FTF | FREESCALE TECHNOLOGY FORUM 2015

High-Performance Motor Control
for Space Control Application

FTF-ACC-F1373

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JUNE.2015

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External Use

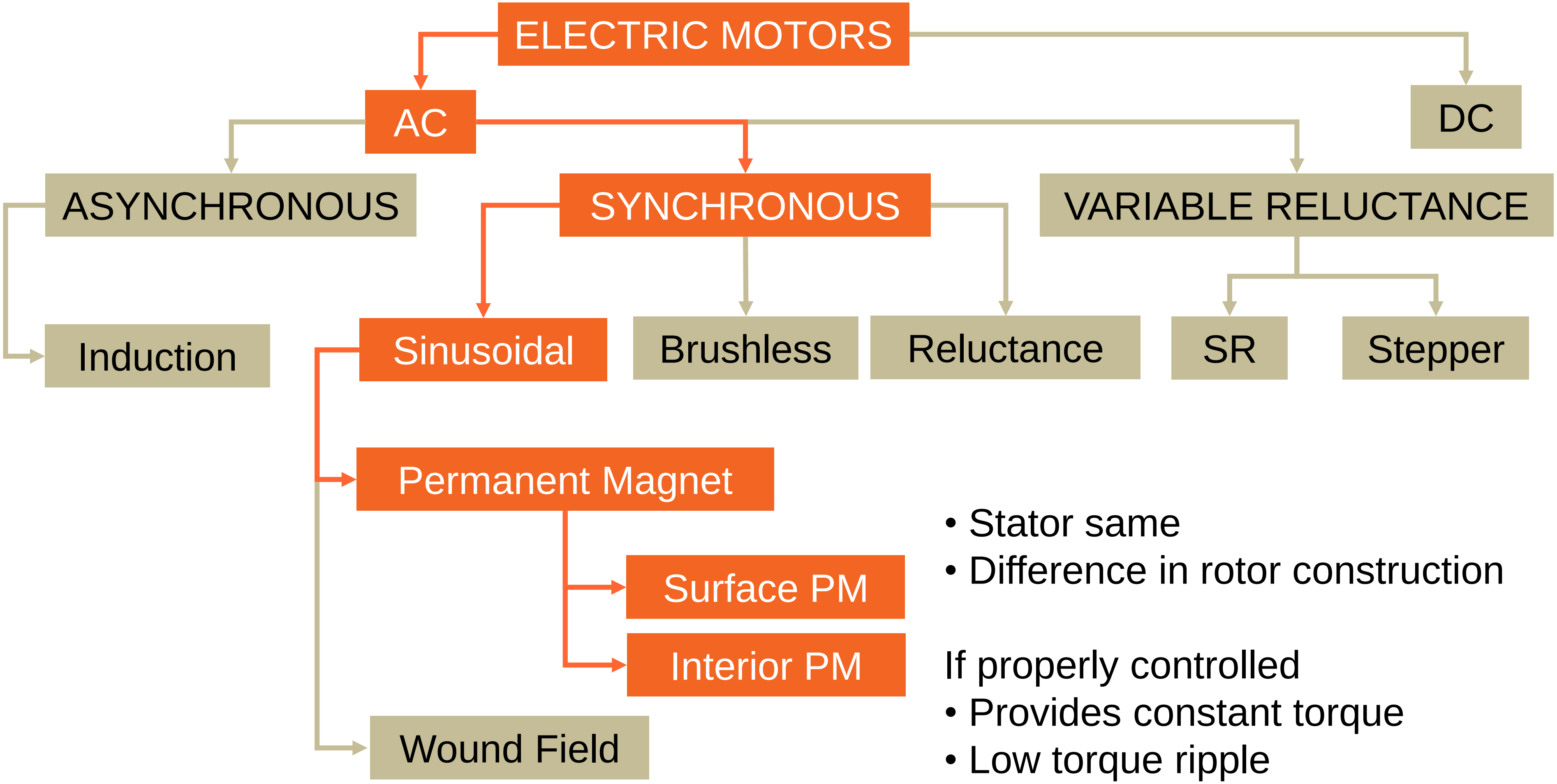
Agenda

- Motor Classification
- Field Oriented Control (FOC) Basics
- FOC Current Loop Design
  - Flux control
  - Torque control
- 3-Phase PMSM FOC Application
  - Current Sensing and Processing
  - Position Sensing and Processing
  - Three Phase Voltage Generation
- Special Motor Control Features on S12ZVM
- PMSM Field Oriented Control Using S12ZVM
- S12ZVM Ecosystem — The Complete Solution
- Summary

Motor Classification

- ✓ **Asynchronous vs. Synchronous**
  Rotor and stator construction, windings, PM magnets
- ✓ **Trapezoidal vs. Sinusoidal PM Machine**
  BLDC, PMSM, flux distribution, Back-EMF shapes, six-step commutation, FOC

Electric Motor Type Classification



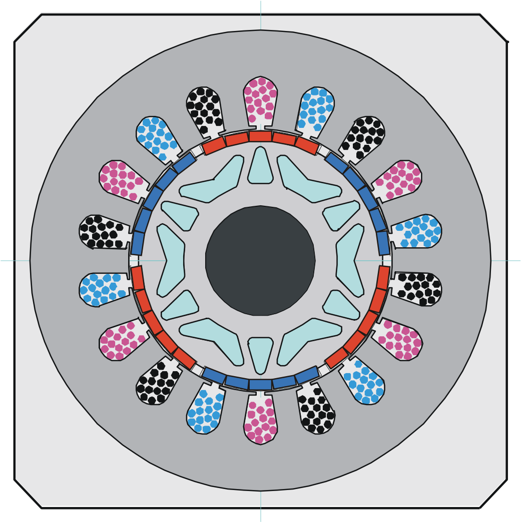
- Stator same
- Difference in rotor construction

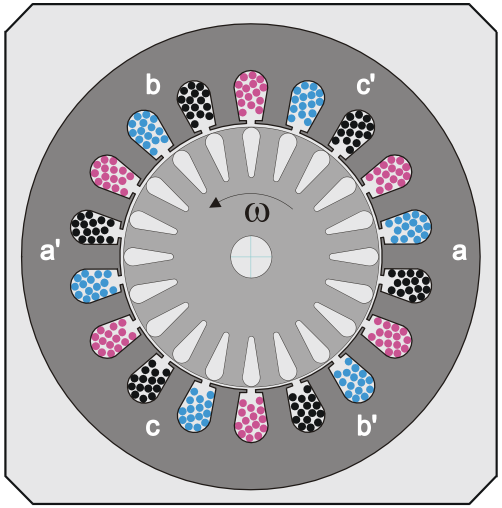
If properly controlled

- Provides constant torque
- Low torque ripple

Asynchronous vs. Synchronous

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



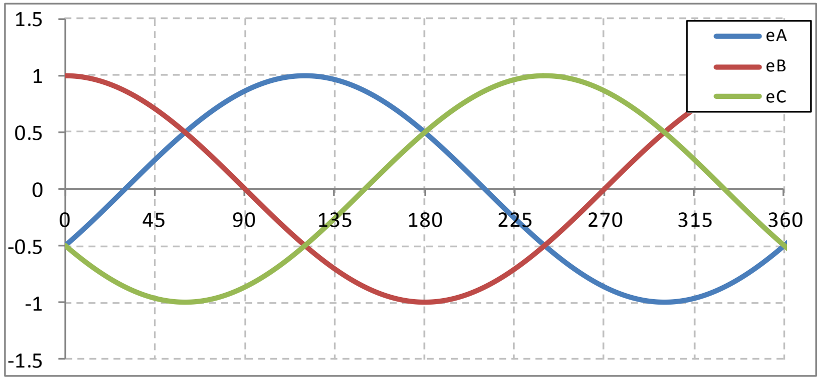


Trapezoidal vs. Sinusoidal PM Machine

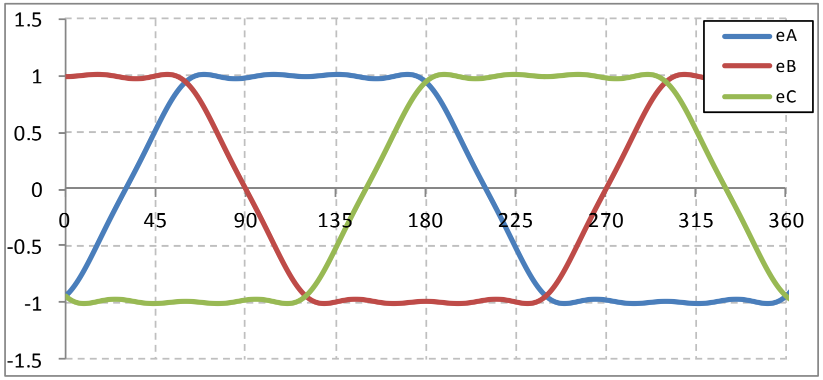
- Sinusoidal" or "Sinewave" machine means Synchronous (PMSM)
- Trapezoidal means brushless DC (BLDC) motors
- Differences in flux distribution
- Six-Step control vs. **F**ield-**O**riented **C**ontrol
- Both requires position information

- 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 more complex



Sinusoidal flux distribution — PMSM Motor



Trapezoidal flux distribution — BLDC Motor

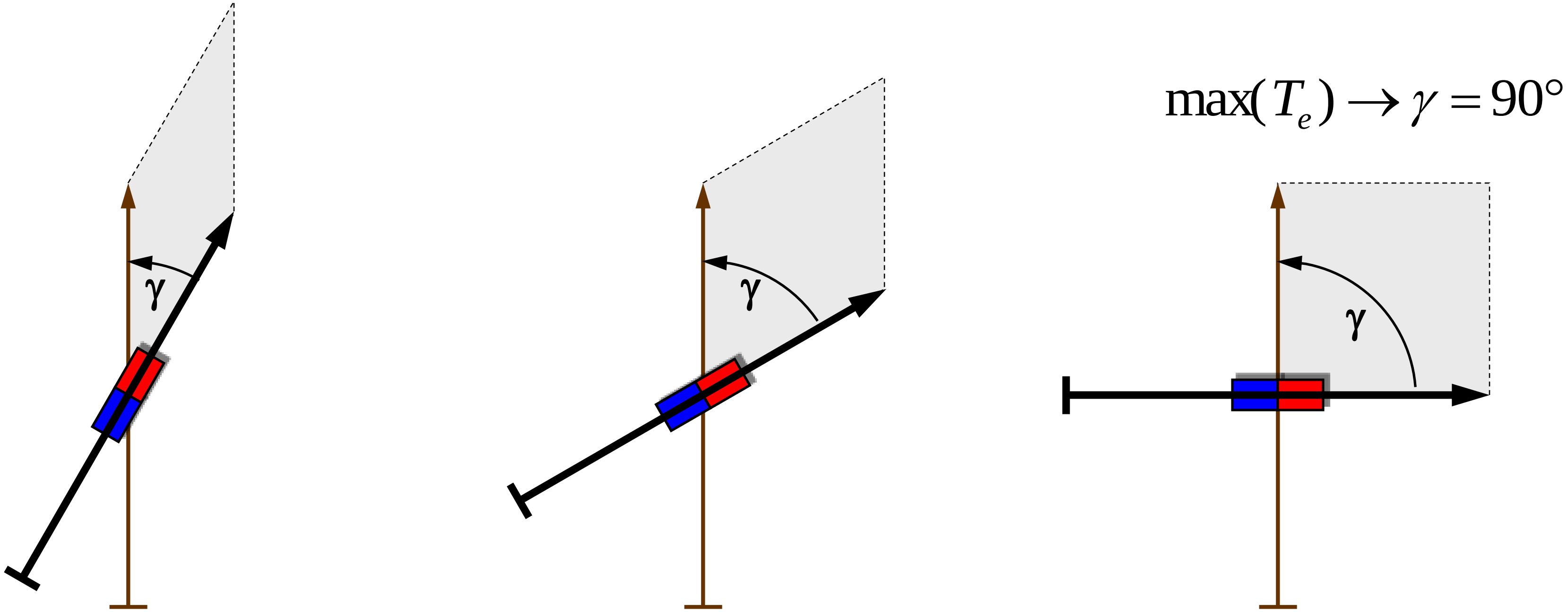
Field Oriented Control

- ✓ **FOC Basics**
  Torque production principle, rotating magnetic field, space vector, FOC transformations
- ✓ **FOC Design**
  Design of control, model, current controller gain calculation, zero cancelation
- ✓ **Current Sensing and Processing**
  Shunt current measurement , ADC triggering, delays involved in PWM driven closed loops
- ✓ **Position Sensing, Sensorless Methods**
  Position processing, sensorless methods, position estimation, saliency based Back-EMF
- ✓ **Three Phase Voltage Generation**
  Basic sinusoidal modulation, modulation index, standard Space Vector Modulation, DC-bus ripple compensation

Torque Production Principle

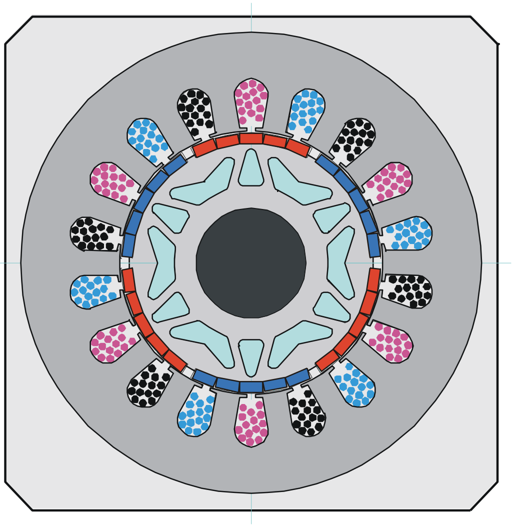
- Electromagnetic torque production by the stator magnetic flux and magnet flux space vectors

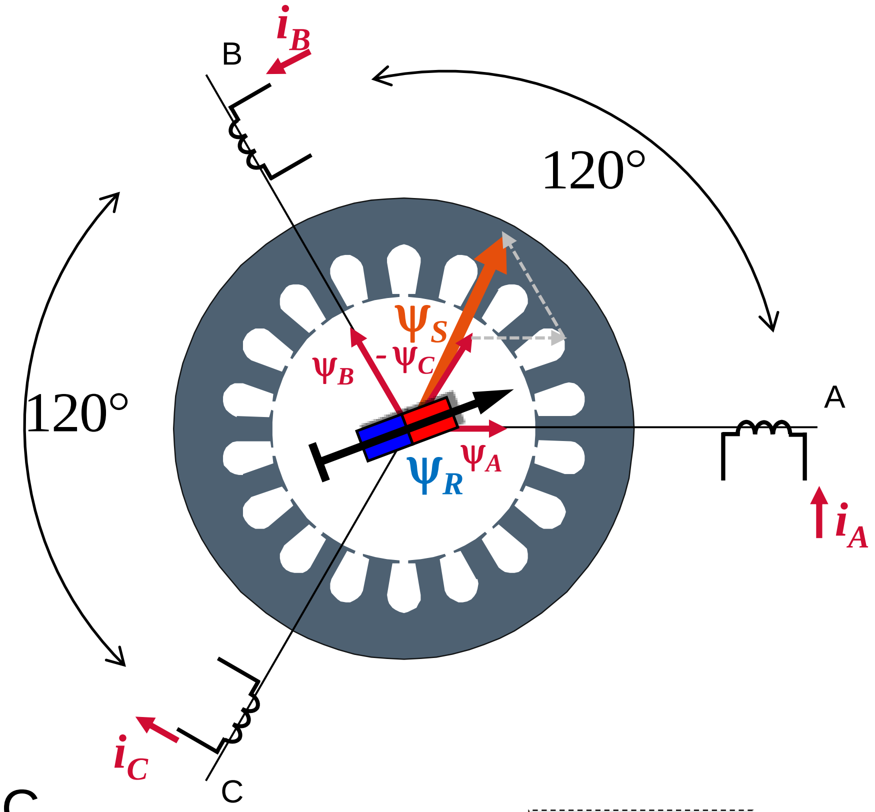
$$T_e = c \cdot \Psi_R \times \Psi_S = c \cdot \left|\Psi_R\right| \cdot \left|\Psi_S\right| \cdot \sin\gamma$$



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

FOC for PMSM

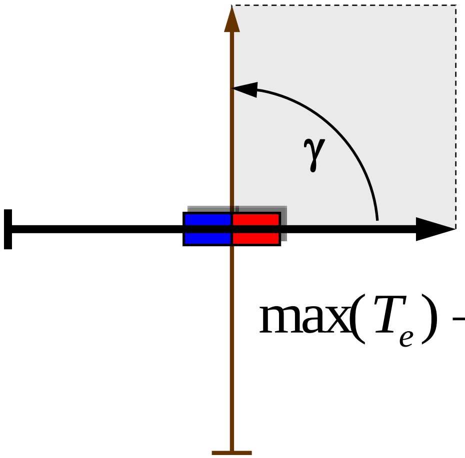




- Controlling currents in phase A,B,C amplitude and position of stator flux vector is controlled as well

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

- Maintaining the angle between stator and rotor flux at 90° torque is maximized

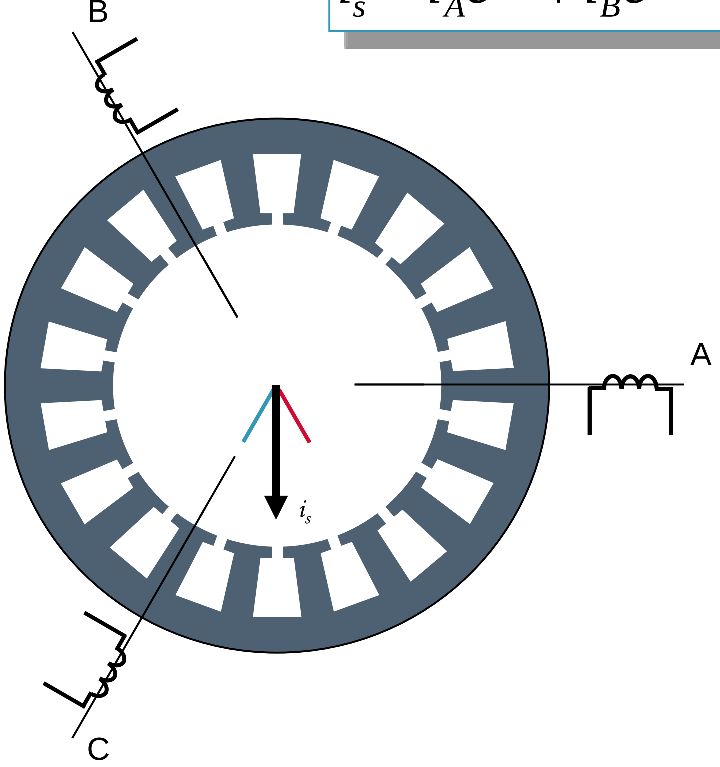


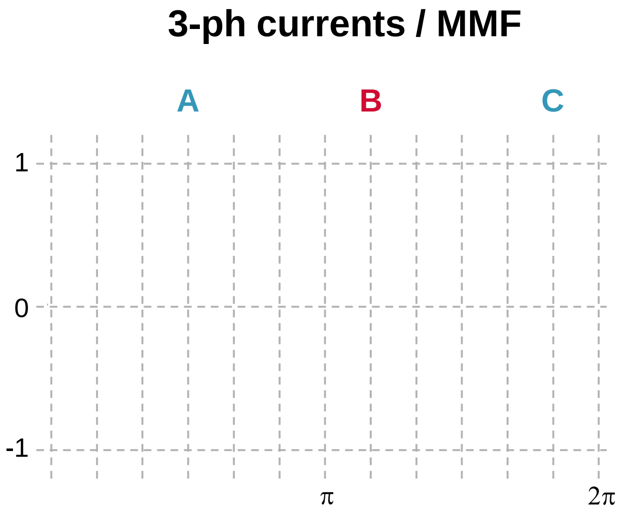
$$\max(T_e) \rightarrow \gamma = 90°$$

Creation of Rotating Magnetic Field

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

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

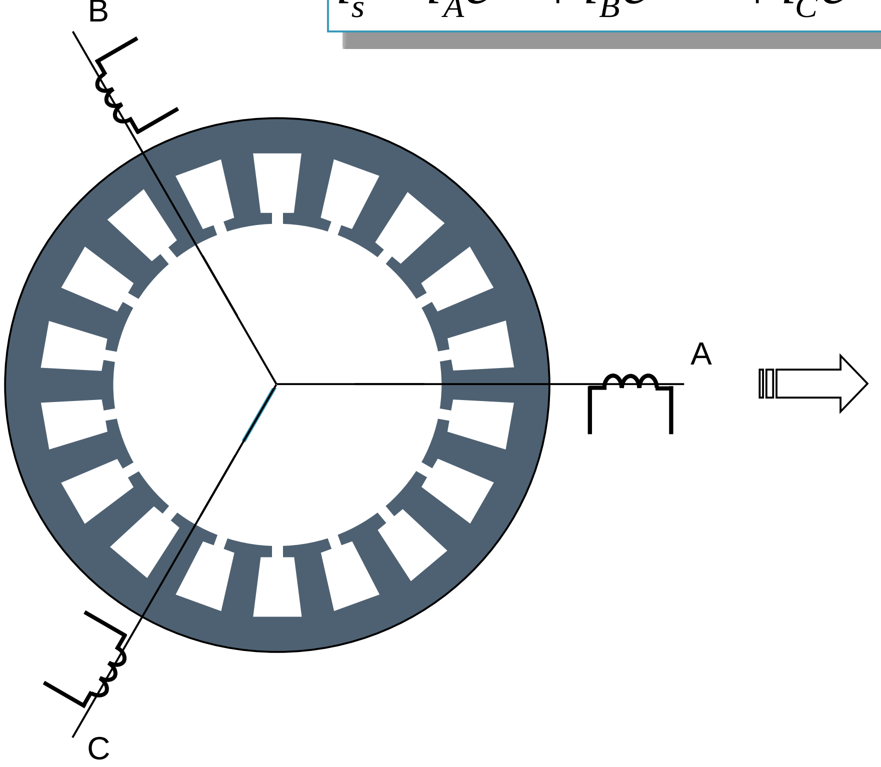


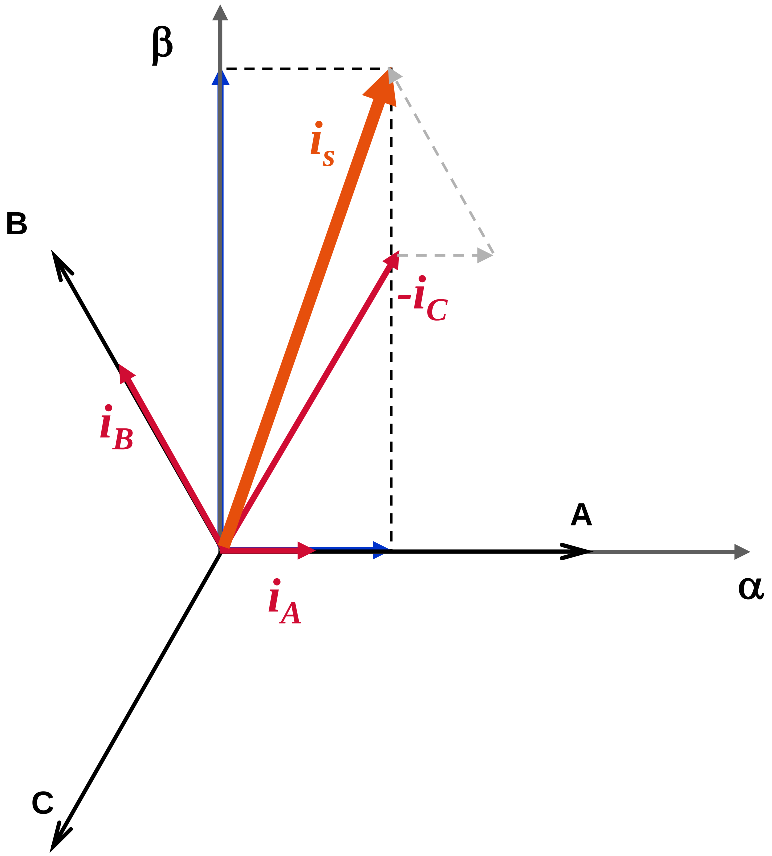


Creating Space Vector

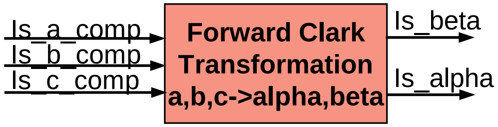
- Because the space vector is defined in the plain (2D), it is sufficient to describe space vector in 2-axis (α,β) coordinate system

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



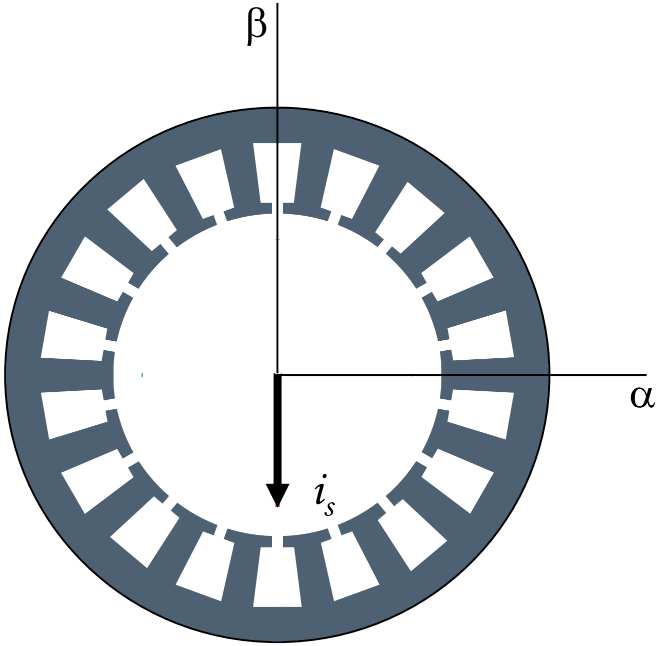


Transformation to 2-ph Stationary Frame


Is_a_comp
Is_b_comp
Is_c_comp

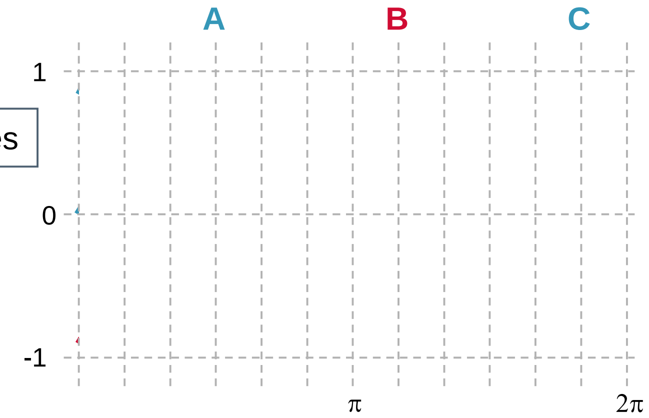
Forward Clark Transformation a,b,c->alpha,beta

Is_beta
Is_alpha

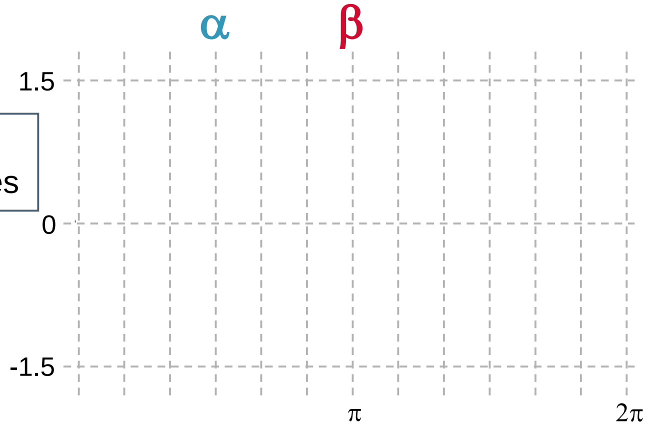


3-ph quantities

3-ph currents / MMF

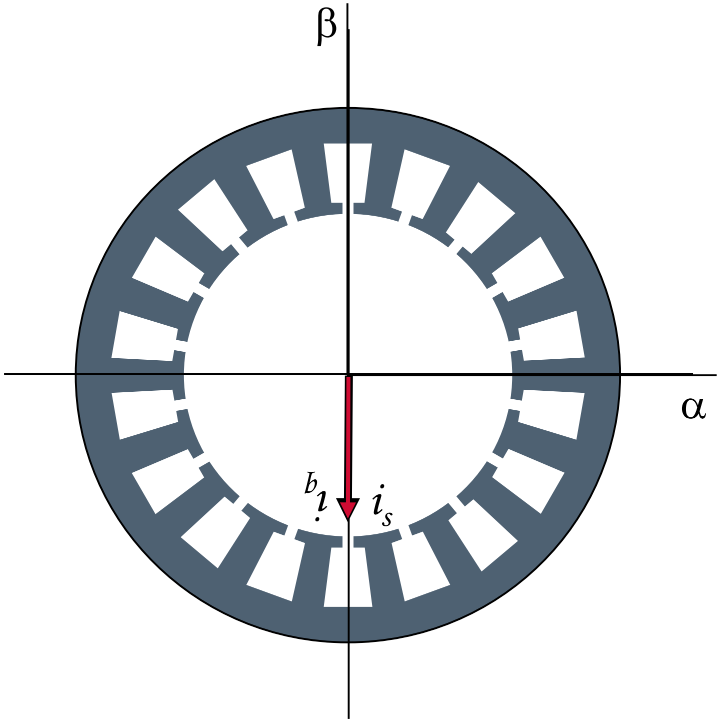


Stationary
2-ph quantities

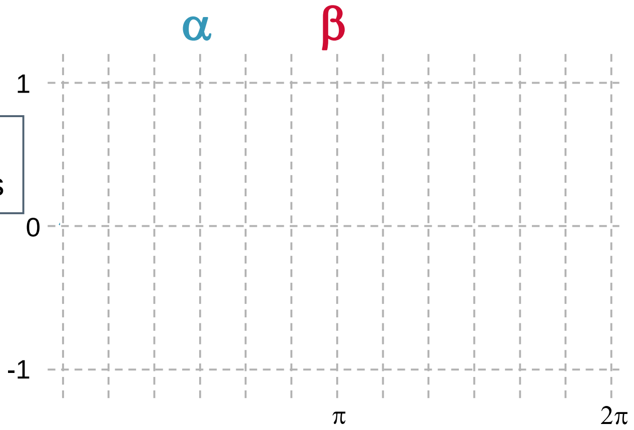


Transformation to 2-ph Synchronous Frame

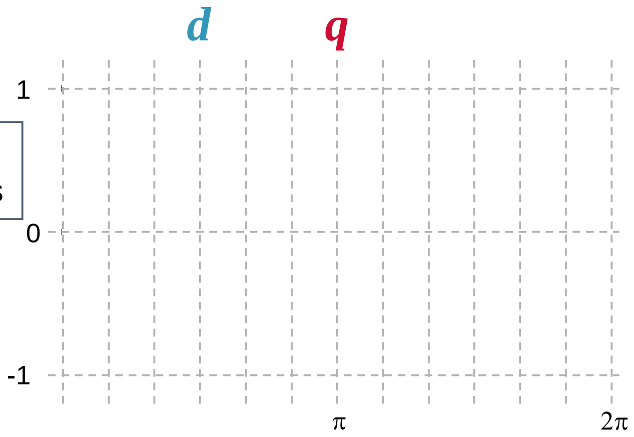
- Position and amplitude of the stator flux/current vector is fully controlled by two DC values



Stationary
2-ph quantities



Rotating
2-ph quantities



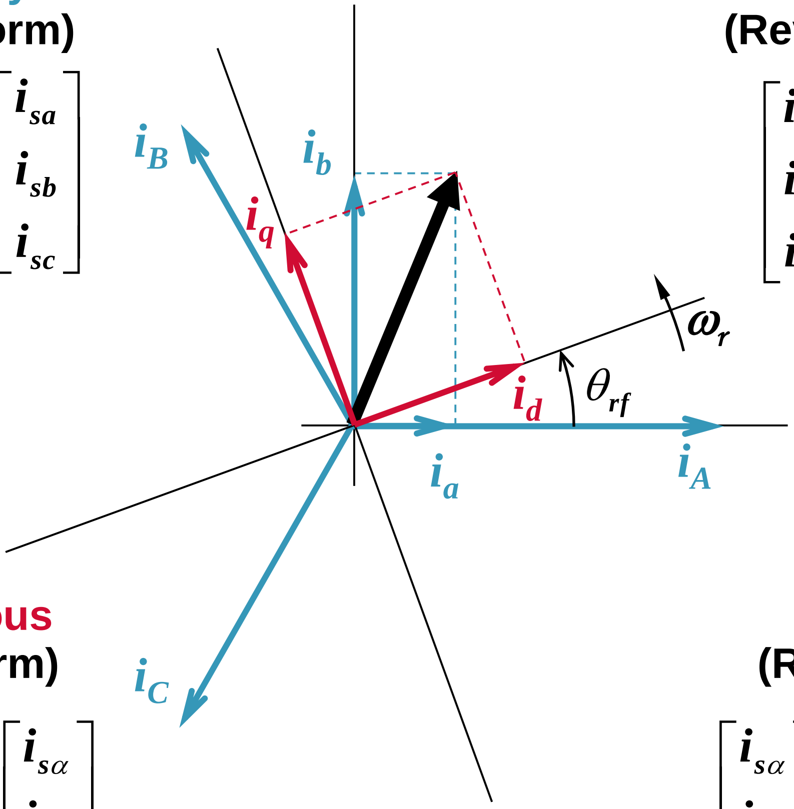
Transformations Summary

3-phase Stationary to 2-phase Stationary (Forward Clark Transform)

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} \frac{3}{2} & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}$$

2-phase Stationary to 3-phase Stationary (Reverse Clark Transform)

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}$$



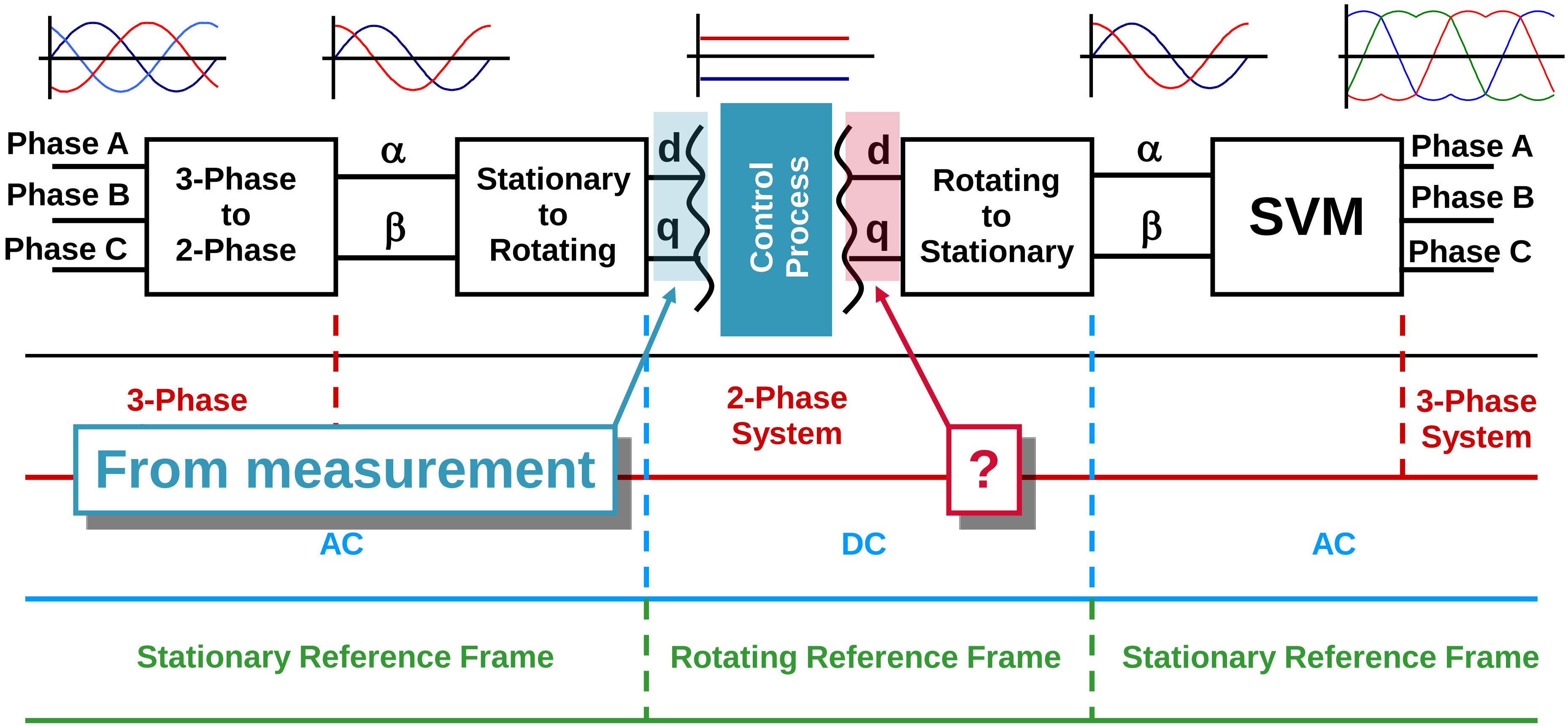
2-phase Stationary to 2-phase Synchronous (Forward Park Transform)

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta_{rf} & \sin\theta_{rf} \\ -\sin\theta_{rf} & \cos\theta_{rf} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}$$

2-phase Synchronous to 2-phase Stationary (Reverse Park Transform)

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta_{rf} & -\sin\theta_{rf} \\ \sin\theta_{rf} & \cos\theta_{rf} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}$$

FOC Transformation Sequencing



Field Oriented Control in Steps

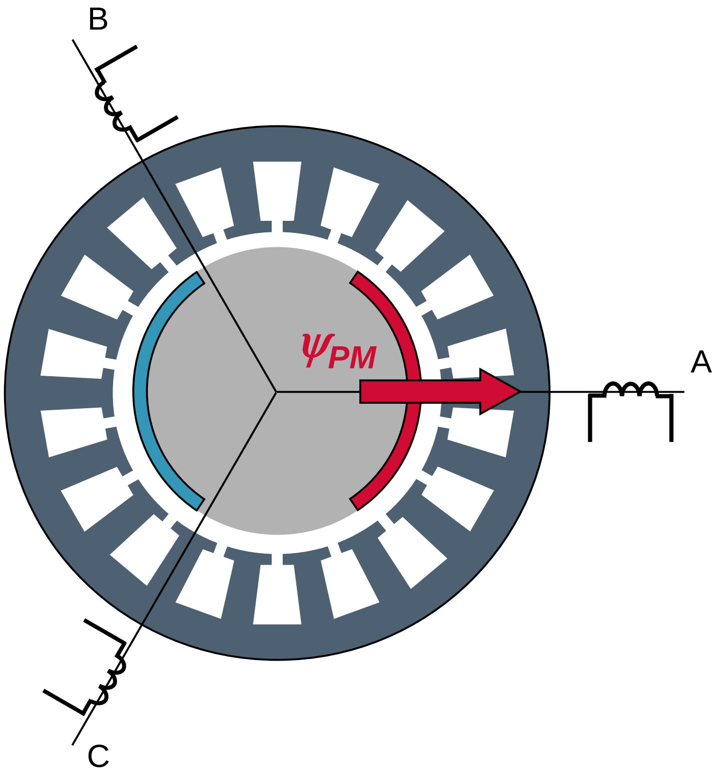
- ✓ Measure and obtain state, variables and quantities (e.g., phase currents, voltages, rotor position, rotor speed)
- ✓ Transform quantities from 3-phase system to 2-phase system (Forward Clark Transform) to simplify the math — lower number of equations
- ✓ Transform quantities from stationary to rotating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

PMSM FOC

Design of control, model, current controller gain calculation, zero cancelation

3-phase PMSM Model

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



Stator voltage equations

Forward Clarke

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

Stator linkage flux

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

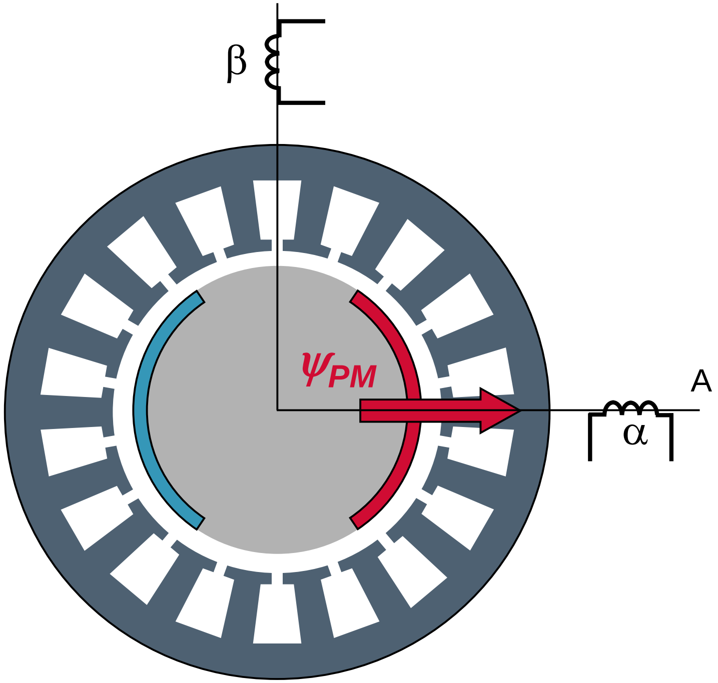
Internal motor torque

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

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

2-phase PMSM Model

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



Stator voltage equations

Forward Park

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

Stator linkage flux

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

Internal motor torque

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

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

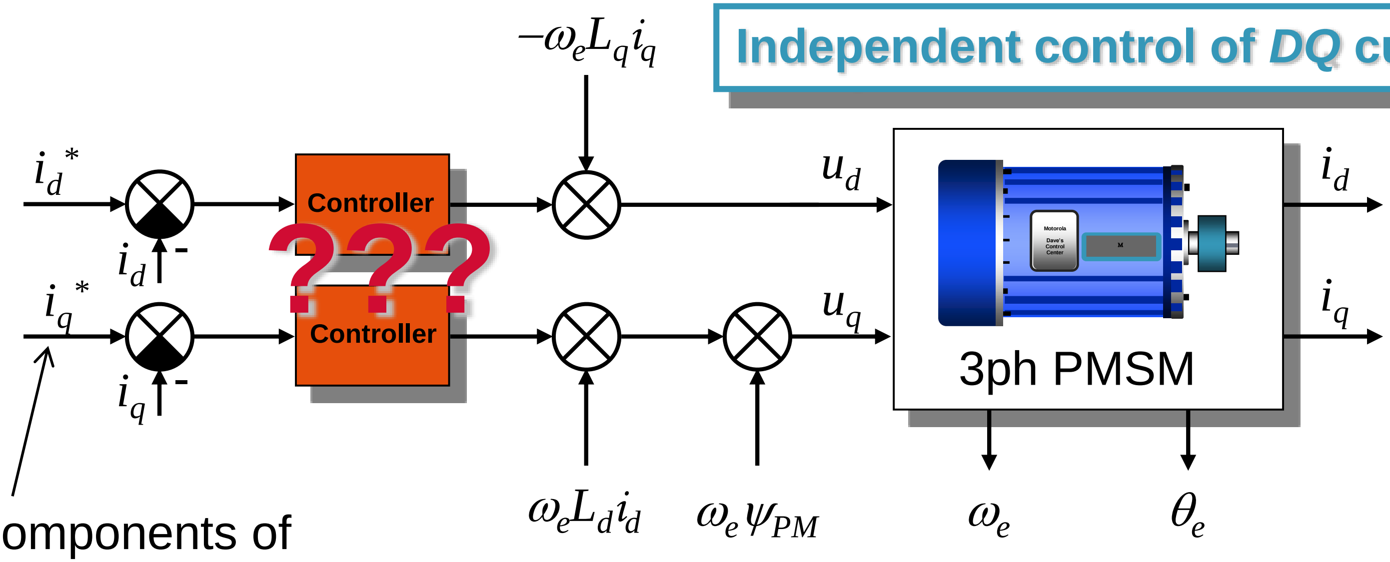
$$T_i = \frac{3}{2} \frac{p_p}{\omega_e} (u_{id} i_d + u_{iq} i_q) = \frac{3}{2} p_p (\Psi_d i_q - \Psi_q i_d) = \frac{3}{2} p_p \cdot \Psi_{PM} i_q$$

PMSM Current Control

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

R-L circuit **cross-coupling** **backEMF**

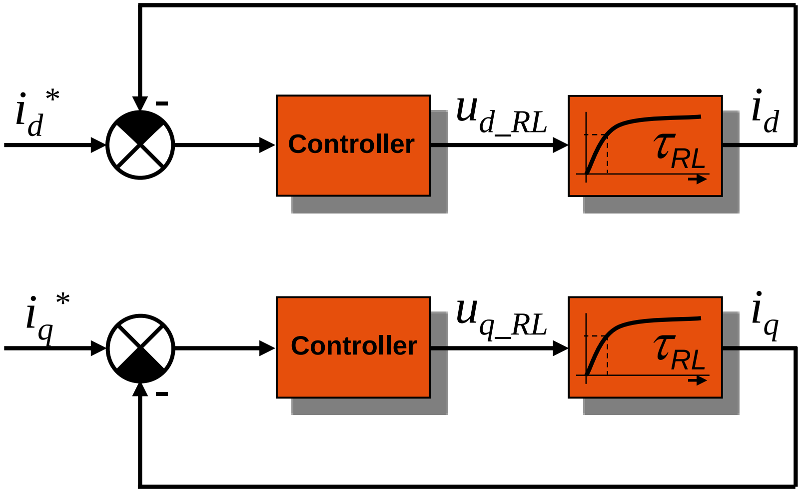
Independent control of *DQ* currents



Two axis components of required current vector

PMSM Current Control

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



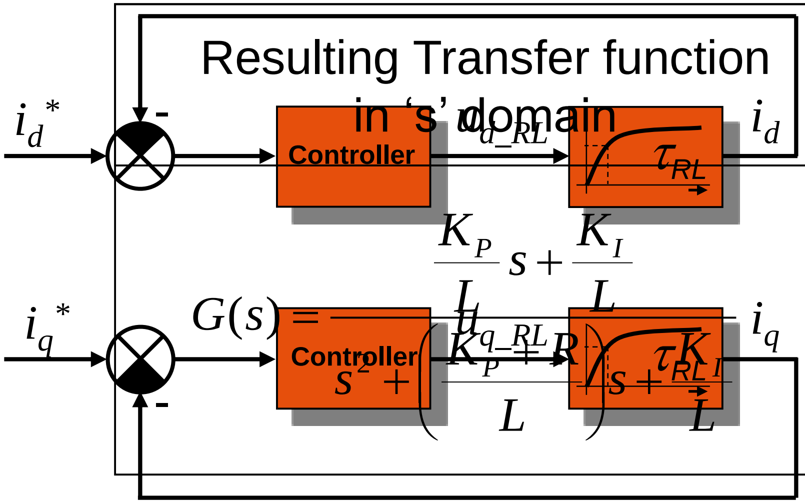
Transfer functions of PI controller and RL model in ‘s’ domain

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

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

PMSM Current Control

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

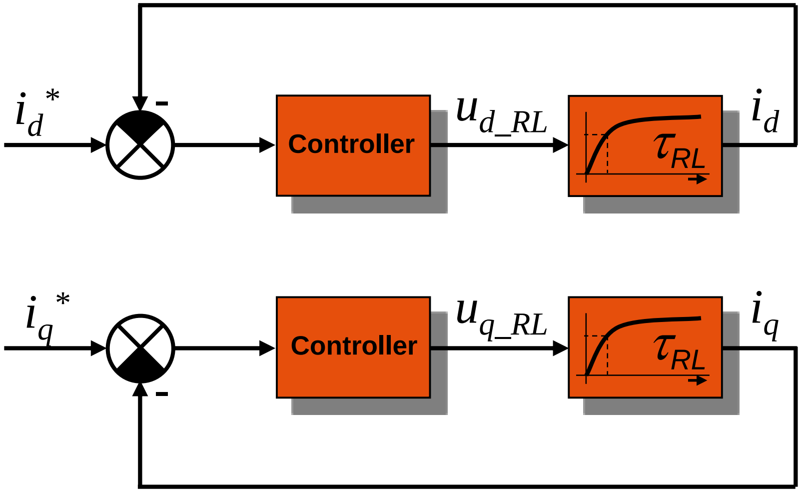


Resulting Transfer function in ‘s’ domain

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

PMSM Current Control

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



Resulting Transfer function
in 's' domain

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

Zero Cancelation

- Design of the controller gains can be done by matching coefficients of characteristic polynomial with those of an ideal 2nd order system.

Transfer function of current loop

zero

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

Transfer function of ideal 2nd order system

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

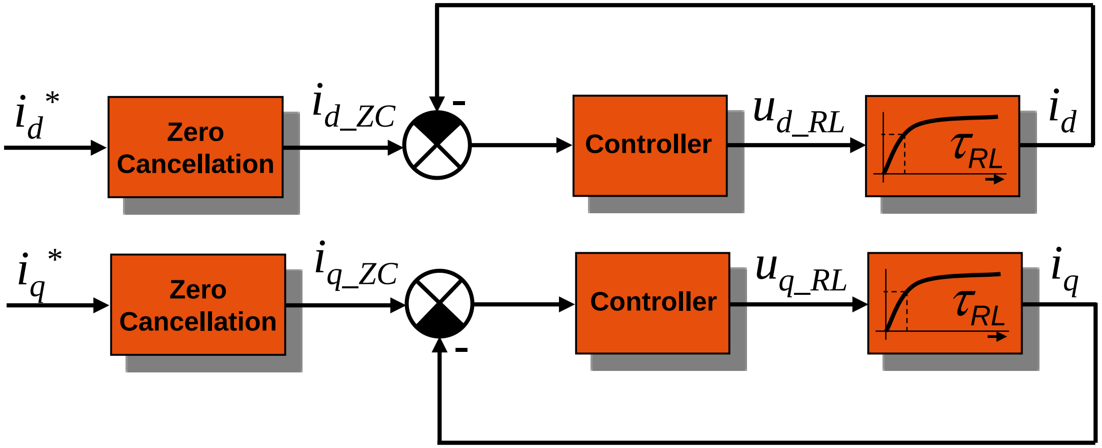
- "Zero" introduced by PI controller at $-K_P/K_I$ adds derivative behavior to the closed loop, creating overshoot during step response

ξ – is damping factor

ω_0 – is natural frequency

Zero Cancelation

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



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

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

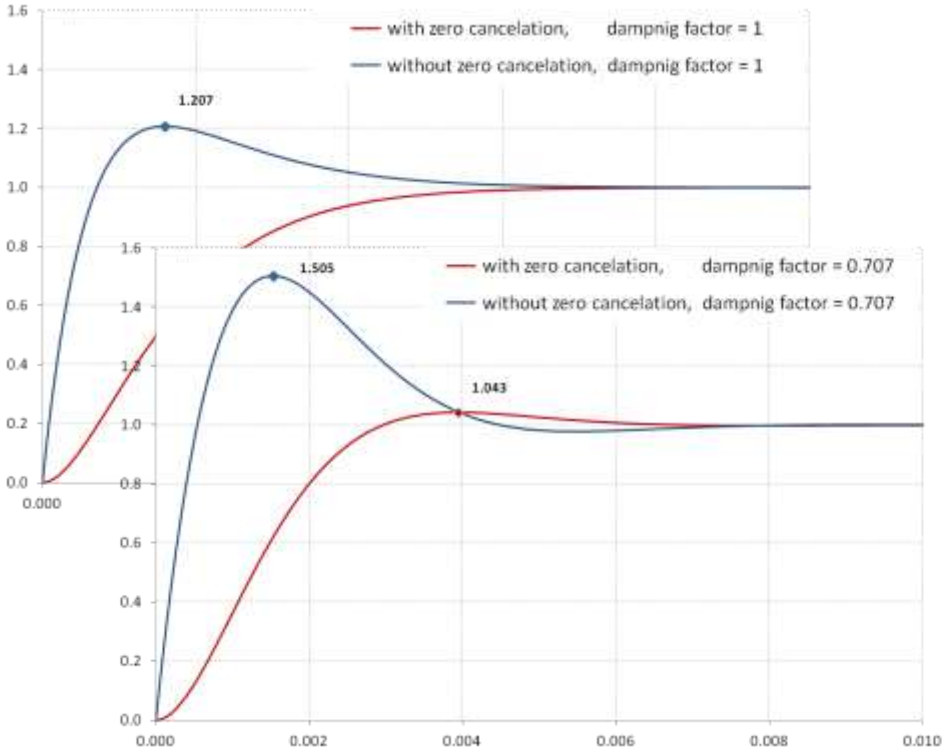
$$G(s) = \frac{\frac{K_I}{L}}{s^2 + \left(\frac{K_P + R}{L}\right)s + \frac{K_I}{L}}$$

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

PI controller gains

$$K_I = \omega_0^2 L$$

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

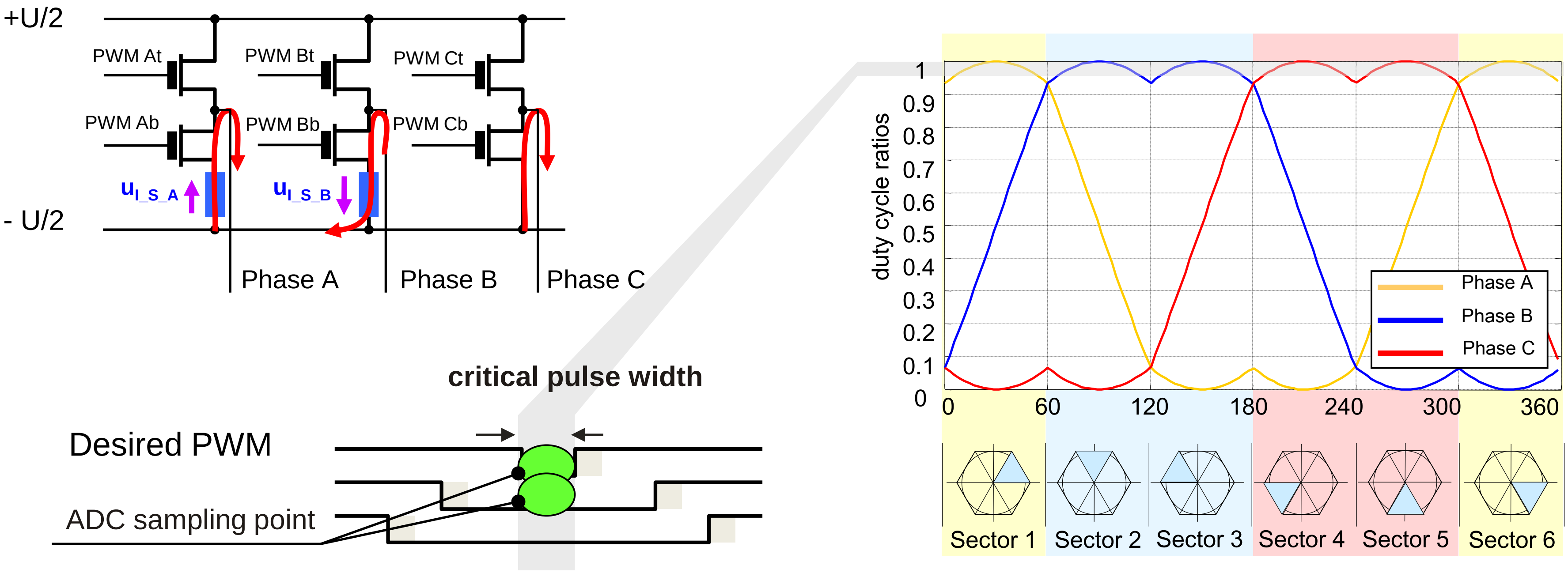


PMSM FOC

Current Sensing and Processing

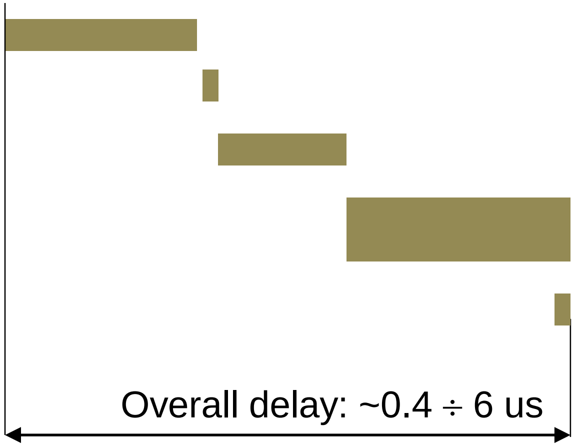
Current Sensing

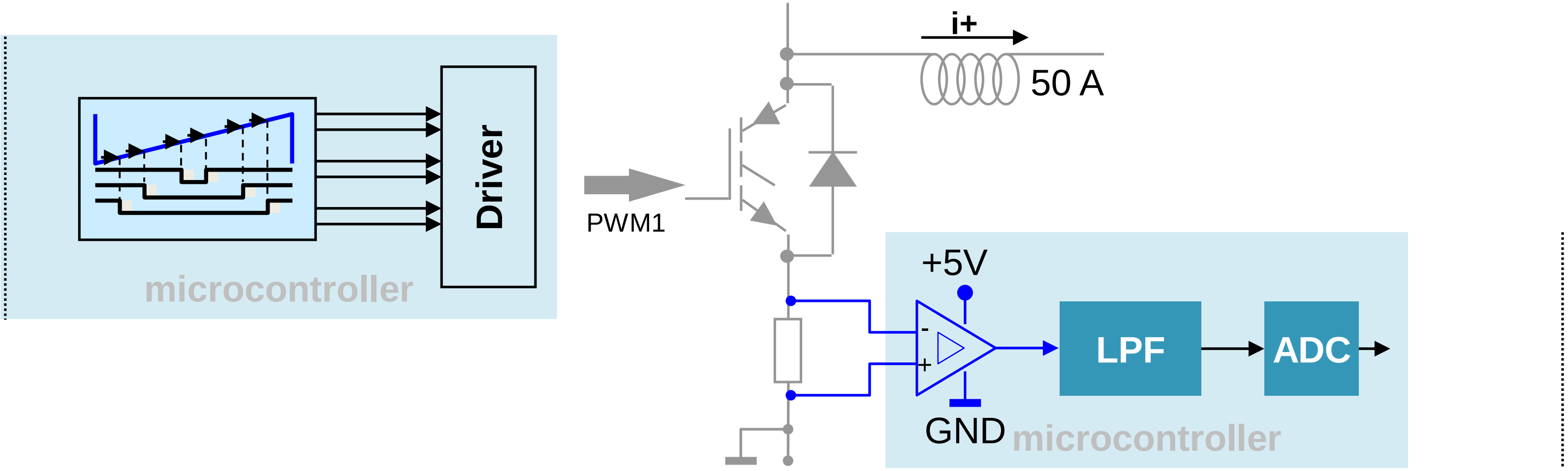
- Bottom transistor must be switched on at least for a critical pulse width to get stabilized current shunt resistor voltage drop
- At any time, this rule needs to be accomplished for the legs where the shunts are located.
- Minimum pulse width defined by system delays and ADC sampling time



Delays Involved in PWM Driven Closed Loops

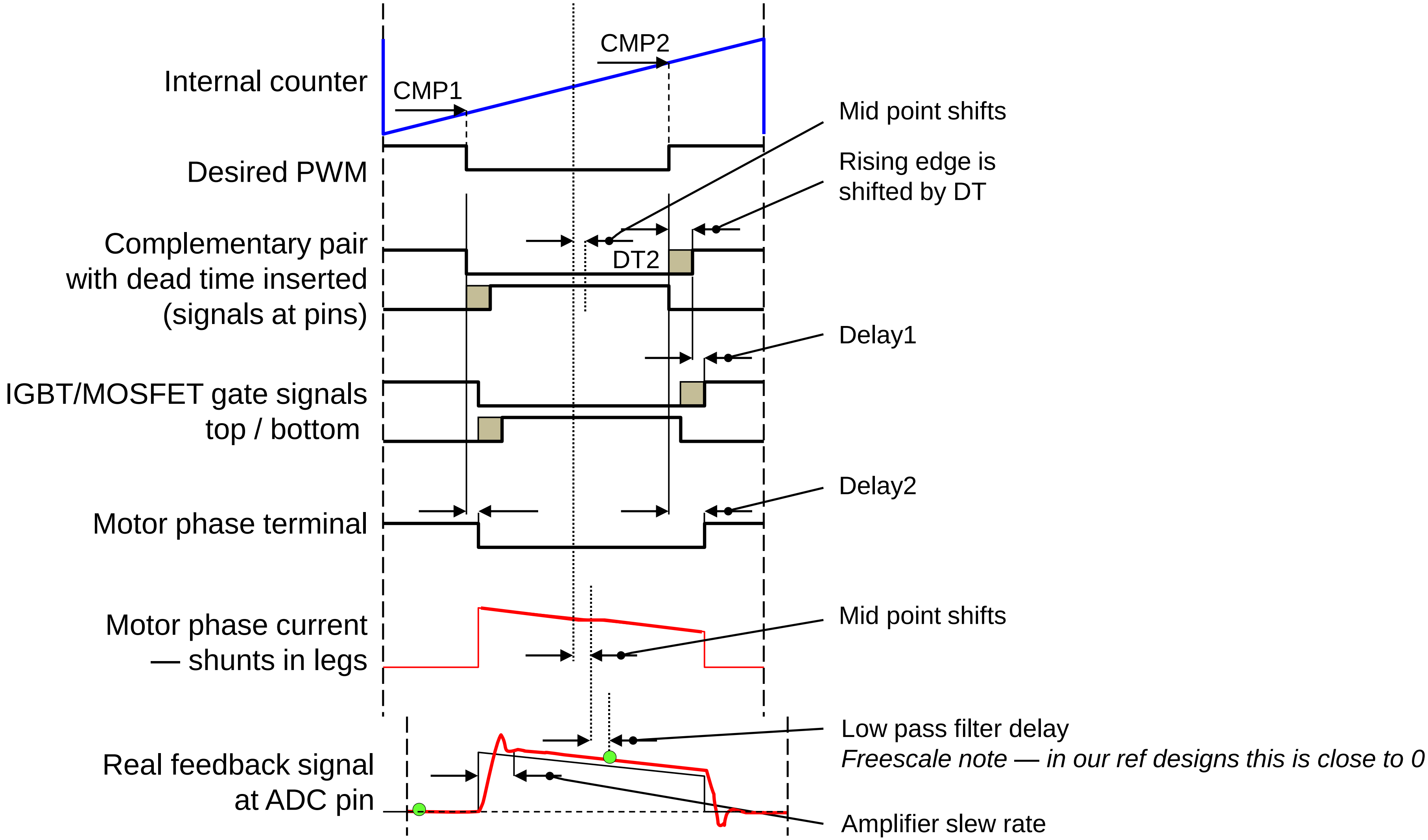
- Delays are chained and are caused by:
  - Dead time insertion
  - MOSFET driver propagation delay
  - MOSFET turn ON/OFF times
  - Amplifier slew rate
  - Low-pass filter delay
  - ADC delays





Delays Involved in PWM Driven Closed Loops

Current Sensing Shunts in Inverter Legs



Internal counter

CMP1

CMP2

Desired PWM

Complementary pair
with dead time inserted
(signals at pins)

DT2

IGBT/MOSFET gate signals
top / bottom

Motor phase terminal

Motor phase current
— shunts in legs

Real feedback signal
at ADC pin

Mid point shifts

Rising edge is
shifted by DT

Delay1

Delay2

Mid point shifts

Low pass filter delay
Freescale note — in our ref designs this is close to 0

Amplifier slew rate

PMSM FOC

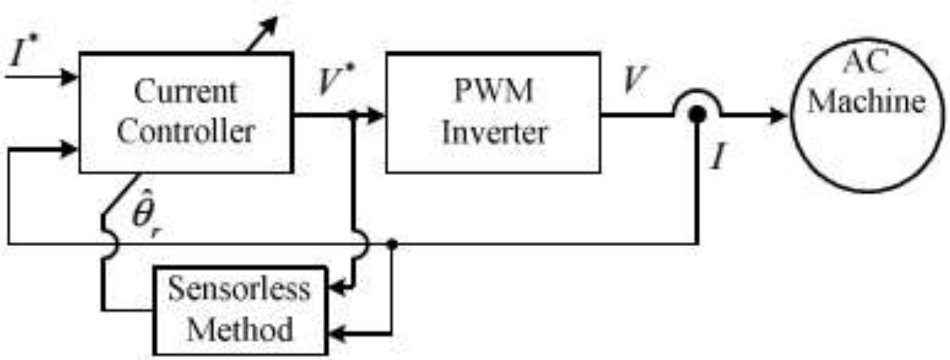
Position Sensing and Processing, Sensorless methods

Rotor Position Sensor Elimination: 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



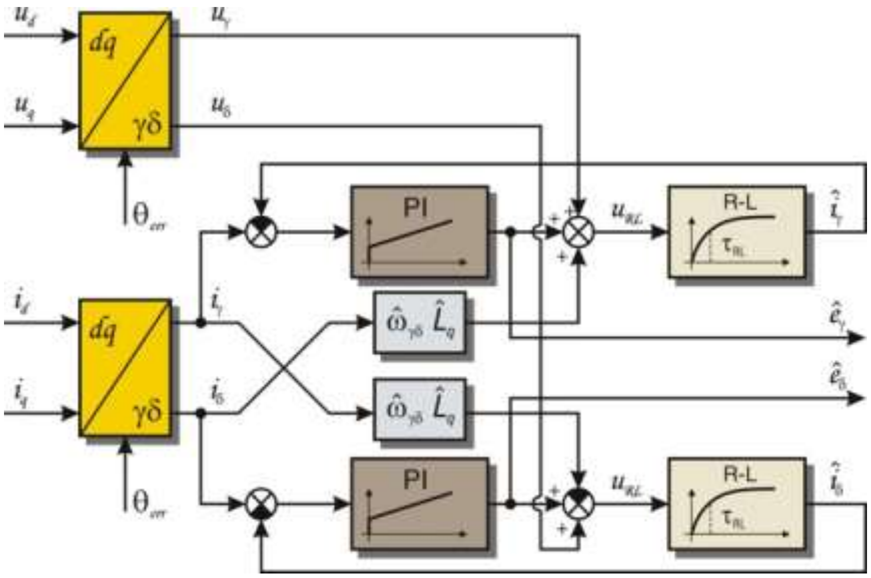
(b) Current control structure by the sensorless method

Classification of Sensorless 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

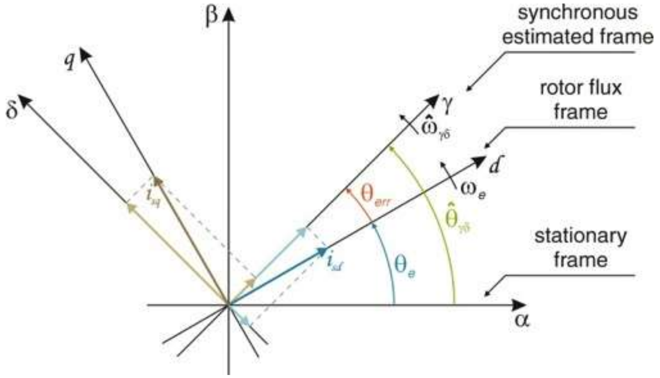
- Methods relaying on **magnetic saliency**
  - Based on inherent characteristic of PM motor called **magnetic saliency**
  - Presets good results in standstill or very low speed region (up to 10% of nominal speed)
  - Commercialized for certain types of PM motors designed accordingly

Saliency Based Back-EMF Observer



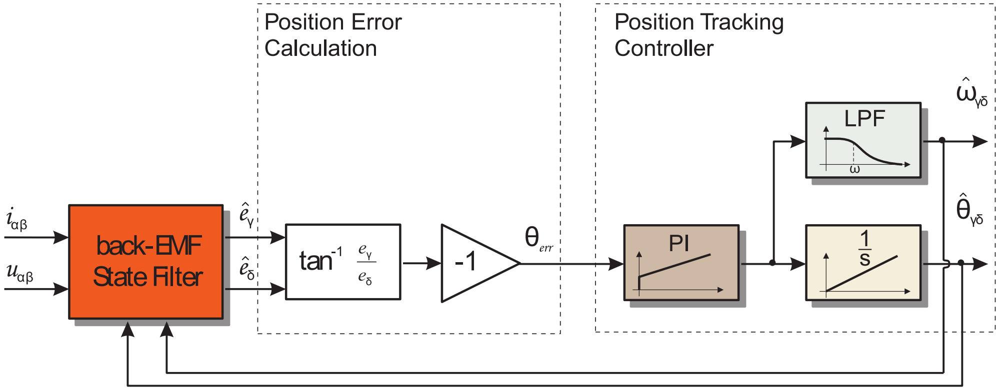
$$\begin{bmatrix} u_\gamma \\ u_\delta \end{bmatrix} = \begin{bmatrix} R_s + sL_d & -\hat{\omega}_{\gamma\delta}L_q \\ \hat{\omega}_{\gamma\delta}L_q & R_s + sL_d \end{bmatrix} \begin{bmatrix} i_\gamma \\ i_\delta \end{bmatrix} + E_{\text{sal}} \begin{bmatrix} -\sin(\theta_{err}) \\ \cos(\theta_{err})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

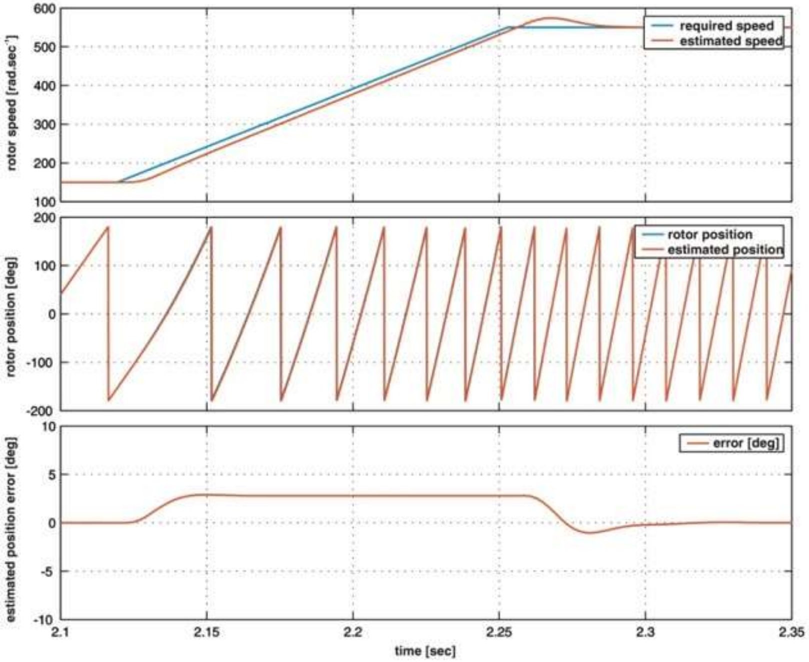
- Saliency based back-EMF voltage is generated due to $L_d \neq L_q$
- Because back-EMF term is not modeled, observer actually acts as a back-EMF state filter
- Observer is designed in synchronous reference frame; i.e. all observer quantities are DC in steady state, making the observer accuracy independent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



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

Position Estimation Using Saliency Based Back-EMF





Position estimation steady state error at constant speed

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

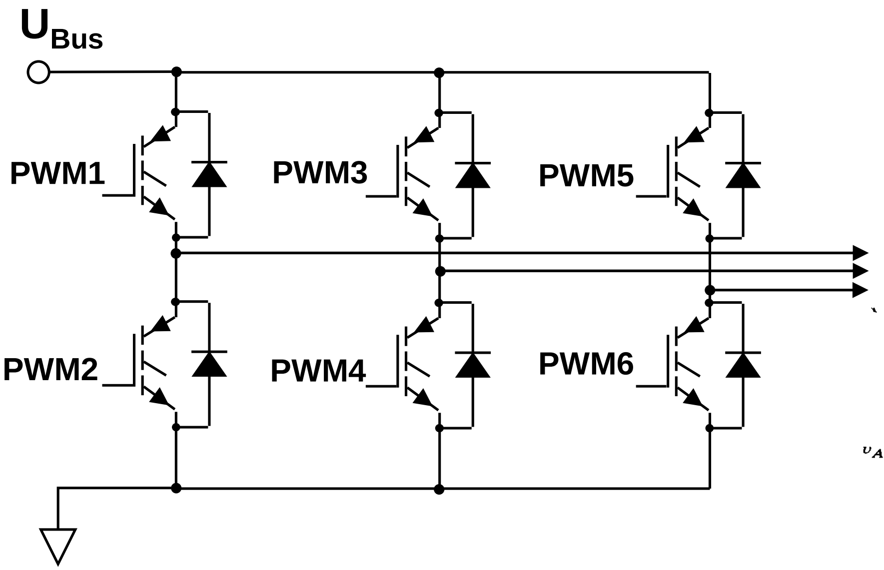
Position estimation steady state error during speed ramp change

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

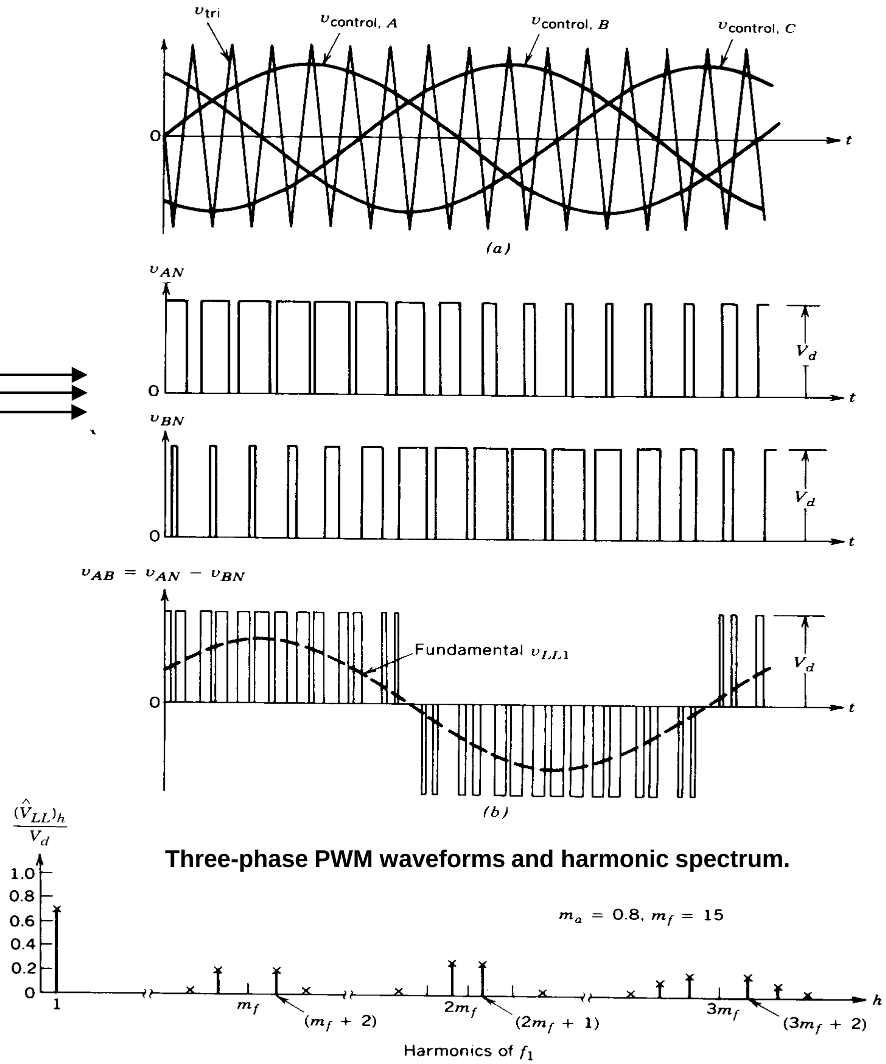
PMSM FOC

Three Phase Voltage Generation

Three Phase Voltage Generation



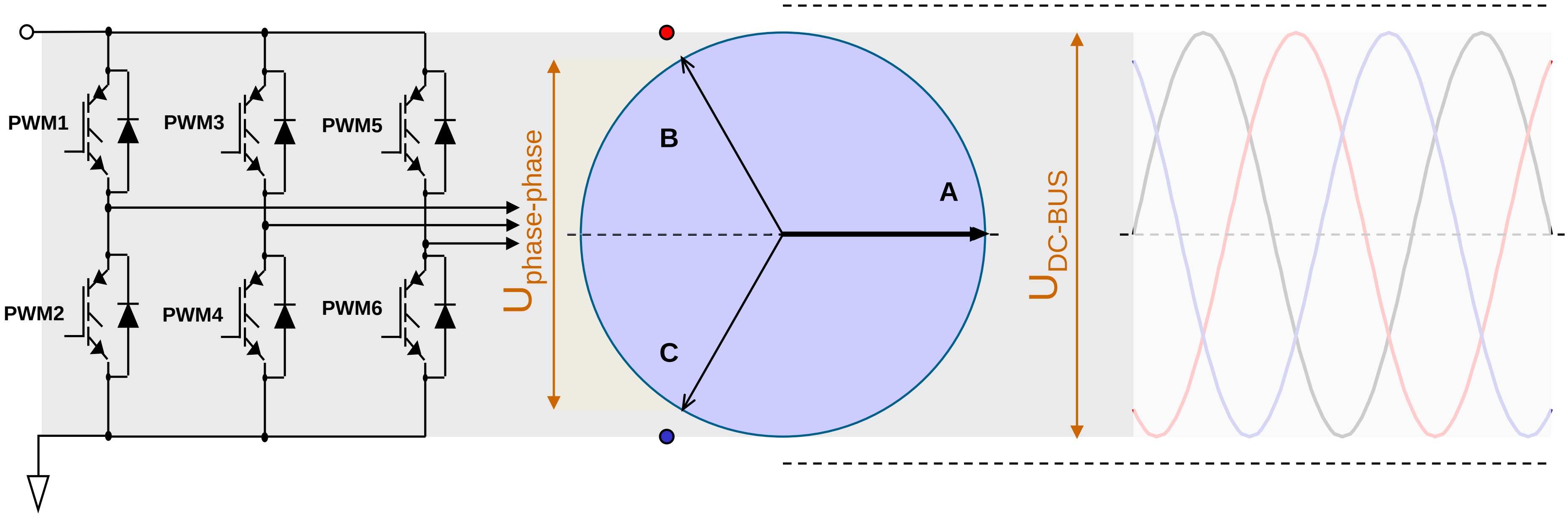
Source: Power Electronics, by Ned Mohan, Tore Undeland, and William Robbins, John Wiley & Sons, 1995



Three-phase PWM waveforms and harmonic spectrum.

Sinusoidal Modulation — Limited in Amplitude

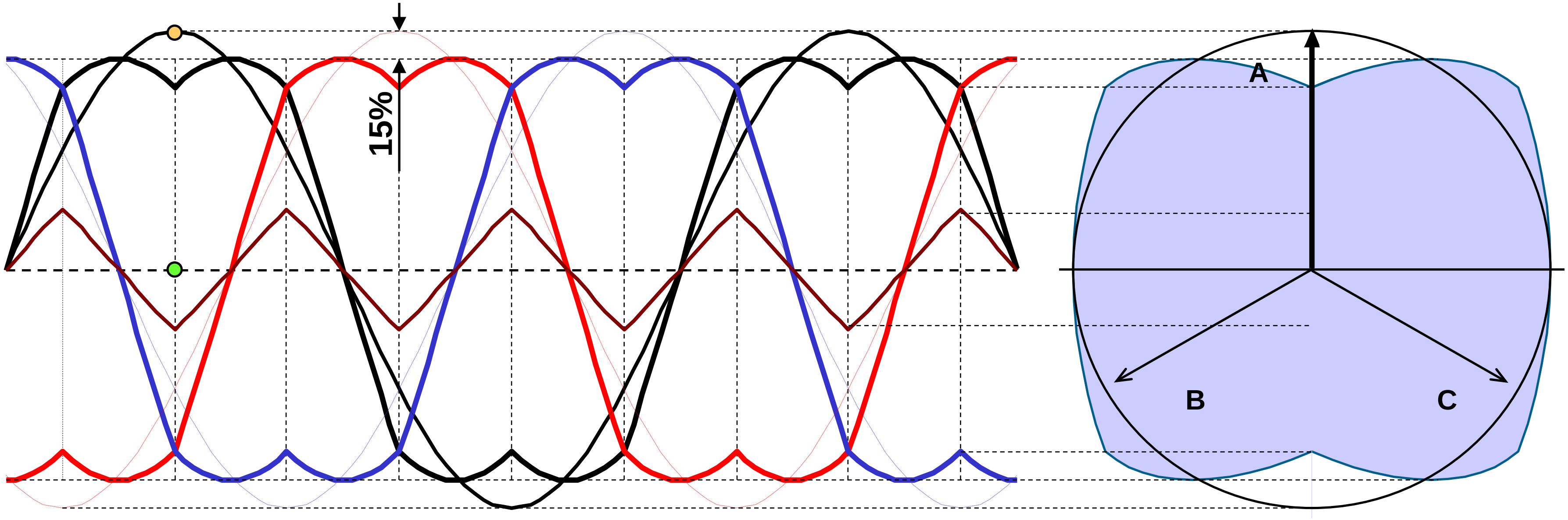
- In sinusoidal modulation the amplitude is limited to half of the DC-bus voltage
- The phase-to-phase voltage is then lower than the DC-bus voltage (although such voltage can be generated between the terminals)



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

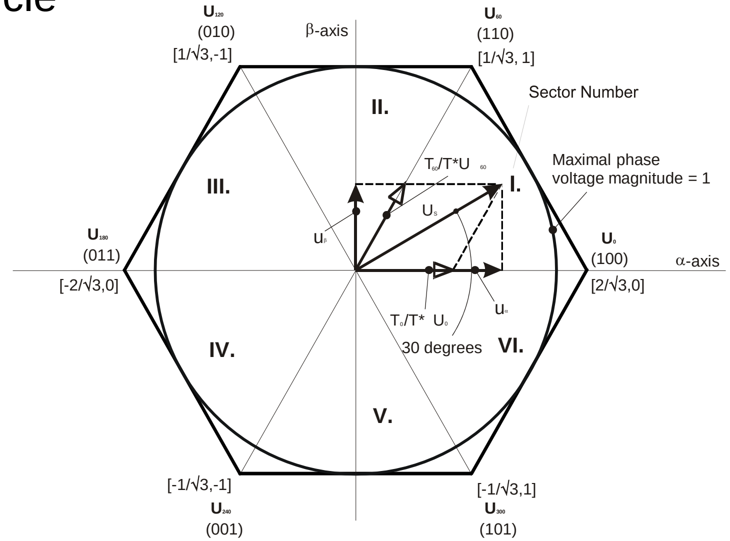
How to Increase Modulation Index

- Modulation index is increased by adding the “shifting” voltage u0 to first harmonic
- “Shifting” voltage u0 must be the same for all three phases, thus it can only contain 3r harmonics!

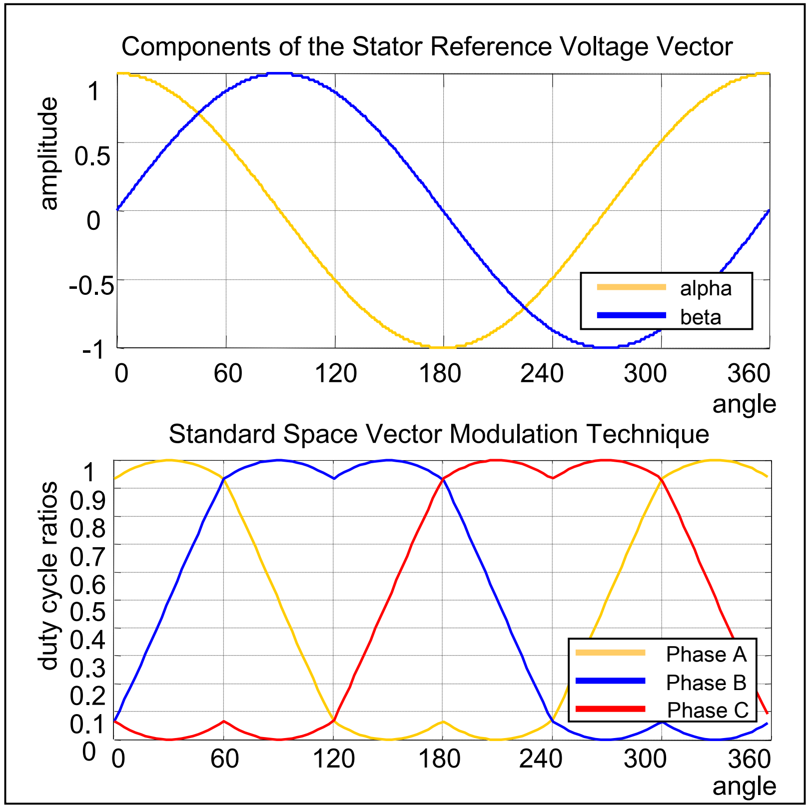


Standard Space Vector Modulation

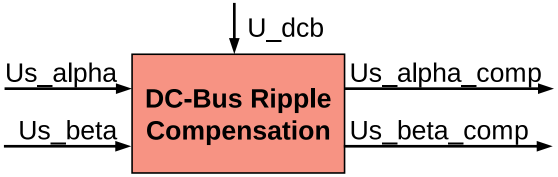
- Transforms directly the stator voltage vectors from the two-phase coordinate system fixed with stator to PWM signals
- Output voltage vector is created by continuous switching of two adjacent vectors and the “NULL” vectors
- Generates maximum phase voltage 0.5773 VDC
- Both nulls O000 and O111 are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



Input & Output waveforms



DC-bus Ripple Compensation


U_dcb

Us_alpha

Us_beta

DC-Bus Ripple Compensation

Us_alpha_comp

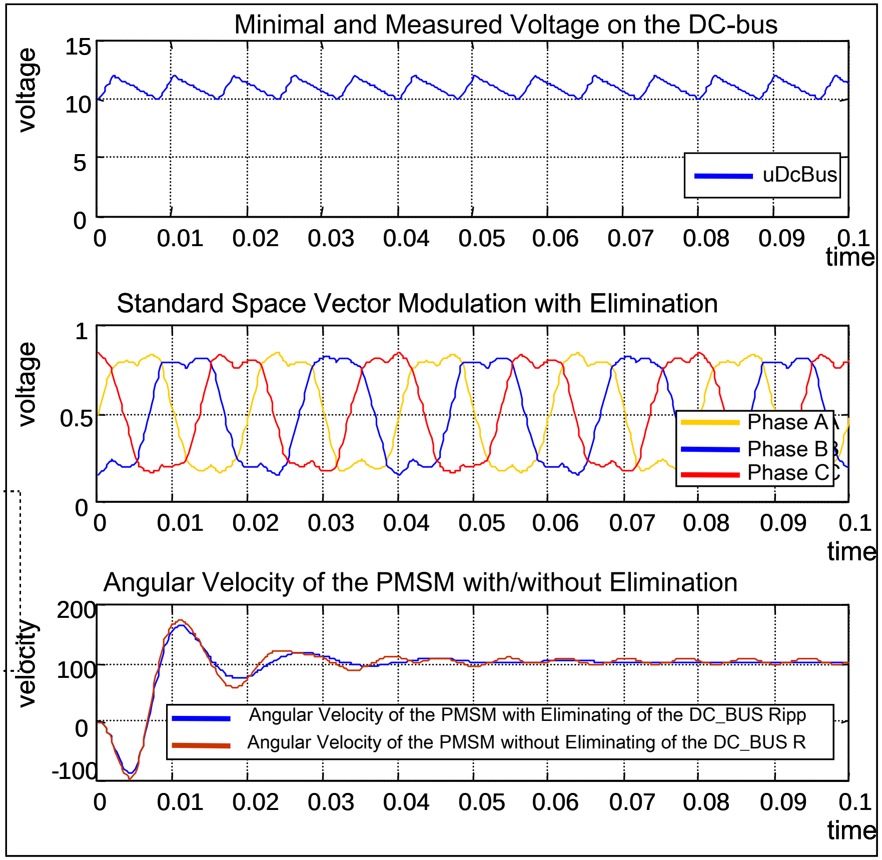
Us_beta_comp

- Compensates the ripple of the output voltages from Power Stage caused by DC-bus voltage ripples

- Improves performance of the drive

$$alpha^* = \begin{cases} \dfrac{invModIndex \cdot alpha}{u\_DcBusMsr/2} & \text{if } |invModIndex \cdot alpha| < \dfrac{u\_DCBusMsr}{2} \\ sign(alpha) \cdot 1.0 & \text{otherwise} \end{cases}$$

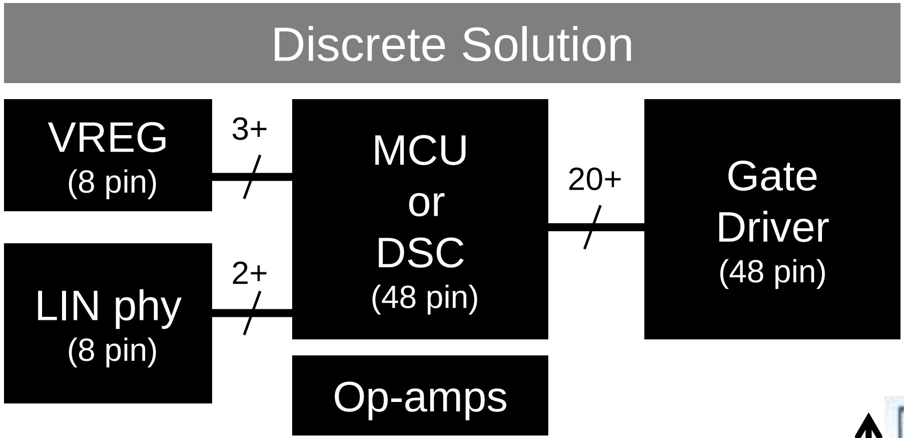
$$beta^* = \begin{cases} \dfrac{invModIndex \cdot beta}{u\_DcBusMsr/2} & \text{if } |invModIndex \cdot beta| < \dfrac{u\_DCBusMsr}{2} \\ sign(beta) \cdot 1.0 & \text{otherwise} \end{cases}$$



Special Motor Control Features on S12ZVM

- ✓ **Single Chip Solution**
  3-ph Motor Control Drive can be done by one IC + power bridge
- ✓ **Feature Set Overview**
  Peripherals, operating voltage ranges, application schematic, ...
- ✓ **Motor Control Features**
  S12Z Core, autonomous peripherals, current measurement & overcurrent protection, ...
- ✓ **PMSM Field Oriented Control**
  Single vs. dual shunt current measurement ...

S12ZVM — Single Chip Solution for 3-ph Motor Control



✓ **Optimize system cost**

4 cm
~1 ½ in.

✓ **Optimize system efficiency**

Vector Control

64 pin

S12ZVM Solution:

- ~ 50 fewer solder joints
- - 2 to 3 cm2 PCB space

Overview of S12ZVM Feature Set

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

Sensor Supply
- 20 mA I/O for sensor

Window Watchdog
- independent RC osc

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

Multiple timers
- IOC/periodic wake-up

CAN Option
- CAN controller

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

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

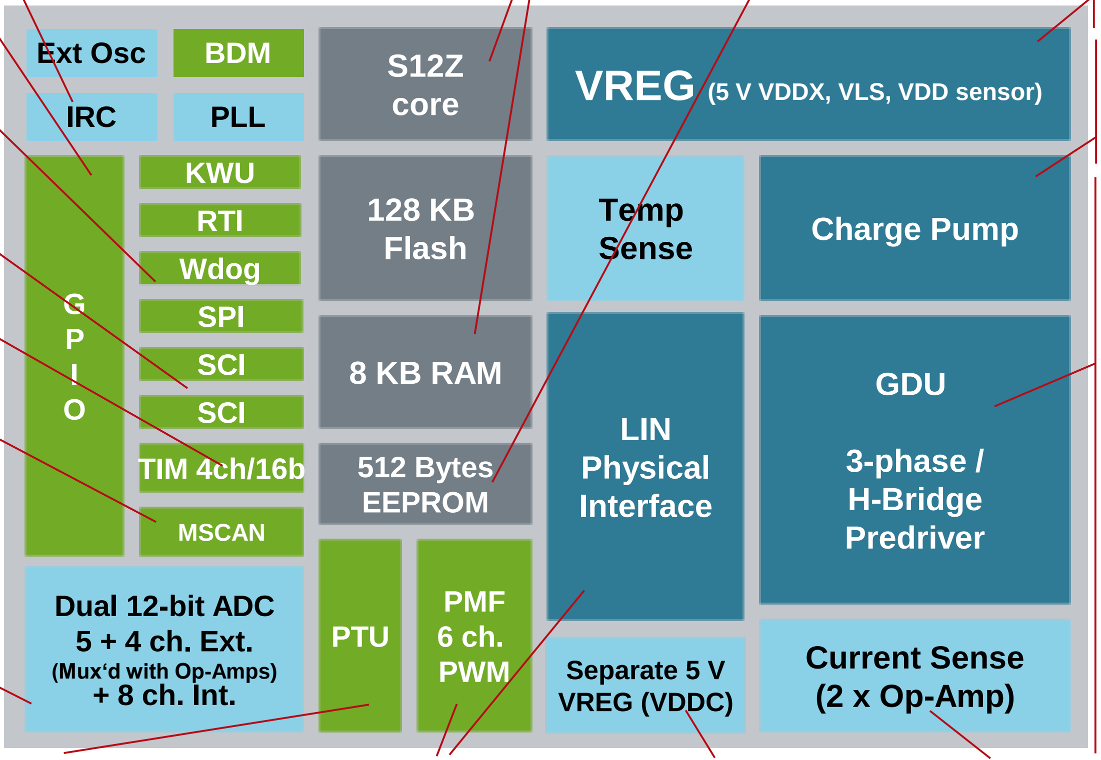
Safe RAM
ECC

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 3.5 V to 26 V
- Bootstrap circuit based
- 11 V 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
- 250 kb/s fast mode
- +/-6 kV

CAN Support
- 5 V Vreg controller for external transceiver

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

Operating Voltage Ranges

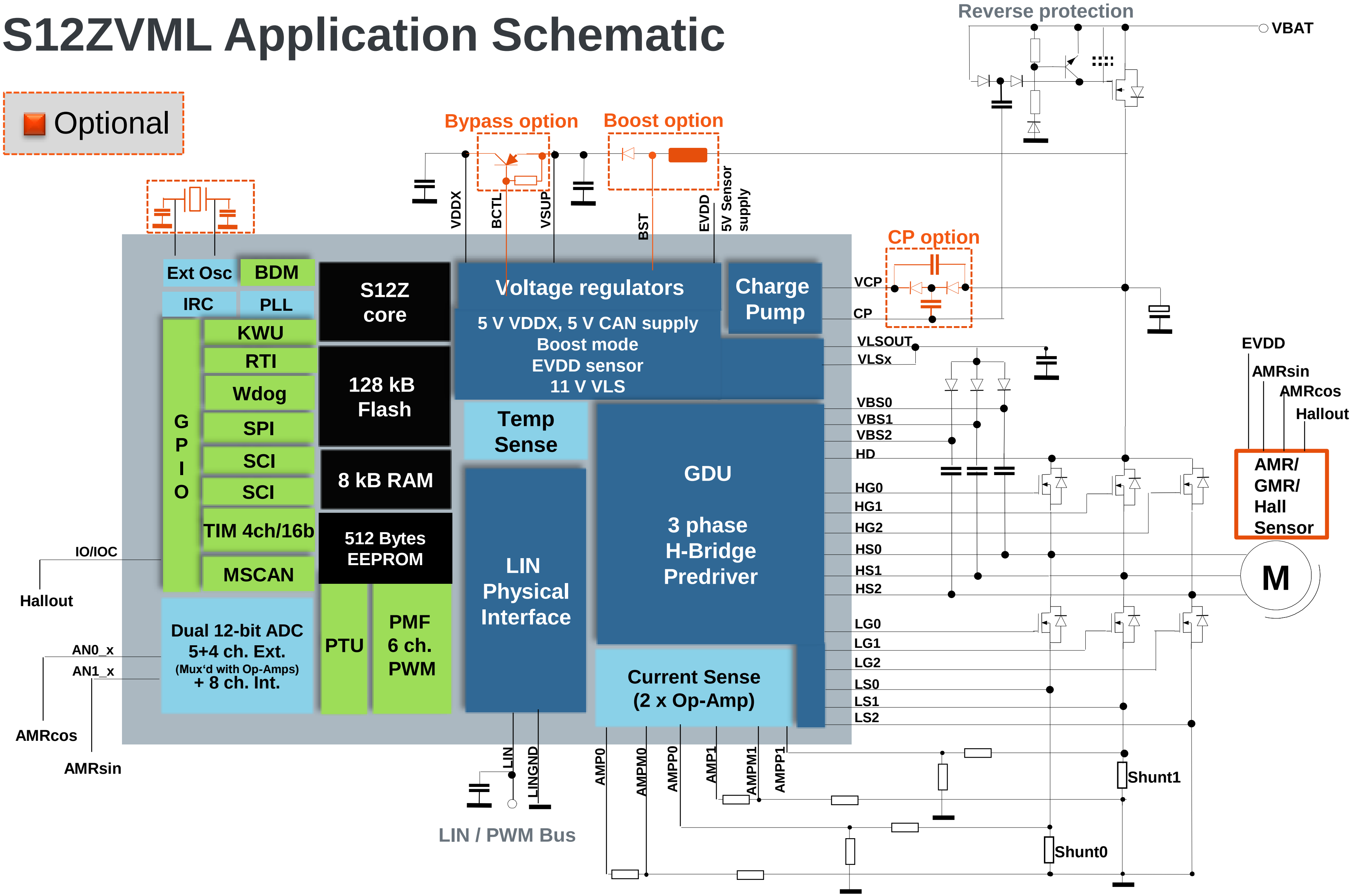
Without Boost

Vsup	MCU	GDU
20 V…40 V	Full	Disabled
7 V…20 V	Full	Enabled Vgs> Vsup — 2*Vbe (5 V min)
6 V...7 V	Full	Disabled
3.5 V...6 V	Full Iddx = 25 mA max if no external PNP	Disabled
<3.5 V	Reset	Disabled

With Boost

Vsup	MCU	GDU
20 V...40 V	Full	Disabled
9.5 V...20 V	Full	Boost OFF for Vsup > 11 V Vgs = 9.6 V
6 V…9.5 V	Full	Boost ON Vgs >9 V
3.5 V...6 V	Full Iddx = 25 mA max if no external PNP	Boost ON Vgs >9 V
<3.5 V	Reset	Disabled

S12ZVML Application Schematic



🟥 Optional

Ext Osc

BDM

IRC

PLL

GPIO

KWU

RTI

Wdog

SPI

SCI

SCI

TIM 4ch/16b

MSCAN

S12Z core

128 kB Flash

8 kB RAM

512 Bytes EEPROM

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

PTU

PMF
6 ch.
PWM

Voltage regulators
5 V VDDX, 5 V CAN supply
Boost mode
EVDD sensor
11 V VLS

Charge Pump

Temp Sense

LIN Physical Interface

GDU
3 phase H-Bridge Predriver

Current Sense (2 x Op-Amp)

AMR/ GMR/ Hall Sensor

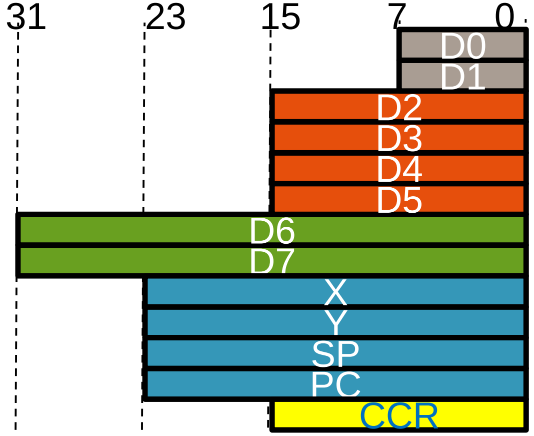
LIN / PWM Bus

S12Z Core: An Optimized Powerful Machine

24-bit address bus maps up to 16 MB (no paging needed!)

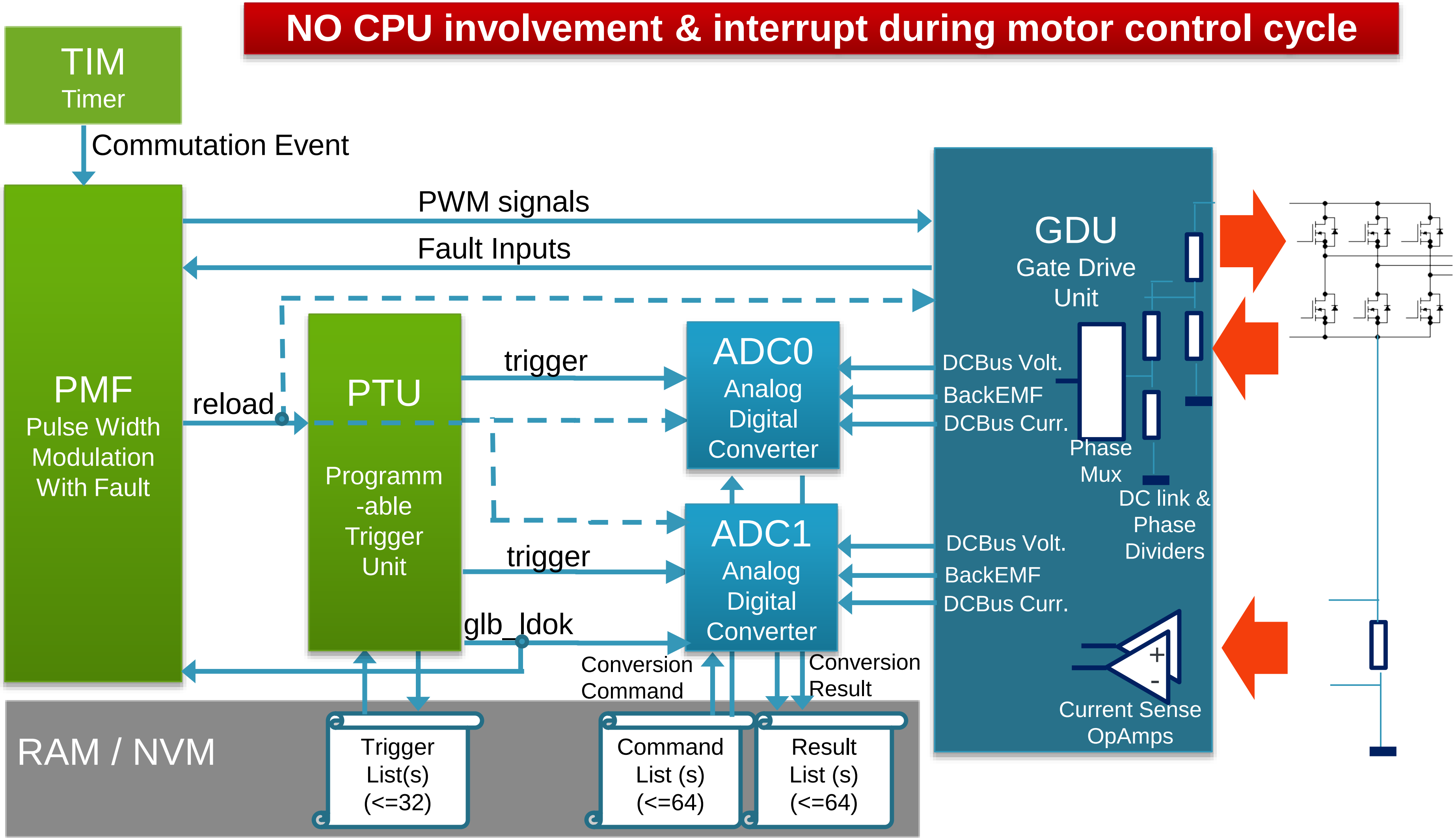
- Harvard Architecture — Parallel data & code accesses
- CPU operates at 100 MHz
- Fractional math support
- Instructions/addressing optimized for C programming
- Multiple length register set optimized for less memory access
- 32-bit data paths, ALU, data registers
- 24-bit address bus, stack pointer, program counter and X/Y index registers
- It has a 16-bit I/O data path
- Handles 8-bit data and indices

Expanded programmer's model



Attribute	S12Z	
Shifter	**32**-bit multi-bit	1 cycle
Multiplier	**32*32** 16*16	2.5 cycles 1 cycle
Divider	32 = **32/32**	18.5 cycles
MAC	32 += **32*32**	3.5 cycles
Fractional math	**Yes**	
Bus speed	50 MHz	

Autonomous Motor Control Loop Implementation



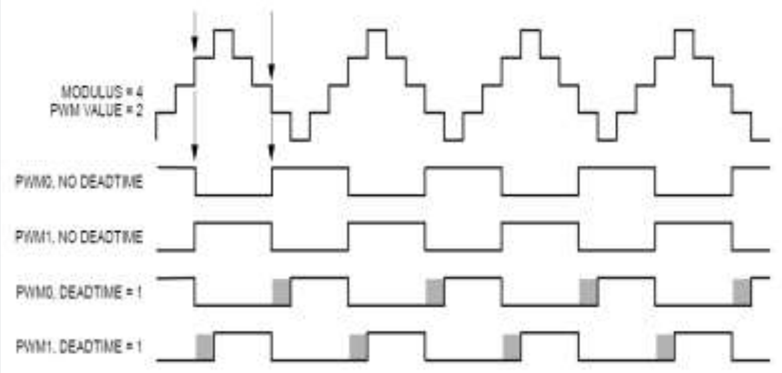
NO CPU involvement & interrupt during motor control cycle

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. 100 MHz)**
- **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 (+ easy masking feature per output)**
- **Programmable fault protection**

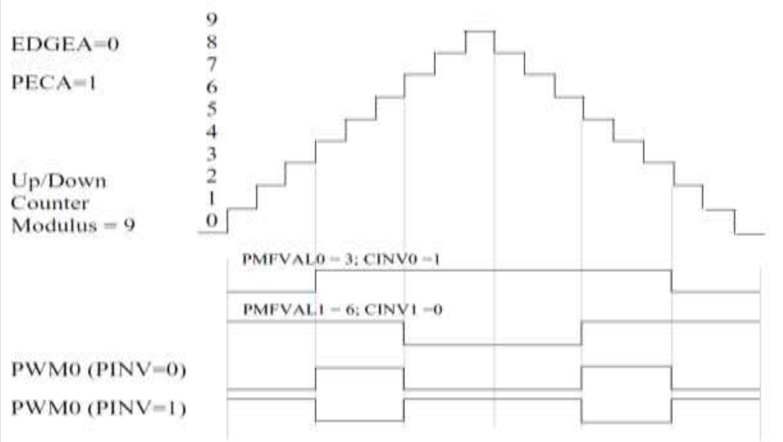
Complementary Mode

with / without dead time insertion



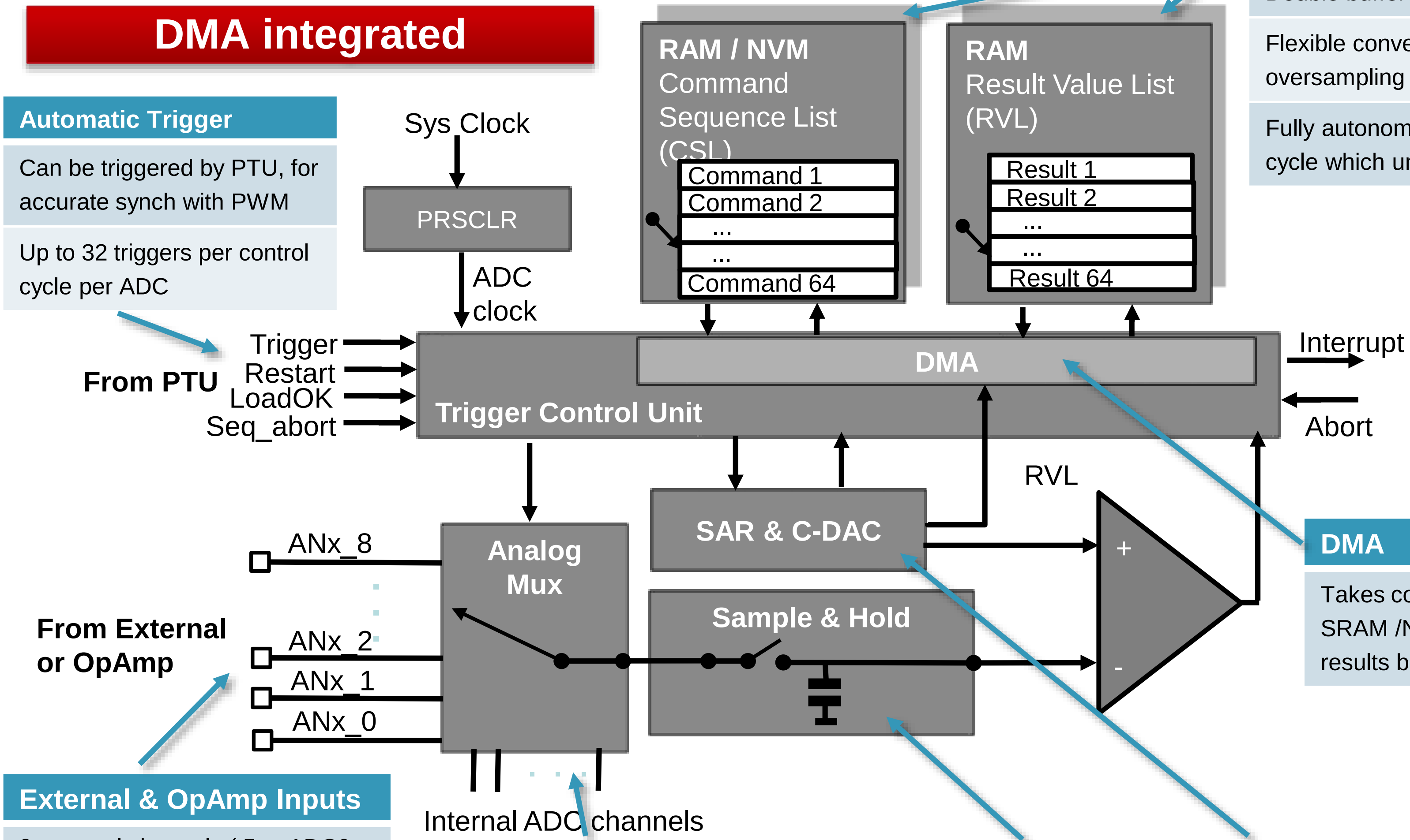
Double-Switching Mode

for single shunt system



2 x 12-bit Analog Digital Converter

DMA integrated



Command and Result List

- Double buffered
- Flexible conversion sequence and oversampling
- Fully autonomous motor control cycle which unloads CPU

Automatic Trigger

- Can be triggered by PTU, for accurate synch with PWM
- Up to 32 triggers per control cycle per ADC

DMA

- Takes commands from SRAM /NVM and stores results back into SRAM

External & OpAmp Inputs

- 9 external channels (5 to ADC0 and 4 to ADC1)
- OpAmp output shared with ADC external channel

Monitoring Internal Signals

- DC link, phase voltages, Vsup
- Vreg & ADC temp sensors
- Bandgap voltage

Sample Time

- Selectable: 480 ns to 2.88 µs

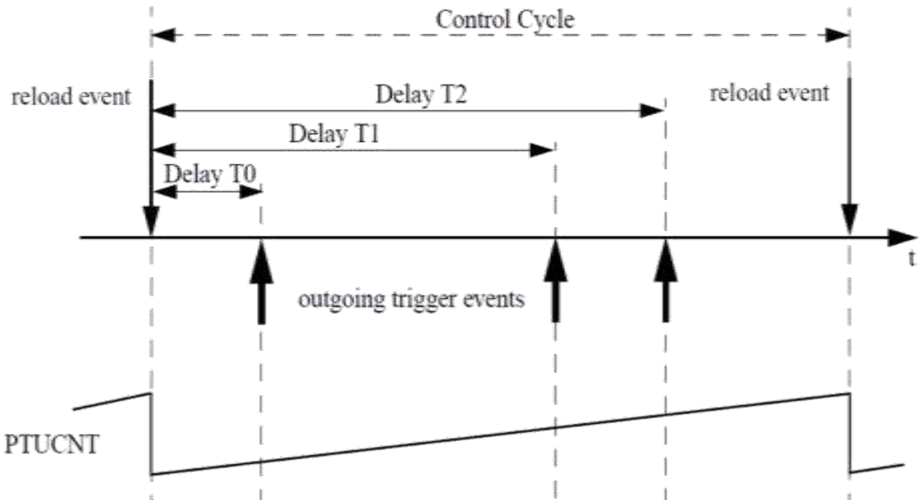
Conversion Time

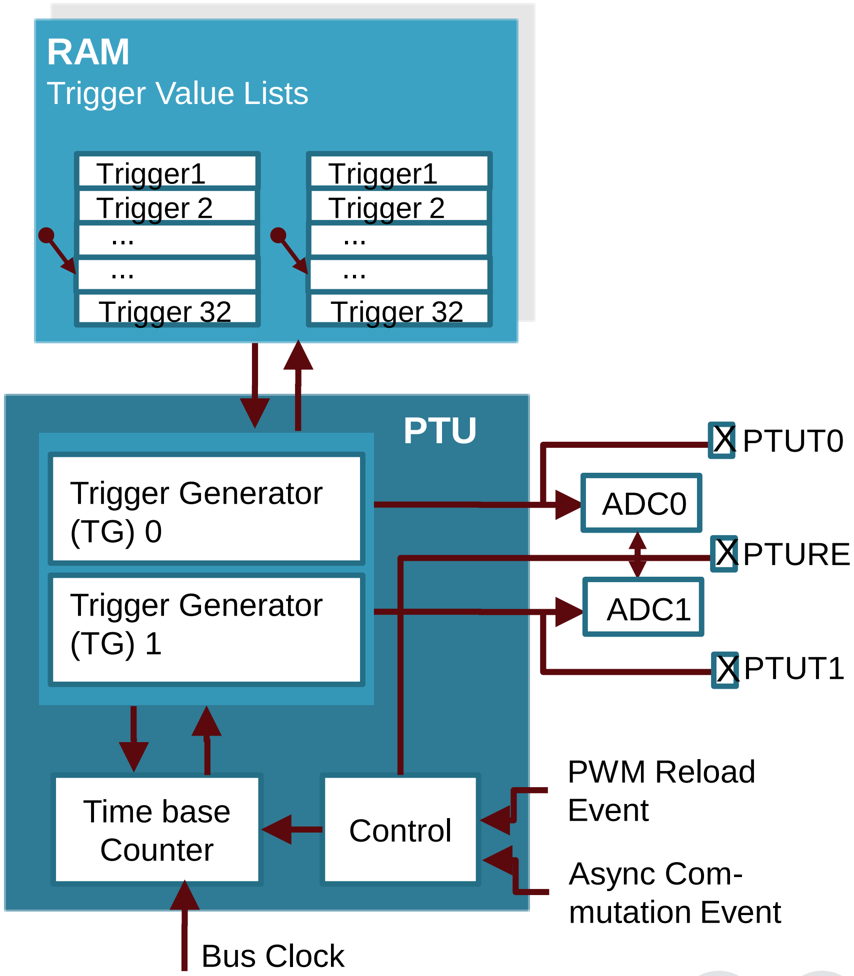
- 1.8 µs @ max. ADC clock for 12-bit

Programmable Trigger Unit (PTU)

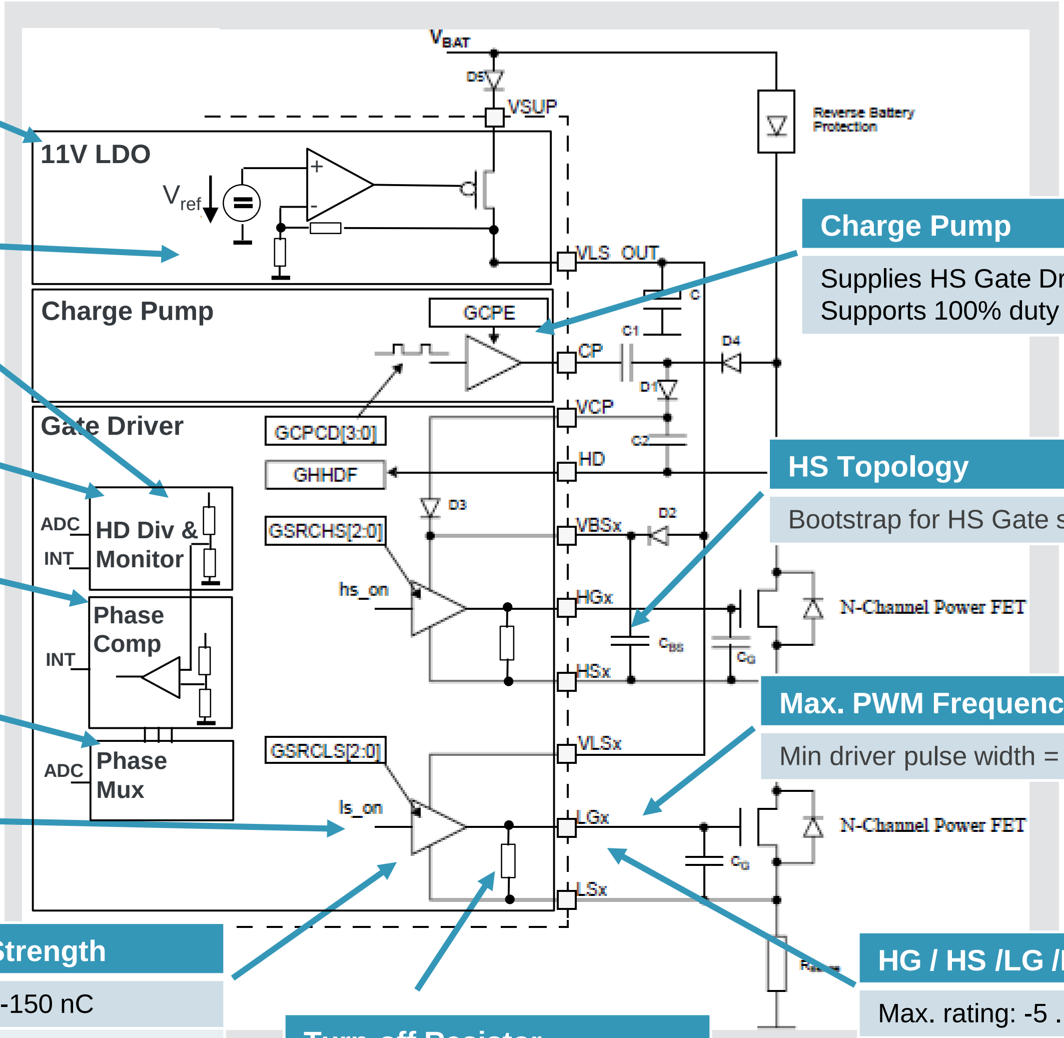
Completely avoids CPU involvement to trigger ADC during the control cycle

- One 16-bit counter as time base
- 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” & trigger event
- Synchronized with PMF and ADC to guarantee coherent update of all control loop modules





Gate Driver Unit (GDU) Topology



11 V LDO

supplies the LS drivers

charges bootstrap cap for the HS drivers

Voltage Monitoring

HD High Voltage Monitor @ typ. 21/27.3 V

VLS Low Voltage trip point: 6.2 .. 7 V

Integrated Dividers

HD: divider 12; HS: divider 6

Phase Comparators

Compares HS against DCbus/2 in hardware

Phase Multiplexer

Switched in each sector

Slew Rate Control

Output current limitation of Iout via selectable Iref

8 selectable slew rates

Drive Strength

Typ 100-150 nC

Typ. 6.3 Ohm Switch on
Typ. 16 Ohm Switch off

Turn-off Resistor

80 kOhm pull down integrated

Charge Pump

Supplies HS Gate Drive
Supports 100% duty cycle

HS Topology

Bootstrap for HS Gate supply

Max. PWM Frequency

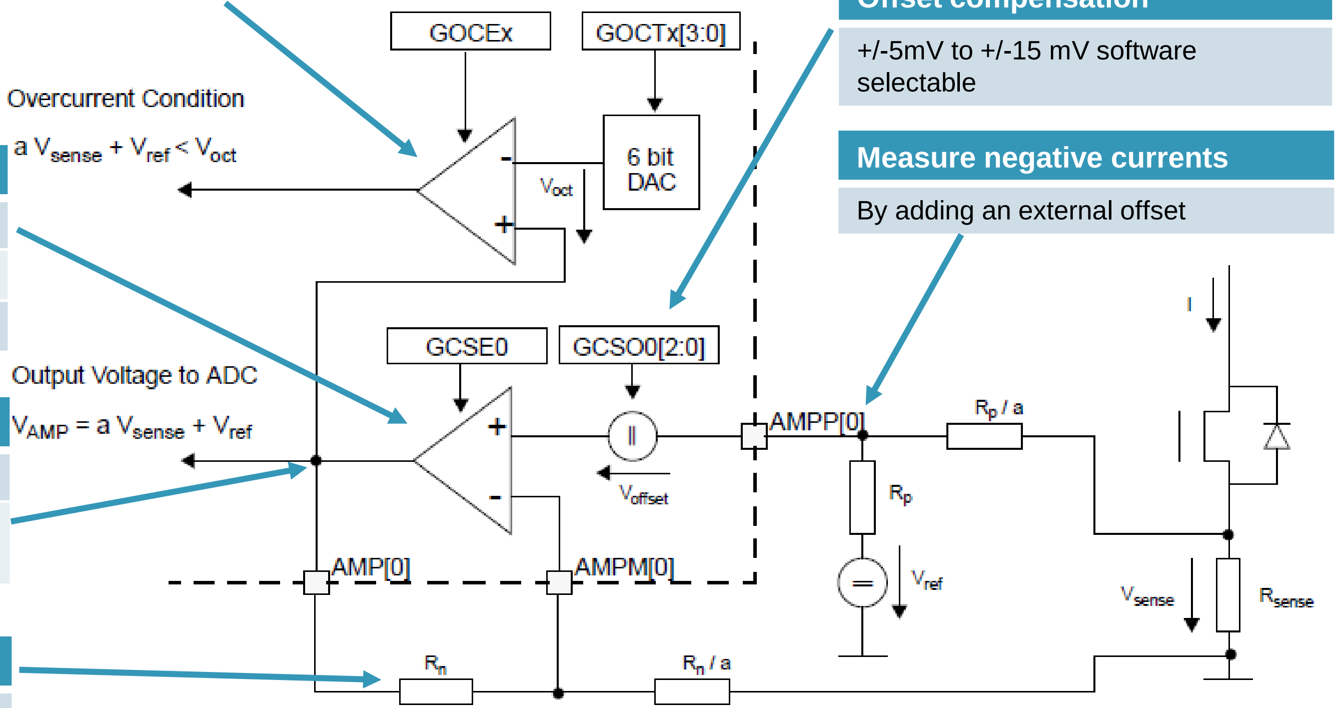
Min driver pulse width = 2 µs

HG / HS /LG /LS

Max. rating: -5 .. 42 V

freescale™

Current Measurement & Overcurrent Protection



Overcurrent Comparator

Flexible programmable with 6-bit DAC

Voltage range: 3.82 V .. VDDA

Current measurement

Two current sense amplifiers

Supports 2-shunt systems

Measures voltage across shunt

Output voltage

Range 0 V .. VDDA

measured on ADC via external channel AMP(0/1)

Gain

Selectable via external resistors

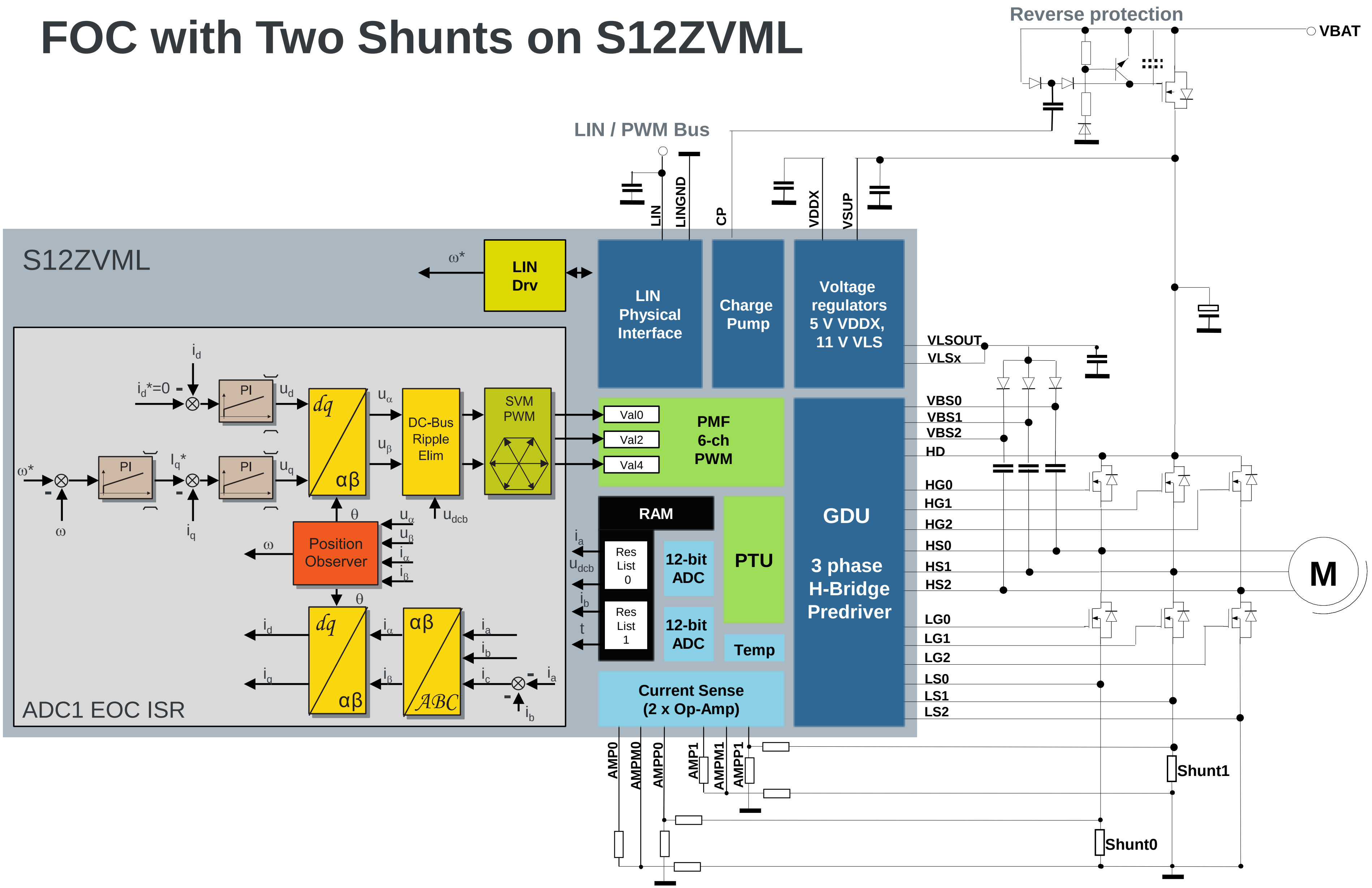
Offset compensation

+/-5mV to +/-15 mV software selectable

Measure negative currents

By adding an external offset

FOC with Two Shunts on S12ZVML



S12ZVM Ecosystem

The Complete Solution

S12ZVM Ecosystem — The Complete Solution

Customer Application Software

MC ToolBox:
Rapid prototyping with
Matlab Simulink

FreeMASTER:
-Graphical User Interface
-Instrumentation

MCAT Tuning Tool

MC Dev Kit Reference Software

LIN 2.1 Drivers

NVM Drivers

CAN/LIN Stack

Math and Motor Control Libraries:
- Standard optimized math functions and motor control algorithms
- Includes Matlab Simulink Models

AUTOSAR OS

Compiler and Debugger

COSMIC Software

iSYSTEM

LAUTERBACH DEVELOPMENT TOOLS

PE micro

CodeWarrior

Graphical Init Tool

Processor Expert

Hardware (Evaluation board, target application)

Freescale production Software

Freescale enablement Software

Third-party production Software

Summary: Simplify Your Design

- ✓ Minimized system cost: Small PCB, minimum external components
- ✓ Scalable approach (memory, boost, bypass, communication interface)
- ✓ CPU offloaded from motor control timing tasks due to autonomous motor control peripherals
- ✓ Complete software & hardware enablement with ready to use reference design and library
- ✓ Higher reliability

www.Freescale.com