SPIN THE BLDC AND PMSM SMART

APF-AUT-T2298

RAYMOND TANG
2016

PUBLIC

SECURE CONNECTIONS
FOR A SMARTER WORLD

Agenda

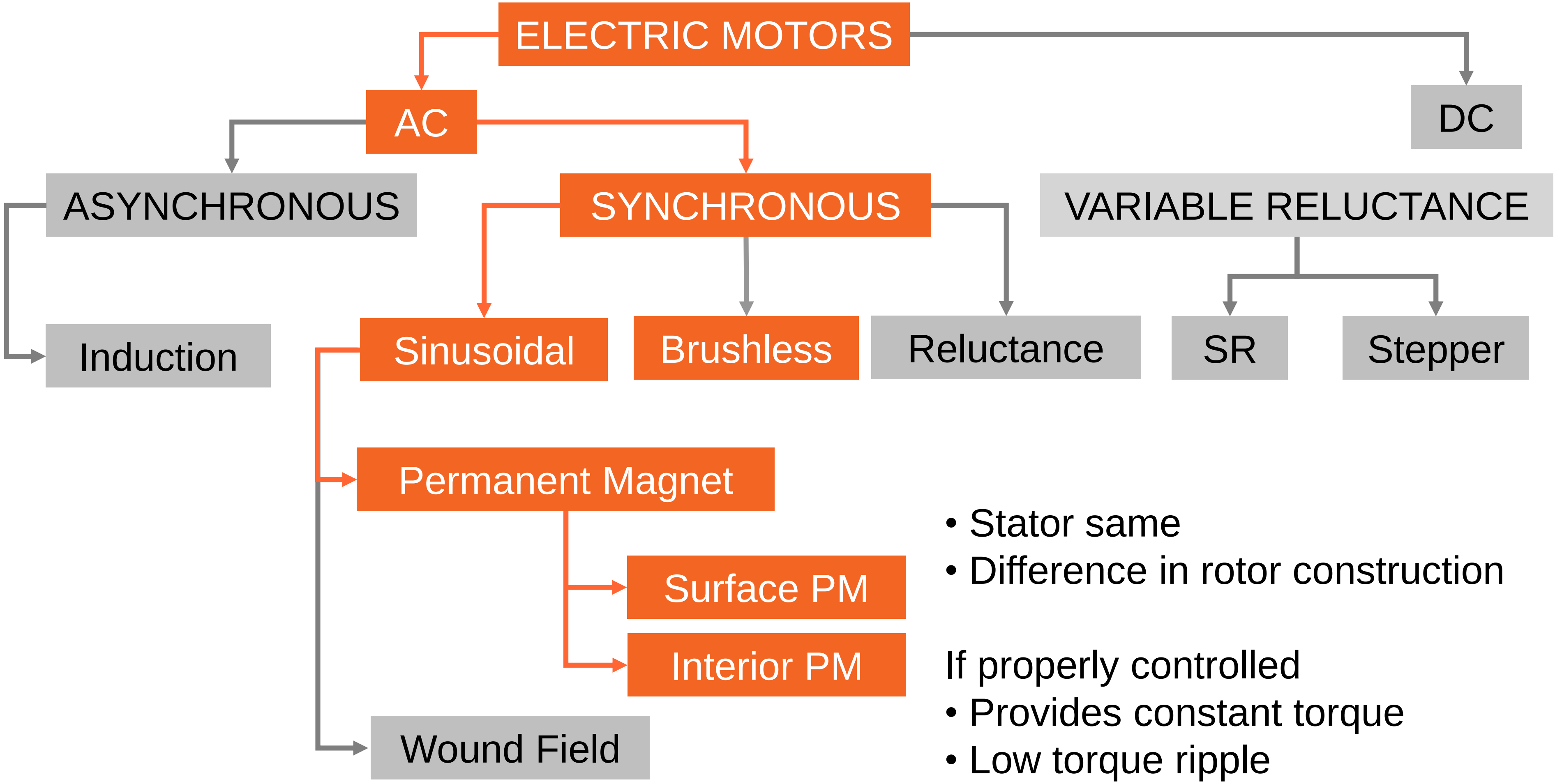
• Motor Classification – BLDC vs PMSM	15m
• S12ZVM Introduction	30m
• BLDC Control – Block commutation	30m
• PMSM Control – FOC	120m
– FOC Basic	
– FOC Loop Design	
– Current Sensing and Processing	
– Position Sensing and Processing	
– Three Phase Voltage Generation	
– Sensor-less	
– Field Weakening	
– MTPA	
• Conclusion	10m

Session Objectives

After completing this session you will be able to:

- Familiar with the key motor control features on the MagniV S12ZVM family
- Know the different between BLDC and PMSM
- Describe the basic idea of Block commutation and Field Oriented Control
- Outline the main elements of a sinusoidal PMSM control technique

Motor Classification – BLDC vs PMSM



- Stator same
- Difference in rotor construction

If properly controlled

- Provides constant torque
- Low torque ripple

Motor Classification – BLDC vs PMSM

- 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

Motor Classification – BLDC vs PMSM

“**Sinusoidal**” or “Sine-wave” machine means PMSM

Trapezoidal means brushless DC motors

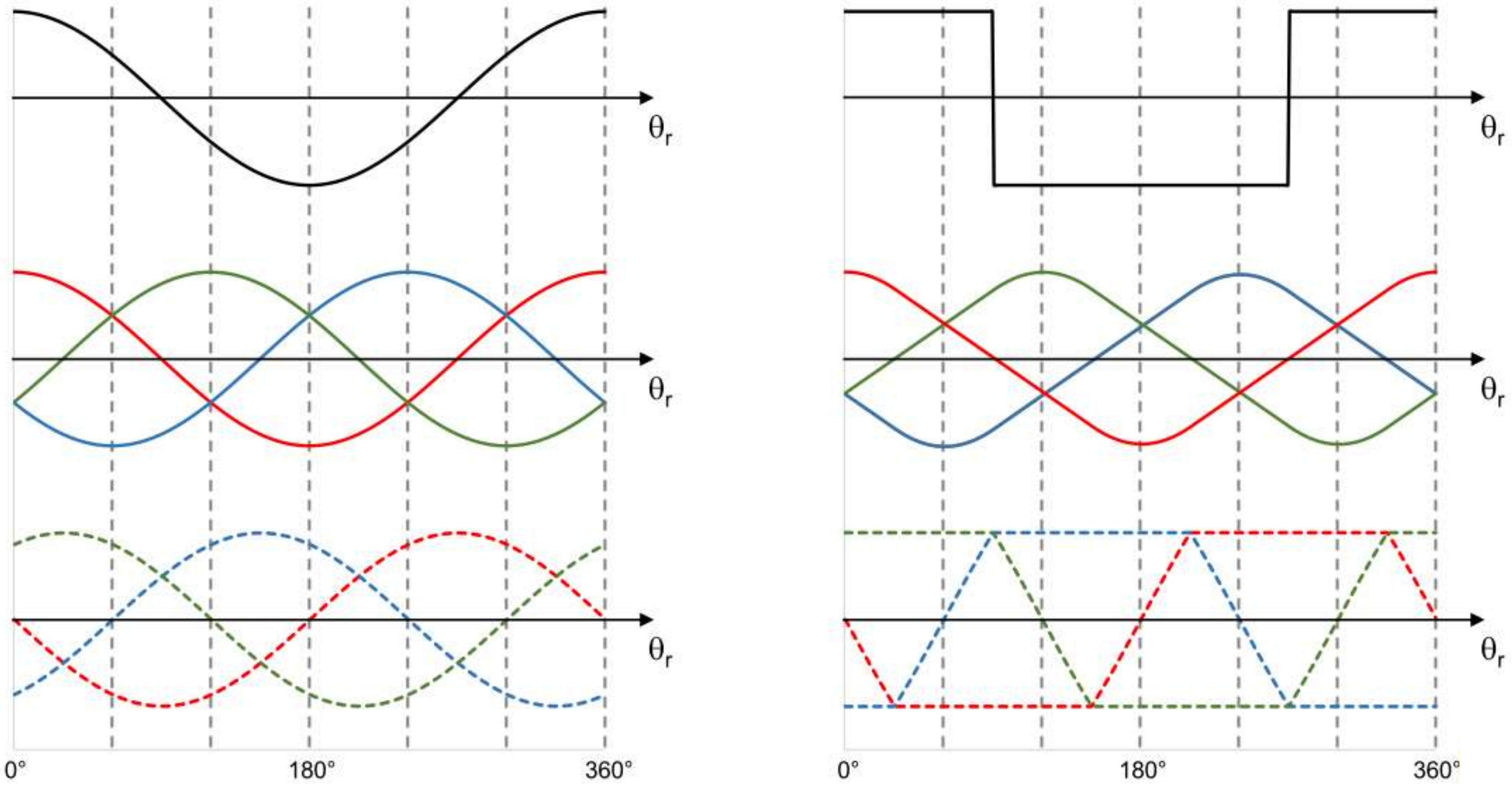
Magnetic Flux Density

Shape of the flux density depends on the magnetization of the PM (radial, parallel) and their displacement

Magnetic Flux Linkage

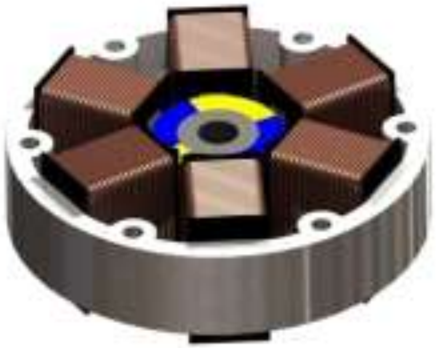
Phase Back EMFs

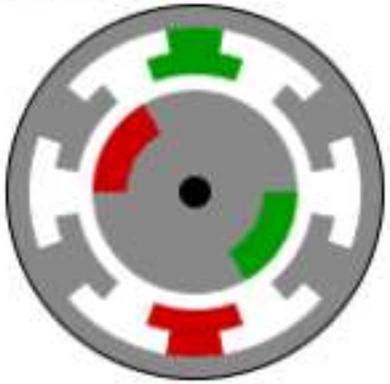
Back EMF depends on the shape of the linkage flux.



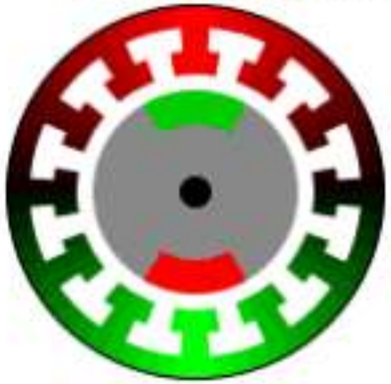
Motor Classification – BLDC vs PMSM

Brushless D.C. Motor





Permanent Magnet Synchronous Motor

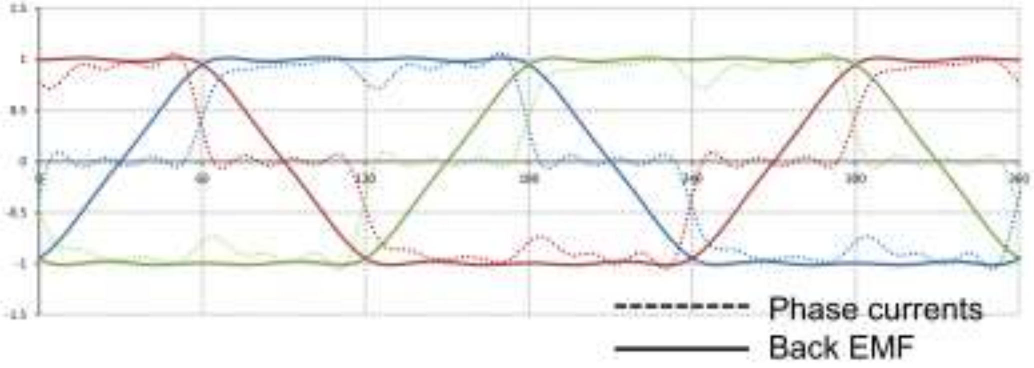


BLDC motor		PMSM motor
3-phase machine with PM on the rotor	=	3-phase machine with PM on the rotor
Rotor position sensing required for rotor flux position	=	Rotor position sensing required for rotor flux position
High torque per frame size	=	High torque per frame size
Synchronous operation	=	Synchronous operation
Good high speed performance (no brush losses)	=	Good high speed performance (no brush losses)
High torque ripple	≠	**Low torque ripple**

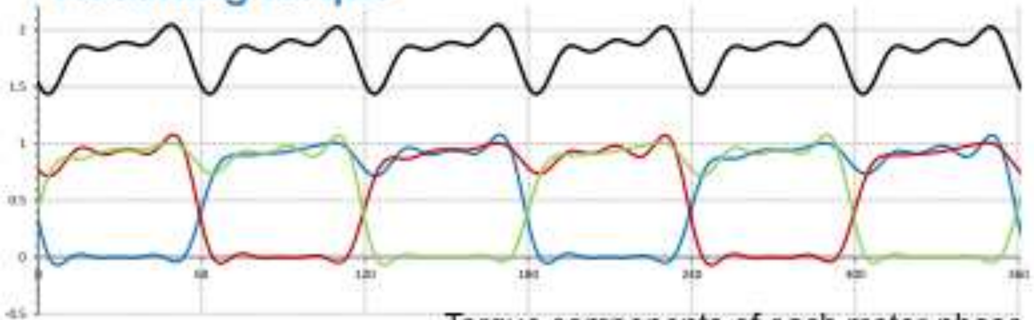
Motor Classification – BLDC vs PMSM

Brushless D.C. Motor

- Trapezoidal Back-EMF
- Six-Step commutation control
- 2 of the 3 stator phases are excited at any time



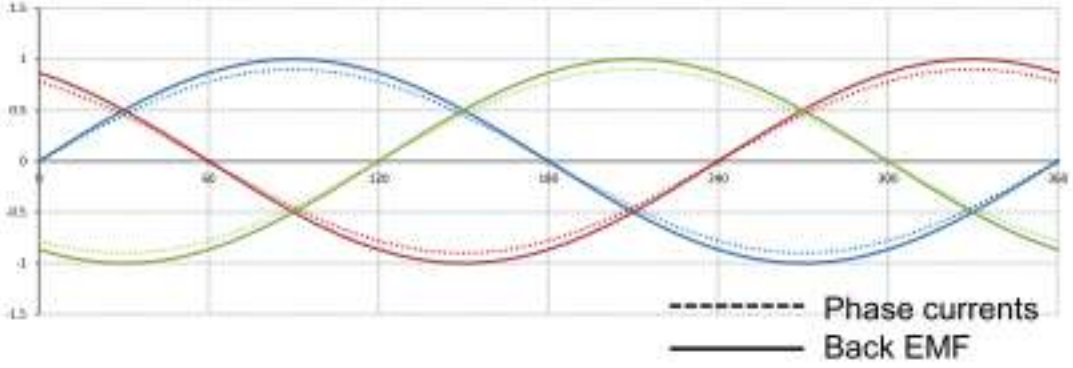
Resulting torque



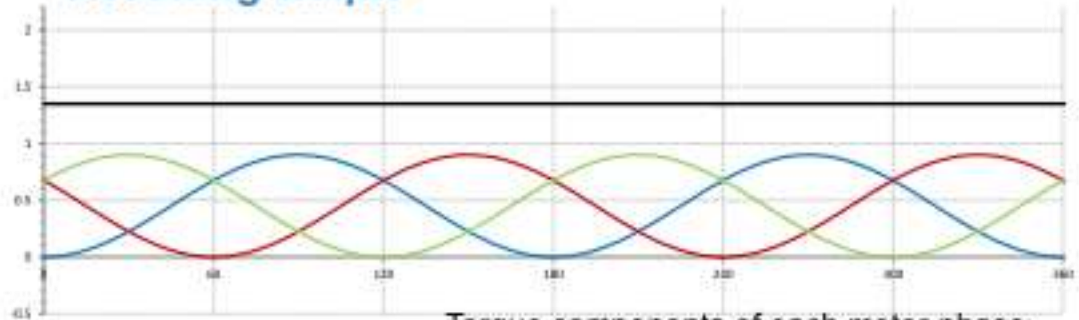
Torque components of each motor phase

Permanent magnet synchronous motor

- Sinusoidal Back-EMF (ideal case)
- Field Oriented Control
- All 3 phases persistently excited at any time



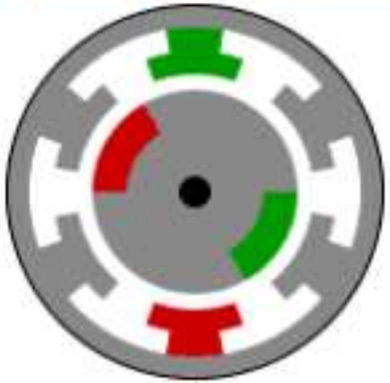
Resulting torque



Torque components of each motor phase

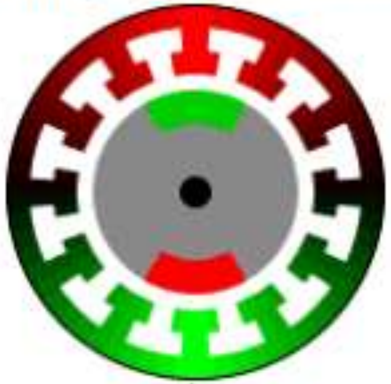
Motor Classification – BLDC vs PMSM

Brushless D.C. Motor



versus

Permanent magnet synchronous motor



BLDC		PMSM
HIGH	Level of torque ripple	LOW
HIGH	Vibration and noise as a consequence of the torque ripple	LOW
HIGH	Electromagnetic compatibility (EMC)	LOW
LOW	Control structure complexity level	HIGH
SHORTER	Execution time of the control approach	LONGER
SIMPLE	Sensorless control	MORE COMPLEX
HIGHER	Heating	LOWER
LOWER	Price	HIGHER

Motor Classification – BLDC vs PMSM

Brushless D.C. Motor

Fuel/liquid pumps with BLDC

Application requirements:

- High speed operation
- Simple sensorless control
- Low cost control solution
- Higher efficiency than DC motor

Permanent magnet synchronous motor

Power steering with PMSM

Application requirements:

- High speed operation
- Smooth torque operation
- Suppressed vibration and acoustic noise

MOTOR CLASSIFICATION – BLDC VS PMSM ANY QUESTIONS?

S12ZVM Introduction - MagniV

S12 MagniV portfolio **simplifies system design** with easy-to-use, expertly integrated **mixed-signal MCUs** for automotive applications

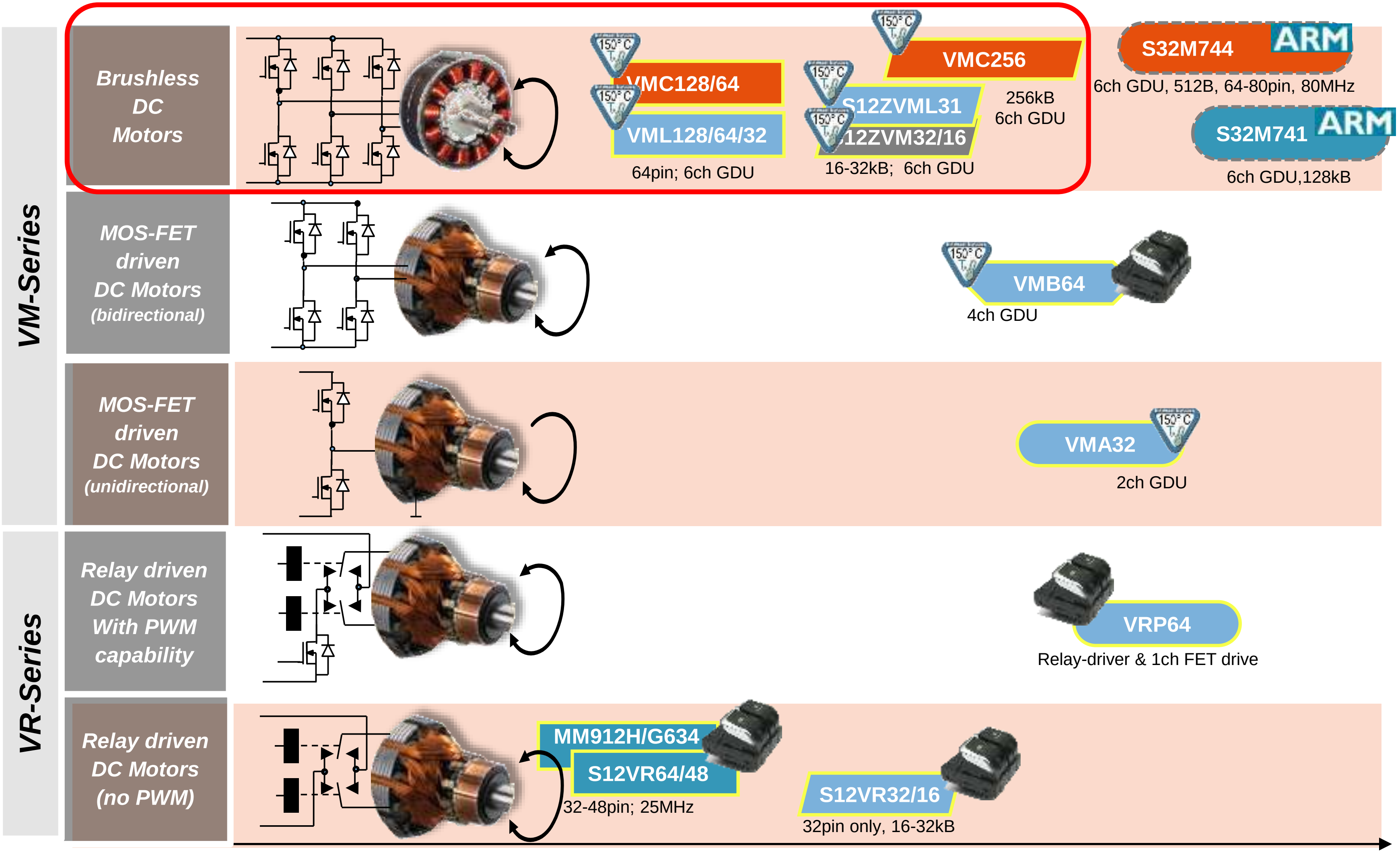
Streamlining automotive engineering with smart analog integration

Fast Prototyping – Speeds time-to-market with proven S12 16-bit MCUs, enabling software compatibility and tool reuse

Optimized Integration – Right blend of digital programmability and high-precision analog, plus a portfolio of scalable memory options

Simplified System Design – MCU with high-voltage analog components helps streamline design and reduce system and development costs

S12ZVM Introduction – VR and VM



VM-Series

Brushless DC Motors

VMC128/64

VML128/64/32

64pin; 6ch GDU

VMC256

S12ZVML31

12ZVM32/16

256kB
6ch GDU

16-32kB; 6ch GDU

S32M744 ARM

6ch GDU, 512B, 64-80pin, 80MHz

S32M741 ARM

6ch GDU,128kB

MOS-FET driven DC Motors (bidirectional)

VMB64

4ch GDU

MOS-FET driven DC Motors (unidirectional)

VMA32

2ch GDU

VR-Series

Relay driven DC Motors With PWM capability

VRP64

Relay-driver & 1ch FET drive

Relay driven DC Motors (no PWM)

MM912H/G634

S12VR64/48

32-48pin; 25MHz

S12VR32/16

32pin only, 16-32kB

- LIN applications
- CAN applications
- PWM controlled apps

Switch panel interface
(HS-drivers & HVIs)
Main usecase: WL/SR

High temp
option (AEC Grade 0)

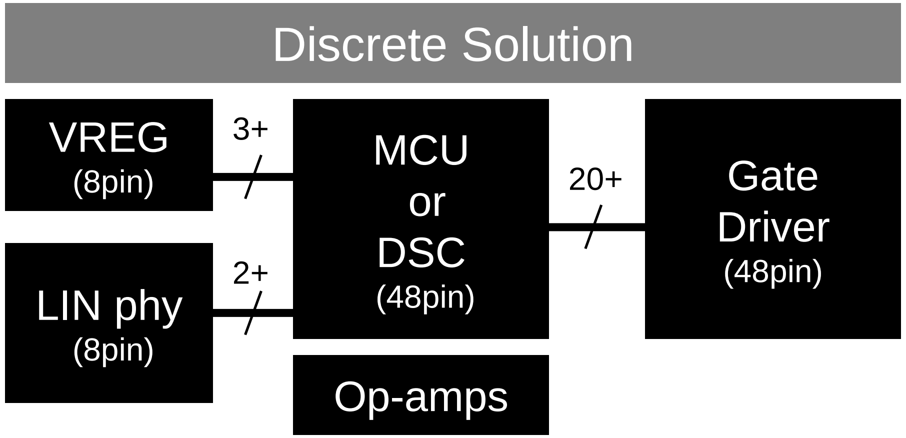
Proposal

Planning

Execution

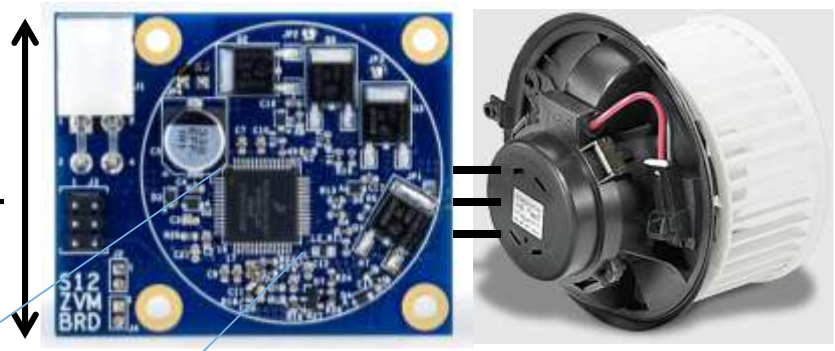
Production

S12ZVM Introduction - Single Chip Solution



Optimize system cost

4cm
~1 ½ in.



Optimize system efficiency

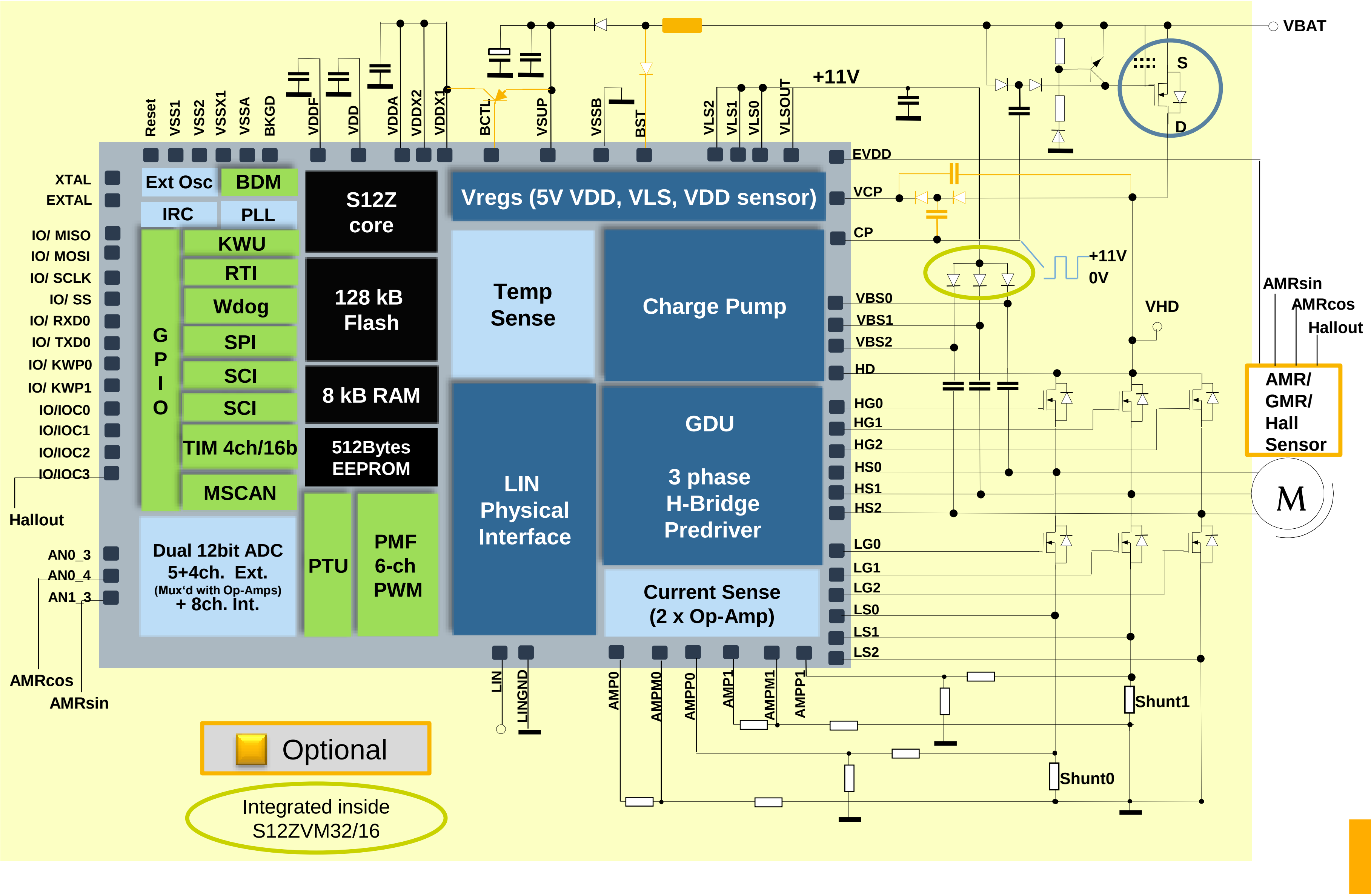
Vector Control

64pin

S12ZVM Solution:

- ~ 50 fewer solder joints
- - 4 to 6 cm2 PCB space

S12ZVM Introduction - Application Use Case



Ext Osc

BDM

IRC

PLL

S12Z core

KWU

RTI

Wdog

SPI

SCI

SCI

TIM 4ch/16b

MSCAN

GPIO

128 kB Flash

8 kB RAM

512Bytes EEPROM

Dual 12bit ADC 5+4ch. Ext. (Mux'd with Op-Amps) + 8ch. Int.

PTU

PMF 6-ch PWM

Vregs (5V VDD, VLS, VDD sensor)

Temp Sense

Charge Pump

LIN Physical Interface

GDU

3 phase H-Bridge Predriver

Current Sense (2 x Op-Amp)

Optional

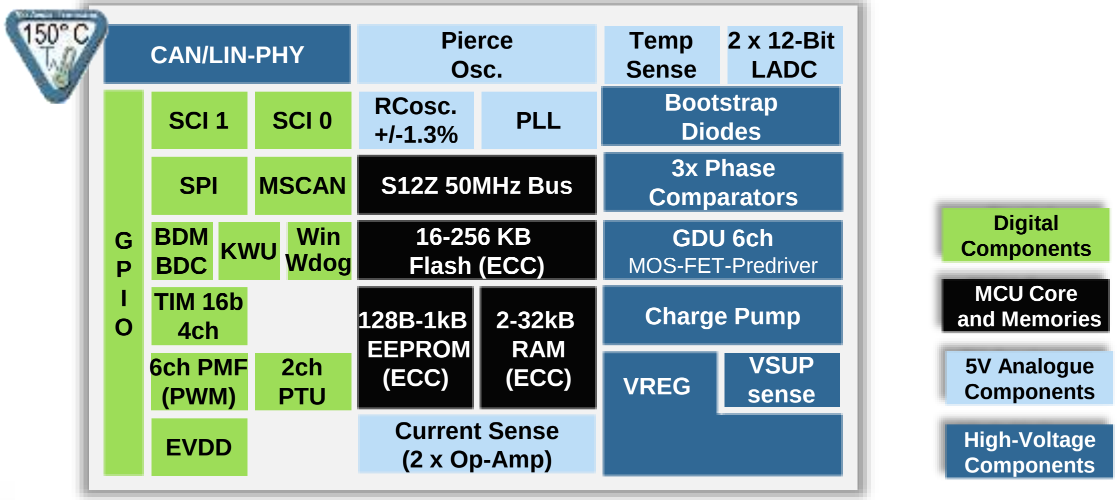
Integrated inside S12ZVM32/16

S12ZVM Introduction - S12ZVM Family

(Carcassonne/Obidos/VMC256) BLDC/PMSM/SR motor control

Key Features:

- S12Z CPU @ 50MHz bus speed
- 6ch Gate Drive Unit (GDU) with 50-150nC total Gate Charge drive capability, incl charge pump for High-Side, Bootstrap diodes for charging external bootstrap capacitors
- Embedded VREG with switchable 5V/20mA sensor supply
- LIN PHY, LIN2.1 / 2.2 / J2602 compliant
- Dual 12bit list-based ADC (LADC), synch with PWM through Programmable Trigger Unit (PTU)
- 2x Op-amp for current sensing



150° C

CAN/LIN-PHY | Pierce Osc. | Temp Sense | 2 x 12-Bit LADC

GPIO

SCI 1 | SCI 0 | RCosc. +/-1.3% | PLL | Bootstrap Diodes

SPI | MSCAN | S12Z 50MHz Bus | 3x Phase Comparators

BDM BDC | KWU | Win Wdog | 16-256 KB Flash (ECC) | GDU 6ch MOS-FET-Predriver

TIM 16b 4ch | 128B-1kB EEPROM (ECC) | 2-32kB RAM (ECC) | Charge Pump

6ch PMF (PWM) | 2ch PTU | VREG | VSUP sense

EVDD | Current Sense (2 x Op-Amp)

Digital Components

MCU Core and Memories

5V Analogue Components

High-Voltage Components

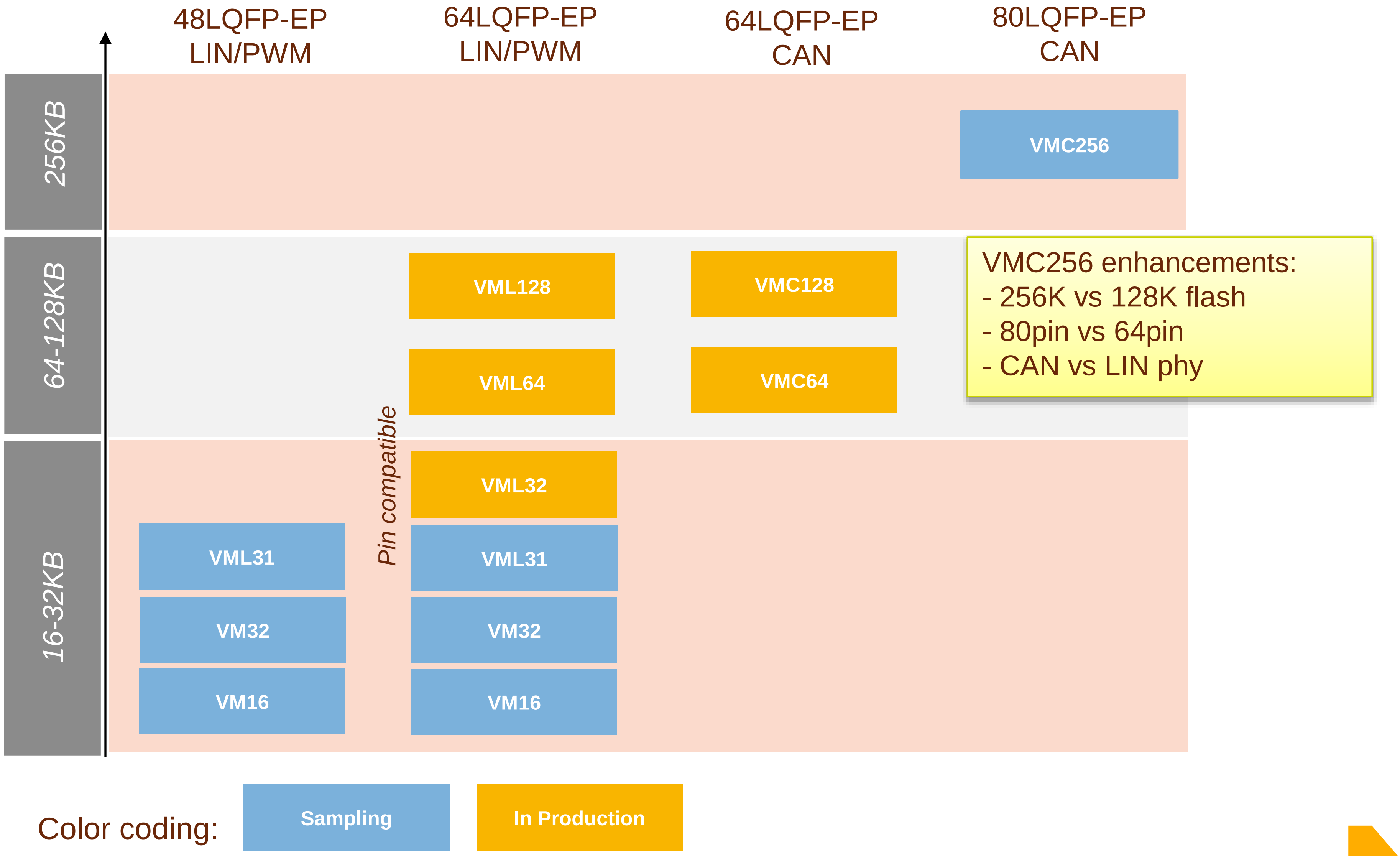
Target applications:

- Sensorless BLDC or PMSM motor control
- Switched Reluctance Motor
- Bidirectional DC motors (H-Bridge)
- Various pumps (oil, fuel, water, vacuum)
- Cooling fan, HVAC blower, Turbocharger

Options:

- Package: 64-LQFP-EP, 48 LQFP-EP, 80-LQFP-EP
- Memory: 16kB / 32kB / 64kB / 128kB / 256kB Flash
- Spec-Options:
  - L with LIN phy
  - C with CAN-PHY (256kB only)
  - C with 2nd Vreg for external CAN phy (128/64kB)
  - “ “ with High Voltage PWM-communication interface
- Temperature: V / M / W (up to 150°C Ta per AEC-Q100 Grade 0)

S12ZVM Introduction - S12ZVM Family Concept



	48LQFP-EP LIN/PWM	64LQFP-EP LIN/PWM	64LQFP-EP CAN	80LQFP-EP CAN
256KB				VMC256
64-128KB		VML128 VML64	VMC128 VMC64	
16-32KB	VML31 VM32 VM16	VML32 VML31 VM32 VM16		

VMC256 enhancements:
- 256K vs 128K flash
- 80pin vs 64pin
- CAN vs LIN phy

Color coding: Sampling In Production

S12ZVM Introduction - BLDC/PMSM Market Segmentation

200+W motors

HVAC Blower

Powered Liftgate

Cooling Fan

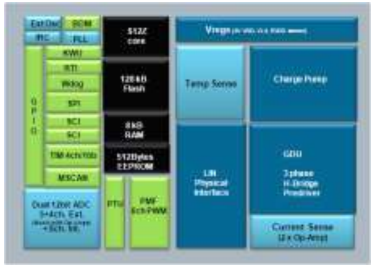
Sliding doors

Fuel pump

Water pump

CAN

(PHY integrated; Potential use for Autodsar)



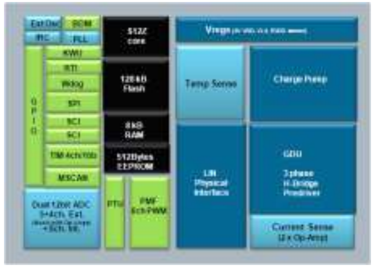
VMC256

(Carcassonne + S12ZVMC256)

lin

CAN

(need ext PHY; Non-Autosar)



Carcassonne

(S12ZVML128/S12ZVMC128)

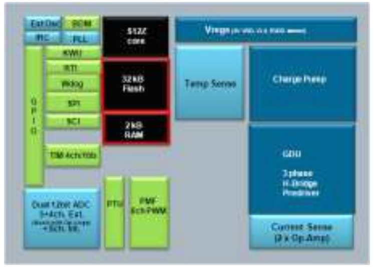
50-200W motors

Reduced GDU drive

Oil pump

PWM

lin



Obidos

(S12ZVML31 / S12ZVM32)

S12ZVM Introduction - Family Feature Set Summary

Connectivity	CAN	LIN	CAN	LIN	CAN	LIN			PWM			
Product Name	VMC256	VML128	VMC128	VML64	VMC64	VML32	VML31	VML31	VM32		VM16	
Package	80LQFP-EP	64LQFP-EP	64LQFP-EP	64LQFP-EP	64LQFP-EP	64LQFP-EP	64LQFP-EP	48LQFP-EP	64LQFP-EP	48LQFP-EP	64LQFP-EP	48LQFP-EP
EEPROM (bytes)	1K	512	512	512	512	512	128	128	128	128	128	128
PHY	CAN	LIN	0	LIN	0	LIN	LIN	LIN	HV	HV	HV	HV
Separate VREG	1+1	0	1	0	1	0	0	0	0	0	0	0
GDU (HS / LS)	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
Bootstrap Diodes	0	0	0	0	0	0	3	3	3	3	3	3
Op Amp	2	2	2	2	2	2	2	1	2	1	2	1
ADC (ext. channels)	8 + 8	4 + 5	4 + 5	4 + 5	4 + 5	4 + 5	4 + 5	1 + 3	4 + 5	1 + 3	4 + 5	1 + 3
MSCAN	1	1	1	1	1	1	0	0	0	0	0	0
SCI	2	2	2	2	2	2	2	1	2	1	2	1
SPI	1	1	1	1	1	1	1	0	1	0	1	0
TIM (IC/OC channels)	4	4	4	4	4	4	4	3	4	3	4	3
PWM channels	6+4	6	6	6	6	6	6	6	6	6	6	6
Internal timers	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API	RTI+API
External FET Nominal Total Gate Charge (nC)	100-150	100-150	100-150	100-150	100-150	100-150	50-80	50-80	50-80	50-80	50-80	50-80
Package Size	12mm x 12mm	10mm x 10mm	10mm x 10mm	10mm x 10mm	10mm x 10mm	10mm x 10mm	10mm x 10mm	7mm x 7mm	10mm x 10mm	7mm x 7mm	10mm x 10mm	7mm x 7mm
Samples	Now	Now	Now	Now	Now	Now	Now	Now	Now	Now	Now	Now
Production release	H2 2016	Q1 2014	Q1 2014	Q1 2014	Q1 2014	Q1 2014	Q1 2016	Q3 2016	Q1 2016	Q3 2016	Q1 2016	Q3 2016

S12ZVM Introduction – S12ZVMC (CAN Version 256KB) Details

MSCAN 2.0A/B
CAN Controller

SPI
As alternative test interf. or for peripherals (sensor)

2x UARTs
As independant Test Intf.

Up to 18 Wakeup pins
Combined with Analog Input pins

4ch 16bit Timer
4ch 16Bit PWM
Hall Inputs, SW timing

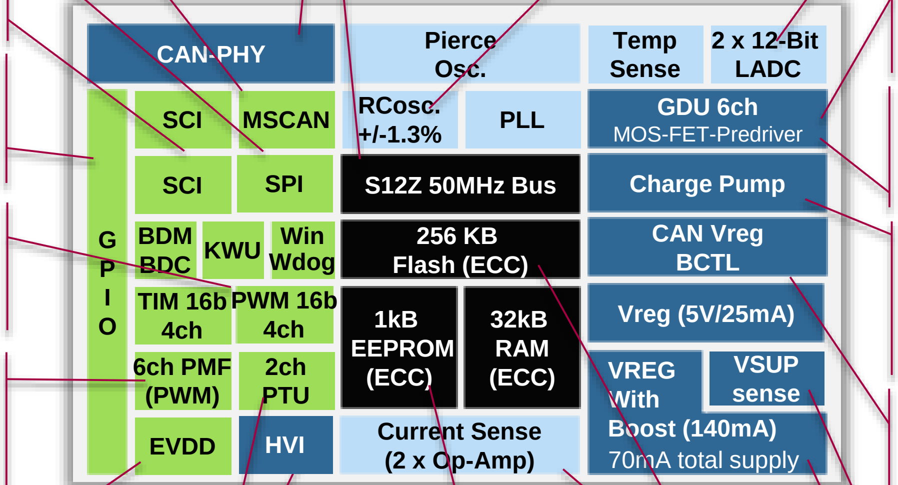
6-ch PMF
15bit PWM for motor control with dead time, fault mgmt

External Supply
5V / 20mA switchable for local (same PCB), over current protected.
Eg. supplying Hallsensors

CAN Physical Layer
(HighSpeed) Supporting dominant Txd timeout

S12Z CPU
16-bit, 32-bit MAC, linear addressing Harvard architech compatible within S12 MagniV

On chip RC OSC
factory-trimmed to +/-1.3%



2 x 12-bit list based ADC
Simultaneous measurement 8+8ch external. Plus int (temp sence, GDU phase, Ref voltages) with DMA

6-ch GDU
Low side and high side FET pre-drivers for each phase with 100-150nC total gate Charge

3x Phase Comparators
for BEMF zero crossing detection in sensorless BLDC

Charge Pump
To support reverse battery protection and boostrap assist for 100% duty-cycle

Voltage Regulators
- For CAN-Phy-supply
- 5V 25mA SC-protected for ext. Peripherals

Vsup sense
Monitoring supply voltage

Voltage Regulator
5V/70mA for whole system

2x Op-Amp for current measurement / sensing

Triggering Unit
Enables sync. between PMF and ADC

High Voltage Inputs
12V Input for Switch-mon. Routable to ADC

EEPROM
4 byte eraseable, 100K program / erase cycles

Flash
512B eras-able. 10K p/e cycles. Suitable for Data

AEC-Q100 Grade 0
Qual'ed up to 150°C Ta

Packaging Option
80LQFP-EP

Digital Components

MCU Core and Memories

5V Analogue Components

High-Voltage Components

S12ZVM Introduction – S12ZVML (128/64/32kB-LIN Version) Details

2x UARTs
One linked to LIN Phy, 2_{nd} as independant Test Intf.

SPI
As alternative test Interf or for peripherals (sensors, …)

MSCAN 2.0A/B
CAN Controller

Up to 18 Wakeup pins
Combined with Analog Input pins

4ch 16bit Timer
Hall Inputs, SW timing

6-ch PMF
15bit PWM for motor control with dead time, fault mgmt

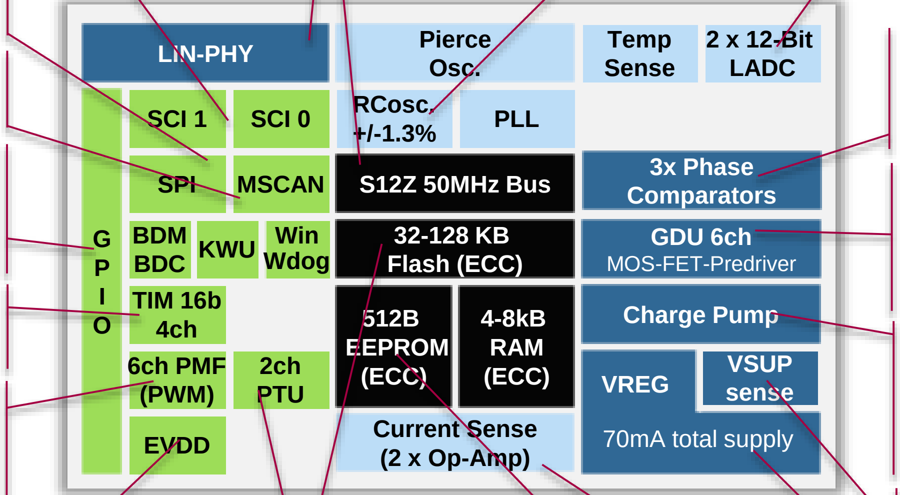
External Supply
5V / 20mA switchable for local (same PCB), over current protected.
Eg. supplying Hallsensors

LIN Physical Layer
LIN2.2 and SAE J2602 compliant +/- 8kV ESD capability

S12Z CPU
16-bit, 32-bit MAC, linear addressing Harvard architech compatible within S12 MagniV

On chip RC OSC
factory-trimmed to +/- 1.3% , meets LIN -needs

2 x 12-bit list based ADC
Simultaneous measurement 5+4ch external. Plus 8ch int (temp sence, GDU phase, Ref voltages) with DMA



🟩 Digital Components

⬛ MCU Core and Memories

▭ 5V Analogue Components

🟦 High-Voltage Components

PTU
Enables synchronization between PMF and ADC

Flash (32/64/128kB)
512B erasable. 10K p/e cycles. Can be used for Data

EEPROM
4 byte eraseable, 100K program / erase cycles

3x Phase Comparators
for BEMF zero crossing detection in sensorless BLDC

6-ch GDU
Low side and high side FET pre-drivers for each phase with 100-150nC total gate Charge

Charge Pump
To support reverse battery protection and boostrap assist for 100% duty-cycle

Vsup sense
Monitoring supply voltage

Voltage Regulator
5V/70mA for whole system

2x Op-Amp for current measurement / sensing

AEC-Q100 Grade 0
Qual'ed up to 150°C Ta

Packaging Option
64LQFP-EP

S12ZVM Introduction – S12ZVMC (128/64kB-CAN Version) Details

2x UARTs
As independant Test Intf.

SPI
As alternative test Interf or for peripherals (sensors, …)

MSCAN 2.0A/B
CAN Controller

Up to 18 Wakeup pins
Combined with Analog Input pins

4ch 16bit Timer
Hall Inputs, SW timing

6-ch PMF
15bit PWM for motor control with dead time, fault mgmt

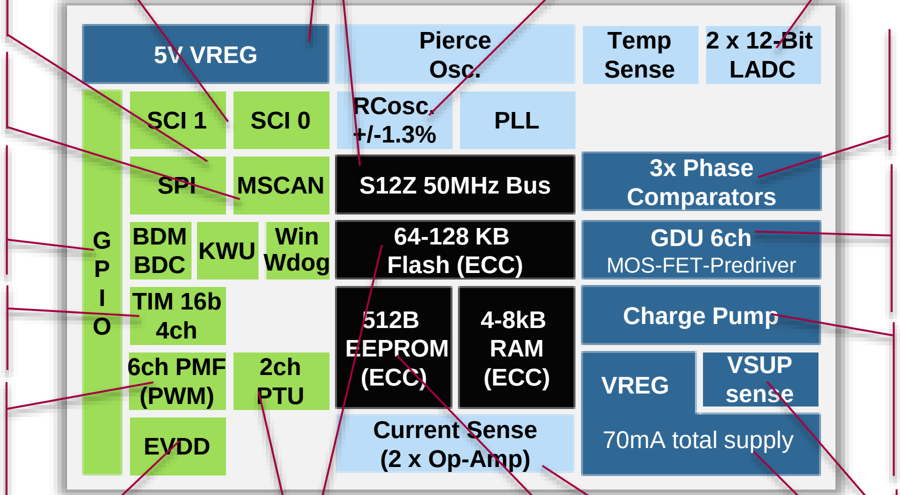
External Supply
5V / 20mA switching for local (same PCB), over current protected.
Eg. supplying Hallsensors

2nd 5V Vreg
For supplying an external CAN-PHY independant from main VREG

S12Z CPU
16-bit, 32-bit MAC, linear addressing Harvard architech compatible within S12 MagniV

On chip RC OSC
factory-trimmed to +/- 1.3%

2 x 12-bit list based ADC
Simultaneous measurement 5+4ch external. Plus 8ch int (temp sence, GDU phase, Ref voltages) with DMA



3x Phase Comparators
for BEMF zero crossing detection in sensorless BLDC

6-ch GDU
Low side and high side FET pre-drivers for each phase with 100-150nC total gate Charge

Charge Pump
To support reverse battery protection and boostrap assist for 100% duty-cycle

Vsup sense
Monitoring supply voltage

Voltage Regulator
5V/70mA for whole system

2x Op-Amp for current measurement / sensing

PTU
Enables synchronization between PMF and ADC

Flash (64/128kB)
512B erasable. 10K p/e cycles. Can be used for Data

EEPROM
4 byte eraseable, 100K program / erase cycles

AEC-Q100 Grade 0
Qual‘ed up to 150°C Ta

Packaging Option
64LQFP-EP

Digital Components

MCU Core and Memories

5V Analogue Components

High-Voltage Components

S12ZVM Introduction – S12ZVM32/VML31 (PWM / LIN Version) Details

LIN Physical Layer
LIN2.2 and SAE J2602 compliant
+/- 8kV ESD capability.
*Devices either have a LIN or HV Physical layer

2x UART
One linked to HV/LIN Phy, 2_{nd} as independent test Intf.

SPI
As alternative test Intf or for peripherals (sensors,.)

Up to 18 Wakeup pins
Combined with Analog i/ps

4ch 16bit Timer
Hall Inputs, SW timing

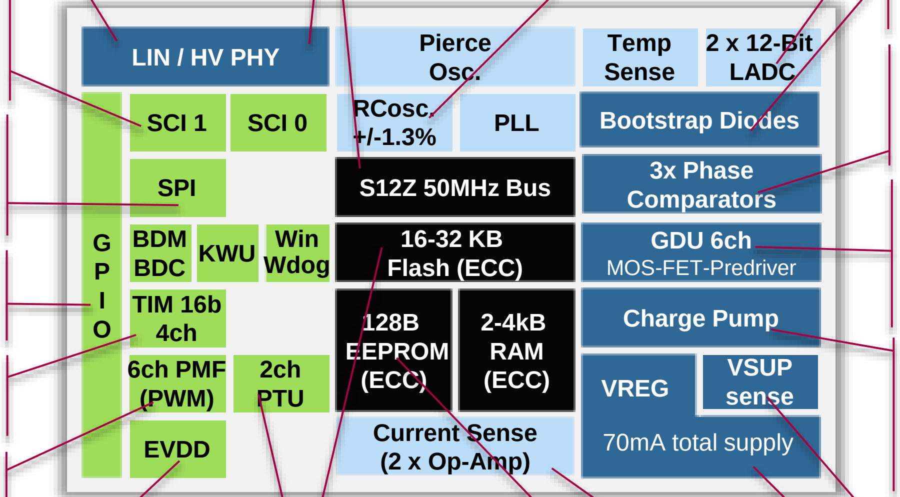
6-ch PMF
15bit PWM for motor control with dead time, fault mgmt

External Supply
5V / 20mA switchable for local (same PCB), over current protected. Eg. supplying Hallsensors

HV PHY
Allows control through 12V PWM. Can be used as LIN during development and reprogramming

S12Z CPU
16-bit, 32-bit MAC, linear addressing Harvard architech compatible within S12 MagniV

On chip RC OSC
factory-trimmed to +/- 1.3%



PTU
Enables synchronization between PMF and ADC

Flash (16/32kB)
512B erasable. 10K p/e cycles. Can be used for Data

EEPROM
4 byte eraseable, 100K program / erase cycles

AEC-Q100 Grade 0
Qual'ed up to 150°C Ta

Packaging Option
64LQFP-EP, 48LQFP-EP

2 x 12-bit list based ADC
Simultaneous measurement 5+4ch external. Plus 8ch int (temp sence, GDU phase, Ref voltages) with DMA

Bootstrap Diodes
3x Bootstrap diodes integrated

3x Phase Comparators
for BEMF zero crossing detection in sensorless BLDC

6-ch GDU
Low side and high side FET pre-drivers for each phase with 50-80nC total gate Charge

Charge Pump
To support reverse battery protection and boostrap assist for 100% duty-cycle

Vsup sense
Monitoring supply voltage

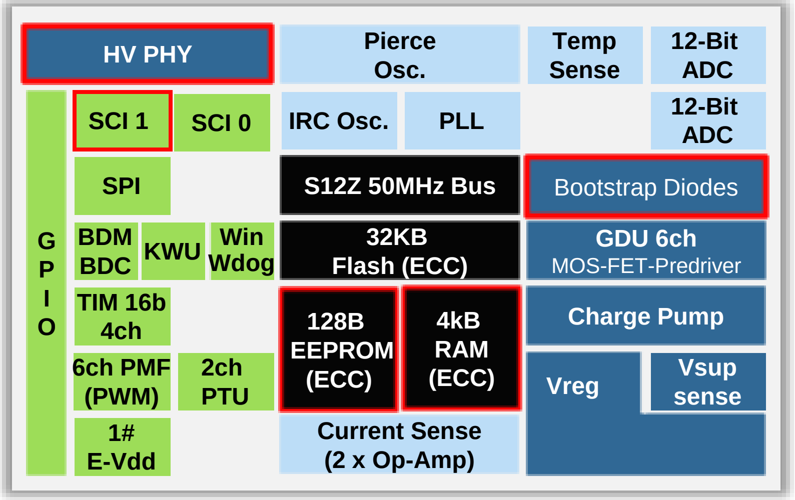
Voltage Regulator
5V/70mA for whole system

2x Op-Amp for current measurement / sensing

- 🟩 Digital Components
- ■ MCU Core and Memories
- 🟦 5V Analogue Components
- 🟦 High-Voltage Components

S12ZVM Introduction - S12ZVM32/16 Feature enhancement

- Feature enhancement since Concept
  - **HVI to HV PHY**: Allows control of S12ZVM directly through 12V PWM command also allows error/ack response
  - **Bootstrap Diodes**: Added diodes internally to charge the external bootstrap capacitors.
  - **4K RAM**: Increased RAM from 2K to 4K. To help write structured code
  - **128B EEPROM**: Added 128B EEPROM
  - **SCI**: Added additional SCI to emulate LIN over HV PHY
  - **48LQFP-EP**: Added additional package with smaller body size (7mm x 7mm). Ideal for smaller motors

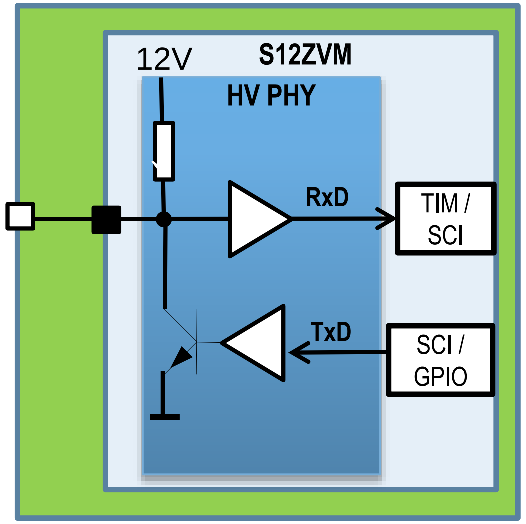


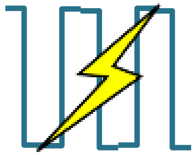
HV PHY
Pierce Osc.
Temp Sense
12-Bit ADC
SCI 1
SCI 0
IRC Osc.
PLL
12-Bit ADC
SPI
S12Z 50MHz Bus
Bootstrap Diodes
GPIO
BDM BDC
KWU
Win Wdog
32KB Flash (ECC)
GDU 6ch MOS-FET-Predriver
TIM 16b 4ch
128B EEPROM (ECC)
4kB RAM (ECC)
Charge Pump
6ch PMF (PWM)
2ch PTU
Vreg
Vsup sense
1# E-Vdd
Current Sense (2 x Op-Amp)

Last Updated: 8th May, 2014

S12ZVM Introduction - HV PHY on S12ZVM

- Allows control of S12ZVM directly through 12V PWM command
- Can respond on error / acknowledgement through open drain mechanism
- Integrates the signal conditioning logic of 12V PWM control signal

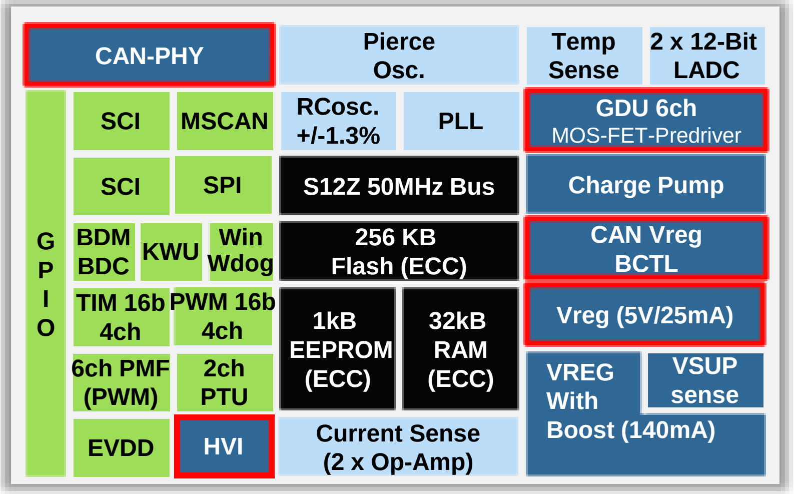




- Can emulate LIN PHY for development purpose, providing unified development process between S12ZVM32 & S12ZVML family
- Supports field re-flashing using LIN boot

S12ZVM Introduction - S12ZVMC256 Feature enhancement

- Feature enhancement vs. VMC/VML128
  - **GDU**: Enhancement to support Switch Reluctance Motors
  - **CAN-PHY**: integrated CAN Physical Interface
  - **Memory**: increased Flash, EEPROM & RAM for carrying more enhanced stacks (CAN / Autosar) / Operating Systems next to advanced Motorcontrol
  - **VREG:** 2 additional Voltage regulators, one for supporting on-chip-CAN-PHY, other for powering peripherals (5V 25mA SC-protected)
  - **HVI:** adding one High Voltage Input (12V Digital Input or 12V ADC with ESD-protection)
  - **PWM:** adding secondary 4ch/16Bit PWM
  - **80LQFP-EP**: More features require larger package

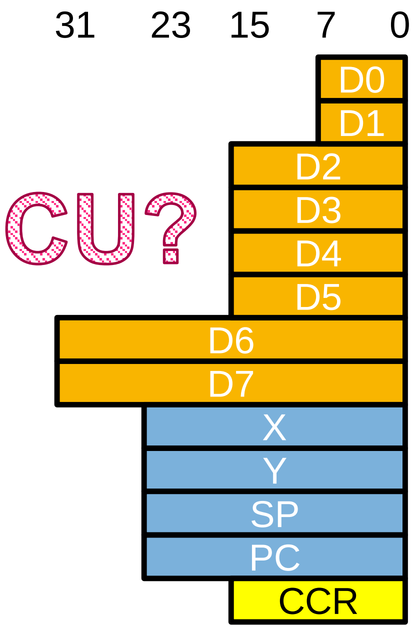


S12ZVM Introduction – S12Z Core

- **24-bit = 16MByte linear address space (no paging)**
- **32-bit wide instruction and data bus**
- **32-bit ALU**
  - Single-cycle 16x16 multiply (2.5 cycles 32x32)
  - MAC unit 32-bit += 32-bit*32-bit (3.5 cycles)
  - Hardware divider 32-bit = 32-bit/32-bit   (18.5 cycles)
  - Single cycle multi-bit shifts (Barrel shifter)
  - Fractional Math support
- **CPU operates at 100MHz**
  - Optimized bus architecture with 100MHz load and store to RAM
  - NVM works with 1 Wait-state => effective 20ns accesses
- **Harvard Architecture => parallel data and code access**
- **Instructions and addressing modes optimized for C-Programming & Compiler**

A 16-bit MCU?

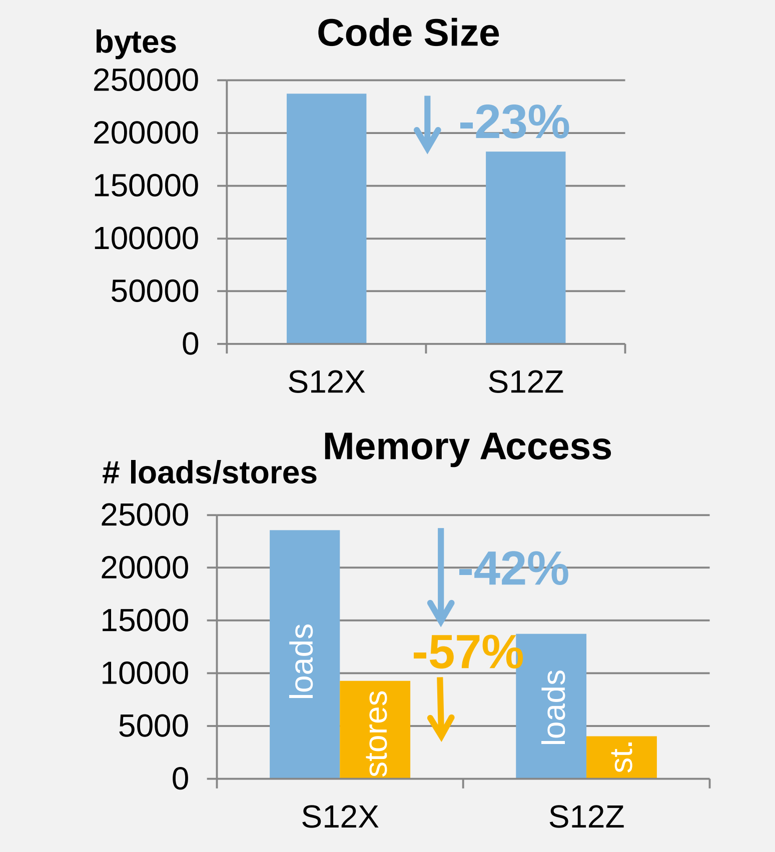
Programmer's Model



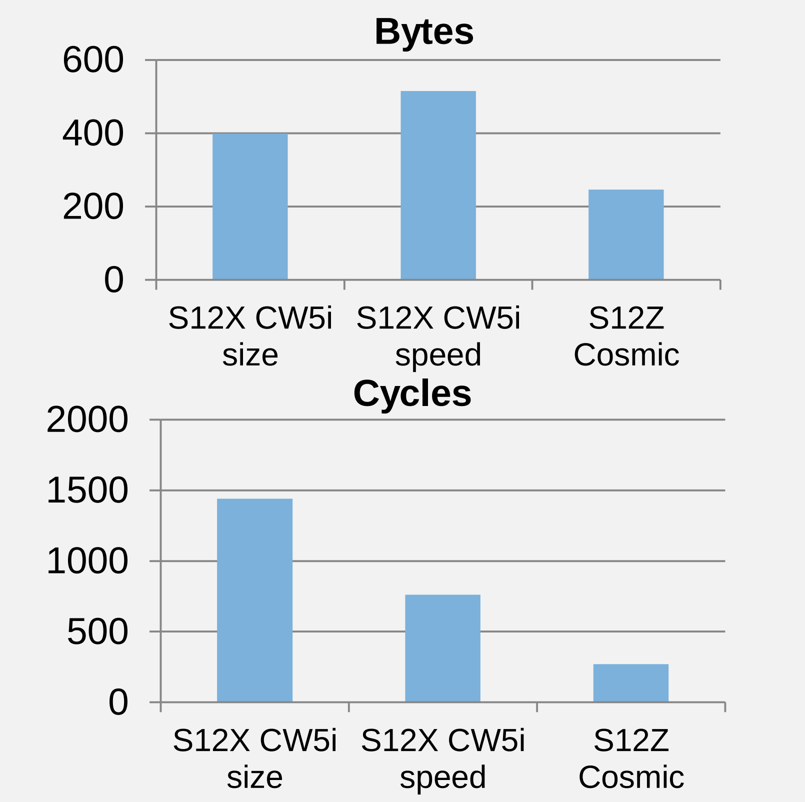
S12ZVM Introduction - S12Z Benchmarks Results

- **S12Z typically saves 20% code size versus S12X**
- **S12Z typically uses 30% less memory accesses than S12X, which saves power**

Large Application Code Example:

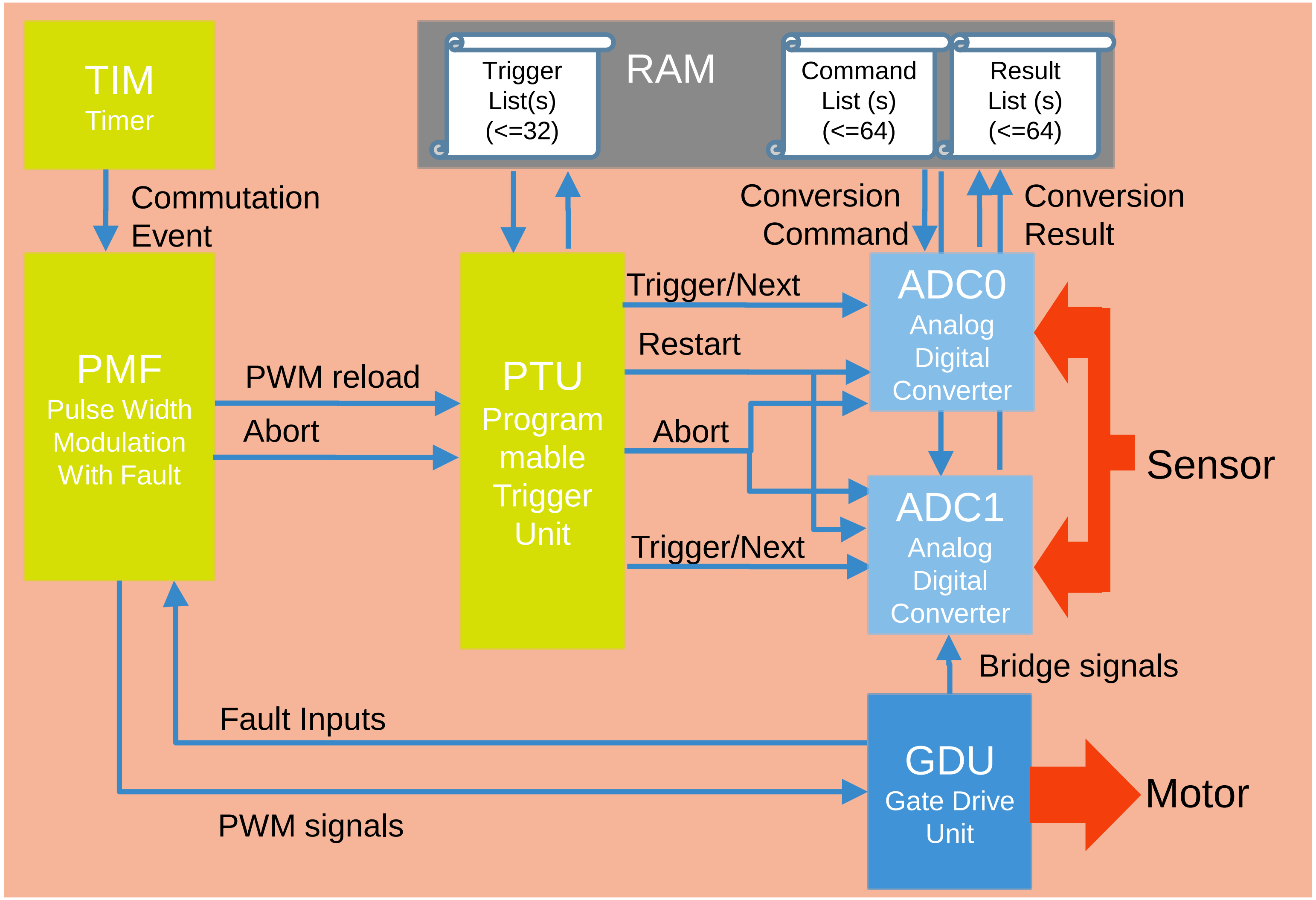


Digital Filter Example:



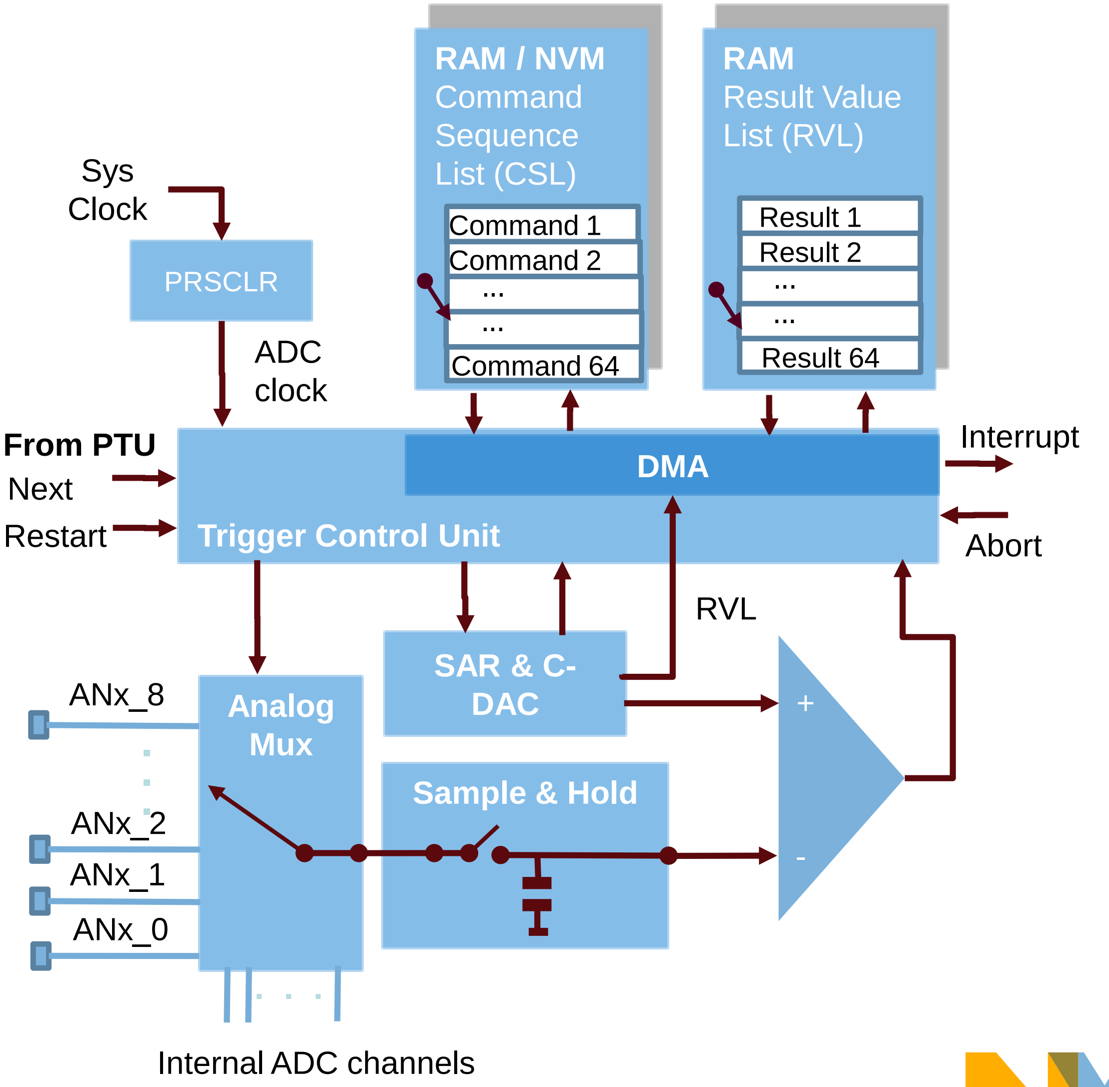
S12ZVM Introduction - Motor Control Loop Implementation

One control cycle can be a PWM cycle or a number of PWM cycles



S12ZVM Introduction - 12-bit SAR ADC

- **2 independent converters:**
  - ADC0 (5 ext ch. + 5 int. ch.)
  - ADC1 (4 ext ch. + 4 int. ch.)
- **List Based Architecture**
  - Double buffered lists -> CPU can load new values in the background
  - Flexible conversion sequence definition and oversampling.
- Can be triggered by PTU, for accurate synch with PWM
- DMA taking commands from SRAM /NVM and storing results back into SRAM



S12ZVM Introduction - Internal Channels

- **Internal Channels give access to following internal signals**

ADC0

Channel Select						ADC Channel	Signal
0	0	1	0	0	0	Internal_0	ADC0 temperature sensor
0	0	1	0	0	1	Internal_1	VREG temperature sensor or Bandgap voltage
0	0	1	0	1	0	Internal_2	GDU phase multiplexer voltage
0	0	1	0	1	1	Internal_3	GDU DC link voltage monitor
0	0	1	1	0	0	Internal_4	BATS VSUP sense voltage

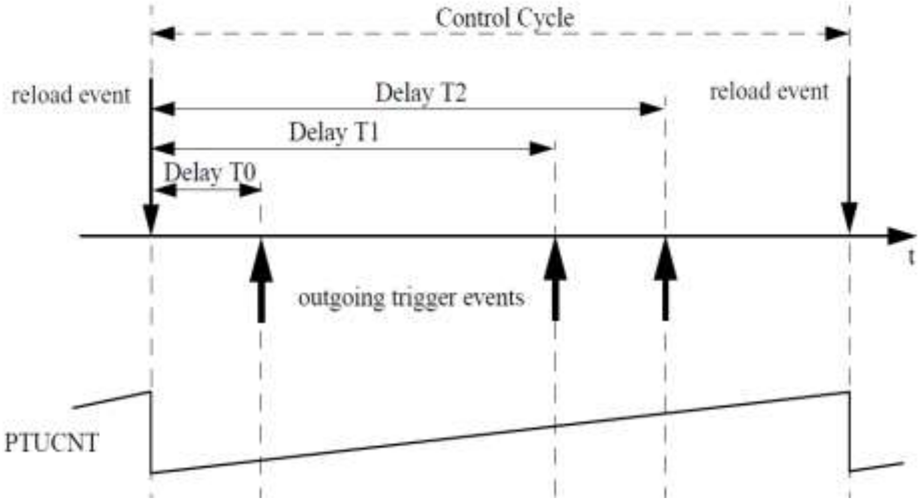
ADC1

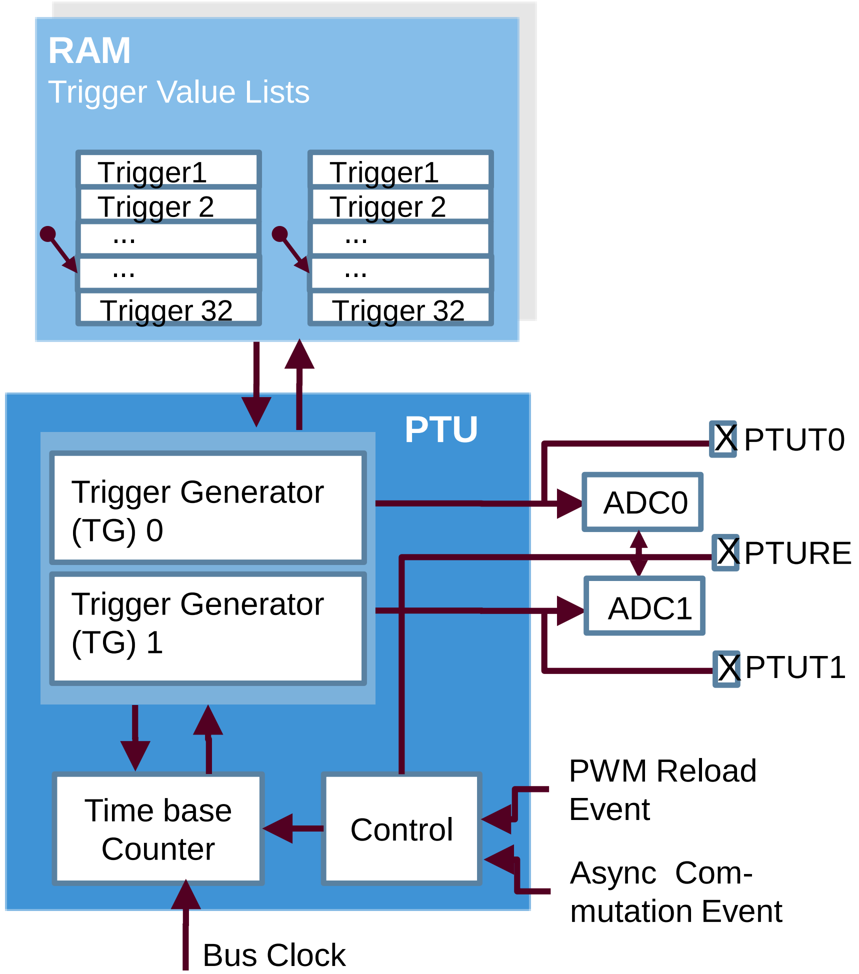
Channel Select						ADC Channel	Signal
0	0	1	0	0	0	Internal_0	ADC1 temperature sensor
0	0	1	0	0	1	Internal_1	VREG temperature sensor or Bandgap voltage
0	0	1	0	1	0	Internal_2	GDU phase multiplexer voltage
0	0	1	0	1	1	Internal_3	GDU DC link voltage monitor

S12ZVM Introduction - Programmable Trigger Unit (PTU)

Completely avoids CPU involvement to trigger ADC during the control cycle

- One 16-bit counter as time base for all trigger events
- Two independent trigger generators (TG)
- Up to 32 trigger events per trigger generator
- Trigger Value List stored in system memory
- Double buffered list, so that CPU can load new values in the background
- Software generated “Reload” event
- Software generated trigger event
- Global Load OK support, to guarantee coherent update of all control loop modules



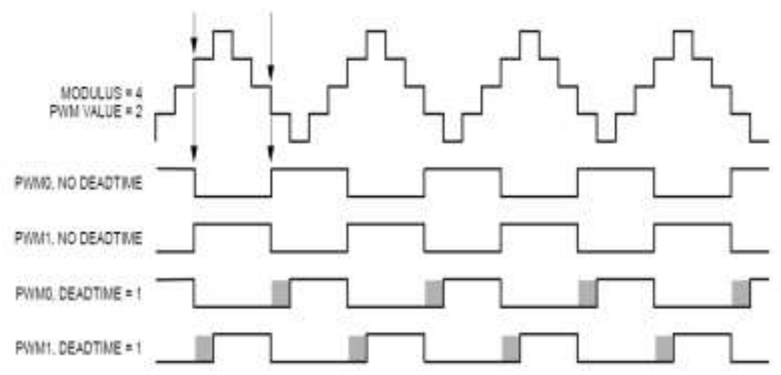


S12ZVM Introduction - Pulse Width Modulator Module (PMF)

- **6 PWM channels, 3 independent counters**
  - Up to 6 independent channels or 3 complementary pairs
- **Based on core clock (max. 100MHz)**
- **Complementary operation:**
  - Dead time insertion
  - Top and Bottom pulse width correction
  - Double switching
  - Separate top and bottom polarity control
- **Edge- or center-aligned PWM signals**
- **Integral reload rates from 1 to 16**
- **6-step BLDC commutation support, with optional link to TIM Output Compare**
- **Individual software-controlled PWM outputs**
- **Programmable fault protection**

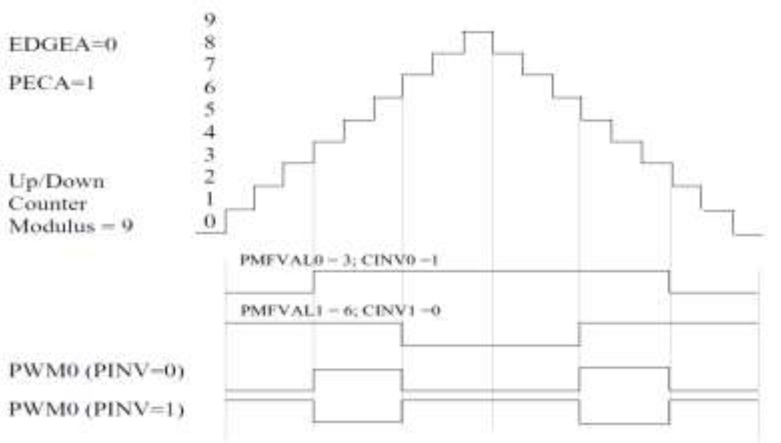
Complementary Mode

with / without dead time insertion



Double-Switching Mode

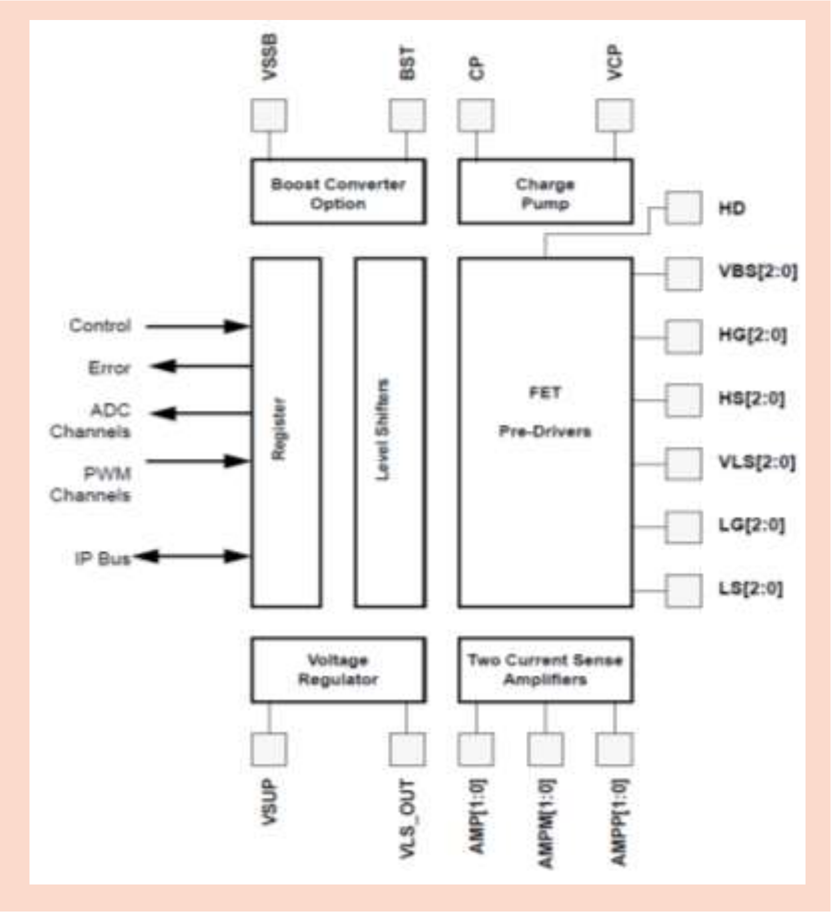
for single shunt system



S12ZVM Introduction - Gate Driver Unit (GDU) Overview

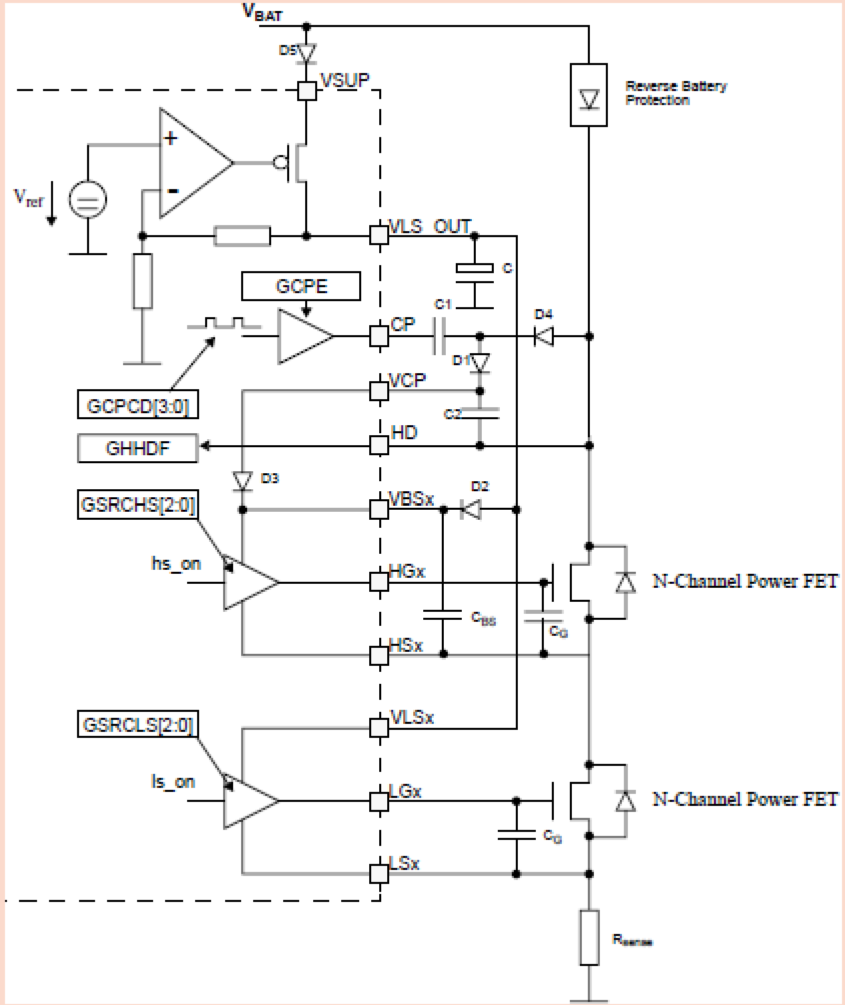
FET pre-driver for 6 N-ch power MOSFETs (3 high-side, 3 low-side)

- 11V regulator to drive external FETs VGS
- Bootstrap circuit for high-side drivers
- Optional charge pump to support static high-side driver operation
- Phase comparators to signal BEMF zero crossing
- Option to route DC Link (HD) or Phase voltage measurement to ADC
- Two current sense amplifiers feeding ADC
- Over- /under- voltage monitoring
- Short circuit protection by monitoring VDS for both LS/ HS
- Step-up (boost) converter option for low supply voltage operation



S12ZVM Introduction - “Half-Bridge” Driver Topology

- 11V LDO supplies the LS drivers, while it charges the bootstrap cap for the HS drivers
- Bootstrap circuit for high side drive, with optional Charge Pump support
- Drives N-channel power MOSFET transistors, up to ~100nC total gate charge
- Programmable slew rate for improved EMC performance
- Under-voltage monitor for 11V LDO; Over-voltage monitor for DC link (HD)



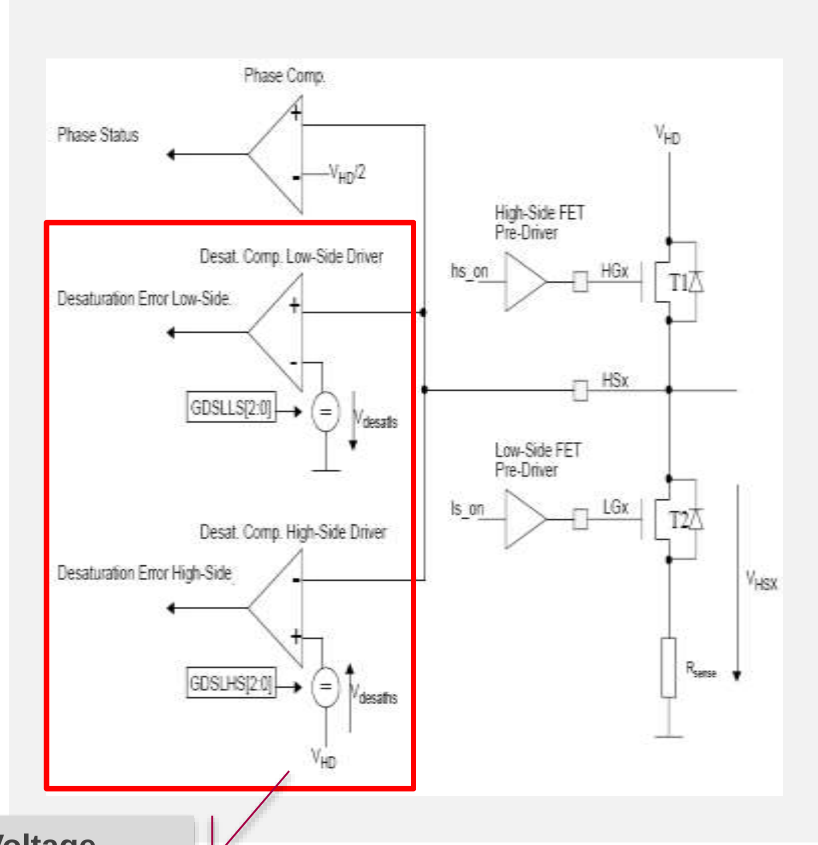
S12ZVM Introduction - HS& LS Protection (Vds Monitoring)

- 6 de-saturation comparators for HS and LS protection

- After turning on (any) high-side or low-side transistor, the HSx voltage is monitored

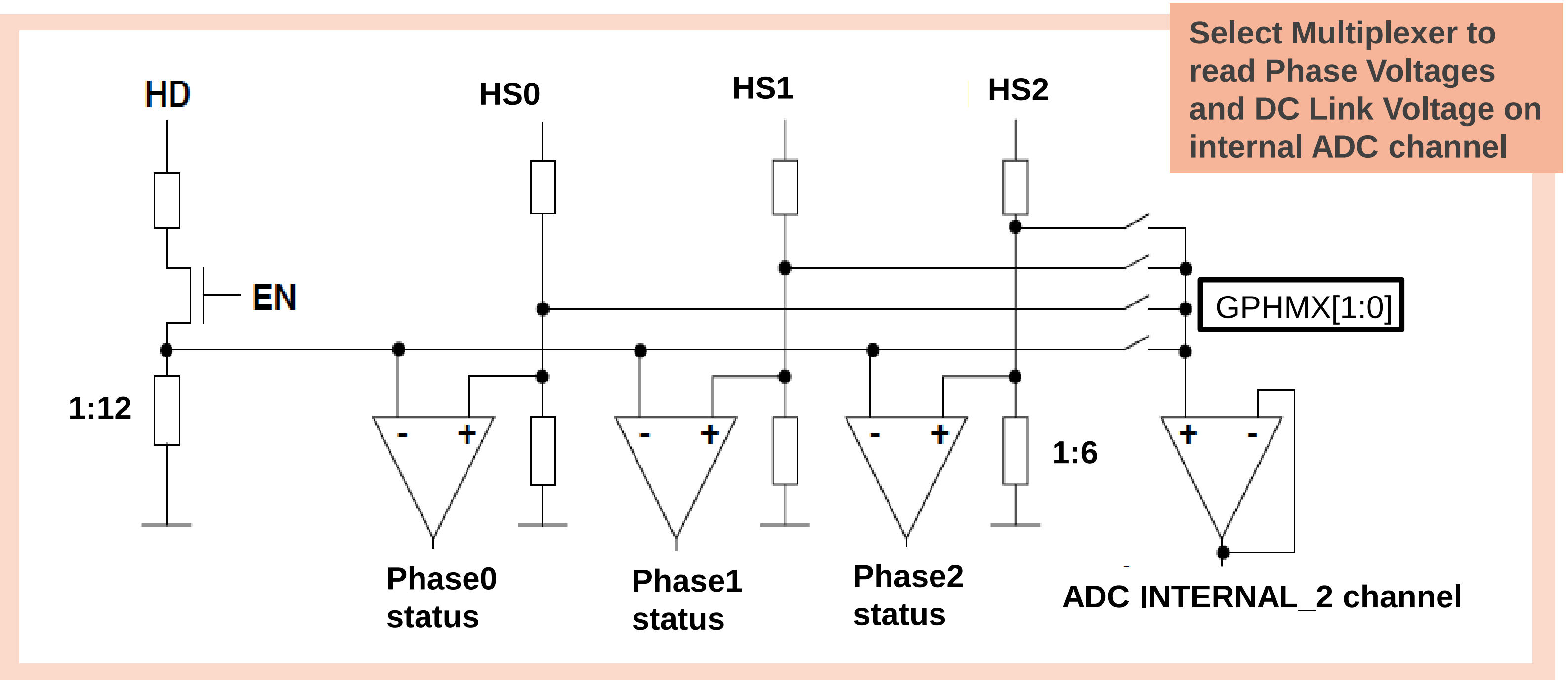
- In case of de-saturation error
  → LS/HS switched off
  → optional interrupt

- Programmable blanking time = delay between driver turn-on and the evaluation of the comparator (~60ns..5us @ 50MHz)



Saturation Voltage programmable from 0.3V to 1.35V in 8 steps (150mV steps)

S12ZVM Introduction - Phase Comparators

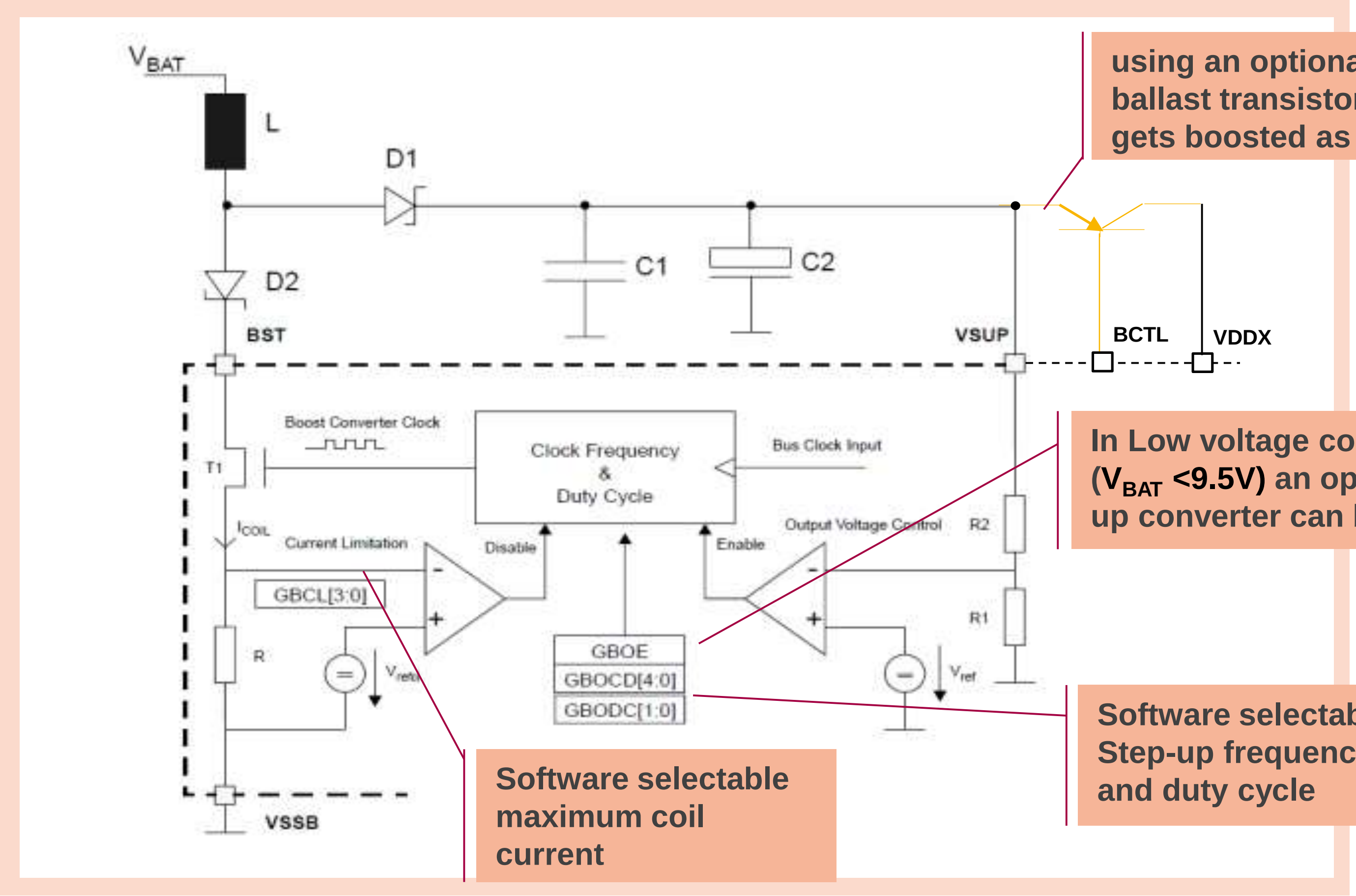


Select Multiplexer to read Phase Voltages and DC Link Voltage on internal ADC channel

- The phase comparators indicate if phase voltage V_{HSx} is greater than $0.5*V_{HD}$
- This can be used for BEMF detection in un-driven phases
- A multiplexer selects if the supply voltage HD or any of the phase voltages is routed to an ADC internal channel

S12ZVM Introduction - Boost (Step-Up) Converter

This option can be used to guarantee a V_{GS} > 9V at low V_{BAT} conditions



using an optional external ballast transistor the core gets boosted as well or not

In Low voltage condition (V_{BAT} <9.5V) an optional step up converter can be enabled

Software selectable Step-up frequency and duty cycle

Software selectable maximum coil current

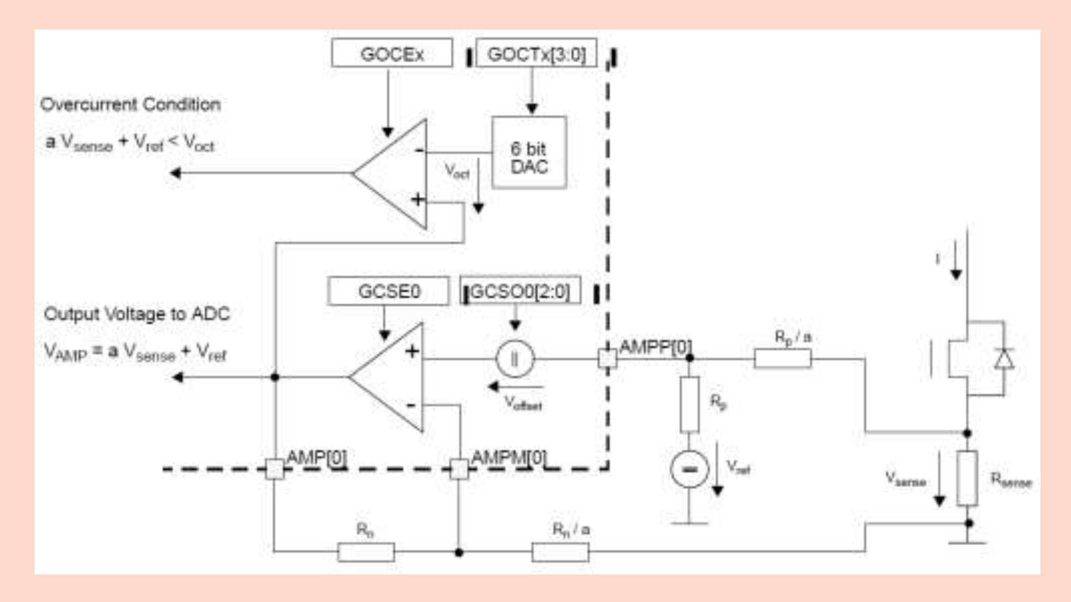
S12ZVM Introduction - Operating Voltage Ranges

Without Boost		
Vsup	**MCU**	**GDU**
26V…40V	Full	Disabled
7V...26V	Full	Enabled Vgs> Vsup – 2*Vbe (5V min)
6V .. 7V	Full	Disabled
3.5V .. 6V	Full Iddx = 25mA max if no external PNP	Disabled
<3.5V	Reset	Disabled

With Boost		
Vsup	**MCU**	**GDU**
26V... 40V	Full	Disabled
9.5V..26V	Full	Boost OFF for Vsup > 11V Vgs = 9.6V
6V…9.5V	Full	Boost ON Vgs >9V
3.5V .. 6V	Full Iddx = 25mA max if no external PNP	Boost ON Vgs >9V
<3.5V	Reset	Disabled

S12ZVM Introduction - Current Sense Amplifier

- Two linear operational amplifiers are provided to amplify voltage across two separate current sense shunt resistors
- Each amplifier drives an ADC channel
- The amplifier closed-loop gain (A_v) can be selected by choosing resistor values populated on the PCB

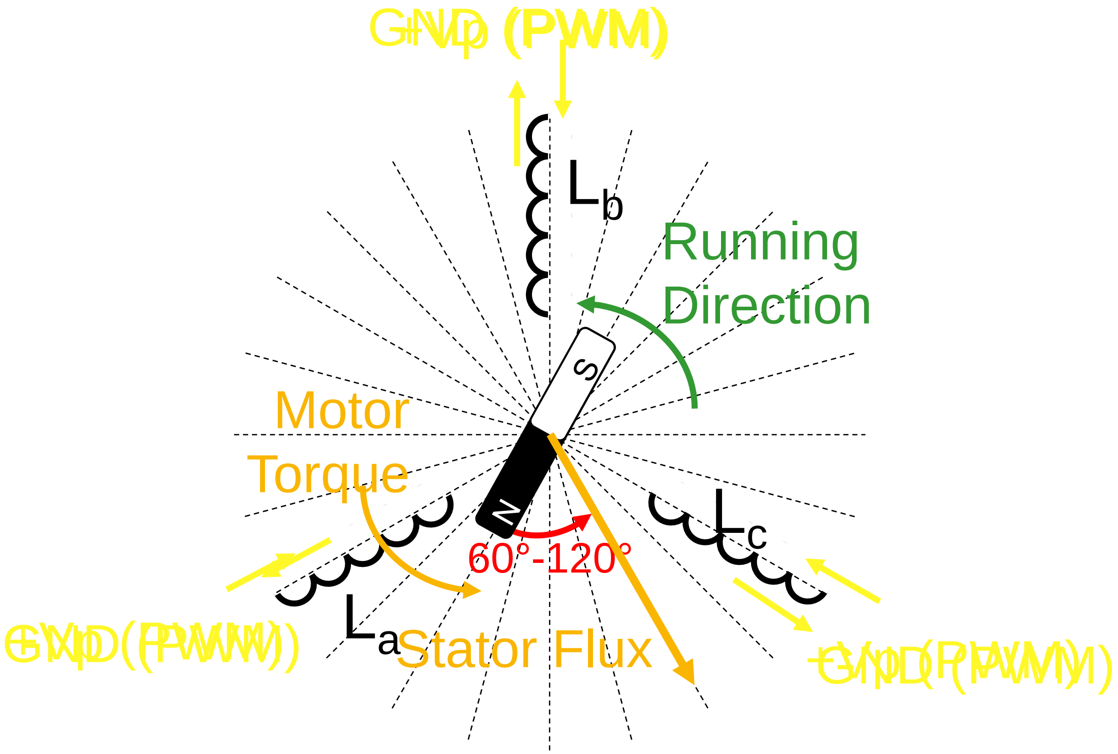


- By applying an offset level (by resistor network), bidirectional current sense can be accomplished
- The amplifier features offset compensation in 8 steps in order to avoid low signal “hiding” near to ground level
- It provides an additional over-current comparator with SW selectable thresholds via a 6-bit ADC

S12ZVM INTRODUCTION

ANY QUESTIONS?

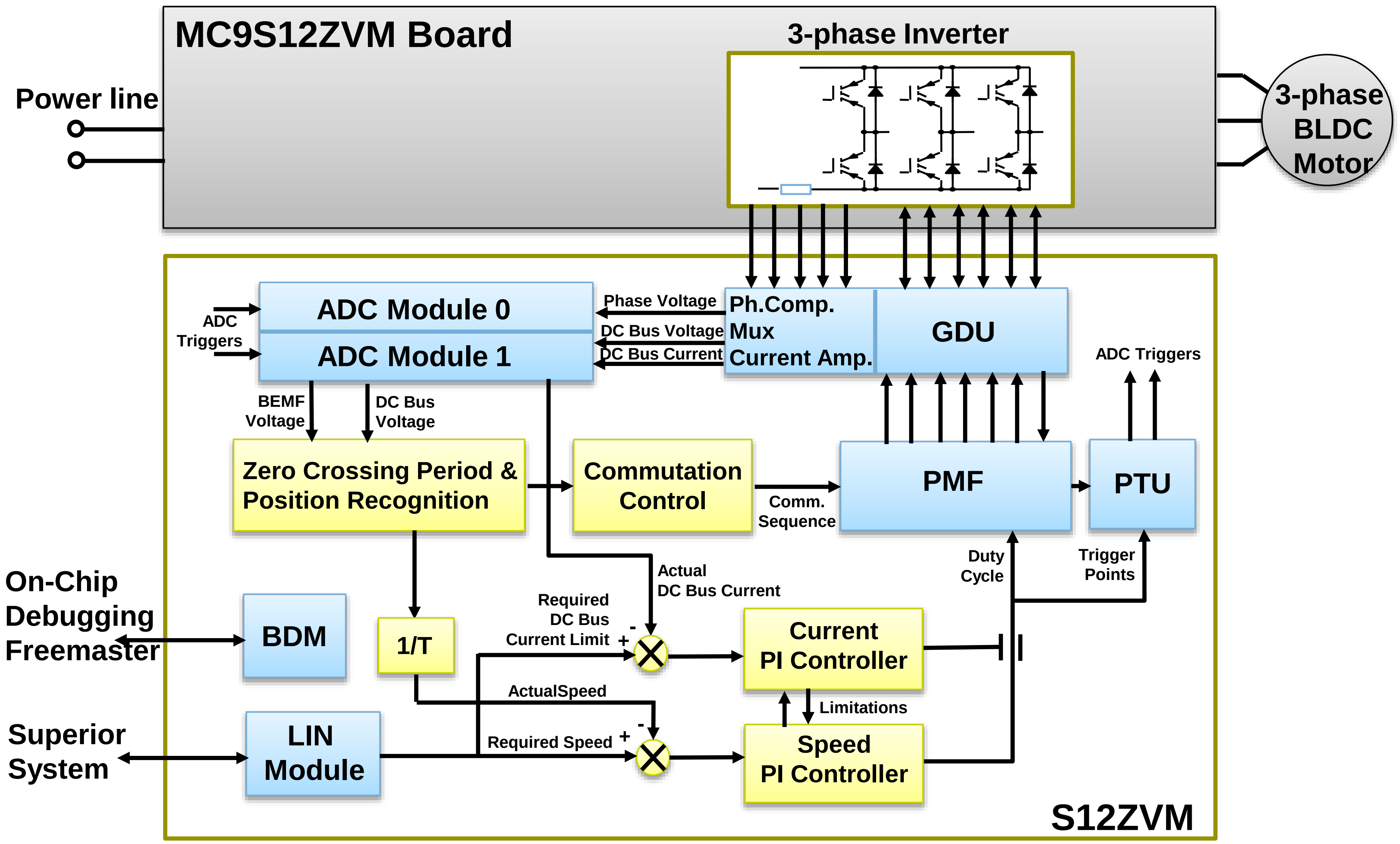
BLDC Control - 6-Step Commutation Principle



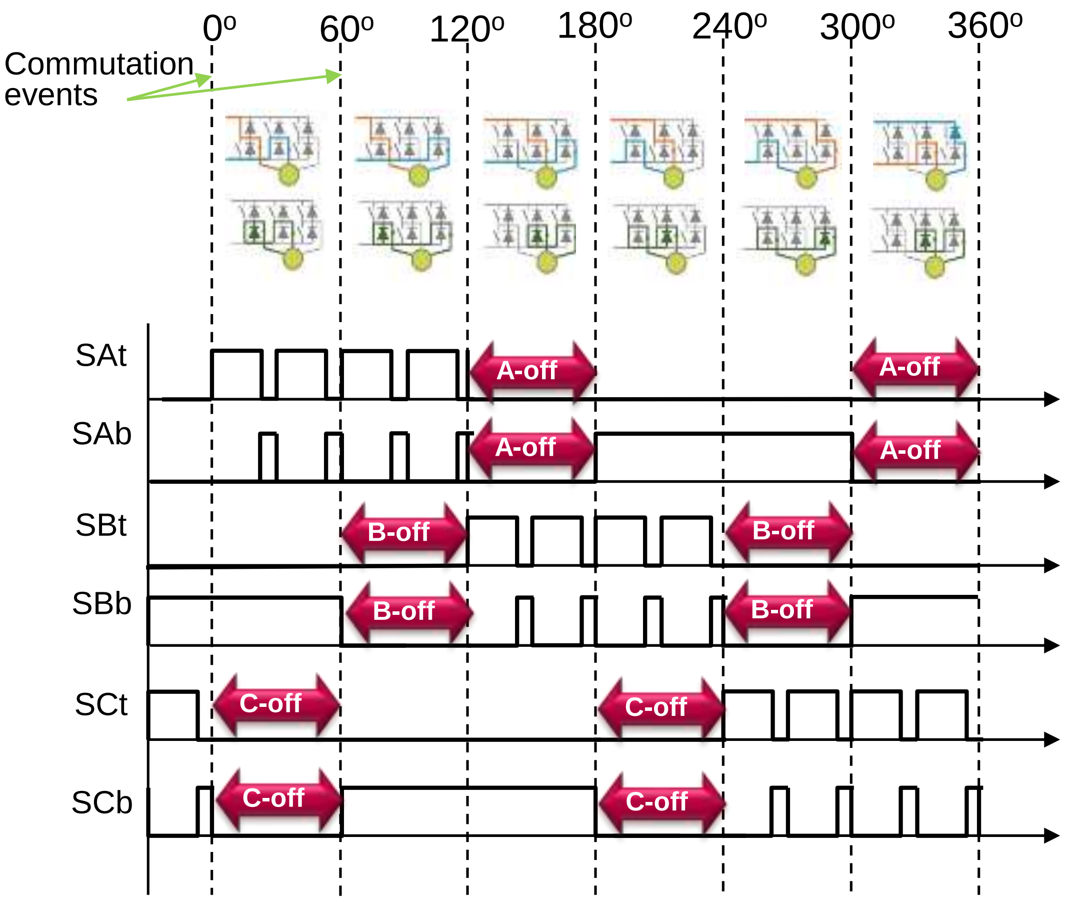
- Stator Field is generated between 60° to 120° to rotor field to get maximal torque and energy efficiency

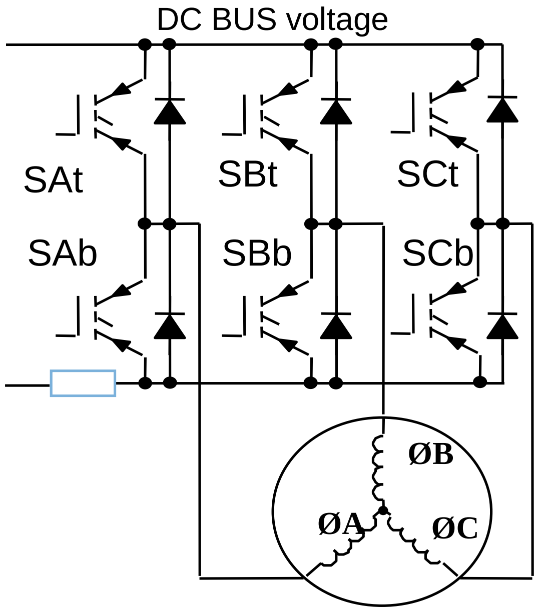
- Six Flux Vectors defined to create rotation

BLDC Control - Example Control Block diagram



BLDC Control - Complementary/Independent Unipolar PWM Switching

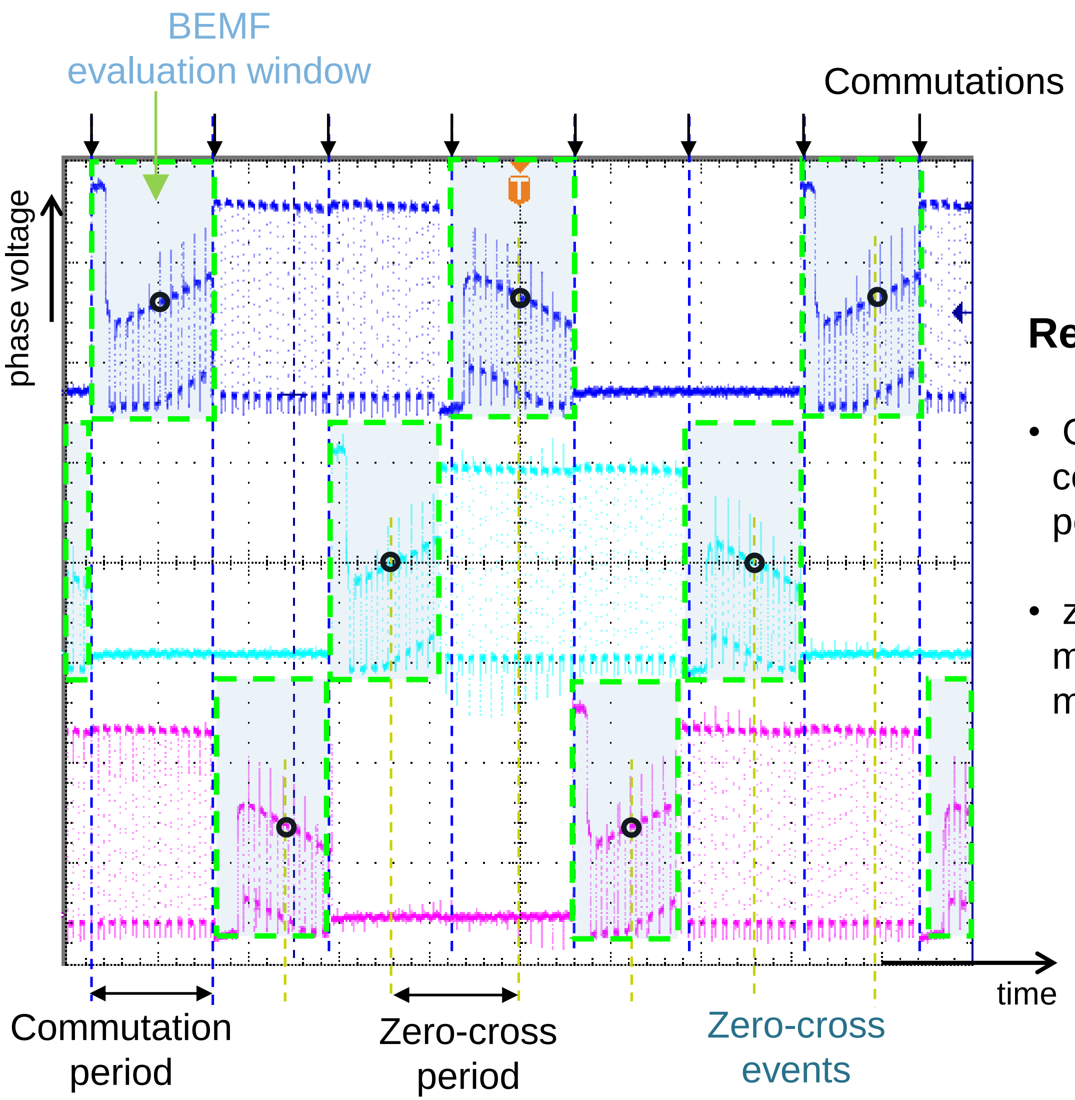




One phase powered by complementary PWM signal, second phase grounded:

- Low MOSFET switching losses
- Low EMC noise

BLDC Control - Back-EMF Zero-Cross Events and Commutations



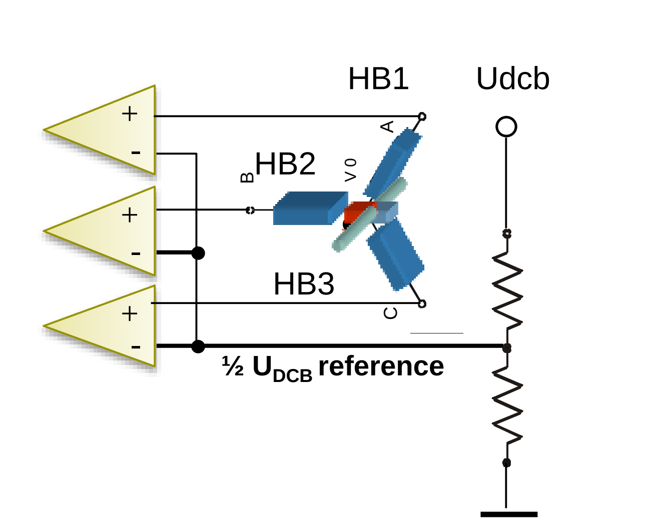
Relationships:

- On constant rotor speed: commutation period = zero-cross period
- zero-cross event occurs in the middle of two commutations (on ideal motor)

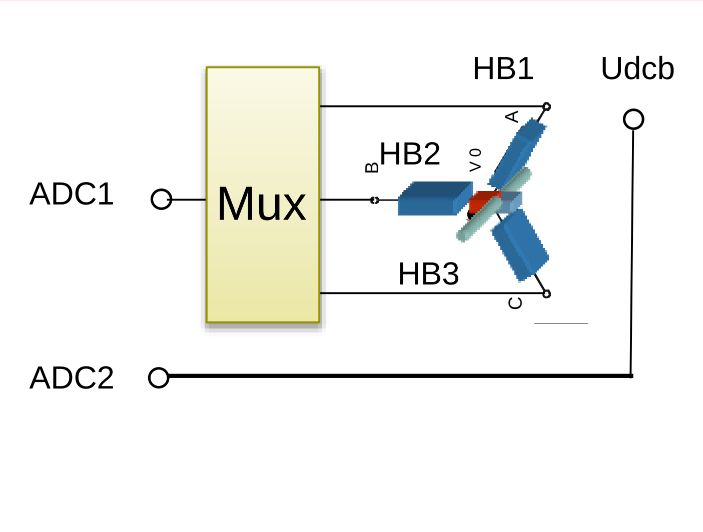
BLDC Control - Zero Crossing Topologies

Both supported by S12ZVM

Using Phase comparators



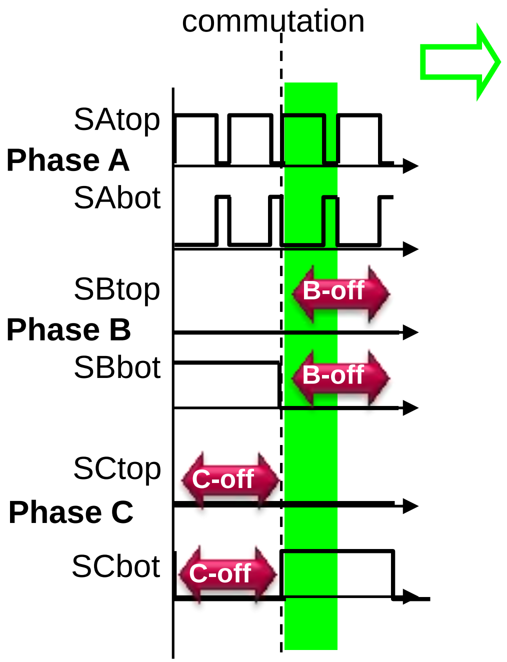
Using SW ADC sensing

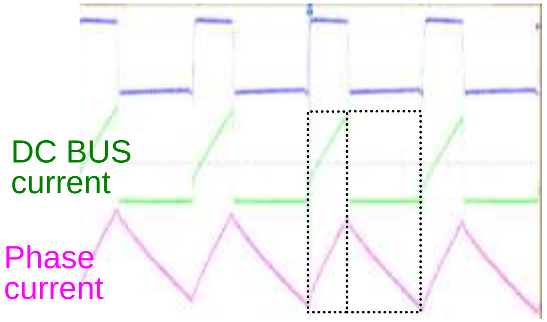


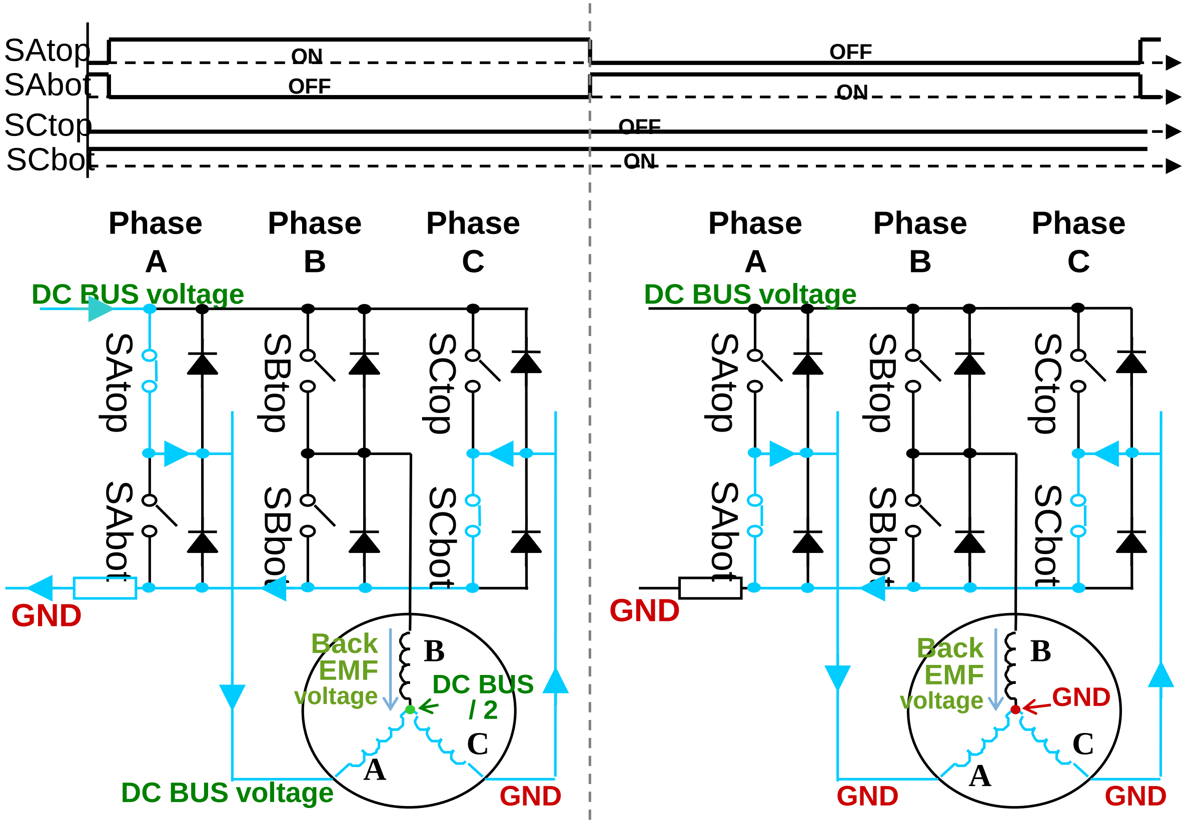
- Comparators implemented internally on S12ZVM
- Little less CPU load

- More accurate zero cross approximation
- More flexibility

BLDC Control - Measurement during PWM Switching







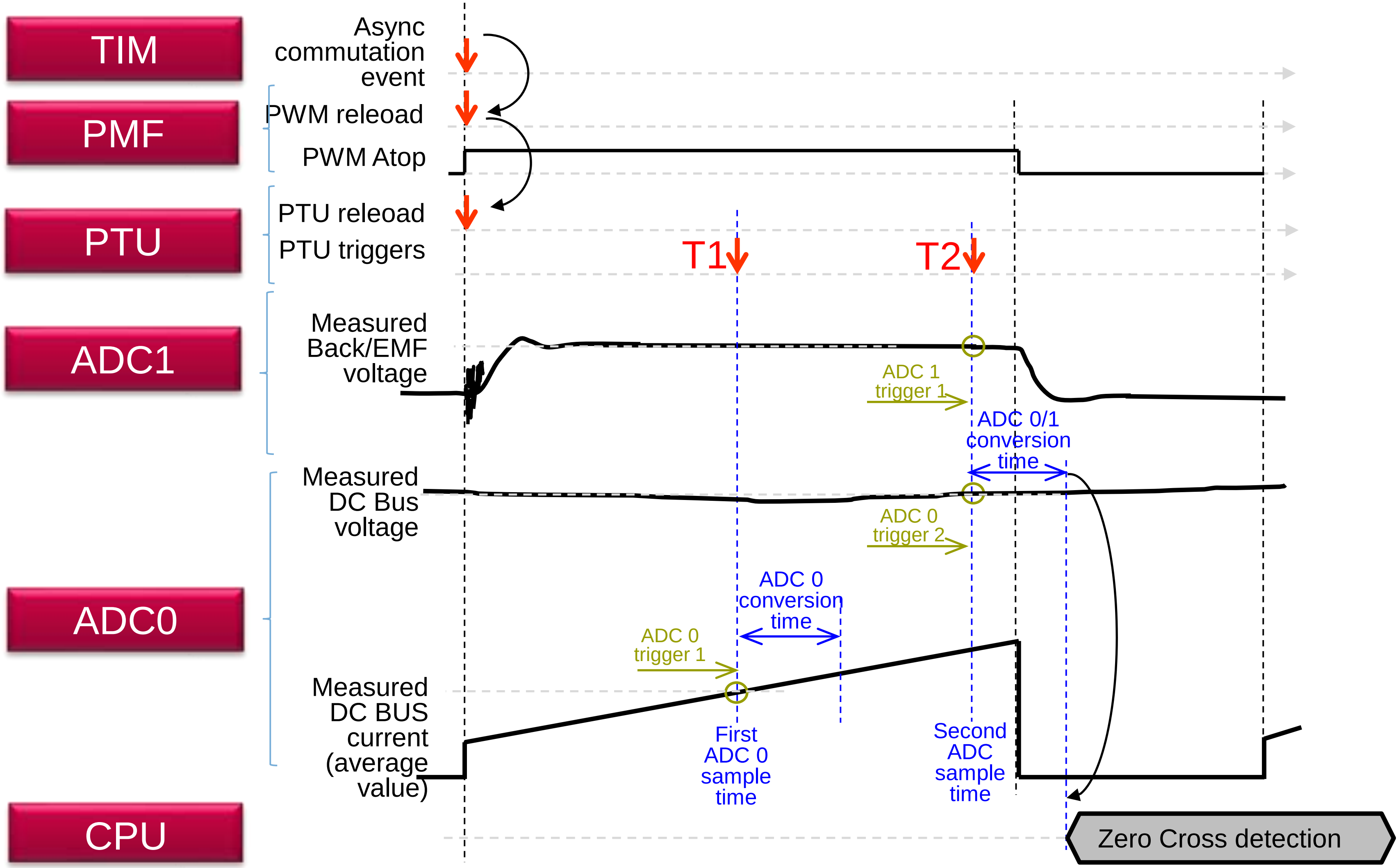
Top MOSFET is ON:

+ Phase current can be measured by DC BUS shunt resistor
+ Back-EMF voltage can be measured both positive and negative

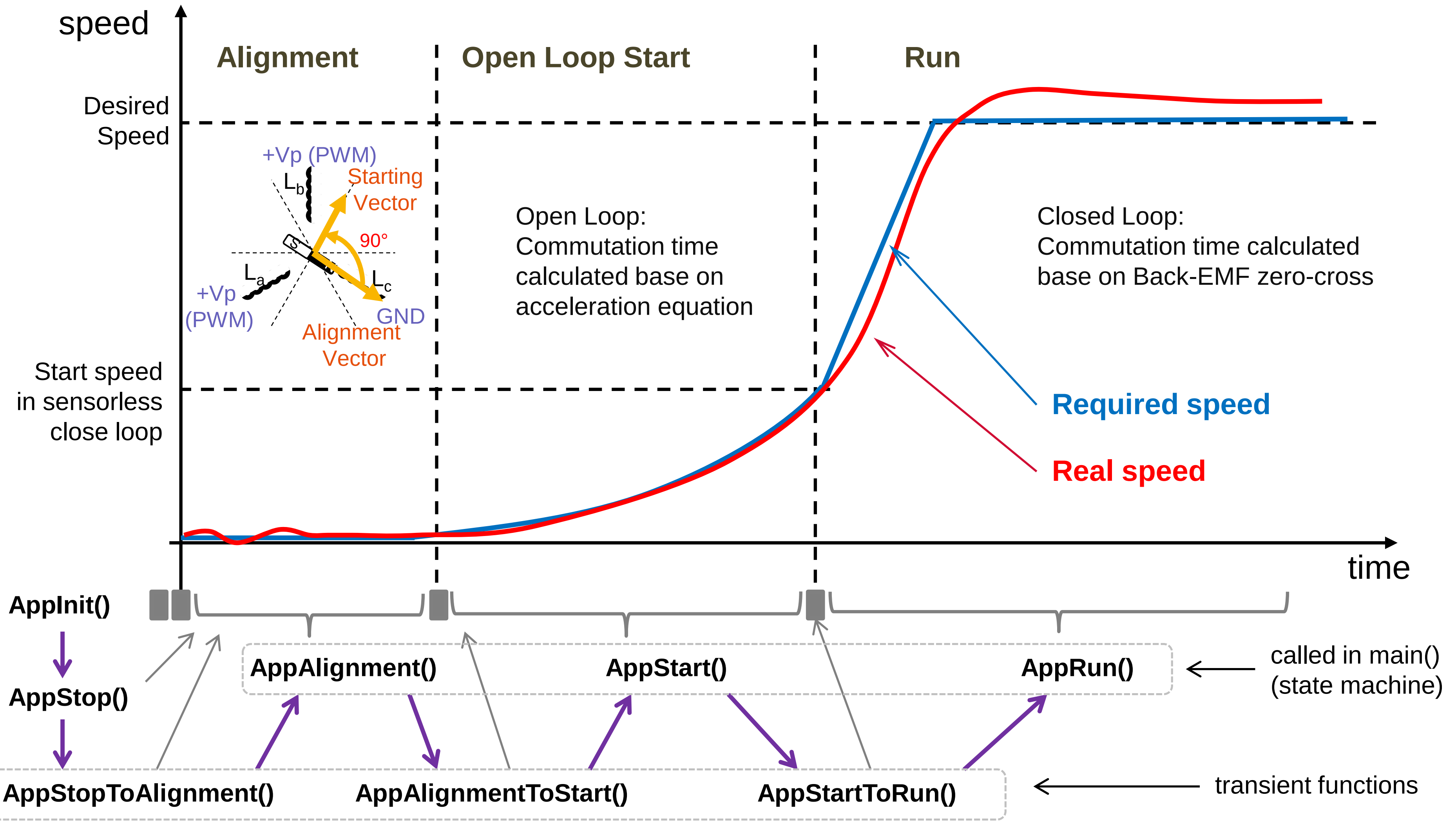
Top MOSFET is OFF:

– Phase current can **NOT** be measured by DC BUS shunt resistor
– **Only positive** Back-EMF voltage can be measured (**zero-cross can not be precisely measured**)

BLDC Control - Module involvement in BLDC SW control loop



BLDC Control - Application State Flow



Open Loop:
Commutation time calculated base on acceleration equation

Closed Loop:
Commutation time calculated base on Back-EMF zero-cross

Required speed

Real speed

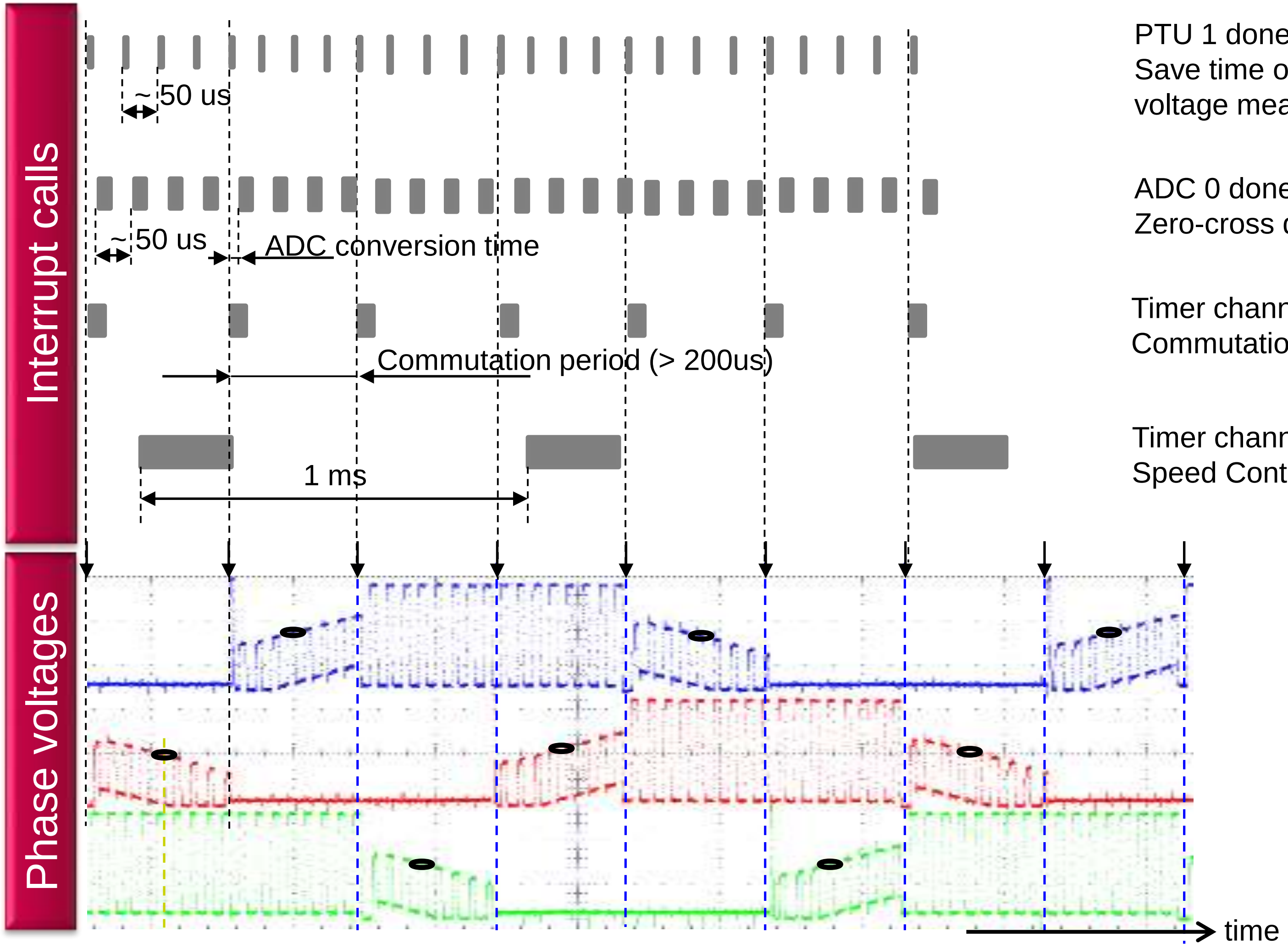
AppInit()

AppStop()

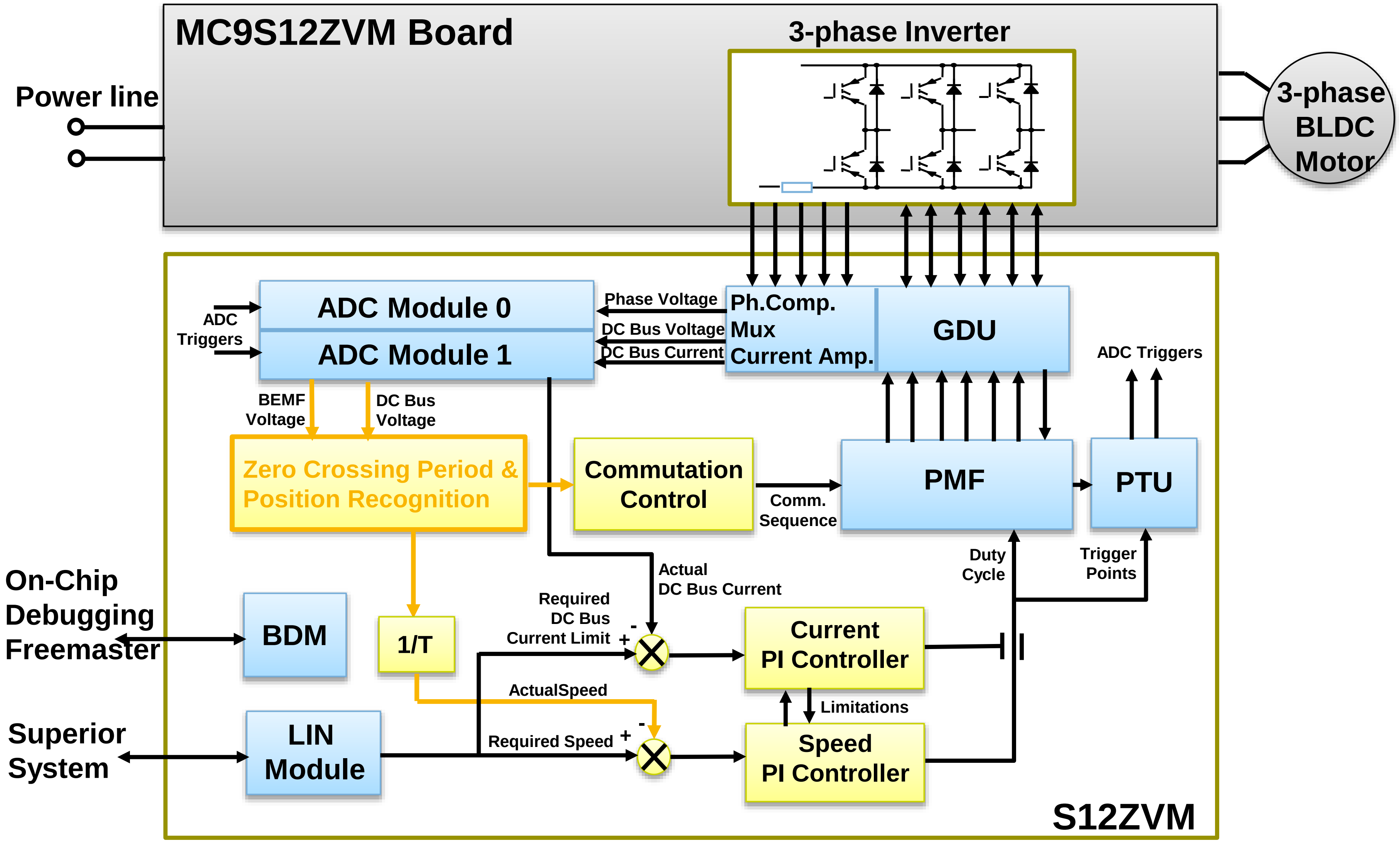
AppAlignment() **AppStart()** **AppRun()** ← called in main() (state machine)

AppStopToAlignment() **AppAlignmentToStart()** **AppStartToRun()** ← transient functions

BLDC Control - Control loop timing and interrupts

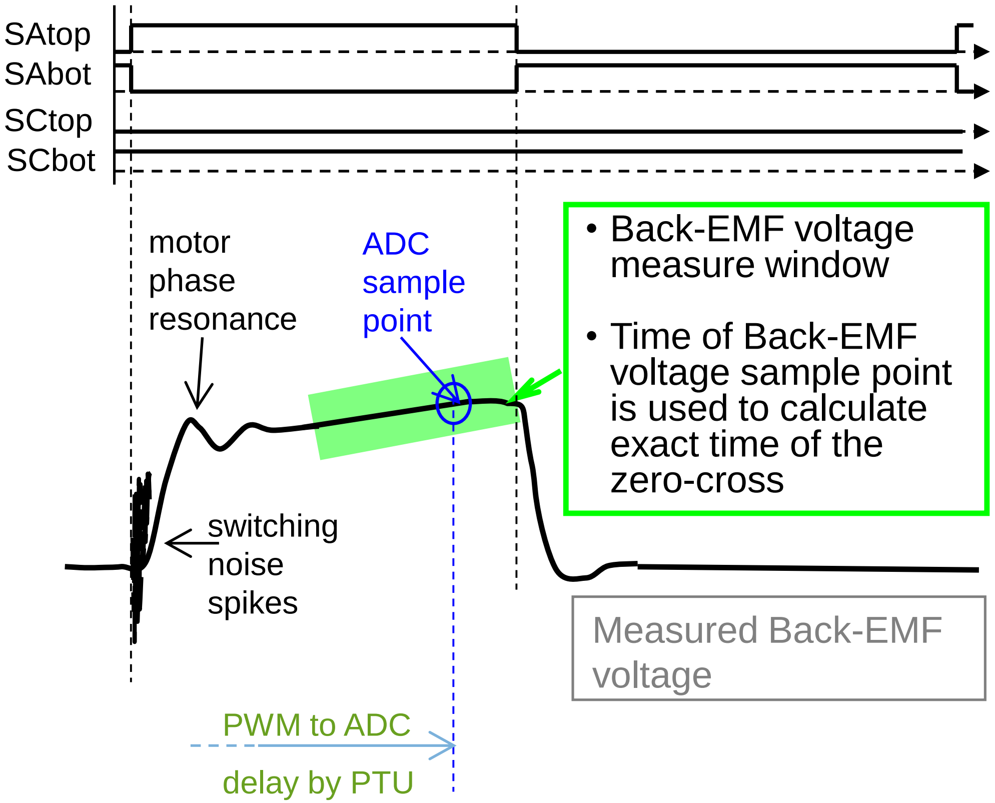


BLDC Control - Example Control Block diagram



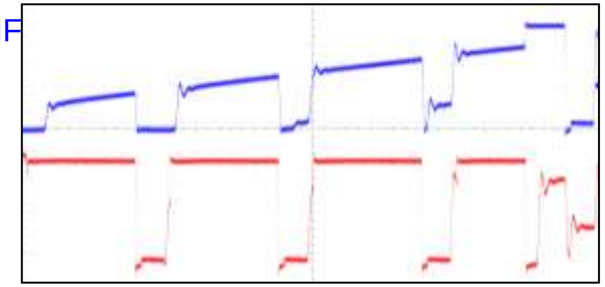
BLDC Control - Back-EMF Voltage Measurement

Back-EMF voltage can not be measured within all the active PWM pulse as there is switching noise and resonance transient at the beginning of the PWM pulse



- Back-EMF voltage measure window
- Time of Back-EMF voltage sample point is used to calculate exact time of the zero-cross

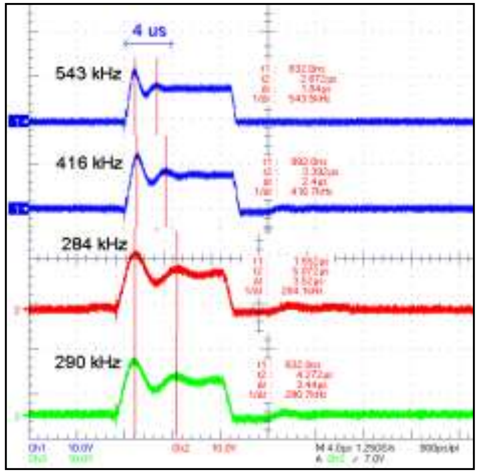
Measured Back-EMF voltage



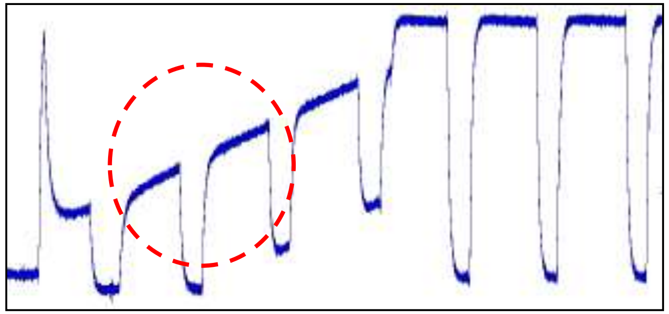
Back-EMF voltage unpowered phase

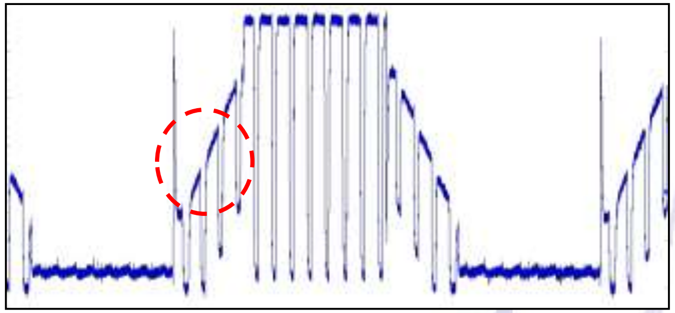
PWM powered phase

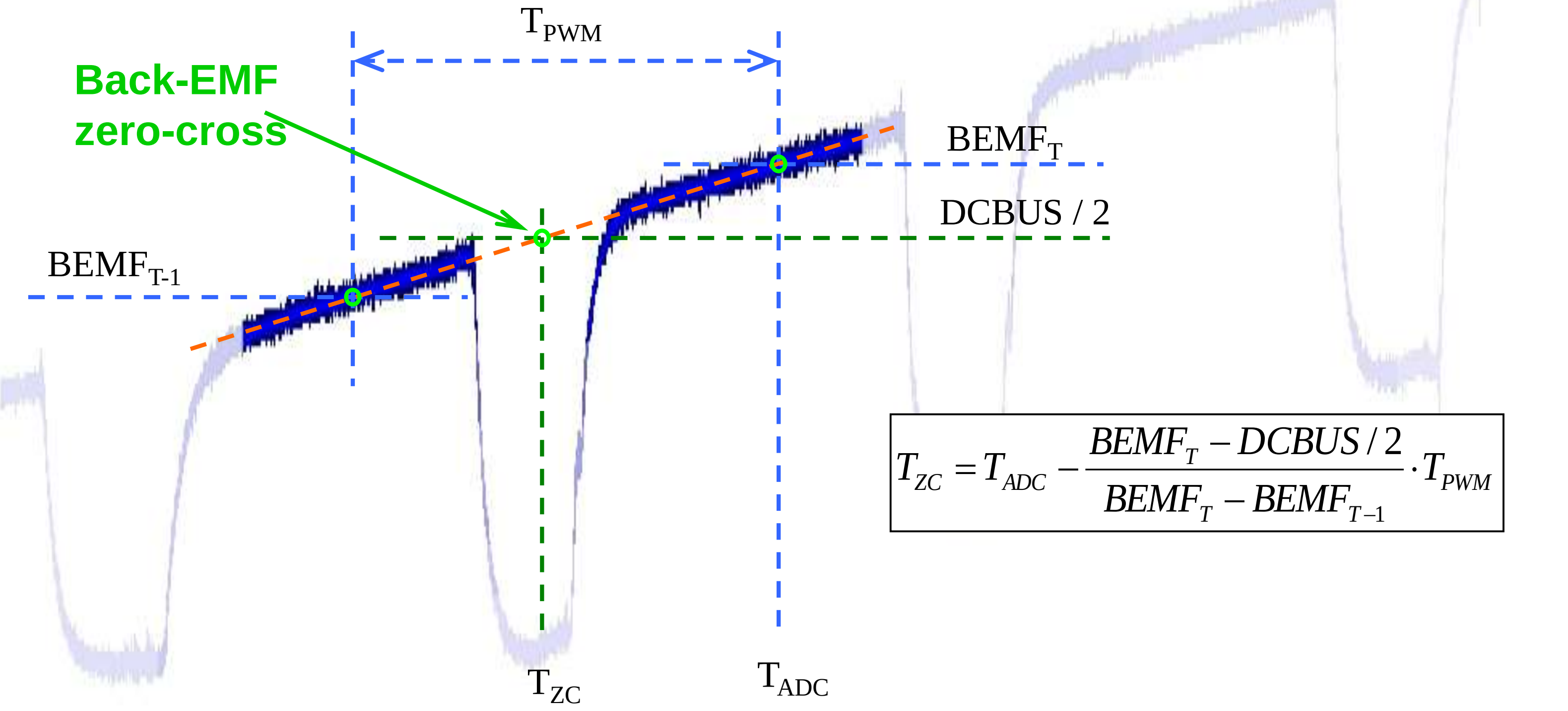
Resonance transient on Back-EMF voltage depends on motor and power stage parameters



BLDC Control - Zero Cross Approximation

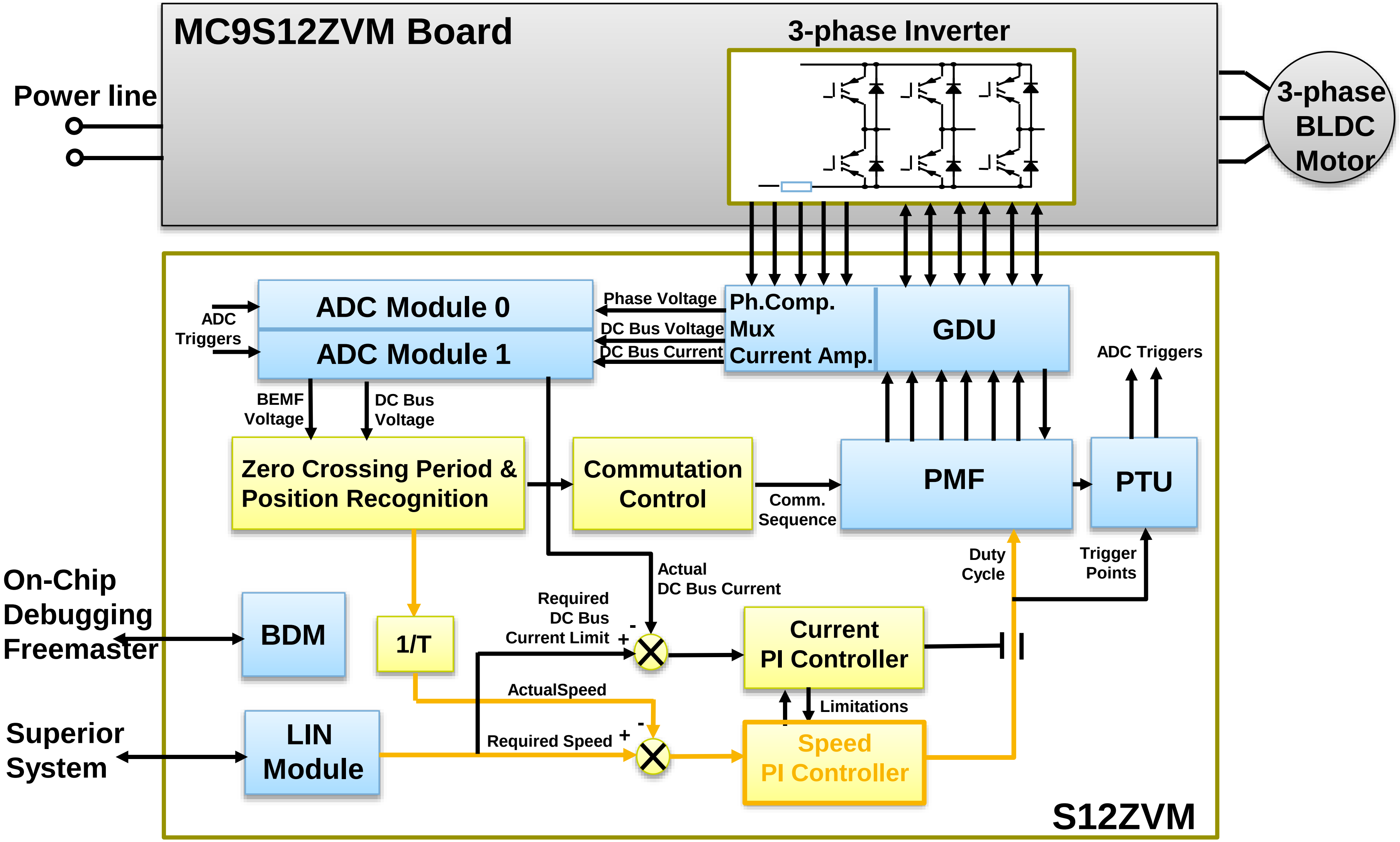




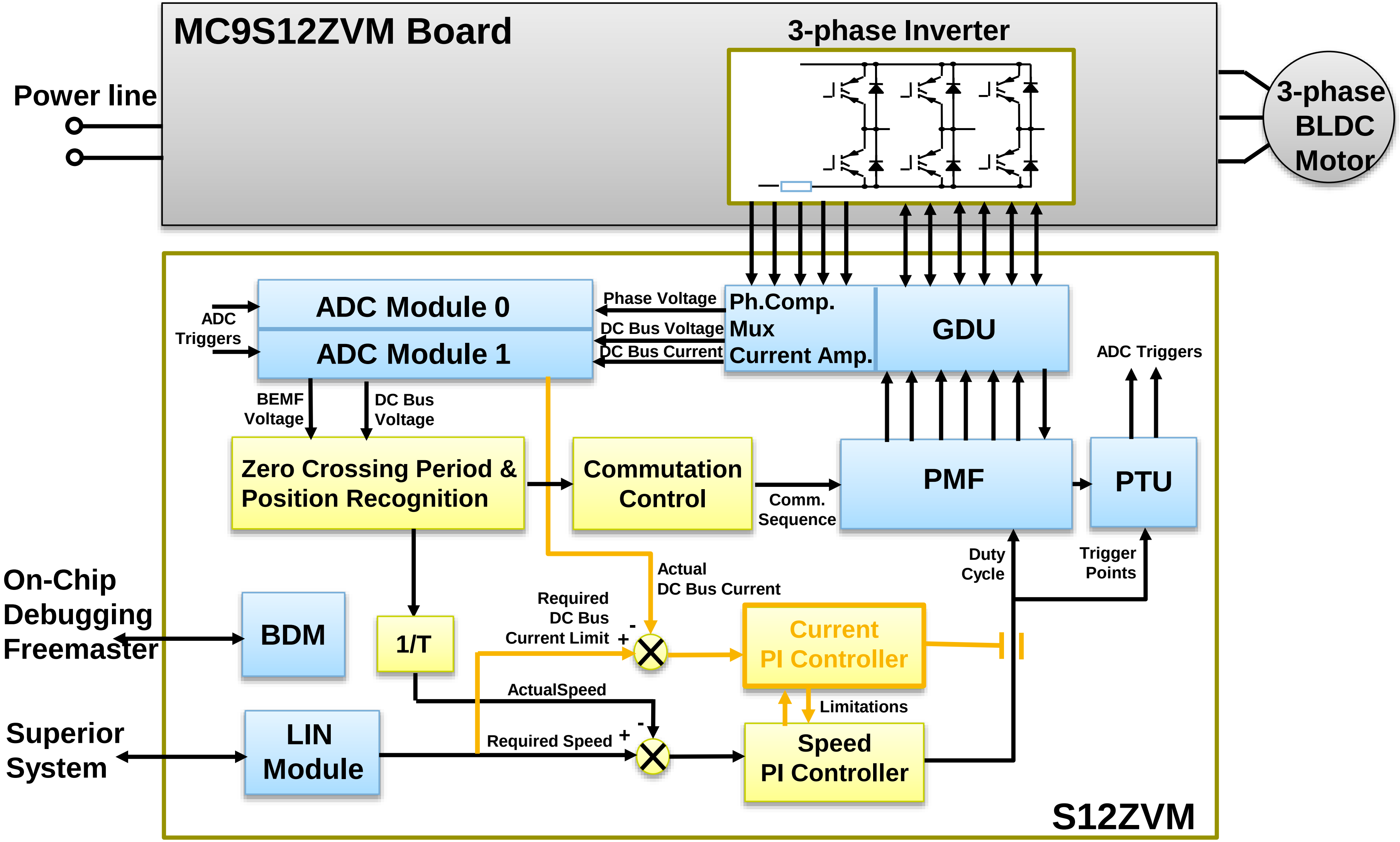


$$T_{ZC} = T_{ADC} - \frac{BEMF_T - DCBUS/2}{BEMF_T - BEMF_{T-1}} \cdot T_{PWM}$$

BLDC Control - Example Control Block diagram



BLDC Control - Example Control Block diagram



BLDC CONTROL – BLOCK COMMUTATION ANY QUESTIONS?

PMSM Control – FOC

- FOC Basic
- FOC Design
- Current Sensing and Processing
- Position Sensing and Processing
- Three Phase Voltage Generation
- Sensor-less
- Field Weakening
- MTPA

FOC Basic - How to Control a PMSM Motor

Measurement

1. Measure and obtain state, phase currents and DC bus voltage

Current Calculation

2. With measured currents, determine current stator flux vector

Position Estimation

3. With measured currents, estimate the actual rotor position

FOC – Forward Transformation

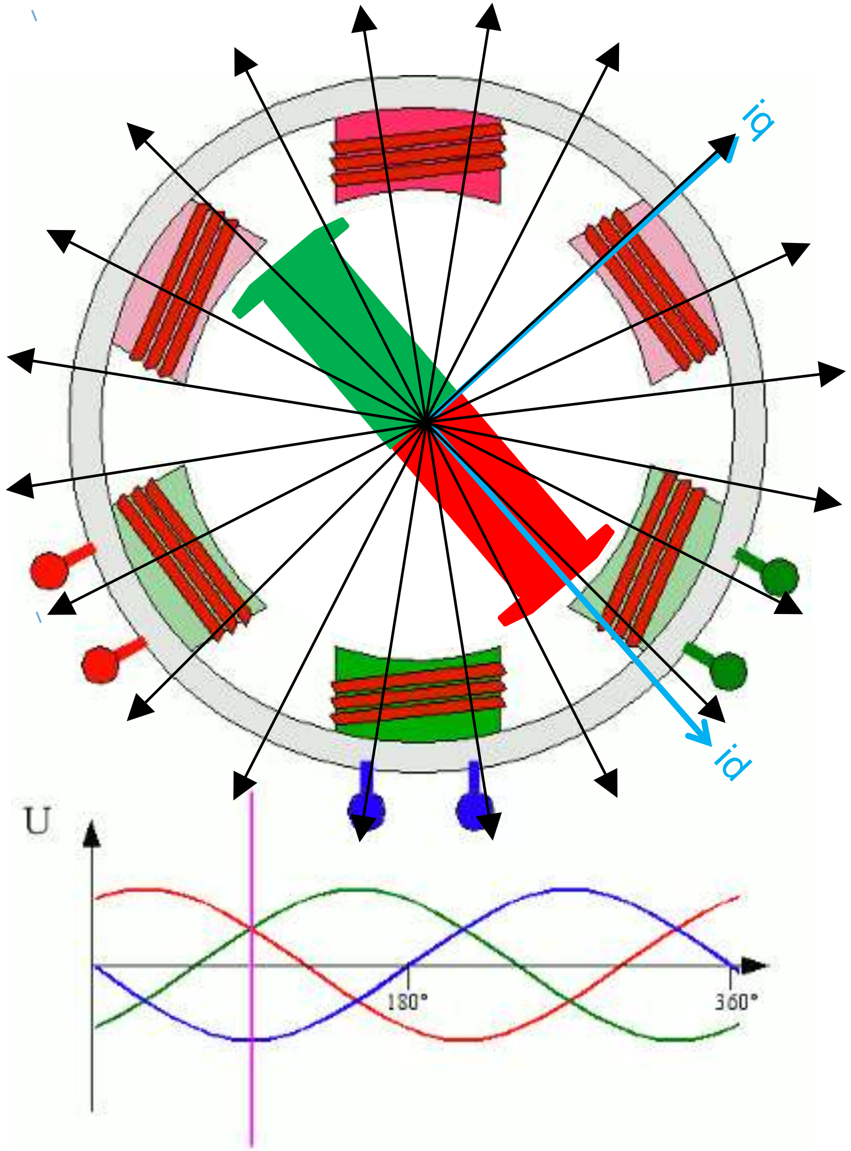
4. With rotor position, determine ideal stator flux vector which is oriented at 90° with respect to rotor flux

FOC – Reverse Transformation

5. Calculate 3 phase voltages to be applied to achieve this stator flux vector

Modulation

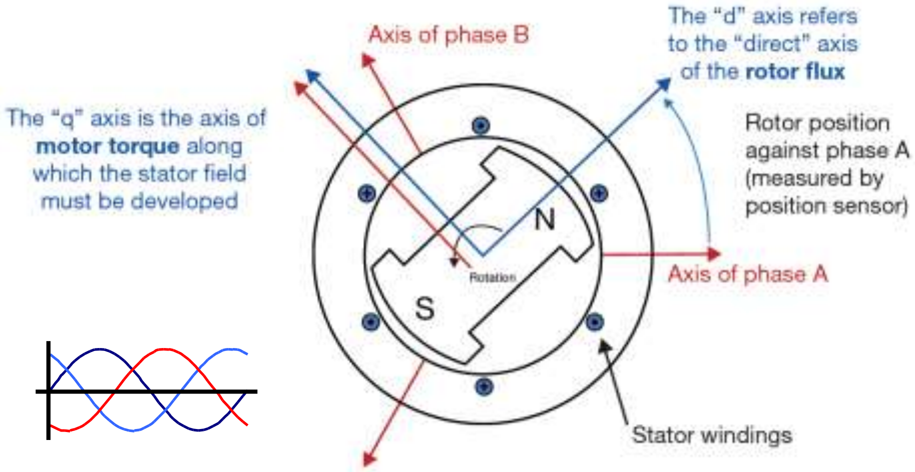
6. Apply voltages to the 3 phases with associated PWM signals



FOC Basic - Why Field Oriented Control?

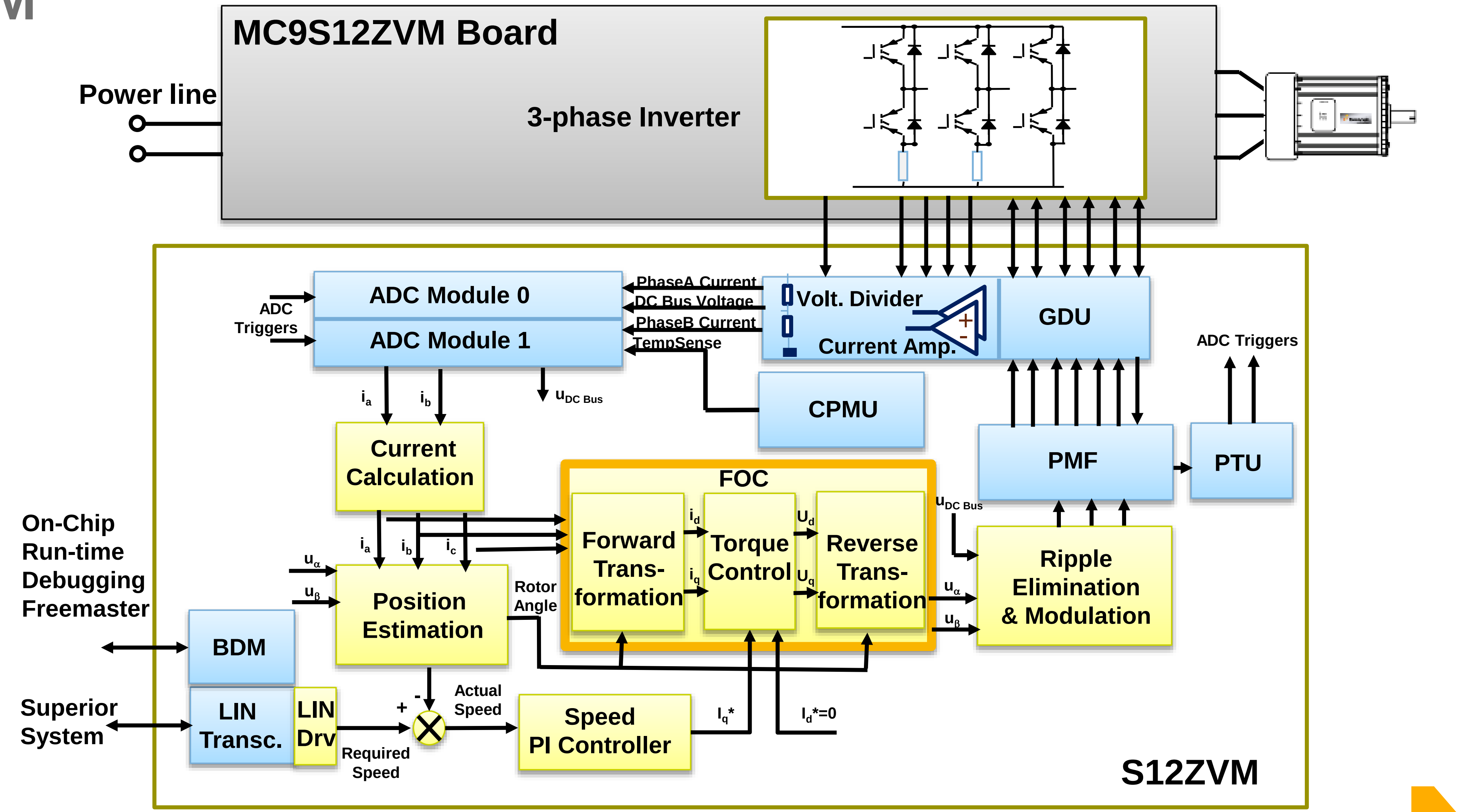
For a PMSM motor, the three sinusodal phase currents have to be controlled to create a flux vector which is perpendicular to the rotor flux current.

- To control the three sinusoidal currents independently would be a very complex mathematical task
- FOC simplifies the math by transforming the 3 phase system to a DC motor system viewing angle
- It decomposes the stator current into:
  - A magnetic field-generating part
  - A torque generating part
- Both components can be easily controlled separately after decomposition

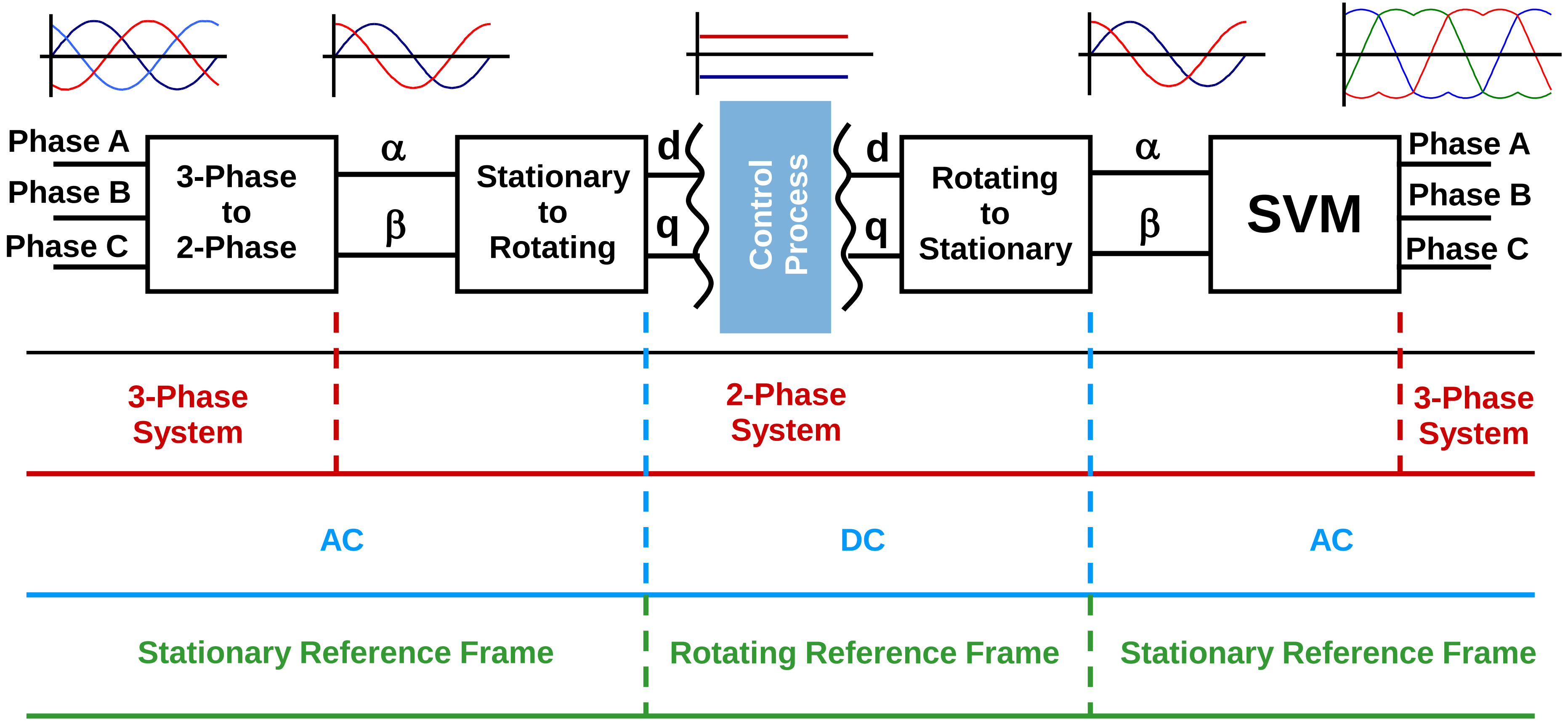


Axis of phase B
The "d" axis refers to the "direct" axis of the **rotor flux**
The "q" axis is the axis of **motor torque** along which the stator field must be developed
Rotor position against phase A (measured by position sensor)
N
S
Rotation
Axis of phase A
Stator windings

FOC Basic - Sensorless PMSM Motor Control Principle on S12ZVM



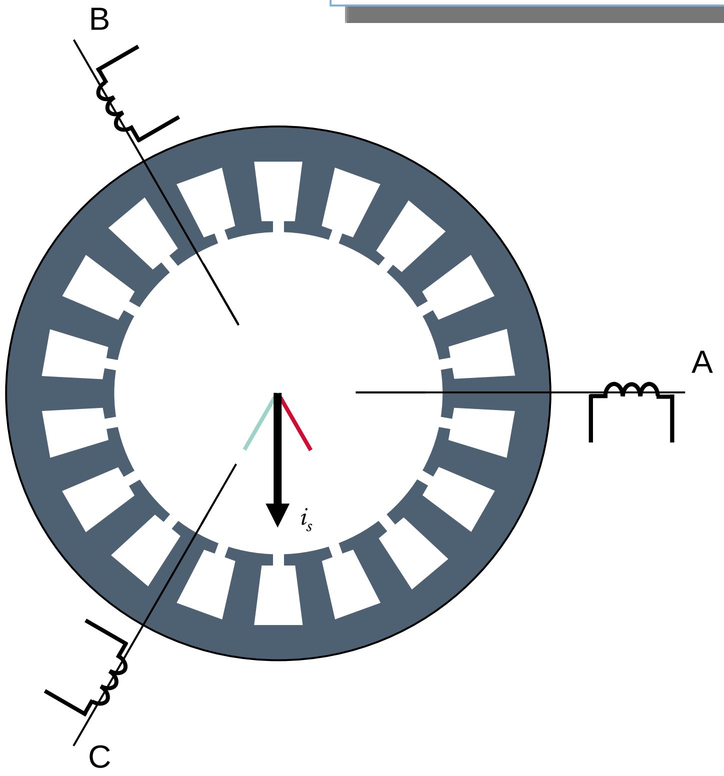
FOC Basic - FOC Transformation Sequencing



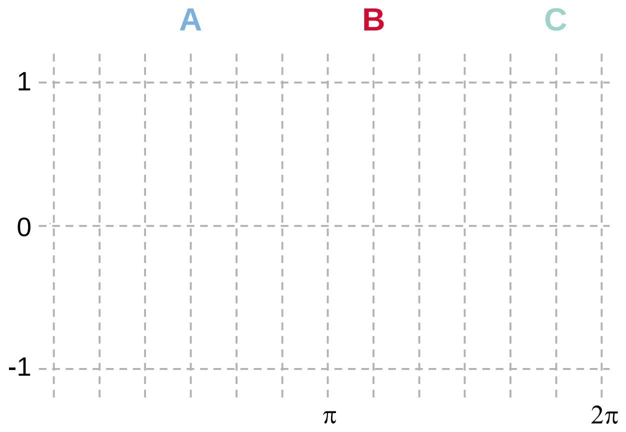
FOC Basic - Creation of Rotating Magnetic Field

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

$$\bar{i}_s = i_A e^{j0} + i_B e^{j120^\circ} + i_C e^{j240^\circ}$$



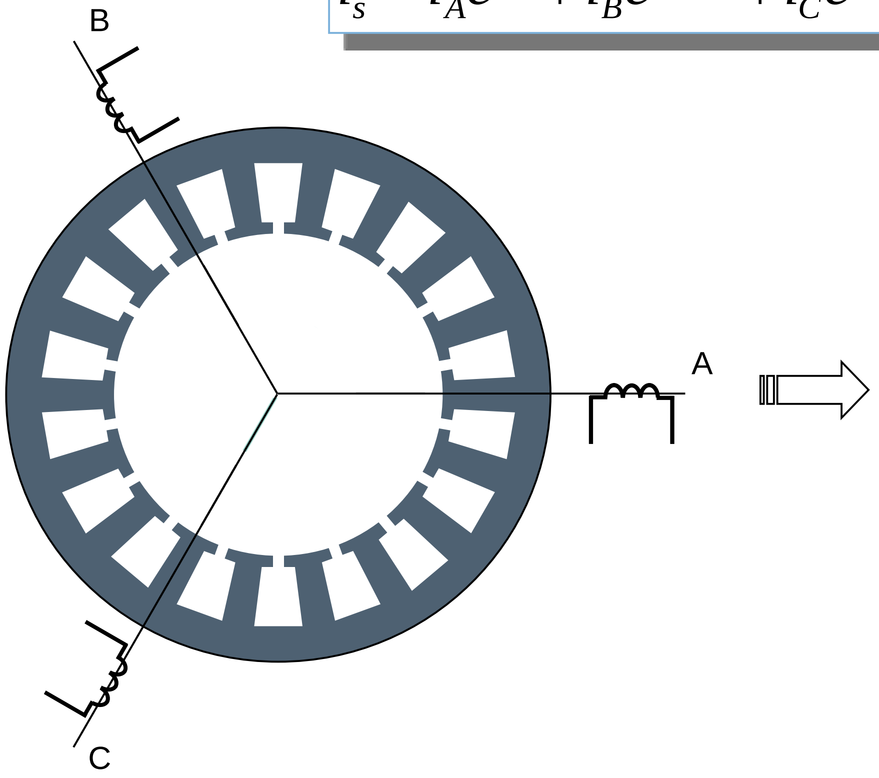
3ph currents / MMF

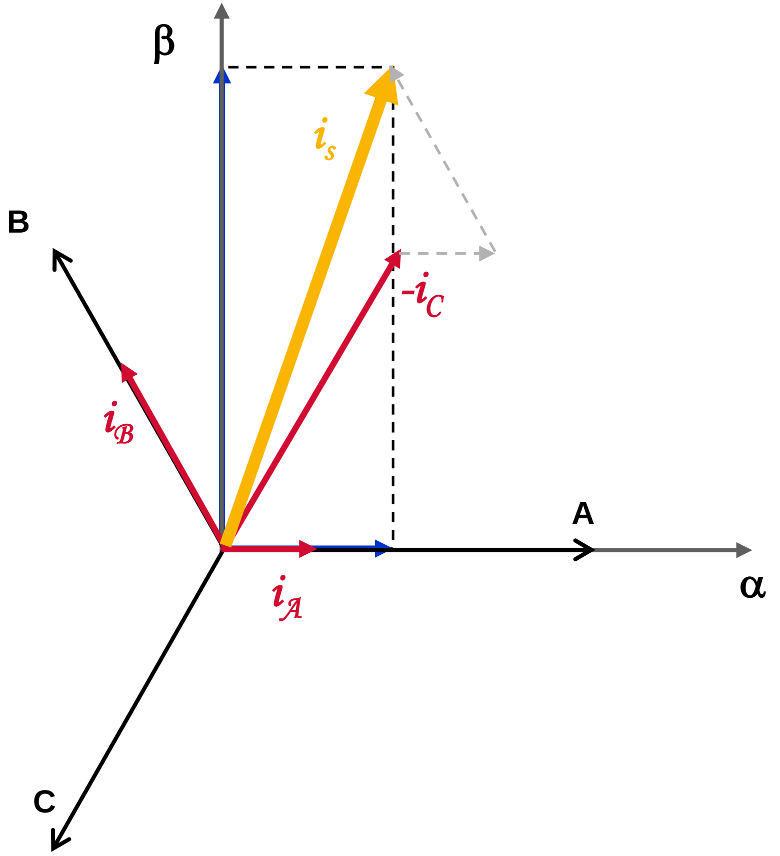


FOC Basic - Creating Space Vectors

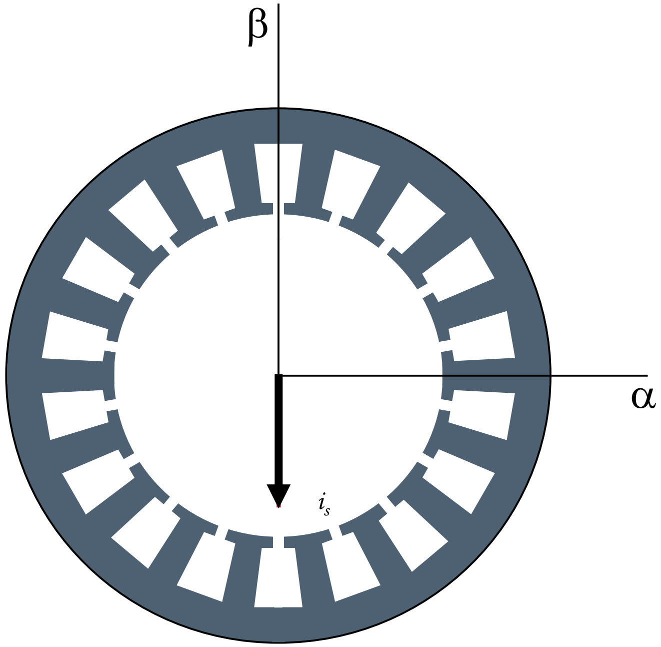
- Because a space vector is defined in a plane (2D), it is sufficient to describe a space vector in a 2-axis (α,β) coordinate system

$$\bar{i}_s = i_A e^{j0} + i_B e^{j120^\circ} + i_C e^{j240^\circ}$$



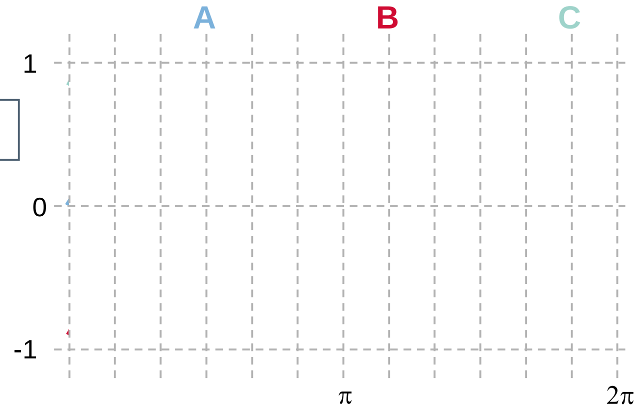


FOC Basic - Transformation to 2-ph Stationary Frame

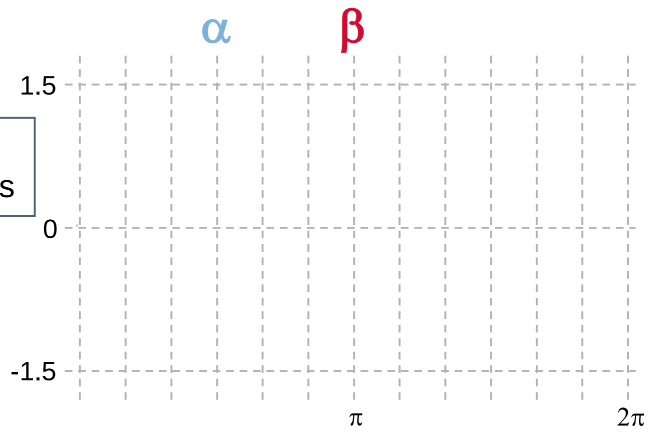


3ph currents / MMF

3ph quantities

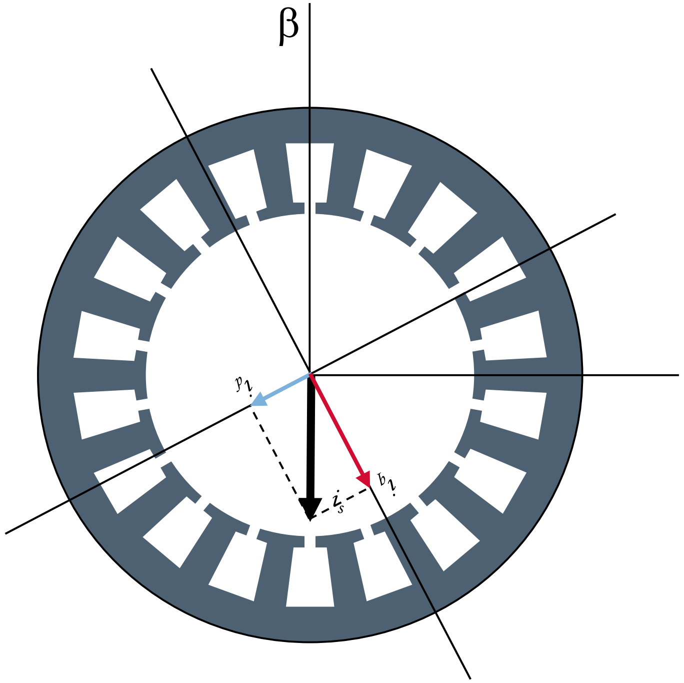


Stationary
2ph quantities

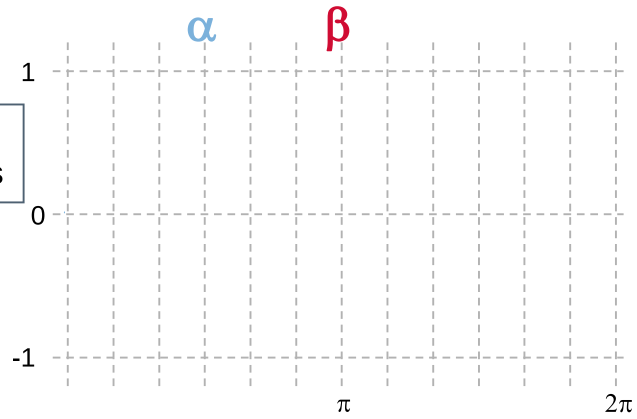


FOC Basic - Transformation to 2-ph Synchronous Frame

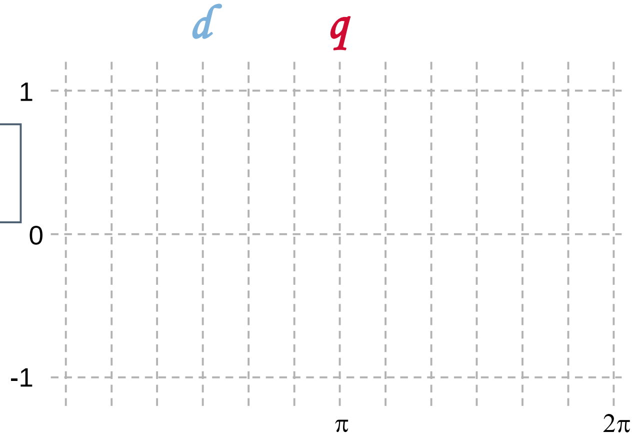
- Position and amplitude of the stator flux/current vector is fully controlled by two DC values



Stationary
2ph quantities

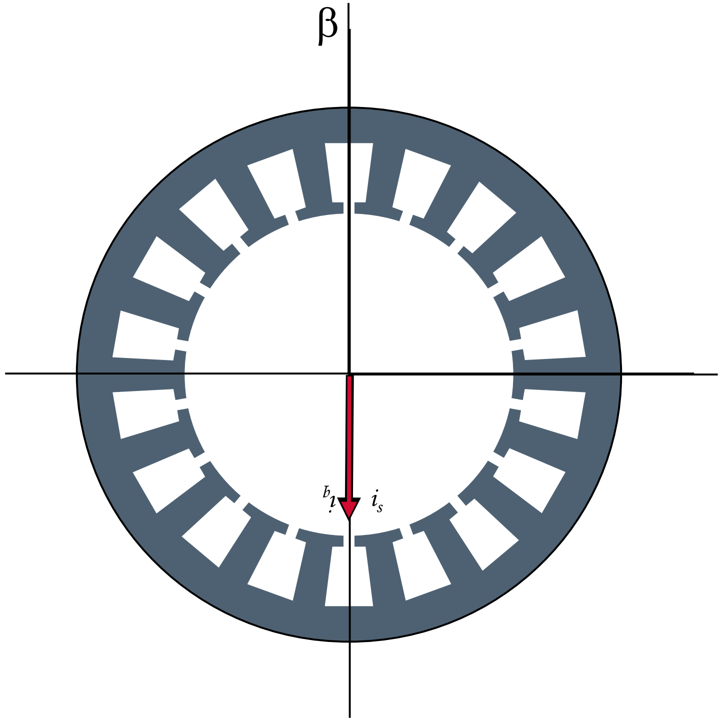


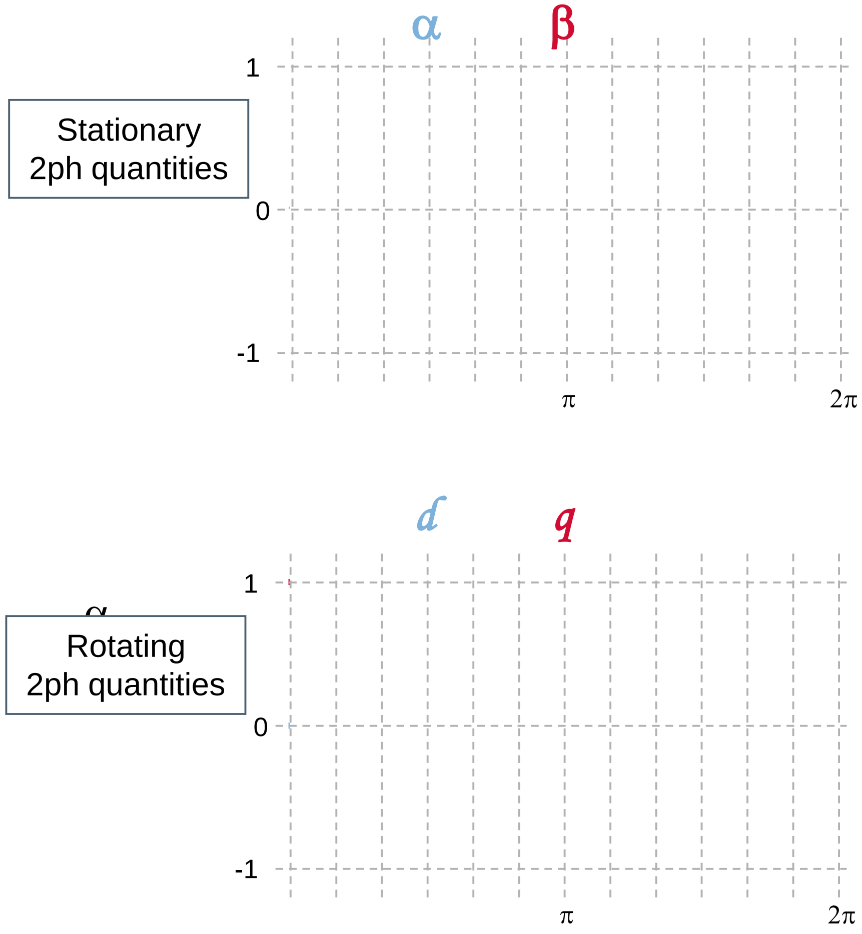
Rotating
2ph quantities



FOC Basic - Transformation to 2-ph Synchronous Frame

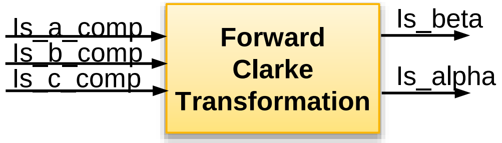
- Position and amplitude of the stator flux/current vector is fully controlled by two DC values




Stationary 2ph quantities

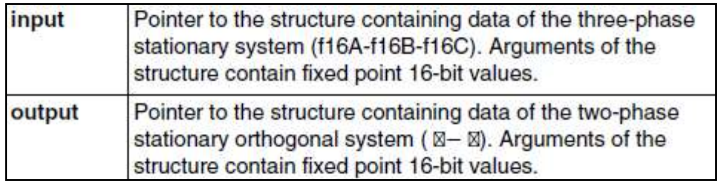
Rotating 2ph quantities

FOC Basic - Application Using Forward Clarke



Motor Control Library Function:

void GMCLIB_Clark_F16
(SWLIBS_2Syst_F16 *const pOut,
const SWLIBS_3Syst_F16 *const pIn);

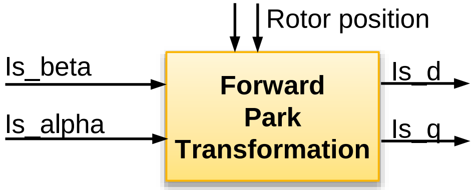


input	Pointer to the structure containing data of the three-phase stationary system (f16A-f16B-f16C). Arguments of the structure contain fixed point 16-bit values.
output	Pointer to the structure containing data of the two-phase stationary orthogonal system (⊠– ⊠). Arguments of the structure contain fixed point 16-bit values.

Called in ATD interrupt:

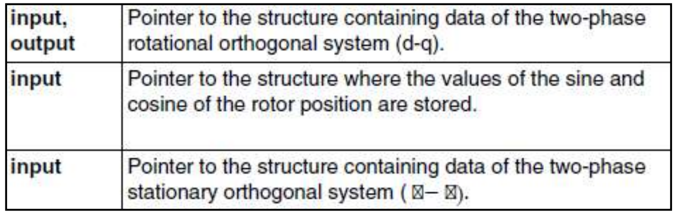
```
static tBool focFastLoop(pmsmDrive_t *ptr)
{
…
            GMCLIB_Clark(&ptr->iAlBeFbck,&ptr->iAbcFbck);

            ptr->thTransform.f16Arg1    = GFLIB_Sin(ptr->pospeControl.thRotEl);
            ptr->thTransform.f16Arg2    = GFLIB_Cos(ptr->pospeControl.thRotEl);

            GMCLIB_Park(&ptr->iDQFbck,&ptr->thTransform,&ptr->iAlBeFbck);
…
            return (true);
}
```

FOC Basic - Application Using Forward Park Transformation



Motor Control Library Function:

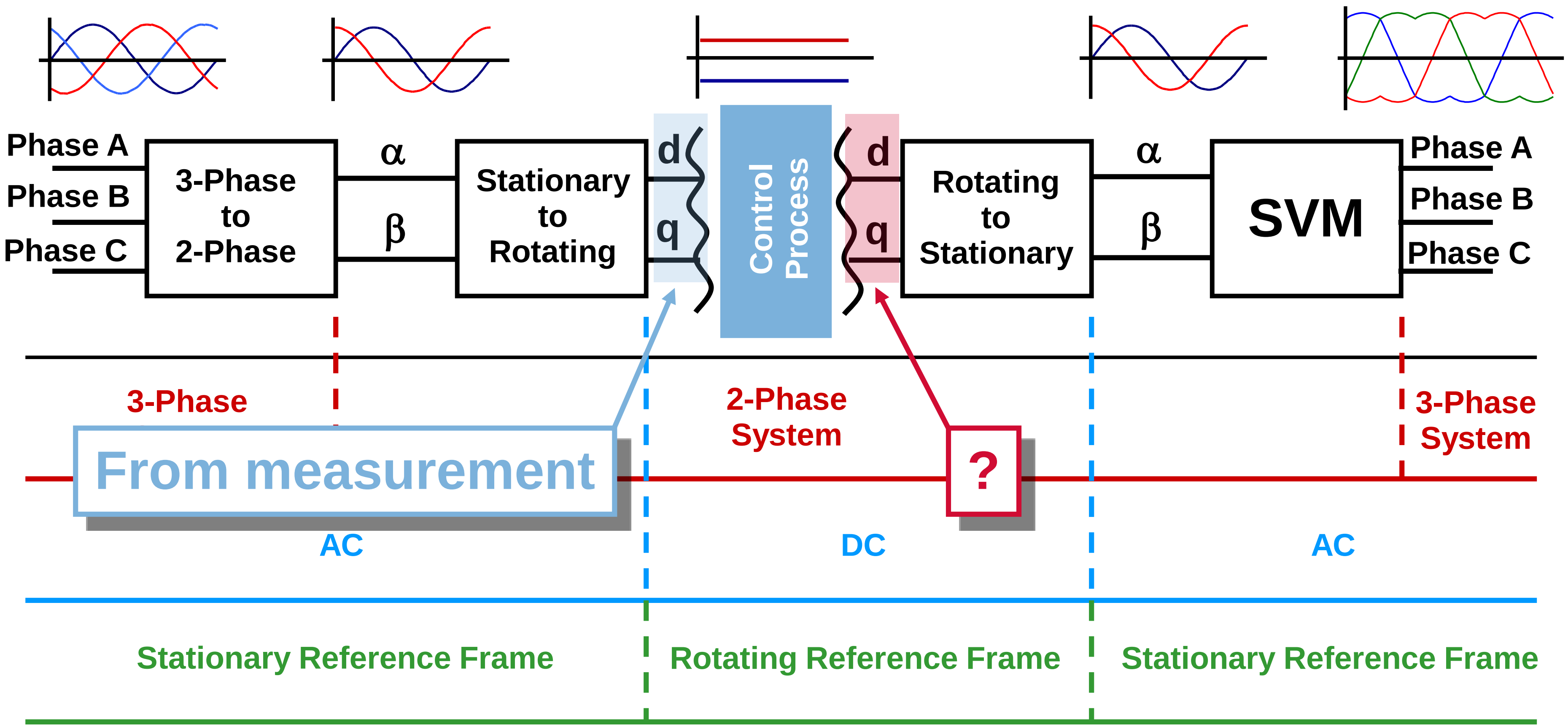
void GMCLIB_Park_F16
(SWLIBS_2Syst_F16 *pOut,
const SWLIBS_2Syst_F16 *const pInAngle,
const SWLIBS_2Syst_F16 *const pIn);););



input, output	Pointer to the structure containing data of the two-phase rotational orthogonal system (d-q).
input	Pointer to the structure where the values of the sine and cosine of the rotor position are stored.
input	Pointer to the structure containing data of the two-phase stationary orthogonal system (▯– ▯).

```
Called in ATD interrupt:
static tBool focFastLoop(pmsmDrive_t *ptr)
{
…
                GMCLIB_Clark(&ptr->iAlBeFbck,&ptr->iAbcFbck);

                ptr->thTransform.f16Arg1    = GFLIB_Sin(ptr->pospeControl.thRotEl);
                ptr->thTransform.f16Arg2    = GFLIB_Cos(ptr->pospeControl.thRotEl);

                GMCLIB_Park(&ptr->iDQFbck,&ptr->thTransform,&ptr->iAlBeFbck);
…
                return (true);
}
```

FOC Basic - FOC Transformation Sequencing

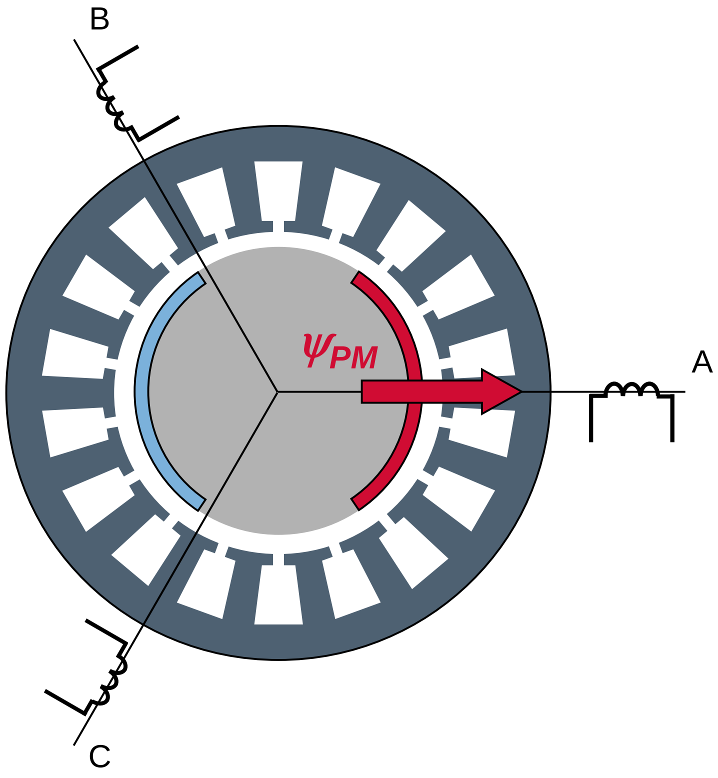


FOC BASIC

ANY QUESTIONS?

FOC Design - 3-phase PMSM Model

- Considering sinusoidal 3-phase distributed winding and neglecting effect of magnetic saturation and leakage inductances



Stator voltage equations

$$\boxed{\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix}} = R_s \boxed{\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix}} + \frac{d}{dt} \boxed{\begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \end{bmatrix}}$$

Forward Clarke

Stator linkage flux

$$\begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \end{bmatrix} = \boxed{\begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix}} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \psi_{PM} \boxed{\begin{bmatrix} \cos(\theta_e) \\ \cos\left(\theta_e - \frac{2}{3}\pi\right) \\ \cos\left(\theta_e + \frac{2}{3}\pi\right) \end{bmatrix}}$$

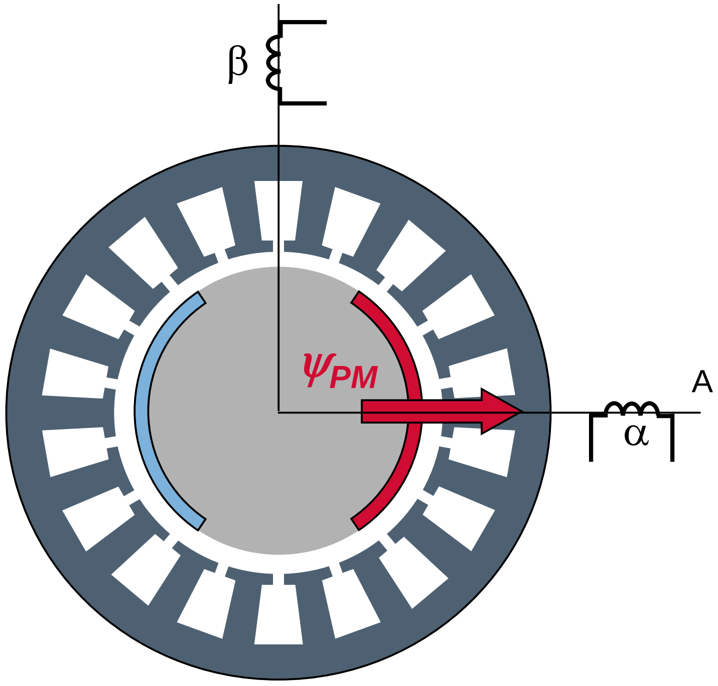
Internal motor torque

$$T_i = \frac{P_i}{\omega_m} = \frac{p_p}{\omega_e}(u_{iA}i_A + u_{iB}i_B + u_{iC}i_C)$$

$$T_i = p_p(-\Psi_{PM} i_A \sin(\theta_e) - \Psi_{PM} i_B \sin(\theta_e - \tfrac{2}{3}\pi) - \Psi_{PM} i_C \sin(\theta_e + \tfrac{2}{3}\pi))$$

FOC Design - 2-phase PMSM Model

- Considering sinusoidal 2-phase distributed winding and neglecting effect of magnetic saturation and leakage inductances



Stator voltage equations

Forward Park

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = R_s \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \psi_\alpha \\ \psi_\beta \end{bmatrix}$$

Stator linkage flux

$$\begin{bmatrix} \Psi_{S\alpha} \\ \Psi_{S\beta} \end{bmatrix} = \begin{bmatrix} L_S & 0 \\ 0 & L_S \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \Psi_{PM}\Big|_{i_{Sd}=0} \cdot \begin{bmatrix} \cos\theta_{re} \\ \sin\theta_{re} \end{bmatrix}$$

Internal motor torque

$$T_i = \frac{3}{2}\frac{p_p}{\omega_e}(u_{i\alpha}i_\alpha + u_{i\beta}i_\beta) = \frac{3}{2}p_p(\Psi_\alpha i_\beta - \Psi_\beta i_\alpha)$$

FOC Basic - Sinusoidal PM Motor Model in *dq* Synchronous Frame

Salient machine model in dq synchronous frame aligned with the rotor

- Stator Voltage Equations

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} s & \omega_e \\ -\omega_e & s \end{bmatrix} \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix}$$

- Stator Flux Linkages of Salient Machine

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \psi_{PM} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

- Resulting stator voltage equations

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \underbrace{\boxed{R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} sL_d & 0 \\ 0 & sL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}}}_{\text{R-L circuit}} + \underbrace{\boxed{\omega_e \begin{bmatrix} -L_q \\ L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix}}}_{\text{cross-coupling}} + \underbrace{\boxed{\omega_e \psi_{PM} \begin{bmatrix} 0 \\ 1 \end{bmatrix}}}_{\text{backEMF}}$$

- Internal motor torque

$$T_i = \frac{3}{2}\frac{p_p}{\omega_e}\left(u_{id} i_d + u_{iq} i_q\right) = \frac{3}{2} p_p \left(\Psi_d i_q - \Psi_q i_d\right) = \frac{3}{2} p_p \cdot \Psi_{PM} i_q$$

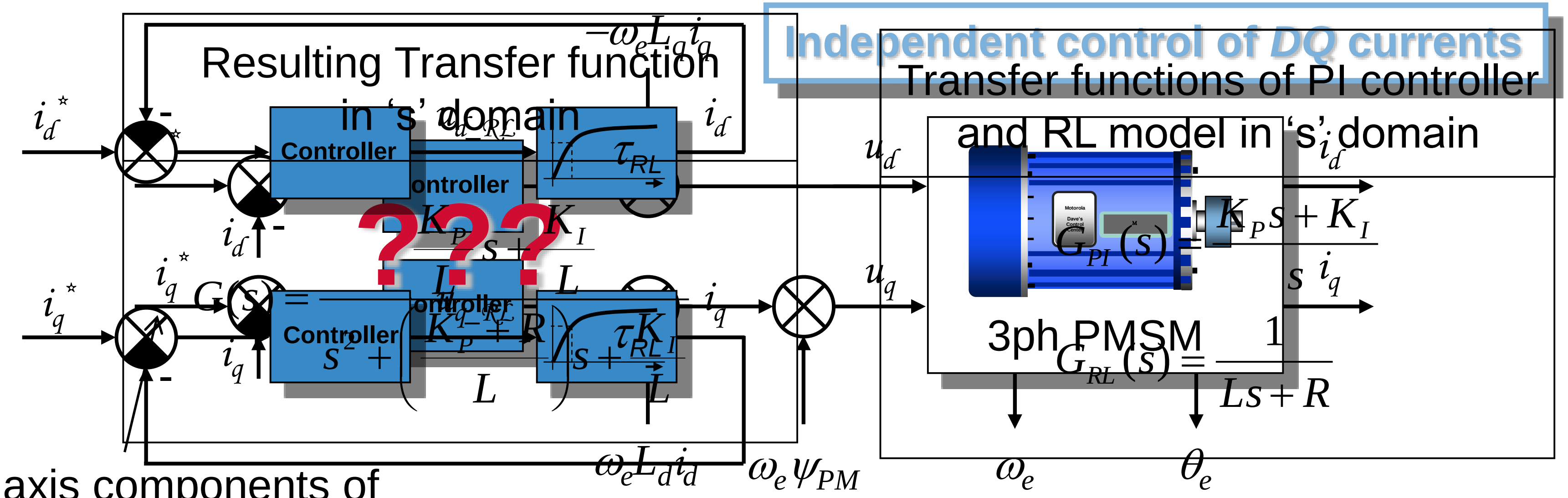
FOC Design - PMSM Current Control

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} sL_d & 0 \\ 0 & sL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_e \begin{bmatrix} -L_q \\ L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \omega_e \psi_{PM} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

R-L circuit

Cross-coupling

backEMF



Resulting Transfer function in 's' domain

$$G(s) = \frac{\frac{K_P}{L}s + \frac{K_I}{L}}{s^2 + \left(\frac{K_P + R}{L}\right)s + \frac{K_I}{L}}$$

Independent control of DQ currents

Transfer functions of PI controller and RL model in 's' domain

$$G_{PI}(s) = \frac{K_P s + K_I}{s}$$

$$G_{RL}(s) = \frac{1}{Ls + R}$$

Two axis components of required current vector

FOC Design - Zero Cancelation

- Controller gain design can be done by matching coefficients of characteristic polynomial with those of an ideal 2nd order system

Transfer function of current loop

$$G(s) = \frac{\frac{K_P}{L}s + \frac{K_I}{L}}{s^2 + \left(\frac{K_P + R}{L}\right)s + \frac{K_I}{L}} = \frac{\frac{K_I}{L}\overbrace{\left(\frac{K_P}{K_I}s + 1\right)}^{\text{zero}}}{s^2 + \left(\frac{K_P + R}{L}\right)s + \frac{K_I}{L}}$$

ξ – is damping factor

ω_0 – is natural frequency

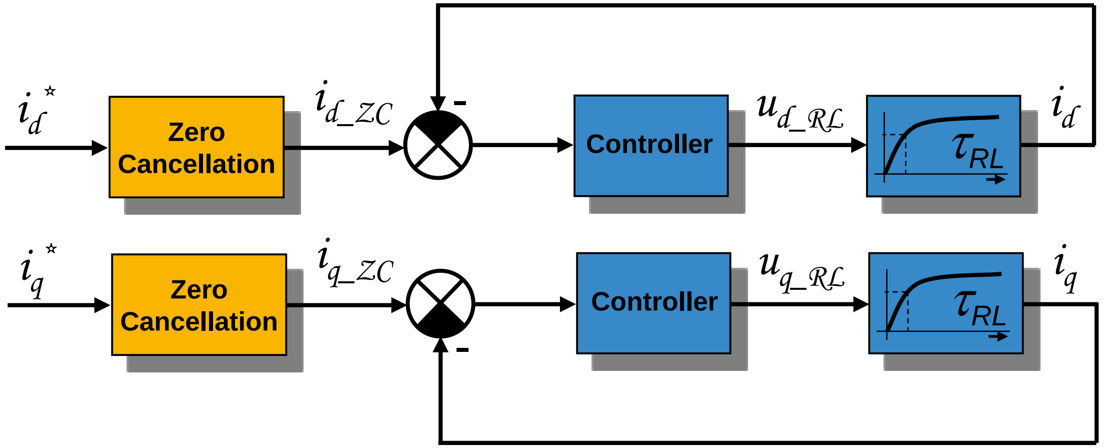
Transfer function of ideal 2nd order system

$$G_{ideal}(s) = \frac{\omega_0^2}{s^2 + 2\xi\omega_0 s + \omega_0^2}$$

- “Zero” introduced by PI controller at $-K_P/K_I$ adds derivative behavior to the closed loop, creating overshoot during step response

FOC Design - Zero Cancelation

- Zero Cancellation placed in the feed-forward path will be designed to compensate the closed loop zero with unity DC gain



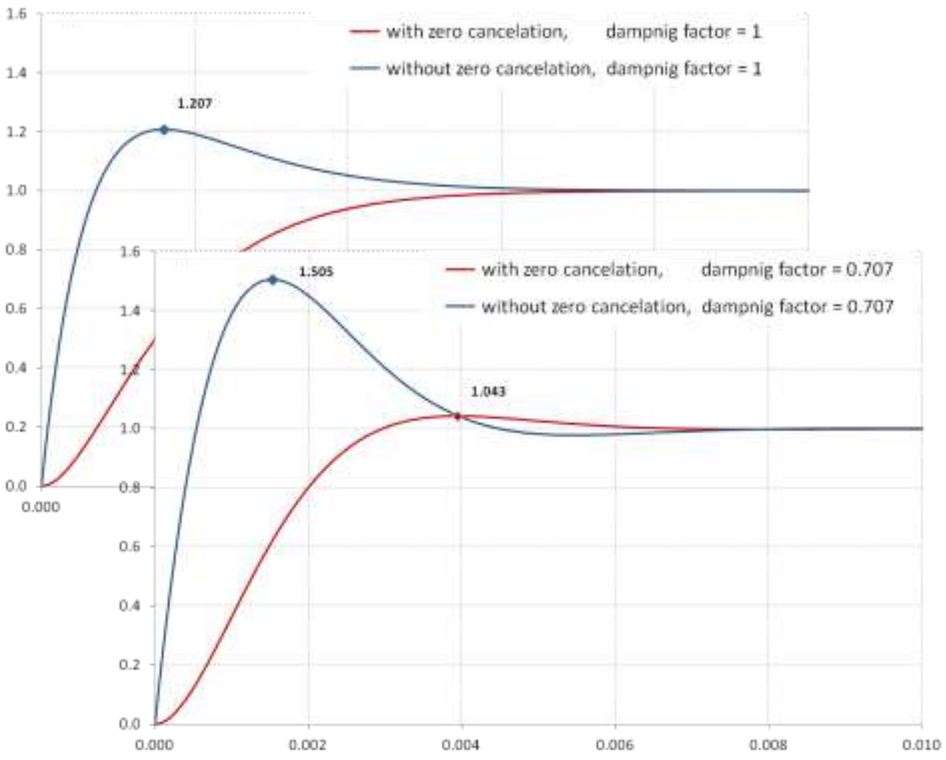
$$G(s) = \underbrace{\frac{1}{\left(\frac{K_P}{K_I}s+1\right)}}_{G_{ZC}(s)} \times \underbrace{\frac{\frac{K_I}{L}\left(\frac{K_P}{K_I}s+1\right)}{s^2+\left(\frac{K_P+R}{L}\right)s+\frac{K_I}{L}}}_{G_{CL}(s)} = \underbrace{\frac{\frac{K_I}{L}}{s^2+\left(\frac{K_P+R}{L}\right)s+\frac{K_I}{L}}}_{G(s)}$$

FOC Design– PI Controller Gain Calculation

- Implementation of Zero Cancellation allows precise matching of characteristic polynomial coefficients
- Enables simple tuning of the current loop bandwidth and attenuation

$$G(s) = \frac{\frac{K_I}{L}}{s^2 + \left(\frac{K_P + R}{L}\right)s + \frac{K_I}{L}}$$

$$G_{ideal}(s) = \frac{\omega_0^2}{s^2 + 2\xi\omega_0 s + \omega_0^2}$$



PI controller gains

$$K_I = \omega_0^2 L$$

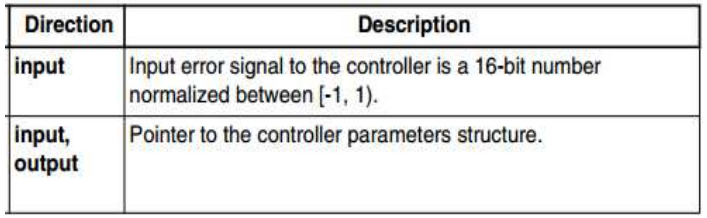
$$K_P = 2\xi\omega_0 L - R$$

FOC Design – Application Using PI Controller

In_Error
parameters
Recurrent Proportional-Integral controller
Output

Motor Control Library Function:

```
tFrac16 GFLIB_ControllerPIrAW_F16
(tFrac16 f16InErr,
GFLIB_CONTROLLER_PIAW_R_T_F16 * pParam)
```

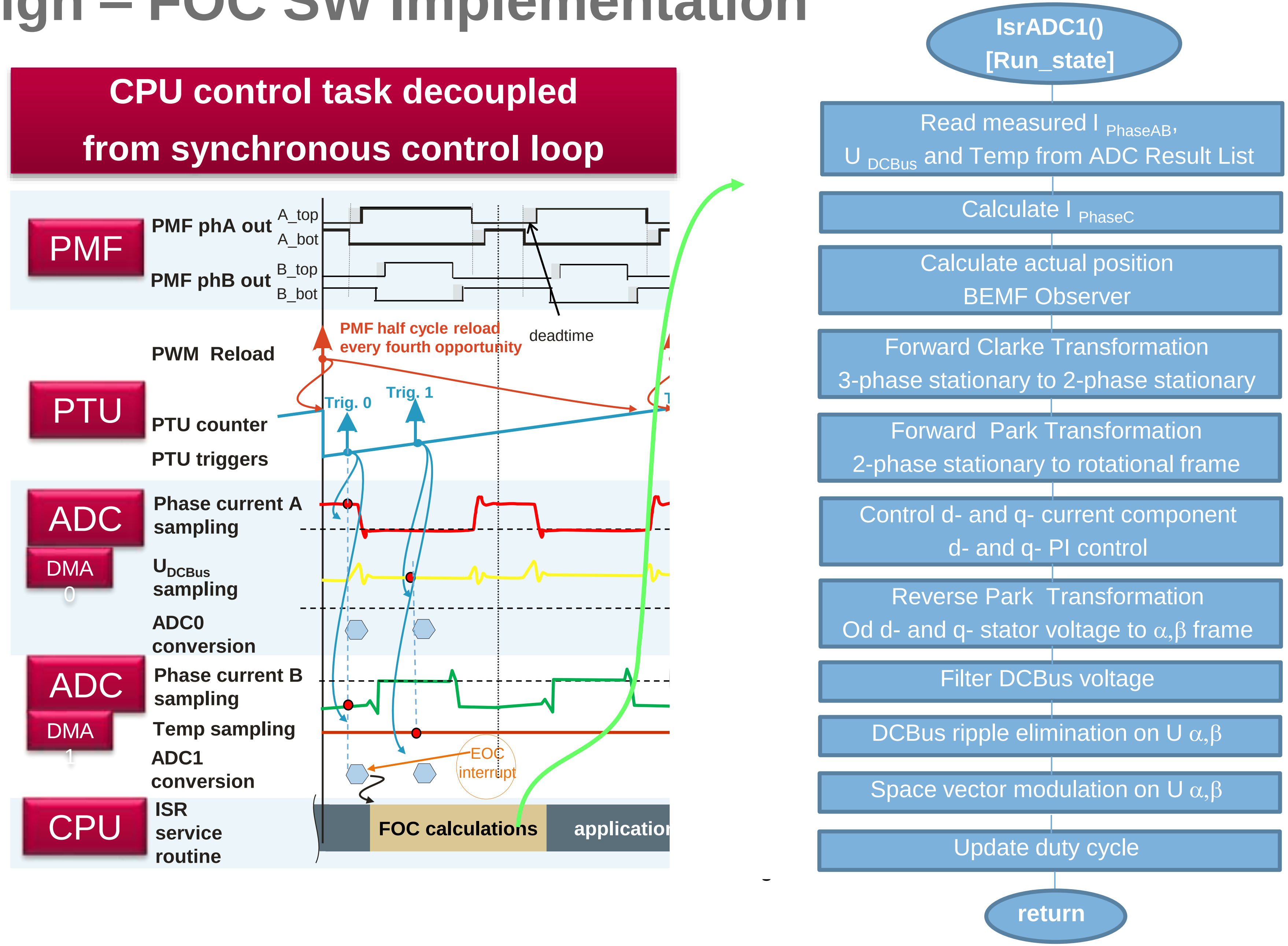


Direction	Description
input	Input error signal to the controller is a 16-bit number normalized between [-1, 1).
input, output	Pointer to the controller parameters structure.

```
Called in ATD interrupt:
static tBool focFastLoop(pmsmDrive_t *ptr)
{
…
                ptr->uDQReq.f16Arg1 = GFLIB_ControllerPIrAW(ptr->iDQErr.f16Arg1,&ptr->dAxisPI);
…
                return (true);
}
```

FOC Design – FOC SW Implementation

CPU control task decoupled from synchronous control loop


PMF
PMF phA out
A_top
A_bot
PMF phB out
B_top
B_bot
deadtime
PMF half cycle reload
every fourth opportunity
PWM Reload
PTU
PTU counter
PTU triggers
Trig. 0
Trig. 1
ADC
DMA 0
Phase current A sampling
U_{DCBus} sampling
ADC0 conversion
ADC
DMA 1
Phase current B sampling
Temp sampling
ADC1 conversion
EOC interrupt
CPU
ISR service routine
FOC calculations
applicatio
IsrADC1() [Run_state]
Read measured $I_{PhaseAB}$, U_{DCBus} and Temp from ADC Result List
Calculate I_{PhaseC}
Calculate actual position BEMF Observer
Forward Clarke Transformation 3-phase stationary to 2-phase stationary
Forward Park Transformation 2-phase stationary to rotational frame
Control d- and q- current component d- and q- PI control
Reverse Park Transformation Od d- and q- stator voltage to α,β frame
Filter DCBus voltage
DCBus ripple elimination on U α,β
Space vector modulation on U α,β
Update duty cycle
return

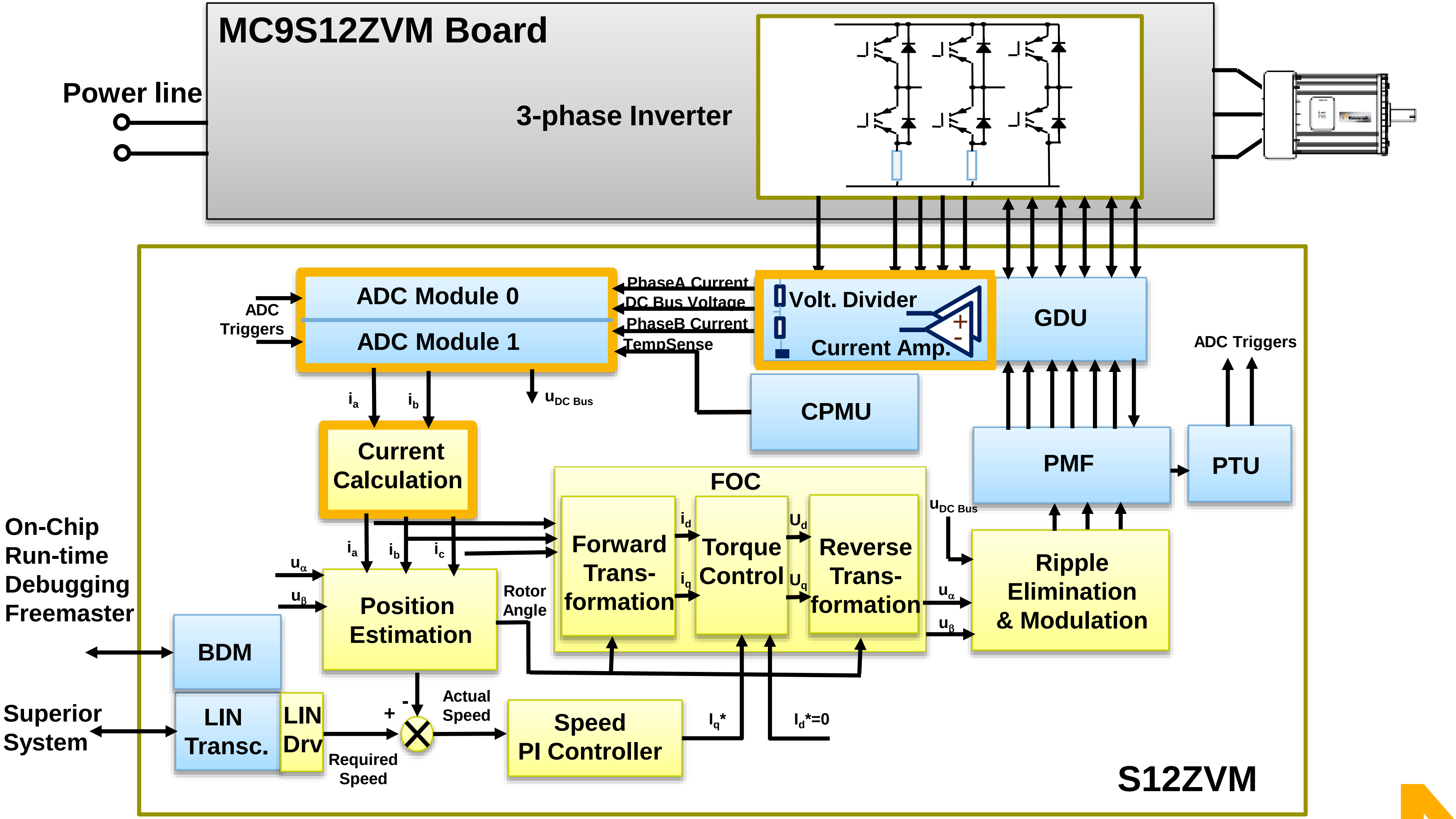
FOC Design – Summary

- 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

FOC DESIGN

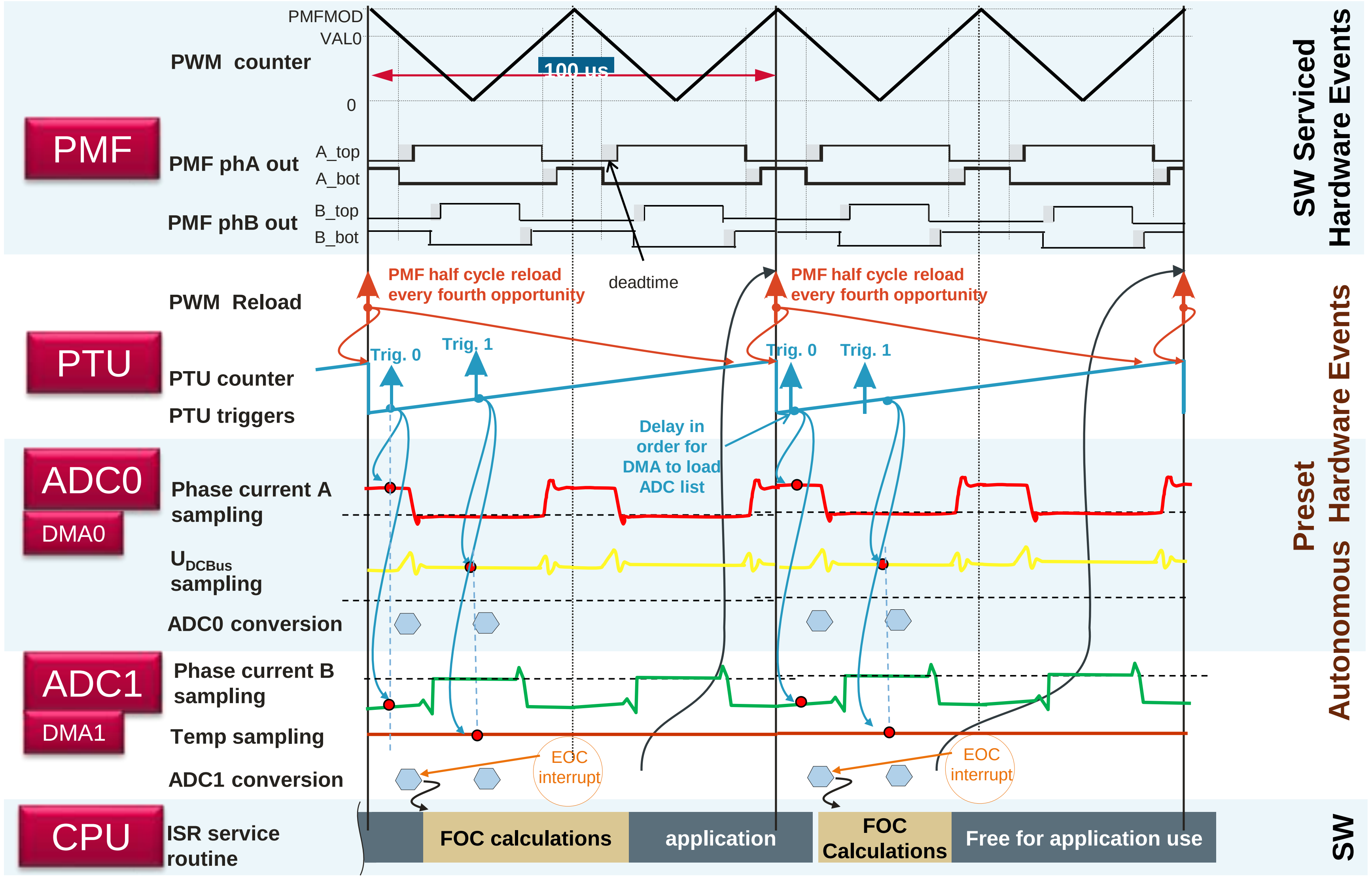
ANY QUESTIONS?

Current Sensing and Processing – Diagram



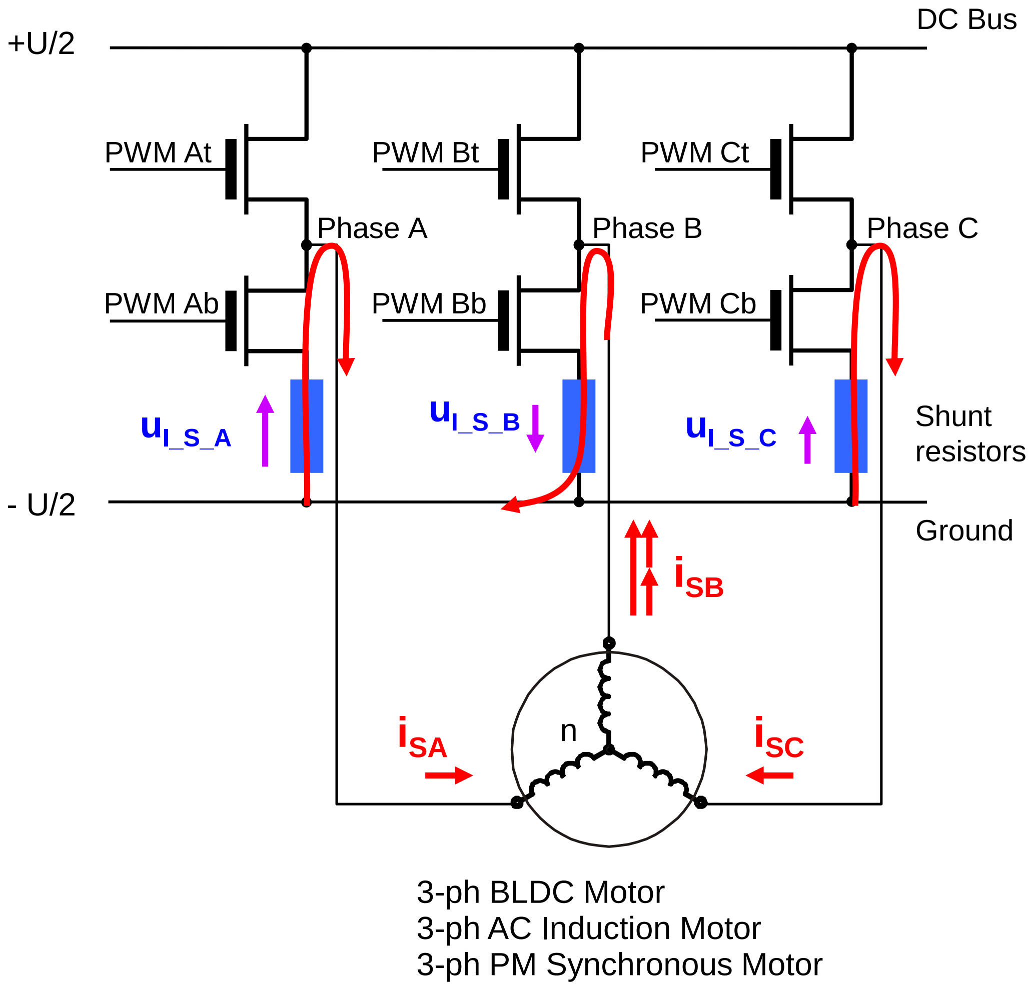
Current Sensing and Processing - PMSM Sensorless Application Example Timing

Two shunts current sensing



Current Sensing and Processing - Current Sensing with Shunt Resistors

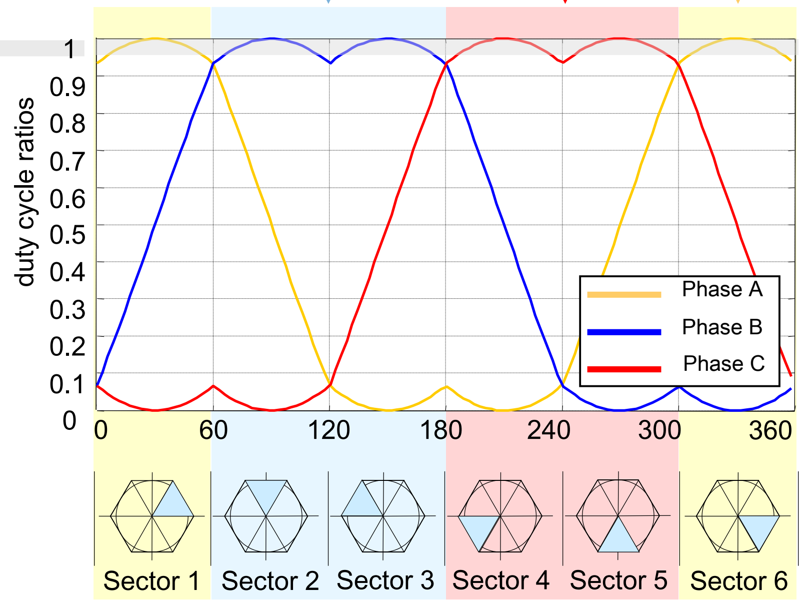
- Shunt resistors voltage drop measured
- SW calculation of all 3 phase currents needed
  - Phase (e.g. Phase A) current sensing possible only when bottom switch (transistor + diode) is conducting
- Dual-sampling required

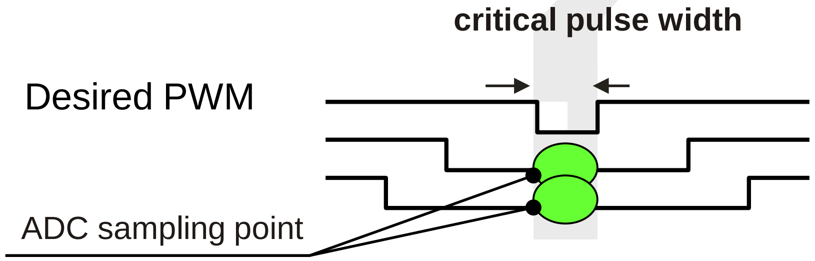


Current Sensing and Processing - Calculation

- Phase currents reconstruction according to Phase PWM signals (sectors 1..6)
- 3rd phase current calculated from 2 measured phases:
  - Sector 1,6: $i_A = -i_B - i_C$
  - Sector 2,3: $i_B = -i_A – i_C$
  - Sector 4,5: $i_C = -i_B - i_A$

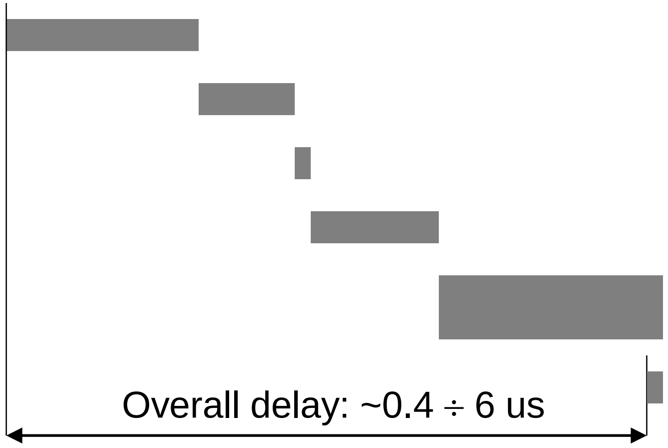
- Bottom transistor must be switched on at least for a critical pulse width to get stabilized current shunt resistor voltage drop
- At any time, at least 2 of 3 phases needs to accomplish this rule

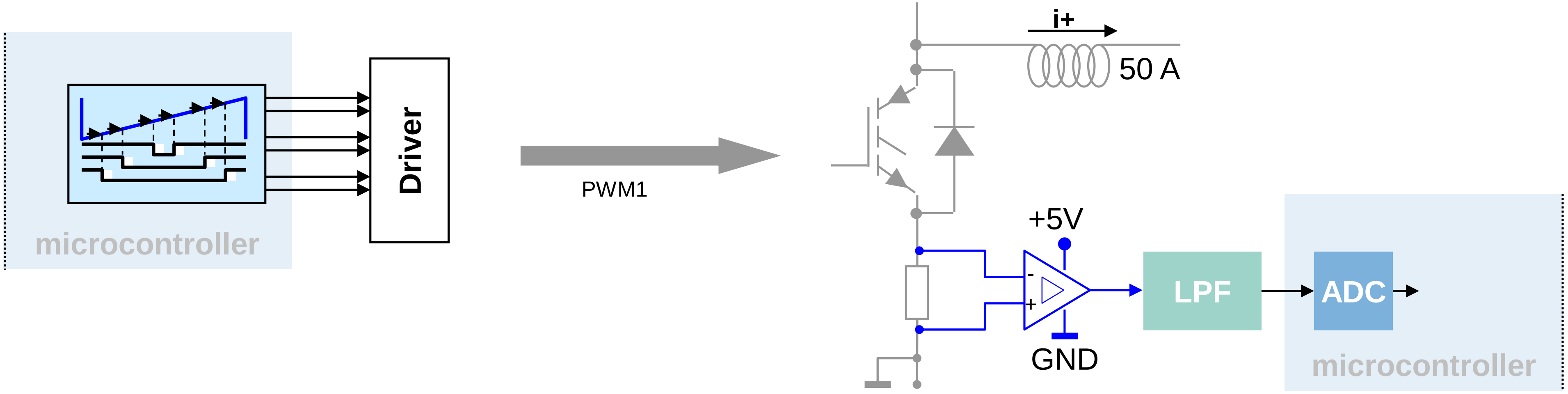




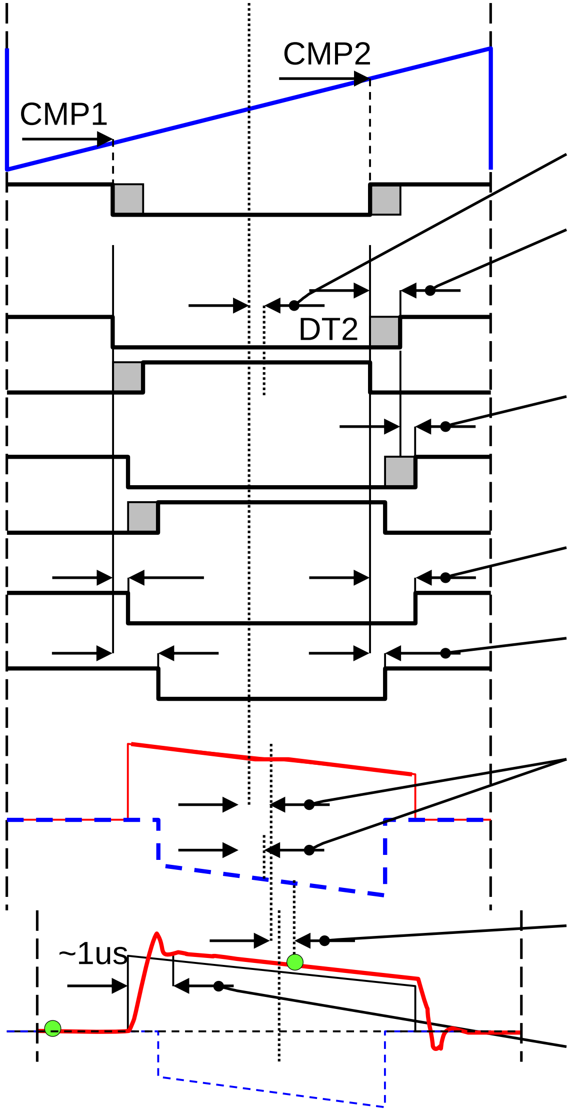
Current Sensing and Processing - Delays Involved in PWM Driven Closed Loops

- Delays are chained and are caused by:
  - Dead time insertion
  - Opto-coupler propagation delay
  - MOSFET Driver propagation delay
  - MOSFET turn ON/OFF times
  - Amplifier slew rate
  - Low-pass filter delay
  - ADC delays





Current Sensing and Processing - Delays Involved in PWM Driven Closed Loops



Internal counter

Desired PWM

Complementary pair
with dead time inserted
(signals at pins)

IGBT/MOSFET gate signals
top / bottom

Motor phase terminal
positive / negative current

Motor phase current
positive / negative
- shunts in legs

Real feedback signal
at ADC pin

Mid point shifts

Rising edge is
shifted by DT

Delay1 = $T_{opto}+T_{preDRV}$= ~300 ns + ~50 ns

Delay2 = $T_{opto}+T_{preDRV}+T_{on}/2+DT$
Delay2 = ~350ns +(0.1÷1 us)/2+(0.3÷4 us)
Delay2 = ~0.5 ÷ 5 us

Delay3 = $T_{opto}+T_{preDRV}+T_{on}/2$= 0.1÷1 us

Mid point shifts
= $T_{opto}+T_{preDRV}+(T_{on}+T_{off})/4$ +(DT1 or DT2)/2 =
= ~300 ns + ~50 ns + (0.2÷2 us)/4 + (0.3÷4 us)/2 =
= ~0.4 ÷ 5 us

Low pass filter delay + T_{opto}: ~1us
FSL note - in our ref designs this is close to 0

Amplifier slew rate: <1 us/full range

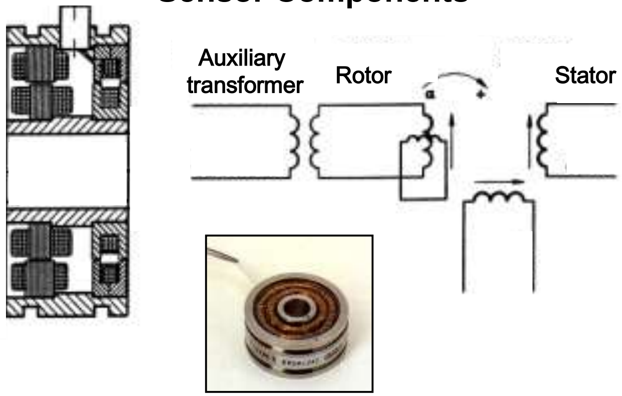
CURRENT SENSING AND PROCESSING

ANY QUESTIONS

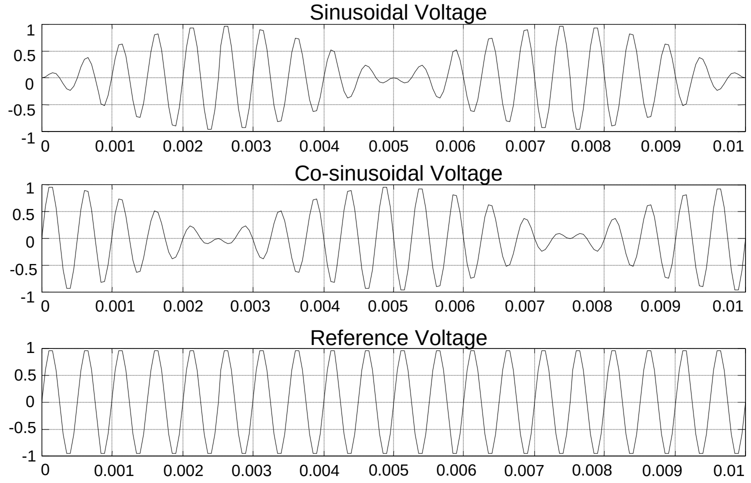
Position Sensing and Processing - Resolvers

- Absolute position transducer
- Based on the transformer theory
- 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
- Widely used in precious positioning applications
- The number of generated sine and cosine cycles per one mechanical revolution depends on the number of resolver pole-pairs (usually 1-3 cycles)

Sensor Components



Sensor Principle



Resolver Parameters:

Electrical Error – +/-10’, Transformation Ratio – 0.5, Phase Shift – +/-10°

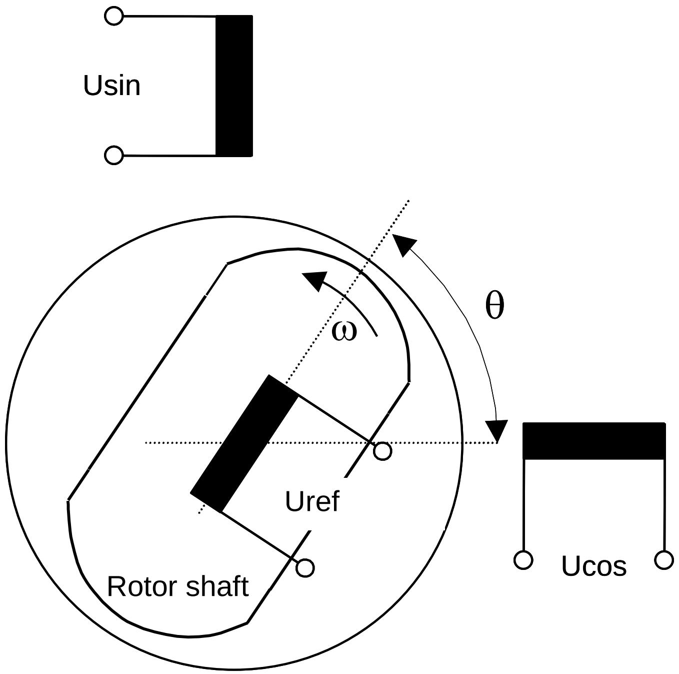
Input Voltage – 4-30V, Input Current – 20-100mA, Input Frequency – 400Hz-10kHz

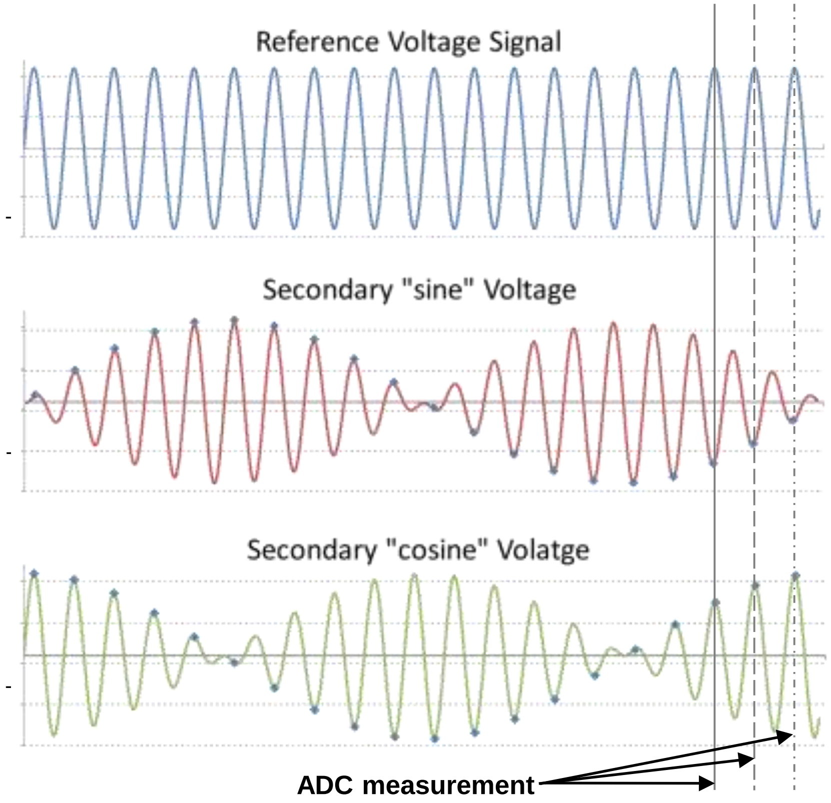
Position Sensing and Processing - Hollow Shaft Resolver

Resolver Basics:

Electrical Error – +/-10’, Transformation Ratio – 0.5, Phase Shift – +/-10°

Input Voltage – 4–30V, Input Current – 20–100 mA, Input Frequency – 400 Hz–10 kHz

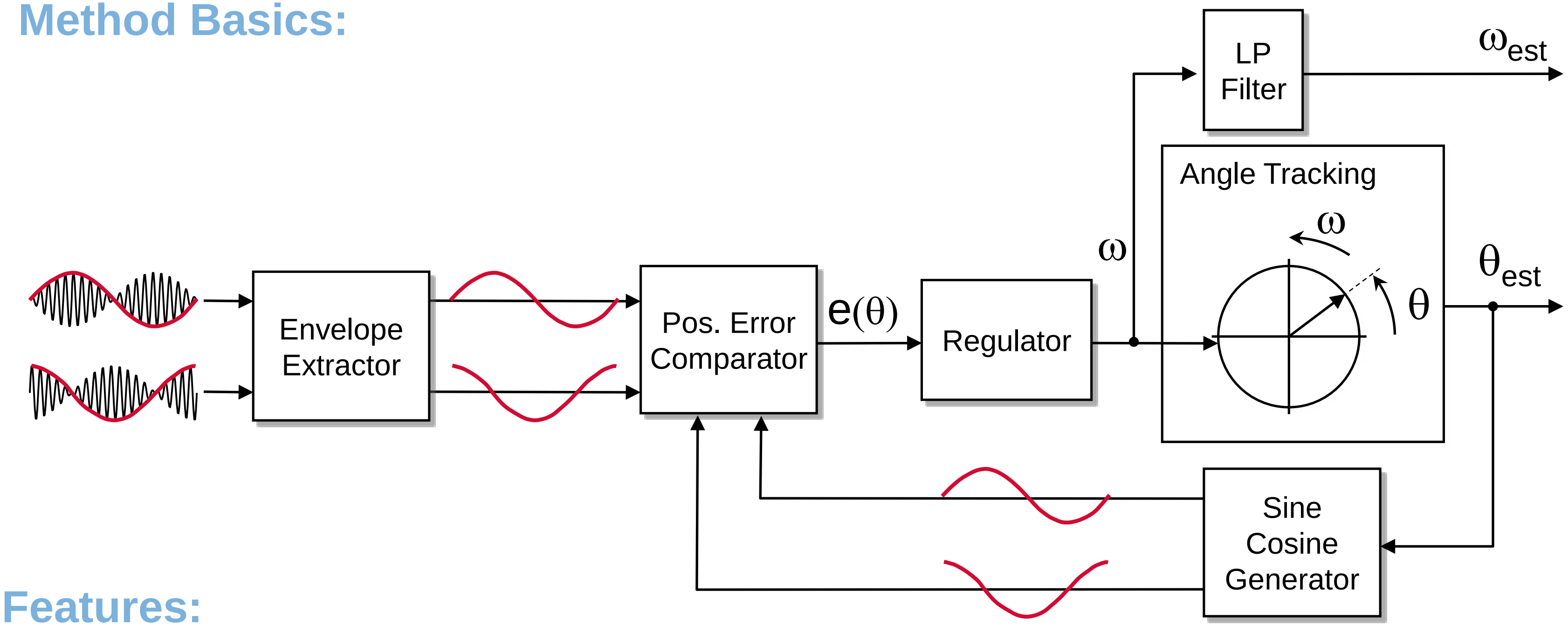




Resolver Parameters:

Position Sensing and Processing - Angle Tracking Observer

Method Basics:

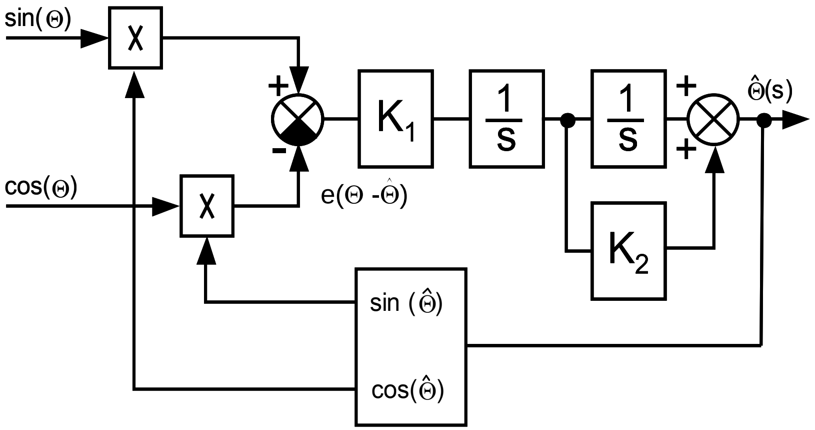


Features:

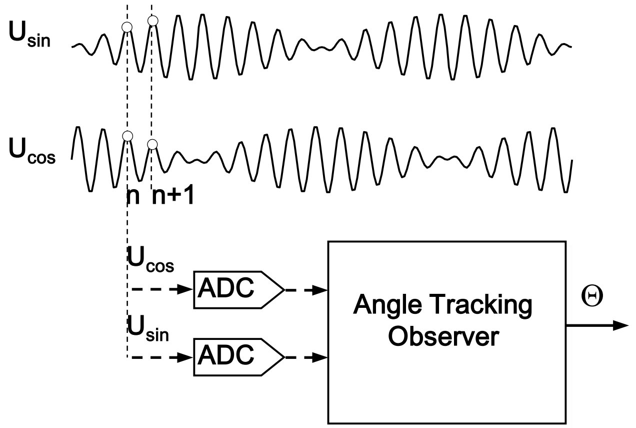
- Robust method in term of noise
- High accuracy of the angle extraction, speed estimation for free as side effect
- Can deal with non-sinusoidal signals/envelops
- Can be implemented fully digitally

Position Sensing and Processing - 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:

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

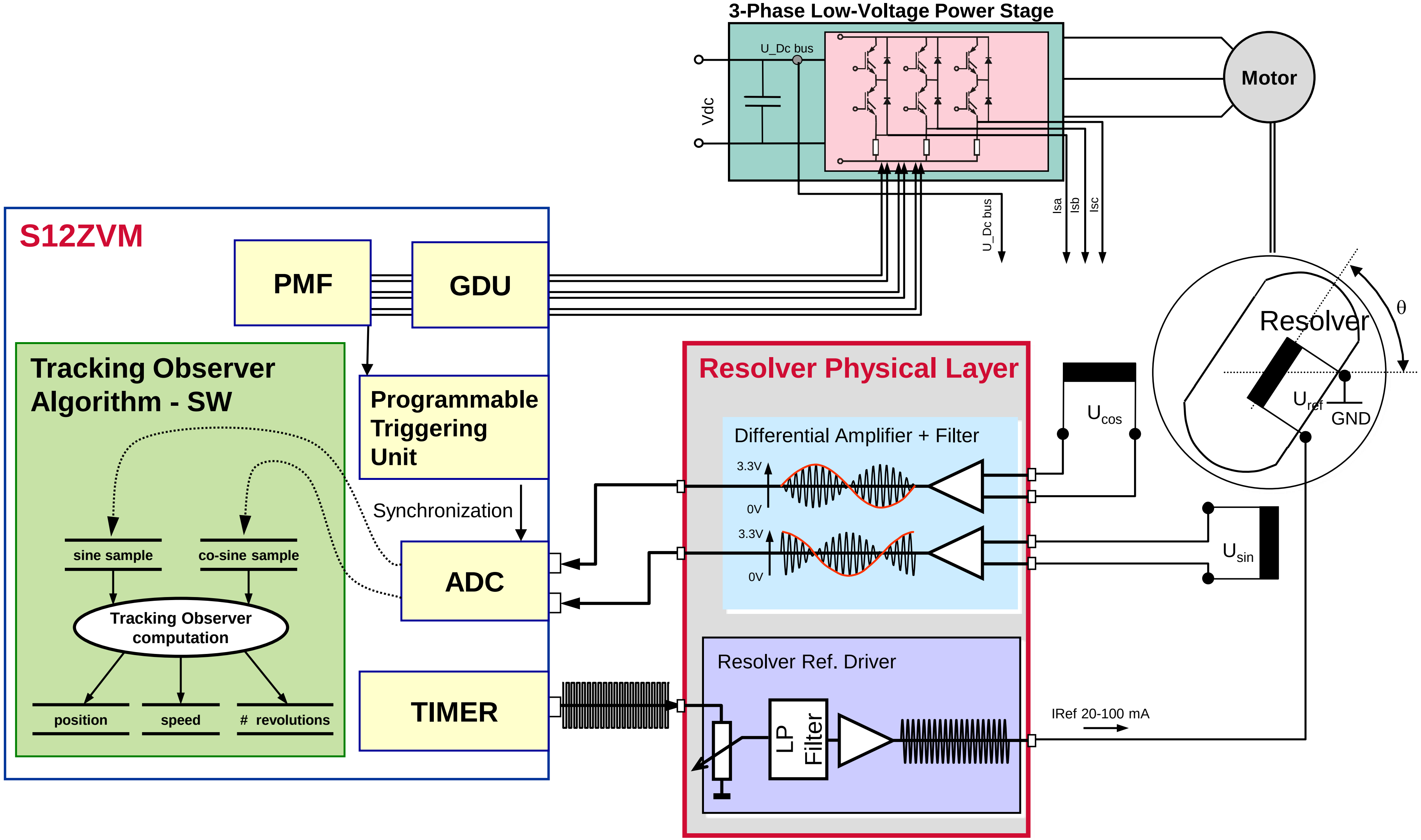
Features:

Non-sensitivity to disturbance and harmonic distortion of the carrier

Non-sensitivity to voltage and frequency changes

High accuracy of the angle extraction

Position Sensing and Processing - Resolver Driver and Interface



Position Sensing and Processing - Experimental Results

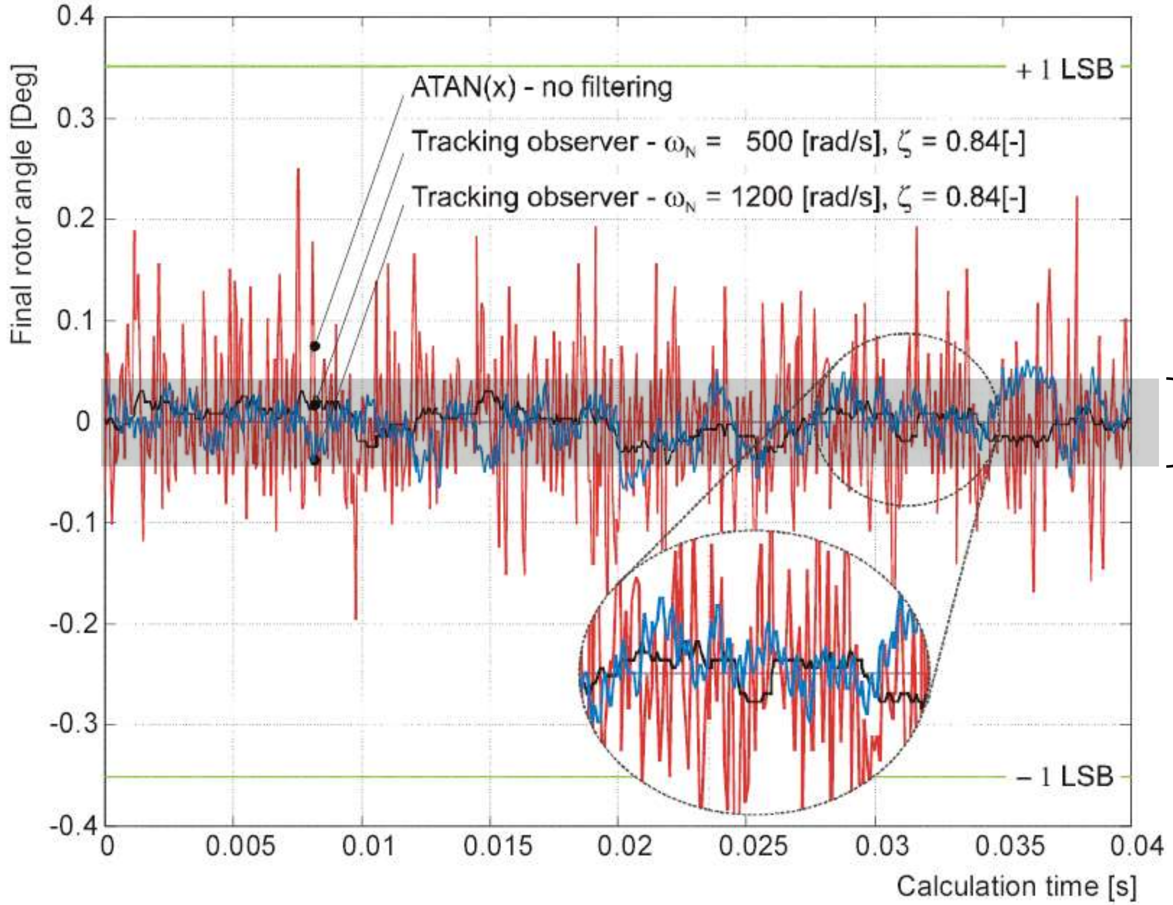


Figure 6-30. Noise of the Rotor Angle Estimation - Effect of Angle Tracking Observer Coefficients.

N = **13-bit**
Error = ± 1LSB

Accuracy

N = **10-bit**
Error = ± 1LSB

±π = ± N-1 bit

Position Sensing and Processing - Resolver Summary

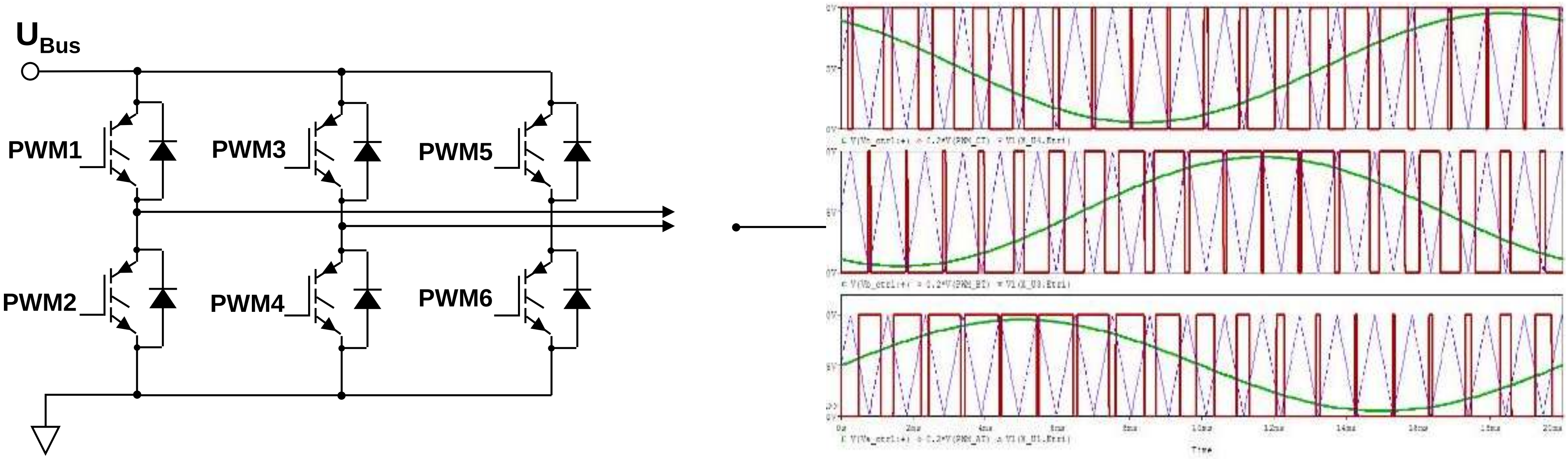
- Achieved 10-bit absolute accuracy and 13-bit resolution (noise level) using on-the-chip ADC
- Dynamic behavior can be fully controlled by the application
- Very little external components needed
- Advanced PMF-ADC-RESOLVER synchronization enables:
  - seamless integration with the main application
  - Coherence of the current and position control “z” domains
  - Automatic envelope extraction (no extra hardware and/or software needed)
- This avoids:
  - unreasonable computational resources for additional carrier frequency tracking observer
  - problems with imprecision caused by harmonic distortion of the carrier signal
  - noise from IGBT/MOSFET switching

POSITION SENSING AND PROCESSING

ANY QUESTIONS

Three Phase Voltage Generation

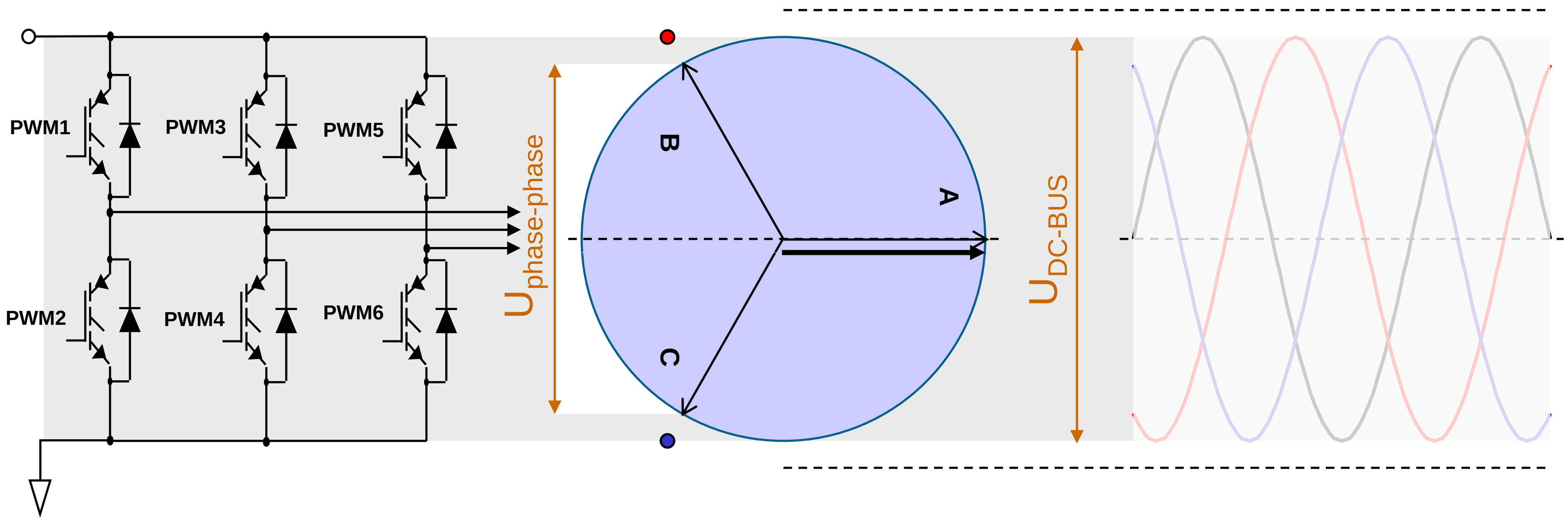
- The average output voltage is proportional to the duty cycle of the switch PWM
- It is regulated to form a sinusoidal shape on all three phases to achieve optimum torque



Source: Strategic Technology Group, India

Three Phase Voltage Generation - Sinusoidal Modulation: Limited in Amplitude

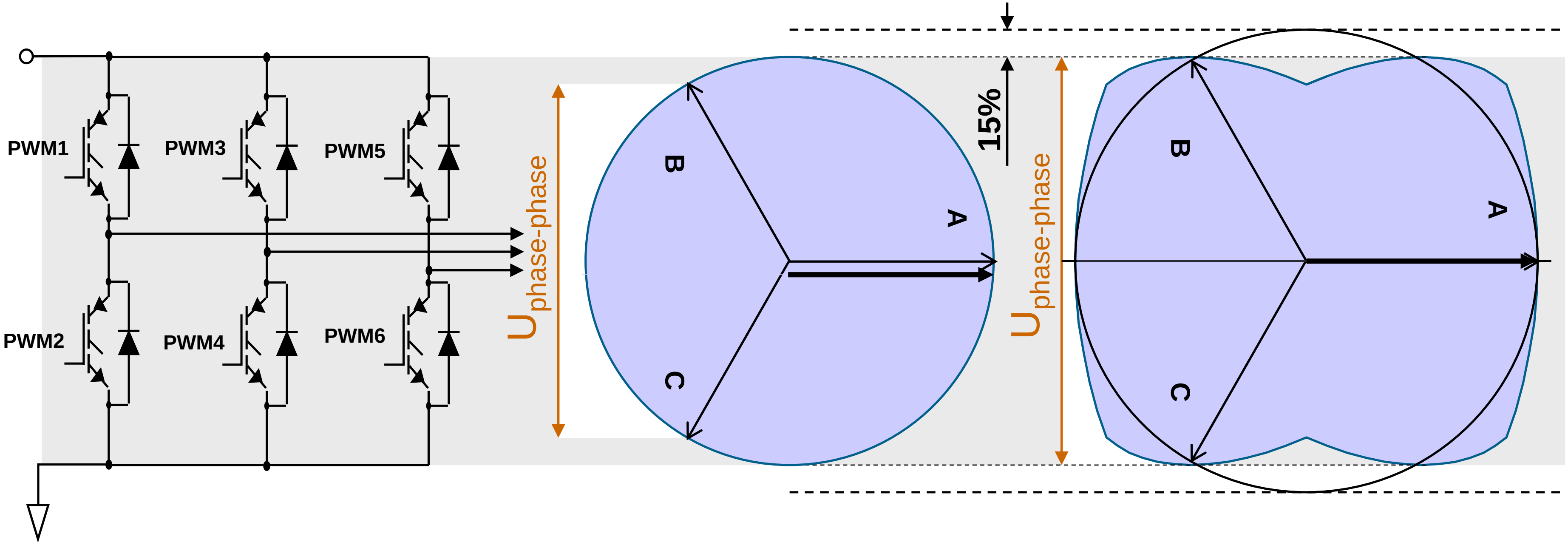
- In sinusoidal modulation, the amplitude is limited to half of the DC-bus voltage
- The phase to phase voltage is then lower then the DC-bus voltage (although such voltage can be generated between the terminals)



Can such a modulation technique be found that would generate full phase-to-phase voltage?

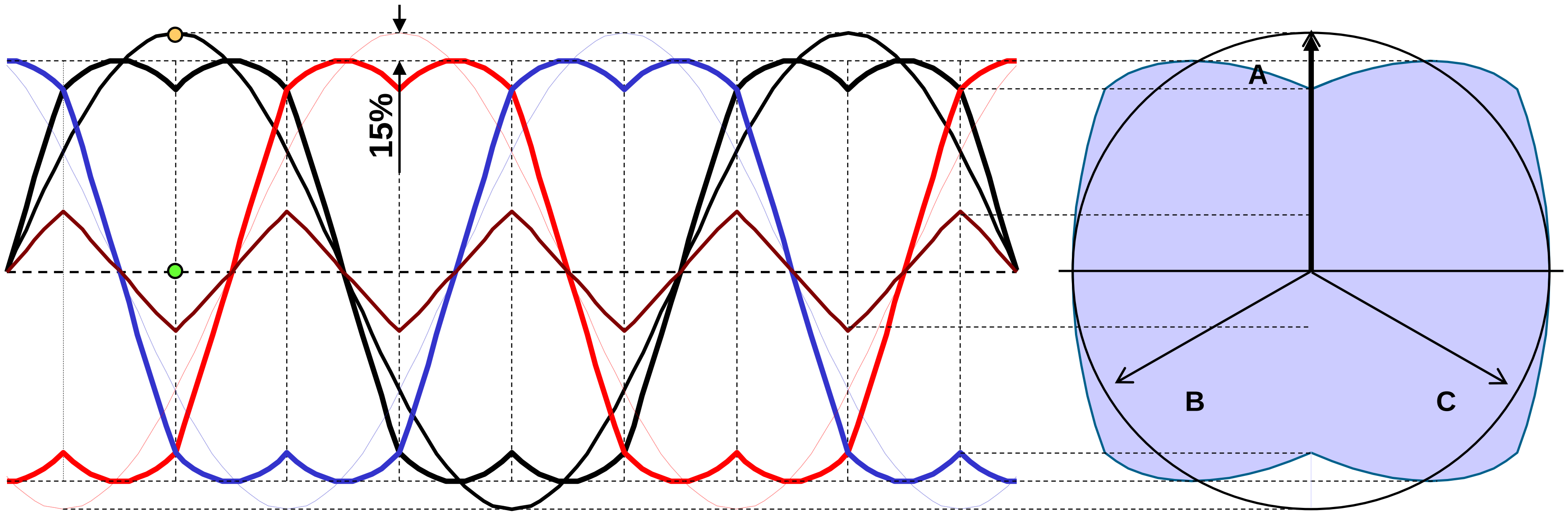
Three Phase Voltage Generation - Phase-to-Phase Voltage Generation

- Full phase-to-phase voltage can be generated by continuously shifting the 3-phase voltage system
- The amplitude of the first harmonic can be then increased by 15.5%



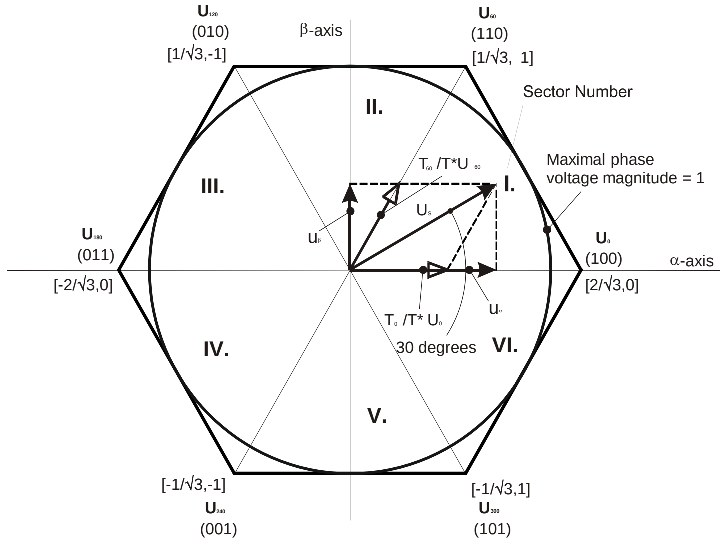
Three Phase Voltage Generation - How to Increase Modulation Index

- Modulation index is increased by adding the “shifting” voltage u_0 to first harmonic
- “Shifting” voltage u_0 must be the same for all three phases, thus it can only contain 3^r harmonics!

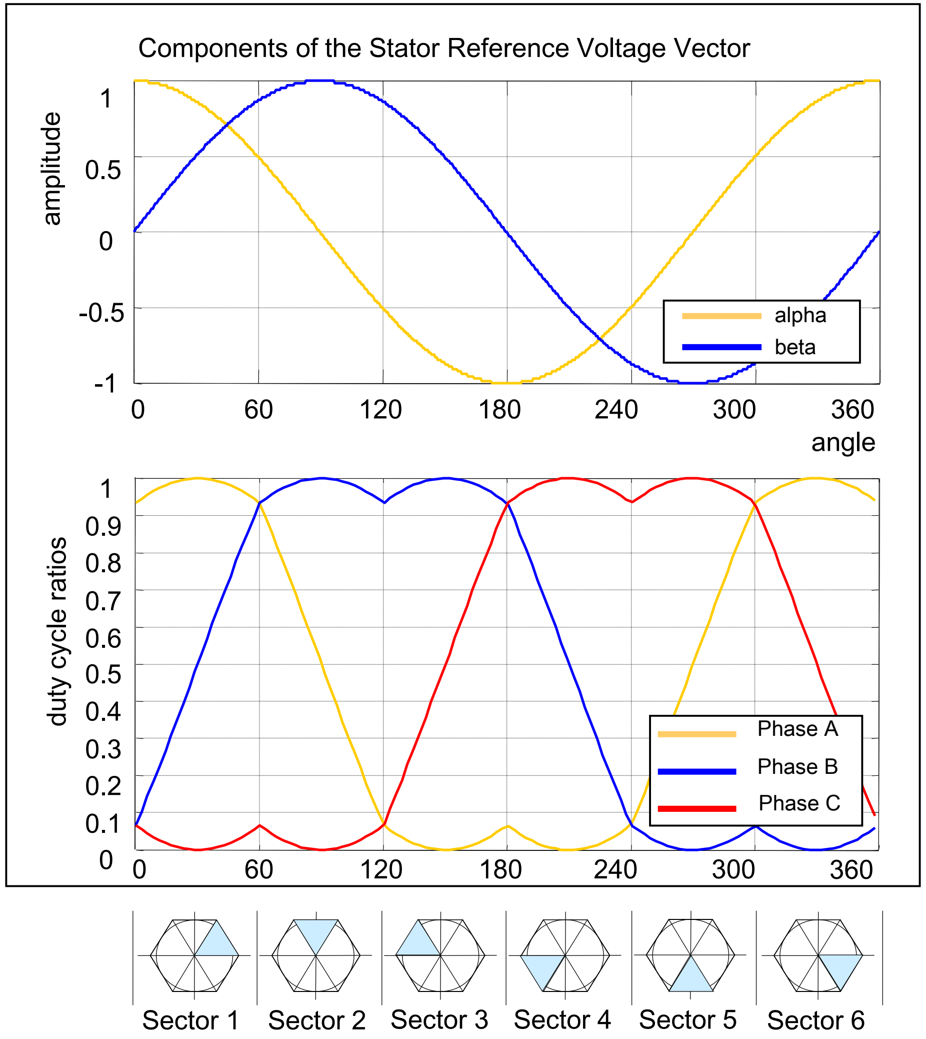


Three Phase Voltage Generation - Standard Space Vector Modulation

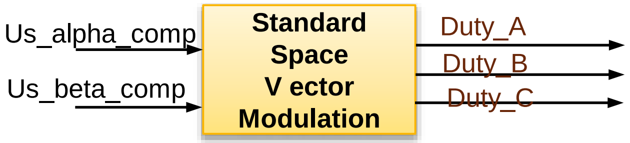
- Transforms directly the stator voltage vectors from the two-phase coordinate system fixed with stator to PWM signals
- Output voltage vector is created by switching continuously between the adjacent base vectors and the “NULL” vectors
- Generates maximum phase voltage 0.5773 VDC
- Both nulls O000 and O111 are generated at each cycle



Input & Output Waveforms

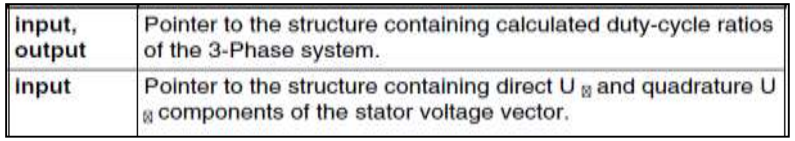


Three Phase Voltage Generation - Application Using SVM



Motor Control Library Function:

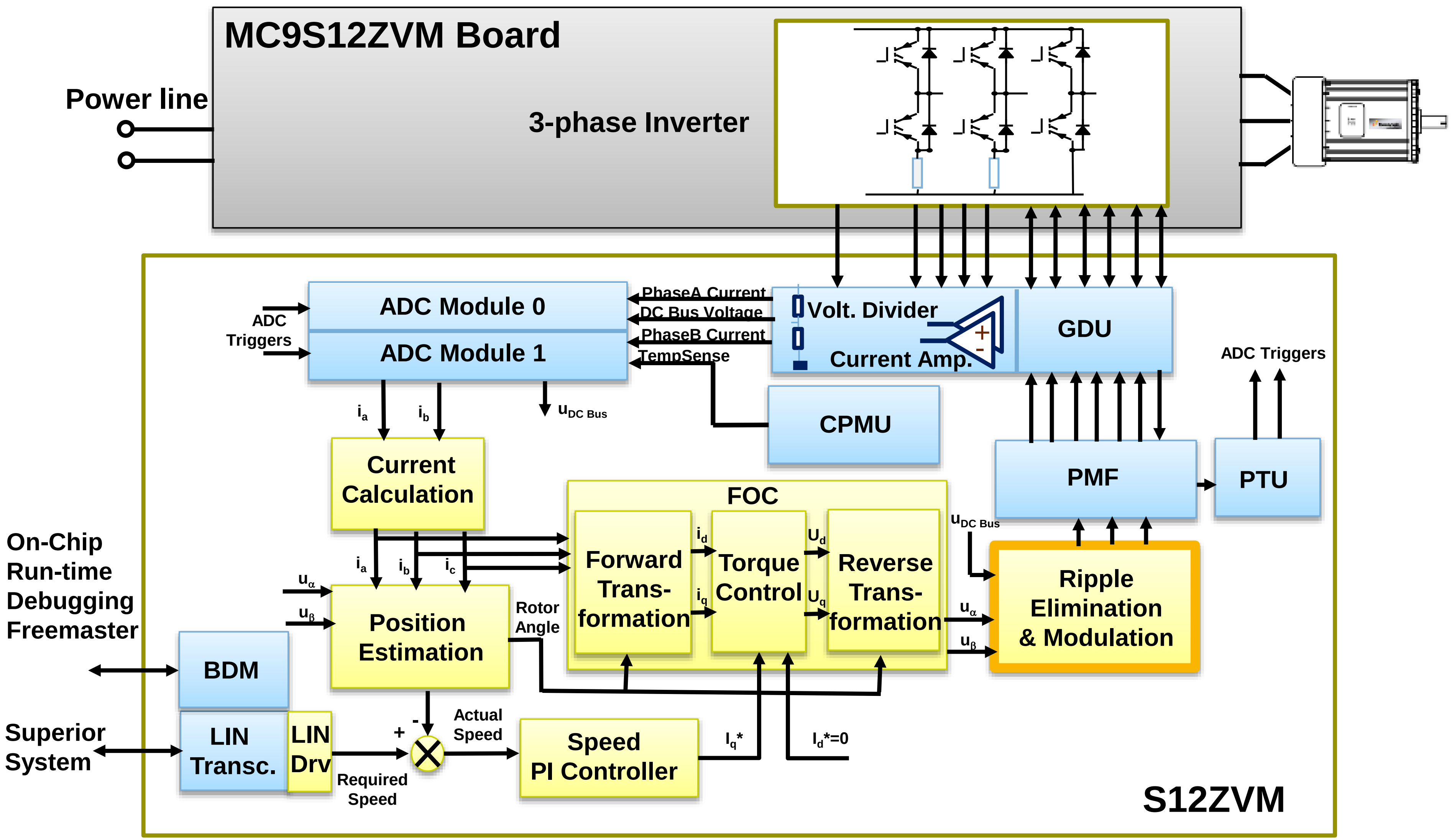
tU32 **GMCLIB_SvmStd_F32**(SWLIBS_3Syst_F32 *pOut, const SWLIBS_2Syst_F32 *const pIn);



input, output	Pointer to the structure containing calculated duty-cycle ratios of the 3-Phase system.
input	Pointer to the structure containing direct U ▯ and quadrature U ▯ components of the stator voltage vector.

```
static tBool focFastLoop(pmsmDrive_t *ptr)
{
GMCLIB_Clark(&ptr->iAlBeFbck,&ptr->iAbcFbck);
…
   GMCLIB_ParkInv(&ptr->uAlBeReq,&ptr->thTransform,&ptr->uDQReq);

   ptr->elimDcbRip.f16ArgDcBusMsr  = meas.measured.f16Udcb.filt;
   GMCLIB_ElimDcBusRip(&ptr->uAlBeReqDCB,&ptr->uAlBeReq,&ptr->elimDcbRip);

   ptr->svmSector   = GMCLIB_SvmStd(&(ptr->pwm16),&ptr->uAlBeReqDCB);

   return (true);
}
```

Three Phase Voltage Generation – DC-bus Ripple Compensation



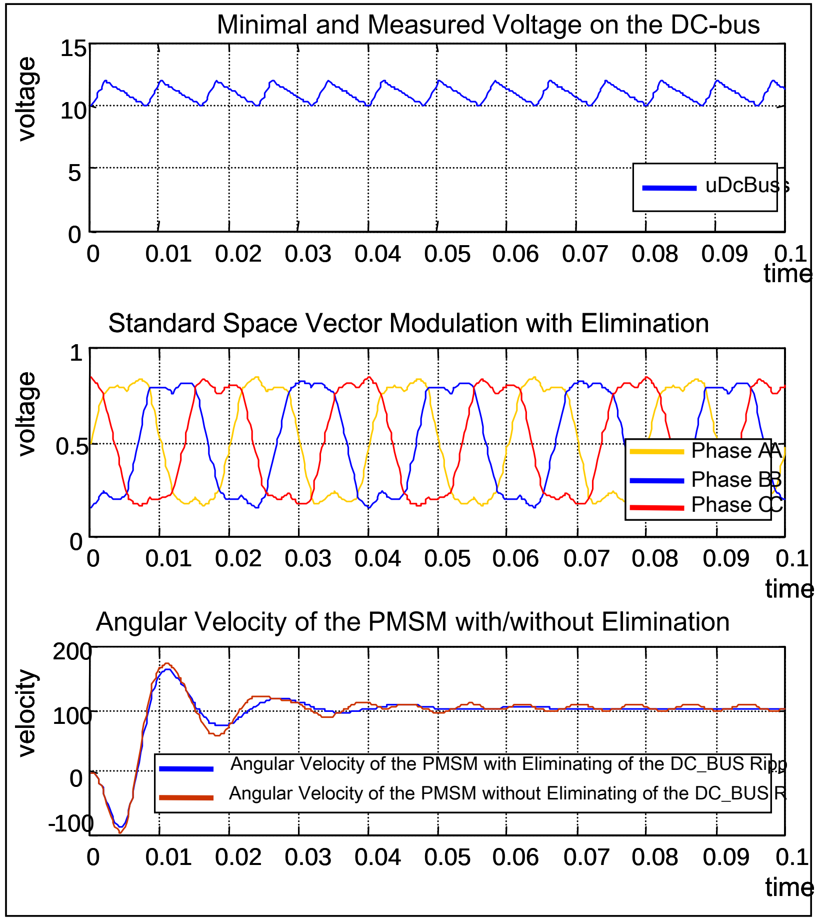
Three Phase Voltage Generation – DC-bus Ripple Compensation

- Compensates the ripple of the output voltages from power stage caused by DC-bus voltage ripples
- Improves performance of the drive
- Compensation uses moving average filtered DCBus voltage and a fixed index

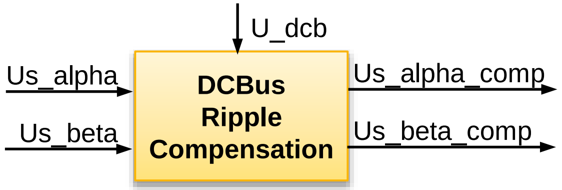
Moving average filtered DCBus voltage

$$u_\alpha^* = \begin{cases} \dfrac{f32\mathrm{ModIndex} \bullet u_\alpha}{f32\mathrm{ArgDcBusMsr}/2} & \text{if } \mathrm{abs}\left(f32\mathrm{ModIndex} \bullet u_\alpha\right) < \dfrac{f32\mathrm{ArgDcBusMsr}}{2} \\ \mathrm{sign}\left(u_\alpha\right) & \text{otherwise} \end{cases}$$

$$u_\beta^* = \begin{cases} \dfrac{f32\mathrm{ModIndex} \bullet u_\beta}{f32\mathrm{ArgDcBusMsr}/2} & \text{if } \mathrm{abs}\left(f32\mathrm{ModIndex} \bullet u_\beta\right) < \dfrac{f32\mathrm{ArgDcBusMsr}}{2} \\ \mathrm{sign}\left(u_\beta\right) & \text{otherwise} \end{cases}$$

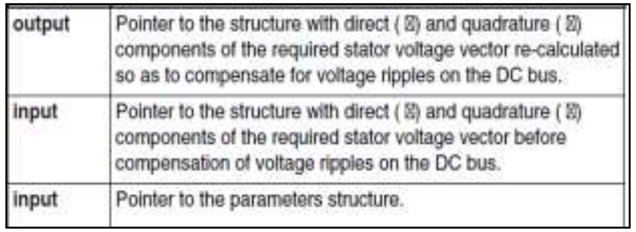


Three Phase Voltage Generation – Application Using DC-bus Ripple Compensation



Motor Control Library Function:

```
void GMCLIB_ElimDcBusRip_F16
(SWLIBS_2Syst_F16 *const pOut,
const SWLIBS_2Syst_F16 *const pIn,
const GMCLIB_ELIMDCBUSRIP_T_F16 *const pParam);
```

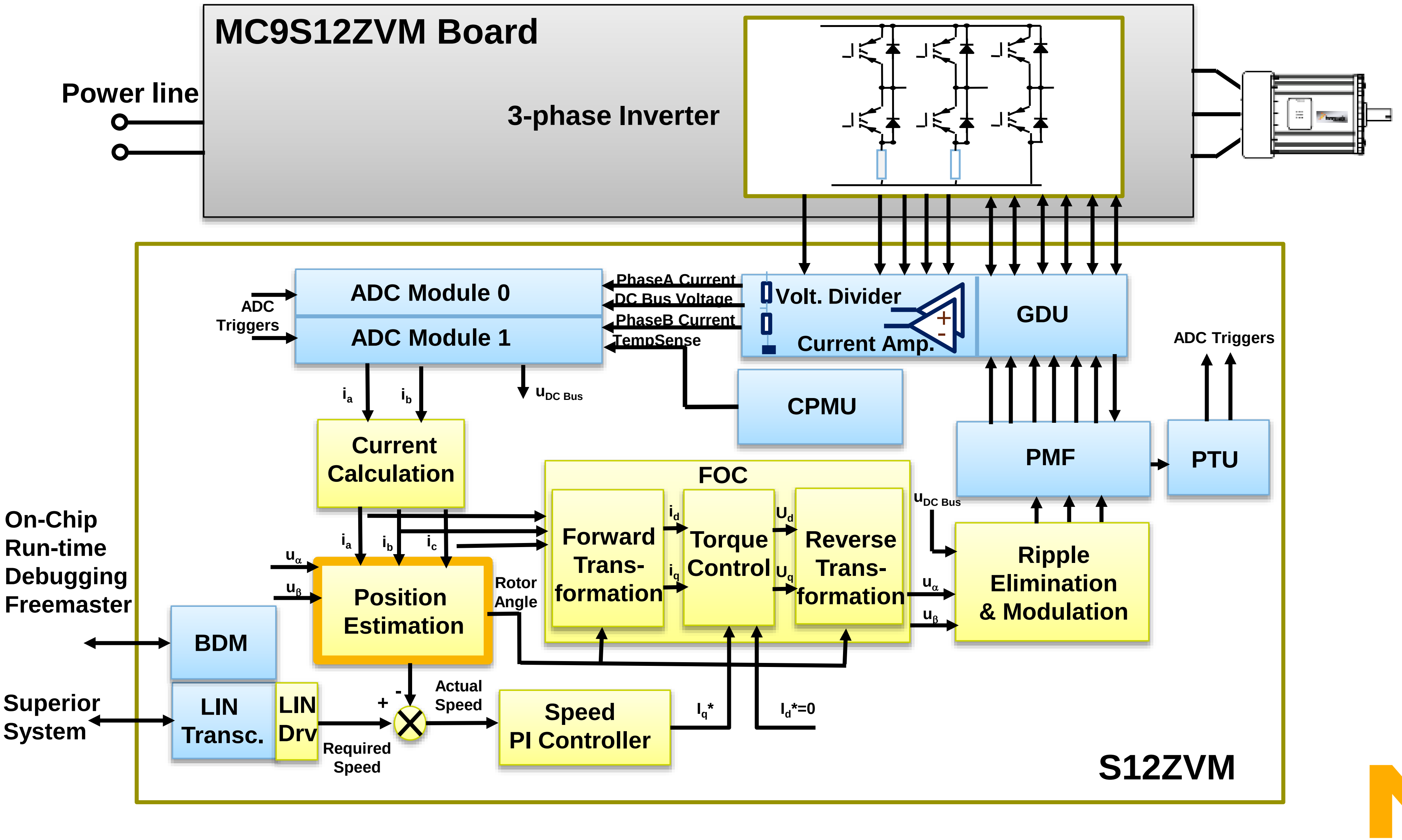


output	Pointer to the structure with direct (▯) and quadrature (▯) components of the required stator voltage vector re-calculated so as to compensate for voltage ripples on the DC bus.
input	Pointer to the structure with direct (▯) and quadrature (▯) components of the required stator voltage vector before compensation of voltage ripples on the DC bus.
input	Pointer to the parameters structure.

```
drvFOC.elimDcbRip.f16ModIndex         = FRAC16(0.866025403784439);
tBool Meas_UdcVoltageMeasure(measModule_t *ptr, GDFLIB_FILTER_MA_T *uDcbFilter)
{
              ptr->measured.f16Udcb.raw   = ADC0ResultList[1]>>1;
              ptr->measured.f16Udcb.filt  = GDFLIB_FilterMA(ptr->measured.f16Udcb.raw, uDcbFilter);
              return(1);
}
static tBool focFastLoop(pmsmDrive_t *ptr)
{
…
              ptr->elimDcbRip.f16ArgDcBusMsr  = meas.measured.f16Udcb.filt;
              GMCLIB_ElimDcBusRip(&ptr->uAlBeReqDCB, &ptr->uAlBeReq, &ptr->elimDcbRip);
              ptr->svmSector   = GMCLIB_SvmStd(&(ptr->pwm16),&ptr->uAlBeReqDCB);
              return (true);
}
```

THREE PHASE VOLTAGE GENERATION ANY QUESTIONS?

Sensor-less – PMSM Sensor-less Diagram

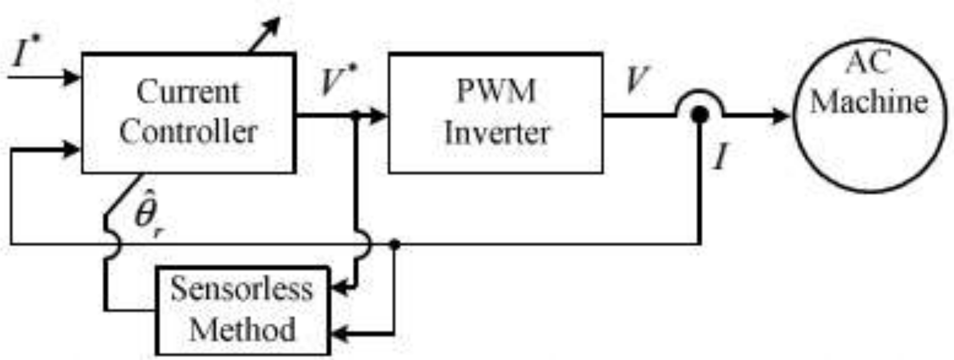


Sensor-less – Introduction

- ***FOC*** requires accurate position and velocity signals

- Sensorless FOC application uses
  - Estimated position
  - Estimated speed

- Position/speed is estimated from measured currents and measured/estimated voltages



(b) Current control structure by the sensorless method

Sensor-less - Classification of Sensor-less Methods

- Model-based methods
  - Based on the electrical model of PM
  - Presets good results in medium and high speed operation (starting from 5% of nominal speed)
  - Broadly commercialized for low-end applications

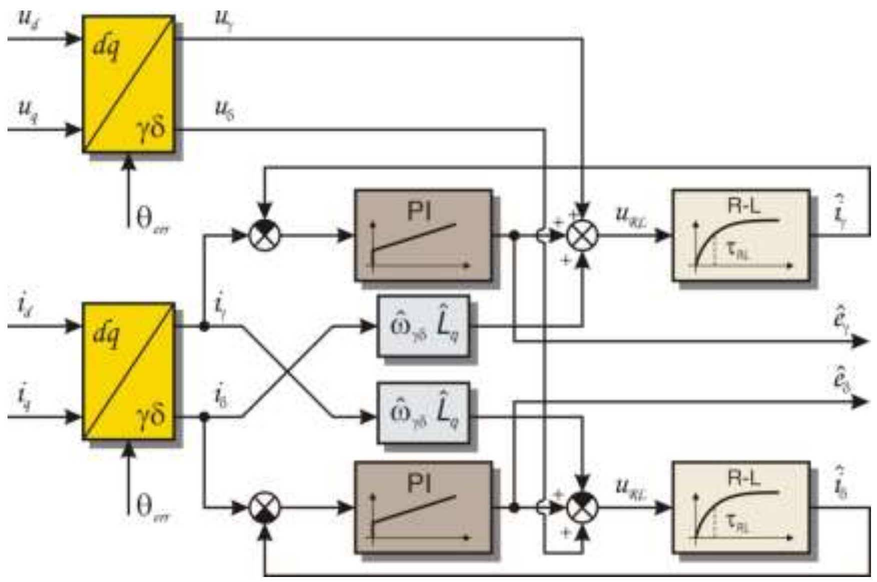
- Methods relaying on **magnetic saliency**
  - Based on inherent characteristic of PM motor called **magnetic saliency**
  - Presets good results in standstill or very low speed region (up to 10% of nominal speed)
  - Commercialized for certain types of PM motors designed accordingly

Sensor-less - Model-based Methods Classification

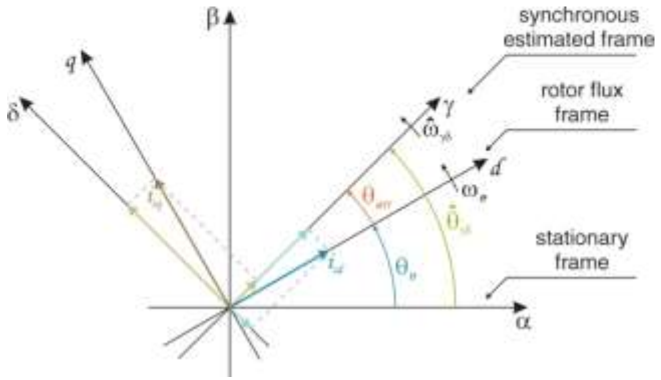
- Back EMF estimation methods
  - Utilize simplified model of PM in d-q estimated frame or so called extended BEMF (NXP approach)
- Voltage/current model methods
  - Difference between the estimated voltage/current and the actual voltage/current is used to extract the position error
- Fundamental voltage feedback methods
  - Output of the current controller is directly used to obtain position error

Sensor-less - Saliency Based Back-EMF Observer

- Saliency based back-EMF voltage is generated due to $L_d \neq L_q$
- Because back-EMF term is not modeled, observer actually acts as a back-EMF state filter
- Observer is designed in synchronous reference frame; i.e. all observer quantities are DC in steady state, making the observer accuracy independent of rotor speed

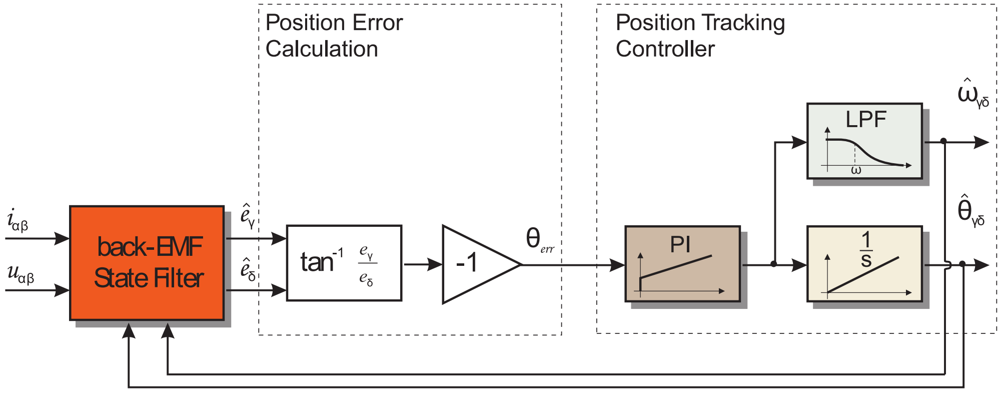


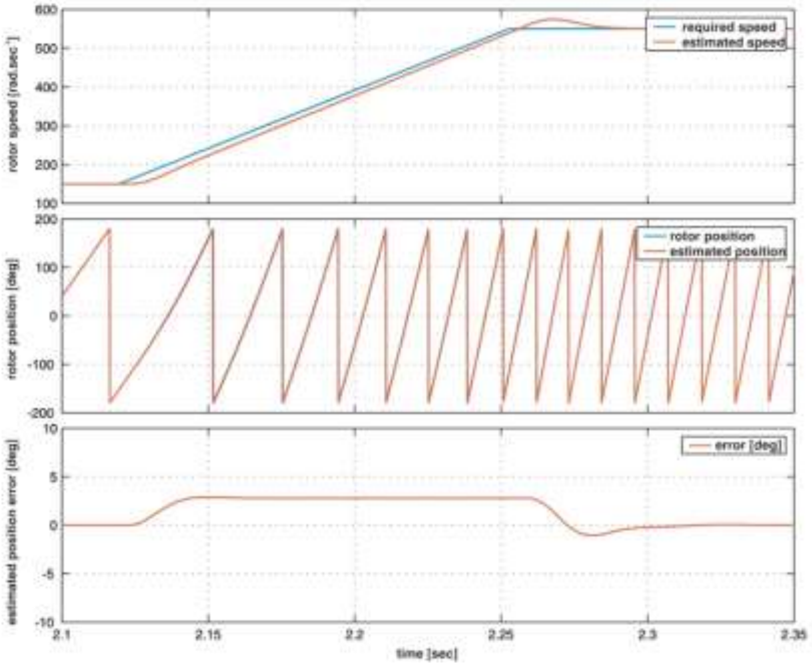
$$\begin{bmatrix} u_\gamma \\ u_\delta \end{bmatrix} = \begin{bmatrix} R_s + sL_d & -\hat{\omega}_{\gamma\delta}L_q \\ \hat{\omega}_{\gamma\delta}L_q & R_s + sL_d \end{bmatrix} \begin{bmatrix} i_\gamma \\ i_\delta \end{bmatrix} + E_{\text{sal}} \begin{bmatrix} -\sin(\theta_{err}) \\ \cos(\theta_{err}) \end{bmatrix}$$



$$\frac{dL}{d\theta}\ \textit{causes}\ \frac{d\lambda}{d\theta}\ \textit{, which when combined with}\ \frac{d\theta}{dt}\ \textit{, causes}\ \frac{d\lambda}{dt} = \textit{voltage}$$

Sensor-less - Position Estimation Using Saliency Based Back-EMF


Position Error Calculation
Position Tracking Controller
$i_{\alpha\beta}$
$u_{\alpha\beta}$
back-EMF State Filter
$\hat{e}_\gamma$
$\hat{e}_\delta$
$\tan^{-1}\frac{e_\gamma}{e_\delta}$
-1
θ_{err}
PI
LPF
ω
$\frac{1}{s}$
$\hat{\omega}_{\gamma\delta}$
$\hat{\theta}_{\gamma\delta}$



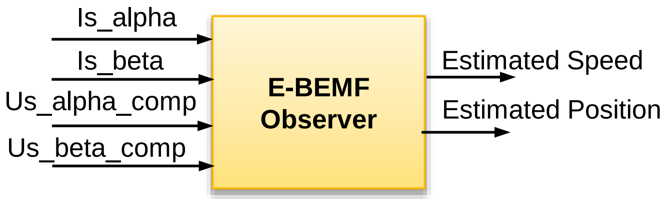
Position estimation steady state error at constant speed

$$\theta_{err_{ss}} = \lim_{s\to 0}\left[\frac{\theta_e(s)s^3}{s^2+K_p s+K_i}\right] = 0$$

Position estimation steady state error during speed ramp change

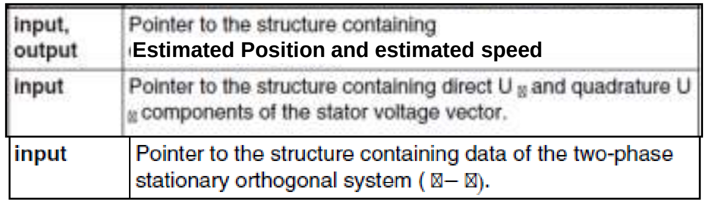
$$\theta_{err_{ss}} = \lim_{s\to 0}\left[\frac{s^2}{s^2+K_p s+K_i}\frac{A}{s^2}\right] = \frac{A}{K_i}$$

Sensor-less - Application using E-BEMF Observer



Advanced Motor Control Library Function (not part of standard library):

```
void ACLIB_PMSMBemfObsrvDQ
(&sensorless->wRotEl,  &sensorless->thRotEl,
iAlBeFbck, uAlBeReq,
&sensorless->bEMFObs);)
```



input, output	Pointer to the structure containing Estimated Position and estimated speed
input	Pointer to the structure containing direct U ⊠ and quadrature U ⊠ components of the stator voltage vector.
input	Pointer to the structure containing data of the two-phase stationary orthogonal system (⊠– ⊠).

Called in ADC interrupt:

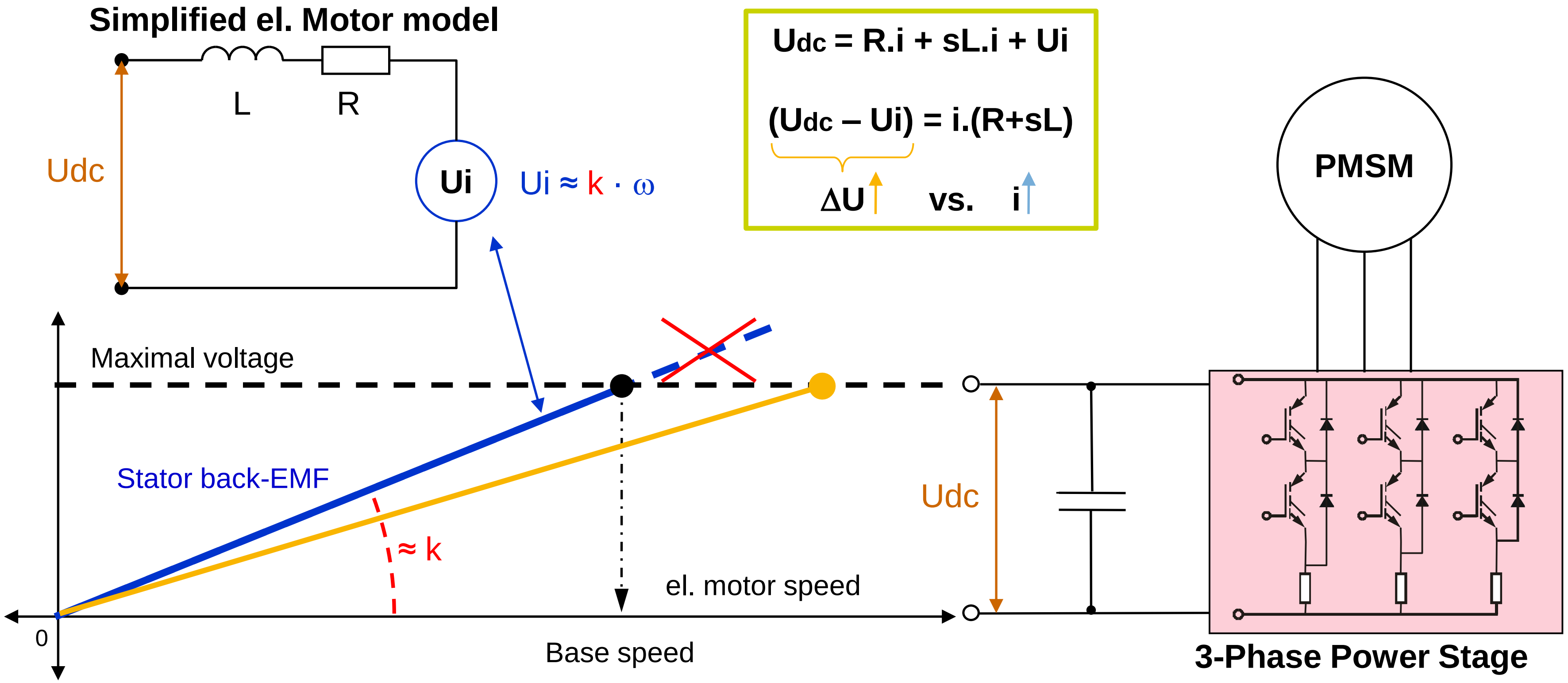
```
void stateRun( )
{
 …
    ACLIB_PMSMBemfObsrvDQ(&sensorless->wRotEl, &sensorless->thRotEl, iAlBeFbck,
uAlBeReq, &sensorless->bEMFObs);
…
   stateRunStatus = focFastLoop(&drvFOC);
…
   Pmf_updateDutycycle(&drvFOC.pwm16);
}
```

SENSOR-LESS

ANY QUESTIONS?

Field Weakening - Concept

- For given strength of the rotor magnetic field there is point (base speed) where external voltage (Udc) can not “push” any more current “into” the el. motor against the back-EMF (Ui).
- Spinning el. motor above the “base speed” requires to lower the back-EMF (Ui) by weakening the rotor magnetic field.



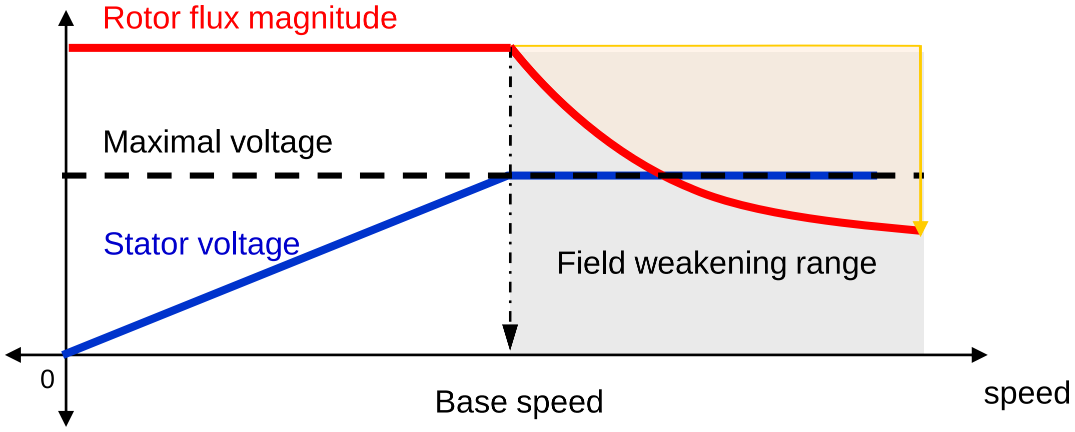
$$\mathrm{Udc} = R.i + sL.i + \mathrm{Ui}$$

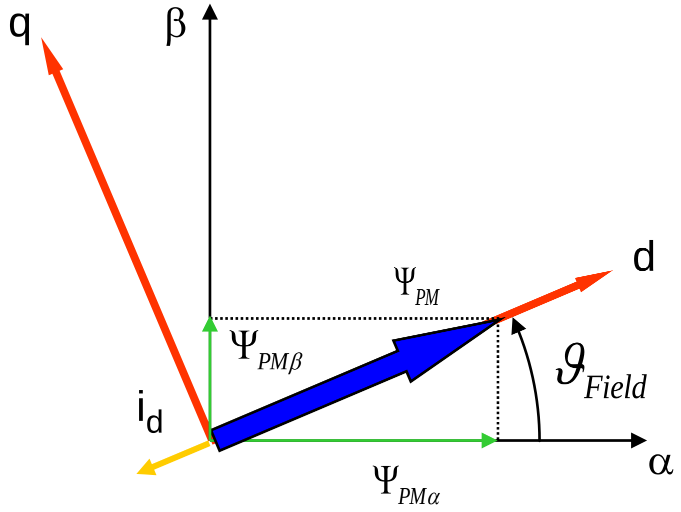
$$\underbrace{(\mathrm{Udc} - \mathrm{Ui})}_{\Delta U \uparrow} = i.(R+sL)$$

vs. $i\uparrow$

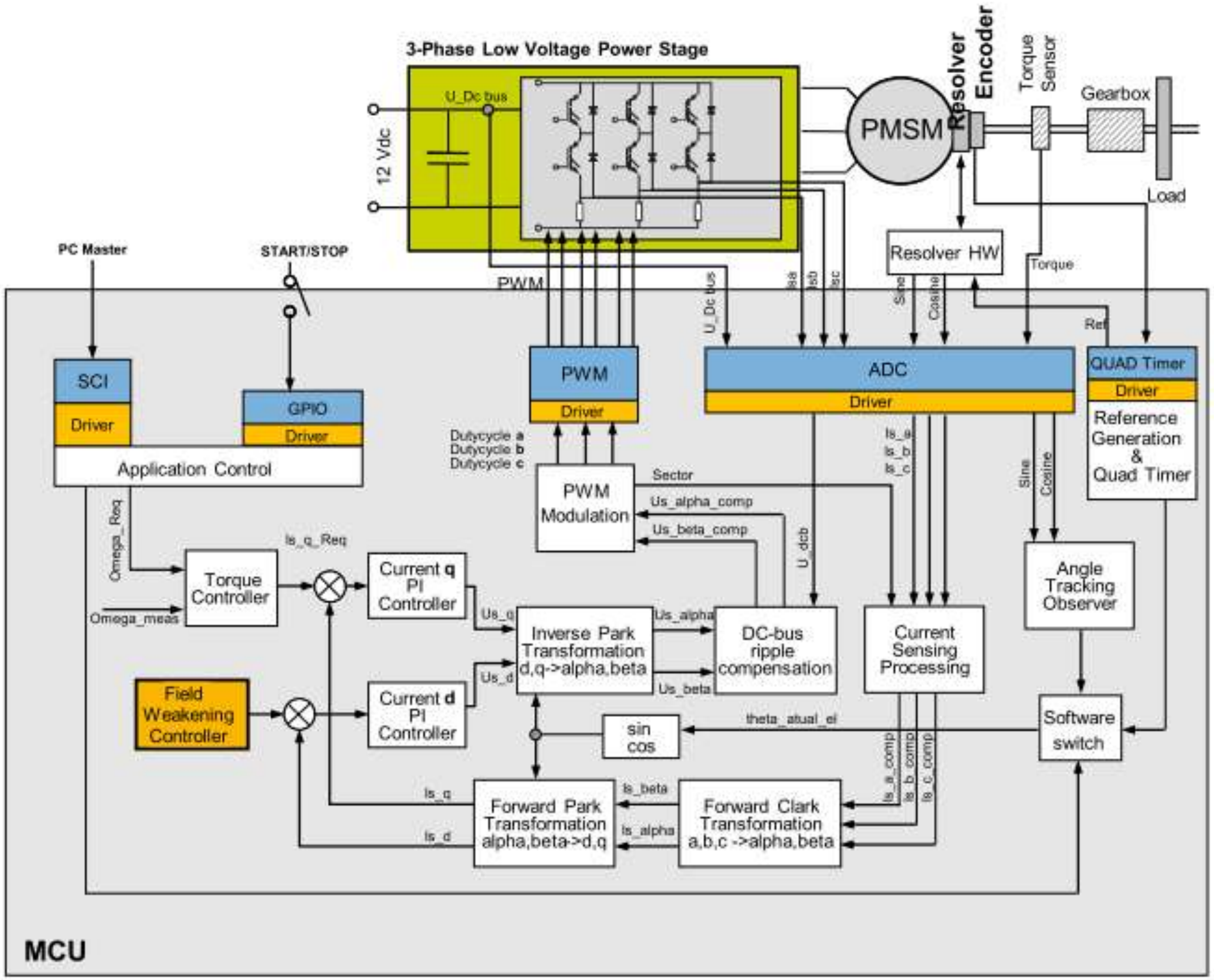
Field Weakening - Why Is It Needed?

- Required to get above motor base speed, where voltage capacity to overcome the back-EMF starts to be limited
- Makes the rotor magnetic field "weaker" in order to lower back-EMF voltage induced in the stator winding
- For PM motors FW means to apply opposite magnetic field to the permanent magnets (since PM rotates this FW field has to rotate as well).
  Note: the FW changes the angle between the stator and the rotor magnetic fluxes (in d, q rotor related coordinates)



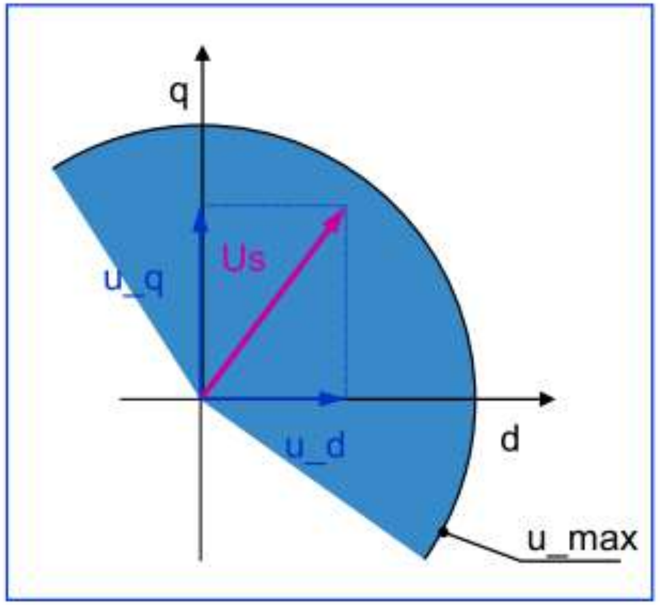


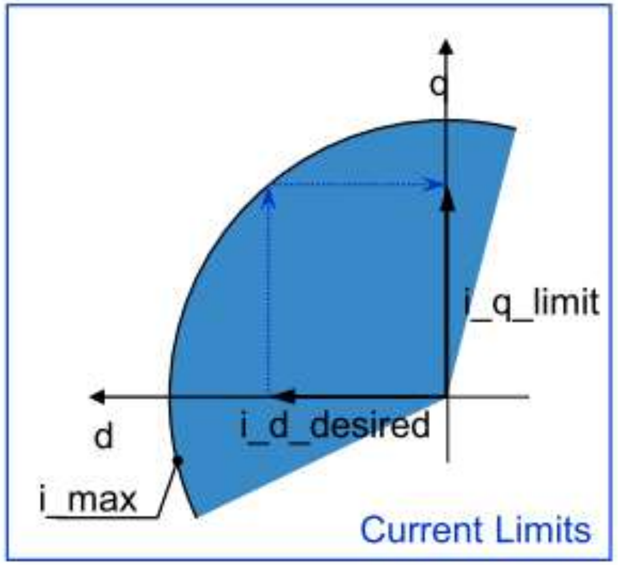
Field Weakening - Block



Field Weakening – Natural Limitations of the Control

- Available voltage amplitude is limited by used type of power stage.
- Phase current amplitude is limited by capabilities of power devices and motor thermal design.
- Field weakening may demagnetize PM





Field Weakening - Possible Approaches

- Look-up Field Weakening Table
- Field Weakening Control 1 – based on FOC voltage amplitude limit
- Field Weakening Controller 2 – based on FOC regulation errors
  Freescale patent pending (PCT/IB2008/051933)

FIELD WEAKENING

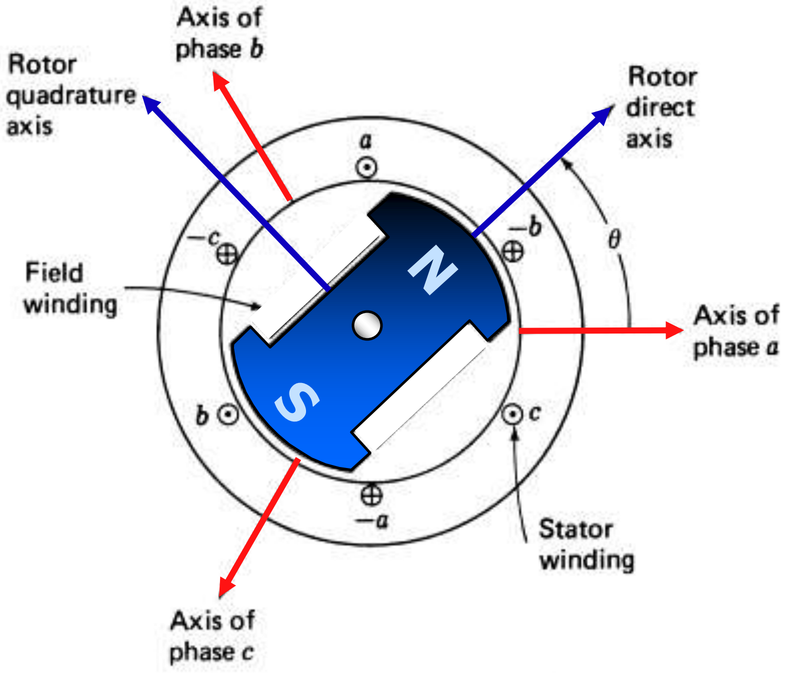
ANY QUESTIONS?

MTPA – PMSM Motor Torque

- Reaction Torque
  - torque generated by mutual interaction between stator and rotor fluxes
- Reluctance Torque
  - arises due to rotor saliency ($X_d \neq X_q$), where the rotor tends to align with the position of minimal reluctance.

The component of current that is "quadrature" to the rotor flux (I_{qs}) is what we need to regulate to control torque.

$$Torque=\frac{3}{2}\frac{P}{2}\left[\overbrace{\psi_{PM}\, i_q}^{\textbf{Reaction Torque}}+\overbrace{\left(L_d-L_q\right) i_d i_q}^{\textbf{Reluctance Torque}}\right]$$



Idealized synchronous machine.

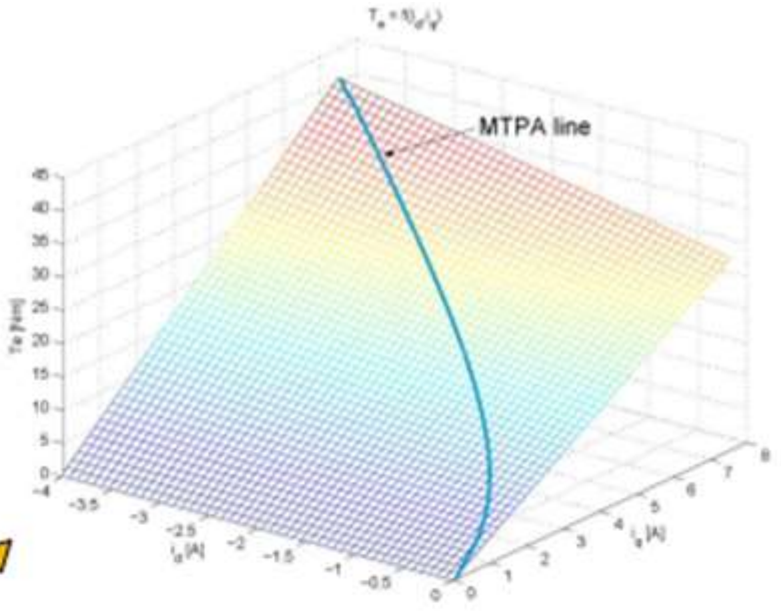
MTPA - What is Maximum Torque Per Ampere Control?

- Control of IPMSM based on adjusting flux producing current i_D such as to utilize reluctance torque
- Flux is regulated in such a way that resulting current vector amplitude, required to develop demanded torque, is as small as possible
- The amount of flux regulation under MTPA control is somehow proportional to the demanded torque (not rotor speed)
- Flux regulation under MTPA control can occur as long as resulting current and voltage vectors reside within drive operating areas

MTPA - Equations

- Torque developed by IPMSM

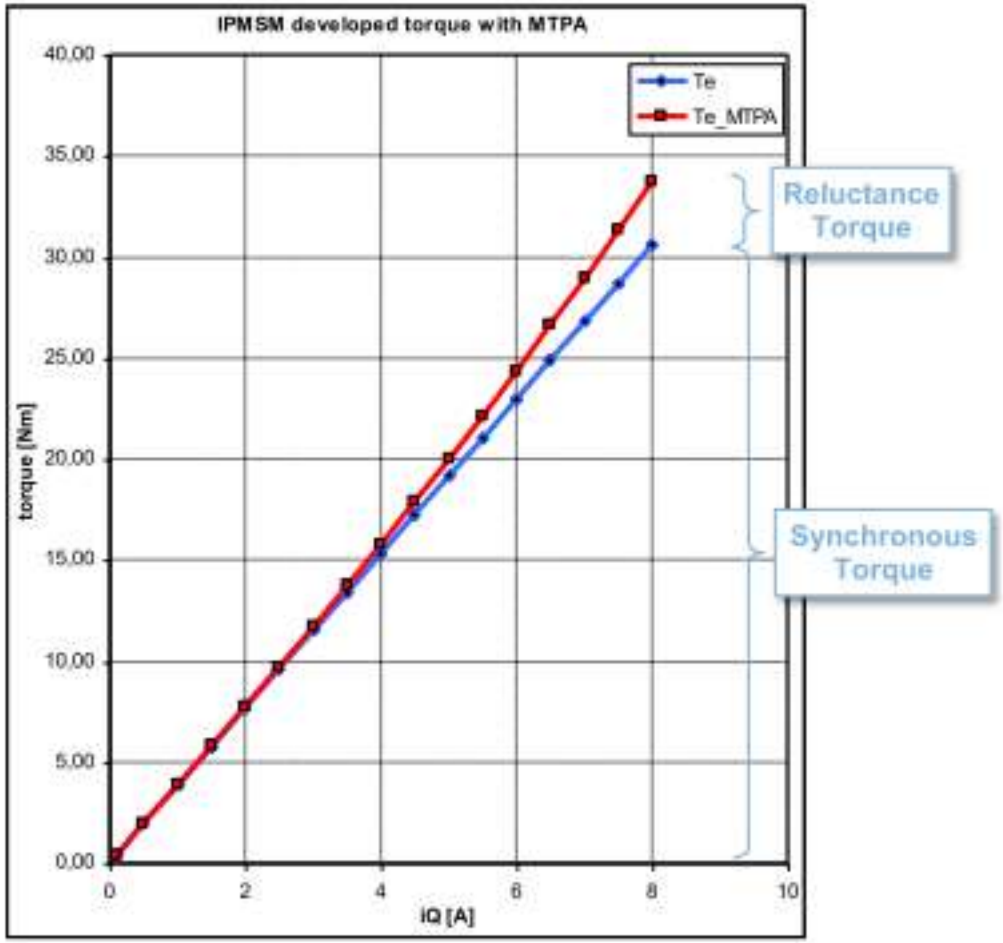
$$T_e = \frac{3}{2} pp \left(\underset{\text{synchronous}}{k_E * i_q} + \underbrace{(L_d - L_q) * i_d * i_q}_{\text{reluctance}} \right)$$



- Maximum Torque per Ampere (MTPA) characteristic is derived for given synchronous torque as:

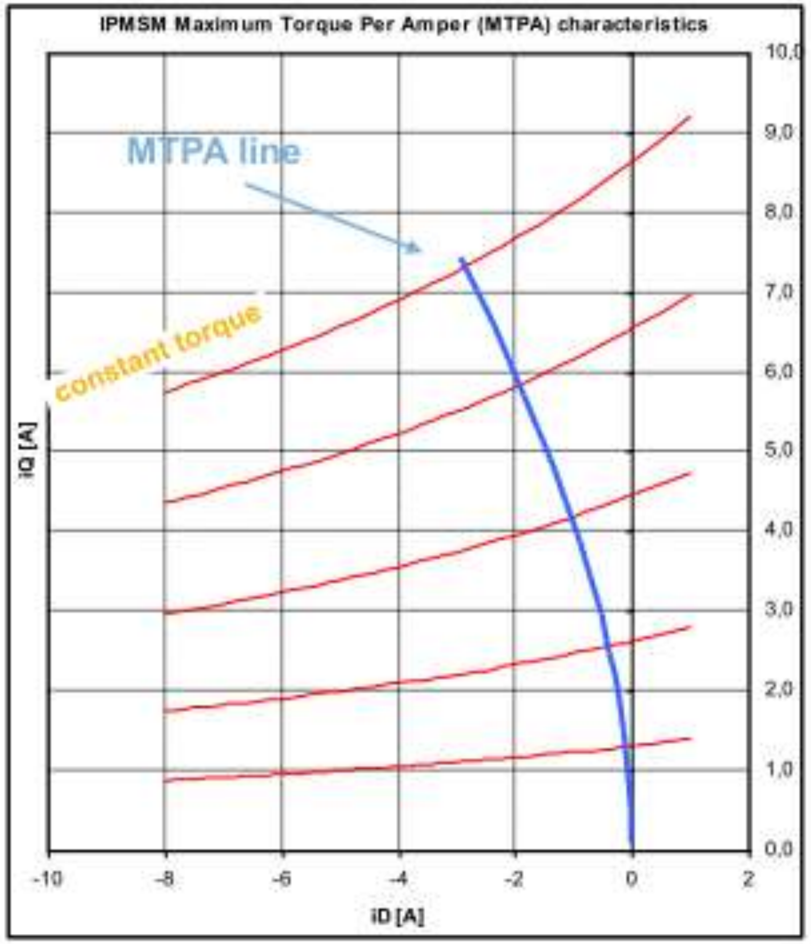
$$\frac{d}{di_d}\left(T_e = f(i_d)\right) = 0 \Rightarrow \boxed{i_d = -\frac{k_E}{2*(L_d - L_q)} - \sqrt{\left(\frac{k_E}{2*(L_d - L_q)}\right)^2 + i_q^2}}$$

MTPA - IPMSM MTPA Characteristics



Reluctance Torque

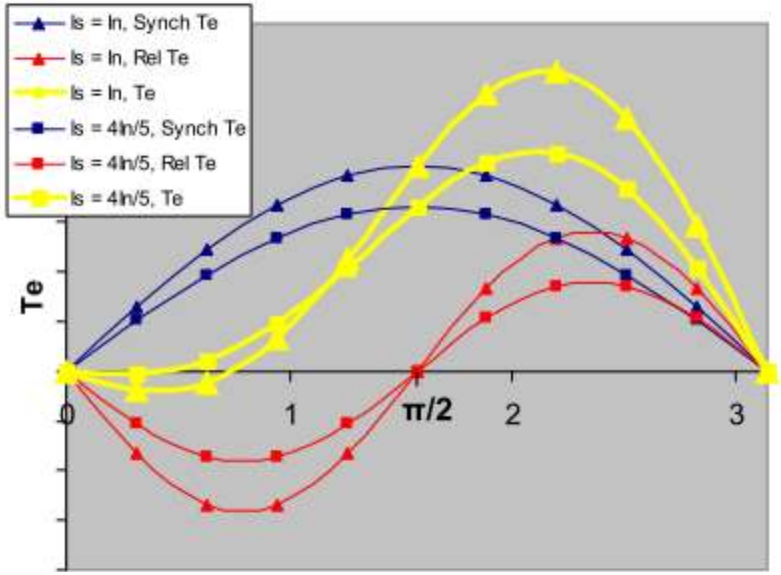
Synchronous Torque



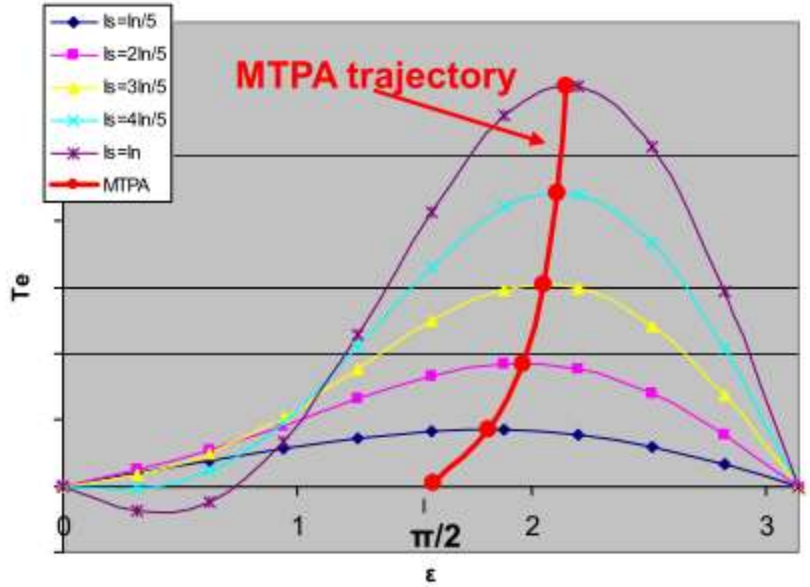
MTPA line

constant torque

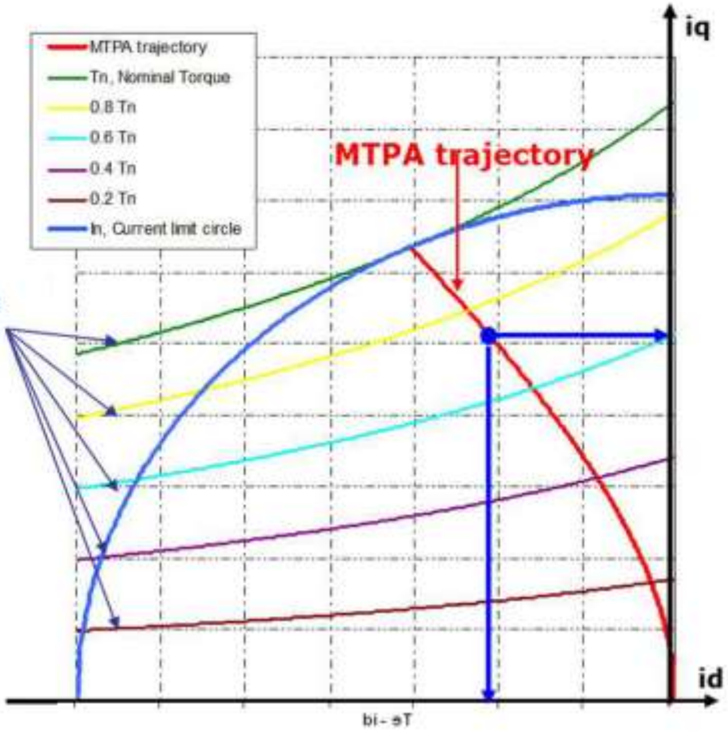
MTPA – Torque Chart



Synchronous torque
Reluctance torque
Total torque



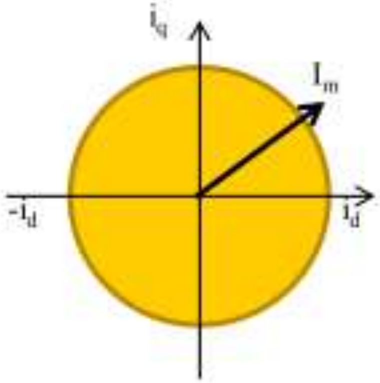
Const Torque Curves



MTPA – Natural Limitations

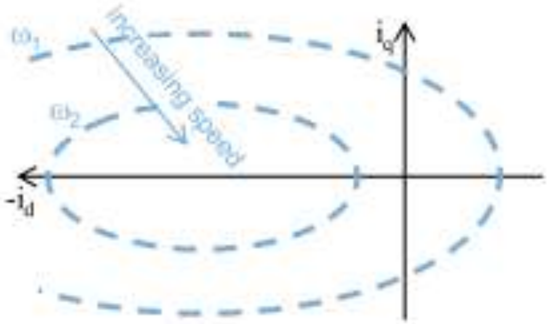
- Maximum current is limited to a circle with amplitude
  - Depends on motor current rating

$$\mathrm{I}_m = \sqrt{i_d{}^2 + i_q{}^2}$$



- Maximum Voltage ellipse constraint imposed on current vector amplitude and angle
  - Shrinks with increased speed

$$\frac{U_m^2}{\omega_e^2} = L_q^2 * i_q^2 + \left(k_\mathrm{E} + L_d * i_d\right)^2$$



- D-axis component of current vector is limited such as to avoid PM demagnetization
  - Depends on motor magnetic design and used PMs

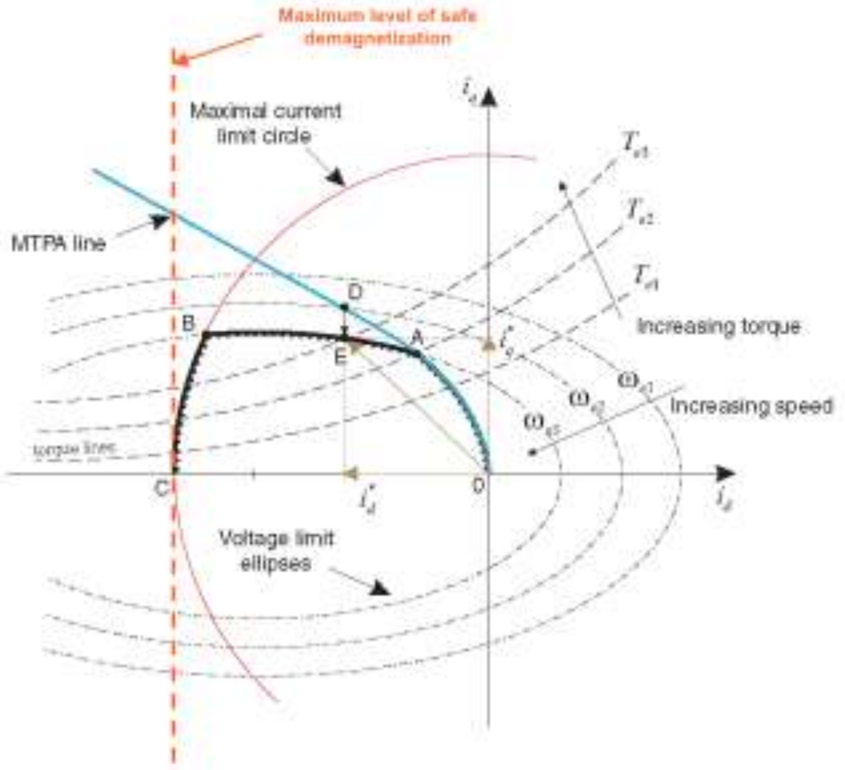
MTPA – Current Circle and Voltage Ellipse Limitations

- Current vector created by DQ-axis currents must lie within area surrounded by current limit circle, voltage limit ellipse and MTPA line.

- Voltage limit ellipse shrinks with increased rotor speed and constrains the MTPA

- Amplitude of current limit circle is constant throughout the motor operation and depends on motor parameters.

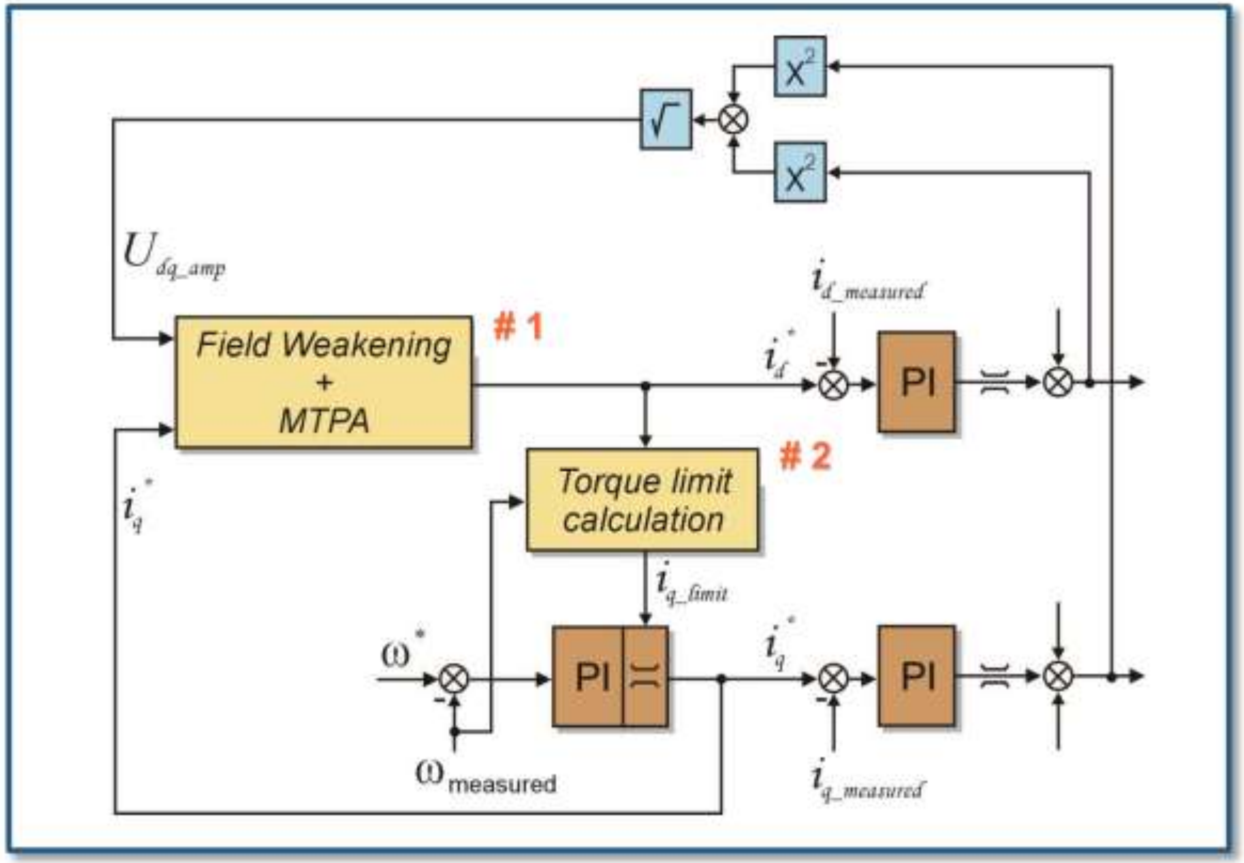
- Depending on parameters of permanent magnets, maximum level of safe demagnetization can not be exceeded



IPMSM operating area surrounded by current limit circle, voltage limit ellipse and MTPA line

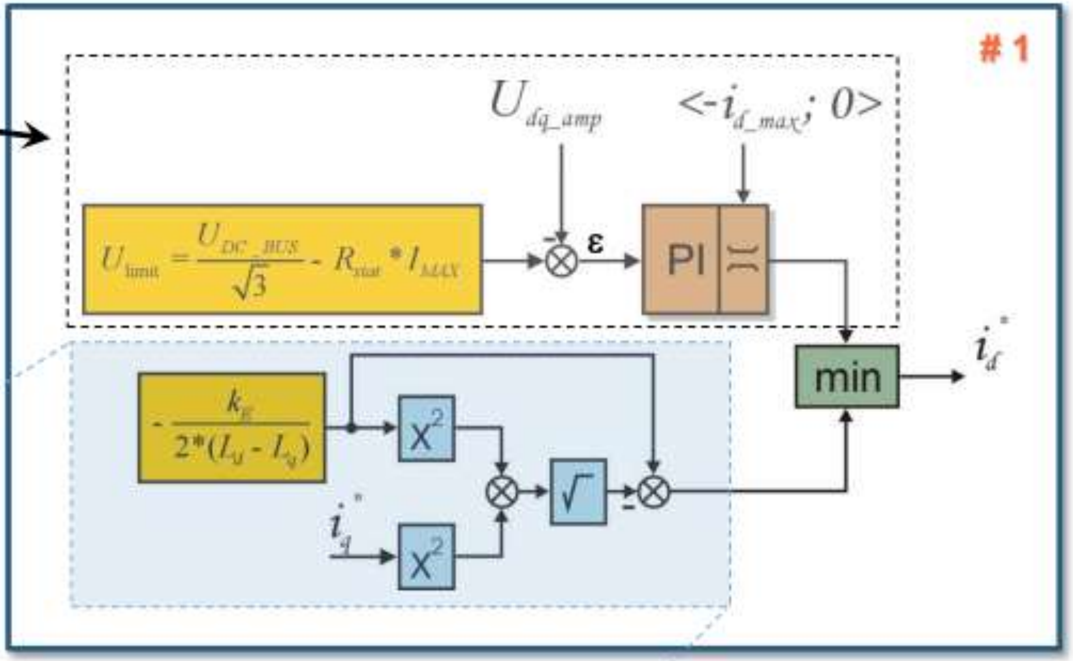
MTPA – Integration of FW-MTPA into FOC

- Field weakening + MTPA provided by close loop regulation of stator d-axis current component and limitation of applied torque



MTPA – Field Weakening Controller + MTPA

Field Weakening Controller



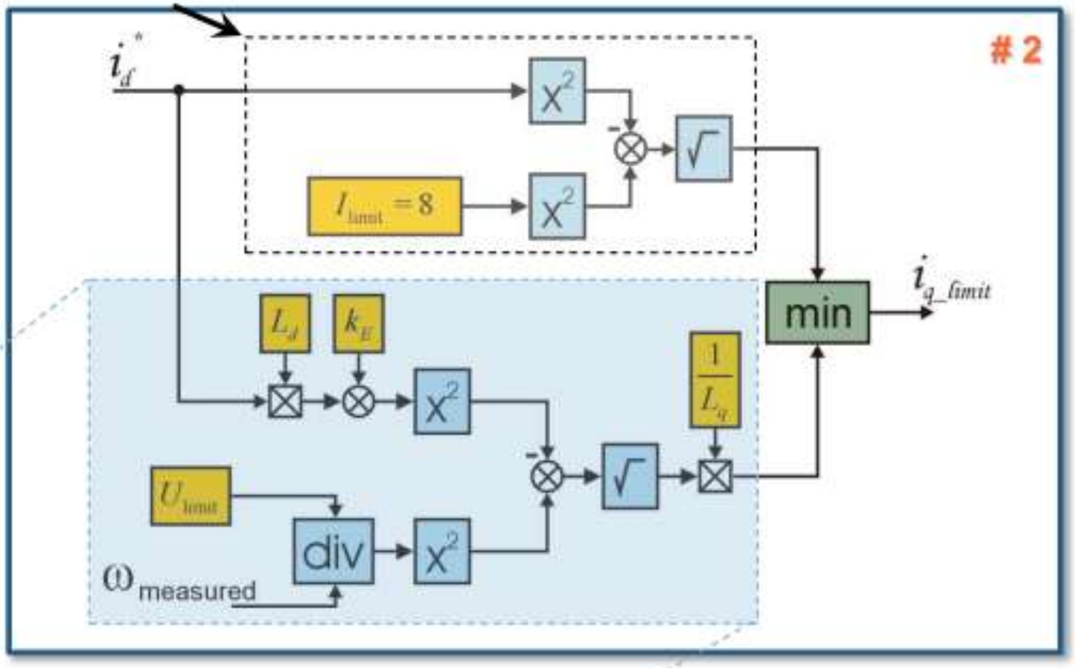
# 1
U_{dq_amp}
$<-i_{d\_max}; 0>$
$U_{limit} = \frac{U_{DC\_BUS}}{\sqrt{3}} - R_{stat} * I_{MAX}$
-
ε
PI
min
i_d^*
$-\frac{k_E}{2*(L_d - L_q)}$
x^2
x^2
$\sqrt{}$
i_q^*
-

Maximum Torque Per Ampere

$$i_d^* = -\frac{k_E}{2*\left(L_d - L_q\right)} - \sqrt{\left(\frac{k_E}{2*\left(L_d - L_q\right)}\right)^2 + i_q^{*2}}$$

MTPA – Torque Limitation

Torque limitation derived from maximum current circle constraint



$$i_{q\_\text{limit}} = \frac{1}{L_q}\sqrt{\left(\frac{U_\text{limit}}{\omega_\text{e}}\right)^2 - \left(k_E + L_d * i_d\right)^2}$$

Torque limitation derived from maximum voltage ellipse constraint

MTPA - Pros and Cons

Pros

- ✓ Minimizes electrical losses
- ✓ Optimizes drive and inverter efficiency
- ✓ Maximum developed torque of FOC with MTPA is greater than that of conventional FOC

Cons

- ➢ Motor parameters LdLq k E has to be identified
- ➢ Requires additional calculation (MULT + SQRT)

- Care must be taken to avoid irreversible demagnetization of permanent magnets.

MTPA

ANY QUESTIONS?

PMSM Control – FOC Summary

- FOC is become more and more popular recent years
- Rotor position is the key for FOC, including resolver and sensor-less method
- Some advanced algorithm are required by customers, Field Weakening, MTPA, IPD, FF, HFI and etc
- NXP has the complete software and Hardware enablement with ready to use

PMSM CONTROL - FOC

ANY QUESTIONS?

NXP

SECURE CONNECTIONS
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