EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

# Moderní mikropočítače a jejich nasazení v aplikacích s elektrickými pohony a spínanými zdroji

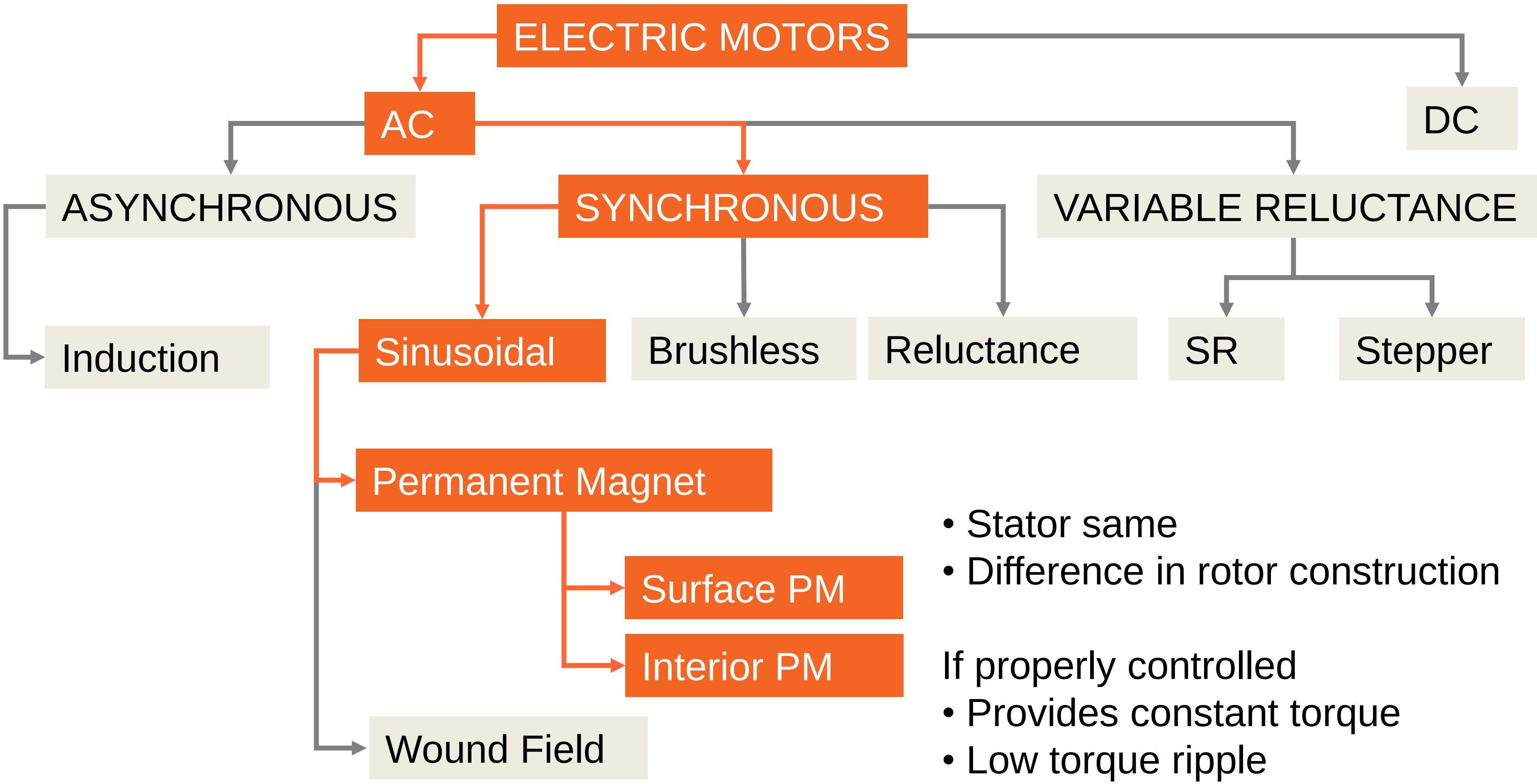
Ing. Jaroslav Lepka

16. prosince 2011

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

# ELECTRIC MOTORS

# Electric Motor Type Classification




- Stator same
- Difference in rotor construction

If properly controlled

- Provides constant torque
- Low torque ripple

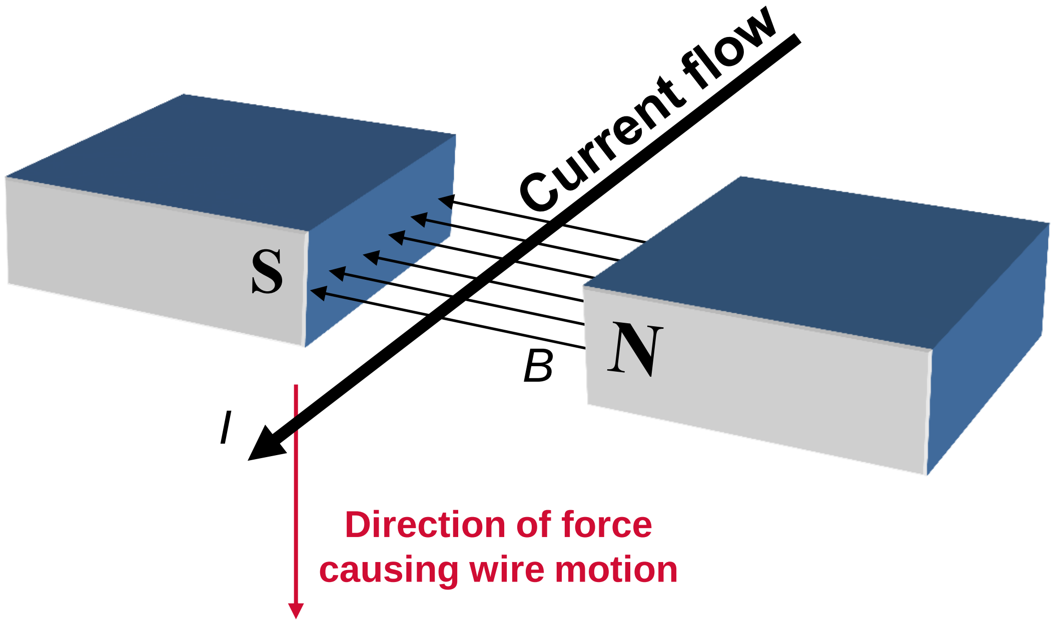
# Electric Motor Type Classification

- DC
  - universal (series)
  - PM
    - brush
    - brushless
- AC
  - polyphase
    - synchronous
      - Excit. winding
      - PM
    - induction
  - single ph.
    - synchronous
    - induction
      - split phase
      - shaded pole
      - capacitor run
      - capac. start
    - universal (series)

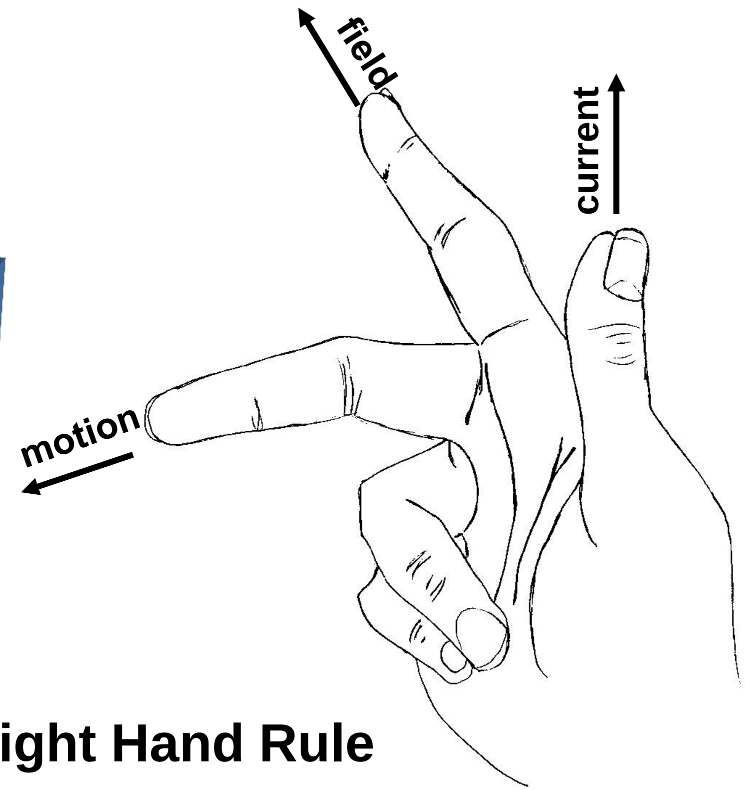
Stepper & Switched Reluctance

# 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”



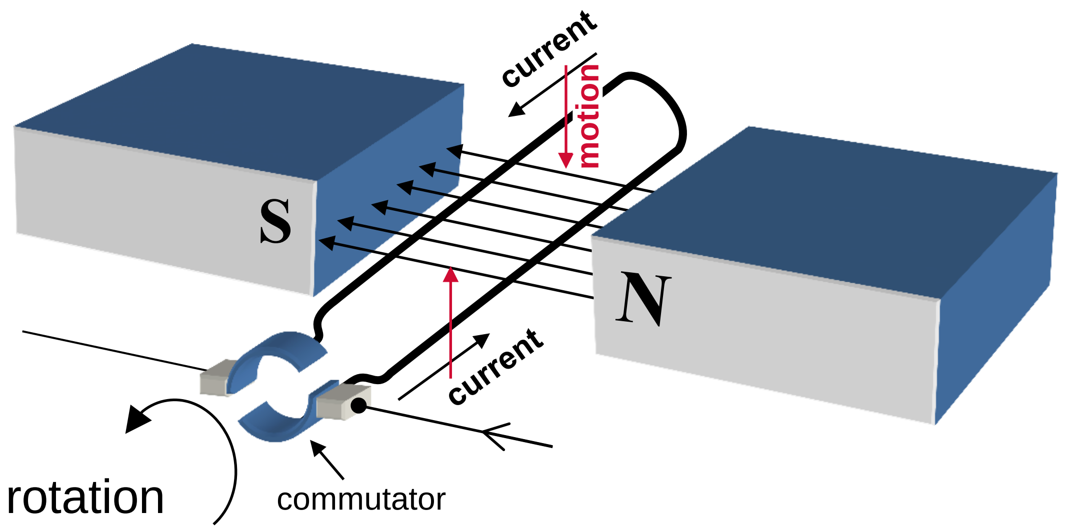

$$F = I.B.l.\sin\theta$$

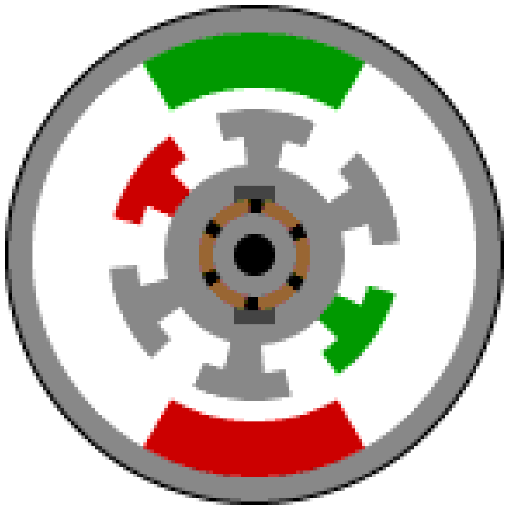



**Right Hand Rule**

# 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°.



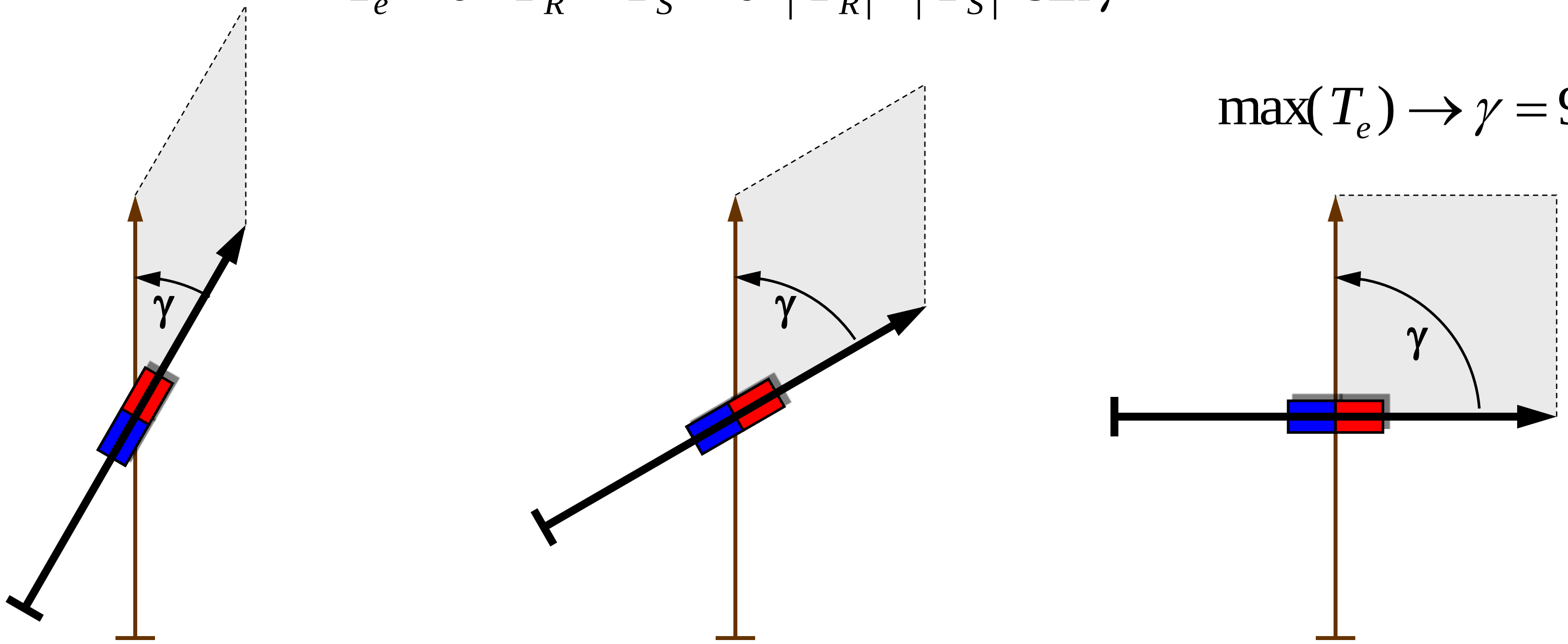



"Mechanical" FOC

# Torque Production Principle

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

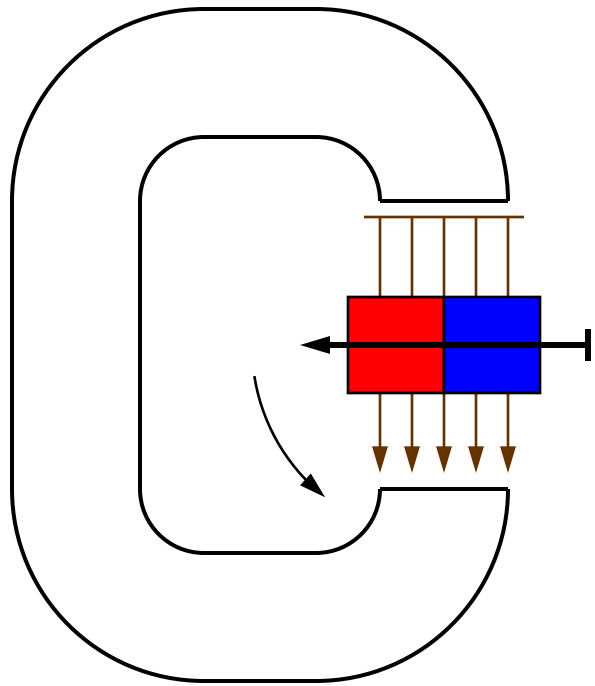
$$T_e = c \cdot \Psi_R \times \Psi_S = c \cdot |\Psi_R| \times |\Psi_S| \cdot \sin\gamma$$




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

# 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

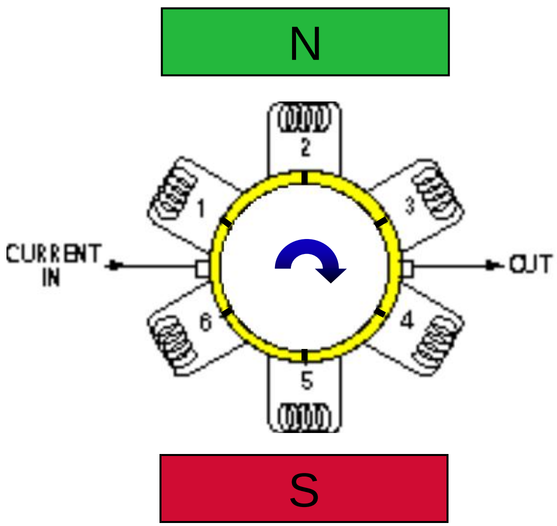


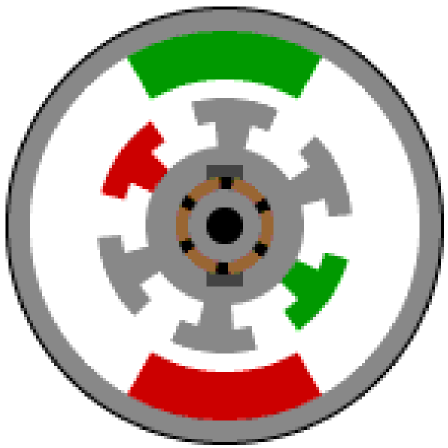
FOC IS SO SIMPLE

# DC MOTOR

# Brush DC Motor Principle

- Brush DC motor commutation

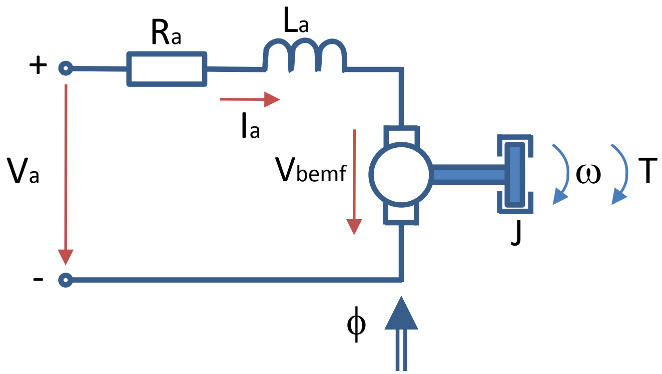


**Rotor flux is perpendicular to stator regardless of rotor position**

Commutator performs mechanical "Vector" Control

# Separately Excited DC Motor




**Equation describing dynamics of electric circuit**

$$V_a = R_a \cdot I_a + L_a \cdot \frac{dI_a}{dt} + V_{bemf}$$

**State equations – motor dynamics**

$$\frac{dI_a}{dt} = \frac{1}{L_a} \cdot \left(V_a - R_a \cdot I_a - V_{bemf}\right)$$

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot \left(T - T_L\right)$$

**Steady state operation**

$$V_a = R_a \cdot I_a + V_{bemf}$$

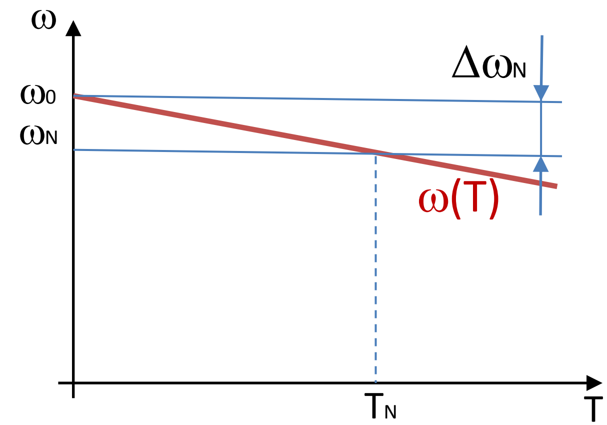
$$\omega = \frac{V_a}{c \cdot \phi} - \frac{R_a}{(c \cdot \phi)^2} \cdot T$$

$$\omega_{0N} = \frac{V_{aN}}{c \cdot \phi}$$

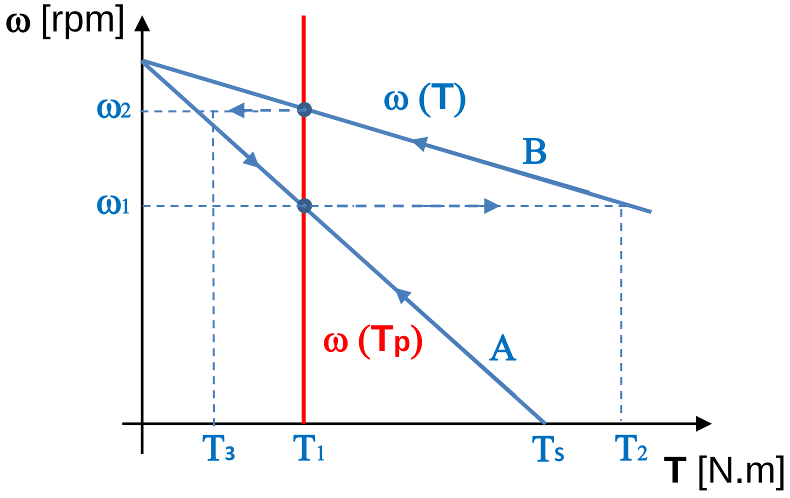
$$\Delta\omega_N = \frac{R_a}{(c \cdot \phi)^2} \cdot T$$

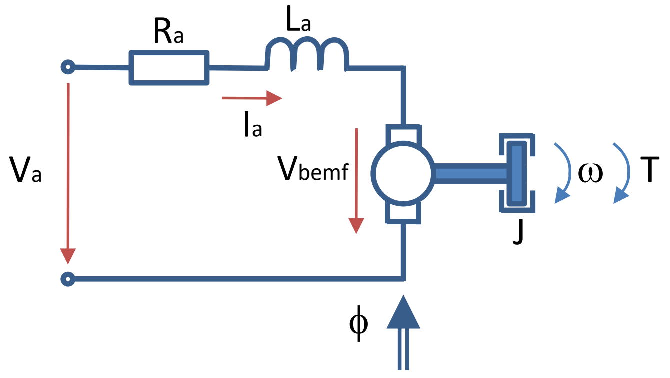
$$V_{bemf} = c \cdot \phi \cdot \omega$$

$$T = c \cdot \phi \cdot I_a$$



# Operational Characteristic of the Drive




$$\omega = \frac{V_a}{c \cdot \phi} - \frac{R_a}{(c \cdot \phi)^2} \cdot T$$

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot (T - T_L)$$

$$\omega_{0N} = \frac{V_{aN}}{c \cdot \phi}$$

# Operational Characteristic of the Drive

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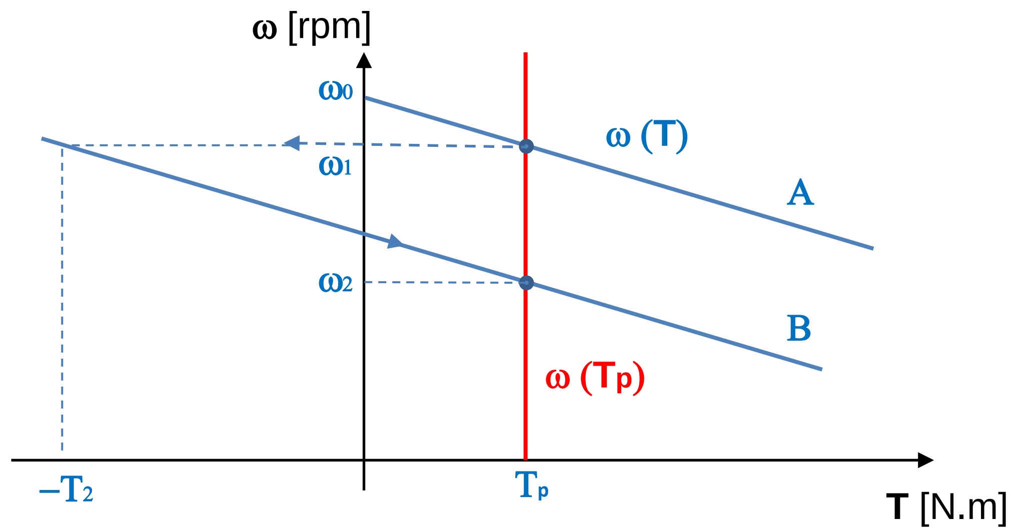
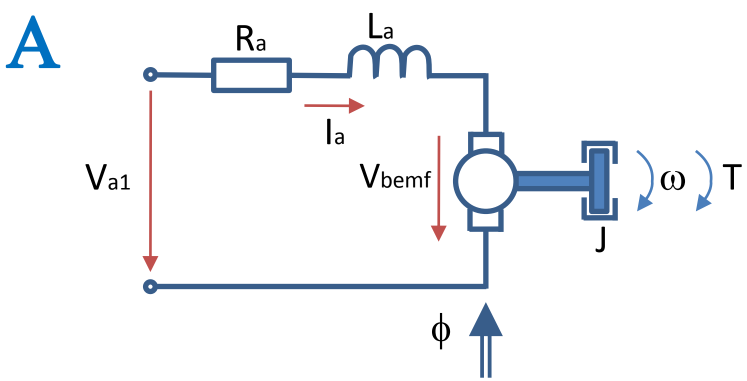
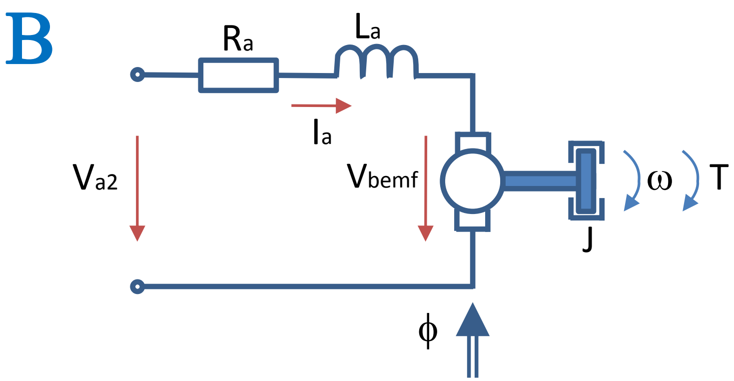
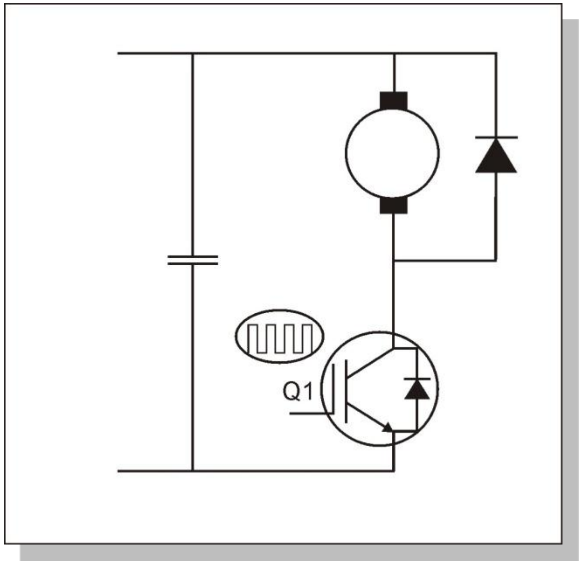


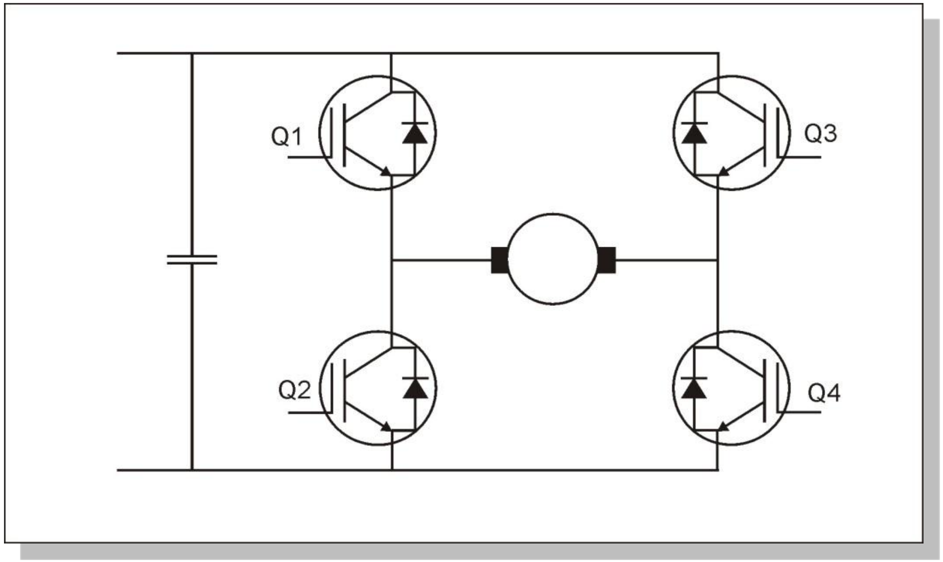



# Brush DC Motor Principle

- Brush DC motor control



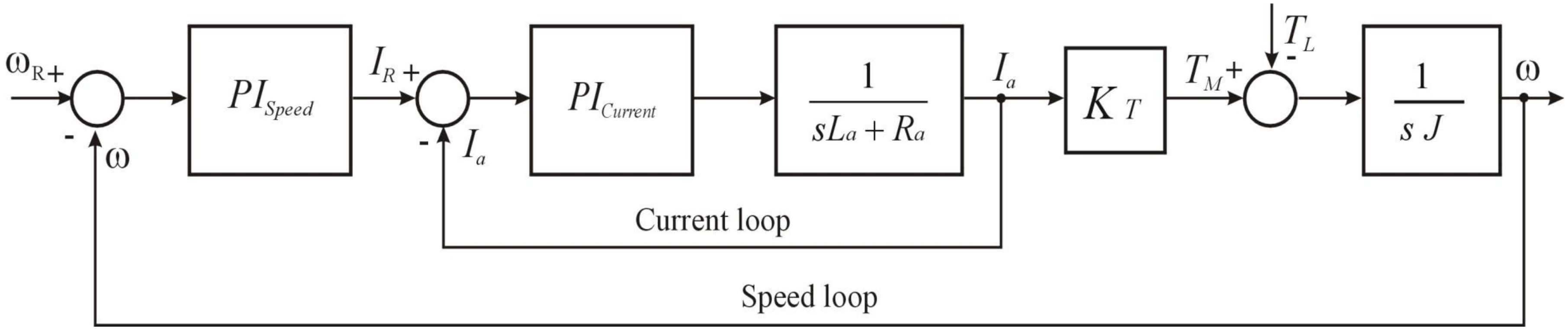

Single quadrant operation




2 & 4 quadrant operation

# Brush DC Motor Speed & Torque/Current Control

- Two control loops
  - Outer control loop – speed control loop
  - Inner control loop – torque/current control loop

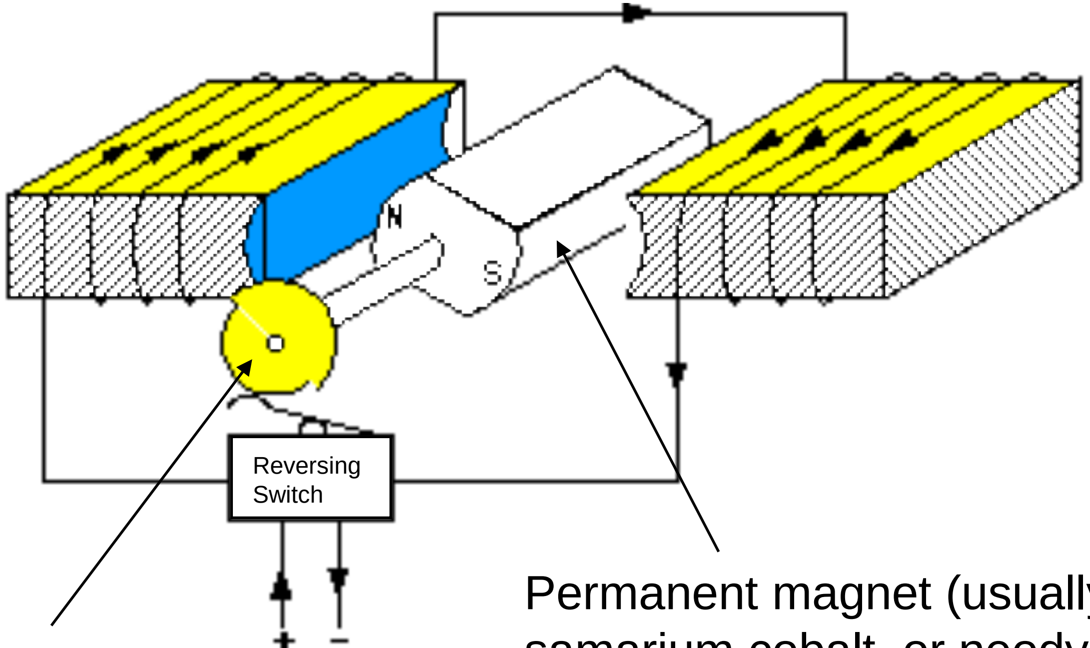


# Brush DC Motor

- **Advantages**
  - Ease to control (self commutating).
  - Lowest rotor inertia (coreless rotors).
  - Lowest total system cost for basic motion.
  - Wound field motors exhibit high starting torque, (series wound) and can run with AC or DC.
- **Drawbacks**
  - Higher maintenance cost due to brush wear.
  - Electrical noise due to mechanical commutation.
  - Maximal speed limited by commutator
  - Heat is generated in armature, which is difficult to remove
  - Friction losses associated with mechanical commutation.
  - Not usable in “intrinsically safe” environments.

# BLDC (BRUSHLESS DC) MOTOR

# Brushless DC Motors – Basic Structure

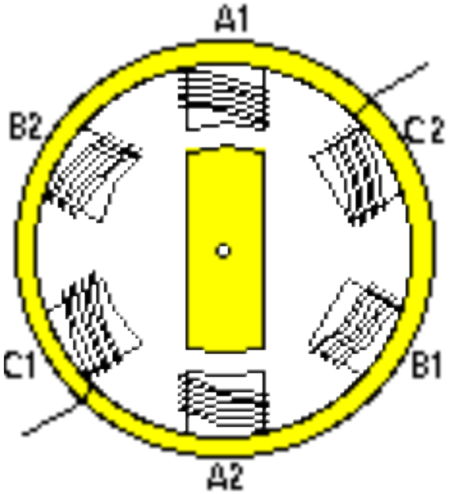


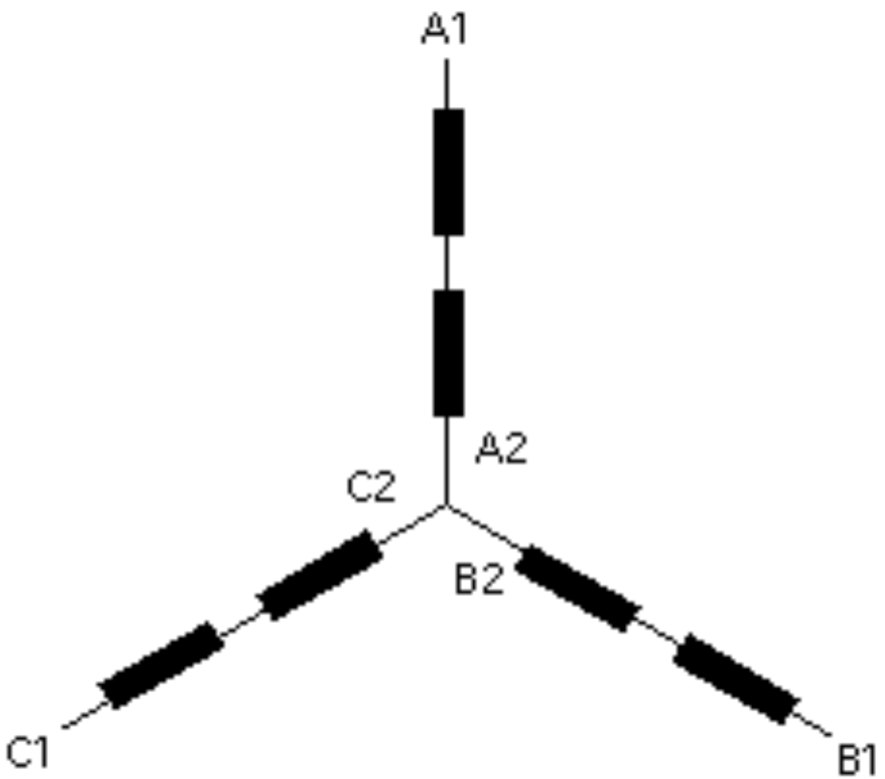

Permanent magnet (usually ferrite, samarium cobalt, or neodymium iron boron)

Requires mechanism to sense rotor position to commutate field properly

This is usually a hall effect sensor array or an encoder

# 3-Phase Brushless DC Motor



# Brushless DC Motor Principle

- Brushless DC motor rotation

  - BLDC motor rotates because of the magnetic attraction between the poles of the rotor and the opposite poles of the stator.
  - If the rotor poles are facing poles of the *opposite* polarity on the stator, a strong magnetic attraction is set up between them.
  - The mutual attraction locks the rotor and stator poles together, and the rotor is literally yanked into step with the revolving stator magnetic field.

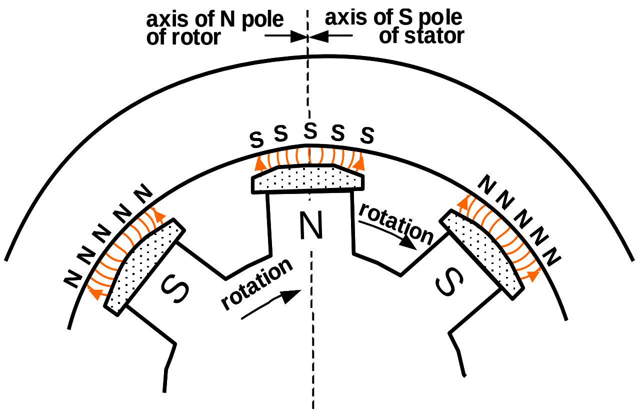



Figure 1- No-load condition

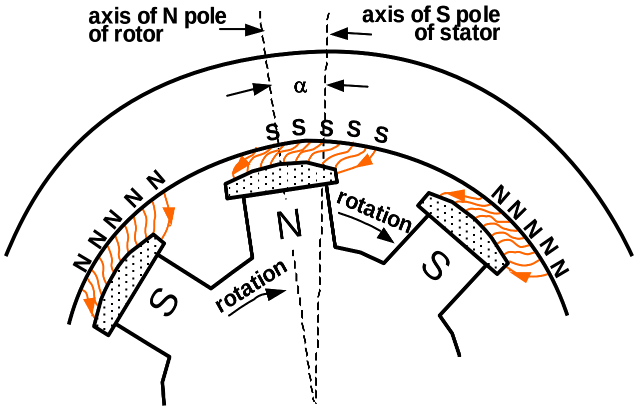
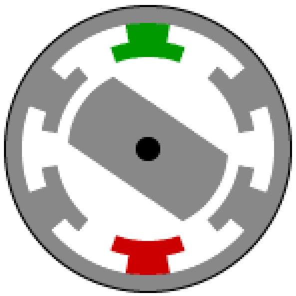
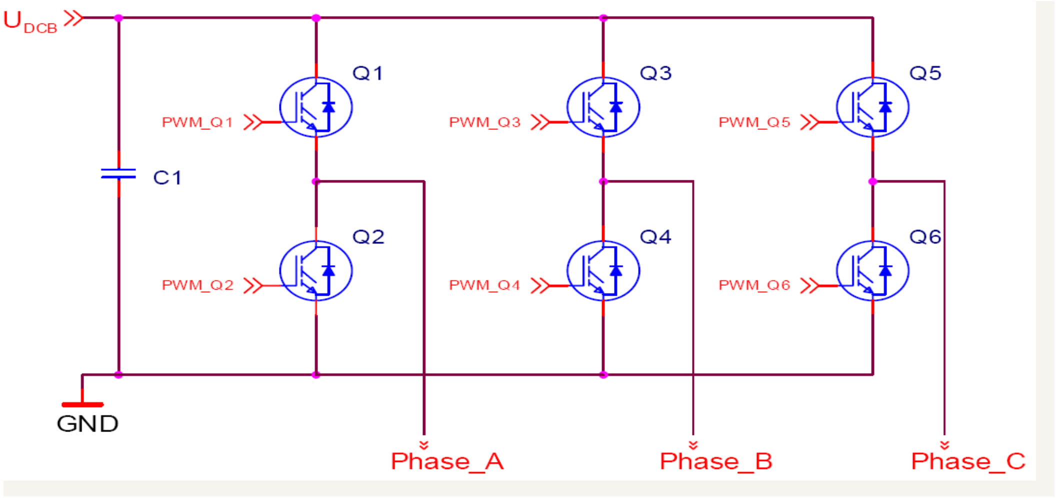



Figure 2- Load condition



# Brushless DC Motor Control

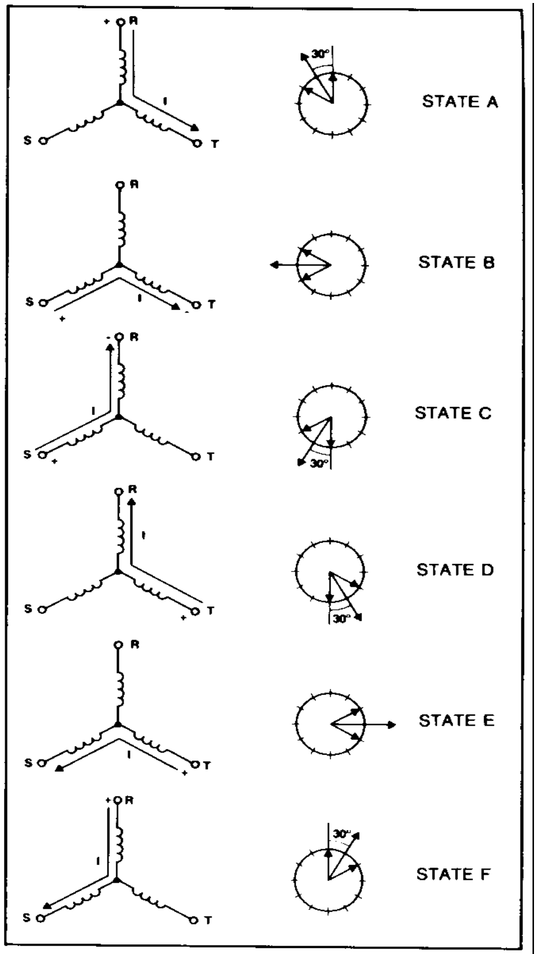
- Six Step BLDC Motor Control
  - Voltage applied on two phases only




*Power Stage*

# Commutation of a Brushless DC Motor

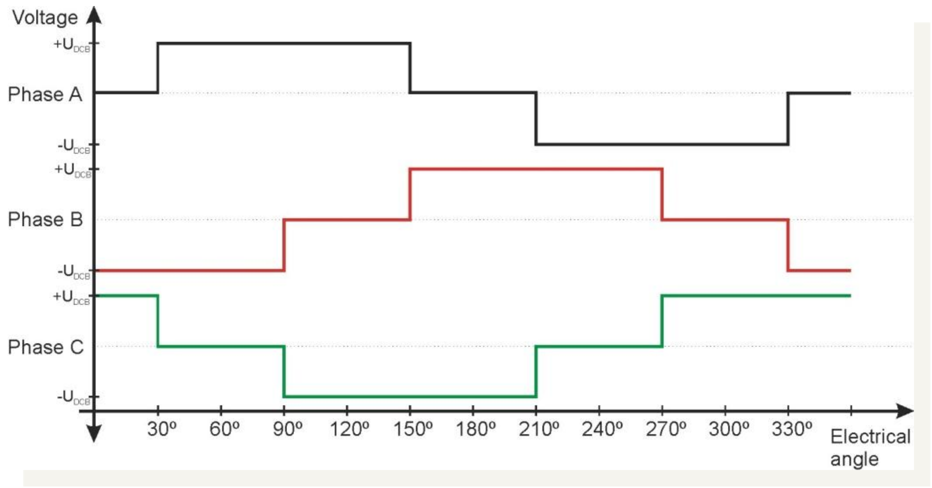
One phase is always unpowered at any given time



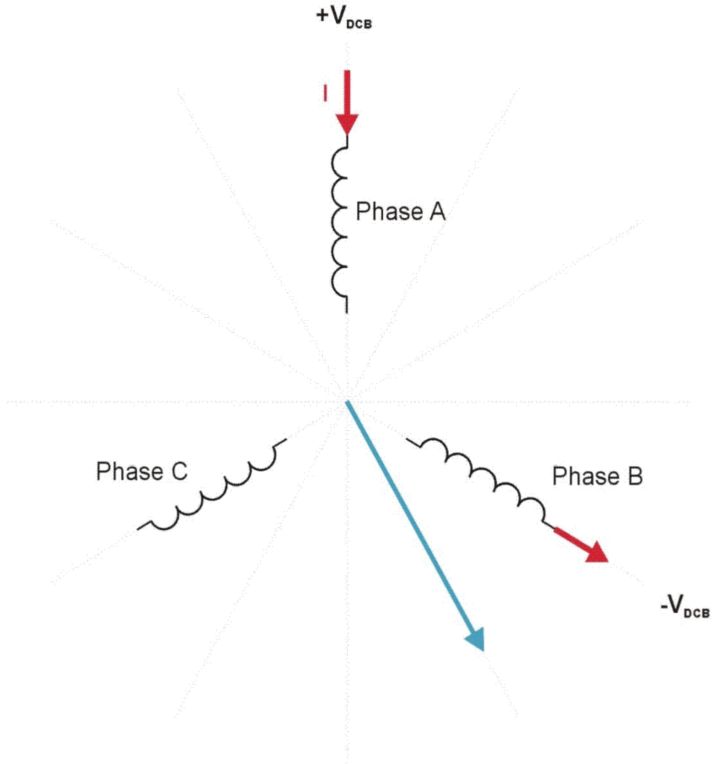
Commutation Sequence.

# Brushless DC Motor Control

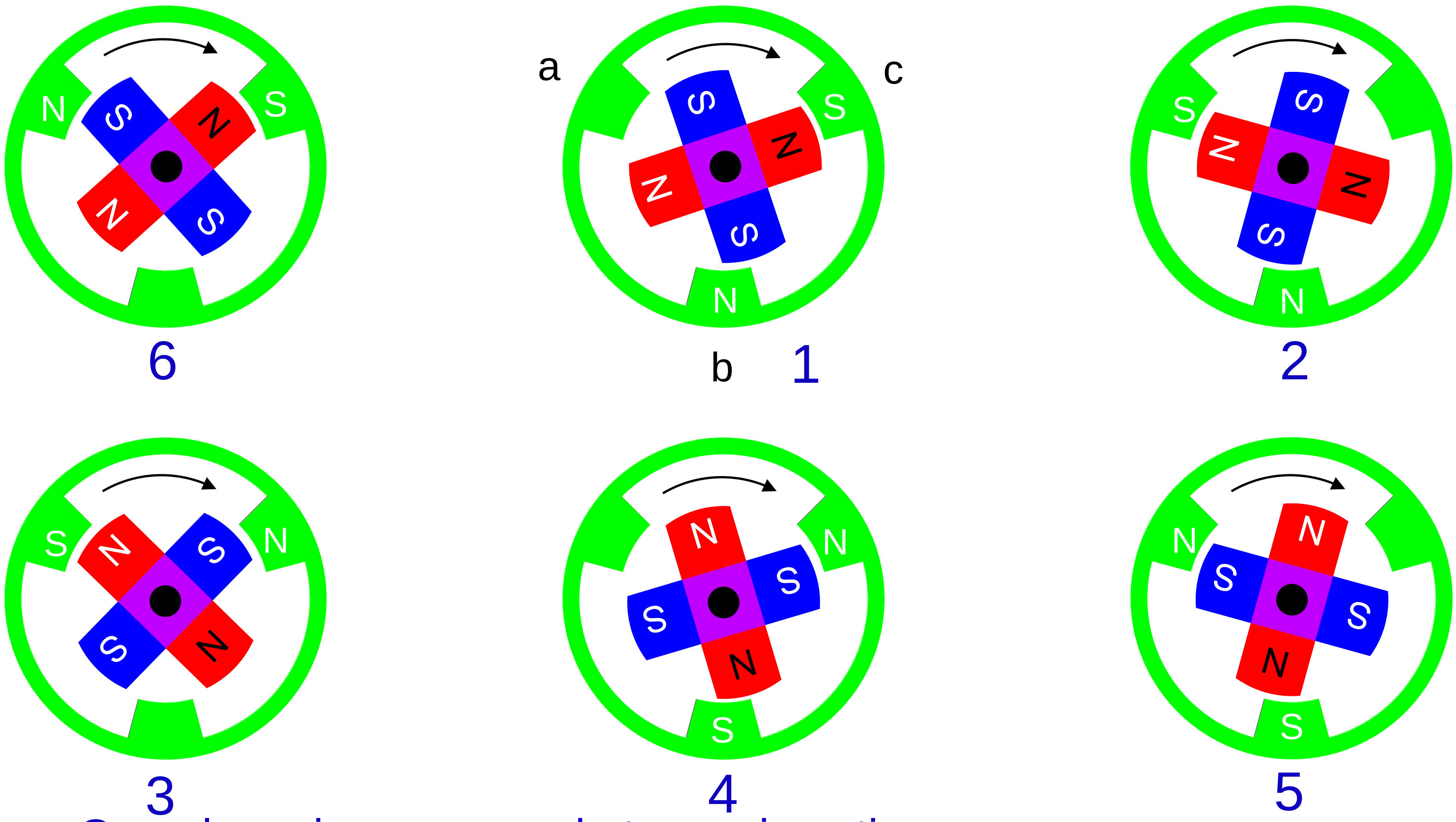
- Six Step BLDC Motor Control
  - Voltage applied on two phases only
  - It creates 6 flux vectors
  - Phases are power based on rotor position
  - The process is called Commutation




*Phase voltages*



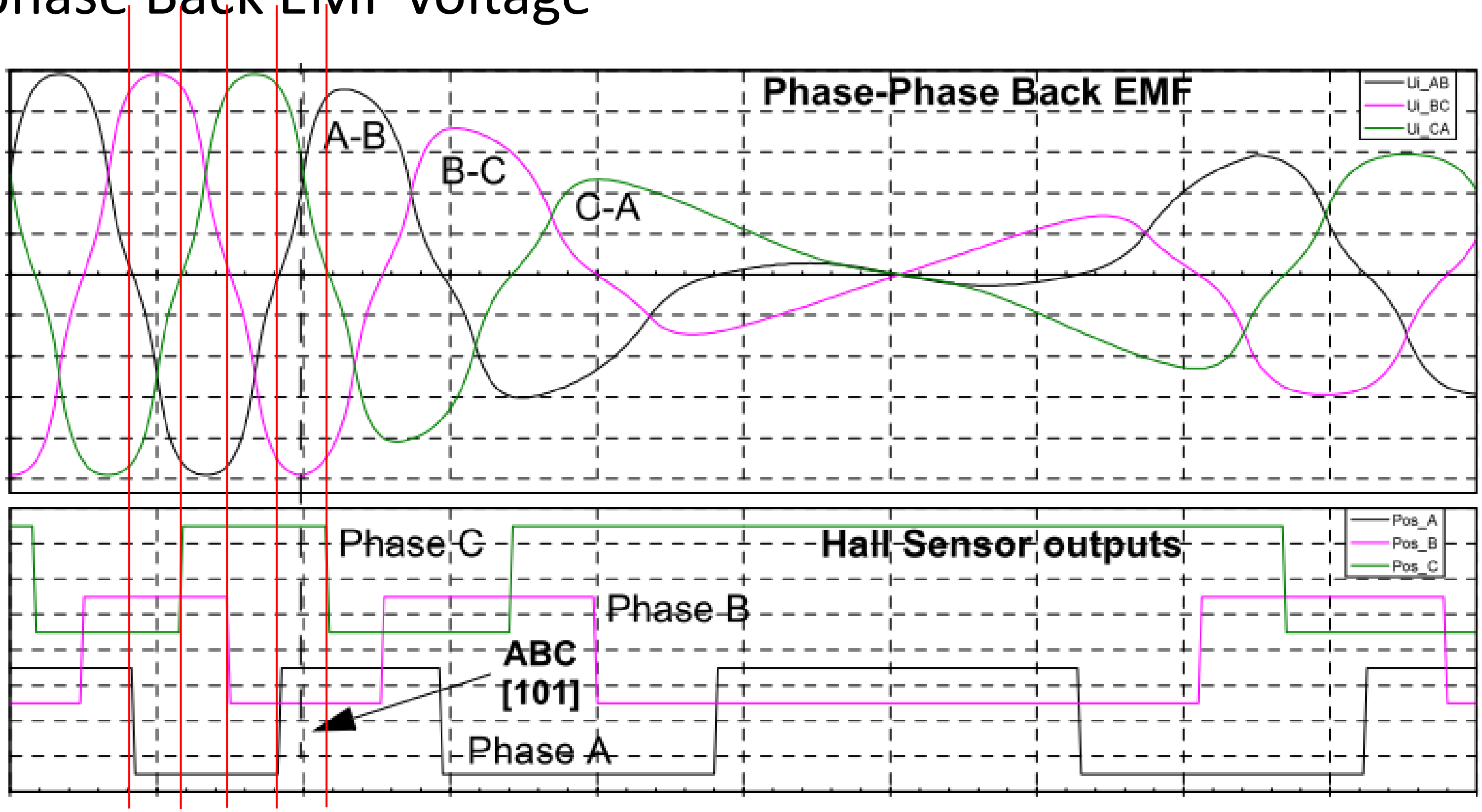
# Commutation of a Brushless DC Motor




One phase is unpowered at any given time.

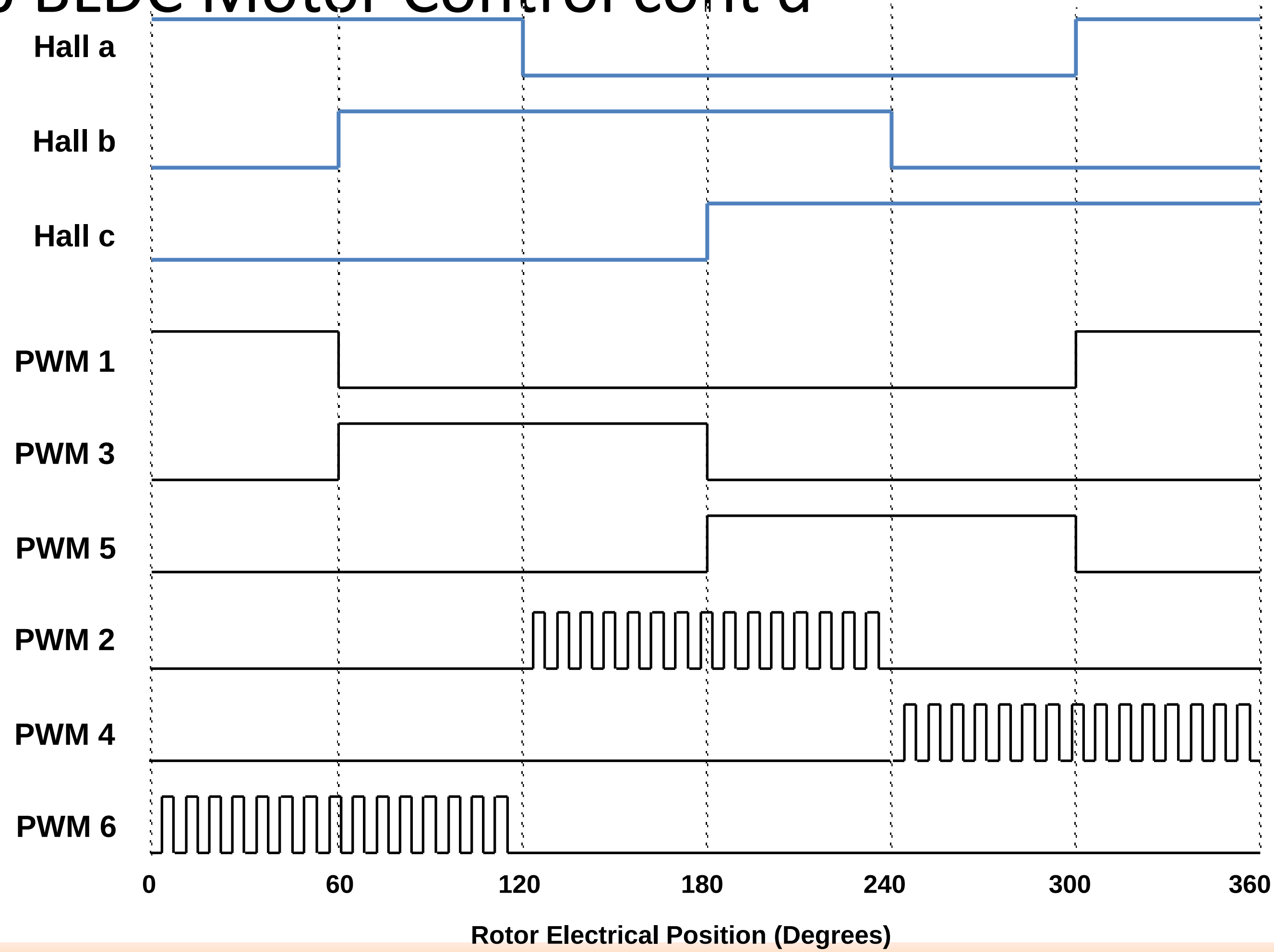
# Commutation Table

- Hall Sensors sense rotor flux and are aligned to phase to phase Back EMF voltage



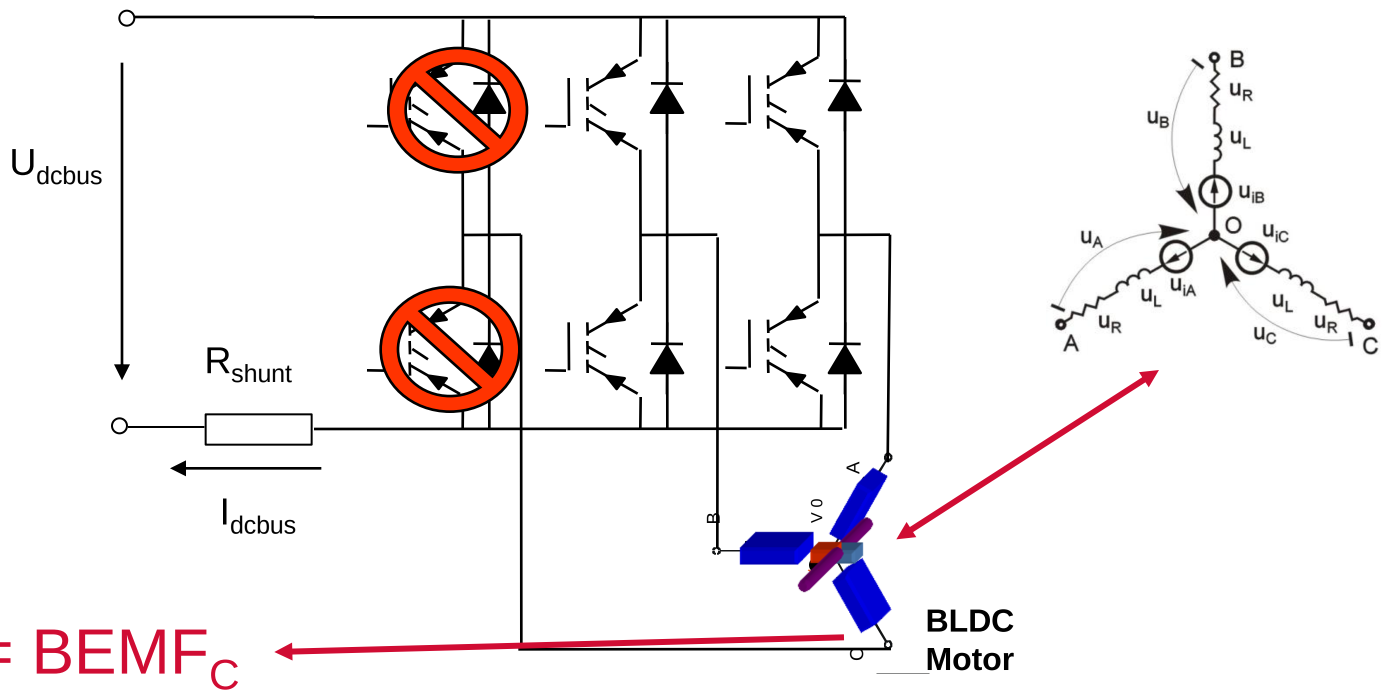
# Brushless DC Motor Control

- Six Step BLDC Motor Control cont'd



# BEMF Voltage Zero Crossing Sensing Condition

1. The measured phase is disconnected from power source
2. There is no current flowing through measured phase



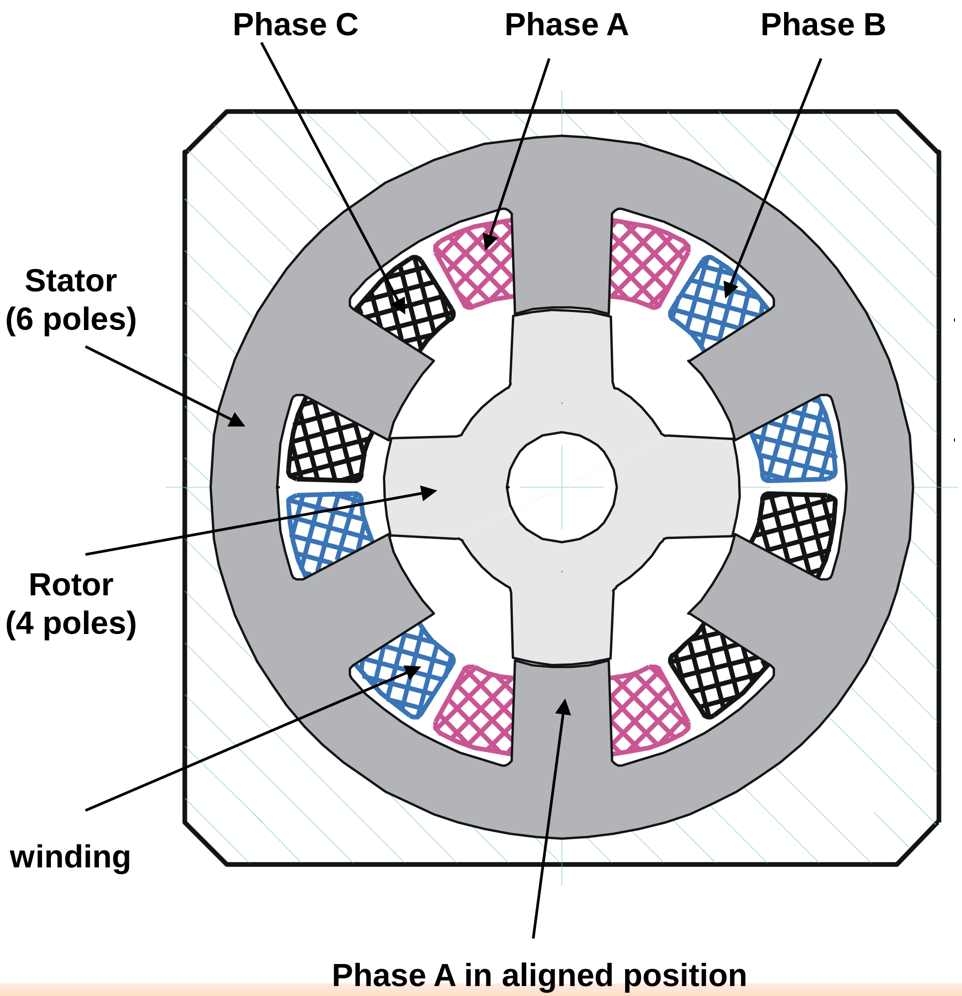

$U_C = BEMF_C$

# BLDC Motor

- **Advantages**
  - Heat is generated in stator:  easy to remove
  - High torque per frame size
  - Reliability due to absence of brushes and commutator
  - Highest efficiency.  Renewed interest for “white goods”
  - Synchronous operation makes field orientation easy
  - Good high speed performance (no brush losses)
  - Precise speed monitoring and regulation possible
- **Drawbacks**
  - Rotor position sensing required for commutation.
  - Torque ripple
  - Position sensor or sensorless technique is required for motor operation
  - Difficult to startup the motor using sensorless technique

# SR (SWITCHED RELUCTANCE) MOTOR

# 3-Phase SR Motor
## (6 stator / 4 rotor poles)

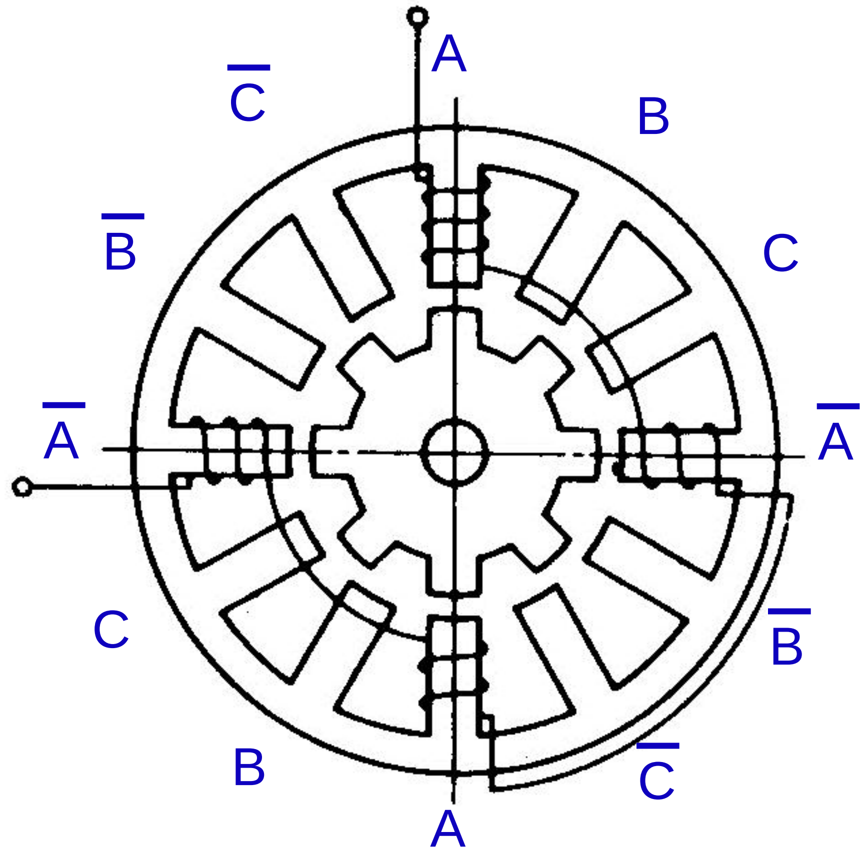



- Low-cost machine
- Both stator and rotor have salient poles
- Winding on stator
- Characterized by magnetization characteristic $\Psi(i, \theta)$
- Inductance profile linked with rotor position
- Requires position information for phases commutation

- Suitable stator/rotor poles ratio configuration (the higher number of phases, the lower torque ripple):
  - 2-phase: 4/2
  - 3-phase: 3/2, 6/2, 6/4, 6/8, 12/8, 2/10, 24/32
  - 4-phase: 8/6
  - 5-phase: 10/8
  - 7-phase: 14/12

# 3-Phase SR Motor

## (12 stator / 8 rotor poles)

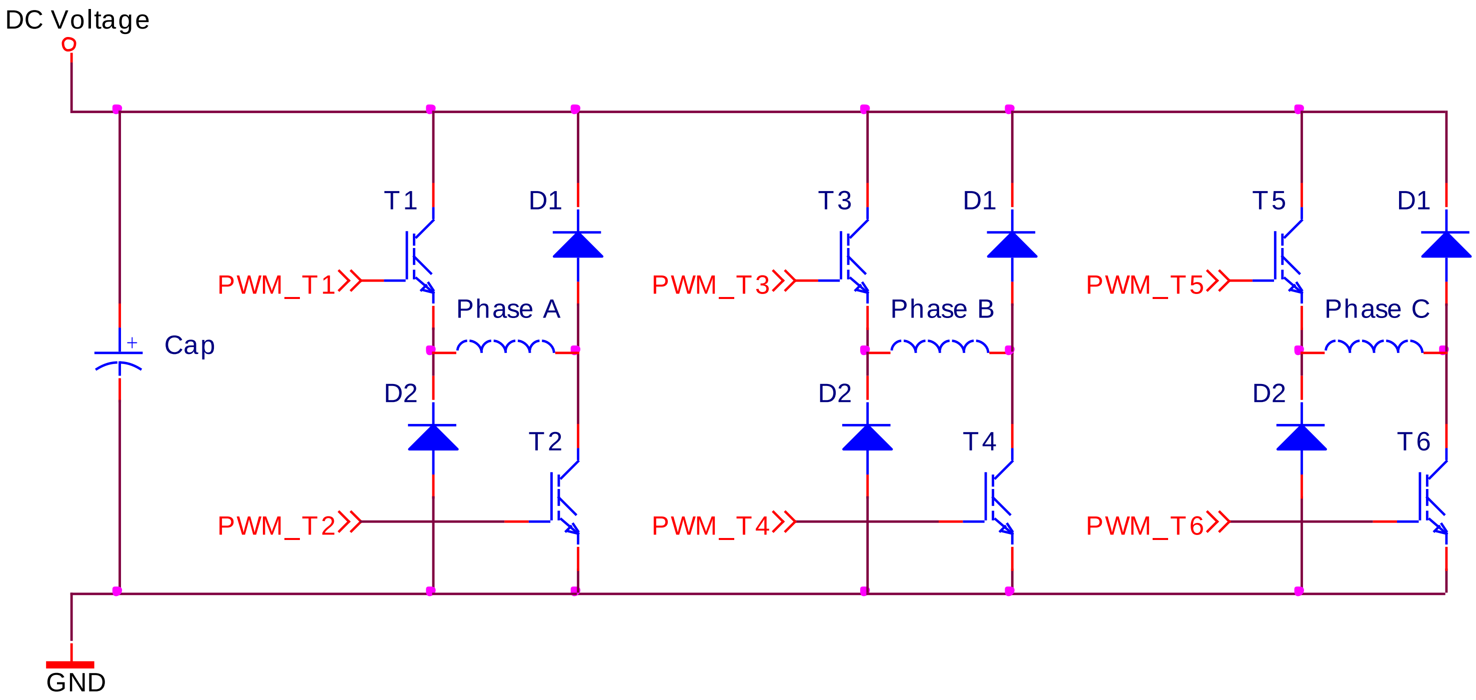



Variable-reluctance stepping motor

**No permanent magnets in stator or rotor**

# SR Motor - Control Electronic

## 3-Phase SR Power Stage

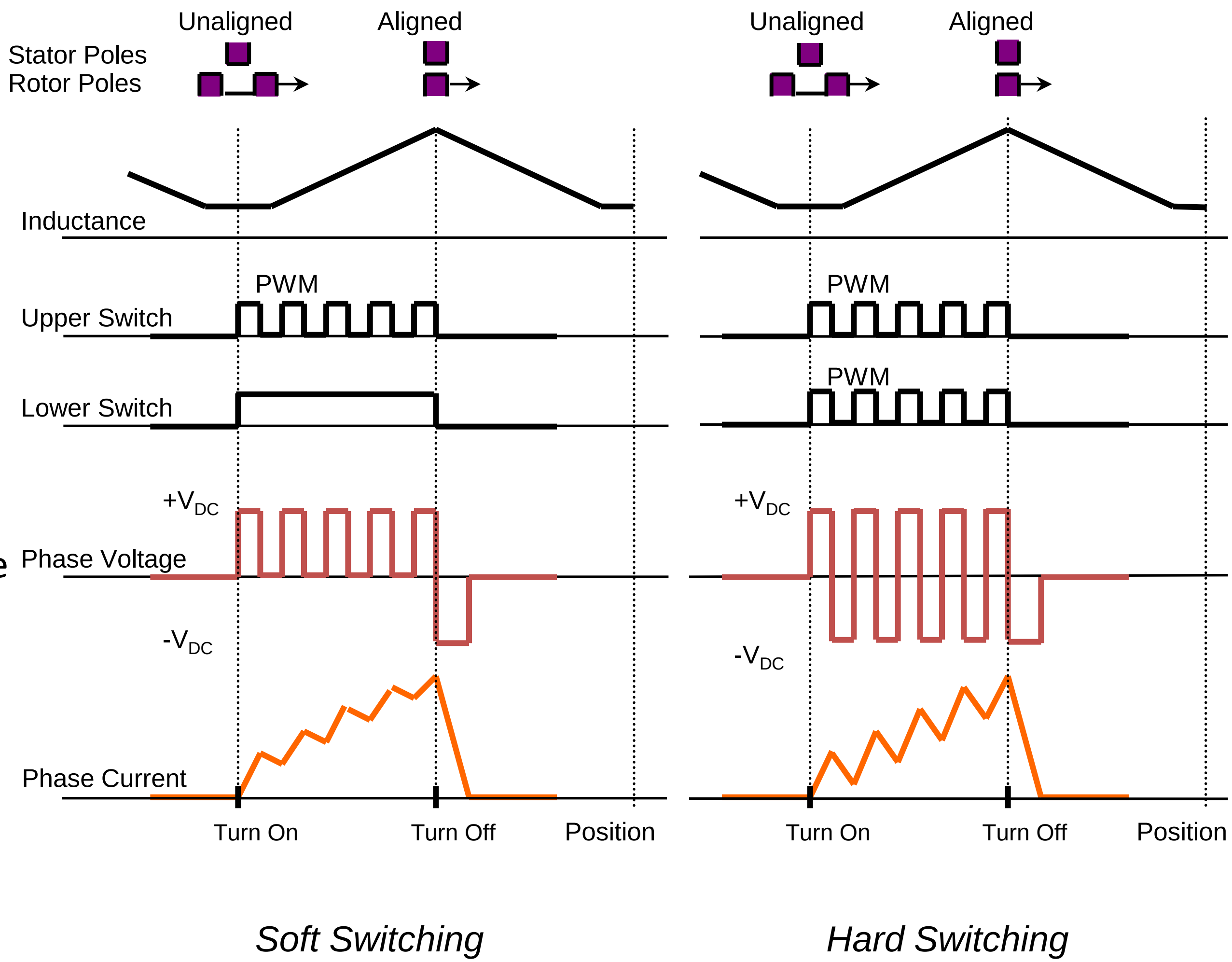



- Configuration: two switches per phase
- Full independent control of individual phases

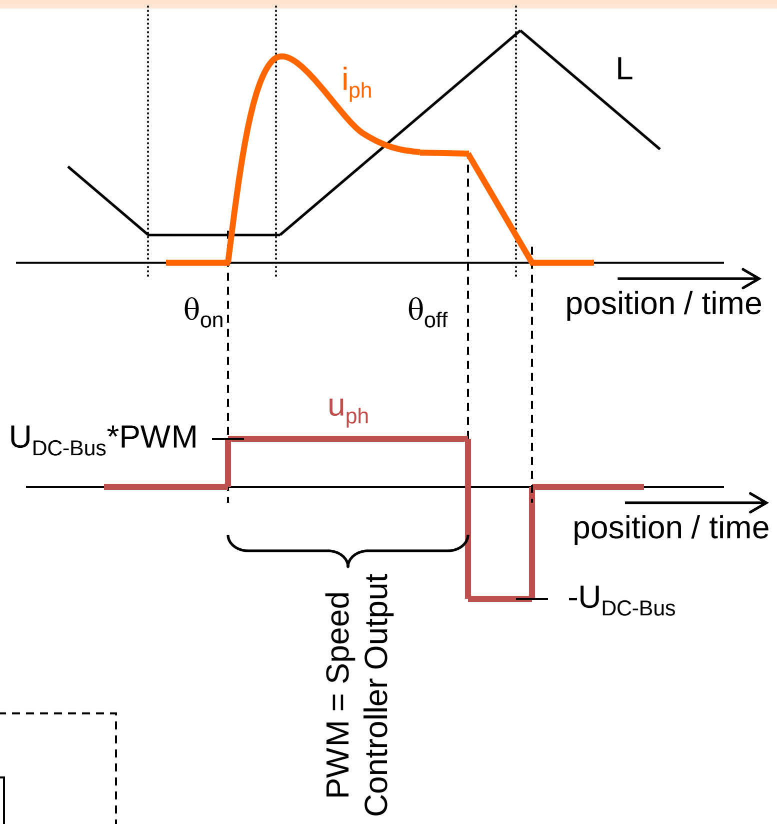
# SR Motor - Switching Technique

## Soft Switching, Hard Switching

- **Soft switching**
  - low current ripple
  - motoring mode
- **Hard switching**
  - high current ripple
  - generator mode

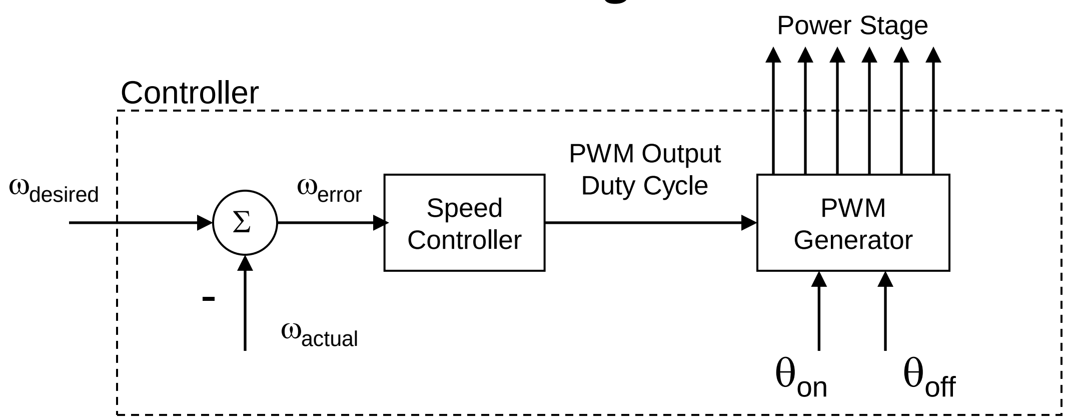


# SR Motor - Voltage Control



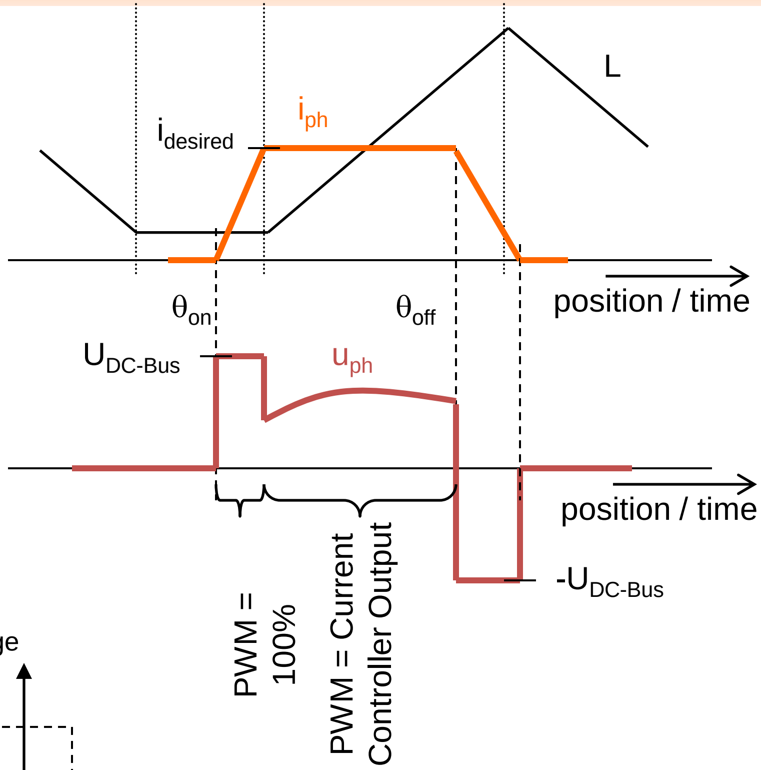

- Output voltage is controlled by the speed controller
- Output voltage is constant during the stroke

## *Block Diagram*

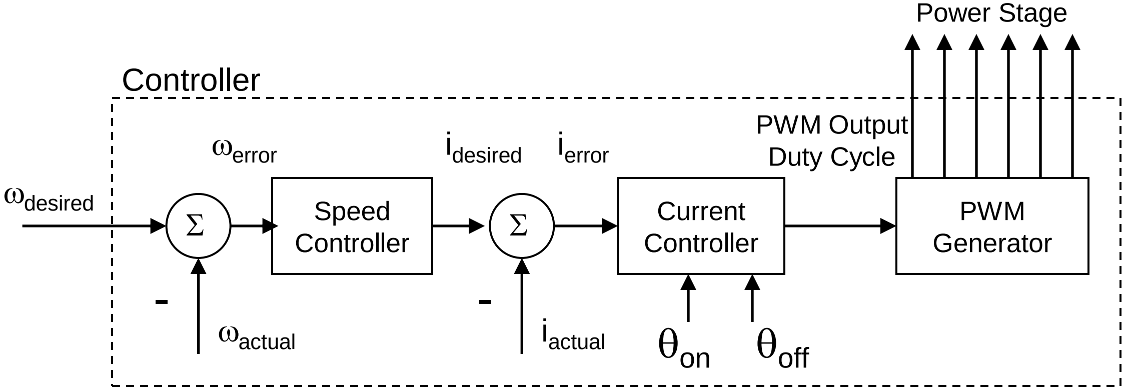


# SR Motor - Current Control

- Speed controller generates desired current
- Output voltage is controlled by current controller



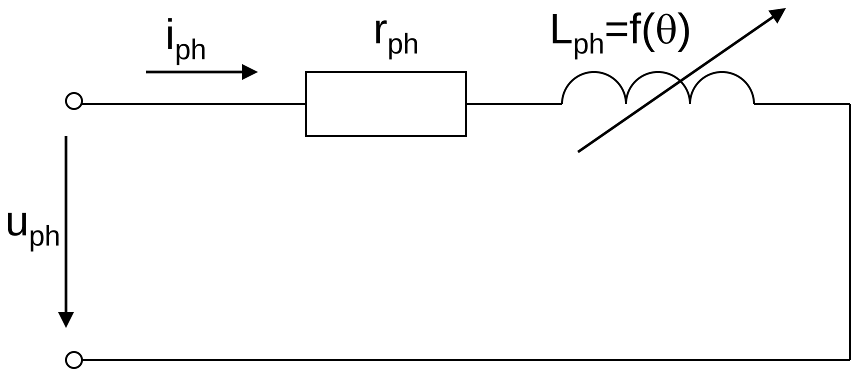

## *Block Diagram*



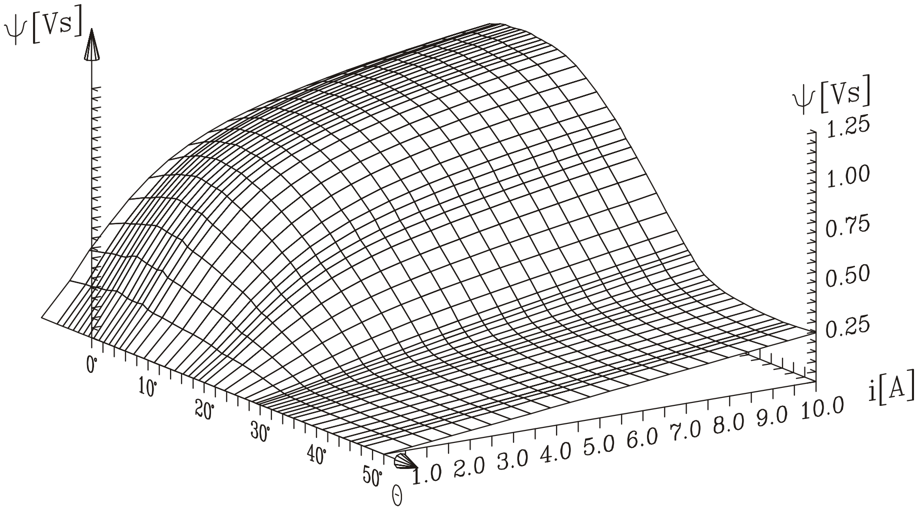
# Mathematical Description of SR Motor

## Electrical Circuit

*Electrical diagram of one motor phase*




*Magnetization characteristic* $\Psi_{ph}(I_{ph}, \theta_{ph})$




$$u_{ph}(t) = r_{ph} \cdot i_{ph}(t) + u_{Lph}(t)$$

$$u_{Lph}(t) = \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{dt} = \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{di_{ph}} \cdot \frac{di_{ph}}{dt} + \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{d\theta_{ph}} \cdot \frac{d\theta_{ph}}{dt}$$

# Mathematical Description of SR Motor (4)

Phase voltage:

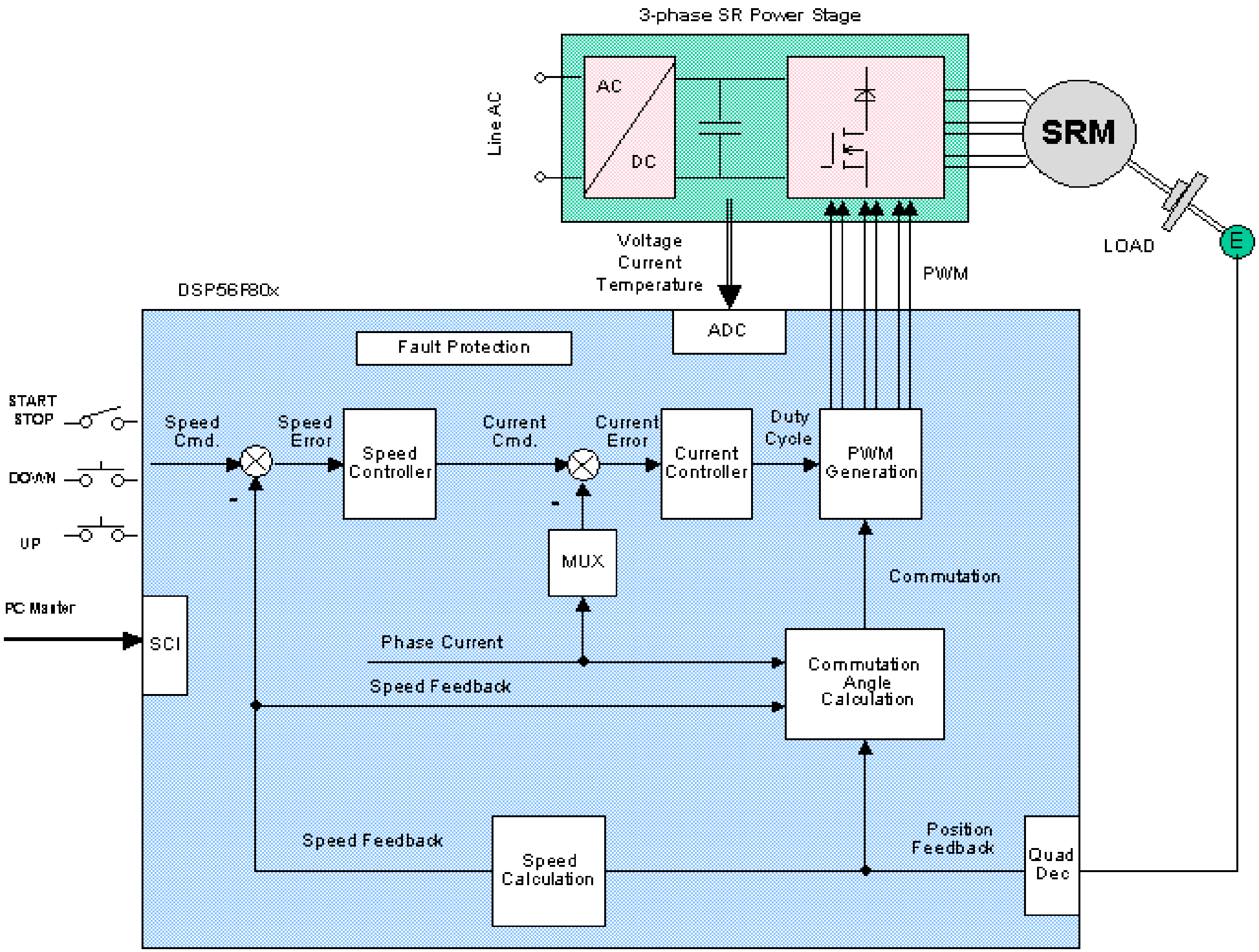
$$u_{ph}(t) = r_{ph} \cdot i_{ph}(t) + \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{dt}$$

$$u_{ph}(t) = r_{ph} \cdot i_{ph}(t) + \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{di_{ph}} \cdot \frac{di_{ph}}{dt} + \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{d\theta_{ph}} \cdot \frac{d\theta_{ph}}{dt}$$

Torque generated by one phase:

$$M_{ph} = \int_{0}^{i_{ph}} \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{d\theta_{ph}} di$$

# SR Motor – Application Concept



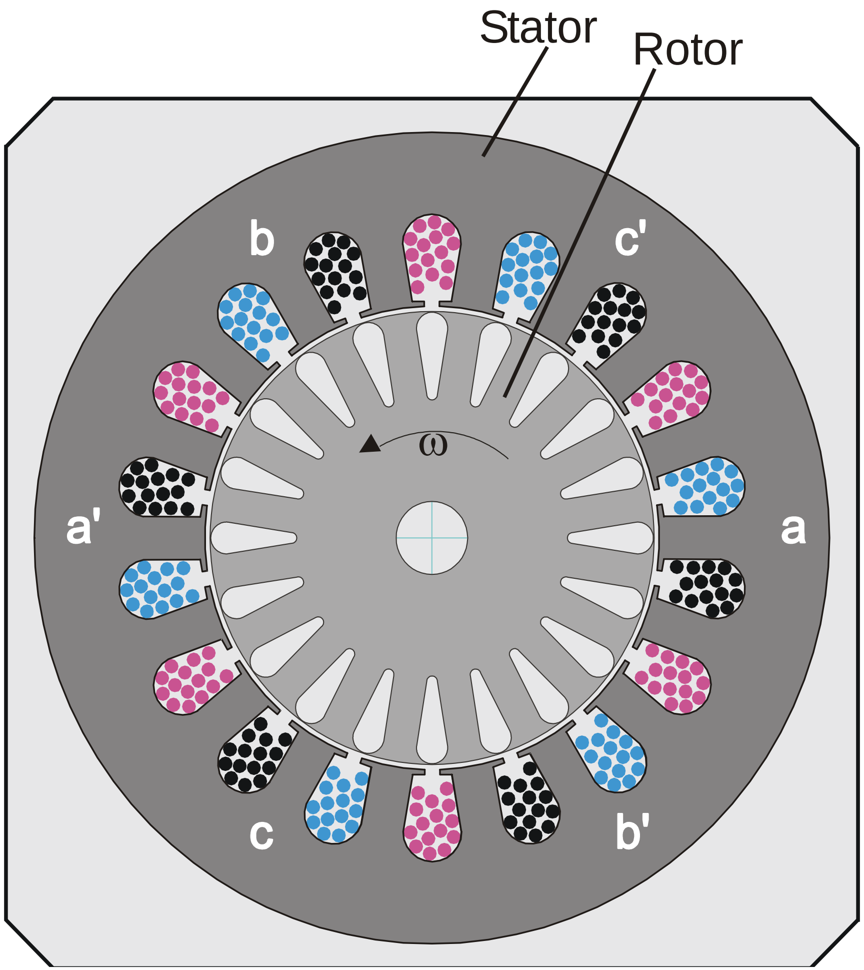
# SR Motor

- **Advantages**
  - Low cost resulting from simple construction
  - High reliability
  - High fault tolerance
  - Heat is generated in stator:  easy to remove
  - High speed operation possible
- **Drawbacks**
  - Acoustically noisy
  - High vibration
  - Magnetic nonlinearities make smooth torque control difficult
  - Dependent on electronic control for operation

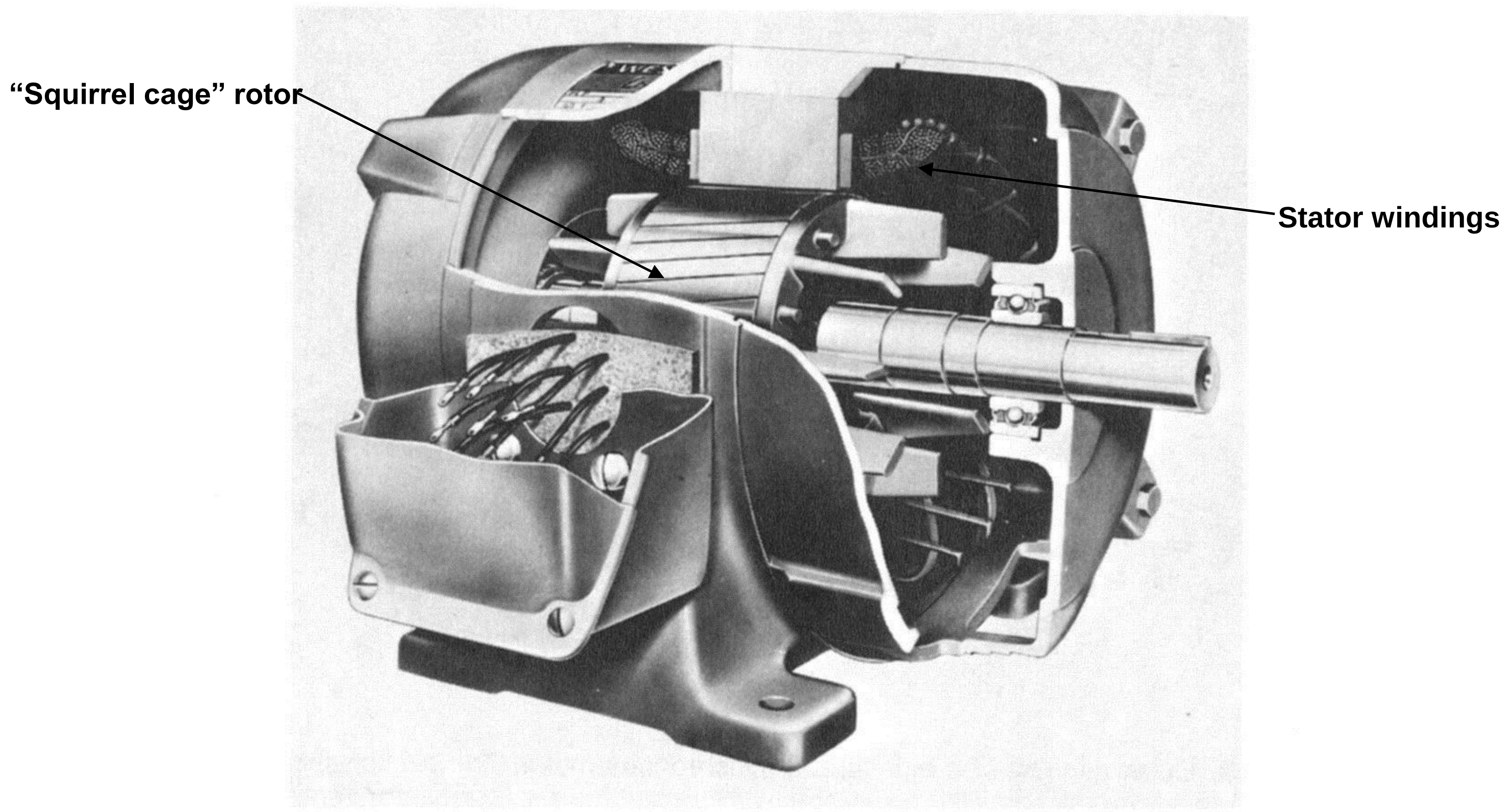
# AC INDUCTION MOTOR – ACIM (ASYNCHRONOUS)

# ACIM Basics

- AC Induction Motor
  - **Fed from 3-ph source of the alternating voltage to the stator**
  - **Simple squirrel cage rotor, no brushes, no permanent magnets**
  - **Speed control requires varying stator frequency**
  - **Low maintenance cost**



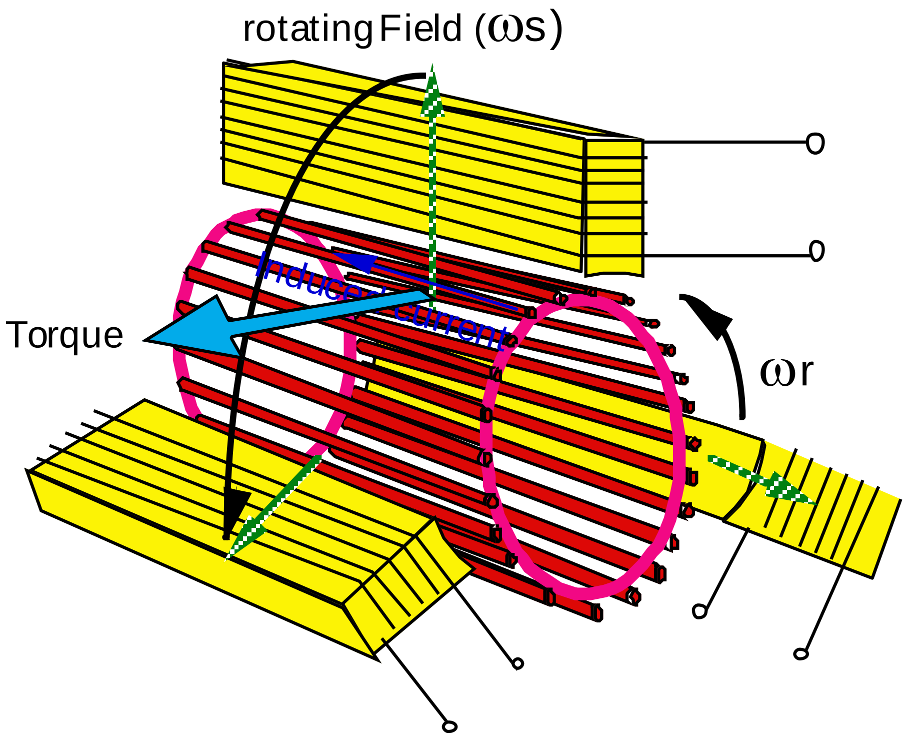
# Cutaway of Squirrel-Cage Induction Motor



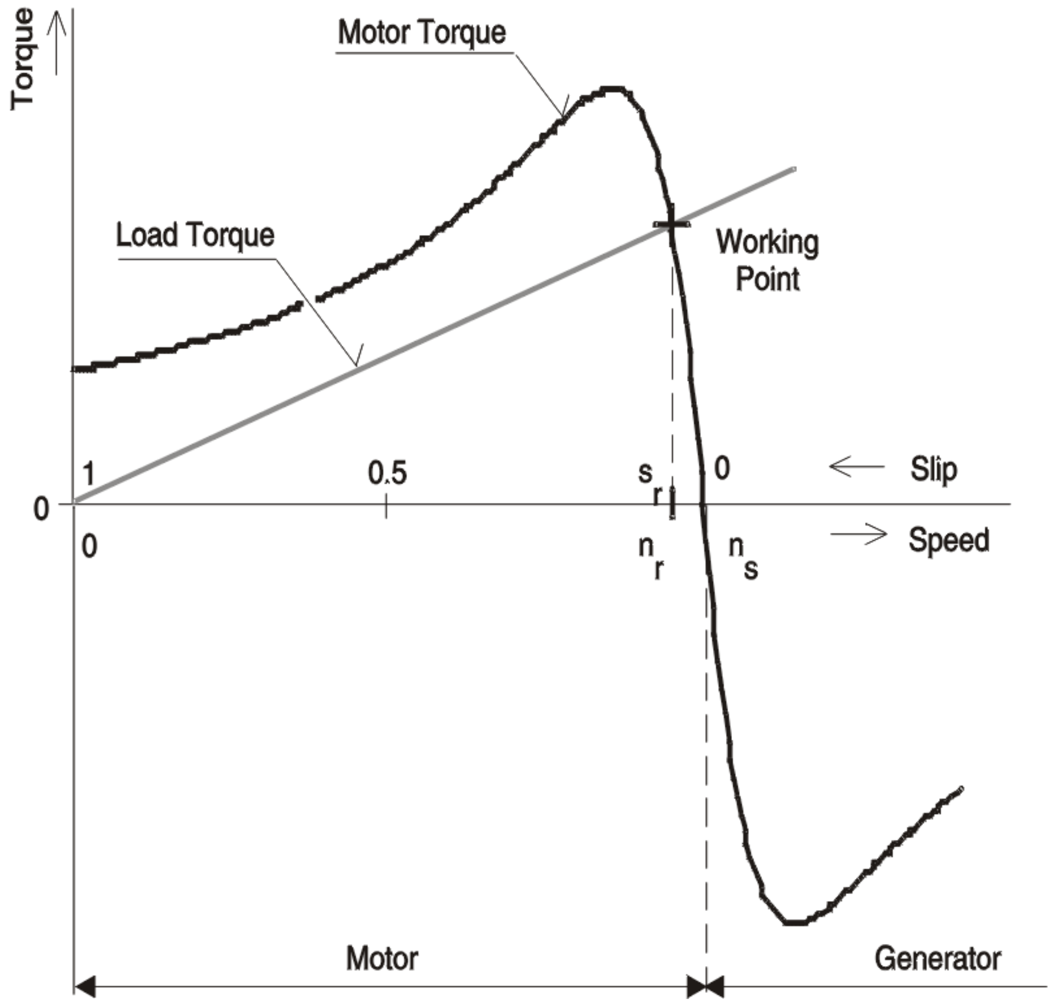

Cutaway view of a squirrel-cage induction motor. (*Westinghouse Electric Corporation.*)

# AC Induction Motor - Asynchronous

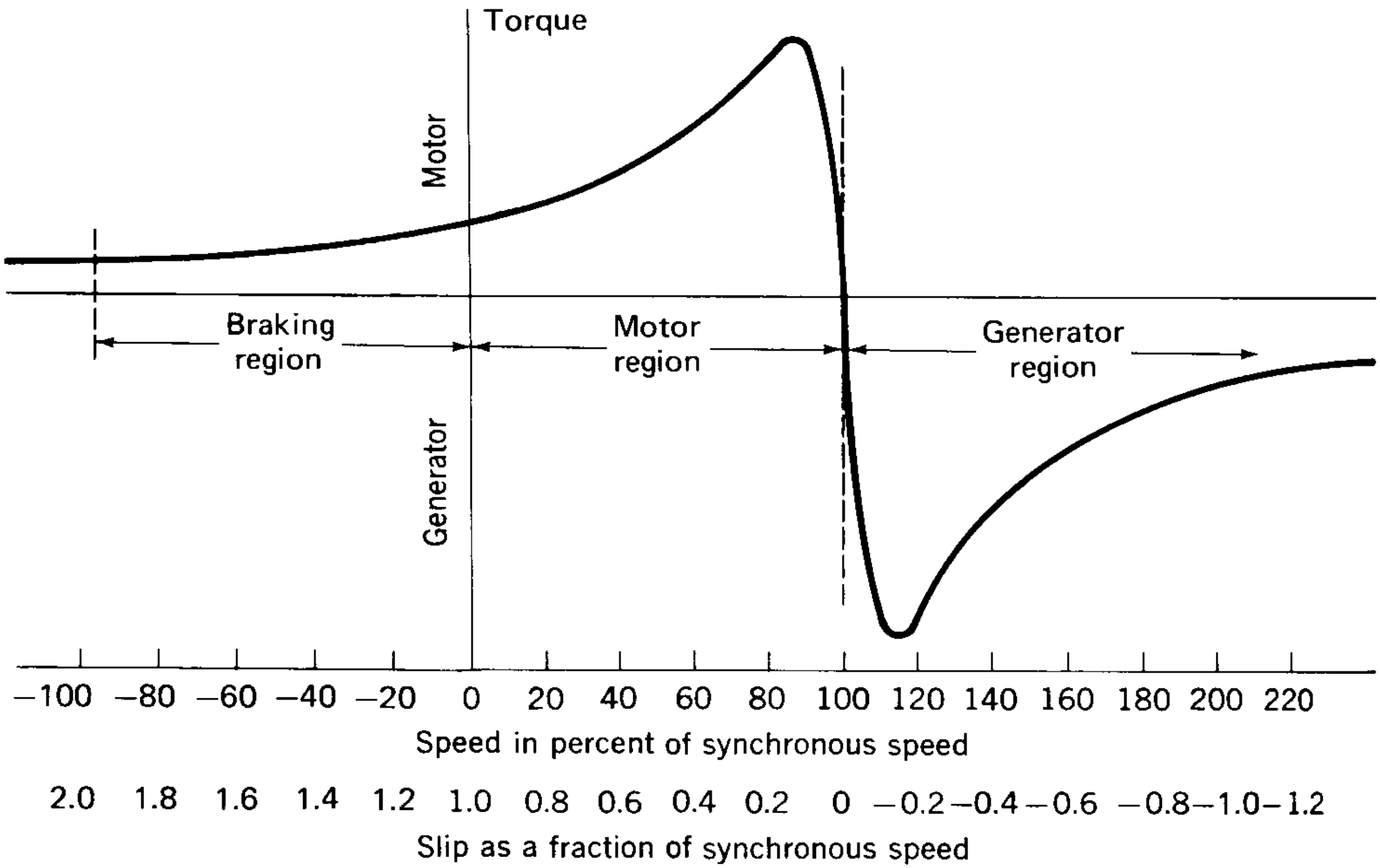
- **Motor time constant causes slip**
- **Slip is proportional to torque**
- **Suitable for variable speed applications**
- **light load typically inefficient**



# ACIM - Torque-Speed Profile

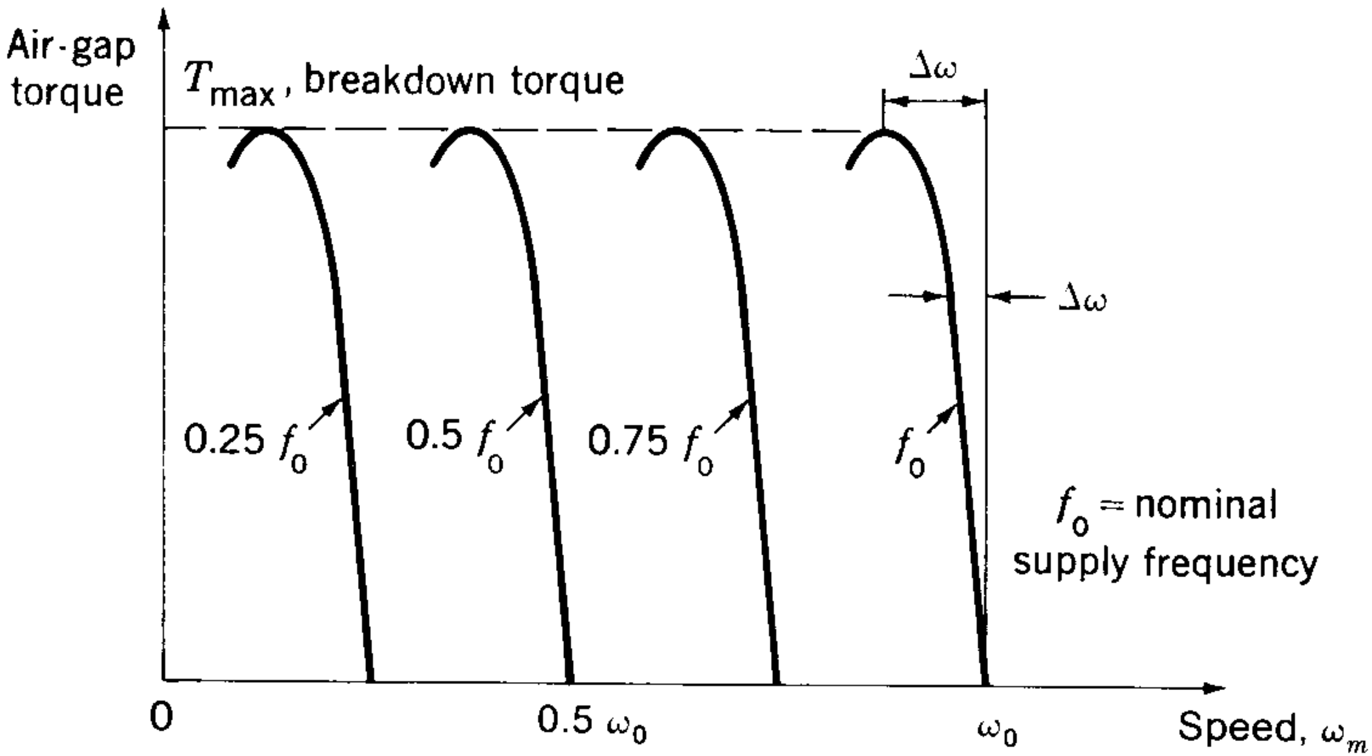


# Induction Machine as a Motor and a Generator




**Induction machine torque-slip curve showing braking, motor, and generator regions.**

# Speed Control by Varying Voltage and Frequency




**Idealized torque-speed curves of an induction motor under adjustable frequency control.**

# ACIM - Control Techniques Example

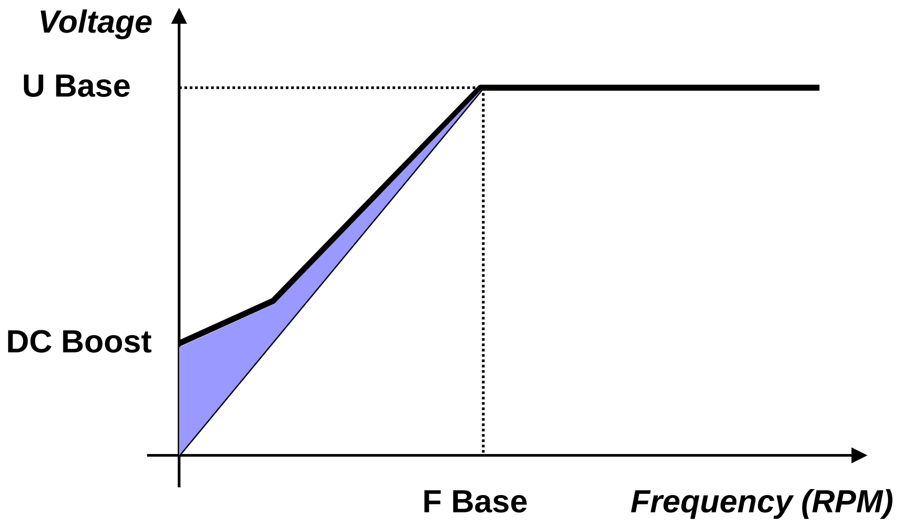
- Voltage per Hertz control (V/Hz)
- Voltage per Hertz control with speed closed loop
- Sensorless Voltage per Hertz control with slip compensation
- Optimized slip control
- Speed Vector Control
- Torque Vector Control
- Servo Control - Position Vector Control
- Sensorless Vector Control
- Direct torque control

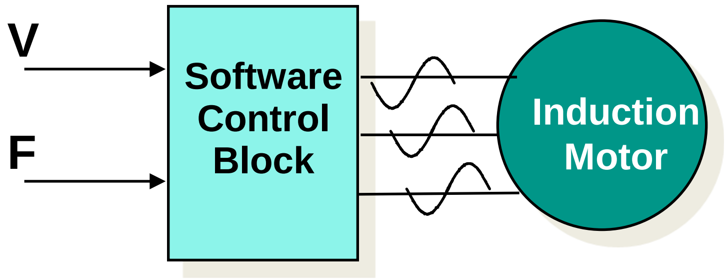
# V/Hz Control

**USE:** Low cost industrial drives.

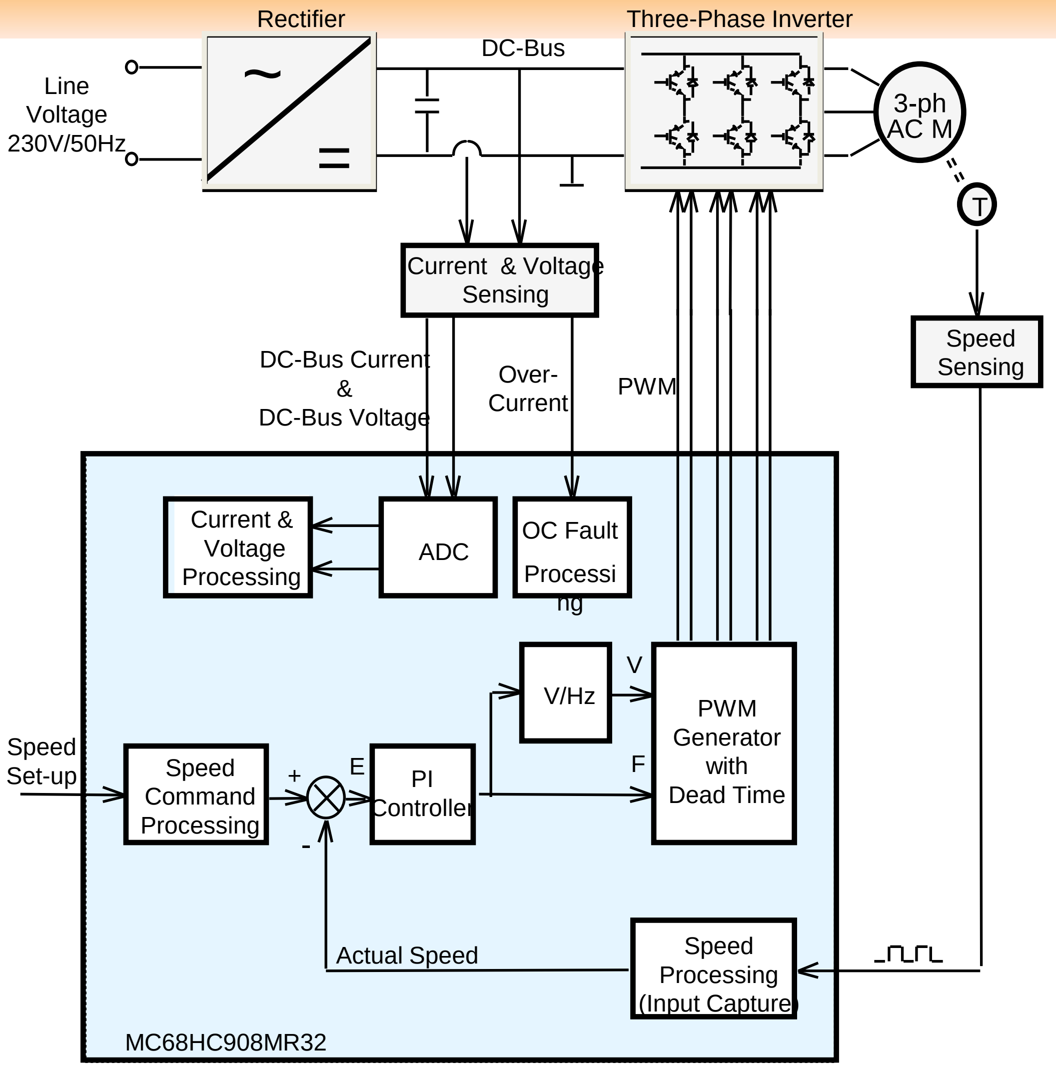
**CONTROL:** VOLTAGE (Amplitude and Freq)

**OPERATION:** Attempts to keep magnetizing current constant by varying stator voltage with frequency.



# ACIM - V/Hz Control Block Diagram



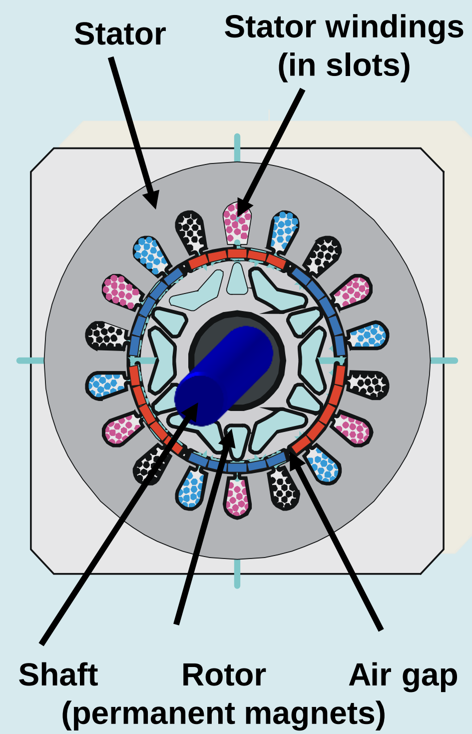
# ACI Motor

- **Advantages**
  - Low cost per horsepower
  - Inherent AC operation (Direct connection to AC line)
  - No permanent magnets (very rugged)
  - No brushes.  Very low maintenance
  - Available in wide range of power ratings
  - Low rotor inertia
- **Drawbacks**
  - Inefficient at light loads.
  - Speed control requires varying stator frequency.
  - Position control difficult (field orientation required).

# PMS (PERMANENT MAGNET SYNCHRONOUS) MOTOR

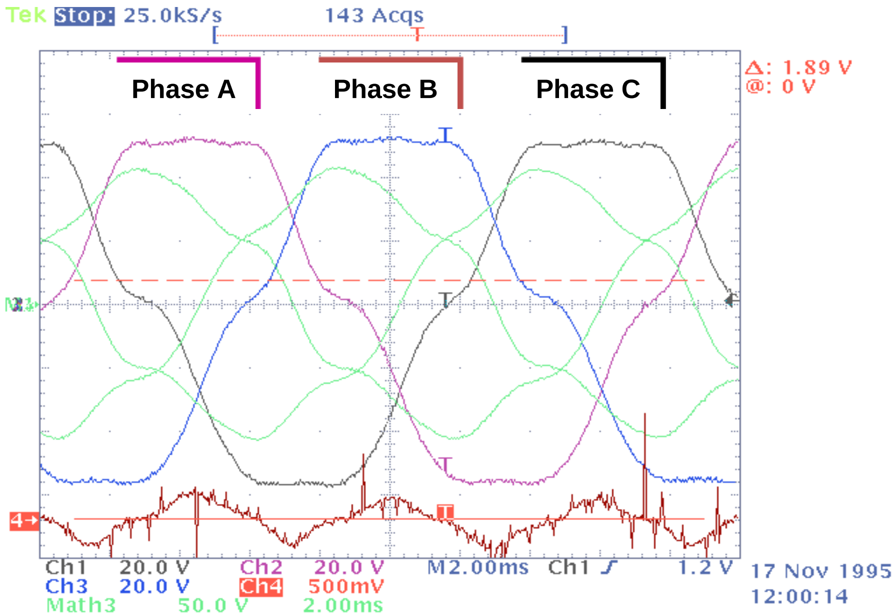
# PMS Motor vs. ACI Motor

- 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

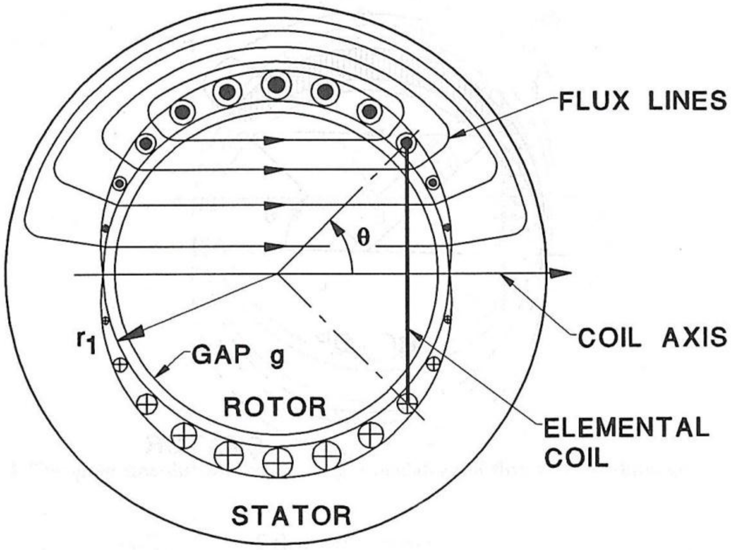


# PMS Motor vs. Brushless DC Motor

- PMS Motor versus BLDC Motor
  - The design of both motors is nearly the same. The biggest difference is that PMS motor uses sinusoidally distributed stator windings whereas the BLDC motor uses salient type field coils. The BLDC has trapezoidal shape of Back-EMF. The PMSM motor has sinusoidal shape of Back-EMF.




Trapezoidal Back-EMF voltage

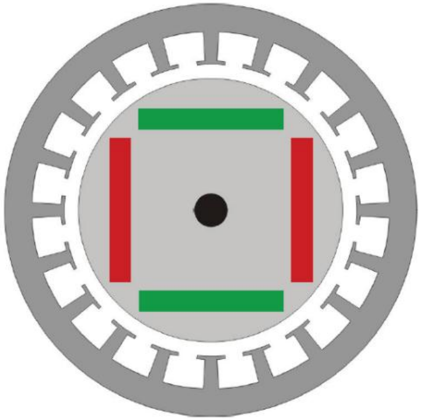



Sinusoidal winding distribution

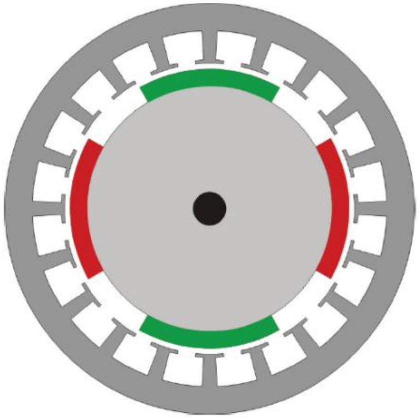
*Source: Hendershot J. R. Jr, Miller TJE: Design of brushless permanent-magnet motors*

# PMS Motor – Rotor Construction

- Rotor with buried interior magnets – salient design
  - Ld ≠Lq
  - Reluctance torque generation

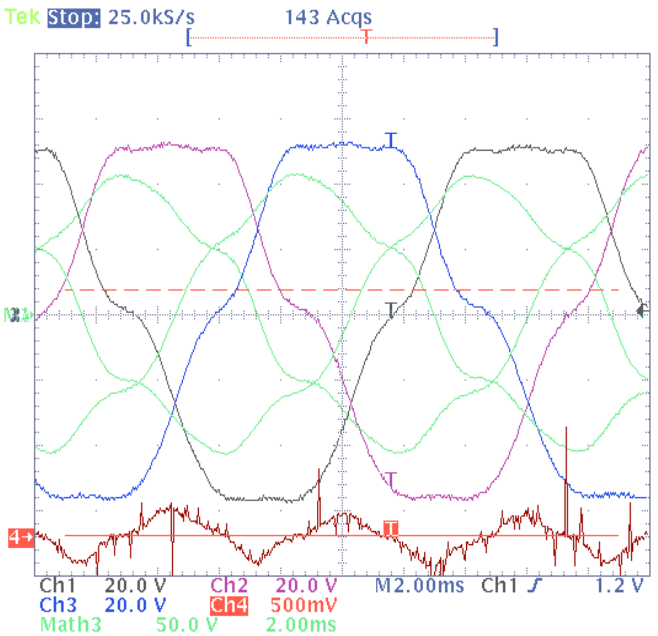


- Rotor with surface mounted magnets – non-salient design
  - Ld = Lq
  - No reluctance torque genereted



# 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



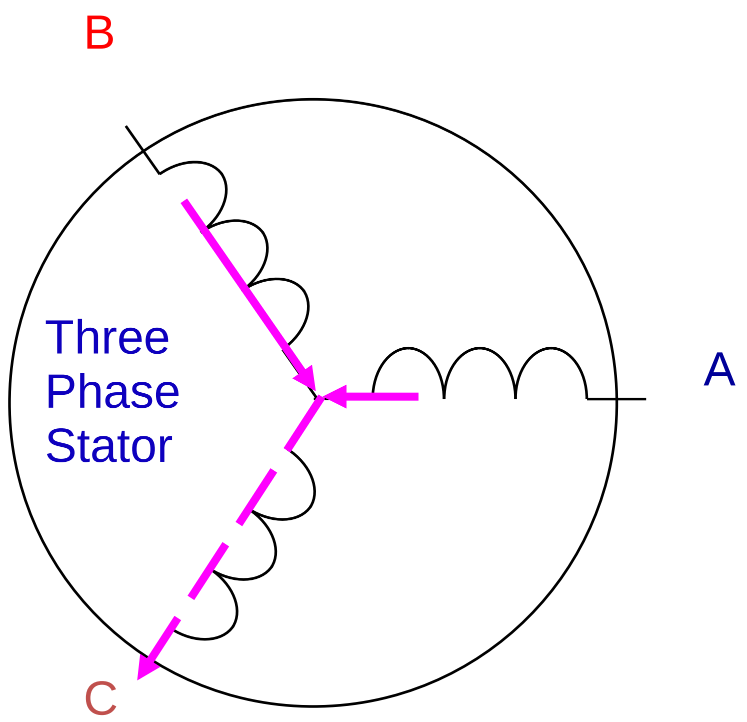
# PMS Motor

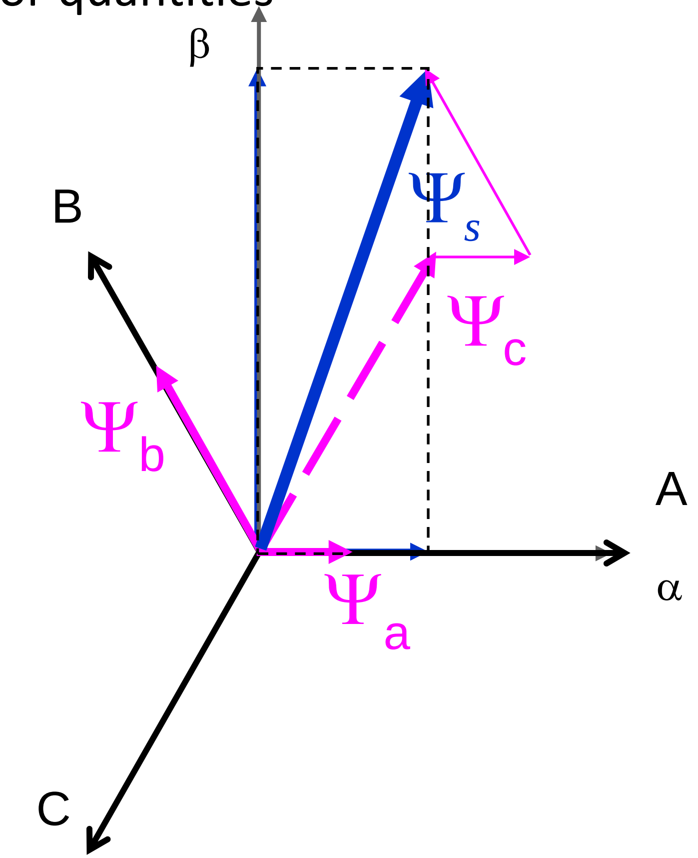
- **Advantages**
  - Heat is generated in stator:  easy to remove
  - High torque per frame size
  - Reliability due to absence of brushes and commutator
  - Highest efficiency.  Renewed interest for “white goods”
  - Synchronous operation makes field orientation easy
  - Good high speed performance (no brush losses)
  - Precise speed monitoring and regulation possible
  - Smooth torque
- **Drawbacks**
  - Rotor position sensing required for commutation.
  - Position sensor or sensorless technique is required for motor operation
  - Difficult to startup the motor using sensorless technique

# FOC FUNDAMENTALS
# (FIELD ORIENTED CONTROL)

# Creating Space Vector

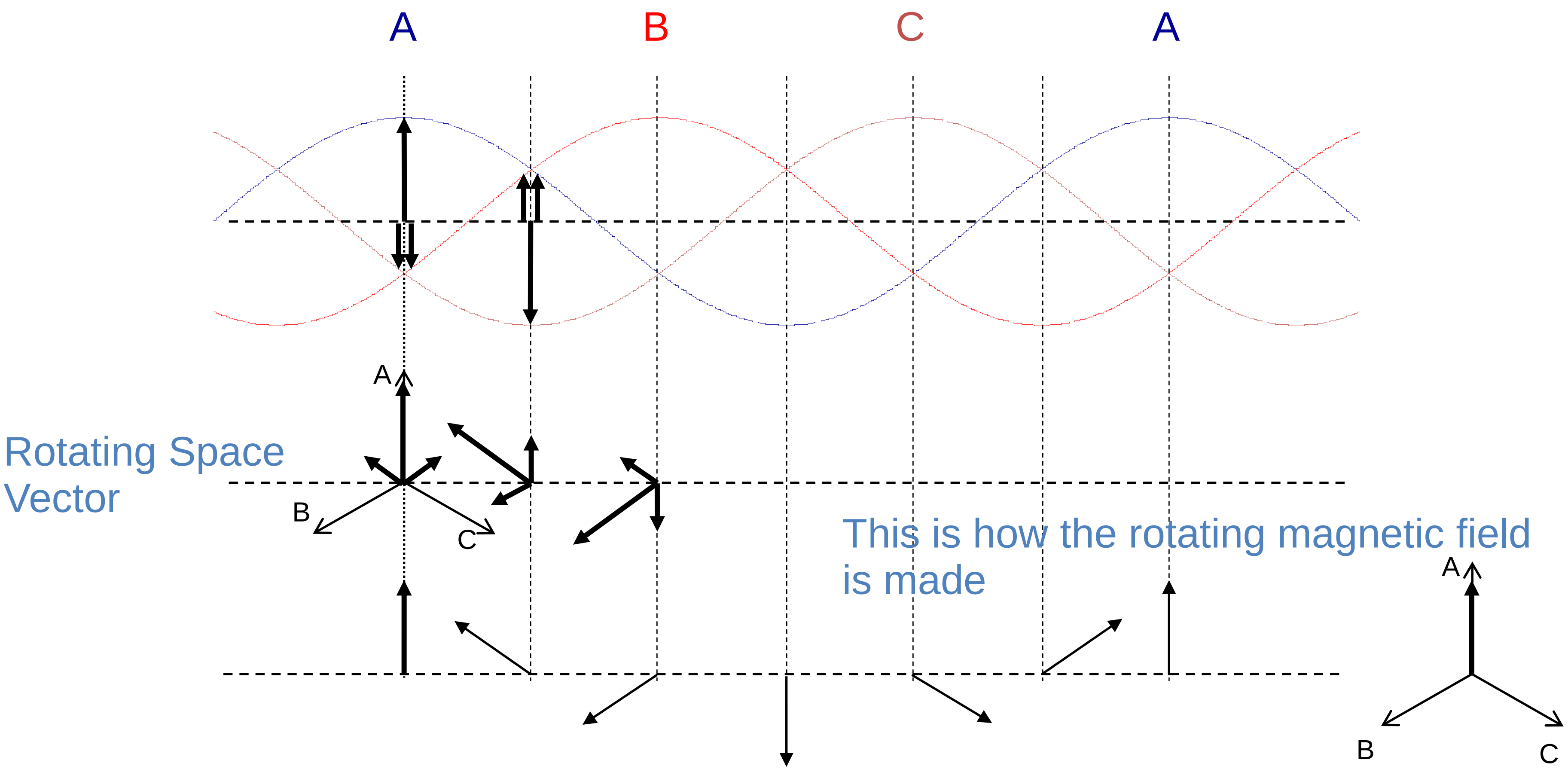
- The space-vectors can be defined for all motor quantities




- 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

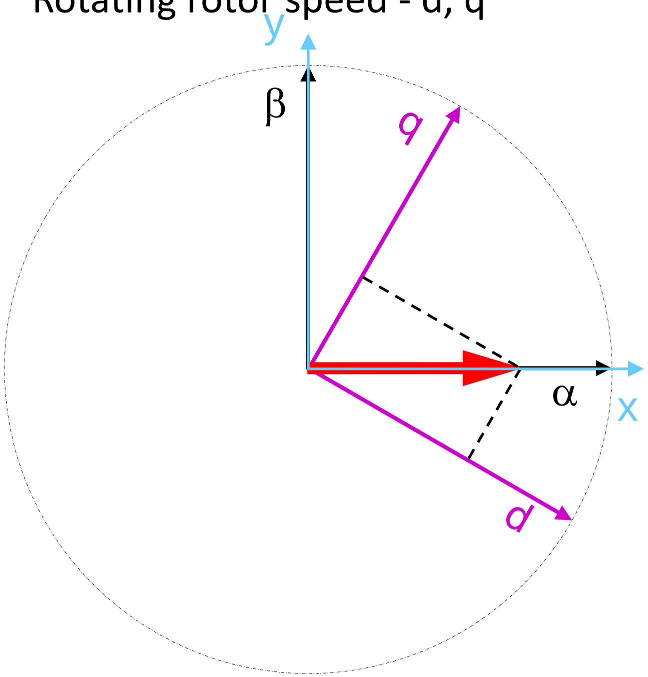
# Space Vector Rotation

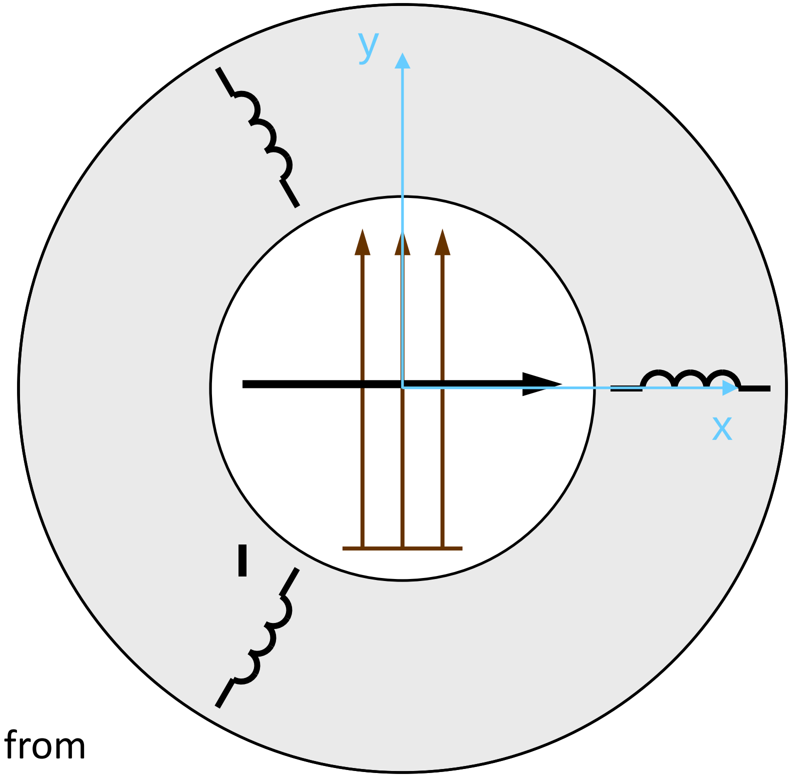



- To reverse rotation direction, swap the connection of any two phases

# Coordinate Systems - Reference Frames

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



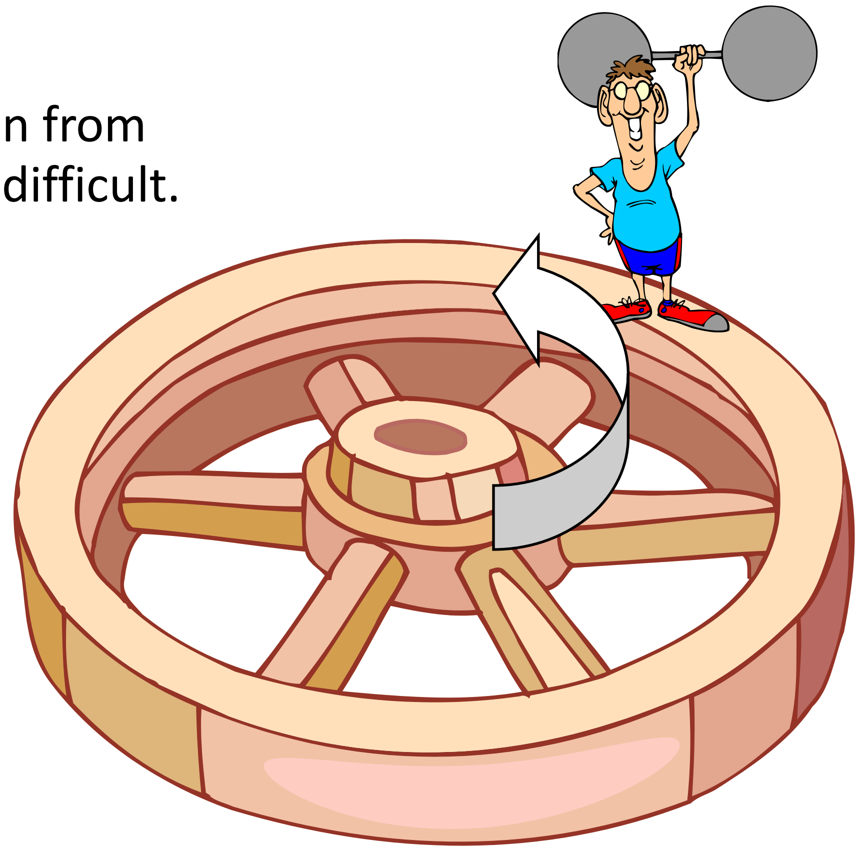

- All rotating quantities are “rectified” when viewed from reference frame that rotates synchronously with rotor

# 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

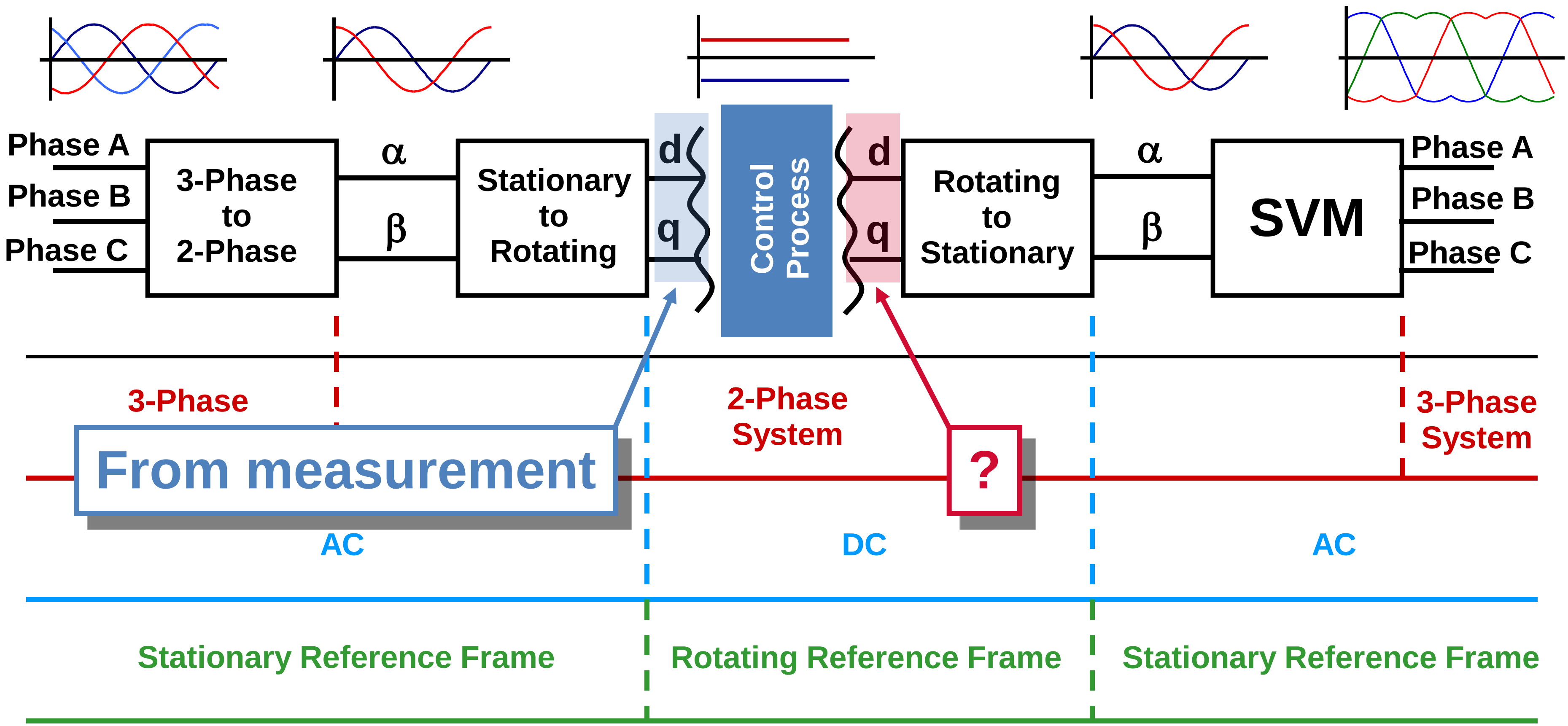
4. Calculate control action (when math is simplified and machine is “DC”)

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

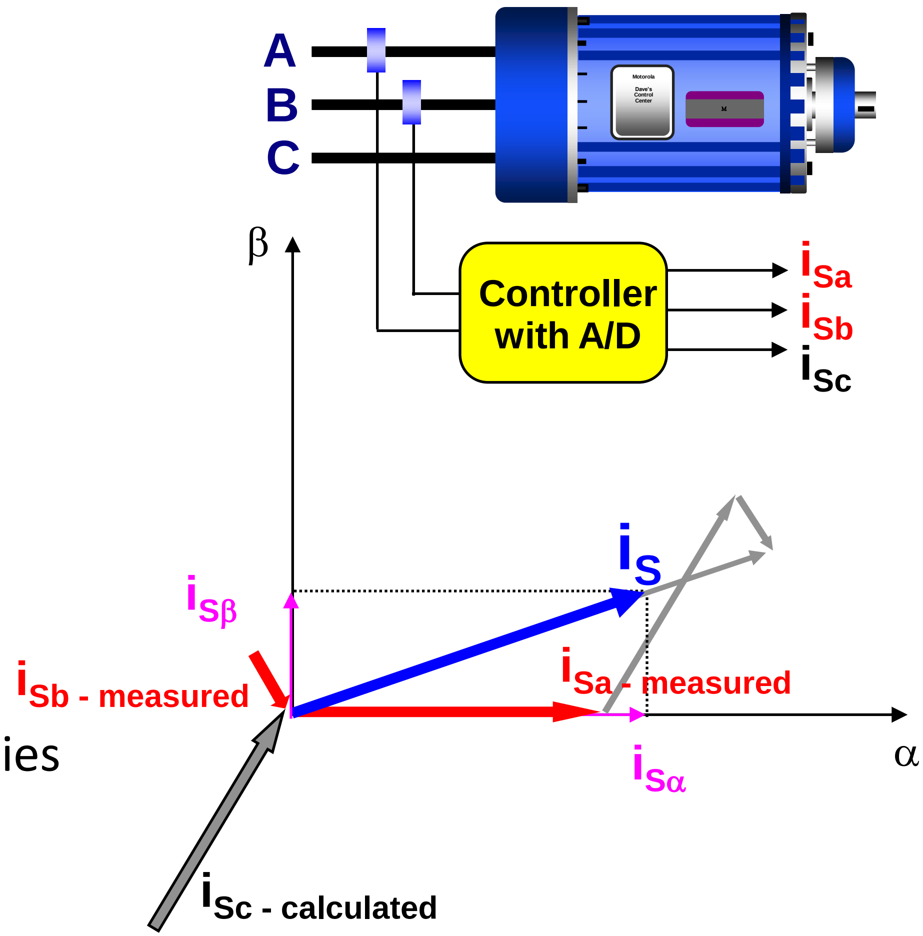
- Space-Vector Definition:

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

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

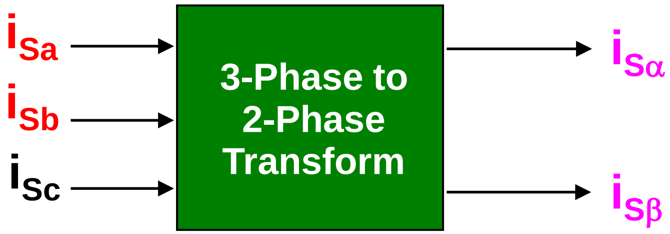
$$a = e^{j2\pi/3}, a^2 = e^{j4\pi/3}$$

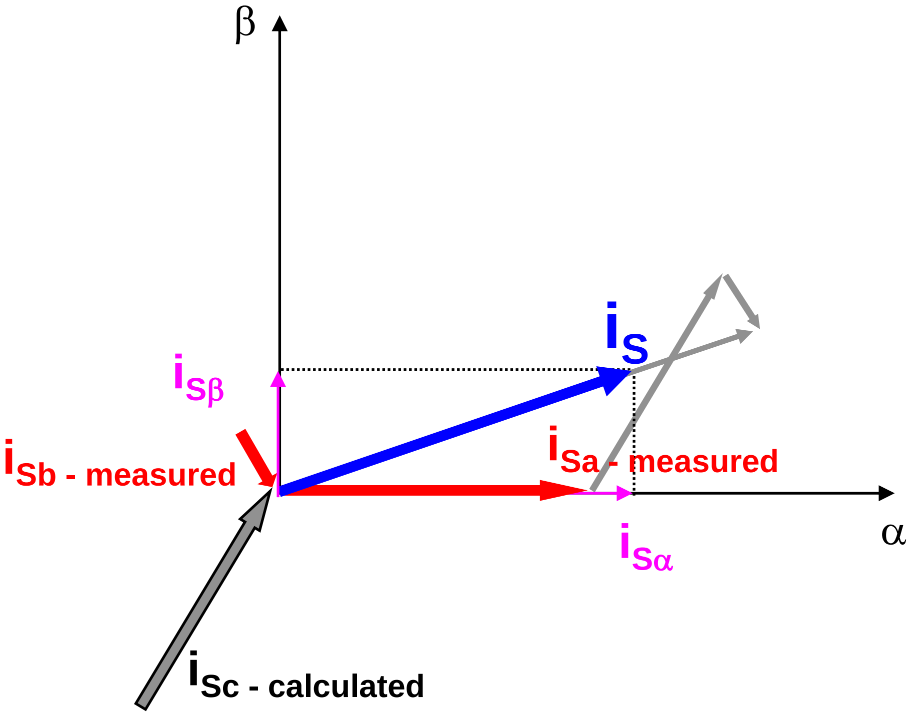
- The space-vectors can be defined for all motor quantities



- Clarke Transformation:
  - transforms the 3-phases a,b,c to the two-phase coordinate system α, β

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".



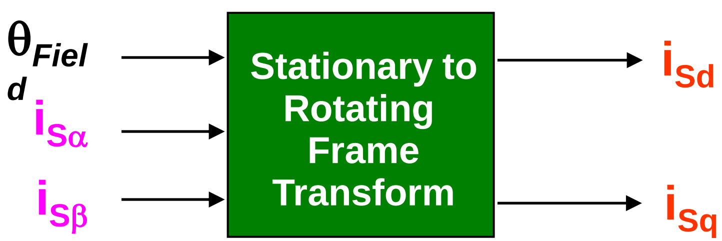




$$i_{s\alpha} = i_{sa}$$

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

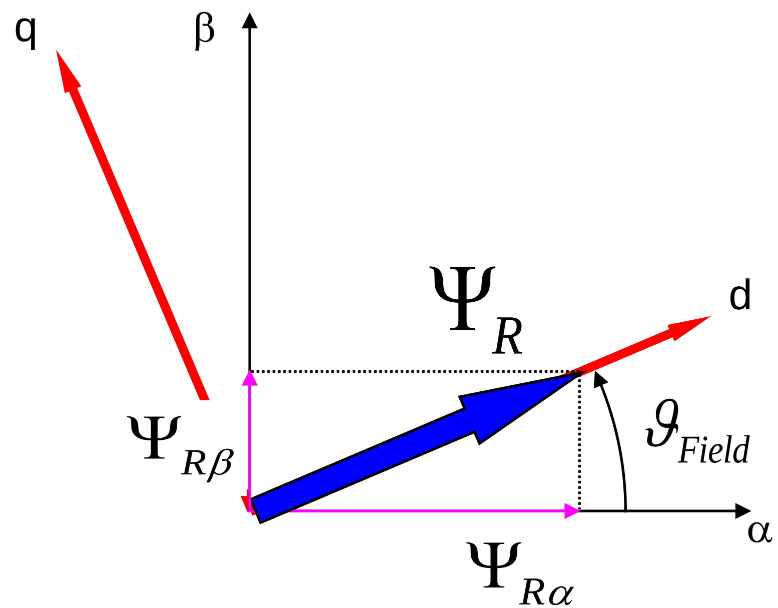
# Space Vector Basics cont'd

- 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.



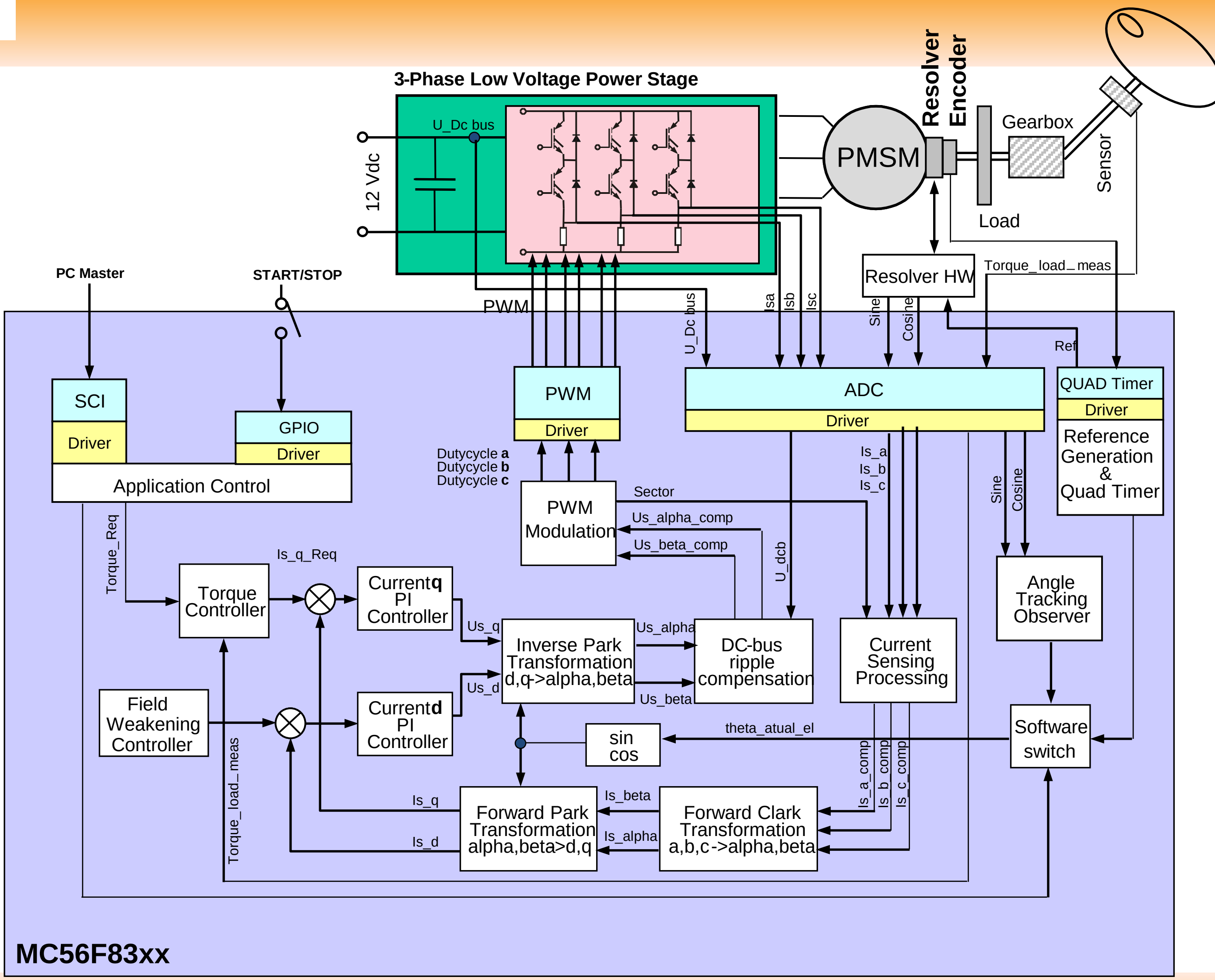

$$i_{sd} = i_{s\alpha} \cos\theta_{Field} + i_{s\beta} \sin\theta_{Field}$$

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




**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



# BRAKING SYSTEM – WEDGE BRAKE

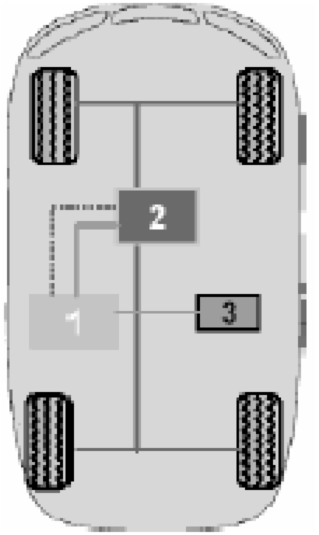
## Electro-Hydraulic Brakes (EHB)

- 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

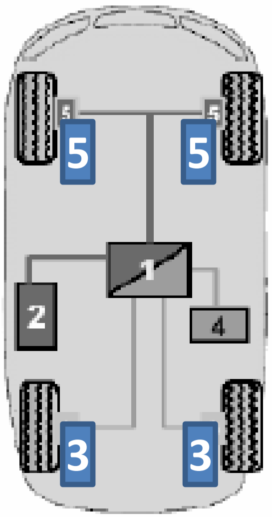


# Braking Systems – Summary cont'd

## 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)

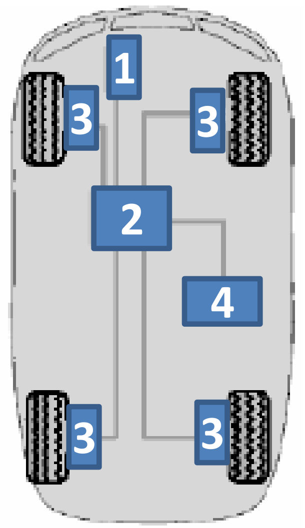
- The braking force is generated directly at each wheel by high-performance electric motors, controlled by an ECU, and executed by signals from an electronic pedal module
- brake-by-wire technology
- The EMB processing components must be networked using high-reliability bus protocols that ensure comprehensive 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

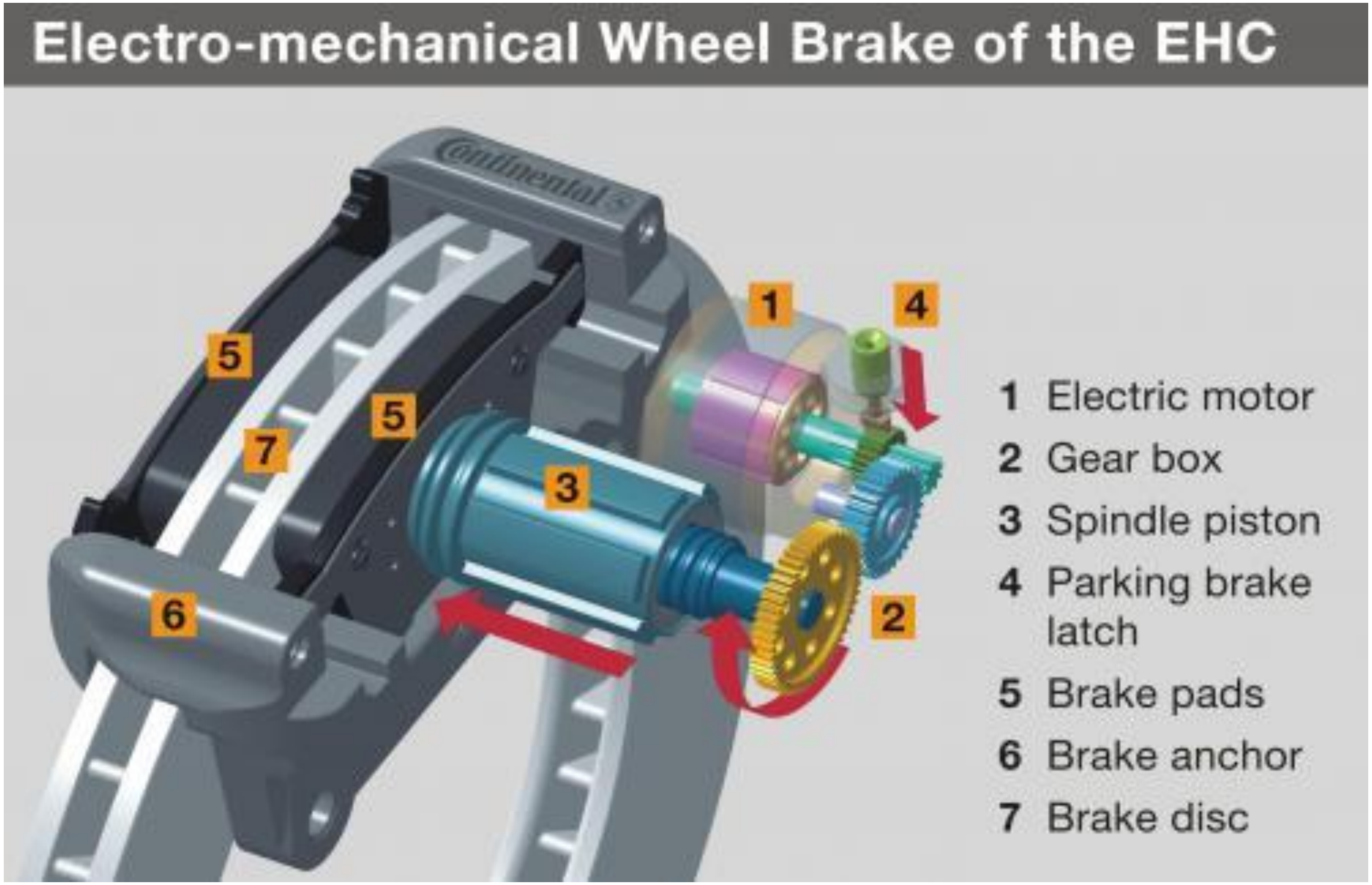
## Electro-Mechanical Brake (EMB)

- 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

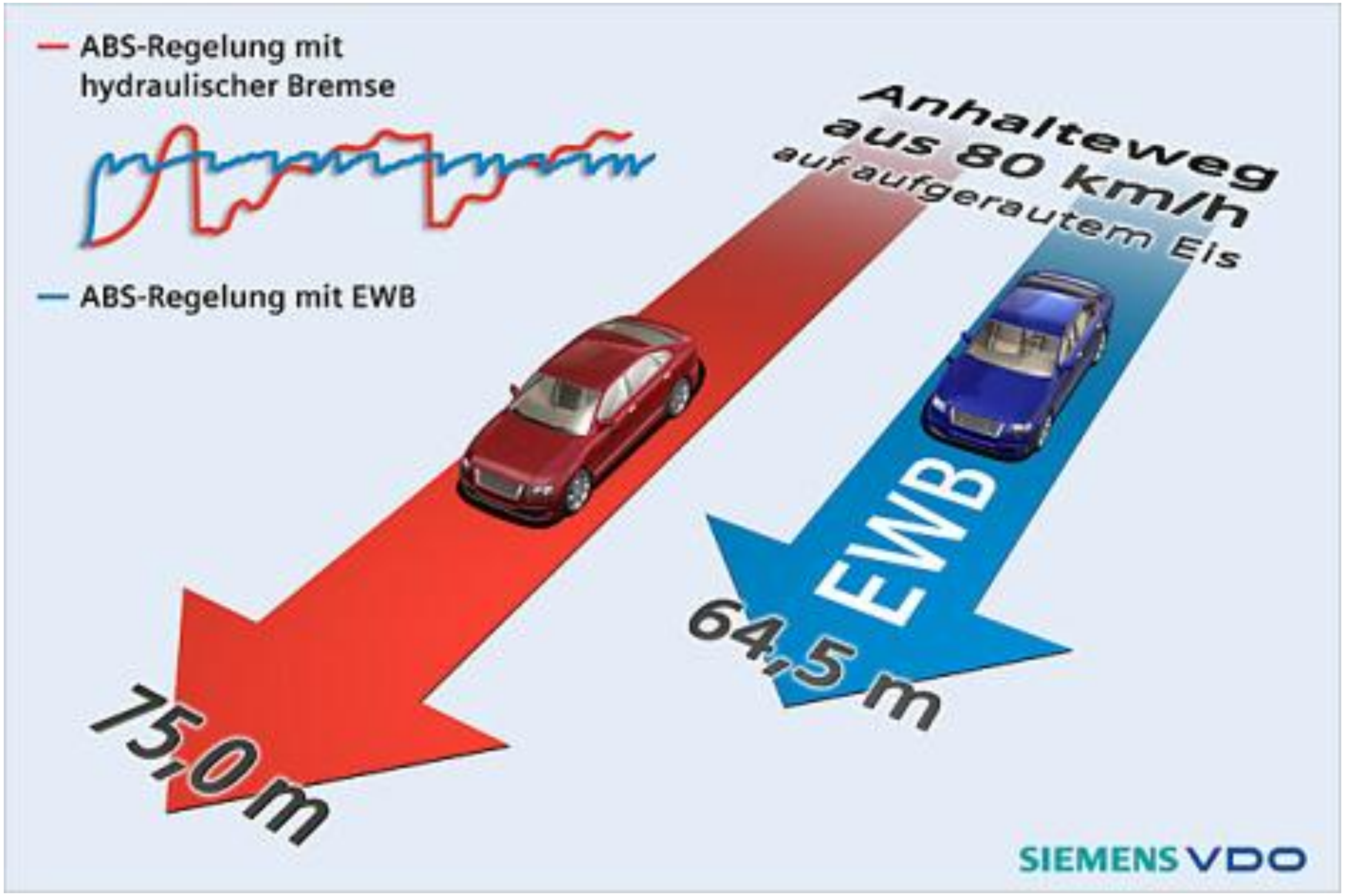


# Wedge Brake System -eBrake

## 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

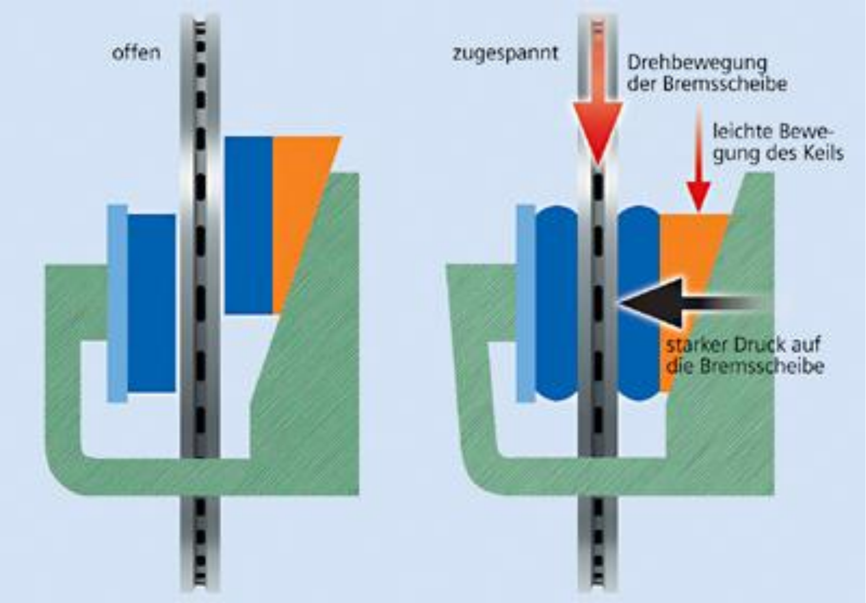
# Wedge Brake System -eBrake



# 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

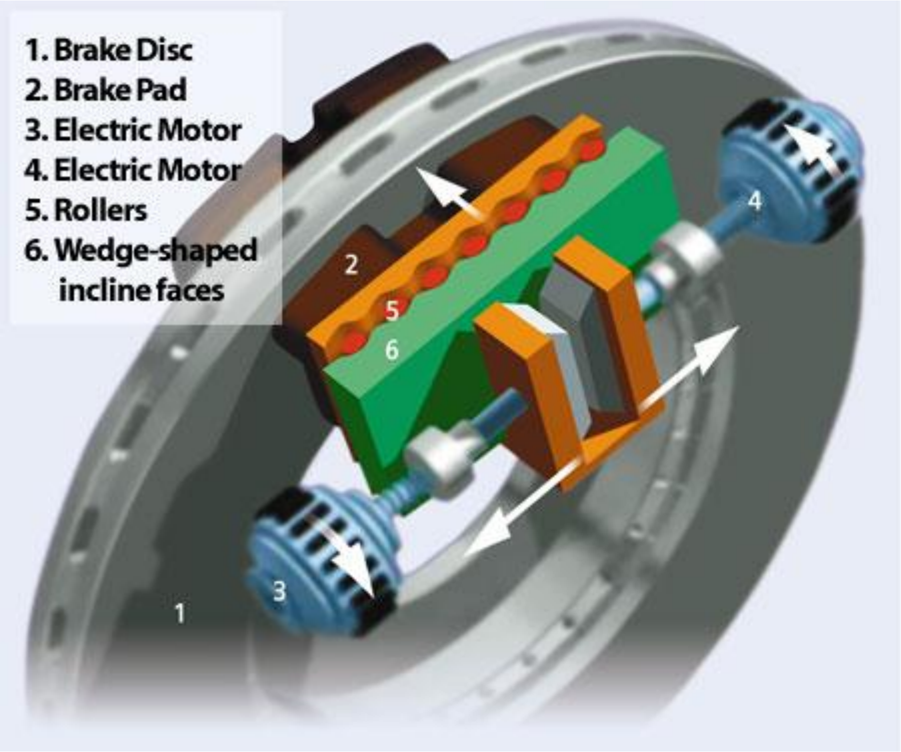
- Benefit of eBrake would be reduction of the force required from the brake actuator
- The eBrake® solves this problem elegantly by using a wedge to generate the clamping forces
- This exploits self-reinforcement of the braking forces by the rotating brake disc to minimize the actuation forces

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

- 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 ($C^* \to \infty$), 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

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

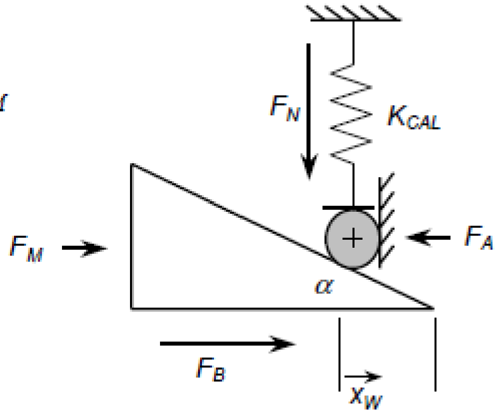
Simple model of the friction in the rollers

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

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**

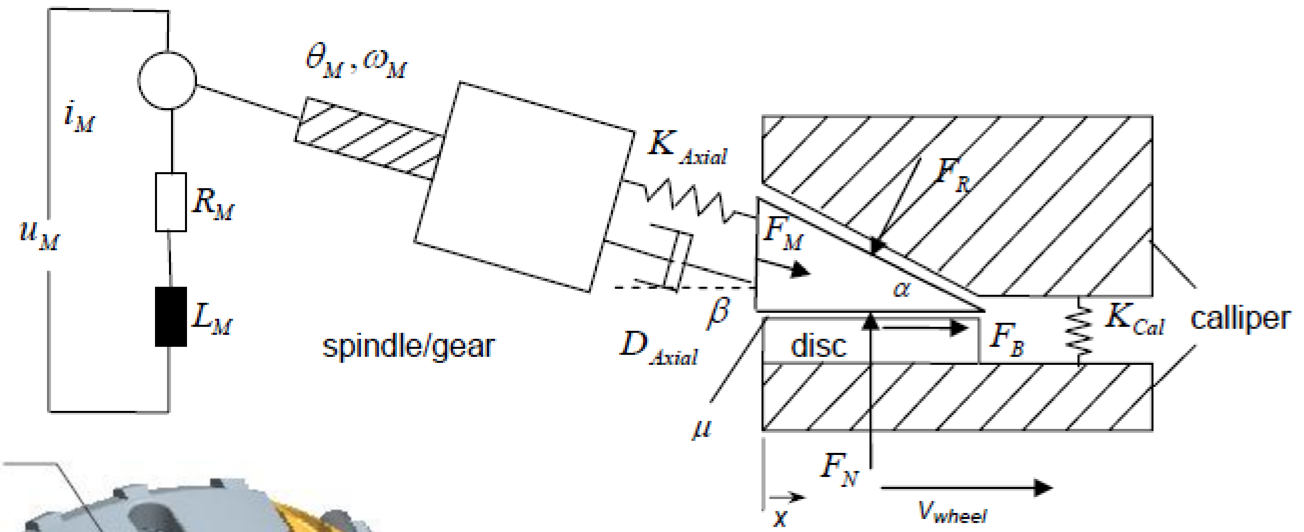


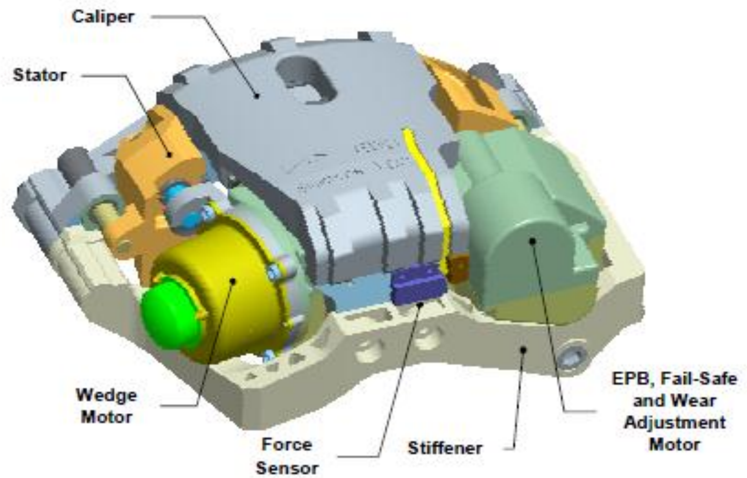

The braking torque is given by using the pads on both sides of the calliper and multiplying by their effective radius

$$M_B = 2\mu_B F_N r_B$$

# Wedge Brake System -eBrake

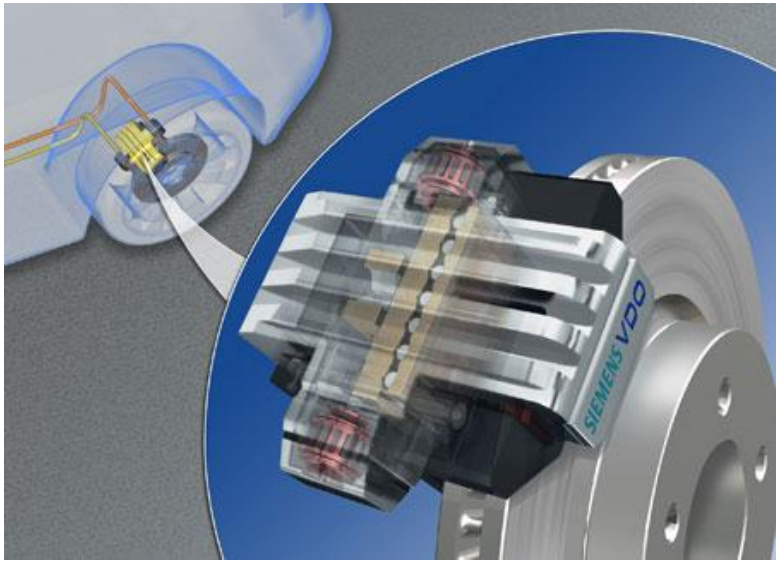
## Simplified Model of the Electrical Wedge Brake

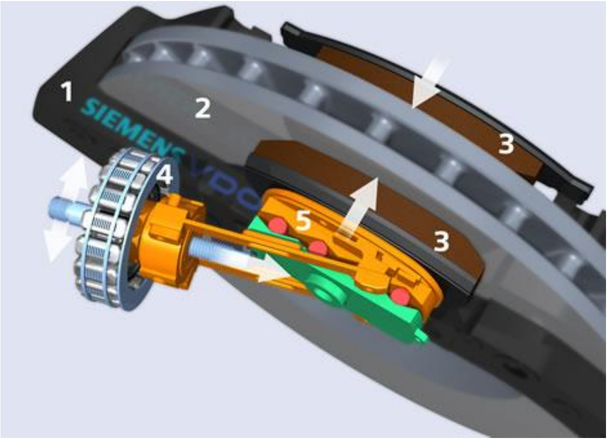


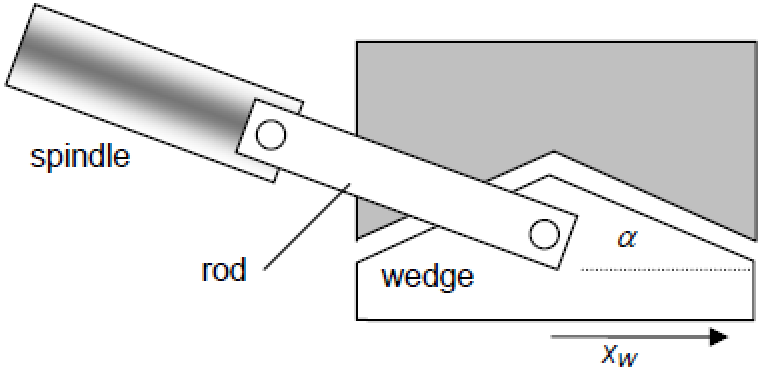




**PT1 Prototype (90kN / 4500 Nm)**

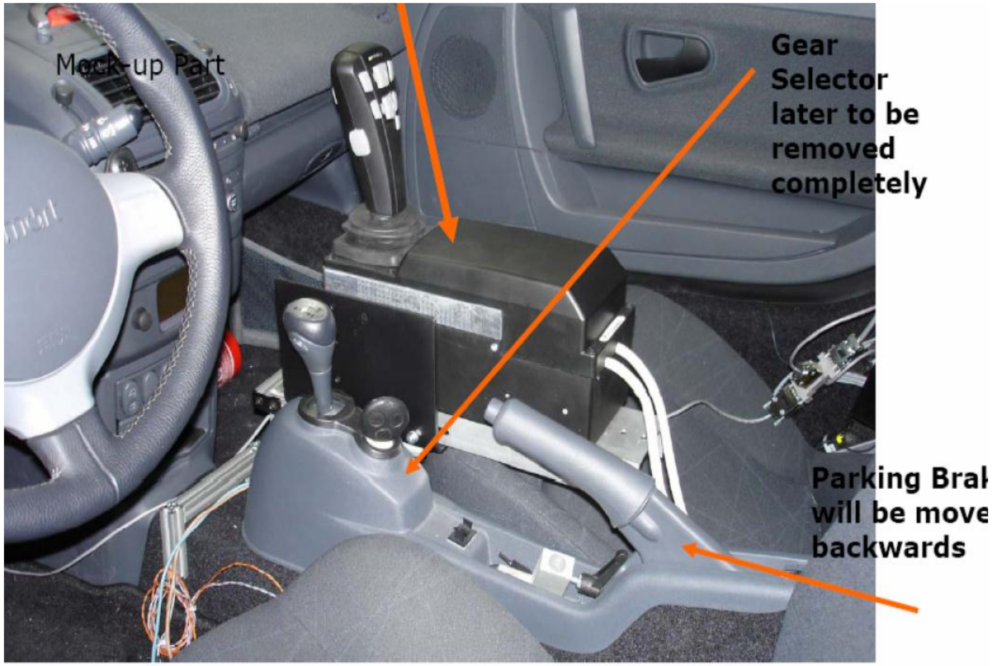
# Wedge Brake System -eBrake





# Wedge Brake System -eBrake



# Wedge Brake System -eBrake

# 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

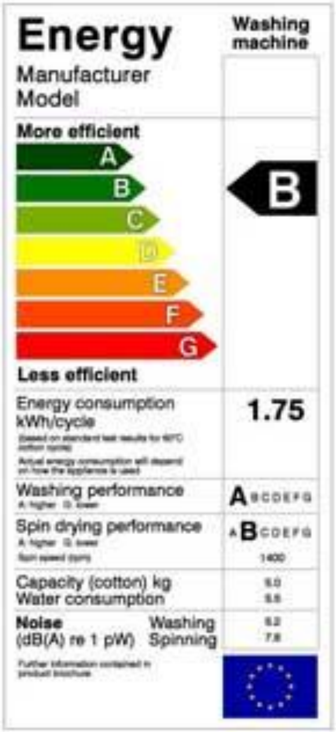
## Typical parameters

- 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

## Washing machine energy labels

- Washers currently carry EU energy ratings between A and G
- Energy efficiency rating is calculated by measuring energy (kWh) used per kilogram of washing during a typical 60°C cotton cycle, typically with 6 kg load of washing.
- In late 2011 or early 2012 this method will change to a weighted average of 60°C and 60°C cycles



# 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. 750 W
- 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

## 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
    $L_d < L_q$

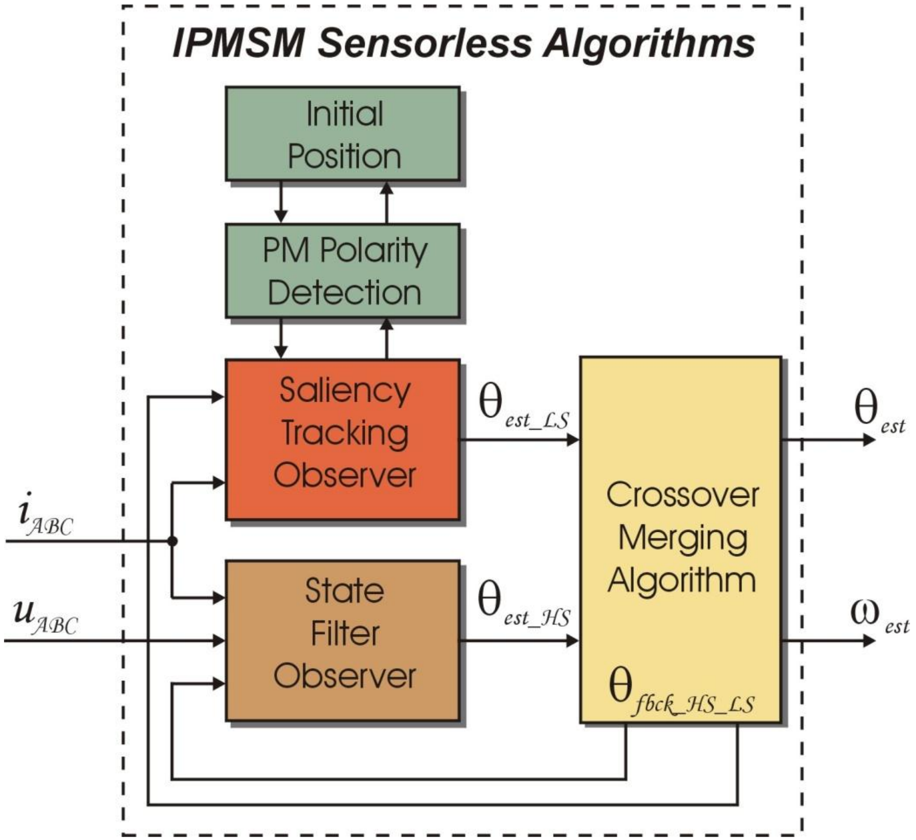
# Washers – Pancake Motor cont'd

# IPMSM Sensorless Algorithms

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

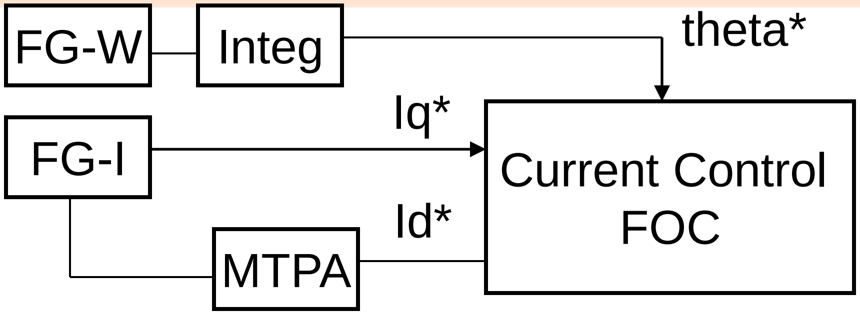
- Crossover Merging Algorithm based on FUZZY logic merges the two algorithm outputs into a single position/speed estimation.

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



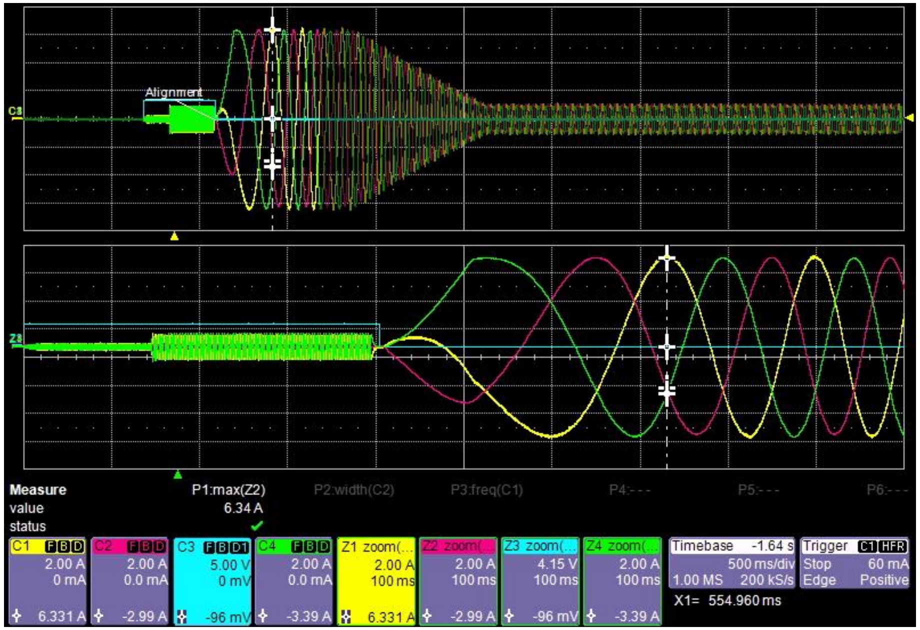
# Open Loop Start Up

- **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

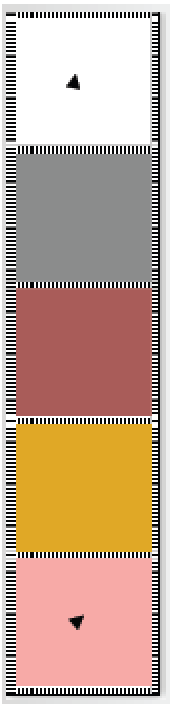
# Washers – Manufacturers

| Manufacturing group name | Country of head office | Market share 1993 | Principal brand names 1995 |
|---|---|---|---|
| Bosch-Siemens | Germany | 16.2% | Bosch/Siemens/Neff/Constructa/Hausgeräte/ Balay/Gaggenau |
| Electrolux | Sweden | 11.4% | Electrolux/Zanussi/Castor/Arthur Martin/ Faure/Husquarna/Zanker/Zoppas |
| Whirlpool International | Netherlands | 10.3% | Whirlpool/Philips/Bauknecht/Laden/Radiola |
| Merloni | Italy | 9.4% | Ariston/Indesit/Scholtes/Smeg/Ignis/Blue Air |
| Miele | Germany | 7.4% | Miele |
| GDA | United Kingdom | 7.1% | Creda/Hotpoint |
| ELFI | Italy | 6.9% | Blomberg/Brandt/De Dietrich/Ocean/ Thermor/Thomson/Vedette |
| AEG* | Germany | 6.4% | AEG |
| Crosslee | United Kingdom | 6.4% | |
| Candy | Italy | 3.8% | Candy/Rosieres/Otsein |
| Others | | 14.7% | |

# Wash Performance Testing

## 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

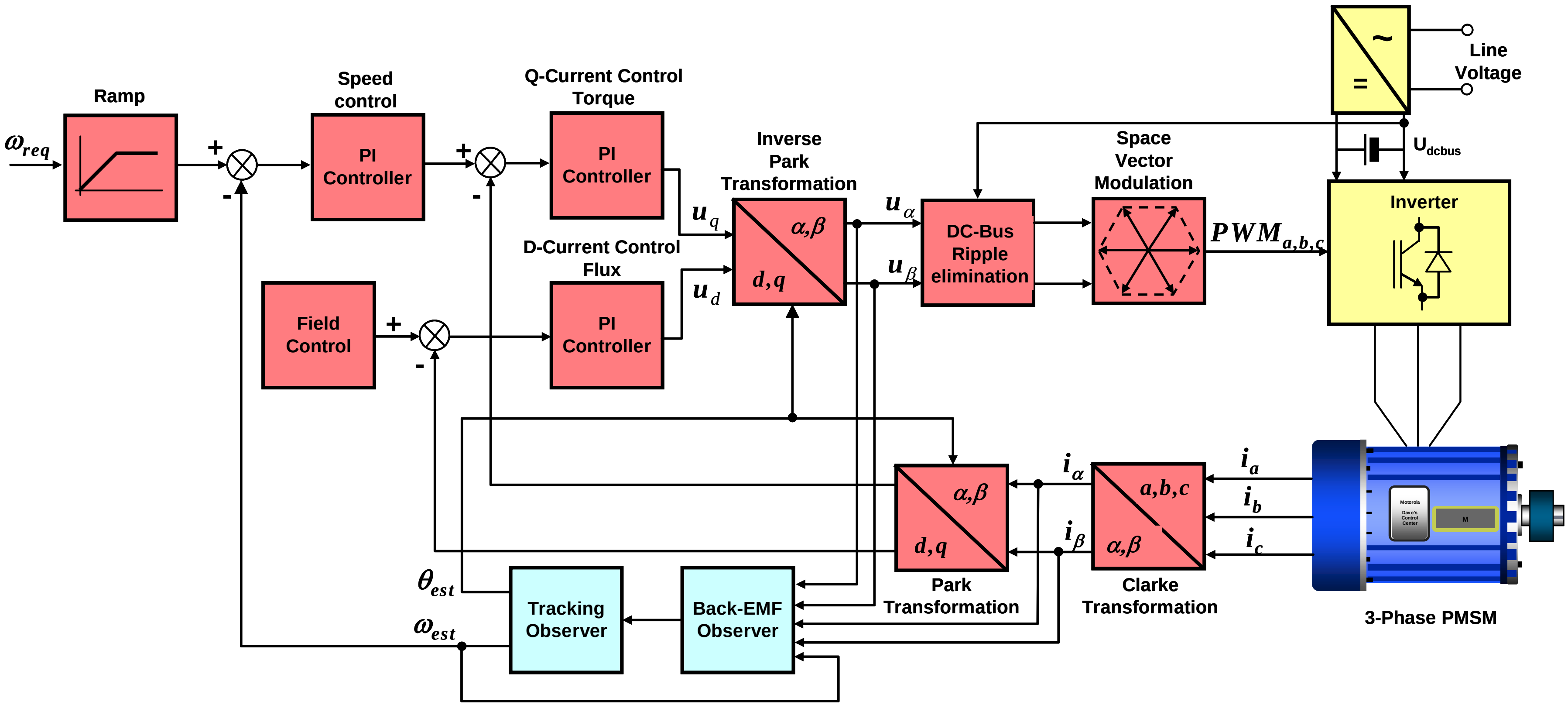
**Each sample is 15 x 15 cm**

# 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



# SOLAR ENERGY – PHOTOVOLTAIC TECHNOLOGY

# Solar Energy

- At sun's surface, the density of the radiated flux's energy is approximately 63,000 kW per square meter. This flux drops as the square of the distance from the Sun.
- The yearly average density of Sun's irradiance at the top Earth's atmosphere on an imaginary surface perpendicular to the sunlight rays is approximately
  - 1366 watt per square meter according to information from National Institute of Standards and Technology (NIST)
  - 1361 $W/m^2$ according to NASA measurements
- This value is called **solar constant**, although actually it is not really a constant: it slightly varies throughout the year and also through 11-year cycles.

# Solar Technology

- **Single Crystal Silicon Cells (c-Si)**
  - high sunlight into electricity conversion efficiency – about 16%
  - high cost
- **Polycrystalline Silicon Cells (mc-Si)**
  - lower sunlight into electricity conversion efficiency – about 12%
  - medium cost
- **Thin-Film Solar Cells (ribbon Silicon)**
  - lowest sunlight into electricity conversion efficiency – about 8%
  - lowest cost
- **Copper Indium Gallium Selenide Solar Cells**
  - high sunlight into electricity conversion efficiency – up to 20%
  - high cost
  - need some exotic materials - availability
- **Multi Junction Devices**
  - highest sunlight into electricity conversion efficiency – up to 40%
  - highest cost

# PV Solar Panel Construction

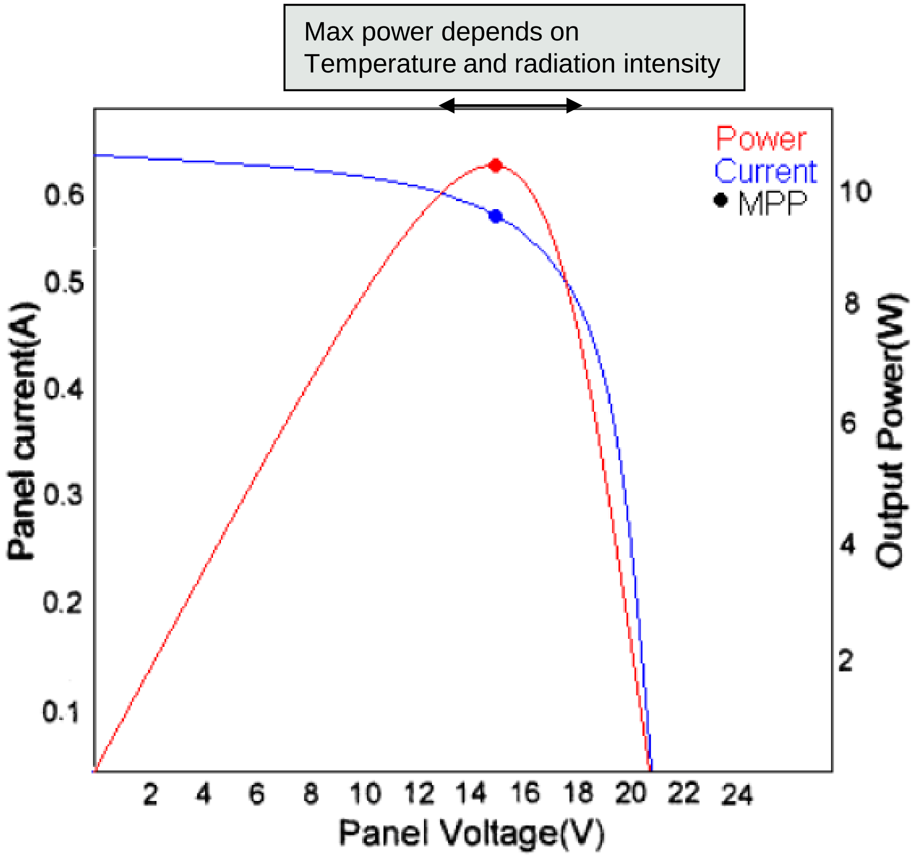
Solar panels are collected from several silicon cells electrically connected in series, to maintain usable output voltage level.

Mostly used:

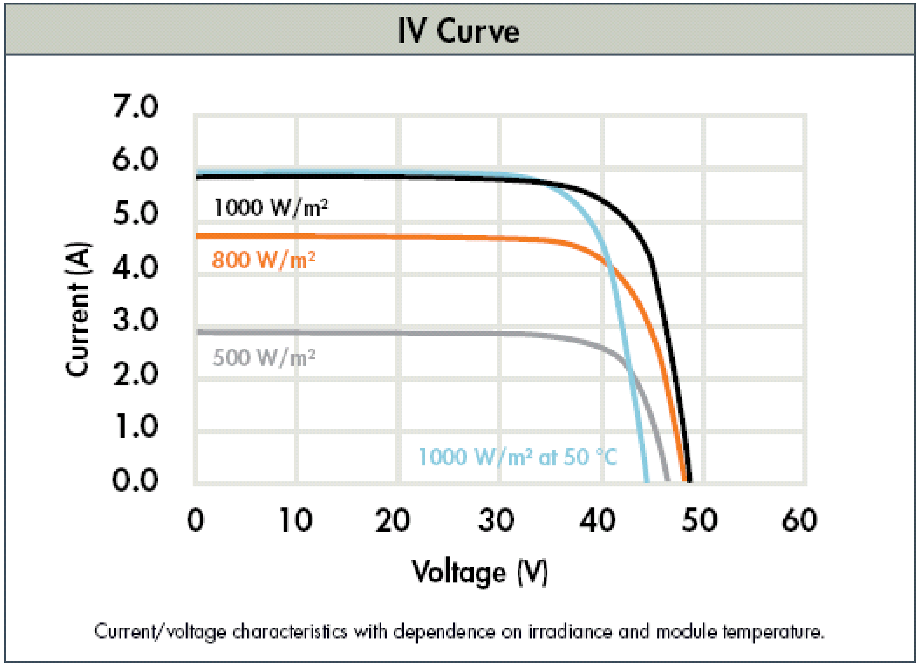
| Number of cells in series | Maximum power point output voltage level [V] |
|---|---|
| 36 | 17 |
| 48, 50 | 24 |
| 39, 40 | 17 |
| 72 | 34 |
| 96 | 53 |

# Role of Maximum Power Point Tracking - Solar Panel I-V Curve

- To get maximum power from a PV panel required operating at the optimum voltage.
- This voltage varies with irradiance intensity and temperature
- Maximum Power Point Tracking (MPPT) devices are essentially DC/DC converters which maintain the optimum voltage
- Today nearly all inverters contain MPPT
- Some inverters have 3 MPPT controllers – called multi-string



# Example of PV Solar Panel Properties




Example of V-A characteristic of 230W mono-crystalline solar panel from SunPower type SPR-230-WHT.

Number of cells: 72

Efficiency: 18,5%

Max-power: U = 41V;

I = 5,61A;

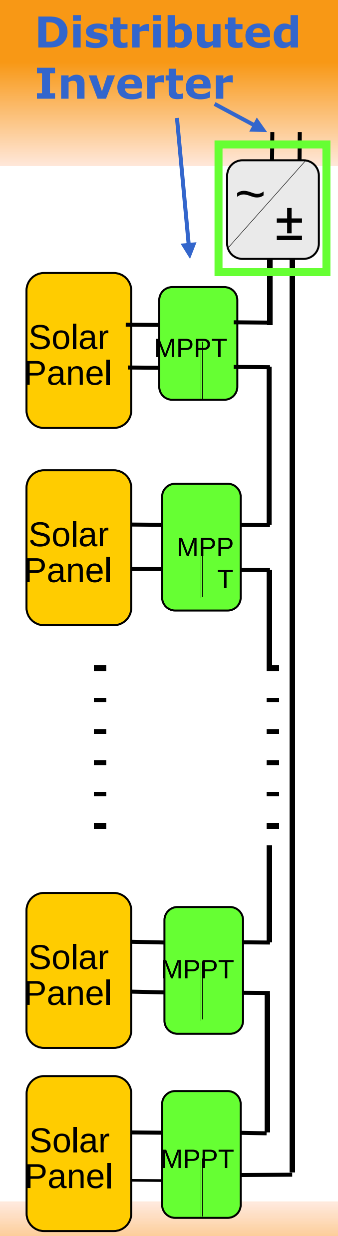
# SolarEdge Solution

Distributed Power Harvesting system contains:

- Innovative in-panel digital power ASIC
- Centralized, one stage, DC-to-AC inverter per array

Distributed system offers major advantages:

- MPPT circuit per panel solves Panel Mismatch, and Partial Shading
- Fixed string voltage enables very simple system design, system feedback and very easy/fast trouble shooting
- In-panel electronics increases system safety for both installer, electrician and fireman
- Power-line-communication offers a new level of monitoring which enables new services



# PV Systems – Off-Grid vs. Grid-Tie

DC

DC/DC converter

AC

DC/AC inverter

200W or less

0.2 to 12 kW

Off-Grid

Off-Grid

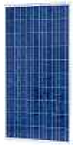
Grid-tie

Grid-tie

Grid-tie

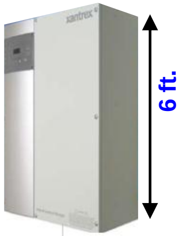
Off-Grid

**Up to 1 kW**




Grid-Tie Residential

**Up to 12 kW, single-phase**

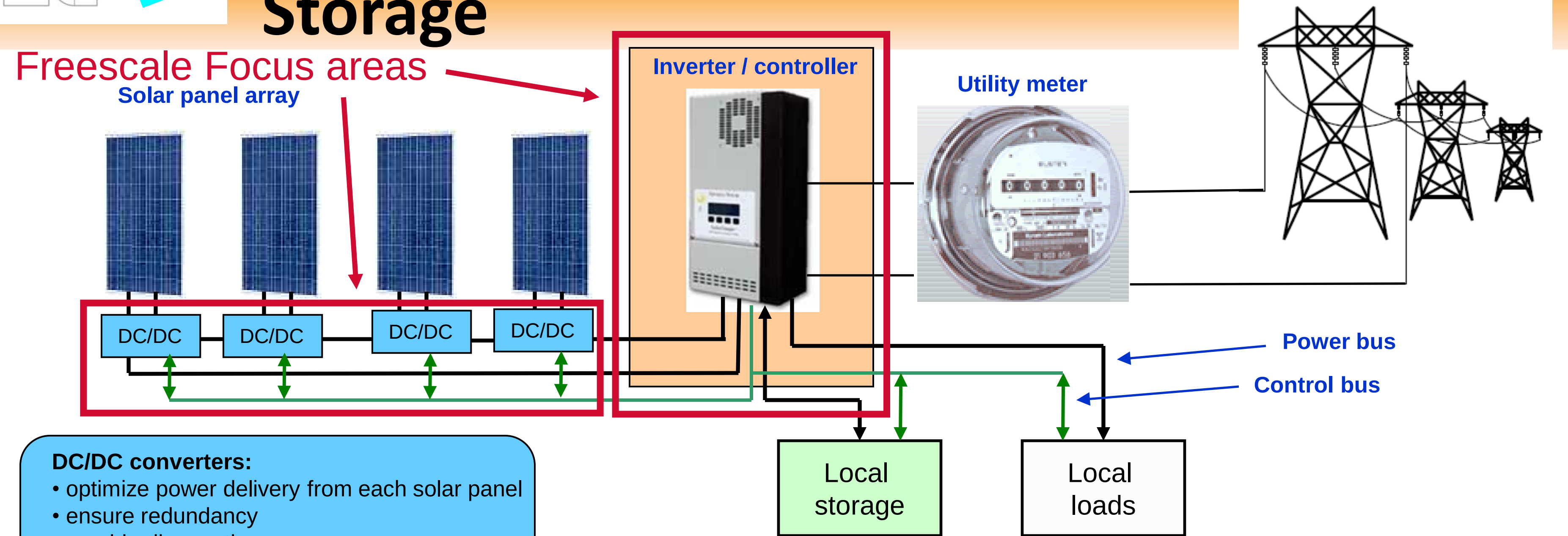



Grid-Tie Industrial

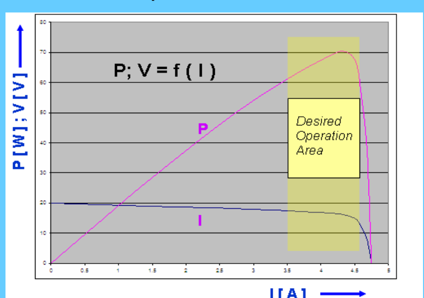
**12 kW to MWs, 3-phase**

>90% of PV installations (on a power-basis) are grid-tie

# PV System Example – Grid Tie with Local Storage




**DC/DC converters:**
- optimize power delivery from each solar panel
- ensure redundancy
- provide diagnostics
- indicate performance of each panel
- helps indicate degradation
- assist in failure prediction

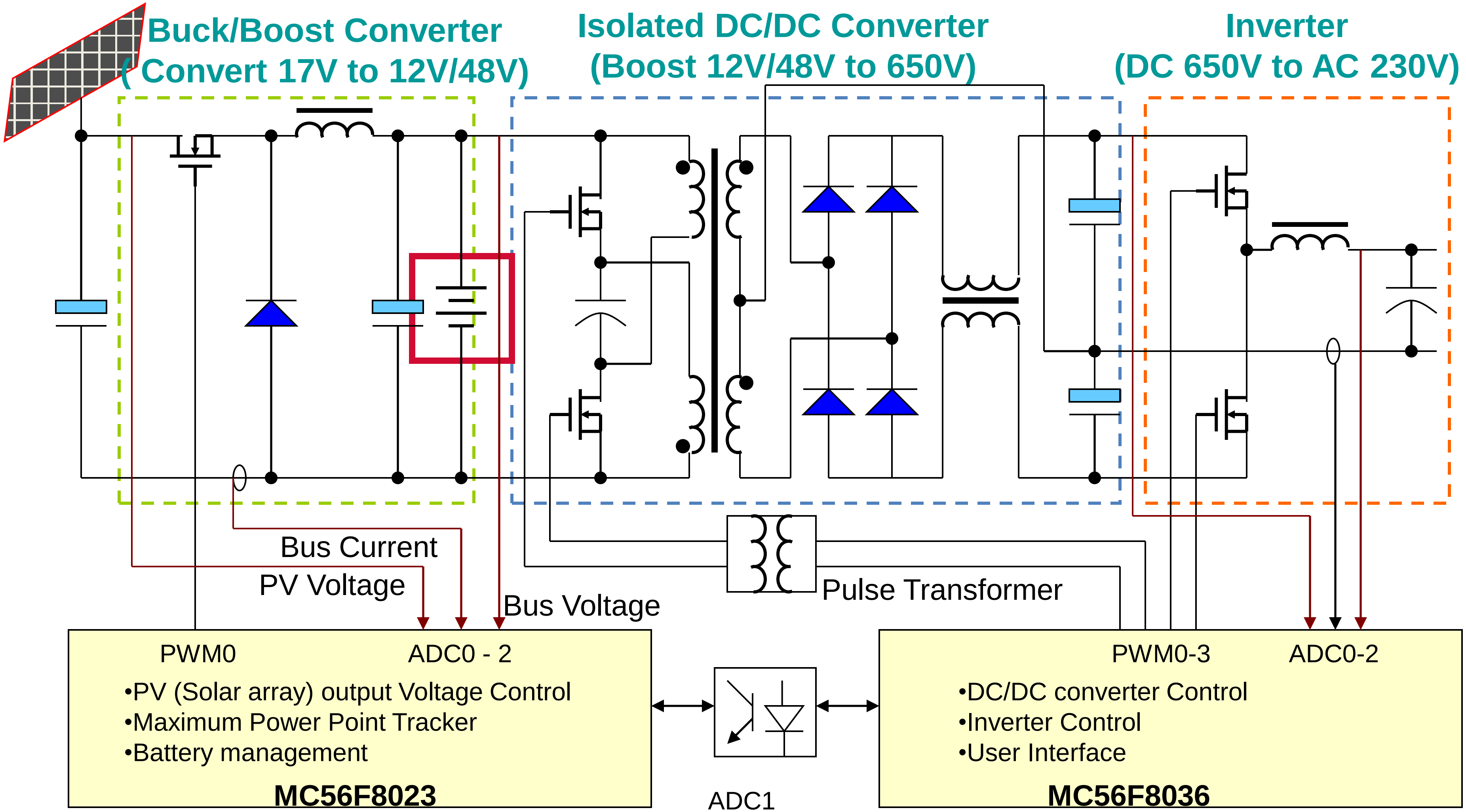



**FSL Power/Control module**
- converts DC into AC power
- control & collects data from DC/DCs
- controls battery
- coordinates power delivery to utility grid
- coordinates major local loads
- optimize gain
- drive interfaces

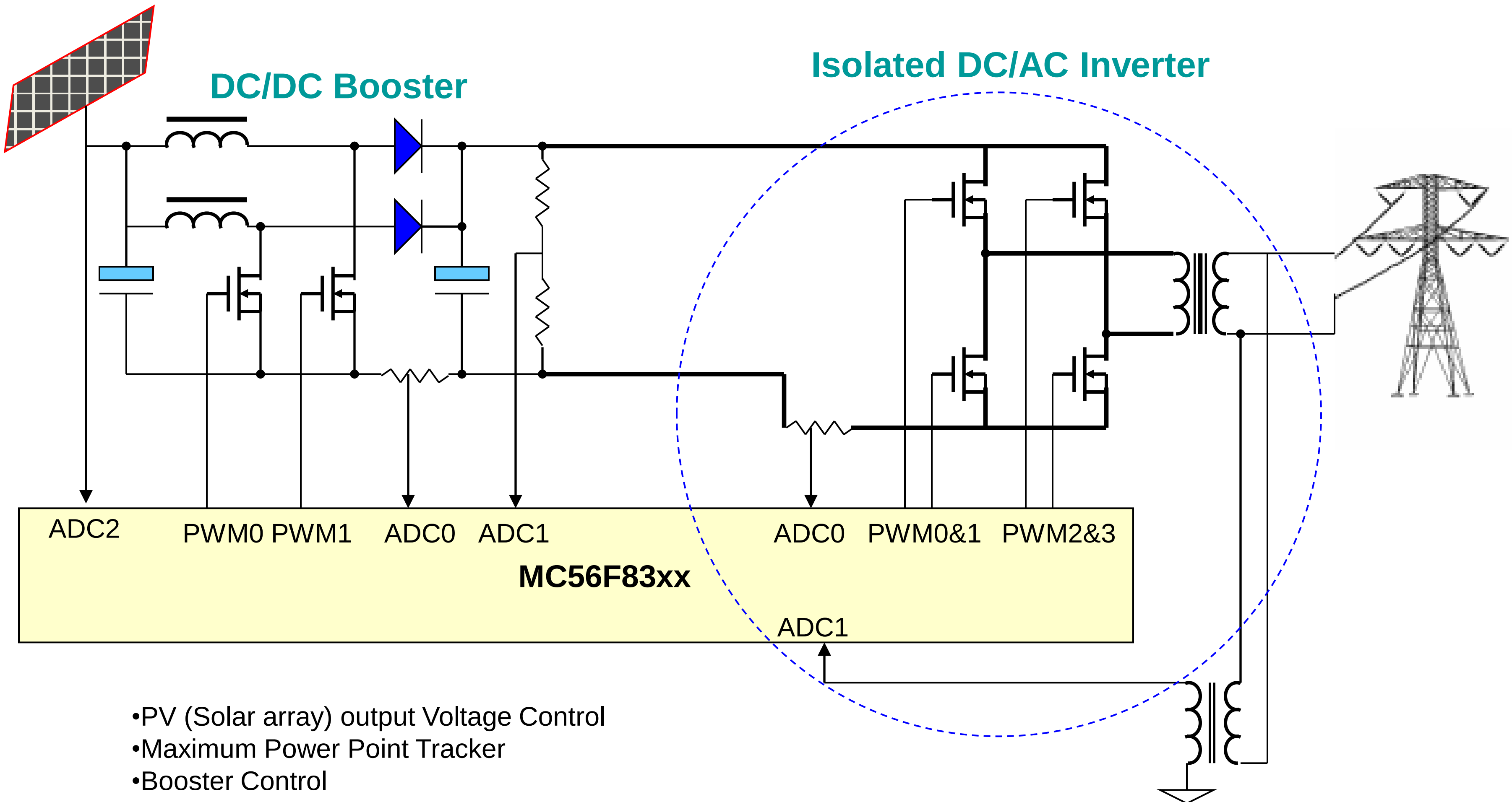
**Local storage:**
- provides storage during lower energy demand
- assists in grid balance (islanding)
- optimize gain
- serves as a backup source during power failure

Optimized Solar Energy System ensures maximum capture of Solar Energy along with minimum operating cost. It provides redundancy with backup power to the customer and at the same time it interacts with utility command center to optimize grid conditions.

# Off-Grid Isolated Solar Inverter
# - For Residential (less than 1KW)

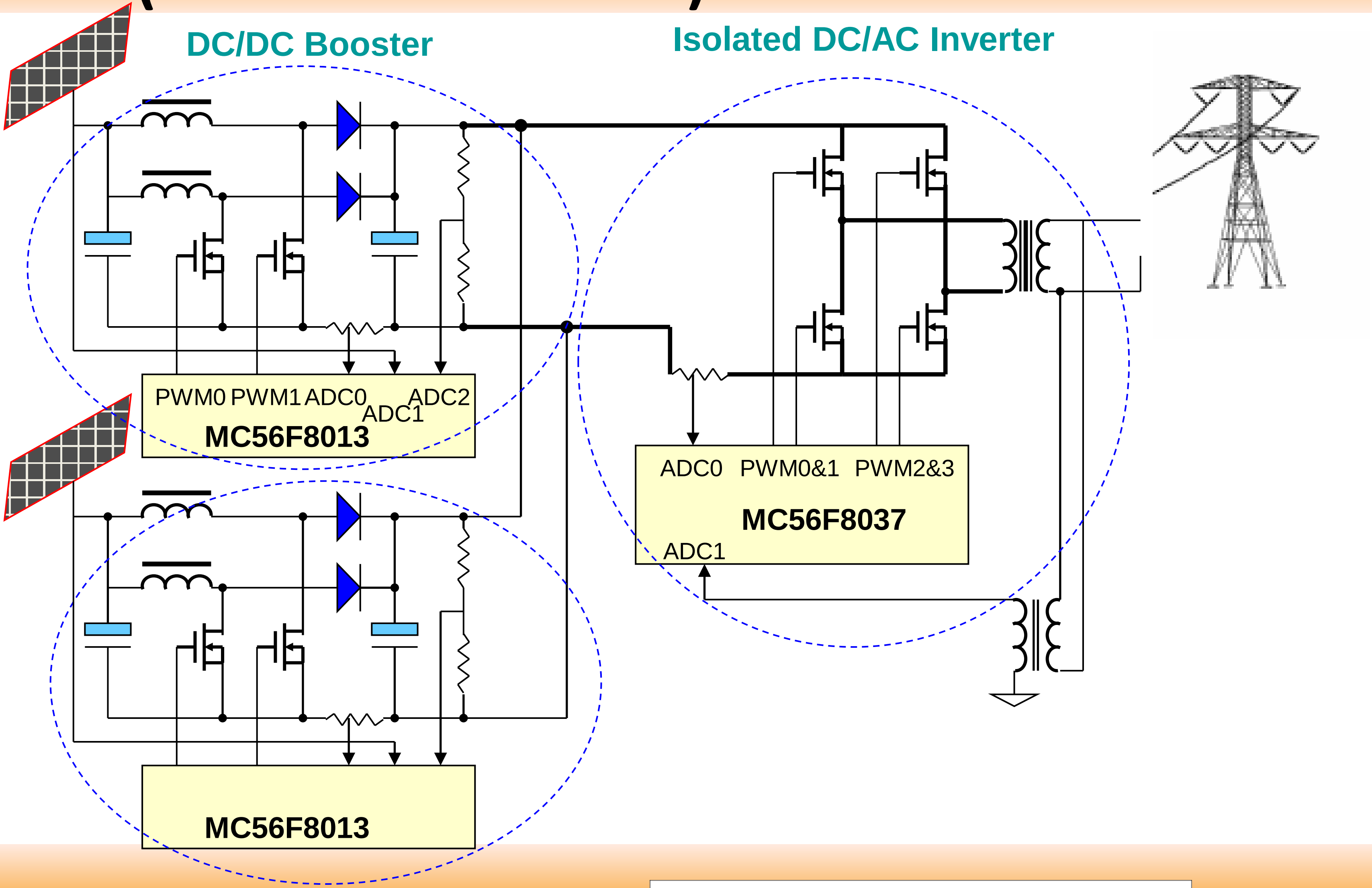


# Grid-Tied Solar Generator-Low Power ( less than 3KW)




- •PV (Solar array) output Voltage Control
- •Maximum Power Point Tracker
- •Booster Control
- •Inverter Control

# Grid-Tied Solar Generator-High Power (Greater than 3KVA)



# THANK YOU