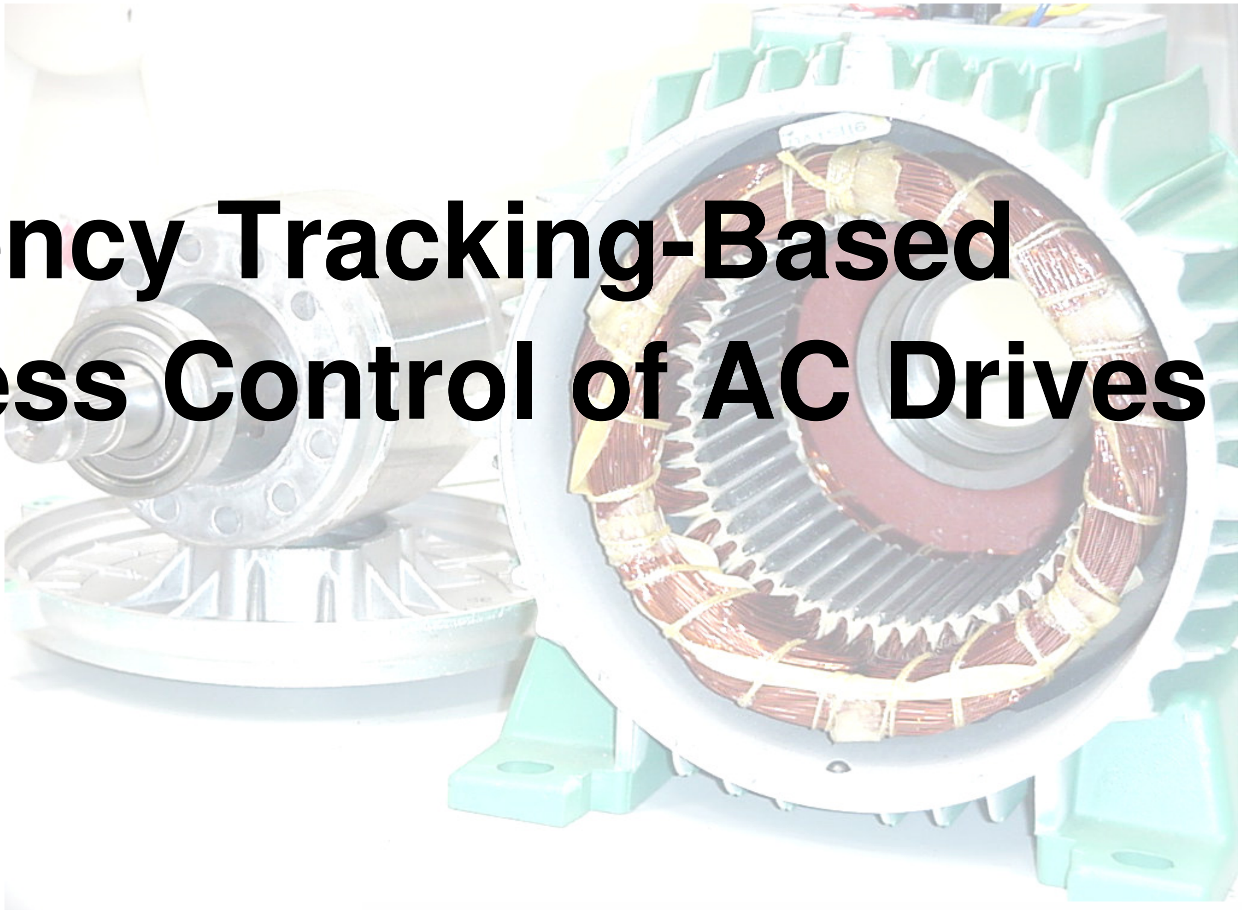
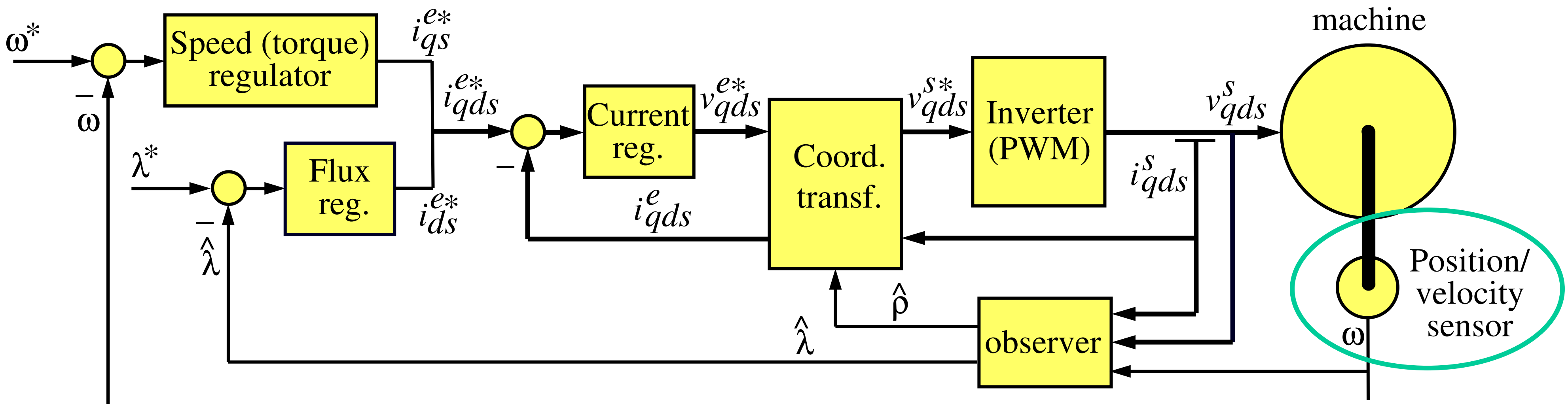


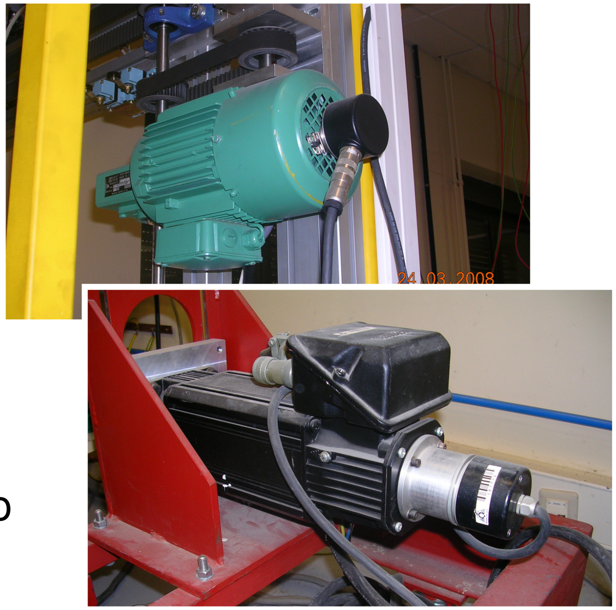
Saliency Tracking-Based Sensorless Control of AC Drives

INGENIERÍA DE SISTEMAS
Y AUTOMÁTICA

Universidad de Oviedo

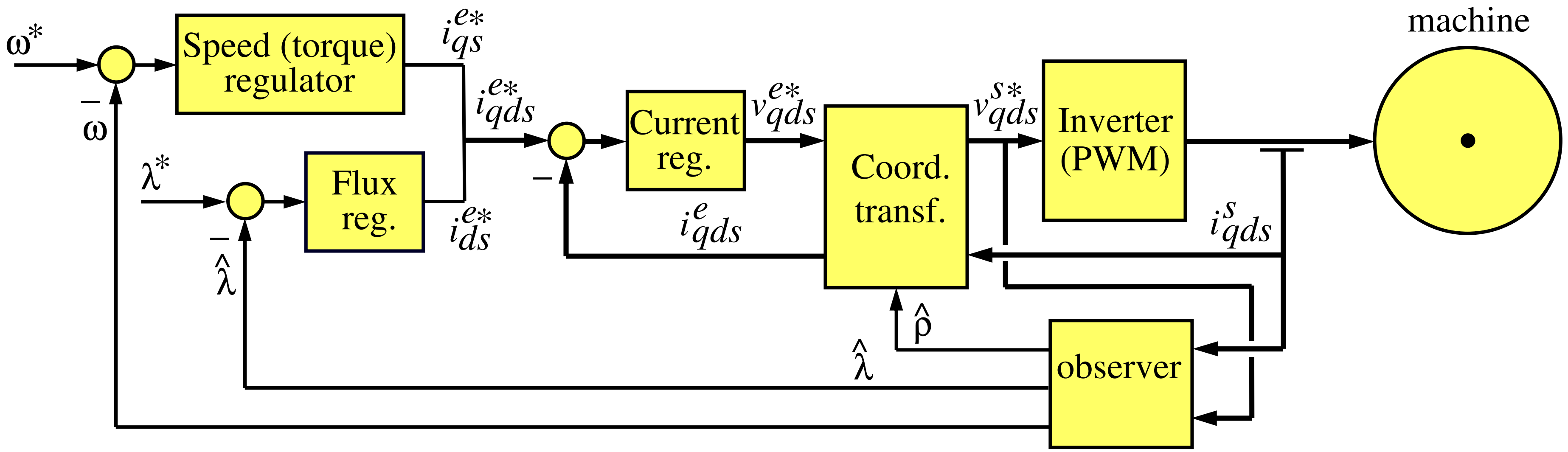
Sensorless control of AC drives: Motivation





- ✓ Velocity/position estimation is normally needed for two different purposes:
  - Flux angle estimation for flux and torque control.
  - Motion control (velocity/position regulation).
- ✓ Incremental encoder is currently the most commonly used sensor.
- ✓ Elimination of the position sensor (and cabling) has advantages in terms of 1) cost, 2) robustness and 3) space.
- ✓ Sensorless control has been a major field of research for the last two decades.

Sensorless control of AC drives



✓ Elimination of the position sensor (and cabling) has advantages in terms of:

- Cost.
- Robustness.
- Space.

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

✓ Two different approaches: <u>model based</u> methods and <u>saliency tracking based</u> methods.

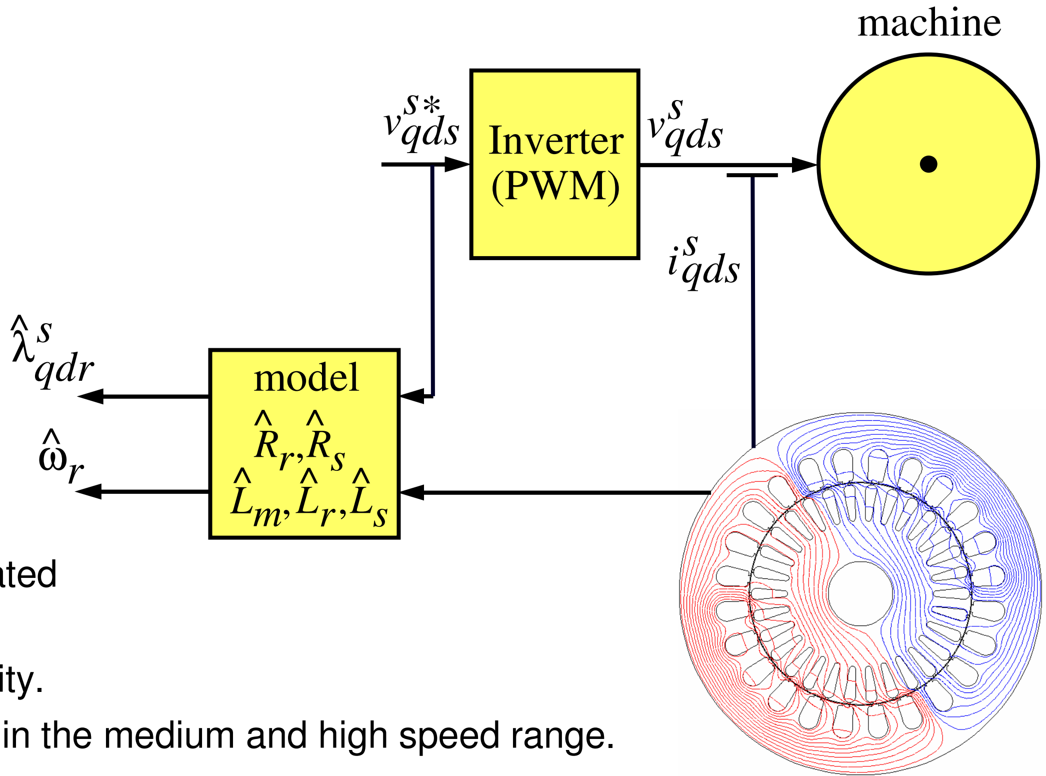
Model based sensorless methods

Induction machine model (complex vector notation, stationary reference frame)

$$p i^s_{qds} = \frac{1}{L_{\sigma s}}\left(v^s_{qds} - R'_s\, i^s_{qds} + \frac{L_m}{L_r}\omega_{br}\lambda^s_{qdr}\right)$$

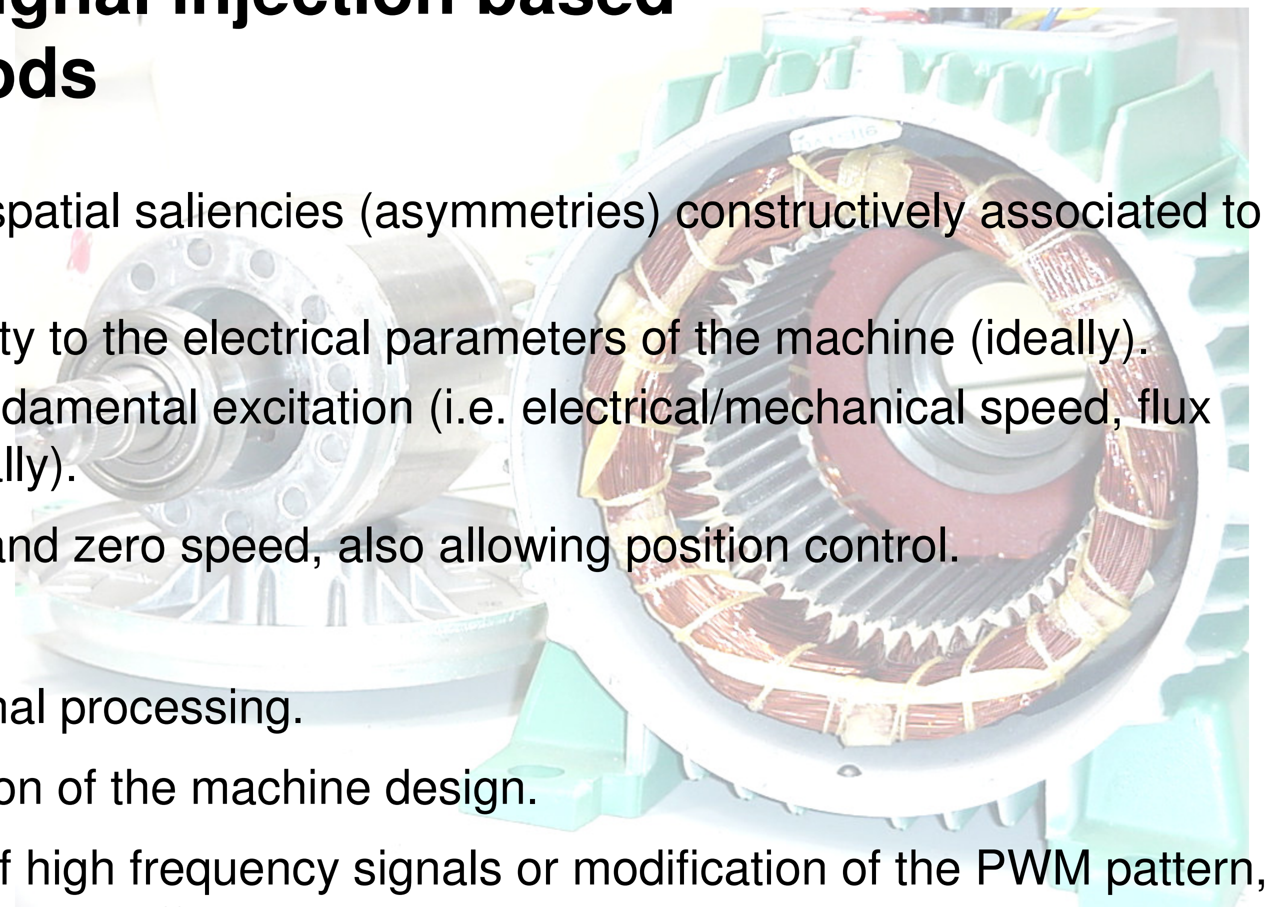
$$p\lambda^s_{qdr} = \frac{L_m}{L_r} R_r\, i^s_{qds} - \omega_{br}\lambda^s_{qdr}$$

$$\omega_{br} = \frac{R_r}{L_r} - j\omega_r \;,\quad L_{\sigma s} = L_s - \frac{L_m^2}{L_r} \;,\quad R'_s = R_s + \left(\frac{L_m}{L_r}\right)^2 R_r$$



- ✓ These methods use (in different forms) the back emf induced in the stator windings.
- ✓ Stator currents are normally (and easily) measured.
- ✓ Stator voltages are not normally measured, but estimated from the voltage command to the inverter.
- ✓ The model suffer from a significant parameter sensitivity.
- ✓ Accurate speed (and flux) estimation can be obtained in the medium and high speed range.
- ✓ Significant problems arise in the low speed range, mainly coming from errors in the stator resistance estimation and in the voltage measurements.
- ✓ Position control is not possible (no back emf exists at zero speed).

High frequency signal injection based sensorless methods



- ✓ These methods track spatial saliencies (asymmetries) constructively associated to the rotor.
- ✓ No parameter sensitivity to the electrical parameters of the machine (ideally).
- ✓ 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.

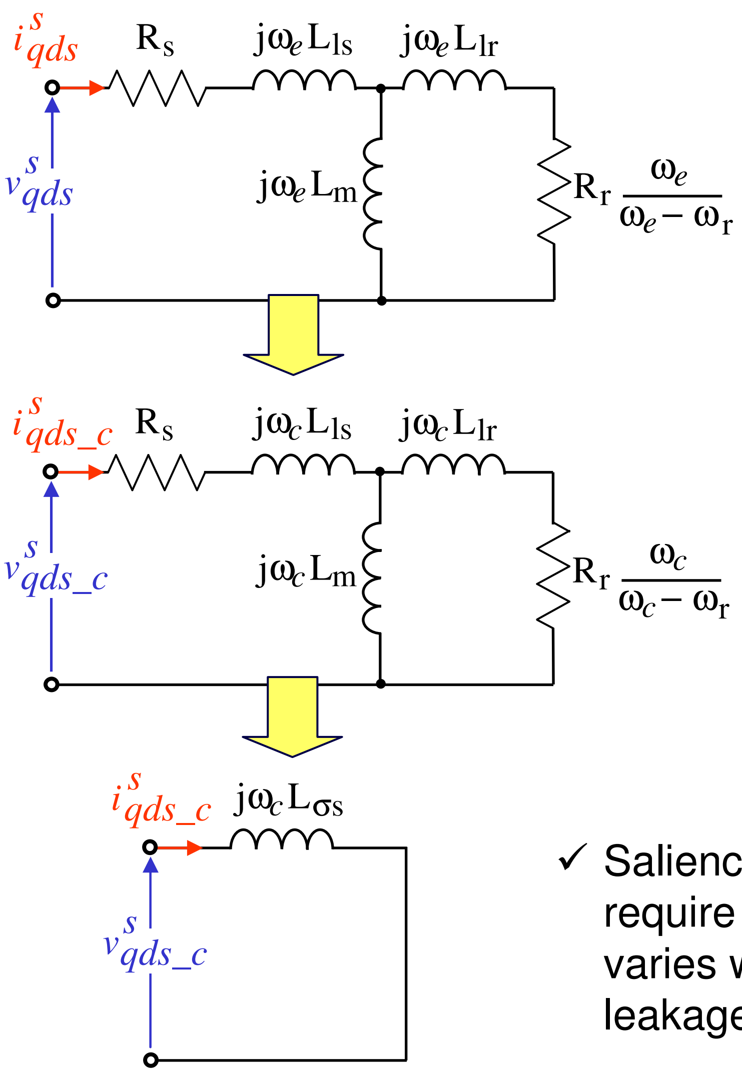
- ✘ Often complicated signal processing.
- ✘ May require modification of the machine design.
- ✘ Require the injection of high frequency signals or modification of the PWM pattern, what can result in unwanted effects (vibration, noise, additional losses, reduction of the voltage available for the fundamental operation of the machine, …).
- ✘ May require additional sensors (voltage sensors, di/dt sensors, …).

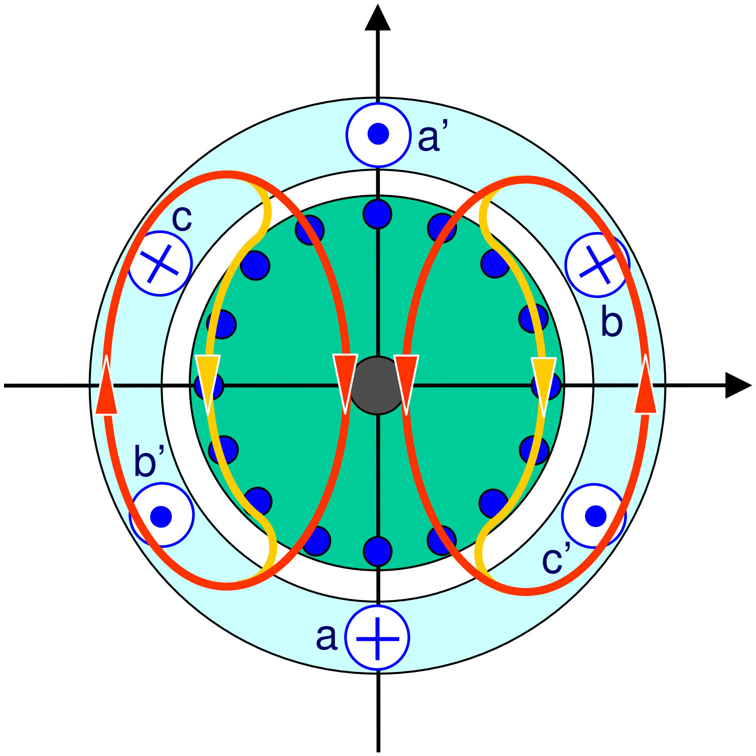
High frequency model of induction machines

Conventional Steady-State Equivalent Circuit
($\omega_e \approx \omega_r$)

High Frequency Circuit
($\omega_c >> \omega_r$)

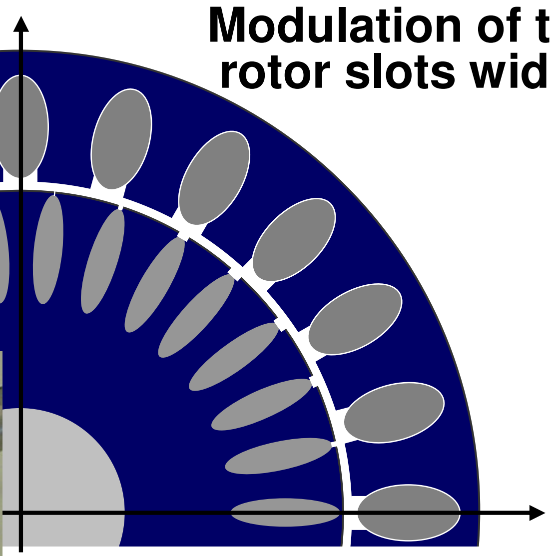
High Frequency Equivalent Circuit



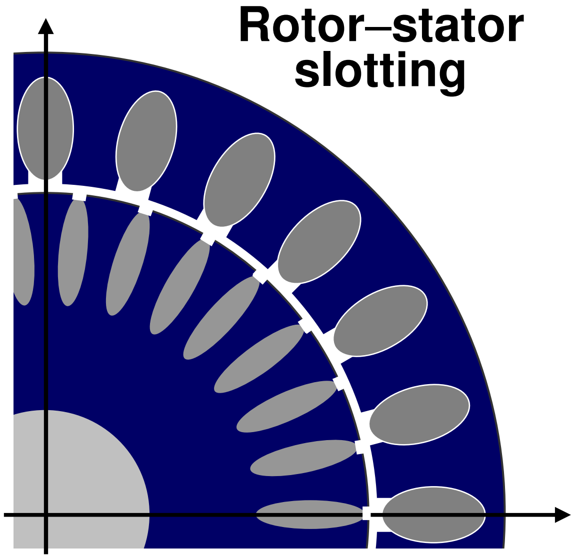


- ✓ Saliency tracking-based sensorless methods require that the stator transient inductance varies with the rotor position (through the rotor leakage inductance)

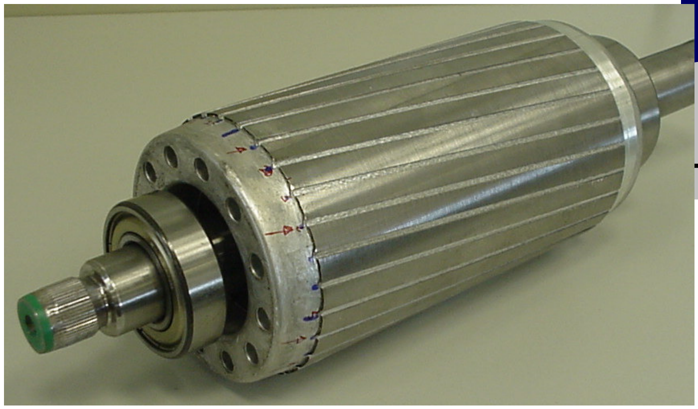
Spatial saliencies in induction machines

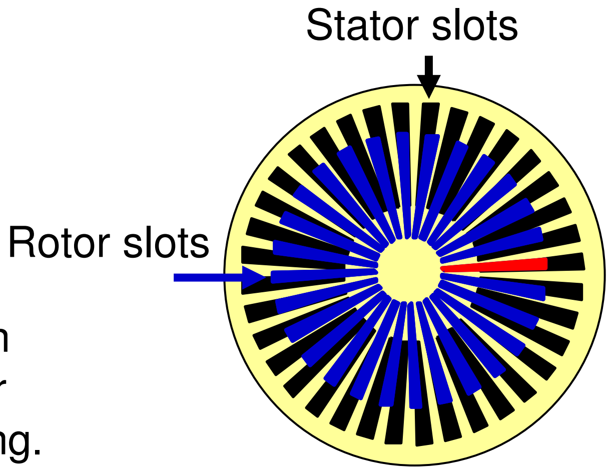


Modulation of the rotor slots width



Rotor–stator slotting





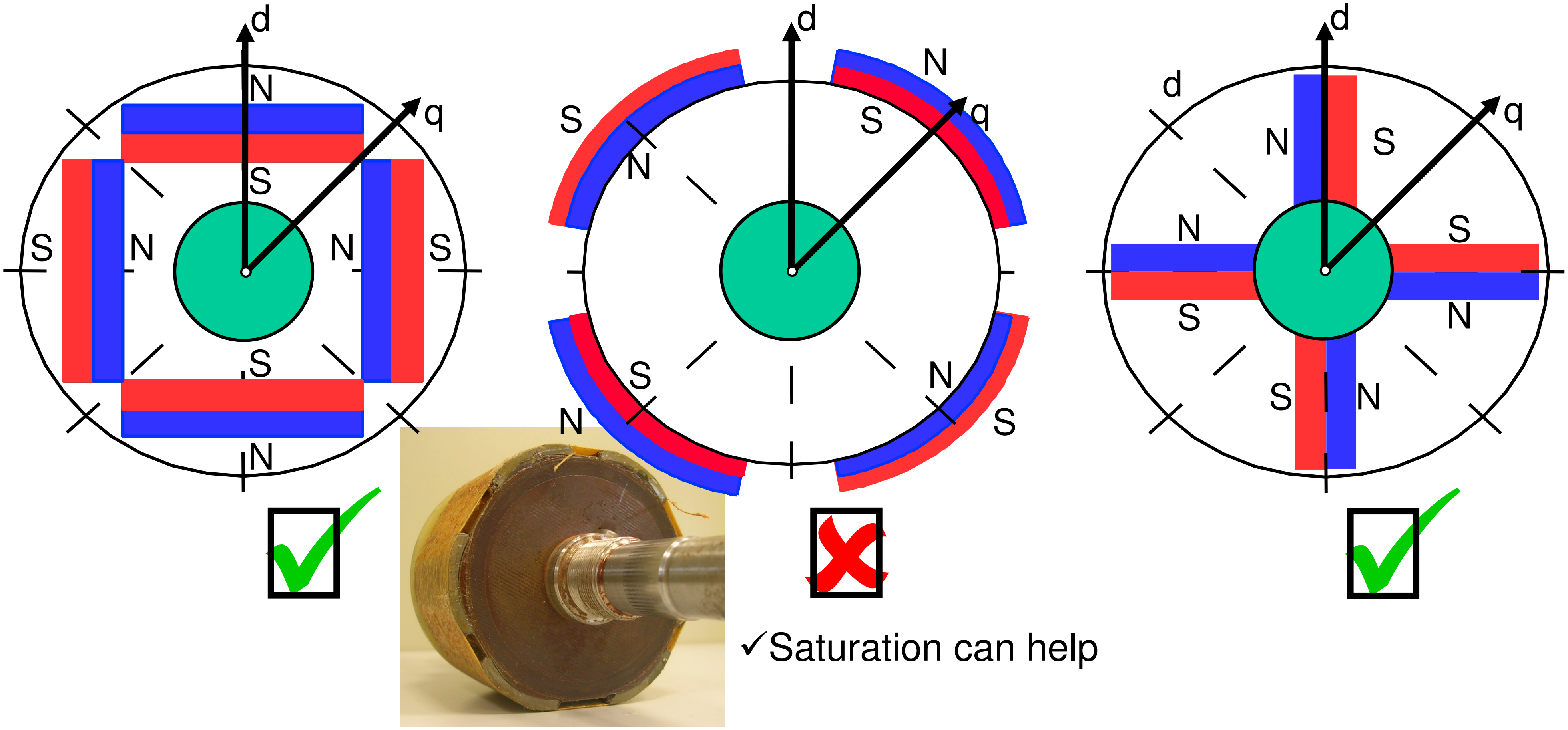
- ✓ Modulation of the rotor slots width implies a modification of the manufacturing process, or post-manufacturing machining.
- ✓ Rotor-stator slotting can be present in standard machines with open or semi-open rotor slots (depends on the number of rotor and stator slots, and number of poles), the rotor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

Spatial saliencies in permanent magnet machines

Radial flux, interior permanent magnet machines

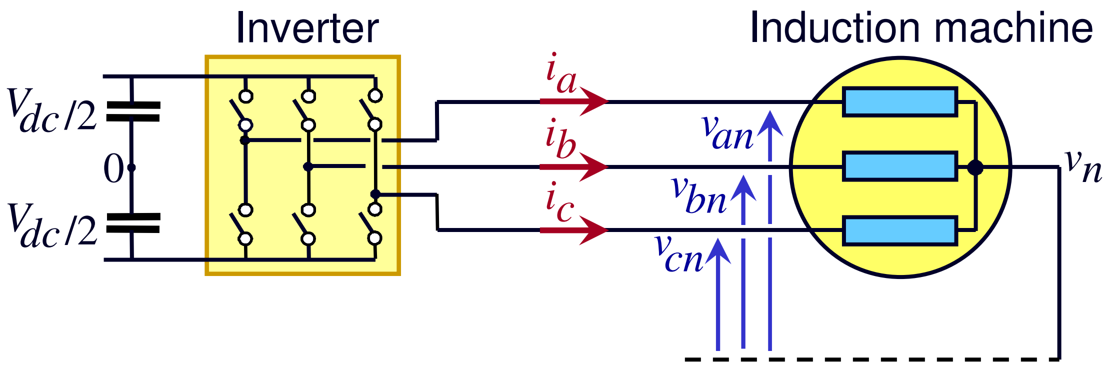
Radial flux, surface permanent magnet machines

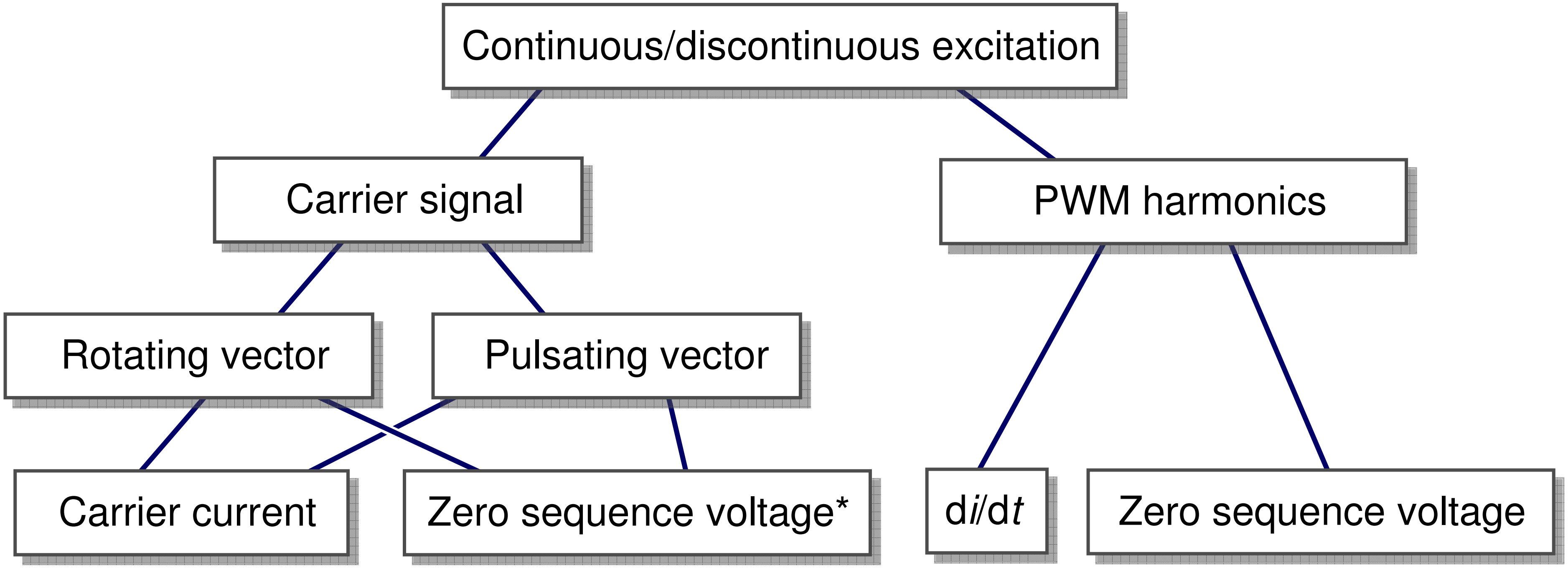
Tangential flux, interior permanent magnet machines



✓Saturation can help

Forms of high frequency excitation and resulting high frequency signals




Continuous/discontinuous excitation

Carrier signal

PWM harmonics

Rotating vector

Pulsating vector

Carrier current

Zero sequence voltage*

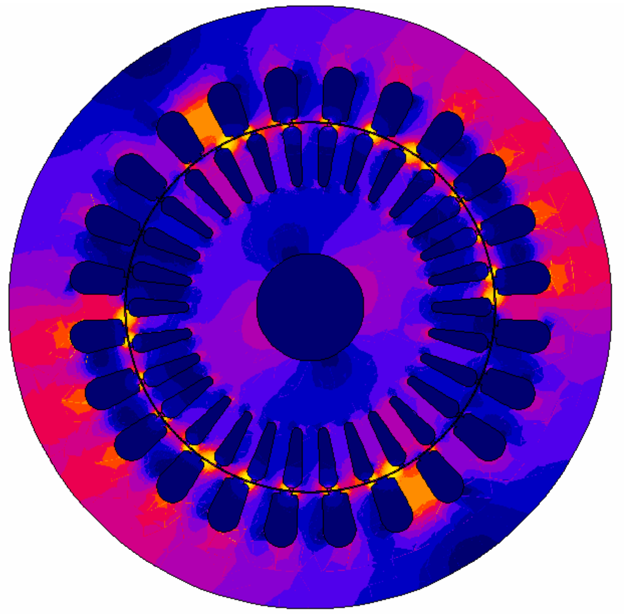
di/dt

Zero sequence voltage

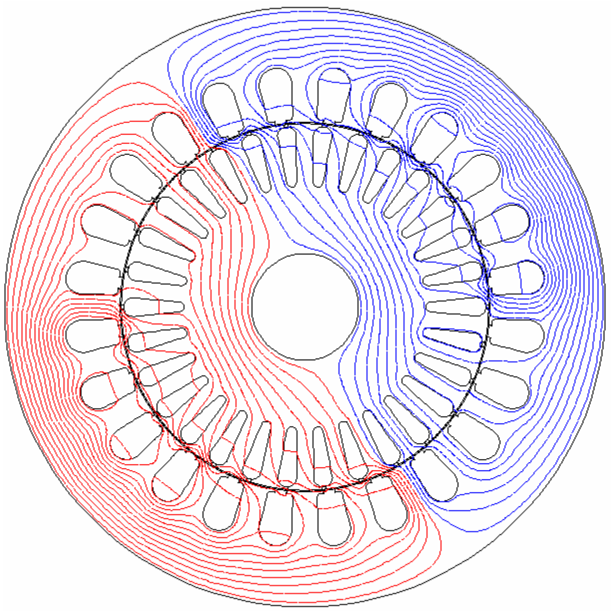
* Zero sequence current for delta-connected machines

Spatial phasors

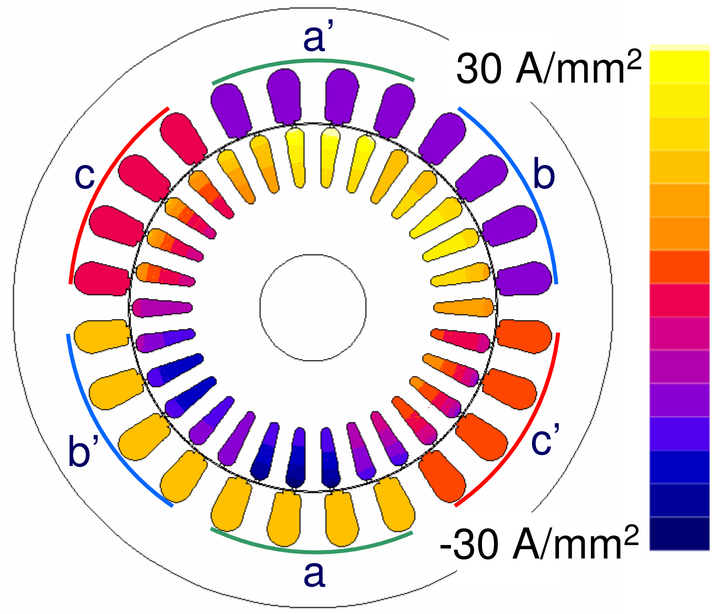
FEM Simulation of a two-pole Induction Machine



Flux density



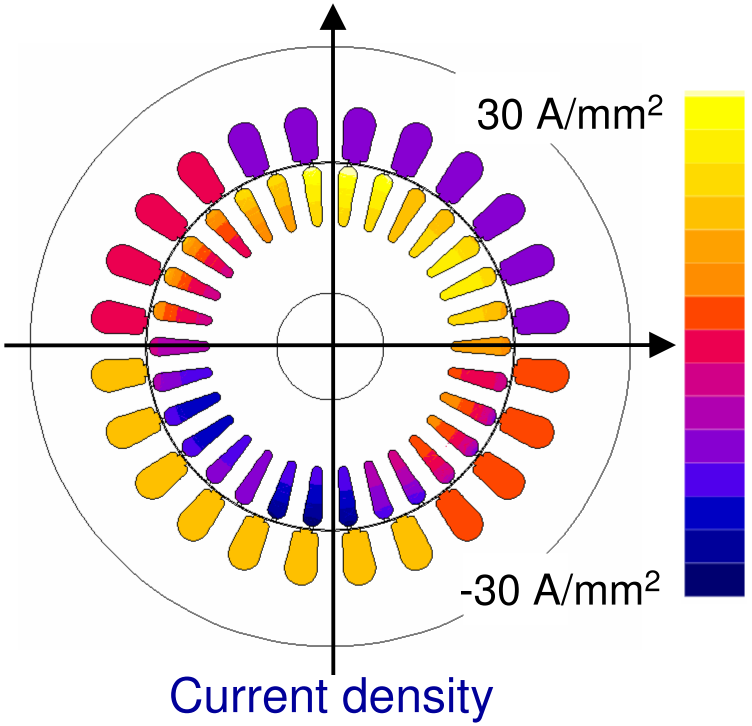
Flux lines

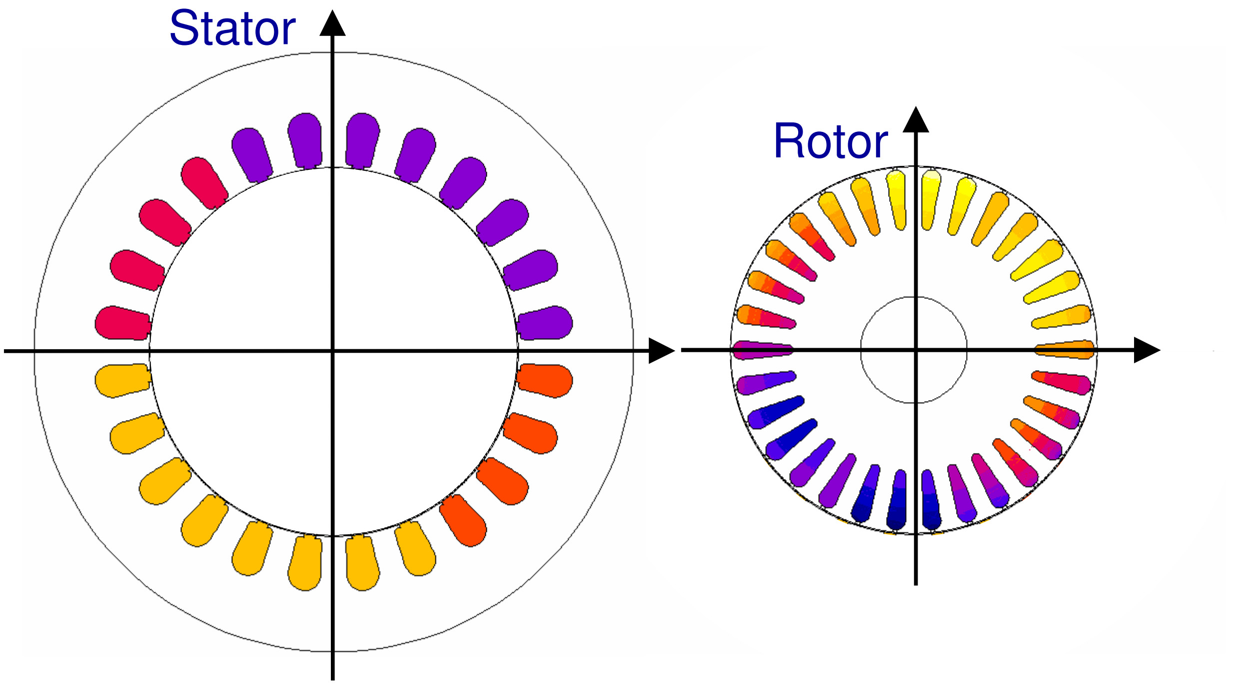


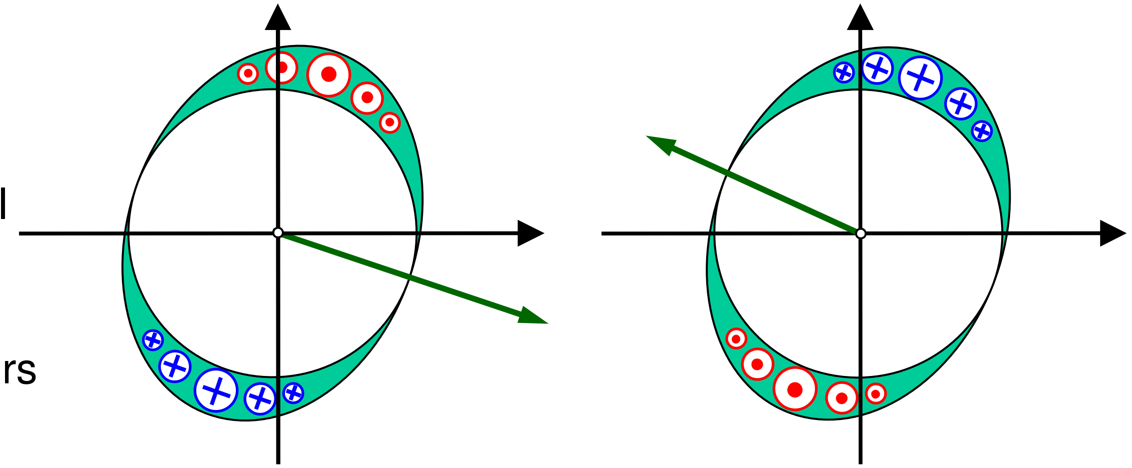
Current density

- ✓ There are three stator windings separated 120 electrical degrees from each other.
- ✓ However, electromagnetic variables involved in the electro-mechanical power conversion that takes place within the machine have a *quasi-sinusoidal* spatial distribution with a period equal to 360 electrical degrees.
- ✓ All electromagnetic quantities can be represented by a complex vector (spatial phasor).

The current sheet and the current complex vector

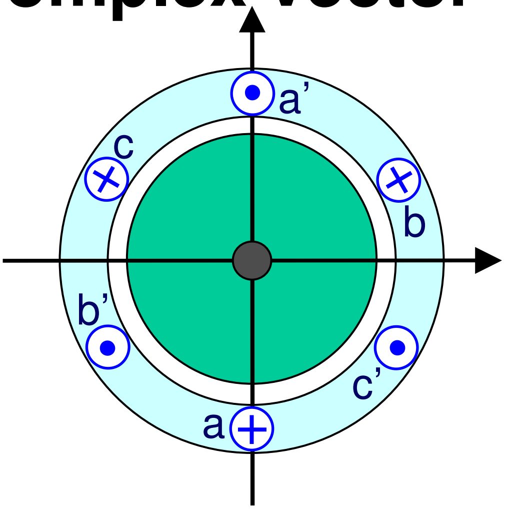


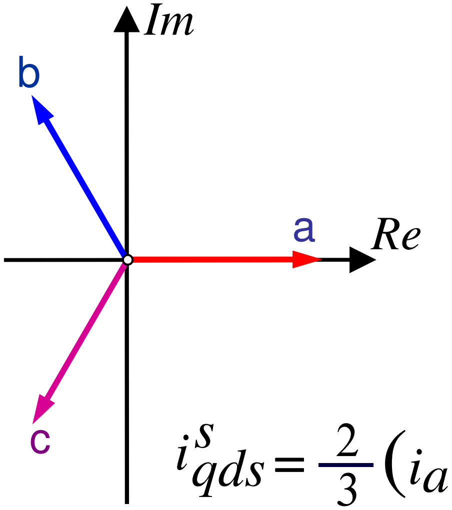


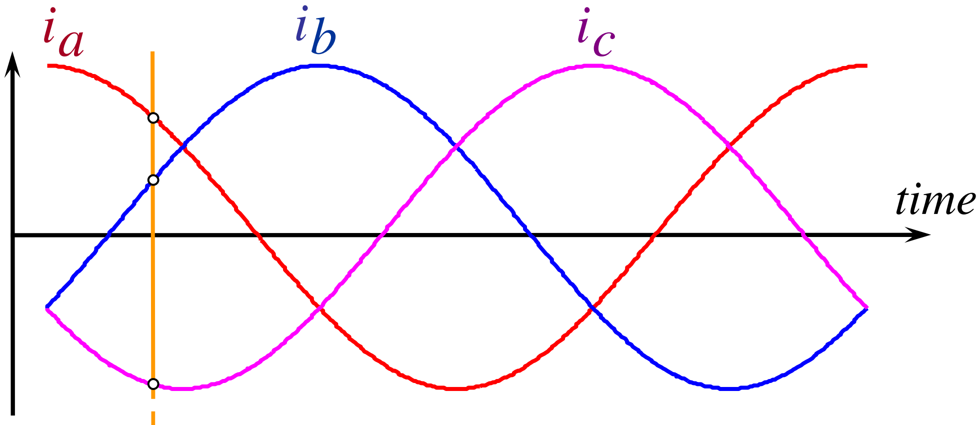


- ✓ The current sheet has a quasi-sinusoidal spatial distribution.
- ✓ The current complex vector is orthogonal to the current sheet, its magnitude being proportional to the total current.
- ✓ Similarly, flux and voltage complex vectors can also be defined.

The stator current sheet and the stator current complex vector



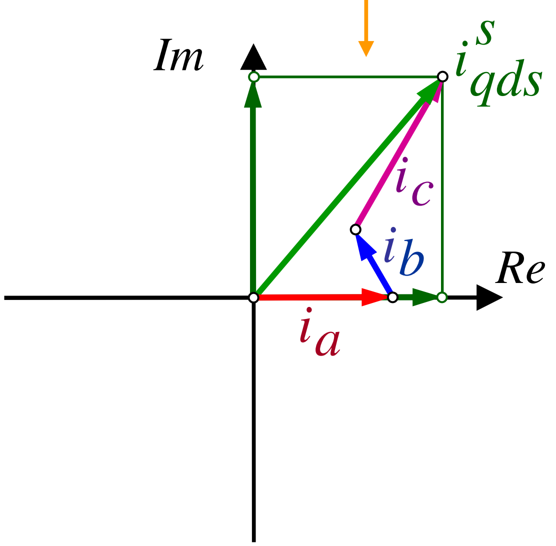


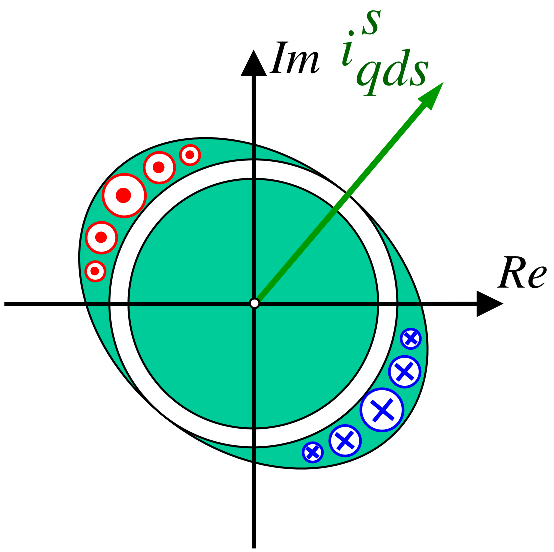


$$i^s_{qds} = \frac{2}{3}\left(i_a + i_b\, e^{j2\pi/3} + i_c\, e^{j4\pi/3}\right) = i^s_{ds} + j\cdot i^s_{qs}$$

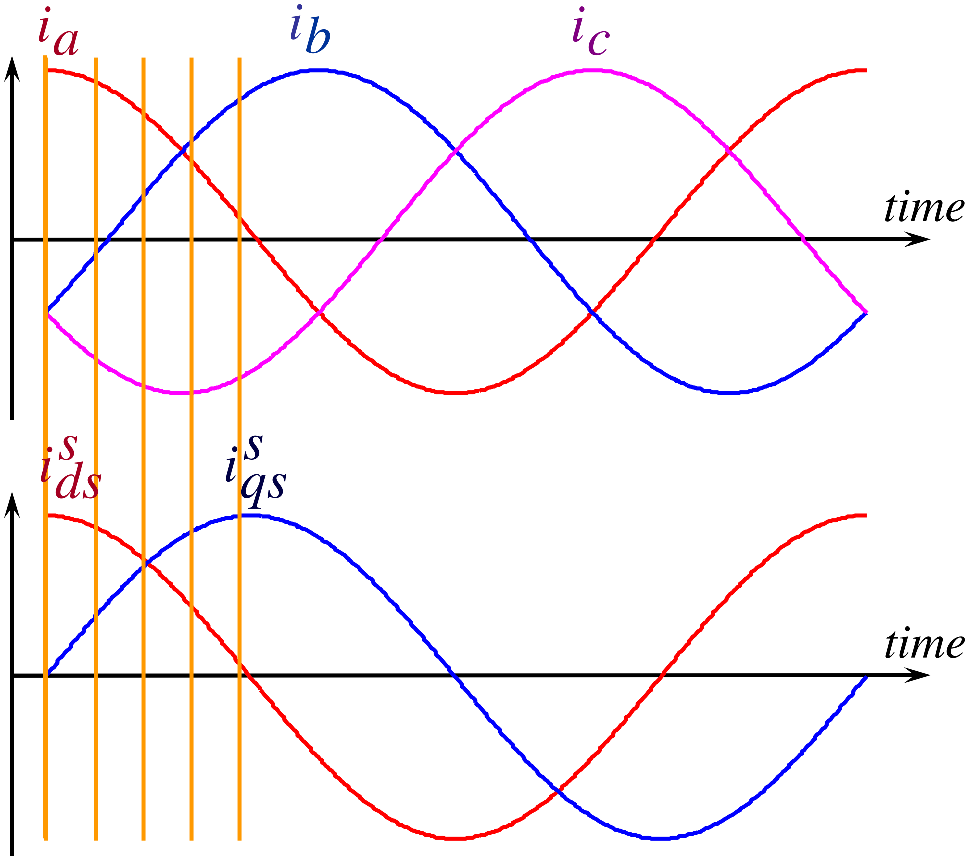
✓ The stator current complex vector is obtained using the measured phase currents and the knowledge of the stator windings spatial position.

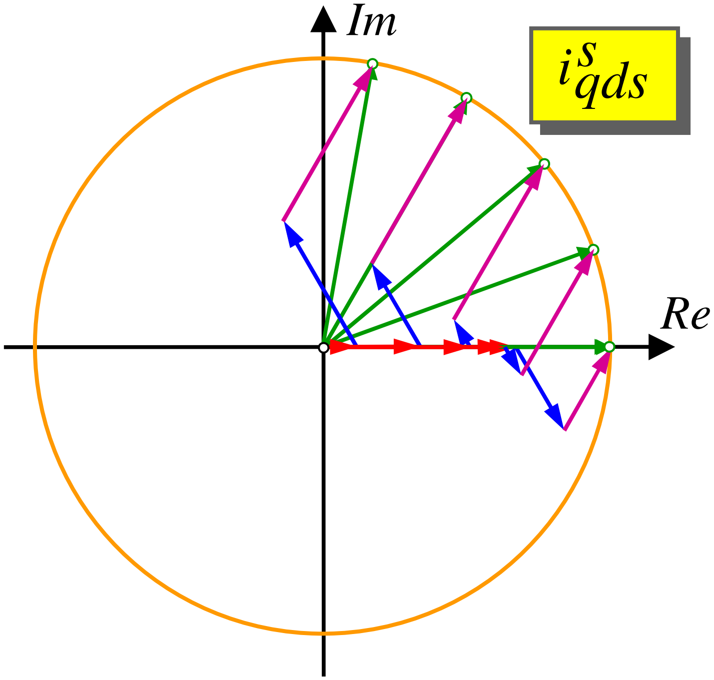
✓ The rotor current complex vector could be obtained in a similar fashion. This is not possible however for the case of squirrel cage induction machines.

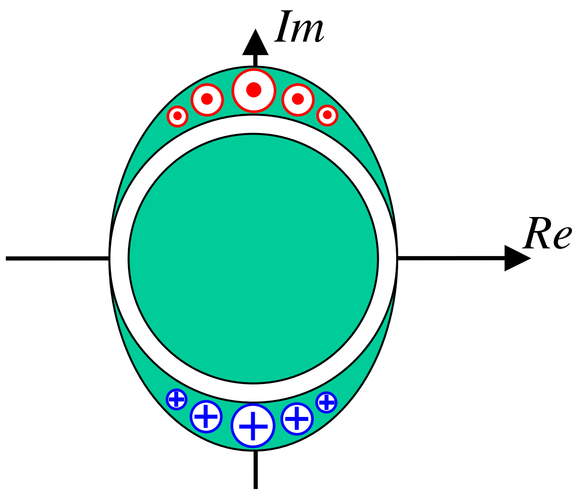




The stator current sheet and the stator current complex vector

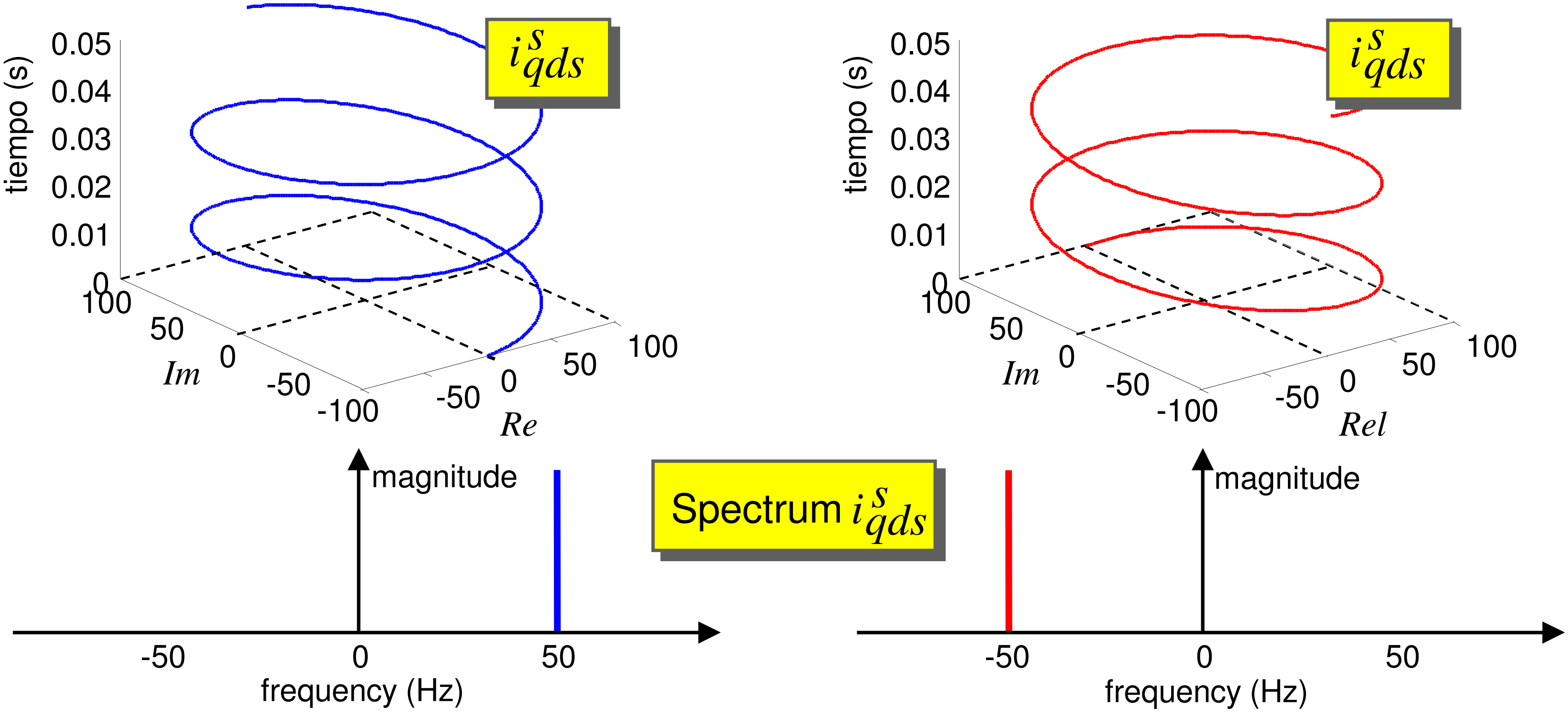






$$i_{qds}^{s} = \frac{2}{3}\left(i_a + i_b \, e^{j2\pi/3} + i_c \, e^{j4\pi/3}\right) = i_{ds}^{s} + j \cdot i_{qs}^{s}$$

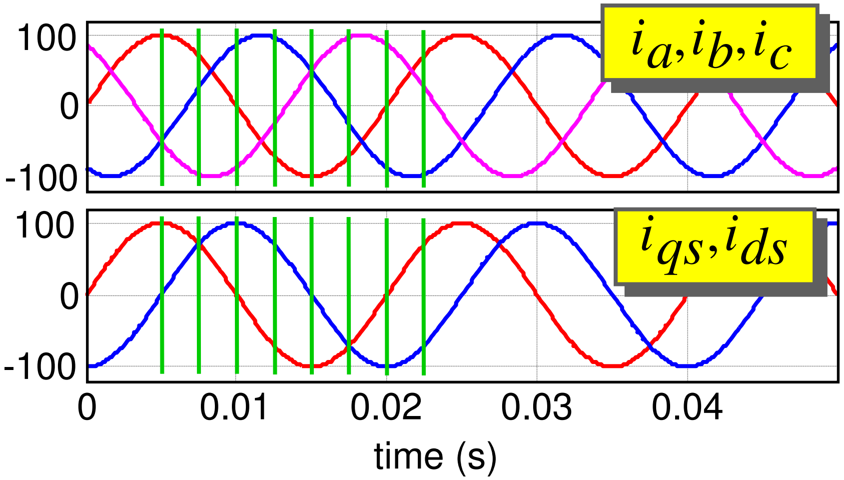
The Fourier Transform of a complex signal



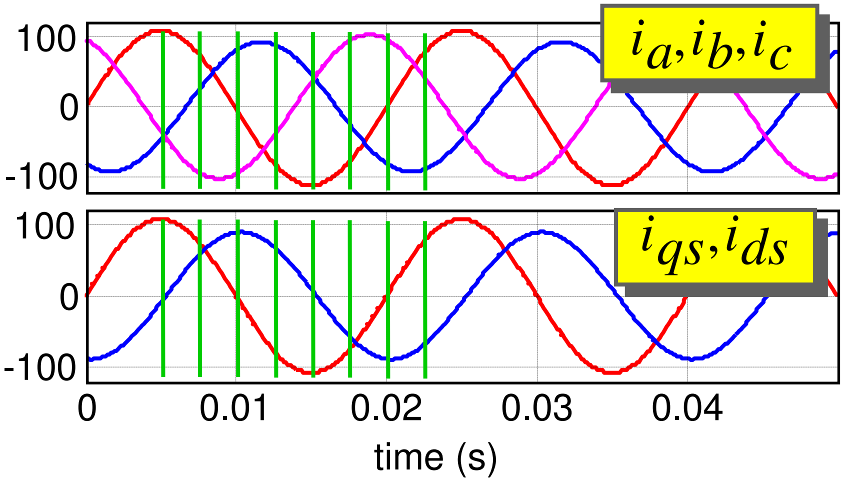
- ✓ The Fourier Transform of a complex vector signal decomposes the signal in individual rotating complex vectors.
- ✓ Complex vectors can rotate both forward and backward ⇨ the frequency spectrum will contain both of positive and negative frequencies.

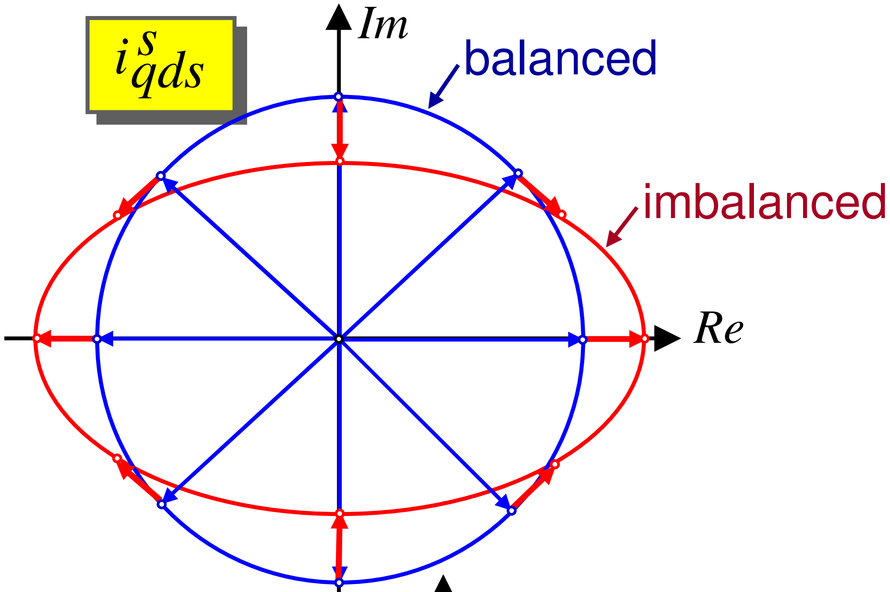
The Fourier Transform of a complex signal

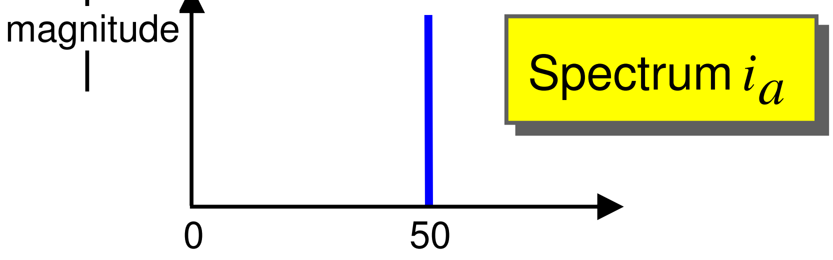
Balanced three-phase system

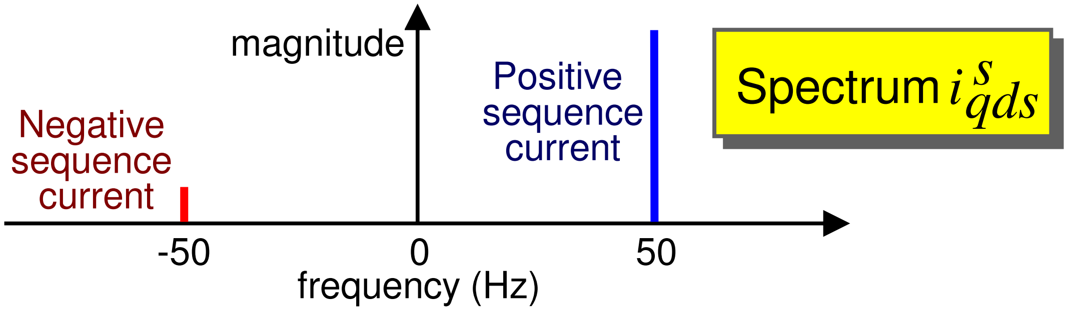


Imbalanced three-phase system



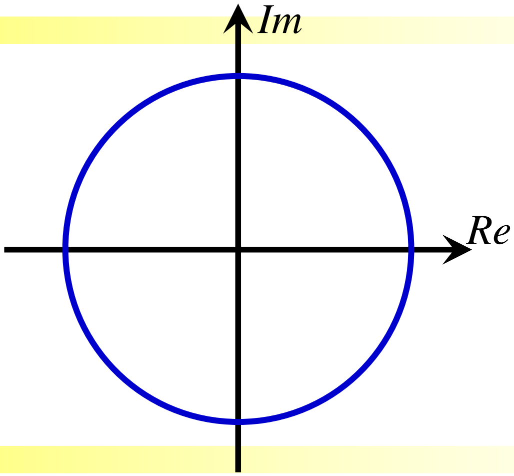


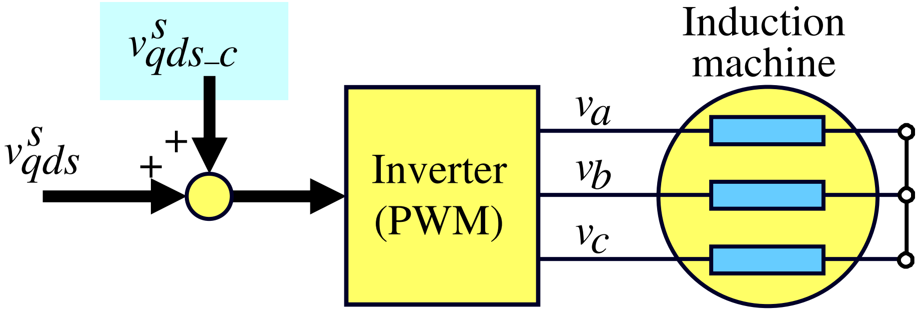




Rotating carrier voltage vector excitation

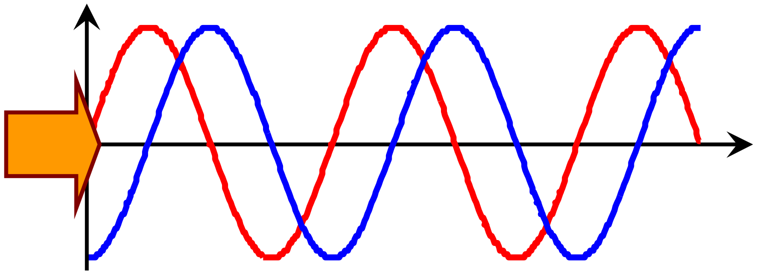
$$v^s_{qds\_c}=V_c\,e^{j\omega_c t}$$





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

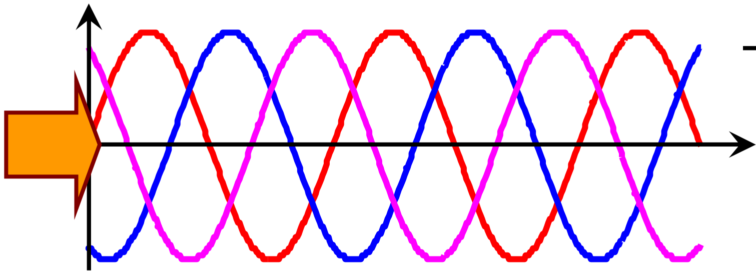
$$v^s_{ds}=V_c\cos(\omega_c-\frac{\pi}{2})$$

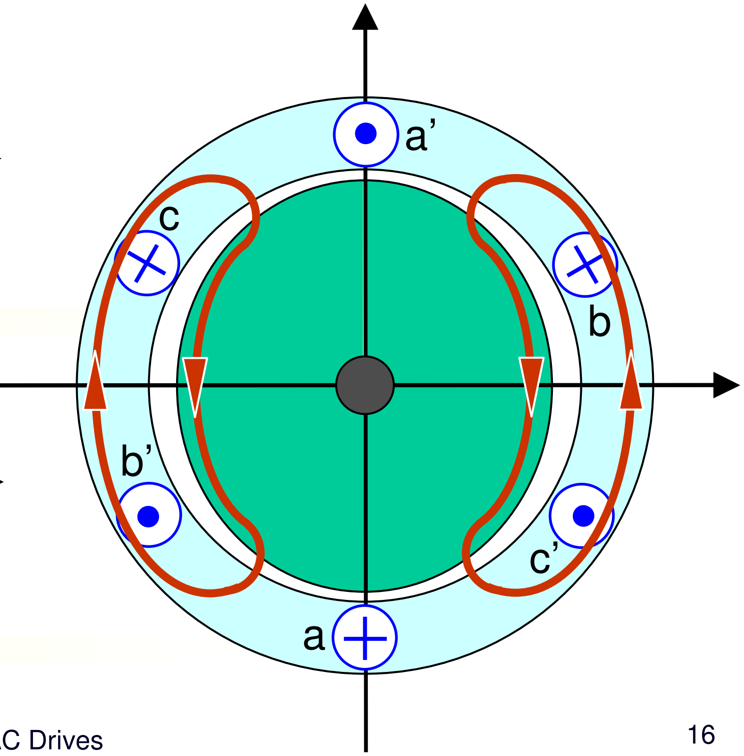


$$v_a=V_c\cos(\omega_c)$$

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

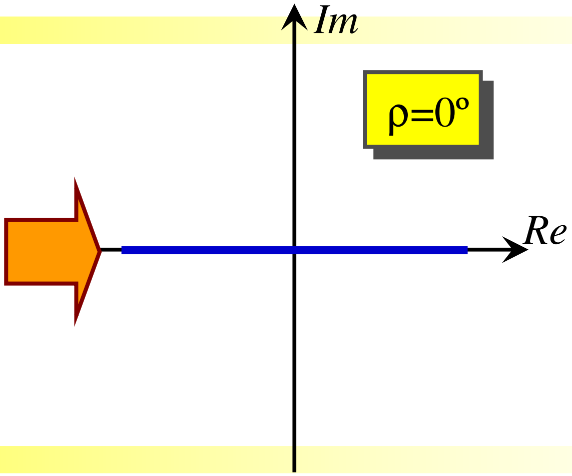
$$v_c=V_c\cos(\omega c-\frac{4\pi}{3})$$

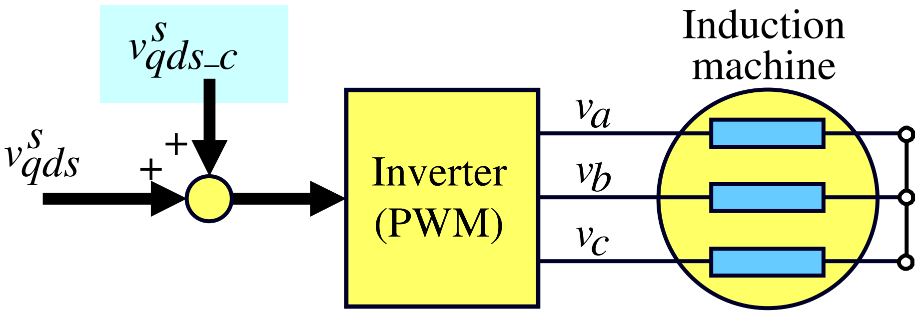




Amplitude modulated carrier voltage vector excitation

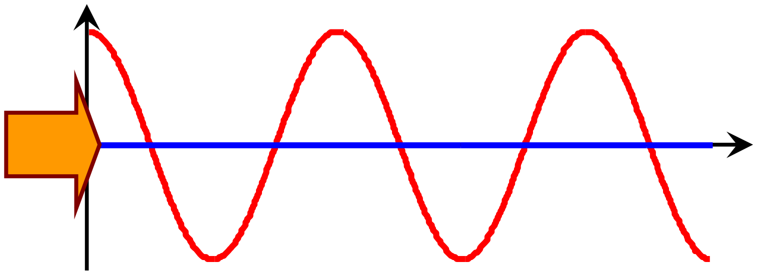
$$v^s_{qds\_c} = V_c \cos(\omega_c) e^{j\rho t}$$





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

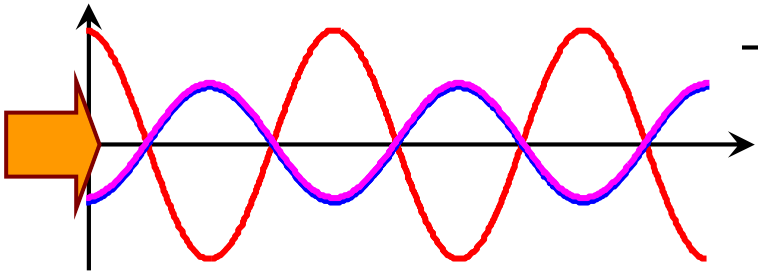
$$v^s_{ds} = V_c \cos(\omega_c) \sin(\rho)$$

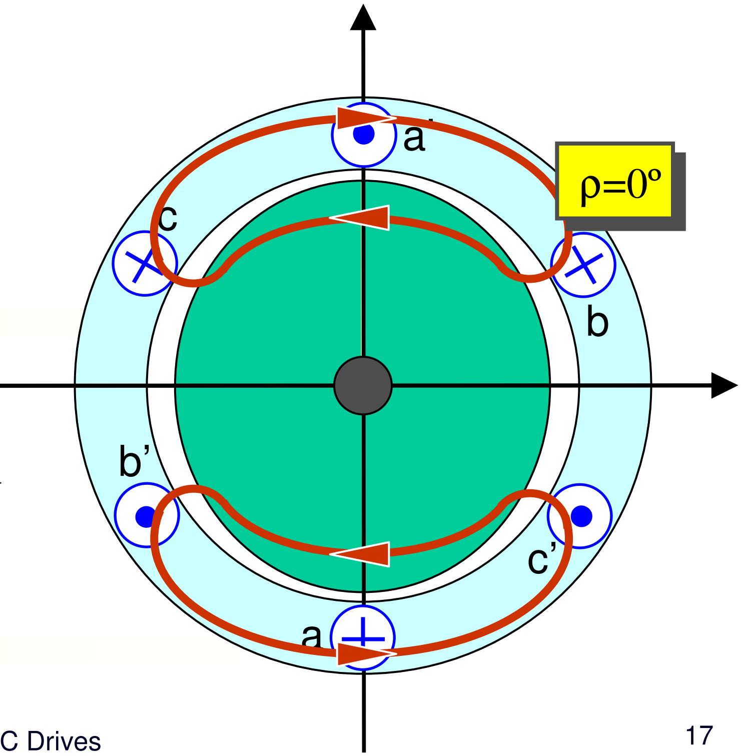


$$v_a = V_c \cos(\omega_c) \cos(\rho)$$

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

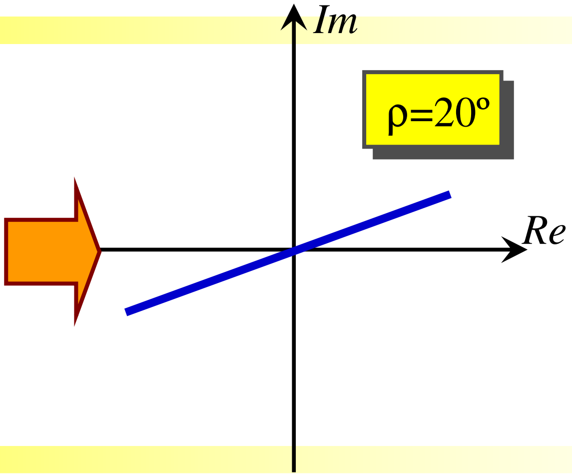
$$v_c = V_c \cos(\omega_c) \cos(\rho - \frac{4\pi}{3})$$

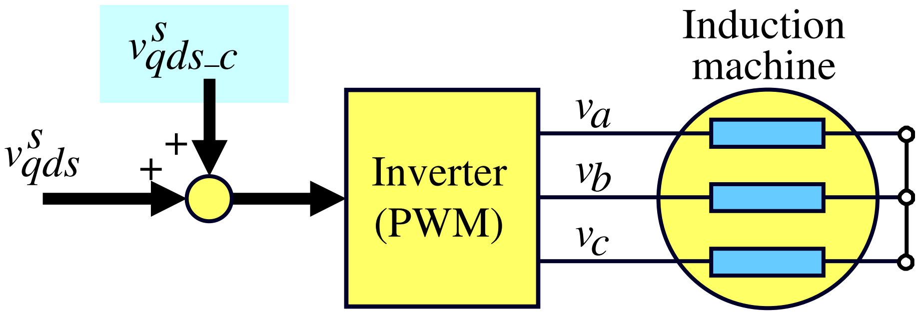




Amplitude modulated carrier voltage vector excitation

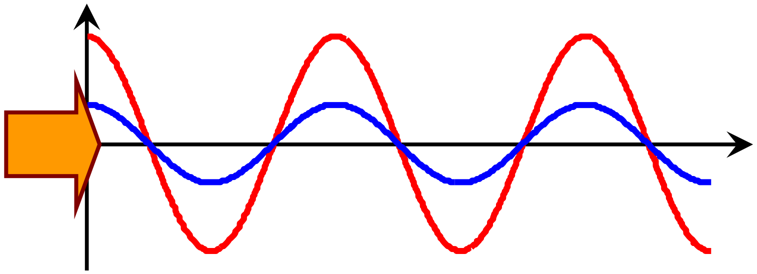
$$v^s_{qds\_c} = V_c \cos(\omega_c) e^{j\rho t}$$





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

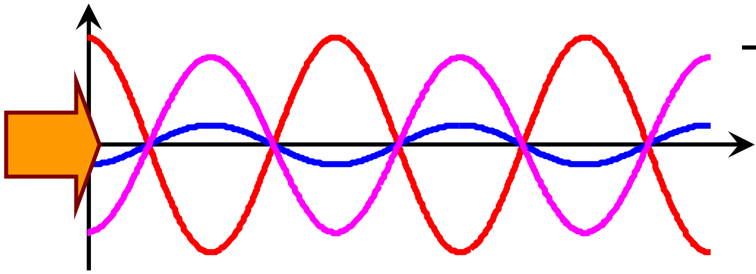
$$v^s_{ds} = V_c \cos(\omega_c) \sin(\rho)$$

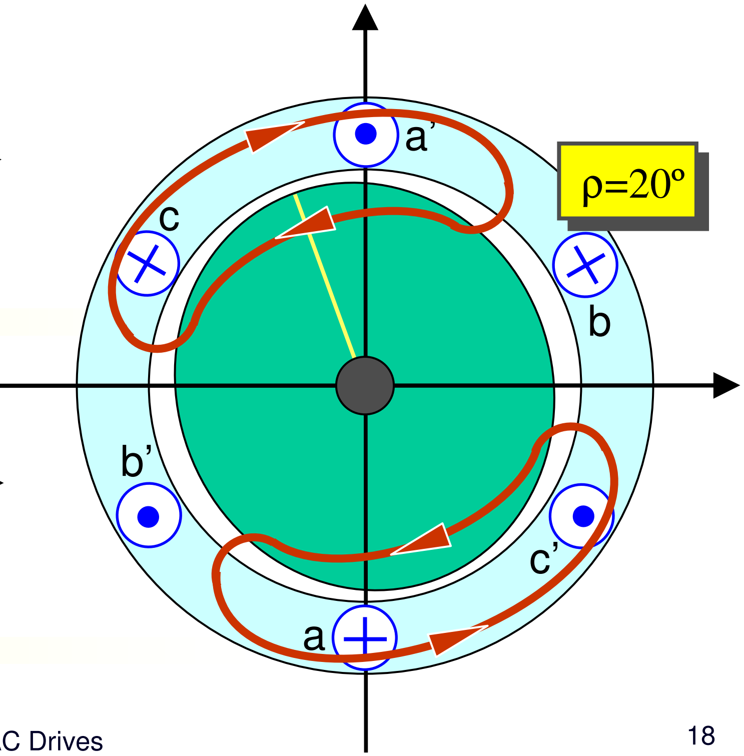


$$v_a = V_c \cos(\omega_c) \cos(\rho)$$

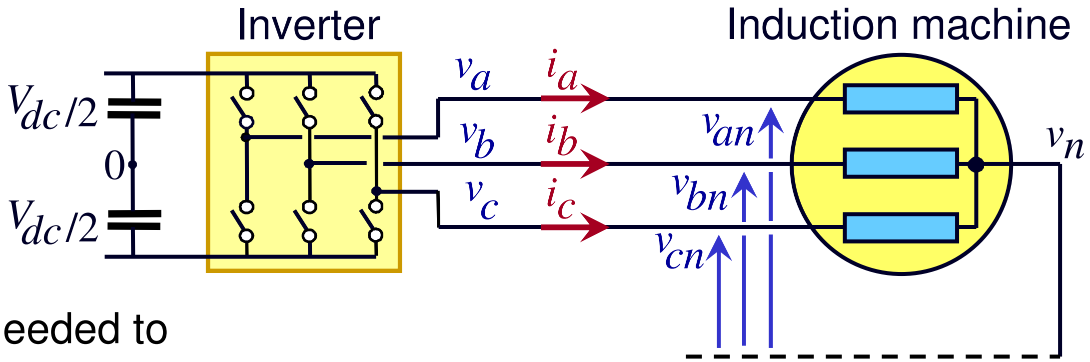
$$v_b = V_c \cos(\omega_c) \cos(\rho - \frac{2\pi}{3})$$

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

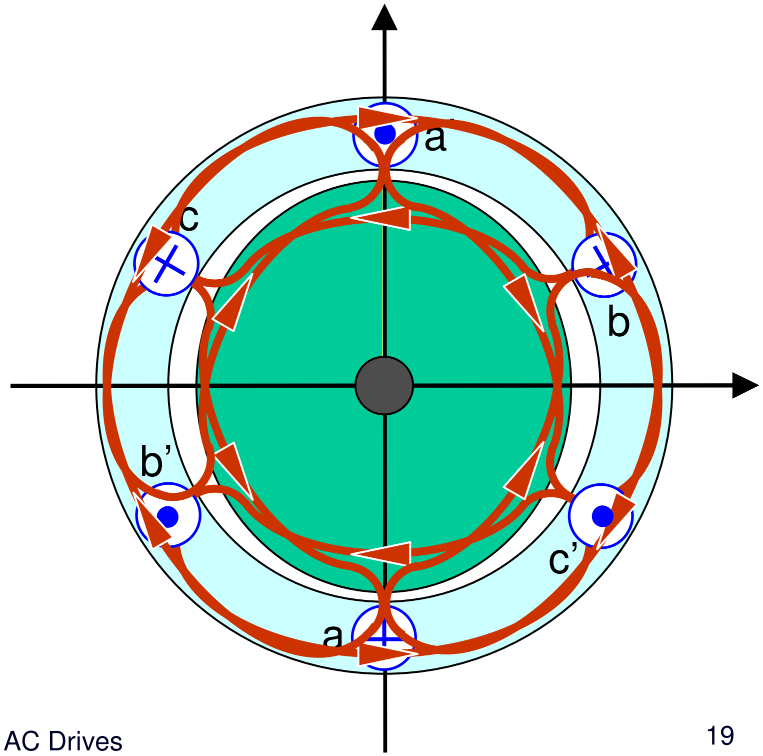




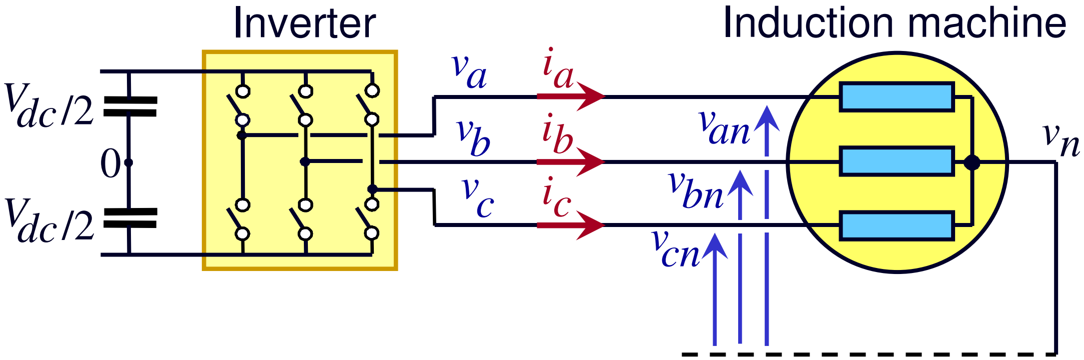
PWM harmonics based high frequency excitation

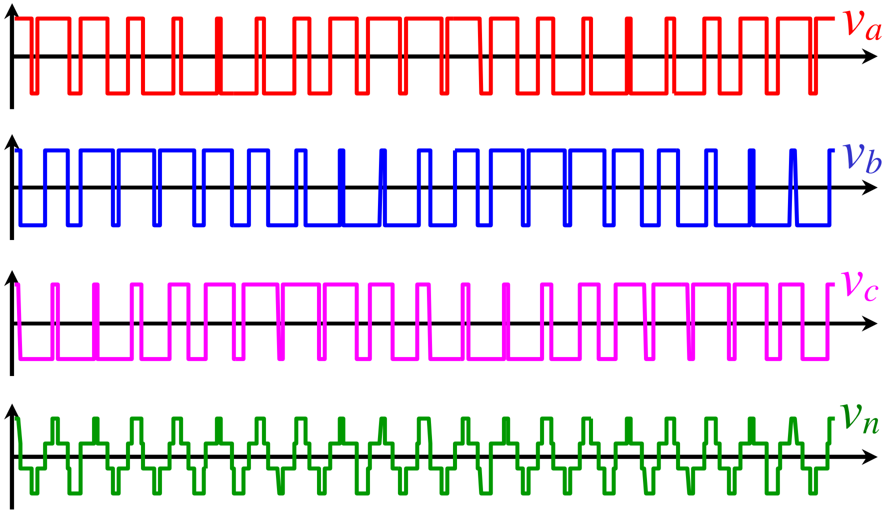


- ✓ Makes uses of the fast PWM transitions.
- ✓ Modification of th normal PWM pattern is needed to obtain suitable information.
- ✓ Different variables can be measured to detect the saliency position:
  - Zero sequence voltage.
    - Requires an additional sensor and access to the terminal box.
    - Strongly influenced by parasitic phenomena (cables length, cables shielding, …).
  - di/dt (currents derivative). Though the current derivative could initially be derived from two current measurements, di/dt sensors normally need to be used in practice (e.g. Rogowski coils).
- ✓ Acquisition of signals is complicated, as needs to be synchronized with PWM transitions.

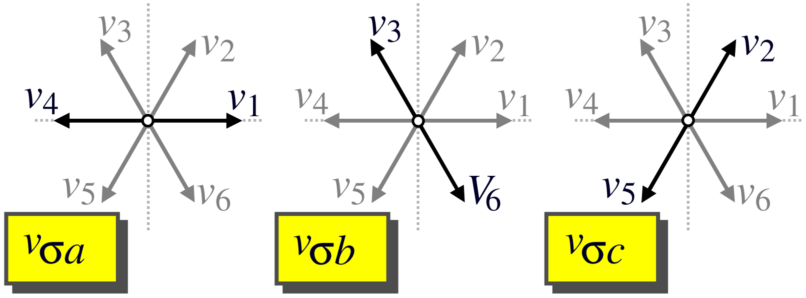


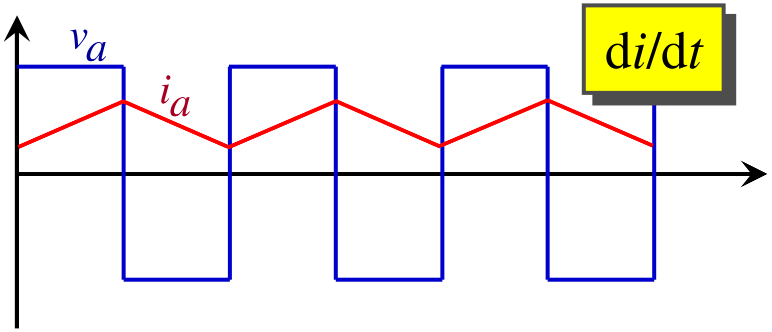
PWM harmonics based high frequency excitation





Zero-sequence voltage



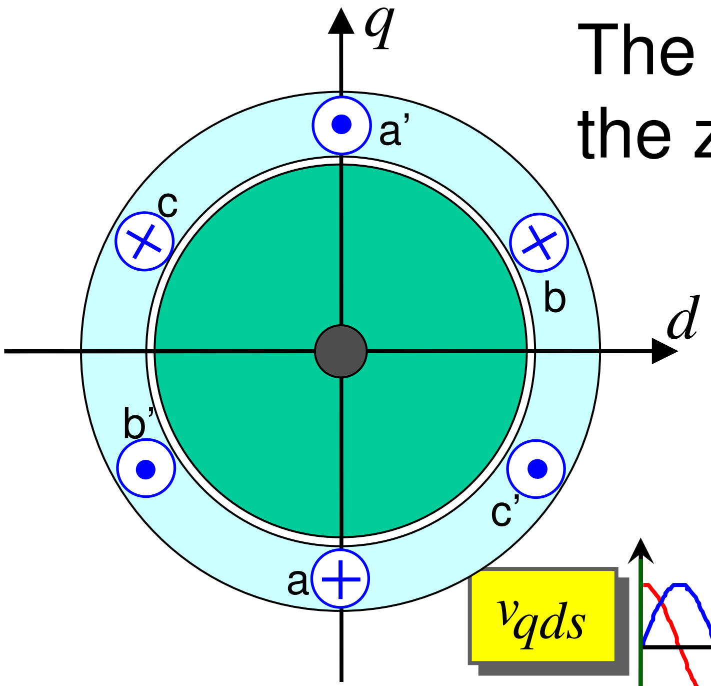


$$v_\sigma = \frac{v_{an} + v_{bn} + v_{cn}}{3}$$

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

Rotating carrier voltage vector excitation:

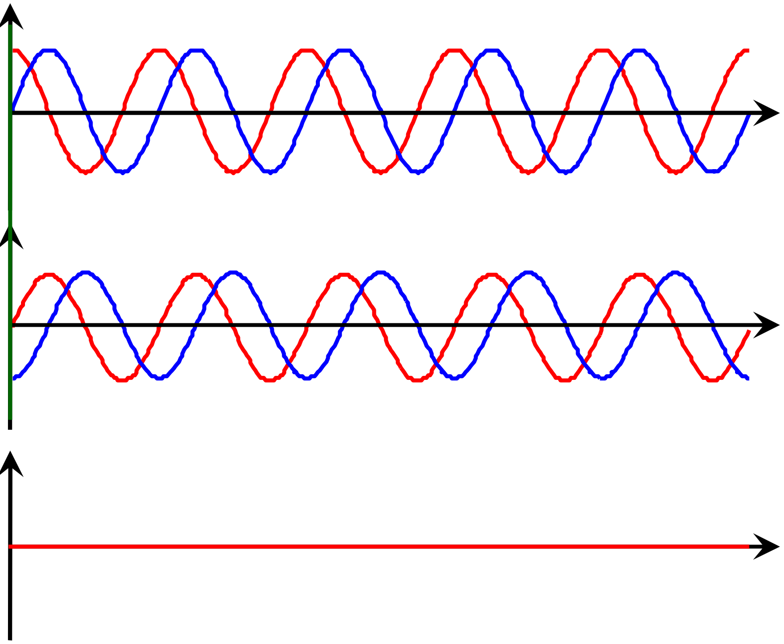
The carrier signal current and the zero sequence carrier signal voltage



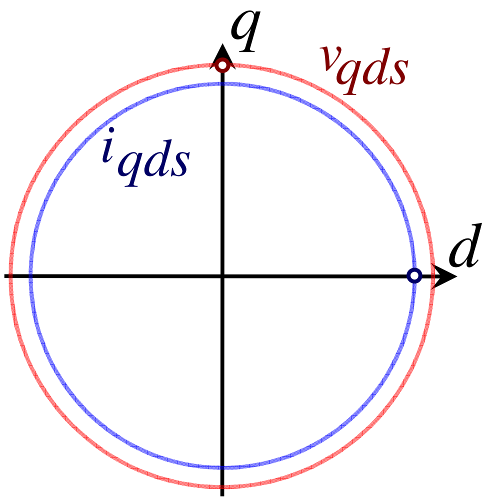
Symmetric machine

- The carrier current trajectory is a circle.

- There is no zero sequence carrier signal voltage.

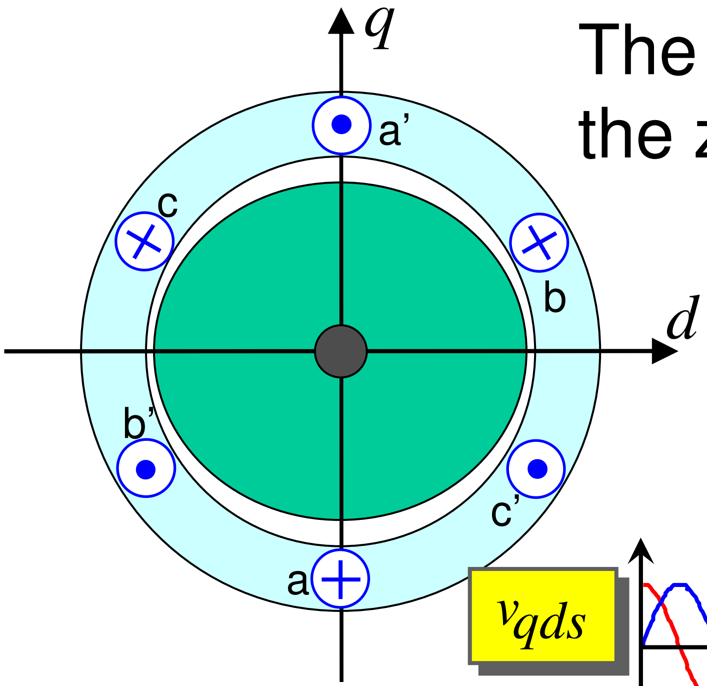


$$v_0 = \frac{(v_{an} + v_{bn} + v_{cn})}{3}$$



Rotating carrier voltage vector excitation:

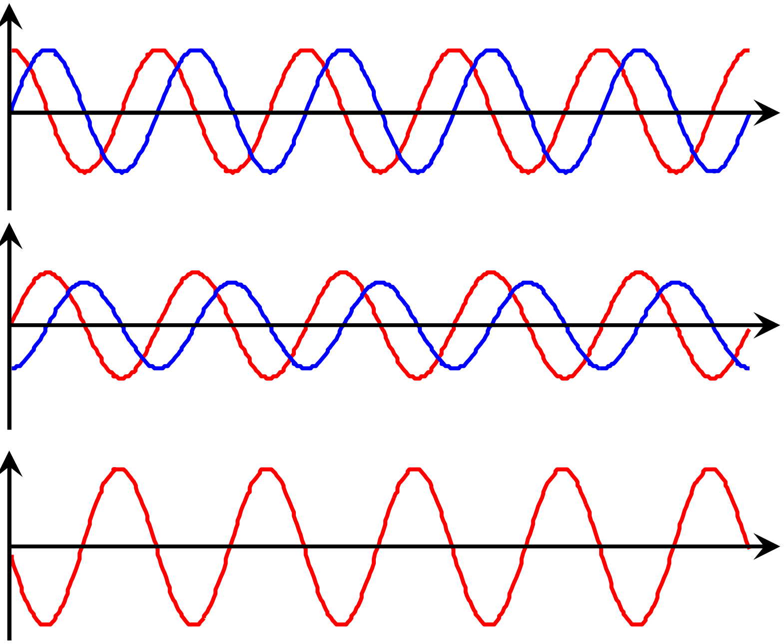
The carrier signal current and the zero sequence carrier signal voltage



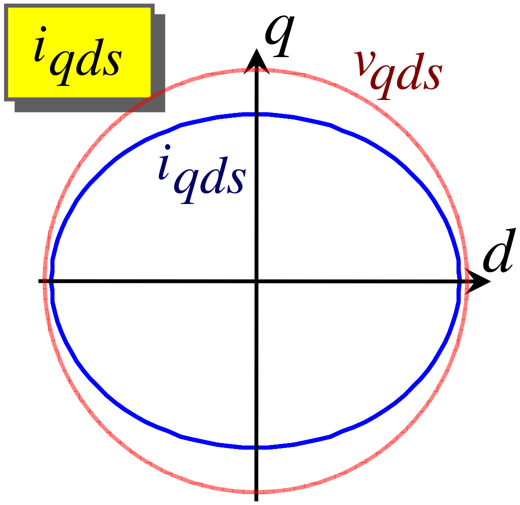
Asymmetric machine

- 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



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



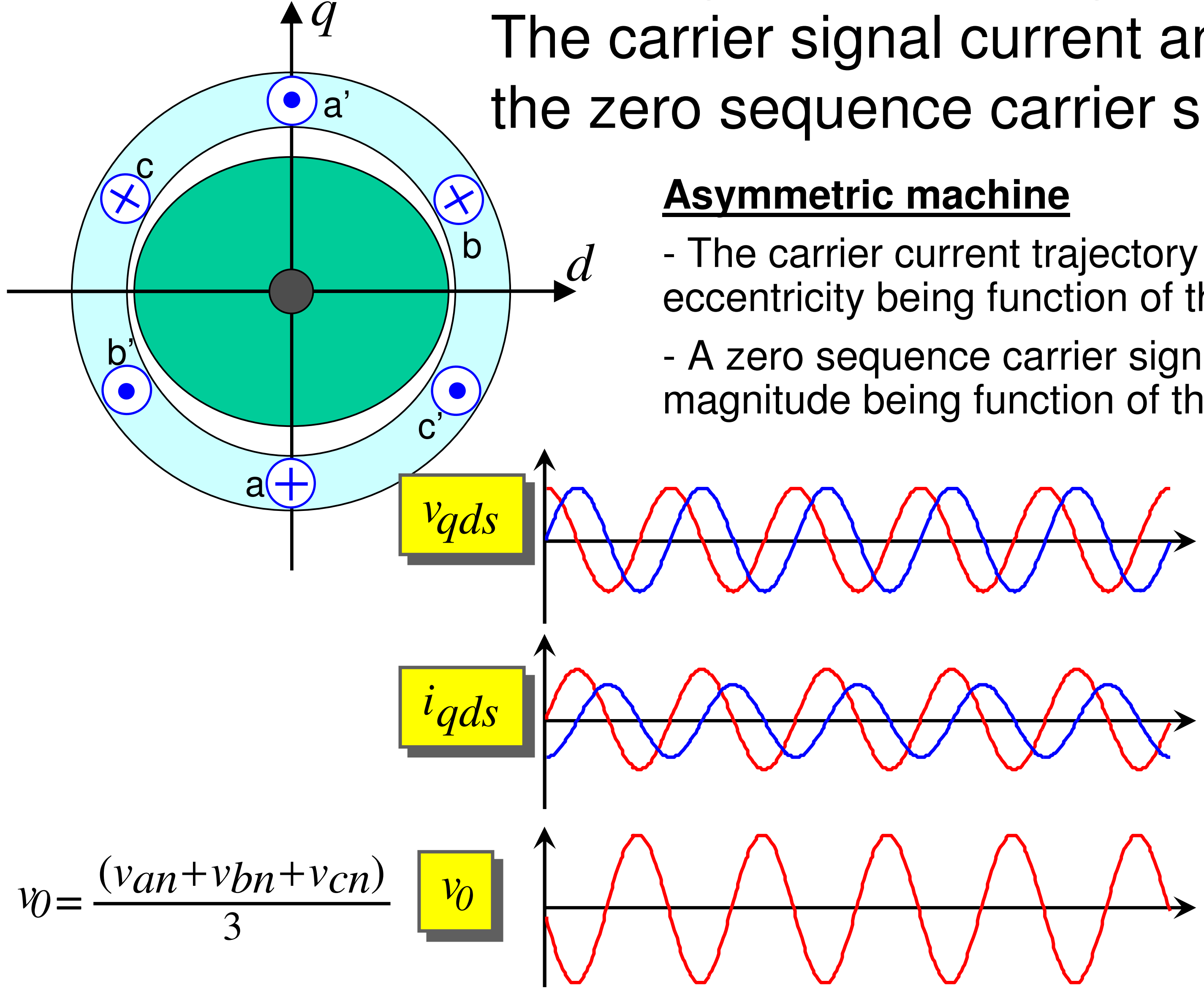
Rotating carrier voltage vector excitation:

The carrier signal current and the zero sequence carrier signal voltage

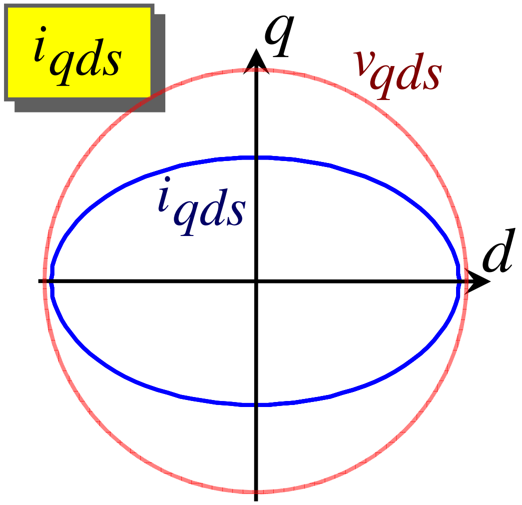
Asymmetric machine

- The carrier current trajectory is an ellipsis, its eccentricity being function of the level of asymmetry.

- A zero sequence carrier signal voltage exists, its magnitude being function of the level of asymmetry.

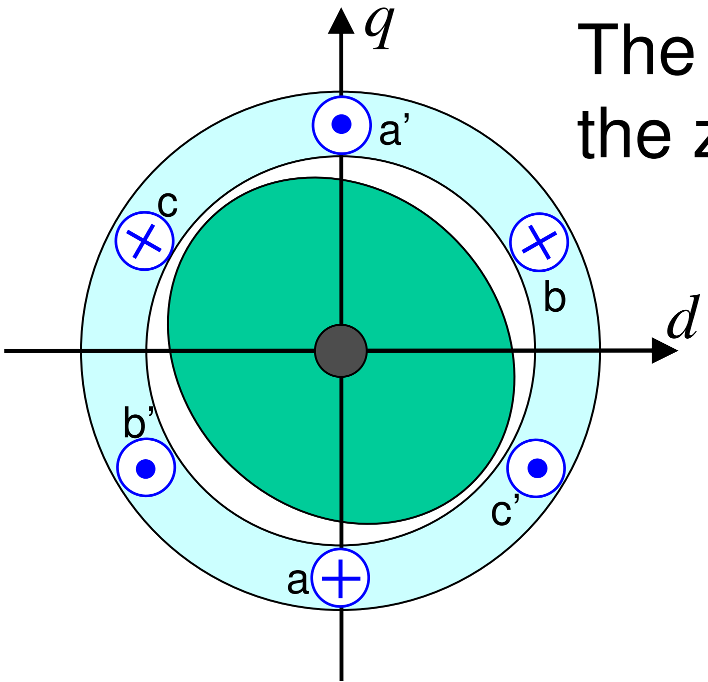


$$v_0 = \frac{(v_{an}+v_{bn}+v_{cn})}{3}$$



Rotating carrier voltage vector excitation:

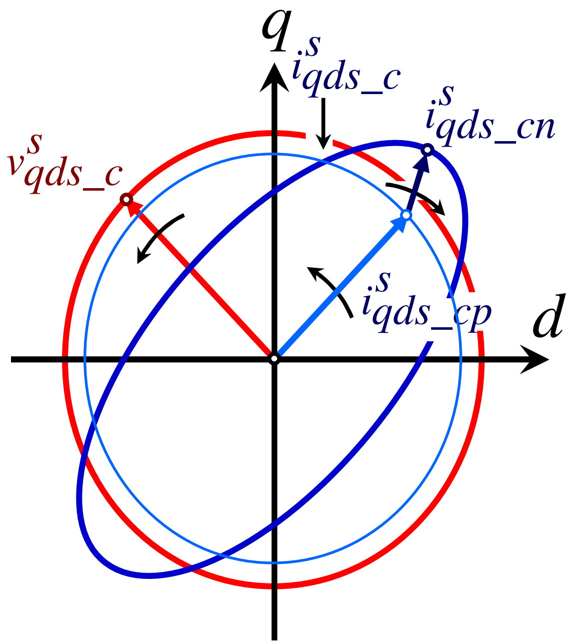
The carrier signal current and the zero sequence carrier signal voltage



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

$$i^s_{qds\_c} = -jI_{cp} e^{j\omega_c t} - jI_{cn} e^{j(h\theta_e - \omega_c t)} = i^s_{qds\_cp} + i^s_{qds\_cn}$$

$$v^s_{0sc} = V_{0ch}\cos(\omega_c t + h\theta_e) + V_{0c2h}\cos(\omega_c t - 2h\theta_e)$$



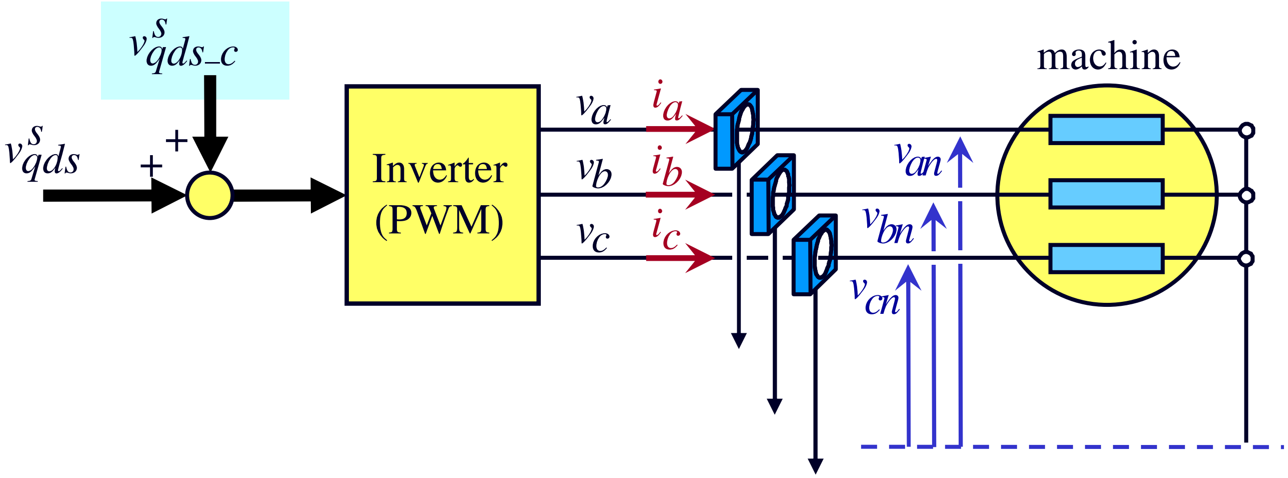
$i^s_{qds\_cp}$: Positive sequence carrier signal current. Results from the symmetric part of the machines, and does not contain any saliency related information.

$i^s_{qds\_cn}$: Negative sequence carrier signal current. Results from the asymmetric part of the machine and contains information on the magnitude and spatial position of the saliency.

v^s_{0sc} : Zero sequence carrier signal voltage. Results from the asymmetric part of the machine and contains information on the magnitude and spatial position of the saliency.

Measurement of the carrier signals:

The carrier signal current and
the zero sequence carrier signal voltage



$$i^s_{qds}=\frac{2}{3}\left(i_a+i_b\,e^{j2\pi/3}+i_c\,e^{j4\pi/3}\right)$$

- Complex vector signal (at least two sensors are needed)
- Current sensors are normally present for control/protection purposes

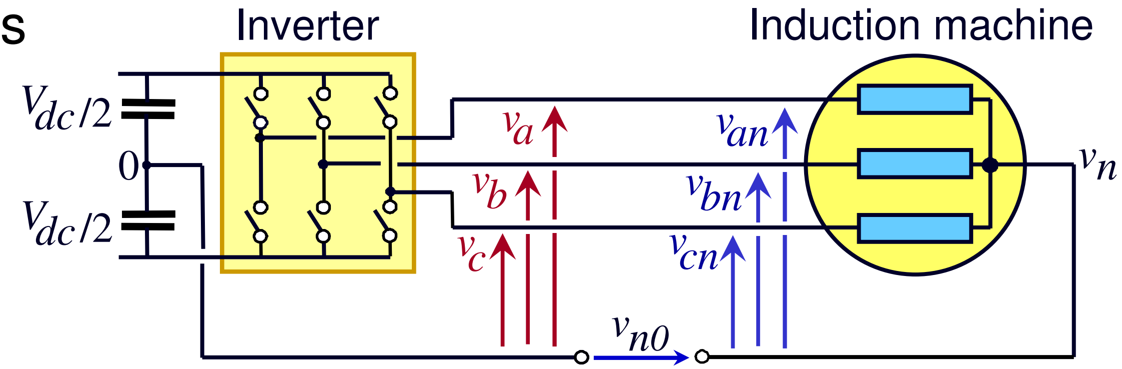
$$v_0=\frac{(v_{an}+v_{bn}+v_{cn})}{3}$$

- Scalar signal (one sensor should be enough)
- Requires access to the terminal box
- Requires an additional sensor

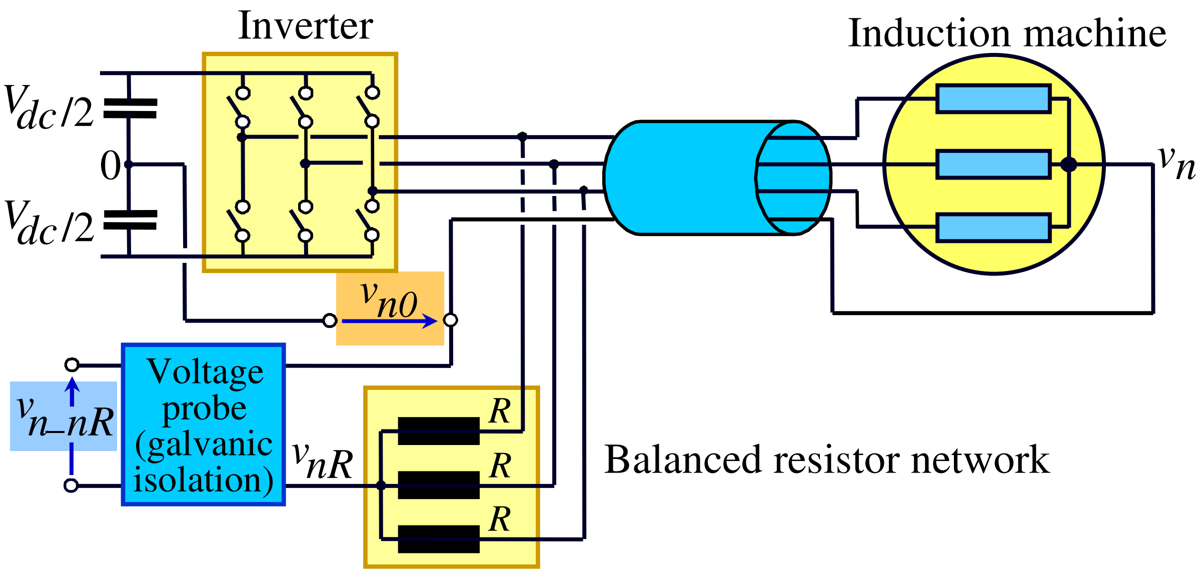
Measurement of the zero sequence voltage

Using three voltage sensors

$$v_{0s}^{s} = \frac{(v_{an}+v_{bn}+v_{cn})}{3}$$



Using an auxiliary resistor network and a single voltage sensor

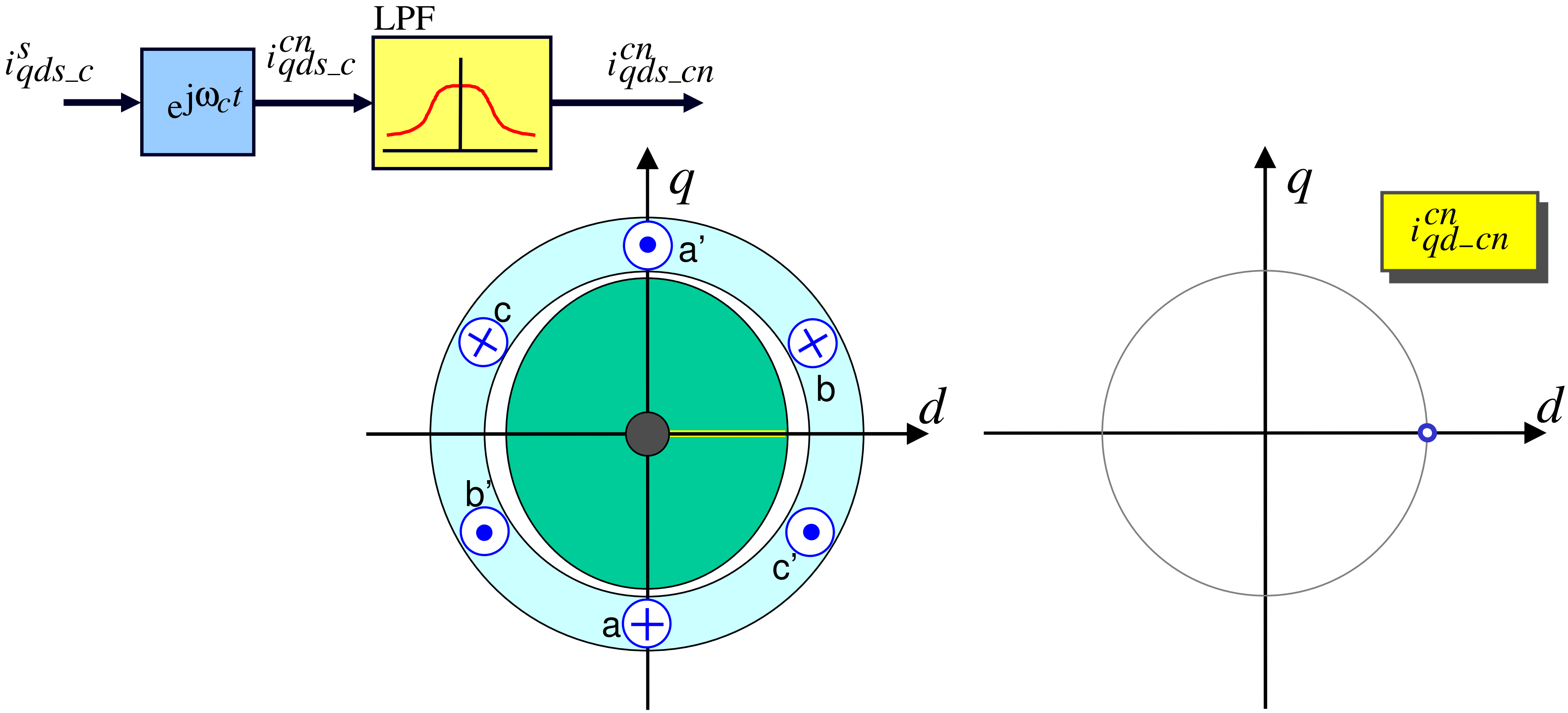


The auxiliary resistor network measures (and decouples) the zero sequence voltage generated by the inverter.

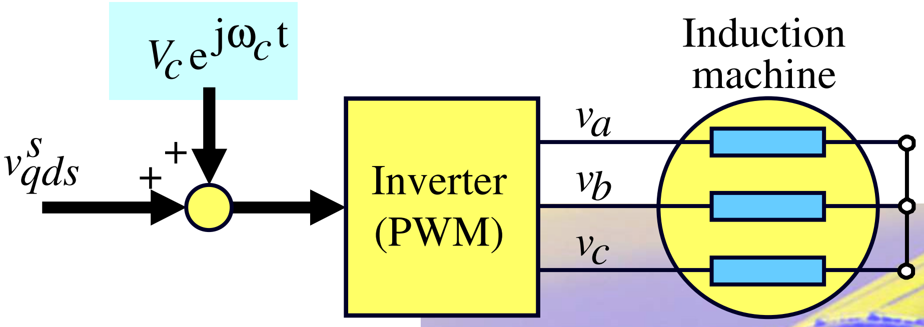
Processing of the carrier signal current:

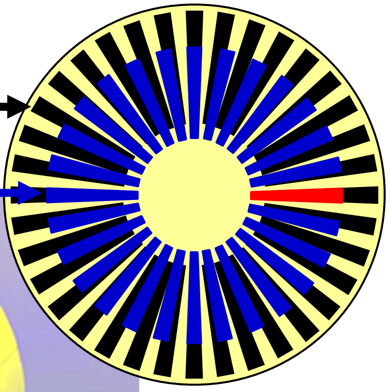
Separation of the negative sequence carrier signal current

$$i^{s}_{qds\_c} = -jI_{cp}e^{j\omega_c t} - jI_{cn}e^{j(2\theta_r - \omega_c t)}$$



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

1.1 kW, p=4

S=36, R=28, skewed

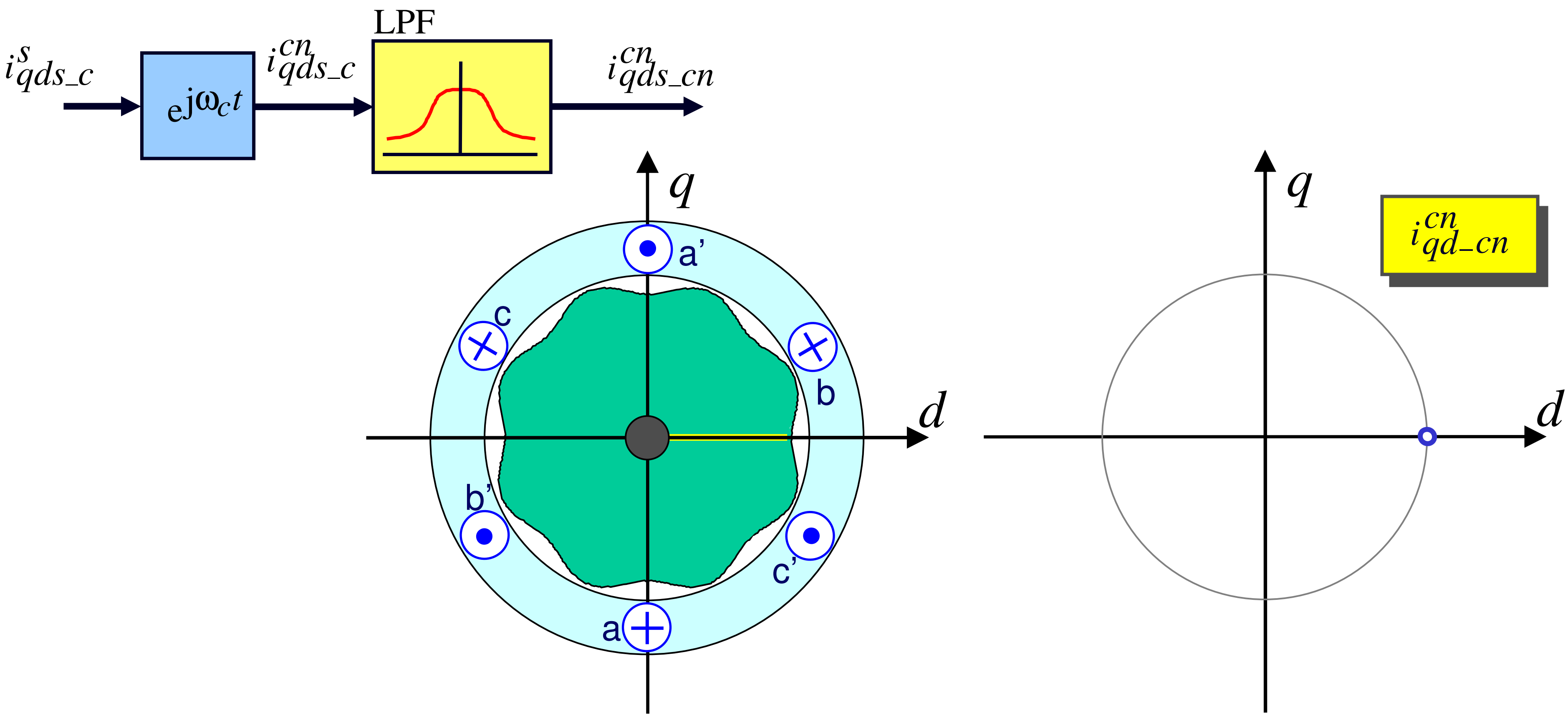
The saliency rotates at a frequency $\dfrac{R \cdot \omega_{rm}}{|R-S|}$

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

Processing of the carrier signal current:

Separation of the negative sequence carrier signal current

$$i^s_{qds\_c} = -jI_{cp}e^{j\omega_c t} - jI_{cn}e^{j(8\theta_r - \omega_c t)}$$



Secondary saliencies: Saturation induced saliencies

✓Injection of fundamental current during the normal operation of the machine results in additional saliencies (asymmetries).

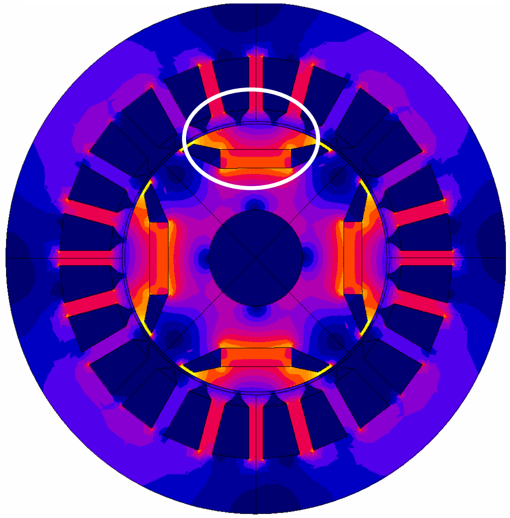
✓These saliencies are caused (and therefore related) to the fundamental fluxes, acting like a disturbance to the rotor position dependent saliency.

✓Saturation results in:

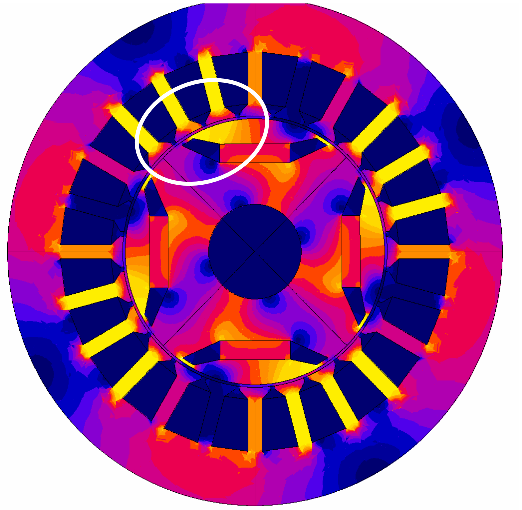
  - Shift of the saliency angle.
  - Variations of the saliency ratio.
  - Secondary spatial harmonics of the saliency (i.e. saliencies with a non-sinusoidal spatial distribution).

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

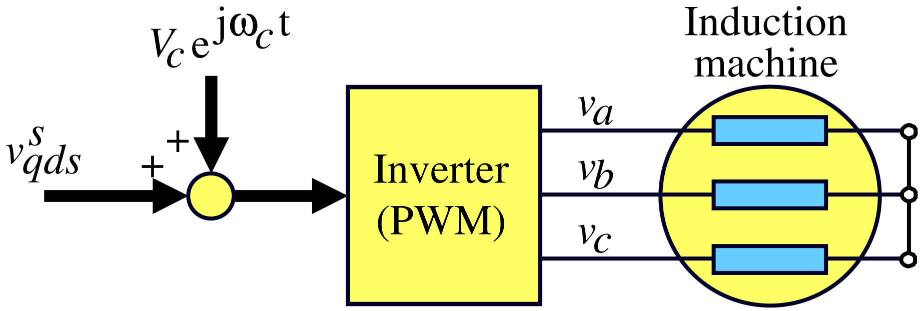
IPMSM, no load

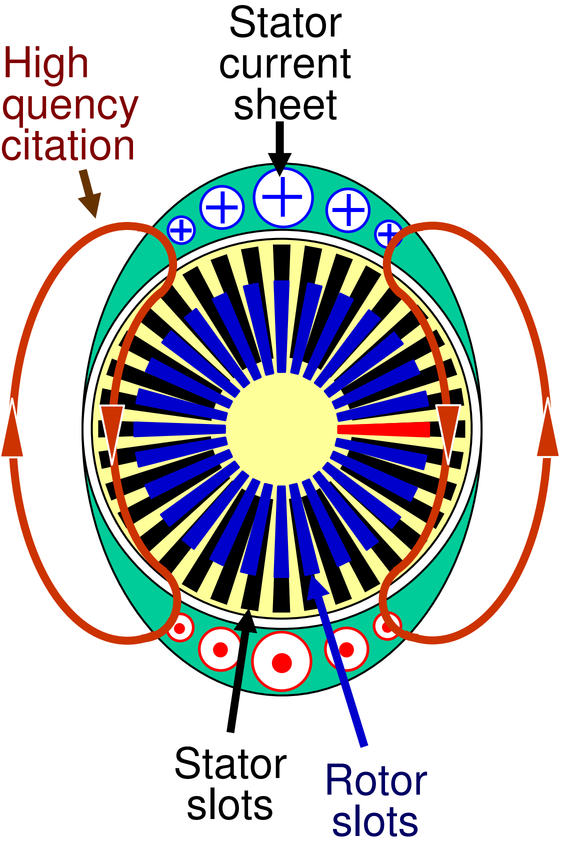


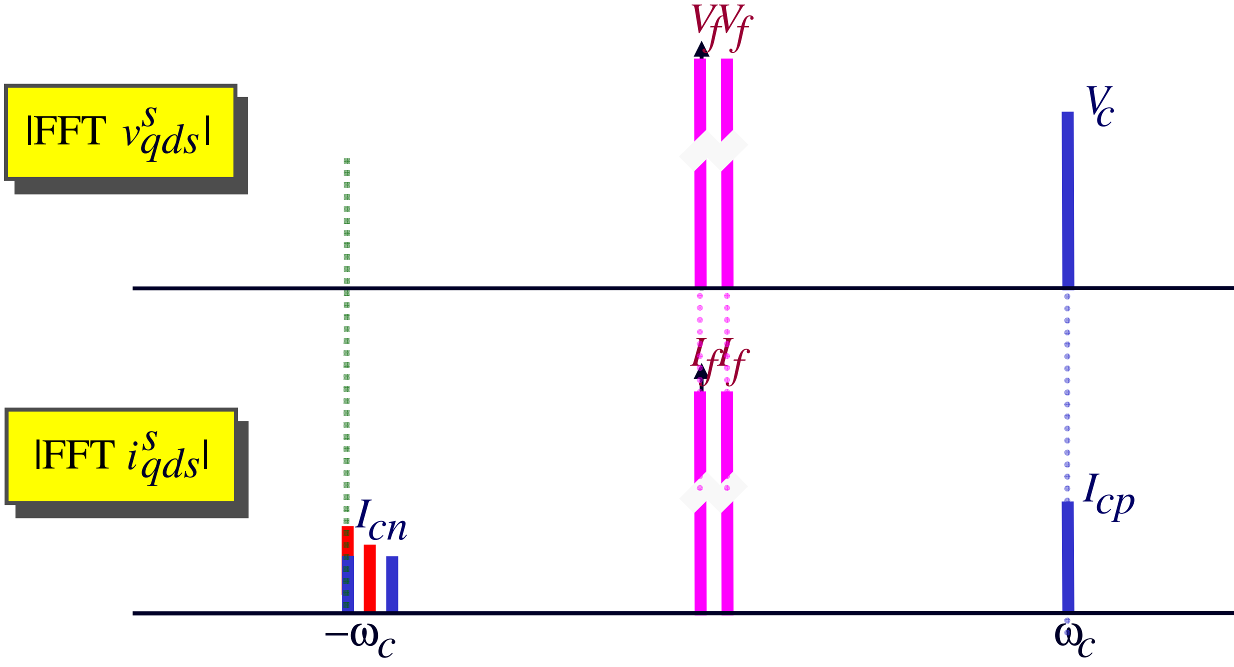
IPMSM, rated torque



Secondary saliencies:
Saturation induced saliencies

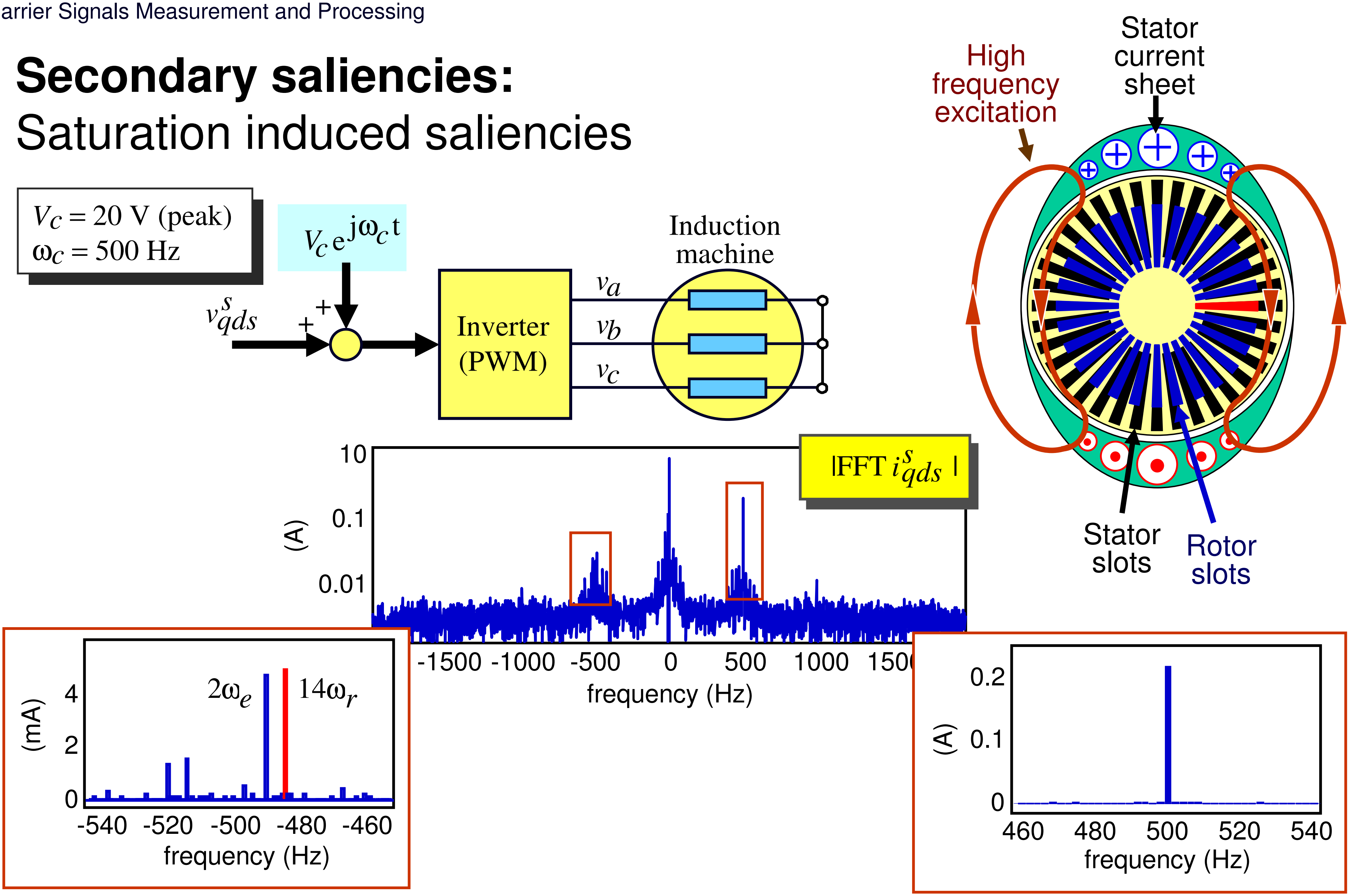




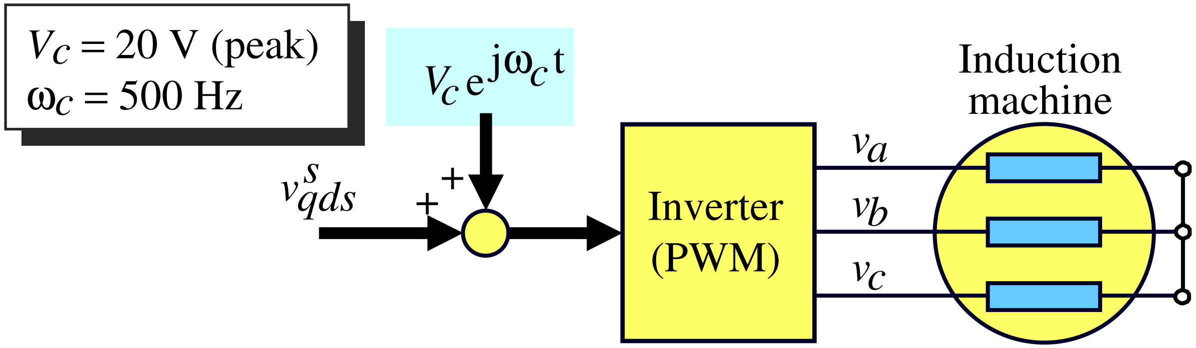


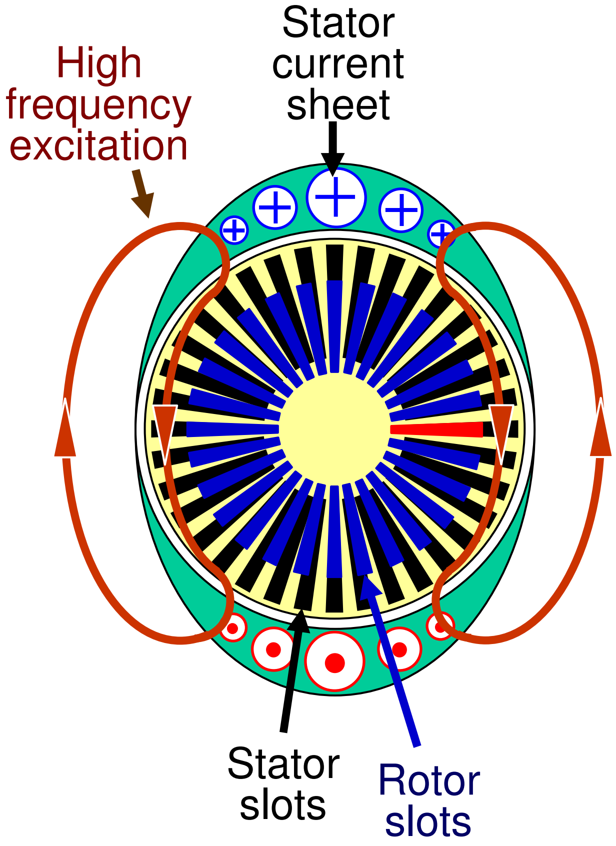
Secondary saliencies:
Saturation induced saliencies

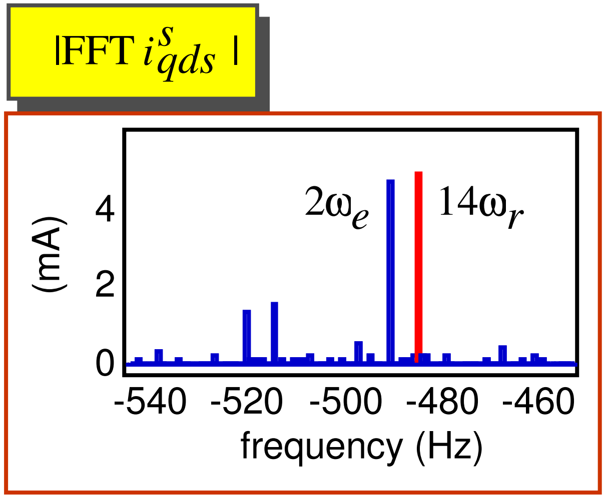
$V_c = 20$ V (peak)
$\omega_c = 500$ Hz



Secondary saliencies:
Saturation induced saliencies

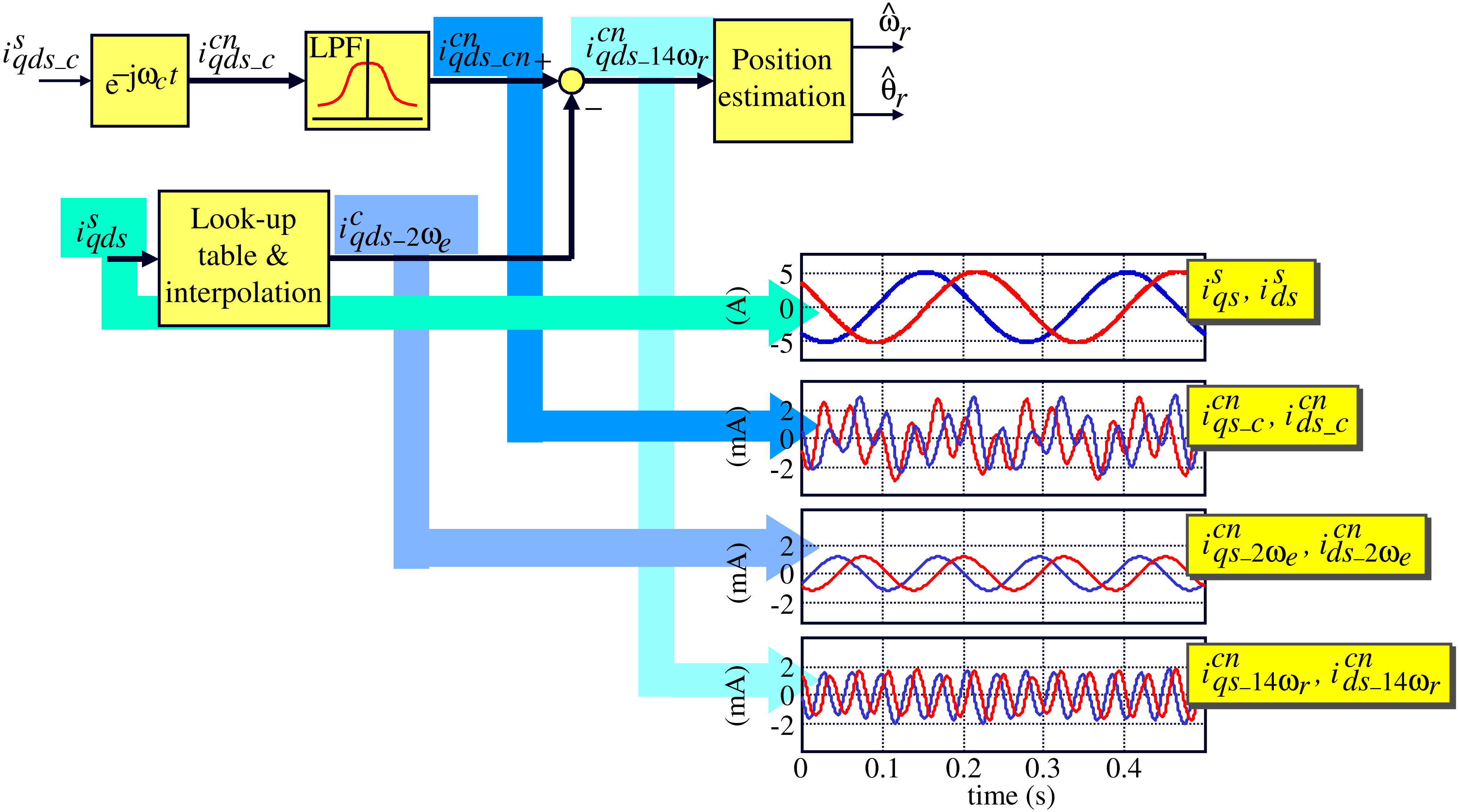






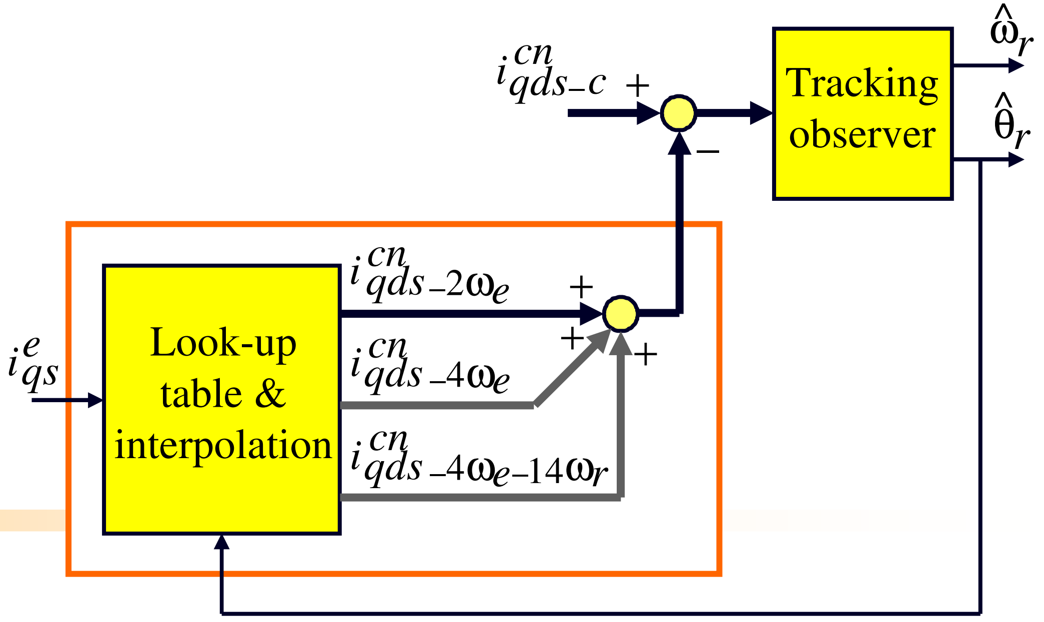
- Saturation-induced saliencies produce additional components of the negative sequence carrier signal current.
- Accurate rotor position estimation requires these saturation-induced saliencies be compensated for.
- They are measured during an off-line commissioning process, then compensated during the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

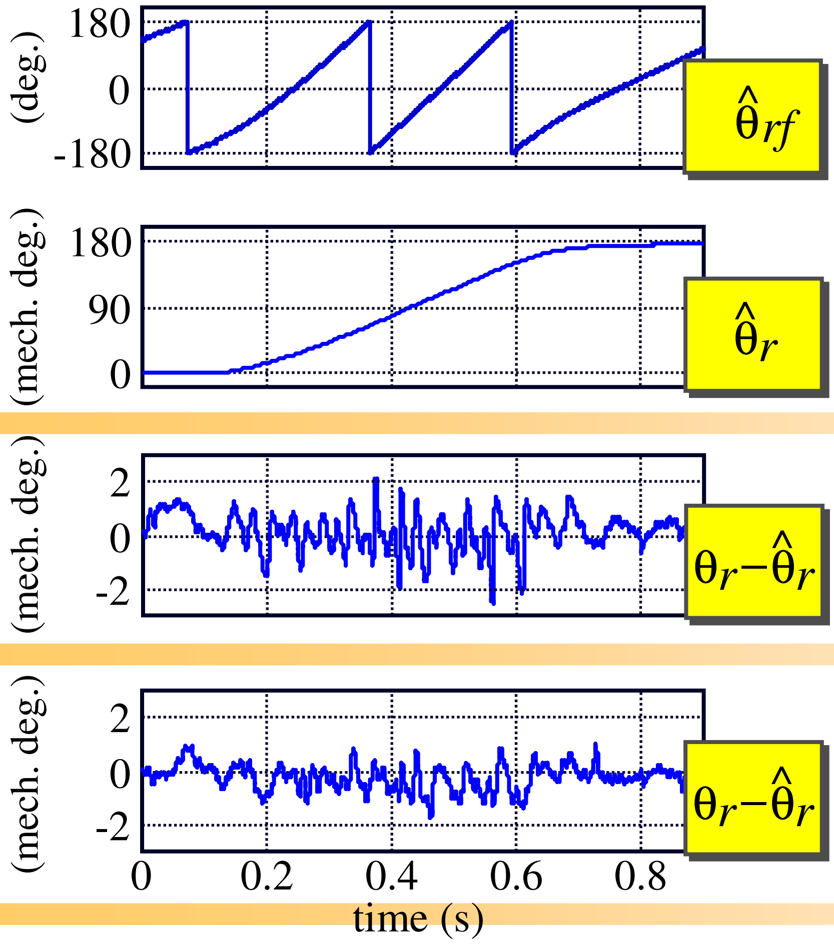
Modeling and compensation of saturation induced saliencies



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.

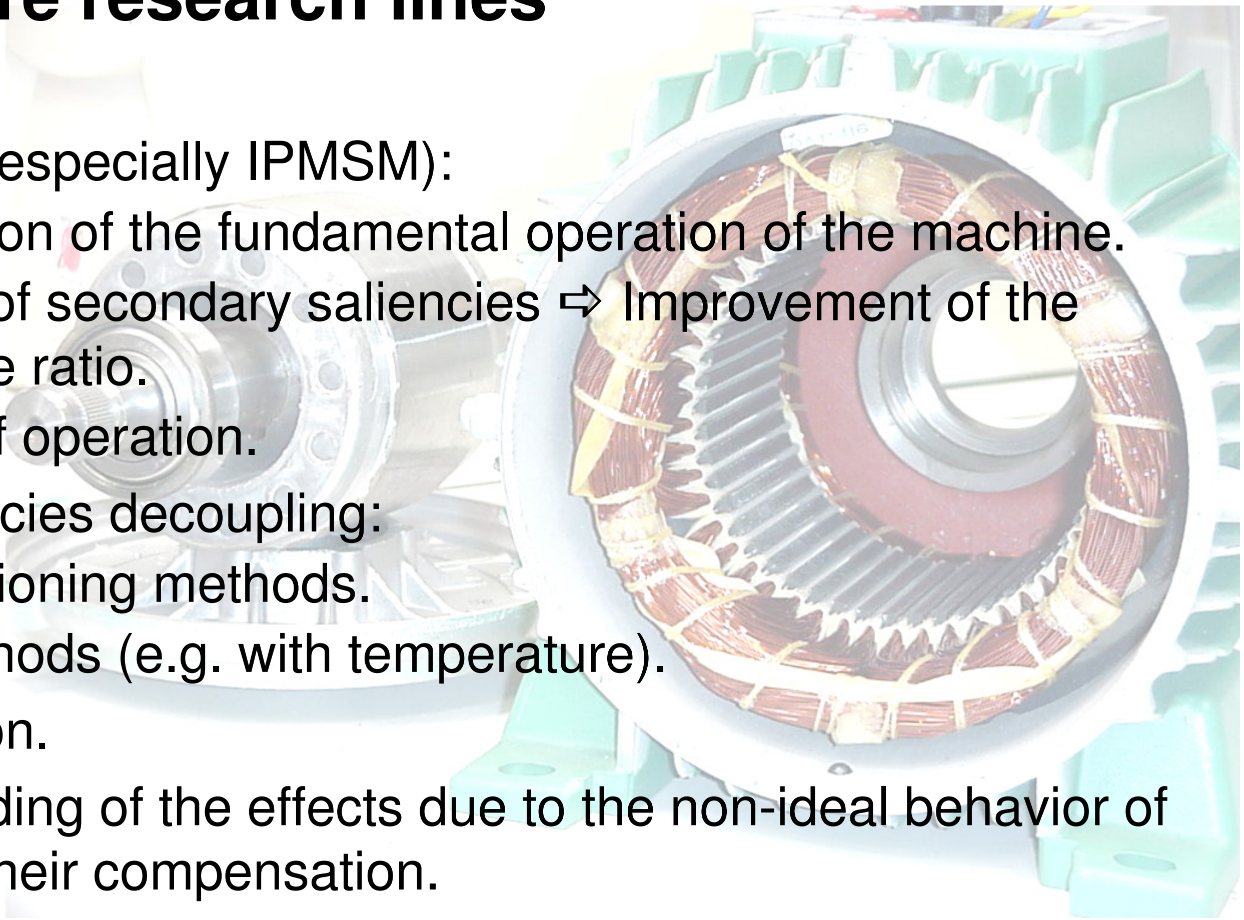




$2\omega_e$ component compensated

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

Ongoing and future research lines



- ✓ Machine design (especially IPMSM):
  - No deterioration of the fundamental operation of the machine.
  - Minimization of secondary saliencies ⇨ Improvement of the signal to noise ratio.
  - Wide range of operation.
- ✓ Secondary saliencies decoupling:
  - Self-commissioning methods.
  - Adaptive methods (e.g. with temperature).
- ✓ Dynamic operation.
- ✓ Better understanding of the effects due to the non-ideal behavior of the inverter and their compensation.
- ✓ Forms of high frequency excitation.
- ✓ Signal acquisition and processing.
- ✓ **What the limits of the method are?**

Publications

- ✓ Some 20 IEEE Transactions papers.
- ✓ Some 30 international conference papers