16.810 Guest Lecture

AZURE
DYNAMICS

About the Speaker

- Grew up in Zürich, Switzerland
- Got the EV “bug” in 1992
- Joined Solectria in 1999
- Now power electronics R&D Manager at Azure Dynamics

Beat Arnet

Azure Dynamics Overview

- Proprietary Hybrid Electric Vehicle technology – cost effective components and state-of-the-art software controls:
  - 70+ dedicated engineers worldwide
  - Strategic supply chain relationships
- Business strategy focused on urban commercial and military vehicles:
  - Series and parallel hybrid technology
  - Value proposition driven
- Growing customer base:

  Frito Lay, US Postal Service, Purolator, Canada Post, BOEDC, AM General, US DOD, Smiths Electric Vehicles & Charmer Sunbelt
- Publicly traded stock:
  - Canada's TSX Exchange - AZD
  - London's AIM Exchange - ADC

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Azure Dynamics Operations

BOSTON is focused on delivering cost effective components and parallel hybrid drive systems

- 50 employees
- Over 4,000 electric & hybrid vehicle drive systems in use worldwide
- 78,000 sq ft facility
- ISO 9001:2000 certified

VANCOUVER is focused on vehicle integrations and operating system efficiencies

- 55 employees
- Modern 21,000 sq ft facility

COVENTRY (UK) is focused on delivering cost effective components and the opening of continental Europe

- Sales
- Integration engineering support
- 8 employees
- 5,000 sq ft facility

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Vehicle Powertrain Offering

Product	Weight	Applications
G1 Series & Electric	9,000 to 16,000 lbs	Delivery Vans, Shuttle Buses, Specialty Vehicles
G2 Series & Electric	5,000 to 8,500 lbs	Delivery Vans, Taxis, Specialty Vehicles
P1 Parallel	10,000 to 18,000 lbs	Delivery Vans, Shuttle Buses, Specialty Vehicles, Military (HMMWV)
P2 Parallel	22,000 to 35,000 lbs	Delivery Trucks, Transit Buses, Trash Haulers, Military (FMTS)

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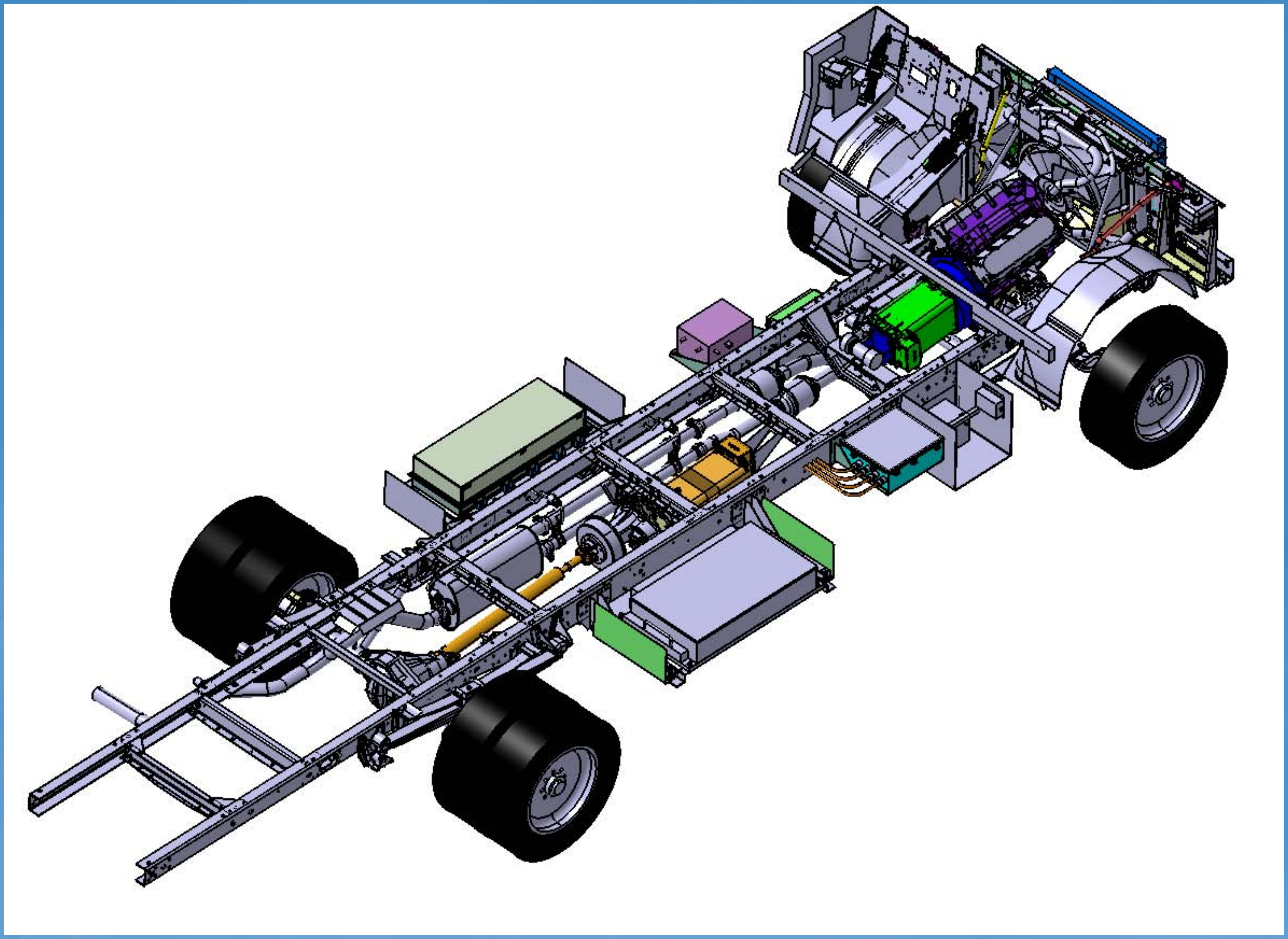
Purolator Series Hybrid



Presentation Outline

- Who is Azure Dynamics?
- How can we reduce vehicle CO_2 emissions?
- The electric drive is at the heart of most solutions!
- Electric drive lesson:
  - Electric Motors, Inverters, Space-Vectors, Clarke & Park Transformation, PWM, Vector Control, Torque-Speed Envelopes
- Real world challenges
- Skills and tools of the trade
- Azure Product Development Process
- Show & tell

AZURE DYNAMICS

How to reduce vehicle CO_2 emissions?

?

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How to reduce vehicle CO_2 emissions?

- Decrease vehicle weight
- Increase vehicle efficiency (Tank-to-Wheels)
  - Reduce aerodynamic drag
  - Reduce rolling resistance
  - Increase powertrain and drivetrain efficiency
  - Use more efficient energy sources
  - Utilize energy sources with low CO_2 emissions
- Improve Well-to-Tank efficiency

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What an Electric Drive Can Do...

- Regenerative braking
- Waste-heat recovery
- Electrification of auxiliaries
- Engine load leveling
- Decoupling of engine speed
- Engine idle stop
- Use of non fossil fuel
  - BEVs
  - FCEVs
  - Plugin-HEVs

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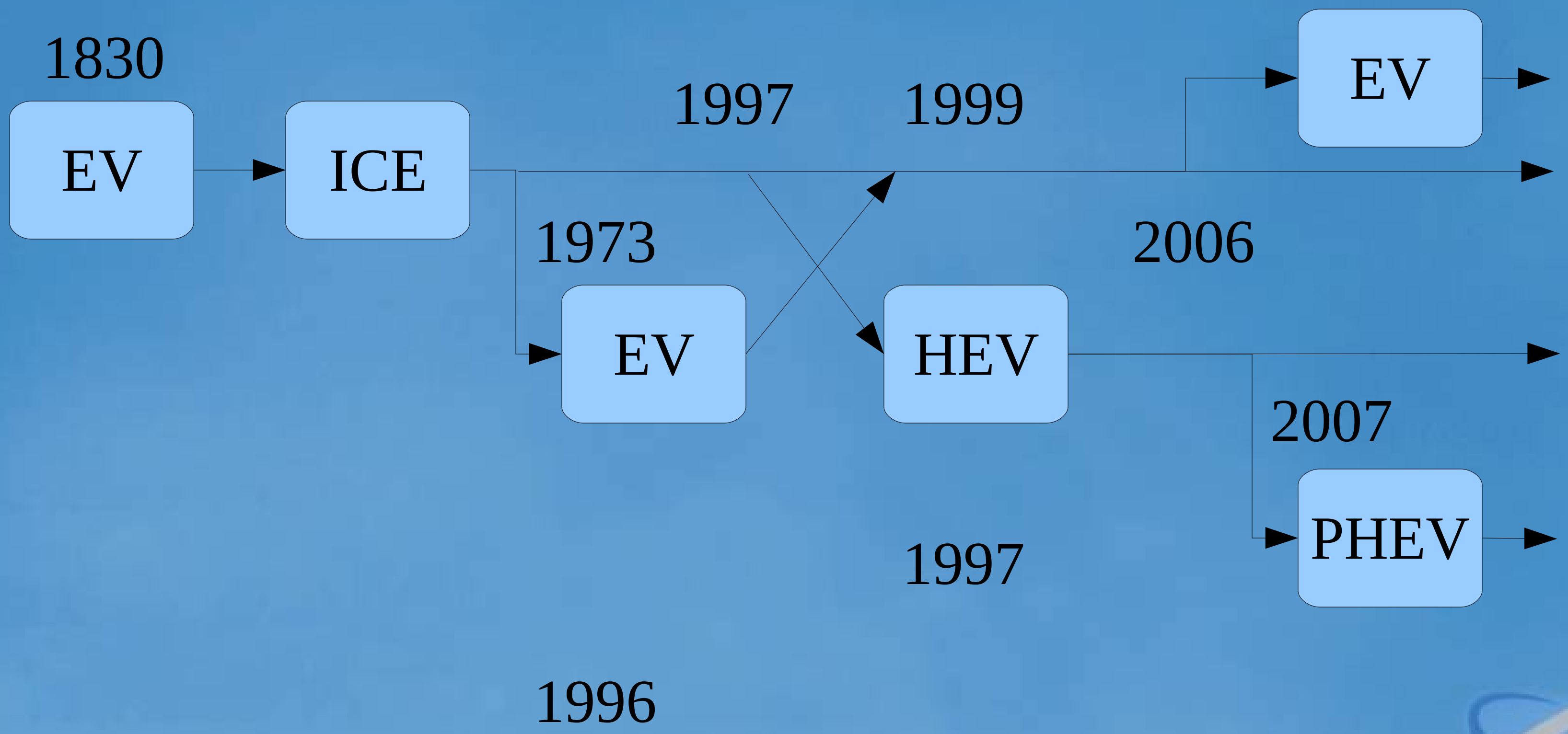
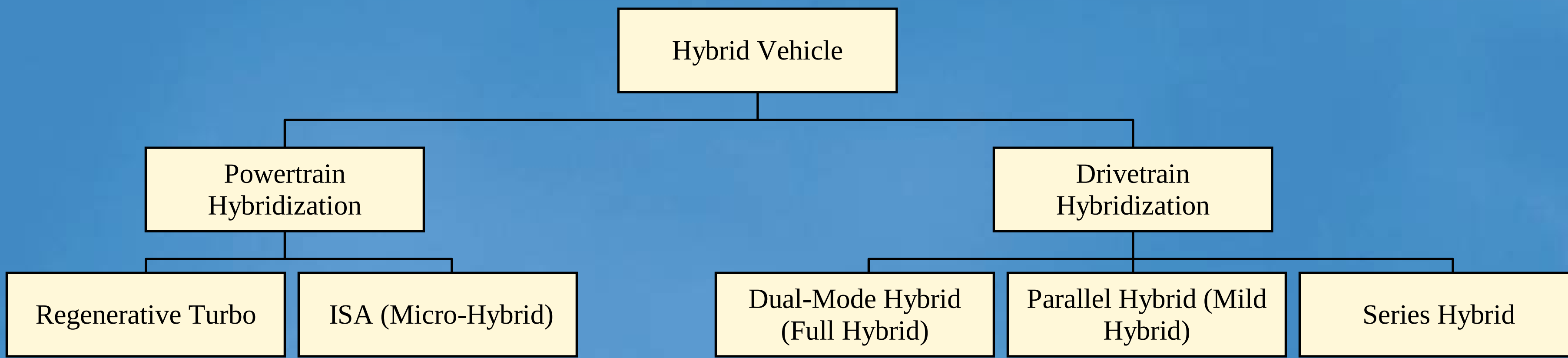
Electric Drives for Vehicles, once hot, then cold, and now in again



Hybrid Vehicle Categories

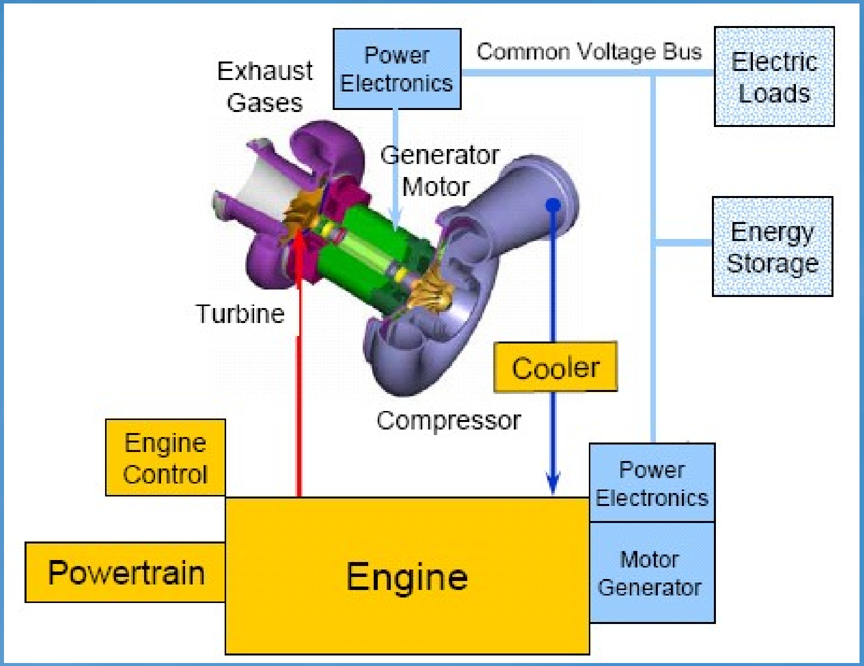


Plugin Hybrids – Make a lot of "noise"

- Charged at night when utility has excess power
- Most commutes all electric
- "Unlimited" range
- Could be part of V2G system
- BUT:
  - Expensive battery
  - Reduced efficiency when in HEV mode
  - Increase SOx

Waste Heat Recovery

- Turbocharger with an integrated turbo-shaft motor/generator
- Crankshaft motor/generator
- Small battery
- Can provide up to 5% of fuel savings in certain driving conditions
- Examples: Caterpillar ETC



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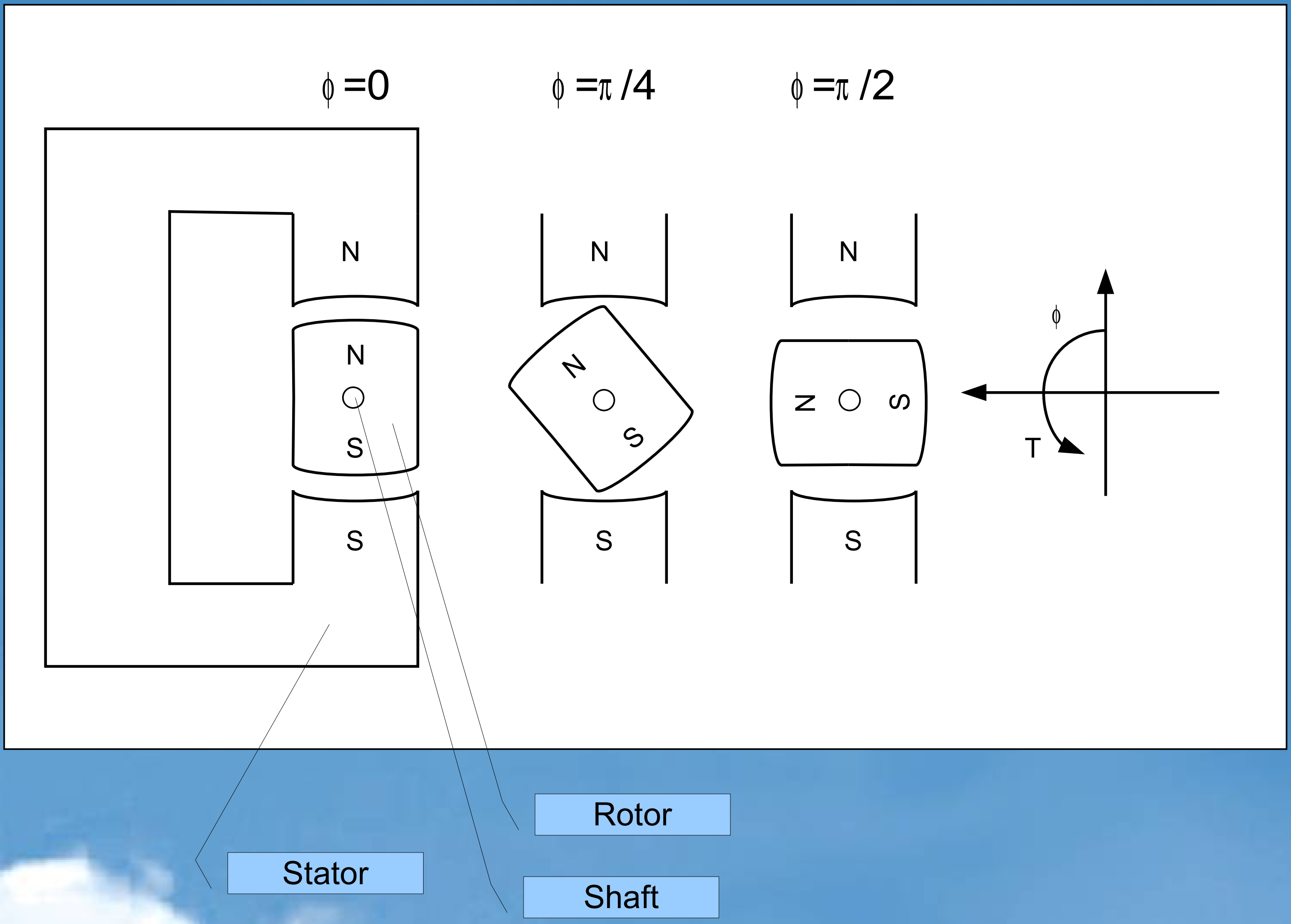
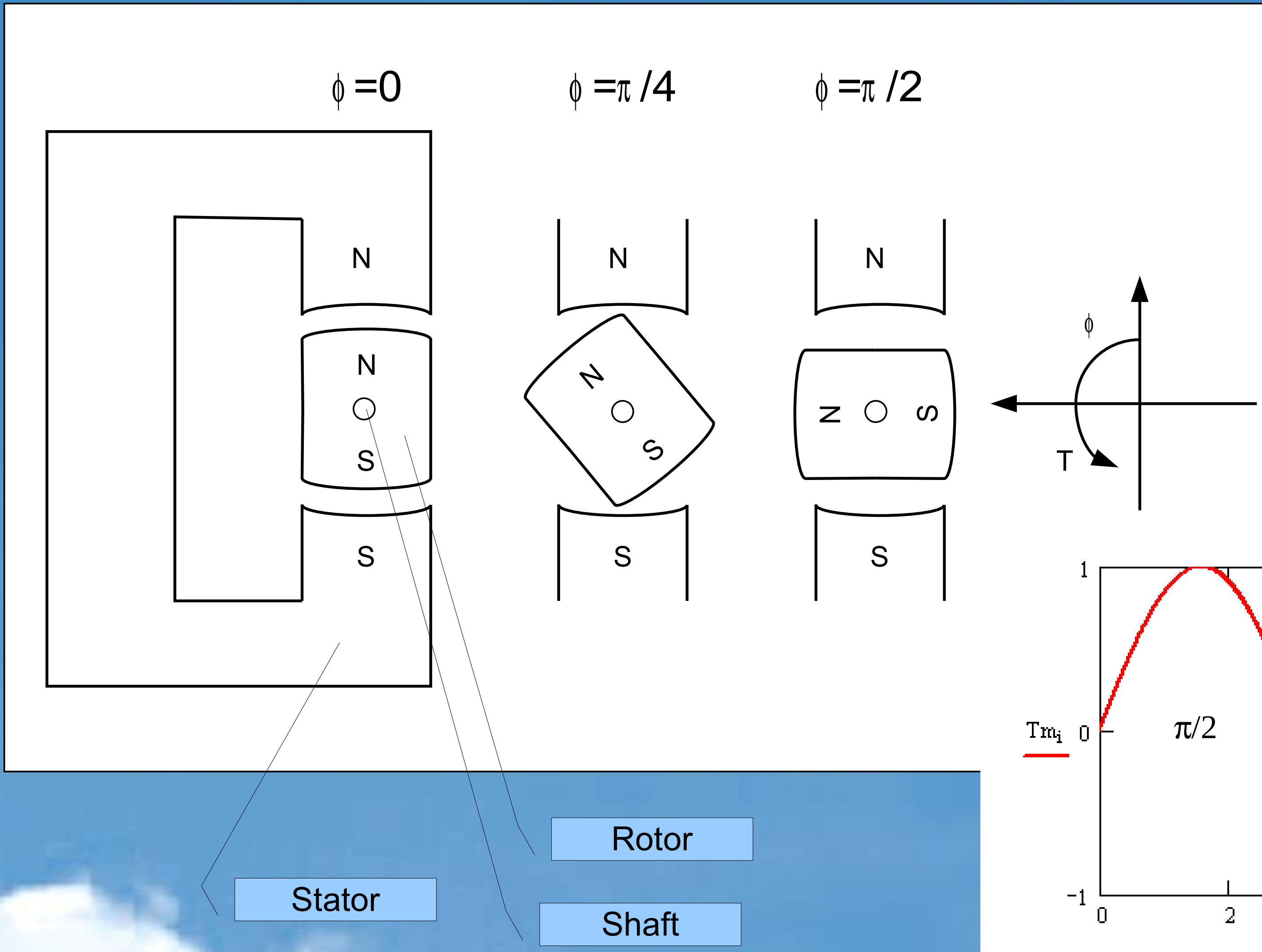
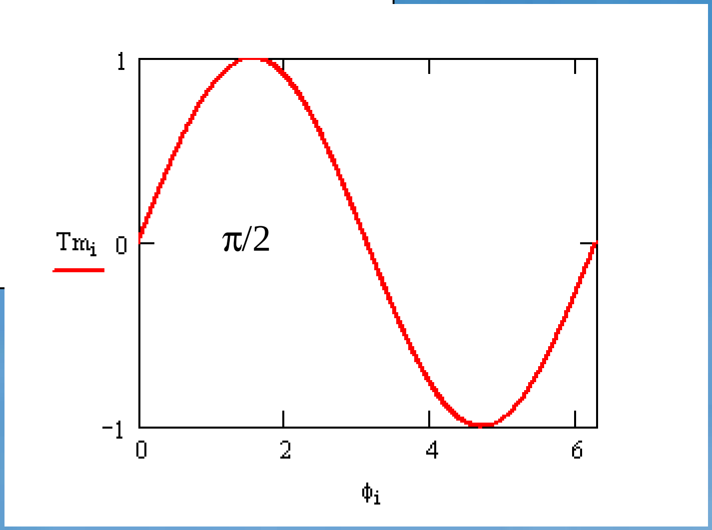
AZURE DYNAMICS

Magnet Motor

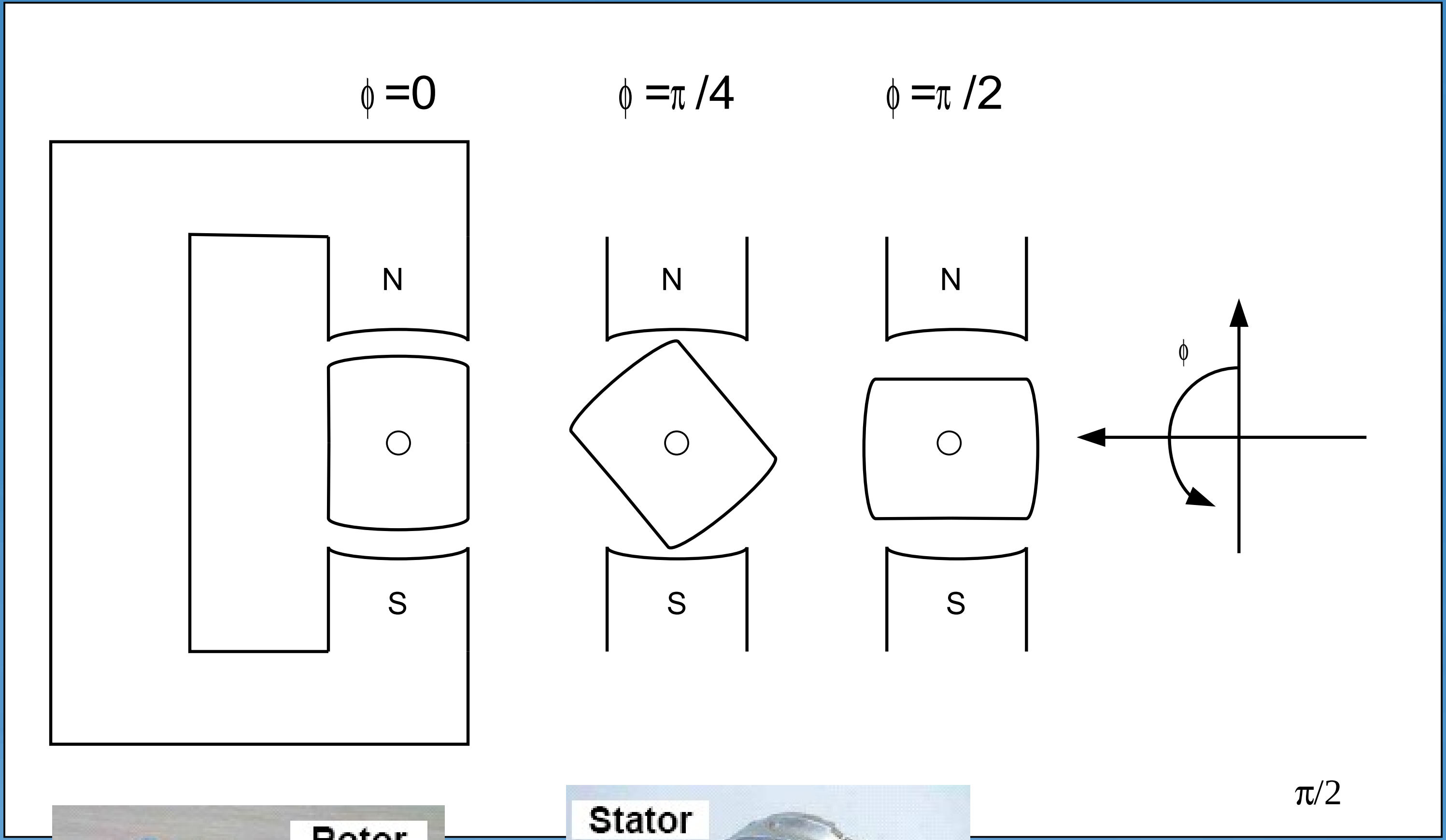


Magnet Motor

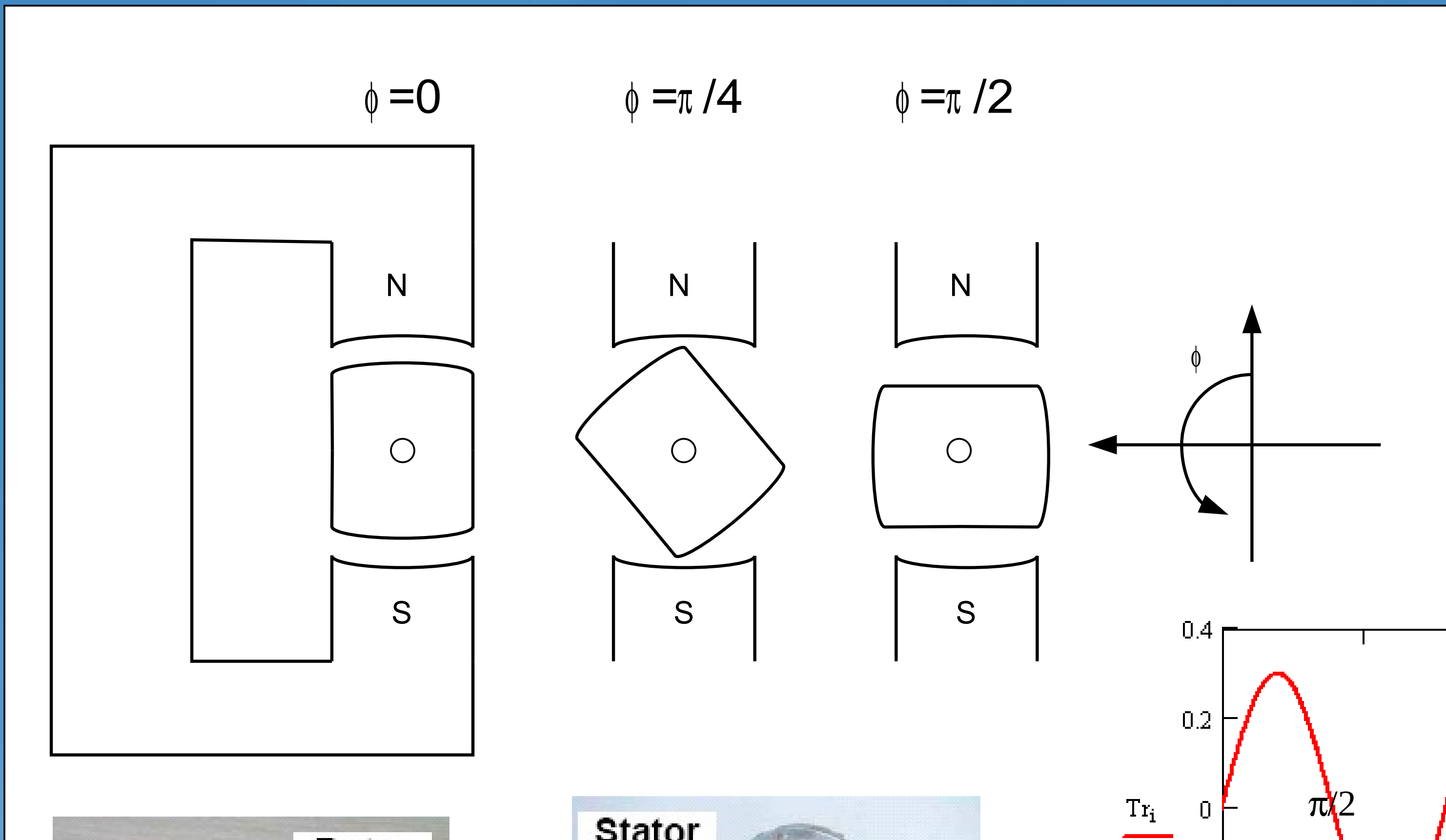


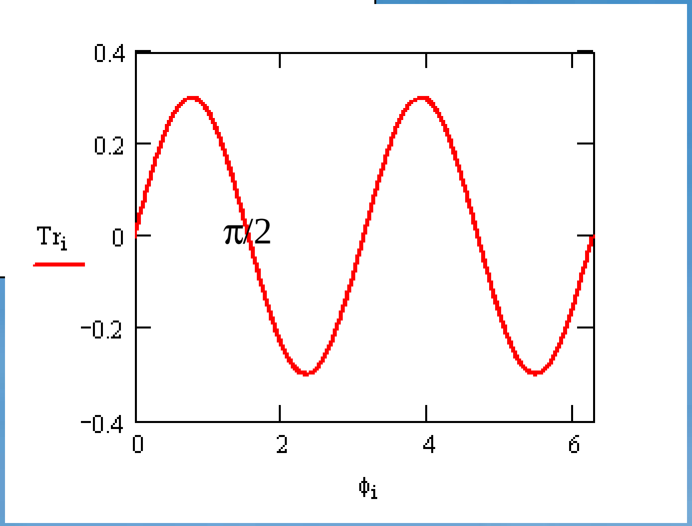


Variable Reluctance Rotor



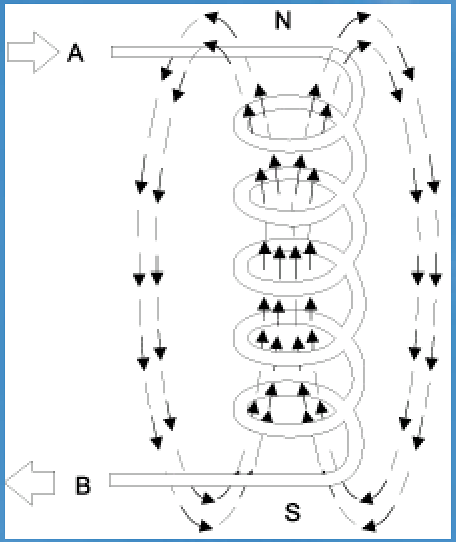
Variable Reluctance Rotor





Summary: Torque Production

- Torque is produced by:
  - Interaction of two magnetic fields
  - Interaction of a magnetic field and saliency (reluctant torque)
- A magnetic field can be produced by:
  - Permanent magnets
    - Ferrite
    - AlNiCo
    - SmCo (most expensive, but highest temperature rating)
    - NdFeB (most affordable and powerful rare earth)
  - Current in a coil (electromagnet)



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Major Electric Motor Types

	Stator	Rotor
DC Motor	PM	EM
Switched Reluctance	EM	VR
PM Motor	EM	PM (+VR)
Induction Motor	EM	EM

- PM: Permanent Magnet
- EM: Electromagnet
- VR: Variable Reluctance

- All electric motors require at least one (rotating) electromagnet

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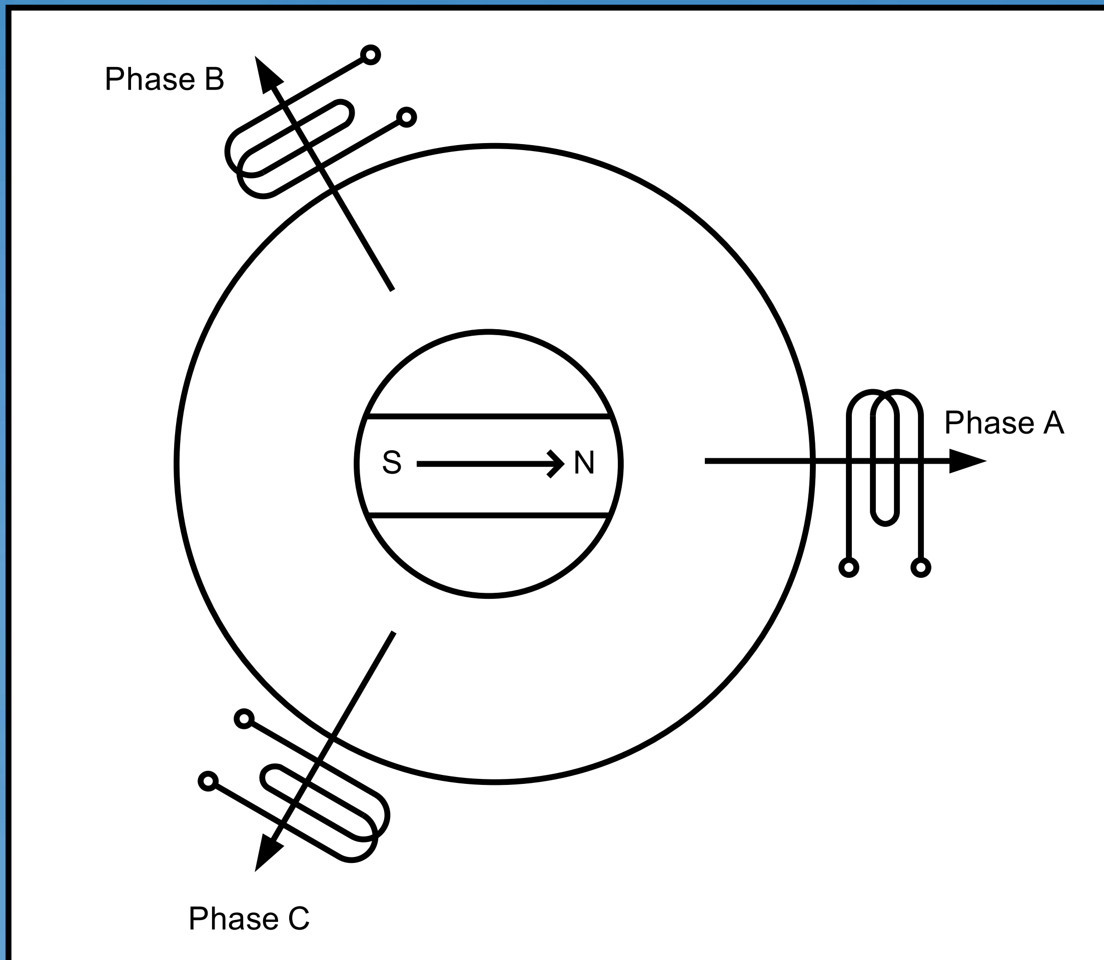
Phase B
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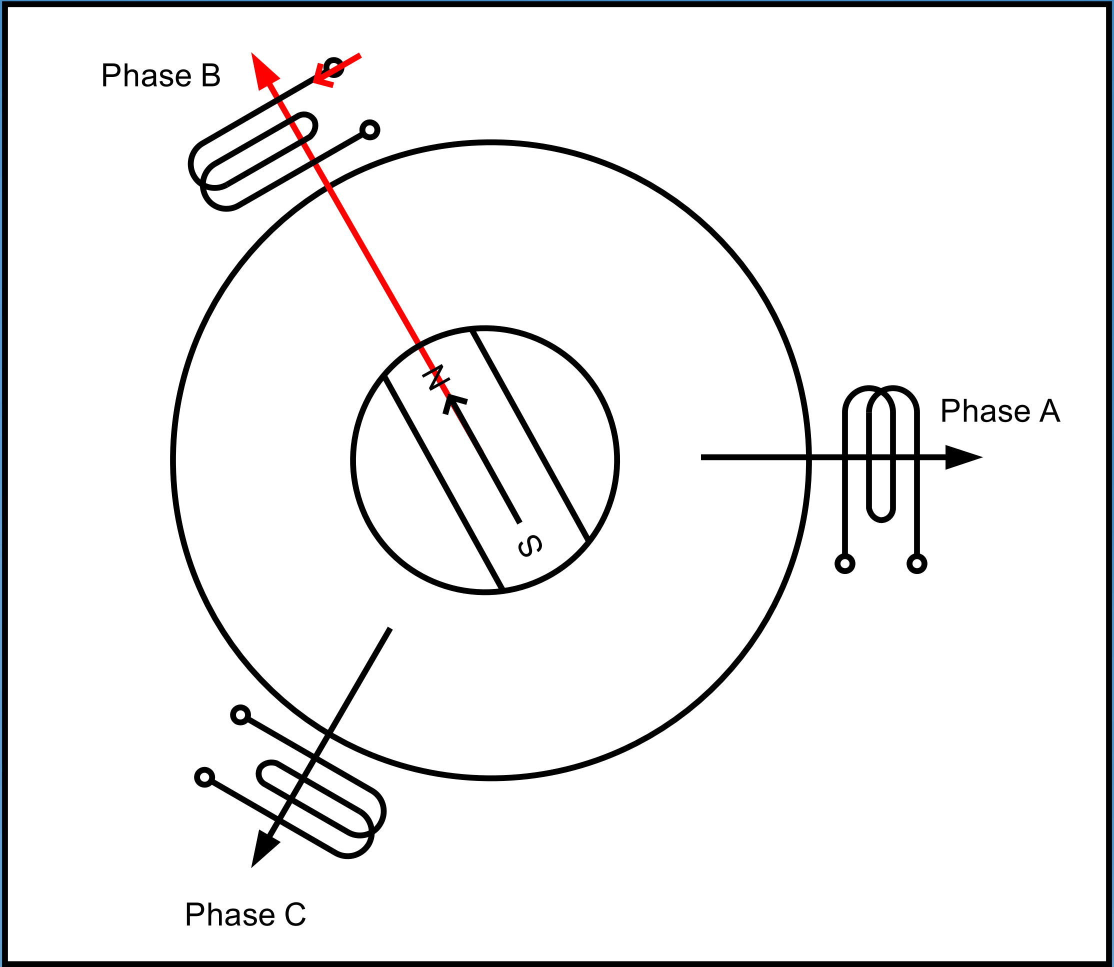
N
Phase A
Phase C



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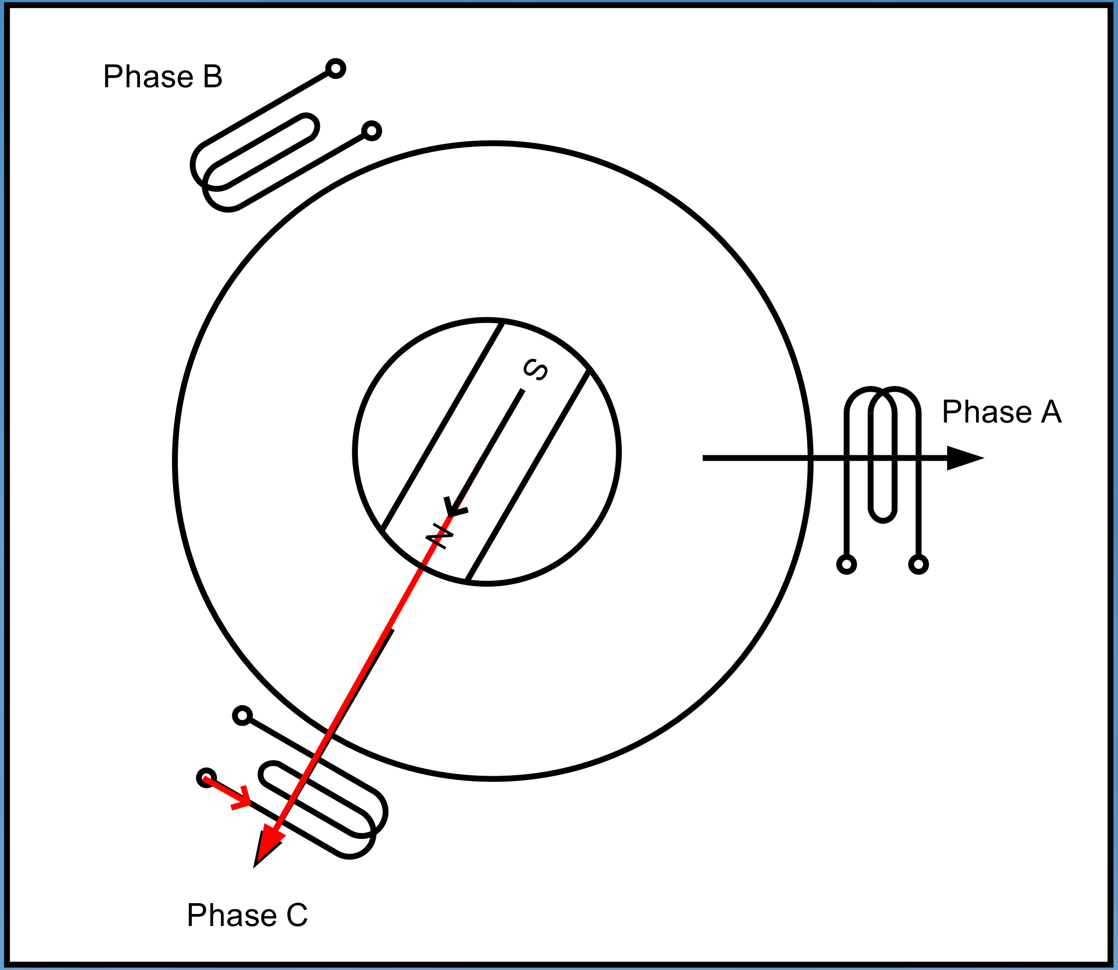
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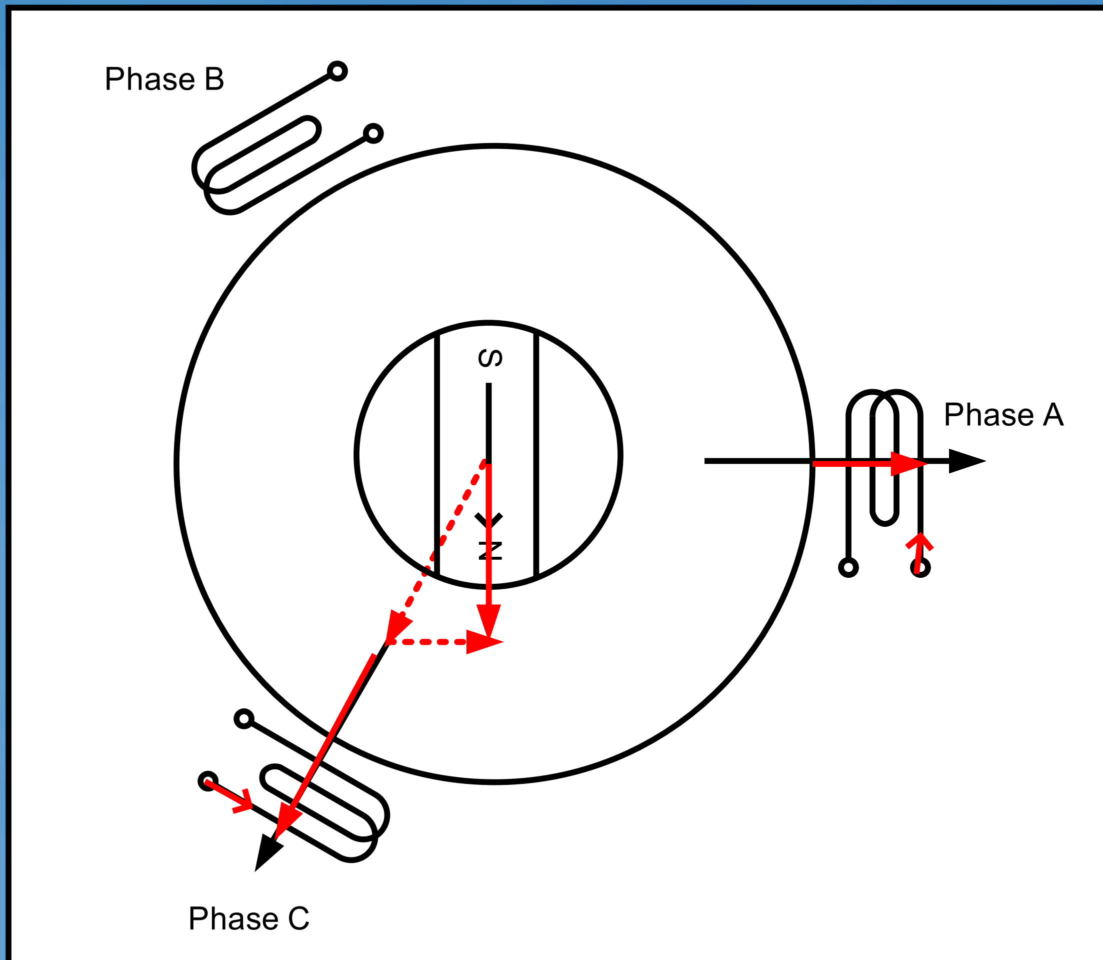

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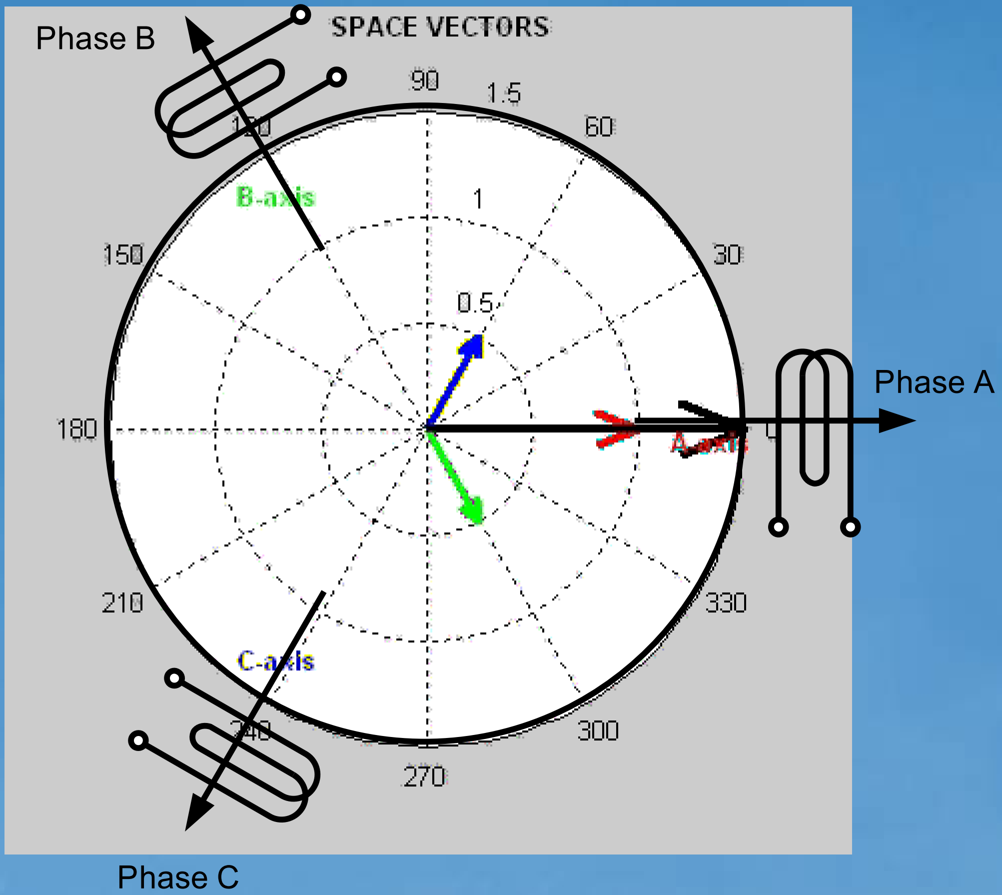
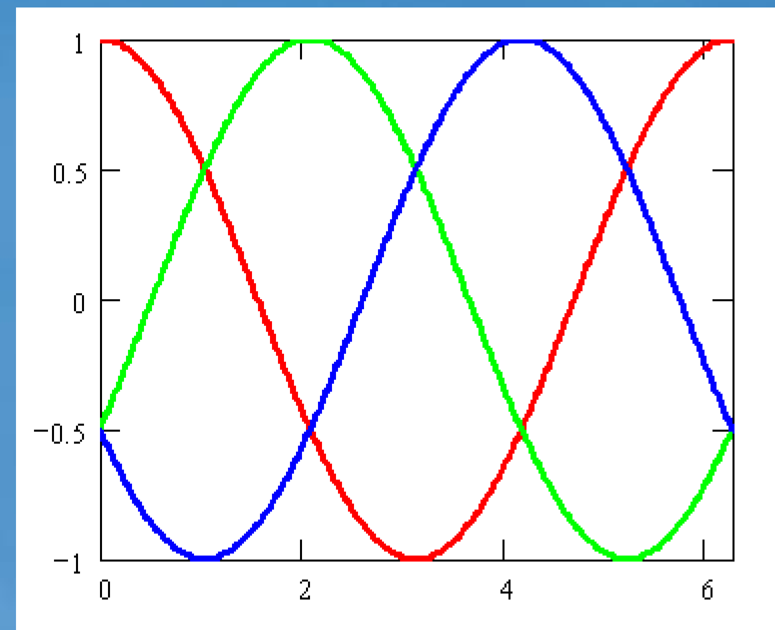
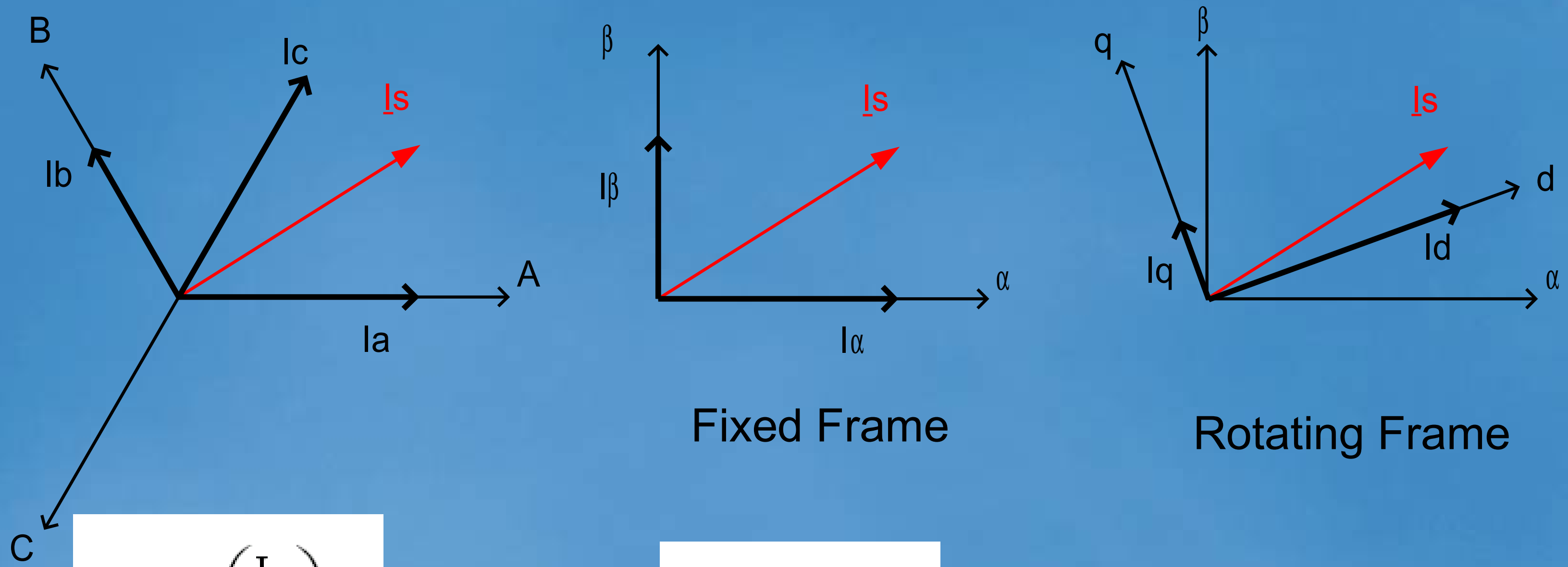


Stator Flux Vector



Phase Currents

Space Vectors



$$I_s = \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix}$$

Clarke

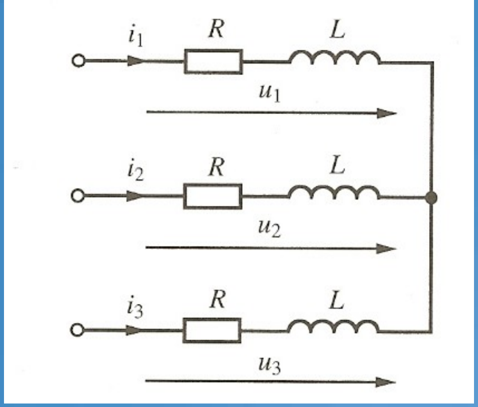
$$I_s = \begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix}$$

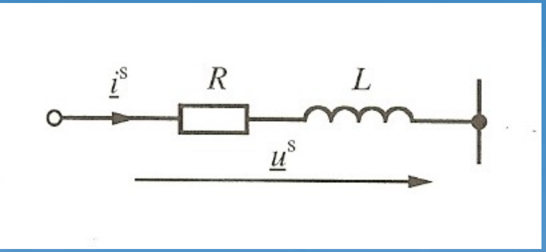
Park

$$I_s^{dq} = I_s \cdot e^{j \cdot \phi}$$

$$I_a + I_b + I_c = 0$$

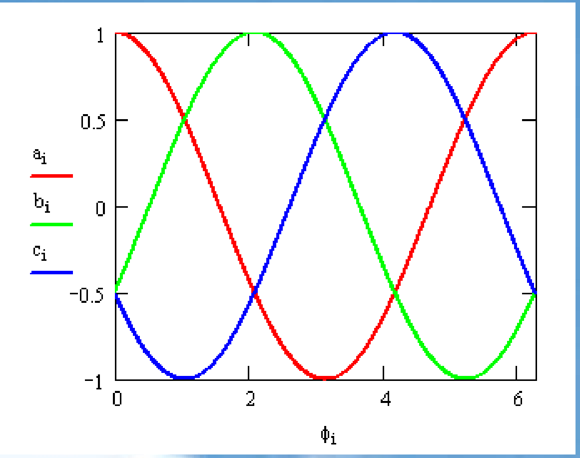
“Complex” makes it less complex





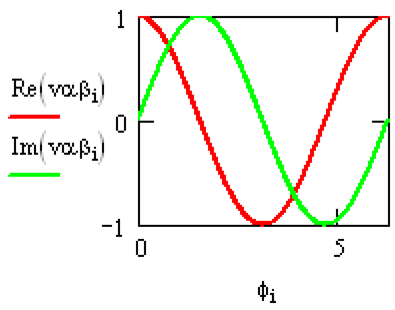
Clarke

Park



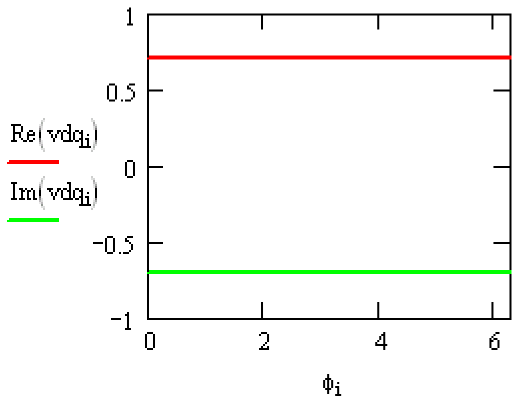
$$\alpha_i := a_i \qquad \beta_i := \frac{1}{\sqrt{3}}\left(b_i - c_i\right)$$

$$v\alpha\beta_i := \alpha_i + j \cdot \beta_i$$

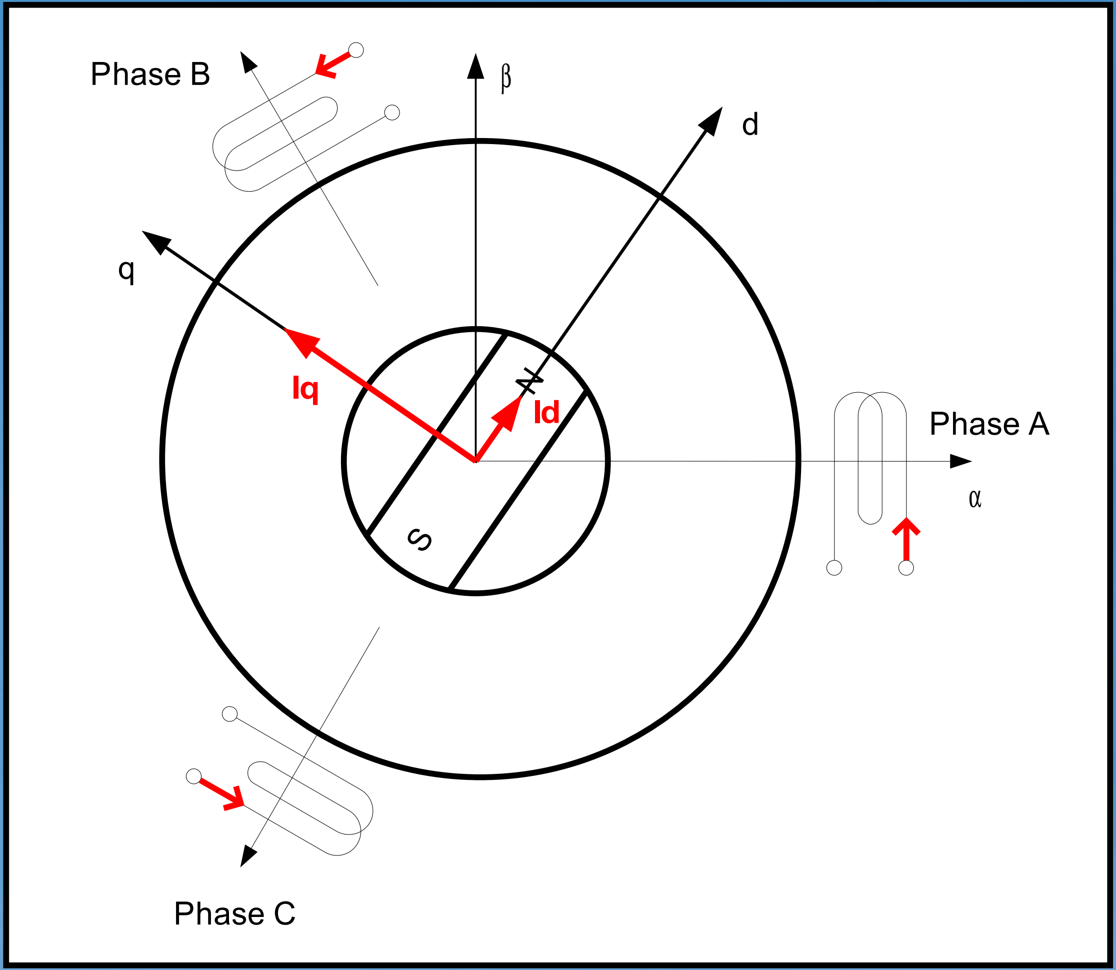


$$\phi 0 := \frac{\pi}{4}$$

$$vdq_i := v\alpha\beta_i \cdot e^{-j\cdot(\phi_i+\phi 0)}$$



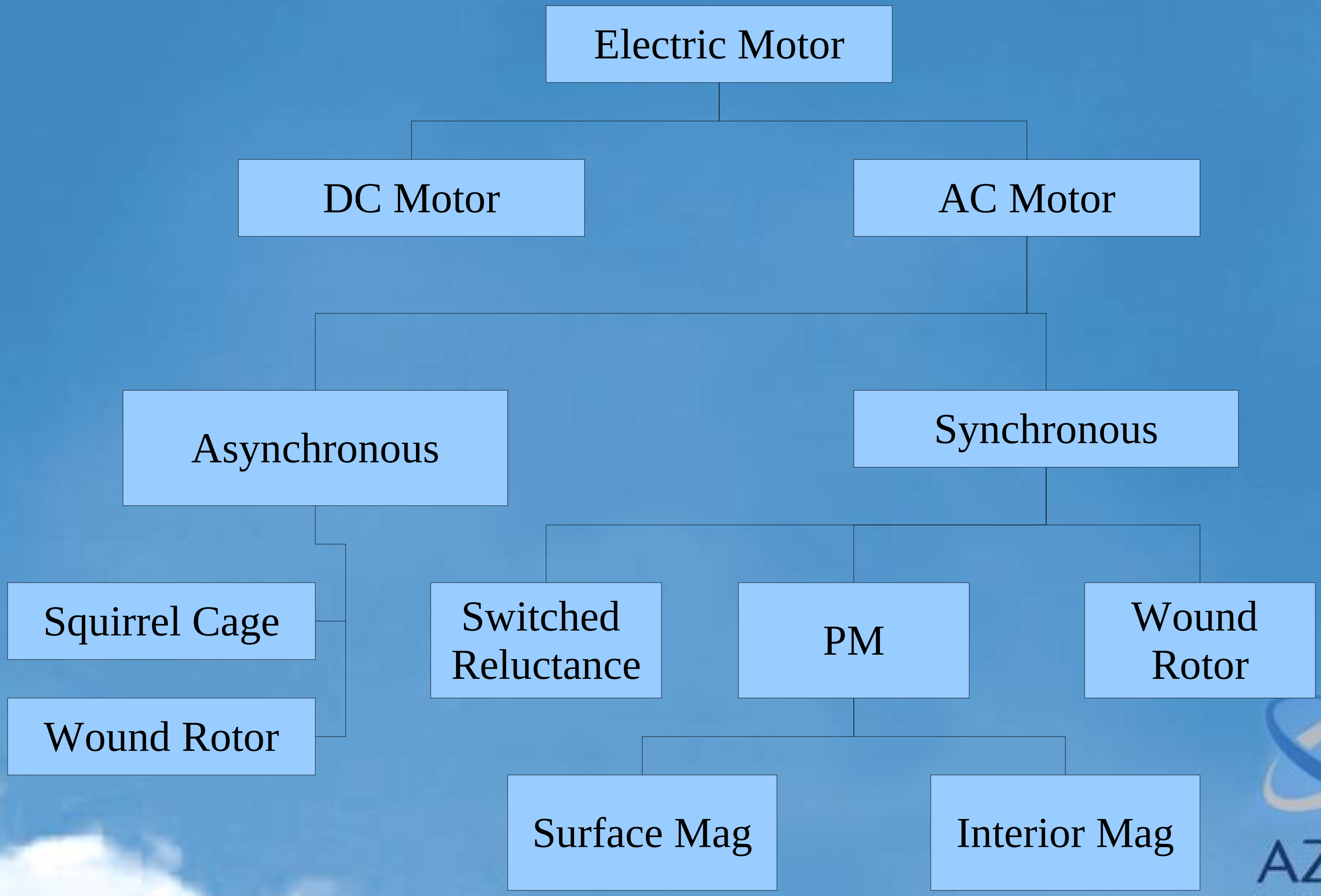
Vector Control



Creating a rotor field

- A electromagnet on the rotor can be achieved by:
  - Brushes and commutators (using a DC source)
  - Slip rings (with an AC source)
  - Induction (shorted rotor winding)

Motors for Electric Traction



Motors: Summary

- Mostly AC motors used for HEVs and EVs
  - PM Motors for Ford, Honda and Toyota Hybrids
  - Induction Motors for EVs and Azure Hybrids
- Torque is produced by
  - Interaction of two magnetic fields
  - Interaction of a magnetic field with variable reluctance
- A rotating stator field can be produced by a three-phase winding and sinusoidal currents
- A rotor field can be produced by
  - Permanent magnets
  - External supplied winding
  - Induced currents in shorted winding
- Space vectors lend themselves well for modeling motors

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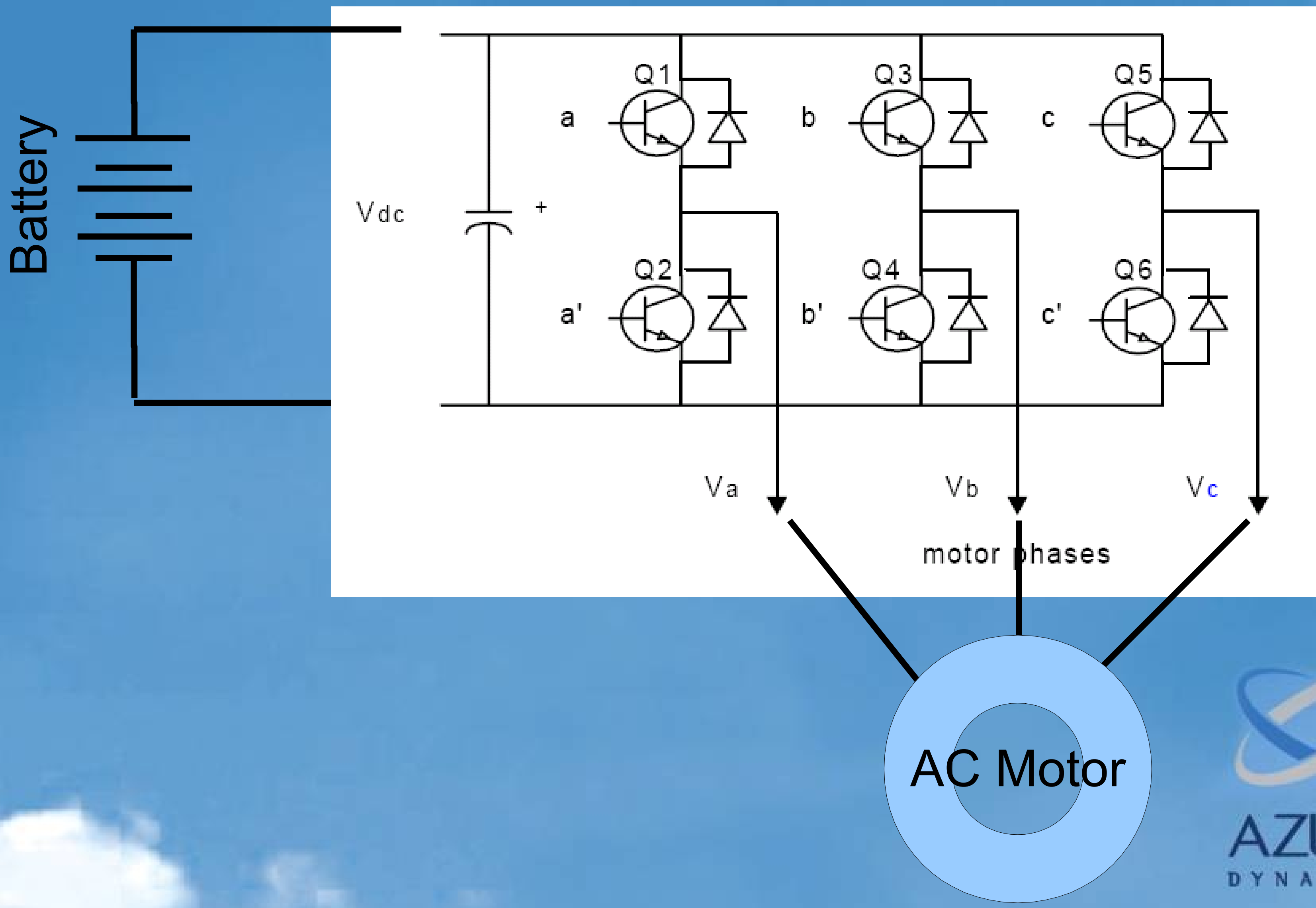
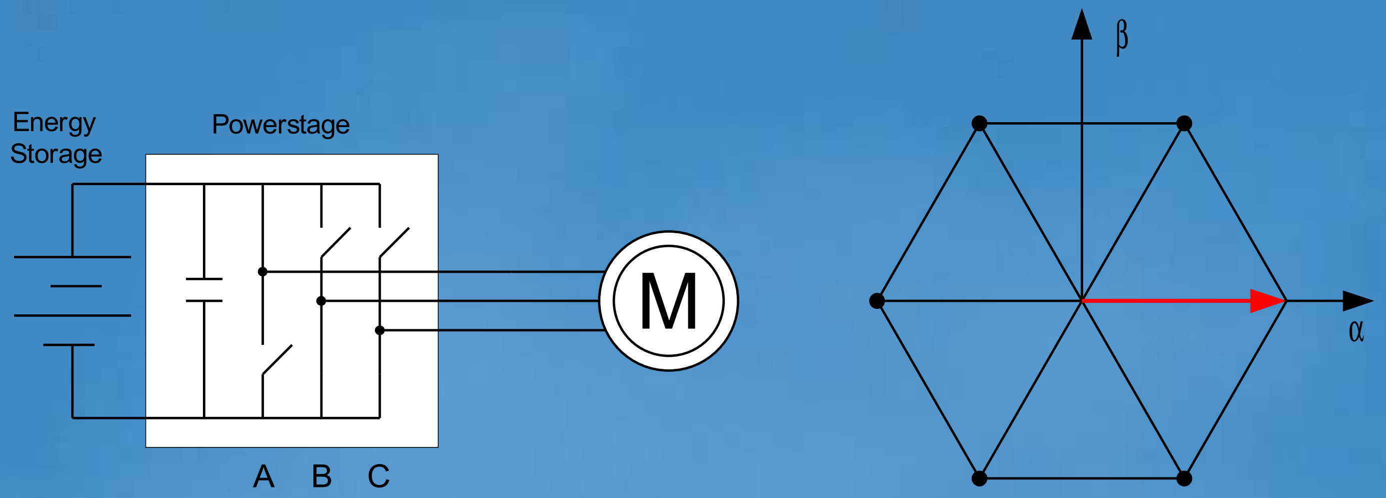
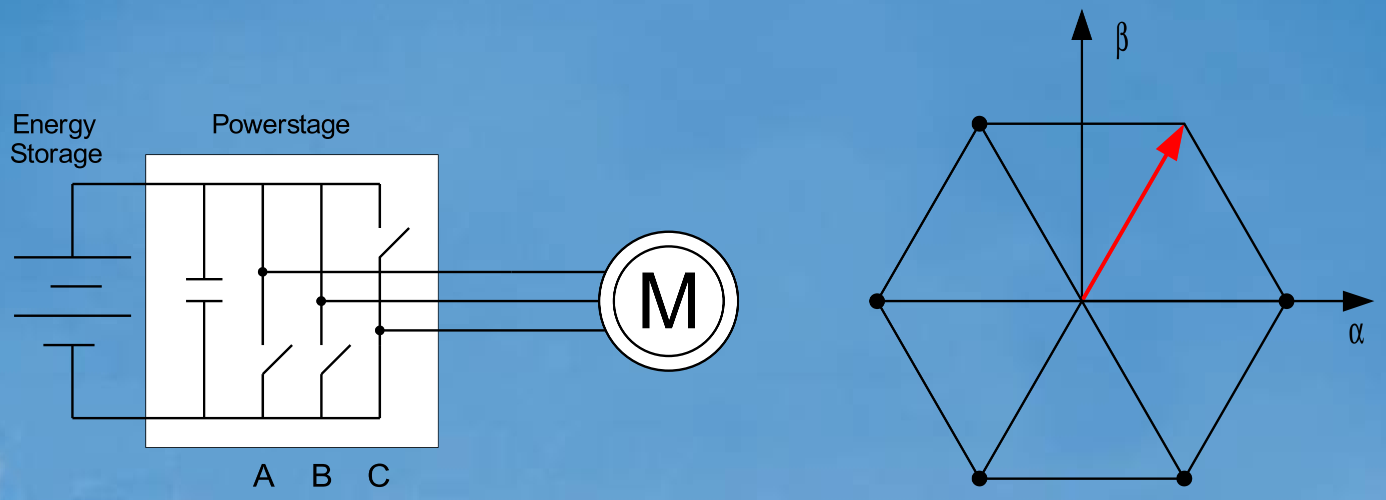
Inverter: How to control drive a AC Motor with a DC source

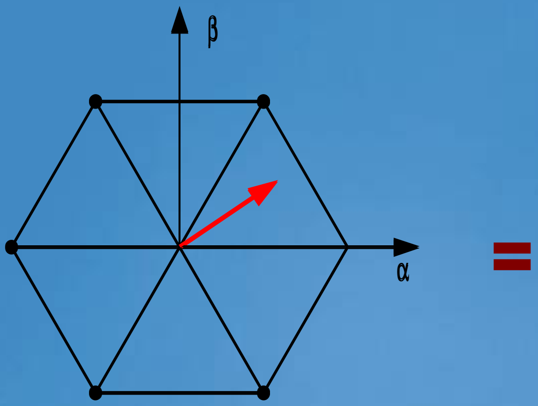


The Voltage Hexagon

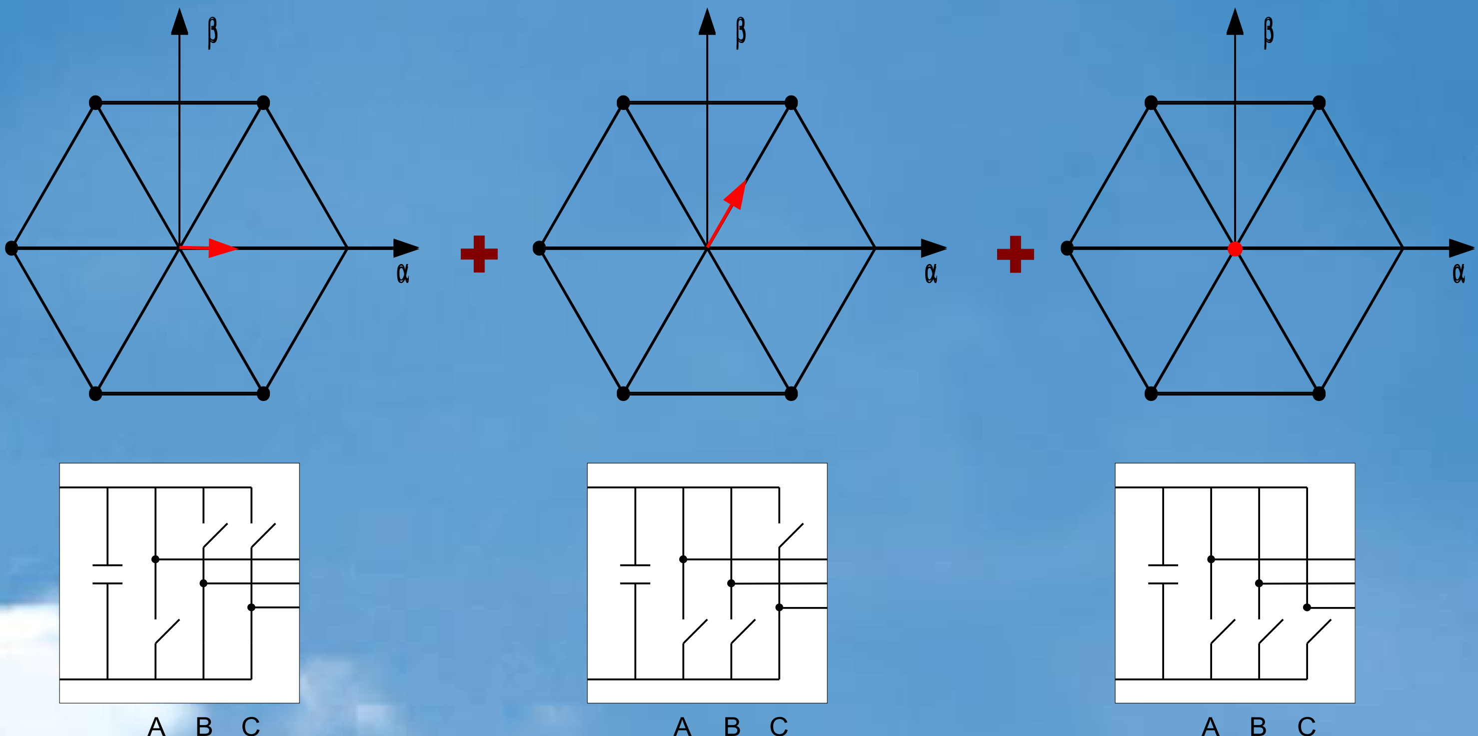




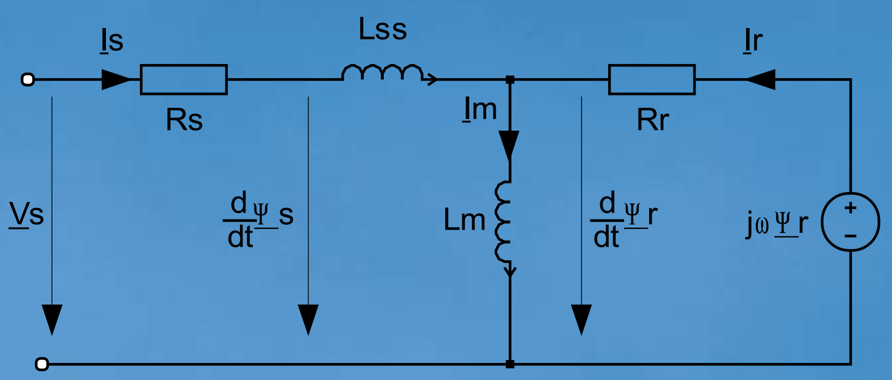
Space Vector Pulse Width Modulation

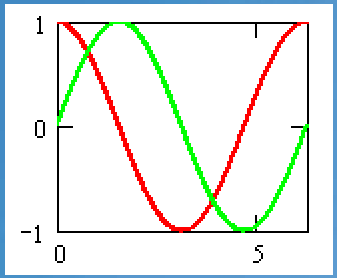


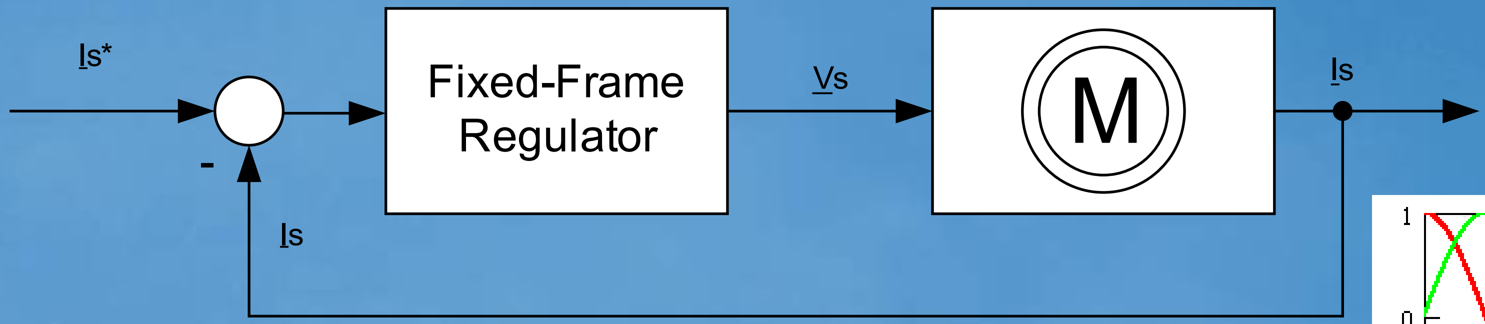
- Arbitrary voltage vectors are created by time averaging fundamental vectors

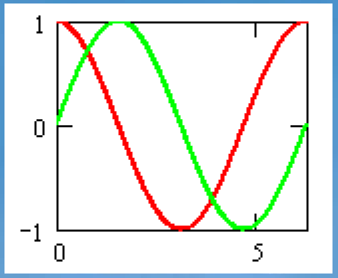


Motor Current Control

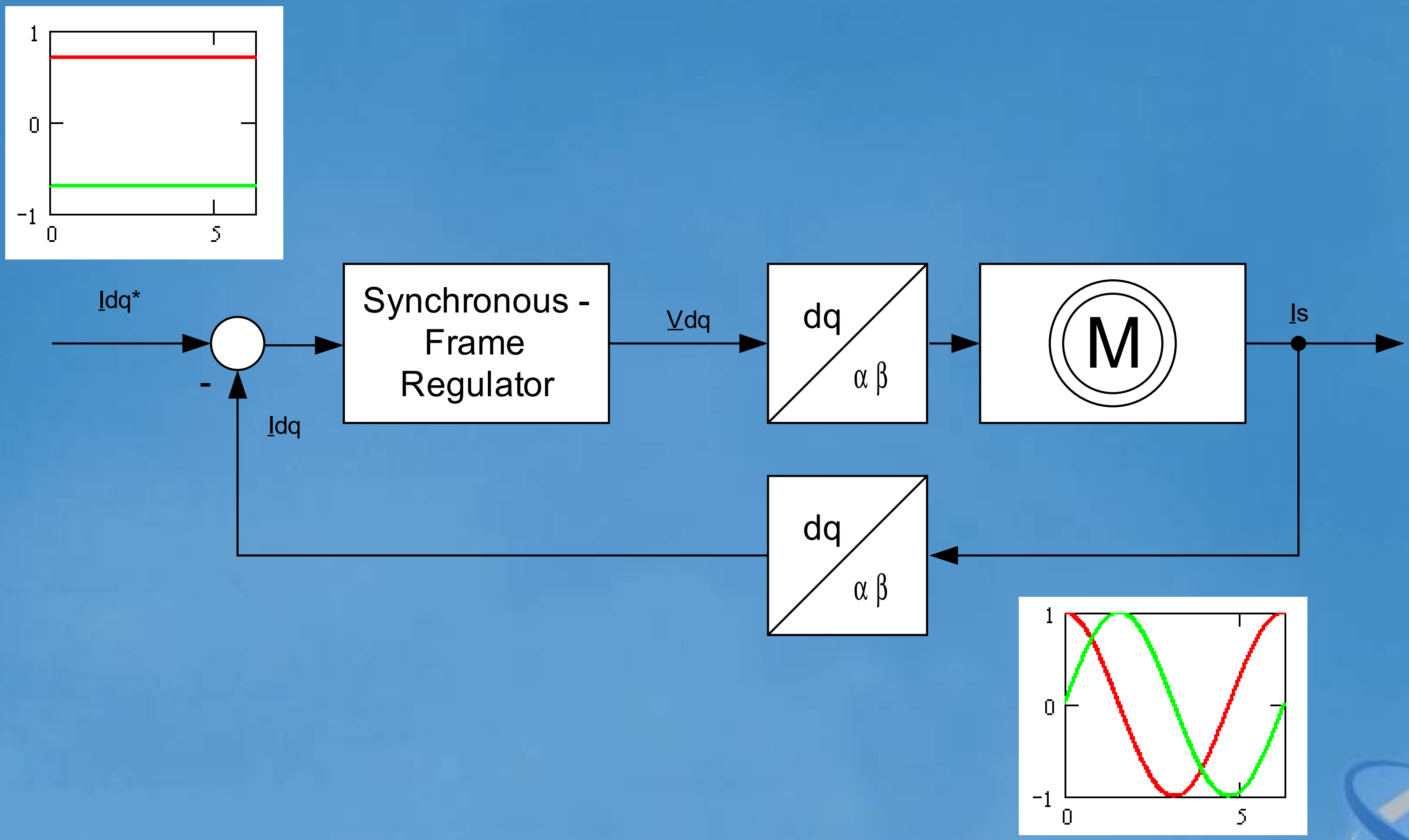




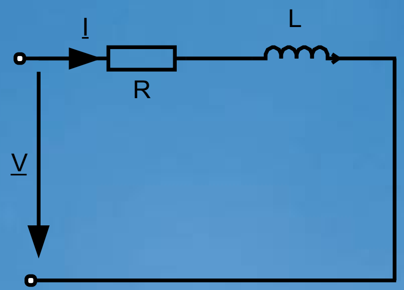


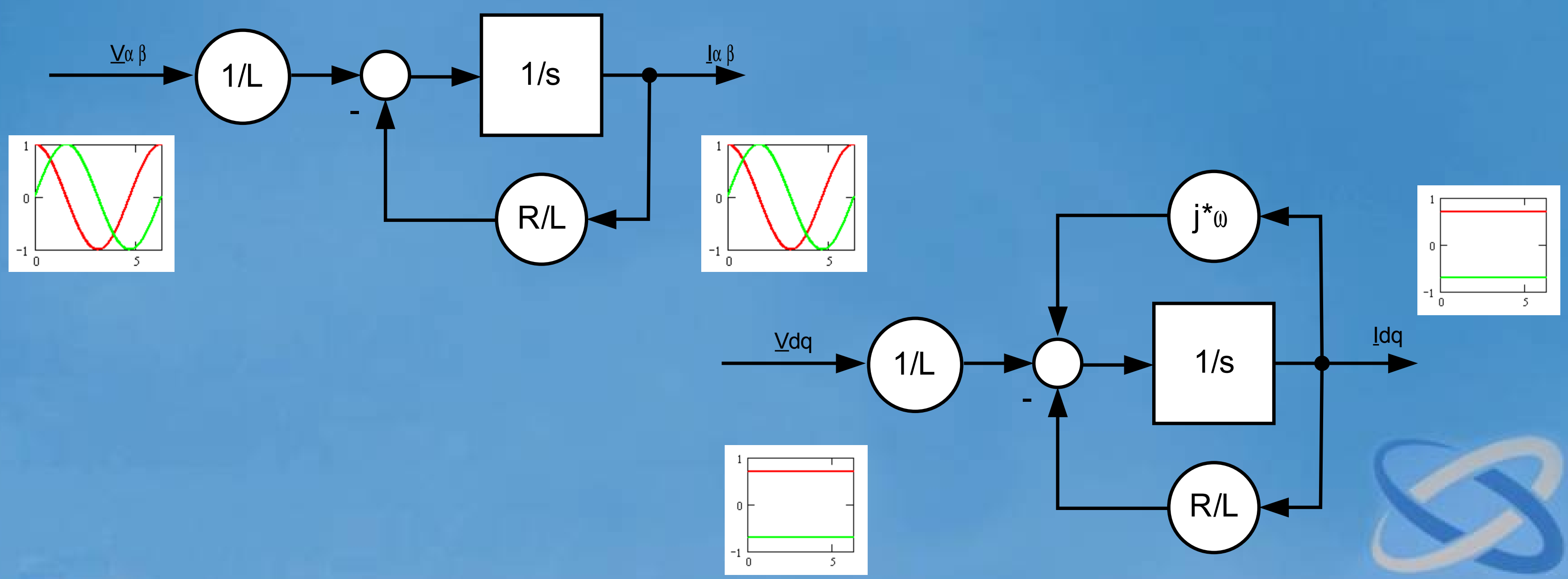


Synchronous-Frame Regulator

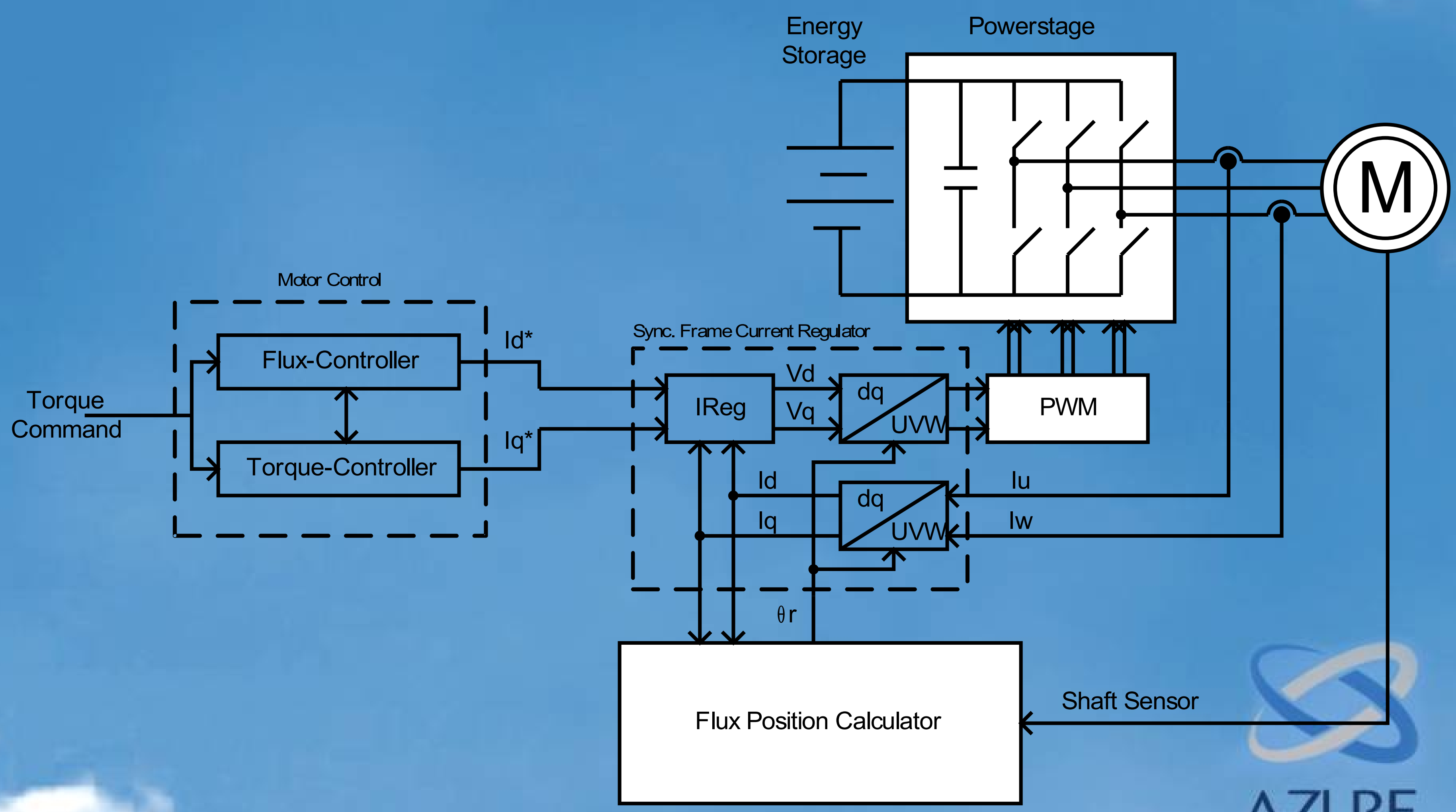


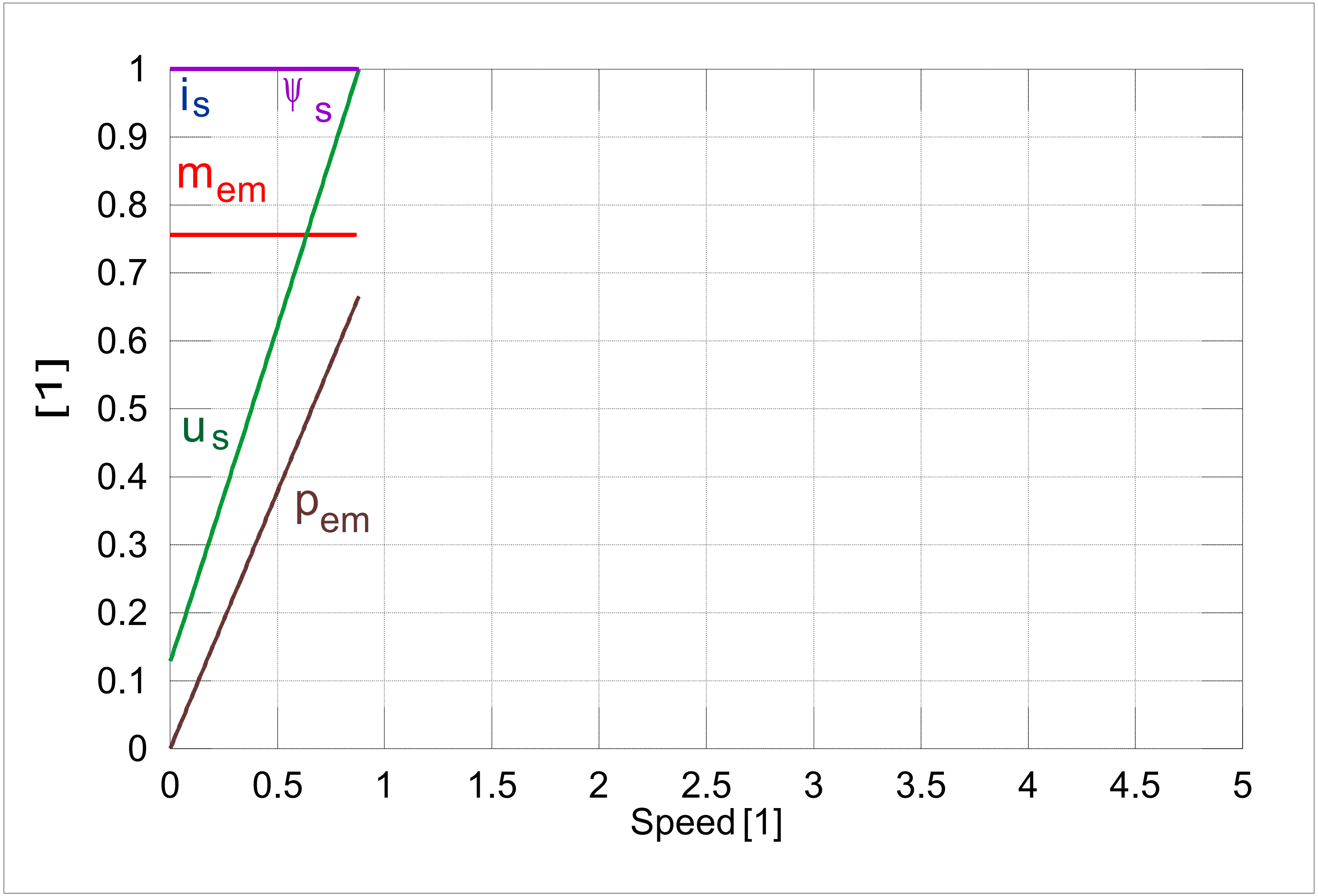
Cross-coupling due to Park Transformation





Field Oriented Electric Drive





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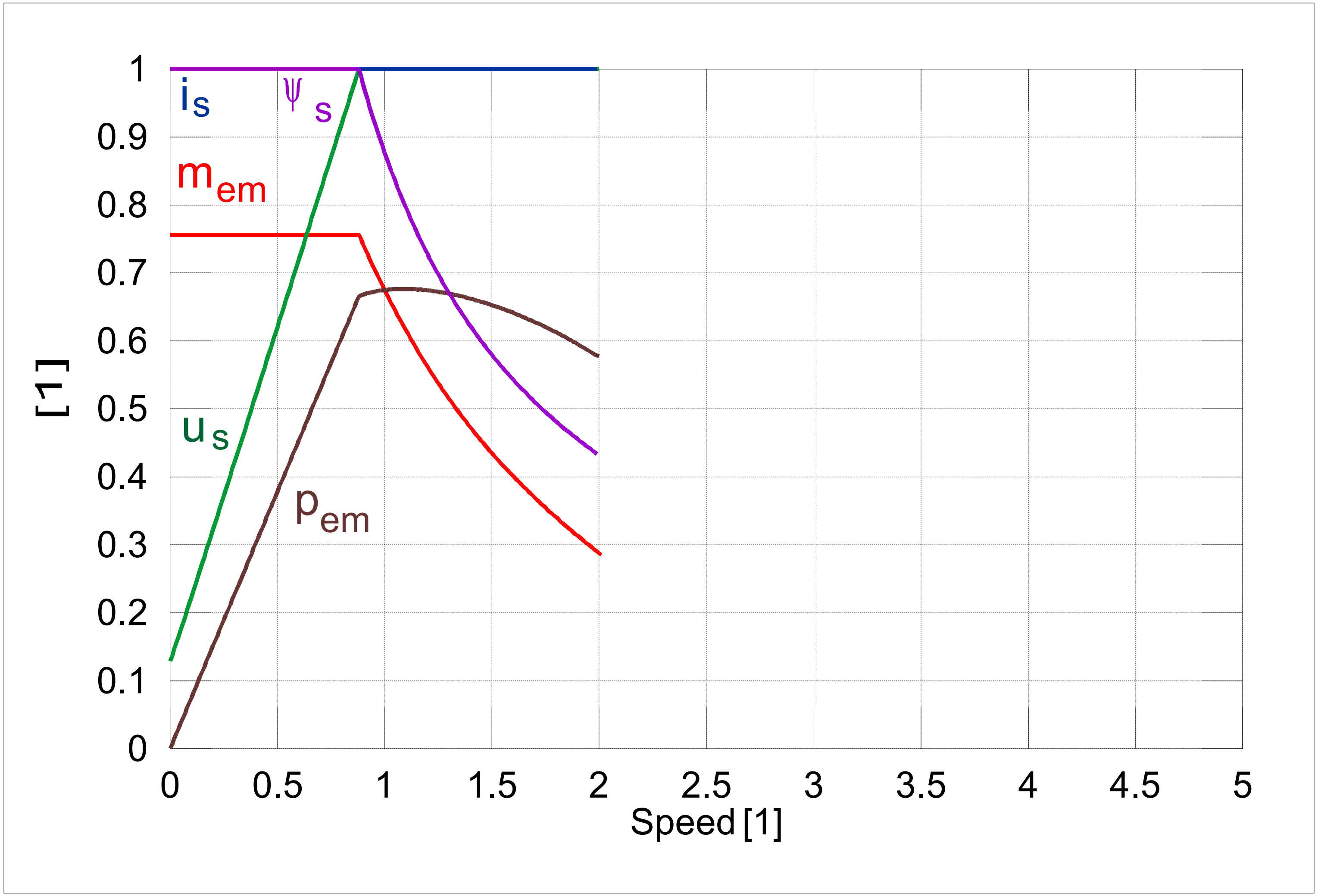

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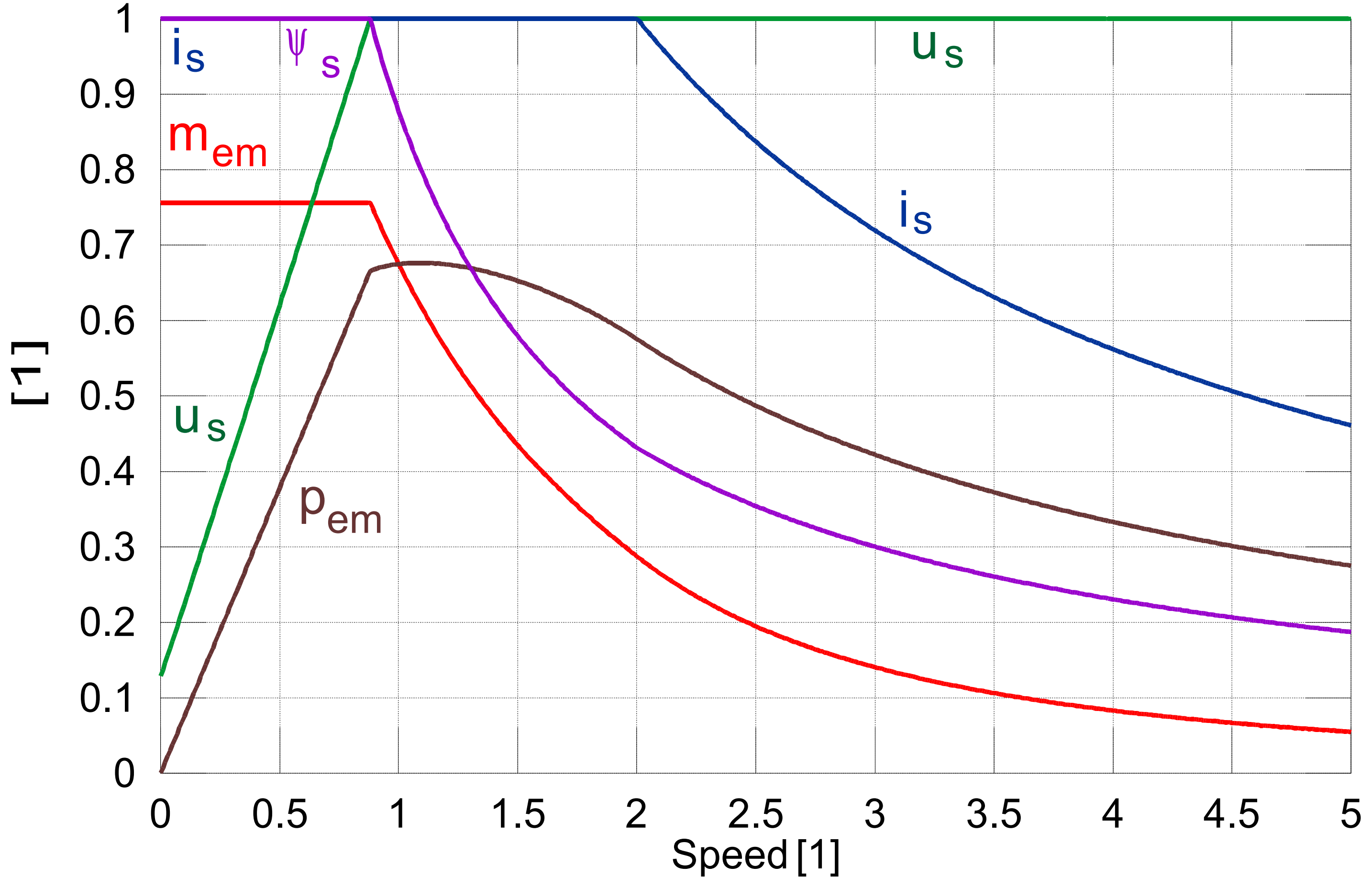

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Inverters: Summary

- Inverters convert DC into three-phase AC
- Space vectors can be used for modeling inverters
- Pulse width modulation allows for the generation of arbitrary voltage vectors
- Motor currents are controlled by modulating phase voltage
- Typically, the current regulator is implemented in a rotating synchronous frame
- Speed-dependent cross-coupling exists in the synchronous frame
- Motor torque and flux are controlled by direct and quadrature currents
- The torque-speed envelope of an electric drive is limited by motor parameters, DC voltage and phase current limit

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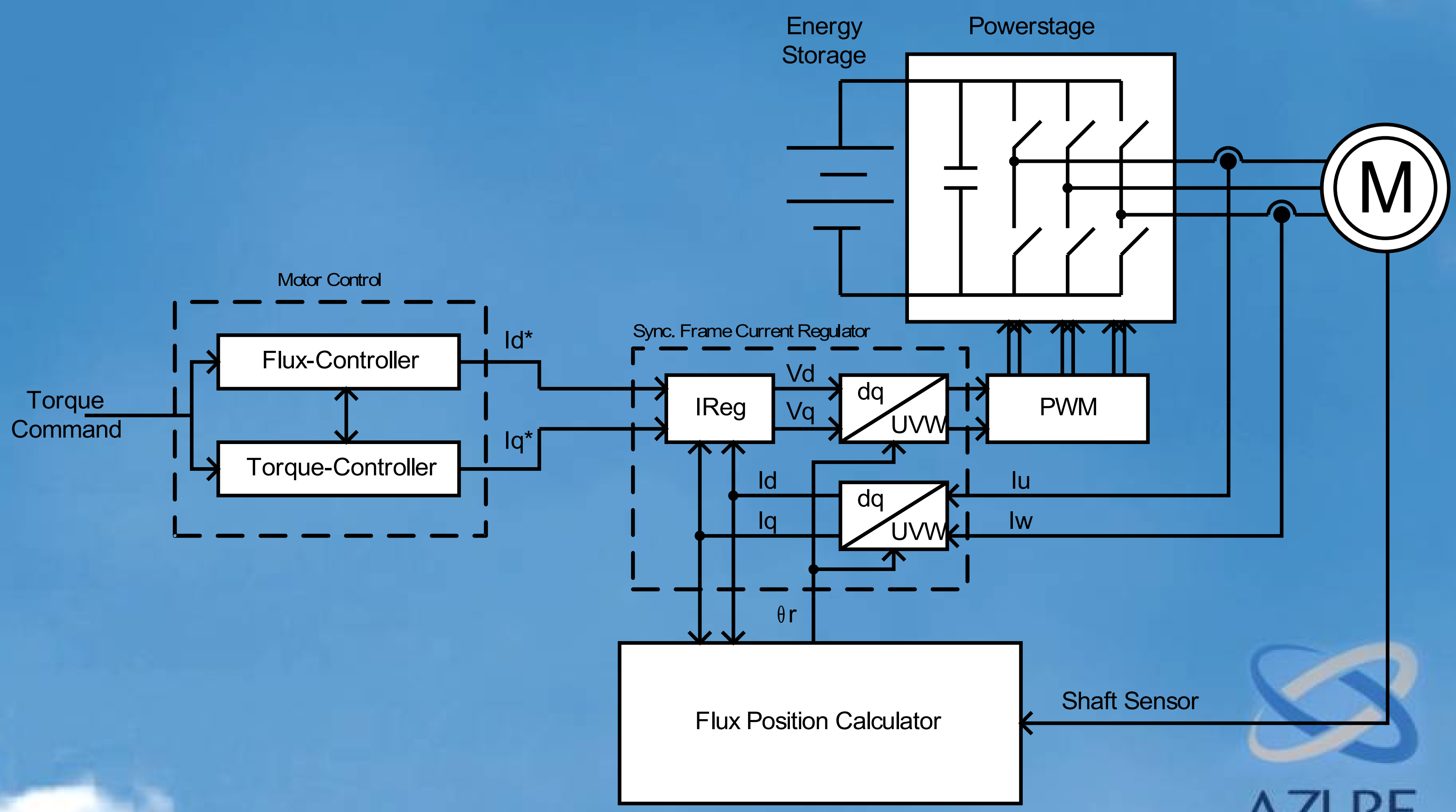
AZURE DYNAMICS

Real World Challenges are Everywhere...



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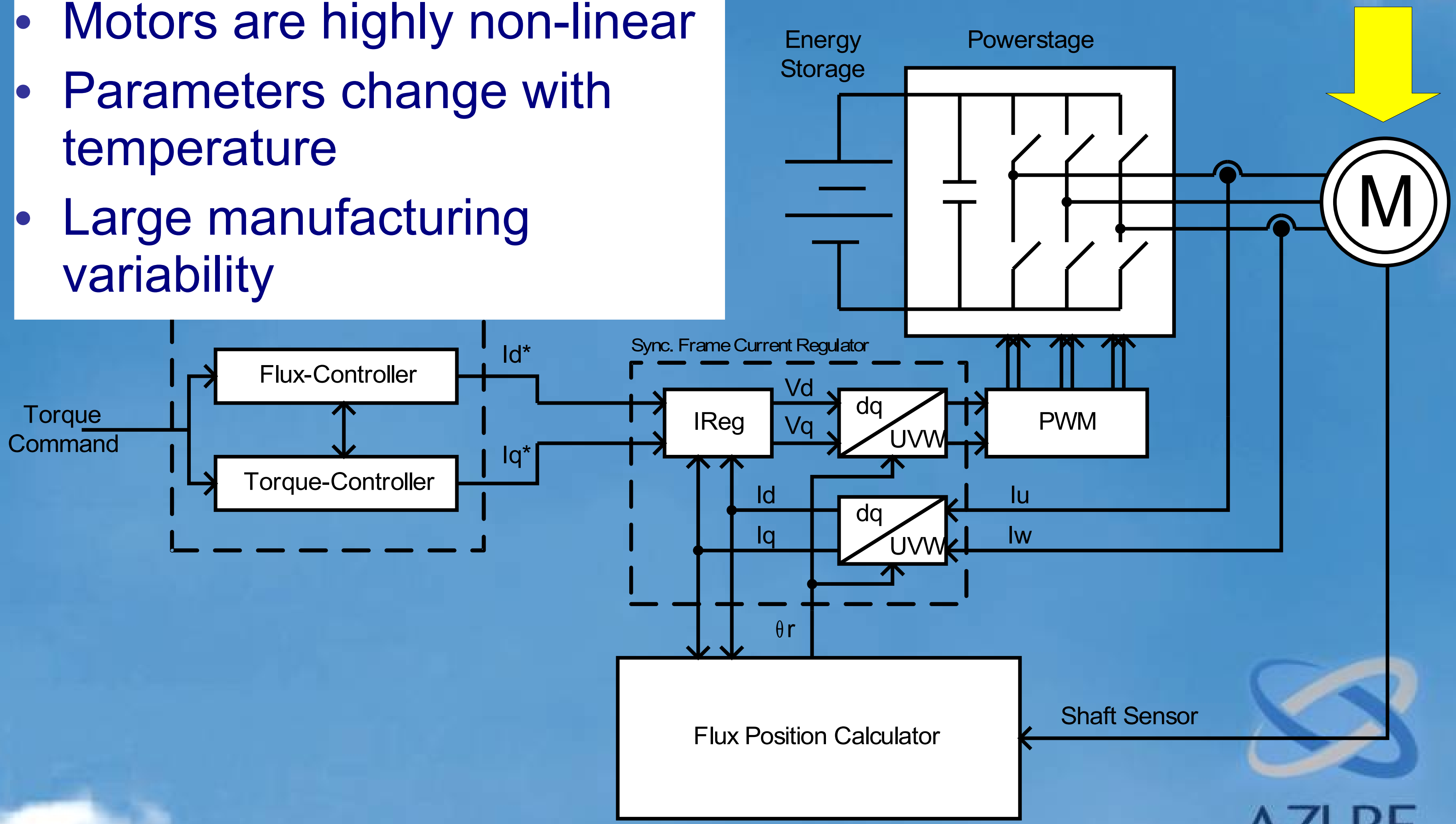
Real World Challenges are Everywhere...

- Motors are highly non-linear
- Parameters change with temperature
- Large manufacturing variability



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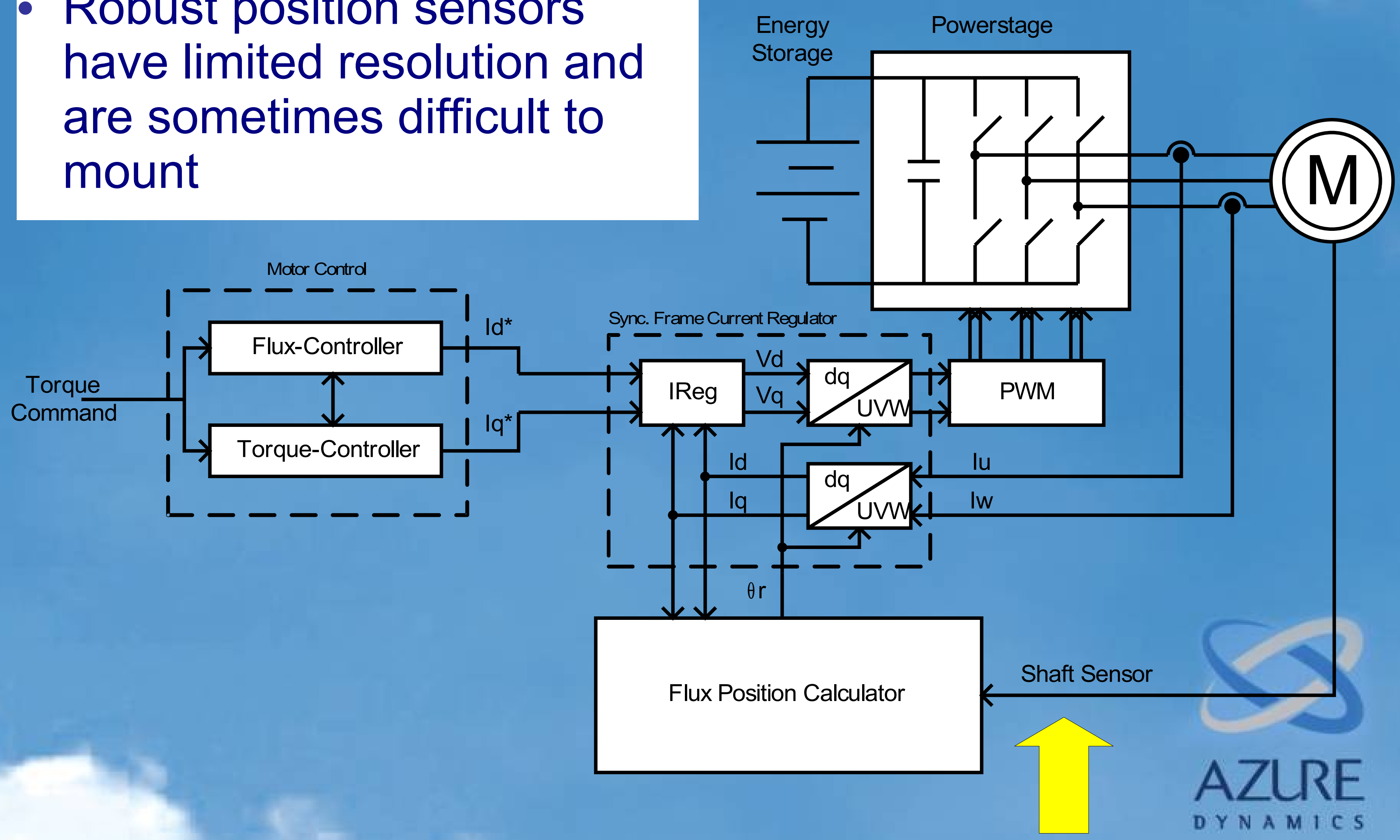
Real World Challenges are Everywhere...

- Robust position sensors have limited resolution and are sometimes difficult to mount



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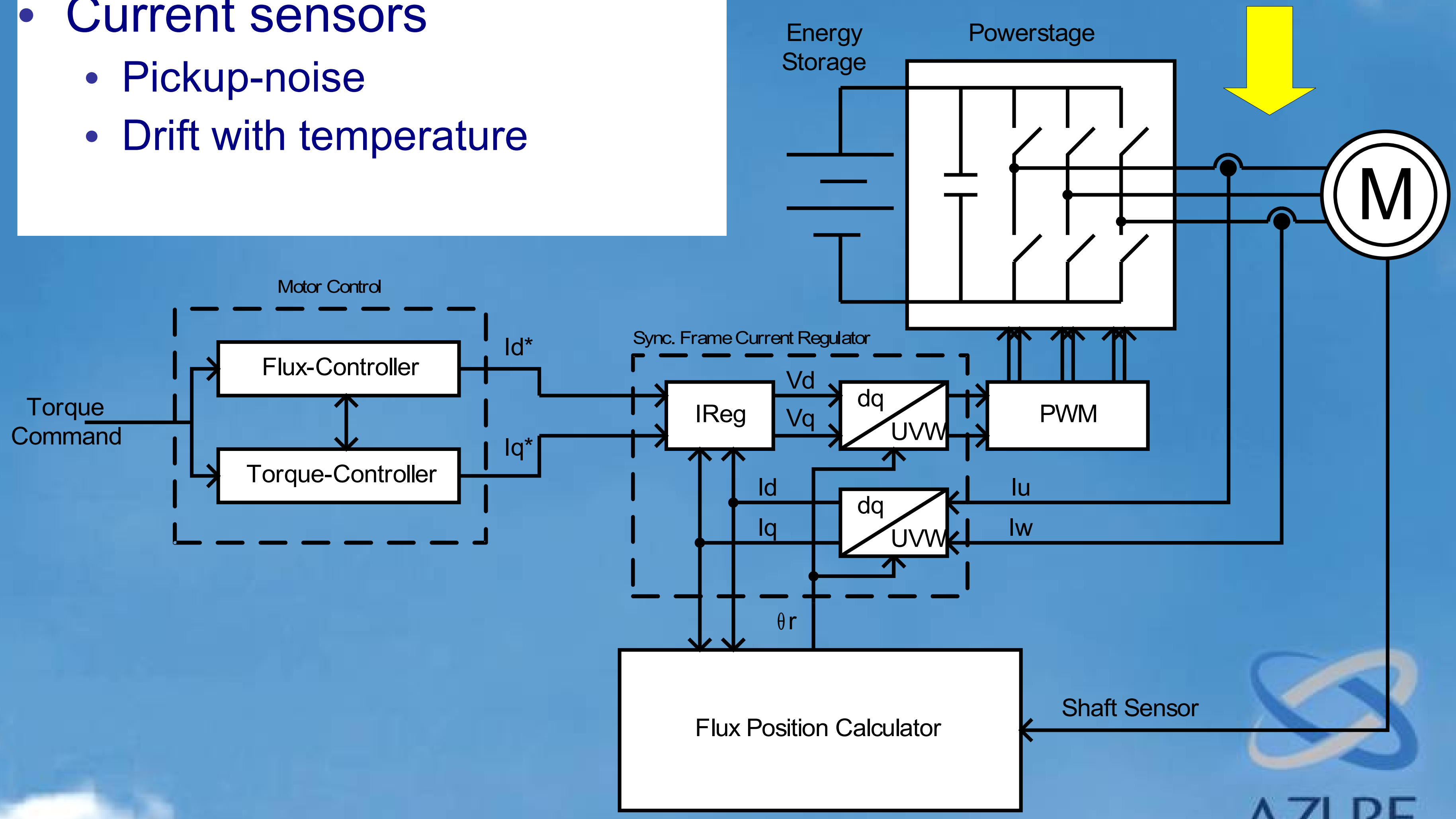
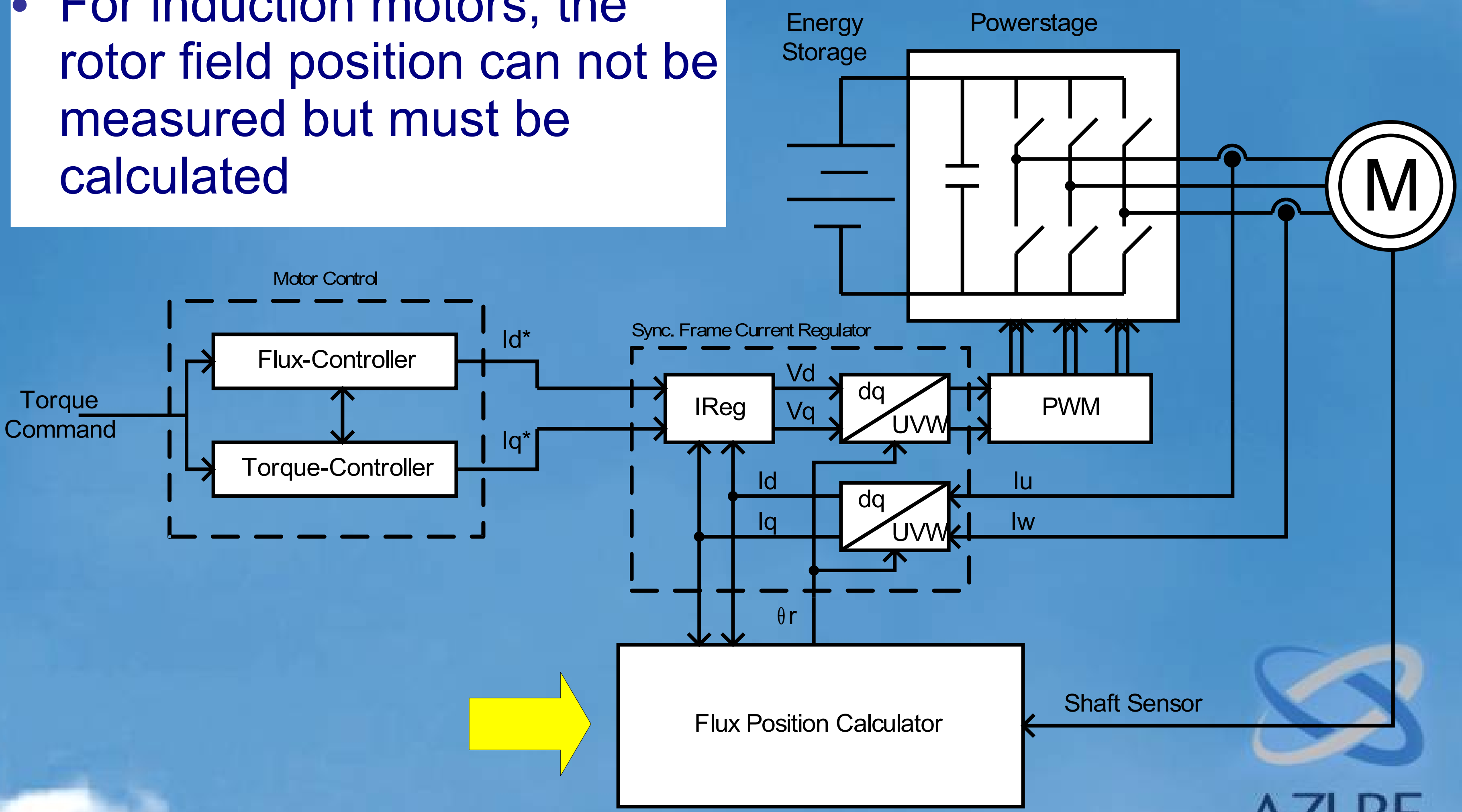
Real World Challenges are Everywhere...

- Current sensors
  - Pickup-noise
  - Drift with temperature



Real World Challenges are Everywhere...

- For induction motors, the rotor field position can not be measured but must be calculated



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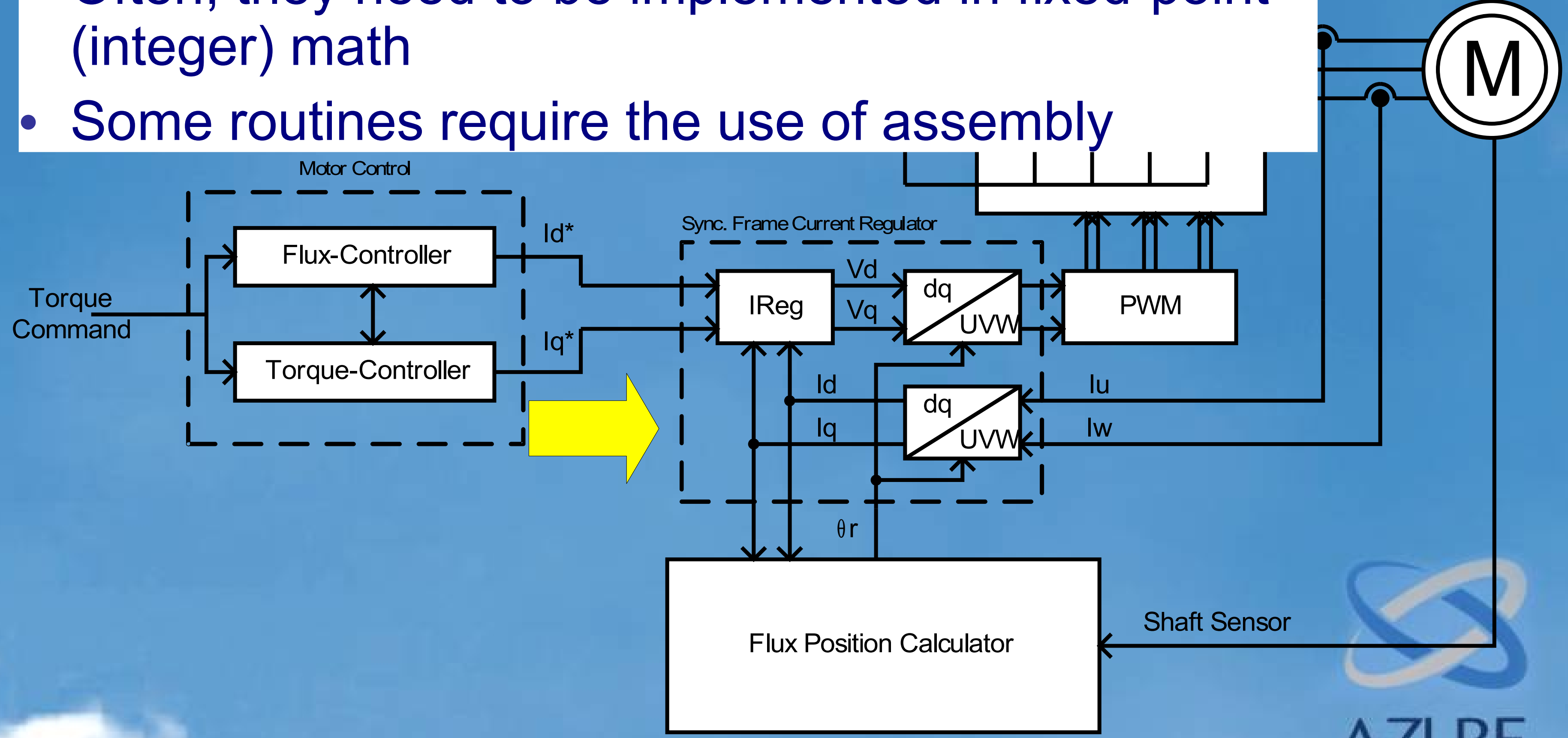
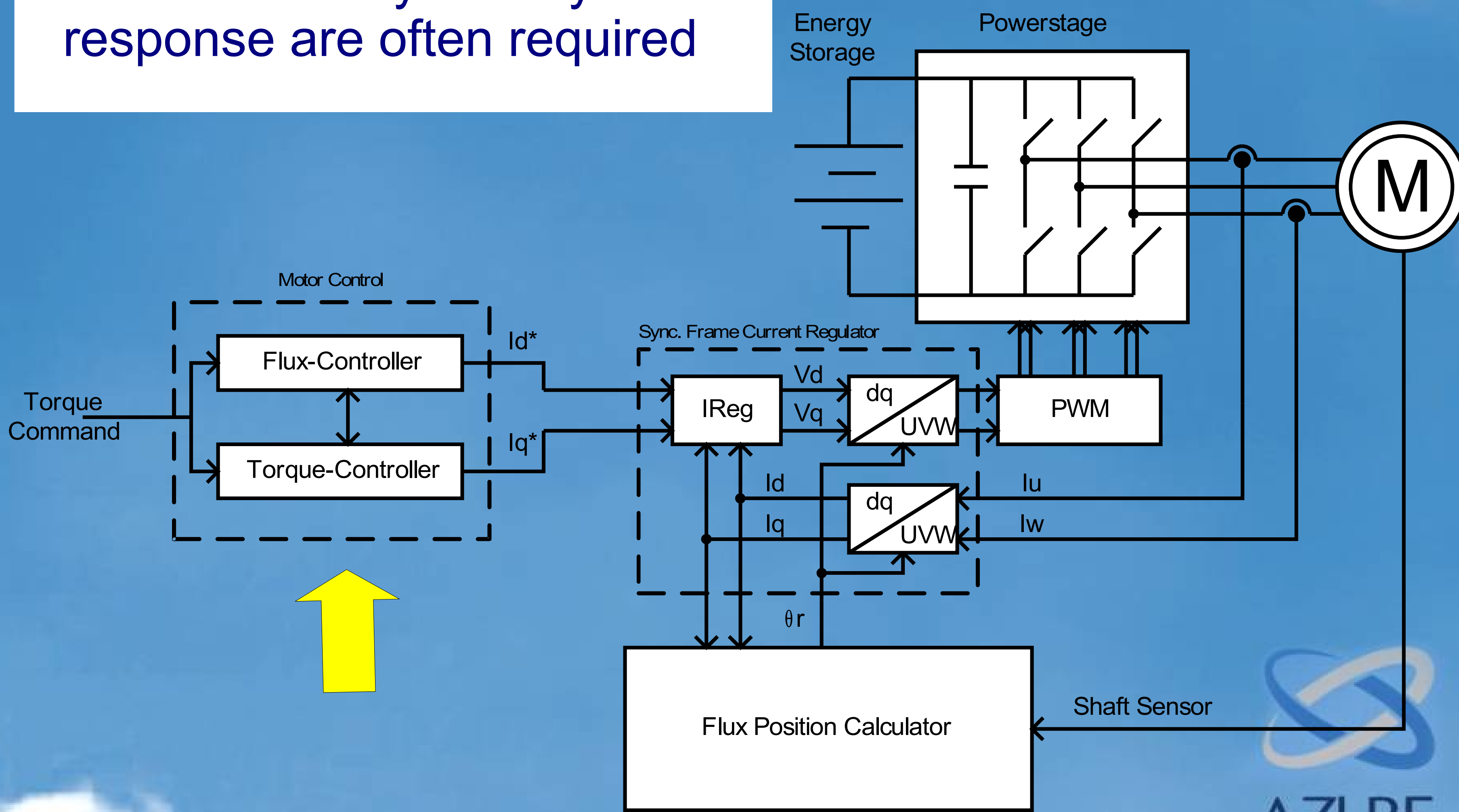
Real World Challenges are Everywhere...

- Synchronous frame current regulators require a good amount of processing power
- Often, they need to be implemented in fixed-point (integer) math
- Some routines require the use of assembly



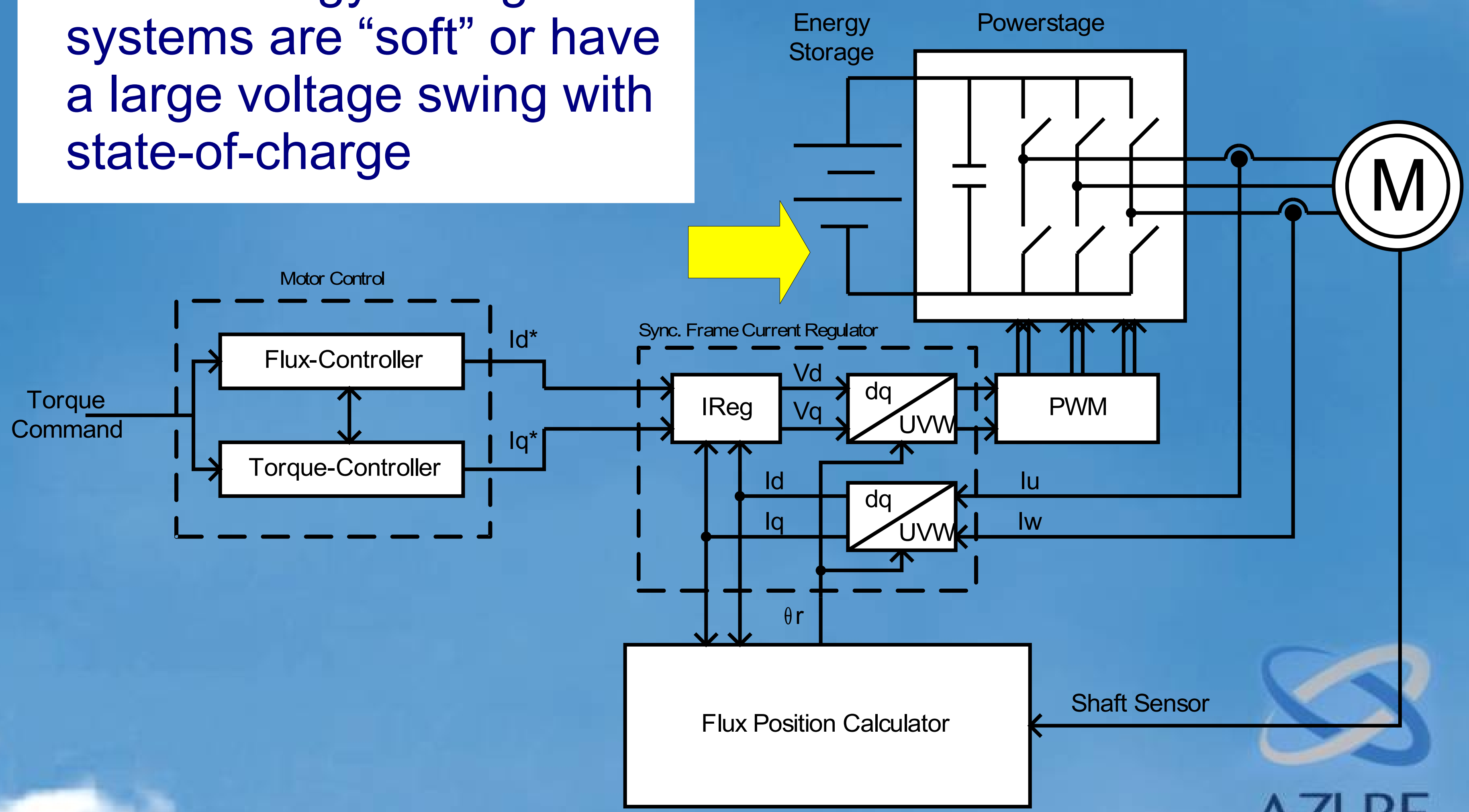
Real World Challenges are Everywhere...

- Good efficiency **and** dynamic response are often required



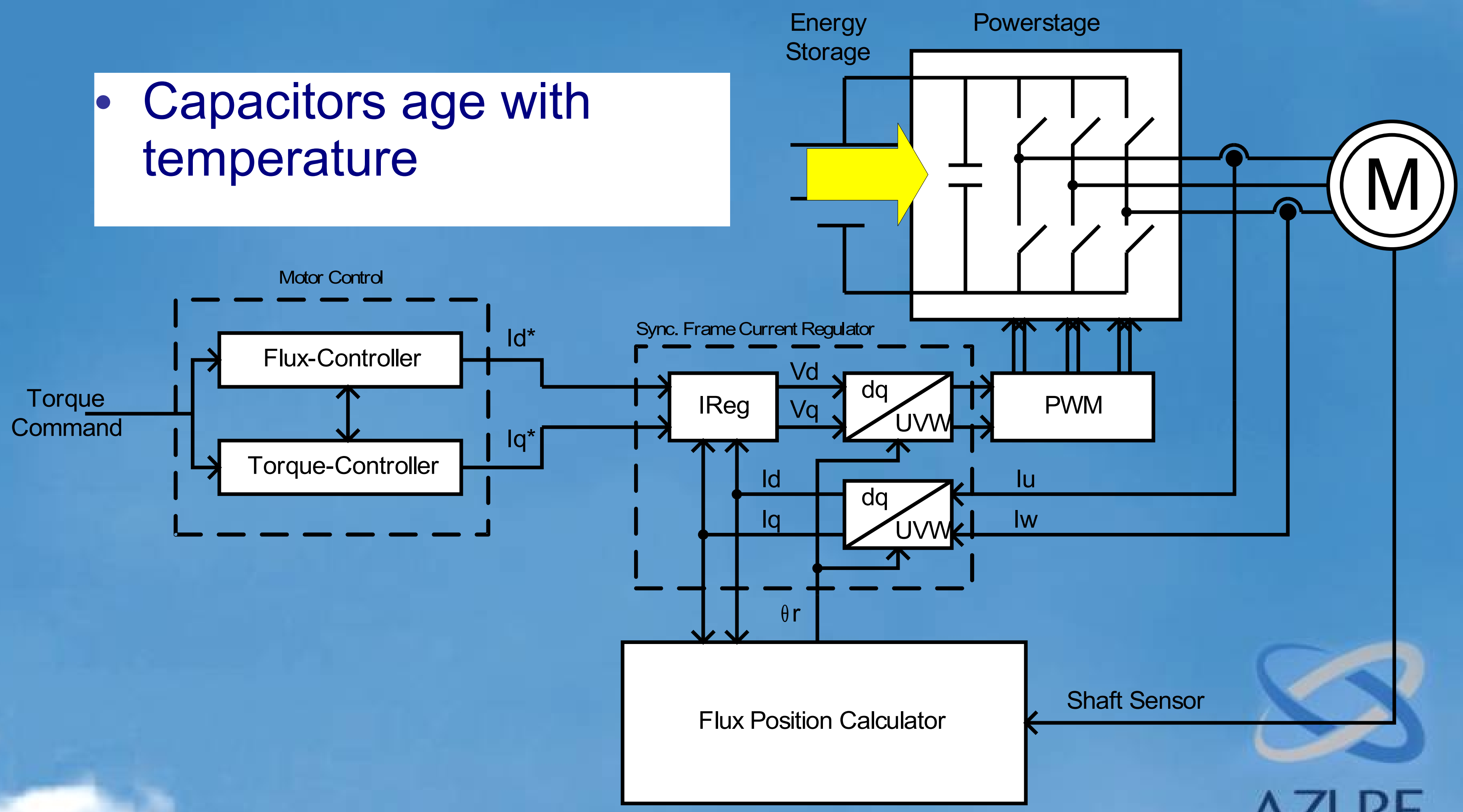
Real World Challenges are Everywhere...

- Some energy storage systems are “soft” or have a large voltage swing with state-of-charge



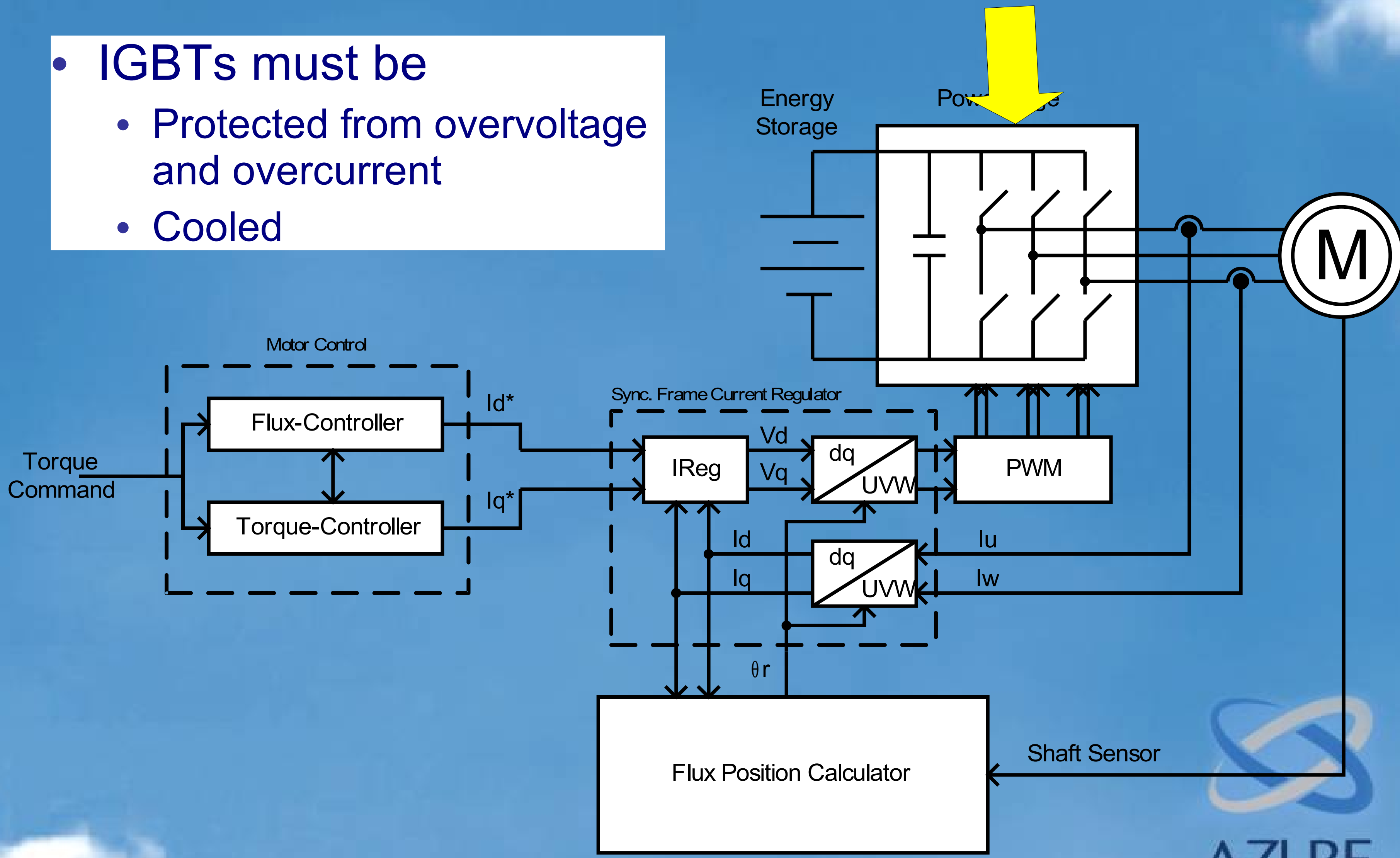
Real World Challenges are Everywhere...

- Capacitors age with temperature



Real World Challenges are Everywhere...

- IGBTs must be
  - Protected from overvoltage and overcurrent
  - Cooled



AZURE DYNAMICS

Real World Challenges are Everywhere...

- The two biggest challenges for automotive application:
  - High temperature operation
    - Allowing engine coolant to be used to cool the power-electronics
    - Allowing for the inverter to be integrated into the motor or packaged next to an engine or exhaust system
  - Low EMI
    - No interference with other components, such as communications for entertainment or safety devices

Presentation Outline

- Who is Azure Dynamics?
- How can we reduce vehicle CO_2 emissions?
- The electric drive is at the heart of most solutions!
- Electric drive lesson:
  - Electric Motors, Inverters, Space-Vectors, Clarke & Park Transformation, PWM, Vector Control, Torque-Speed Envelopes
- Real world challenges
- Skills and tools of the trade
- Azure Product Development Process
- Show & tell

AZURE DYNAMICS

Skills and tools of the trade

- Design electric drives is very multidisciplinary!
- What engineers need to know:
  - Control theory
  - Signal processing
  - Embedded system control
  - Analog and digital electronics
  - Power electronics
  - Packaging
  - Thermal modeling
- Most important: get hands-on experience as soon as possible.

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Lab Work

- Digital and analog circuit prototyping
- Powerstage development
- EMC testing

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DYNAMICS

Dynamometer Testing

- Motor parameters identification
- Efficiency measurements
- Thermal testing
- Control algorithm development

CAD and Thermal Modeling

- Solid models for packaging
- Heat flow analysis
- Resonant mode analysis

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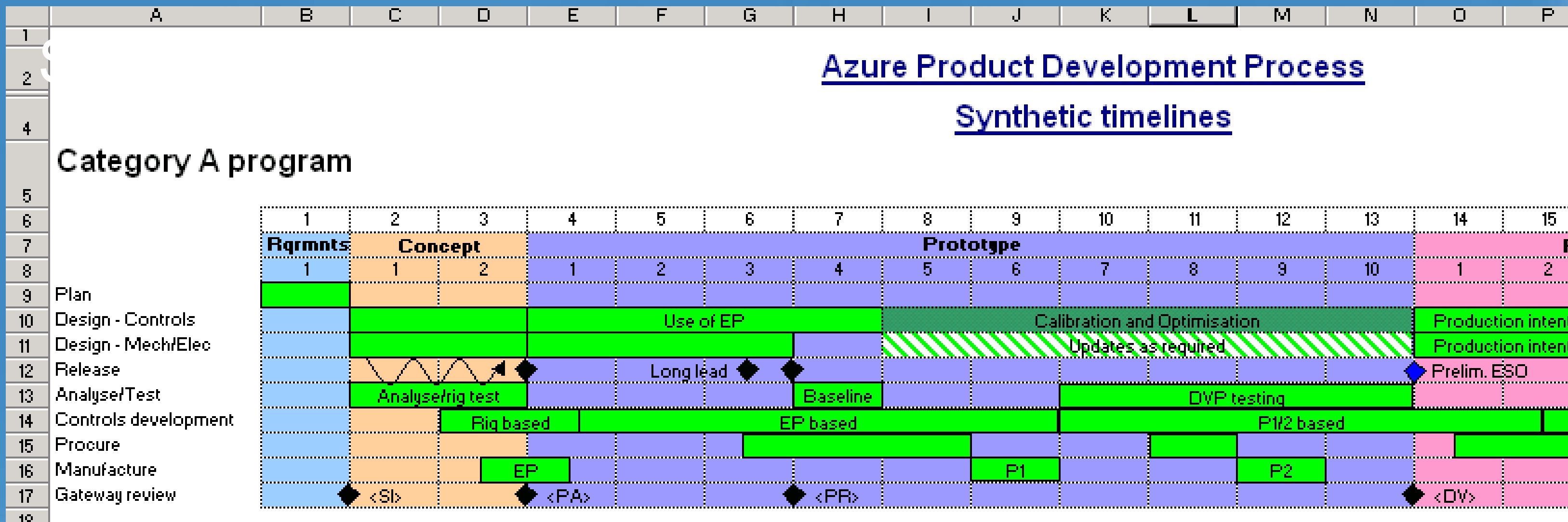
Azure PDP

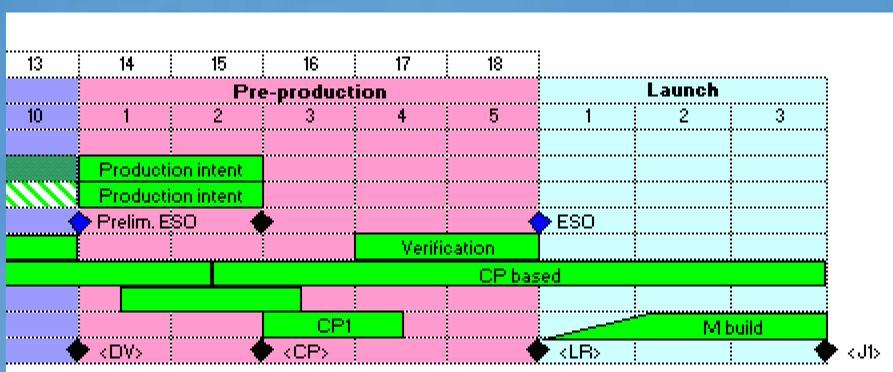
Scope it
Concept it
Design and test it
Optimise and productionise it
Produce it

- Single process for all product development - System, Sub-system and Component
- Five phase process
- Three categories of program (high, medium and low levels of complexity)
- Synthetic timelines for each program category
- Gateways control the progression of the process
- Seven formal gateways
- Mini process prescribed for each phase
- Prescribed mandatory deliverables for each phase
- Key company officer sign-off mandatory to conclude each phase

AZURE DYNAMICS

Synthetic Timelines





- SI: Strategic Intent
- PA: Program Approval
- PR: Prototype Release
- DV: Prototype DVP
- CP: Confirmation Prototype
- LR: Launch Readiness
- J1: Start of Production

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