NXP | FTF 2016 TECHNOLOGY FORUM

S12 MAGNIV: HIGH-SPEED PERMANENT MAGNET MOTOR CONTROL WITH S12ZVM MCU

FTF-AUT-N1806

MAREK STULRAJTER
SYSTEM APPLICATION ENGINEER
FTF-AUT-N1806
MAY 18, 2016

PUBLIC USE

WHAT YOU WILL LEARN?

- What PM motor and How they are used in automotive domain?
- What are the conventional PM motor control approaches?
- Where are the limits of standard control techniques?
- When and How to use advanced/modified control techniques?

PERMANENT MAGNET MOTORS IN AUTOMOTIVE

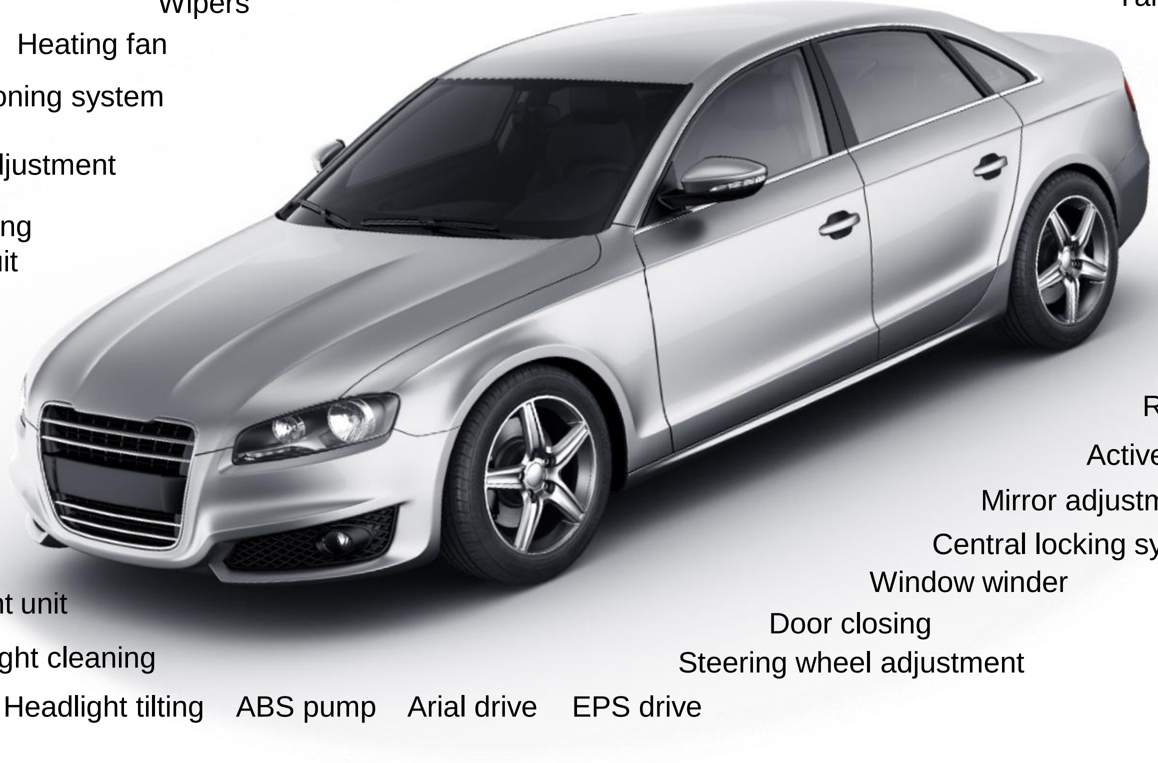
Electric Motor Applications in Automotive

DC motor applications

Stepper motor applications

BLDC motor applications

PMSM motor applications



Convertible/Sliding roofs

Circular pump for stationary heating system

Motor for stationary heating system

Idle position adjustment system

Cooling fan for air conditioning system

Wipers

Tailgate closing

Heating fan

Rear windscreen wiper

Heating and air conditioning system

Fuel pump

Ergonomic backrest, headrest adjustment

Belt system

Circular pump for heating
and cooling water circuit

Seat control

Headrest adjustment

Engine cooling fan

Backrest adjustment

Starter

Rear seat adjustment

Alternator, generator

Active suspension

Scavenging pump,
high-pressure pump

Mirror adjustment

Central locking system

Window winder

Headlight range adjustment unit

Door closing

Headlight cleaning

Steering wheel adjustment

Headlight tilting

ABS pump

Arial drive

EPS drive

Electric Motor Applications in Automotive

Our Main Focus Today!

DC motor applications

Stepper motor applications

BLDC motor applications

PMSM motor applications

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Door closing

Headlight cleaning

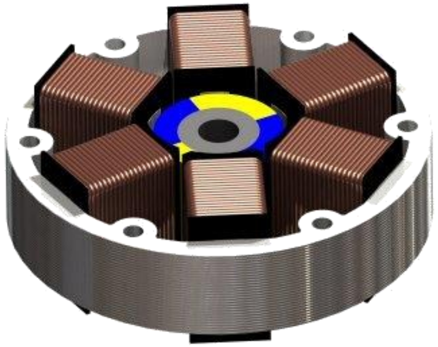
Steering wheel adjustment

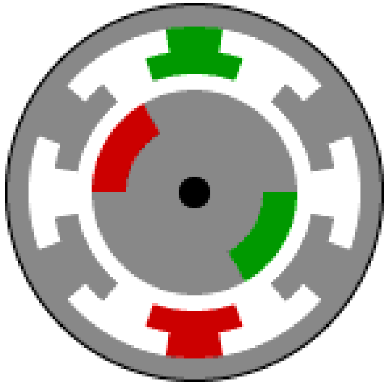
Headlight tilting ABS pump Arial drive EPS drive

PMSM VS BLDC

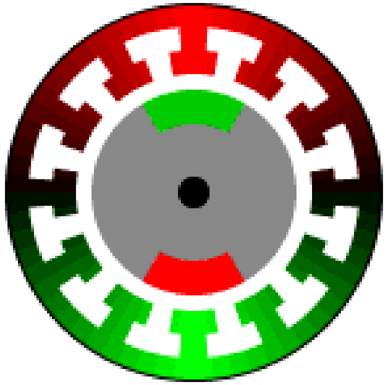
Basic PM Motor Features and Comparison

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**

Magnetic Field Distribution in PM Motors

The characteristic “Trapezoidal” or “Sinusoidal” is linked with the shape of Back EMF of PM motor.

Magnetic Flux Density

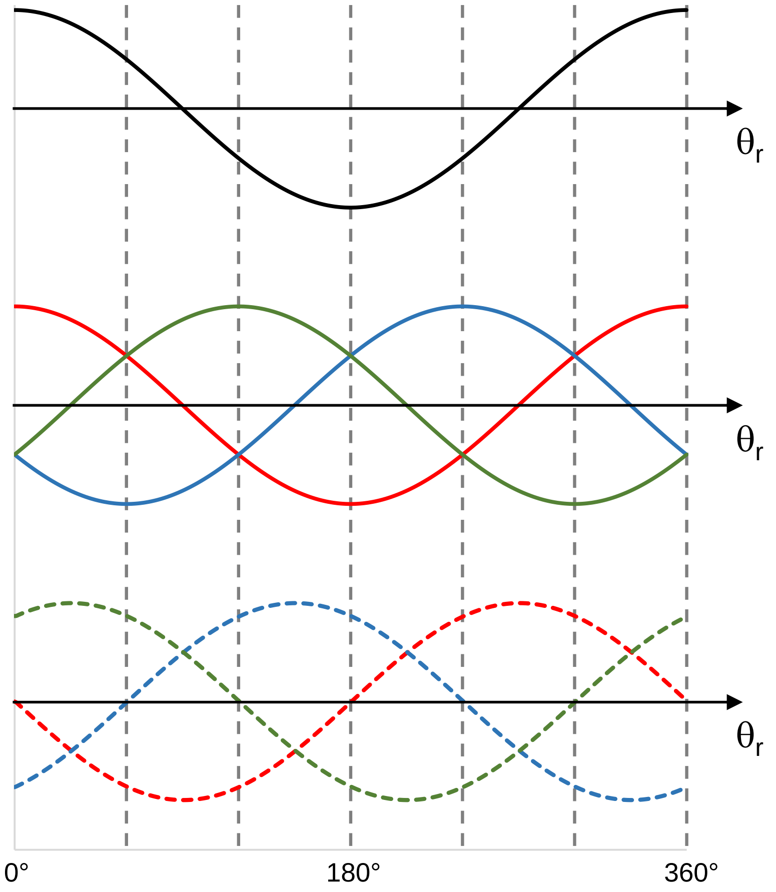
Shape of the flux density depends on the magnetization of the PM (radial, parallel) and their displacement

Magnetic Flux Linkage

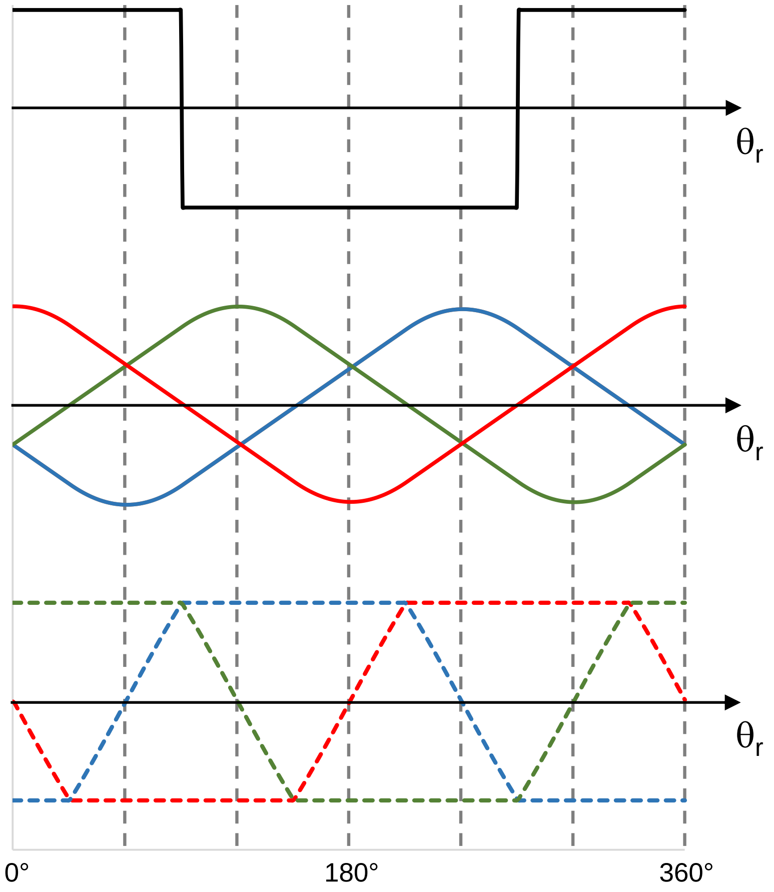
Phase Back EMFs

Back EMF depends on the shape of the linkage flux.

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



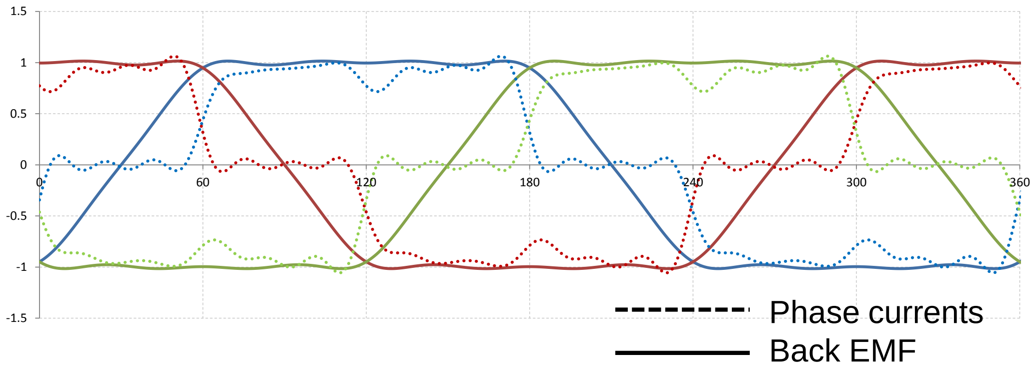
Trapezoidal means brushless DC motors



Torque Ripple of PM Motors

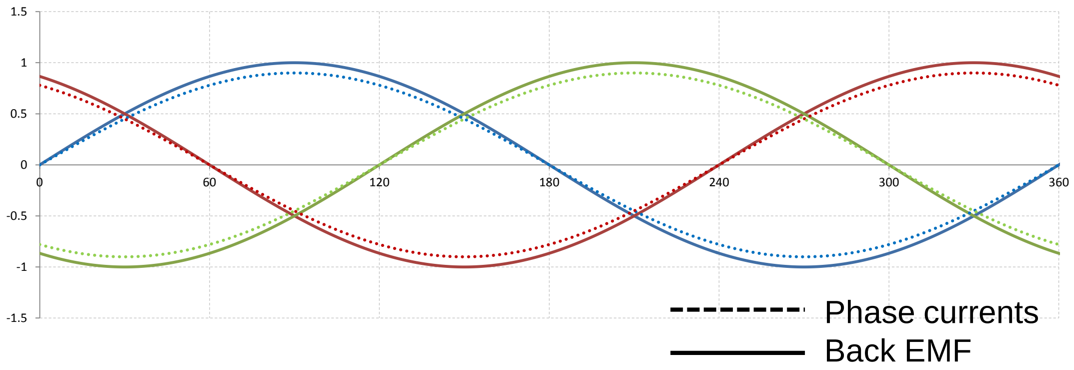
Brushless D.C. Motor

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

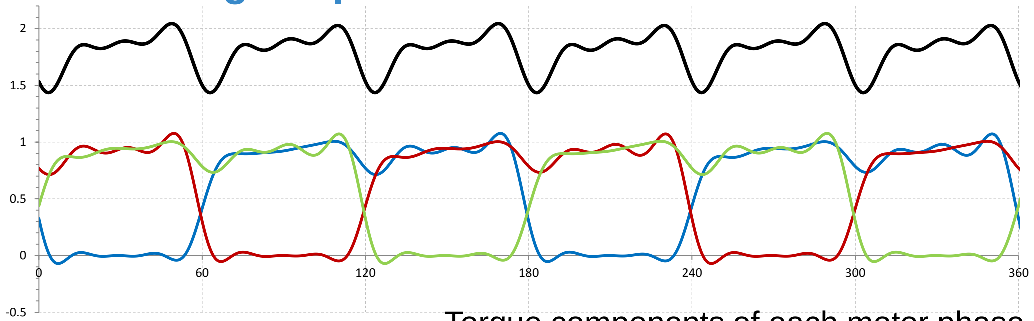


Permanent magnet synchronous motor

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

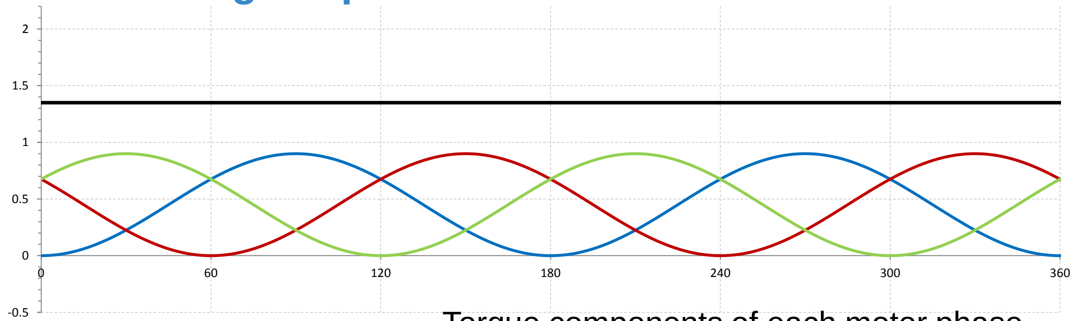


Resulting torque



Torque components of each motor phase

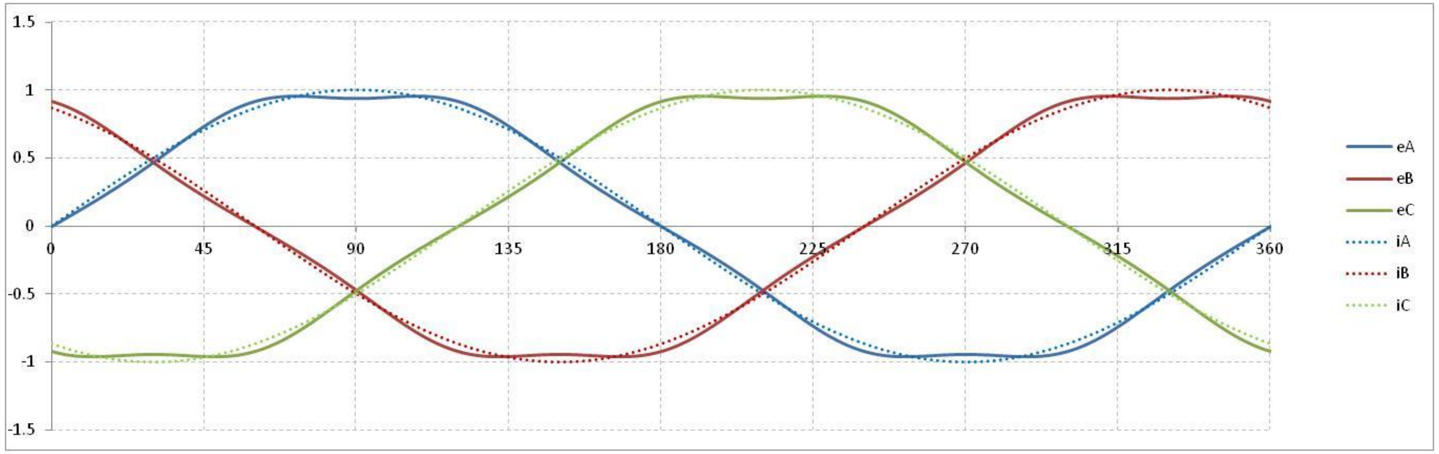
Resulting torque



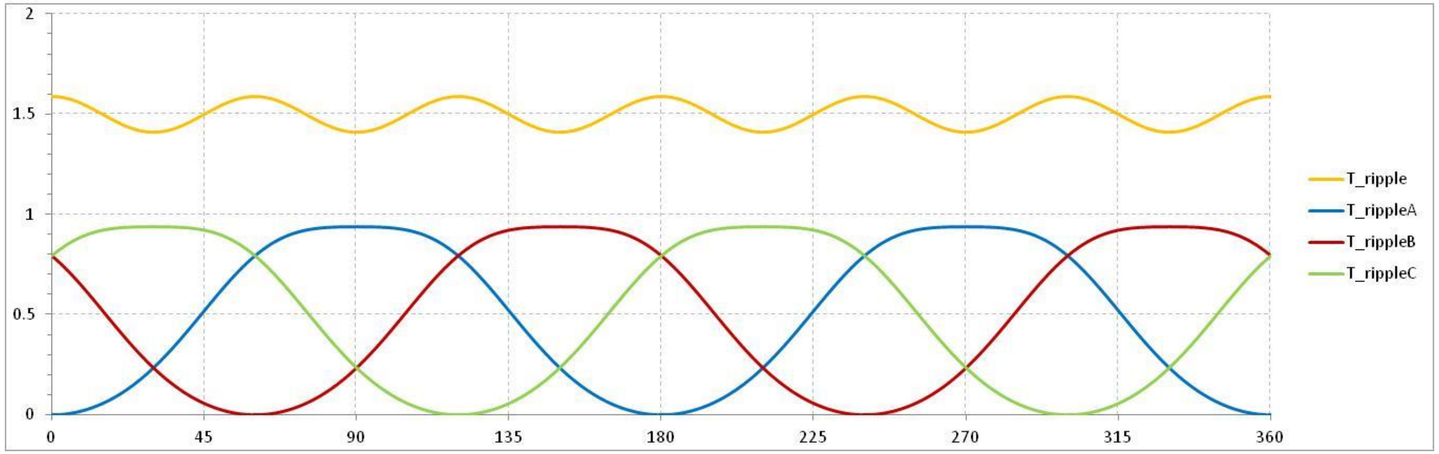
Torque components of each motor phase

Torque Ripple of PM Synchronous Motor

- Phase back-EMF with 5th and 7th harmonics (close to the real PMSM)
- Sinusoidal phase currents



Back EMF
Phase currents

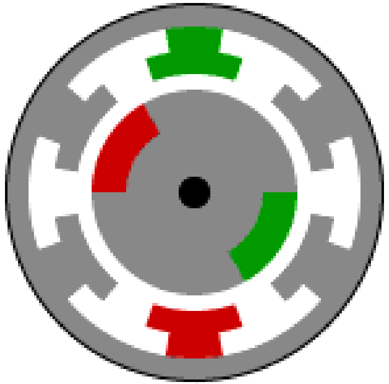


Resulting torque

Torque components of each motor phase

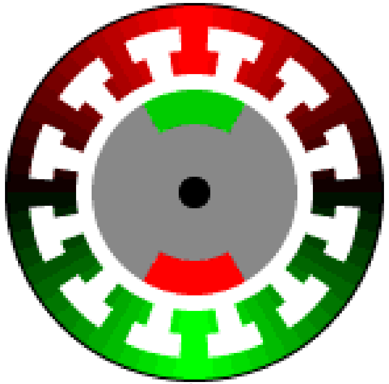
PM Motors in Automotive

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

PM Motors in Automotive - Example

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

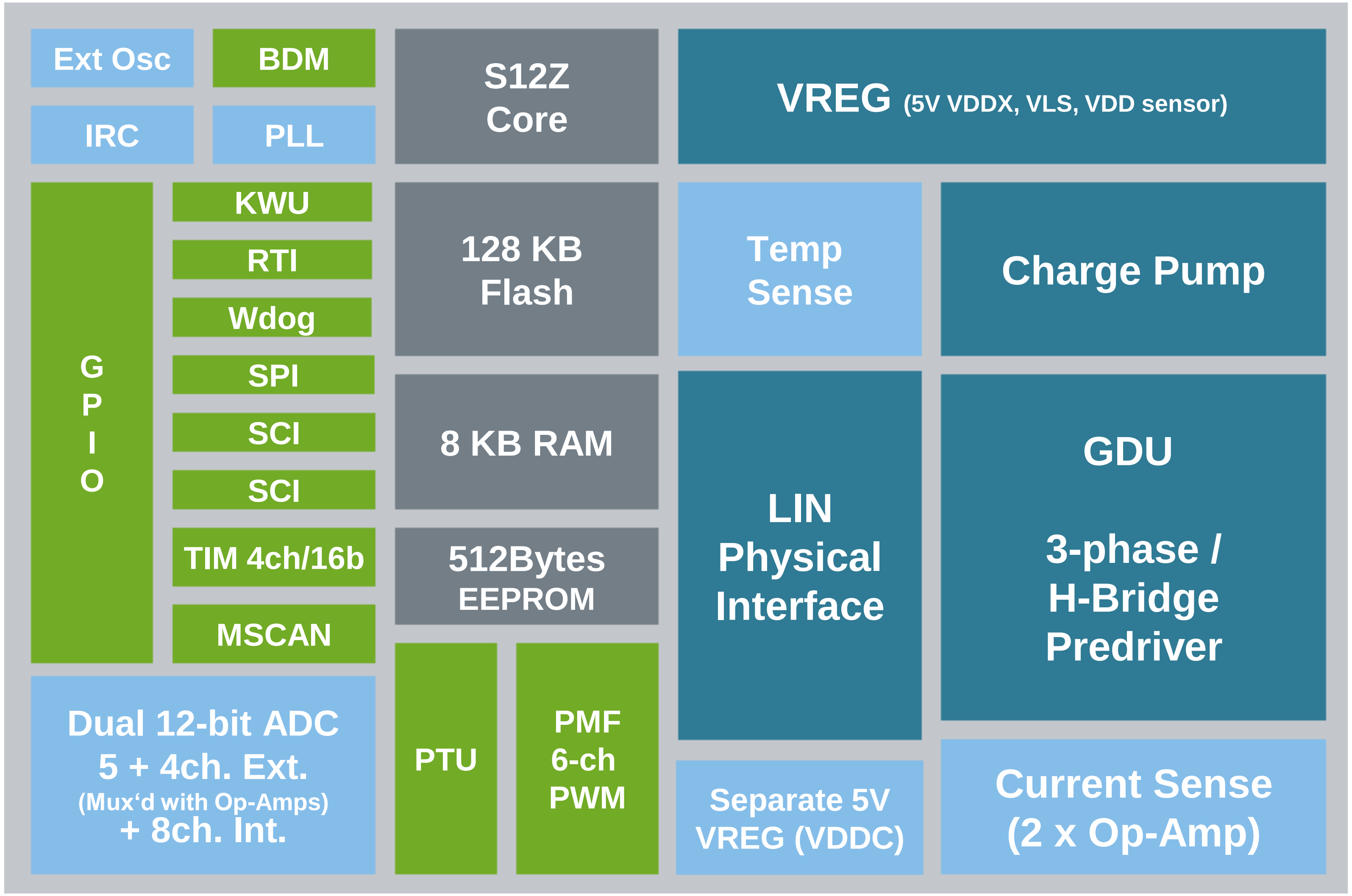
Power steering with PMSM

Application requirements:

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

S12ZVM
MOTOR CONTROL
SPECIFIC HIGHLIGHTS

Overview of S12ZVM Feature Set



Ext Osc

BDM

IRC

PLL

S12Z Core

VREG (5V VDDX, VLS, VDD sensor)

GPIO

KWU

RTI

Wdog

SPI

SCI

SCI

TIM 4ch/16b

MSCAN

128 KB Flash

8 KB RAM

512Bytes EEPROM

Temp Sense

Charge Pump

LIN Physical Interface

GDU

3-phase / H-Bridge Predriver

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

PTU

PMF 6-ch PWM

Separate 5V VREG (VDDC)

Current Sense (2 x Op-Amp)

Overview of S12ZVM Feature Set

Internal RC osc.
- +/-1.3% over tmp

Window Watchdog
- independent RC osc

Sensor Supply
- 20mA I/O for sensor

2 UARTs
- ne linked to LIN Phy
- 2nd as test interface

Multiple timers
- IOC/periodic wakeup

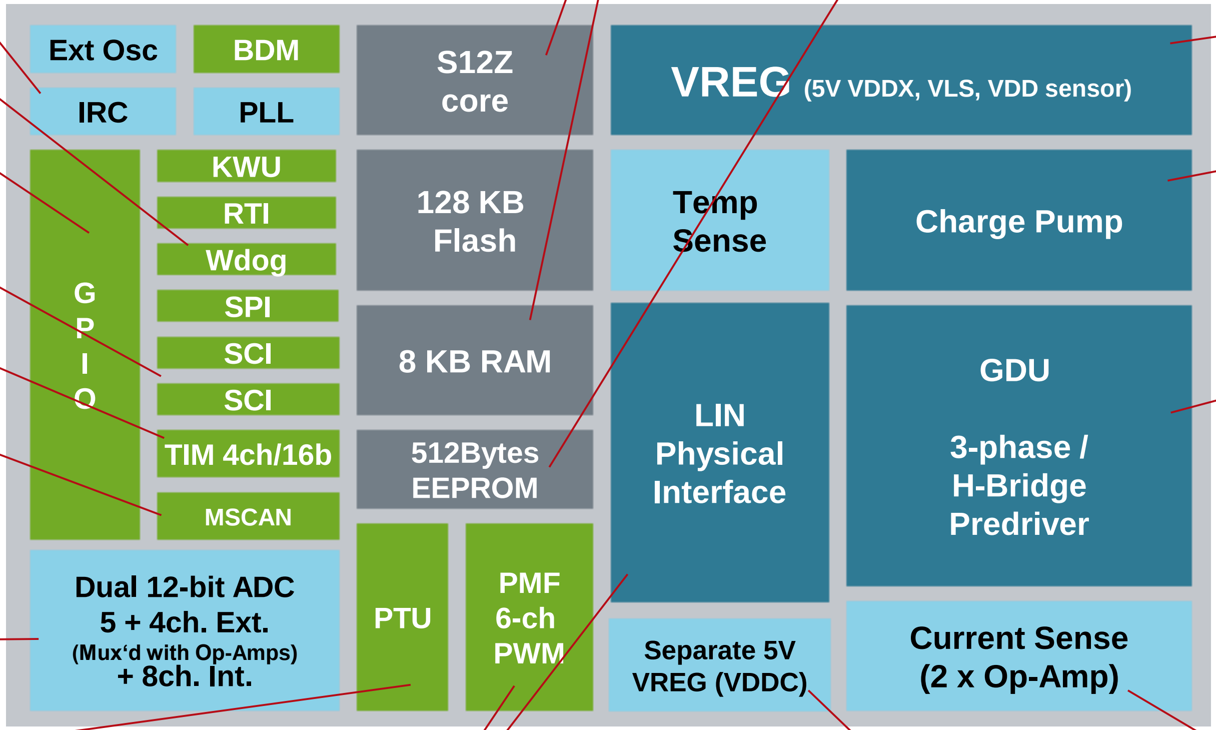
CAN Option
- CAN controller

Two 12bit ADC
- List Based Architecture allows flexible definition of order and number of conversions
- 2.5µs conv. time

New S12Z CPU
- Up to 100MHz
- 32-bit ALU & 32-bit MAC unit,
- Optimized 32-bit math. operations

Safe RAM
ECC

Flash& EEPROM
- ECC
- Memory Protection
- Margin Read



Voltage Regulator
- Boost Option
- Support for external ballast transistor
- Vbat sense

Charge Pump
- Optional to support 100% duty cycle

Gate Drive Unit
- Operational from 3.5V to 26V
- Bootstrap circuit based
- 11V Vreg
- Phase comparators
- Desaturation comp. for HS/LS protection
- Under-/Over-voltage detection
- DC-link and phase voltage internally accessible on ADC
- Selectable HS/LS slew rate

Programmable Trigger Unit
- Synchronize ADC to PWM
- Trigger Command list with up to 32 triggers per cycle

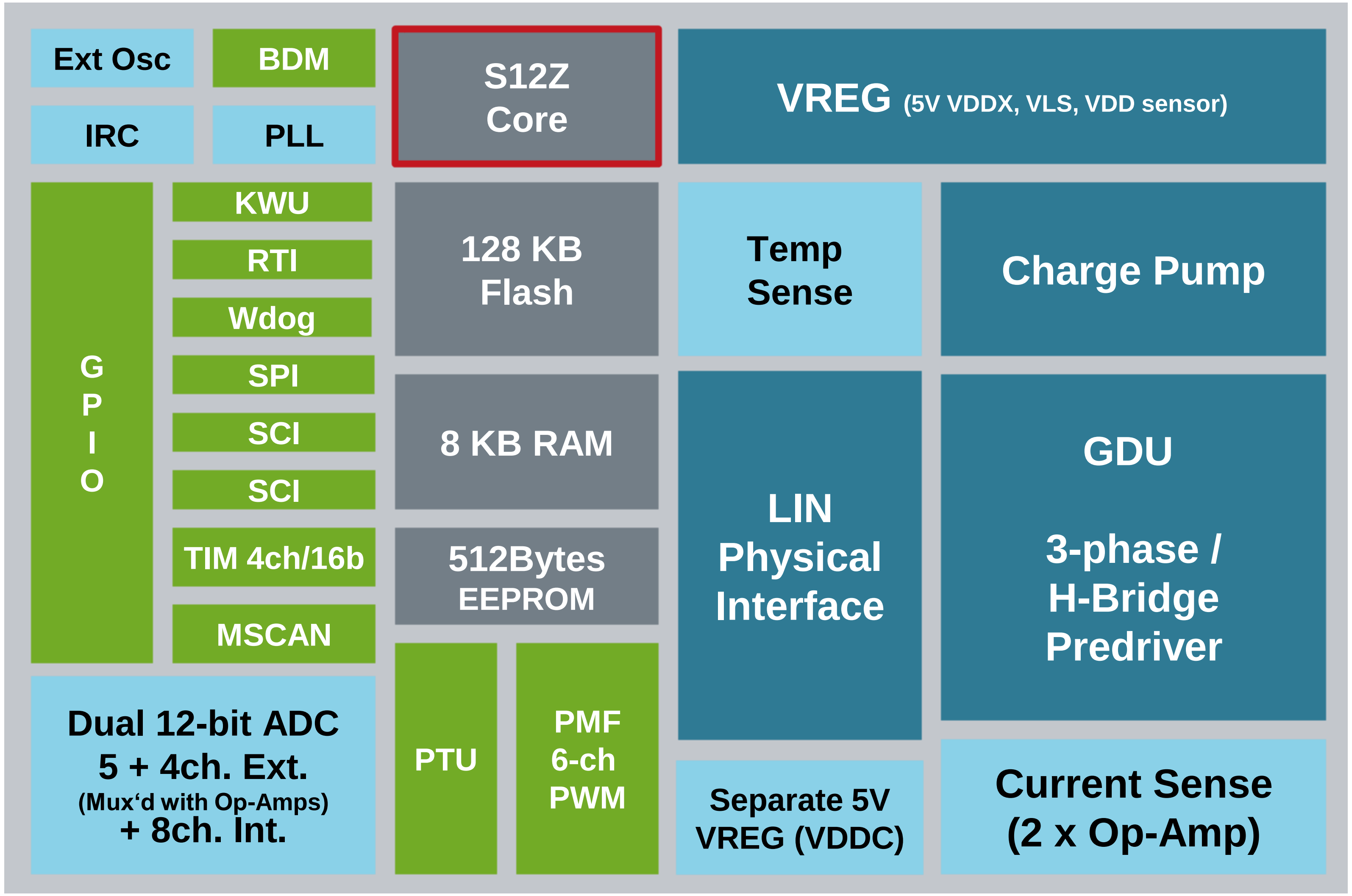
PWM Module
- Complementary mode with deadtime ctrl.
- Fault protection
- Double-Switching

LIN Physical Interface
- 250kb/s fast mode
- +/-6kV

CAN Support
- 5V Vreg controller for external transceiver

Current Sense Amplifiers
- 2-shunt system supported with additional selectable over-current protection comparator

S12Z Core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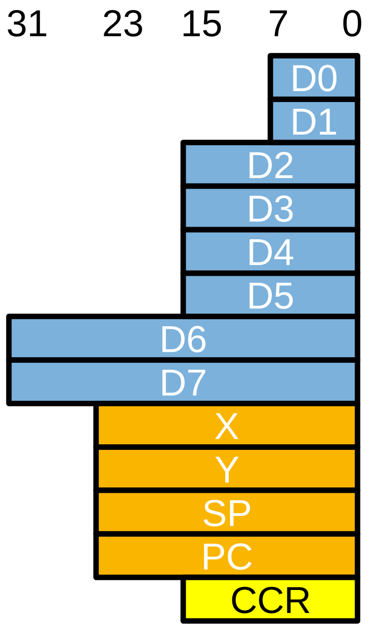
5 + 4ch. Ext.
(Mux'd with Op-Amps)
+ 8ch. Int.
PTU
PMF 6-ch PWM
Separate 5V VREG (VDDC)
Current Sense (2 x Op-Amp)

S12Z CPU Architecture… a 16-bit MCU?

- **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**

Programmer’s Model



31 23 15 7 0

D0

D1

D2

D3

D4

D5

D6

D7

X

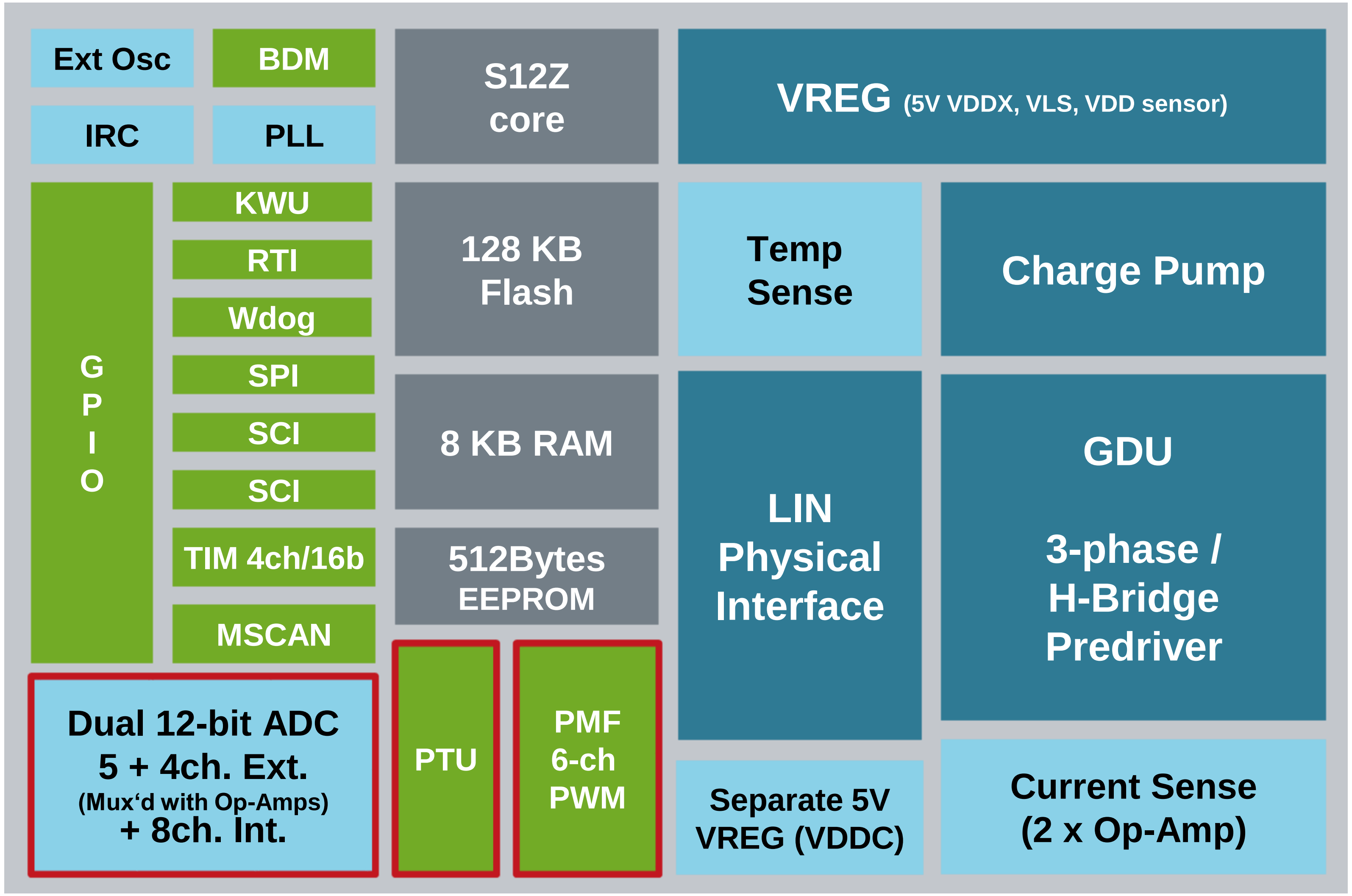
Y

SP

PC

CCR

Motor Control Loop Related Modules



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PTU

PMF 6-ch PWM

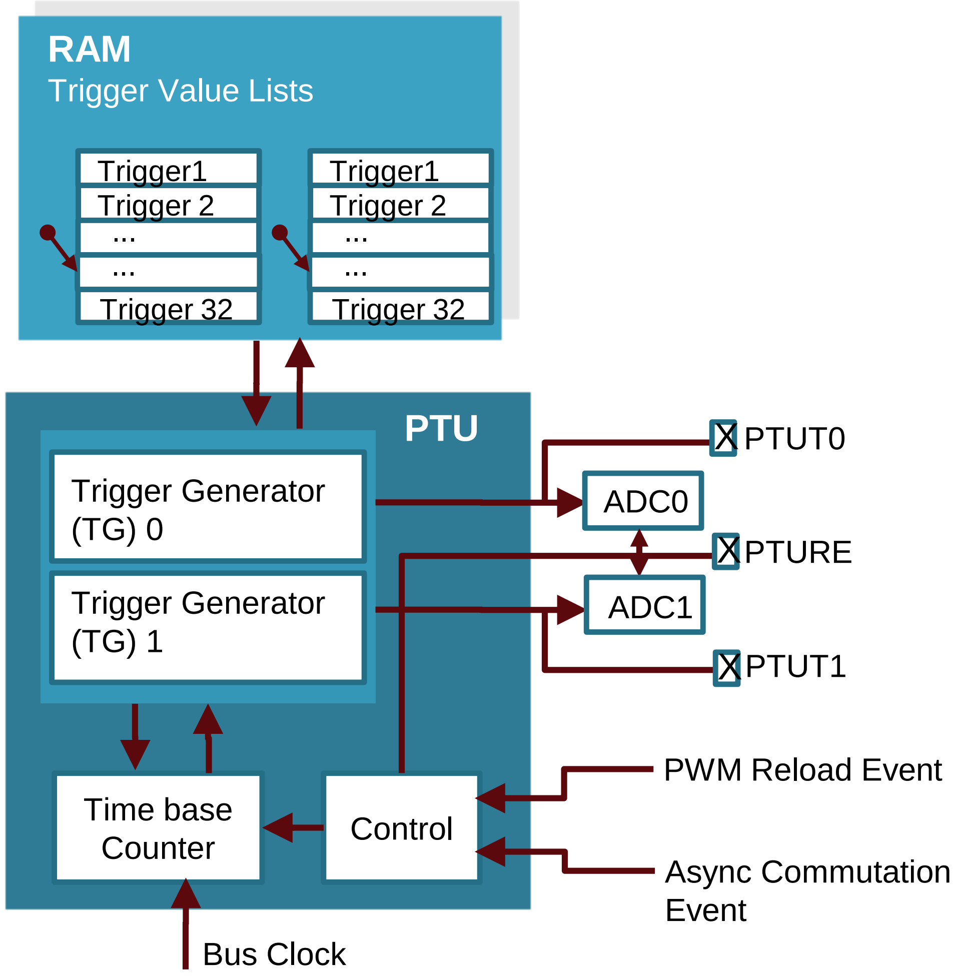
Separate 5V VREG (VDDC)

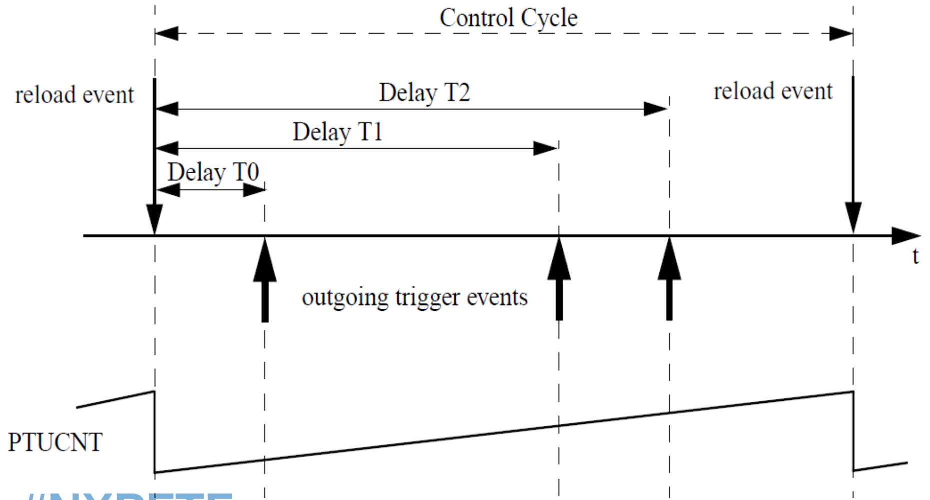
Current Sense (2 x Op-Amp)

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, 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



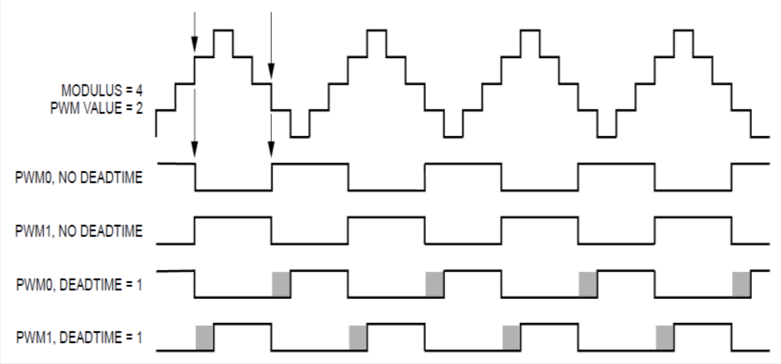


Pulse Width Modulator Module (PMF)

- **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**

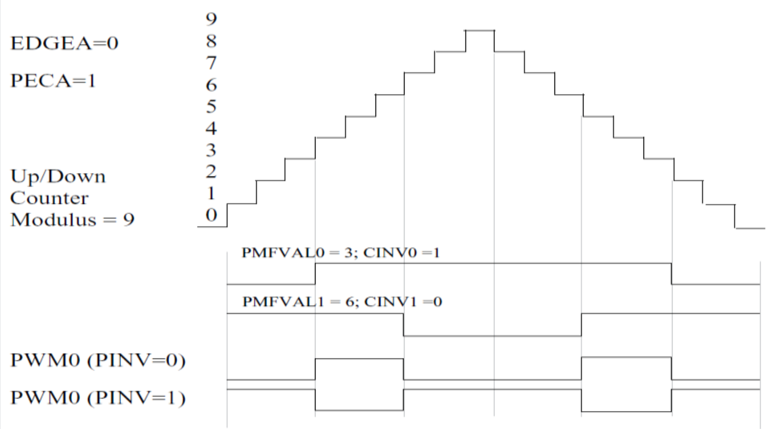
Complementary Mode

with / without dead time insertion



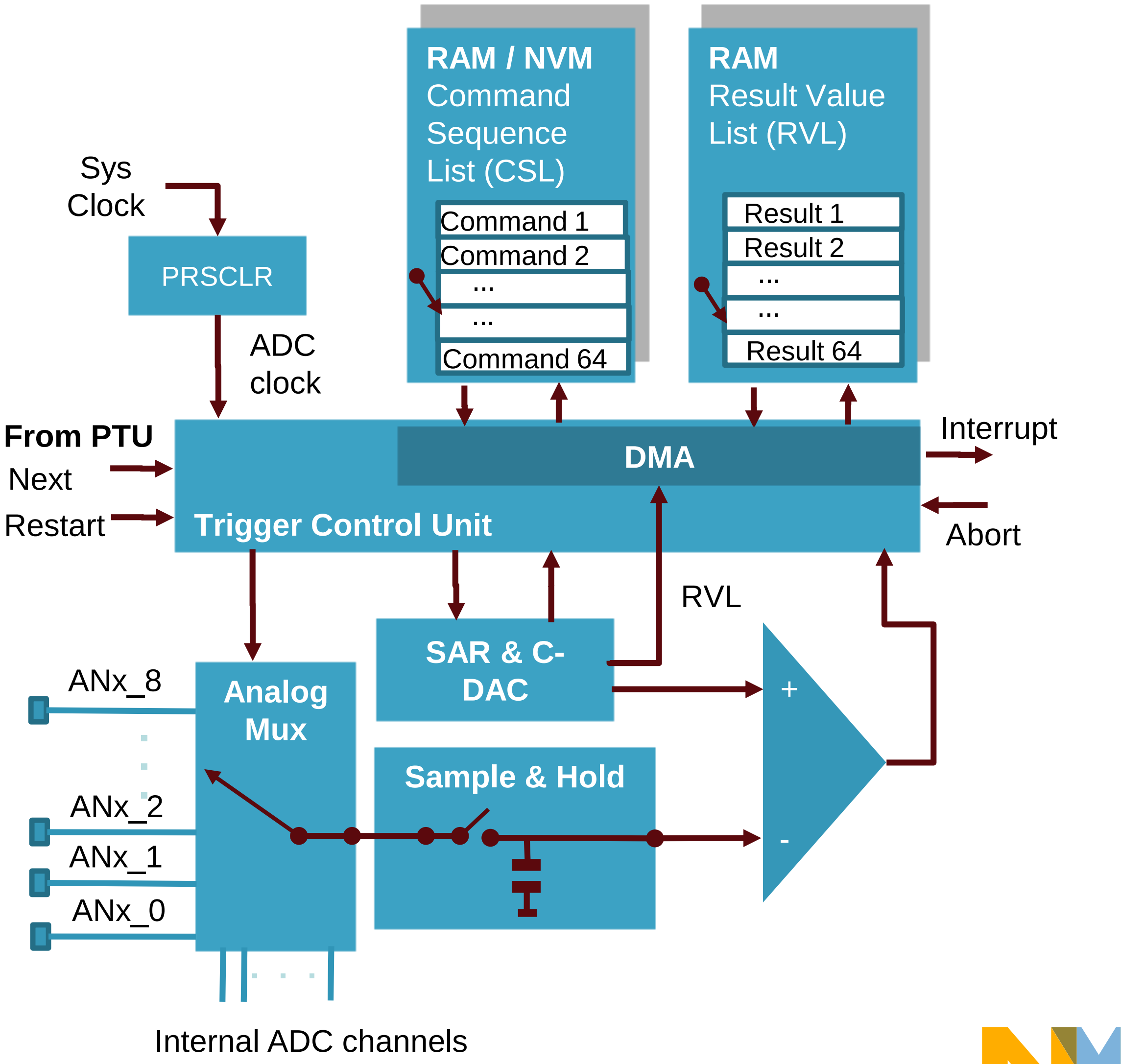
Double-Switching Mode

for single shunt system



12-bit SAR Analog-to-Digital (ADC)

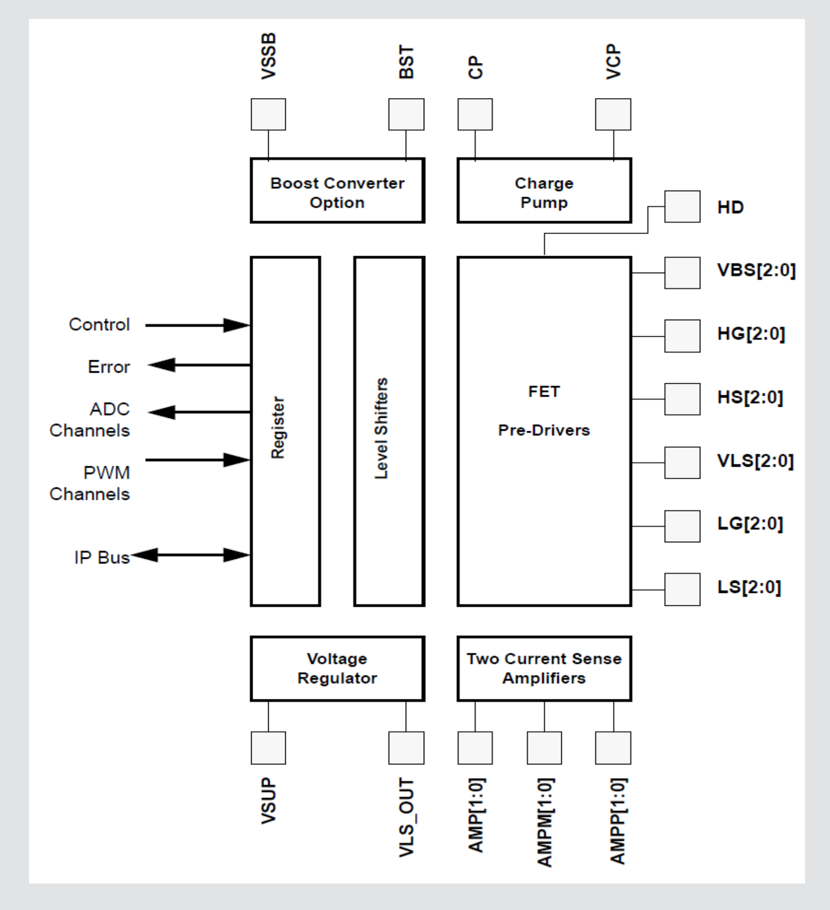
- **2 independent converters:**
  - ADC0 (5 ext ch. + 5 int. ch.)
  - ADC1 (4 ext ch. + 4 int. ch.)
- 2.5µsec conversion time
- **List Based Architecture**
  - Double buffered lists -> CPU can load new values in the background
  - Flexible conversion sequence definition and oversampling.
- Can be triggered by PTU, for accurate synch with PWM
- DMA taking commands from SRAM /NVM and storing results back into SRAM



Gate Driver Unit (GDU) – Overview

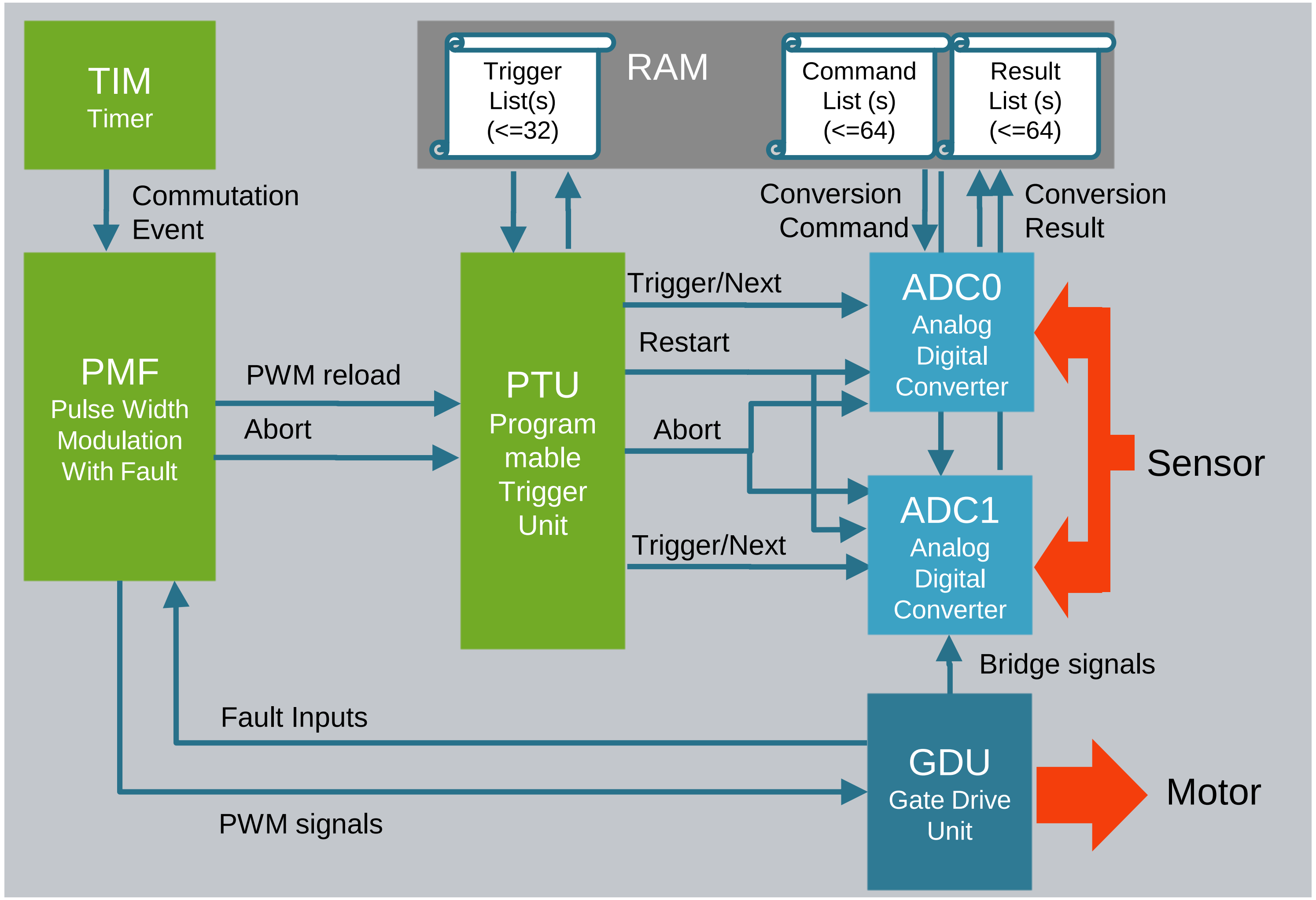
FET pre-driver for 6 N-ch power MOSFETs (3 high-side, 3 low-side)

- 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



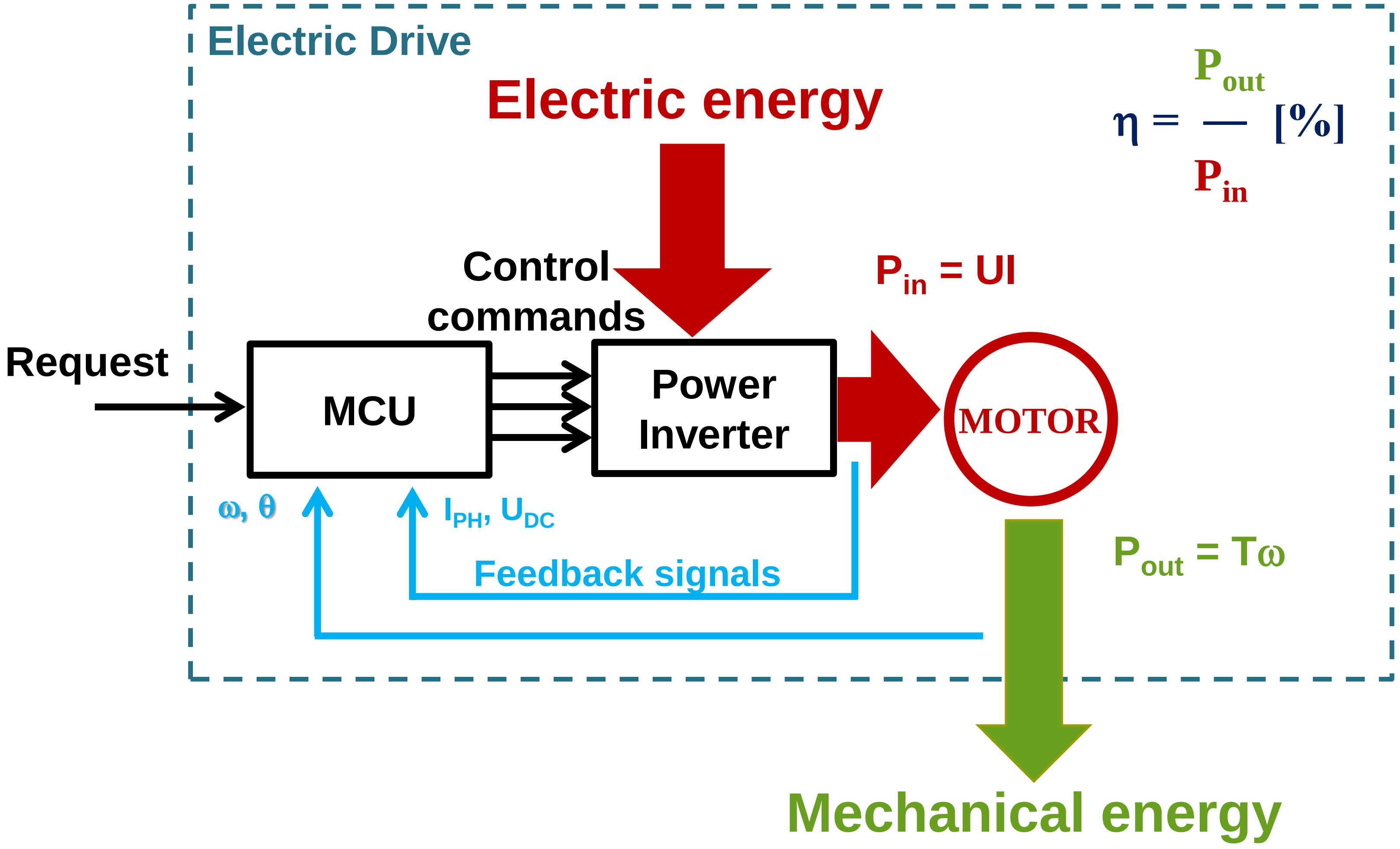
Motor Control Loop Implementation

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



MOTOR CONTROL TECHNIQUES

Electric Drive General Concept

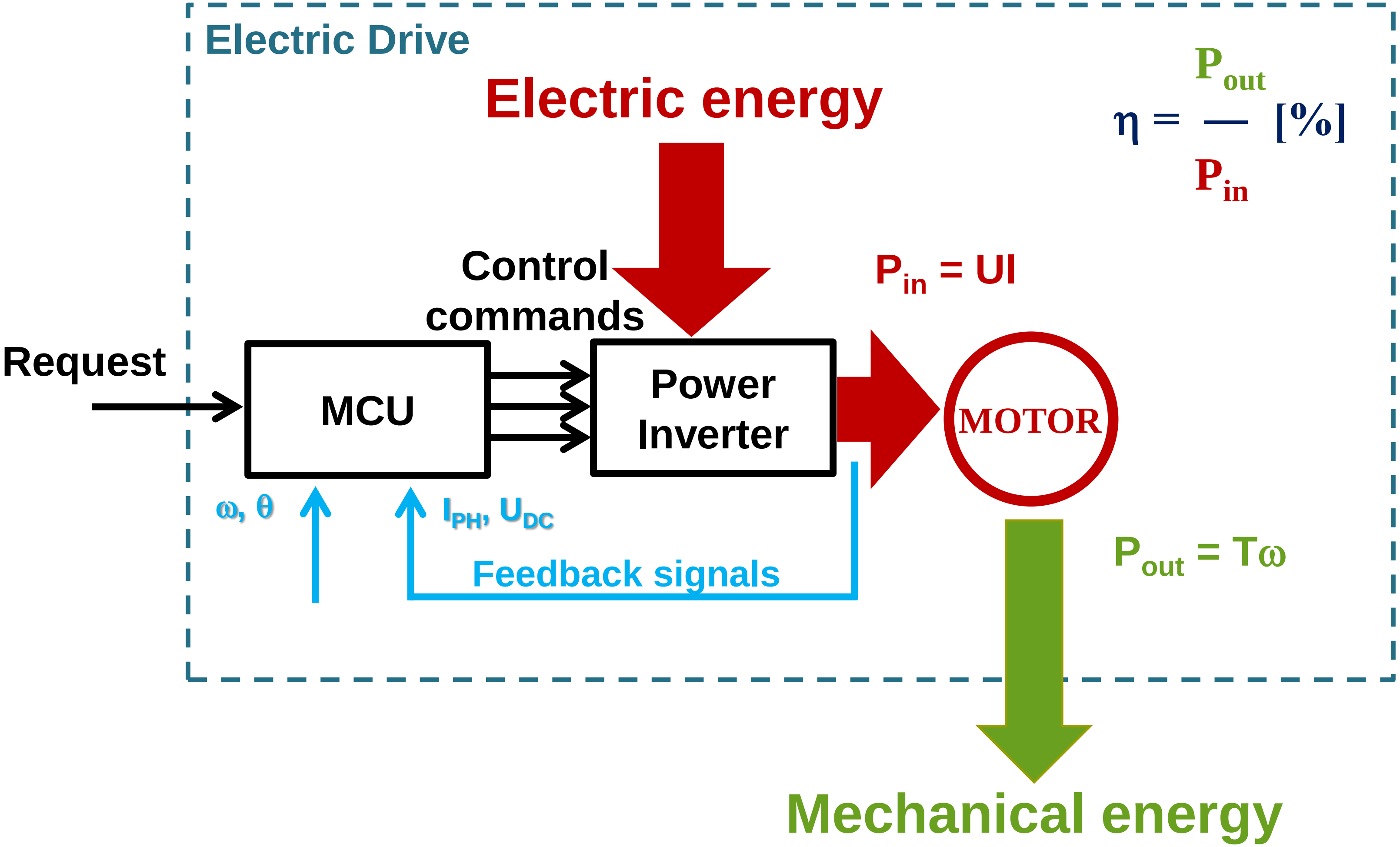


PM motor control strictly requires the information about the actual rotor position and speed.

According to the rotor position and speed loop:

- Sensored control (resolver, encoder, hall ...)
- Sensorless control

Electric Drive General Concept



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- **Sensorless control**

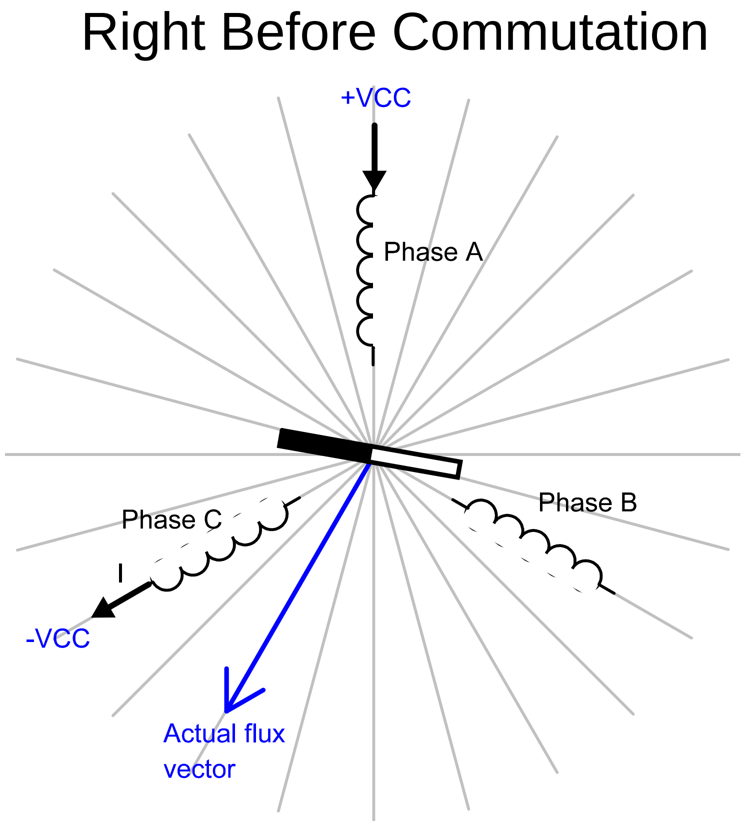
Our Main Focus Today!

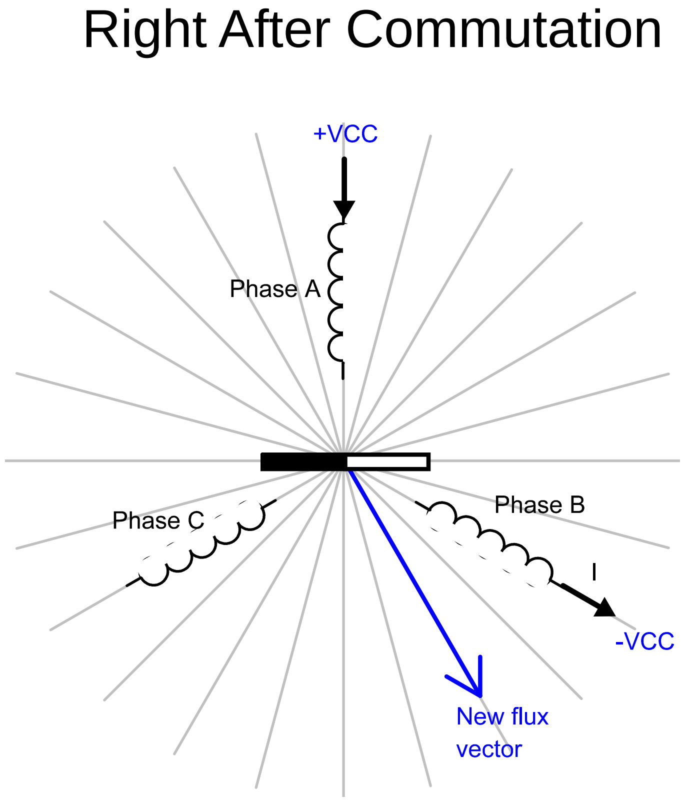
BLDC 6-STEP COMMUTATION CONTROL

SENSORLESS

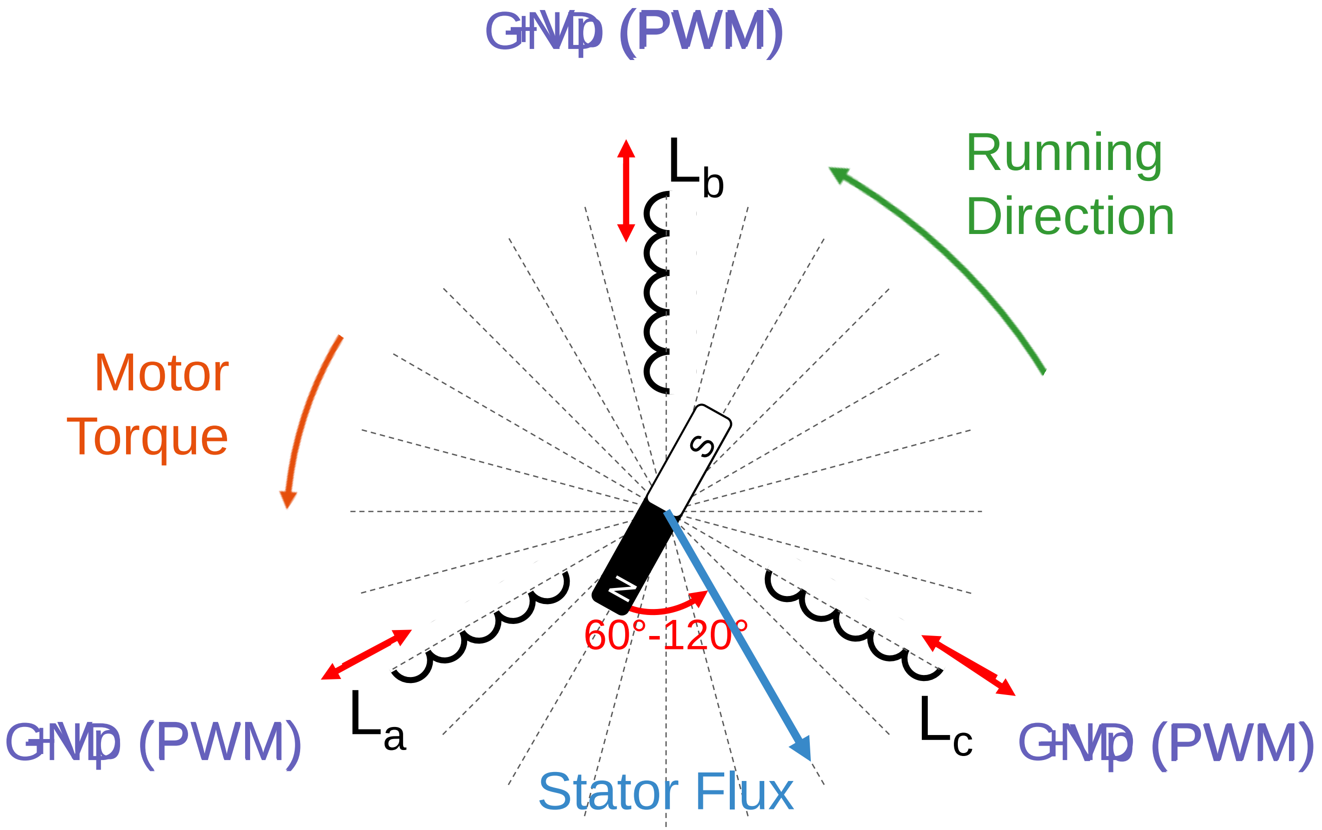
BLDC Control Approach

- Stator field is maintained 60° to 120° relative to rotor field
- Therefore the rotor flux position must be measured/estimated



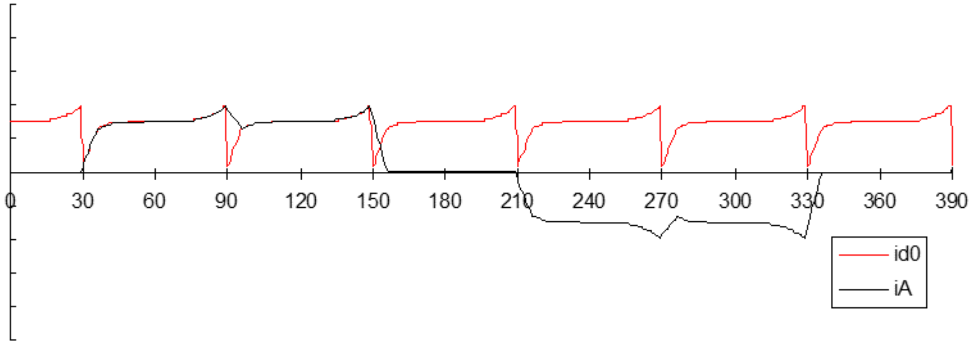


BLDC 6-Step Commutation Principle



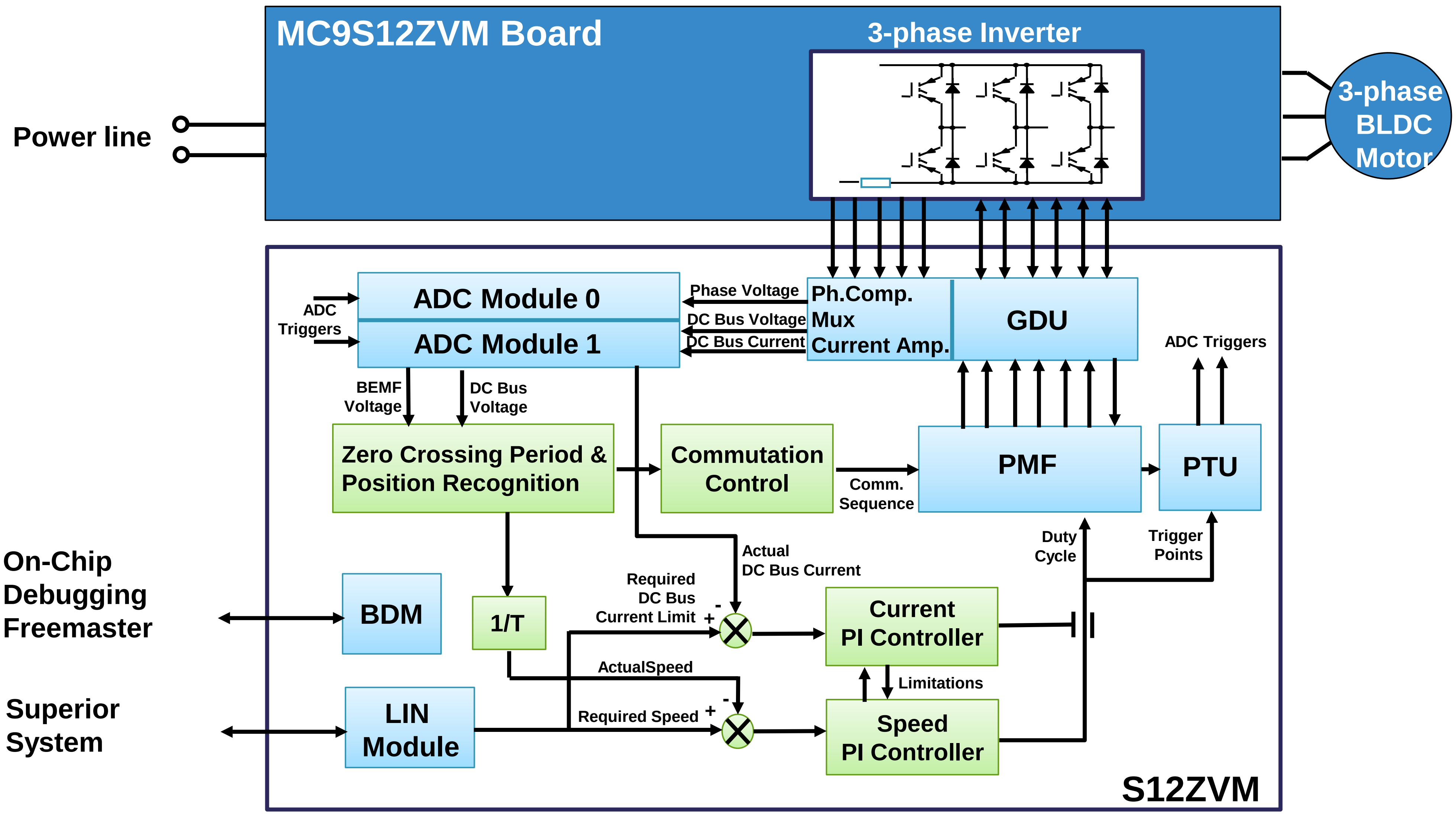
- Stator field is generated between 60° to 120° to rotor field to get maximal torque (@ 90°) and energy efficiency

- Six resulting flux vectors defined by the six voltage vectors to create rotation

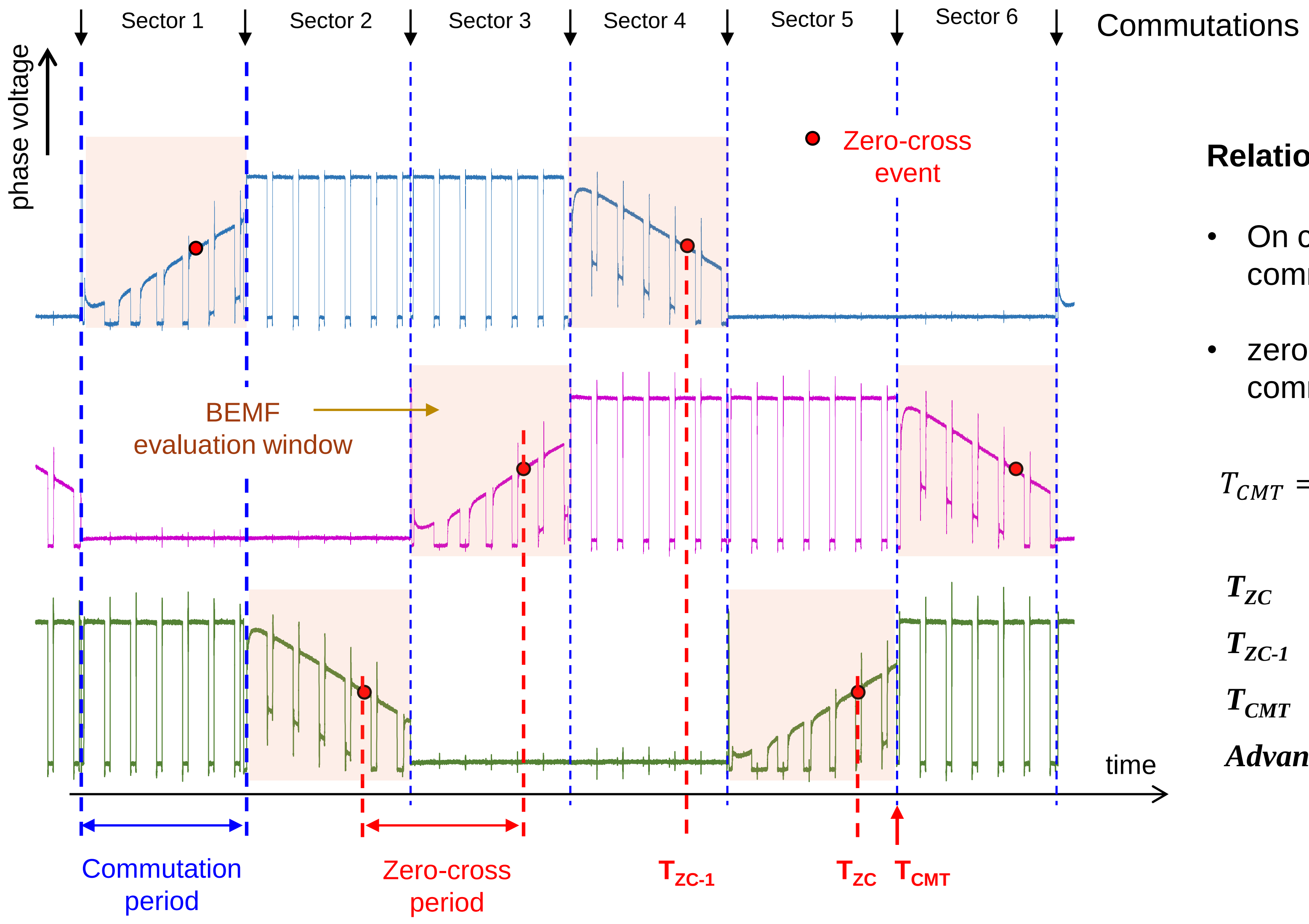


Current behavior during the commutation

Example Control Block Diagram – S12ZVM



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)

$$T_{CMT} = T_{ZC} + AdvanceAngle \frac{(T_{ZC} - T_{ZC-1})}{2}$$

T_{ZC} – time of actual zero-cross

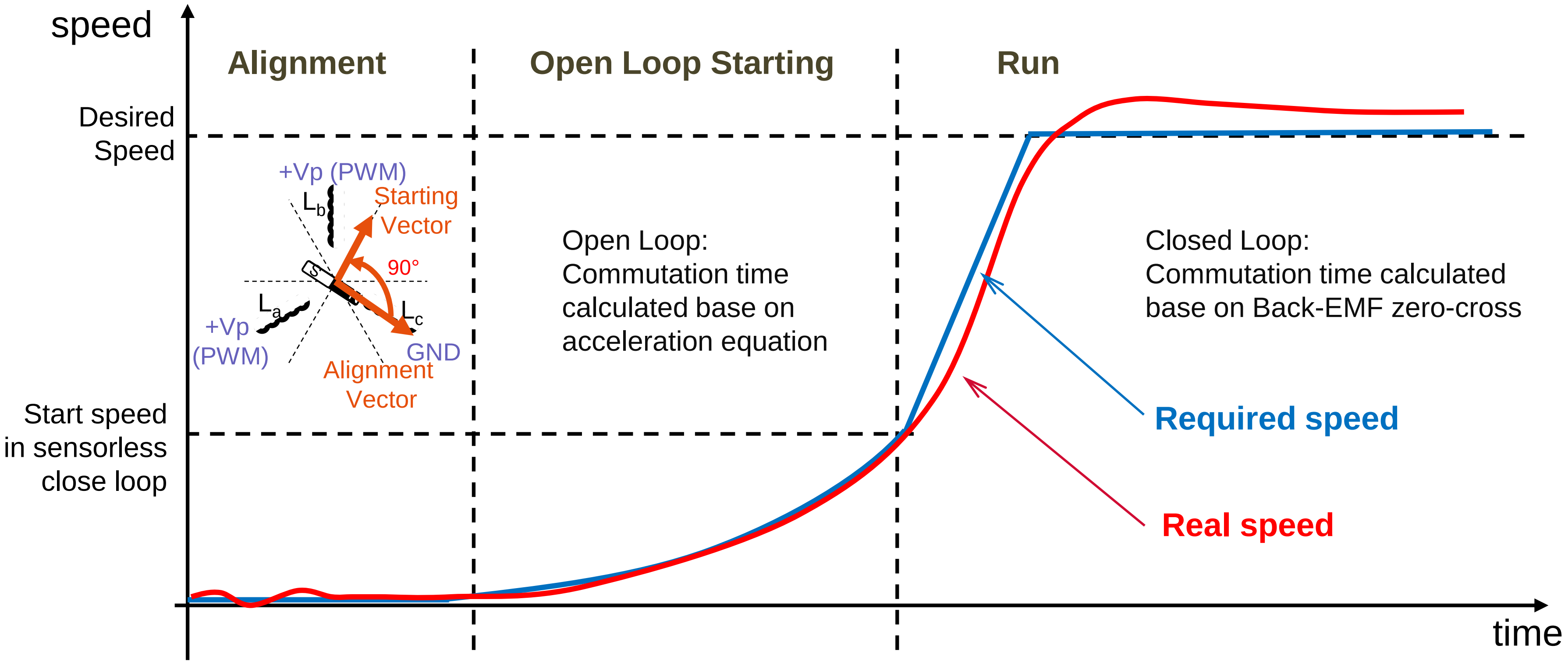
T_{ZC-1} – time of previous zero-cross

T_{CMT} – time of next commutation

AdvanceAngle - constant in the range 0.7 to 0.95
(depends on motor parameters)

BLDC Motor Startup States

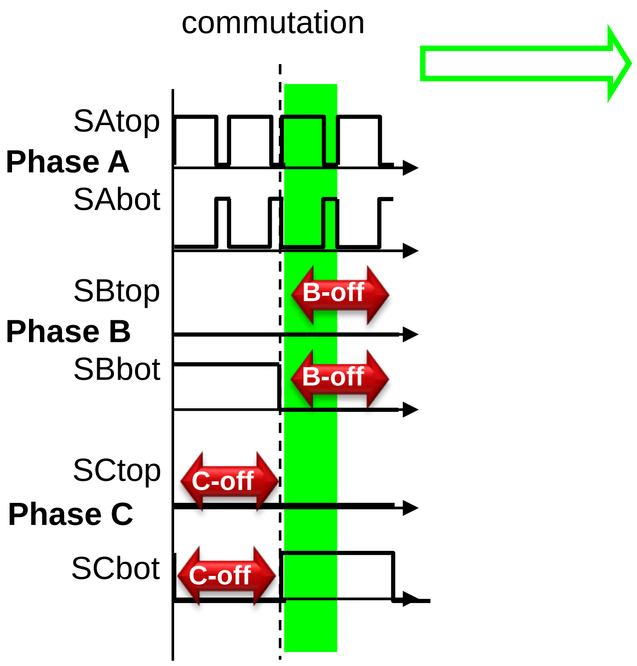
The open-loop starting sequence ensures motor running at enough high speed and so the zero-cross events can be successfully detected and sensorless closed loop control can follow.

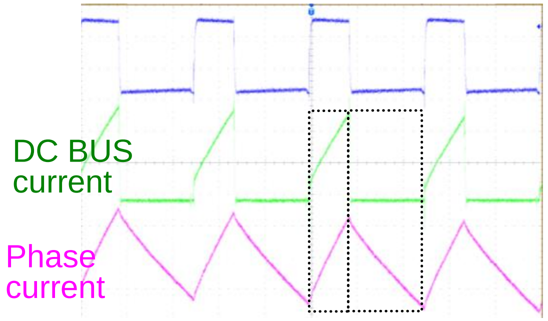


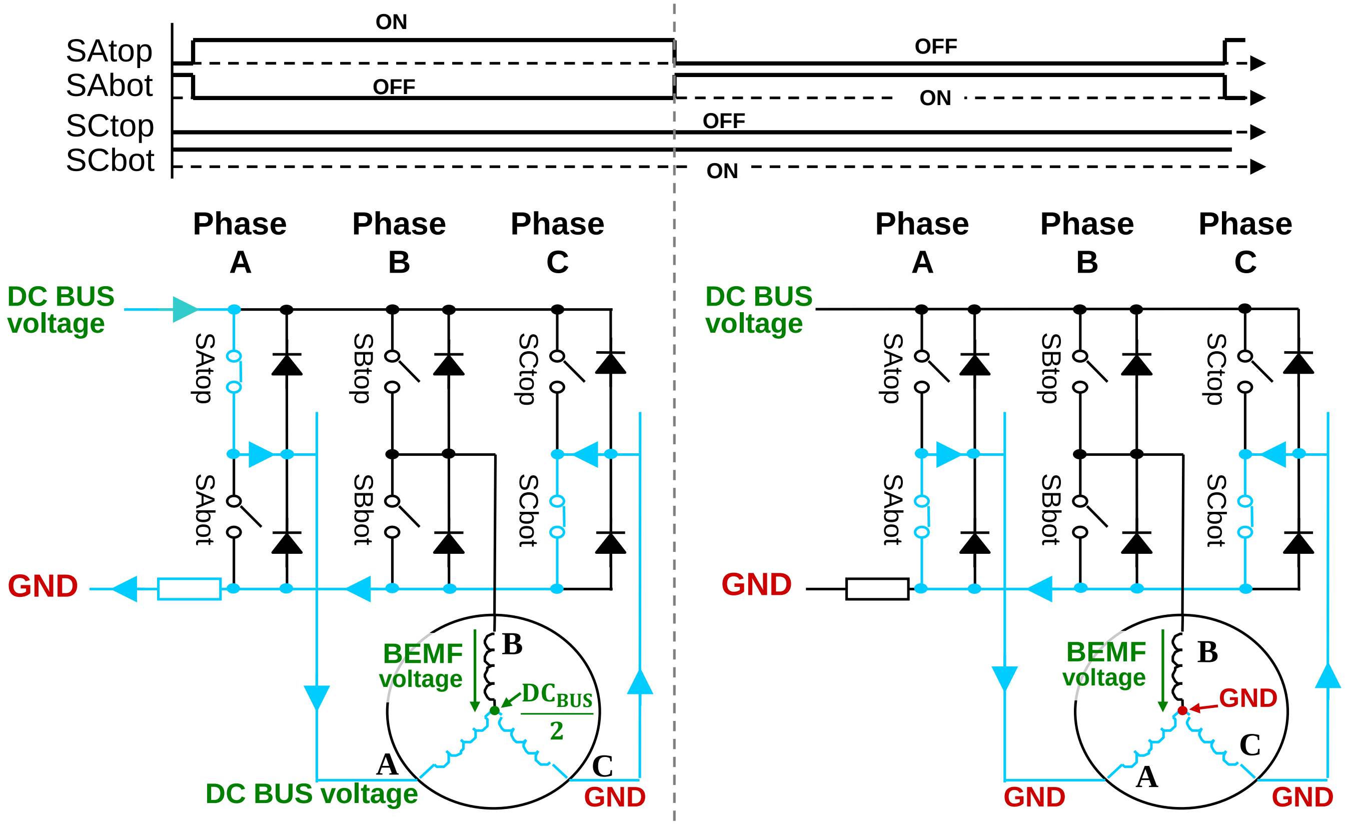
Open Loop:
Commutation time calculated base on acceleration equation

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

Measurement During PWM Switching







Top MOSFET is ON:

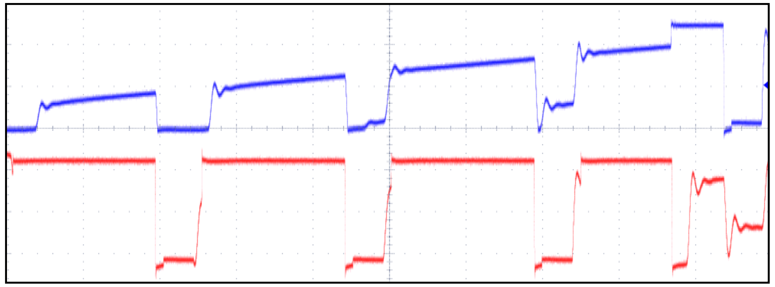
+ Phase current can be measured by DC BUS shunt resistor
+ Back-EMF voltage can be measured both positive and negative

Top MOSFET is OFF:

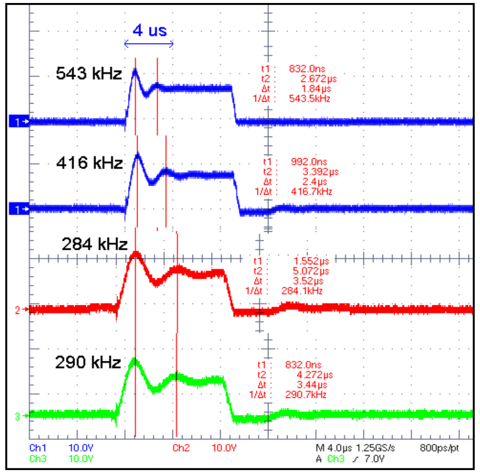
– Phase current can **NOT** be measured by DC BUS shunt resistor
– **Only positive** Back-EMF voltage can be measured (**zero-cross can not be precisely measured**)

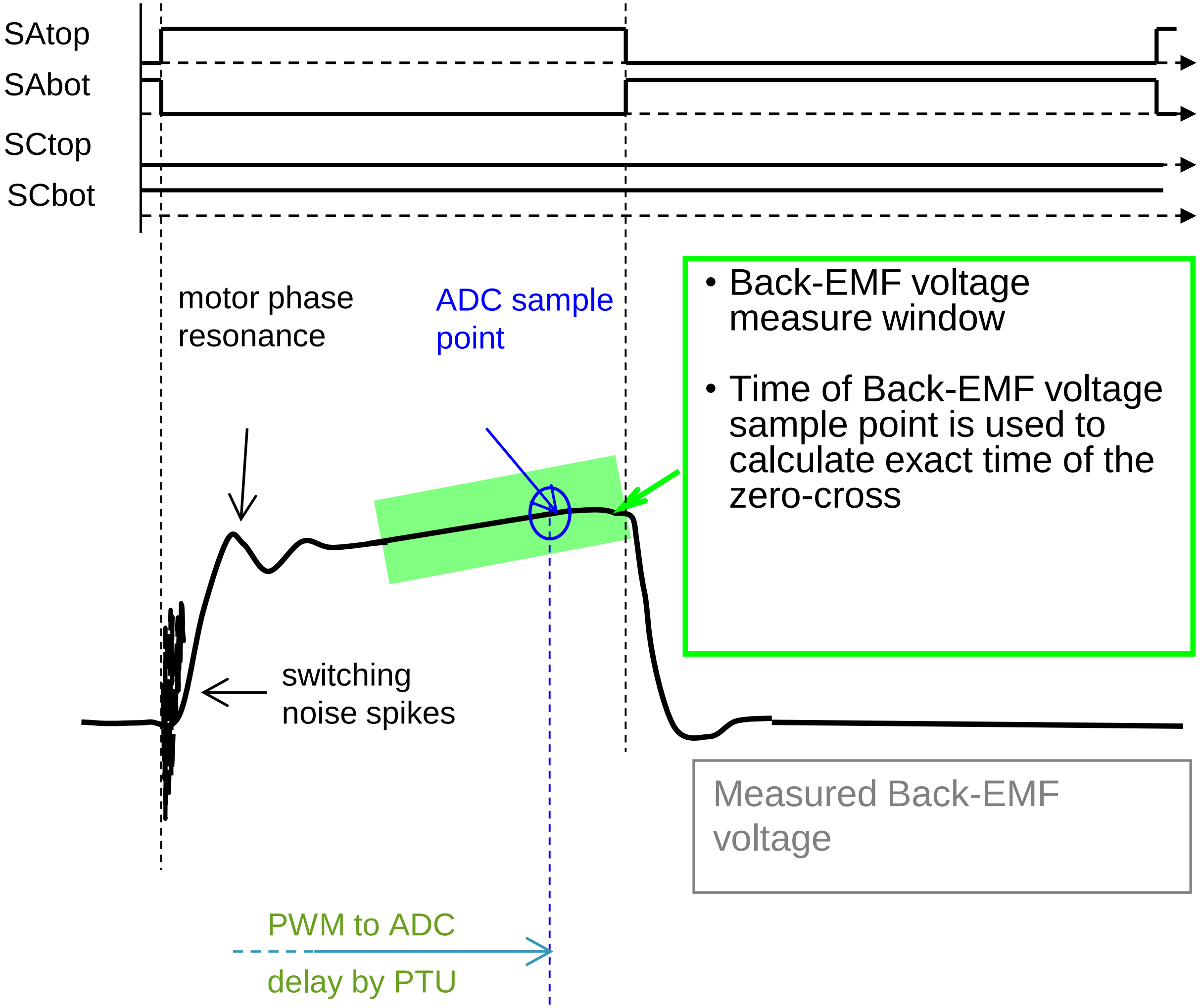
Back-EMF Voltage Measurement

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



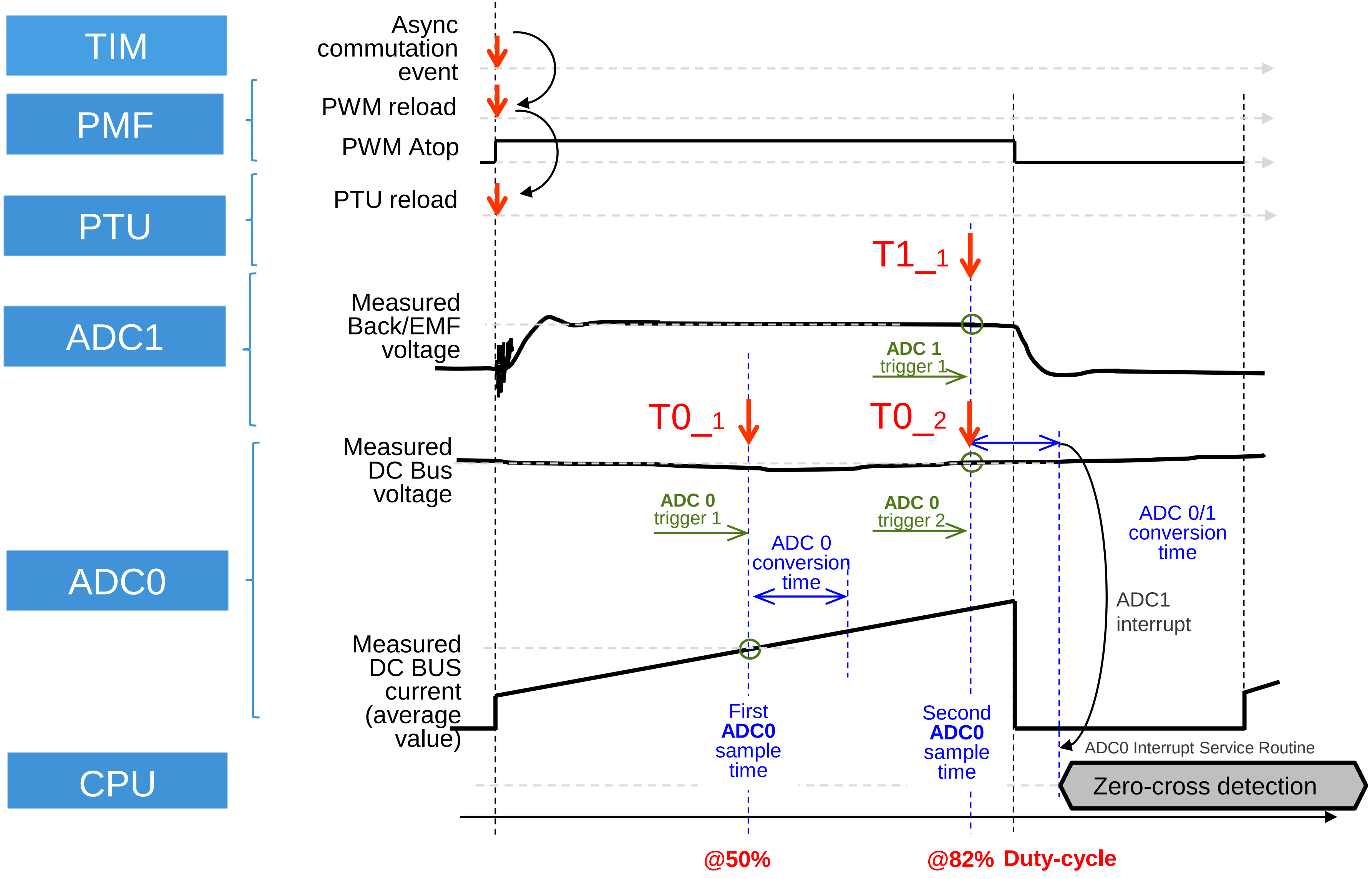
Resonance transient on Back-EMF voltage depends on motor and power stage parameters



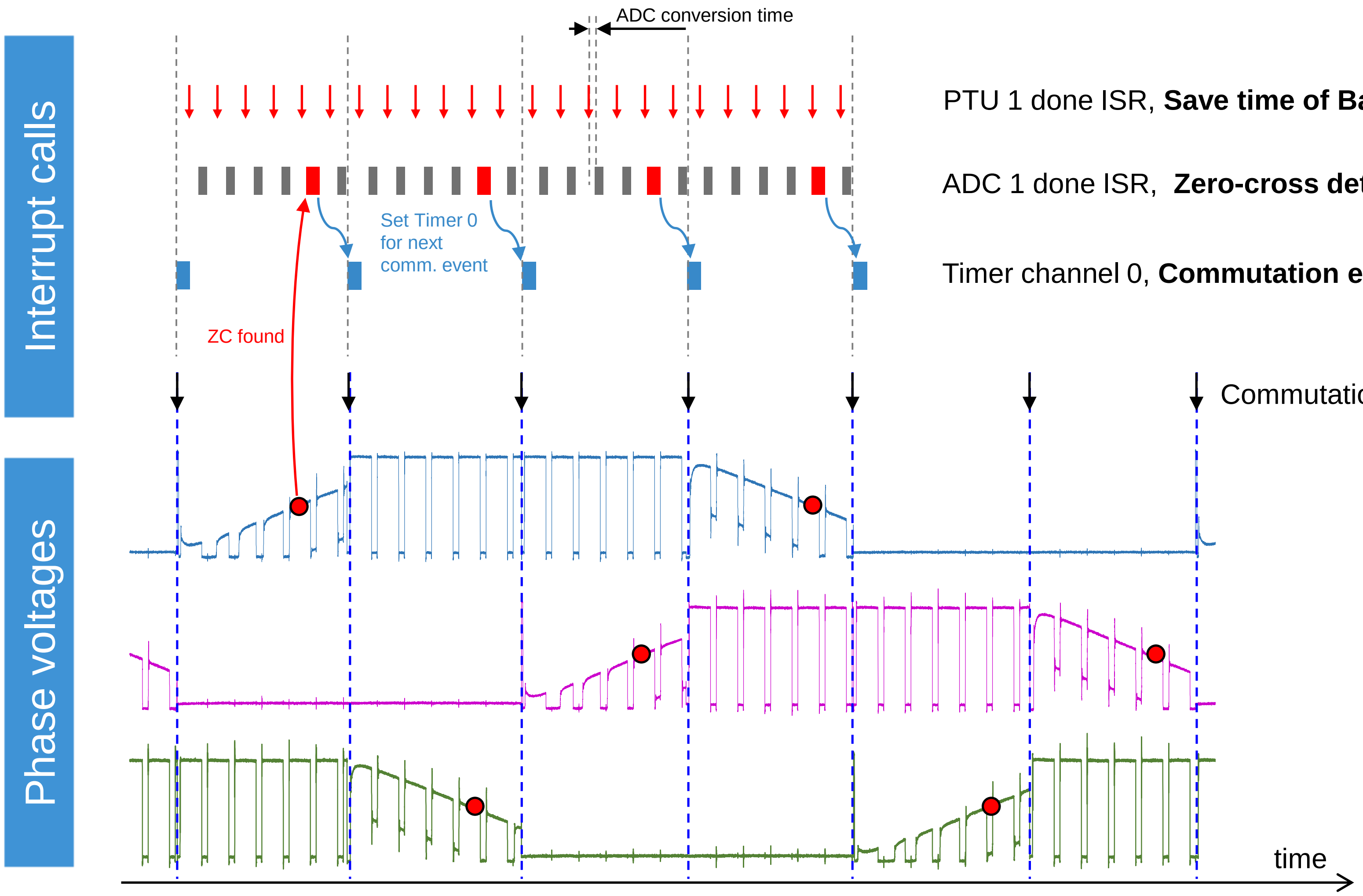


- Back-EMF voltage measure window
- Time of Back-EMF voltage sample point is used to calculate exact time of the zero-cross

S12ZVM Modules Involvement in BLDC Control Loop



Control Loop Timing and Interrupts



PTU 1 done ISR, **Save time of Back-EMF voltage measurement**

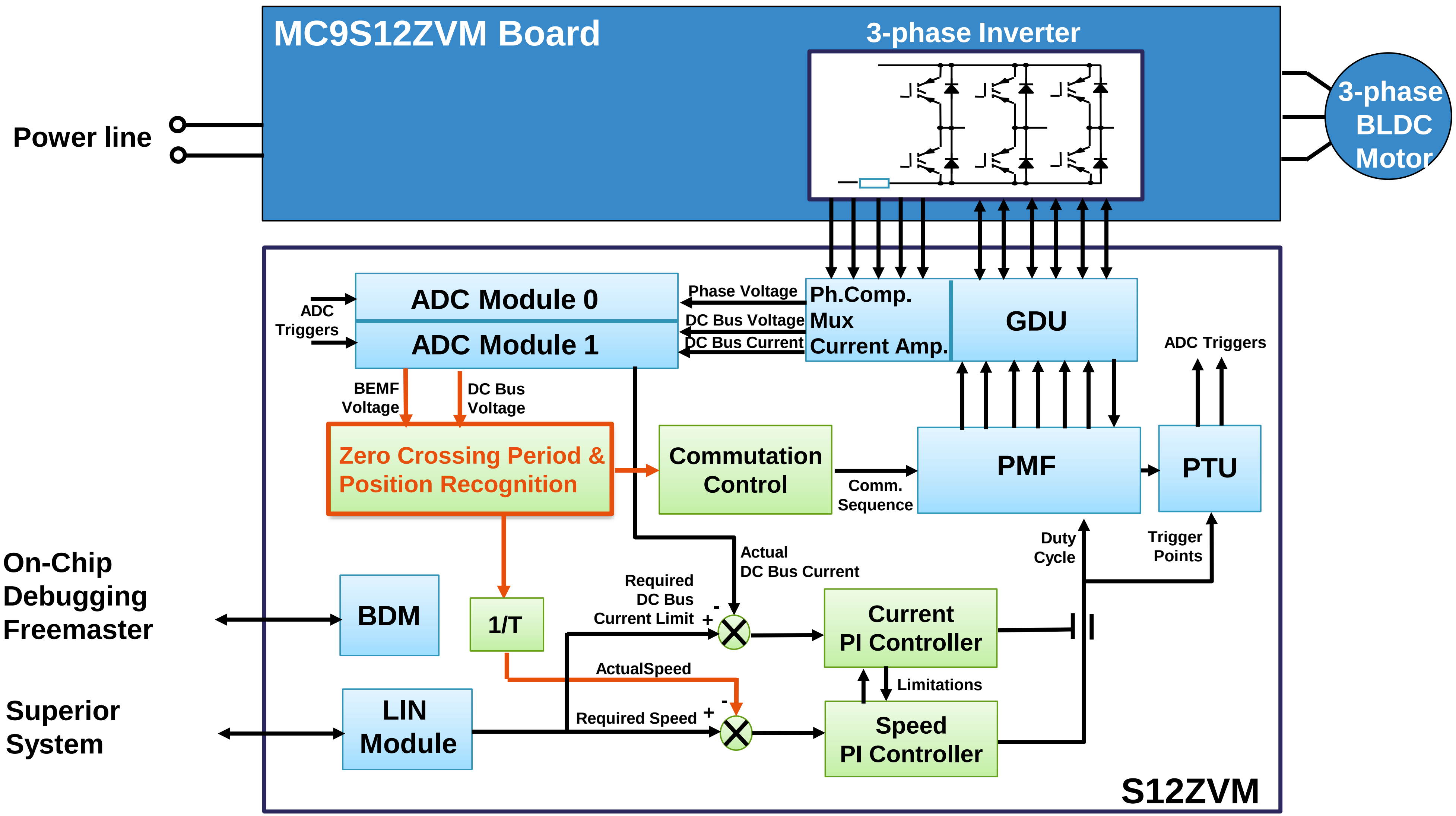
ADC 1 done ISR, **Zero-cross detection**

Timer channel 0, **Commutation event**

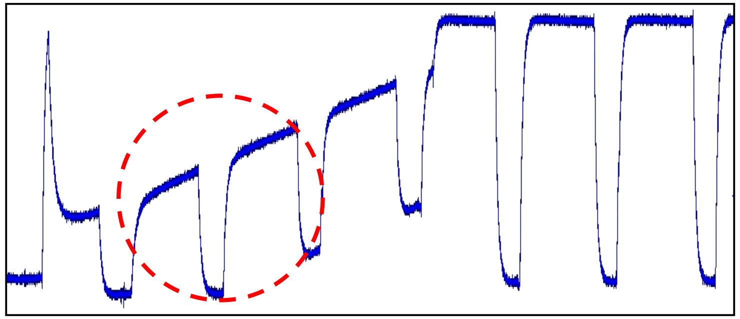
Commutations

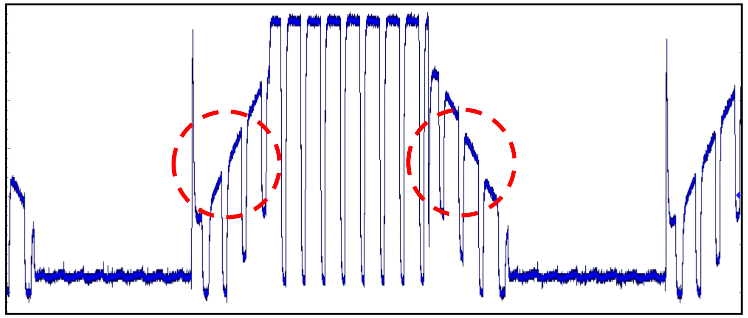
Timer channel 3 is utilized for Speed Control Loop. It runs in 1ms loop.

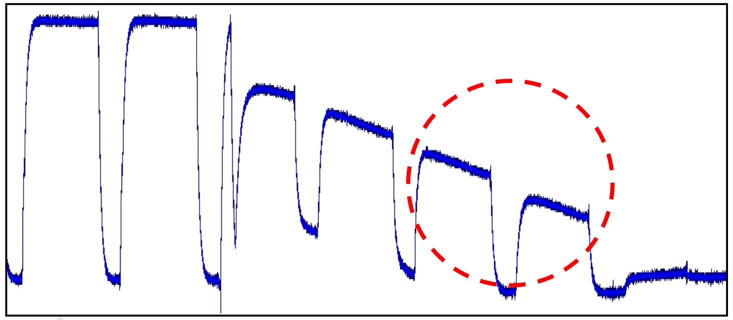
Example Control Block Diagram

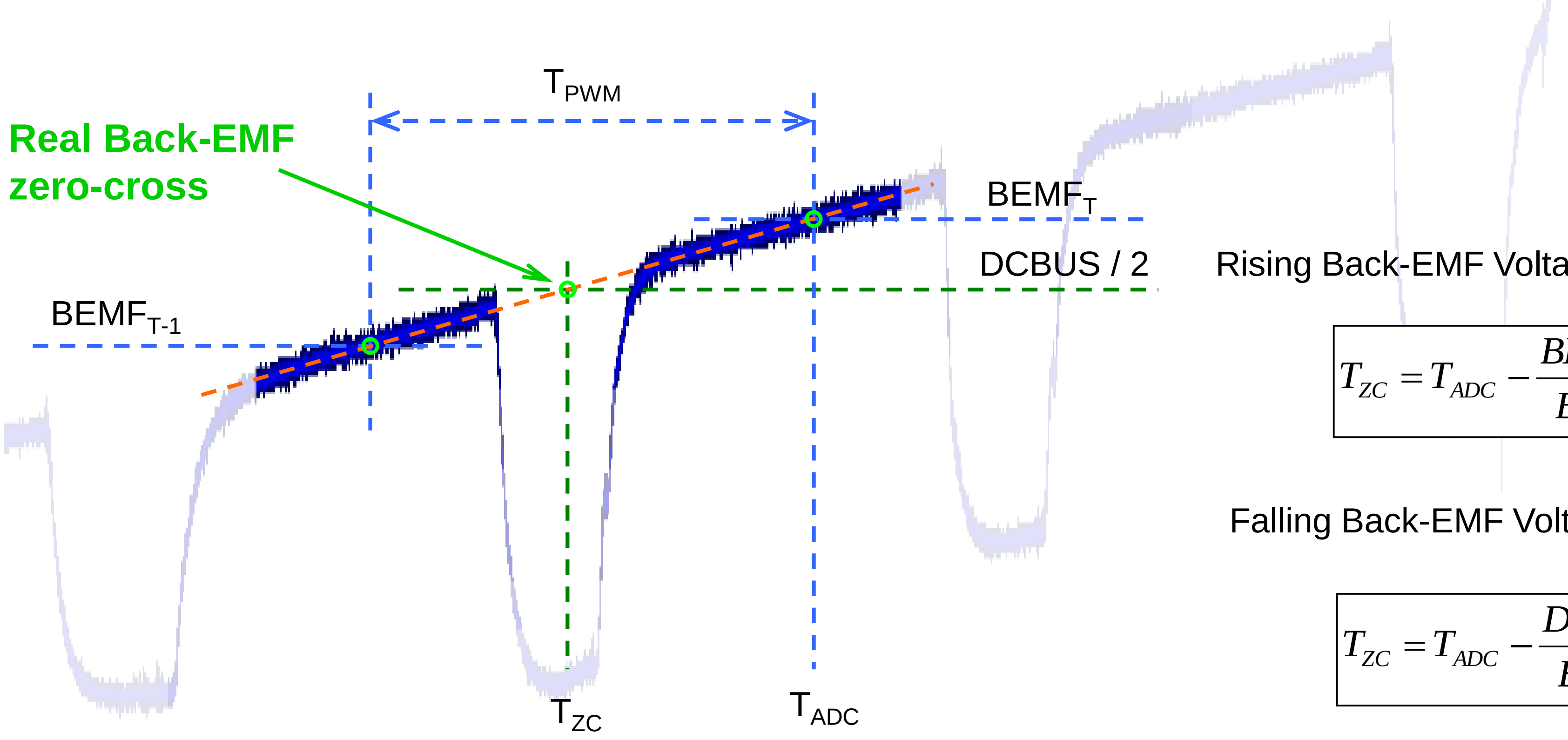


Zero Cross Linear Interpolation









Rising Back-EMF Voltage ADC samples interpolation

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

Falling Back-EMF Voltage ADC samples interpolation

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

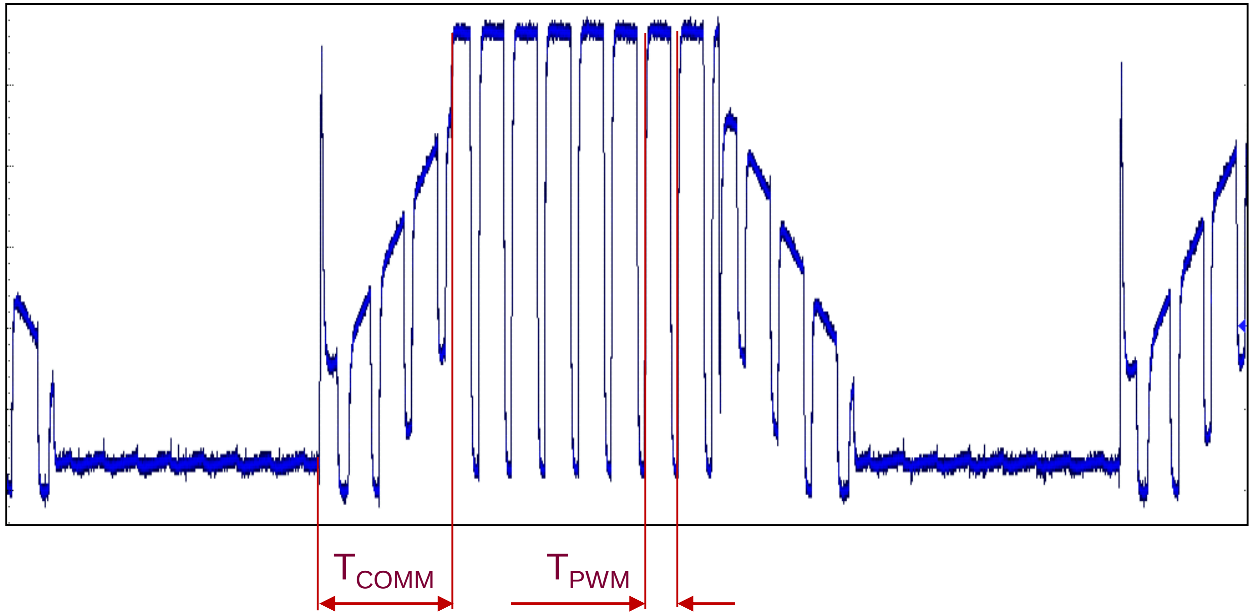
WHAT IS A HIGH SPEED MOTOR?

High-Speed Electric Motors

- Naturally high speed motors
  - Nominal (base) speed of the motor is so high that the frequencies of the motor quantities (voltage, current) are out of the sampling range

- Forced high speed operation
  - Motor is forced (controlled) to run over the base speed. An advanced control technique known as a Field Weakening is used to control the motor over the base speed.
  - Achieved speed of the motor is so high that the frequencies of the motor quantities (voltage, current) are out of the sampling range

High-Speed Motor Definition



From mechanical speed in rpm units:

$$T_{COMM} = \frac{1}{6 \times \frac{Nominal\ Speed_{[rpm]} \times Motor\_pp}{60}}$$

where, *Motor_pp* defines the number of motor pole-pairs

From angular electric speed in rad/s units:

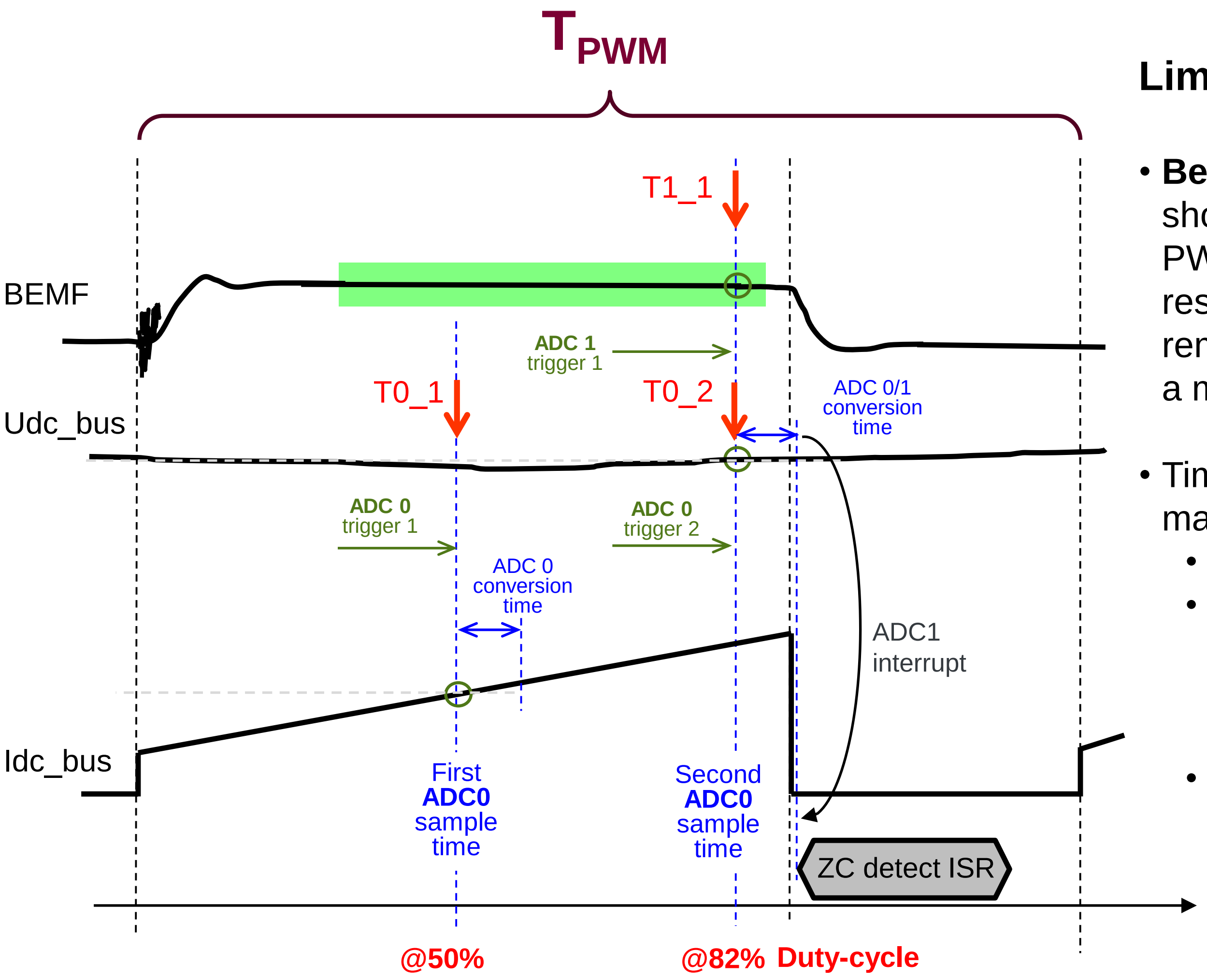
$$T_{COMM} = \frac{1}{6 \times \frac{Nominal\ Speed_{[rad\ s^{-1}]}}{2\pi}}$$

Assuming the above described ZC detection method, the ratio between T_{COMM} and T_{PWM} should be higher than four. Four PWM pulses during the commutation period ensure enough high probability of a successful zero-cross detection and subsequently sensorless operation.

In case this ratio is less than four, there are two ways how to solve this issue:

- Set-up new T_{PWM} in order to increase the number of PWM pulses in Back EMF signal
- Adopt different zero-cross detection approach

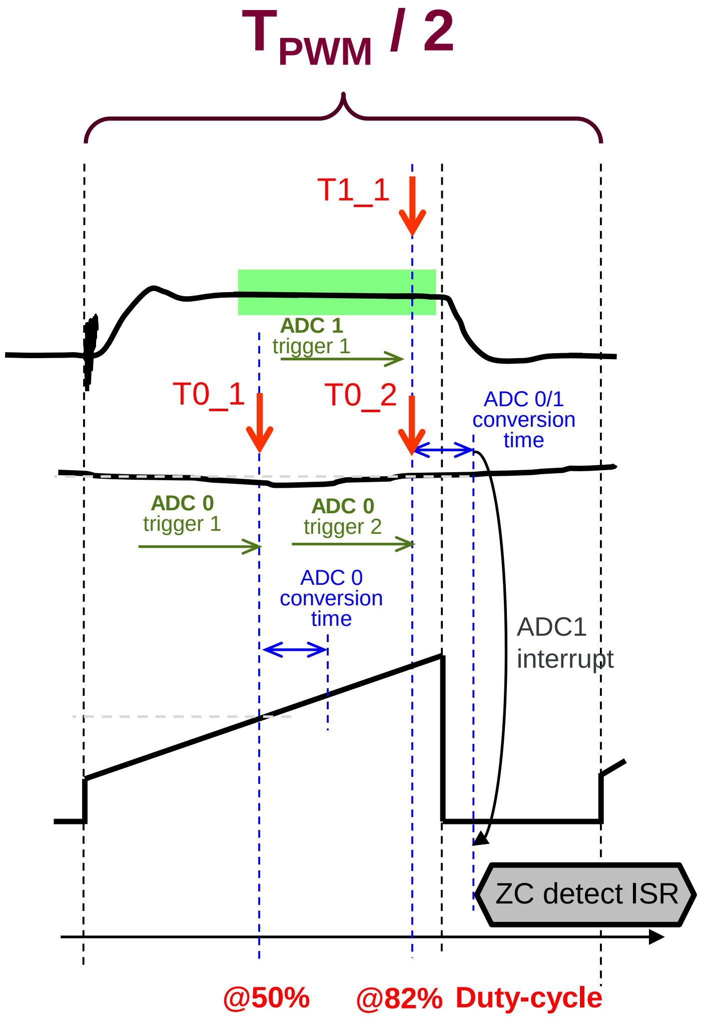
Set-up New T_{PWM} Period



Limitations:

- **Bemf measure window** is shorter because of the shorter PWM pulse. Moreover, the resonant transient on Bemf remains the same. It depends on a motor and VSI.

- Time for executing the **ZC ISR** may be limited because:
  - PWM pulse is half width
  - Execution time of ISR remains the same. It depends on the CTU clock frequency not PWM freq.
  - ADC conversion time does not change as well



BLDC 6-STEP COMMUTATION CONTROL

HIGH SPEED OPERATION

Conventional 6-step Control Approach – Summary

- Is based on the measurement of the Bemf signal in disconnected motor phase
- Zero-crossings in the Bemf are detected and the time of the occurrence is captured
- The time of actual Bemf zero-cross and the last-one indicates how fast the motor runs and when the next commutation should appear
- Next commutation sequence is calculated as half of the delta of last two zero-cross instances
- Since the Bemf signal is PWM-ed, the measurement has to be performed within each PWM pulse
- The more PWM pulses in Bemf the better for control algorithm

Conventional 6-step Control Approach – Limitation

To stress the aforementioned limitations, a real high speed BLDC motor is used as an example:

- Rated mechanical speed = 60 k rpm, (freq. = 1 KHz)
- Motor pole-pairs = 2
- PWM frequency (T_{PWM}) = 20 KHz (50µs)

The commutation period according to:

$$T_{COMM} = \frac{1}{6 \times \frac{Nominal\ Speed_{[rpm]} \times Motor\_pp}{60}}$$

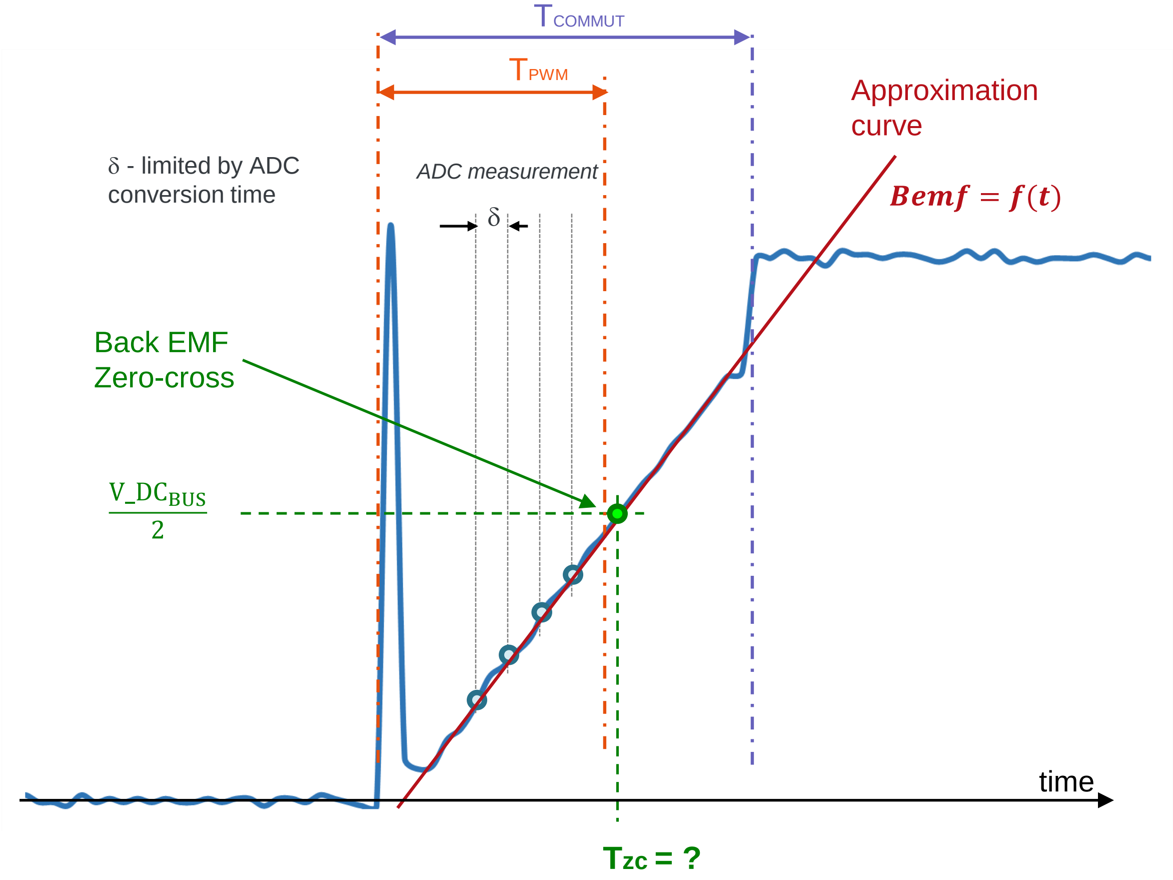
The commutation period = 1/12KHz = 83.3µs (@ full speed and rated voltage supply)

The ratio T_{COMM} / T_{PWM} = ~**1,667 of PWM pulses** will be seen in measured BEMF within the commutation period

Conclusion: considerably limited number of PWM pulses in the BEMF does not allow to use a standard Zero-cross detection method. **A new approach utilizing the BEMF oversampling and its shape reconstruction has been proposed an developed**.

Introduction to BEMF Oversampling

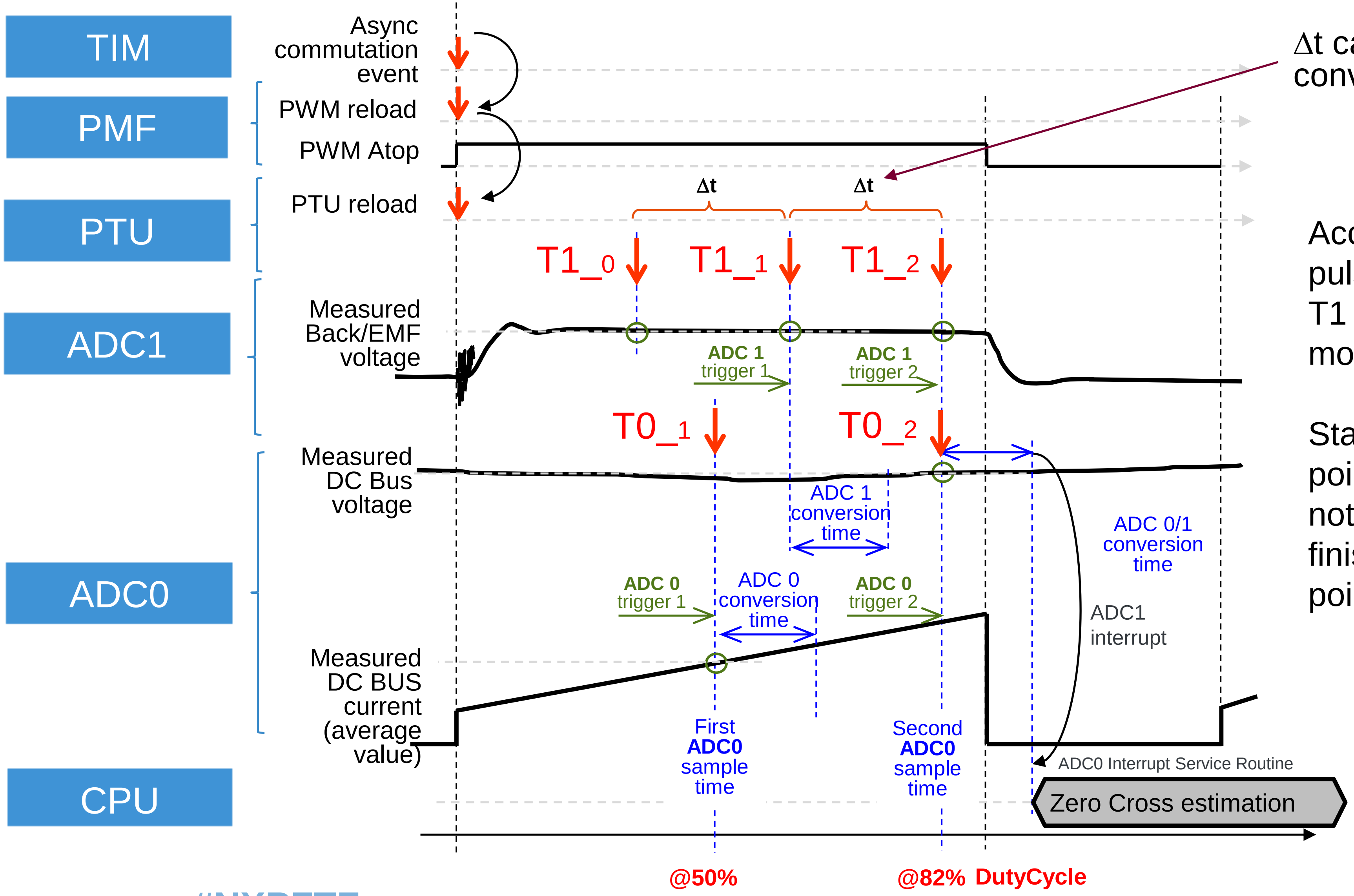
The main idea is to get more samples of the BEMF envelope within a PWM pulse instead of one sample.



The captured samples are then used for modeling the relationship between BEMF voltage and sampling instances using a least squares (LSQ) method. LSQ method is a standard approach in linear regression analyses to approximate the oversampled (overdetermined) system.

Reconstructed envelope of the BEMF voltage represents the time dependent function that can be used to calculate the zero-cross instance (T_{ZC}) even if the zero-cross event appeared out of the oversampled BEMF region.

S12ZVM Modules Involvement – Oversampling Approach



Δt cannot be less than ADC conversion time = 2.5µs

According to the PWM pulse width, the trigger list T1 can be dynamically modified and extended.

Starting with single trigger point when PWM pulse is not wide enough and finishing with three trigger points.

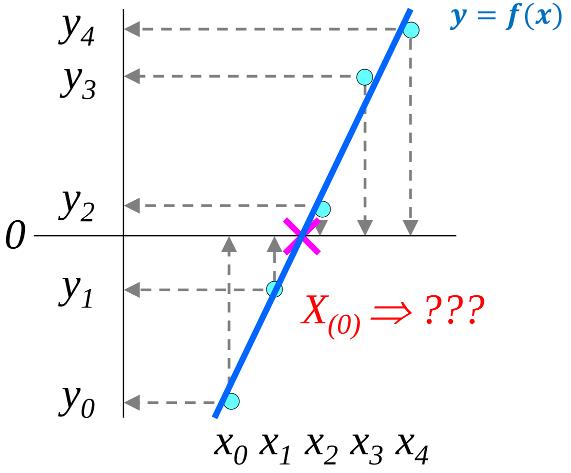
Approximation by Least Squares Method

General Zero-crossing calculation form:

$$a_1\left(x_{(0)} - x_0\right) + a_0 = 0$$

$$x_{(0)} = -\frac{a_0}{a_1} + x_0$$

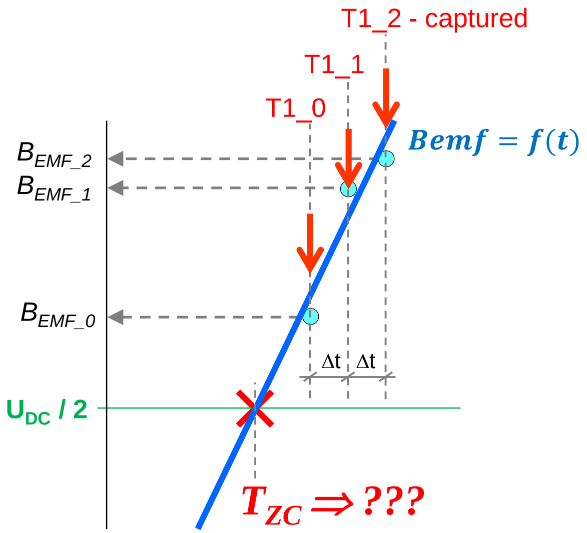
X0 – time of the first sample
X(0) – time of the zero-cross



BEMF Zero-crossing is calculated from:

$$a_1\left(T_{ZC} - T_{1\_0}\right) + a_0 = \frac{U_{DC}}{2}$$

$$T_{ZC} = \frac{U_{DC}}{2a_1} - \frac{a_0}{a_1} + \overbrace{\left(T_{1\_2} - 2\Delta t\right)}^{\text{T1\_0 – time of the first sample}}$$



Where coefficients $a_{0,1}$ for n-points approximation are given as follows:

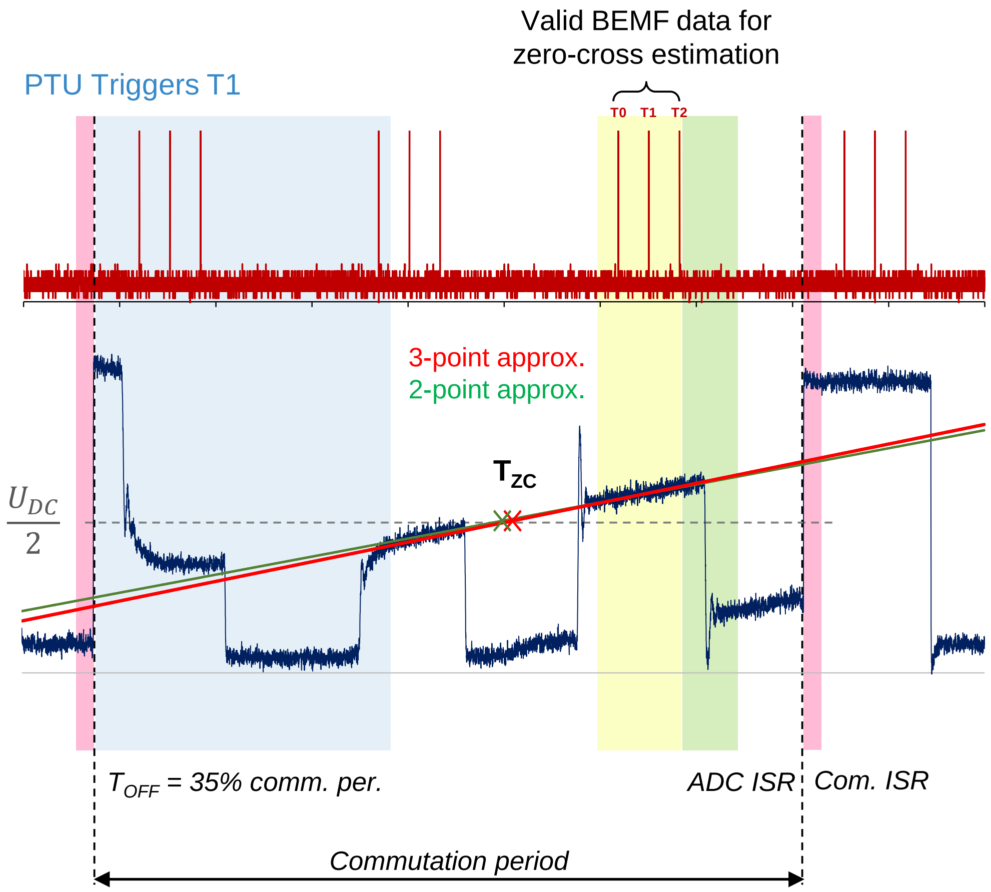
$$\begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \begin{bmatrix} 0.8333 & 0.333 & -0.1667 \\ -0.5 & 0 & 0.5 \end{bmatrix} \begin{bmatrix} B_{EMF(1)} \\ B_{EMF(2)} \\ B_{EMF(3)} \end{bmatrix}$$

3 points approximation

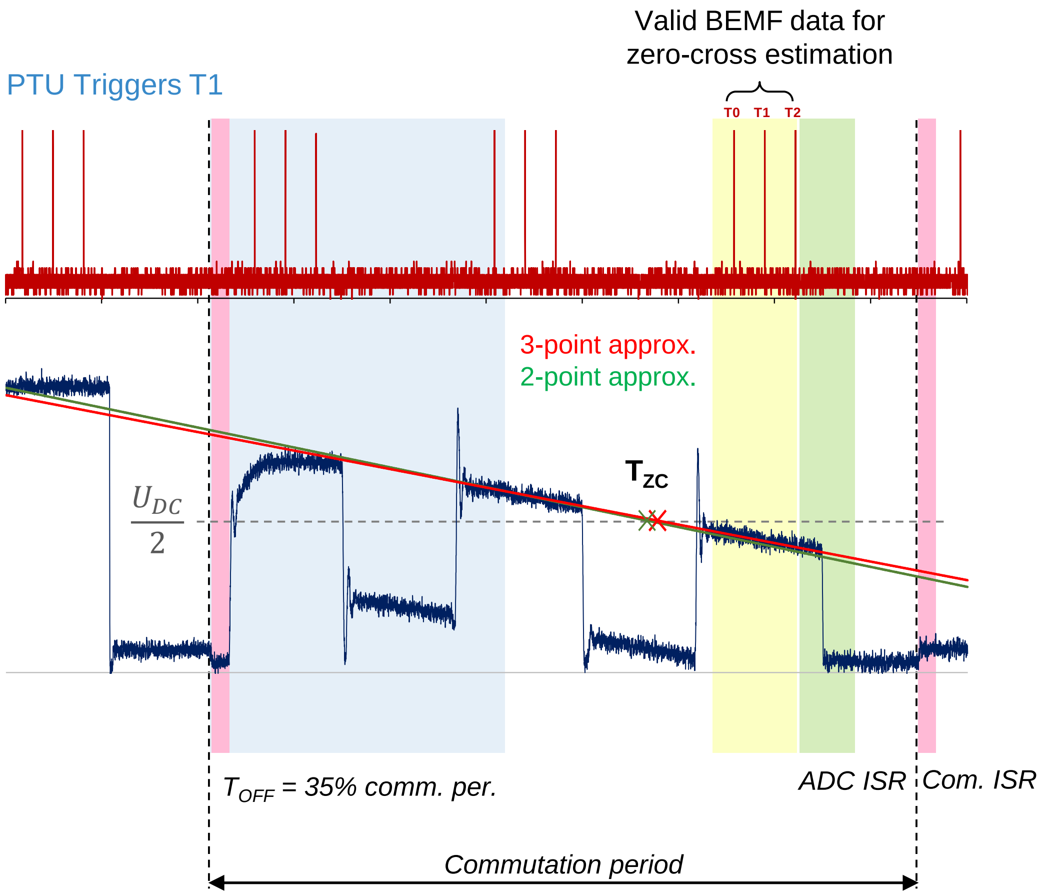
$$\begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} B_{EMF(1)} \\ B_{EMF(2)} \end{bmatrix}$$

2 points approximation

LSQ Approximation vs. Real Back EMF Voltages

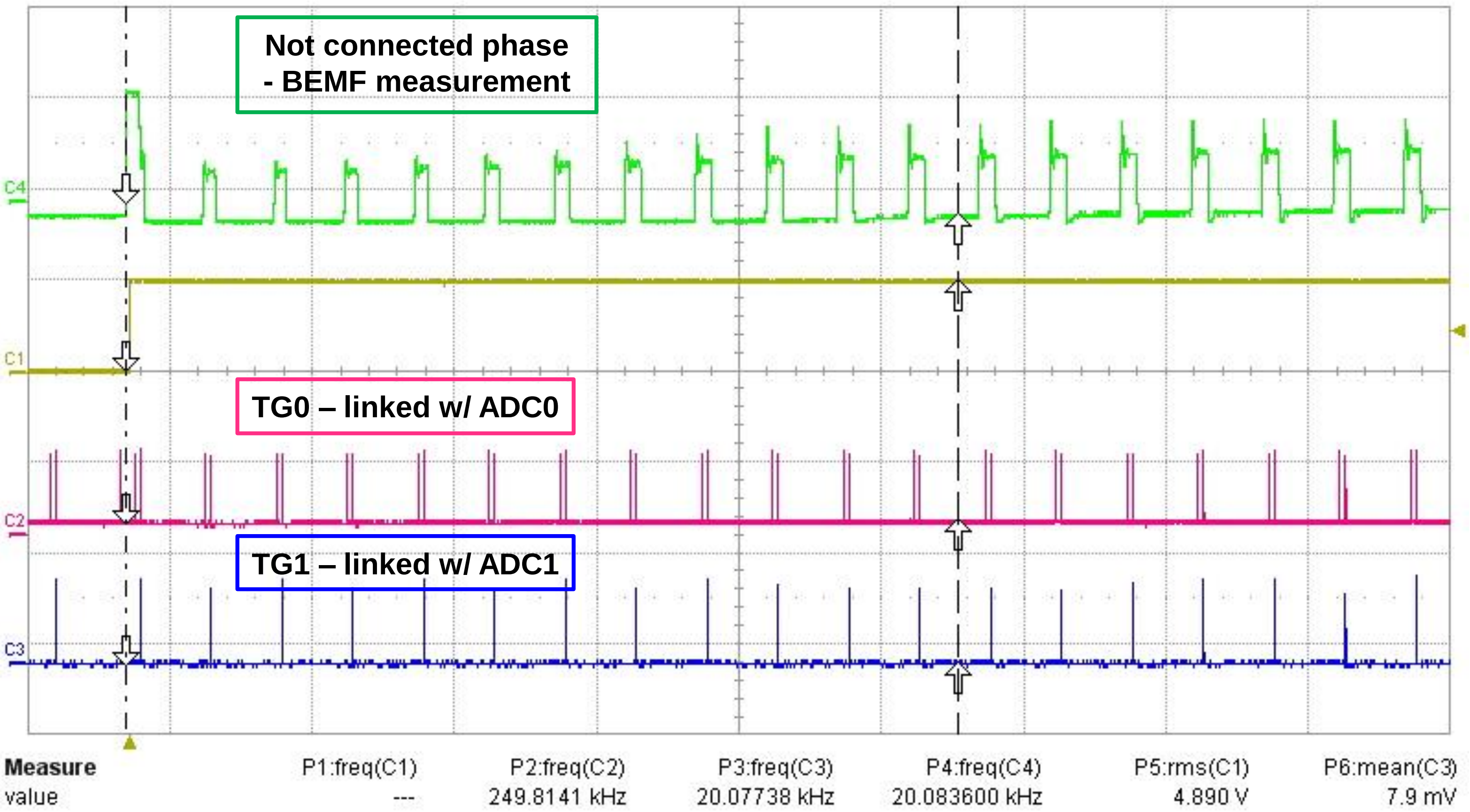


Raising Back EMF

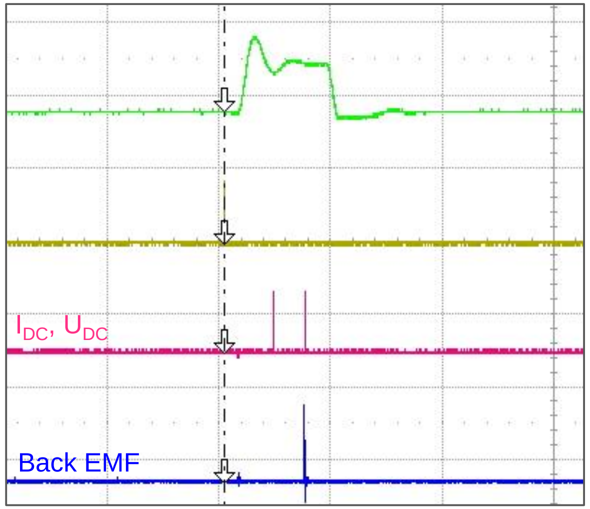


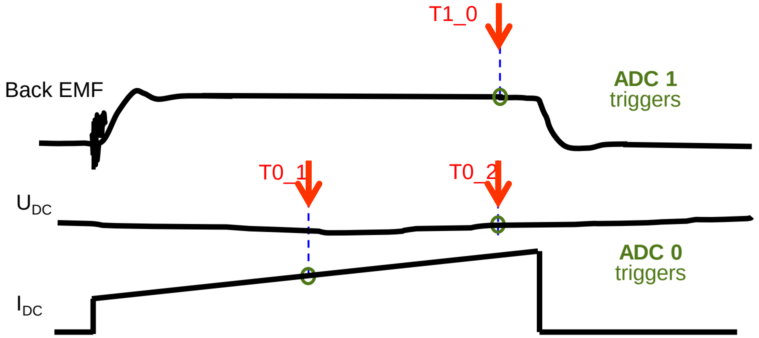
Falling Back EMF

Dynamical Arrangement of PTU Triggers at Low Speed



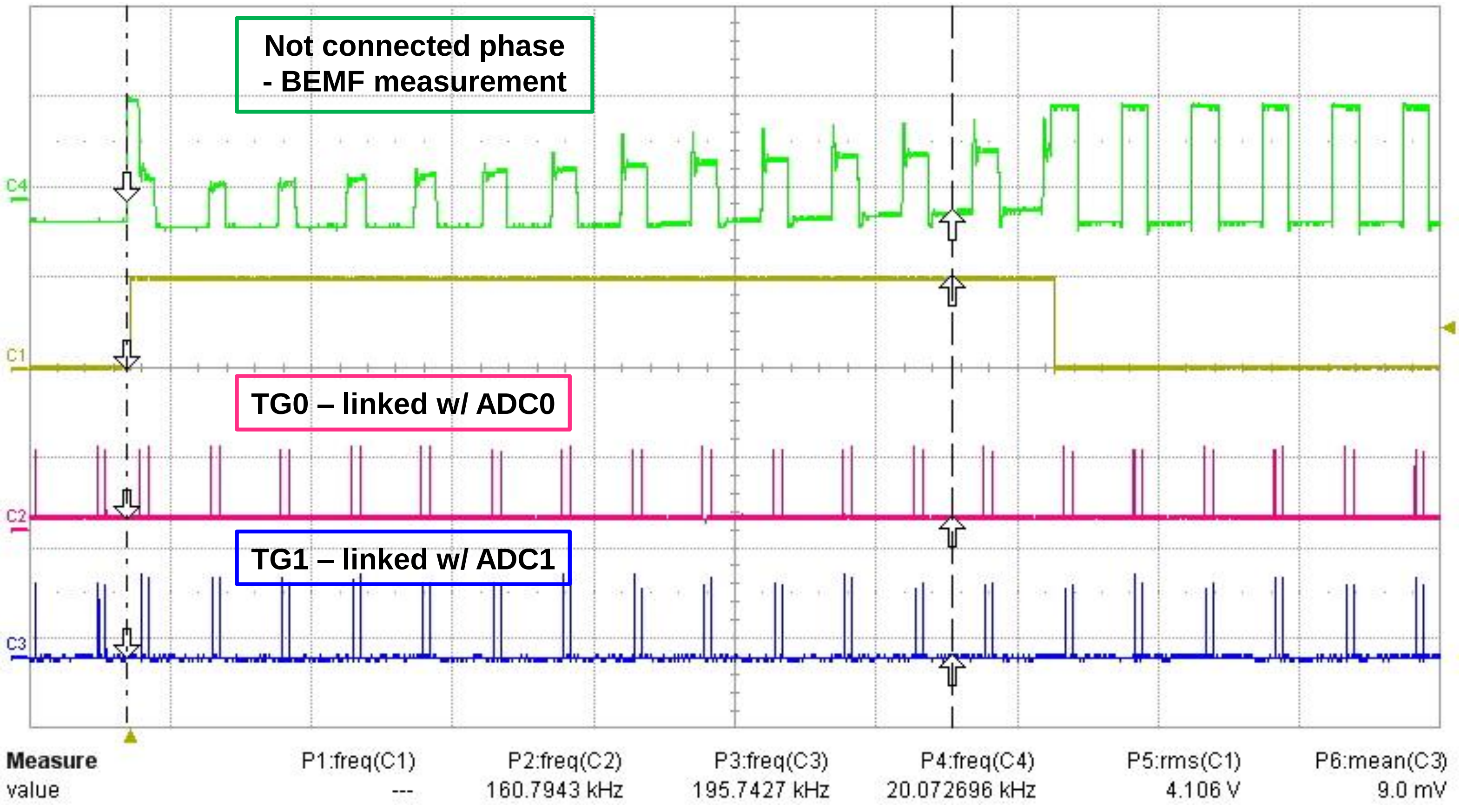
Measure	P1:freq(C1)	P2:freq(C2)	P3:freq(C3)	P4:freq(C4)	P5:rms(C1)	P6:mean(C3)
value	---	249.8141 kHz	20.07738 kHz	20.083600 kHz	4.890 V	7.9 mV





This example shows the advantage of S12ZVM to manage dynamically the trigger events, in other words, dynamically extend the Trigger List and Result Value List in RAM.

Dynamical Arrangement of PTU Triggers at Medium Speed

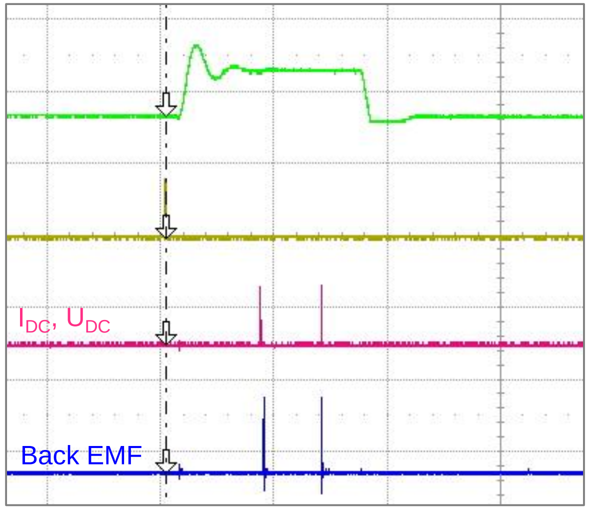


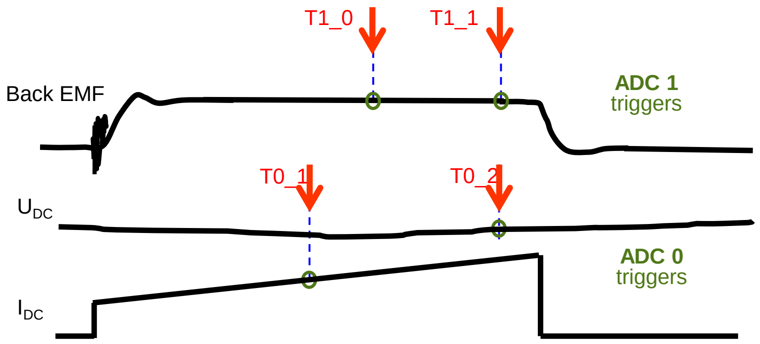
Not connected phase - BEMF measurement

TG0 – linked w/ ADC0

TG1 – linked w/ ADC1

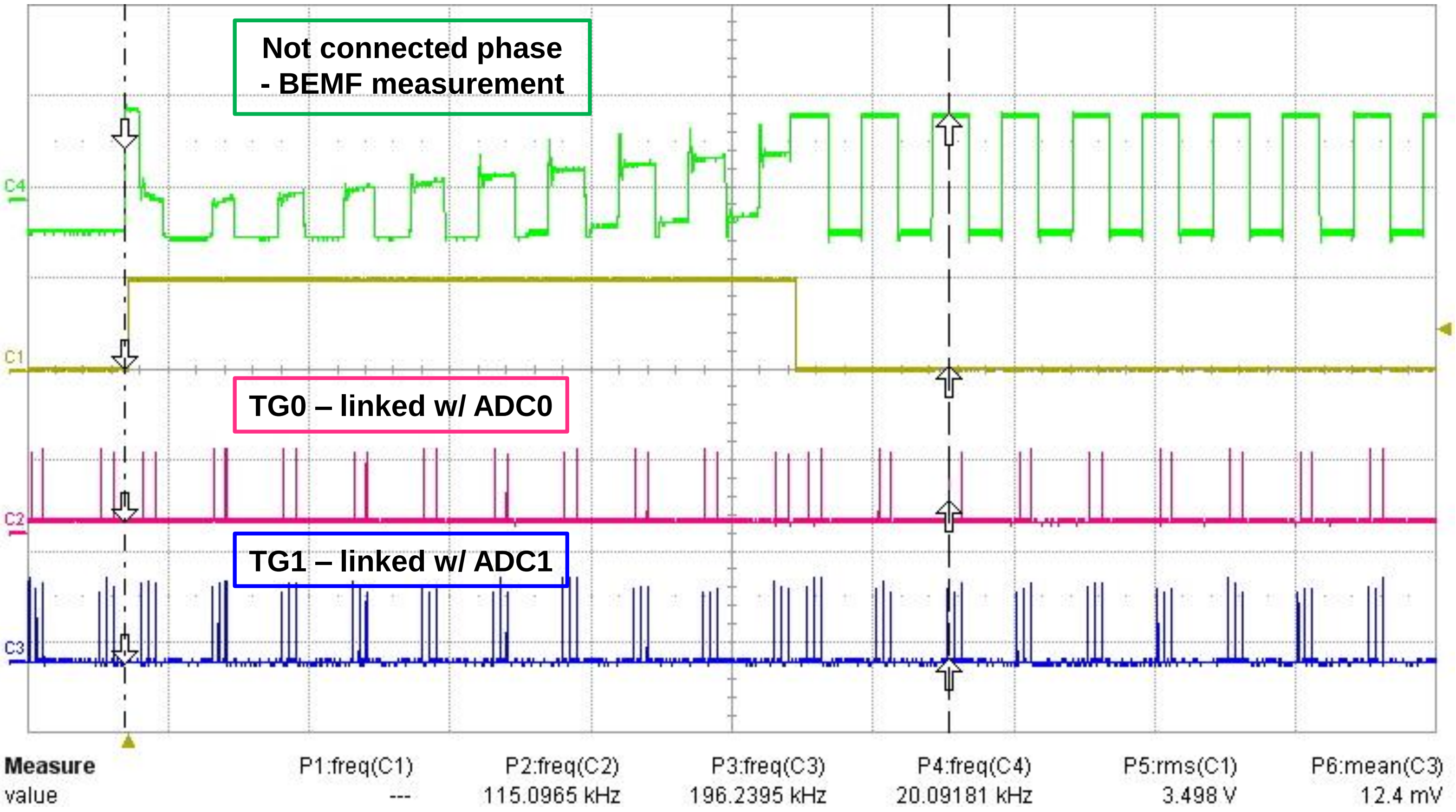
```
Measure      P1:freq(C1)   P2:freq(C2)    P3:freq(C3)    P4:freq(C4)     P5:rms(C1)   P6:mean(C3)
value            ---       160.7943 kHz   195.7427 kHz   20.072696 kHz    4.106 V       9.0 mV
```





This example shows the advantage of S12ZVM to manage dynamically the trigger events, in other words, dynamically extend the Trigger List and Result Value List in RAM.

Dynamical Arrangement of PTU Triggers at High Speed

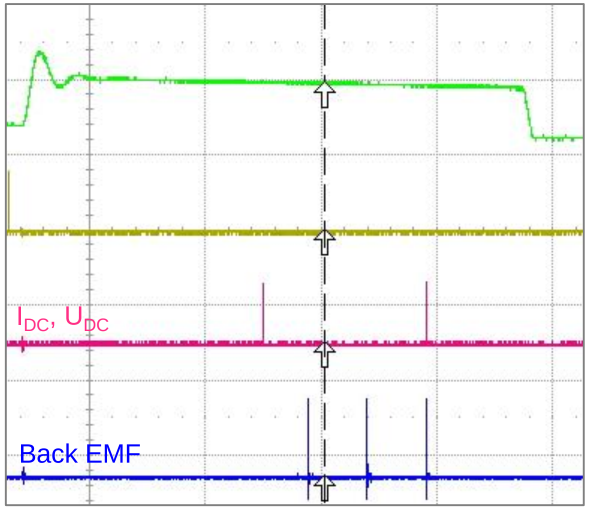


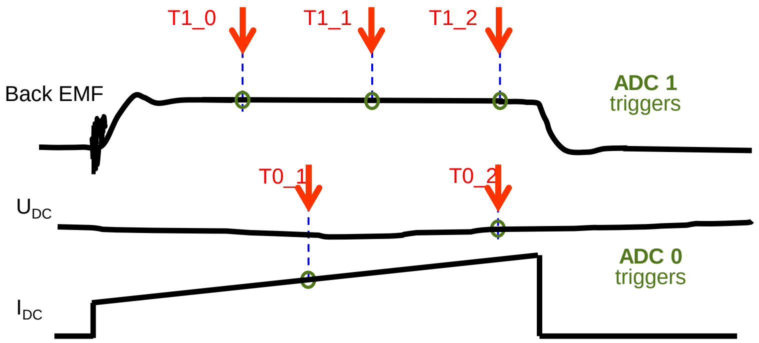
Not connected phase
- BEMF measurement

TG0 – linked w/ ADC0

TG1 – linked w/ ADC1

Measure	P1:freq(C1)	P2:freq(C2)	P3:freq(C3)	P4:freq(C4)	P5:rms(C1)	P6:mean(C3)
value	---	115.0965 kHz	196.2395 kHz	20.09181 kHz	3.498 V	12.4 mV

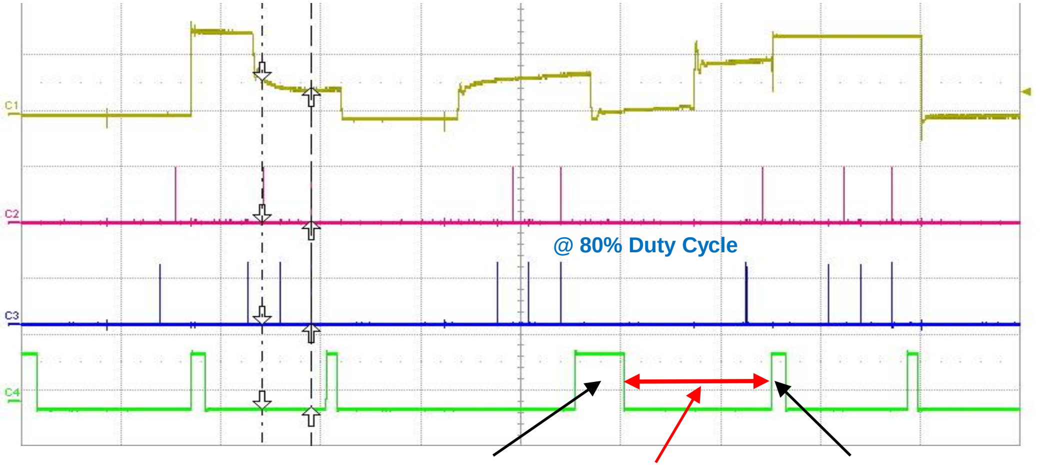




This example shows the advantage of S12ZVM to manage dynamically the trigger events, in other words, dynamically extend the Trigger List and Result Value List in RAM.

PTU Triggers Collisions @ Higher Speeds

Low-speed region

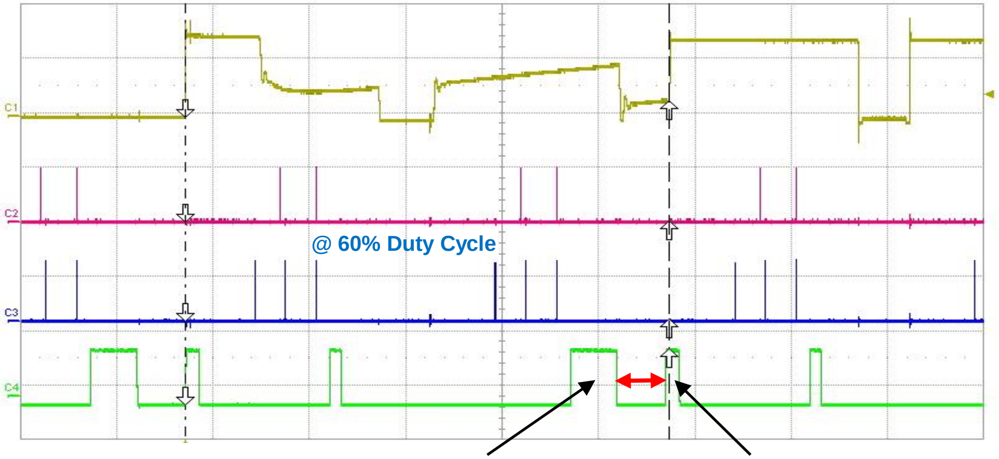


ADC ISR

Gap between ISRs

Com. ISR

Mid-speed region



ADC ISR

Gap between ISRs

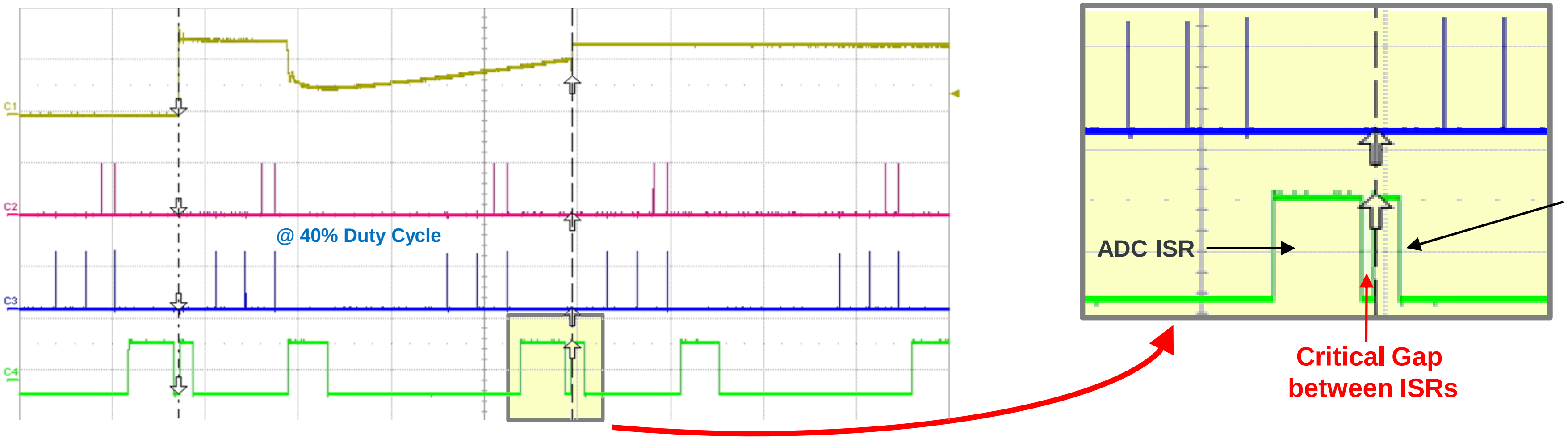
Com. ISR

Commutation ISR = 2.8µs

ADC ISR = 10µs

High-speed region

Detail



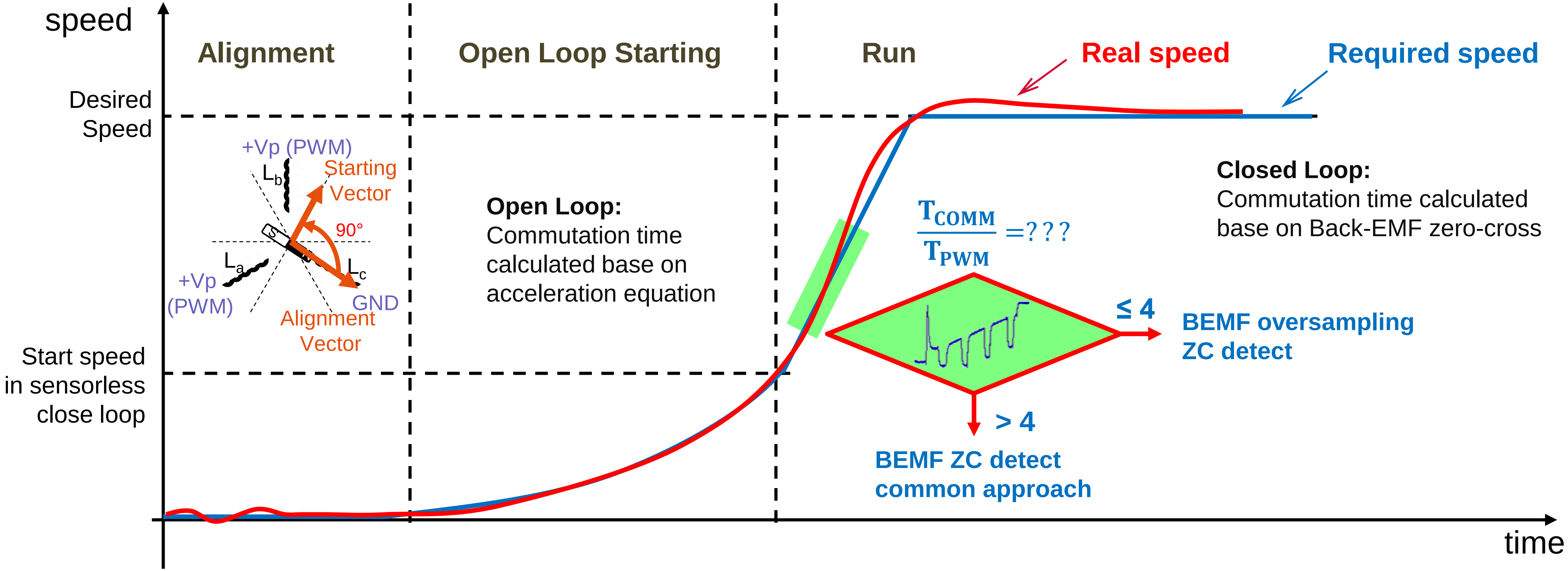
ADC ISR

Commutation ISR

Critical Gap between ISRs

BLDC Motor Startup States

The open-loop starting sequence ensures motor running at enough high speed and so the zero-cross events can be successfully detected and sensorless closed loop control can follow. In case the condition of too little PWM pulses within a commutation period is evaluated, the approach of detecting the BEMF zero-cross is switched from standard one to the BEMF oversampling technique.

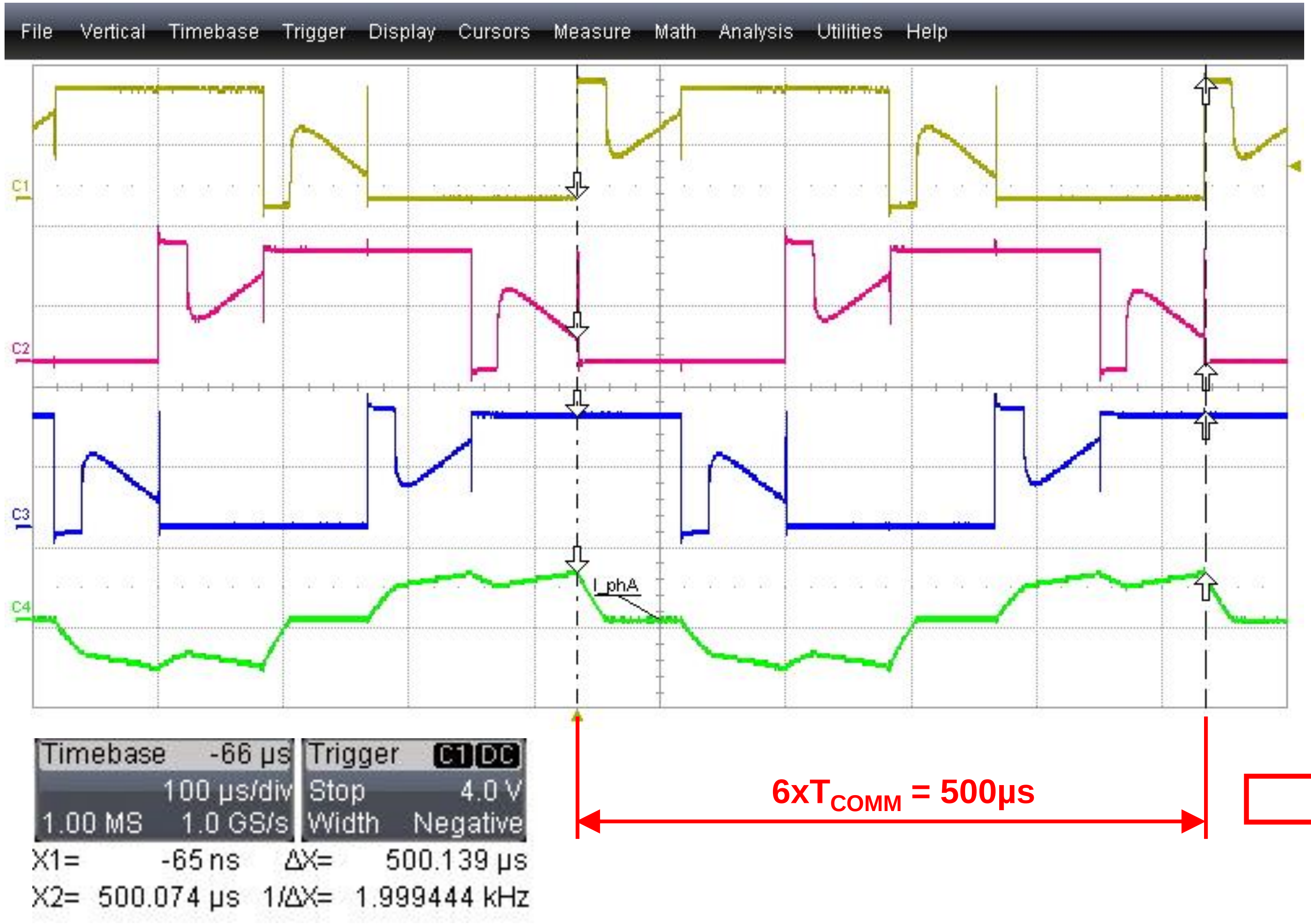


Open Loop:
Commutation time calculated base on acceleration equation

$$\frac{T_{COMM}}{T_{PWM}} = ???$$

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

Experimental Verification



Timebase -66 µs | 100 µs/div | 1.00 MS | 1.0 GS/s

Trigger C1 DC | Stop 4.0 V | Width Negative

X1= -65 ns ΔX= 500.139 µs

X2= 500.074 µs 1/ΔX= 1.999444 kHz

$6xT_{COMM}$ = 500µs

Rated mechanical speed = 60 000 rpm

Motor pole-pairs = 2

PWM frequency (T_{PWM}) = 20 KHz (50µs)

The commutation period:

$$T_{COMM} = \frac{1}{6 \times \frac{Nominal\ Speed_{[rpm]} \times Motor\_pp}{60}}$$

Resulting mechanical speed:

$$NominalSpeed_{[rpm]} = \frac{1}{6 \times T_{COMM}} \times \frac{60}{Motor\_pp}$$

$$\boldsymbol{Nominal\ Speed_{[rpm]} = 60\,000\ rpm}$$

$$\boldsymbol{Required\ Speed_{[rpm]} = 60\,000\ rpm}$$

PMSM FIELD ORIENTED CONTROL

SENSORLESS

Field Oriented Control Principle

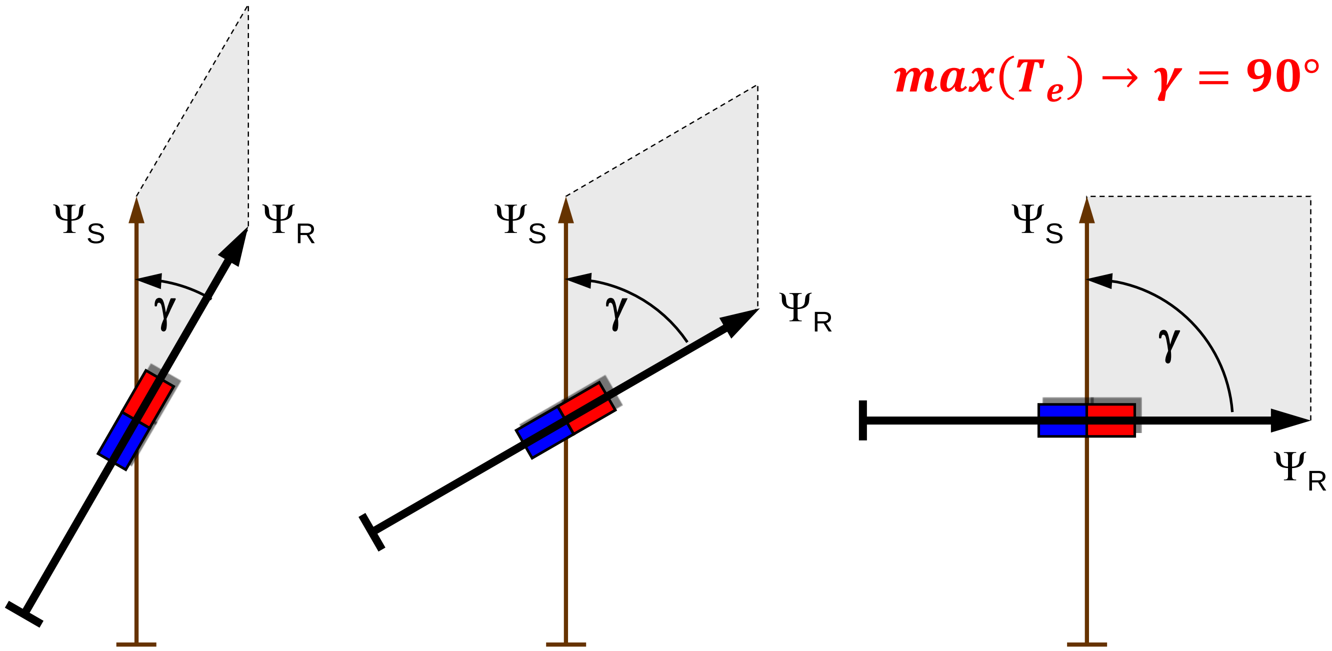
All is about magnetic fields interaction!

- Rotor Magnetic field
- Stator Magnetic field

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

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

$$\boldsymbol{max(T_e) \rightarrow \gamma = 90°}$$



FOC allows to control the motor at **max(T_e)**.

Why Field Oriented Control?

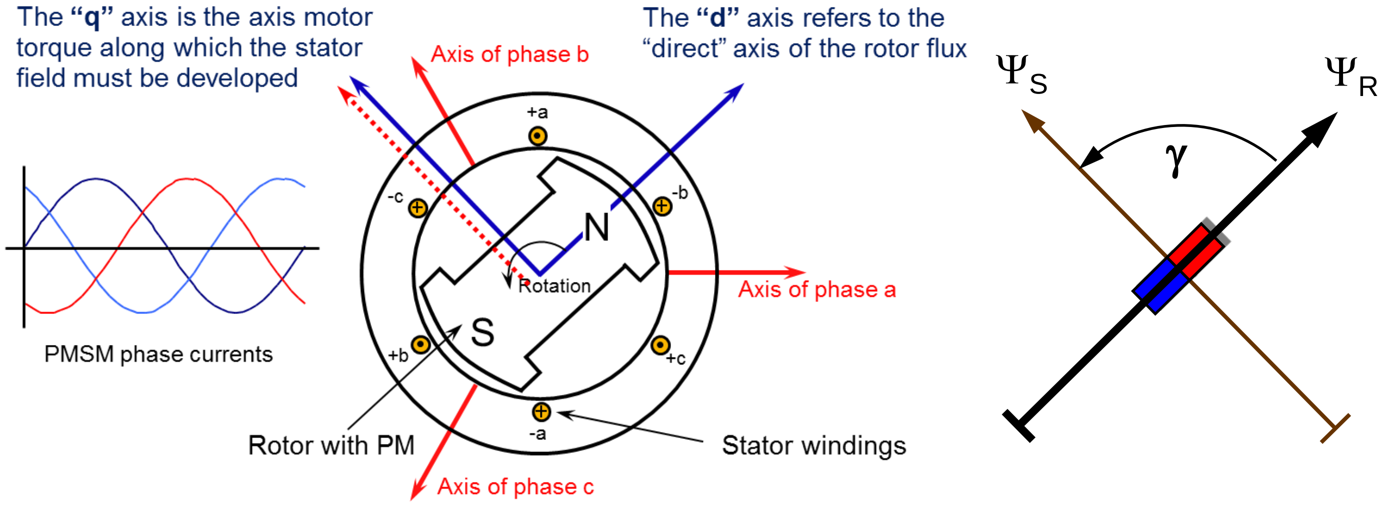
For a PMSM motor the 3 sinusodal phase currents have to be controlled to create a flux vector which is perpendicular to the rotor flux current

- To control the three sinusoidal currents independantly would be a very complex mathematical task

- FOC simplifies the math by transforming the 3 phase system to a DC motor system viewing angle

- FOC decomposes the stator current into two components:
  - i_D – Flux-producing component
  - i_Q – Torque-producing component

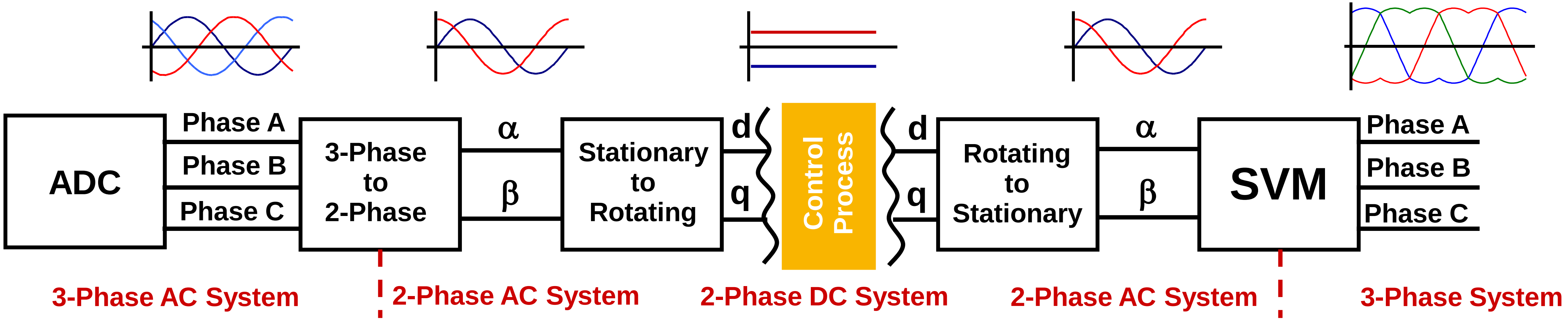
- Better performance
  - Full motor torque capability at low speed
  - Better dynamic behavior
  - Higher efficiency for each operation point in a wide speed range
  - Decoupled control of torque and flux
  - Natural four quadrant operation


The **“q”** axis is the axis motor torque along which the stator field must be developed

The **“d”** axis refers to the “direct” axis of the rotor flux

PMSM phase currents

Field Oriented Control in Steps

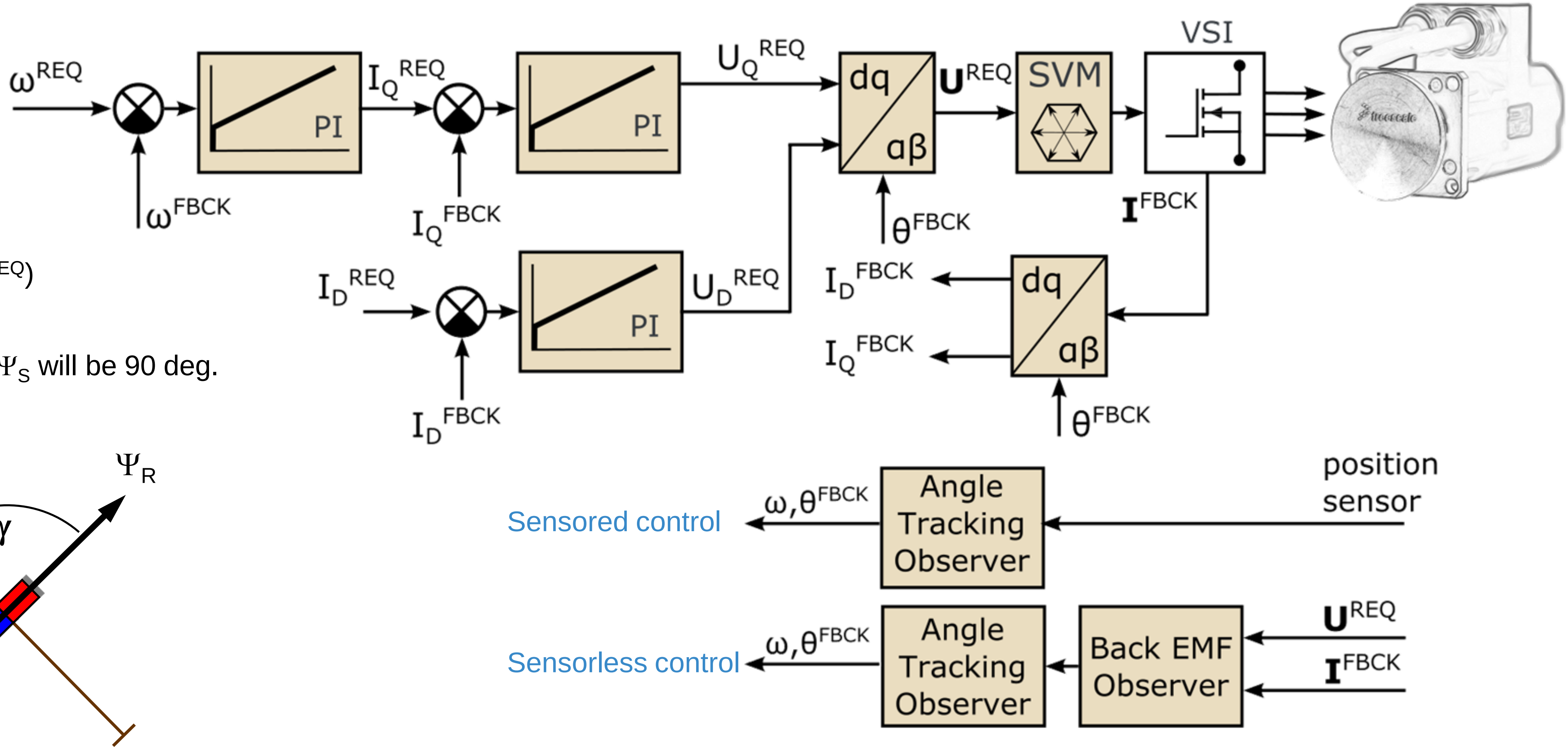


1. Measure obtain state variables quantities (e.g. phase currents, voltages, rotor position, rotor speed …).
2. Transform quantities from 3-phase system to 2-phase system (Forward Clark Transform) to simplify the math - lower number of equations
3. Transform quantities from stationary to rotating reference frame - “rectify” AC quantities, thus in fact transform the AC machine to DC machine
4. Calculate control action (when math is simplified and machine is “DC”)
5. Transform the control action (from rotating) to stationary reference frame
6. Transform the control action (from 2-phase) to 3-phase system
7. Apply 3-phase control action to el. motor

Transformation benefits:

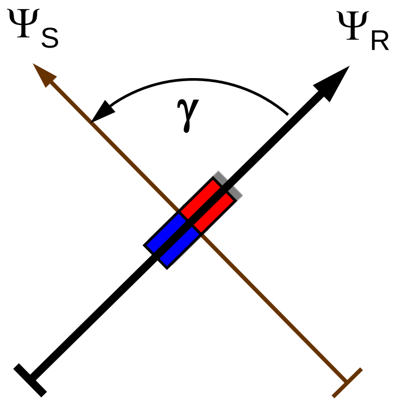
- Reduce 3ph system to 2ph system
- Eliminates the AC component

FOC PMSM Control Structure

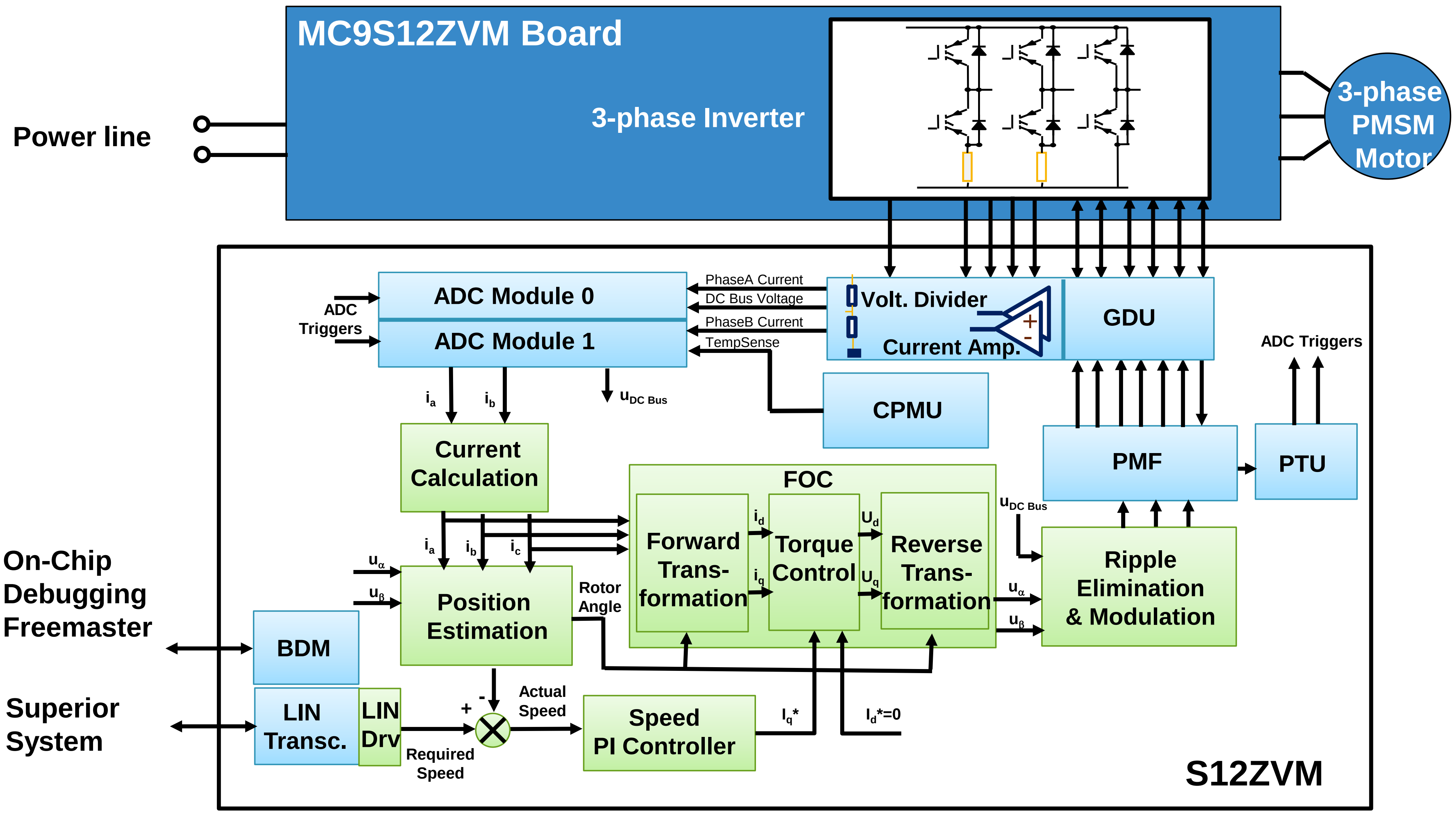


$\Psi_S = f(I_Q^{REQ}, I_D^{REQ})$

If $\mathbf{I_D^{REQ}}$ **= 0** then Ψ_S will be 90 deg. shifted to Ψ_R.



Sensorless PMSM Control Block Diagram on S12ZVM

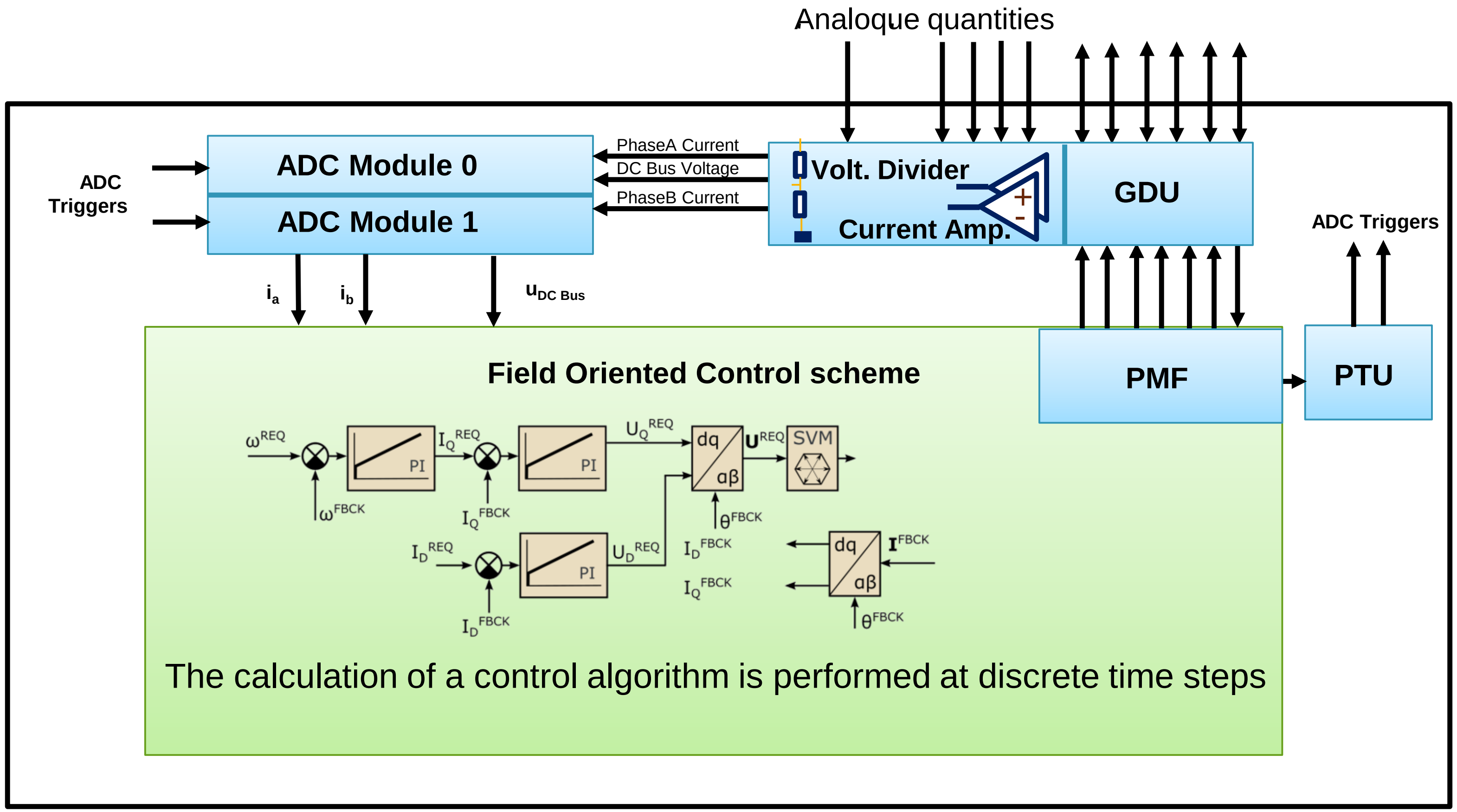


DISCRETE CONTROL THEORY

Discrete Control Introduction

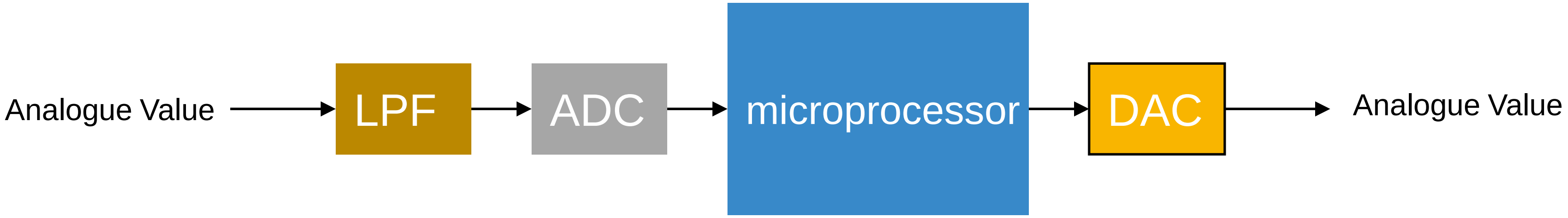
Discrete Control System is a system, where at least one continuous variable in the system is transformed at periodic time instances into the time sequence of numeric values (train of samples).

The A/D peripheral module receives the analog signal proportional to the motor current and DC bus voltage.
The samples of the motor current are converted into digital words and used as the feedback signal to the current controller.



The calculation of a control algorithm is performed at discrete time steps

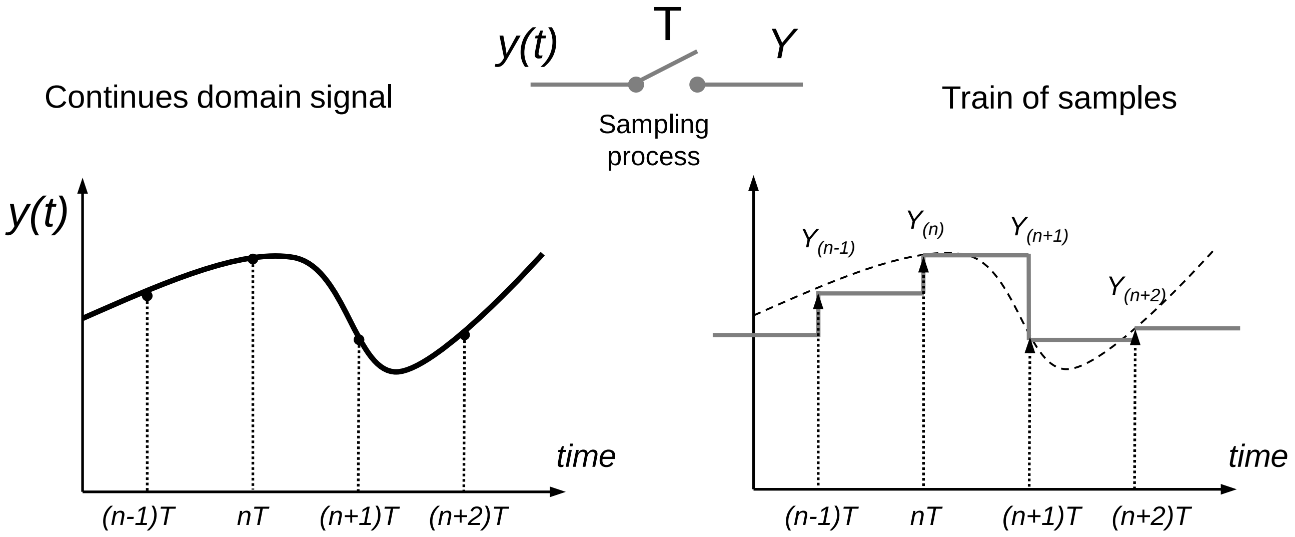
Signal Data Handling in MC Systems



- Most of the motor control system uses typical signal processing structure
  - The output of the ADC is a stream of sampled **fixed word** length values which represent the analogue input signal at the discrete sample points
  - The resolution of these samples is thus limited to the data representation width internal to the ADC and microprocessor
- This means, a value (translated from the analogue domain) which would be one of an infinite possible values must be represented by one from a finite word length system
- Proper signal scaling and data formatting must be done to **avoid overflow** and **achieve** required **resolution**

Sampling Process

The loss of information is the inevitable consequence of the sampling process. Indispensable for the digital implementation of control laws, the sampling relates to the conversion of signals from their real-time, continuous domain form y(t), into their digital counterparts (Yn). The sample Yn is the digital word representing the analog signal y(t) acquired at the instant t = nT, converted into a number to be used by the control algorithm.



The digital implementation implies an intrinsic deterioration of signals due to time and amplitude discretization

Rules to Select Right Sampling Period

Content TBD …

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