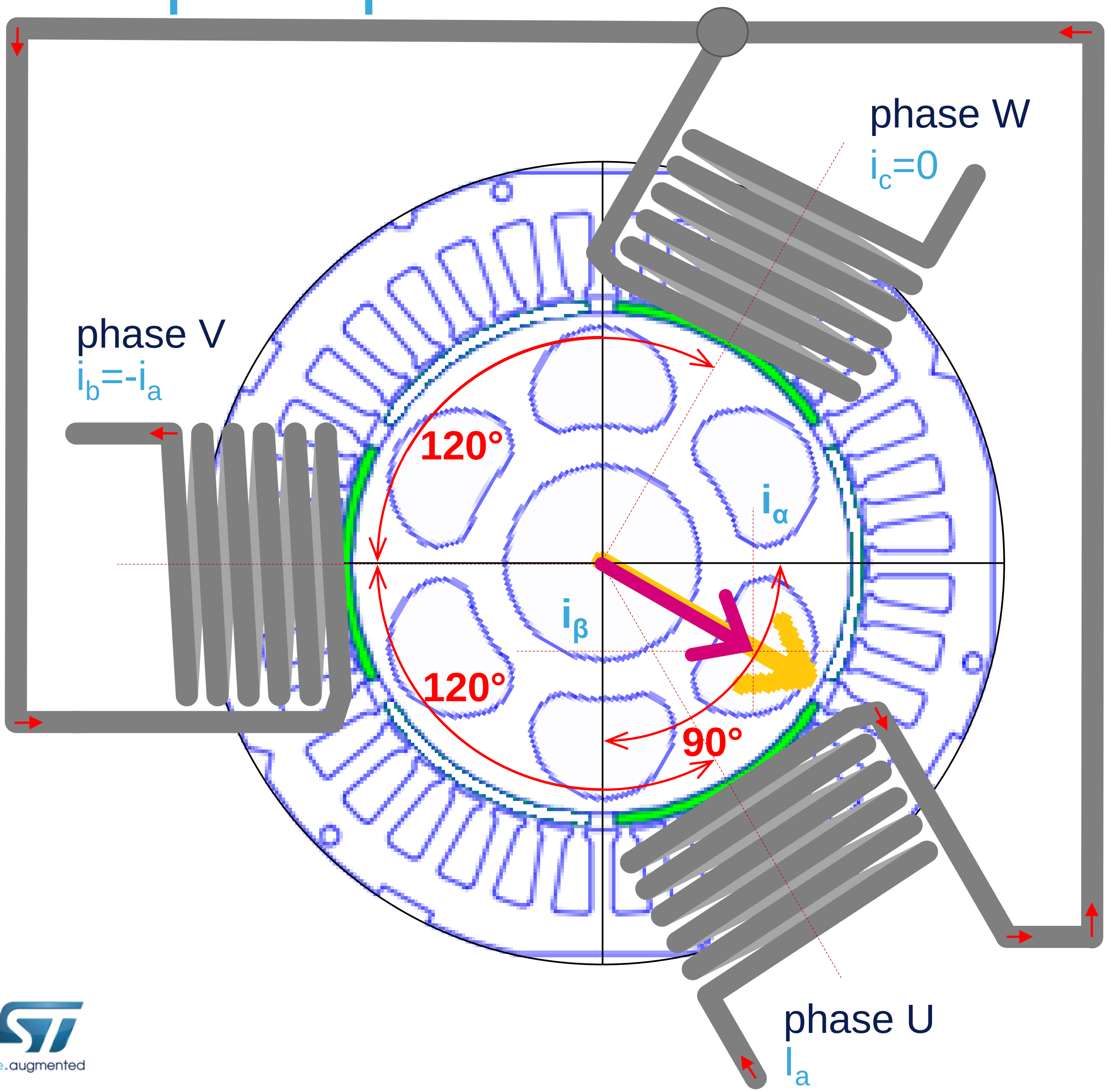
PMSM FOC principle

- Field Oriented Control: stator currents (Field) are controlled in amplitude and phase (Orientation) with respect to the rotor flux
  - ➢current sensing is mandatory (3shunt/1shunt/ICS)
  - ➢speed / position sensing is mandatory (encoder/Hall/sensorless alg)
  - ➢current controllers needed (PI/D,FF)



Momentum T_e is maximized if…

FOC principle – Clarke transformation



Clarke:

transforms

i_a, i_b, i_c (120°)

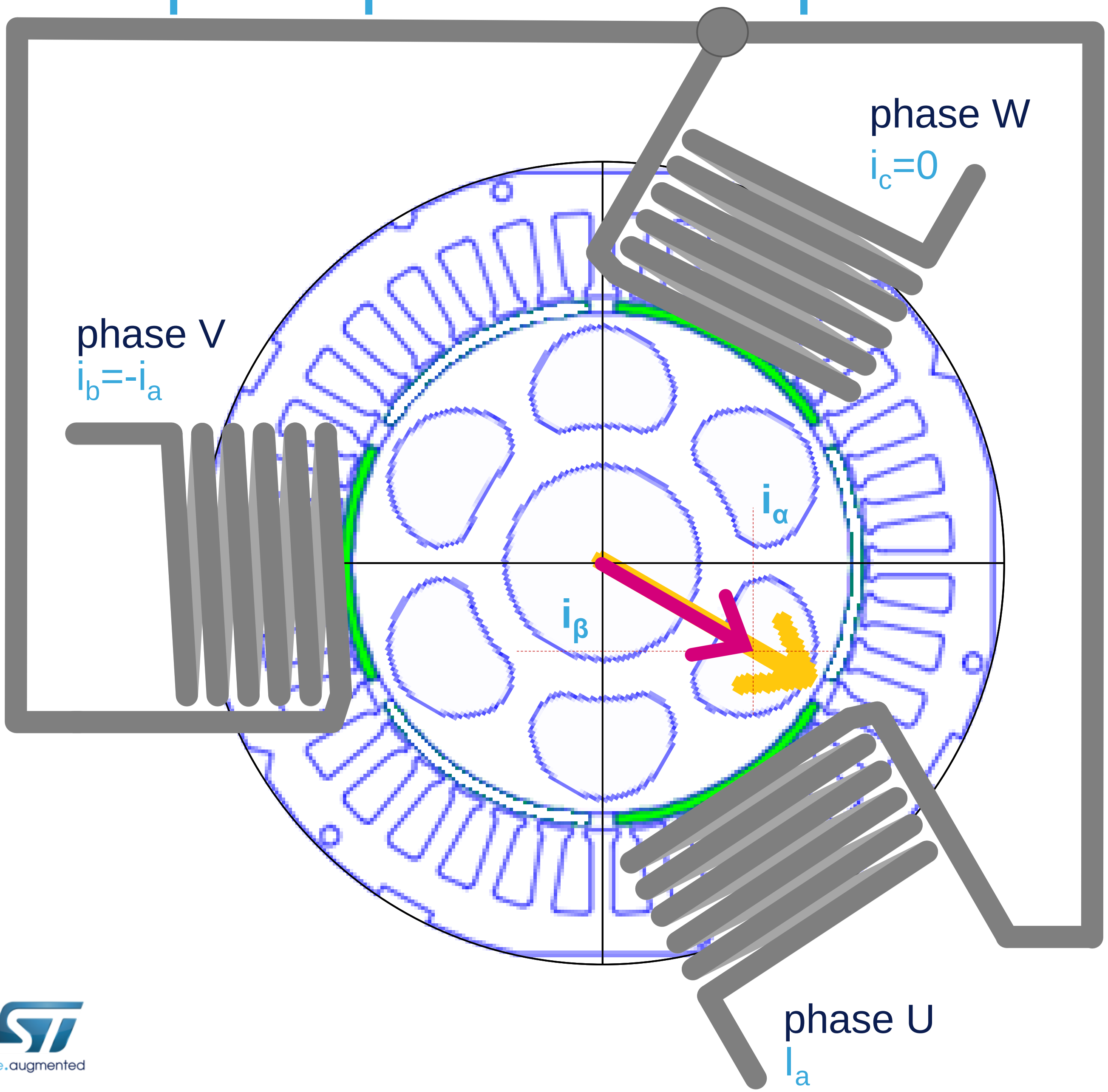
to

i_α, i_β (90°)

considering

$i_a + i_b + i_c = 0$

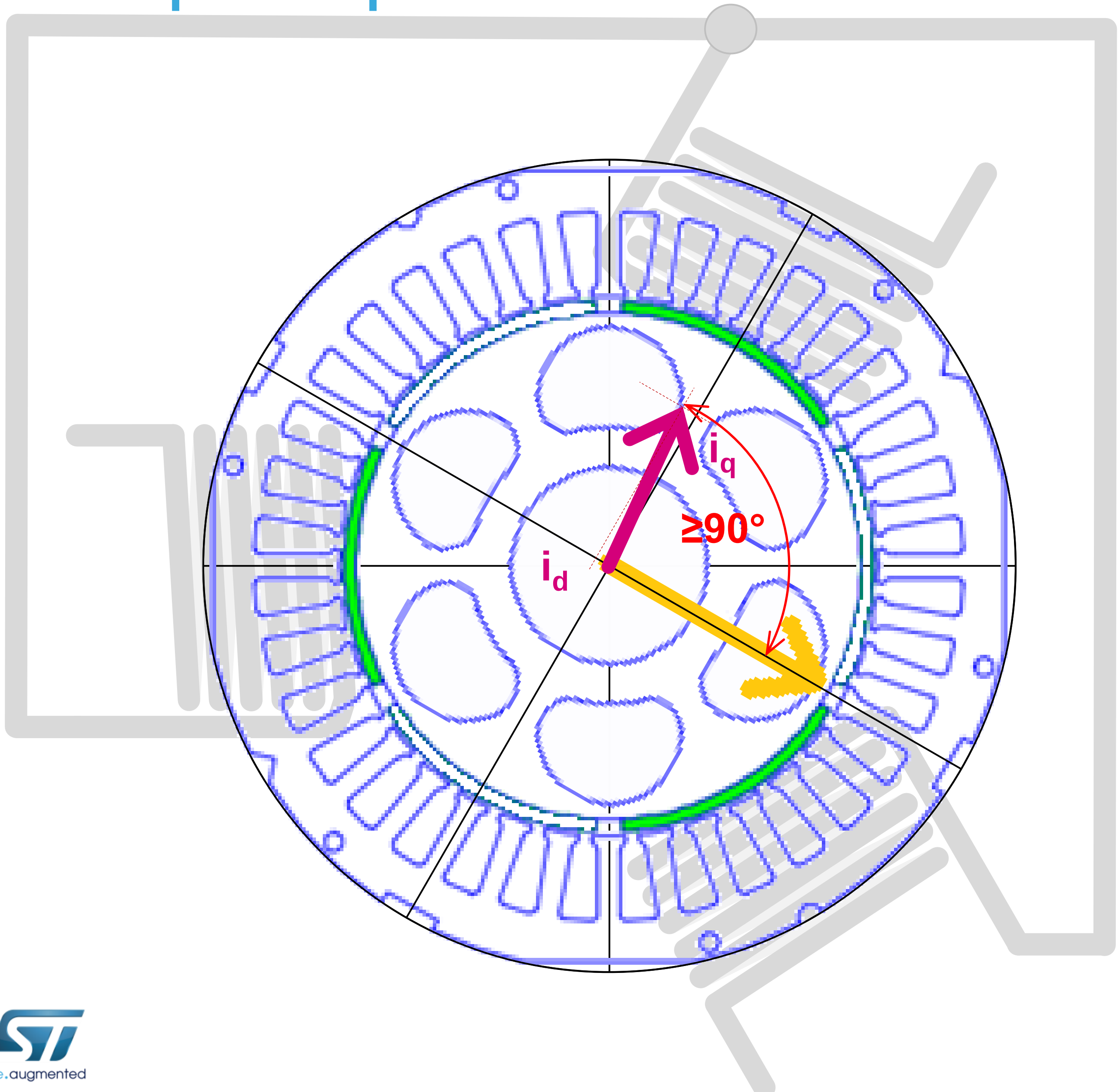
FOC principle – axes spin with the rotor



Lock of axial system to rotor position

Control mechanism stabilizes angle difference between rotor and stator fields close to 90° (or a little more if MTPA algorithm is used)

FOC principle – Park transformation

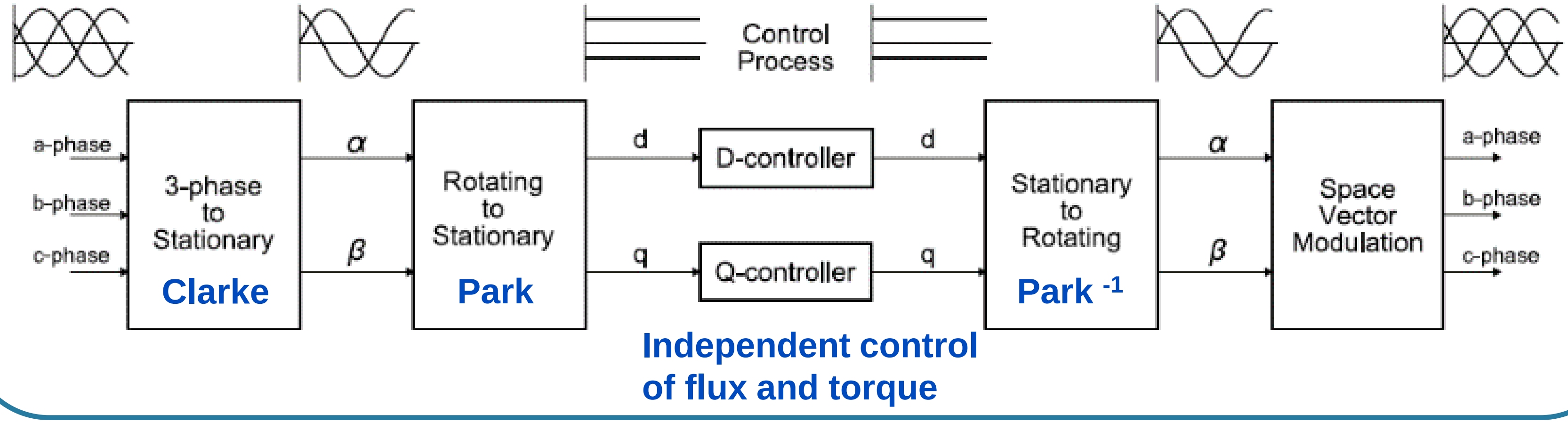


Park:

transforms rotating i_α, i_β to steady values i_q, i_d seen from the rotor view

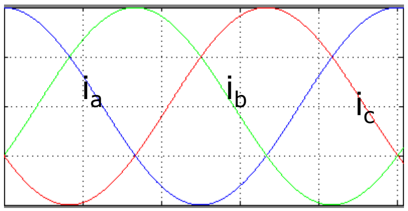
Why FOC ?

- Best energy ***efficiency*** even during ***transient operation.***
- ***Responsive speed control*** to load variations.
- ***Decoupled control*** of both electromagnetic torque and flux.
- Acoustical ***noise reduction*** due to sinusoidal waveforms.
- Active ***electrical brake*** and ***energy reversal.***



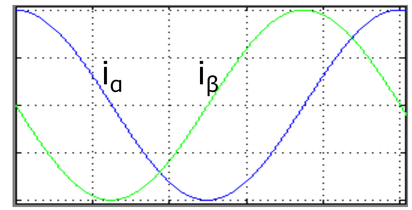
PMSM FOC overview: reference frame transformations

- Clarke: transforms i_a, i_b, i_c (120°) to i_α, i_β (90°)

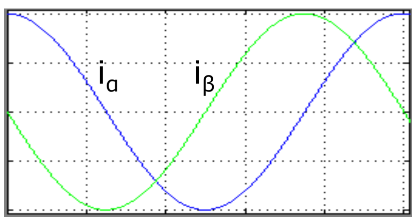


$$i_\alpha = i_{as}$$

$$i_\beta = -\frac{i_{as} + 2i_{bs}}{\sqrt{3}}$$

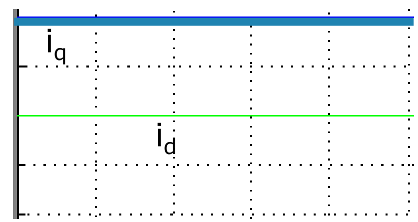


- Park: currents i_α, i_β , transformed on a reference frame rotating with their frequency, become DC currents i_q, i_d (90°) – a demodulation

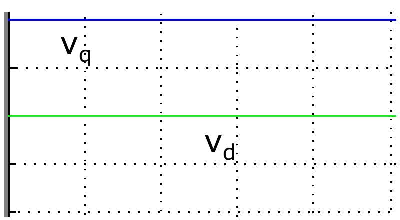


$$i_{qs} = i_\alpha \cos\theta_r - i_\beta \sin\theta_r$$

$$i_{ds} = i_a \sin\theta_r + i_\beta \cos\theta_r$$

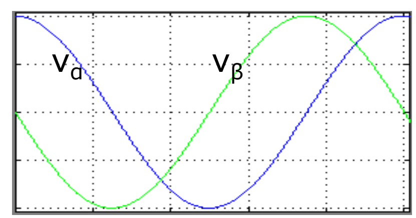


- PI regulators now work efficiently in a 'DC' domain; their DC outputs, voltage references v_q, v_d are handled by the Reverse Park into AC domain (v_α, v_β)



$$v_\alpha = v_{qs} \cos\theta_r + v_{ds} \sin\theta_r$$

$$v_\beta = -v_{qs} \sin\theta_r + v_{ds} \cos\theta_r$$



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