# Automotive Electric Drives
# An Overview


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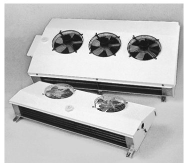



# Targets

- Overview of high performance automotive electric drives

- Overview of permanent magnet synchronous motor (PMSM) drives as one of the most competitive technology

# Contents

# Introduction

## Importance of electric actuation in automotive

- Clear trend in the automotive industry to use more electric drive systems in order to satisfy the demands for
    - lower fuel consumption and lower pollution level
    - higher vehicle performance (higher comfort, dynamic behaviour, etc.)

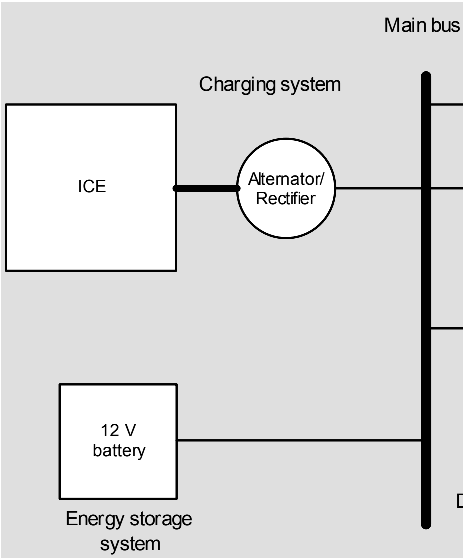
- Features of electric actuation
  - proven technology
  - high reliability
  - high efficiency of the energy conversion
  - precise controllability of the energy flow

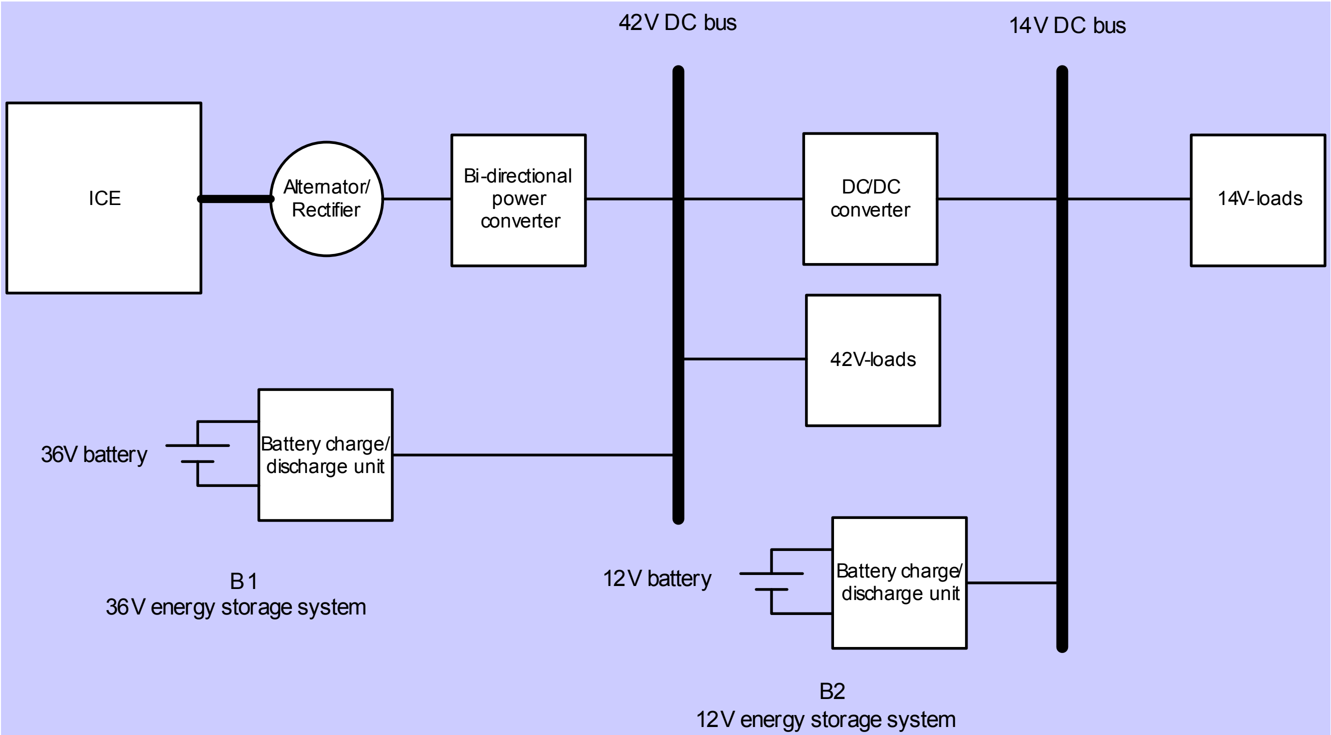
# Introduction

## Drastic growing of vehicular electric load demands - up to 10 kW

Consequence: higher voltage levels become mandatory

12/42/...288/... V

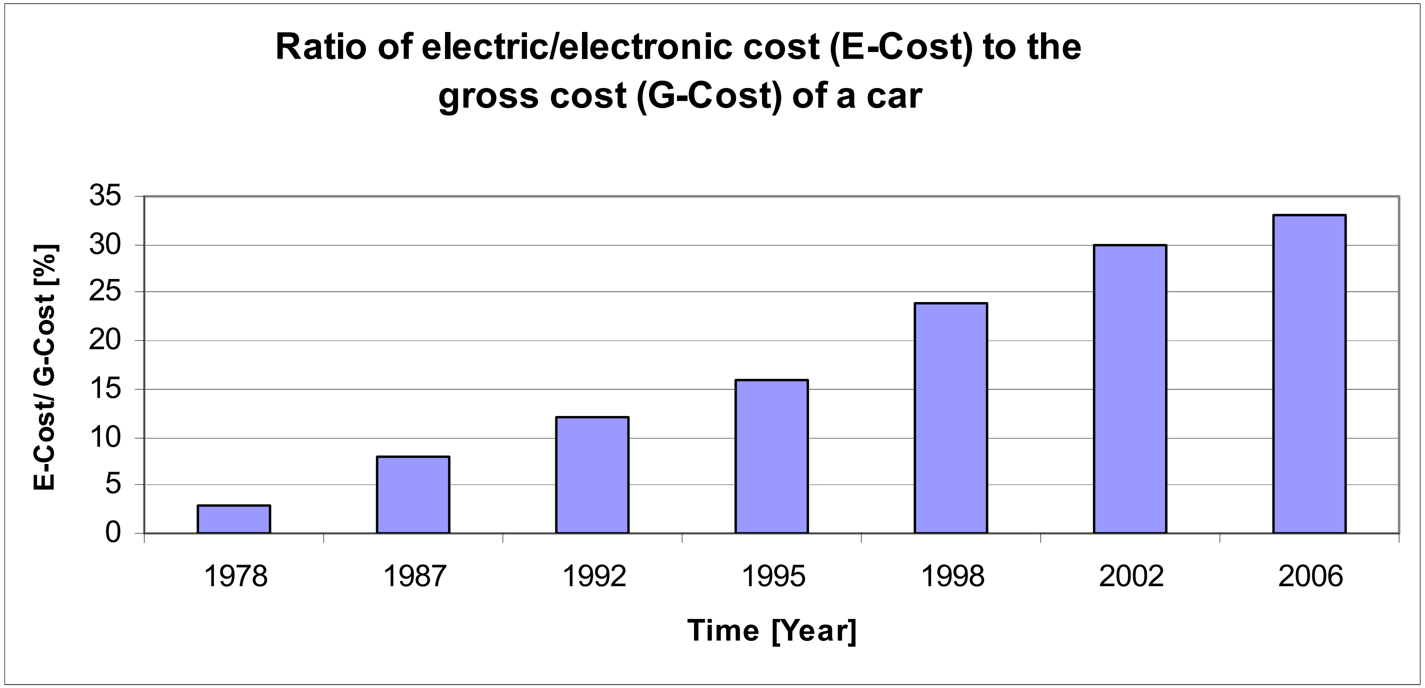



**Conventional vs. advanced power system architecture**

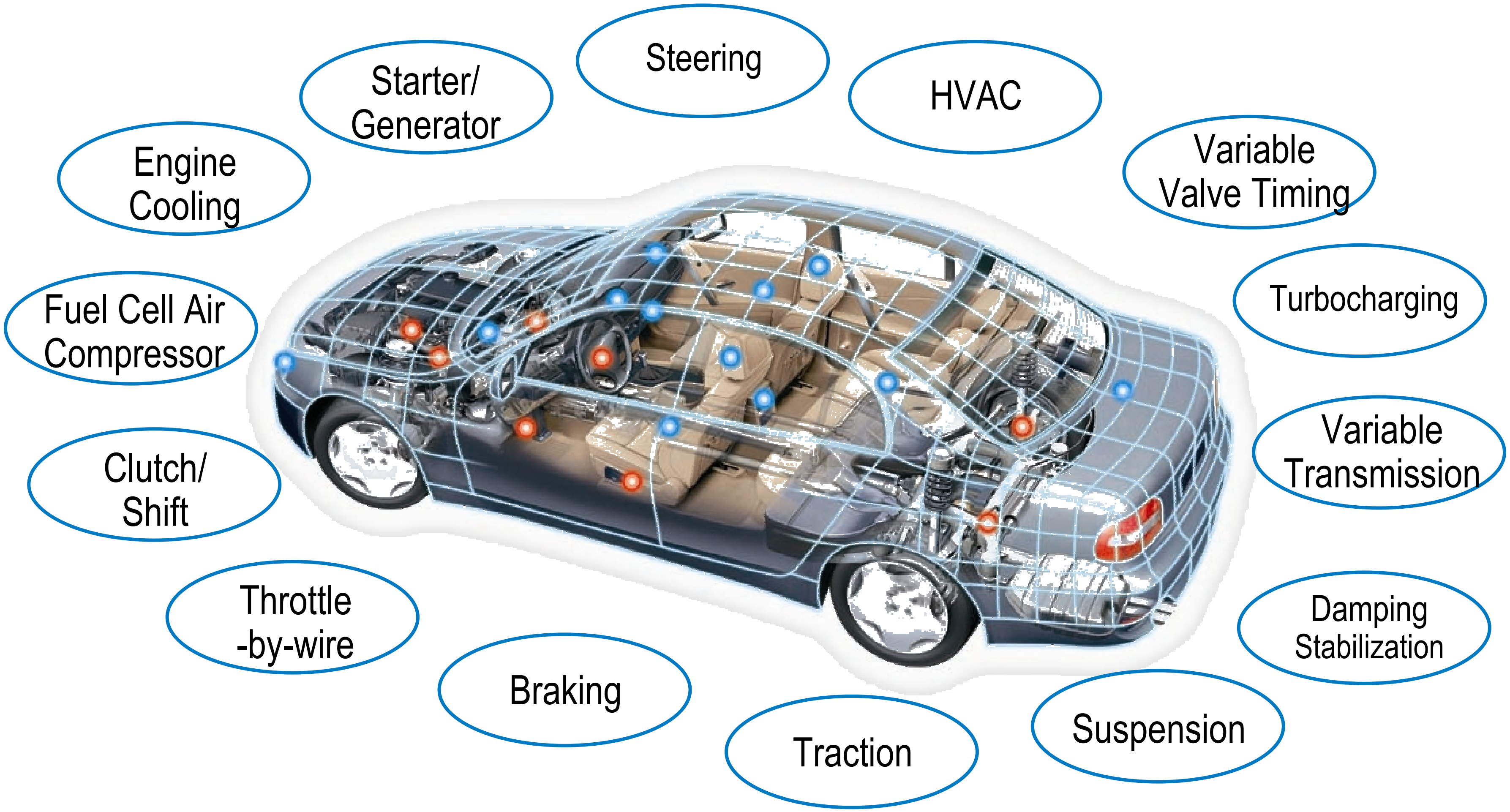
# Introduction

## Evolution of the costs of electric/electronic equipment of a car



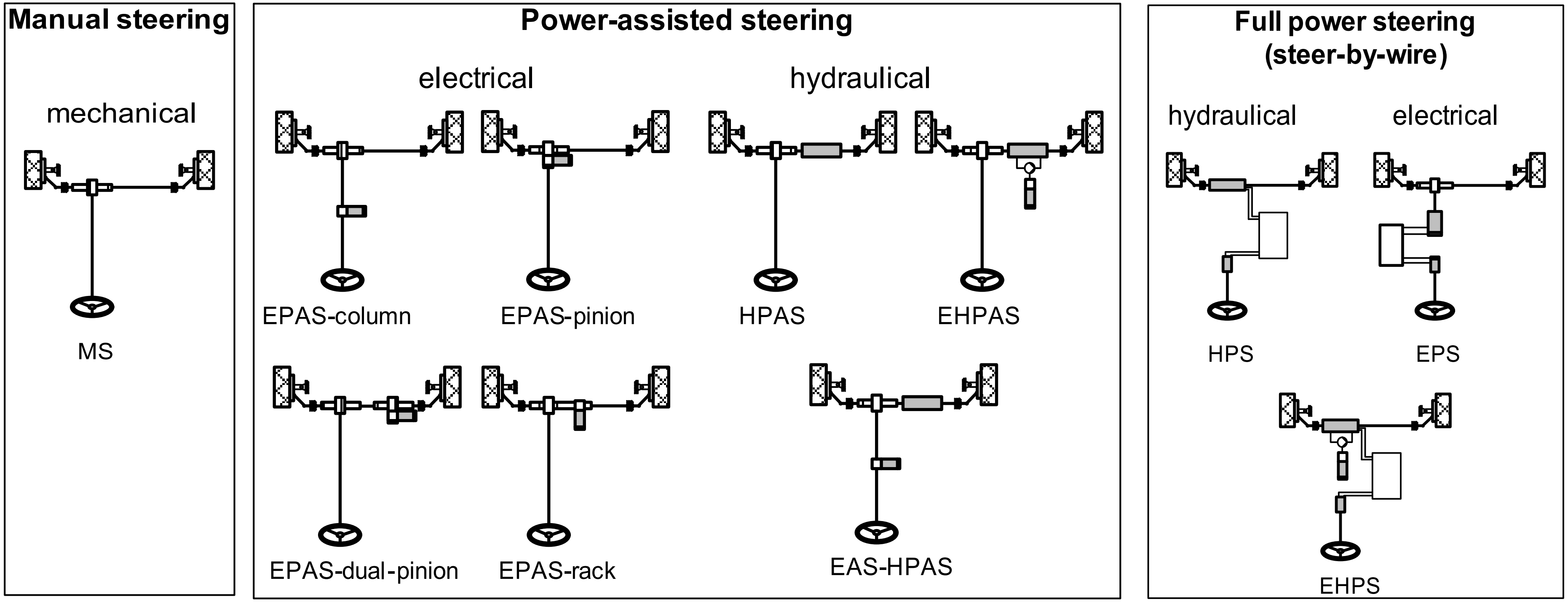
# Introduction

Schematic overview of high performance automotive applications



# Introduction

## Steering systems - classification

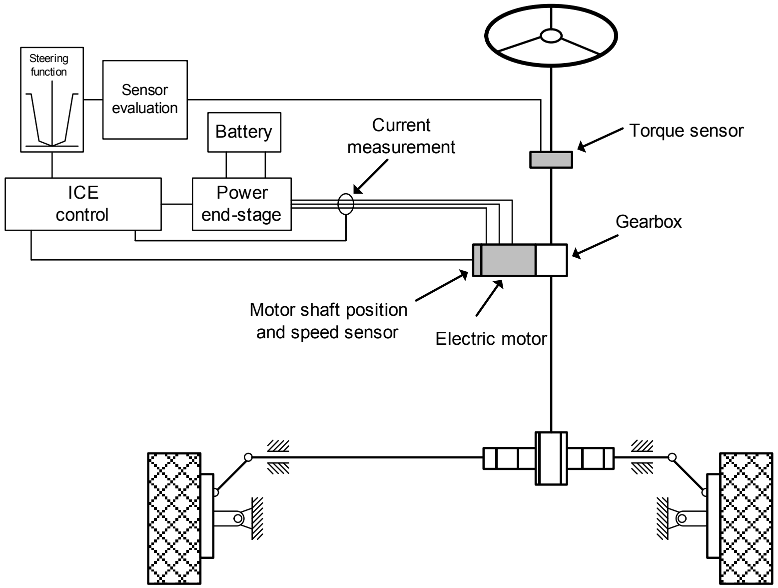


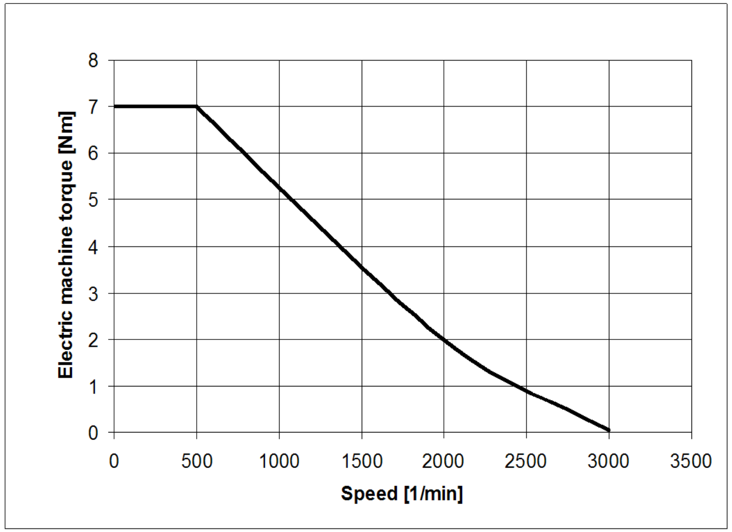

Steering parameters (steering torque and steering angle)

- torque assistance
- angle assistance

# Introduction

## Power assisted steering systems (torque assistance)




| Parameter | Units | Value |
|---|---|---|
| Peak stall torque | Nm | 7 |
| Base speed | 1/min | 500 |
| Maximal speed | 1/min | 2000 |
| DC-bus voltage | V | 12 |
| Duty cycle | - | S3-5% |
| Environment temperature | °C | - 40 … 125 |

*Table 1-II Specification data for the electric motor of an electric power assisted steering system*

**Key performance parameters**

> high torque density

> very low cogging torque (below 20 mNm peak-to-peak)

> low torque pulsations

> low acoustic noise

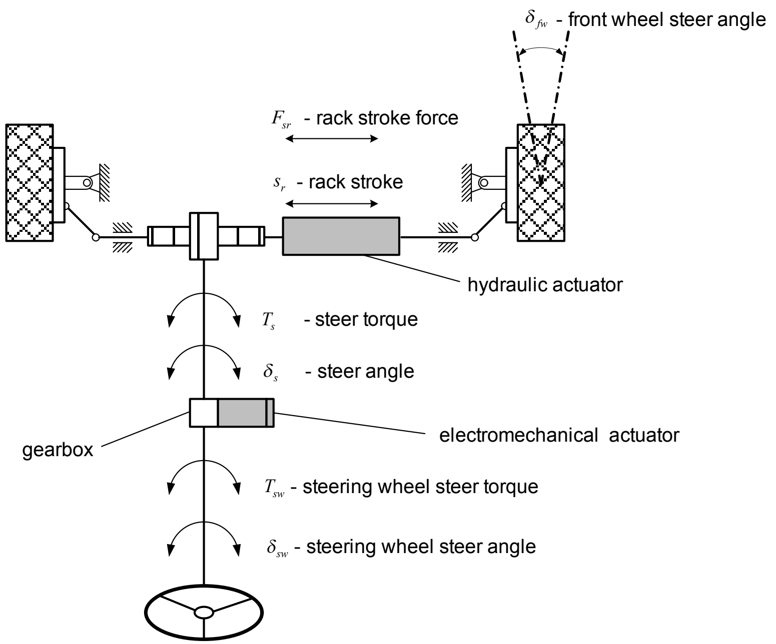
> high energy efficiency

**Candidates**

- sinusoidal vector current controlled PMSM - only proper candidate
- lower demanded peak torque - induction motor (poor energy efficiency)

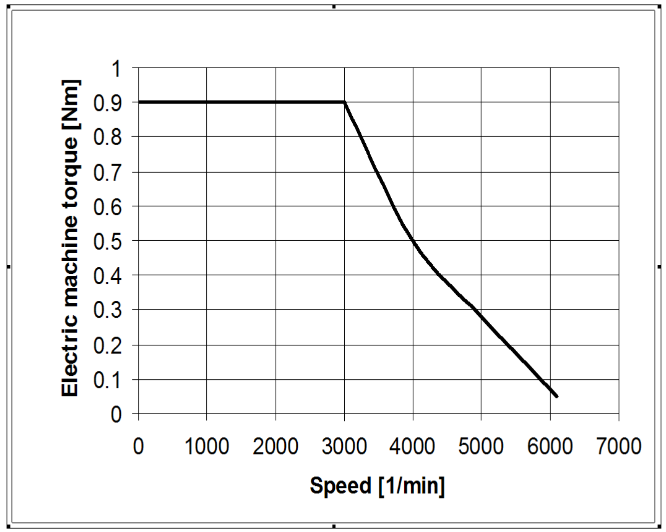
# Introduction

## Active steering systems (angle assistance)




| Parameter | Units | Value |
|---|---|---|
| Peak stall torque | Nm | 0.9 |
| Base speed | 1/min | 3000 |
| Maximal speed | 1/min | 6000 |
| DC-bus voltage | V | 12 |
| Duty cycle | - | S3-5% |
| Environment temperature | °C | - 40 … 125 |

*Table 1-III Specification data for the electric motor of an electric active front steering system*



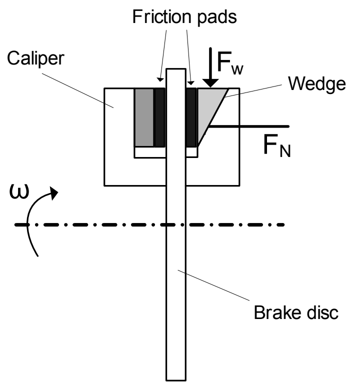

**Key performance parameters**

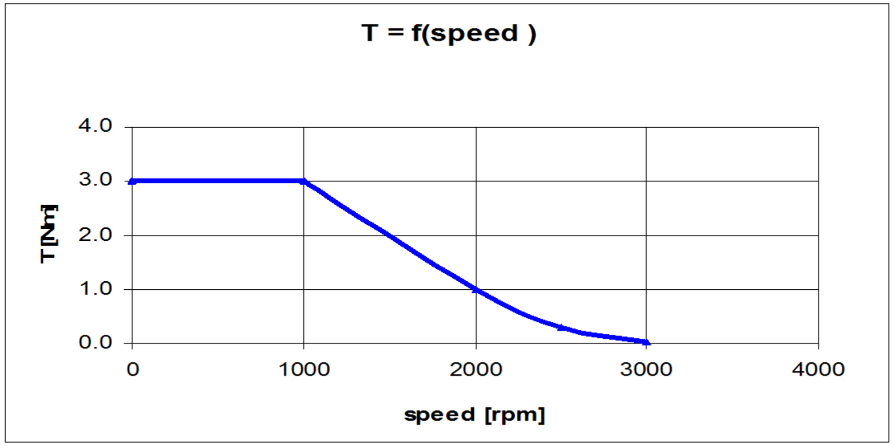
- high torque density
- very low cogging torque (below 20 mNm peak-to-peak)
- low torque pulsations
- low acoustic noise

**Candidate**

- sinusoidal vector current controlled PMSM

Wedge brake




| Parameter | Units | Value |
|---|---|---|
| Peak stall torque | Nm | 3.0 |
| Base speed | 1/min | 1000 |
| Maximal speed | 1/min | 3000 |
| DC-bus voltage | V | 12 |
| Duty cycle | - | S3-5% |
| Environment temperature | °C | - 40 … 125 |

*Table 1-IV Specification of an electric machine for an electromechanical brake*

**Key performance parameters**

- high torque density
- high temperature resistance

**Candidate**

- trapezoidal PMSM

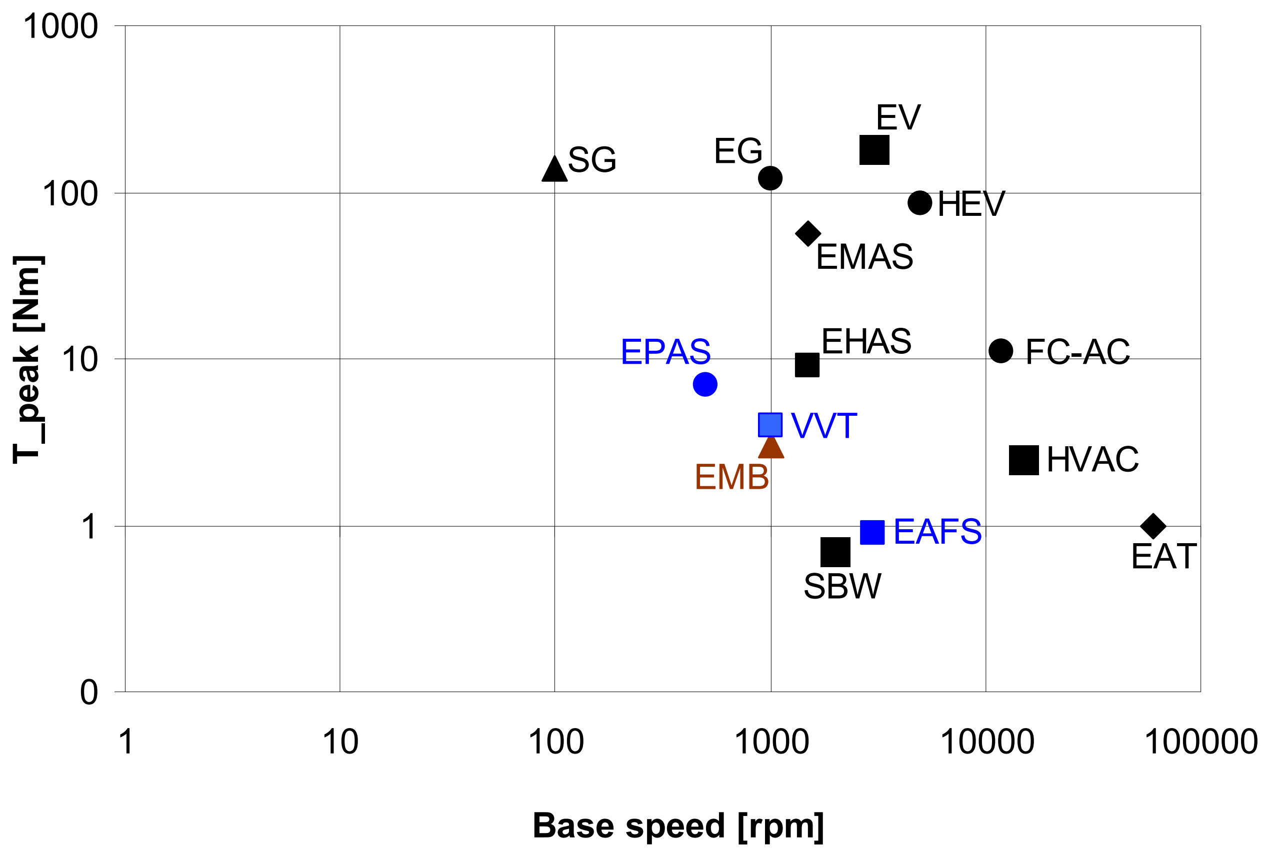
# Introduction

**High-speed automotive applications - specification and competing technologies**

| Application | $T_{peak}$ [Nm] | $n_{base}$ [rpm] | $n_{max}$ [rpm] | Competing motor technologies |
|---|---|---|---|---|
| Compressor for air conditioner | 2.5 | 15000 | 17000 | PMSM |
| Air compressor for fuel cells | 11 | 12000 | 14000 | PMSM |
| Engine cooling systems (electric water pump) | 0.955 | 5000 | >> | PMSM, SR |
| Electrical assisted turbocharger | 1 | 60000 | 120000 | IM, PMSM, SR |

# Introduction

## Automotive electric drives: torque-speed demands




| Application | Description |
|---|---|
| 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 |

# Introduction

## Automotive requirements, constraints and implications for electric actuation systems

Technical and economical parameters:

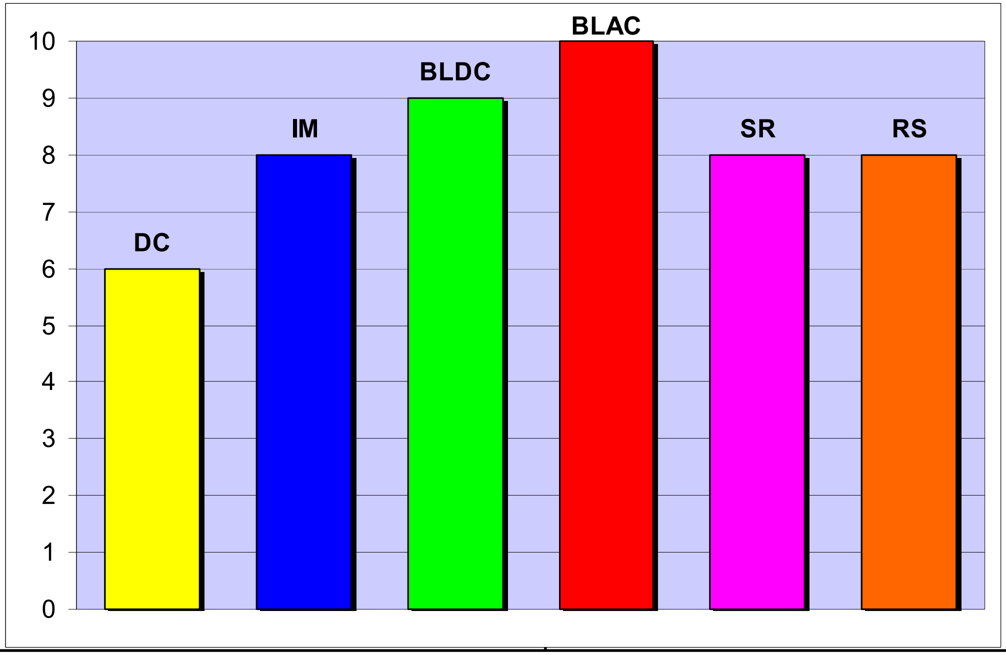
- high reliability
- high energy efficiency
- low costs
- compact size
- low weight
- variable speed control in wide torque-speed ranges
- low acoustic noise level
- long life cycle

# Introduction

## Competing electric drives technologies for automotive applications

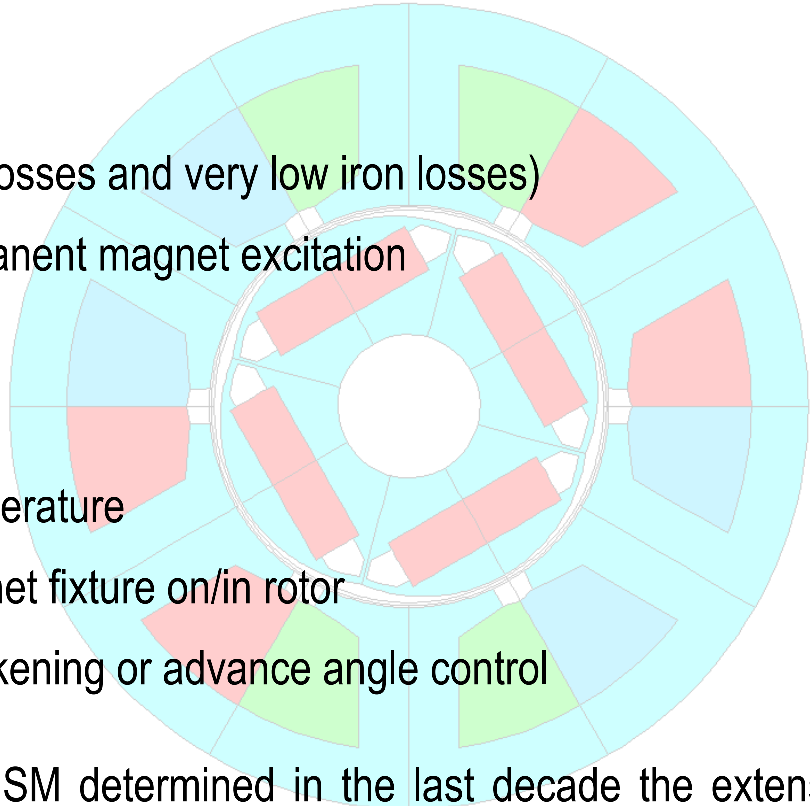
| | DC | IM | PMSM BLDC | PMSM BLAC | SR | RS |
|---|---|---|---|---|---|---|
| Torque density | - | - | + | + | - | - |
| Torque/Amp | - | - | + | + | - | - |
| Peak to continuous torque capability | - | - | + | + | - | - |
| Variable speed control | + | - | - | - | - | - |
| Torque/inertia ratio | - | - | + | + | + | - |
| 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 | + | - | + | - | - | - |

- permanent magnet brushed dc (DC)
- induction (IM)
- permanent magnet trapezoidal (BLDC)
- permanent magnet sinusoidal (BLAC)
- switched-reluctance (SR)
- reluctance synchronous (RS)



# PMSM drives

•For <u>high performance</u> automotive applications the PMSM represent one of the best candidates



## PMSM advantages

- high efficiency (in rotor - no copper losses and very low iron losses)
- high torque density due to the permanent magnet excitation

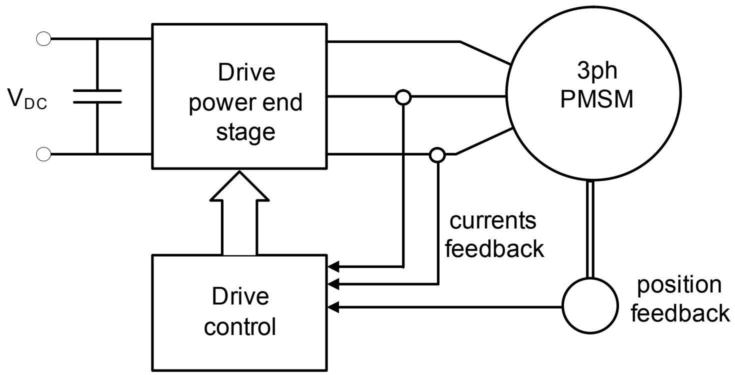
## PMSM drawbacks

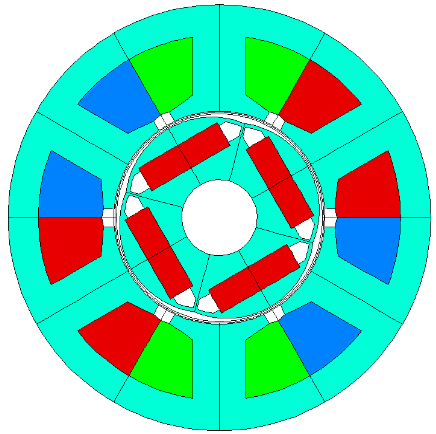
- high cost of the permanent magnets
- risk of demagnetization at high temperature
- increased effort for permanent magnet fixture on/in rotor
- additional control effort for field weakening or advance angle control

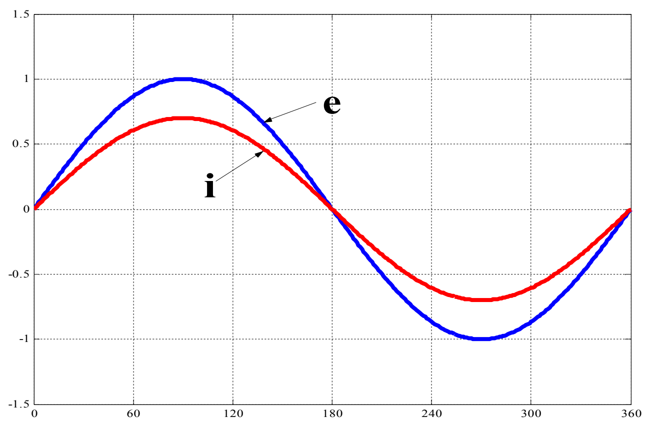
The technical advantages of the PMSM determined in the last decade the extension of their area of application in the automotive industry

# PMSM drives technologies

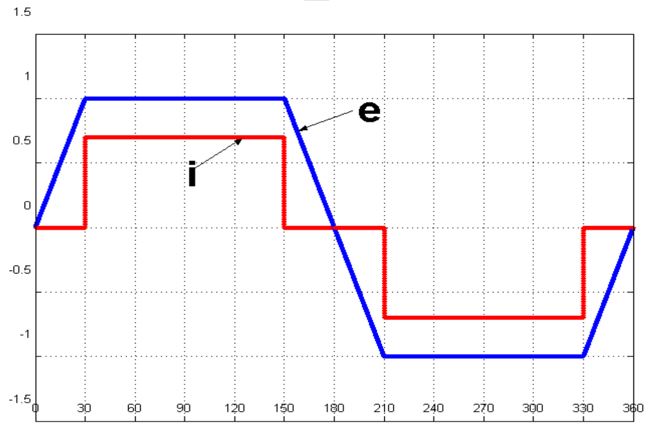
## Classification based on the shape of back-EMF and excitation currents






sinusoidal machine (BLAC) and control

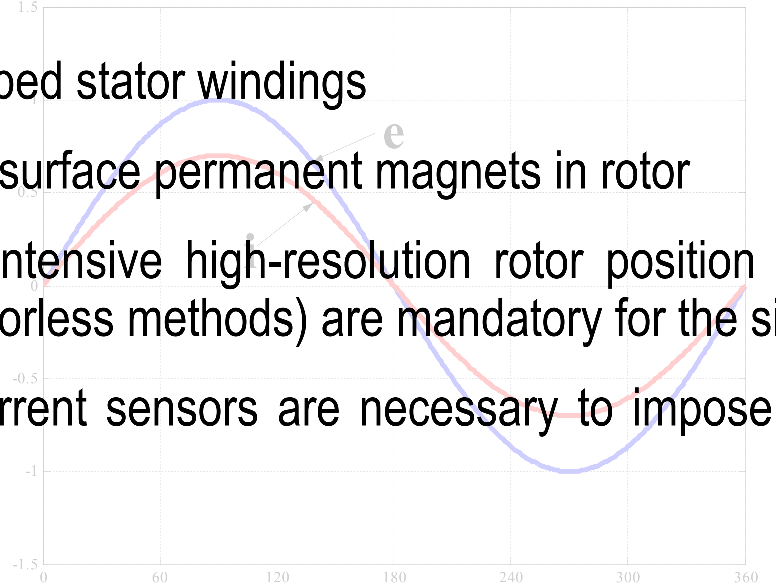



trapezoidal machine (BLDC) and control

# 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

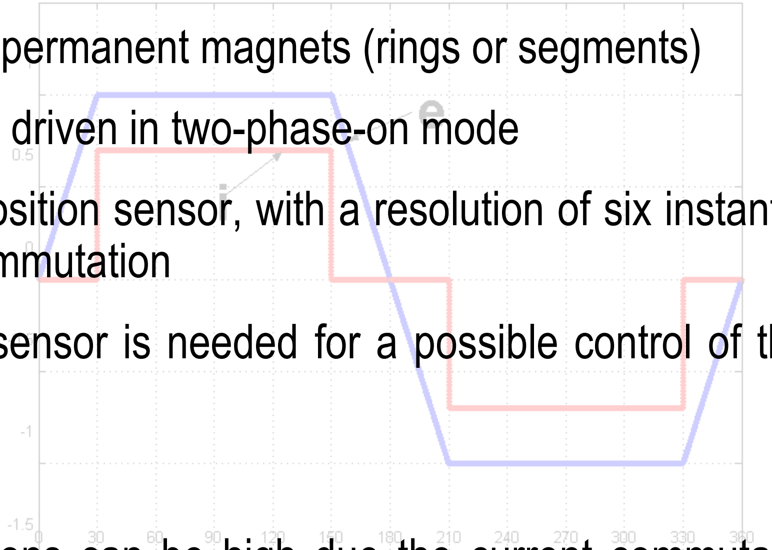



Due to the low torque ripple <u>sinusoidal PMSM drive</u> is the only proper technology for high performance applications

# PMSM drives technologies

## BLDC motors and drives

- trapezoidal back-EMF shape and trapezoidal current in order to get good 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 drives technologies

## PMSM design

Motor design – selection of the motor topology based on a **quality factor** (taking into account the cogging torque behaviour and the magnitude of the winding factor of the mmf-fundamental)

Quality factors for small PMSM (up to 24 stator slots and 16 rotor poles)

| 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 |

PMSM with **single-layer** concentrated windings

| 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 |

PMSM with **two-layer** concentrated windings

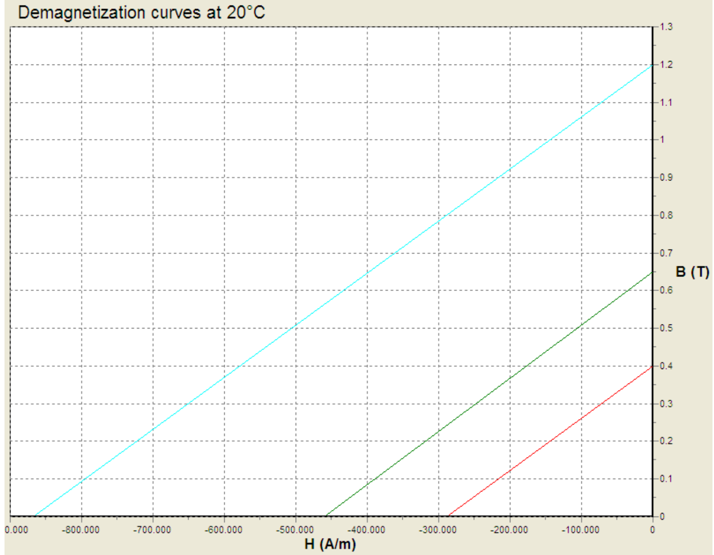
# PMSM design aspects

## Materials for active components of PMSM

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

For high torque density applications only sintered NdFeB-magnets

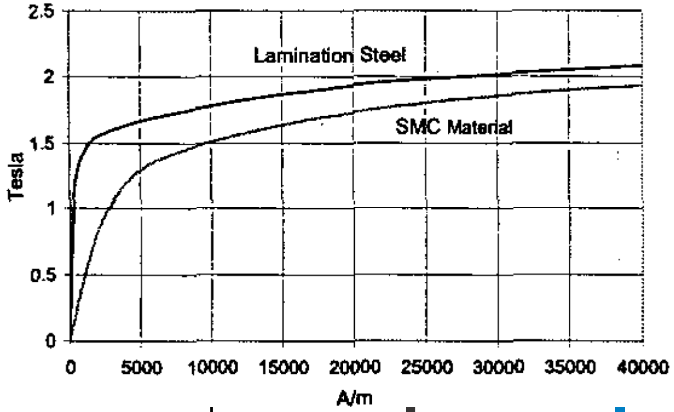
| | residual flux density T | intrinsic coercivity $_JH_c$ kA/m | maximum energy product kJ/m³ |
|---|---|---|---|
| sintered ferrite | 0.4 | 300 | 40 |
| bonded NdFeB | 0.7 | 800 | 80 |
| sintered NdFeB | 1.2 | 1900 | 280 |




- **Soft magnetic materials**
  - cold rolled magnetic lamination (CRML) steel
  - soft magnetic composites (SMC) for “3-D design” and manufacturing capabilities

Conventional lamination steel is mandatory for high torque density applications

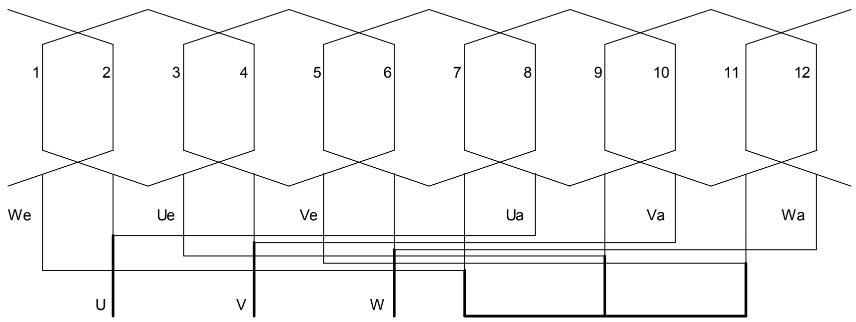
| | saturation flux density T | relative permeability - | core loss (1.5 $T_{peak}$, 50 Hz) W/kg |
|---|---|---|---|
| CRML steel | 2.0 | 2000-3000 | 2.7-8.0 |
| SMC | 1.8 | ~ 500 | 10 |



**Transition from conventional overlapped to non-overlapped (concentrated, tooth-wound) winding systems**

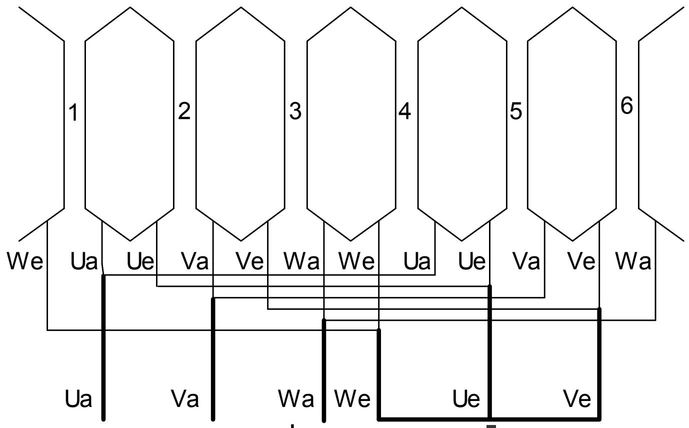
- conventional overlapped winding

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




- non-overlapped (concentrated, tooth-wounded) 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 automotive applications

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

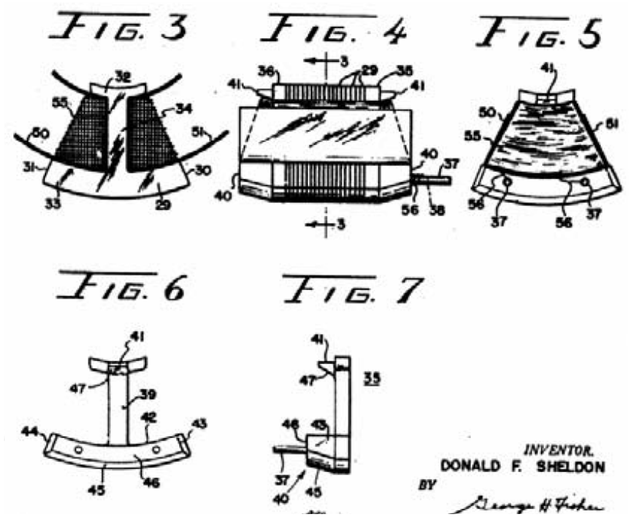


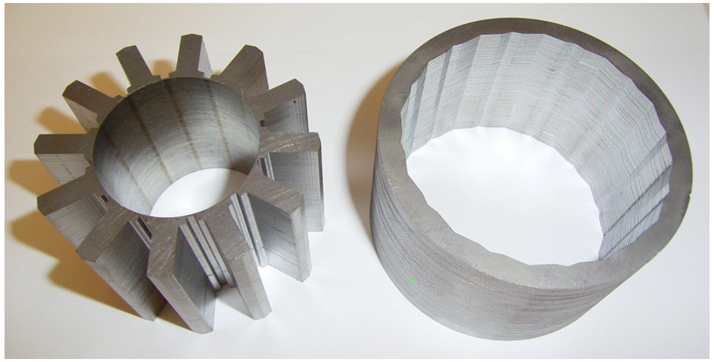
# PMSM design aspects

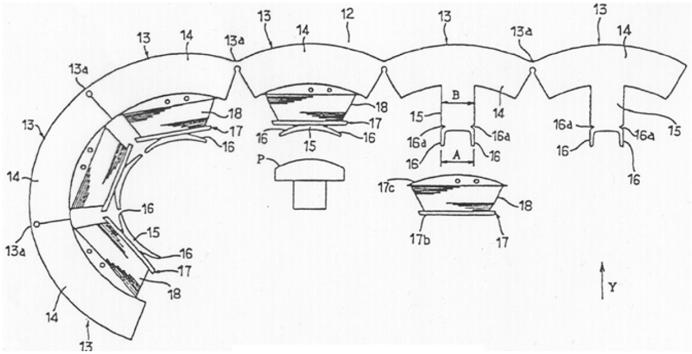
## Construction and manufacturing technologies for PMSM – modular stators

New <u>modular stator</u> 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

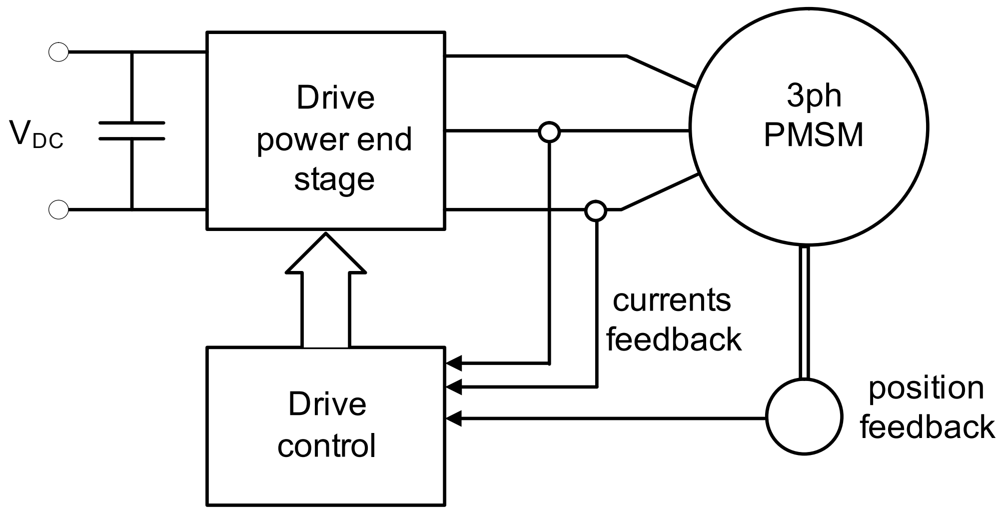




# Fundamental control issues

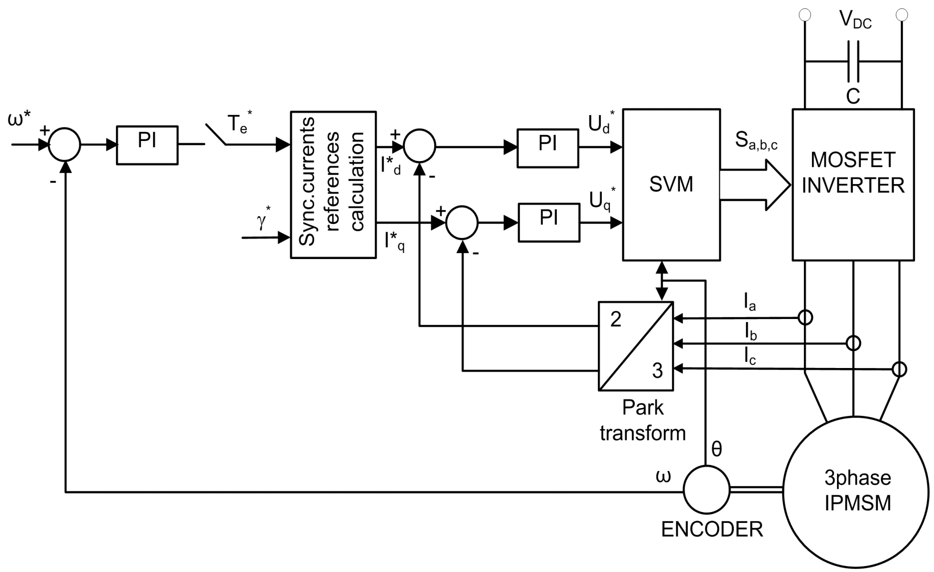
- Accurate stator current synchronization with the rotor position is mandatory for good quality torque



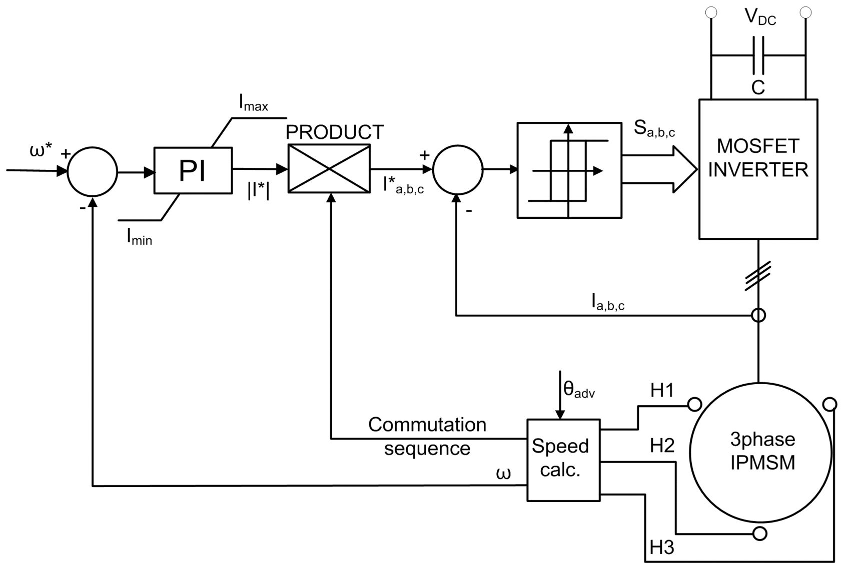

**Basic configuration of a drive system with a three-phase PMSM - used for both types of PMSM**

- 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)

- sinusoidal indirect current vector control




- trapezoidal current control



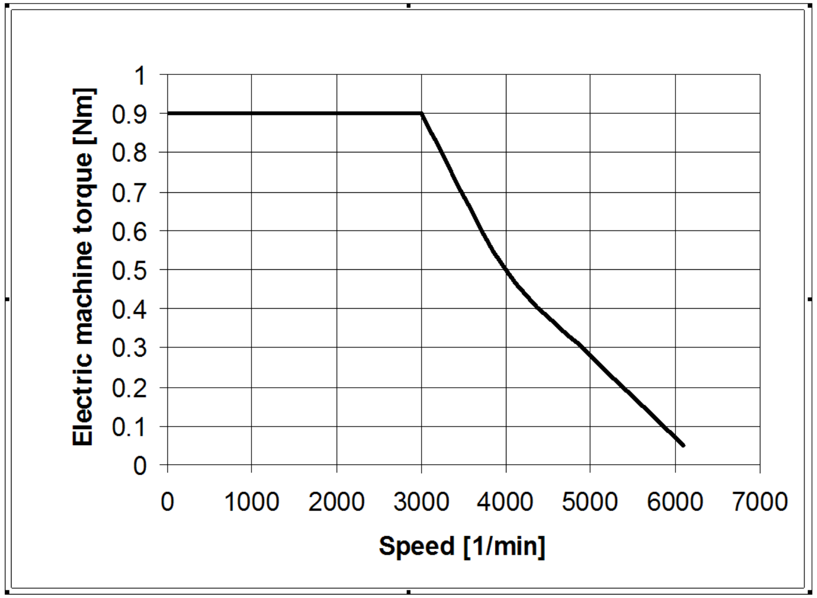


ebmpapst

# Case study

## Sinusoidal vs. trapezoidal PMSM for electric active front steering

EAFS-motor specification and design constraints

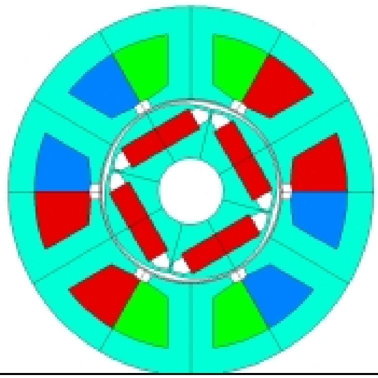
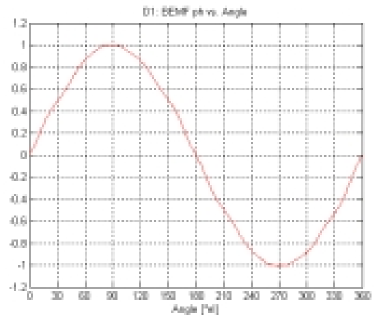



| Parameter | Units | Value |
|---|---|---|
| Peak stall torque | Nm | 0.9 |
| Base speed | rpm | 3000 |
| Maximal speed (no-load) | rpm | 6000 |
| DC-bus voltage | V | 12 |
| Duty cycle | - | S3-5% |
| Environment temperature | °C | - 40 … 125 |

| 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 |

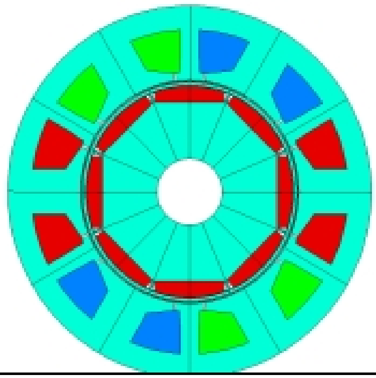
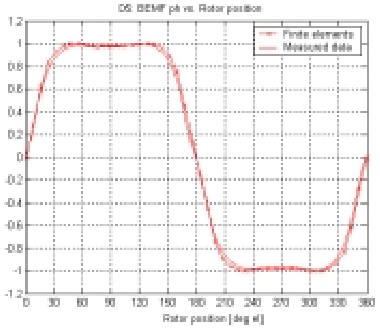
# Case study

## BLAC - favourite solution

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

# Case study

## BLDC - favourite solution

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

# Case study

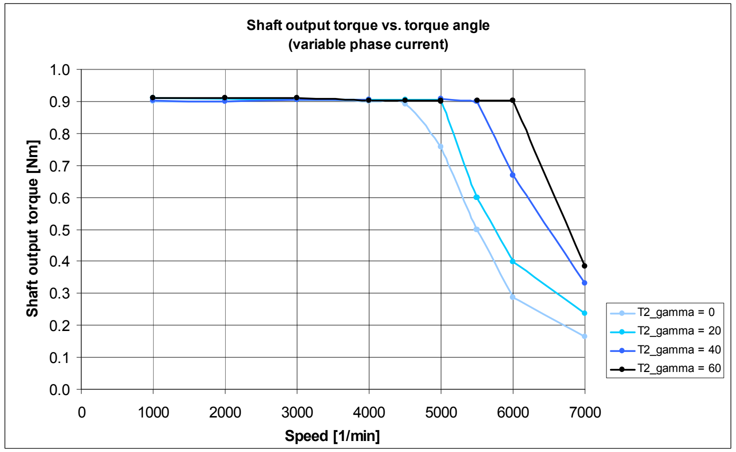
## BLAC drive - experimental results

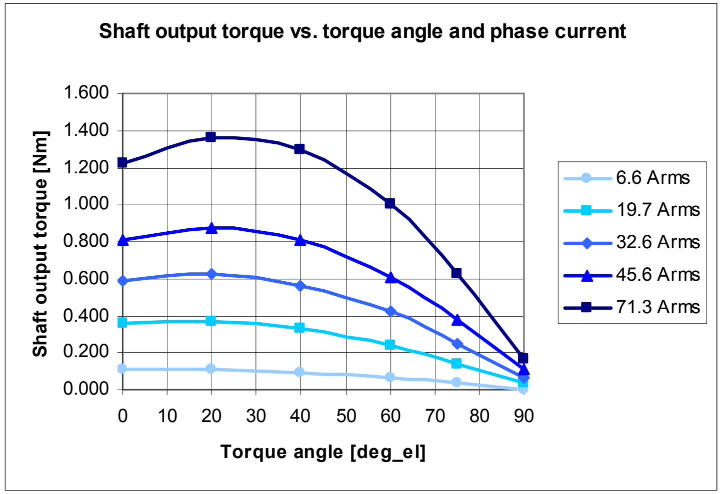
The torque production

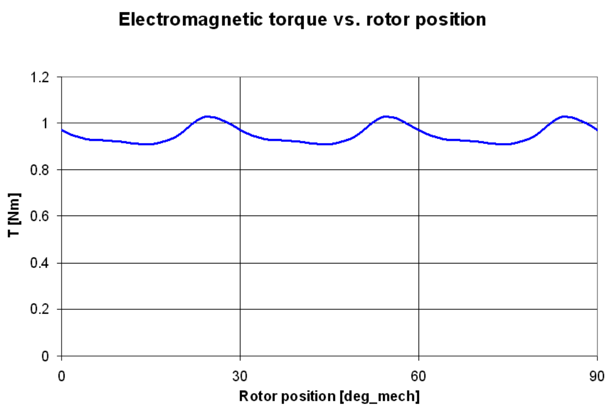
$$T_{em} = \frac{3}{2} p\left(\psi_{PM} I_q - \left(L_d - L_q\right) I_d I_q\right)$$

can be maximized through optimizing the torque angle $\gamma$

- torque vs. speed characteristics for different torque angle $\gamma$
- torque vs. torque angles for different phase currents
- torque pulsations



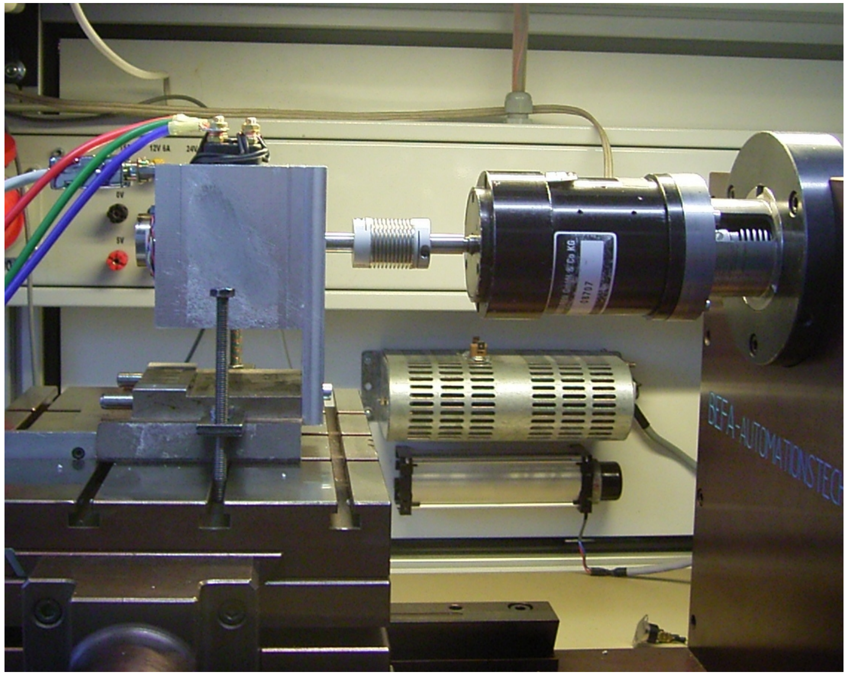



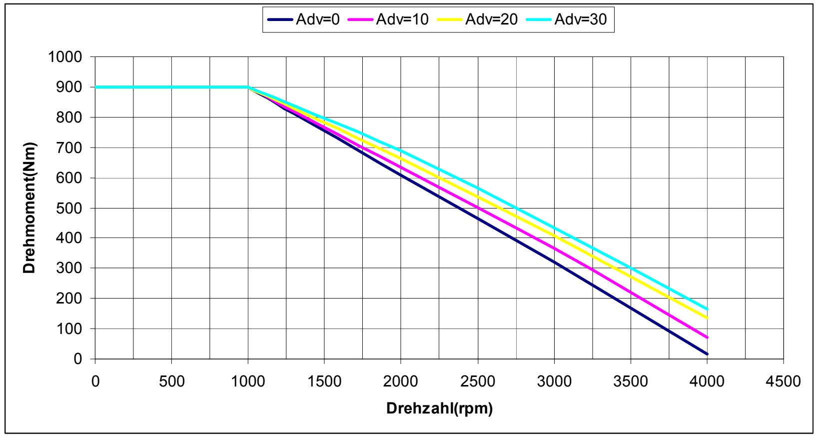



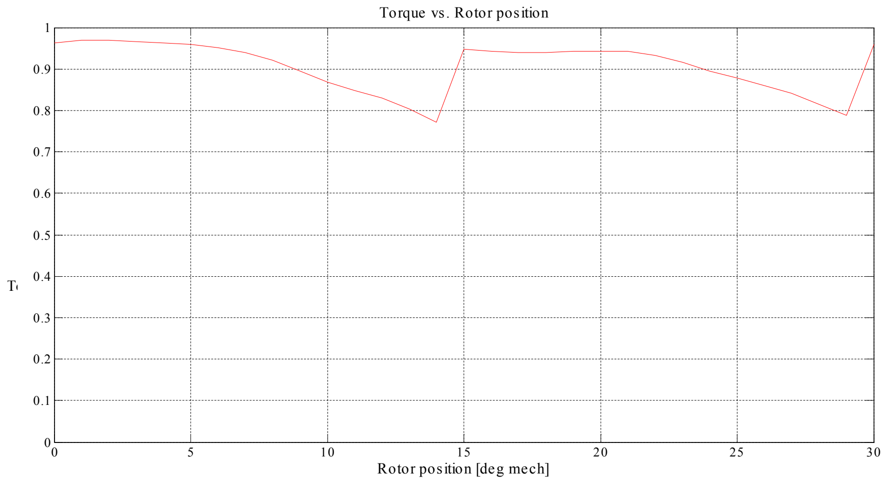
# Case study

## BLDC drive - experimental results

- BLDC motor mounted together with servo drive and torque transducer
- measured torque-speed characteristics for different advance angle values
- measured torque pulsations for the BLDC motor



# Conclusion

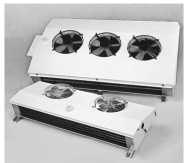
- Aim of this presentation
  - overview of high performance automotive electric drives
    - typical specification
    - key performance parameters
    - proper candidates
  - overview of permanent magnet synchronous motors technology
    - BLAC drive have the *lower pulsating torque* and the *best acoustical behaviour* but the *control structure is more complex* than in the case of the trapezoidal drive, as it requires the presence of a *more expensive position sensor* (encoder) in comparison with the 3 Hall sensors required in the trapezoidal drive and requires at least 2 current sensors
    - BLDC drive is *more simple* and only one current sensor could solve the current acquisition issue resulting in much lower costs of the drive, but has higher current peaks (higher current from the DC supply and higher torque pulsations

Thank you

for your attention!





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