Small Permanent Magnet Synchronous Motor Technology
An Overview

Dr. Dorin ILES

Head R&D Laboratory for Electric Drives

Target

- Comprehensive overview of small permanent magnet synchronous motor technology – one of the most competitive type of electric machines and drives

Contents

Introduction

Competing electric motor/drives technologies for high performance applications

	DC	IM	PMSM BLDC	PMSM BLAC	SR	RS
Torque density	-	-	+	+	-	-
Torque/Amp	-	-	+	+	-	-
Peak to continuous torque capability	-	-	+	+	-	-
Variable speed control	+	-	-	-	-	-
Torque/inertia ratio	-	-	+	+	+	-
Energy efficiency	-	-	+	+	-	-
Speed range	-	+	-	-	+	+
Torque pulsations	-	+	-	+	-	+
Cogging torque	-	+	-	-	+	+
Temperature sensitivity (PM demagnetization)	-	+	-	-	+	+
Robustness	-	+	-	-	+	+
Fault tolerance Failure modes	+	-	-	-	+	-
Acoustic noise	-	+	-	+	-	+
Power converter requirements	+	-	-	-	-	-
Machine construction	-	-	+	+	+	+
Manufacturing technology	+	-	+	+	+	-
Reliability	-	+	+	+	+	+
Design and manufacturing experience	+	+	-	-	-	-
Customer acceptance	+	+	-	-	-	-
Motor cost	+	-	-	-	+	-
Drive system cost	+	-	+	-	-	-

DC - permanent magnet brushed dc

IM - induction

BLDC - permanent magnet trapezoidal

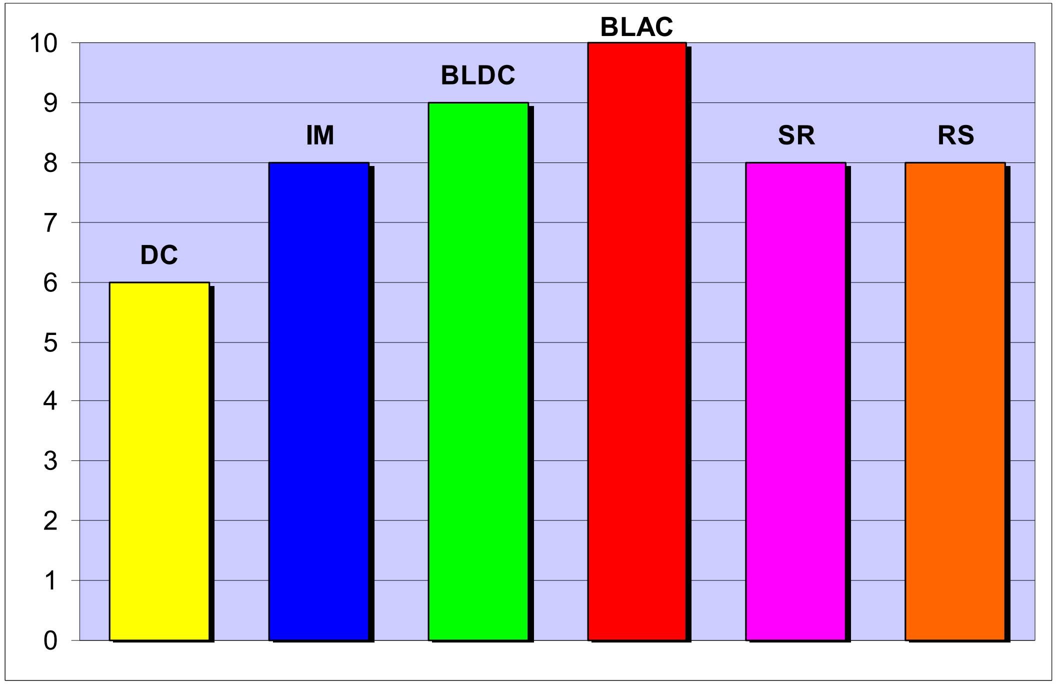
BLAC - permanent magnet sinusoidal

SR - switched-reluctance

RS - reluctance synchronous

Introduction

Competing electric motor/drives technologies for <u>high performance</u> applications



DC - permanent magnet brushed dc

IM - induction

BLDC - permanent magnet trapezoidal

BLAC - permanent magnet sinusoidal

SR - switched-reluctance

RS - reluctance synchronous

Introduction

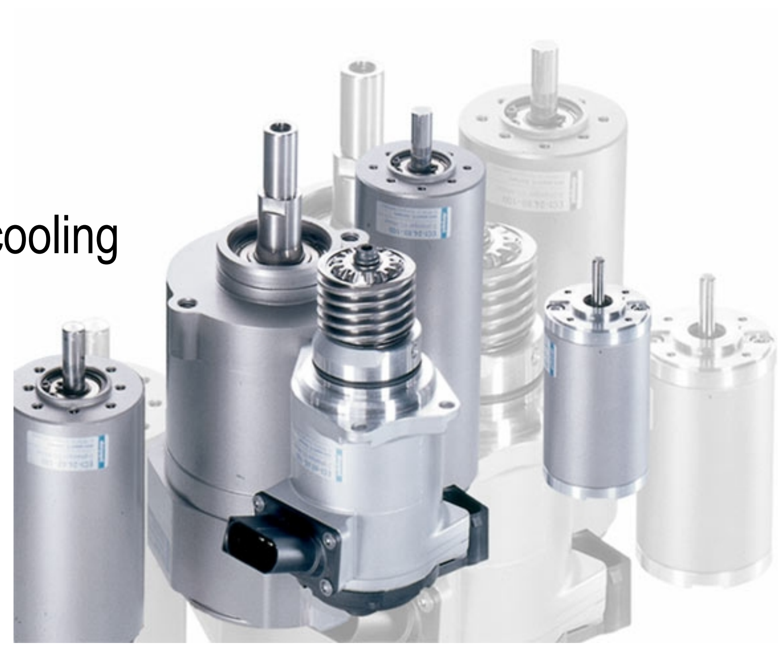
PMSM advantages and drawbacks

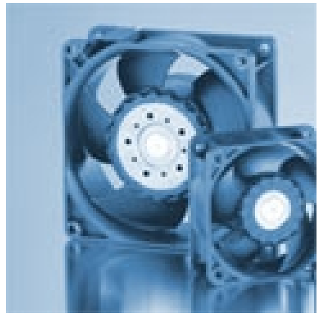
- In comparison with other conventional electric machines PMSM have two main advantages
    - high efficiency (in the rotor: no copper losses and very low iron losses)
    - high torque density due to the permanent magnet excitation

- PM excitation has also some drawbacks
    - high cost of the permanent magnets
    - risk of demagnetization at high temperature
    - increased effort for permanent magnet fixture on/in rotor
    - additional control effort for field weakening or advance angle control

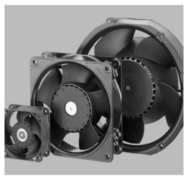
PMSM applications

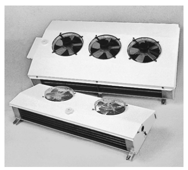
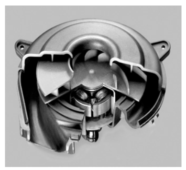
- The field of actual high performance applications spans a wide range of applications
  - industrial
  - medical
  - electronic cooling
  - automotive
  - aerospace







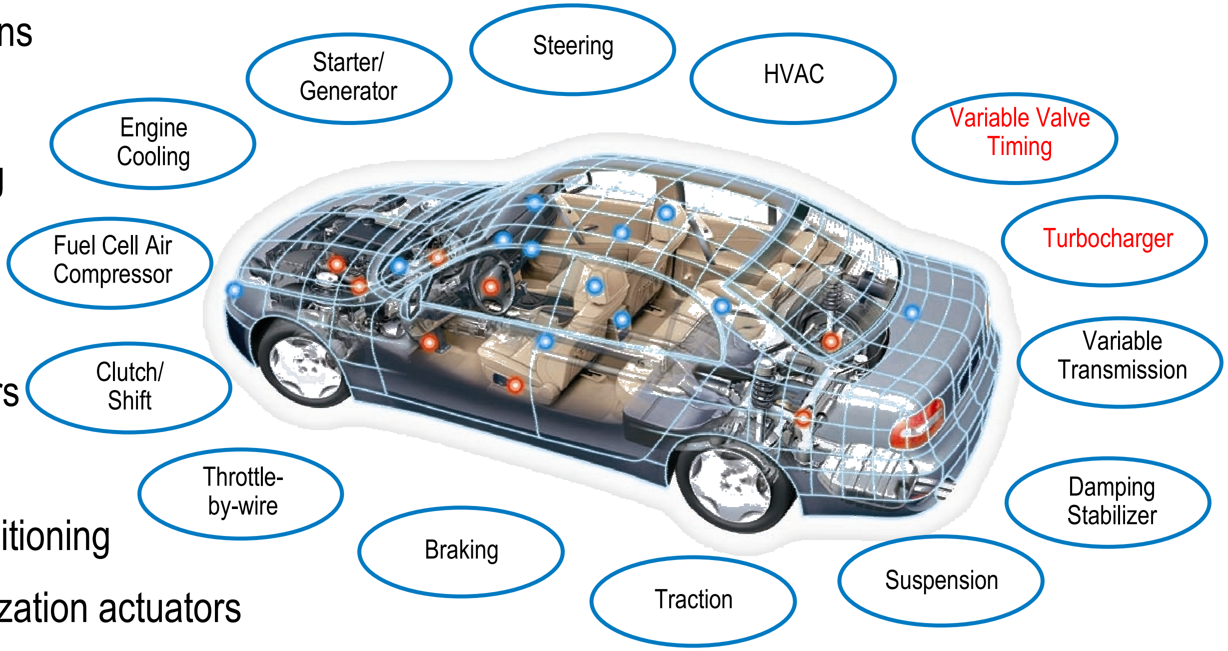


PMSM applications

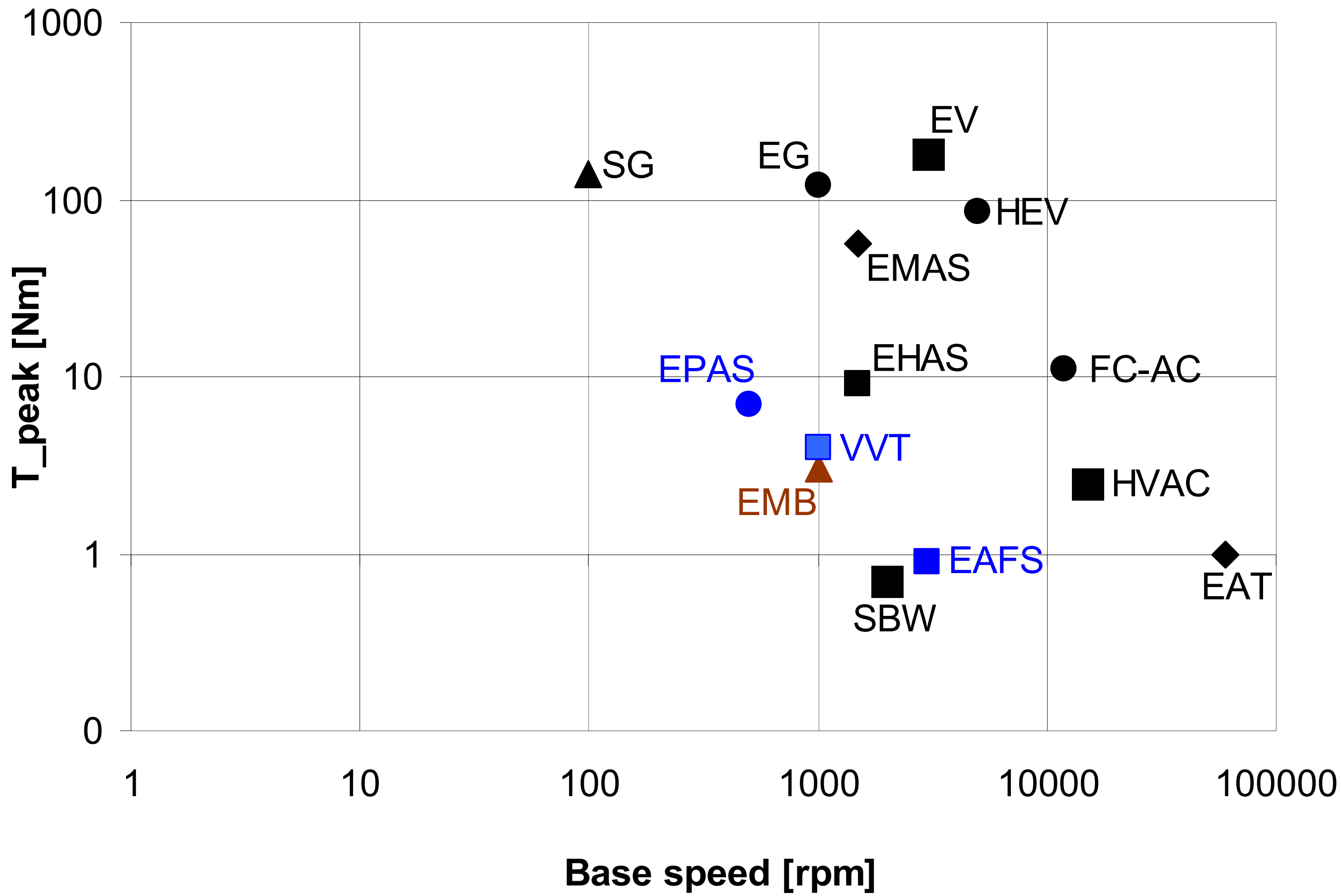
Schematic overview of automotive applications

- Some significant automotive applications
  - steering systems
    - active (front, rear) steering
    - power steering
    - steer-by-wire
  - clutch- and shift-by wire actuators
  - electromechanical brakes
  - heating, ventilation, and air conditioning
  - suspension, damping and stabilization actuators
  - starter-generators (integrated and belt driven)
  - traction motors for
    - electric vehicles (EV)
    - hybrid electric vehicles (HEV)
    - fuel cell vehicles (FCEV)



PMSM applications

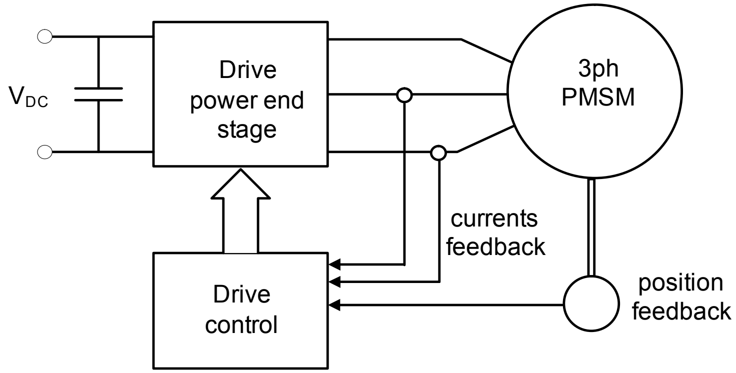
Torque-speed demands for automotive applications

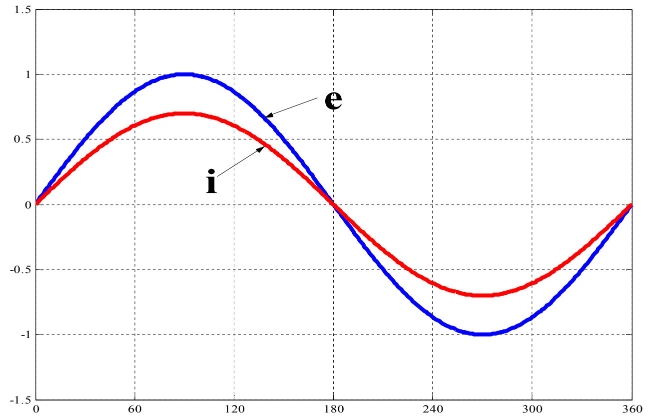


EPAS	Electric power assisted steering
EAFS	Electric assisted front steering
EMB	Electromechanical brake (wedge)
SBW	Shift-by-wire
HVAC	Air compressor for air conditioner
FC-AC	Air compressor for fuel cells
EG	Electric gearbox
EHAS	Electro-hydraulic active suspension
EMAS	Electromechanical active suspension
EAT	Electrical assisted turbochargers
VVT	Variable valve timing
SG	Starter-generators
EV	Electric vehicle traction
HEV	Hybrid electric vehicle traction

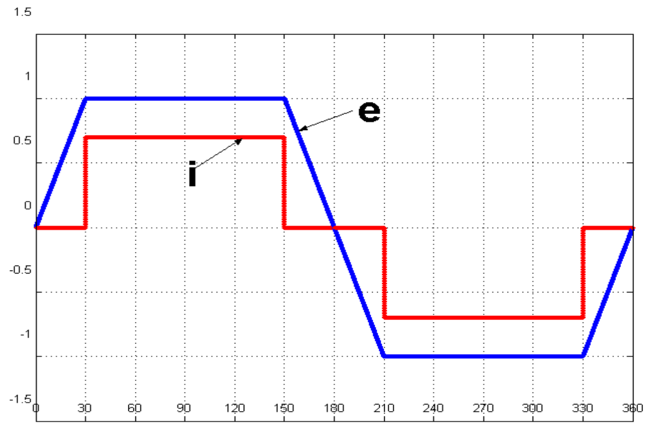
PMSM drives technologies

Classification based on the shape of back-EMF and excitation currents





sinusoidal machine (BLAC) and control



trapezoidal machine (BLDC) and control

PMSM drives technologies

BLAC motors and drives

- sinusoidal back-EMF shape and sinusoidal currents in order to get optimal torque quality
- usually overlapped stator windings
- mostly skewed surface permanent magnets in rotor
- complex, cost-intensive high-resolution rotor position sensors like encoder or resolver (or sensorless methods) are mandatory for the sinusoidal current control
- at least two current sensors are necessary to impose the shape of the phase currents

Due to the low torque ripple sinusoidal PMSM drive is the only proper technology for high performance applications

PMSM drives technologies

BLDC motors and drives

• trapezoidal back-EMF shape and trapezoidal current in order to get optimal torque quality

• usually concentrated stator windings

• surface mounted permanent magnets (rings or segments)

• BLDC motors are driven in two-phase-on mode

• a simpler rotor position sensor, with a resolution of six instants per electrical period, may be used for the commutation

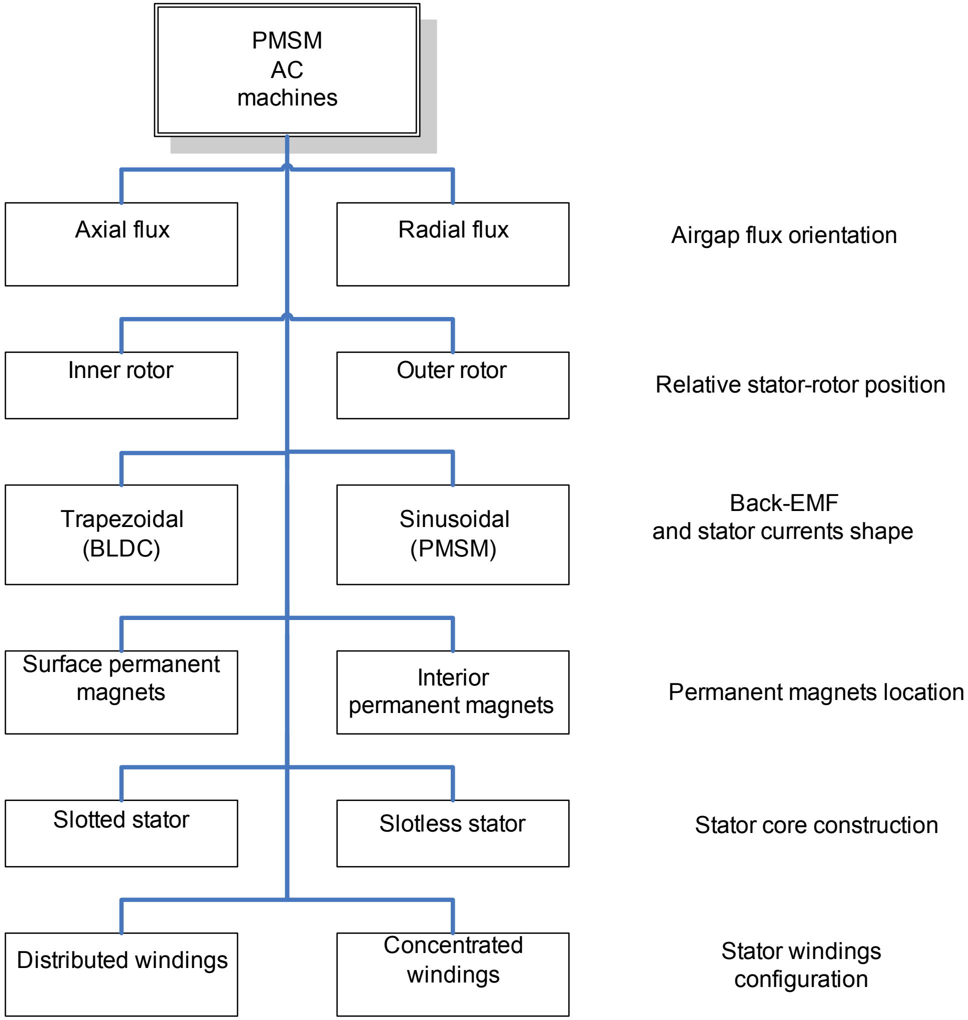
• a single current sensor is needed for a possible control of the current in the two motor phases

The torque pulsations can be high due the current commutation and back-EMF shapes with remarkable distortions

This simple control strategy is very often employed in low performance applications, where the required torque quality is not too high

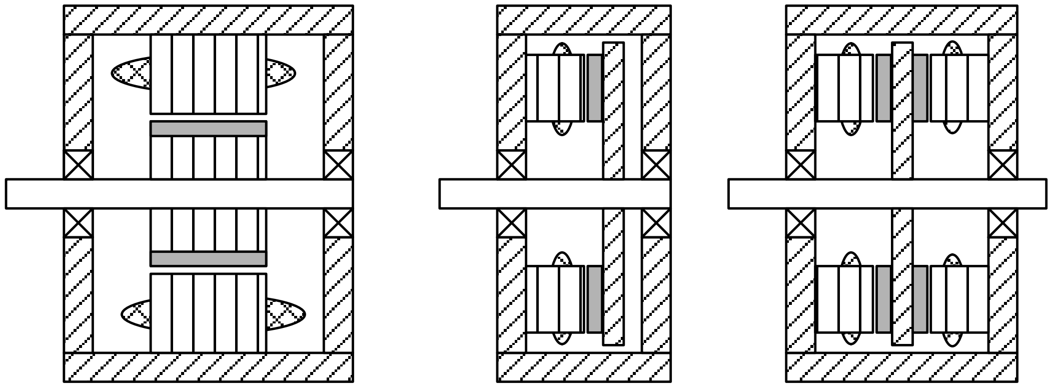
PMSM types and topologies

PMSM classification



PMSM types and topologies

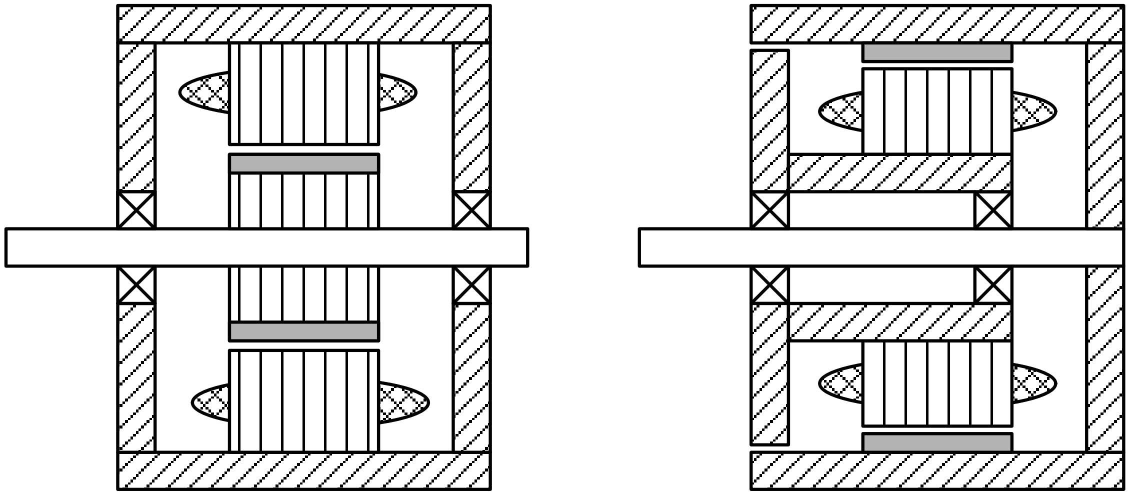
Airgap flux orientation



Radial vs. axial field PMSM (inner rotor radial, single sided axial, double sided axial configurations)

PMSM types and topologies

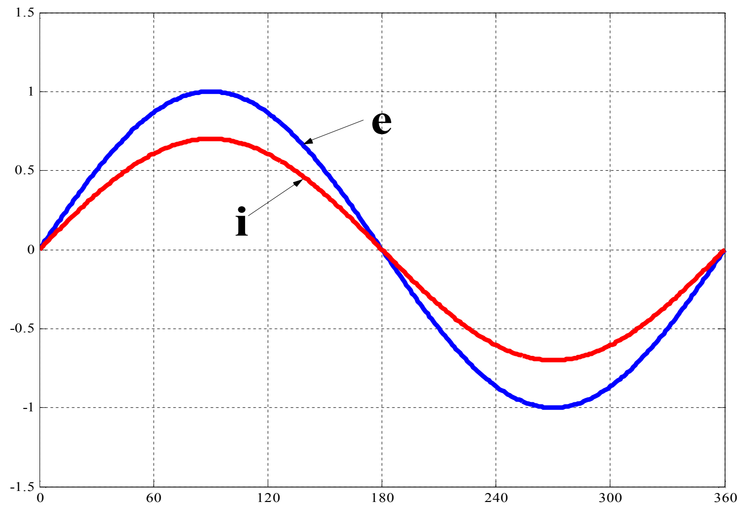
Relative stator-rotor position

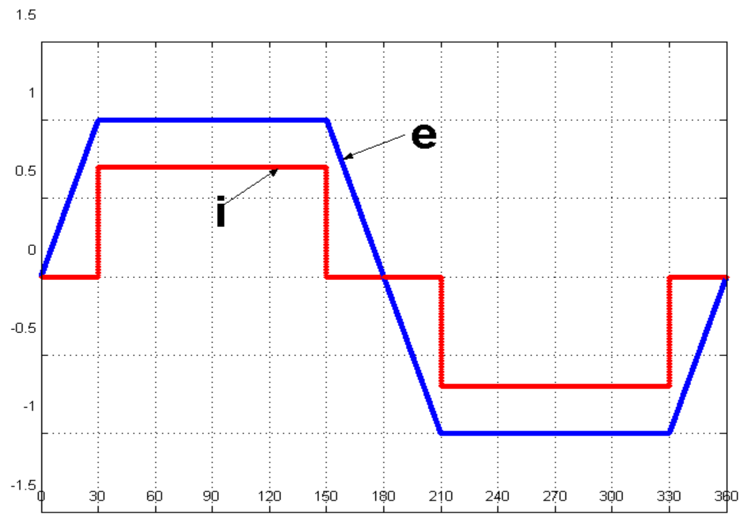


Inner- vs. outer-rotor PMSM

PMSM types and topologies

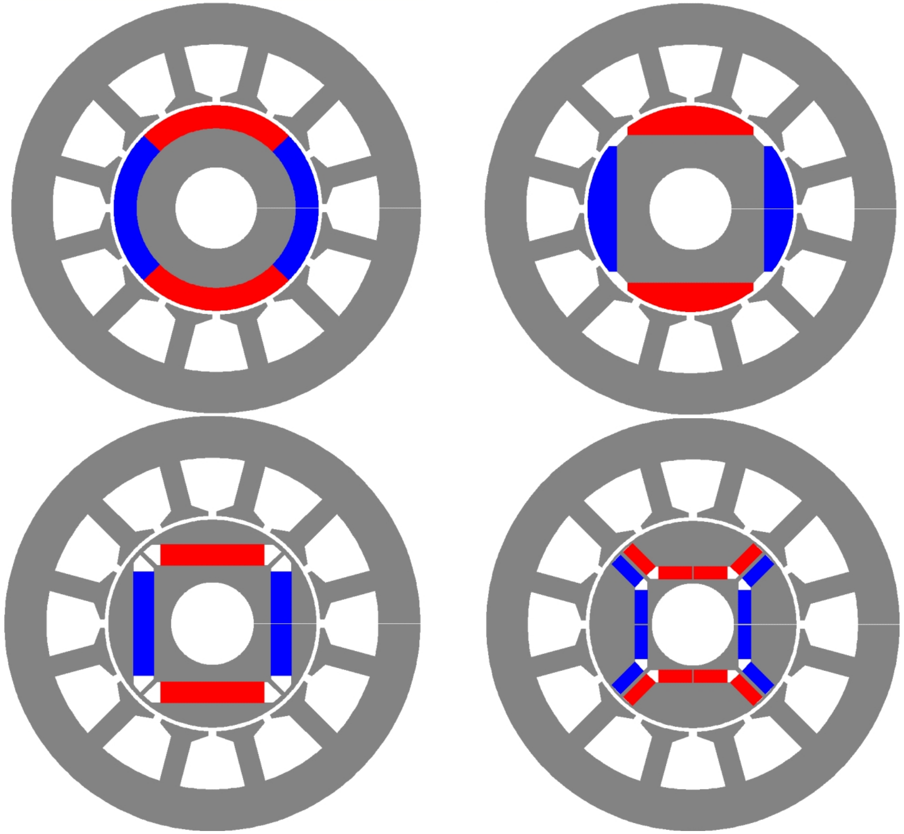
BEMF-shape





PMSM types and topologies

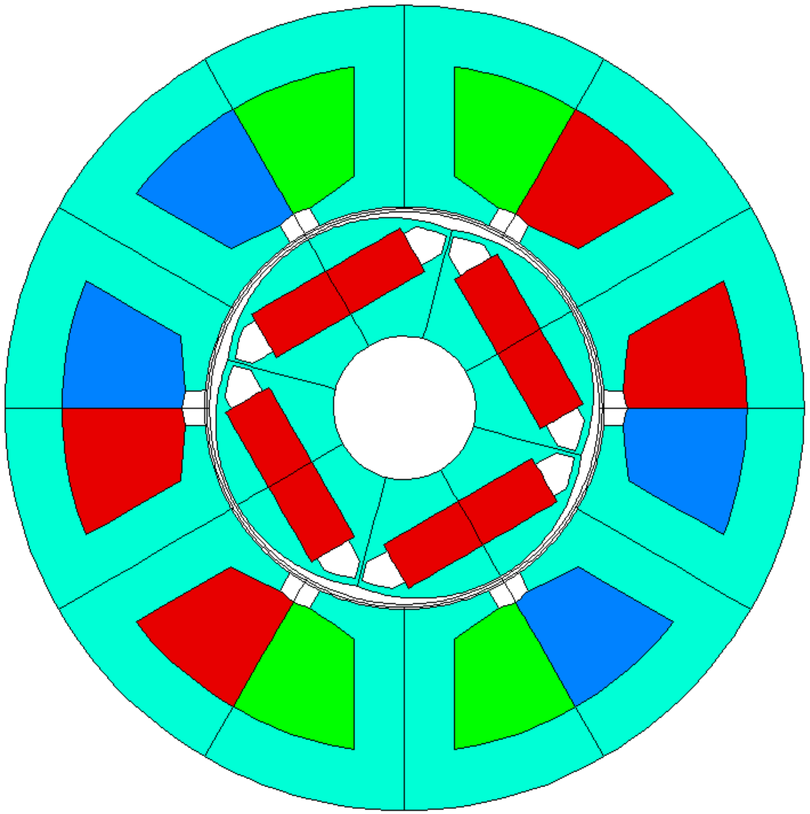
Permanent magnets location



Materials used for PMSM

Active materials

- **Permanent magnets – field excitation**
- **Soft magnetic materials – flux paths**
- **Copper – current conduction**

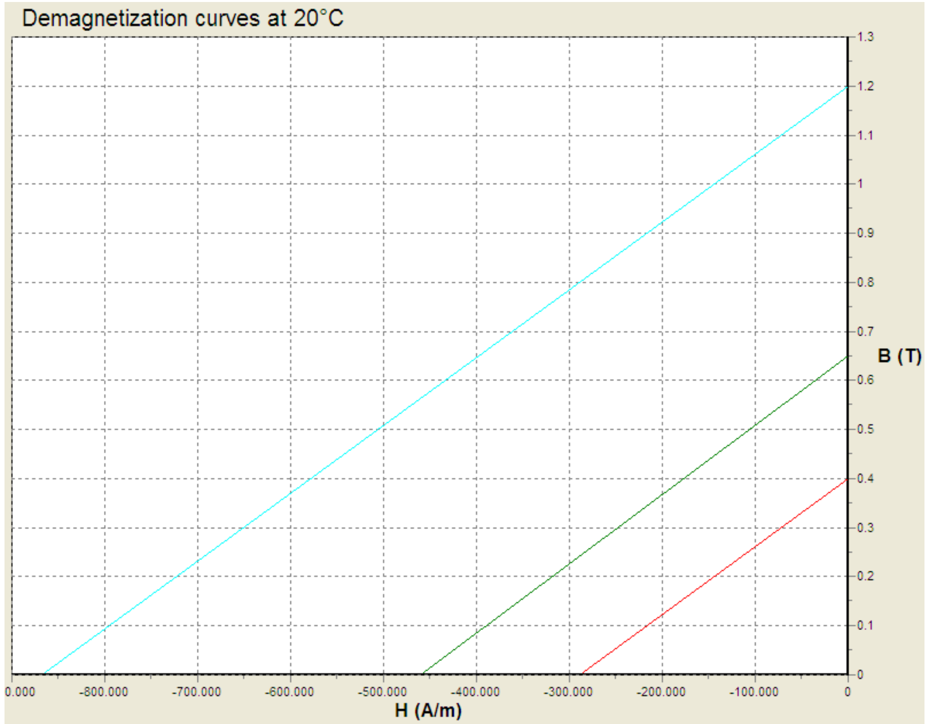


Materials used for PMSM

Permanent magnets

- **Permanent magnets** (manufactured by injection or compression moulding or sintering)
  - ferrites
  - Neodymium-Iron-Boron (NdFeB)

	residual flux density T	intrinsic coercivity $_JH_c$ kA/m	maximum energy product kJ/m^3
sintered ferrite	0.4	300	40
bonded NdFeB	0.7	800	80
sintered NdFeB	1.2	1900	280



- For high torque density applications only sintered NdFeB-magnets can be considered

Materials used for PMSM

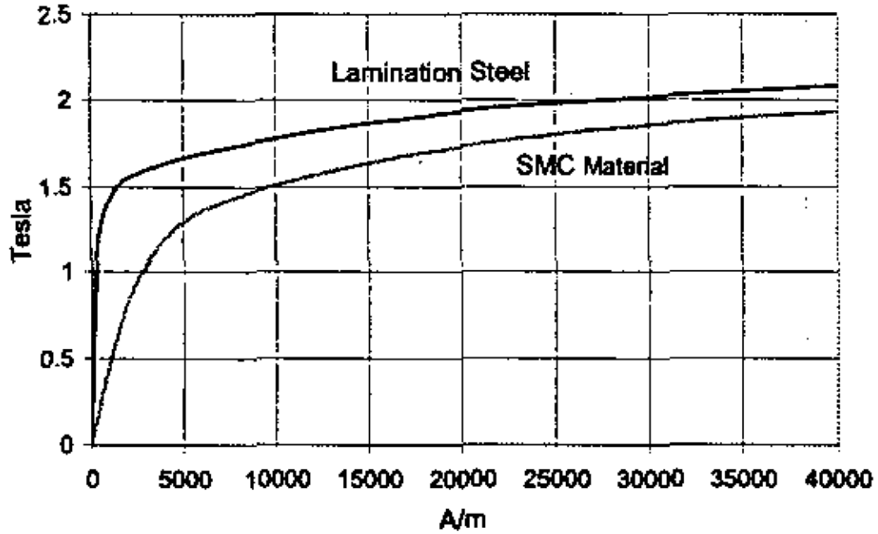
Soft magnetic (core)

Soft magnetic materials

- cold rolled magnetic lamination (CRML) steel
- soft magnetic composites (SMC) for "3-D design"

and good construction and manufacturing capabilities

	saturation flux density T	relative permeability -	core loss (1.5 T_{peak}, 50 Hz) W/kg
CRML steel	2.0	2000-3000	2.7-8.0
SMC	1.8	~ 500	10



Comparison of typical B-H curves for lamination steel and SMC material

Conventional lamination steel is mandatory for high torque density applications

Construction and manufacturing technologies for PMSM

Major trends

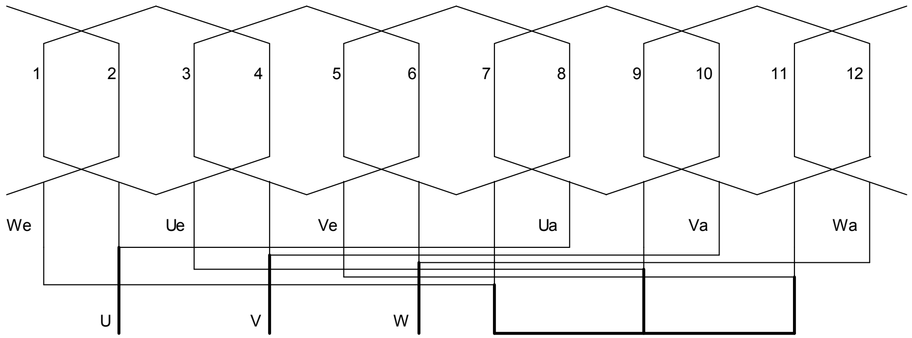
- Transition from conventional overlapped to non-overlapped (concentrated, tooth-wound) winding systems
- Modular stators
- Rotors with interior (embedded) permanent magnets

Construction and manufacturing technologies for PMSM

Winding systems

• conventional overlapped winding

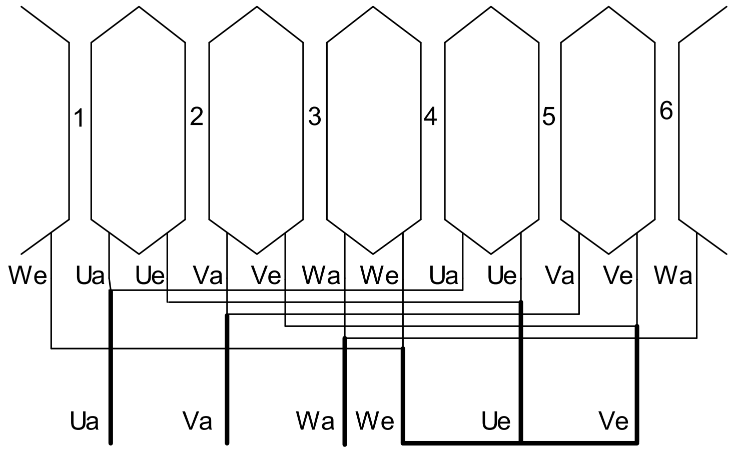
Q=12, m=3, 2p=4 Y||



• non-overlapped (concentrated, tooth-wound) windings

- short end turns of the concentrated winding lead to a reduction of the copper losses
- needle winding technology offers major advantages for coils with lower number of turns and higher wire diameter, like in PMSM for low voltage and/or high speed applications

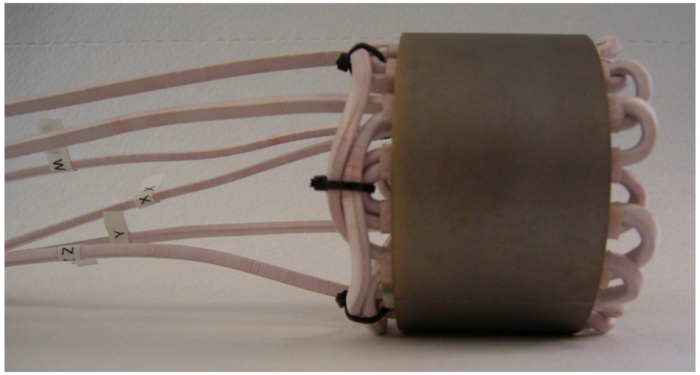
Q=6, m=3, 2p=4 Y||

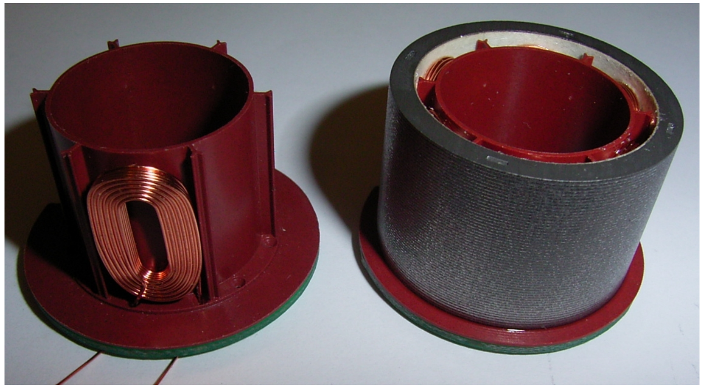


Construction and manufacturing technologies for PMSM

Advanced winding techniques

- moulded hair-pin winding
- single-turn wave litz winding
- slotless-PMSM winding



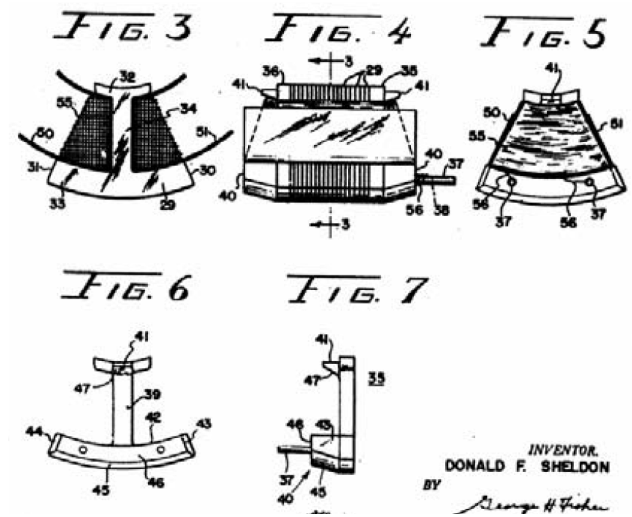


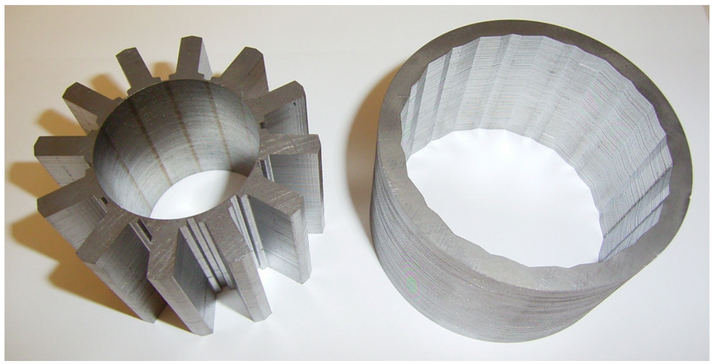
Construction and manufacturing technologies for PMSM

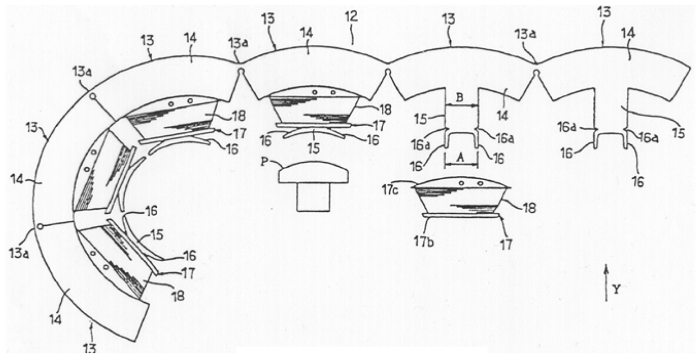
Modular stators

New modular stator solutions (in order to increase the slot fill factor, especially for coils with higher wire diameter)

- teeth-and-yoke stator segments
- two-part stators
- rolled stator







PMSM analysis

Electromagnetic analysis aspects - Basics of PMSM modeling

Taking into account only the modeling approaches with concentrated parameters (FE-modeling and analysis will not be treated) for the PMSM the employed machine models can be classified considering following three criteria

- chosen reference coordinates
  - phase coordinates modeling (natural coordinates or abc-frame of reference)
  - synchronous axes (dq) coordinates modeling
- nature of states variables
  - current state variables (CSV) modeling
  - flux state variables (FSV) modeling
- nature of modeling domain
  - frequency domain (steady state modeling)
  - time domain (transient modeling)

PMSM analysis

Transient FSV-model in phase coordinates for PMSM

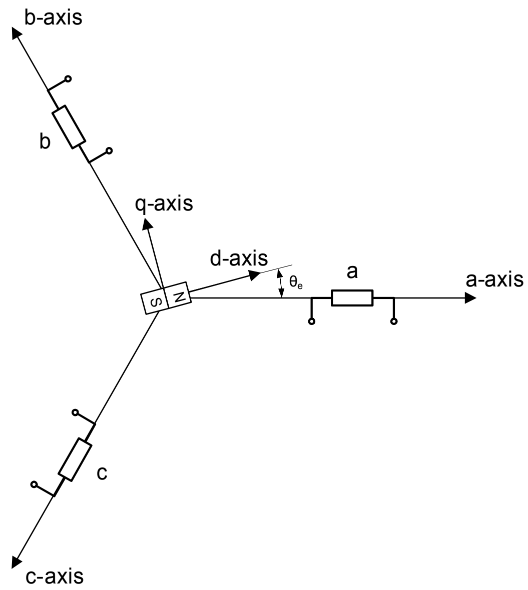
PMSM abc-frame of reference with stationary phase axes

Voltage equations

$$v_a = R_a i_a + \frac{d\psi_a}{dt}$$

$$v_b = R_b i_b + \frac{d\psi_b}{dt}$$

$$v_c = R_c i_c + \frac{d\psi_c}{dt}$$



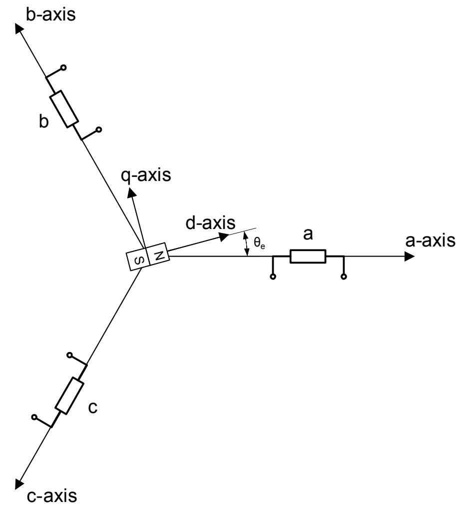
Flux linkage vector - function of

- machine topology
- geometry
- materials
- excitation (PM, currents)
- relative windings-PM position
- PM-temperature

PMSM analysis

Transient CSV-model in phase coordinates for PMSM

PMSM abc-frame of reference with stationary phase axes



Voltage equations

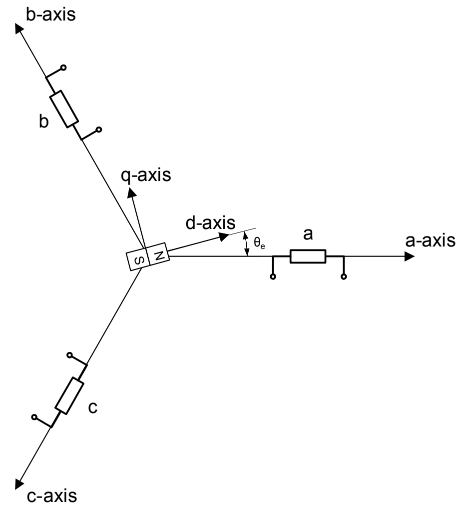
$$v_a = R_a i_a + L_{aa}\frac{di_a}{dt} + L_{ab}\frac{di_b}{dt} + L_{ac}\frac{di_c}{dt} + \omega_e i_a \frac{dL_{aa}}{d\vartheta_e} + \omega_e i_b \frac{dL_{ab}}{d\vartheta_e} + \omega_e i_c \frac{dL_{ac}}{d\vartheta_e} + e_{a\_PM}$$

$$v_b = R_b i_b + L_{ba}\frac{di_a}{dt} + L_{bb}\frac{di_b}{dt} + L_{bc}\frac{di_c}{dt} + \omega_e i_a \frac{dL_{ba}}{d\vartheta_e} + \omega_e i_b \frac{dL_{bb}}{d\vartheta_e} + \omega_e i_c \frac{dL_{bc}}{d\vartheta_e} + e_{b\_PM}$$

$$v_c = R_c i_c + L_{ca}\frac{di_a}{dt} + L_{cb}\frac{di_b}{dt} + L_{cc}\frac{di_c}{dt} + \omega_e i_a \frac{dL_{ca}}{d\vartheta_e} + \omega_e i_b \frac{dL_{cb}}{d\vartheta_e} + \omega_e i_c \frac{dL_{cc}}{d\vartheta_e} + e_{c\_PM}$$

PMSM analysis

dq0-coordinate transformation



- eliminates the rotor position dependence of inductances
- direct transformation $(abc \rightarrow dq0)$

$$v_d = \frac{2}{3}\left[v_a \cos(\theta_e) + v_b \cos\left(\theta_e - \frac{2\pi}{3}\right) + v_c \cos\left(\theta_e - \frac{4\pi}{3}\right)\right]$$

$$v_q = \frac{2}{3}\left[-v_a \sin(\theta_e) - v_b \sin\left(\theta_e - \frac{2\pi}{3}\right) - v_c \sin\left(\theta_e - \frac{4\pi}{3}\right)\right]$$

$$v_0 = \frac{2}{3}\left(\frac{1}{2}v_a + \frac{1}{2}v_b + \frac{1}{2}v_c\right) = 0$$

- inverse transformation $(dq0 \rightarrow abc)$

$$v_a = v_d \cos(\vartheta_e) - v_q \sin(\vartheta_e) + v_0$$

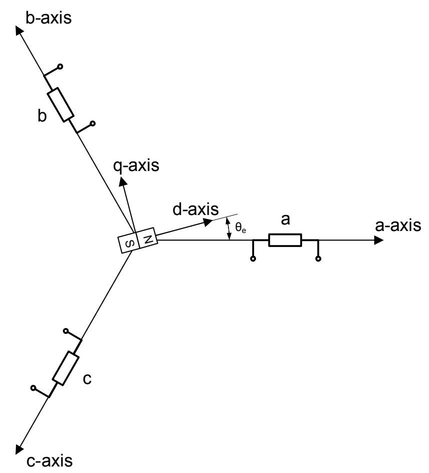
$$v_b = v_d \cos\left(\vartheta_e - \frac{2\pi}{3}\right) - v_q \sin\left(\vartheta_e - \frac{2\pi}{3}\right) + v_0$$

$$v_c = v_d \cos\left(\vartheta_e - \frac{4\pi}{3}\right) - v_q \sin\left(\vartheta_e - \frac{4\pi}{3}\right) + v_0$$

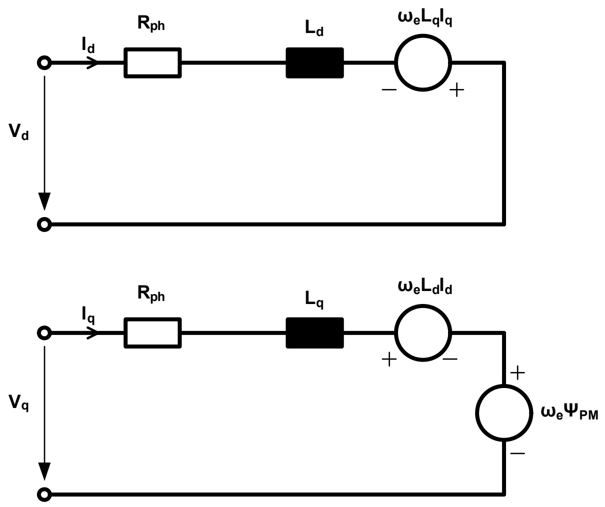
PMSM analysis

Transient CSV-model in synchronous coordinates for PMSM

PMSM rotor-synchronous (dq)-frame of reference



dq-equivalent circuit



Voltage equations

$$v_d = Ri_d + \frac{d\psi_d}{dt} - \omega_e \psi_q$$

$$v_q = Ri_q + \frac{d\psi_q}{dt} + \omega_e \psi_d$$

dq-axis fluxes

$$\psi_d = L_d^{inc} i_d + \psi_{PM}$$

$$\psi_q = L_q^{inc} i_q$$

PMSM analysis

Transient CSV-model in synchronous coordinates for PMSM

CSV-model

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{v_d}{L_d^{inc}} - \dfrac{R}{L_d^{inc}} i_d + \dfrac{\omega_e L_q^{inc}}{L_d^{inc}} i_q \\ \dfrac{di_q}{dt} = \dfrac{v_q}{L_q^{inc}} - \dfrac{R}{L_q^{inc}} i_q - \dfrac{\omega_e L_d}{L_q^{inc}} i_d - \dfrac{\omega_e \psi_{PM}}{L_q^{inc}} \end{cases}$$

electromagnetic torque

$$t_{em} = \frac{3}{2} p\left(\psi_{PM} i_q - \left(L_d^{inc} - L_q^{inc}\right) i_d i_q\right).$$

dynamic equation

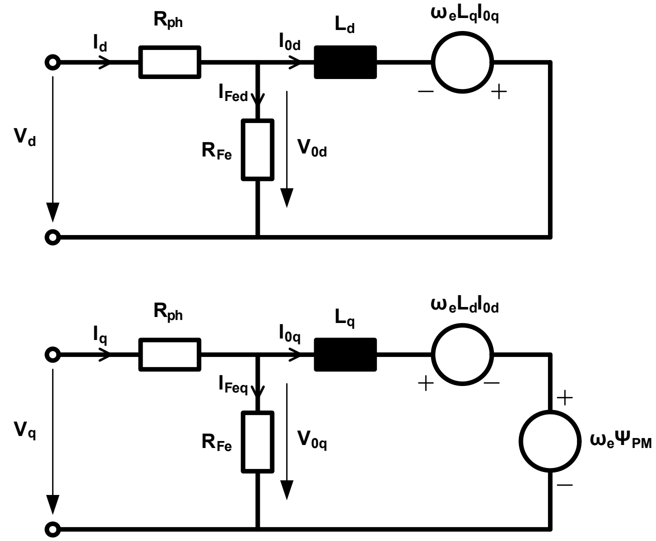
$$\frac{d\omega_m}{dt} = \frac{1}{J_r}\left(t_{em} - B\omega_m - t_L\right)$$

J_r - polar moment of inertia of the rotor, B - coefficient of viscous friction, t_L - load torque

PMSM analysis

Special physical phenomena in PMSM

The estimation of the mentioned machine parameters (resistances, inductances, fluxes) is influenced by several special physical phenomena within the PMSM



- iron core saturation

$$L_d = L_d(i_d)$$
$$L_q = L_q(i_q)$$

- iron core losses

- cross-saturation between the two orthogonal axes in the dq-model

$$L_d = L_d(i_d, i_q)$$
$$L_q = L_q(i_d, i_q)$$

- harmonics (spatial and time harmonics) for several physical quantities

$$\psi_{PM}(\theta_e) = \sum_{n=1}^{\infty} \psi_{PM\_n}(\theta_e) = \sum_{n=1}^{\infty} A_n \cos(n\theta_e - \varphi_n) \qquad L_{ij}(\theta_e) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\theta_e + \varphi_n)$$

- temperature effects (modification of machine parameters with temperature)

$$R(\theta_2) = R(\theta_1)\left[1 + \alpha_{\rho_{Cu}}(\theta_2 - \theta_1)\right] \qquad B_r(\theta_2) = B_r(\theta_1)\left[1 + \alpha_{B_r}(\theta_2 - \theta_1)\right]$$

PMSM analysis

Thermal analysis aspects

Employing an one body (one source of losses) thermal model the temperatures for the different parts of the machine can be calculated

• temperature rise of winding, permanent magnet and frame

$$\Delta T_{co} = k_{duty} P_{loss} R_{th\_co\_amb}$$

$$\Delta T_{PM} = k_{duty} P_{loss} R_{th\_PM\_amb}$$

$$\Delta T_{fr} = k_{duty} P_{loss} R_{th\_fr\_amb}$$

k_{duty} - factor taking into account the duty cycle

$R_{th\_co\_amb}$ - thermal resistance winding-ambient

$R_{th\_PM\_amb}$ - thermal resistance PM-ambient

$R_{th\_fr\_amb}$ - thermal resistance frame-ambient

PMSM analysis

Thermal analysis aspects

• thermal resistance frame-ambient

$$R_{th\_fr\_amb} = \frac{1}{A_{fr} h_{tr\_fr\_amb}}$$

A_{fr} - frame area

$h_{tr\_fr\_amb}$ - heat transfer coefficient through conduction, convection and radiation

• thermal resistances winding-ambient and PM-ambient

$$R_{th\_co\_amb} = \frac{1}{A_{fr} h_{tr\_co\_amb}}$$

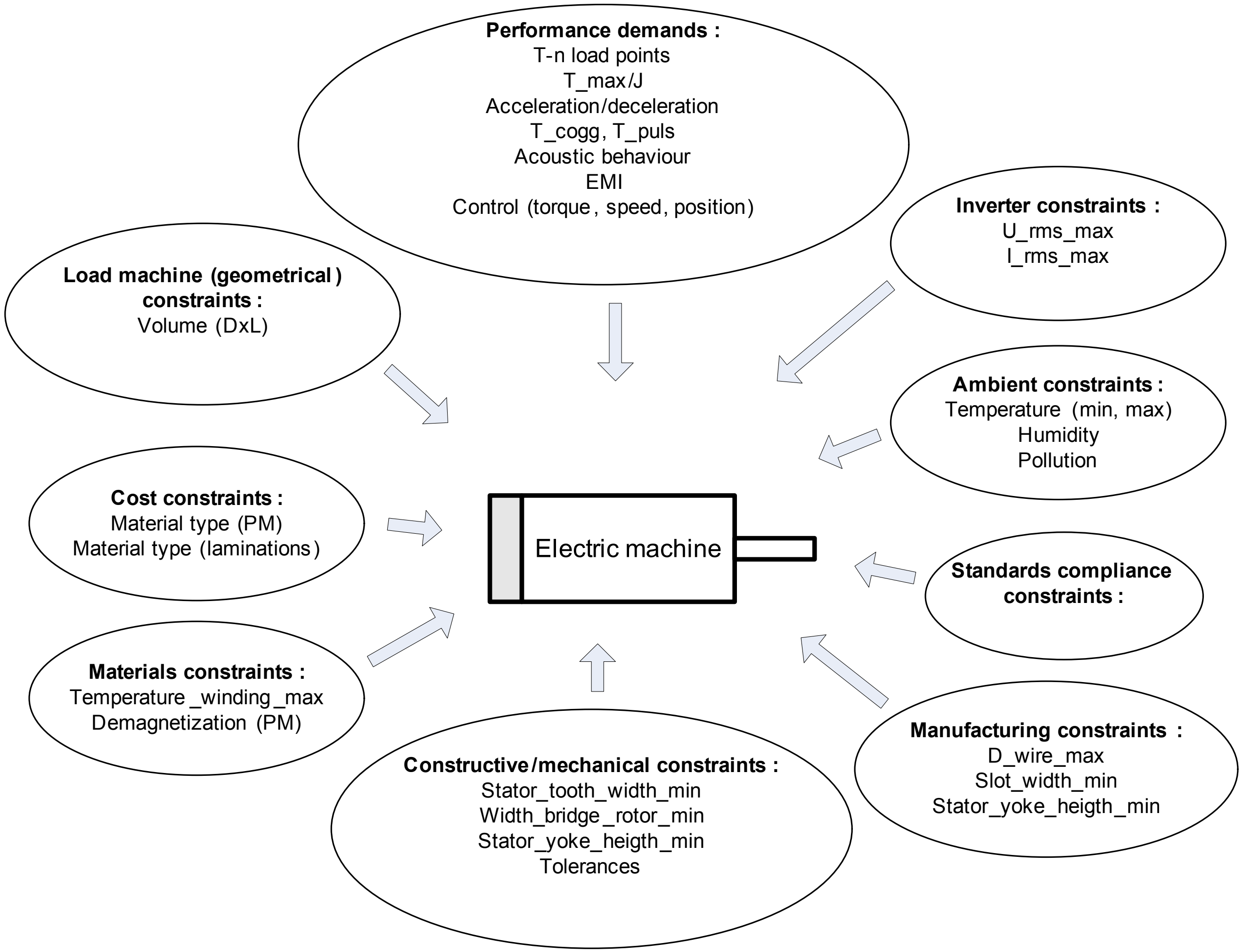
$$R_{th\_PM\_amb} = \frac{1}{A_{fr} h_{tr\_PM\_amb}}$$

• absolute winding, PM and frame temperatures

$$T_{co} = T_{amb} + \Delta T_{co} \qquad T_{PM} = T_{amb} + \Delta T_{PM} \qquad T_{fr} = T_{amb} + \Delta T_{fr}$$

PMSM design aspects

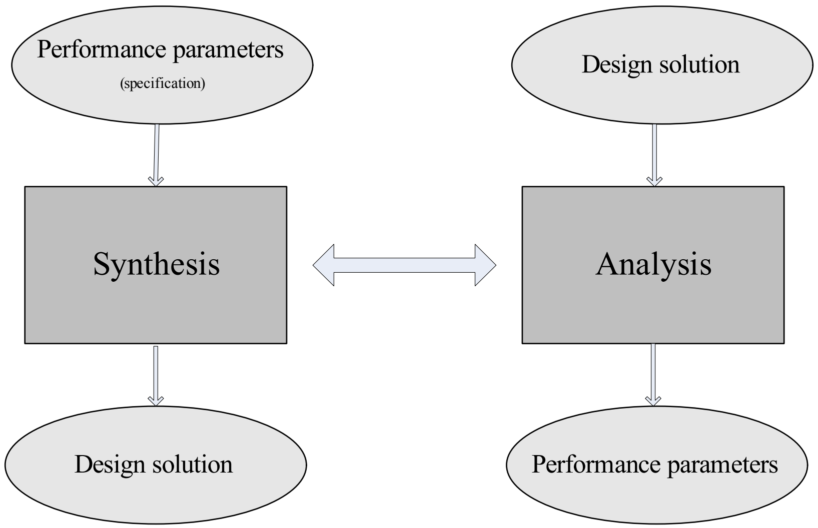
Electromagnetic design – demands and constraints

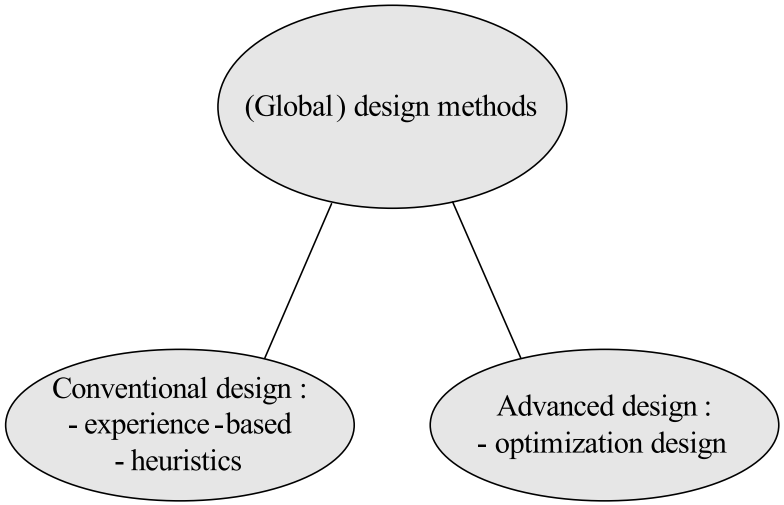


PMSM design aspects

Electromagnetic design methods for electric machines

- Design (synthesis) vs. analysis





- Conventional (experience-based) design vs. optimization design

PMSM design aspects

Electromagnetic design

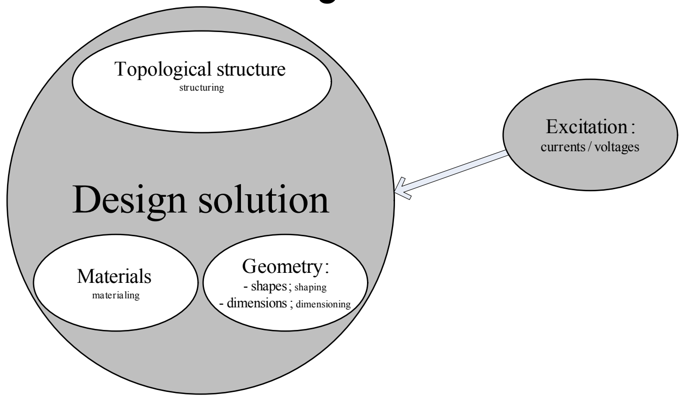
Conventional (experience-based) design process includes

- analysis of specifications
- selection (experience-based) of topological structure
- selection (experience-based) of
  - active materials (soft magnetic, hard magnetic, conducting)
  - passive materials (insulating)
- dimensioning (experience-based) of geometry
- parameter and performance calculation
- choice of manufacturing technologies
- costs prediction

PMSM design aspects

Experience-based design

- Motor design problem for a specific application is to find a set consisting of
    - topological structure
    - materials
    - geometry (shapes and dimensions)

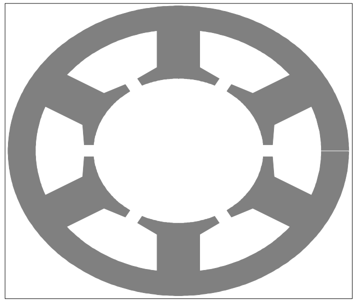


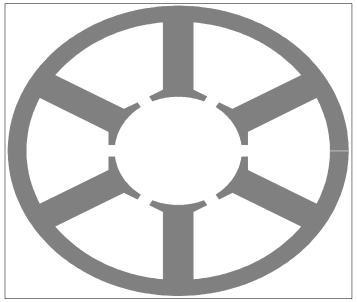
- Traditional method is based on design engineers experience
- This approach involves an immense effort, since it assumes the mastering of a wide area of technical knowledge
- The conventional synthesis (design) process for electric machines, although based on a highly-developed theory and affording extended mathematical skills, has a fuzzy and heuristic nature, as it can not be carried out in a straightforward, closed way

PMSM design aspects

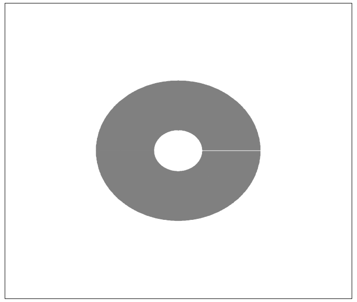
Electromagnetic design/synthesis approaches

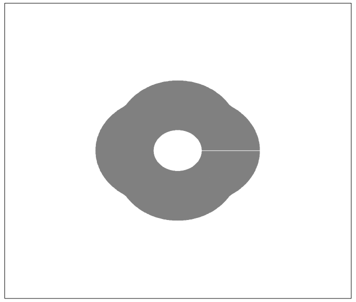
- sizing



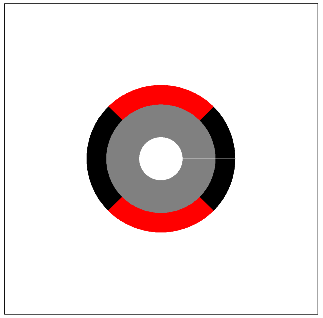


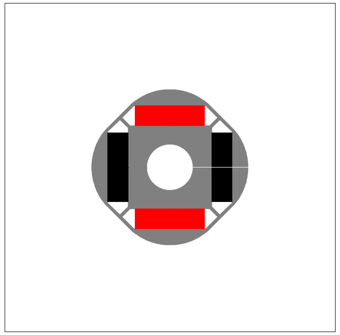
- shaping





- structuring





PMSM design aspects

Experience-based design

- Experience-based topology (configuration or structure) selection – crucial design issue
- Selection of
    - direction of the airgap field (radial, axial, or transversal field structure)r
    - relative rotor-stator position (interior or exterior rotor structure)
    - number of phases in stator (usually three or even more phases for high performance applications)
    - number of stator slots
    - number of rotor poles
    - structure of winding system
        - one/two layers
        - overlapped/non-overlapped
        - electrically balanced/non-balanced
        - fully/partially wound stator

PMSM design aspects

Topology selection based quality factors

ns \ np	2	4	6	8	10	12	14	16
3								
6		10	21	15				
9		27	12	69	86	24	28	26
12				21	58		81	42
15			7	46	26	49	210	230
18				34	61	31	106	131
21				42	83	52	36	266
24					52		94	42

Quality factors for small (up to 24 stator slots and 16 rotor poles) PMSM with symmetrically **single-layer** concentrated windings

PMSM design aspects

Topology selection based quality factors

ns \ np	2	4	6	8	10	12	14	16
3	5	10						
6		10		21	26			
9		22	16	70	84	28	60	97
12				21	56		78	42
15			14	75	26	54	200	228
18				39	58	31	114	134
21				79	119	44	36	289
24					56		128	42

Quality factors for small (up to 24 stator slots and 16 rotor poles) PMSM with symmetrically **two-layer** concentrated windings

PMSM design aspects

Experienced-based sizing (dimensioning)

- Starting with a set of known *key design parameters* it is possible to determine the complete design

- Key design parameters can be
  - dimensional proportions
  - mechanical, electric, magnetic loadings

- The number of these key design parameters can vary

- It is possible to minimize this number by introducing proper additional design constraints and a few “given” geometrical dimensions (e.g. airgap length)

PMSM design aspects

Experienced-based sizing (dimensioning)

- One possible way to choose the key design parameters

$$f_{sav}, \lambda, B_{g1}, B_{ys}, B_{ts}, B_{yr}\ j$$

f_{sav} - average surface force density

λ - ratio outer rotor diameter to stack length

B_{g1} - amplitude of the first harmonic of the airgap flux density

B_{ys} - maximal stator yoke flux density

B_{ts} - maximal stator tooth flux density

B_{yr} - maximal rotor yoke flux density

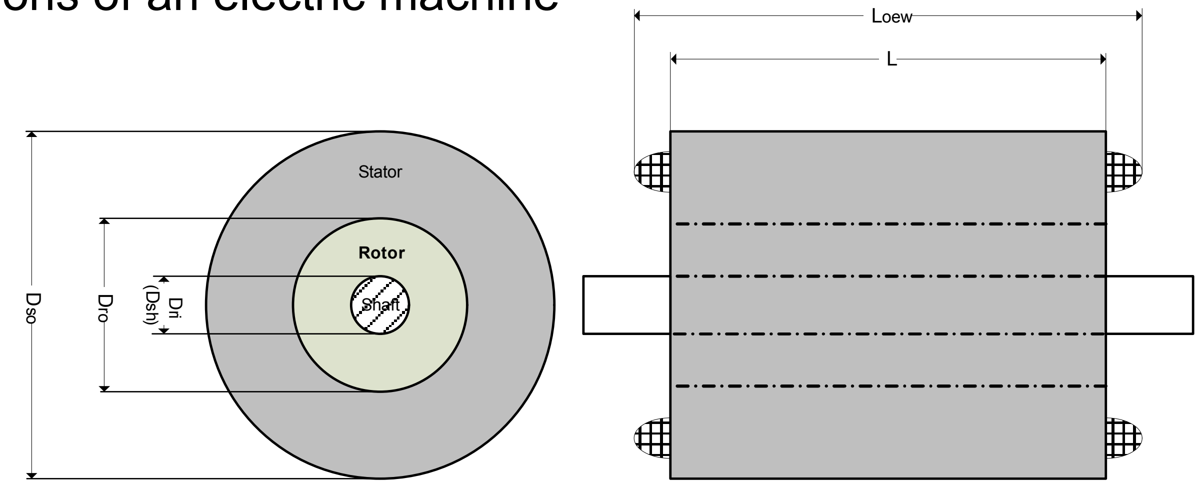
j - current density in the stator winding

- These key design parameters may also be chosen as *design variables in an optimization design process*

PMSM design aspects

Experienced-based sizing (dimensioning)

- Key geometrical dimensions of an electric machine



- The average surface force density is defined

$$f_{sav} = \frac{2T_e}{\pi D_{ro}^2 L}$$

T_e - electromagnetic torque

D_{ro} - outer rotor diameter

L - stack length

- The ratio outer rotor diameter to stack length

$$\lambda = \frac{D_{ro}}{L}$$

PMSM design aspects

Experienced-based sizing (dimensioning)

• Given the required electromagnetic torque in the specification and knowing (experience) the values of the key design parameters the dimensioning process can be done

• outer rotor diameter $$D_{ro} = \sqrt[3]{\frac{2\lambda T_e}{\pi f_{sav}}}$$

• stack length $$L = \frac{D_{ro}}{\lambda}$$

• Motor geometry dimensioning using adopted values for the magnetic and electric loadings in the stator and rotor

• Motor parameter and performance (including losses, efficiency, temperature rise, weight, costs)

Experimental analysis

- Goal - to offer accurate estimated and validated
  - *machine parameters* which can be used for later system simulations and control tasks
  - *machine operational performance parameters* as validation of the design method and design solution

- The *measurement procedure* consists of several tests chosen to allow the estimation of machine parameters and operational parameters in different approaches and in a wide area of variation

Experimental analysis

Overview of measurement procedure

- Standstill tests
- Running tests
- Thermal analysis
- Vibro-acoustic analysis

Experimental analysis

Overview of measurement procedure - Standstill tests

- Resistances
  - phase
  - line-line
- Inductances (RLC-bridge, AC-, DC-decay method)
  - phase self
  - line-line
  - phase leakage
  - saturated synchronous
  - decoupled saturated sysnchronous

Experimental analysis

Overview of measurement procedure - Running tests

- unloaded machine
  - machine parameters
    - no-load phase&line-line BEMF
    - friction torque
    - no-load iron losses torque
    - cogging torque

- loaded (current controled) motor
  - machine parameters
    - synchronous inductances
    - dq-flux linkages
    - iron losses
  - machine operational parameters
    - torque-speed char.
    - efficiency-speed char.

- loaded generator
  - generator characteristics
    - torque-speed char.
    - efficiency-speed char.

- faulted inverter/machine
  - braking torque-speed char.
  - braking current-speed char.

Experimental analysis

Overview of measurement procedure – Thermal and vibroacoustic analysis

- Thermal analysis

  - steady state characteristics
    - continuous duty cycle SOA

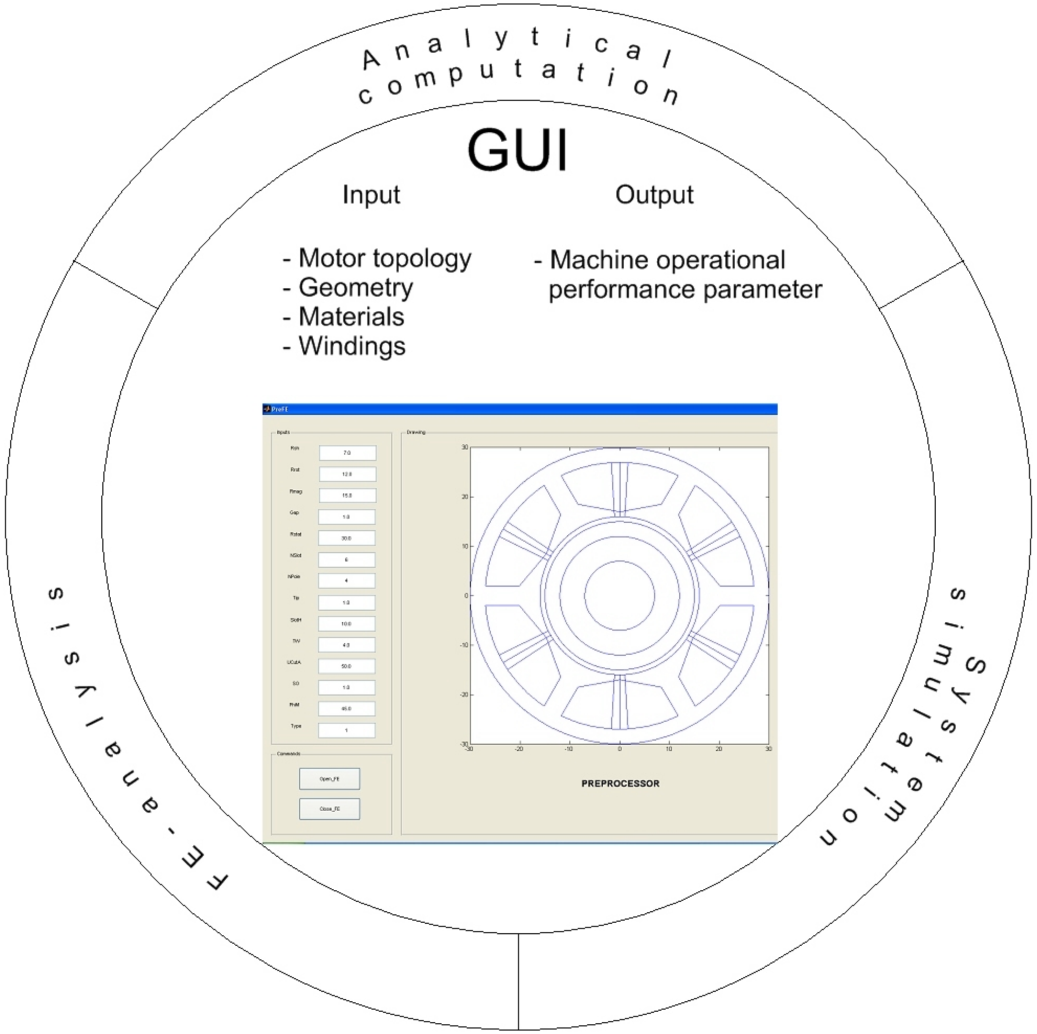
  - transient parameters
    - thermal resistances
    - thermal capacities

- Vibro-acoustic analysis

  - time-domain signals
    - vibration
    - sound

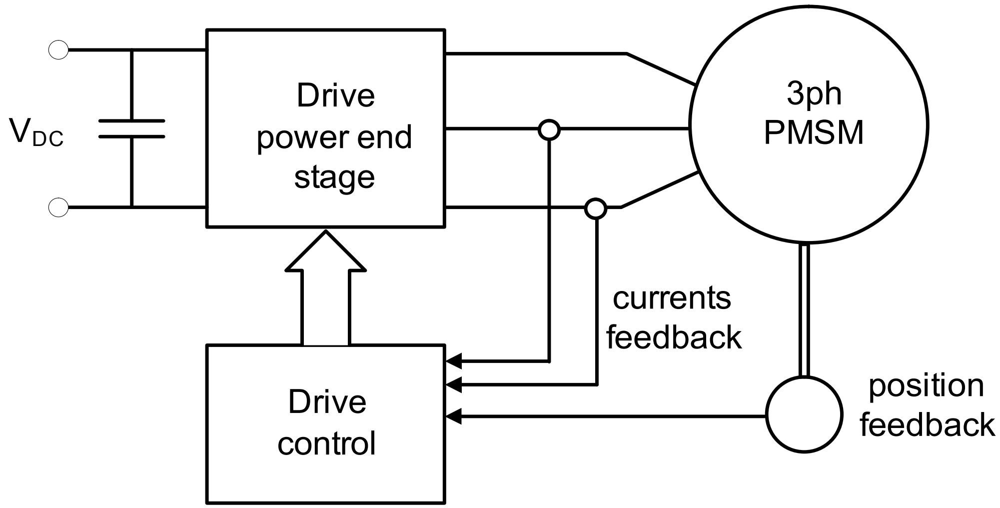
  - frequency-domain signals (frequency spectrum)
    - vibration
    - sound

Software-tools for PMSM design and analysis



Fundamental control issues

- Accurate stator current synchronization with the rotor position is mandatory for good quality torque



Basic configuration of a drive system with a three-phase PMSM - used for both types of PMSM

- Rotor position feedback
  - trapezoidal PMSM-drive: three Hall-elements (with a resolution of 60 electrical degrees)
  - sinusoidal PMSM-drive: higher resolution rotor position sensor (encoder or resolver)

Fundamental control issues

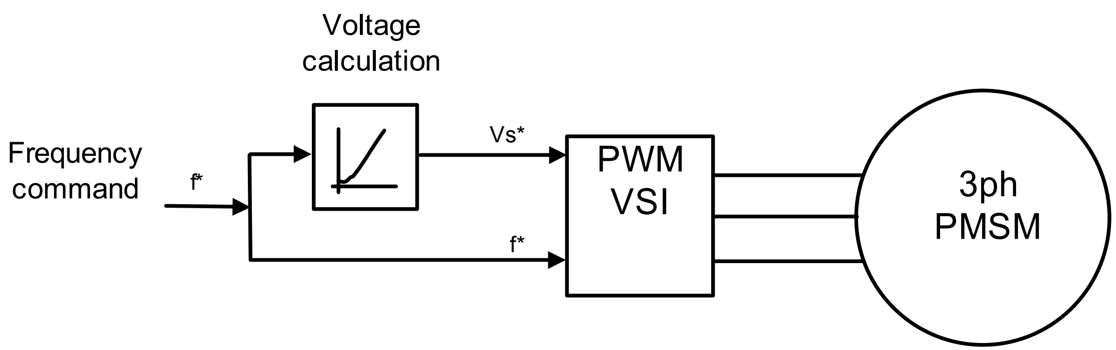
Basic control methods

- Two different major classes of control techniques are available for the two PMSM types:
  - trapezoidal control for trapezoidal excited machines
  - sinusoidal control for sinusoidal machines
- The different applications require
  - torque
  - speed
  - position control
- Therefore a wide range of controller types may be used (e.g. classical proportional-integral, adaptive, or intelligent)
- For high performance applications - where a high quality of the torque output is crucial - closed-loop sinusoidal vector current control is mandatory
- In the following only the control methods for sinusoidal PMSM will be presented

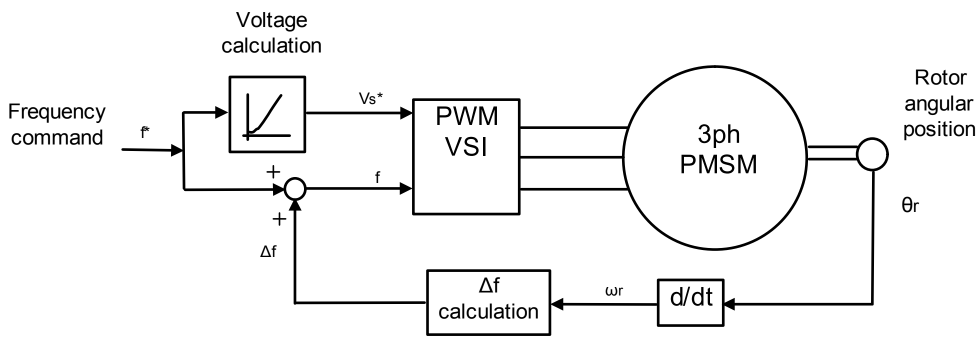
Fundamental control issues

V/s (scalar) control

• PMSM with rotor damper cage - simple open-loop V/f control method to achieve speed control for some applications like pumps and fans with slower dynamic response



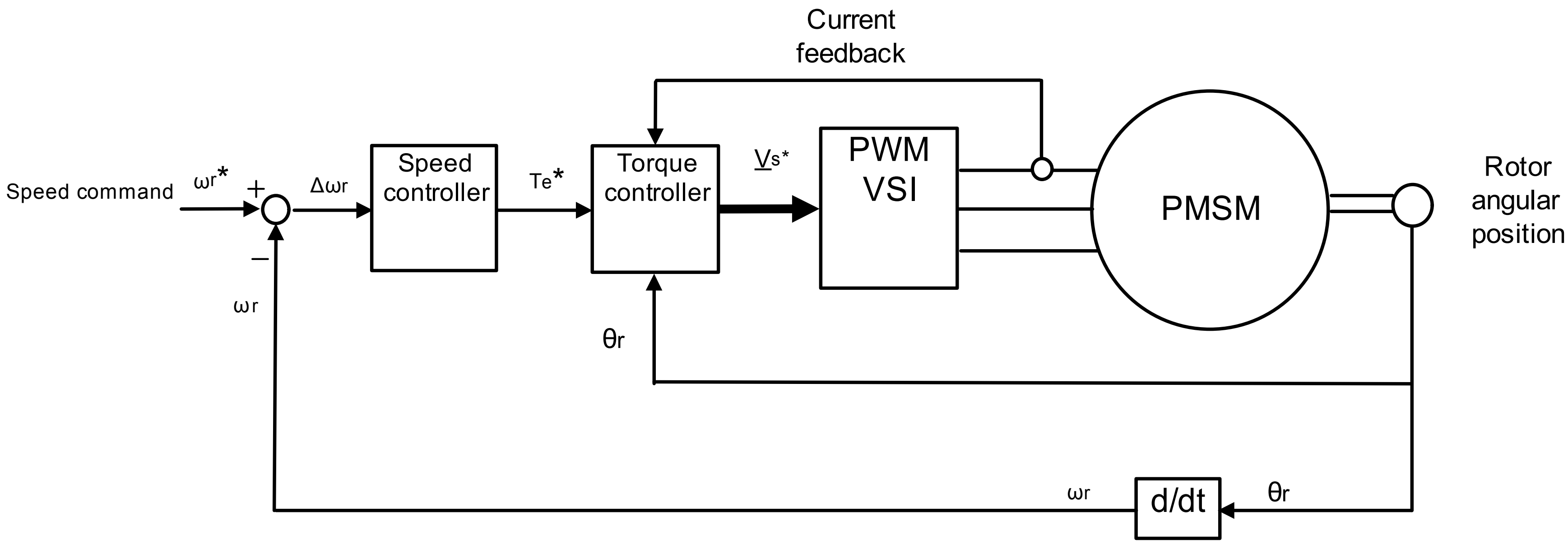
• PMSM without rotor cage - control scheme with speed information for the synchronization of the currents and rotor frequency (closed-loop control with rotor frequency and not rotor position monitoring for lower dynamic performance applications)



Fundamental control issues

Closed-loop torque and speed

• For higher performance torque and speed control structures can be employed using current and rotor angular position feedback (for the speed control a second speed control loop is necessary)



Fundamental control issues

Position sensorless control

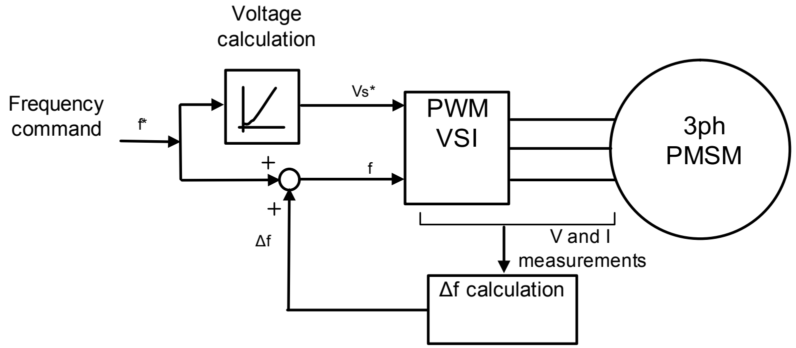
- In the above presented closed-loop control methods the presence of the rotor angular position sensor is mandatory for the stator current excitation synchronization with the rotor position
- The rotor position sensor is undesired
  - costs
  - mechanical mounting
  - sensitivity to temperature and vibration
  - need of wired connection to the controller

- In the last decade a lot of research work was done in order to find control methods which can work properly without rotor position sensors – position sensorless control

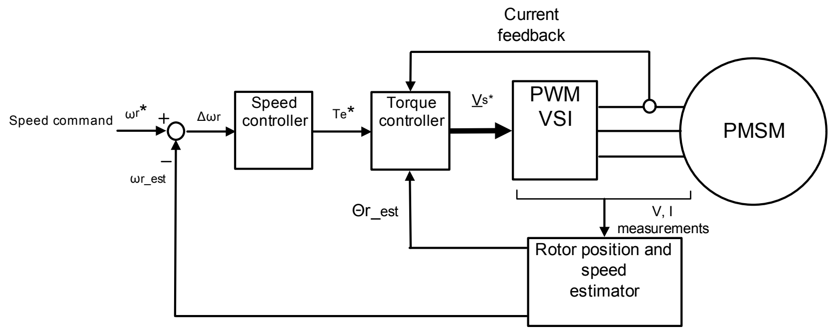
Fundamental control issues

Position sensorless control

• <u>V/f closed-loop</u> position sensorless <u>speed control</u> - the measurement of currents and voltages at the motor terminals or DC-link are used to calculate the error in the synchronization of the stator current excitation and the rotor speed



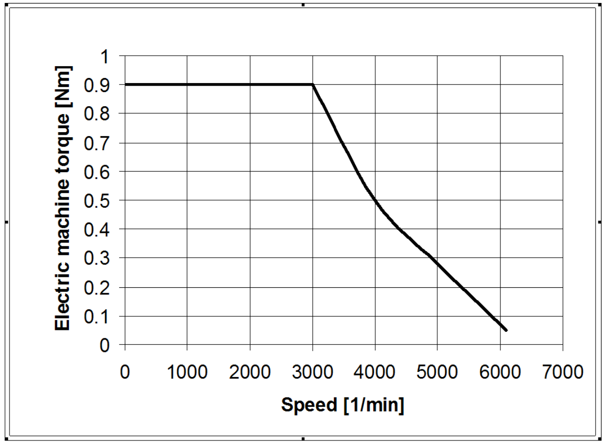
• <u>Closed-loop</u> position-sensorless <u>torque and speed control</u> using an accurate *rotor angular position and speed estimation* from the measured voltages and currents at the motor terminals or DC-link



Case study

PMSM for an electric active front steering drive

- illustrate relevant aspects related to the motor design and control for the sinusoidal and trapezoidal technologies
- motor specification, geometrical and technological design constraints for both technologies

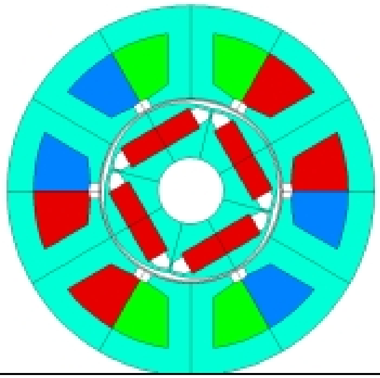
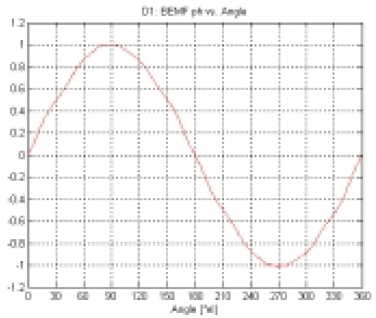


Parameter	Units	Value
Peak stall torque	Nm	0.9
Base speed	rpm	3000
Maximal speed (no-load)	rpm	6000
DC-bus voltage	V	12
Duty cycle	-	S3-5%
Environment temperature	°C	- 40 … 125

Parameter	Units	Value
Stator outer diameter, D_{so}	mm	56
Shaft diameter, D_{shaft}	mm	10
Stack length, L_{stack}	mm	45
Winding system	-	concentrated

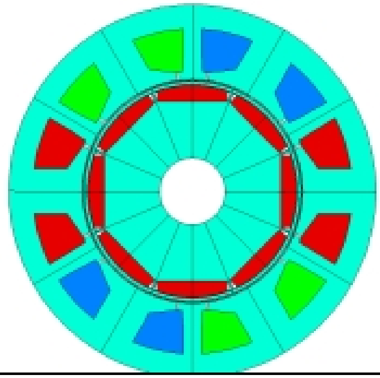
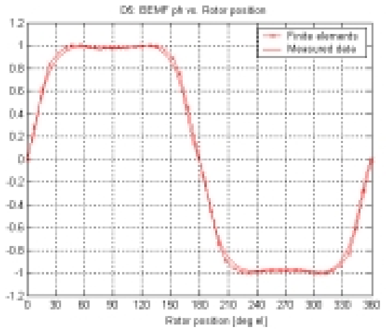
Case study

PMSM for an electric active front steering drive – Sinusoidal design solution

Solution	Cross-section	BEMF-shape	Motor constant k_M [Nm/√W] (@ 30 % slot fill factor)	Cogging torque peak-peak [Nm]
BLAC-D1			0.096	18

Case study

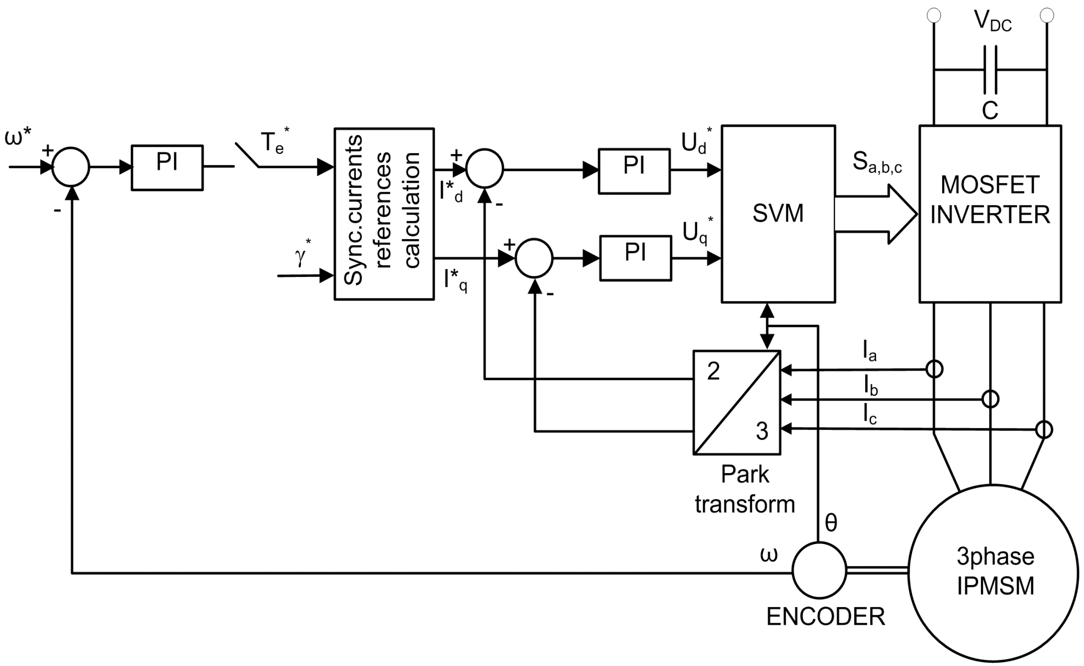
PMSM for an electric active front steering drive – Trapezoidal design solution

Solution	Cross-section	BEMF-shape	Motor constant k_M [Nm/√W] (@ 30 % slot fill factor)	Cogging torque peak-peak [Nm]
BLDC-D5			0.147	13

Case study

PMSM for an electric active front steering drive

Sinusoidal indirect current vector control structure



Case study

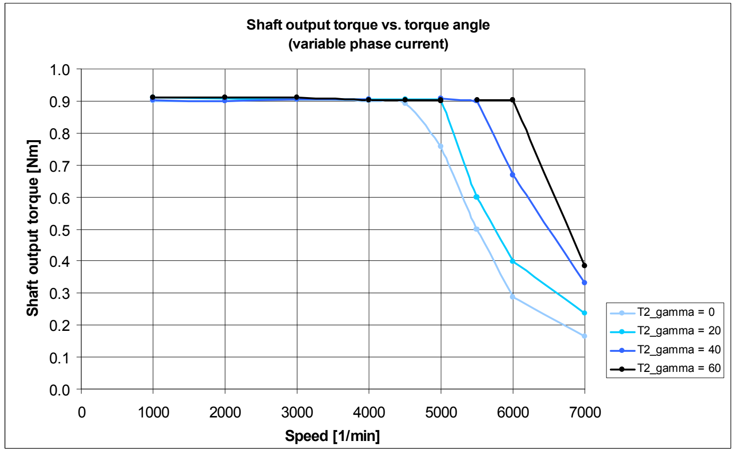
PMSM for an electric active front steering drive – BLAC experimental results

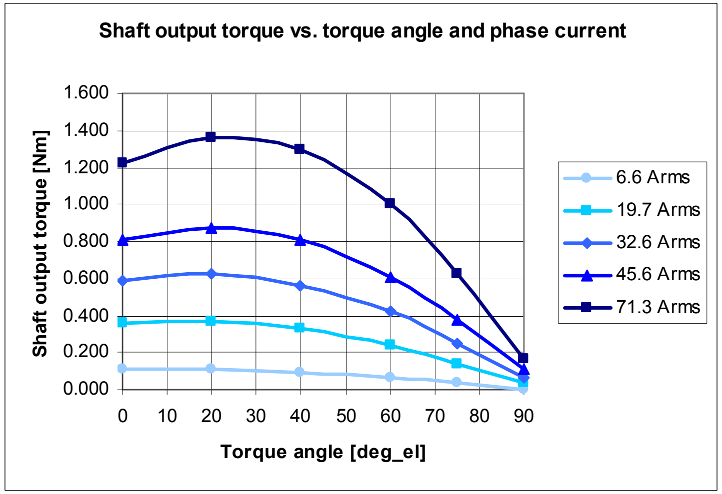
The torque production

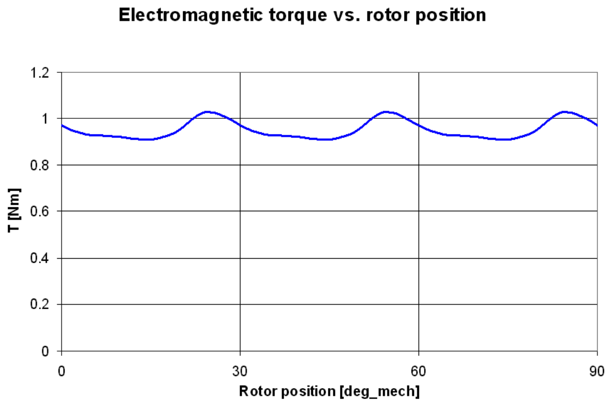
$$T_{em} = \frac{3}{2} p\left(\psi_{PM} I_q - \left(L_d - L_q\right) I_d I_q\right)$$

can be maximized through optimizing the torque angle γ

- torque vs. speed characteristics for different torque angle γ
- torque vs. torque angles for different phase currents
- torque pulsations







Conclusion

- PMSM technology was presented in an overview covering a wide area
- Included material is intended to give an orientation and to facilitate individual in-depth work in particular cases

Thank you

for your attention!