Sensorless Control of AC Drives at Very Low and Zero Speed

Fernando Briz

Power Electronics and Electric Drives Lab

INGENIERÍA DE SISTEMAS Y AUTOMÁTICA

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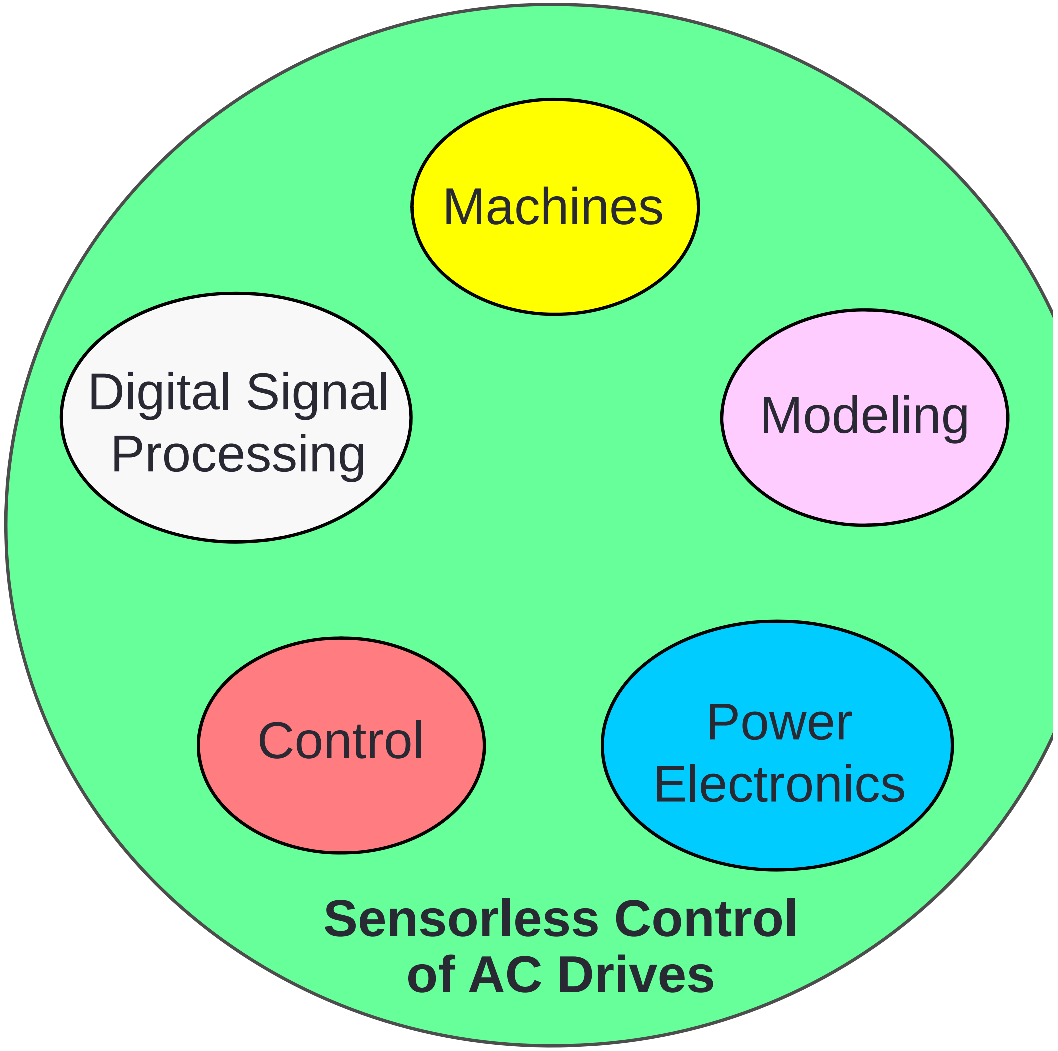
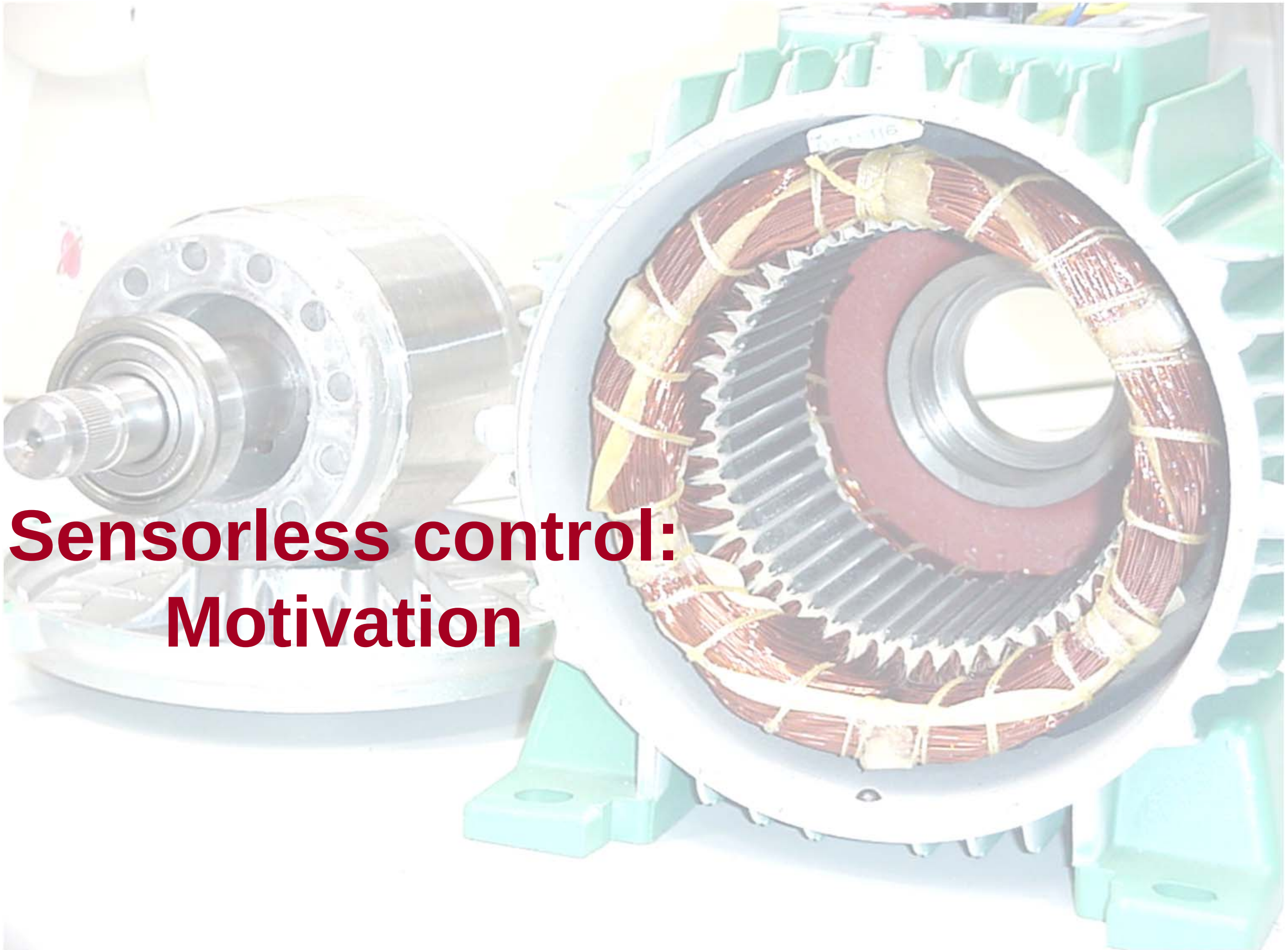

Machines
Digital Signal Processing
Modeling
Control
Power Electronics
Sensorless Control of AC Drives

Contents



Sensorless control: Motivation

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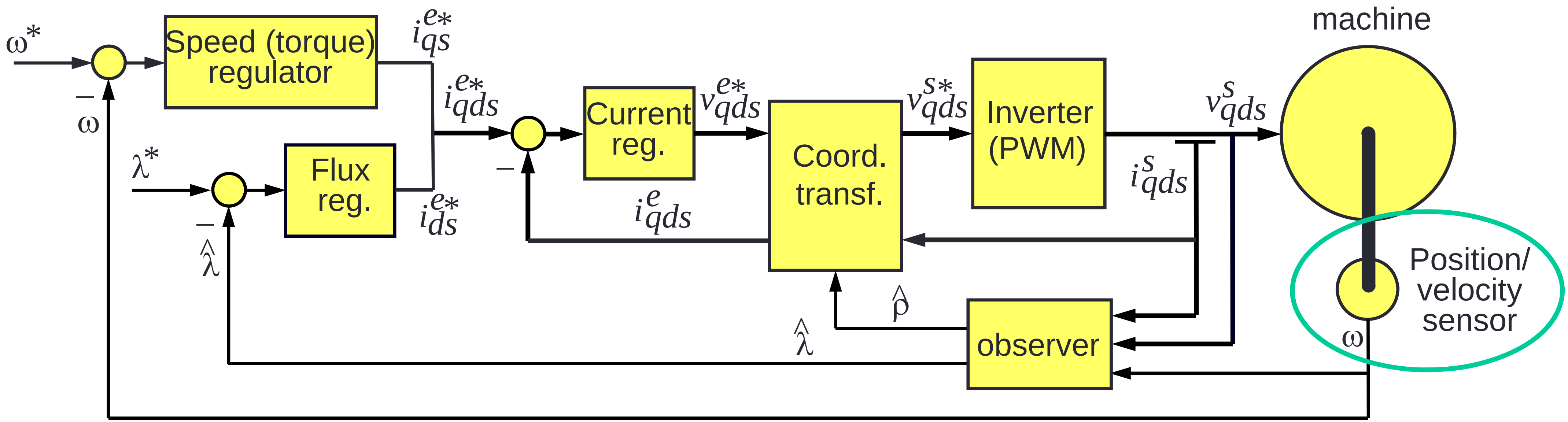

✓ *Sensorless* control deals with methods developed to eliminate the velocity/position sensor

✓ Velocity/position estimation is normally needed for two different purposes in medium-high performance electric drives:
- Flux angle (IM) / magnet angle (PMSM) location for flux and torque control
- Motion control (velocity/position regulation)

✓ Elimination of the position sensor (and cabling) has advantages in terms of:
- cost
- robustness
- space / motor design (e.g. hollow shaft motors)
- operational limits (temperature, maximum speed, vibration, …)

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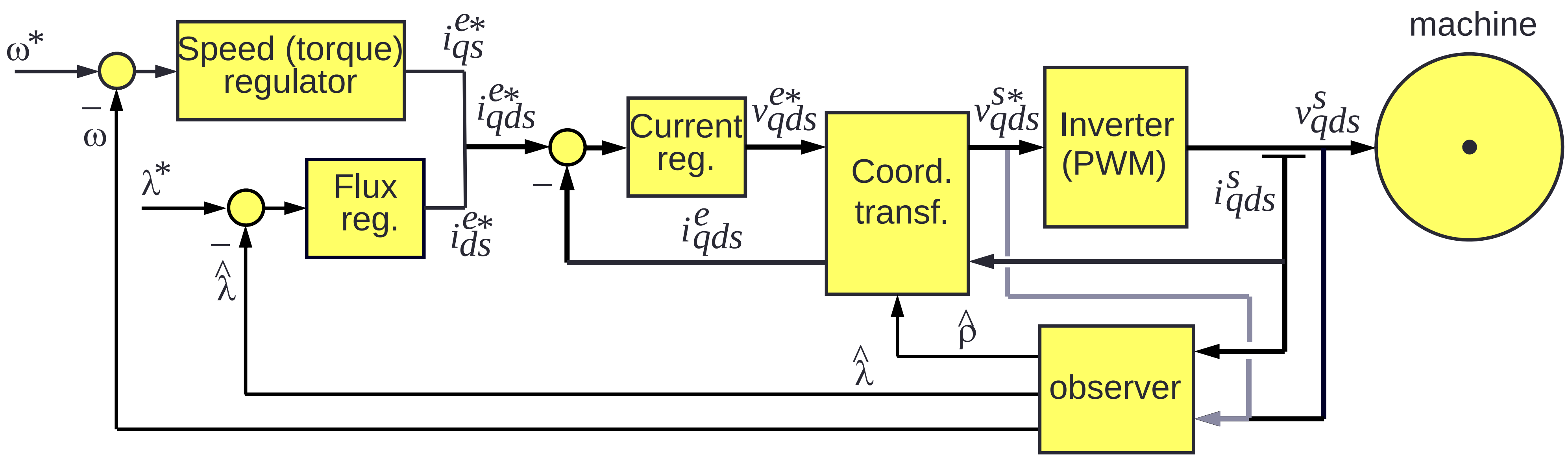

✓ Elimination of the position sensor requires the use of some form of observer, its inputs normally being already available electric quantities

✓ Two different approaches:

- model based methods
- saliency tracking based methods

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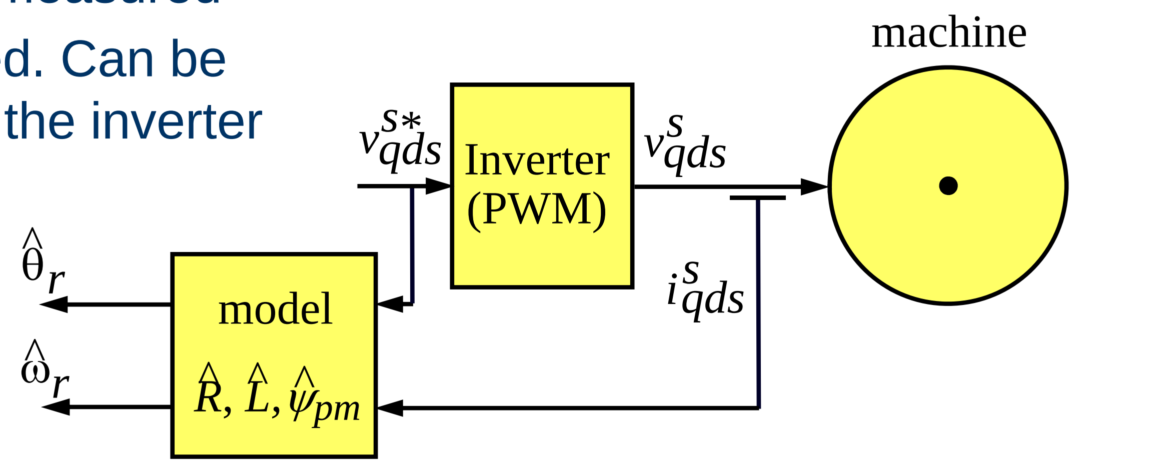
Model based sensorless methods

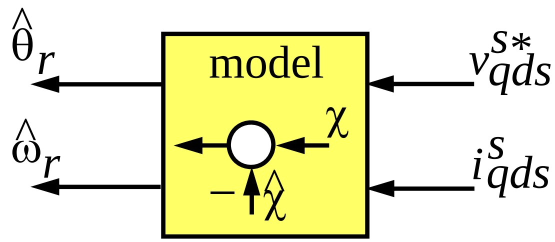
- ✓Based on the back emf induced in the stator windings, use the fundamental model of the machine
- ✓Stator currents are normally (and easily) measured
- ✓Stator voltages are not normally measured. Can be estimated from the voltage commands to the inverter

Various approaches

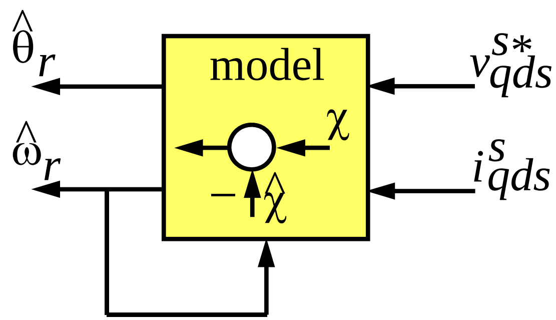
- ✓Estimators (open loop)



- ✓Observers (closed-loop)



- ✓Adaptive models



Model based sensorless methods:
The stator voltage, the stator flux and the bemf

✓ Stator voltage and back-emf equations

$$\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} = R \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} + p\,L \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} + \begin{bmatrix} e_{ds}^{s} \\ e_{qs}^{s} \end{bmatrix}$$

$$\begin{bmatrix} e_{ds}^{s} \\ e_{qs}^{s} \end{bmatrix} = \omega_r\, \psi_{pm} \begin{bmatrix} -sin(\theta_r) \\ cos(\theta_r) \end{bmatrix}$$

Complex vector form

$$v_{qds}^{s} = (R + p\,L)\, i_{qds}^{s} + j\omega_r\, \psi_{pm}\, e^{j\theta_r}$$

✓ Stator voltage & stator flux equations

$$\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} = R \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} + p \begin{bmatrix} \psi_{ds}^{s} \\ \psi_{qs}^{s} \end{bmatrix}$$

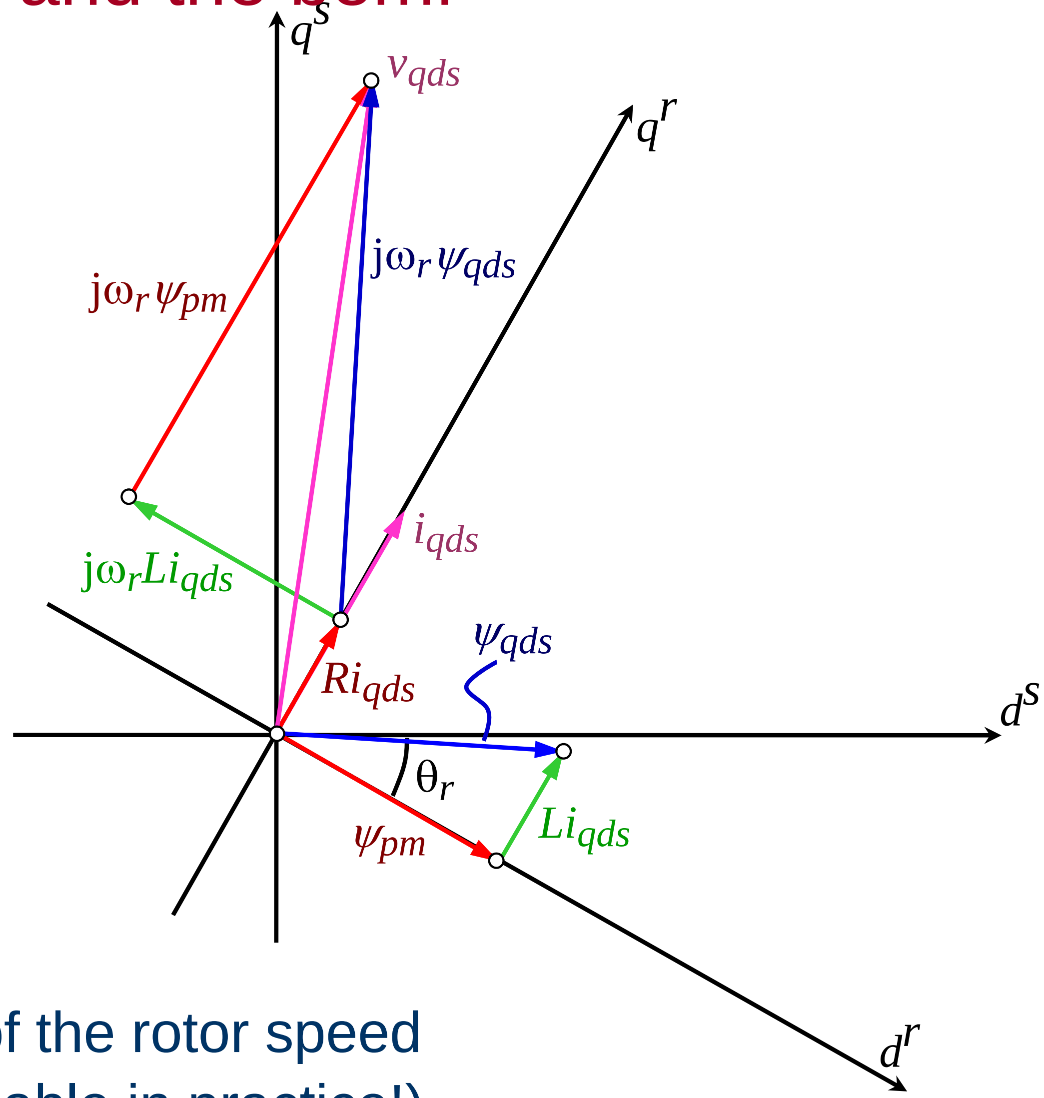
$$\begin{bmatrix} \psi_{ds}^{s} \\ \psi_{qs}^{s} \end{bmatrix} = L \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} + \psi_{pm} \begin{bmatrix} -sin(\theta_r) \\ cos(\theta_r) \end{bmatrix}$$

Complex vector form

$$v_{qds}^{s} = R\, i_{qds}^{s} + p\, \psi_{qds}^{s}$$

$$\psi_{qds}^{s} = L\, i_{qds}^{s} + \psi_{pm}\, e^{j\theta_r}$$

Model based sensorless methods:
The stator voltage, the stator flux and the bemf



Back emf

$$v^s_{qds} = (R + pL)\, i^s_{qds} + j\omega_r\, \psi_{pm}\, e^{j\theta_r}$$

Stator flux

$$v^s_{qds} = R\, i^s_{qds} + p\, \psi^s_{qds}$$

$$\psi^s_{qds} = L\, i^s_{qds} + \psi_{pm}\, e^{j\theta_r}$$

✓ *Back-emf* vs. stator flux

- *Back-emf* proportional to speed
  ⇨ =0 at zero speed!
- Stator flux magnitude is independent of the rotor speed
  ⇨ Requires pure integration (not viable in practice!)

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Model based sensorless methods:
The stator voltage, the stator flux and the bemf

Back emf

$$v^s_{qds} = (R + p\,L)\, i^s_{qds} + j\omega_r\, \psi_{pm}\, e^{j\theta_r}$$

Stator flux

$$v^s_{qds} = R\, i^s_{qds} + p\, \psi^s_{qds}$$

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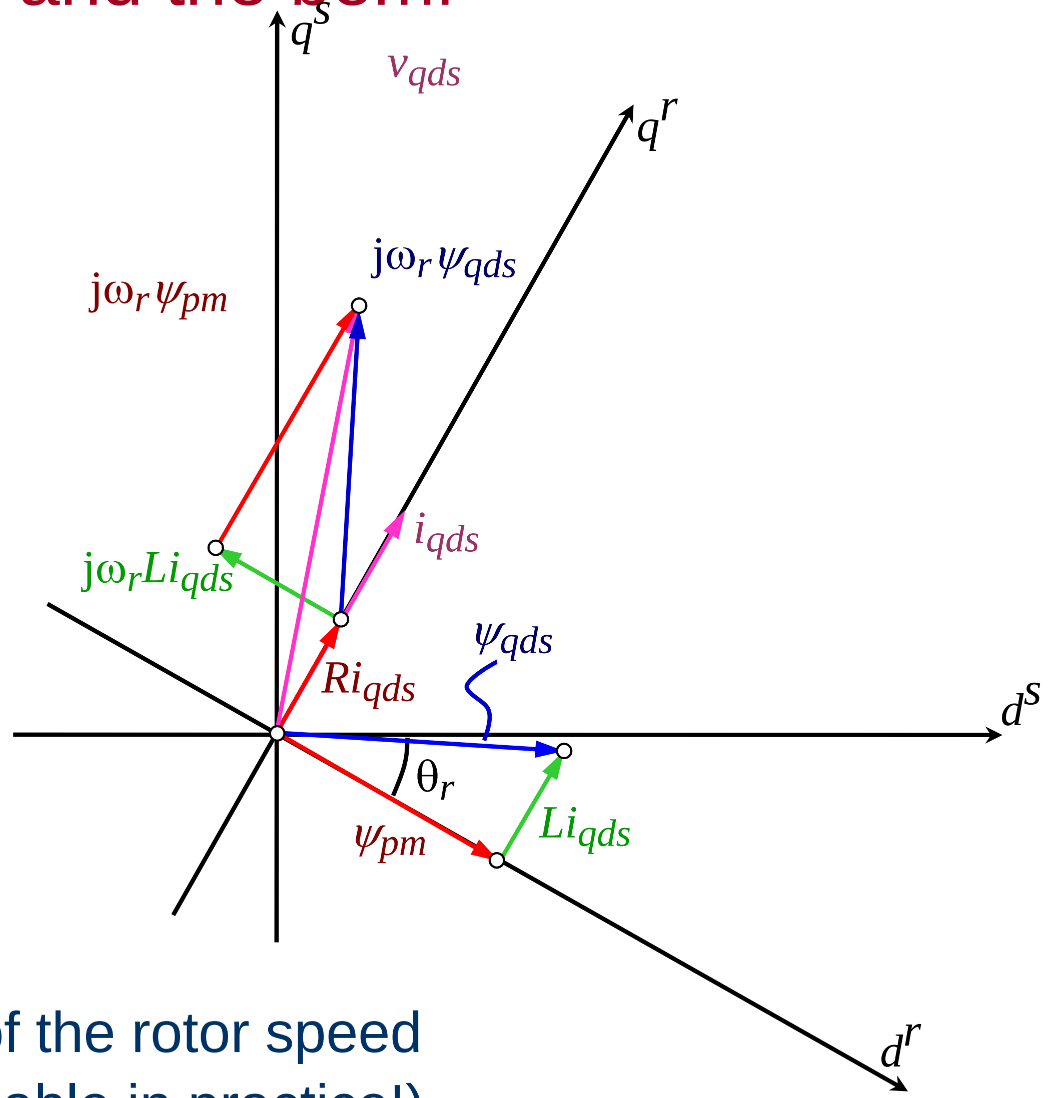

✓ *Back-emf* vs. stator flux

- *Back-emf* proportional to speed
  - ⇨ =0 at zero speed!
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  - ⇨ Requires pure integration (not viable in practice!)

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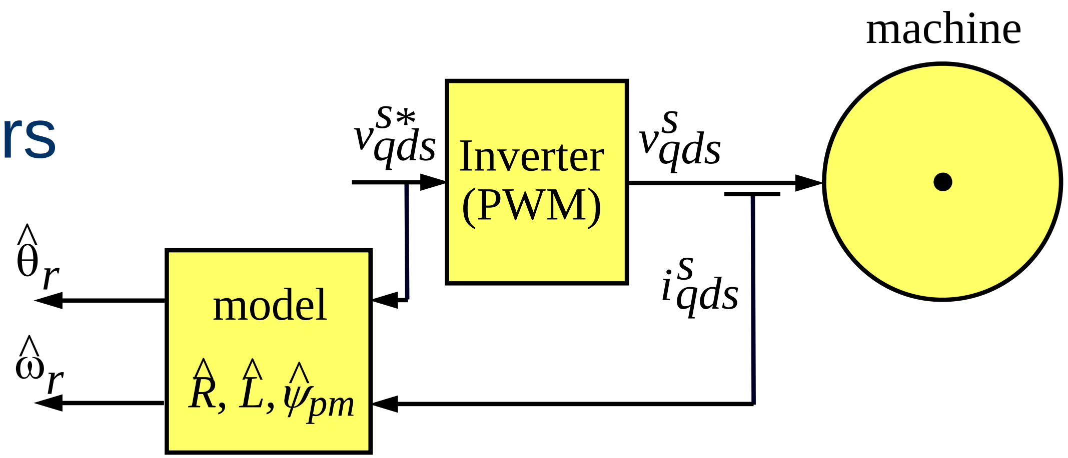
Model based sensorless methods:
Limitations & concerns

✓ Closed-loop methods (observers, adaptive models, …) introduce correction mechanisms to reduce the parameter sensitivity and other sources of error

- voltage drops in the power devices
- inverter deadtime
- errors due to sensors



✘ Can not work at very low and zero speed (no back-emf)

✘ Not valid for position control

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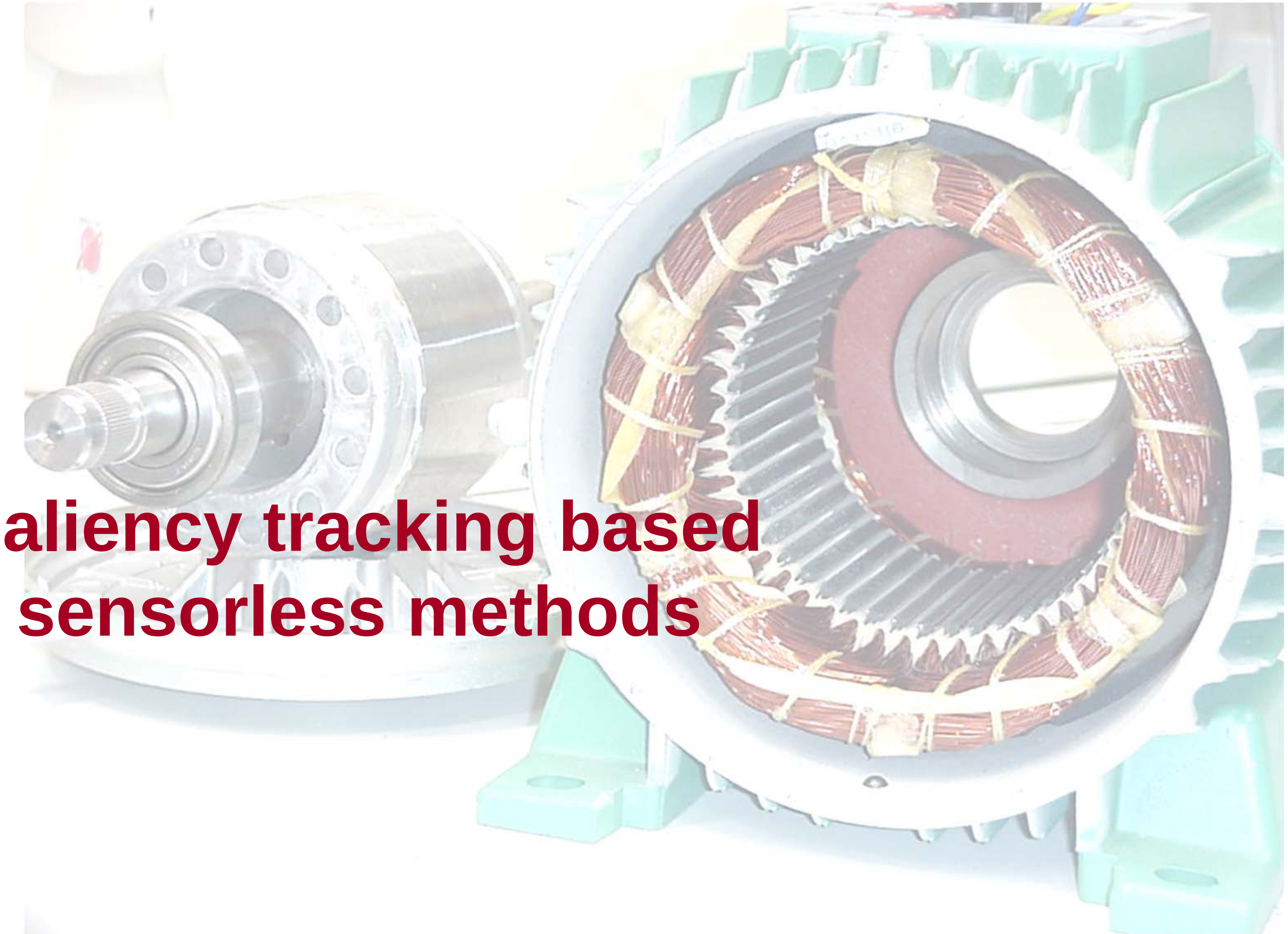
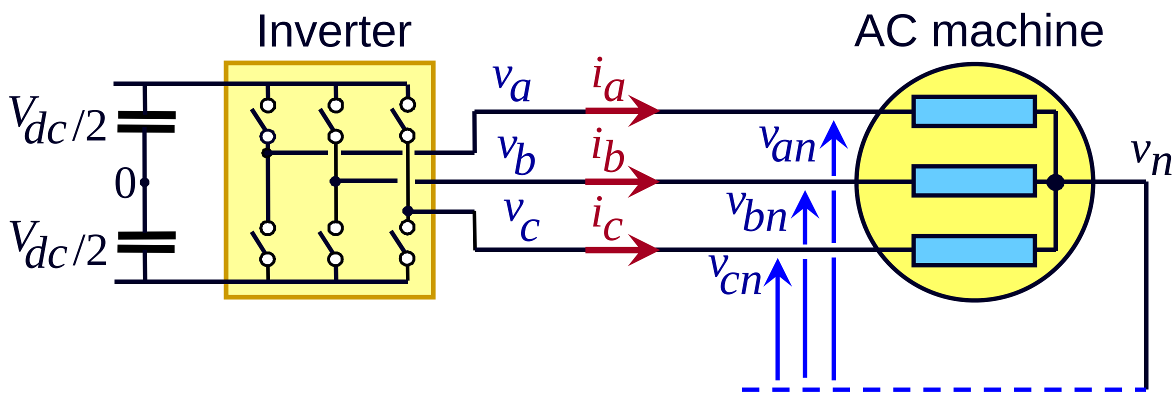


Saliency tracking based sensorless methods

The concept

Inject some form of high frequency signal via inverter, which interacts with the rotor asymmetries, and produce some measurable effects in the terminal electrical variables (stator currents and voltages)



Some early papers:

Jansen, P.L.; Lorenz, R.D., "Transducerless position and velocity estimation in induction and salient AC machines," *Industry Applications Society Annual Meeting, 1994., Conference Record of the 1994 IEEE* , vol., no., pp.488-495 vol.1, 2-6 Oct 1994

Schroedl, M., "Sensorless control of AC machines at low speed and standstill based on the “INFORM” method," *Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS '96., Conference Record of the 1996 IEEE* , vol.1, no., pp.270-277 vol.1, 6-10 Oct 1996

High frequency signal injection based methods vs. model based sensorless methods

Pros

- ✓ Reduced parameter sensitivity
- ✓ Independent of the fundamental excitation (i.e. electrical/mechanical speed, flux and torque levels, ideally)
- ✓ Can work at very low and zero speed, also allowing position control (totally true!)

Cons

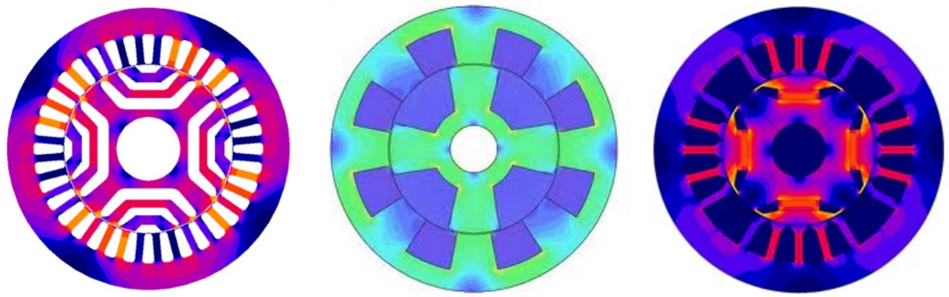
- ✗ The machine design is important
- ✗ Some concepts/implementations require additional sensors (voltage sensors, d*i*/d*t* sensors, …)
- ✗ Require the injection of high frequency signals or modification of the PWM pattern, what can result in unwanted effects (vibration, noise, additional losses, …)

Spatial saliencies (asymmetries) in AC machines

Saliency tracking based sensorless methods track spatial saliencies (asymmetries) constructively associated to the rotor

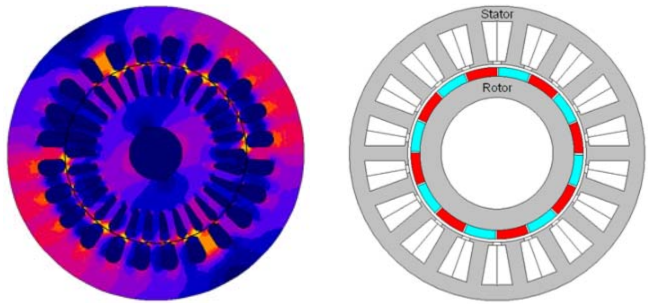
✓ Saliencies are intrinsic to some machine designs

- Synchronous reluctance machines
- Switched reluctance machines
- Interior permanent magnet machines
  - ➪ This designs would be therefore natural candidates (in principle)



✓ Some machines are typically designed to be non salient

- Induction machines
- Surface permanent magnet machines
  - ➪ This designs would be therefore not so good candidates (in principle)



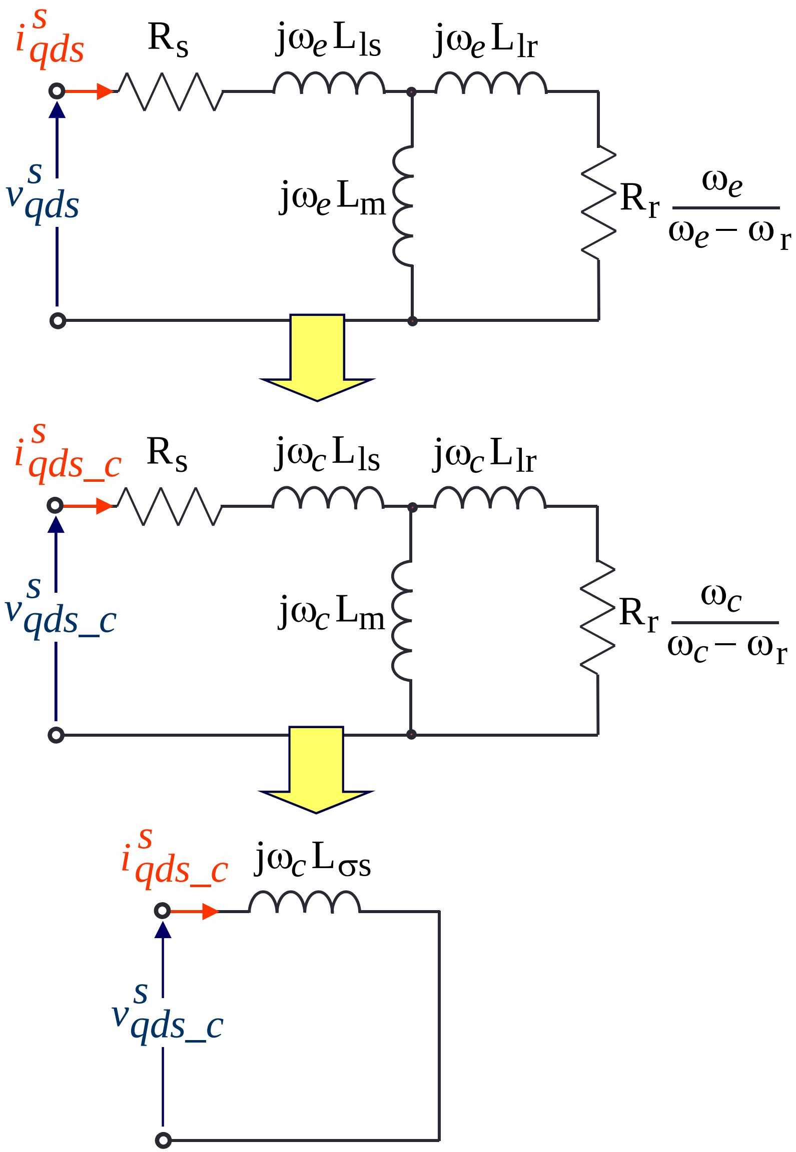
High frequency model of three-phase AC machines:

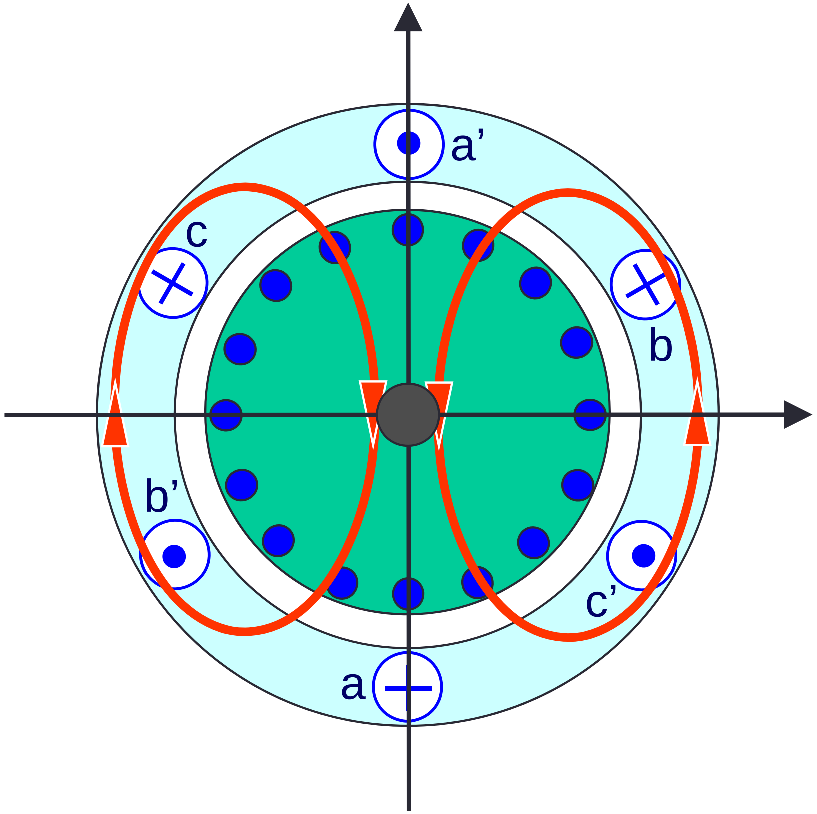
Induction machines

Conventional steady-state equivalent circuit ($\omega_e \approx \omega_r$)

High frequency circuit ($\omega_c \uparrow\uparrow$, $\omega_c >> \omega_r$)

High frequency equivalent circuit



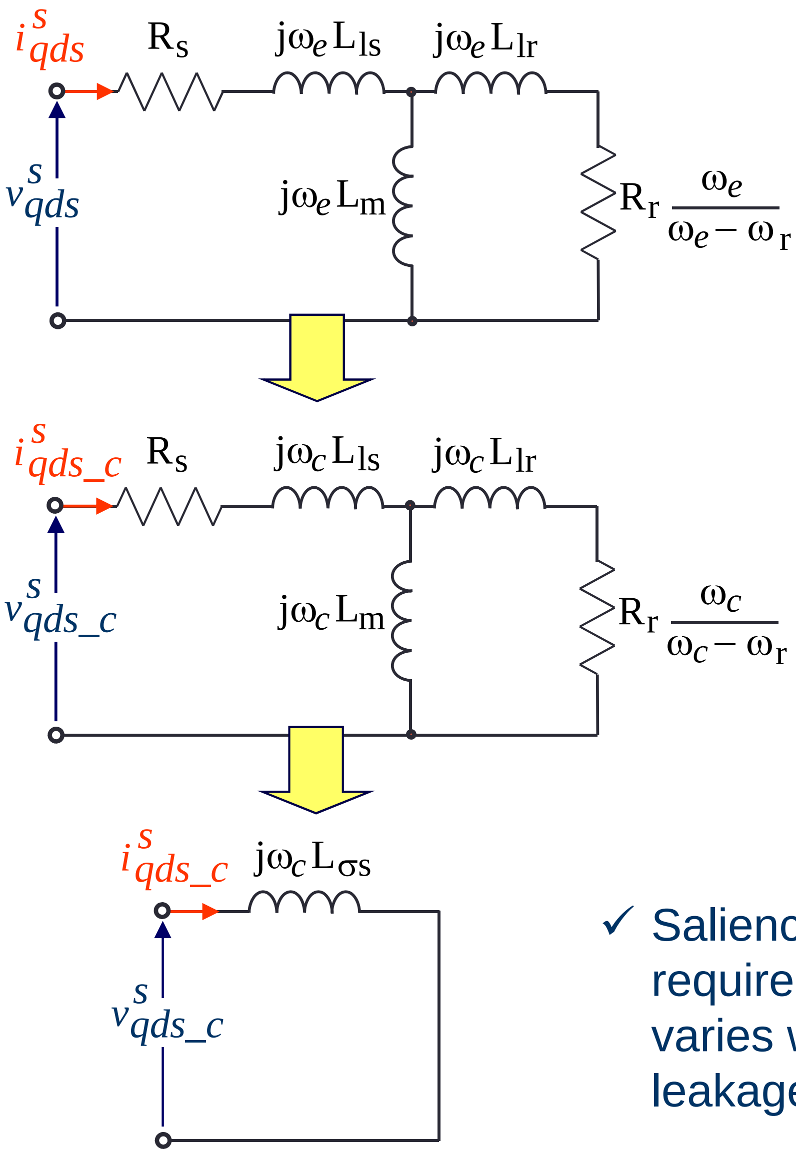


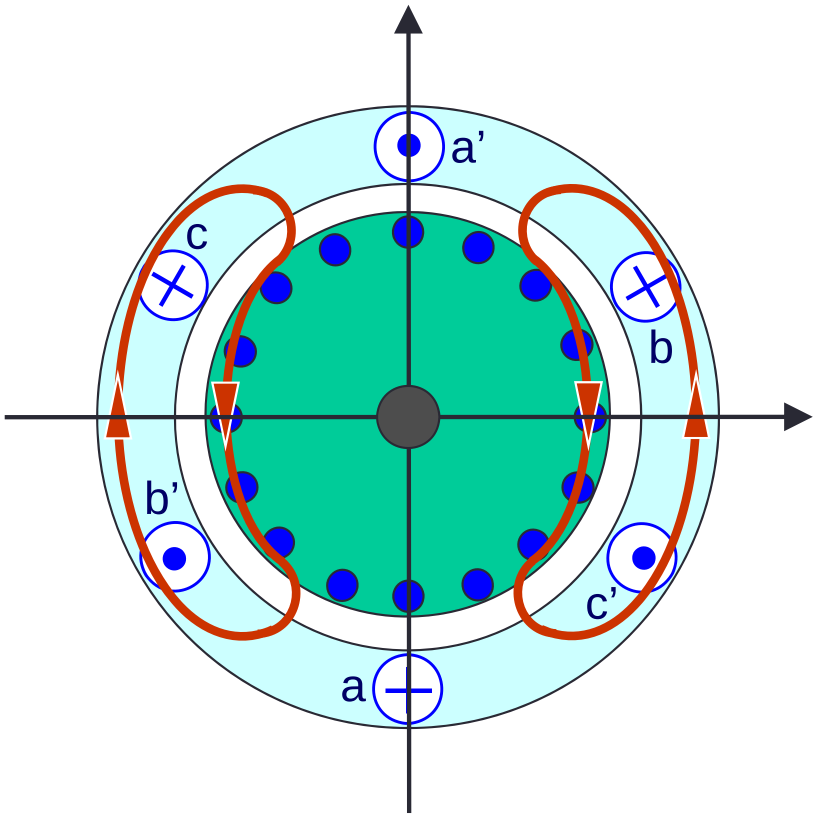
High frequency model of three-phase AC machines:
Induction machines

Conventional steady-state equivalent circuit $(\omega_e \approx \omega_r)$

High frequency circuit $(\omega_c \uparrow\uparrow, \omega_c >> \omega_r)$

High frequency equivalent circuit

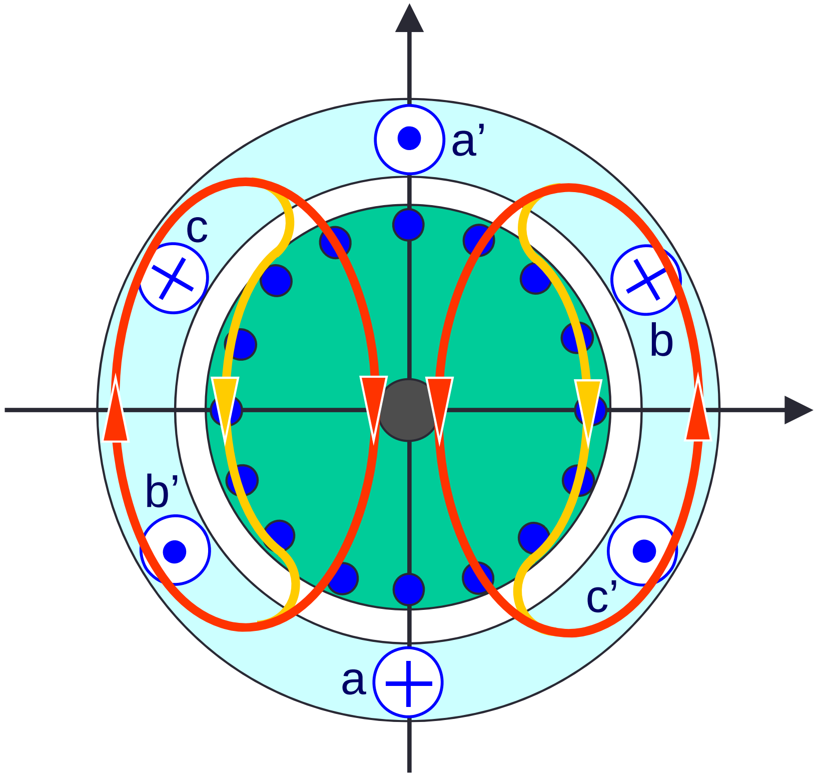




- ✓ Saliency tracking-based sensorless methods require that the stator transient inductance varies with the rotor position (through the rotor leakage inductance)

High frequency model of three-phase AC machines:

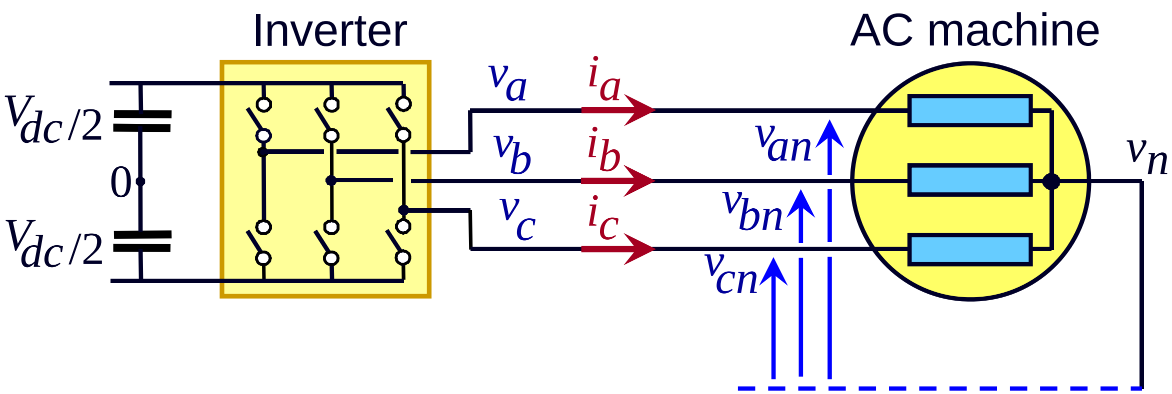
Induction machines



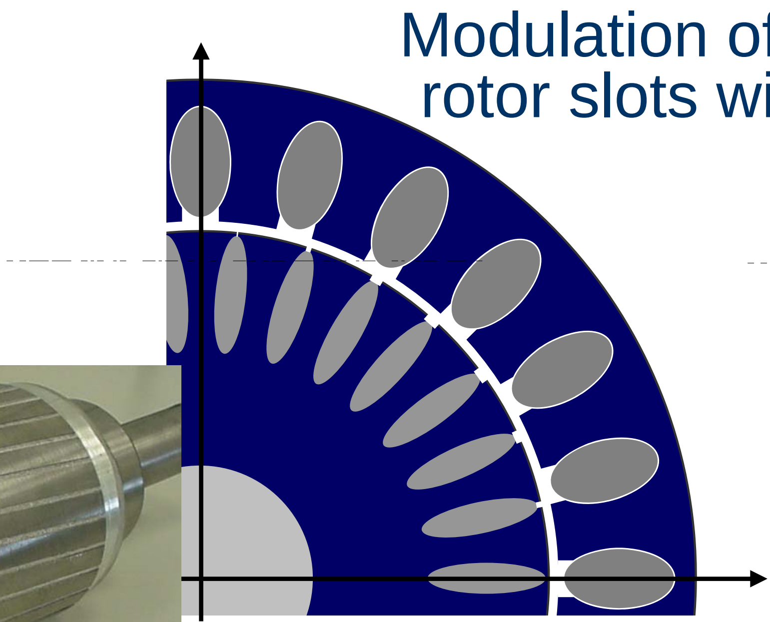
Non-salient (symmetric) rotor

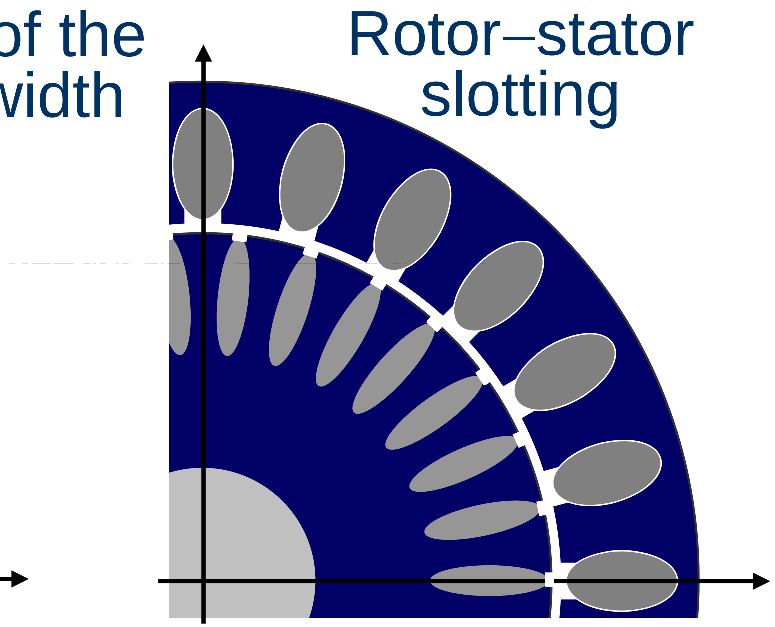
- No information related to the rotor position present in the electrical quantities (voltages, currents)

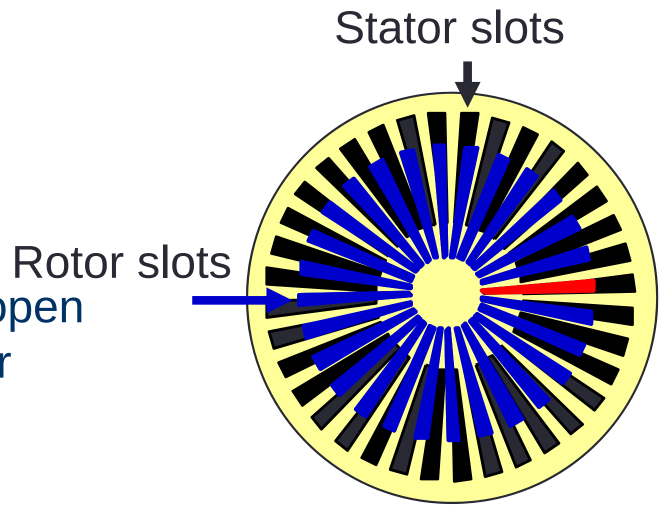
$$v_{an} = L_{\sigma s}\frac{\mathrm{d}i_a}{\mathrm{d}t}$$
$$v_{bn} = L_{\sigma s}\frac{\mathrm{d}i_b}{\mathrm{d}t}$$
$$v_{cn} = L_{\sigma s}\frac{\mathrm{d}i_c}{\mathrm{d}t}$$



Spatial saliencies in induction machines



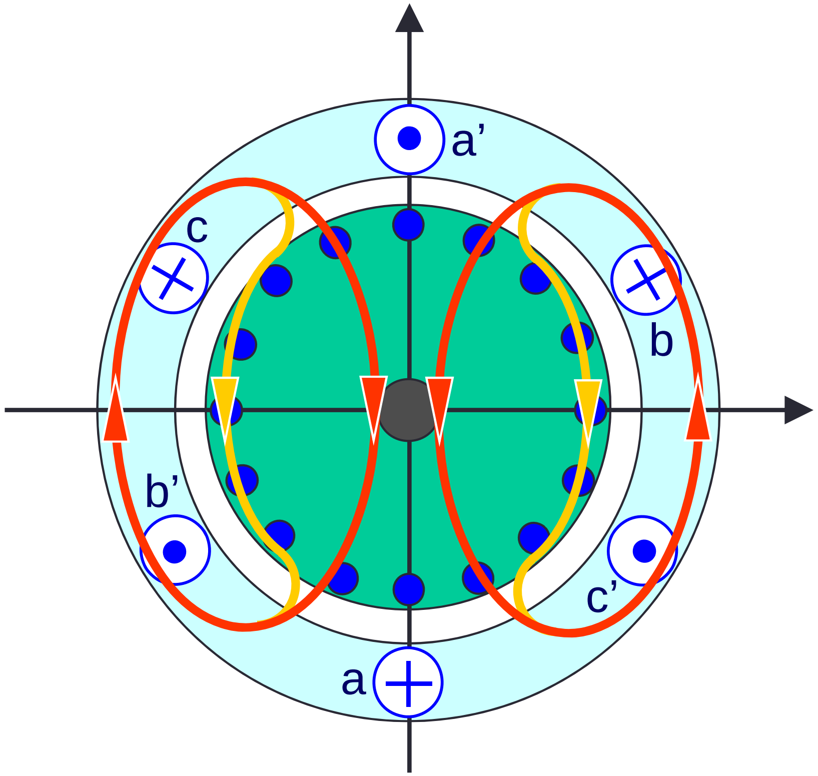




- ✓ Modulation of the rotor slots width implies a modification of the manufacturing process, or post-manufacturing machining
- ✓ Rotor-stator slotting in present in standard machines designs with open or semi-open rotor slots (depends on the number of rotor and stator slots and number of poles)
- ✓ Rotor skew angle strongly affects

High frequency model of three-phase AC machines:

Induction machines



Salient (asymmetric) rotor

- Information related to the rotor position present in the electrical quantities (voltages/currents)

$$v_{an} = (\Sigma L_{\sigma s} + 2\Delta L_{\sigma s}\cos(h\theta_r))\frac{\mathrm{d}i_a}{\mathrm{d}t}$$

$$v_{bn} = (\Sigma L_{\sigma s} + 2\Delta L_{\sigma s}\cos(h\theta_r - \frac{2\pi}{3}))\frac{\mathrm{d}i_b}{\mathrm{d}t}$$

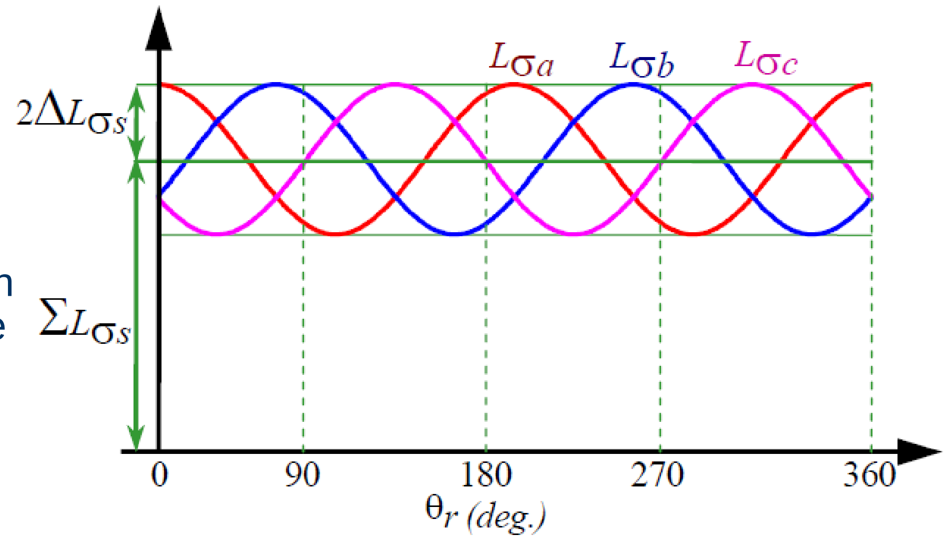
$$v_{cn} = (\Sigma L_{\sigma s} + 2\Delta L_{\sigma s}\cos(h\theta_r - \frac{4\pi}{3}))\frac{\mathrm{d}i_c}{\mathrm{d}t}$$

$$\Sigma L_{\sigma s} = \frac{L_{\sigma qs} + L_{\sigma ds}}{2}$$ average stator transient inductance in a saliency synchronous reference frame

$$\Delta L_{\sigma s} = \frac{L_{\sigma qs} - L_{\sigma ds}}{2}$$ differential stator transient inductance in a saliency synchronous reference frame

h: Harmonic order of the saliency

θ_r: Angular position of the saliency (normally the rotor angle)



High frequency model of three-phase AC machines: Induction machines

Transformation to an equivalent *qd0* model

$$v_{an} = (\Sigma L_{\sigma s} + 2\Delta L_{\sigma s}\cos(h\theta_r))\frac{\mathrm{d}i_a}{\mathrm{d}t}$$

$$v_{bn} = (\Sigma L_{\sigma s} + 2\Delta L_{\sigma s}\cos(h\theta_r - \frac{2\pi}{3}))\frac{\mathrm{d}i_b}{\mathrm{d}t}$$

$$v_{cn} = (\Sigma L_{\sigma s} + 2\Delta L_{\sigma s}\cos(h\theta_r - \frac{4\pi}{3}))\frac{\mathrm{d}i_c}{\mathrm{d}t}$$

$$[v_{qs}^{s} \;\; v_{ds}^{s} \;\; v_{0s}^{s}]^{\mathrm{T}} = L_{\sigma qds0}^{s}\frac{\mathrm{d}}{\mathrm{d}t}[i_{qs}^{s} \;\; i_{ds}^{s} \;\; i_{0s}^{s}]^{\mathrm{T}}$$

$$L_{\sigma qd0s}^{s} = \Sigma L_{\sigma s}\left[\, I \,\right] + \Delta L_{\sigma s}\begin{bmatrix} \cos(h\theta_r) & -\sin(h\theta_r) & 2\cos(h\theta_r) \\ -\sin(h\theta_r) & -\cos(h\theta_r) & 2\sin(h\theta_r) \\ \cos(h\theta_r) & \sin(h\theta_r) & 0 \end{bmatrix}$$

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High frequency model of three-phase AC machines:
Induction machines

High frequency model in the stationary reference frame of salient induction machine in the stationary reference frame

$$\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \Sigma L + \Delta L cos(h\theta_r) & -\Delta L sin(h\theta_r) \\ -\Delta L sin(h\theta_r) & \Sigma L - \Delta L cos(h\theta_r) \end{bmatrix} p \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}$$

$$\Sigma L_{\sigma s} = \frac{L_{\sigma qs} + L_{\sigma ds}}{2}$$ average stator transient inductance in a saliency synchronous reference frame

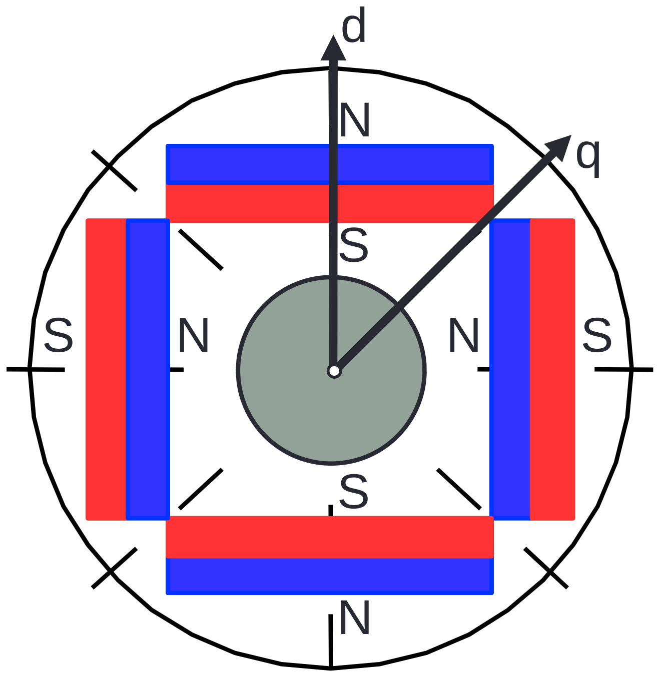
$$\Delta L_{\sigma s} = \frac{L_{\sigma qs} - L_{\sigma ds}}{2}$$ differential stator transient inductance in a saliency synchronous reference frame

h: Harmonic order of the saliency

θ_r: Angular position of the saliency (normally the rotor angle)

- If a high frequency voltage is injected, the resulting high frequency currents will be modulated by the rotor position dependent saliency
- It is also feasible to inject a high frequency current the induced high frequency voltage will be modulated by the rotor position dependent saliency

High frequency model of three-phase AC machines:
PM machines



IPMSM model in rotor coordinates

$$\begin{bmatrix} v_{ds}^r \\ v_{qs}^r \end{bmatrix} = \begin{bmatrix} R & -\omega_r L_q \\ \omega_r L_d & R \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + p \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \omega_r \psi_{pm} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

High frequency model (also valid for SynRM)

- Resistive terms can be neglected
- No high frequency component in the back-emf

Rotor synchronous reference frame

$$\begin{bmatrix} v_{ds}^r \\ v_{qs}^r \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix}$$

Stationary reference frame

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} \Sigma L + \Delta L cos(2\theta_r) & -\Delta L sin(2\theta_r) \\ -\Delta L sin(2\theta_r) & \Sigma L - \Delta L cos(2\theta_r) \end{bmatrix} p \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix}$$

Cross saturation was neglected!!

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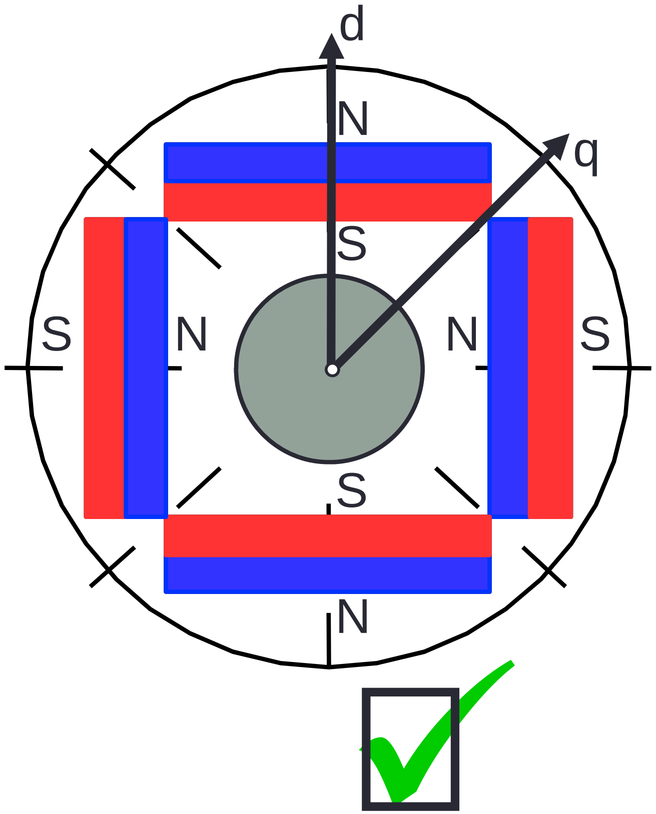
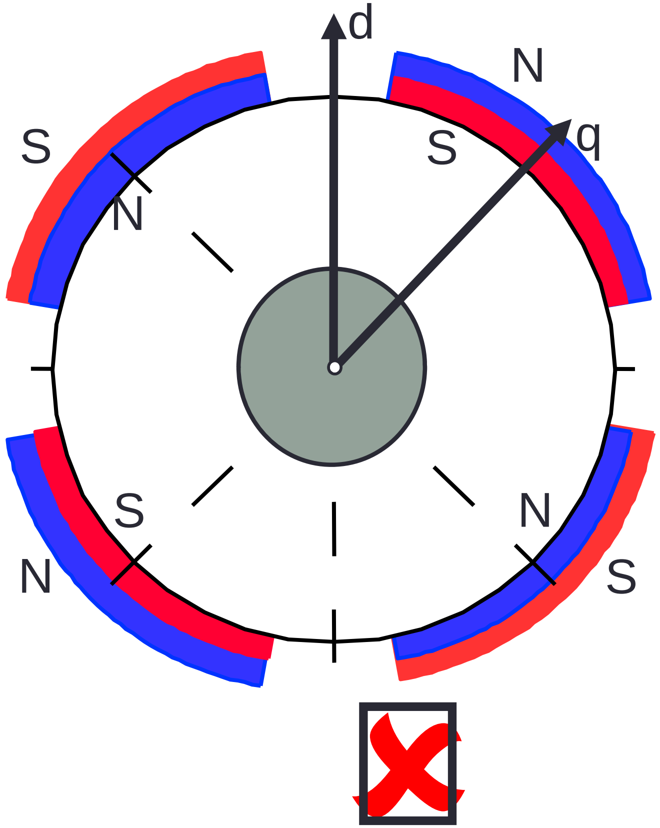
Spatial saliencies in permanent magnet machines

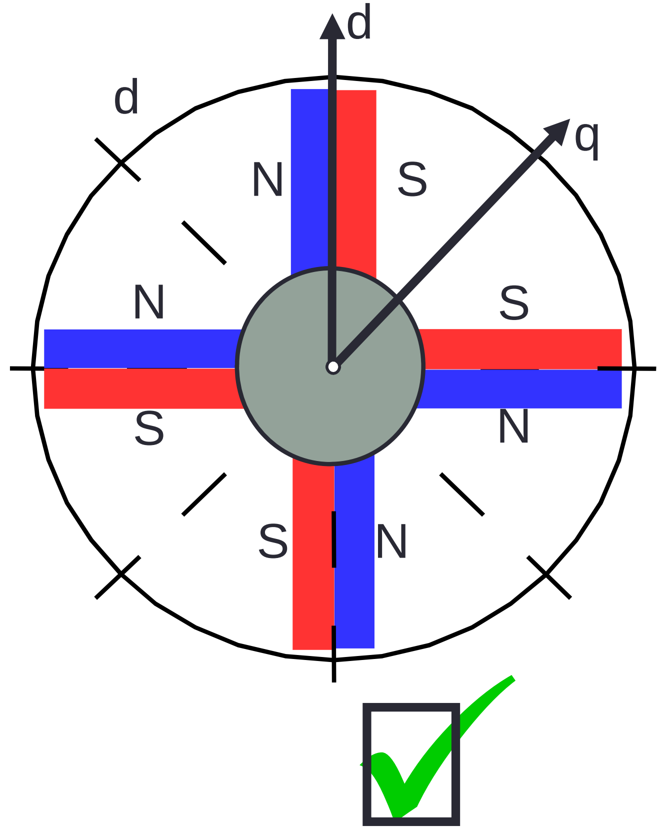
Radial flux, interior permanent magnet machines



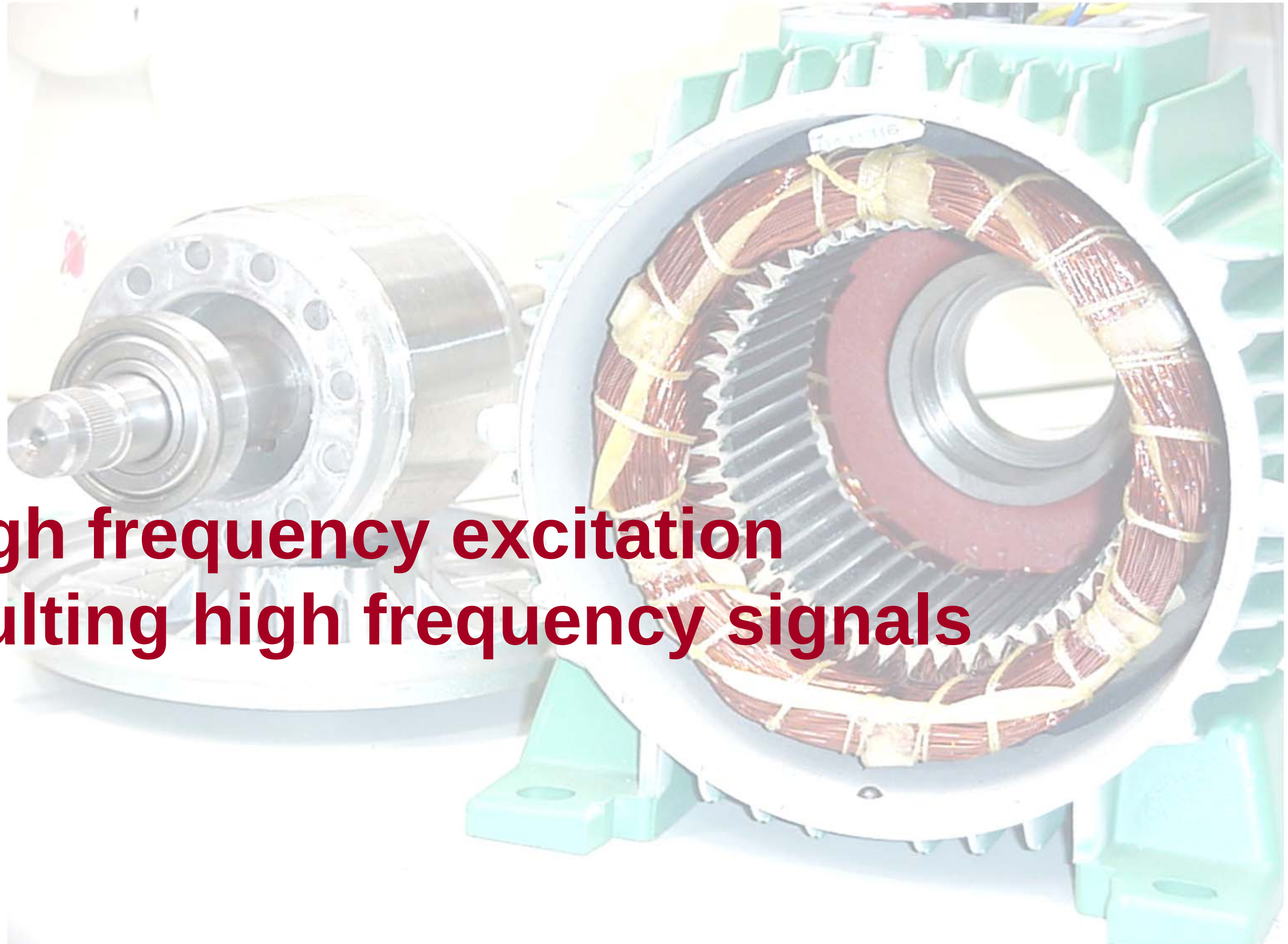
Radial flux, surface permanent magnet machines



Tangential flux, interior permanent magnet machines



✓Saturation can help



High frequency excitation
and resulting high frequency signals

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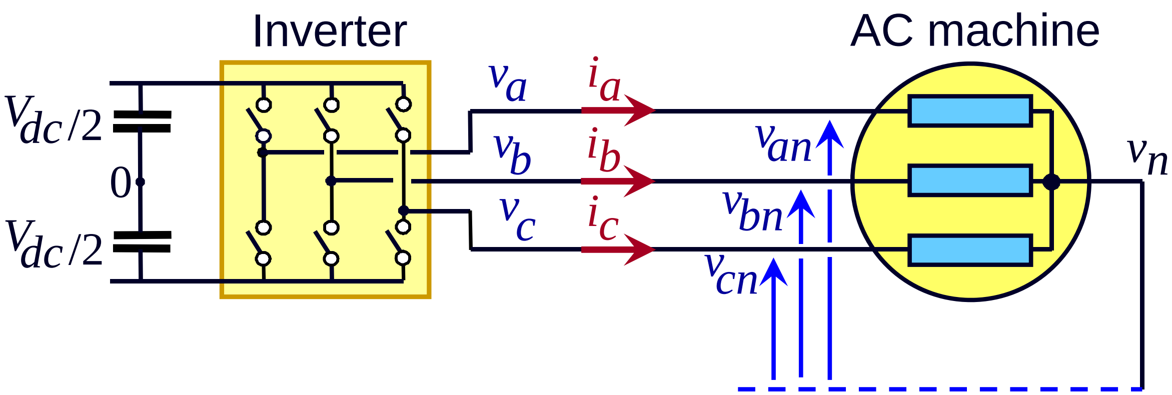
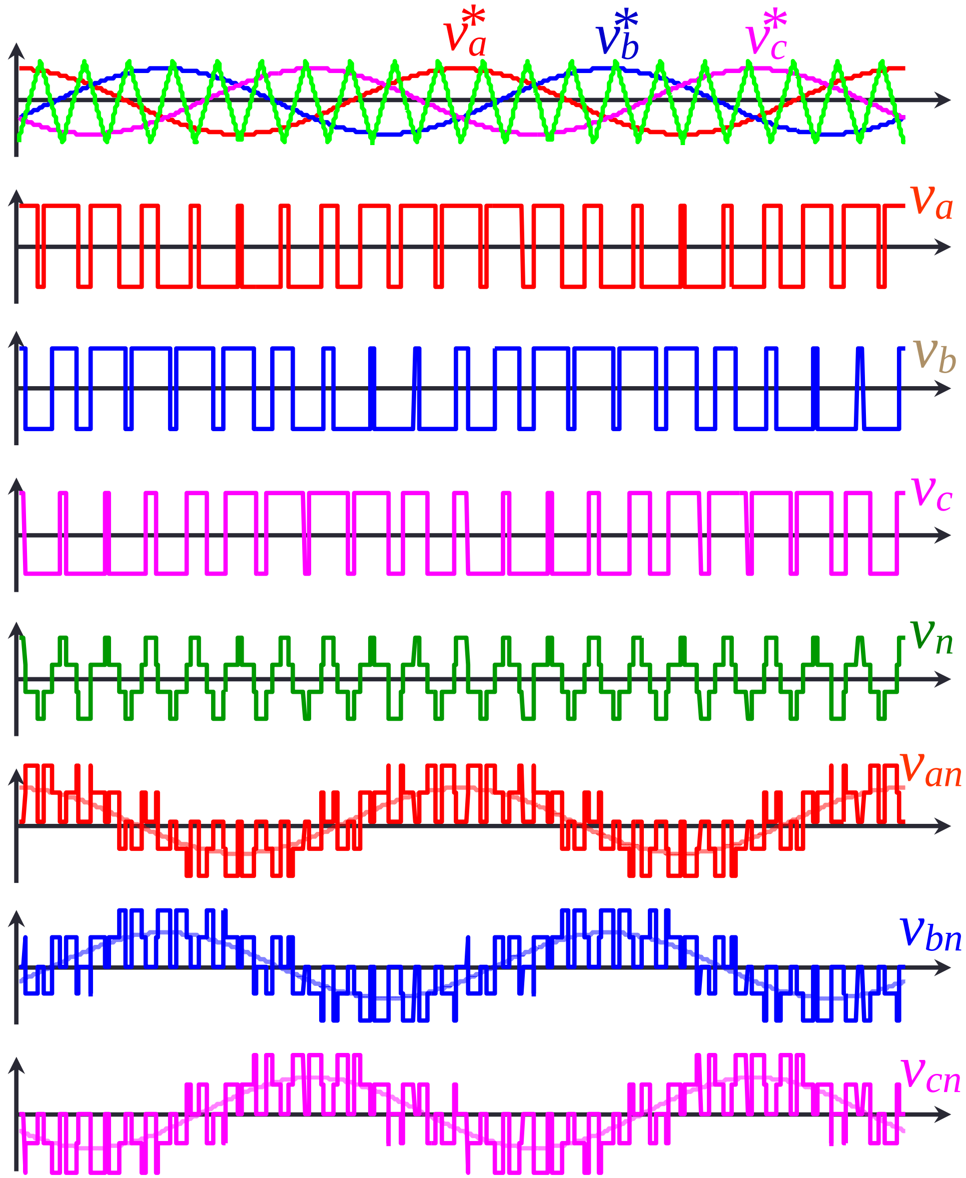
Forms of high frequency excitation and resulting high frequency signals





- ✓ Saliency tracking based sensorless methods use the inverter to inject some form of high frequency excitation
- ✓ The high frequency excitation shouldn't interfere with the fundamental excitation, which is responsible of the electromechanical power conversion performed by the electric drive

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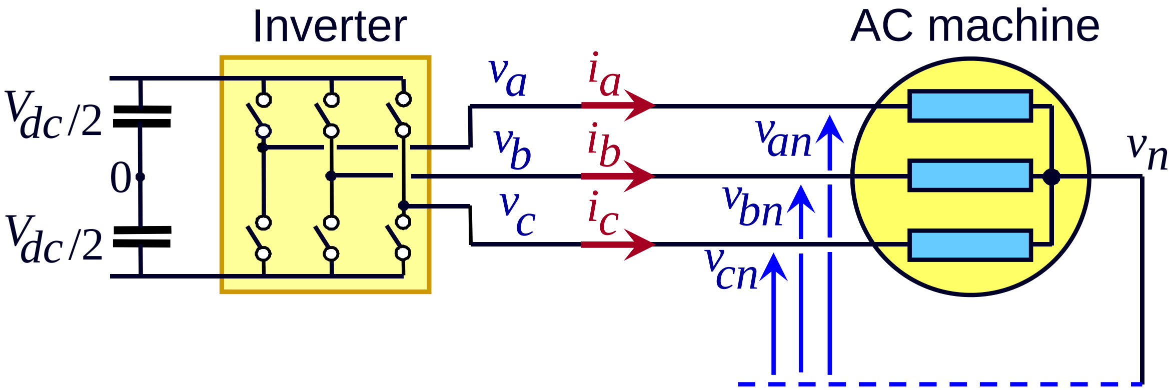
Forms of high frequency excitation and resulting high frequency signals



Many options, two key issues:

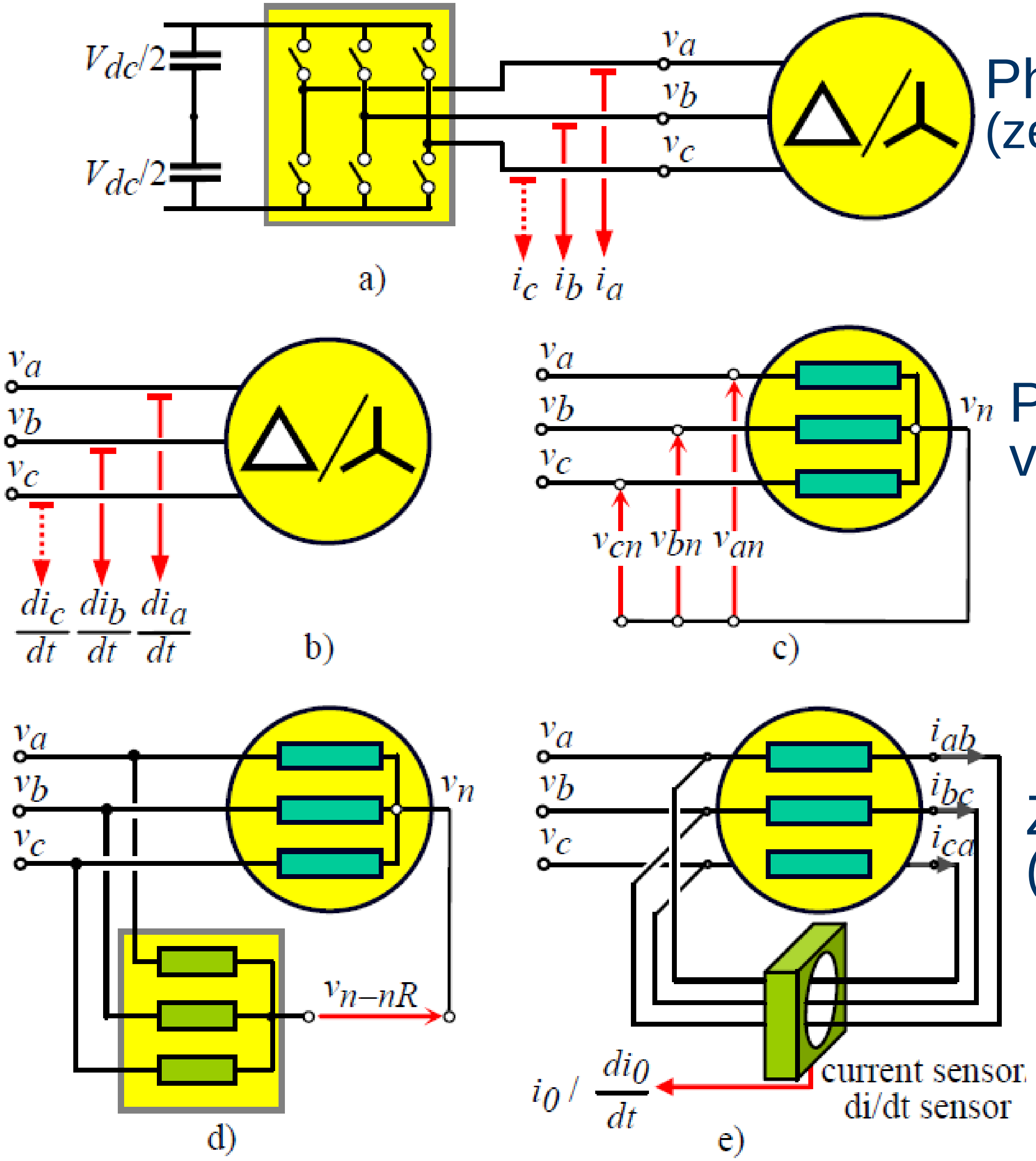
High frequency excitation

- Continuous / discontinuous
- Periodic / PWM commutations
- Voltage / current

Number and type of the signals to be measured

- Phase currents
- Phase-neutral voltages
- *di/dt*
- Zero sequence voltage/current

Measured signals for the proposed concetps



Phase currents (zero cost)

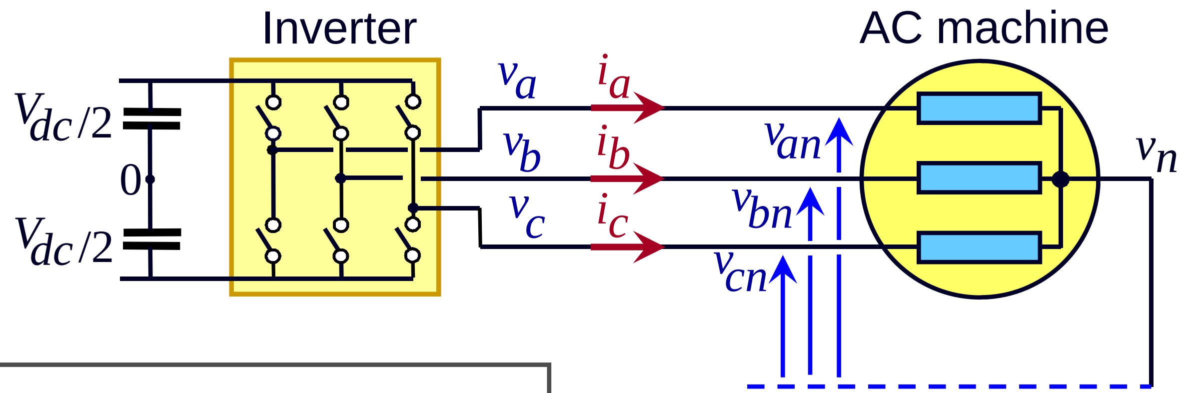
Phase currents derivative

Phase-to-neutral voltage

Zero sequence voltage (homopolar voltage)

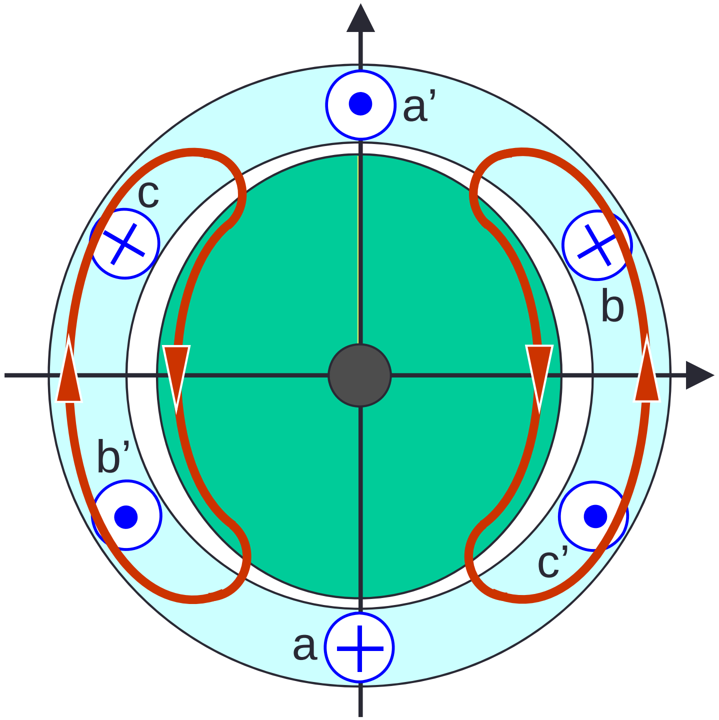
Zero sequence current (homopolar current)

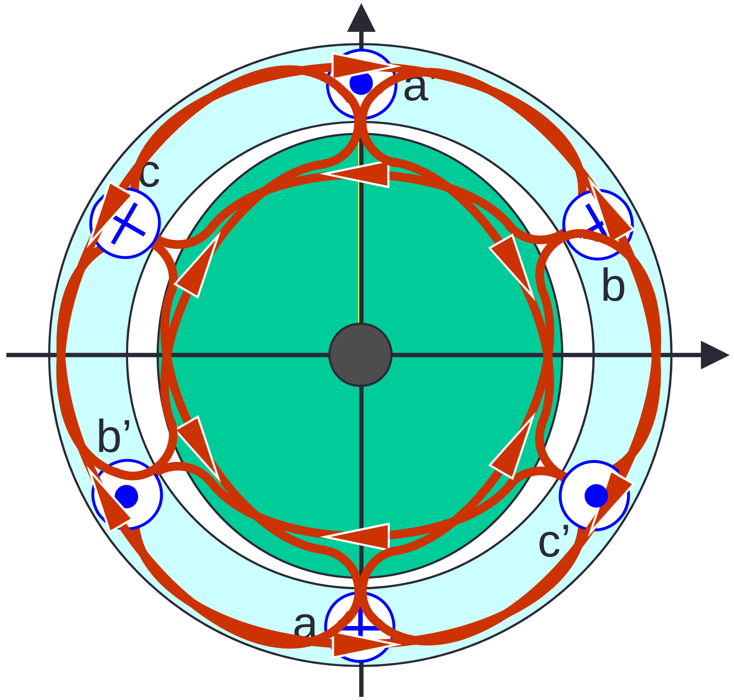
Two examples of high frequency excitation



- Continuous excitation
  - Carrier signal
    - Carrier current
    - Zero sequence voltage*
  - PWM commutations
    - d*i*/d*t*
    - Zero sequence voltage

* Zero sequence current for delta-connected machines





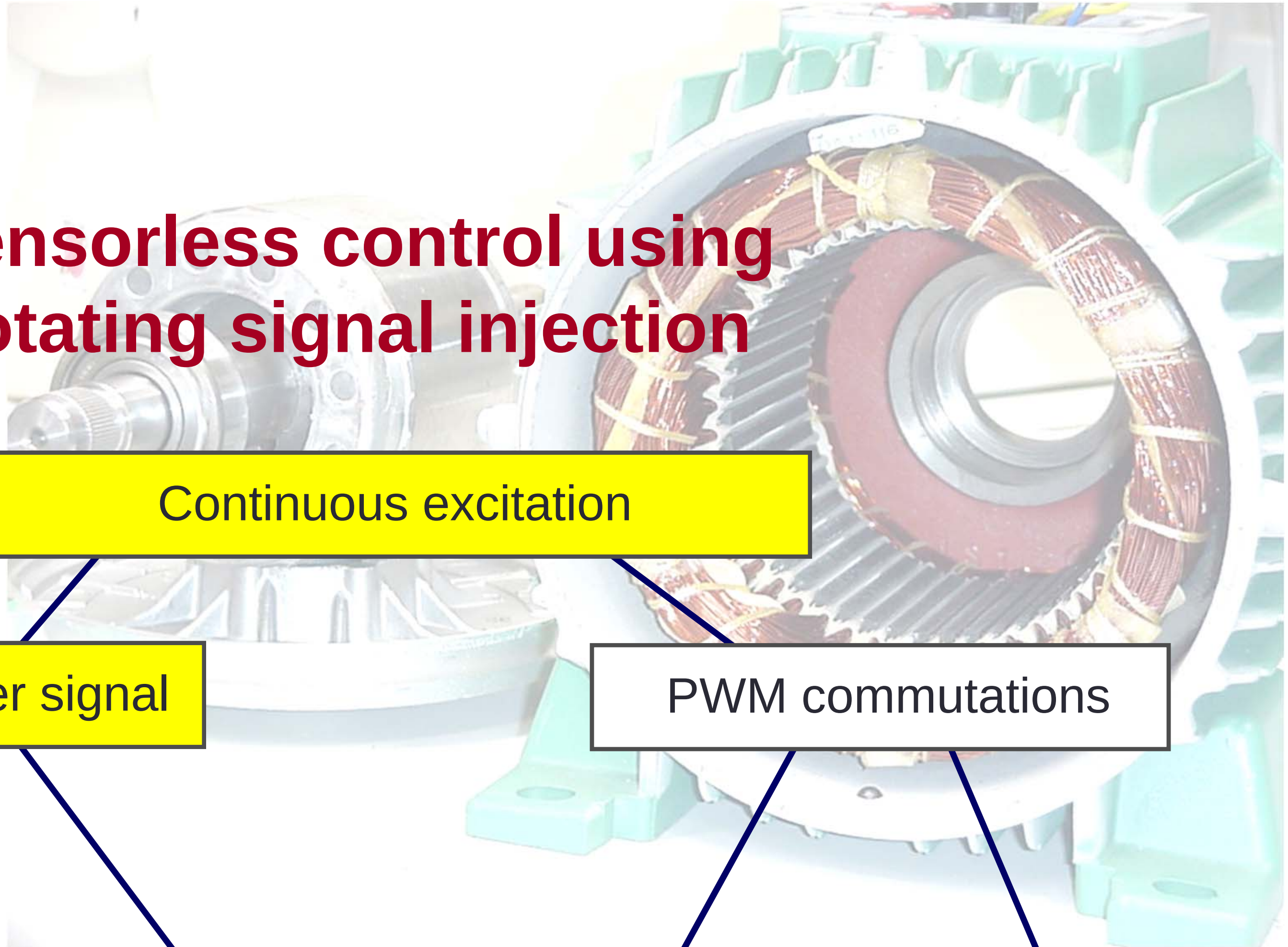
Rotating vector

frequency-based

PWM harmonics

time-based

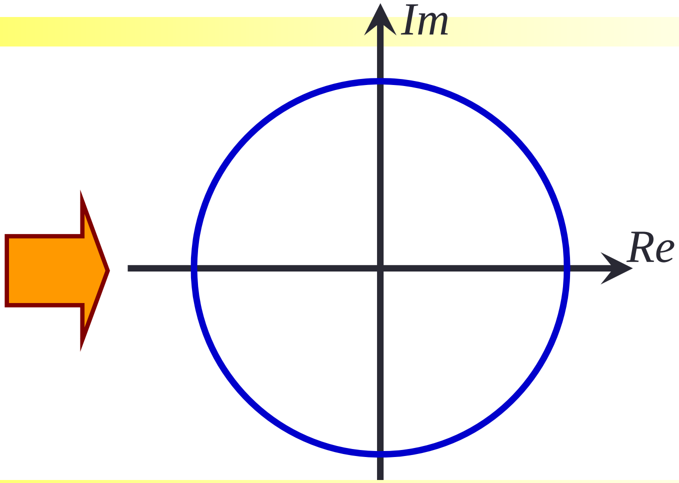
Sensorless control using rotating signal injection

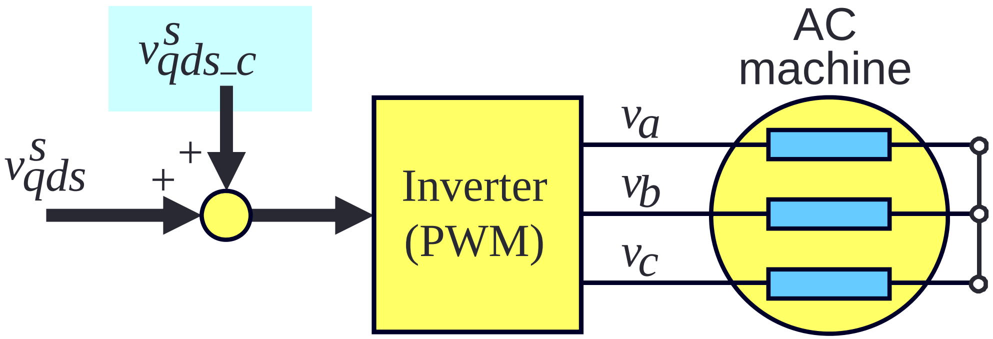


- Continuous excitation
  - Rotating carrier signal
    - Carrier current
    - Zero sequence voltage*
  - PWM commutations
    - d*i*/dt
    - Zero sequence voltage

Rotating carrier voltage vector excitation

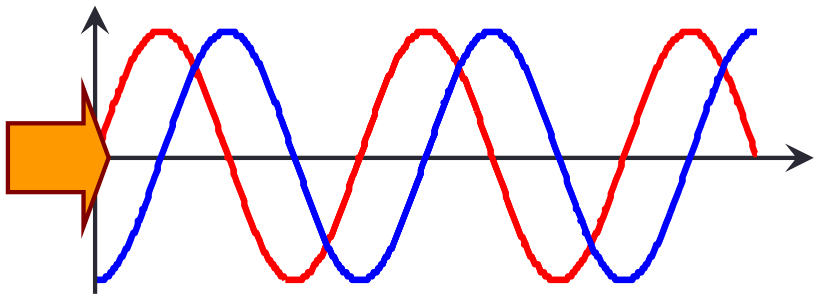
$$v^s_{qds\_c} = V_c\, e^{j\omega_c t}$$





$$v^s_{ds} = V_c \cos(\omega_c)$$

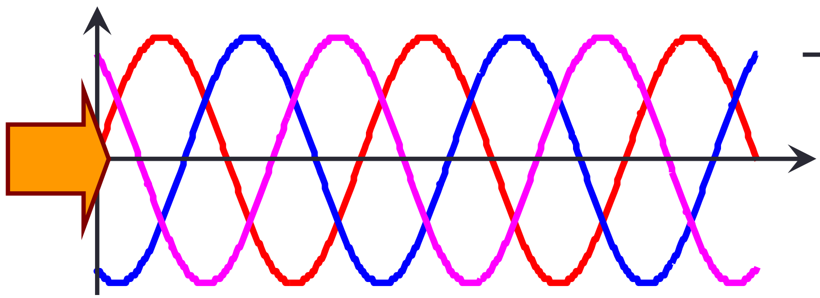
$$v^s_{ds} = V_c \cos(\omega_c - \frac{\pi}{2})$$

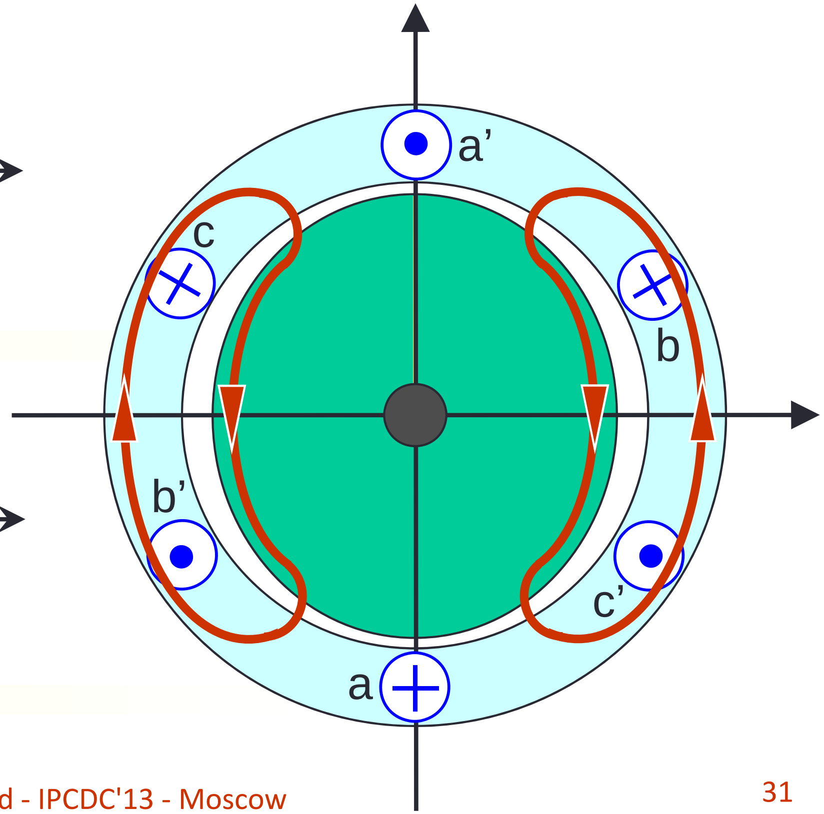


$$v_a = V_c \cos(\omega_c)$$

$$v_b = V_c \cos(\omega_c - \frac{2\pi}{3})$$

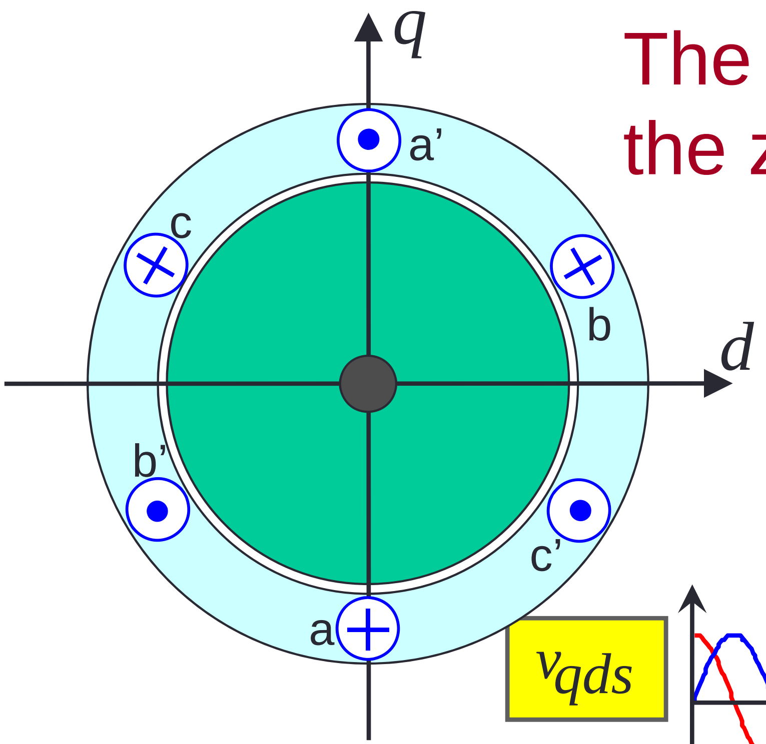
$$v_c = V_c \cos(\omega_c - \frac{4\pi}{3})$$





Rotating carrier voltage vector excitation:

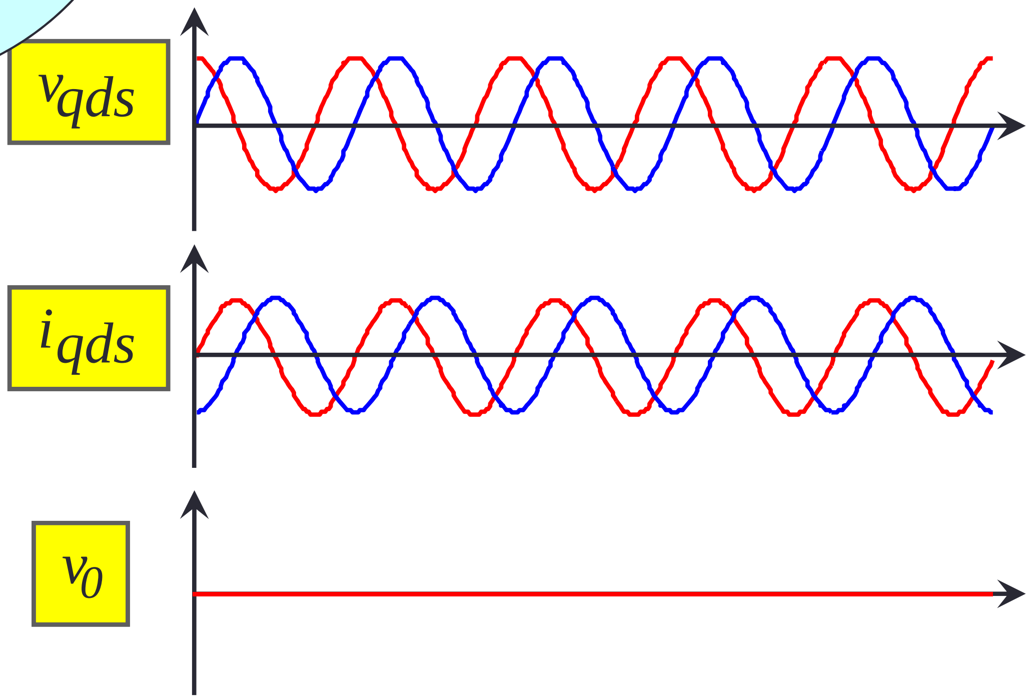
The carrier signal current and the zero sequence carrier signal voltage

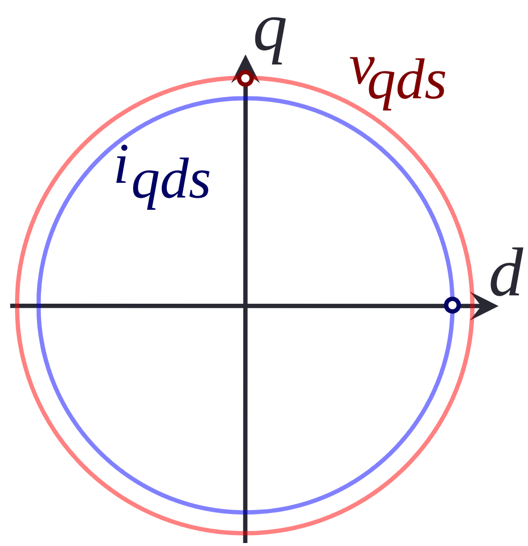


Symmetric machine

- The carrier current trajectory is a circle

- There is no zero sequence carrier signal voltage

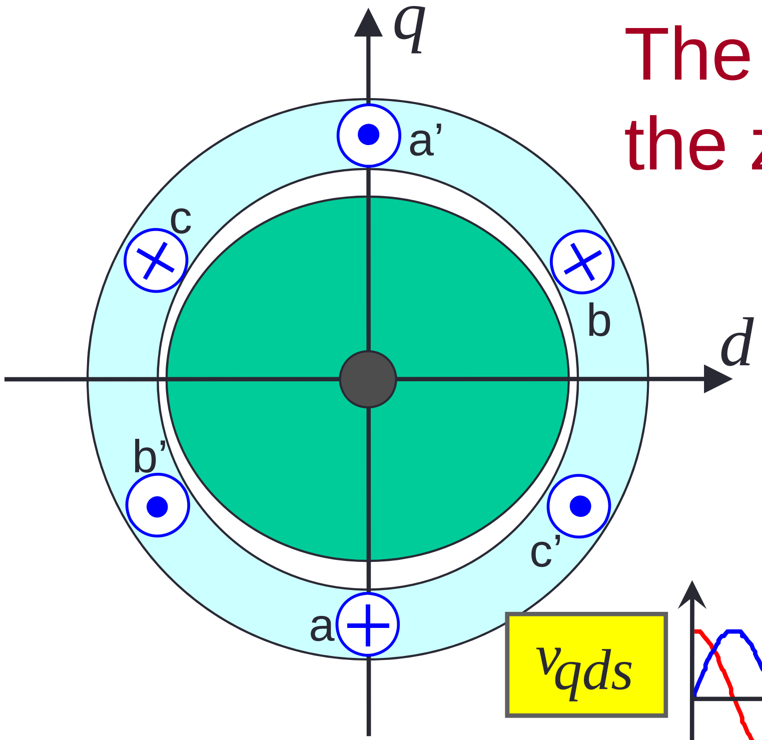




$$v_0 = \frac{(v_{an}+v_{bn}+v_{cn})}{3}$$

Rotating carrier voltage vector excitation:

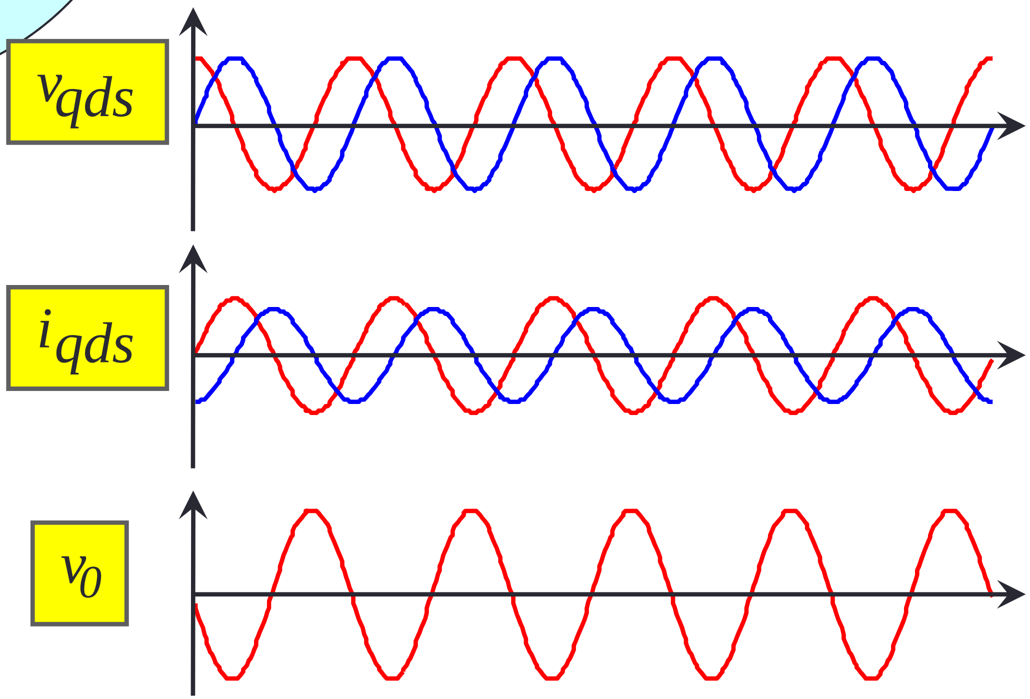
The carrier signal current and the zero sequence carrier signal voltage

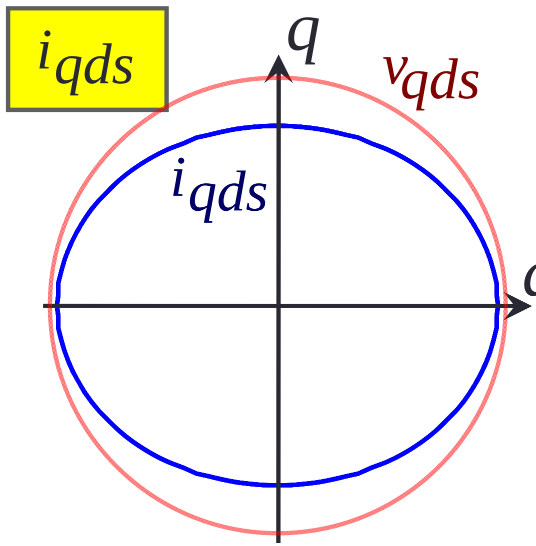


Asymmetric machine

- The carrier current trajectory is an ellipsis, its orientation being function of the saliency phase angle

- A zero sequence carrier signal voltage exists, its phase angle being function of the saliency phase angle

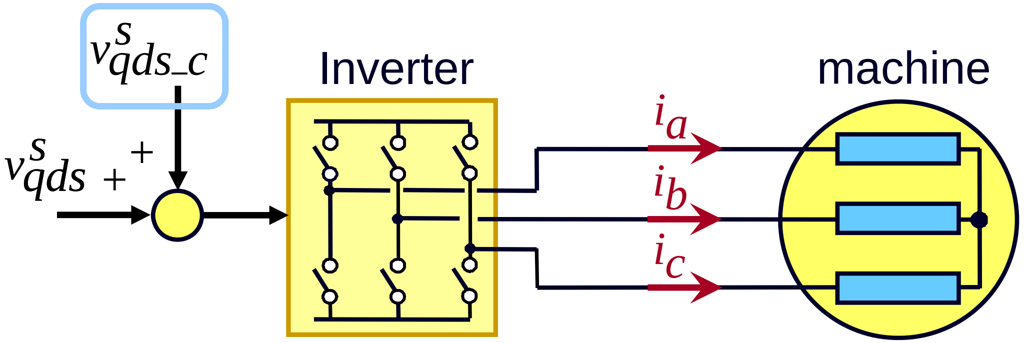




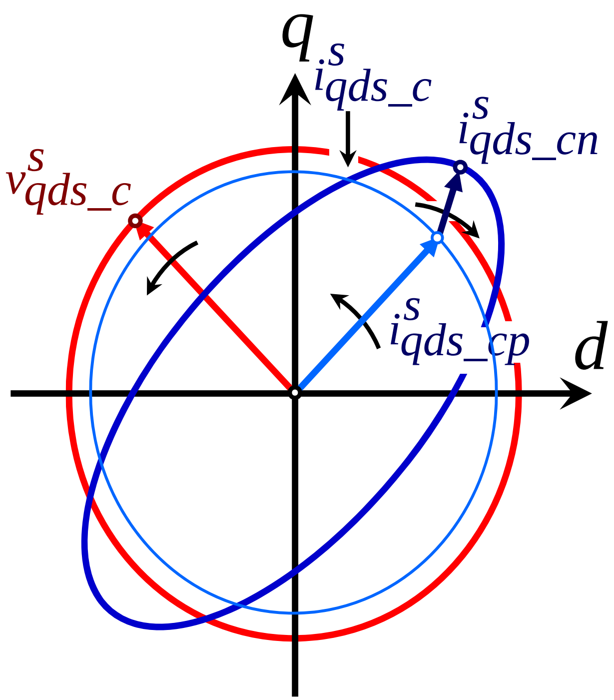
$$v_0 = \frac{(v_{an}+v_{bn}+v_{cn})}{3}$$

Rotating carrier voltage vector excitation:

The carrier signal current

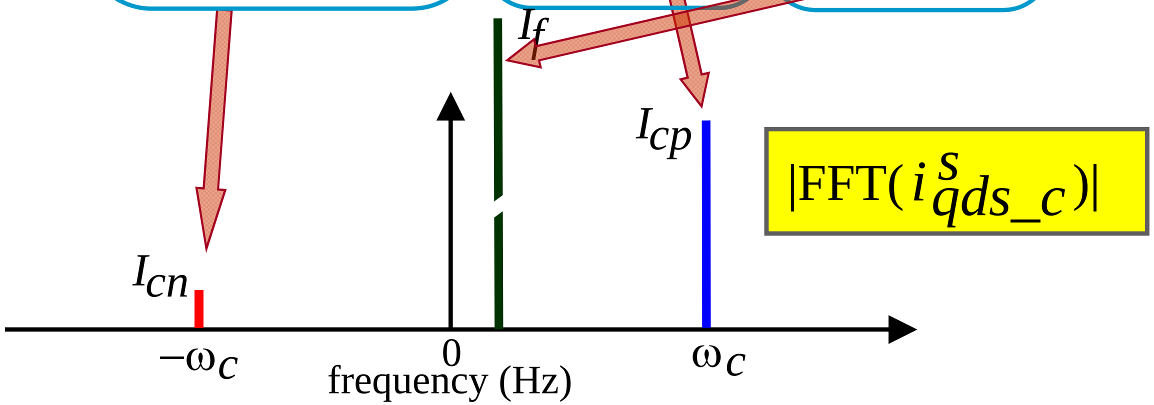


- ✓ The carrier current consists of a negative sequence and a positive sequence component
- ✓ During the normal operation of the drive there is also a fundamental current, which is responsible of the electromechanical power conversion



Negative sequence (its phase is modulated by the rotor position)	Positive sequence (no rotor position information)	Fundamental current
$i^s_{qds\_cn}$	$i^s_{qds\_cp}$	

$$i^s_{qds\_c} = -j\, I_{cn}\, e^{j(h\theta_r - \omega_c t)} - j\, I_{cp}\, e^{j\omega_c t} + I_f\, e^{j\omega_e t}$$



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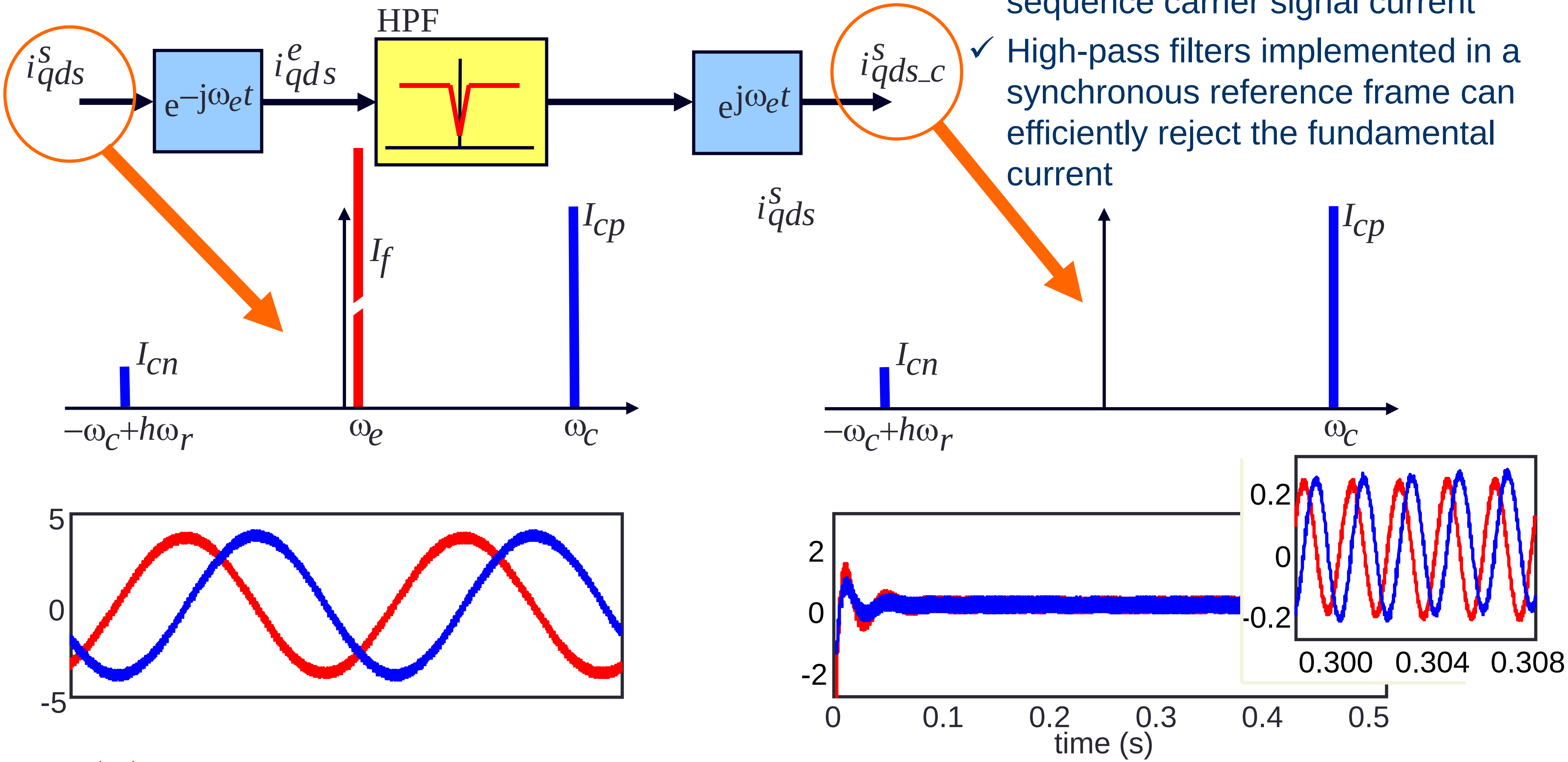
Processing of the carrier signal current:
Elimination of the fundamental current

$$i_{qds}^{s} = I_f\, e^{j\omega_e t} - j\, I_{cp}\, e^{j\omega_c t} - j\, I_{cn}\, e^{j(h\theta_r - \omega_c t)}$$

- ✓ The fundamental current can be easily in the range of three-full orders of magnitude larger than the negative sequence carrier signal current
- ✓ High-pass filters implemented in a synchronous reference frame can efficiently reject the fundamental current



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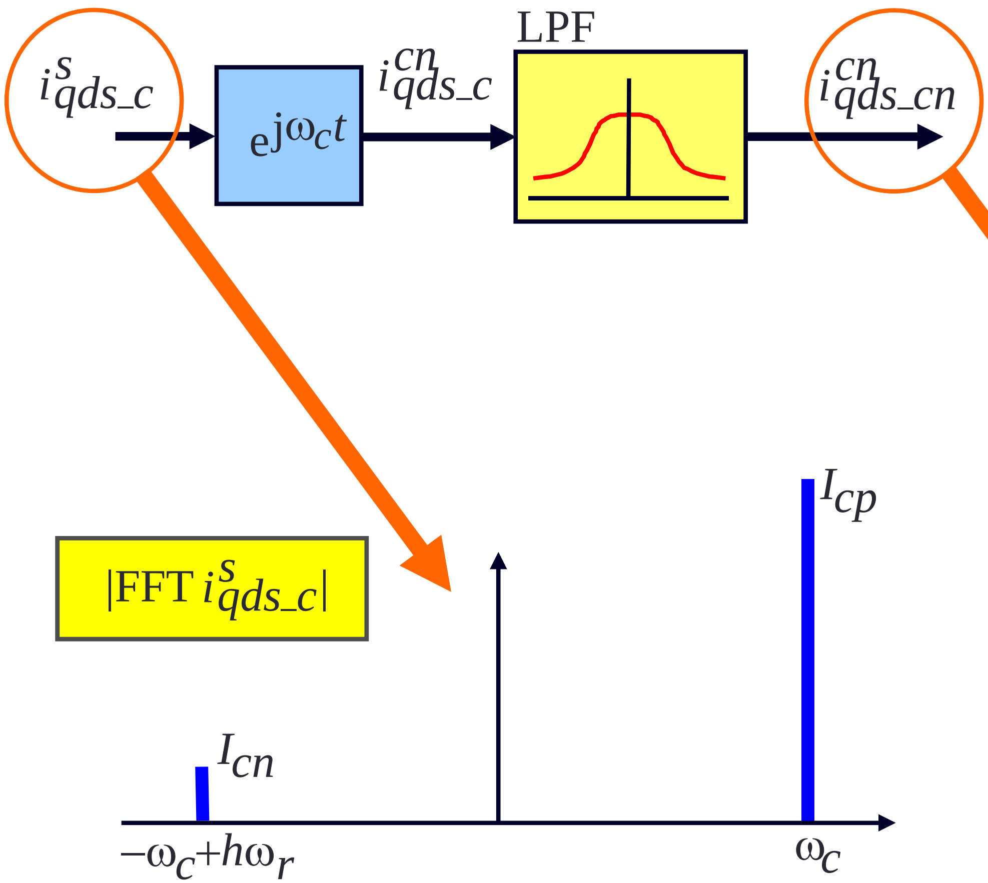
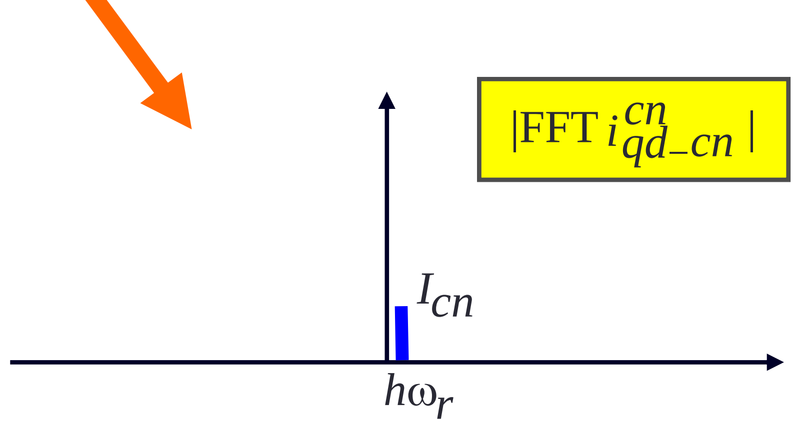
Processing of the carrier signal current:

Separation of the negative sequence carrier signal current

$$i^{s}_{qds\_c} = -\mathrm{j}\, I_{cp}\, e^{\mathrm{j}\omega_c t} - \mathrm{j}\, I_{cn}\, e^{\mathrm{j}(h\theta_r - \omega_c t)}$$

- ✓ Synchronous filters can efficiently separate the negative sequence carrier signal current
- ✓ Additional advantages are obtained when implemented as a low-pass filter in the negative sequence reference frame. By doing so, the negative sequence carrier signal current becomes modulated around dc (instead of around the carrier frequency)





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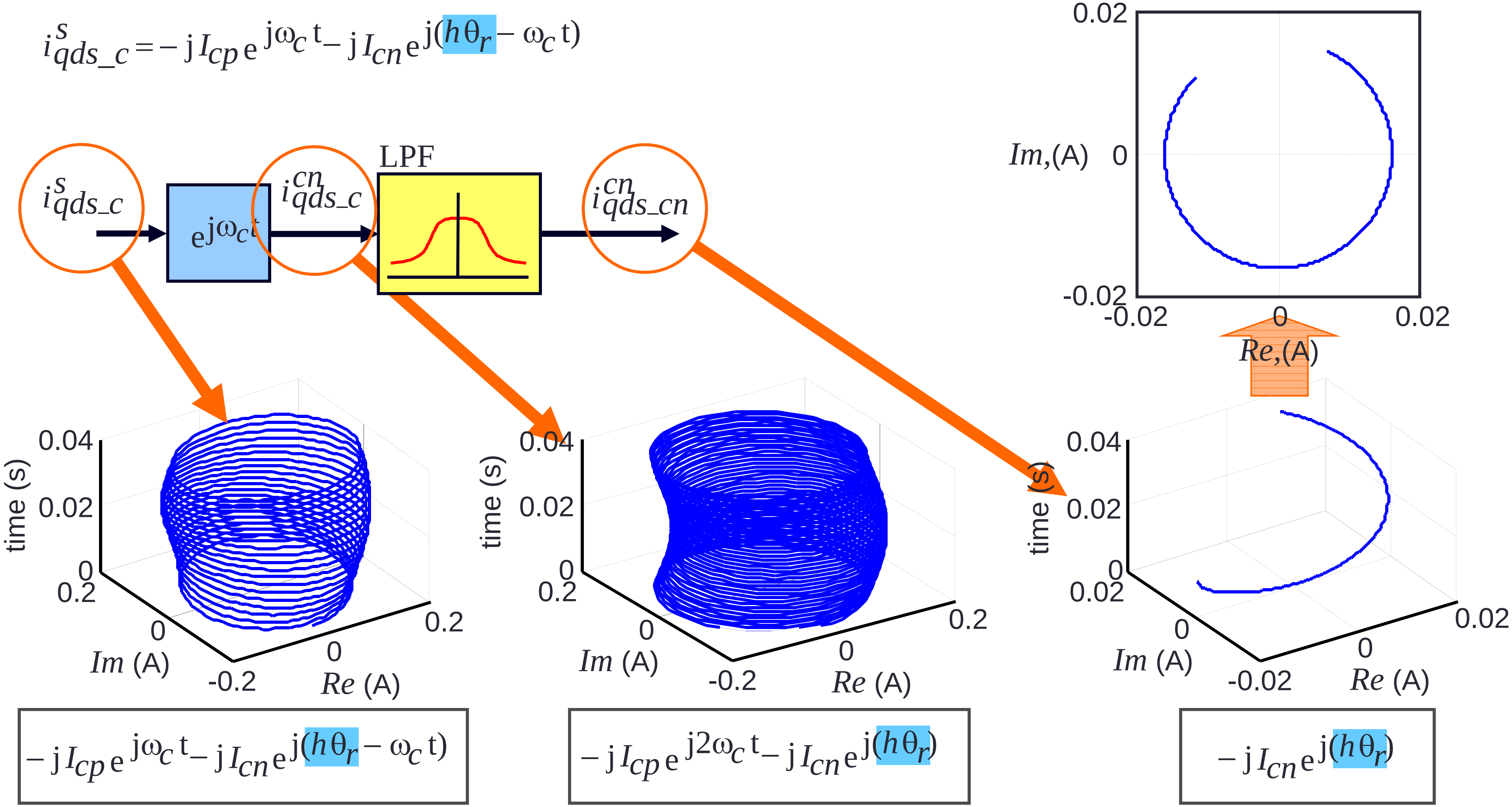
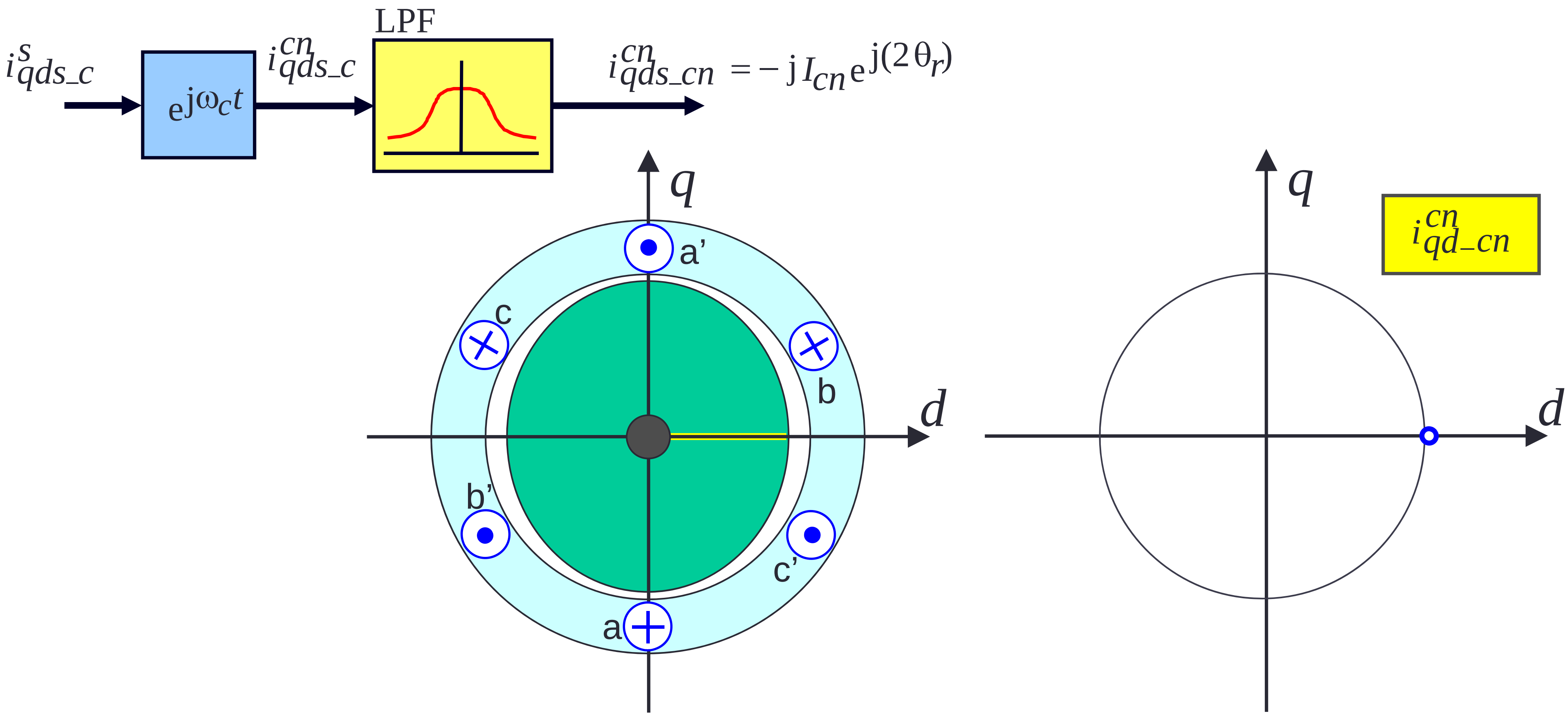
Processing of the carrier signal current:
Separation of the negative sequence carrier signal current

$$i^{s}_{qds\_c} = -\mathrm{j}\, I_{cp}\, \mathrm{e}^{\mathrm{j}\omega_c t} - \mathrm{j}\, I_{cn}\, \mathrm{e}^{\mathrm{j}(h\theta_r - \omega_c t)}$$

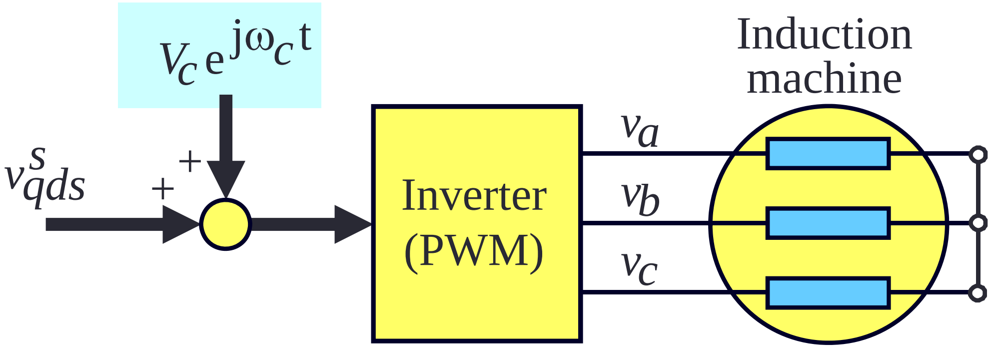


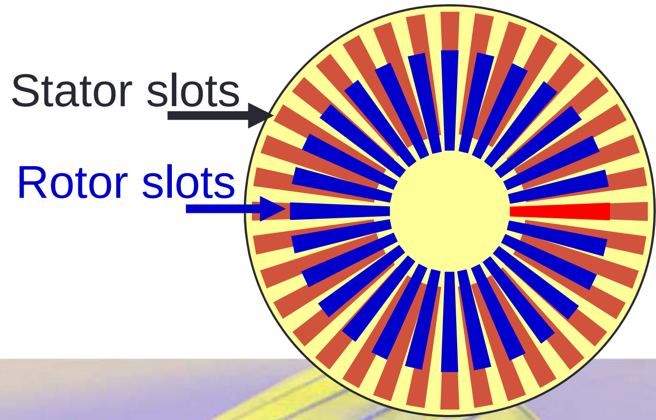
Processing of the carrier signal current:

The negative sequence carrier signal current



Rotor position estimation using the stator and rotor slotting saliency





Requirement for rotor-stator slotting saliencies to couple with the stator windings and produce measurable signals:

$$|R-S| = n \cdot p$$

R, S, p number of rotor, stator slots and poles

$n = 1,2,4,5,7,8, \ldots$

Induction Motor Parameters

S=36

R=28

The saliency rotates at a frequency $\dfrac{R \cdot \omega_{rm}}{|R-S|}$

The resulting component rotates at a frequency $R \cdot \omega_{rm}$

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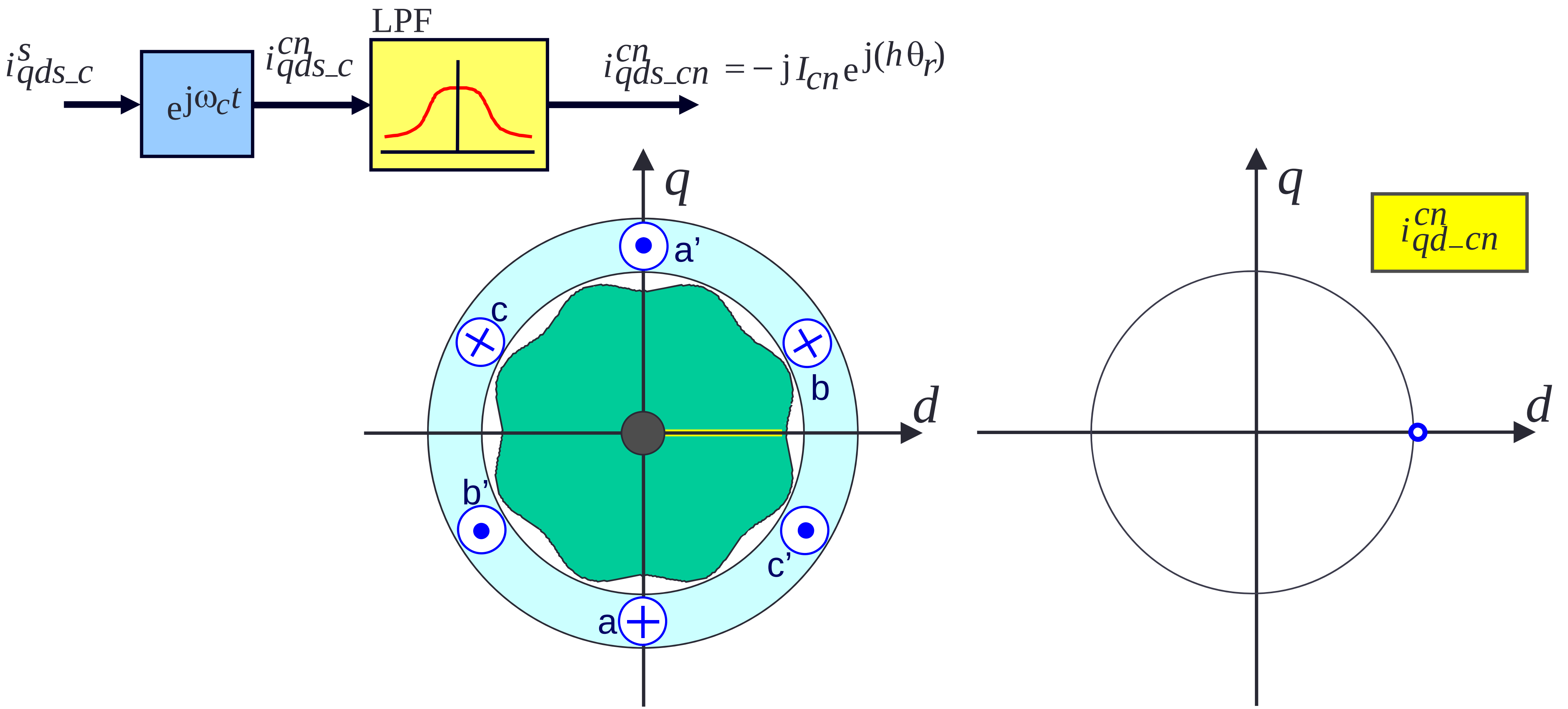
Processing of the carrier signal current:

The negative sequence carrier signal current



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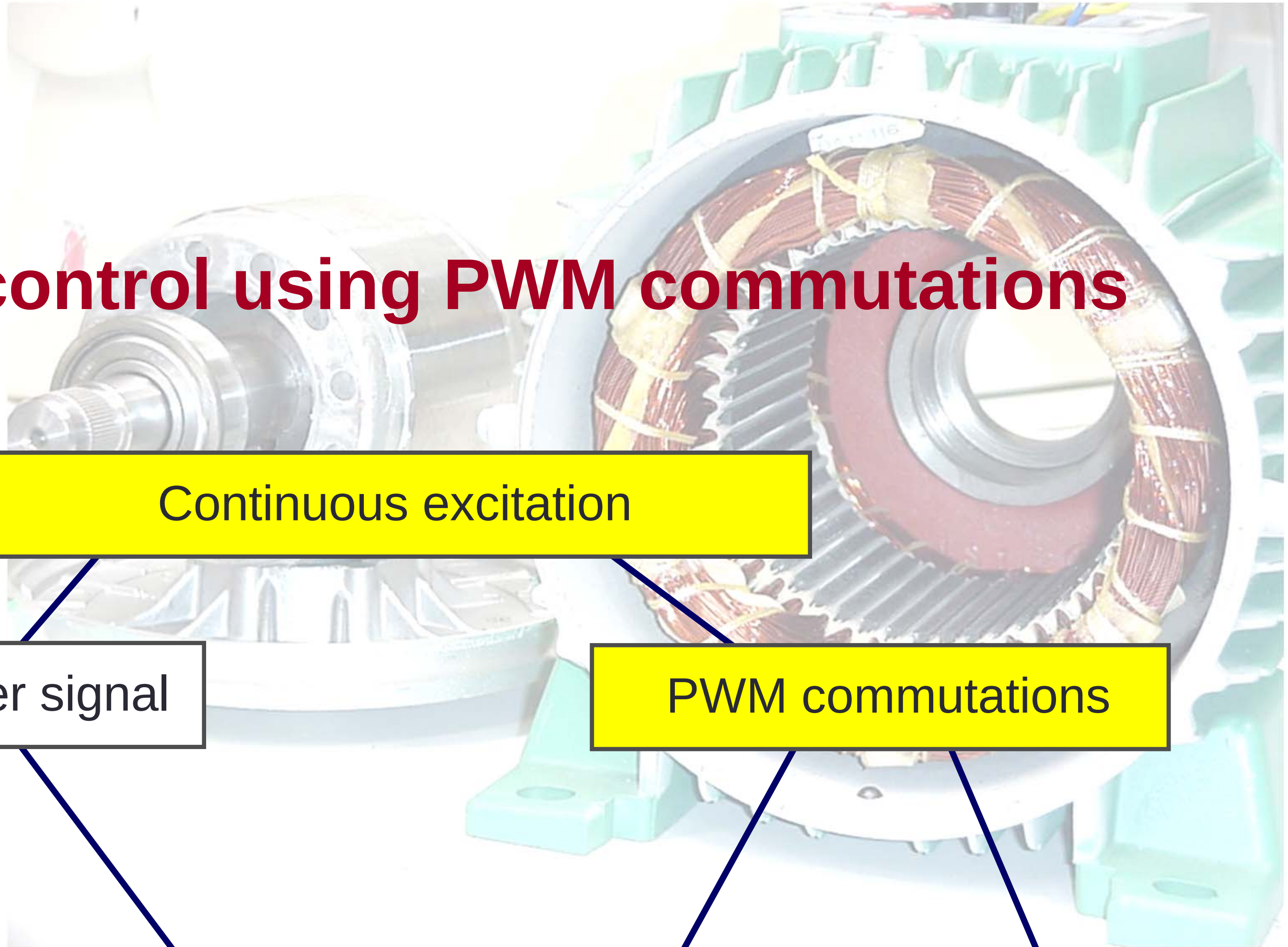
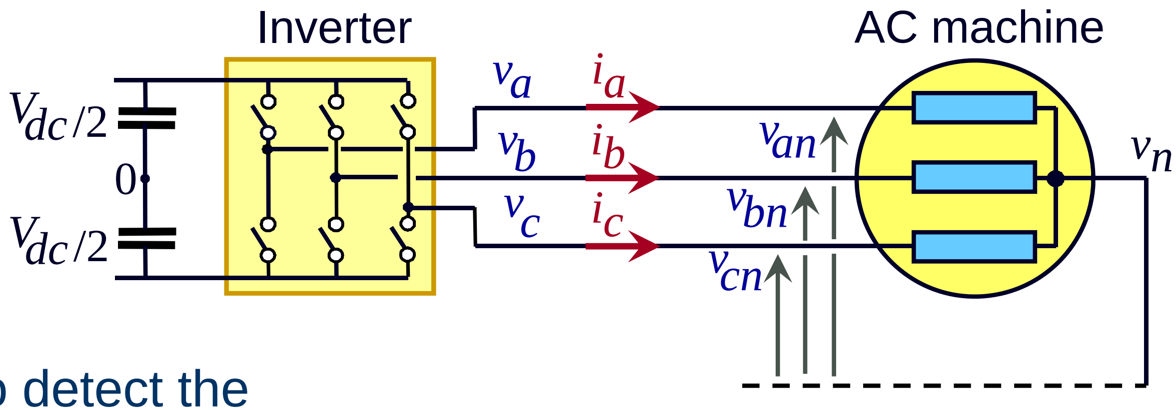
Sensorless control using PWM commutations



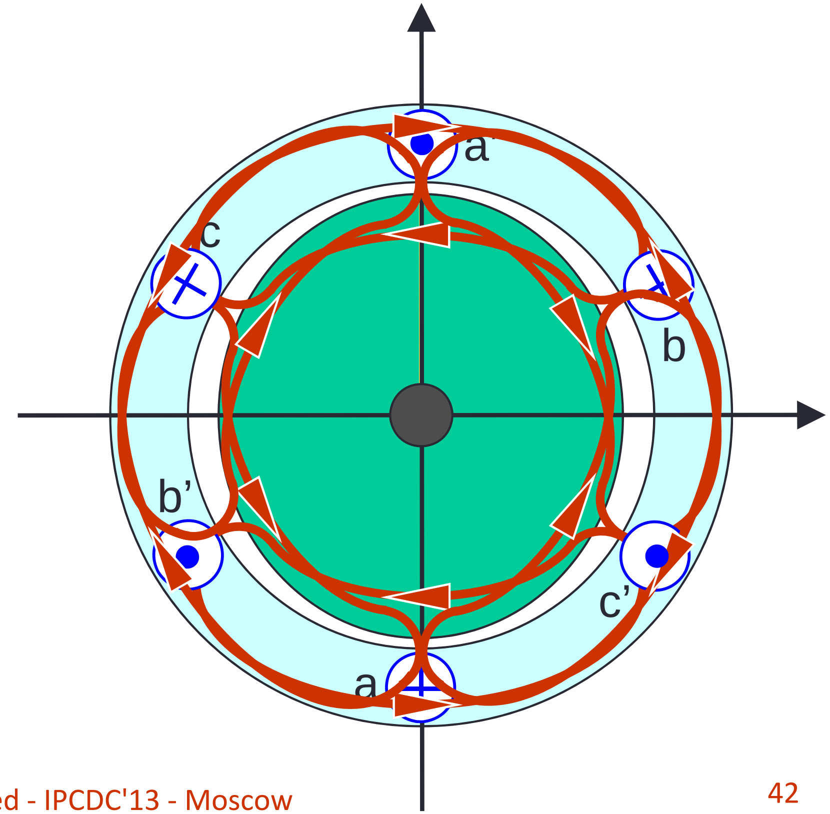
- Continuous excitation
  - Rotating carrier signal
    - Carrier current
    - Zero sequence voltage*
  - PWM commutations
    - d*i*/d*t*
    - Zero sequence voltage

PWM based high frequency excitation

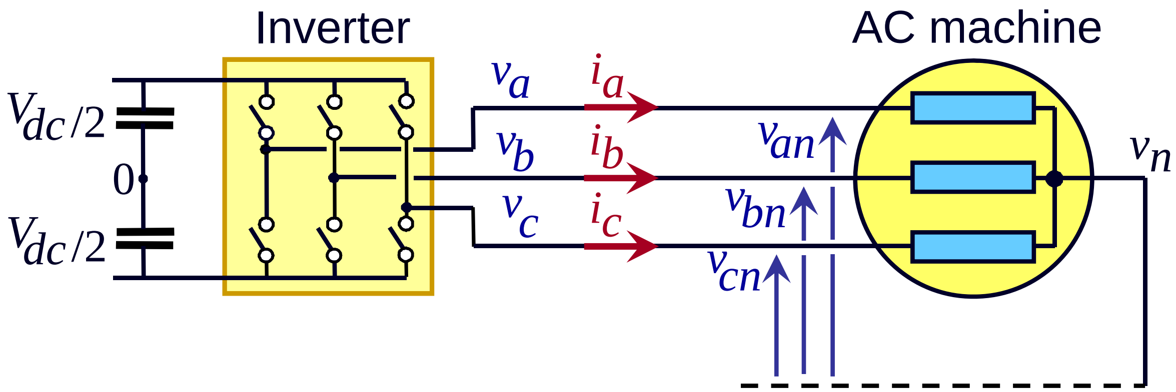
- ✓ Makes uses of the fast PWM commutations
- ✓ Modification of the normal PWM pattern is needed to obtain suitable information



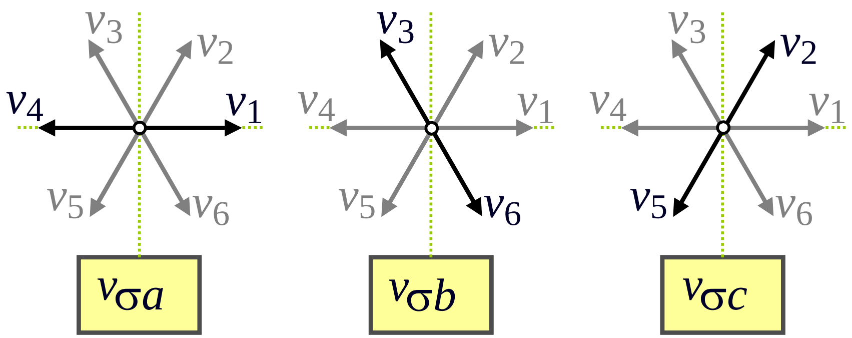
- ✓ Different variables can be measured to detect the saliency position:
  - Zero sequence voltage
    - Requires additional sensors and access to the terminal box
  - di/dt (currents derivative). Though the current derivative could initially be derived from two current measurements, di/dt sensors (e.g. Rogowski coils) often used in practice
- ✓ Acquisition of signals needs to be synchronized with the PWM transitions
- ✓ Strongly influenced by parasitic phenomena (ringing caused by cables length, cables shielding, …)



PWM based high frequency excitation:
Zero sequence voltage



$$v_\sigma = \frac{v_{an} + v_{bn} + v_{cn}}{3}$$



$$v_{qd\sigma} = \frac{2}{3}\left(v_{\sigma a} + v_{\sigma b}\, e^{j2\pi/3} + v_{\sigma c}\, e^{j4\pi/3}\right) = V\, e^{j(h\theta_r)}$$

- ✓Requires the excitation of the three inverter *directions* → this implies a modification of the PWM pattern, as normally only two active vectors per switching period are used in practice
- ✓A minimum duration for each active state is needed to allow the signals to settle down before performing the measurement. This results in a further distortion of the PWM pattern

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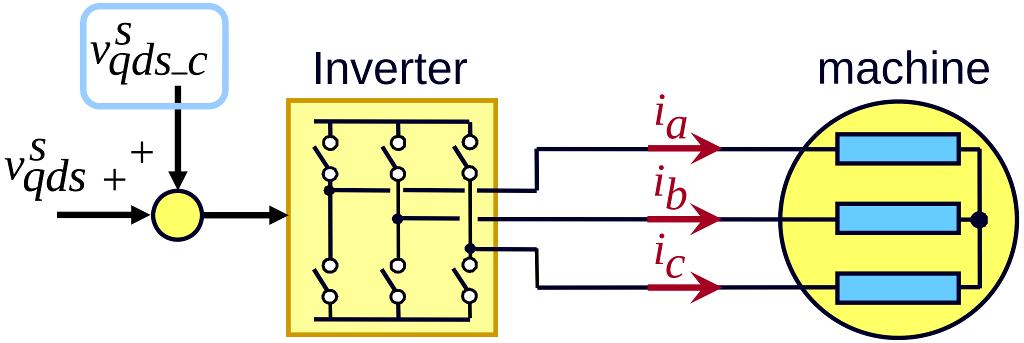
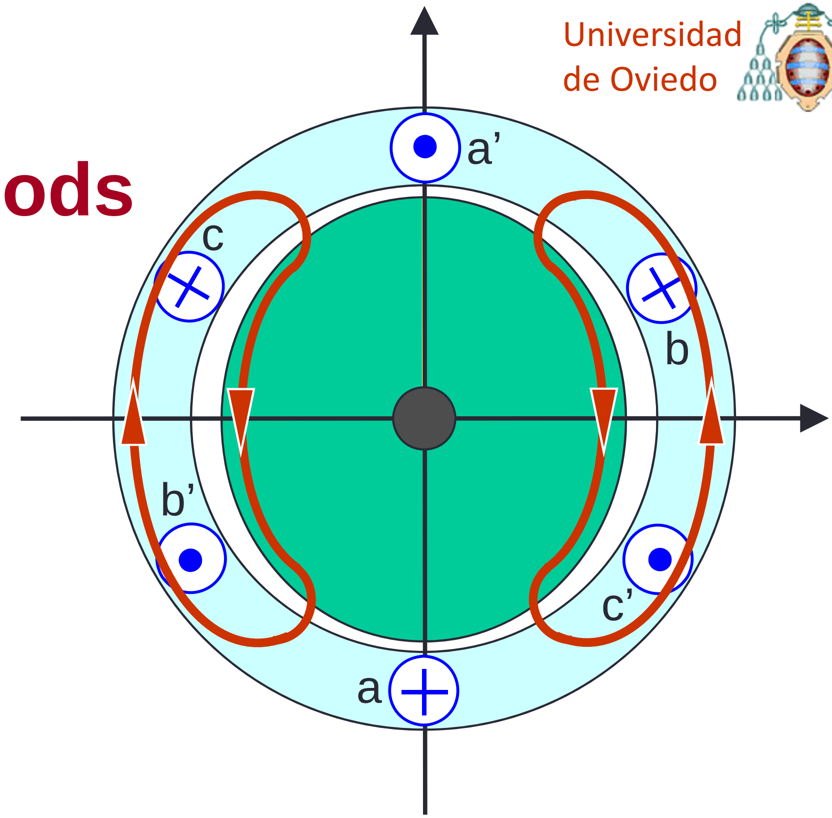
Carrier Signal Injection Based Methods





Pros

- ✓ Relatively easy to implement using existing hardware
  - No need of extra sensors if the high current is used
  - No changes in the current regulation loops
  - No changes in the PMW configuration
- ✓ Computationally burden affordable with existing digital signal processors
- ✓ Highly insensitive to inverter-to-machine cabling, grounding configuration, …

Cons

- ✓ Distortion due the to the non-ideal behavior of the inverter (mainly inverter dead-time) ⇨ injecting a clean high frequency signal might not be that easy
- ✓ Risk of interference of the high frequency signals with the fundamental current regulator
- ✓ Noise, vibration and additional losses due to the injected high frequency signal

⇨ both can be alleviated increasing the frequency of the carrier signal

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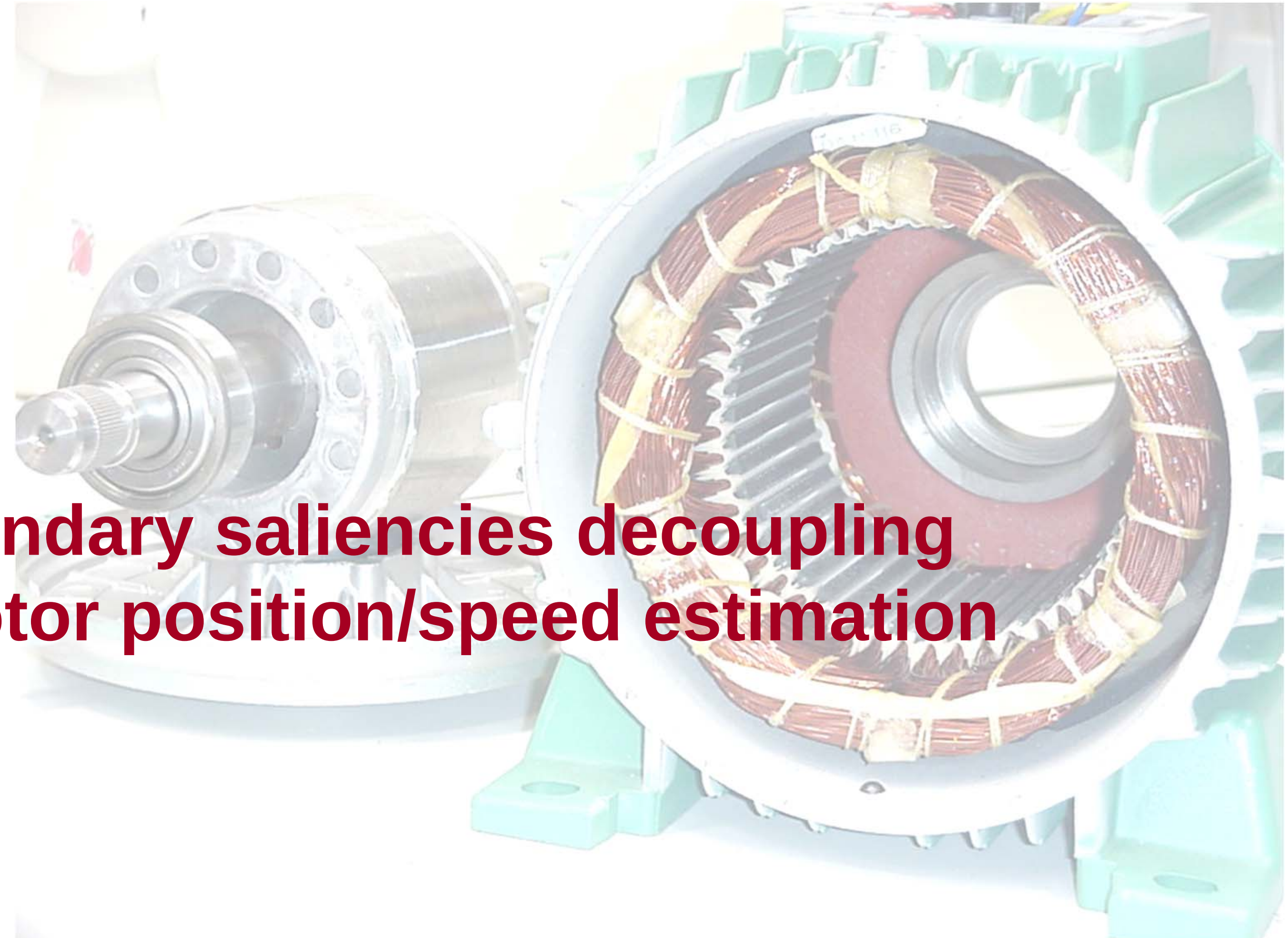


Secondary saliencies decoupling and rotor position/speed estimation

Secondary saliencies: Saturation induced saliencies

✓Injection of fundamental current during the normal operation of the machine produces additional saliencies (asymmetries)

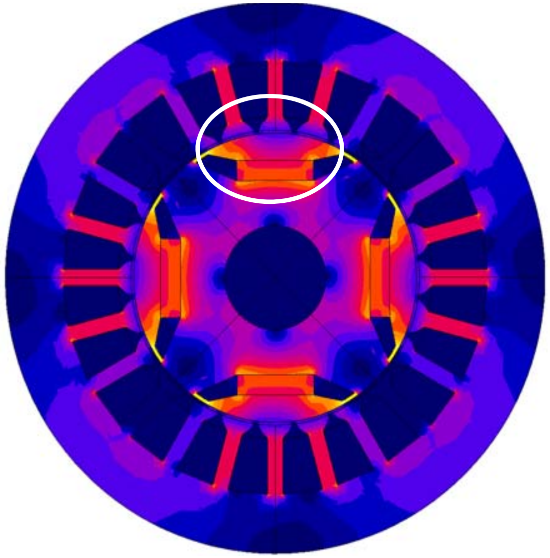
✓These saliencies are caused (and therefore related) to the fundamental currents/fluxes, acting like a disturbance to the rotor position dependent saliency

✓Saturation results in:

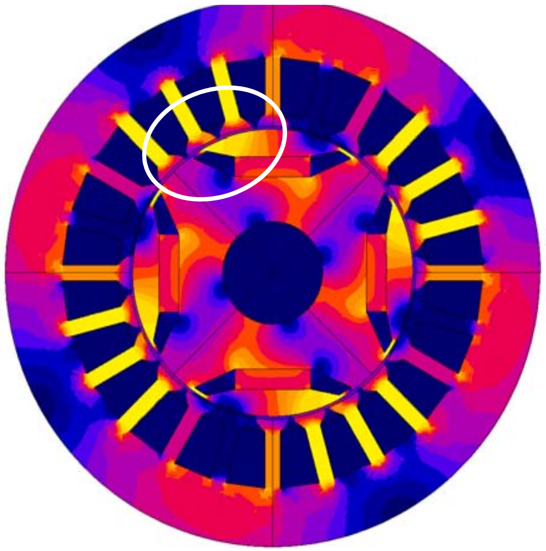
- Shift of the saliency angle
- Variations of the saliency ratio
- Secondary spatial harmonics of the saliency (i.e. saliencies with a non-sinusoidal spatial distribution)

✓Decoupling of secondary saliencies is mandatory practically always to obtain adequate accuracy, and very often even stable

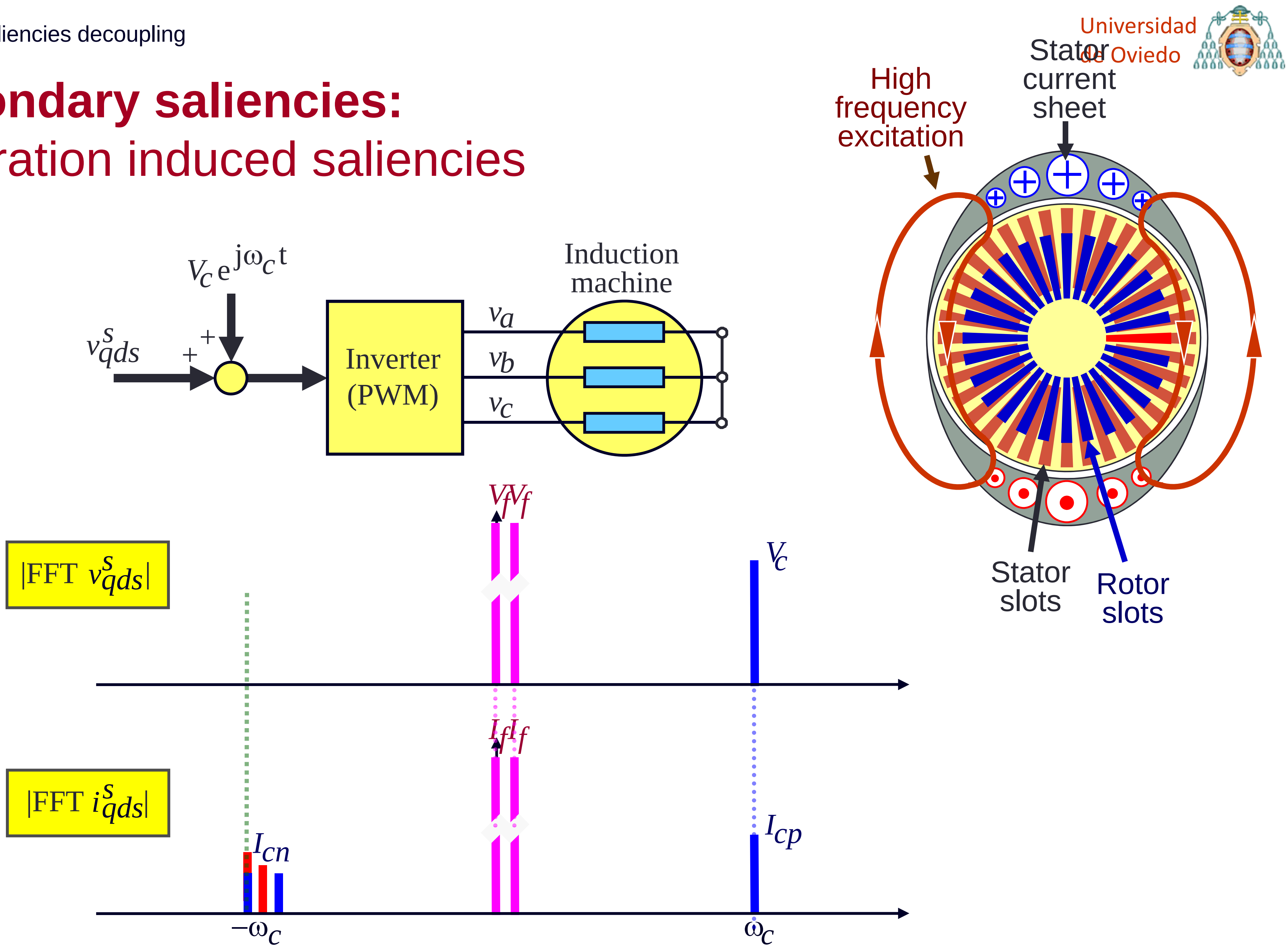
IPMSM, no load



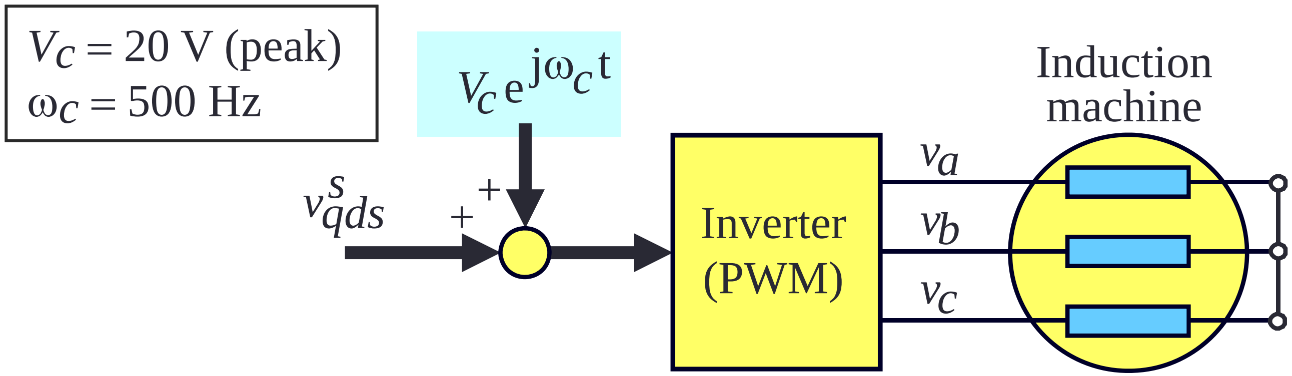
IPMSM, rated torque

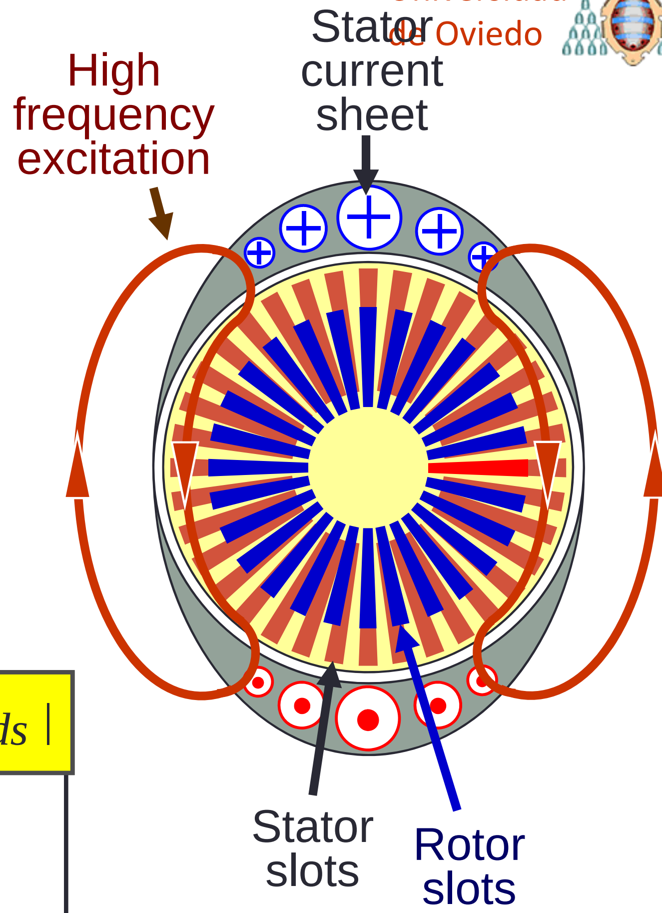


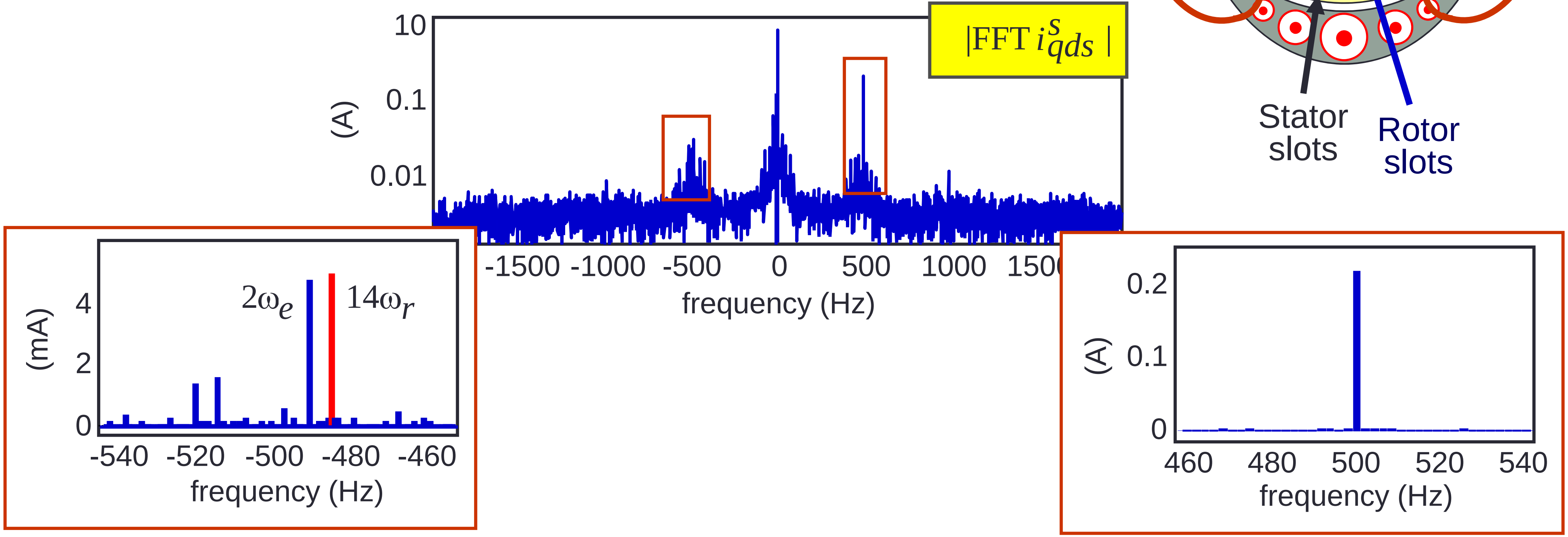
Secondary saliencies:
Saturation induced saliencies



Secondary saliencies:
Saturation induced saliencies

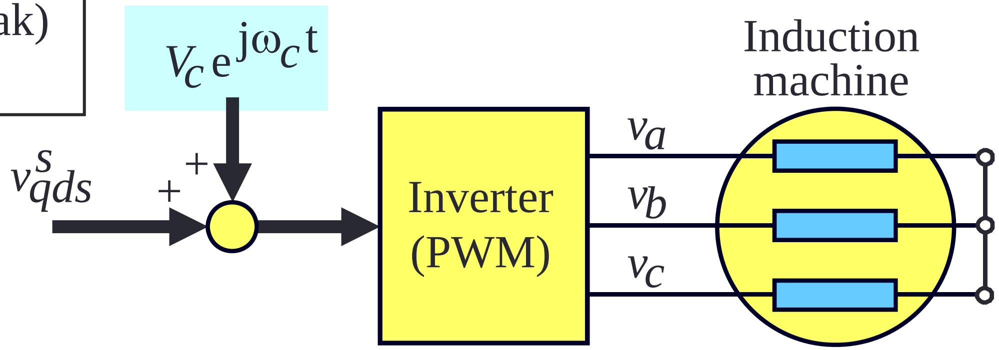


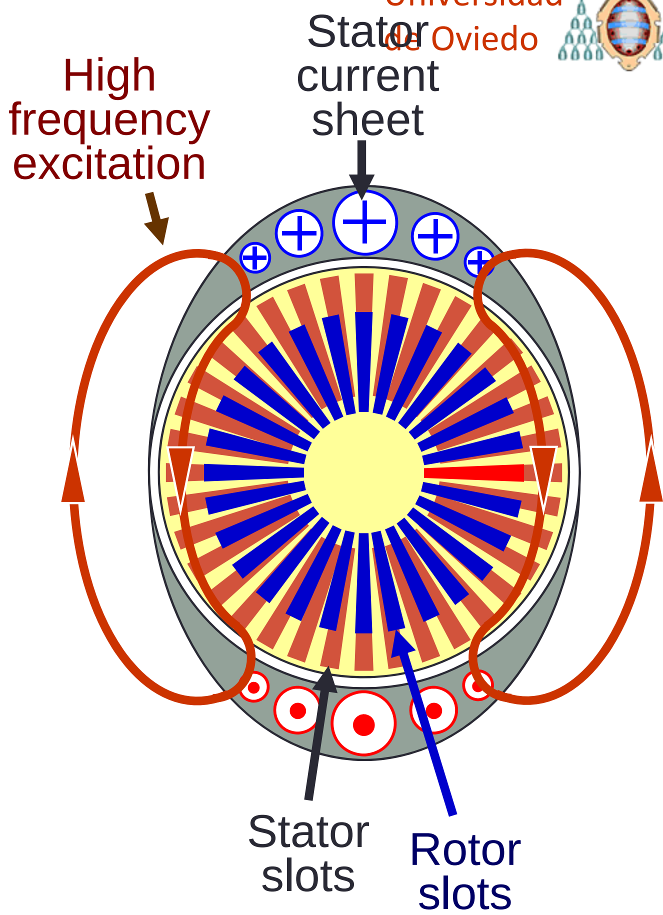


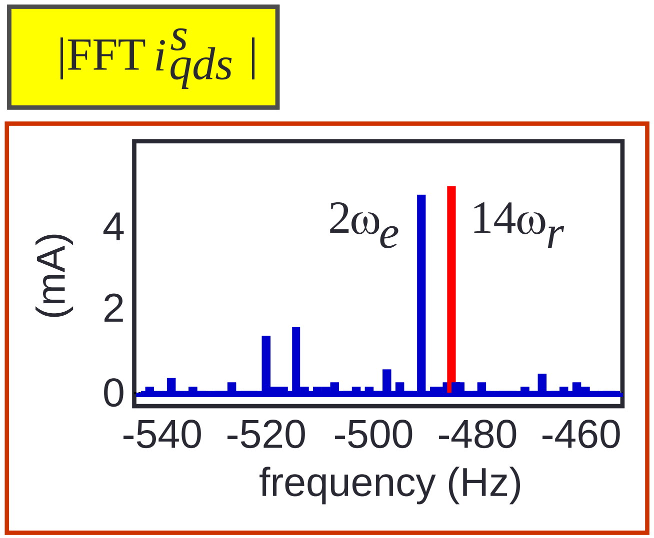


Secondary saliencies:
Saturation induced saliencies

$V_c = 20$ V (peak)
$\omega_c = 500$ Hz

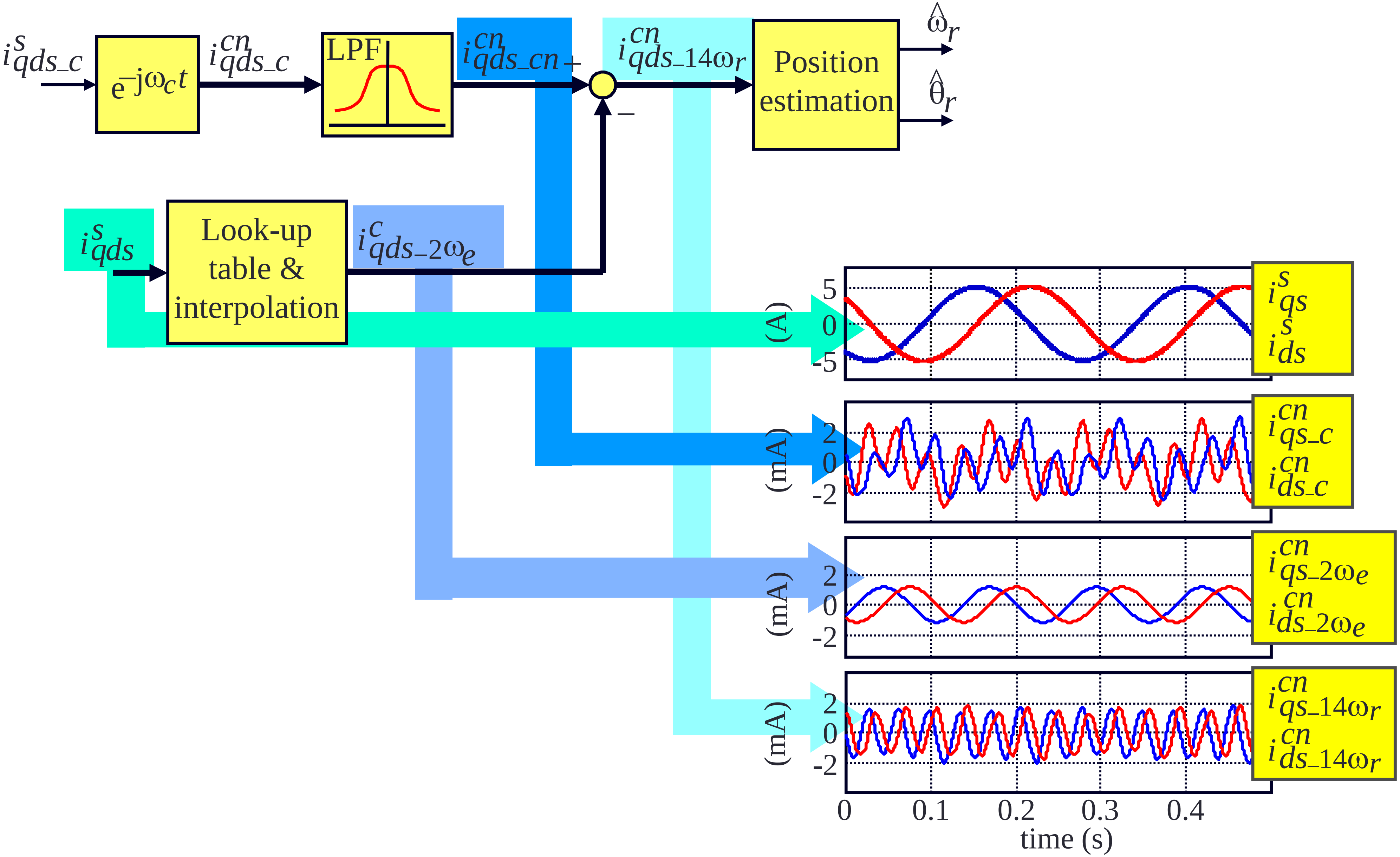


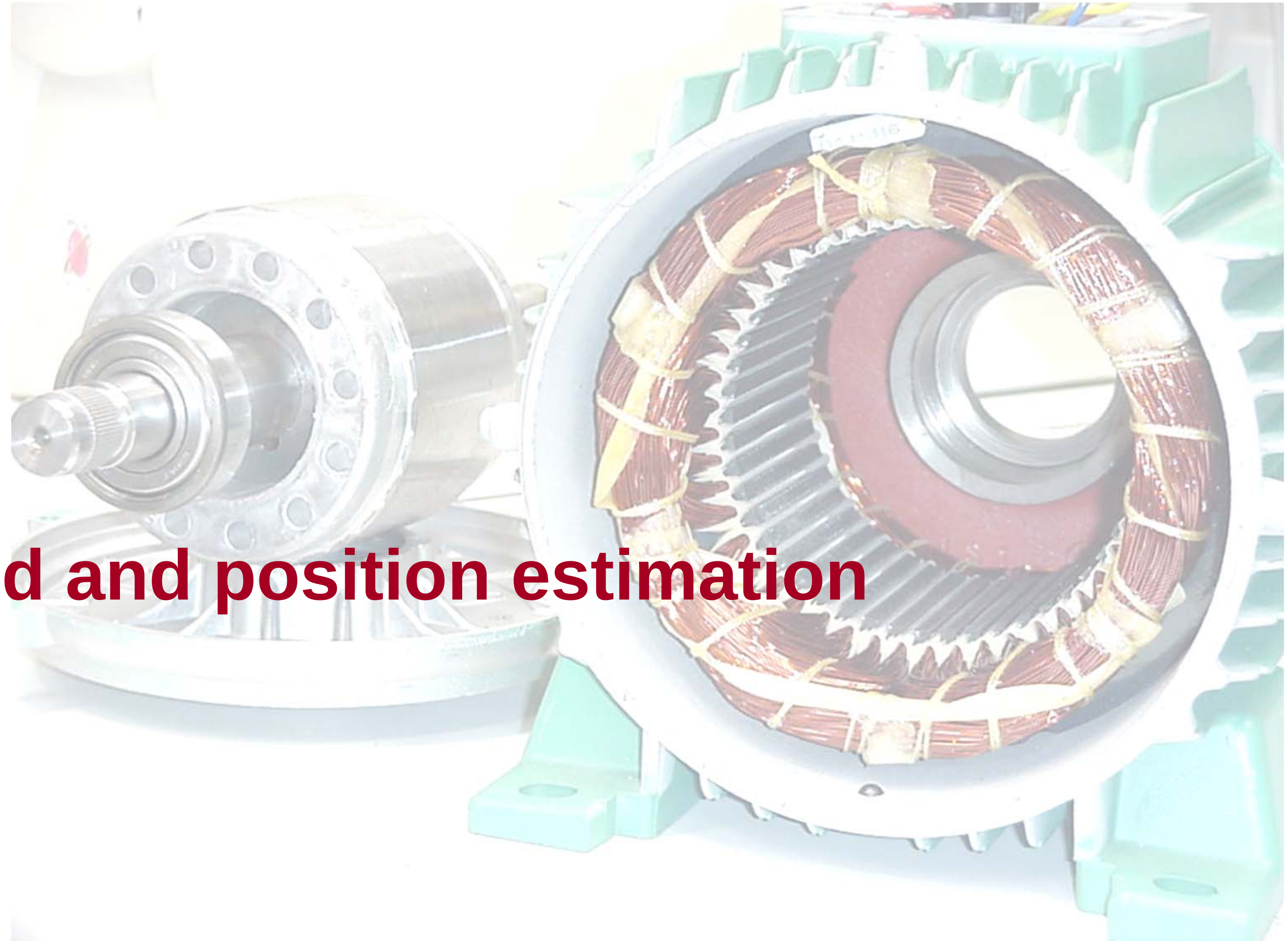




- Saturation-induced saliencies produce additional components of the negative sequence carrier signal current
- Accurate rotor position estimation requires these saturation-induced saliencies be compensated for
- They are measured during an off-line commissioning process, then compensated during the regular sensorless operation of the drive

Modeling and compensation of saturation induced saliencies



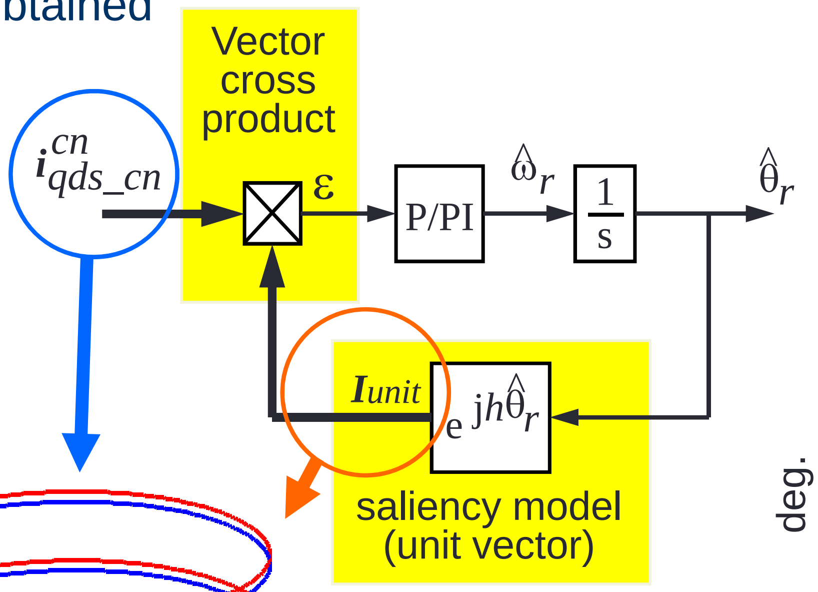


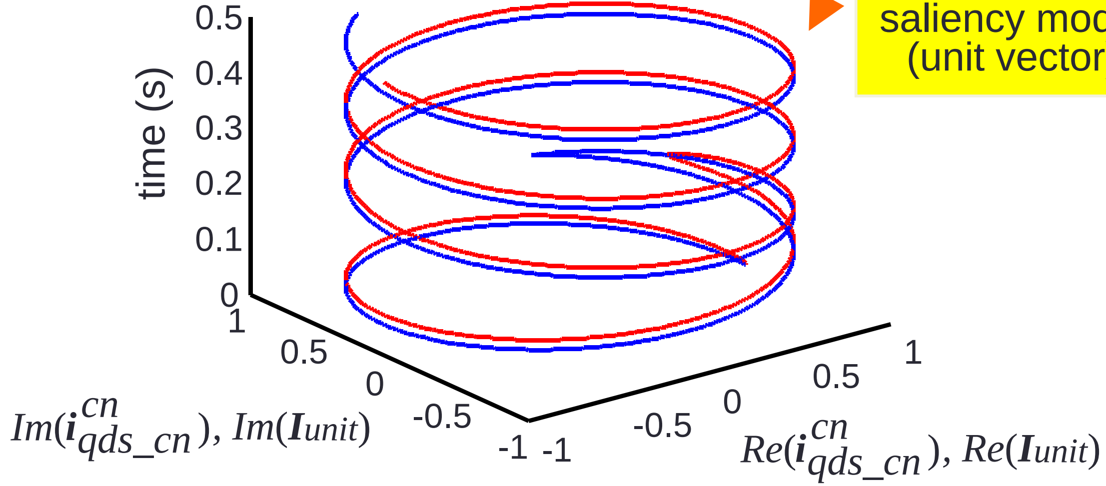
Speed and position estimation

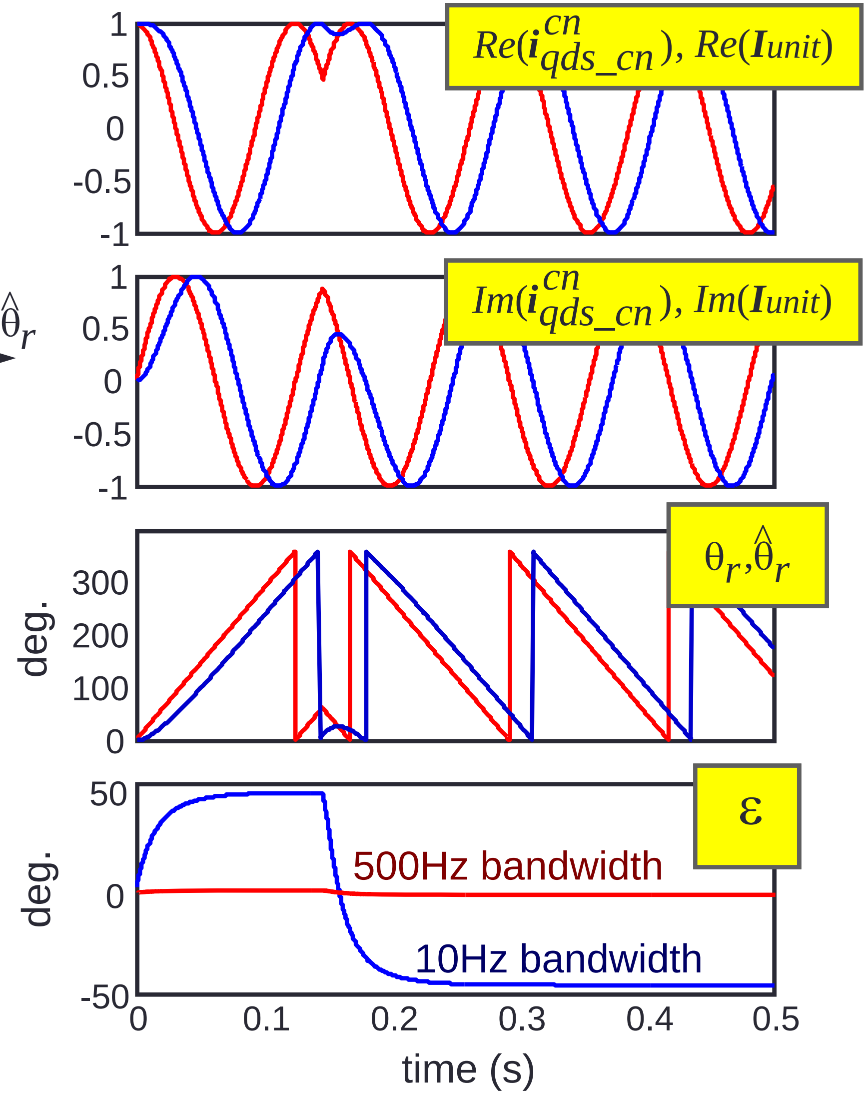
Rotor and velocity estimation using PLL

- PLLs can be used to estimate the rotor position from the negative sequence carrier signal current with reduced computational requirements
- Speed is automatically obtained

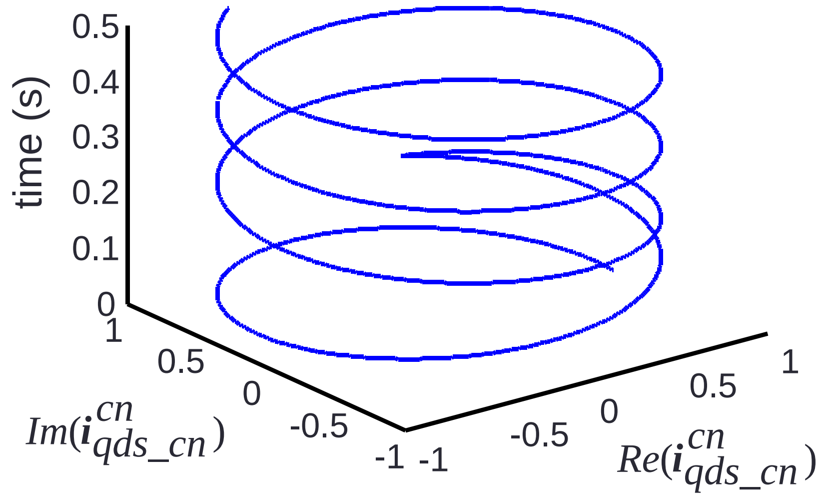
$$\varepsilon = I_{cn}\, sin(h(\theta_r - \hat{\theta}_r))$$

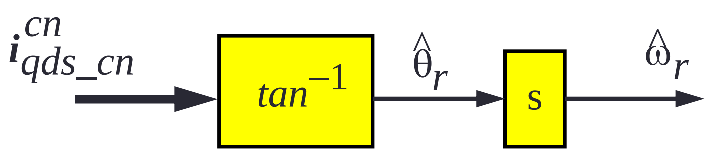


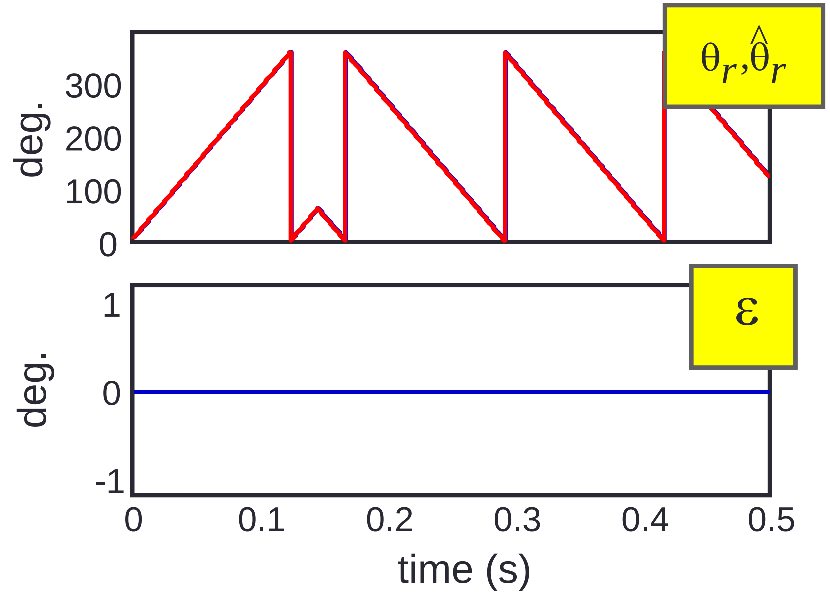




Rotor and velocity estimation using a *tan*$^{-1}$ function





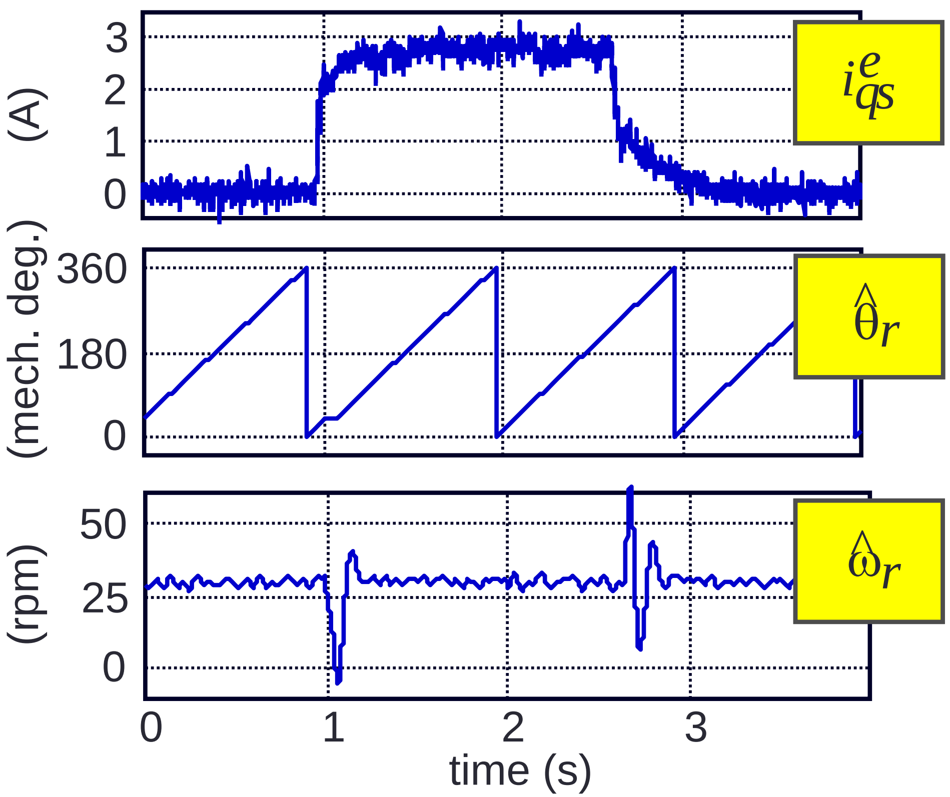


- Zero-lag position estimation can be potentially achieved
- Low-pass filtering is required in practice to limit the effects of noise present in the signals, therefore limiting the bandwidth
- Derivation of the position is needed to estimate the rotor speed
- Trigonometric functions are computationally expensive in general

Sensorless velocity and position control

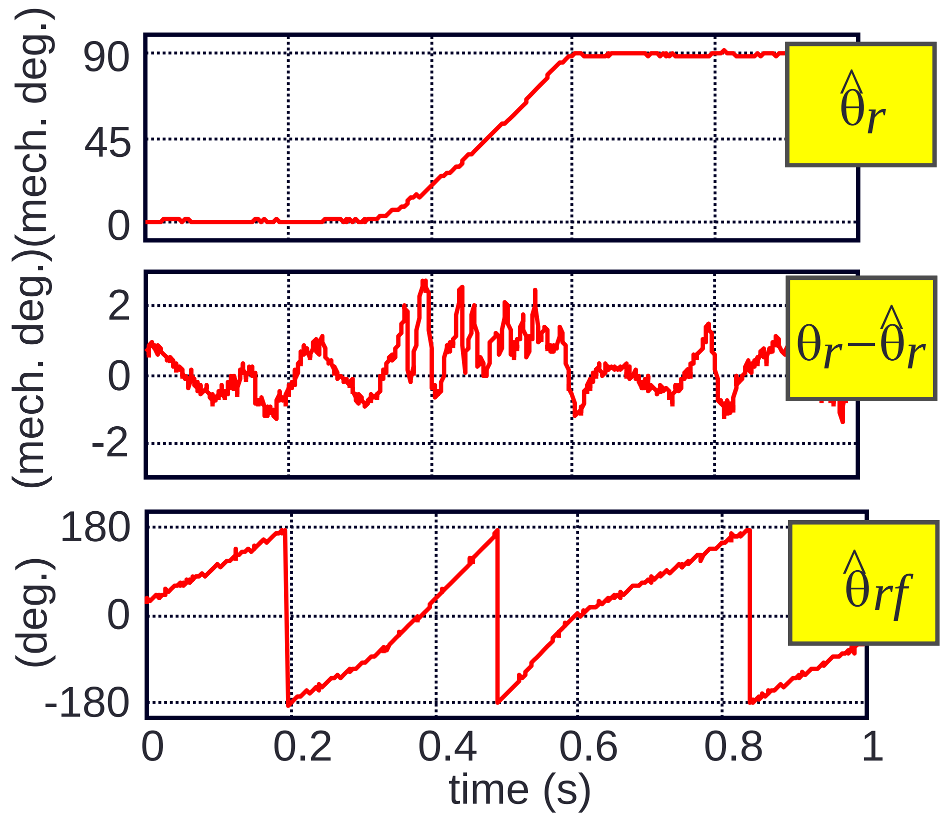
Sensorless velocity control

- Machine operated at rated flux, constant speed
- Rated load applied to the machine



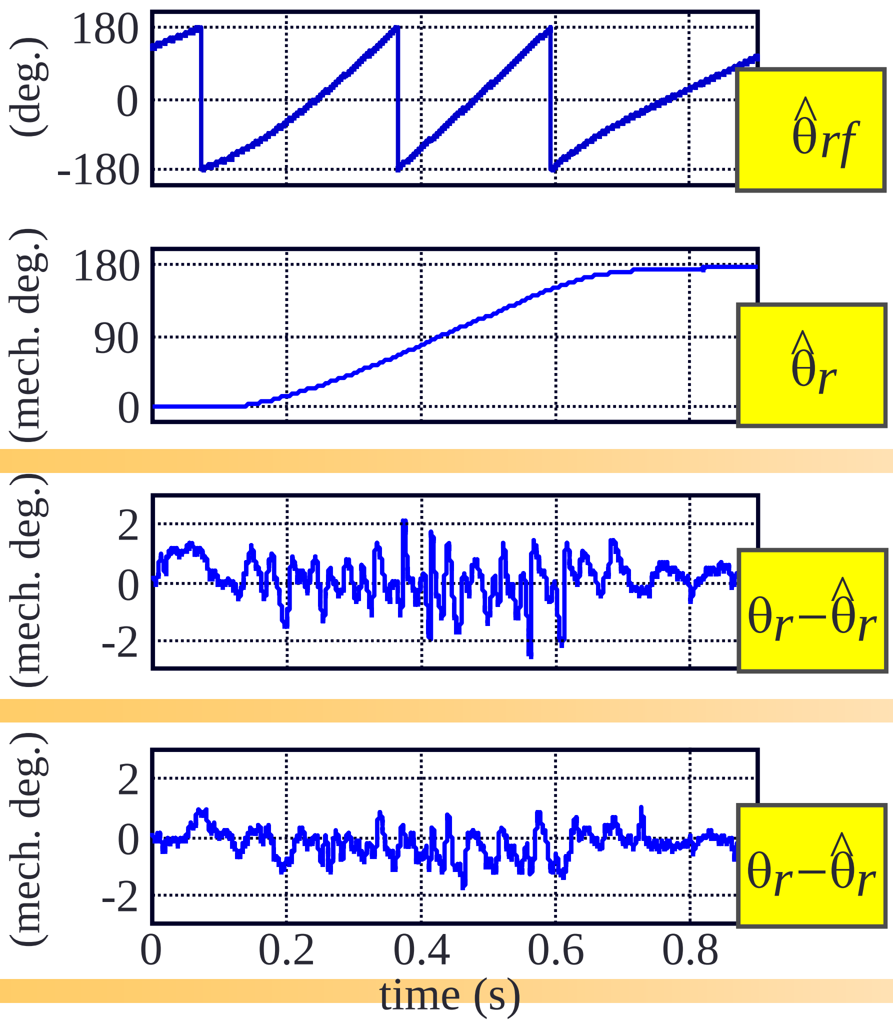
Sensorless position control

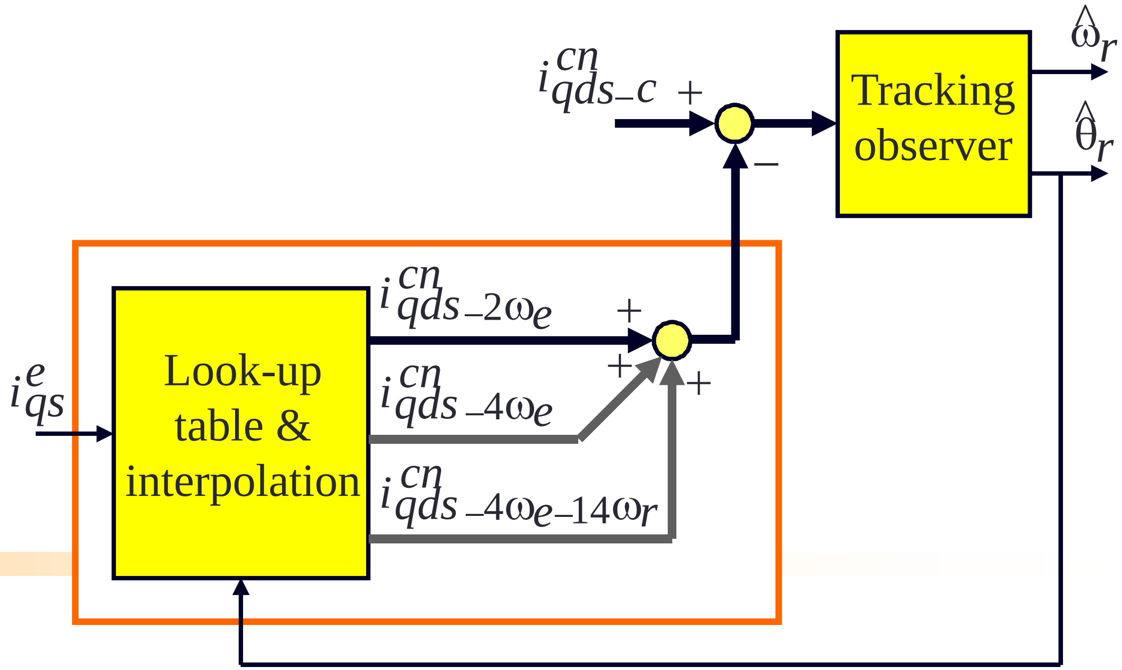
- Position step from 0 to 90º is commanded
- Machine operated at rated flux, 80% rated load



Sensorless position control:
Secondary saliencies decoupling

- Carrier voltage: ω_c=3750 Hz, V_c=15 V (peak) (carrier current ≈1% rated current)
- Machine operated at rated flux, 80% rated load



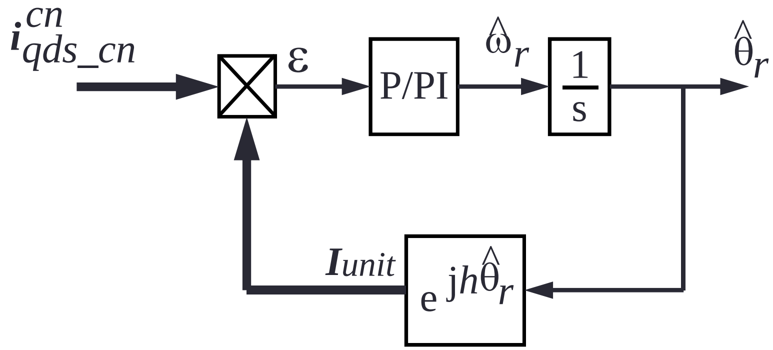


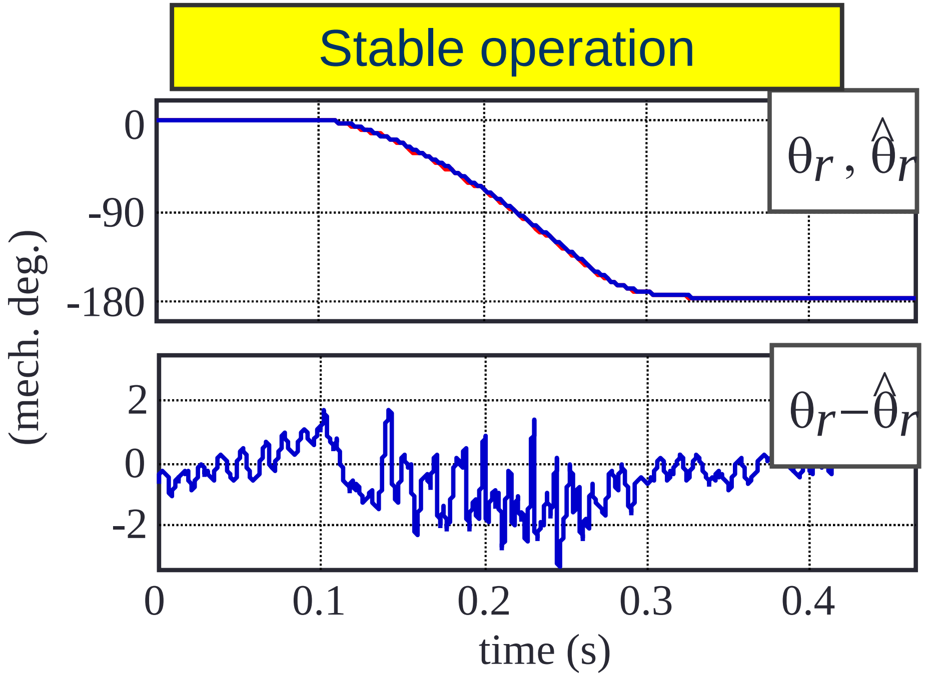
$2\omega_e$ component compensated

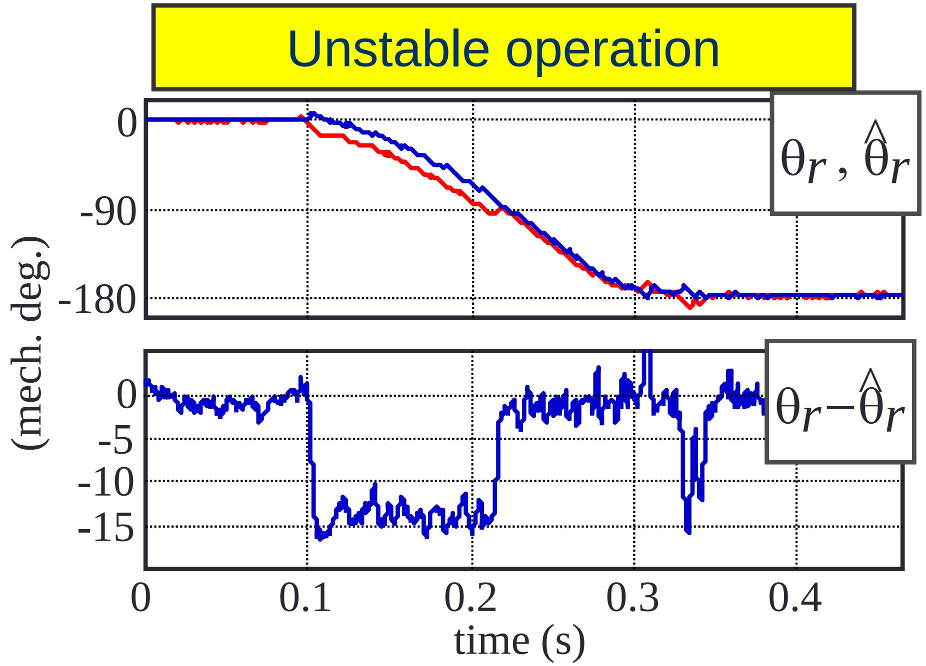
$2\omega_e$, $-4\omega_e$ and $-2\omega_e-14\omega_r$ components compensated

Sensorless position control:
Stable and unstable operation

- Carrier voltage: ω_C=1500 Hz, V_C=20 V (peak)
- Machine operated at rated flux, 80% rated load







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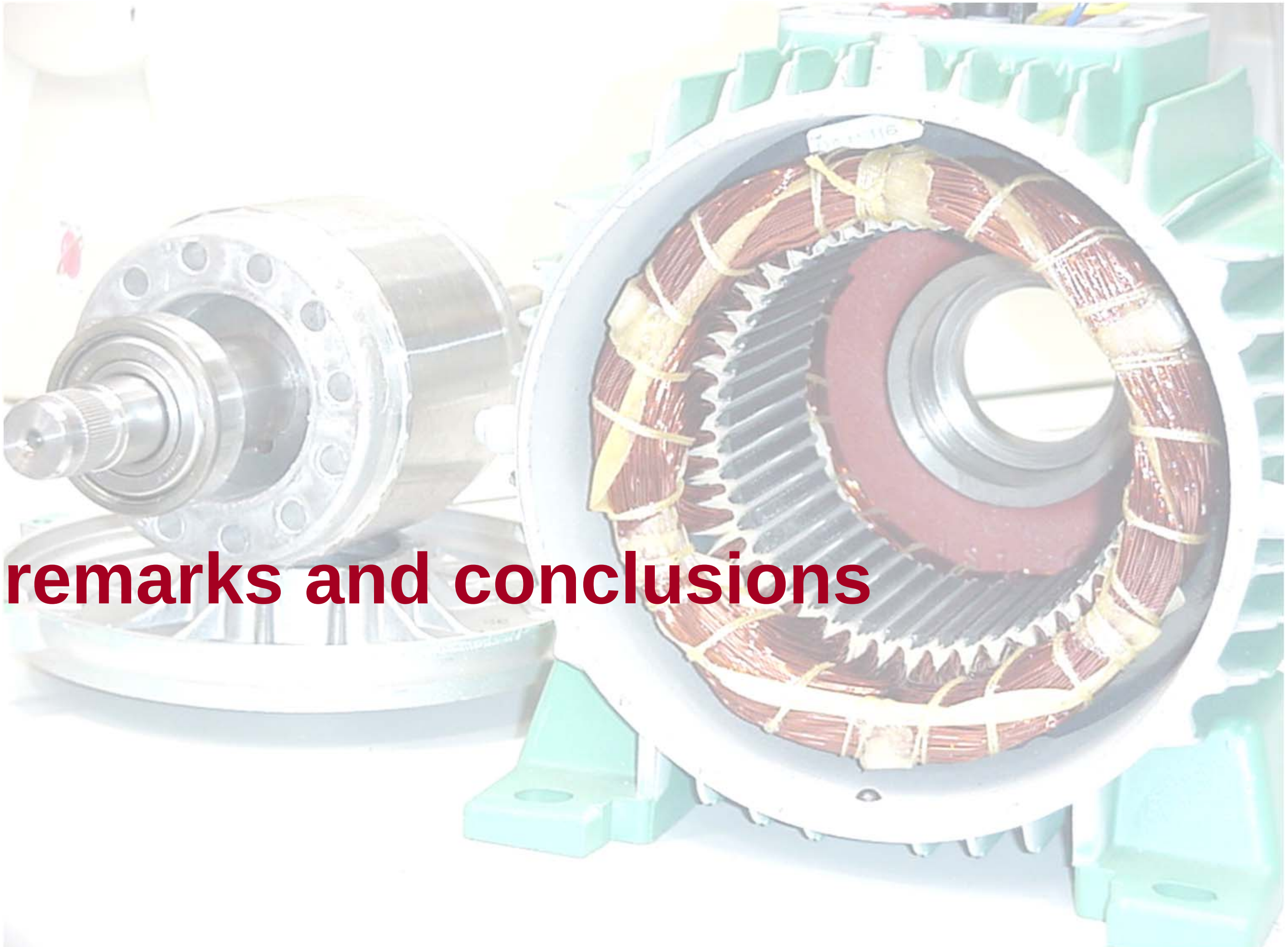

Final remarks and conclusions

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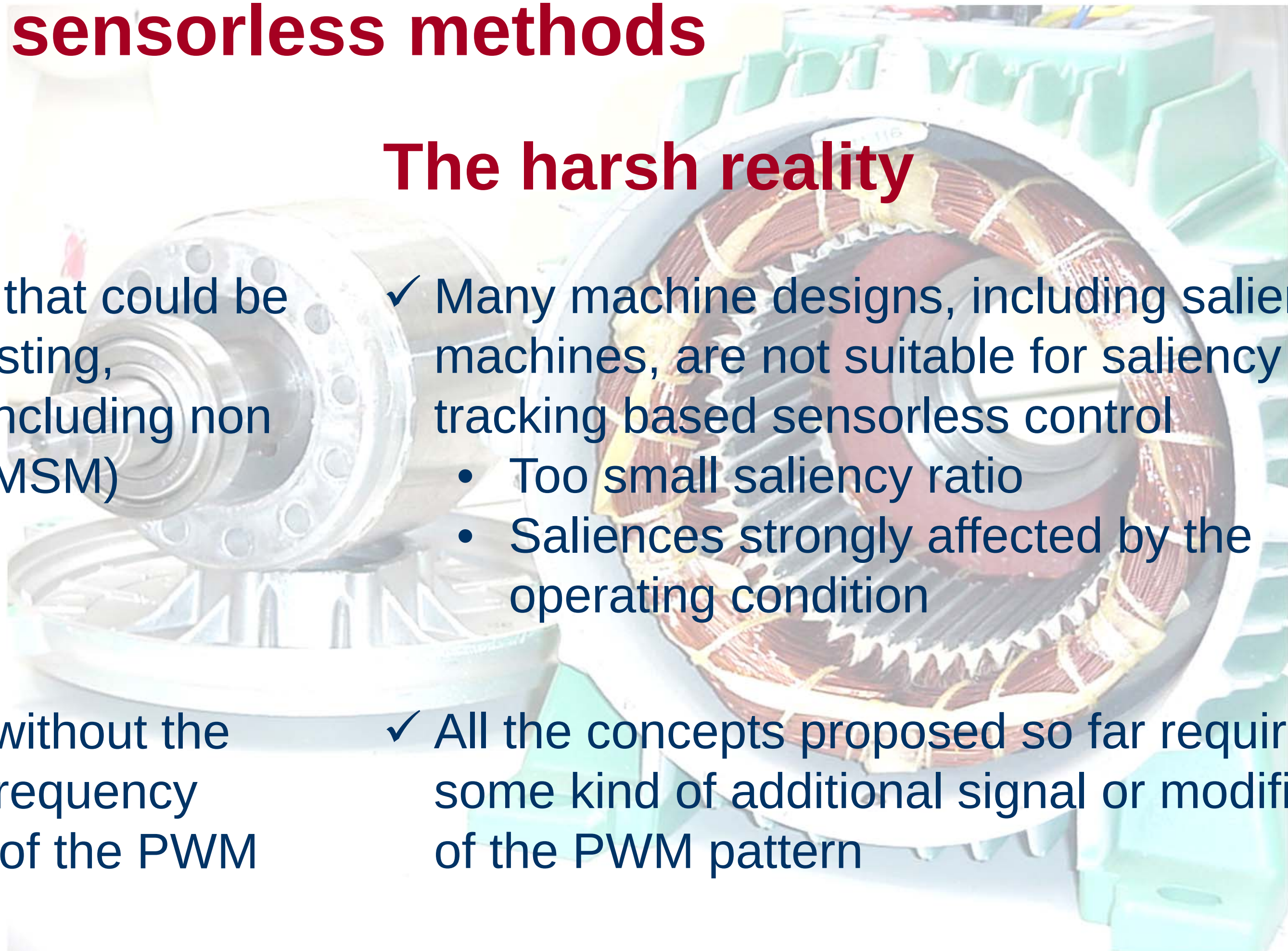
Saliency tracking sensorless methods



The dream

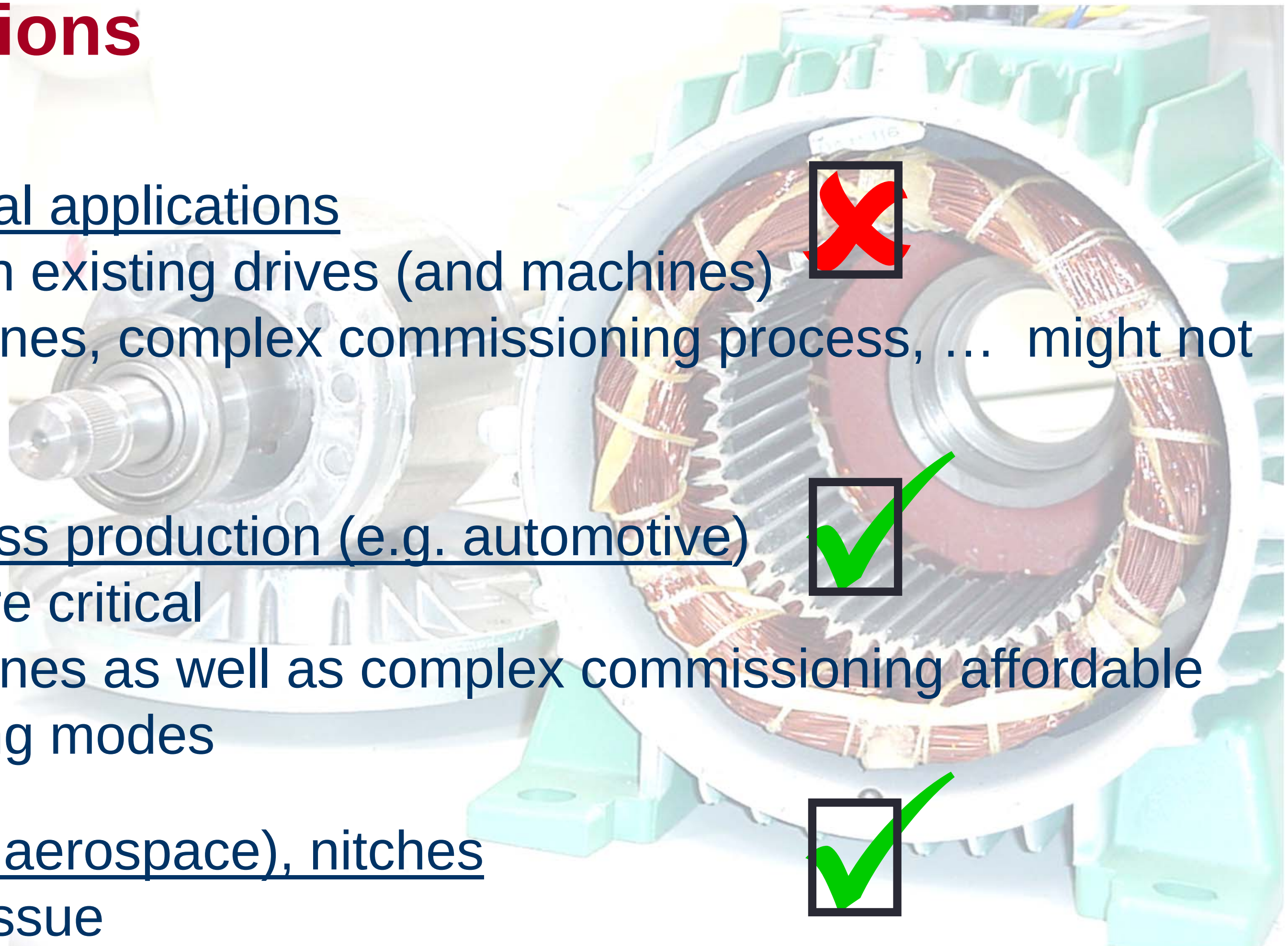
- ✓ Development of methods that could be used with any already existing, standard, AC machines, including non salient machines (IM, SPMSM)
- ✓ Methods that could work without the need of any kind of high frequency excitation or modification of the PWM pattern

The harsh reality

- ✓ Many machine designs, including salient machines, are not suitable for saliency tracking based sensorless control
  - Too small saliency ratio
  - Saliences strongly affected by the operating condition
- ✓ All the concepts proposed so far require some kind of additional signal or modification of the PWM pattern

✓ **Still the only option for very low speed and/or position sensorless control!**

Potential applications



<u>General purpose industrial applications</u>

- Difficult to integrate in existing drives (and machines)
- Design of new machines, complex commissioning process, … might not be justified

<u>Specific applications, mass production (e.g. automotive)</u>

- Cost and reliability are critical
- Design of new machines as well as complex commissioning affordable
- Well defined operating modes

<u>Critical applications (e.g. aerospace), nitches</u>

- Often cost is not an issue
- Reliability is critical, also weight and volume saving
- Design of new machines as well as complex commissioning affordable
- Well defined operating modes

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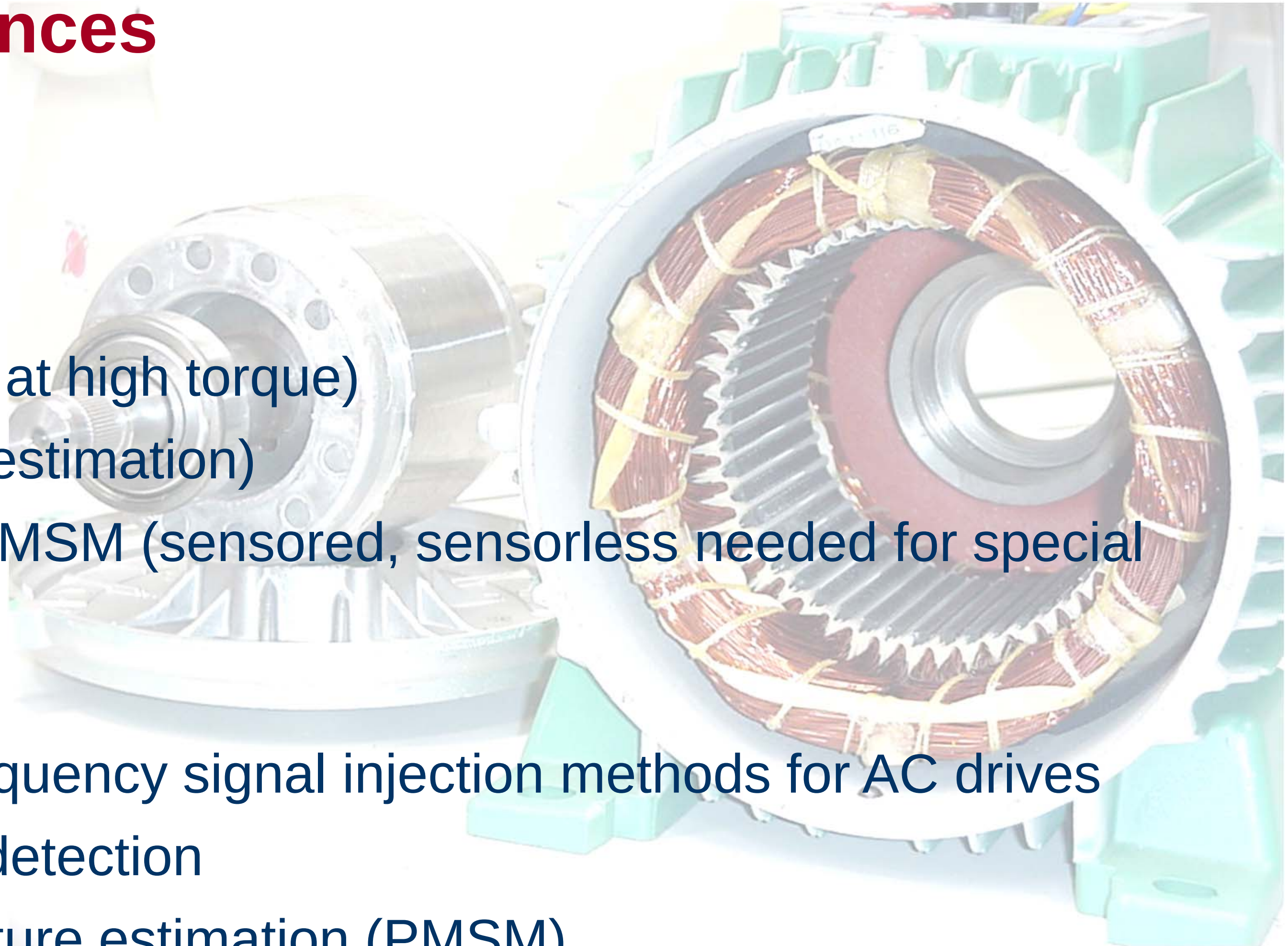
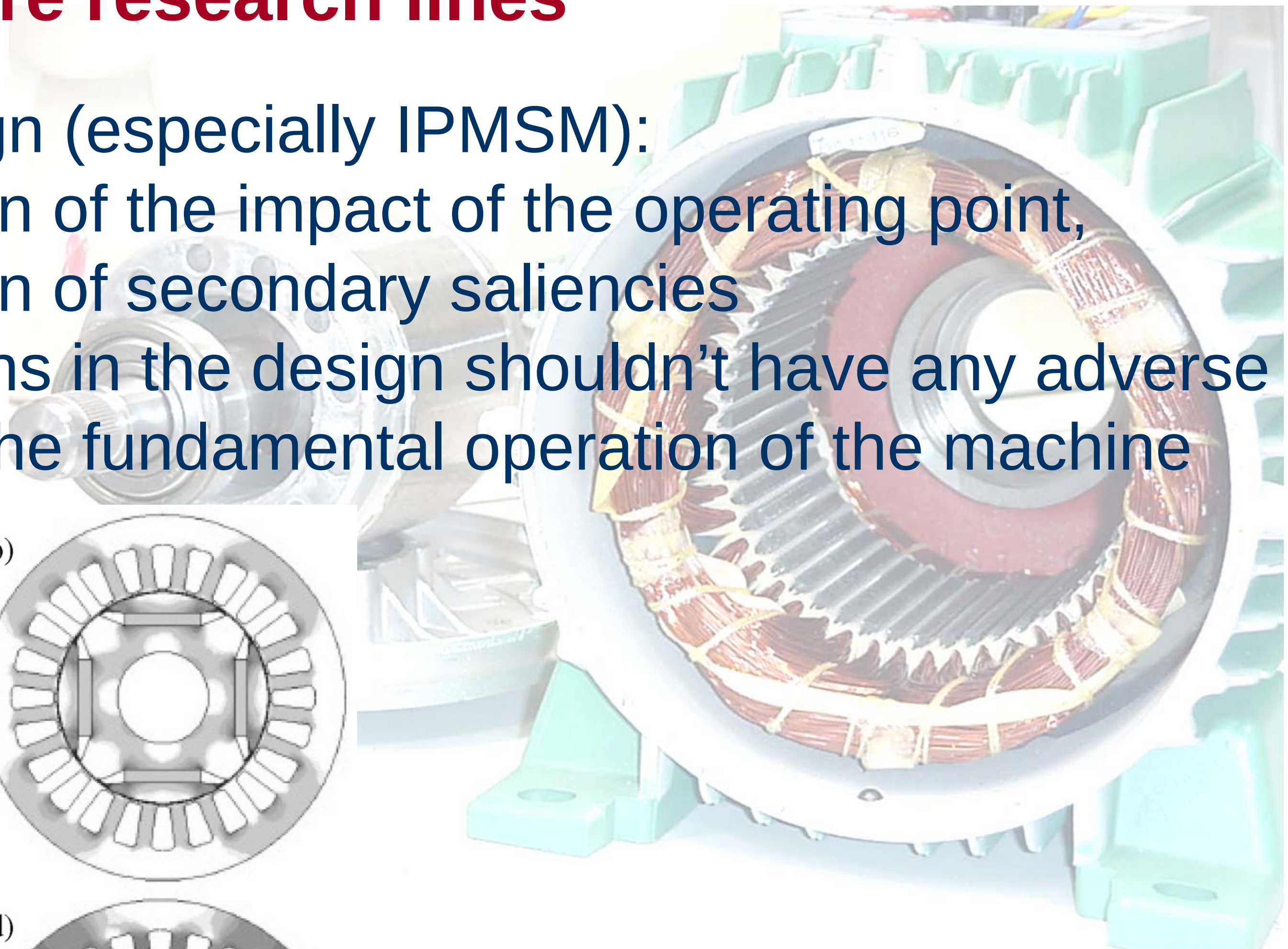
Industrial experiences



- ✓ Traction
- ✓ Compressors (startup at high torque)
- ✓ Lifts (magnet polarity estimation)
- ✓ Wind turbines using PMSM (sensored, sensorless needed for special modes of operation)

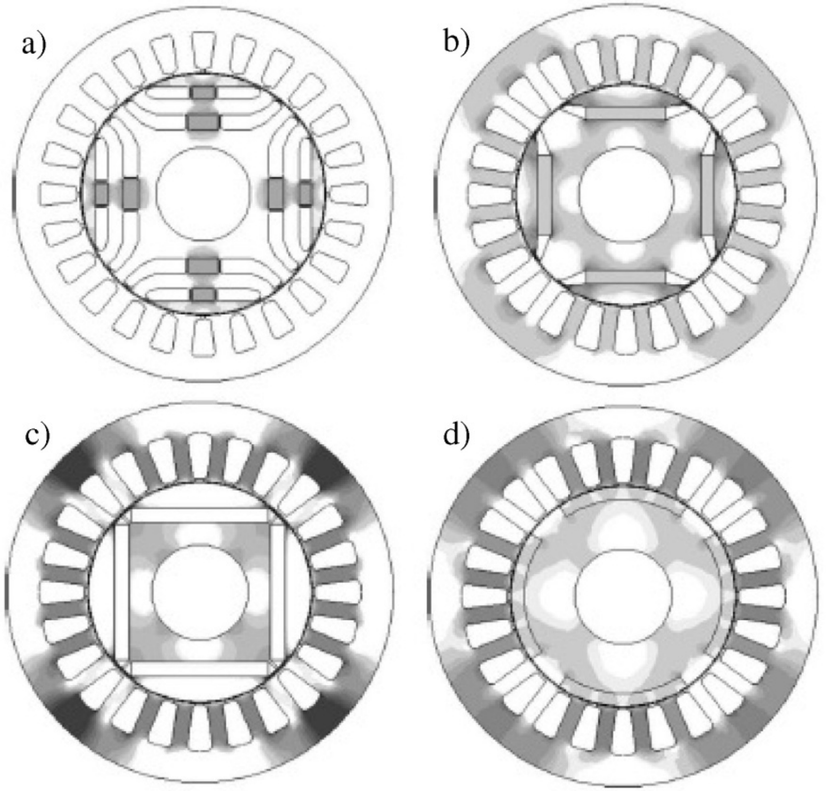
- ✓ Other uses of high frequency signal injection methods for AC drives
  - Diagnostics/fault detection
  - Magnets temperature estimation (PMSM)

Ongoing and future research lines



✓Machine design (especially IPMSM):

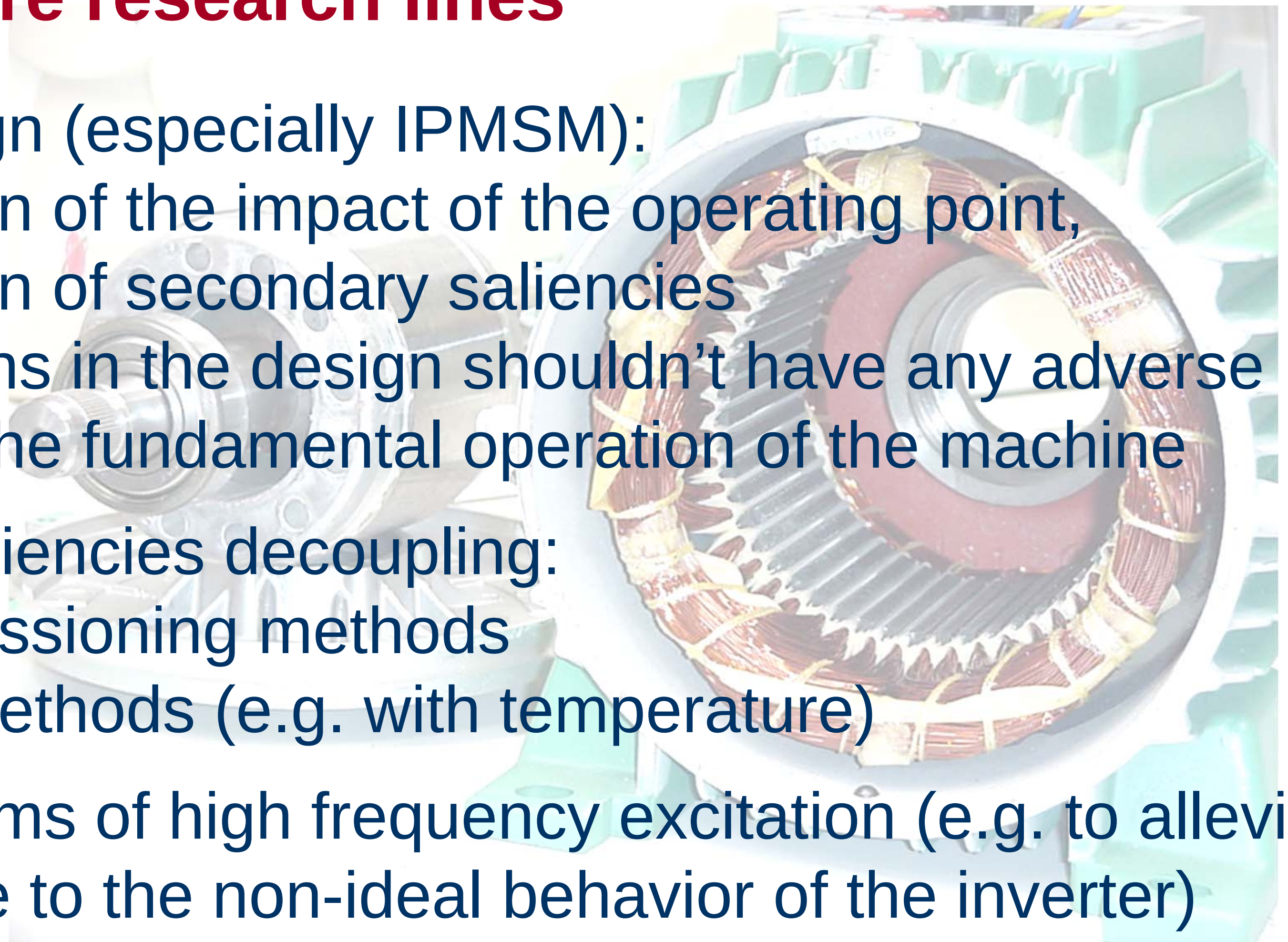
- Minimization of the impact of the operating point, minimization of secondary saliencies
- Modifications in the design shouldn't have any adverse impact on the fundamental operation of the machine



Bianchi, N.; Bolognani, S.;, "Influence of Rotor Geometry of an IPM Motor on Sensorless Control Feasibility," IEEE Trans. Ind. Appl., vol.43, no.1, pp.87-96, Jan.-feb. 2007.

Bianchi, N.; Bolognani, S.; Ji-Hoon Jang; Seung-Ki Sul; , "Advantages of Inset PM Machines for Zero-Speed Sensorless Position Detection," IEEE Trans. Ind. Appl., vol.44, no.4, pp.1190-1198, July-aug. 2008.

Ongoing and future research lines



- ✓Machine design (especially IPMSM):
  - Minimization of the impact of the operating point, minimization of secondary saliencies
  - Modifications in the design shouldn’t have any adverse impact on the fundamental operation of the machine
- ✓Secondary saliencies decoupling:
  - Self-commissioning methods
  - Adaptive methods (e.g. with temperature)
- ✓Alternative forms of high frequency excitation (e.g. to alleviate the effects due to the non-ideal behavior of the inverter)

- ✓**What the limits of these methods are?**