INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

# Současné trendy vývoje moderních aplikací s elektrickými pohony

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Tato prezentace je spolufinancována Evropským sociálním fondem a státním rozpočtem České republiky.

# Časový rozvrh

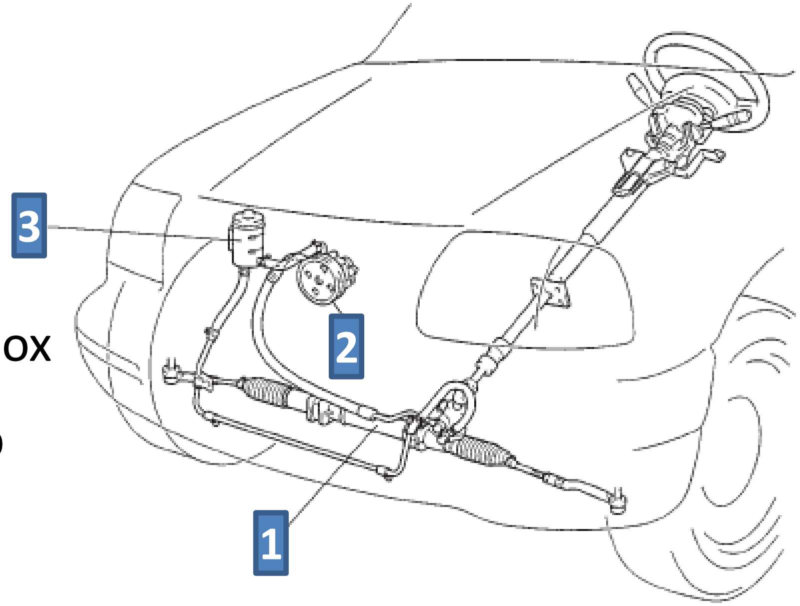
- 09:00 – 10:30 – blok 1
- 10:30 – 10:45 – přestávka
- 10:45 – 12:00 – blok 2
- 12:00 – 13:00 – oběd
- 13:00 – 14:15 – blok 3
- 14:15 – 14:30 – přestávka
- 14:30 – 15:45 – blok 4
- 15:45 – 16:00 – přestávka
- 16:00 – 17:00 – blok 5

# EPS – Electric Power Steering

# HPS – Hydraulic Power Steering

## Drawbacks

- Complexity – high cost
- "On" all the time and powered by engine–low fuel economy and safety concern
- Hard to integrate new technologies in




1. Power steering gearbox
2. Power steering pump
3. Oil tank

*Source: SAE TECHNICAL PAPER SERIES 1999-01-0401 by Dominke Peter and Ruck Gerhard ZF Lenksysteme GmbH*

# EPS – Electric Power Steering

## Adwantages

- Up to 4% improvement in fuel economy - The energy consumption of an EPS system is typically less than 7 percent of a conventional hydraulic rack and pinion power steering system
- Reduced parasitic losses — the system only uses energy when the driver steers, improving system efficiency and reducing emissions and overall energy use. In addition, an integrated EPS system eliminates the need for steering pump, pulley, belt, reservoir and hydraulic lines
- Reduce maintenance and recycling cost
- Reduced assembly time (up to 4 minutes)
- Enhanced safety (still operate even if engine is stalled)
- Safety and convenience — automakers are rapidly increasing the amount of safety and performance electronics integrated into vehicle systems, such as lane departure warning, parking assist, speed-sensitive steering and other stability control systems that can compensate for wind shear, road surface imperfections and vehicle alignment to deliver on-center feel.
- EPS systems have a distinct noise, vibration and harshness (NVH) advantage, as they operate at levels less than 35 decibels (dB), which is quieter than a typical library at 40 db.

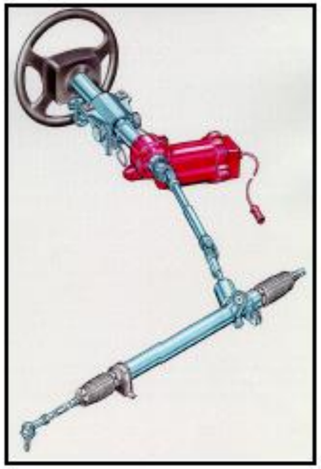
# EPS Classification

## *According to Installation Position of Speed Reducer*

### Column-Type

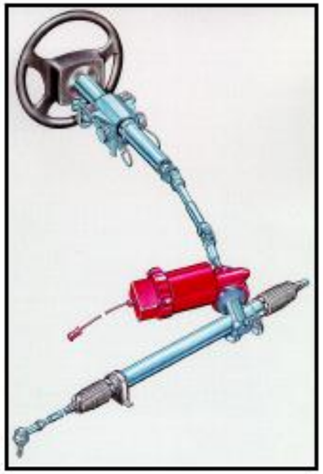
Particularly the steering column variety is an economical solution for small vehicles.

Mass production of this vehicle category will result in an increase of market share for these steering systems, even though vehicles with a higher comfort demand will require this technology later.



### Pinion-Type

The pinion principle is particularly suitable for medium class vehicles, as it combines the technical advantages of the steering column solution with the high rigidity of the mechanical coupling. The advantages are a rather variable matching of the electrical motor via the reduction gear and pinion tooth system. Thus the pinion solution will better cope with the increased custom demands for a quality steering system.



*Source: SAE TECHNICAL PAPER SERIES 1999-01-0401 by Dominke Peter and Ruck Gerhard ZF Lenksysteme GmbH*

# EPS Classification

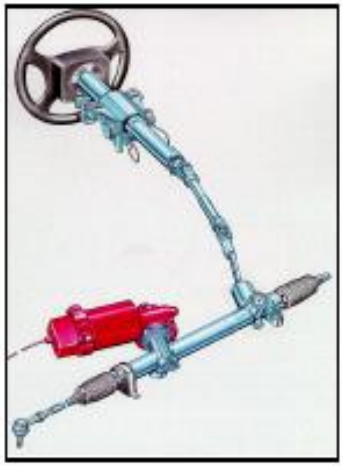
## *According to Installation Position of Speed Reducer*

### Rack- Type

The rack solution is primarily suitable for higher class vehicles. The support torque of the electric motor is transferred directly to the rod via a ball planetary gear, achieving maximum rigidity in force transmission, as well as transferring maximum forces, e.g. for luxury class passenger vehicles.

### Double Pinion Type

The double pinion solution constitutes a compromise between the economical pinion solution and the technically expensive rack solution. Since the transmission ratios of the tooth system to the servo unit can be selected in a different way than the one to the steering column, vehicles with higher tie rod forces can be comprised in such a system.



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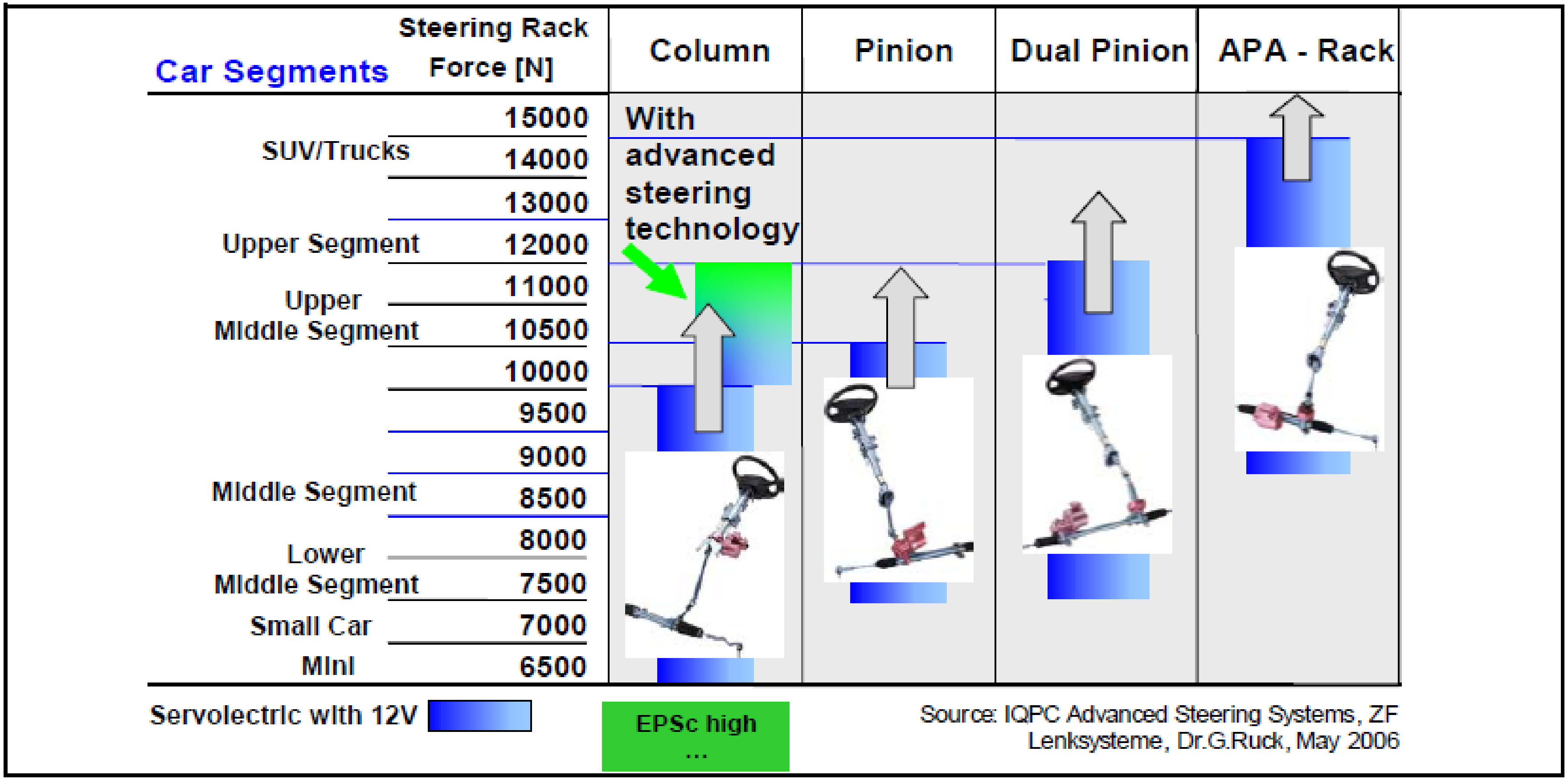
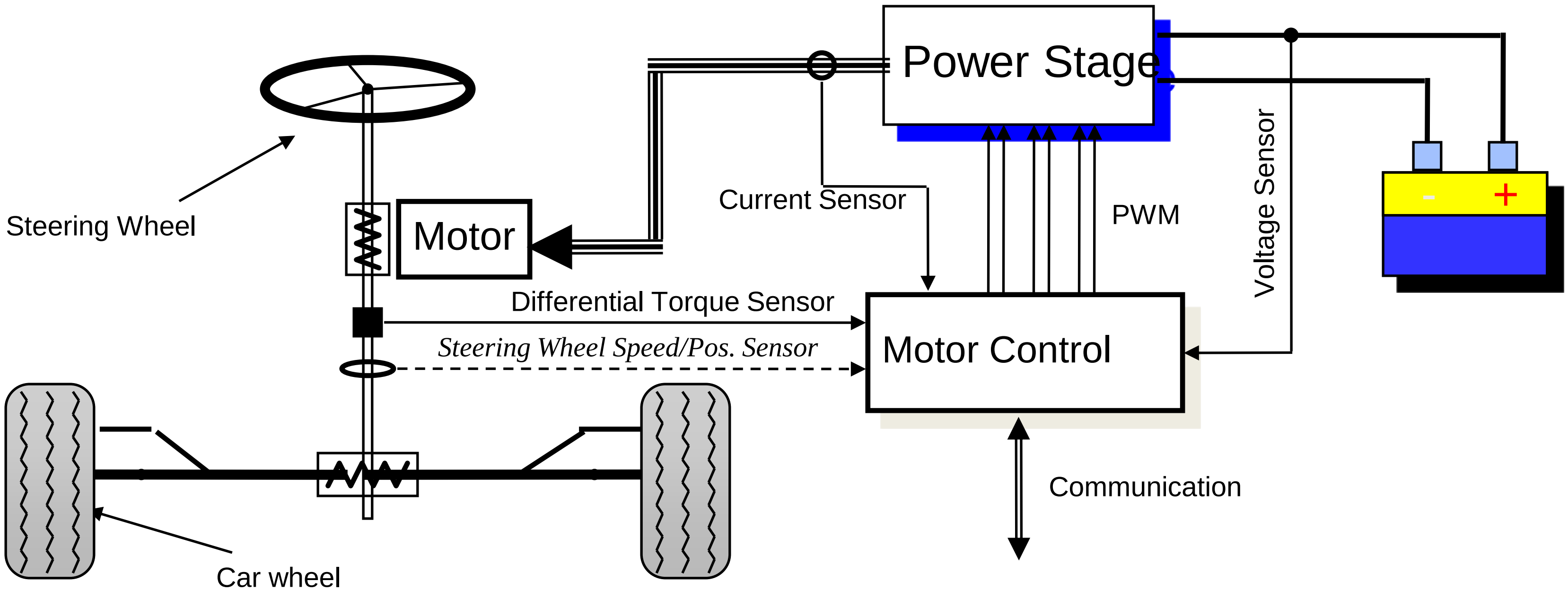
# EPS Application



# EPS – Direct Motor System

- Requirements:
  - High-end motor control (16/32-bit DSP/MCU - or equivalent)
    Fast and precise torque control algorithm for fast steering action
  - electrical hardware (similar complexity as for electro-hydraulic one)




Expensive hydraulic stuff is taken away

# EPS – Motor Types

## Asynchronous Motor

+ Advantages:
  - Can work at high temperature (No Permanent Magnets !)
  - Initial rotor position does not need to be known at start
  - No mag. field when switched OFF
    Very low torque ripples
- Disadvantages:
  - Rotor speed is different from magnetic field speed
  - Lower efficiency
    High-end control algorithm for zero speed torque

## Synchronous Permanent Magnet Motor

+ Advantages:
  - High start up torque - mag. field built in
  - Efficient motor, can be smaller
  - Low torque ripples
- Disadvantages:
  - Can not work at high temperature (PM - Currie Temperature point!)
  - Initial rotor position MUST be known at start
  - Mag. field exists even motor switched OFF

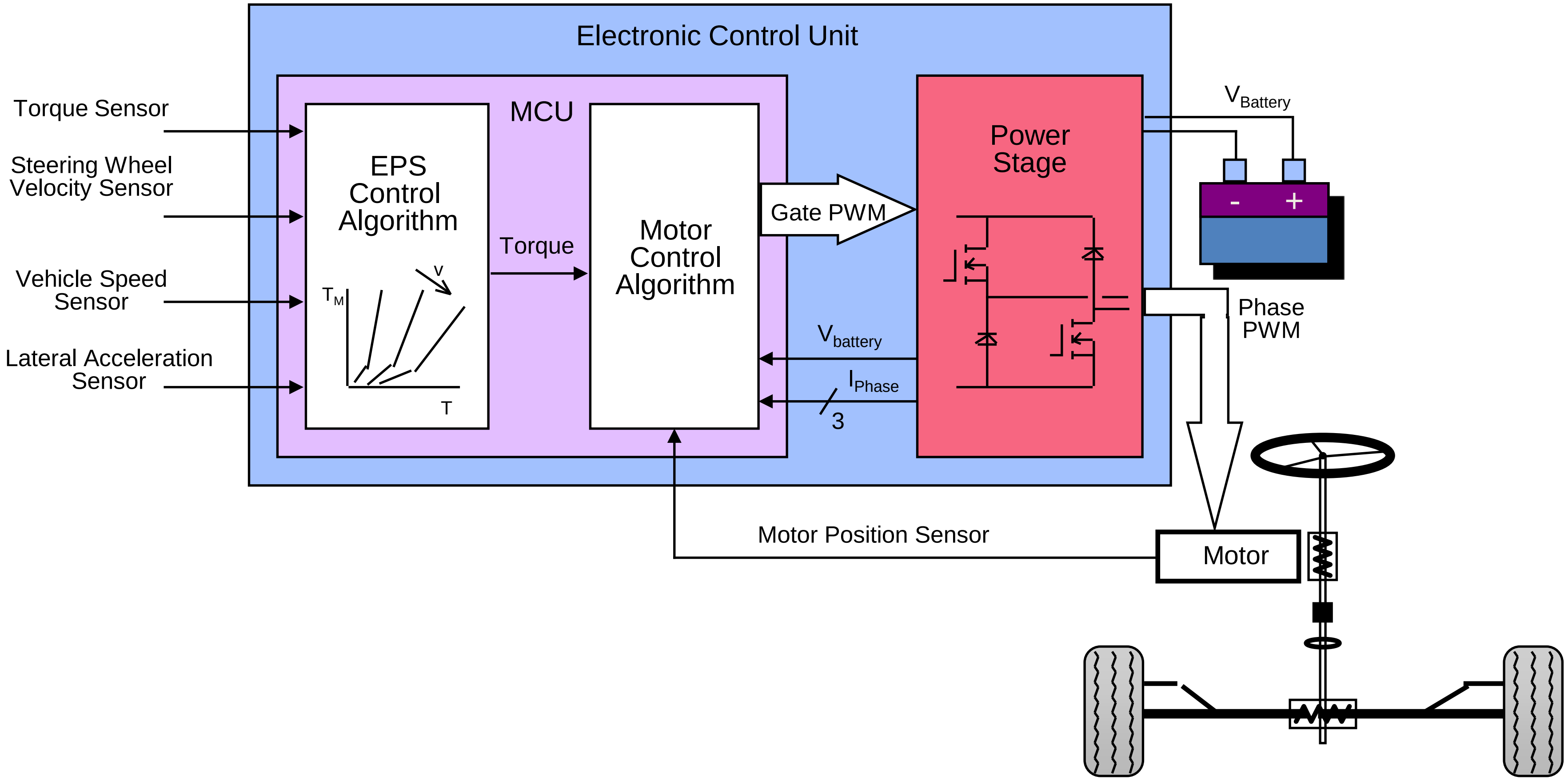
## Brushless DC Permanent Magnet Motor

+ Advantages:
  - High start up torque
  - Efficient motor, can be smaller
- Disadvantages:
  - Can not work at high temperature (PM - Currie Temperature point!)
  - Torque ripples
  - Initial rotor position MUST be known at start

## Switched Reluctance Motor

+ Advantages:
  - Can work at high temperature (No PM !)
  - High start up torque
  - Efficient motor
  - Fault-tolerant power stage topology
- Disadvantages:
  - Initial rotor position MUST be known at start
  - Noisy if not controlled right way
  - Torque ripples
  - High-end control algorithm to minimize torque ripples and noise.

# EPS – Control System



# Electric Motor Type Classification

- ELECTRIC MOTORS
  - AC
    - ASYNCHRONOUS
      - Induction
    - SYNCHRONOUS
      - Sinusoidal
        - Permanent Magnet
          - Surface PM
          - Interior PM
        - Wound Field
      - Brushless
      - Reluctance
    - VARIABLE RELUCTANCE
      - SR
      - Stepper
  - DC

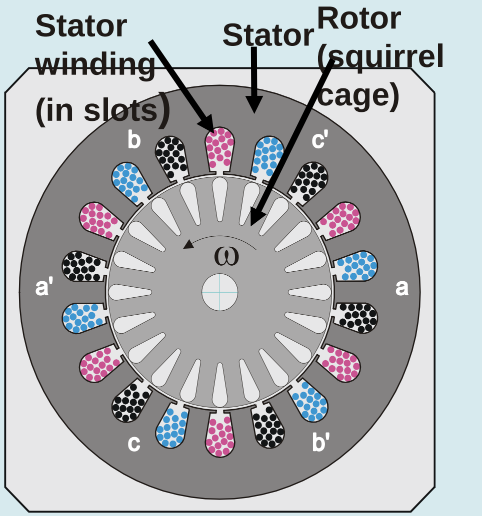
- Stator same
- Difference in rotor construction

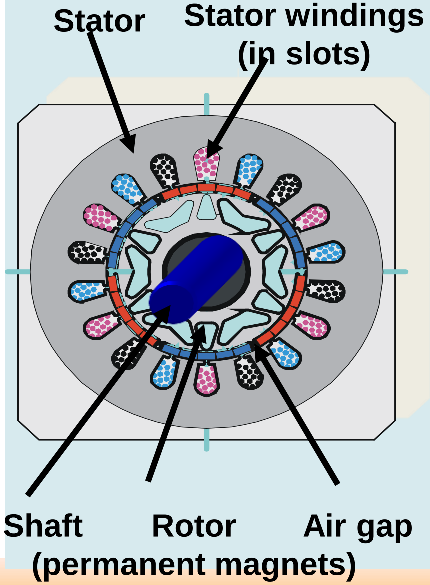
If properly controlled

- Provides constant torque
- Low torque ripple

# Asynchronous vs. Synchronous

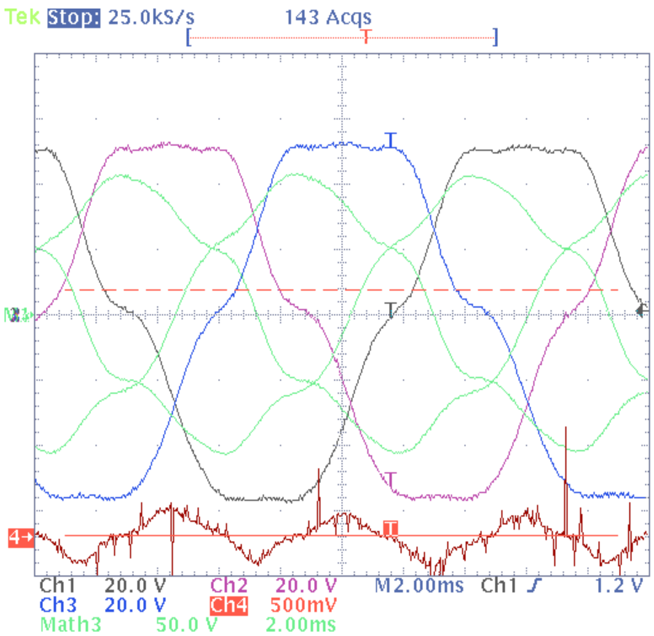
- 3-phase winding on the stator
  - distributed or concentrated
- Assumed sinusoidal flux distribution in air gap
- Different rotor construction & consequences
  - ACIM
    - Squirrel cage (rugged, reliable, economical)
    - No brushes, no PM
    - Low maintenance cost
  - Synchronous
    - Rotor with permanent magnet
    - High efficiency (no rotor loses)
- Synchronous motor rotates at the same frequency as the revolving magnetic field
- Asynchronous means that the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field



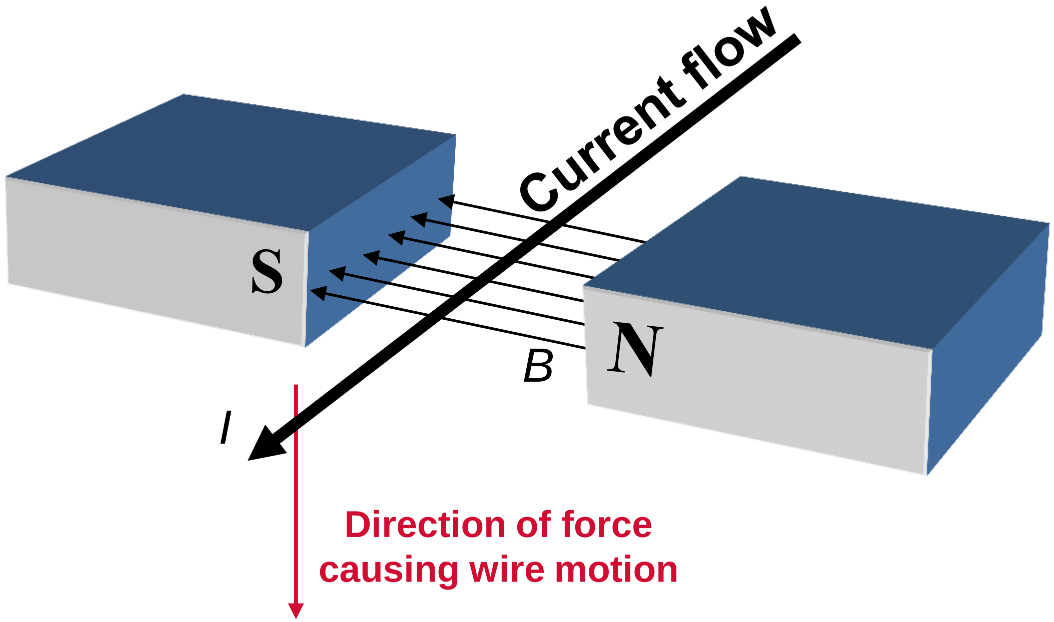
# Trapezoidal vs. Sinusoidal PM Machines

- Sinusoidal" or "Sinewave" machine means Synchronous (PMSM)
- Trapezoidal means brushless DC (BLDC) motors
- Differences in flux distribution
- Six-Step control vs. **F**ield-**O**riented **C**ontrol
- Both requires position information
- BLDC motor control
  - 2 of the 3 stator phases are excited at any time
  - 1 unexcited phase used as sensor (BLDC Sensorless)
- Synchronous motor
  - All 3 phases persistently excited at any time
  - Sensorless algorithm becomes complicated

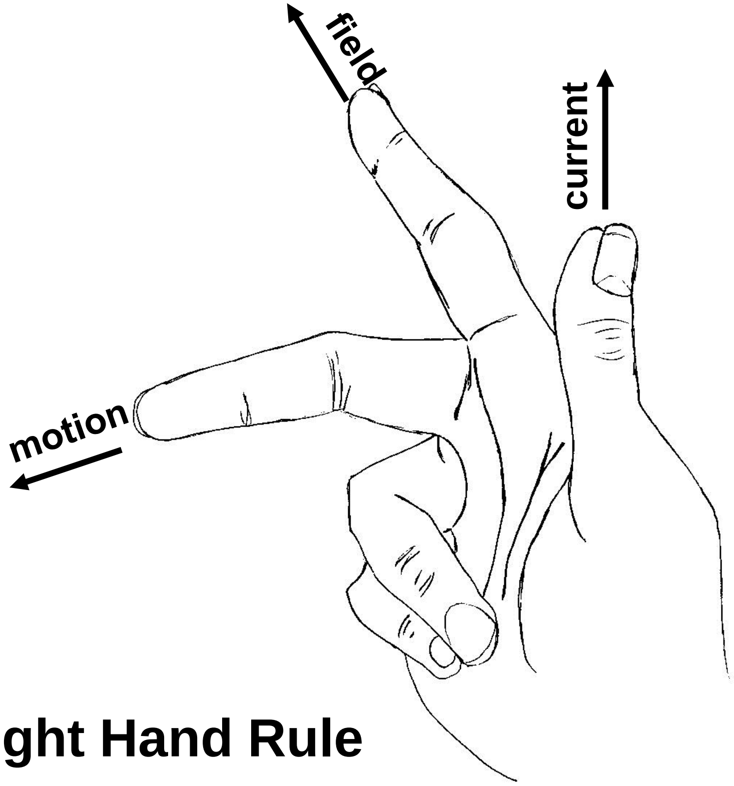


# Motion Force Generation

- Current flowing in a magnetic field results in a force on the conductor
- Orientation of generated force is governed by “Right Hand Rule”



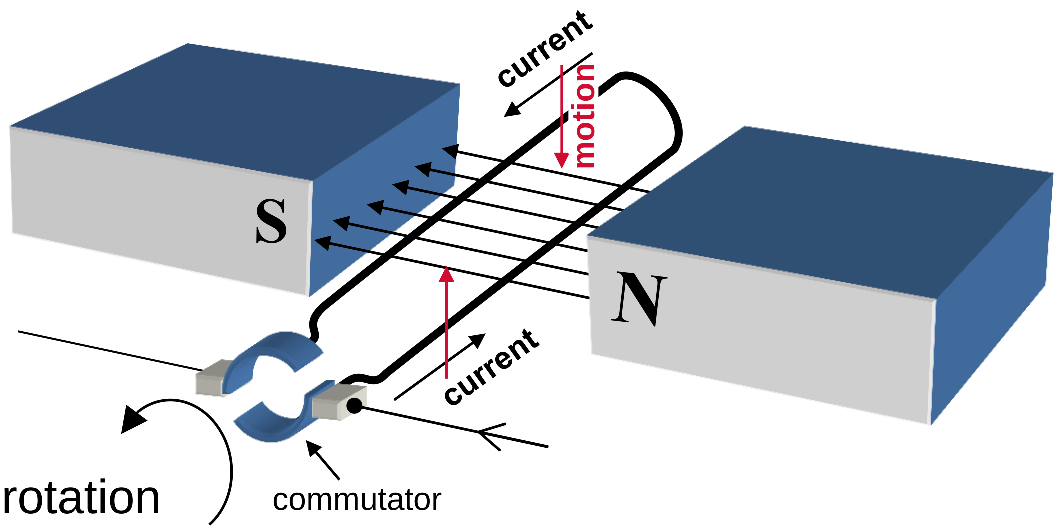

$$F = I.B.l.\sin\theta$$

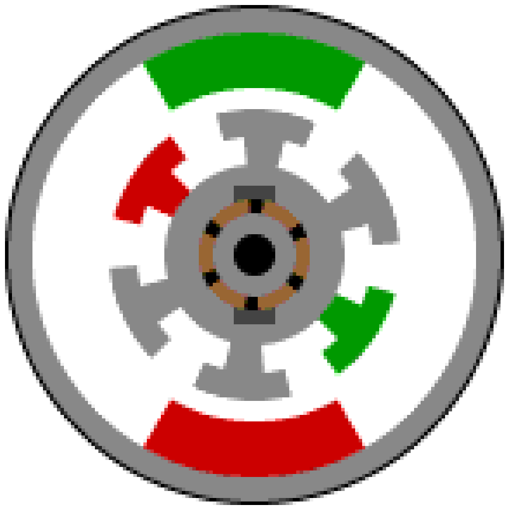



Right Hand Rule

# DC Motor Principle

- The stator of a Permanent Magnet DC Motor is composed of two or more permanent magnet pole pieces.
- The rotor is composed of windings connected to a mechanical commutator, which mechanically ensures the angle between wire current and magnetic field ~ 90°.



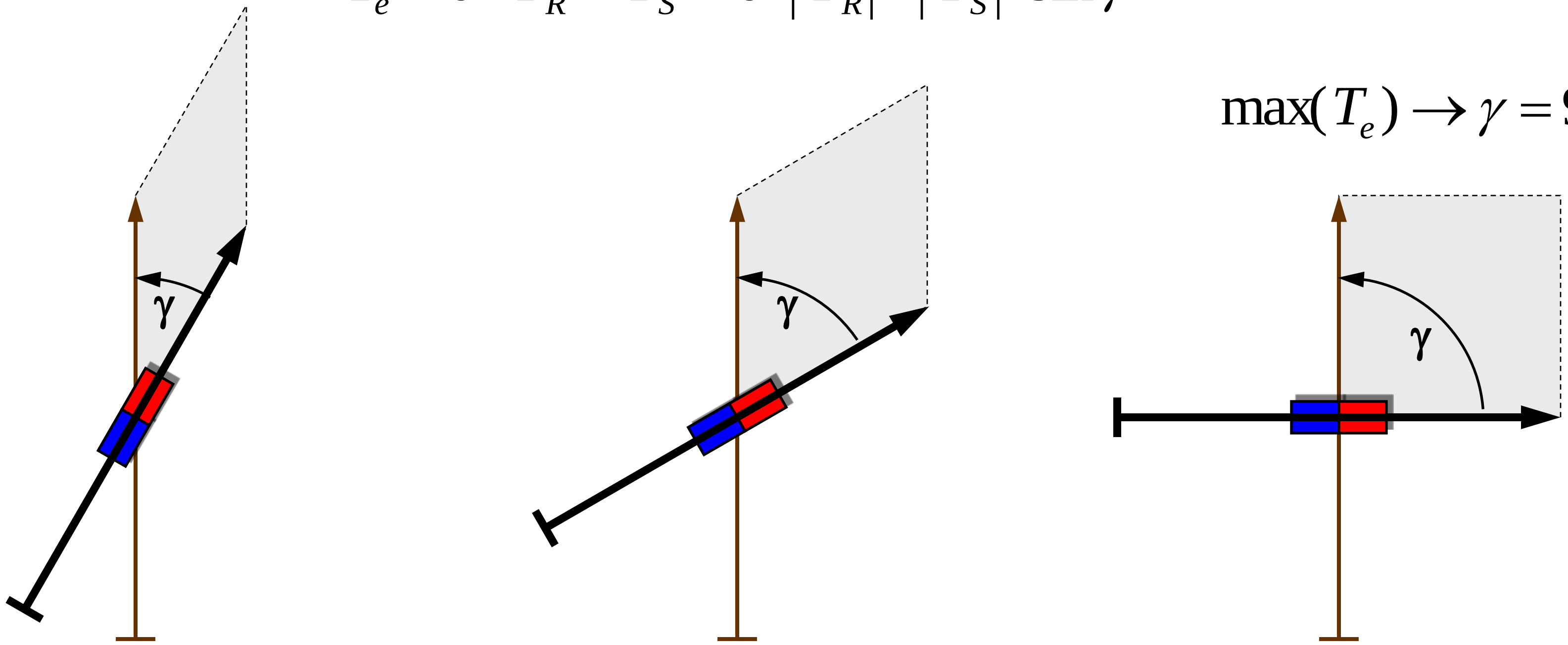
**"Mechanical" FOC**

# Torque Production Principle

- Electromagnetic torque production by the stator magnetic flux and magnet flux space vectors

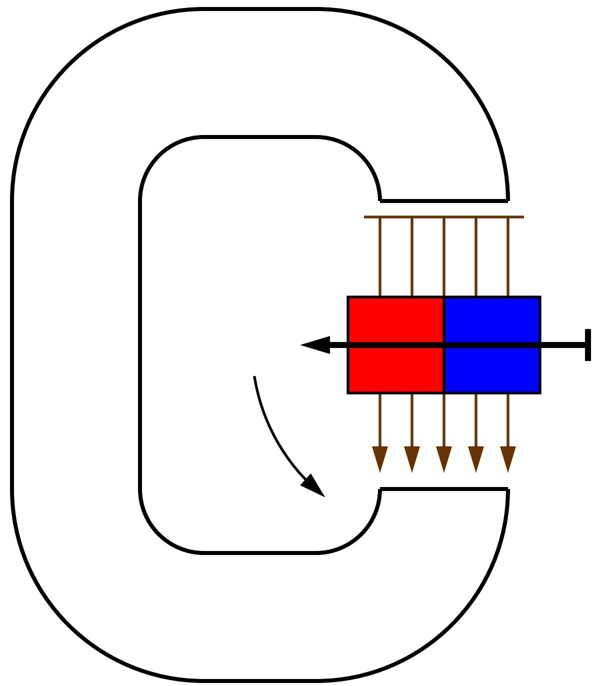
$$T_e = c \cdot \Psi_R \times \Psi_S = c \cdot |\Psi_R| \times |\Psi_S| \cdot \sin\gamma$$

$$\max(T_e) \rightarrow \gamma = 90°$$



# Torque Production Principle

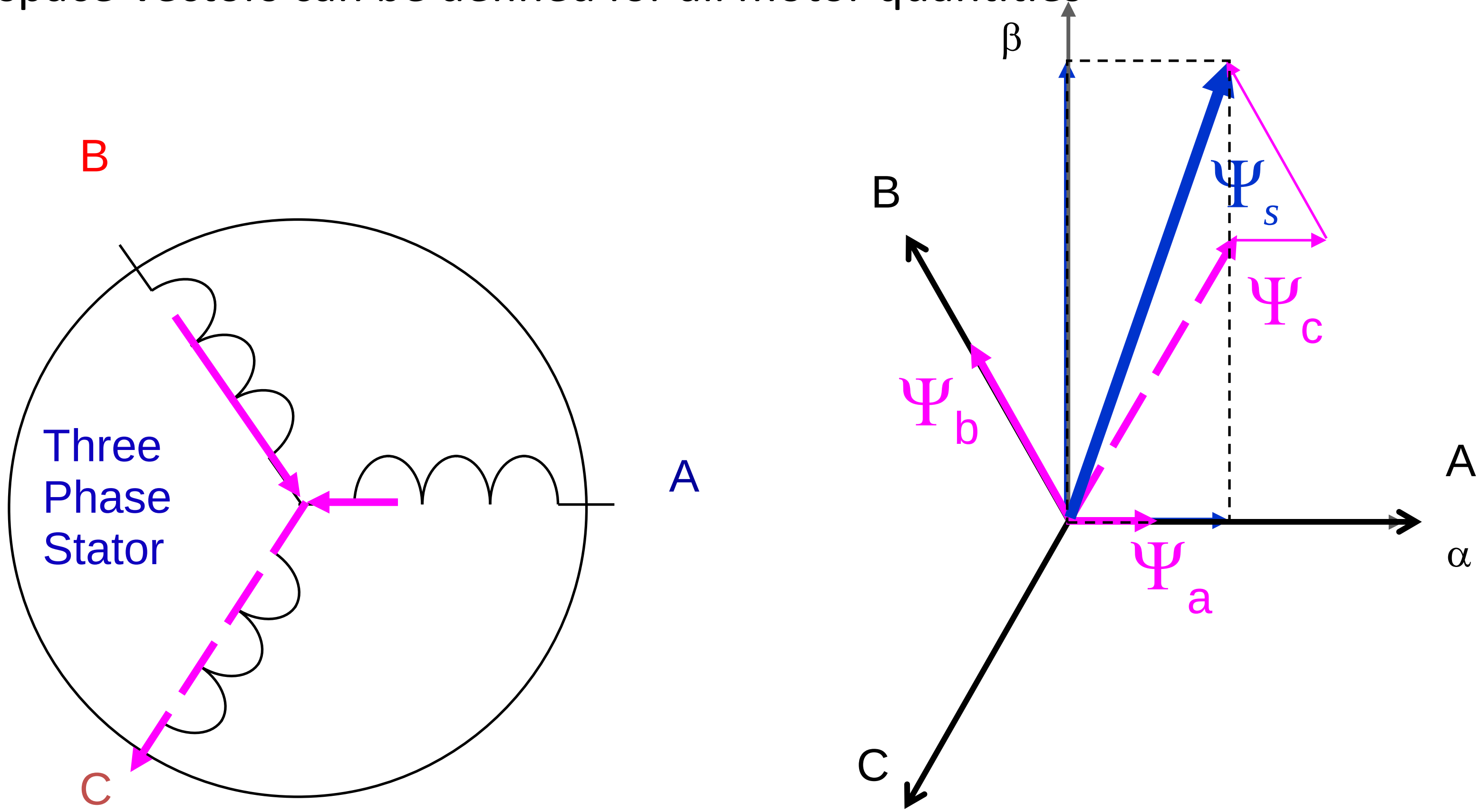
- All is about magnetic fields interaction
  - Rotor Magnetic field
  - Stator Magnetic field
- The torque/force is produced when both fields form an non zero angle
- Having the stator magnetic field leading the rotor magnetic field we form an el. motor
- Then FOC is to control the torque
  - thus also the mag. field angle
  - by strength of the rotor mag. field and
  - by strength of the stator mag. field



FOC IS SO SIMPLE

# Creating Space Vector

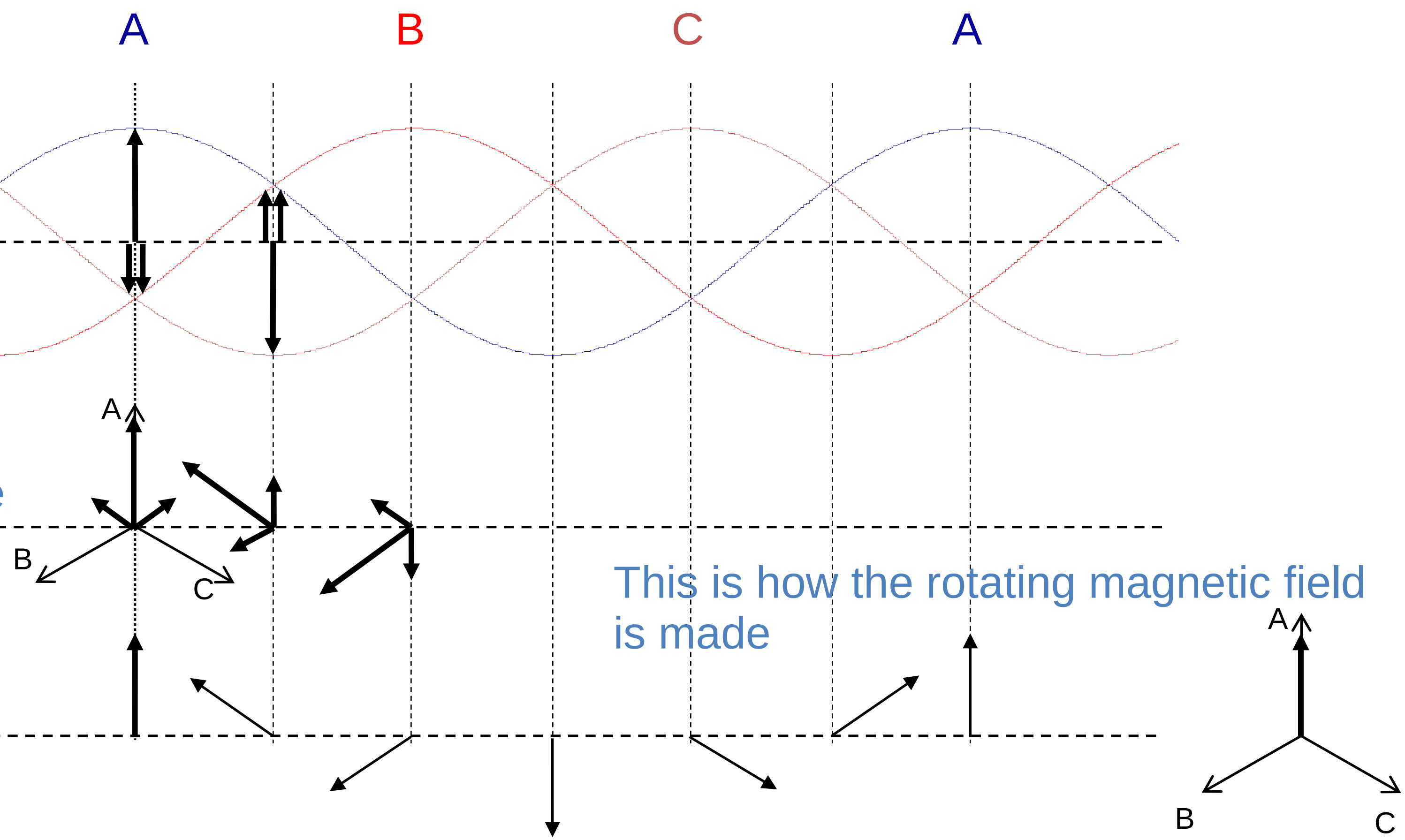
- The space-vectors can be defined for all motor quantities




► Because the space vector is defined in the plain (2D), it is sufficient to describe space vector in 2-axis (a,b) coordinate system - some times also 2-phase system

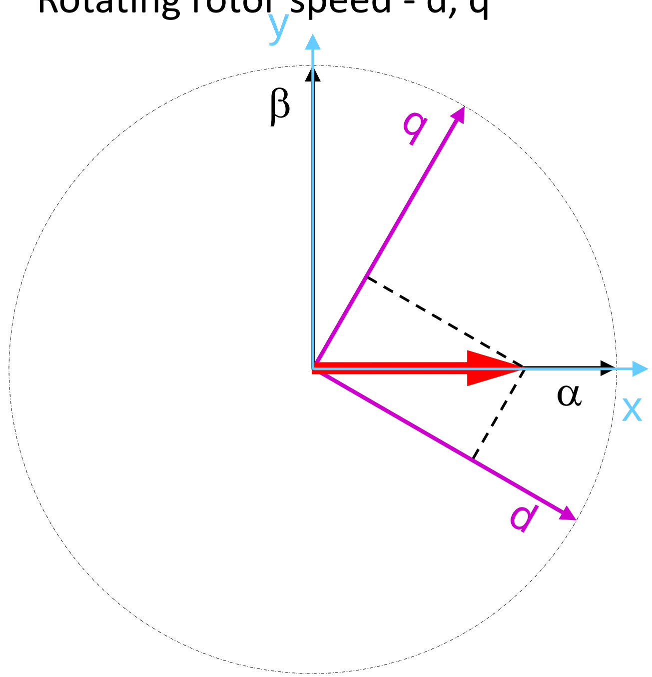
# Space Vector Rotation

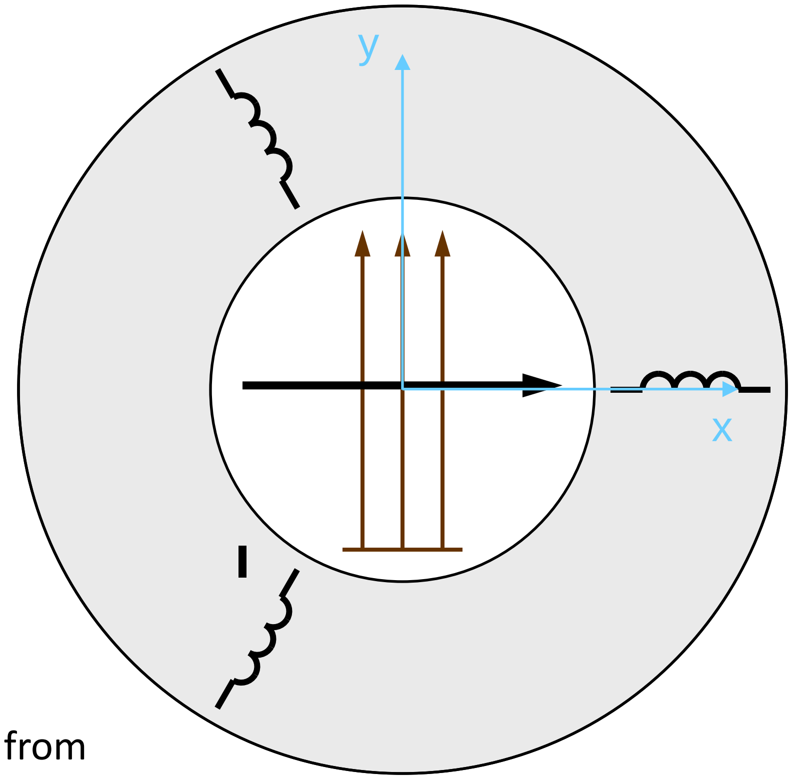
Rotating Space Vector




- To reverse rotation direction, swap the connection of any two phases

- There are the following reference frames
  - Stationary - a, b
  - Rotating arbitrary speed - x,y
  - Rotating rotor speed - d, q



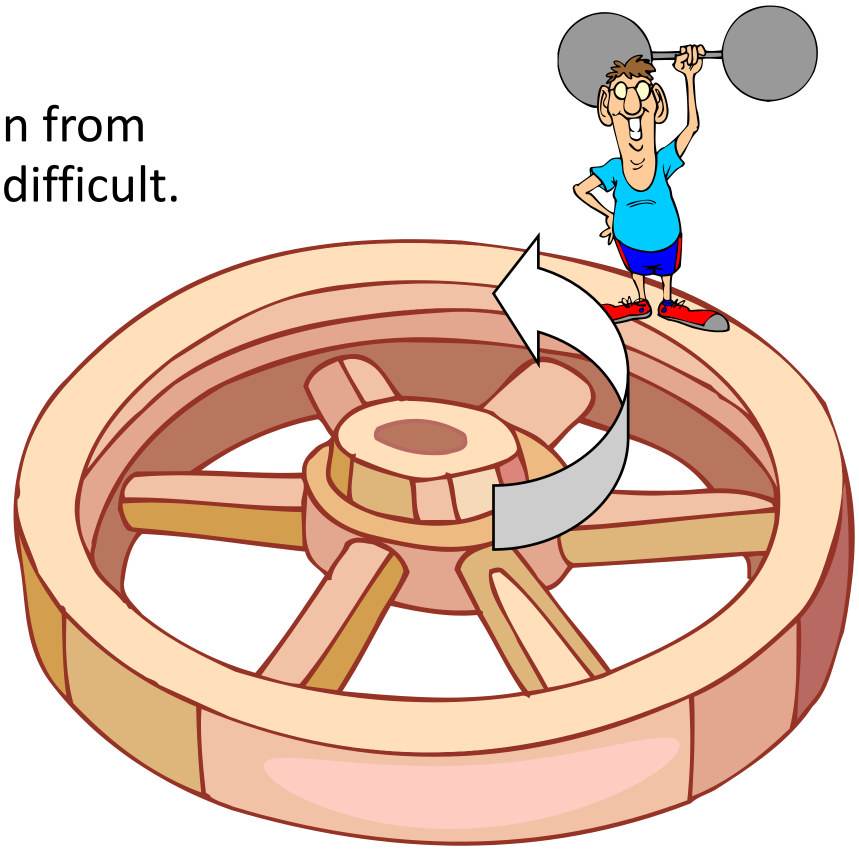

- All rotating quantities are “rectified” when viewed from reference frame that rotates synchronously with rotor

# How Difficult is Then Vector Control

## It depends on your "point of view"!

To mathematically describe barbell motion from a stationary frame of reference would be difficult.

However, by jumping on the wheel, and describing the motion from a rotating frame of reference, simplifies the problem immensely!



# Vector Control in Steps

1. Measure obtain state variables quantities
   (e.g. phase currents, voltages, rotor position, rotor speed …).

2. Transform quantities from 3-phase system to 2-phase system (Forward Clark Transform) to simplify the math - lower number of equations

3. Transform quantities from stationary to rotating reference frame - "rectify" AC quantities, thus in fact transform the AC machine to DC machine

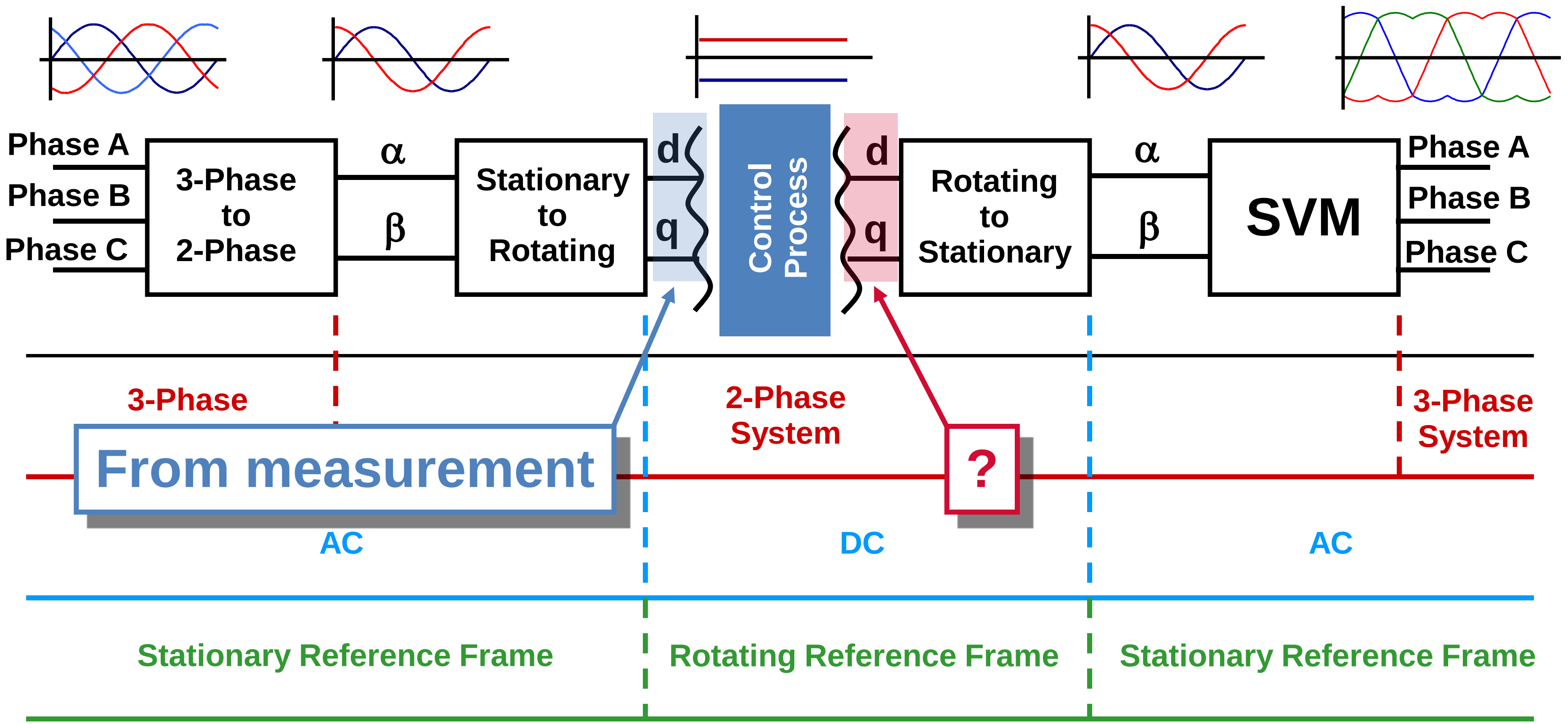
4. Calculate control action (when math is simplified and machine is "DC")

5. Transform the control action (from rotating) to stationary reference frame

6. Transform the control action (from 2-phase) to 3-phase system

7. Apply 3-phase control action to el. motor

# FOC Transformation Sequencing



# Why Field Oriented Control

- Using vector control technique, the control process of AC induction and PM synchronous motors is similar to control process of separately excited DC motors

- In special reference frame, the stator currents can be separated into
  - Torque-producing component
  - Flux-producing component

- Wide variety of control options

- Better performance
  - Full motor torque capability at low speed
  - Better dynamic behavior
  - Higher efficiency for each operation point in a wide speed range
  - Decoupled control of torque and flux
  - Natural four quadrant operation

# Space Vector Basics

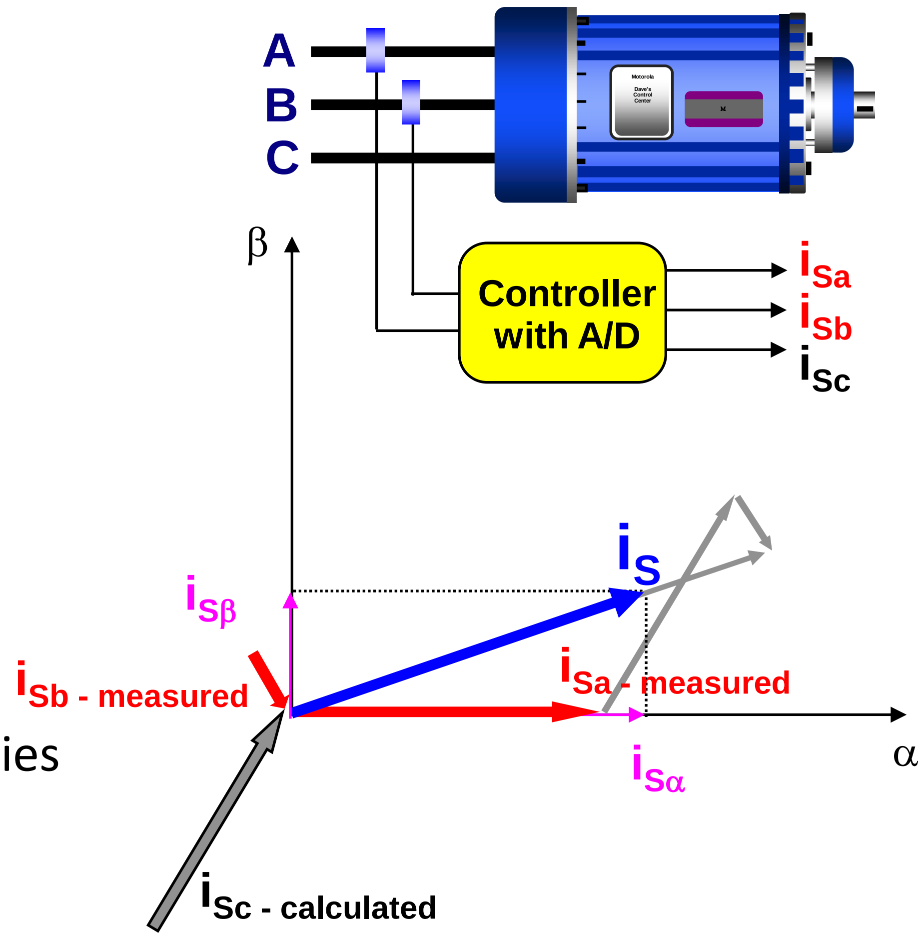
- Space-Vector Definition:

$$\bar{i}_s = i_{sx} + j \cdot i_{sy}$$

$$\bar{i}_s = k\left(i_{sa} + a i_{sb} + a^2 i_{sc}\right)$$

$$a = e^{j2\pi/3}, a^2 = e^{j4\pi/3}$$

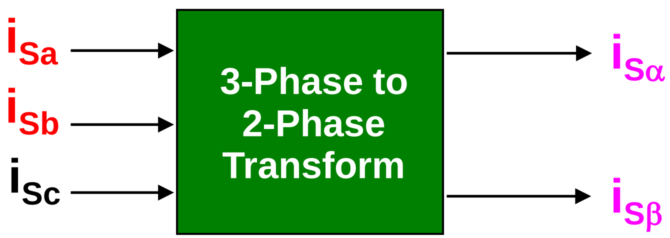
- The space-vectors can be defined for all motor quantities



# Space Vector Basics cont'd

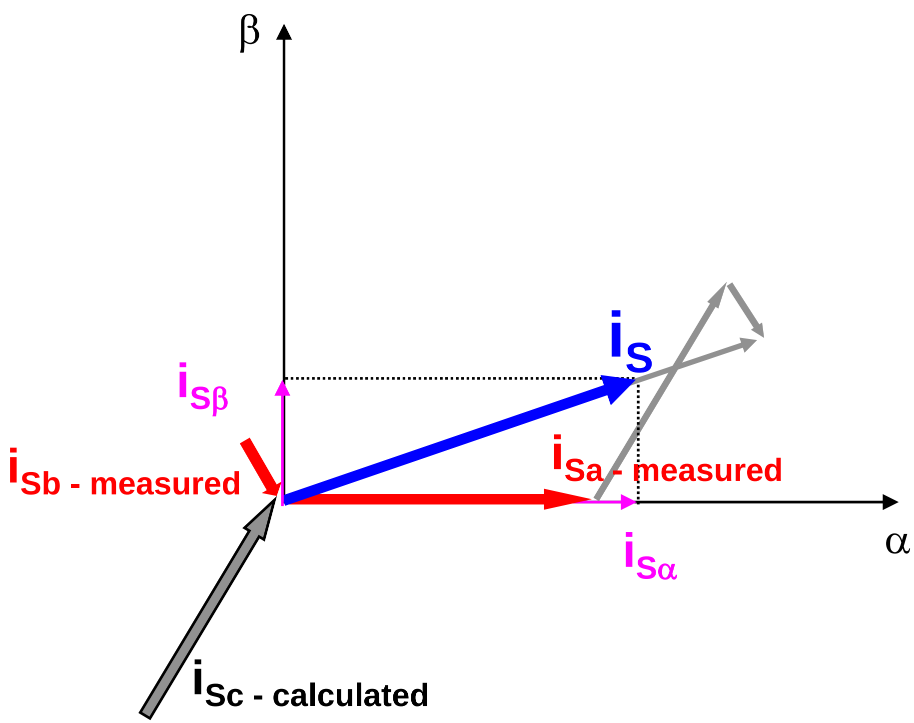
- Clarke Transformation:
  - transforms the 3-phases a,b,c to the two-phase coordinate system $\alpha$, $\beta$

**A, B, and C axes are "fixed" with respect to the motor housing. This reference frame is also called the "stationary frame" or "stator frame".**



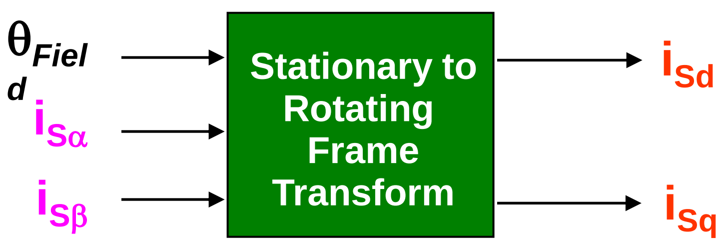

$$i_{s\alpha} = i_{sa}$$

$$i_{s\beta} = \frac{1}{\sqrt{3}} i_{sa} + \frac{2}{\sqrt{3}} i_{sb}$$



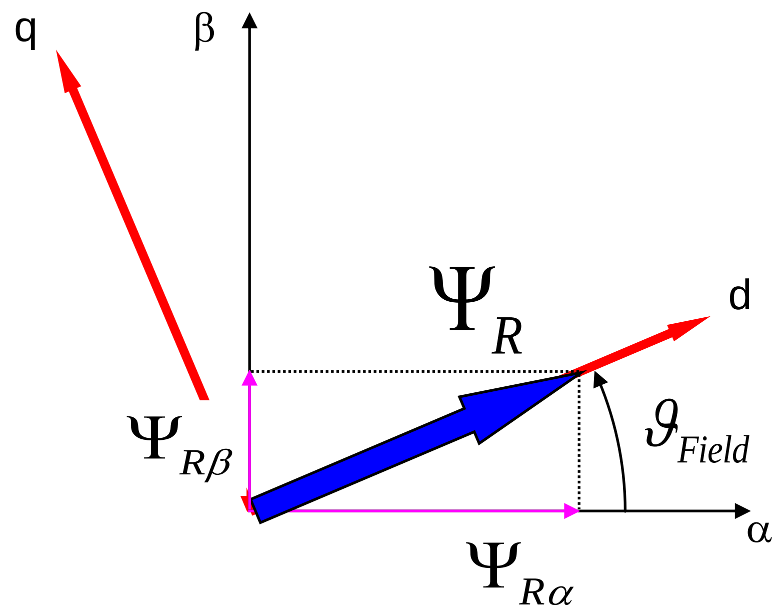
# Space Vector Basics cont'd

- Park Transformation
  - Transformation from the two-phase system fixed to the stator to the d,q coordinate system fixed with the rotor magnetic flux space-vector.



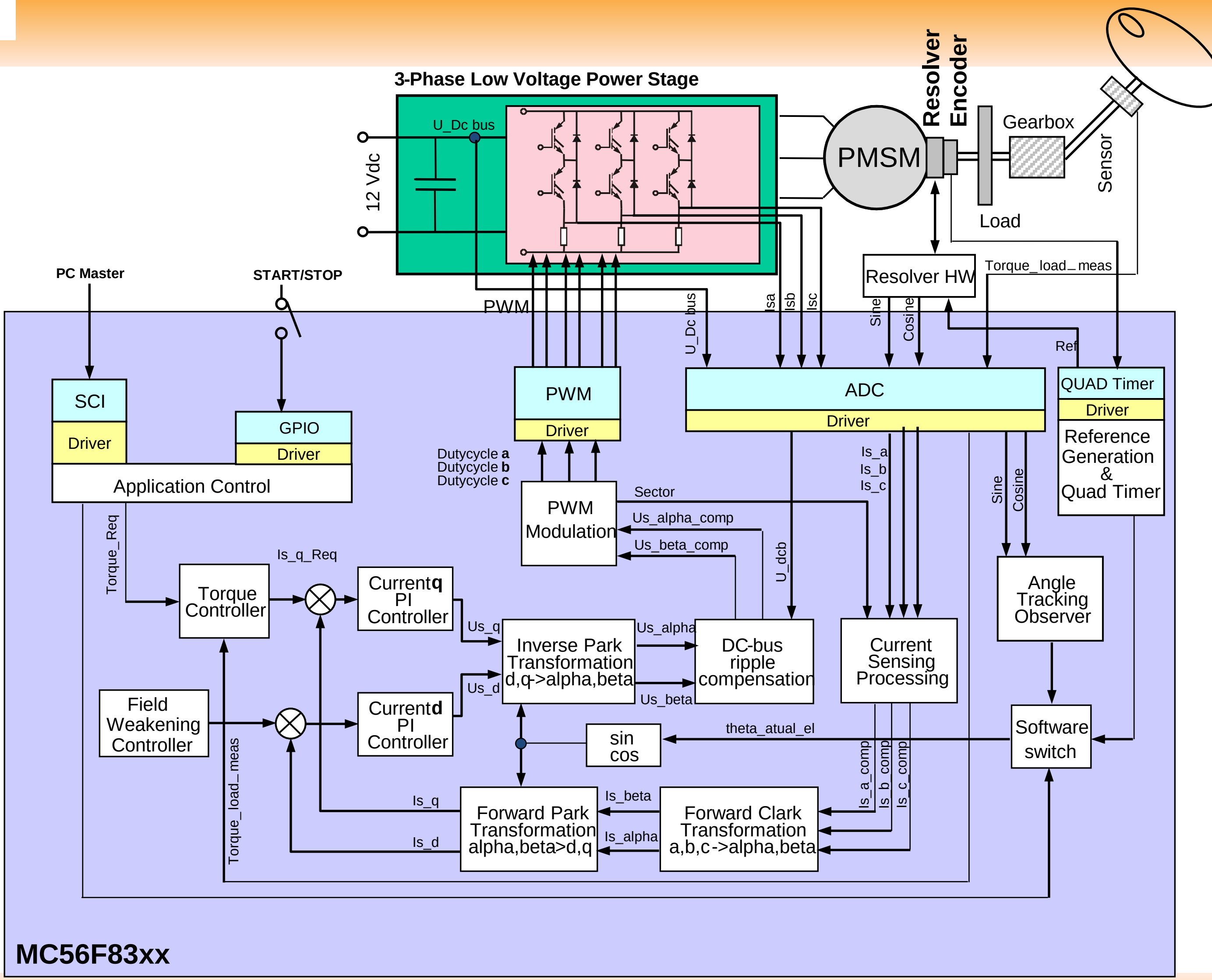

$$i_{sd} = i_{s\alpha} \cos\theta_{Field} + i_{s\beta} \sin\theta_{Field}$$

$$i_{sq} = -i_{s\alpha} \sin\theta_{Field} + i_{s\beta} \cos\theta_{Field}$$




**The flux reference frame (d axis) rotates with respect to the motor housing. It is called the "rotating axis", "synchronous axis", or "field axis".**

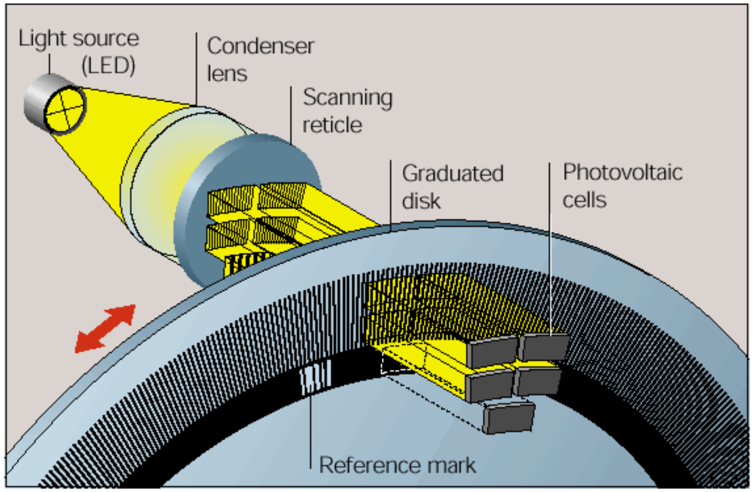
# Application Block Diagram



# Incremental Sensor - Encoder

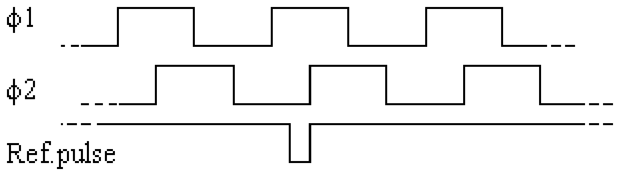
- The current position is calculated by incrementing/decrementing the pulse edges.
- The direction of counting is determined by phase shift of two quadrature pulses.
- The reference pulse is used to denote start point.
- Rotary encoders output the position values over the binary TTL square-waves or serial data interfaces (EnDat, SSI, PROFIBUS-DP)

**Scanning Principle**




Source: Heidenhain

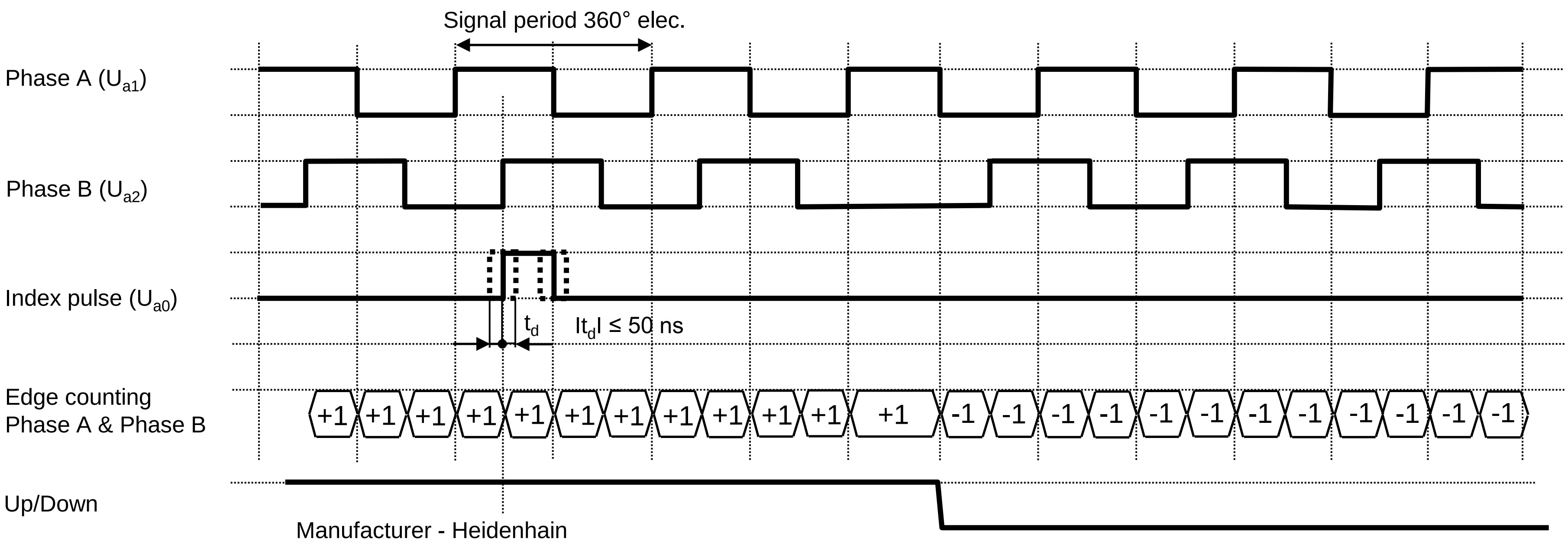
**Incremental Encoder Pulses**




There are 4 phases within one pulse cycle. You need for example (360/0.5)/4=180 pulses per rotation if 0.5deg resolution is wanted.

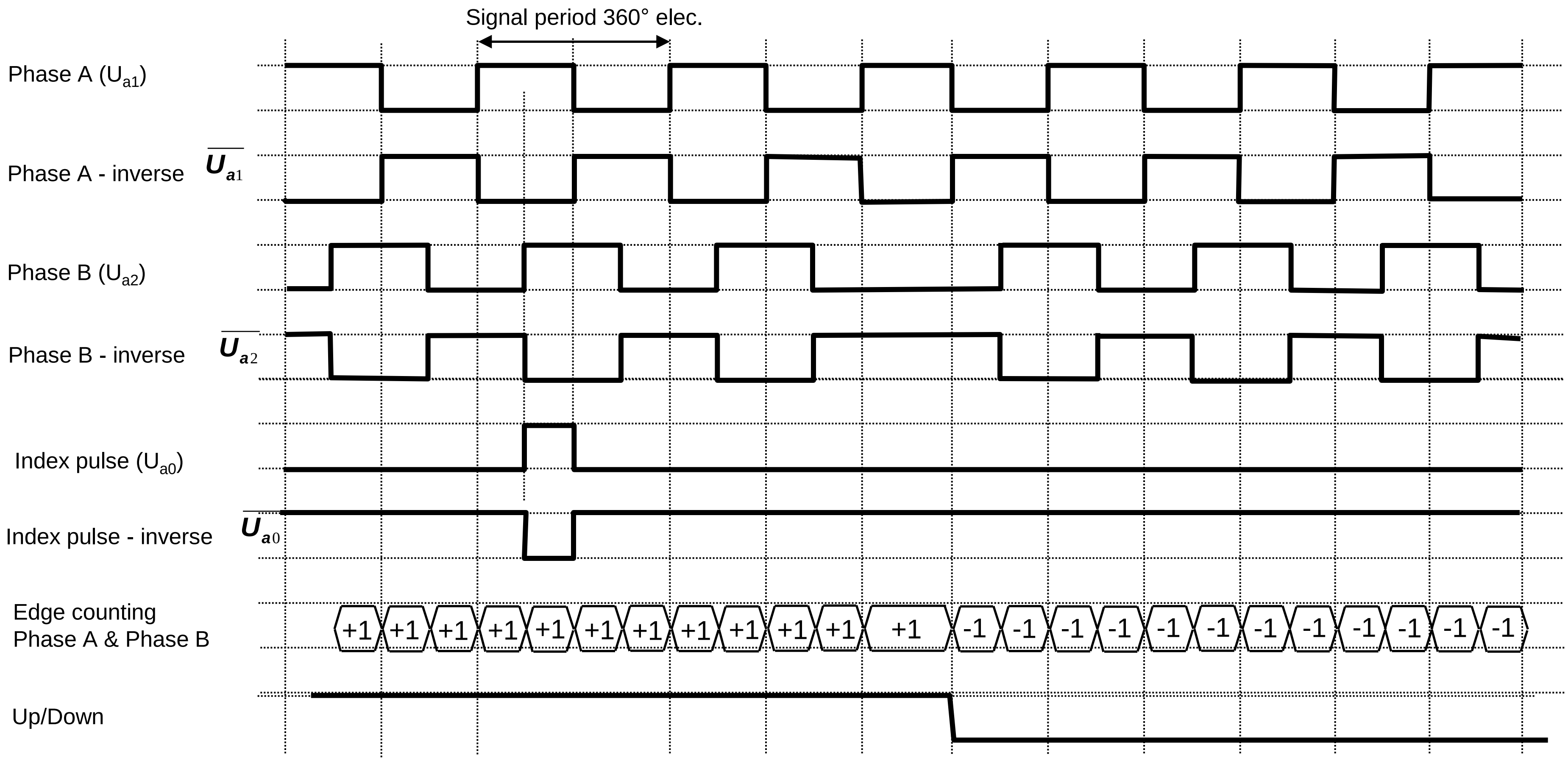
# Precise Incremental Sensor

- The incremental signals are transmitted as the square-wave pulse trains Phase A (Ua1) and Phase B (Ua2), phase-shifted by 90° elec
- The Index pulse (reference mark signal) consists of one or more reference pulses Ua0, which are usually gated with the incremental signals
- In addition, the integrated electronics produce their inverse signals $\overline{U_{a1}}$, $\overline{U_{a2}}$ and $\overline{U_{a0}}$ for noise-proof transmission



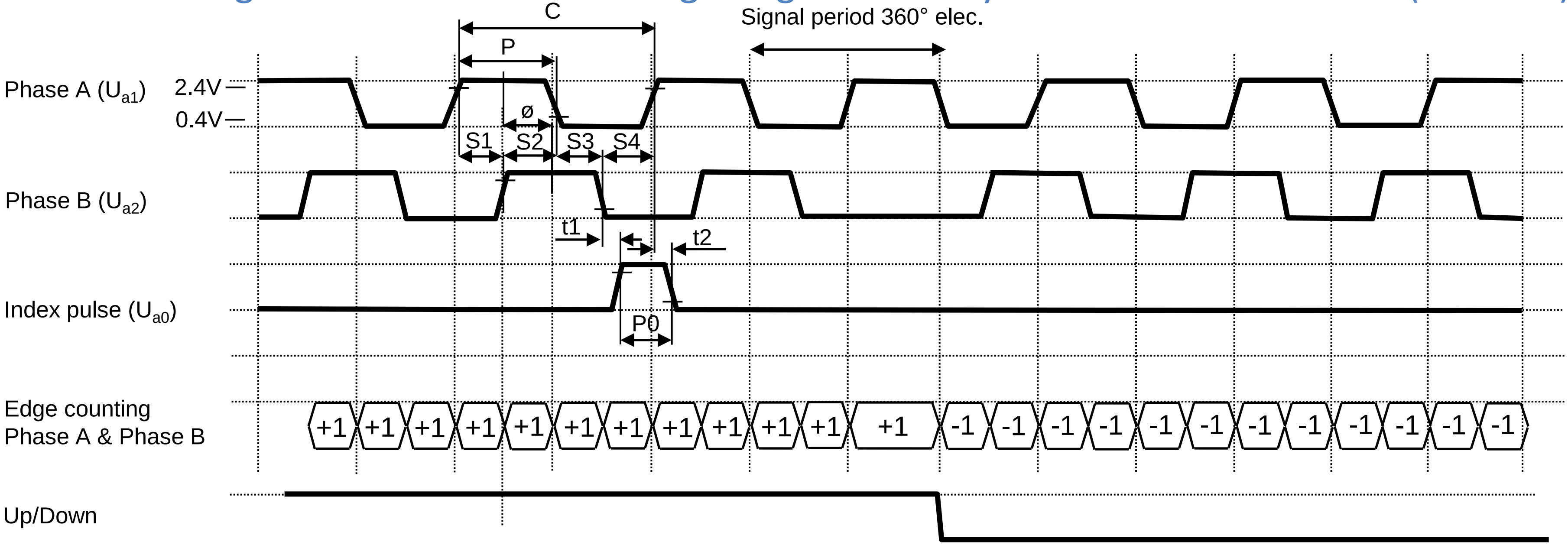
# Precise Incremental Sensor cont'd

## Decoding the Phase A & Phase B signals generated by the incremental sensor (encoder)



# Low Cost Incremental Sensor

Decoding the Phase A & Phase B signals generated by the incremental sensor (encoder)




Manufacturer – Agilent technologies

ΔP – typ 5 – max 45 °e

ΔS - typ 5 – max 45 °e

ΔC – typ 3 – max 7.5 °e

Δø - typ 2 – max 15 °e

ΔΘ – typ 10 – max 40 min. of arc

P0 – min 55 – max 125 °e

t2 – min -300 – max 1000 ns

Rise time – typ 200 ns

Fall time – typ 50 ns

# Low Cost Incremental Sensor cont'd

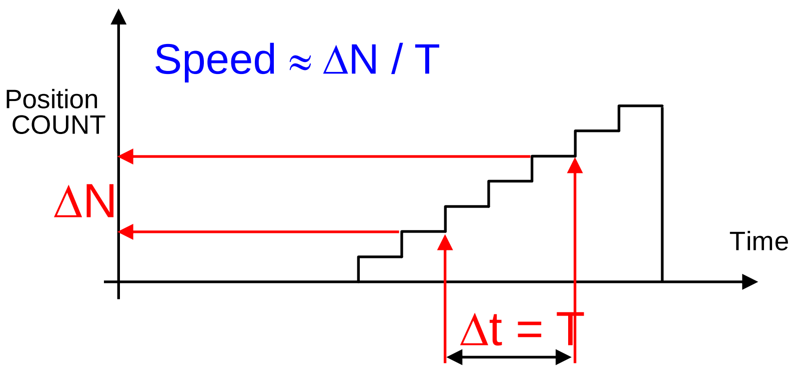
- One Cycle (C): 360 electrical degrees (°e), 1 bar and window pair
- One Shaft Rotation: 360 mechanical degrees, N cycles
- Position Error ($\Delta\Theta$): The normalized angular difference between the actual shaft position and the position indicated by the encoder cycle count
- Cycle Error ($\Delta C$): An indication of cycle uniformity. The difference between an observed shaft angle which gives rise to one electrical cycle, and the nominal angular increment of 1/N of a revolution
- Pulse Width (P): The number of electrical degrees that an output is high during 1 cycle. This value is nominally 180°e or 1/2 cycle
- Pulse Width Error ($\Delta P$): The deviation, in electrical degrees, of the pulse width from its ideal value of 180°e
- State Width (S): The number of electrical degrees between a transition in the output of channel A and the neighboring transition in the output of channel B. There are 4 states per cycle, each nominally 90°e

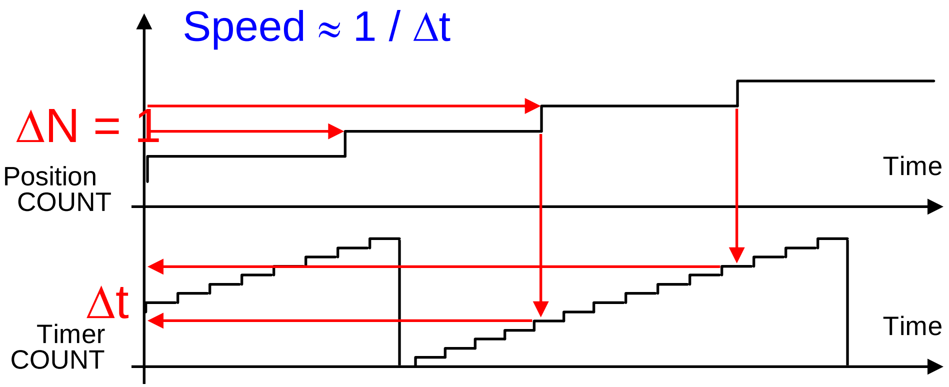
# Low Cost Incremental Sensor cont'd

- One Cycle (C): 360 electrical degrees (°e), 1 bar and window pair.
- State Width Error (ΔS): The deviation, in electrical degrees, of each state width from its ideal value of 90°e.
- Phase (ø): The number of electrical degrees between the center of the high state of channel A and the center of the high state of channel B. This value is nominally 90°e for quadrature output.
- Phase Error (Δ ø): The deviation of the phase from its ideal value of 90°e.
- Index Pulse Width (P0): The number of electrical degrees that an index output is high during one full shaft rotation. This value is nominally 90°e or 1/4 cycle.
- Direction of Rotation: When the code-wheel rotates in the counterclockwise direction (as viewed from the encoder end of the motor), channel A will lead channel B. If the codewheel rotates in the clockwise direction, channel B will lead channel A.
- Note: °e – electrical degree

# Incremental Sensor - Speed Processing

- **Fast moving shaft**
  - The velocity is computed by differentiating the counter value in software
- **Slow moving shaft**
  - The velocity is computed by recording the time between transitions on “PHASEA”, or “PHASEB”, or both



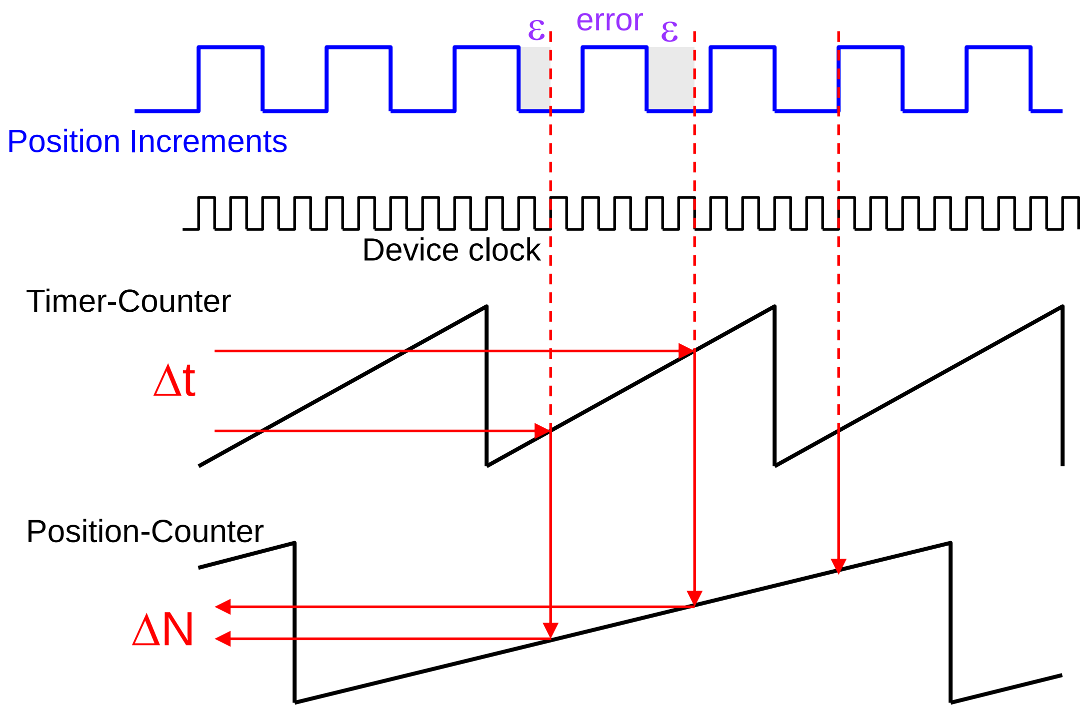




- **Issues**
  - It is almost impossible to design smooth transition between both methods without negative impact to drive performance

# Incremental Sensor - Speed Processing Issues

- Many developers approach is based on simple idea to periodically read the position-counter and the timer-counter  at the same time
  The speed is determined from two successive readings

Speed ≈ ΔN / T




- The disadvantage is that speed precision is limited by the position read precision which is 1 LSB at any speed

# Incremental Sensor - Speed Processing Issues

- The main issue is low effective number bits (ENOB) of the speed measurement process. To improve it, very high resolution (and expensive) incremental sensor would be required
- The issue is best demonstrated on the following example:

## Application Parameters:

| | | |
|---|---|---|
| Nominal speed … | $n$ | 3000 rpm |
| Incr. Sensor … | | 1024 pulses per rev |
| # of counts … | $N_{res}$ | 4096 incr. per rev |
| Speed control period … | $\Delta t_c$ | 1 ms |

$$\text{omega} \approx \frac{\Delta N}{\Delta t_c} \rightarrow \frac{\Delta N \pm \frac{1}{2}\varepsilon}{\Delta t_c} \qquad \varepsilon = 1LSB$$

- The time measurement ($\Delta t_c$) can be supposed precise so the speed measurement ENOB is given by position difference reading

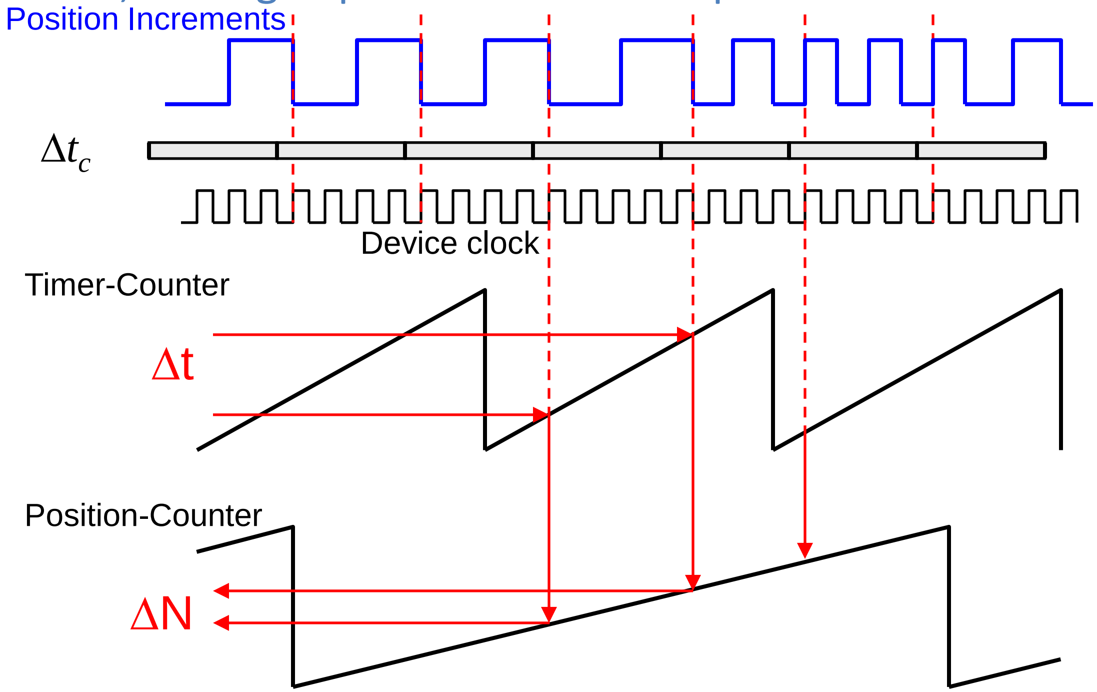
$$\Delta N = \frac{n}{60} \cdot \Delta t_c \cdot N_{res} = \frac{3000\,[\text{rpm}]}{60} \cdot 0.001\,[\text{s}] \cdot 4096\,[\text{LSB/rev}] = 204.8 \rightarrow 204\,[\text{LSB counts}]$$

- This is equivalent to 7.7 bit (@3000 rpm). This is not acceptable for most applications
- To achieve 10 bit equivalence, incremental sensor with 20 480 incr. per rev. would be needed

# Speed Processing - Freescale Solution

- Principle is to measure accurate time (number of clocks) between last captured incremental encoder edges. Captured data are processed with constant computational period ($\Delta t_c$)
- This naturally combines both, the high-speed and the low-speed methods

**Speed ≈ ΔN / T**




- The speed precision is limited by precision of capturing of the incremental encoder edges

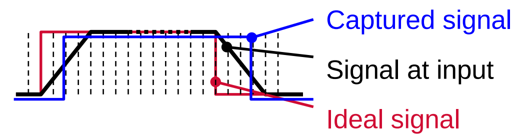
# Speed Processing - Freescale Solution cont'd

- The ENOB of this speed measurement process is stable across whole speed range. It is demonstrated on the following example:

## Application Parameters:

| | | |
|---|---|---|
| Nominal speed … | $n$ | 3000 rpm |
| Incr. Sensor … | | 1024 pulses per rev |
| # of counts … | $N_{res}$ | 4096 incr. per rev |
| Speed control period … | $\Delta t_c$ | 1 ms |
| Time resolution of captured edge caused mainly by finite signal d/dt … | $\tau$ | 100 ns |

$$\text{omega} \approx \frac{\Delta N}{\Delta t_c} \rightarrow \frac{\Delta N}{\Delta t_c} \pm \tfrac{1}{2}\varepsilon \qquad \varepsilon \cong \frac{\Delta N}{\Delta t_c - \frac{1}{2}\tau} - \frac{\Delta N}{\Delta t_c + \frac{1}{2}\tau}$$




- For min. speed the ENOB is the following:. $\varepsilon \cong \frac{1}{1[\text{ms}] - 50[\text{ns}]} - \frac{1}{1[\text{ms}] + 50[\text{ns}]} = 0.1[\text{cnt/s}]$

$$\text{omega} \approx \frac{1}{1[\text{ms}]} \pm 0.05[\text{cnt/s}] = 1000 \pm 0.05[\text{cnt/s}] \quad \rightarrow \quad 10000 \pm 0.5 \rightarrow 13.3\,\text{ENOB}$$

- For nom. speed the ENOB is the following:. $\varepsilon \cong \frac{204}{1[\text{ms}] - 50[\text{ns}]} - \frac{204}{1[\text{ms}] + 50[\text{ns}]} = 20[\text{cnt/s}]$

$$\text{omega} \approx \frac{204}{1[\text{ms}]} \pm 10[\text{cnt/s}] = 204000 \pm 10[\text{cnt/s}] \quad \rightarrow \quad 10200 \pm 0.5 \rightarrow 13.3\,\text{ENOB}$$

- The ENOB in this method is stable across the speed range reach 13.3 bit! Compare to previous 7.7 bit the ENOB is almost doubled

# Incremental Sensor Speed Processing - Summary

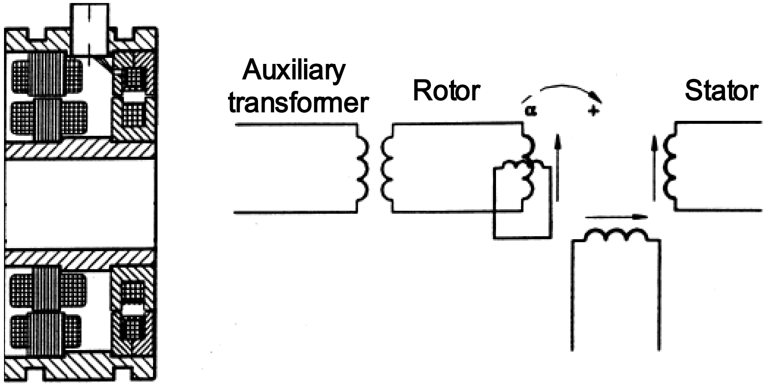
- Incremental sensors are position sensors not speed sensors
- Speed is obtained indirectly, so care must be taken
- Presented principle naturally combines both, the high-speed and the low-speed methods
- Presented principle allows periodic speed processing thus nicely fitting to discrete time-domain control
- When selecting device, make sure its peripherals support demonstrated technique (simultaneous sampling of position and time, triggered by the periodic control)

# Hollow Shaft Resolver

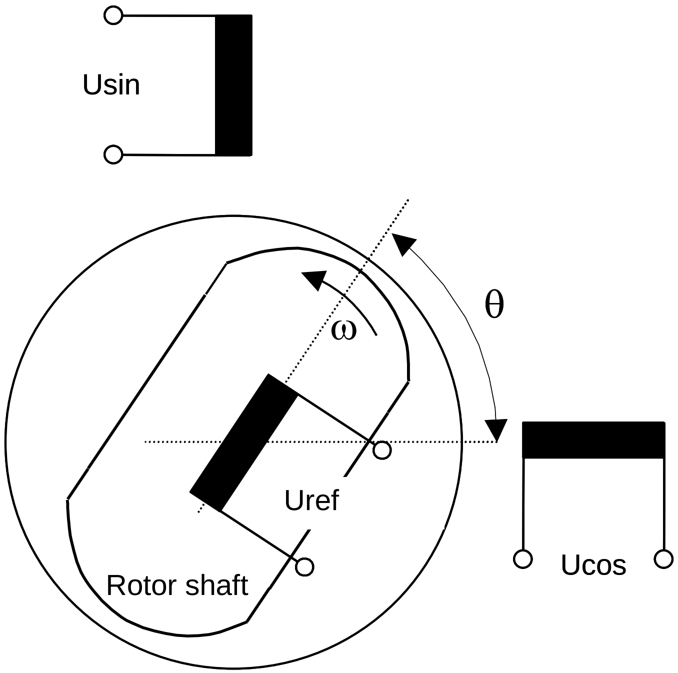
## Resolver Features

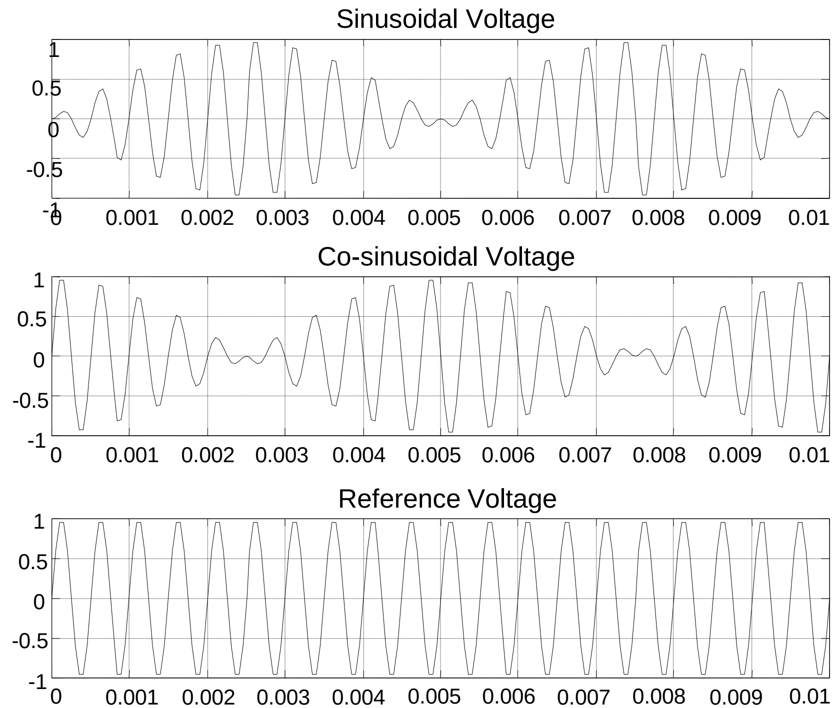
- Rotor is put directly on the drive's shaft
- Stator is fixed on drive's shield
- Simple assembly and maintenance
- No bearings – "unlimited" durability
- Resist well against distortion, vibration, deviation of operating temperature and dust
- Worldwide consumption millions of pieces at present time

**Resolver Construction:**



# Resolver Basics



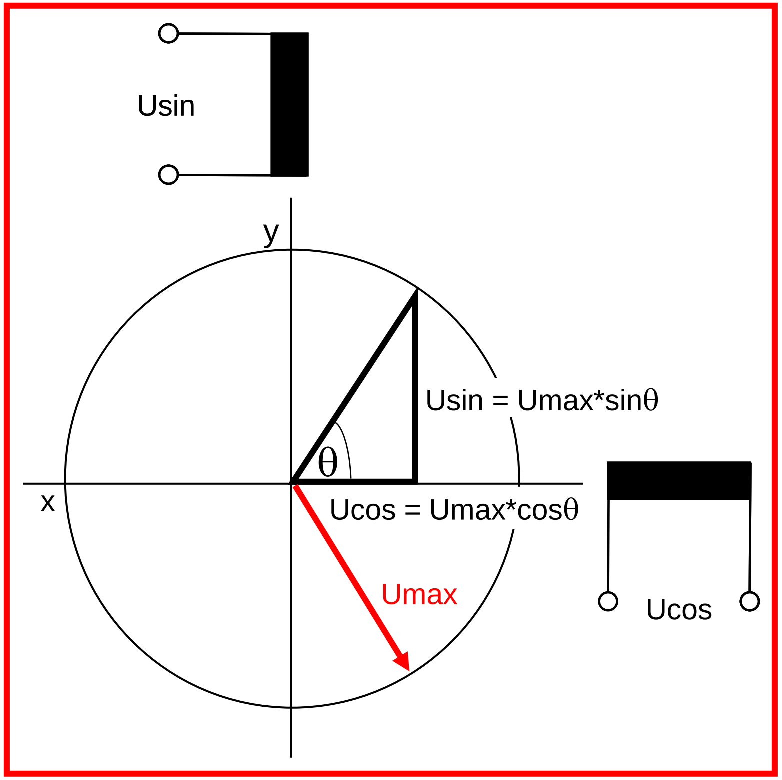




## Typical Resolver Parameters

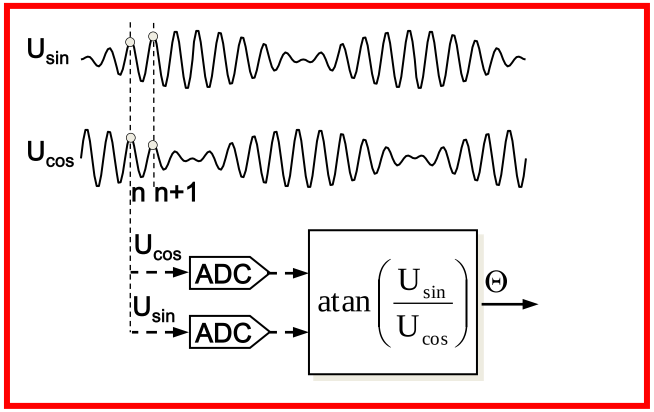
- Electrical Error – +/-10’, Transformation Ratio – 0.5, Phase Shift – +/-10°
- Input Voltage – 4-30V, Input Current – 20-100mA, Input Frequency – 400Hz-10kHz

# Resolver – Angle Extraction Basics

## Method Basics:



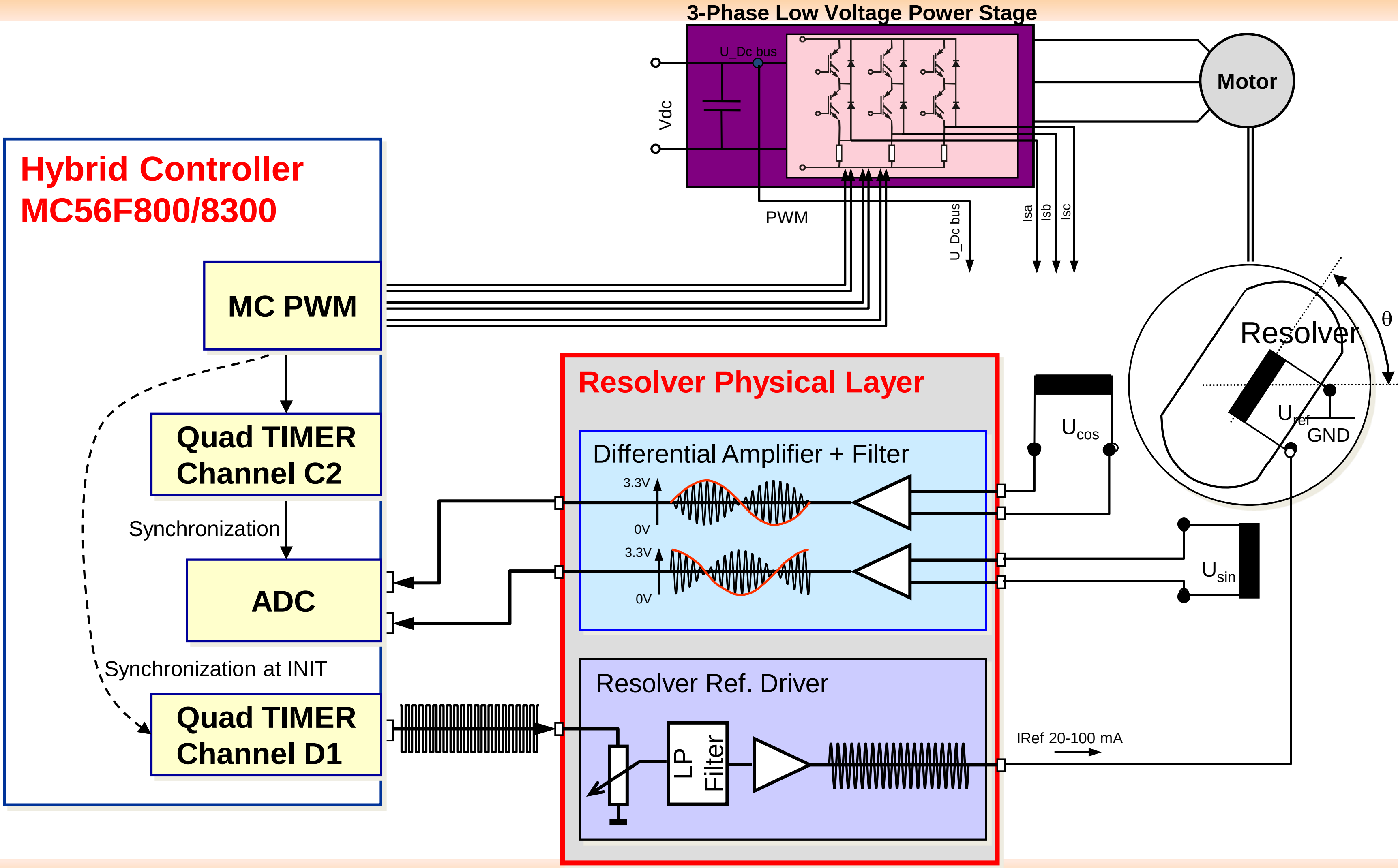

## DSP Calculation:



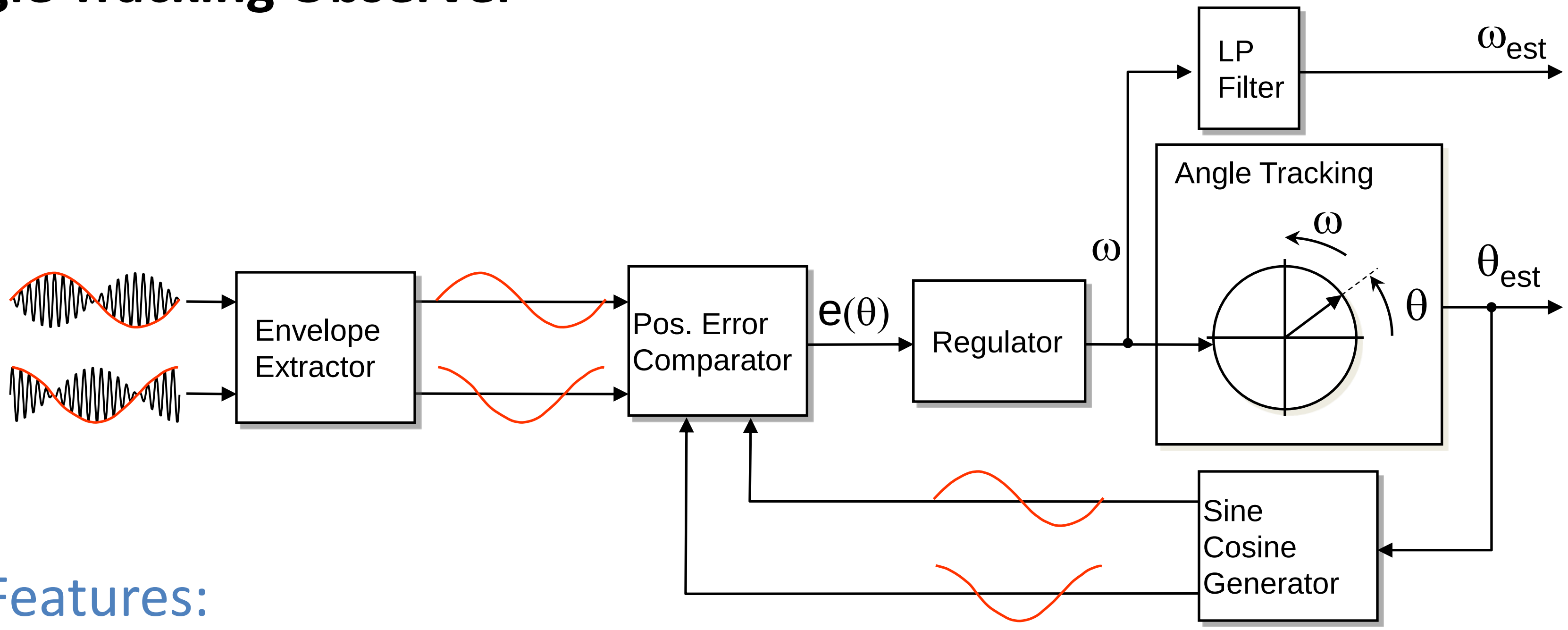

# Features:

- **Simple to implement**
- **Sensitive towards disturbance and harmonic distortion**
- **Need for digital post-filtering**

# Resolver Interface



## Angle Tracking Observer

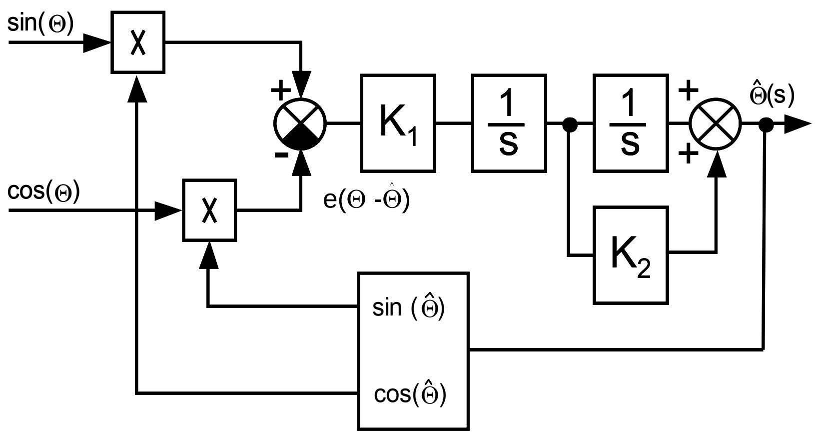



### Features:

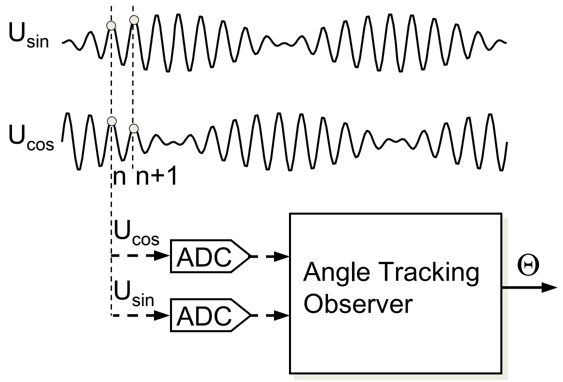
- Robust method in term of noise
- High accuracy of the angle extraction, speed estimation for free as side effect
- Can deal with non-sinusoidal signals/envelops
- Can be implemented fully digitally

# Resolver – Angle Tracking Observer

## Implementation Basics:




## DSP Calculation:




## Angular error evaluation:

$$e\left(\Theta - \hat{\Theta}\right) = \sin(\Theta)\cdot\cos\left(\hat{\Theta}\right) - \cos(\Theta)\cdot\sin\left(\hat{\Theta}\right) = \sin\left(\Theta - \hat{\Theta}\right)$$

$$e\left(\Theta - \hat{\Theta}\right) = \sin\left(\Theta - \hat{\Theta}\right) \approx \Theta - \hat{\Theta} \quad \text{for } \left(\Theta - \hat{\Theta}\right) \leq 7^\circ$$

## Transfer function:

$$F(s) = \frac{\hat{\Theta}(s)}{\Theta(s)} = \frac{K_1\left(1 + K_2 s\right)}{s^2 + K_1 K_2 s + K_1}$$

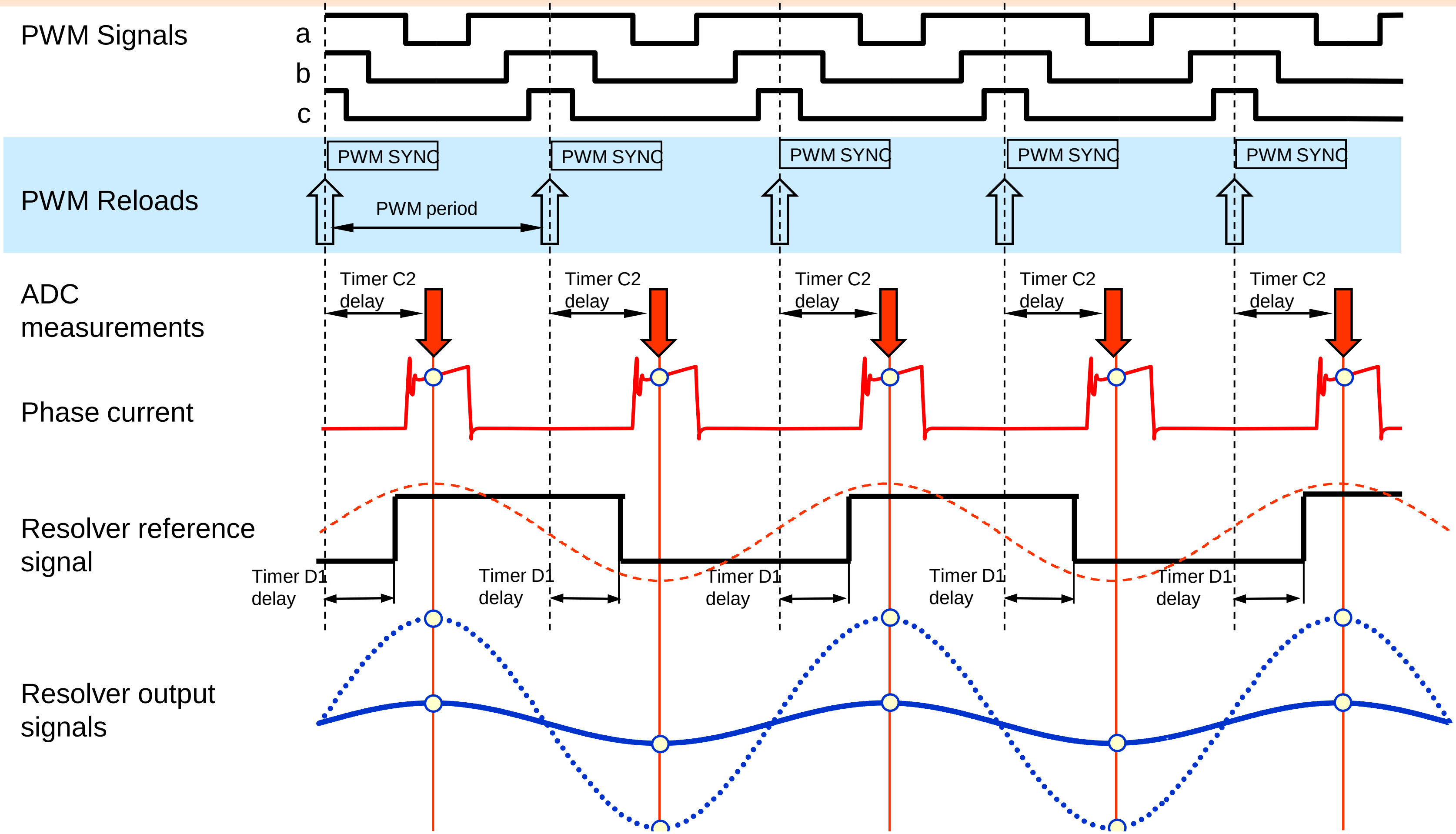
## Features:

Non-sensitivity to disturbance and harmonic distortion of the carrier

Non-sensitivity to voltage and frequency changes

High accuracy of the angle extraction

# Resolver – Signal Synchronization



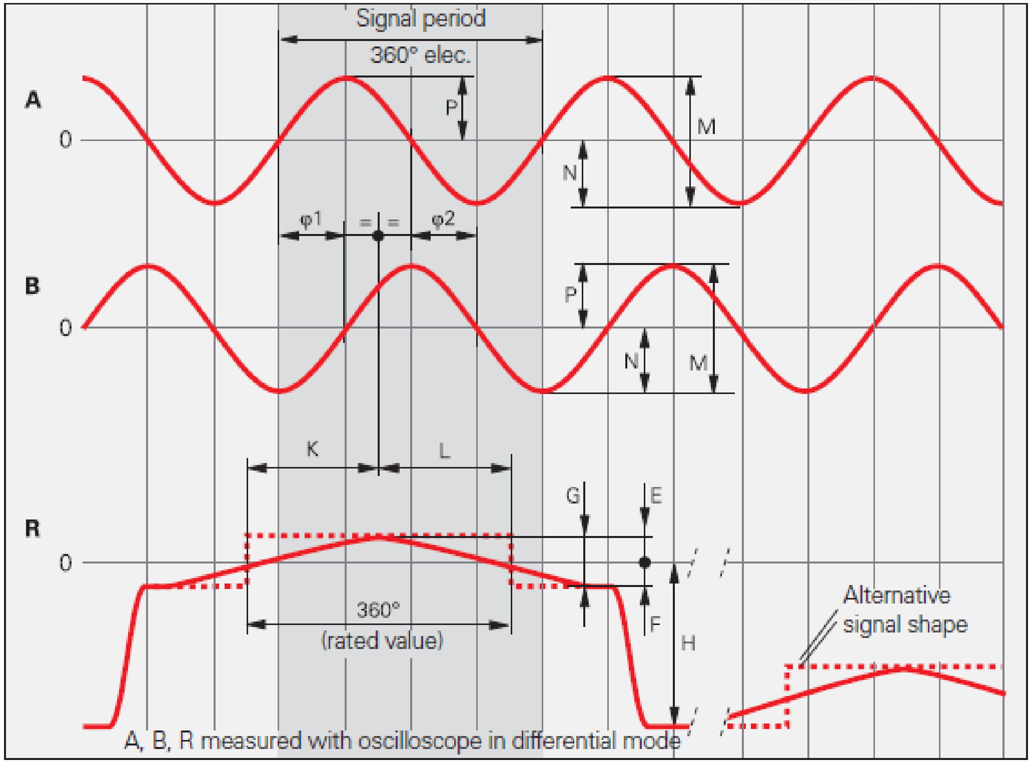

Main goal is to synchronize PWM-ADC-RESOLVER !

Note the envelope extraction is then done automatically.

# Sin/Cos Sensor

- The sinusoidal **incremental signals A and B** are phase-shifted by 90° elec. and have an amplitude of typically 1 Vpp
- Signal amplitude M: 0.6 to 1.2 VPP; typically 1 Vpp
- Asymmetry |P – N|/2M: † 0.065
- Phase angle Iφ1 + φ2I/2: 90° ± 10° elec
- The **reference mark signal R**
- Line counts - typical - 100 200 **250 360 400 500 720 900 1000 1024 1250 1500 2000 2048 2500 3600**

## Heidenhain encoder with 1 Vpp



# Sin/Cos Sensor

## Sensor Types:

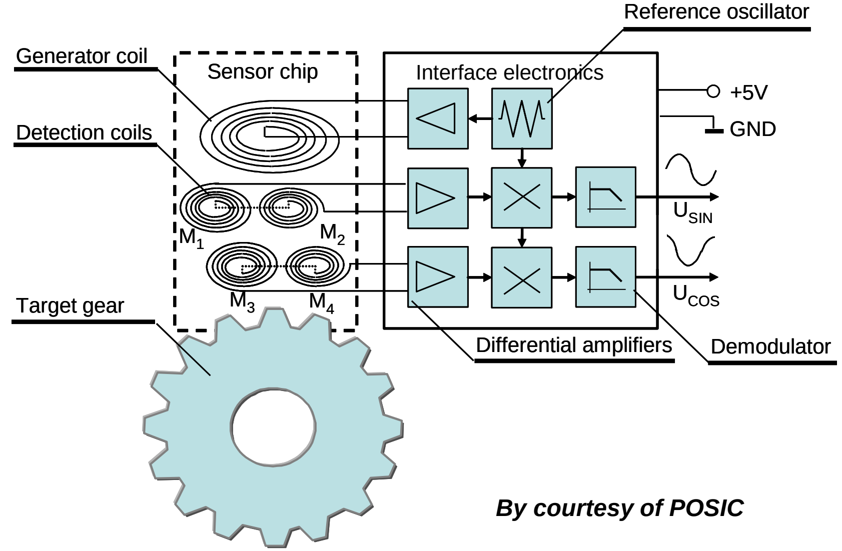
- OPTO-ASIC high-precision sensors using sophisticated sensor array and barcode tracks
- Inductive Micro-coil Sensor
- Magnetic Resistance (MR) Sensors
- Giant Magnetic Resistance (GMR) Sensors

## Sensor Applications:

- Robotics and Industrial applications
- ACIM, PMSM and BLDC drives applications
- Automotive ABS, EPS and Brake applications
- X-by-wire applications

20-bit position accuracy achieved using Sin-Cos Tracking Observer for OPTO-ASIC high-precision sensors !

## Micro-coil Sensor Technology:

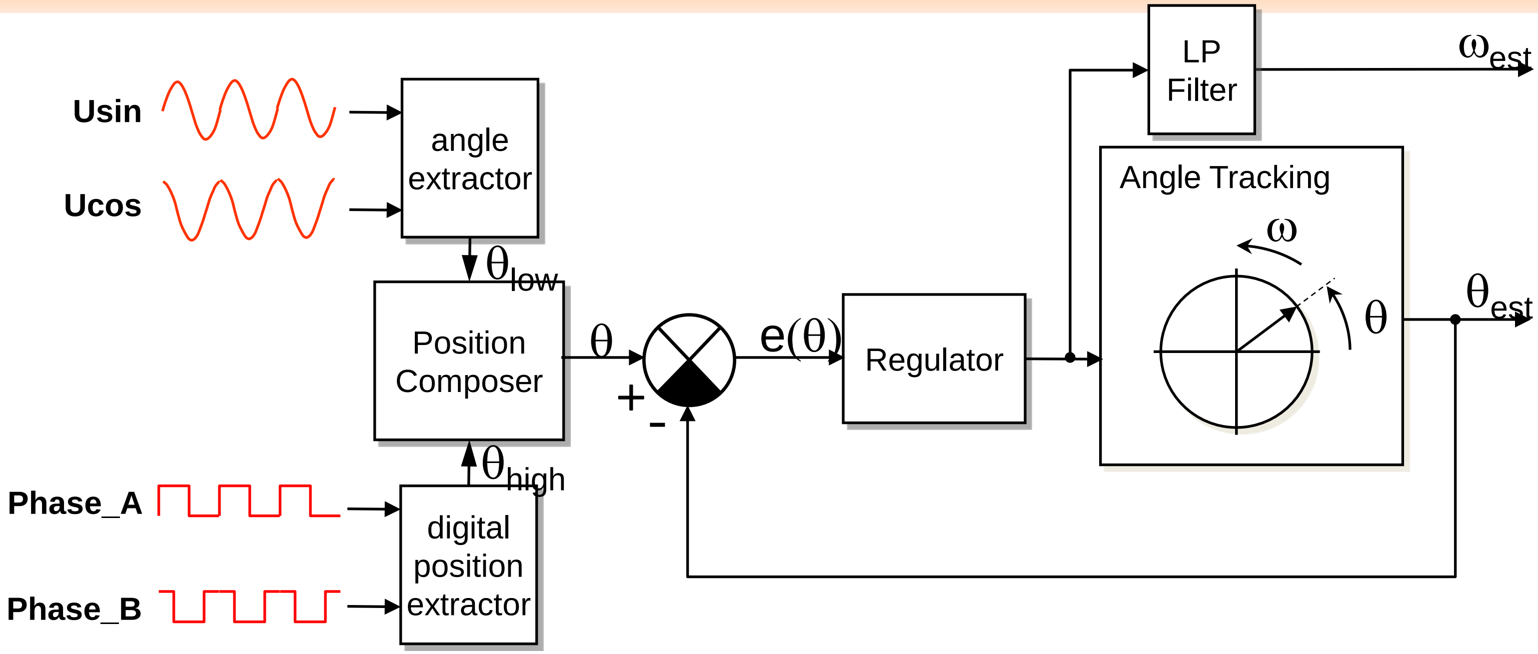



*By courtesy of POSIC*

## Micro-coil Sensor Features:

- Non-contact sensing
- No magnetic target, no bias magnet
- Resist well against distortion, vibration, deviation of operating temperature and dust
- Wide temperature range -40°C to +125°C
- Zero speed operation
- Worldwide consumption millions of pieces
- Simple assembly and maintenance

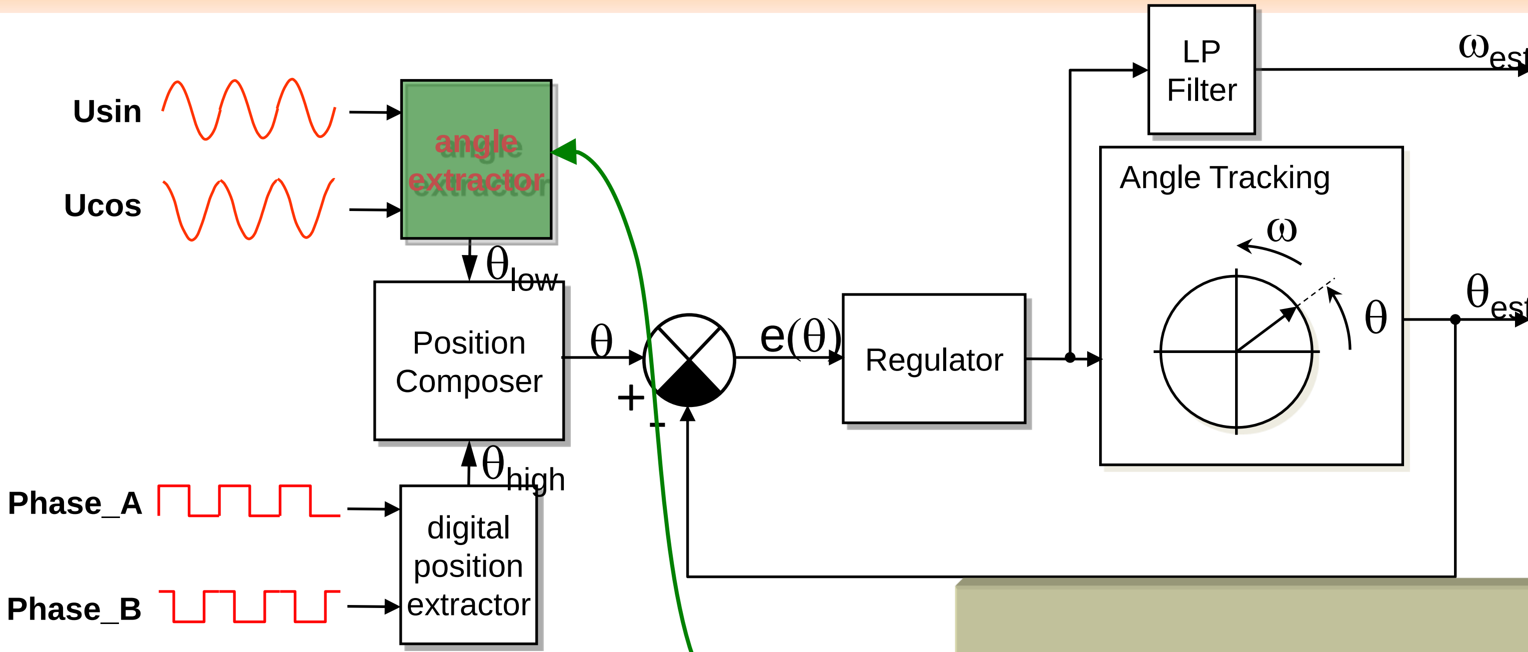
# Sin/Cos Sensor

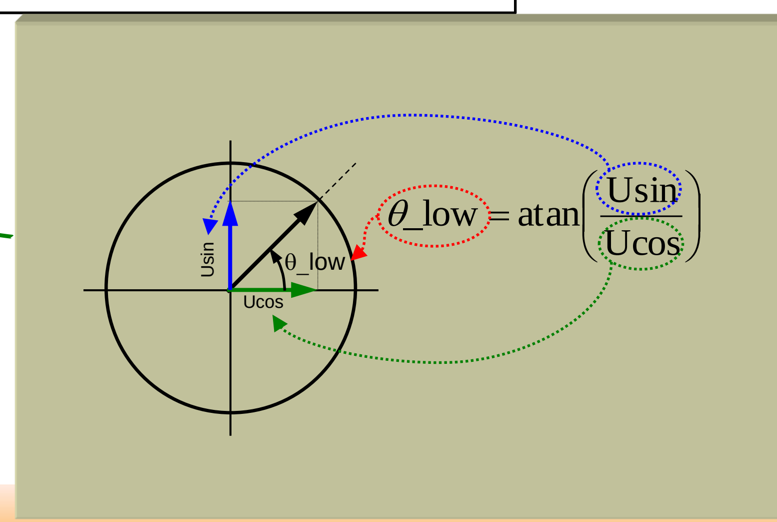



## Features:

- Robust method in terms of noise
- High accuracy of the angle extraction, speed estimation for free as side effect
- Can deal with non-sinusoidal signals/envelops
- Can be implemented fully digitally

# Sin/Cos Sensor

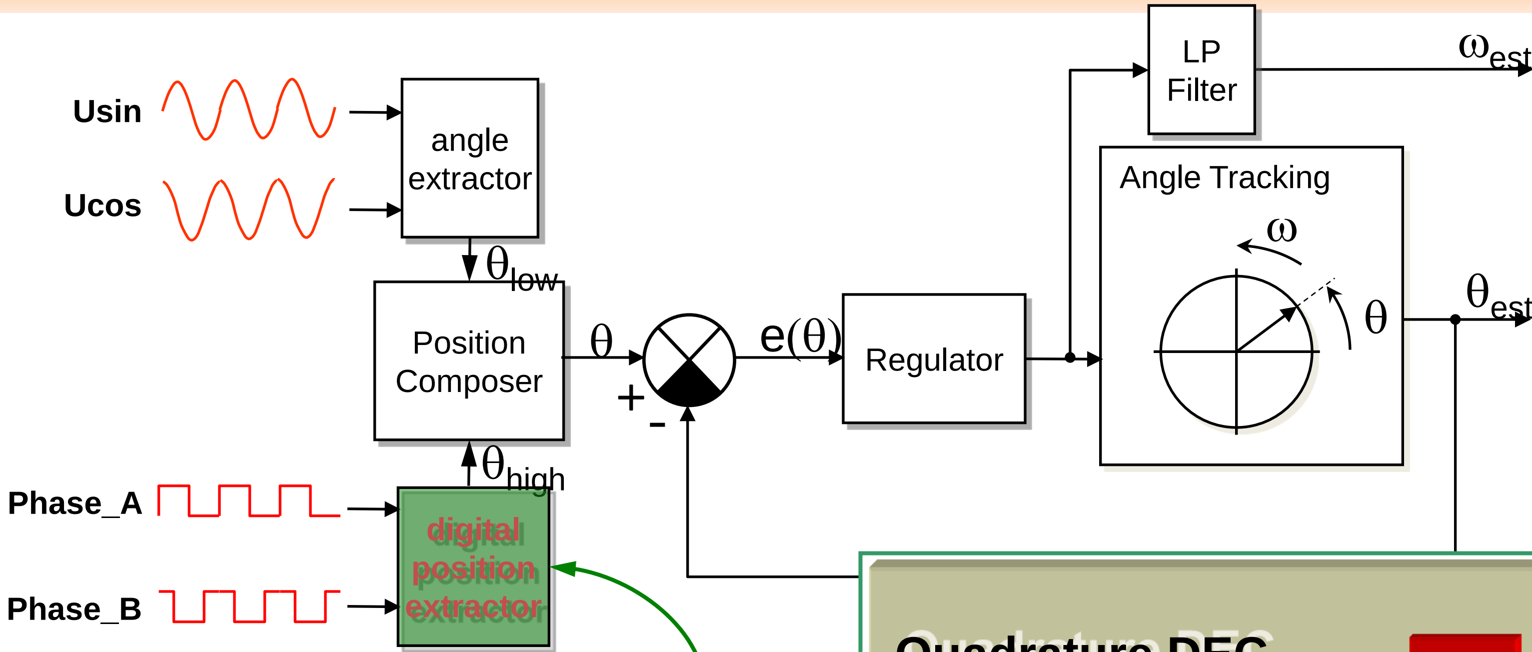



## Features:

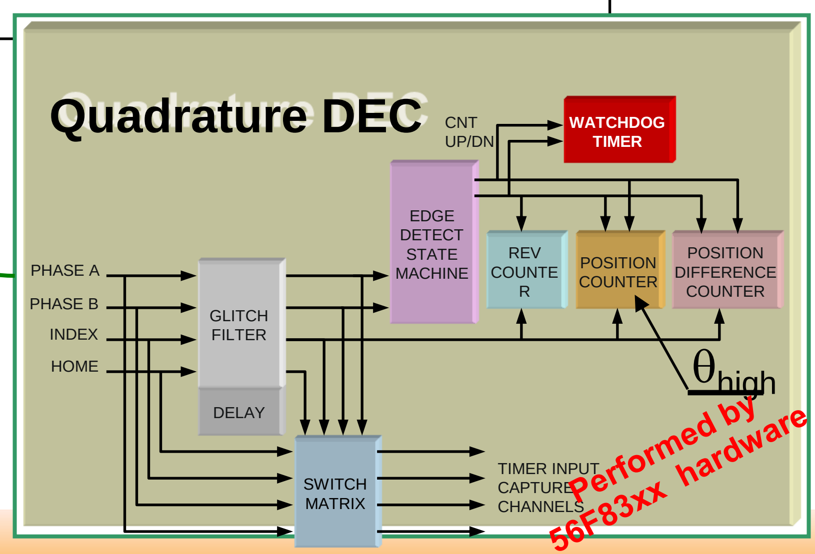
- Insensitive to signal amplitude variation.
- Can deal with non-sinusoidal signals/envelops.
- Can handle non 90° A-B signal phase shift.

# Sin/Cos Sensor

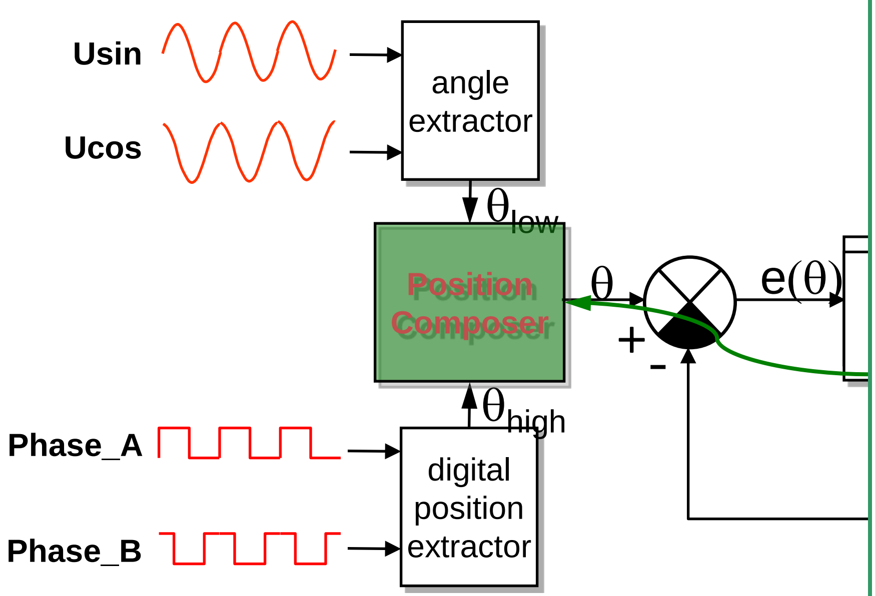


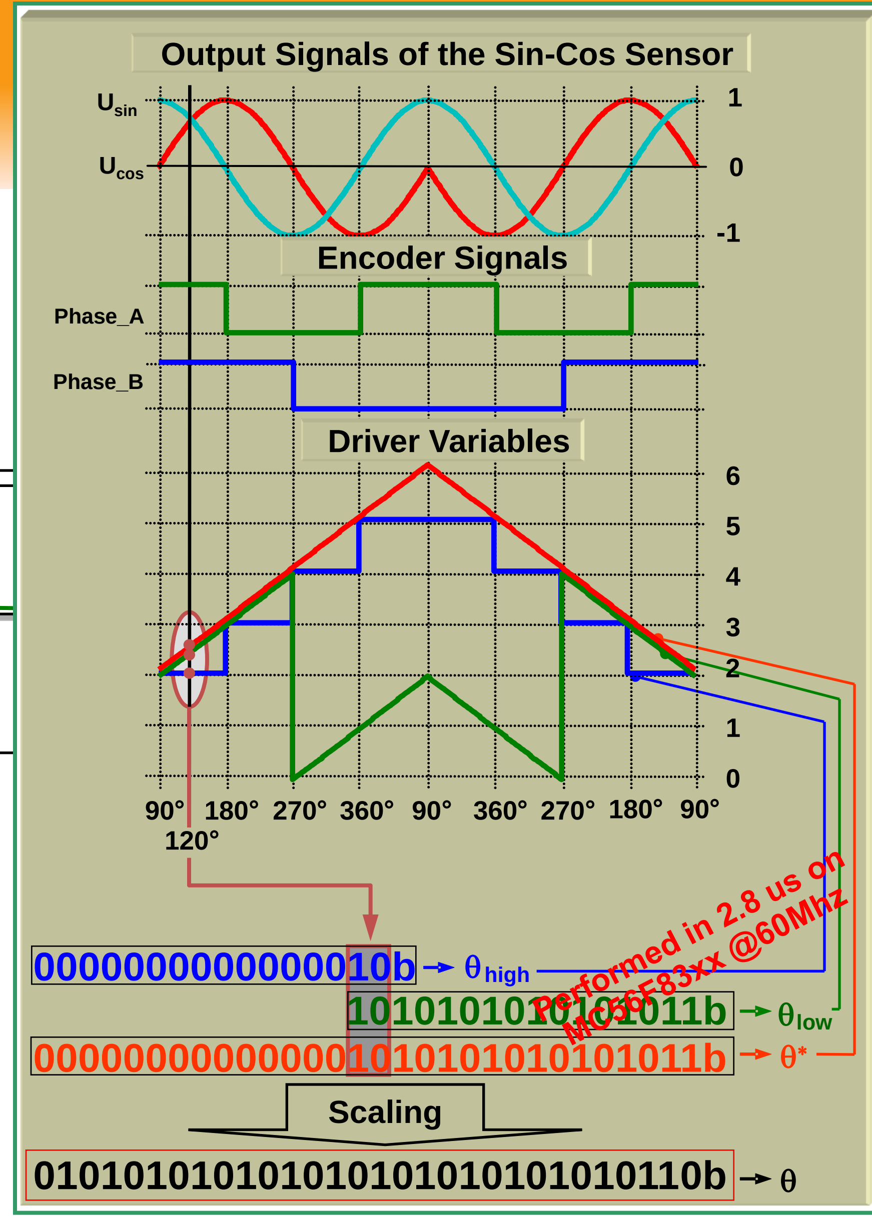

## Features:

- 56F83xx QuadTimer or Quadrature Decoder on-chip peripherals can be used directly for Phase_A and Phase_B decoding
- Phase_A and Phase_B decoding can be synchronized with Usin and Ucos processing to maximize extraction accuracy



# Sin/Cos Sensor




## Features:

- Position Composer:
  - combines rough „digital" position (Quadrature Decoder) with „analogue" fine position (ADC),
  - scales the combination of the „digital"&"analogue" parts into 32-bit range corresponding to ± π.
- Stand alone Position Composer can be used where position filtering and speed estimation is not required.

# Braking System – Wedge Brake

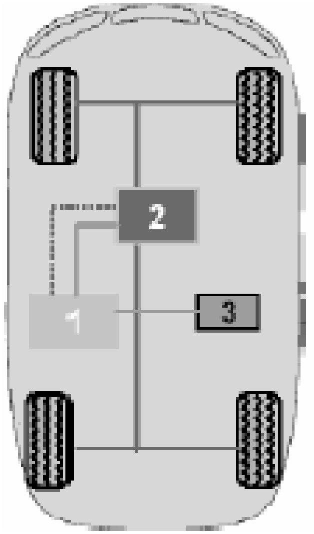
## Electro-Hydraulic Brakes (EHB)

- Hydraulic system actuates the brake calipers
- Depressing the brake pedal the appropriate command is transmitted electronically to electronic controller of the hydraulic unit
- The electronic controller determines the optimum braking pressure

1 - EHB electronic actuator unit with pedal

2 - EHB hydraulic unit

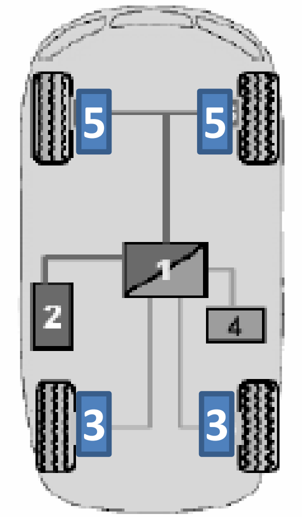
3 - Sensors



# Braking Systems – Summary cont'd

## Hybrid Braking System

- Combination of Hydraulic System with Electro-Mechanical Braking System (EMB)
- EMB for rear wheels – eliminates the need for long hydraulic lines and handbraking cables leading toward the rear axle
- The front axle operates hydraulically, as with conventional braking systems
- This results in a two-circuit system
  - with two hydraulic wheel brakes on the front axle
  - two electro-mechanical wheel brake modules at the rear axle.




1 - Electronic Brake System (EBS) hydraulic unit with Electronic Control Unit (ECU)
2 - Pedal/Booster
3 - EMB wheel brake module
4 – Sensors
5 - Conventional wheel brake

# Braking Systems – Summary cont’d

## Electro-Mechanical Brake (EMB)

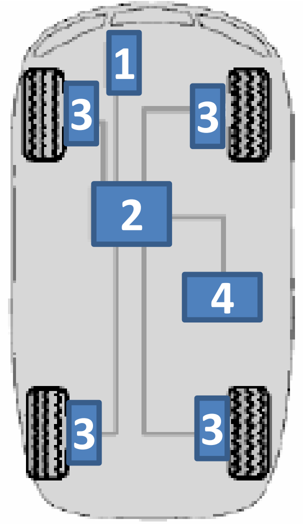
- The braking force is generated directly at each wheel by high-performance electric motors, controlled by an ECU, and executed by signals from an electronic pedal module
- brake-by-wire technology
- The EMB processing components must be networked using high-reliability bus protocols that ensure comprehensive fault tolerance as a major aspect of system design
- The use of electric brake actuators means additional requirements, including motor control operation within a range of 12-volt up to 42-volt power system and high temperatures, and a high density of electronic components

# Braking Systems – Summary cont'd

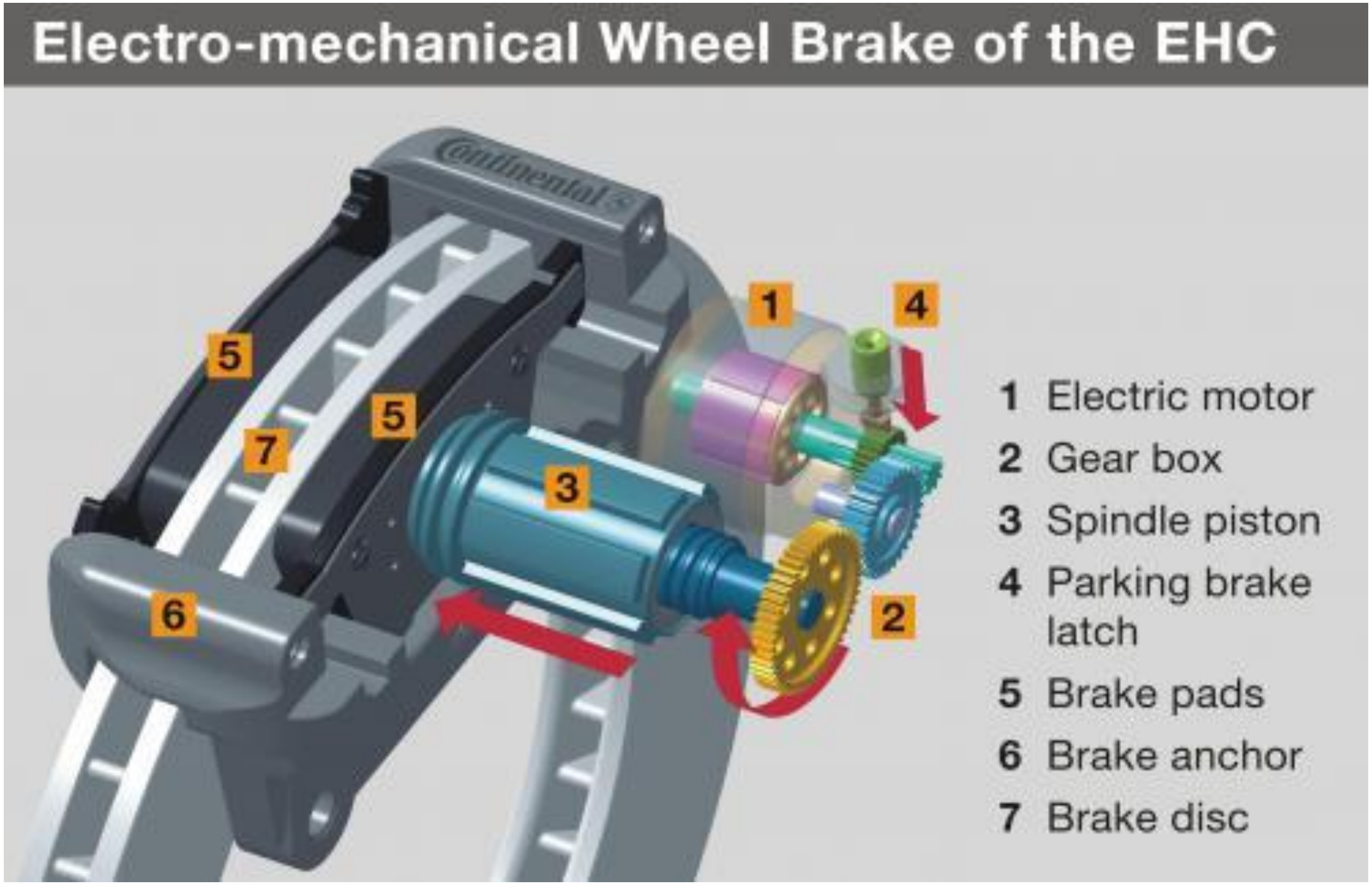
## Electro-Mechanical Brake (EMB)

- The EMB includes all brake and stability functions, such as
  - Anti-lock Braking System (ABS)
  - Electronic Brake Distribution (EBD)
  - Traction Control System (TCS)
  - Electronic Stability Program (ESP)
  - Brake Assist (BA)
  - Adaptive Cruise Control (ACC)

1 - EMB battery
2 - EMB pedal unit with ECU
3 - EMB wheel brake module
4 – Sensors



# Braking Systems – Summary cont'd

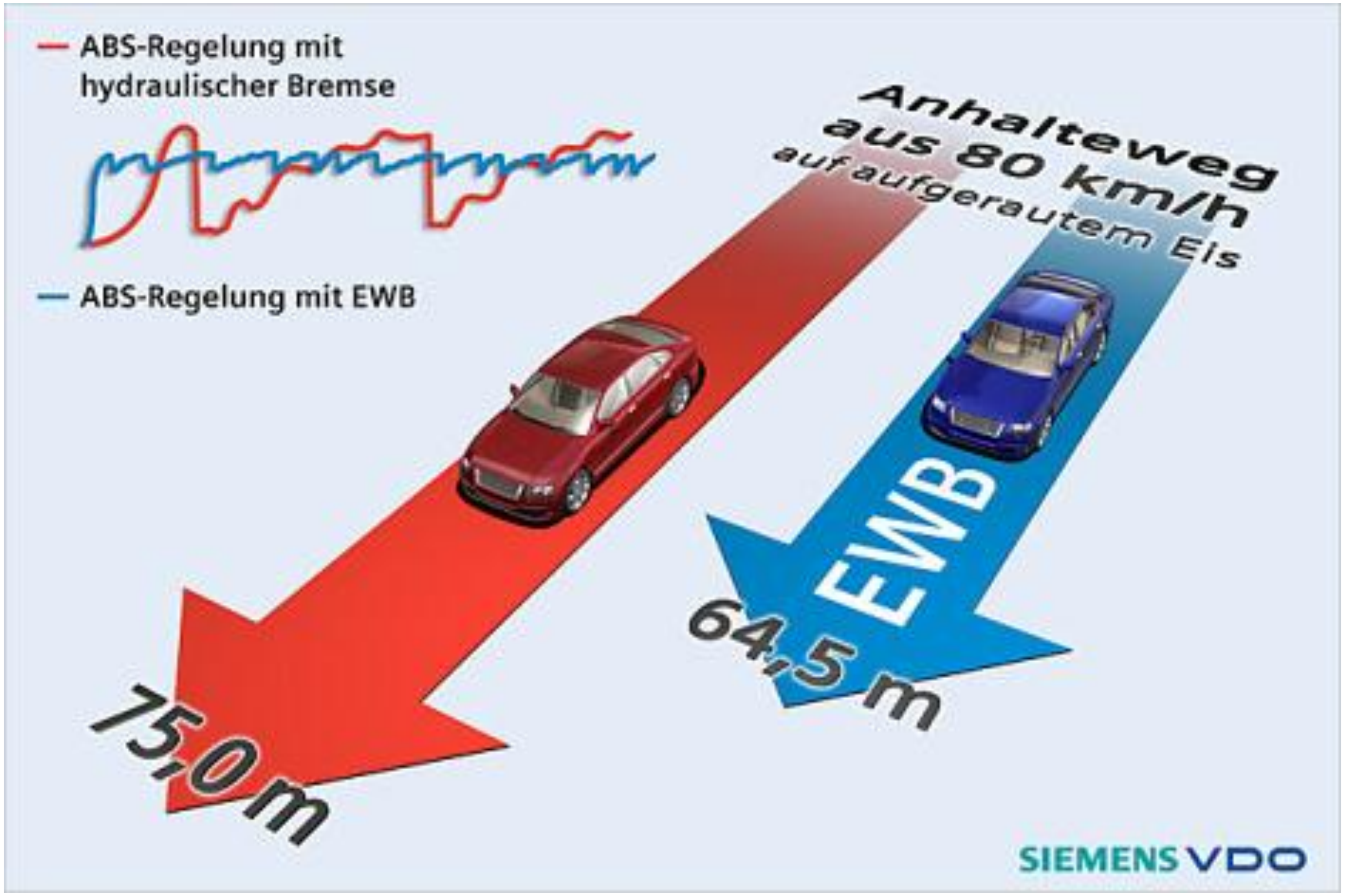


# Wedge Brake System -eBrake

## Electro-Mechanical Brake (EMB)

- The eBrake® is a novel self-reinforcing electromechanical wedge brake
- Invented by the innovative company eStop
- In 2005, Siemens VDO Automotive AG acquired the innovative company eStop
- The EWB is a self-reinforcing electromechanical wedge brake, which operates around the point of maximum self-reinforcement

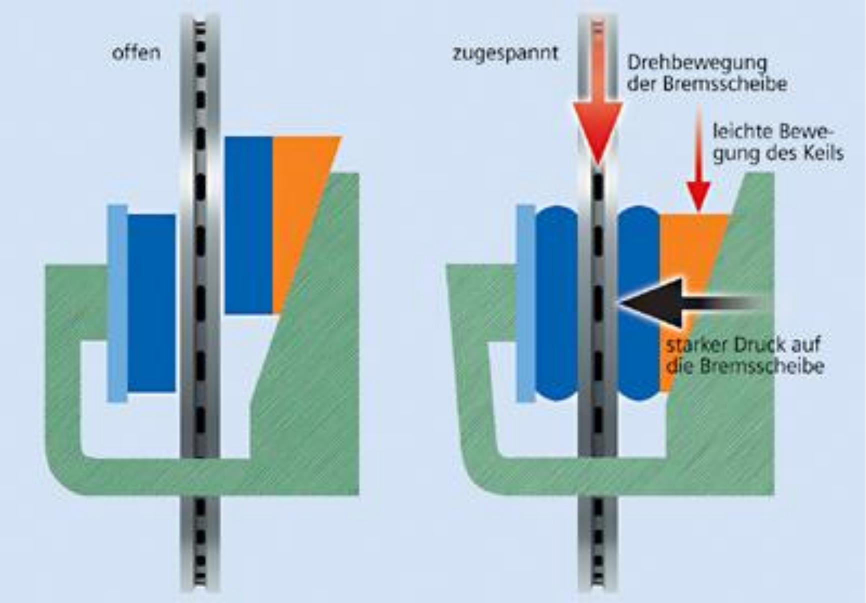
# Wedge Brake System -eBrake



# Wedge Brake System - eBrake

- The stability of the wedge brake varies with the coefficient of friction between brake pad and disk
- At low coefficient of friction, the net force on the wedge acts to push it back out of the caliper
- At high friction coefficient, it pulls it in

- A change in this parameter can therefore result in the wedge jumping across the backlash in the drive mechanism, resulting in a step change in braking force
- To solve this problem, the alpha and beta prototypes both used a tandem motor design, such that the two motors can be used to preload the drive train.



# Wedge Brake System -eBrake

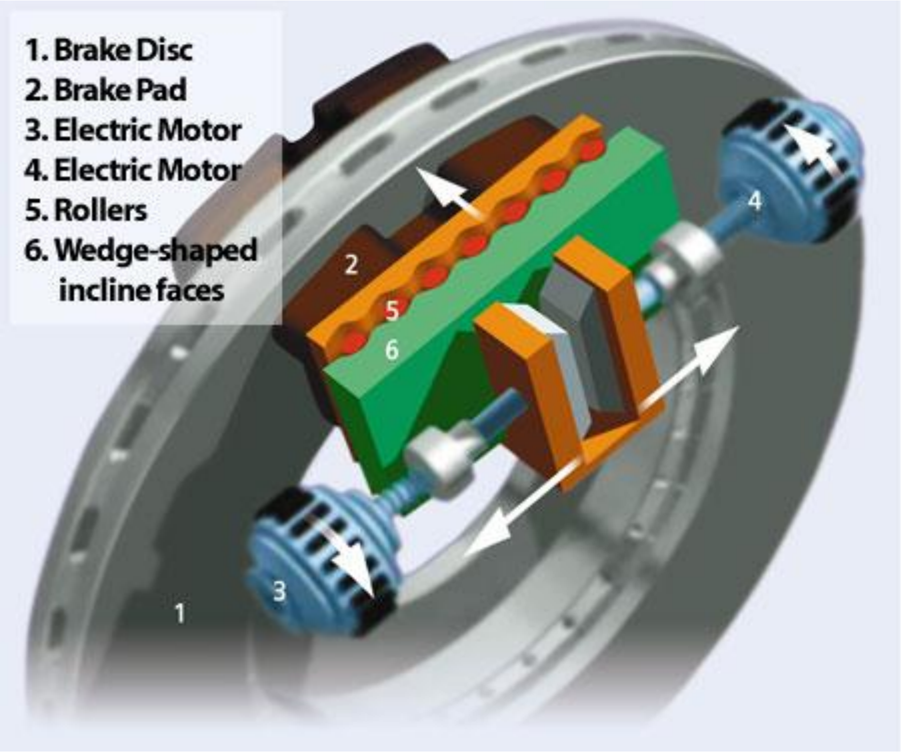
- Benefit of eBrake would be reduction of the force required from the brake actuator
- The eBrake® solves this problem elegantly by using a wedge to generate the clamping forces
- This exploits self-reinforcement of the braking forces by the rotating brake disc to minimize the actuation forces

$$C^* = \frac{\text{Pad Braking Force}}{\text{Brake Actuation Force}} = \frac{2\mu_B}{\tan\alpha - \mu_B}$$

- Ideal operating point - the coefficient of friction is equal to the tangent of the wedge angle - steady-state actuation force required to generate any braking torque is zero
- $C^* > 0$ ($\tan\alpha > \mu_B$) - steady pushing force is required to maintain the braking force
- $C^* < 0$ ($\tan\alpha < \mu_B$) - steady pulling force is required from the actuator to stop the wedge being pulled further in

# Wedge Brake System -eBrake

- optimum performance - it is best to operate around the point at which the characteristic brake factor is infinite ($C^* \rightarrow \infty$), since this minimizes the control forces required
- From a control standpoint, this can be thought of as a point of neutral stability, since any small perturbation in the wedge position will result in it remaining in the new position
- When the coefficient of friction increases, the wedge position becomes unstable and needs to be controlled to stop the wheel jamming



# Wedge Brake System -eBrake

Force normal to the brake disc where $K_{CAL}$ is calliper stiffness

$$F_N = K_{CAL} x_W \tan\alpha$$

Assuming that the disc rotates, the braking force is

$$F_B = \mu_B F_N = \mu_B K_{CAL} x_W \tan\alpha$$

Due to the wedge angle, there is a component of the reaction force in the axial direction

$$F_A = -F_N \tan\alpha$$

Total axial force acting on the wedge is

$$F_W = (\mu_B - \tan\alpha)F_N + F_M$$
$$= (\mu_B - \tan\alpha)K_{CAL} x_W \tan\alpha + F_M$$

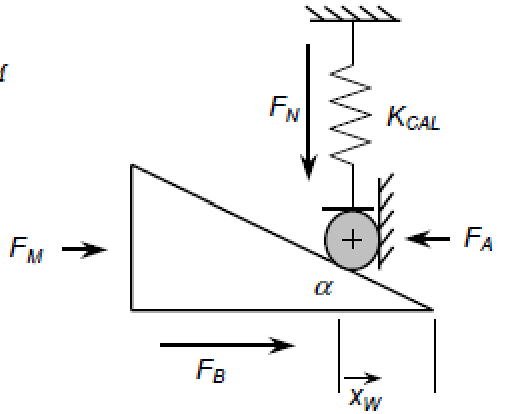
Simple model of the friction in the rollers

$$F_{FRICT_W} = \mu_R F_N$$

Note that self-reinforcement only functions while the wheel is turning. Once it has stopped, then the axial force on the wedge is given by

$$F_W = -K_{CAL} x_W \tan^2\alpha + F_M$$

**Forces on Wedge**

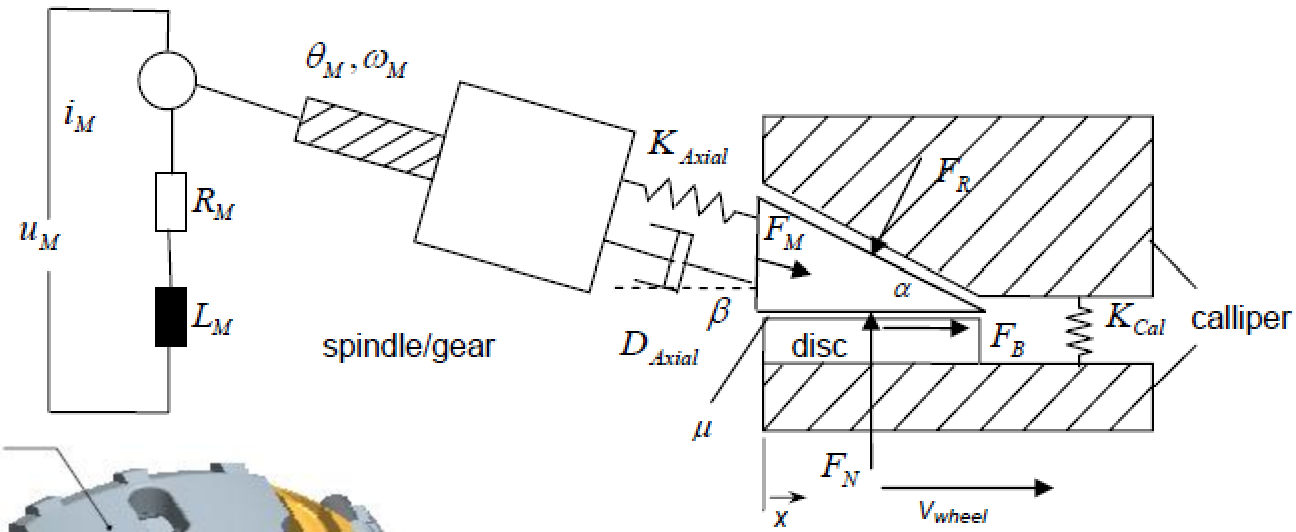


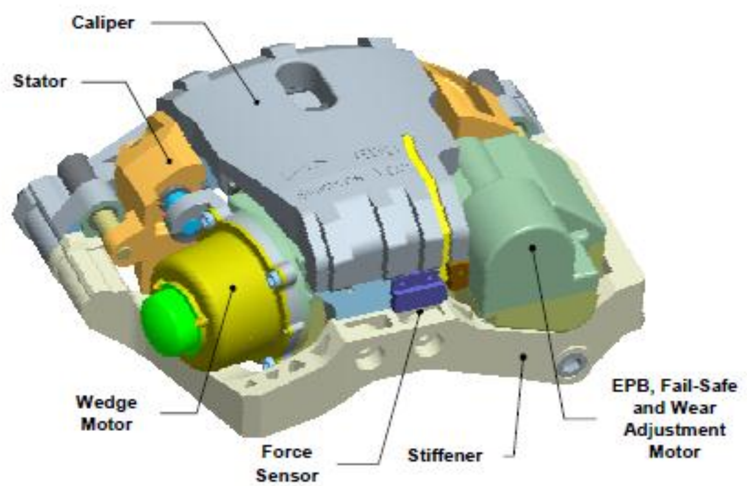

The braking torque is given by using the pads on both sides of the calliper and multiplying by their effective radius

$$M_B = 2\mu_B F_N r_B$$

# Wedge Brake System -eBrake

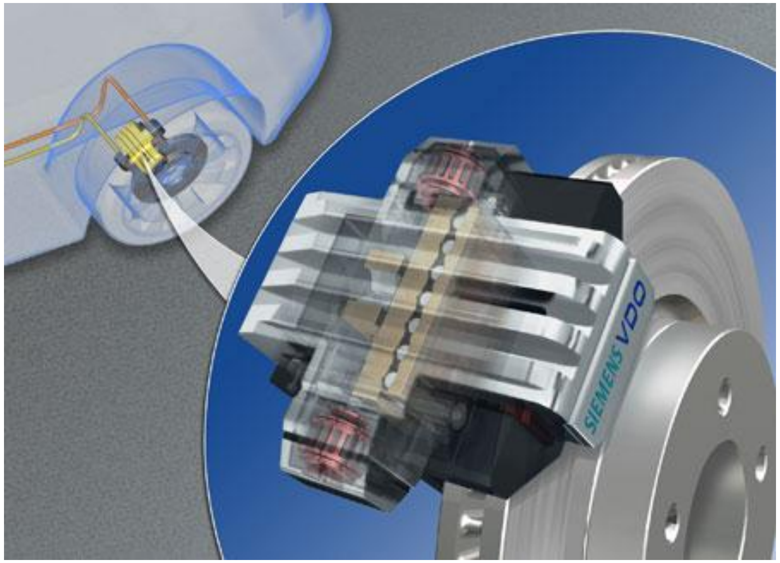
## Simplified Model of the Electrical Wedge Brake

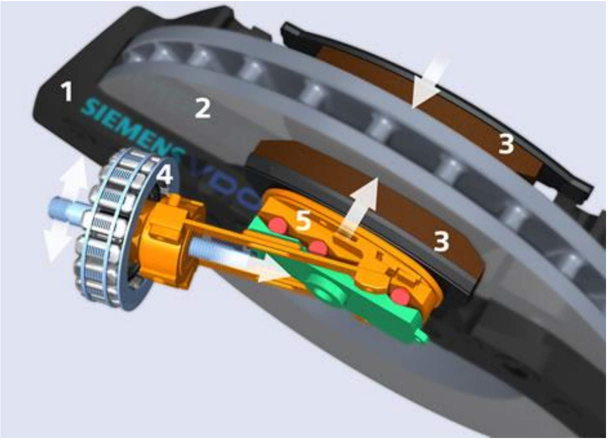


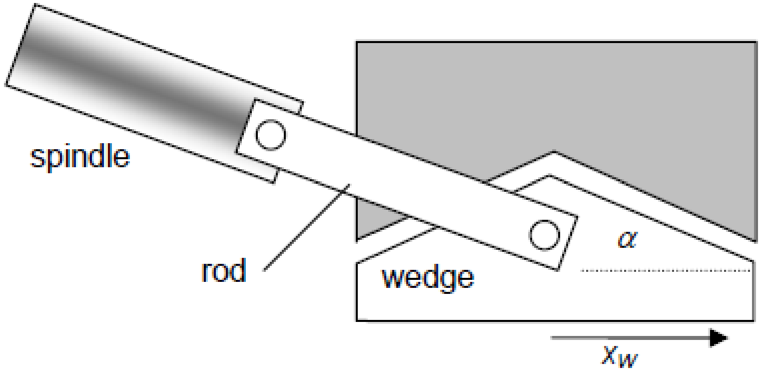




**PT1 Prototype (90kN / 4500 Nm)**

# Wedge Brake System -eBrake

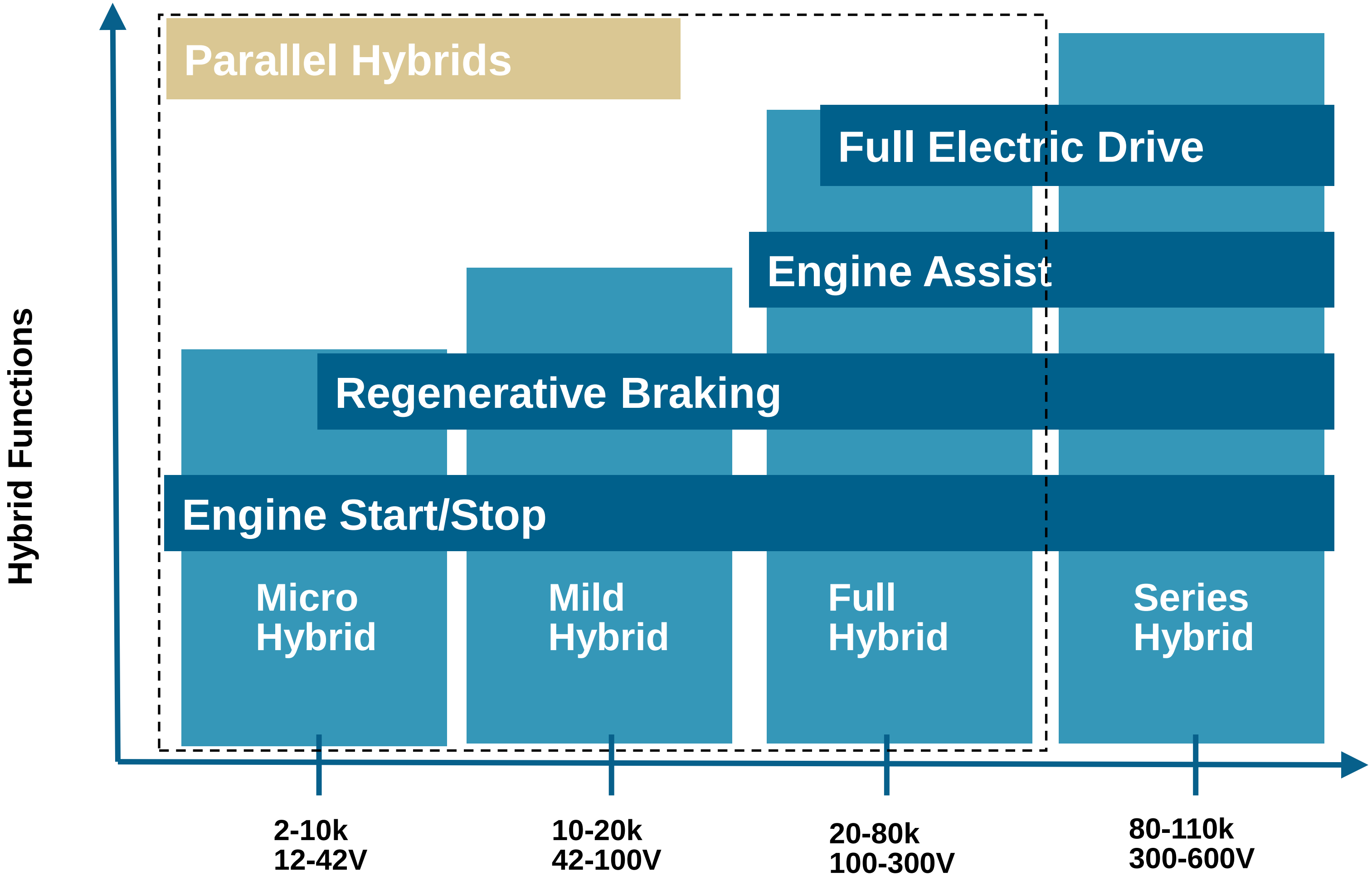


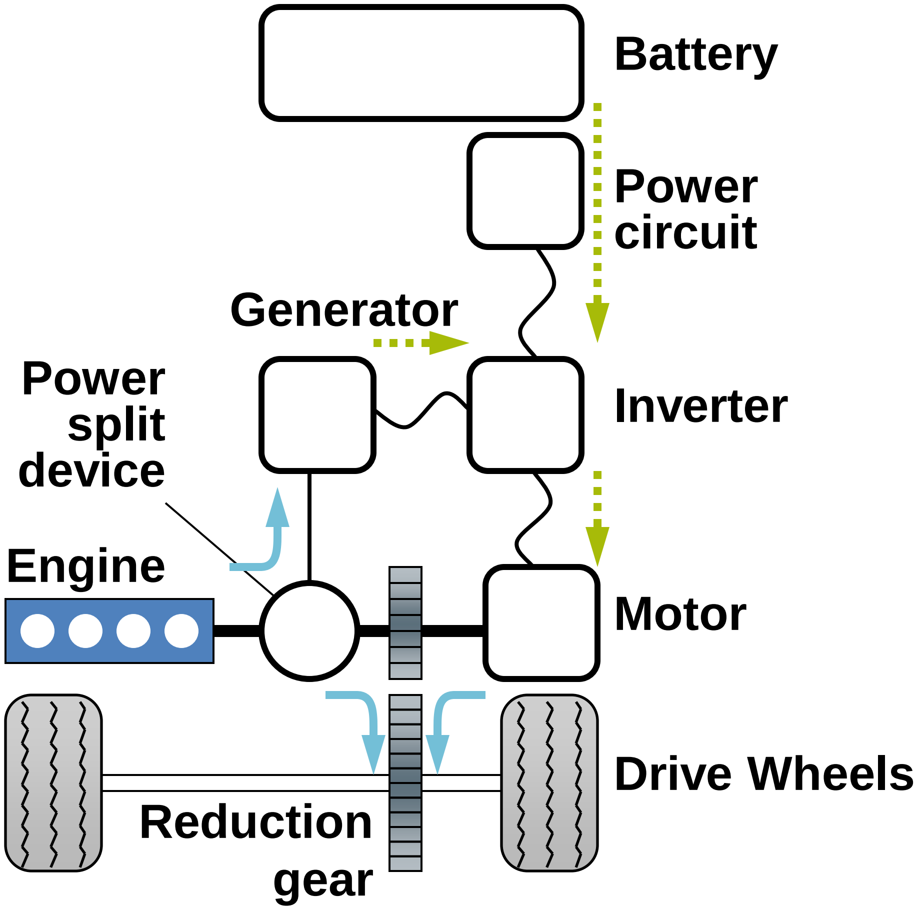



# KERS - Kinetic Energy Recovery System

# Hybrid Powertrain Roadmap

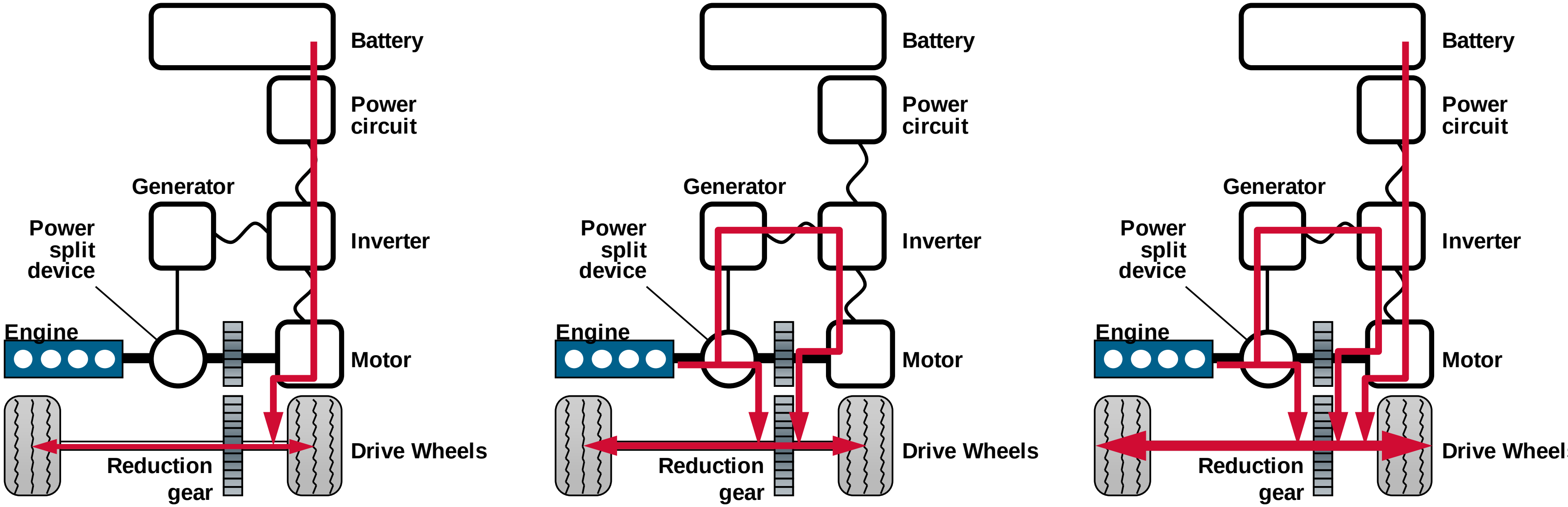


# Typical Hybrid System



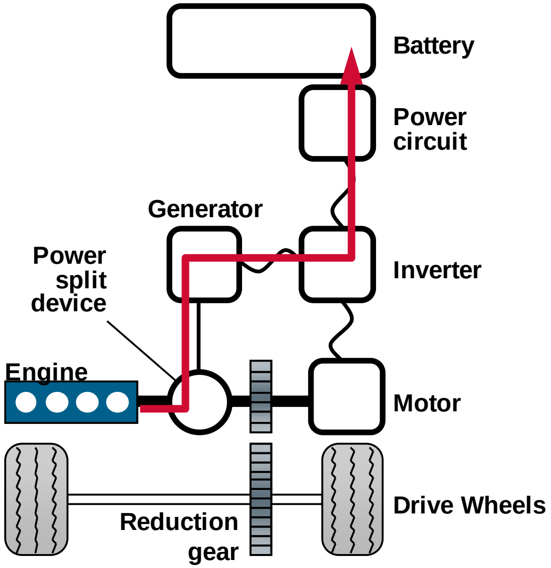

- High efficiency gas engine
- Planetary gear power split device AC synchronous generator
- High voltage AC-DC inverter
- Nickel-metal hydride battery
- Permanent magnet AC motor

# Hybrid Driving Modes

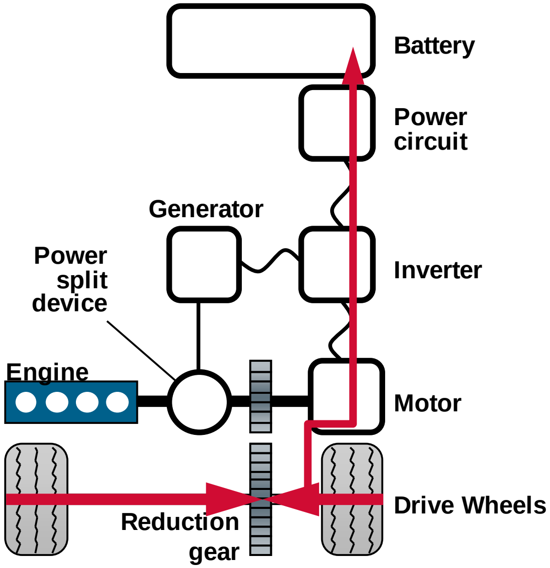



**Low Speed** **Normal Driving** **Sudden Acceleration**

# Hybrid Driving Modes

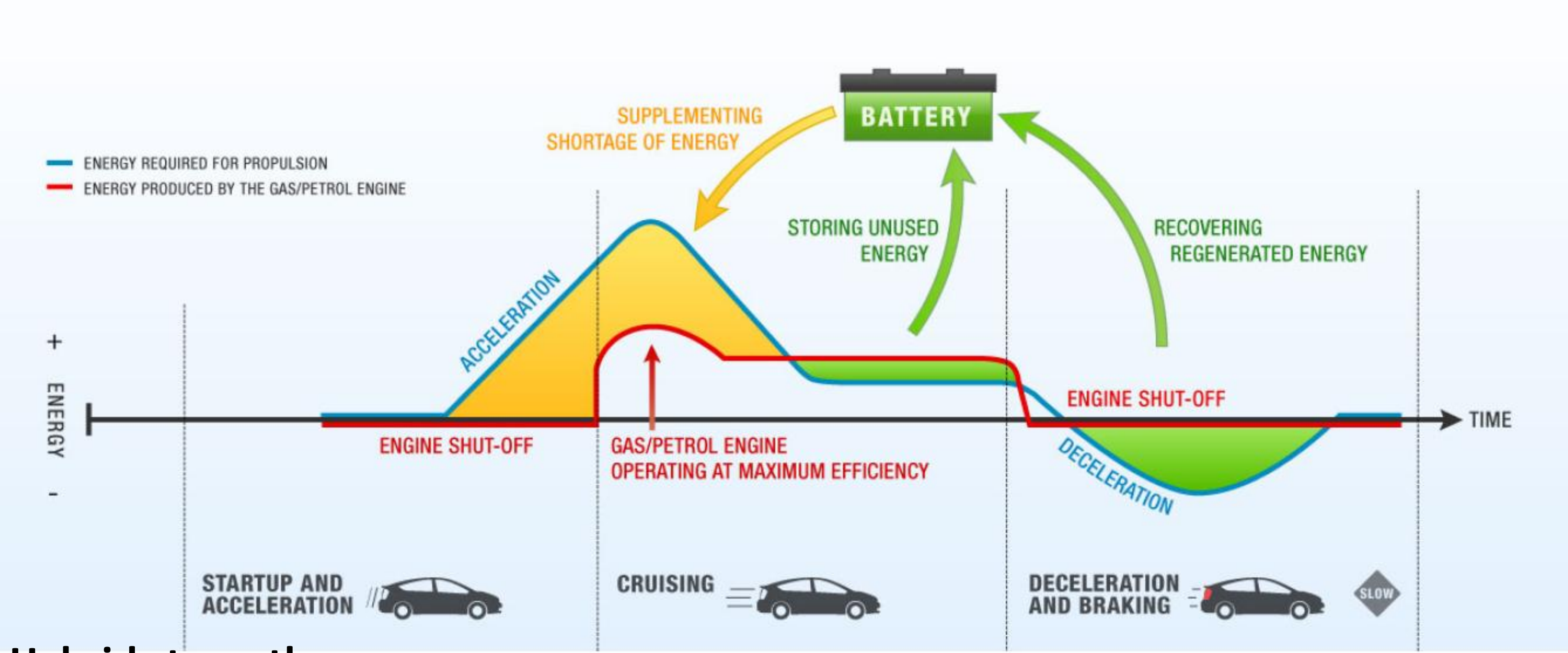



**Battery Charging**




**Regeneration**

# Driving Hybrid



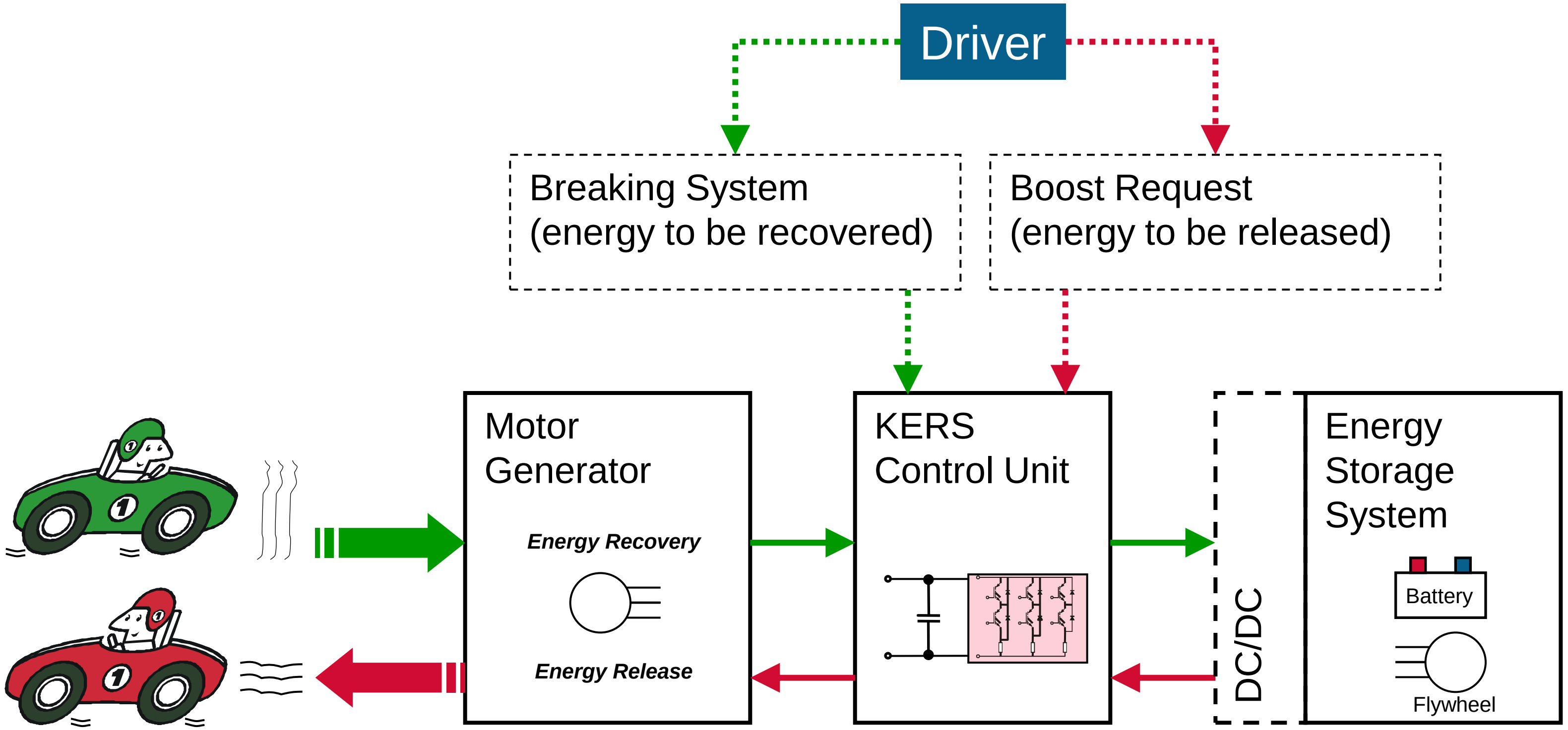

## Hybrid strength

Source: TOYOTA, Hybrid Synergy Drive, Information Portal

- **Regenerative Braking.** The electric motor applies resistance to the drivetrain causing the wheels to slow down. In return, the energy from the wheels turns the motor, which functions as a generator, converting energy normally wasted during coasting and braking into electricity, which is stored in a battery until needed by the electric motor.
- **Electric Motor Drive/Assist.** The electric motor provides additional power to assist the engine in accelerating, passing, or hill climbing. This allows a smaller, more efficient engine to be used. In some vehicles, the motor alone provides power for low-speed driving conditions where internal combustion engines are least efficient.

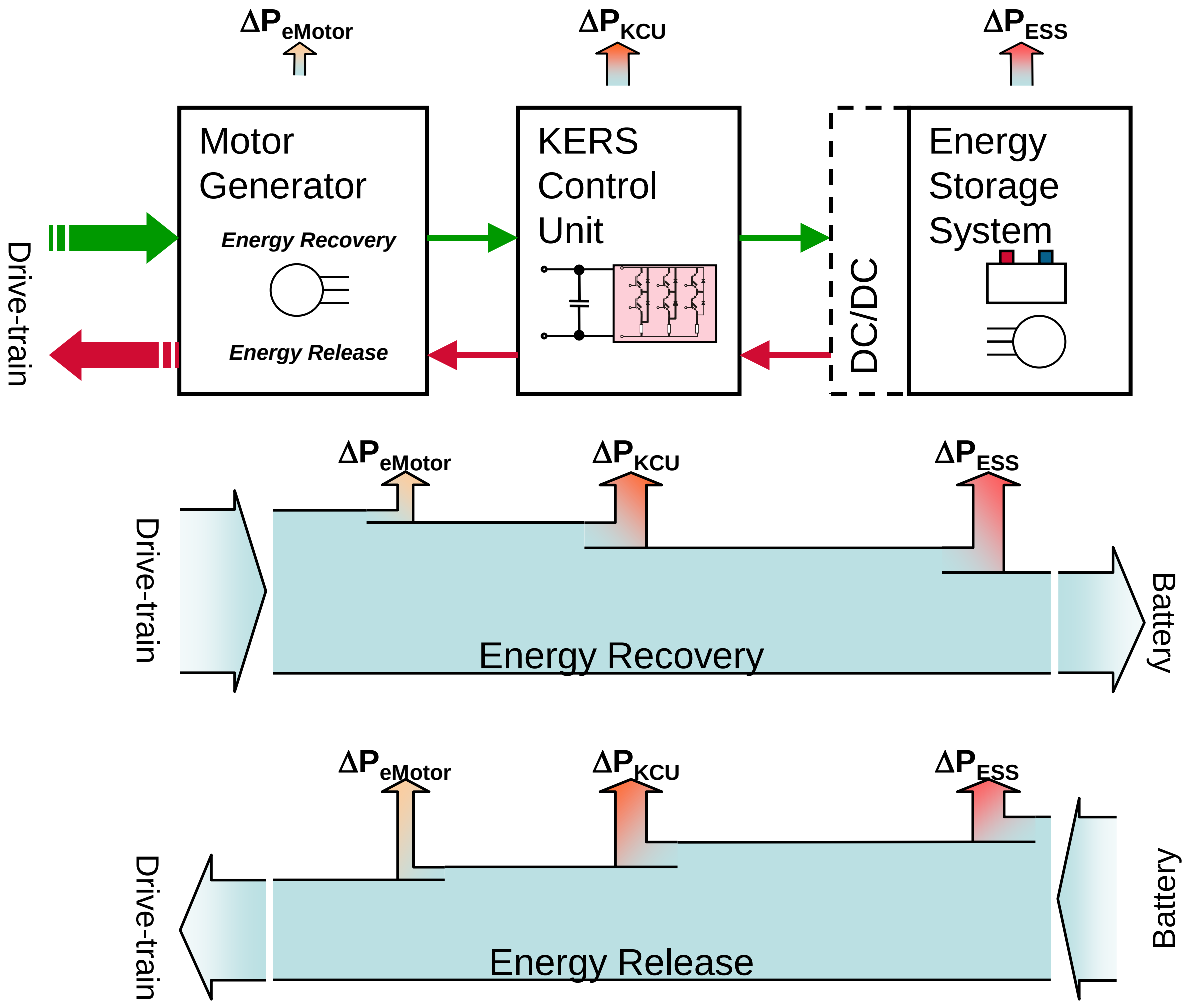
# Kinetic Energy Recovery System (KERS)

- Kinetic Energy Recovery Systems (KERS) are currently in use for the motor sport Formula One's 2009 season, and under development for road vehicles.



# KERS Energy/Power Flow

- Main KCU tasks:
  - control energy flow in the system
  - control eMotor
  - monitor ESS
  - command DC/DC



# Washing Machine Applications

# Washers – Horizontal Type

## Horizontal Washers

- Dominates in EU market
- Variable speed drives
  - Predominantly with ACIM
  - Nowadays PMS  motor
- Washers type
  - Front load washers
  - Top load washers
- Drive construction
  - Belt driven
  - Direct drive

# Washers – Horizontal Type cont'd

**Trends**

- Sinusoidal control
  - Higher efficiency
  - Minimum torque ripple
  - Audible noise reduction
  - Max motor torque utilization
- Sensorless speed control
  - Eliminate position sensor
  - Higher reliability
  - Cost reduction
- Belt drive
  - Legacy WM

# Washers – Horizontal Type cont'd

## Typical parameters

- Motor type
  - 3-ph ACIM – 2-poles
  - 3-ph PMSM – 4-poles up to 8-poles
- Laundry capacity for standard washer size - 60cm x 60cm
  - From 5 kg up to 11 kg
  - Typically – 7 kg or 8 kg
- Energy and water consumption
  - Example for 5 kg or 6 kg washer:
    - From about 43 liter to 65 liter
    - From 0.9 kWh to 1.4 kWh
- Spin speed
  - From 1000 rpm to 1600 rpm
- Wash basket
  - Stainless steel
  - Plastic
- Washer ratings
  - Composed from three parameters:
    - Washing performance rating
    - Energy efficiency rating
    - Spin efficiency rating
  - Examples:
    - AAB
    - AA+A

# Washers – Horizontal Type cont’d

## Typical parameters

- Maximum motor speed
  - 20000 rpm - 3-ph ACIM (2-poles)
  - 17000 rpm - 3-ph PMSM (4-poles up to 8-poles)
- Transmission ratio – Drum to motor
  - From 1:6
  - Up to 1:16
- Motor power
  - Approx. 1 kW
- Motor torque
  - Approx. 2 Nm
  - In some cases 4 Nm

- Washer application consists of:
  - Motor control part
    - FOC
    - Speed closed loop
  - Fault control logic
  - Washer safety
  - Safety class B
  - Application state machine
  - Washing algorithm
  - Communication with main control system

# Washers – Vertical Type

## Vertical Washers

- Dominates in US + AP market (non-EU market)
- Variable speed drives
  - PMS motor
- Washers type
  - Top load washers
- Drive construction
  - Direct drive
- Sinusoidal control
  - Higher efficiency
  - Minimum torque ripple
  - Audible noise reduction
  - Max motor torque utilization

- Sensorless speed control
  - Eliminate position sensor
  - Higher reliability
  - Cost reduction

## Pancake PM Motor

- Interior PM features as
  - 3-phase motor
  - Operates from 300VDC bus
  - 20 poles (10 pole pairs)
- Salient Pole Machine
  - Synchronous + Reluctance Torque developed
  - Difference between D-axis inductance (main flux direction) and the rotor Q-axis (main torque producing direction) inductance
    $L_d < L_q$

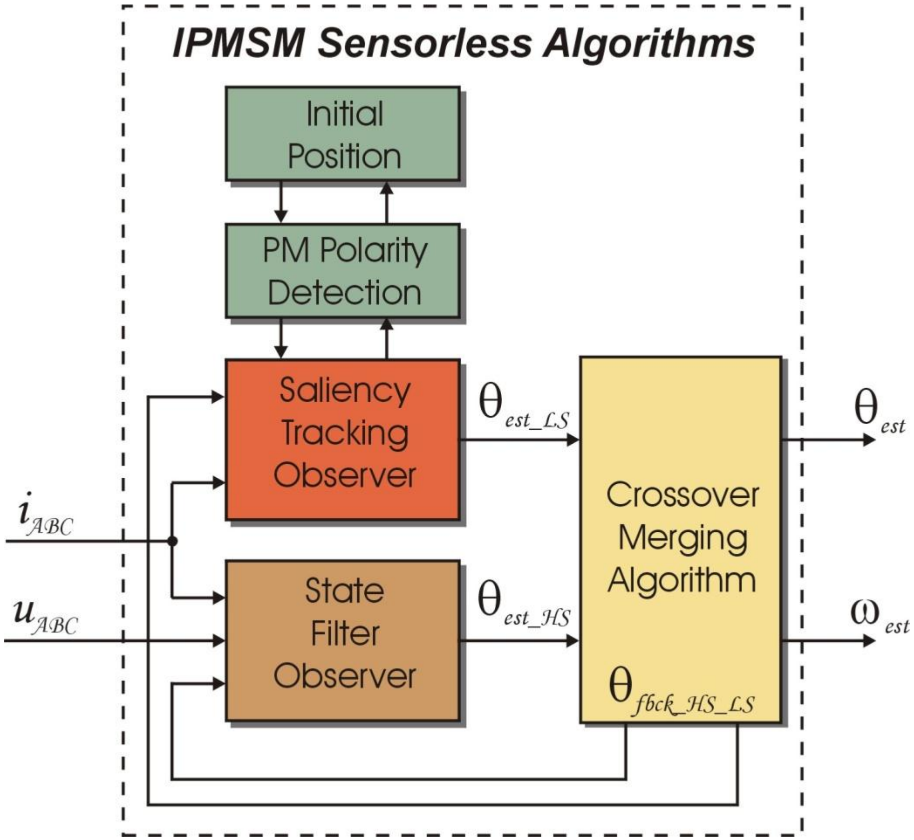
# Washers – Pancake Motor cont’d

# IPMSM Sensorless Algorithms

- **Full Operation Speed Range**
- Covered by two dedicated algorithms

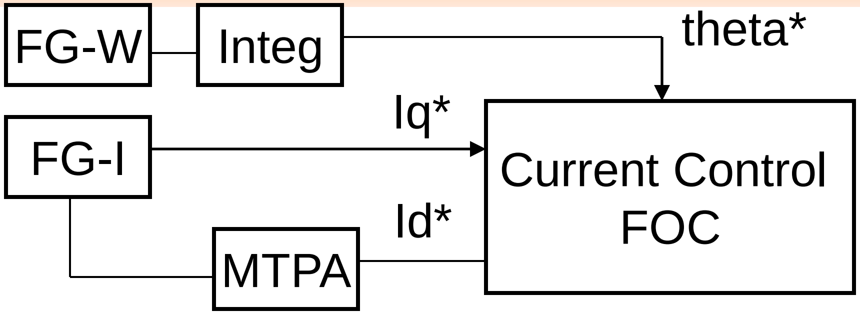
- Crossover Merging Algorithm based on FUZZY logic merges the two algorithm outputs into a single position/speed estimation.

- **Sensorless Algorithms**
- Initial Position Detection
  - avoids conventional alignment
- Low Speed Algorithm
  - saliency tracking observer
- High Speed Algorithm
  - extended back EMF state filter



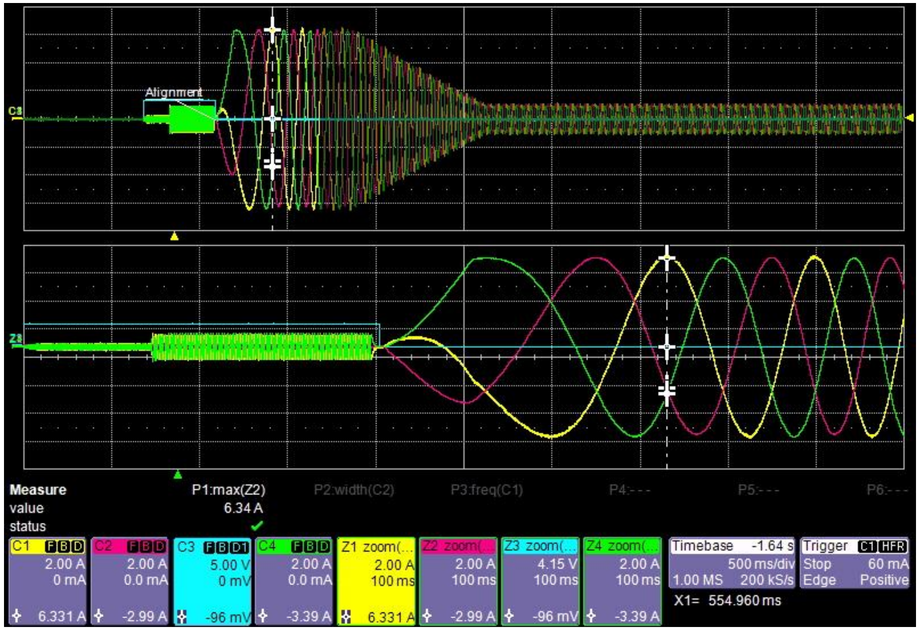
# Open Loop Start Up

- **Starting procedure** differs from V-axis washer
  - No need to operate at low speed (>300[rpm])
  - High start-up torque required to speedup a loaded drum




- Motor accelerated in open loop means NO measured position feedback

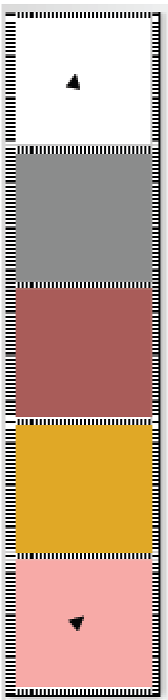
- **FG-I** & **FG-W** carefully chosen in order to assure a safe starting with minimum oscillation up to the maximum torque




- **FG-I –** Current Function Generator
- **FG-W** – Velocity Function Generator
- **MTPA** – Maximum Torque Per Amp
  - applied to improve motor torque capability

## Wash Performance Strips of IEC 60456 Ed.4

EMPA test materials



IEC Cotton, unsoiled, EMPA article 221

IEC Carbon Black / Mineral Oil on Cotton, EMPA article 106

IEC Blood on Cotton, EMPA article 111

IEC Cocoa on Cotton, EMPA article 112

IEC Red Wine on Cotton, EMPA article 114

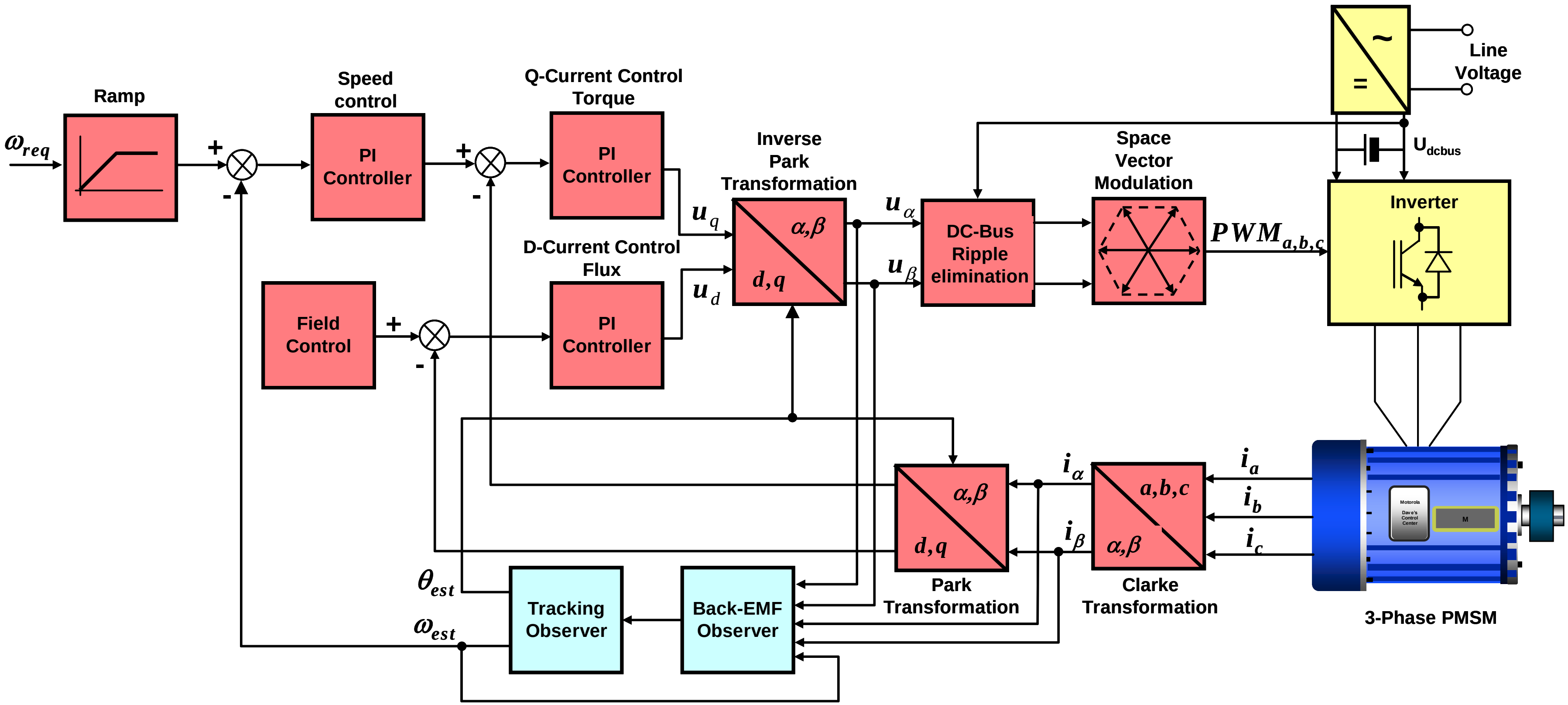
**Each sample is 15 x 15 cm**

# Dishwasher

# Dishwasher Pump

- PMS motor
  - Line voltage of 230 V (Europe)
  - 6 or 8 magnetic poles
  - Nominal power – 80 W
- The water pressure inside the dishwasher is dictated by the physical design of the hydraulic system (pipes, sprinklers, etc.), and can be controlled by varying the speed of the pump
- Mechanical pump speed
  - 1500 rpm up to 3500 rpm
- Water pressure
  - 30 kPa up to 1000 kPa

# Dishwasher Pump Control Algorithm



# Thank you