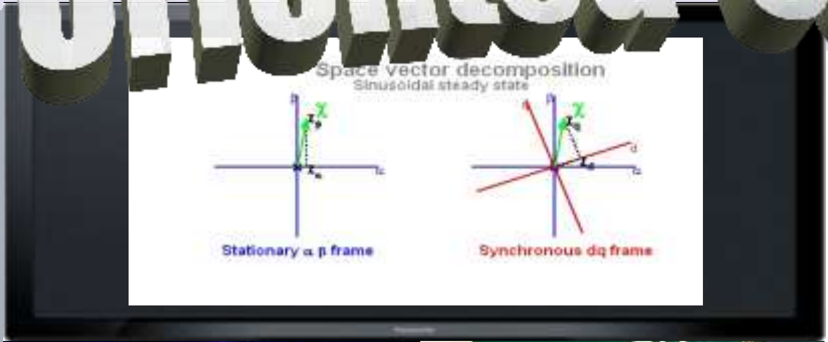
2013 Texas Instruments Motor Control Training Series

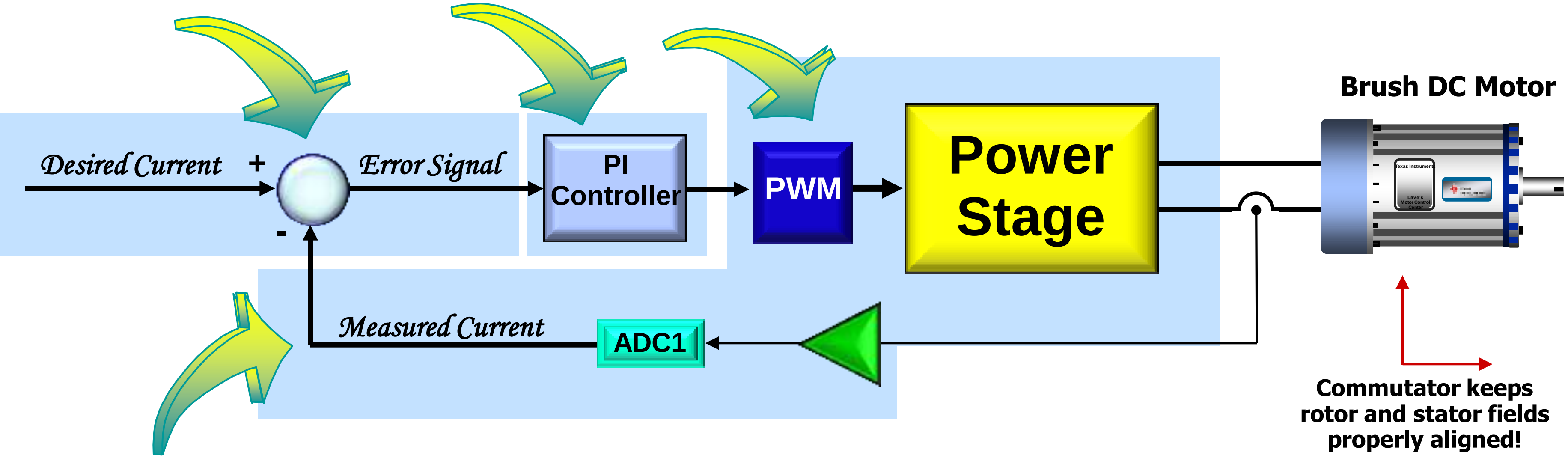
Intro to Field Oriented Control



InstaSPIN Training

TEXAS INSTRUMENTS

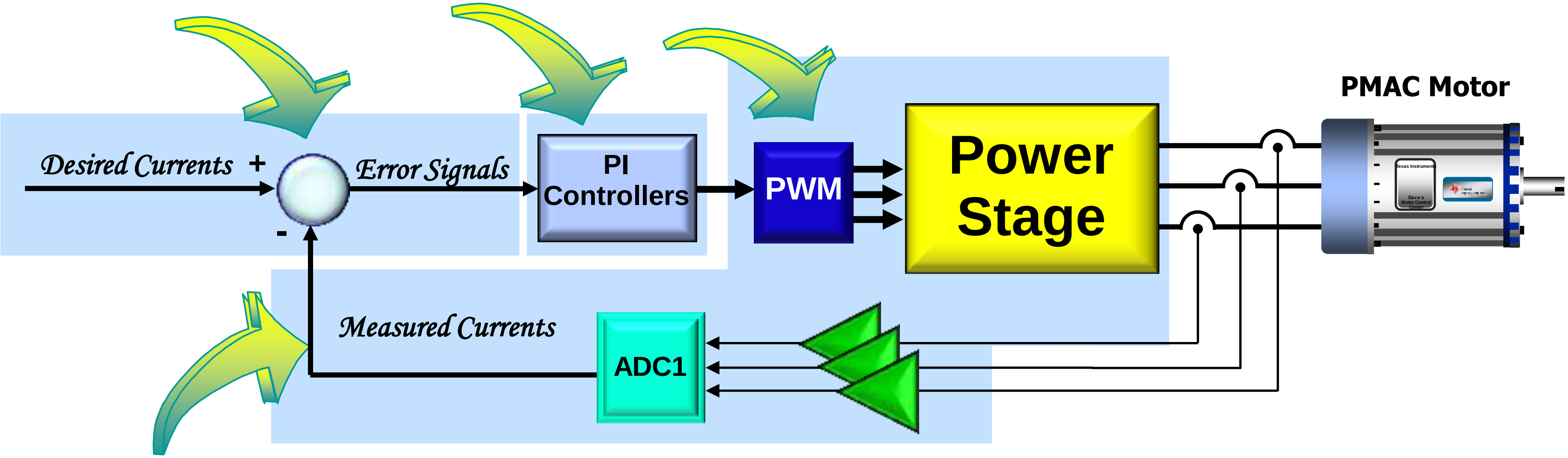
How Do You Control Torque on a DC Motor?



1. *Measure current already flowing in the motor.*
2. *Compare the measured current with the desired current, and generate an error signal.*
3. *Amplify the error signal to generate a correction voltage.*
4. *Modulate the correction voltage onto the motor terminals.*

$$Torque = K_a i$$

How Do You Control Torque on a Permanent Magnet AC Motor?



1. *Measure currents already flowing in the motor.*
2. *Compare the measured currents with the desired currents, and generate an error signals.*
3. *Amplify the error signals to generate a correction voltages.*
4. *Modulate the correction voltages onto the motor terminals.*

$$Torque = \frac{3}{2}\frac{P}{2}\left[\lambda_{dr} I_{qs}\right]^{\dagger}$$

i.e., The Same Way!

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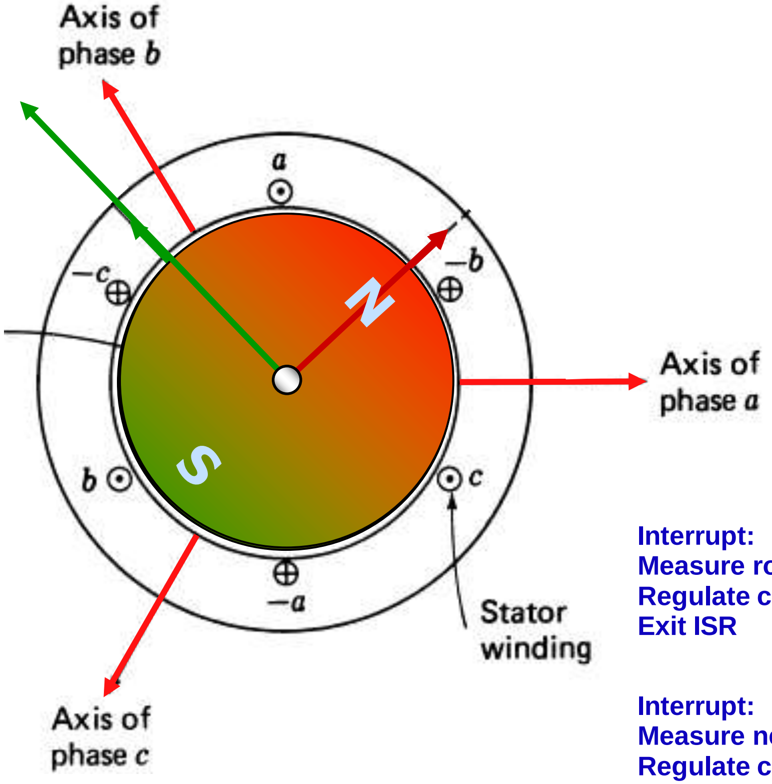
† *Torque expression based on amplitude invariant form of Clarke Transform.*

Field Oriented Control in Real Time

Low Torque

Medium Torque

High Torque



Interrupt:
Measure rotor flux angle
Regulate current vector to be 90º wrt rotor flux
Exit ISR

Interrupt:
Measure new rotor flux angle
Regulate current vector to be 90º wrt rotor flux
Exit ISR

Interrupt:
Measure new rotor flux angle
Regulate current vector to be 90º wrt rotor flux
Exit ISR
⋮

Constant

Constant (for now)

$$Torque = \underset{\text{Constant}}{\frac{3}{2}\frac{P}{2}}\left[\overset{\text{Constant (for now)}}{\lambda_{dr}}\underset{\text{Adjustable}}{I_{qs}}\right]^{\dagger}$$

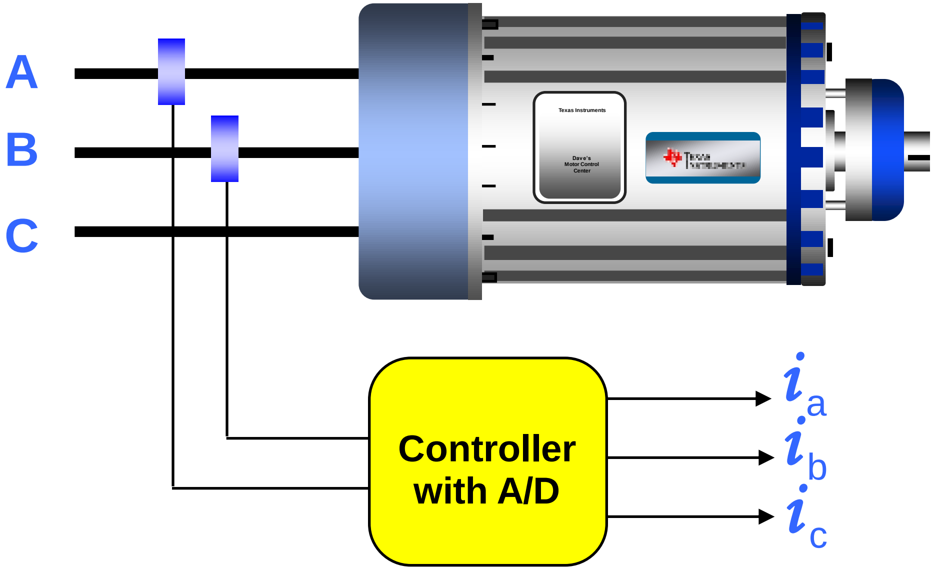
Adjustable

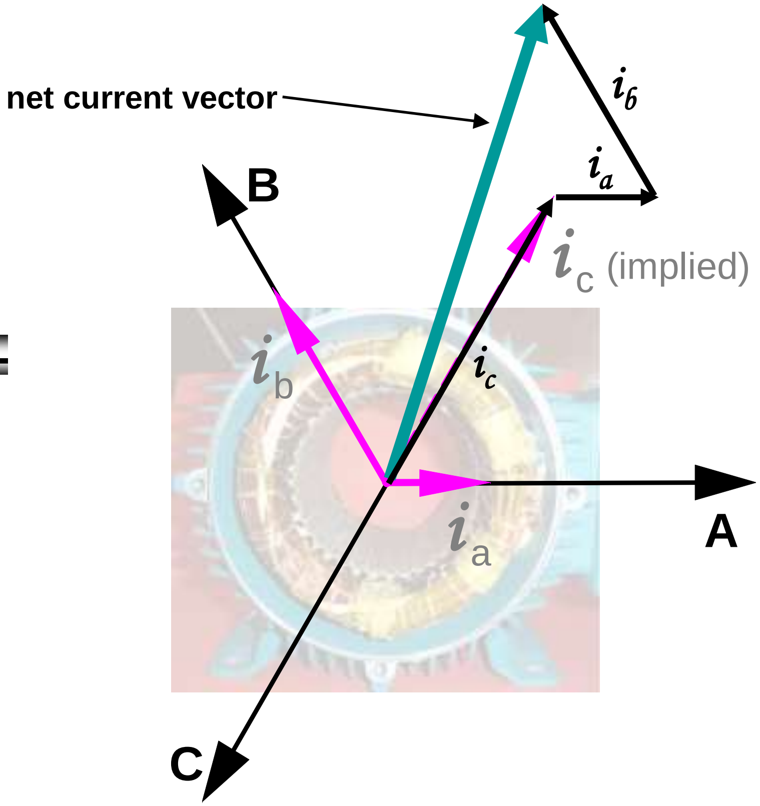
† *Torque expression based on amplitude invariant form of Clarke Transform.*

1. Measure currents already flowing in the motor.

Only 2 phases are measured!
WHY?

A, B, and C axes are “fixed” with respect to the motor housing. This reference frame is also called the “stationary frame” or “stator frame”.





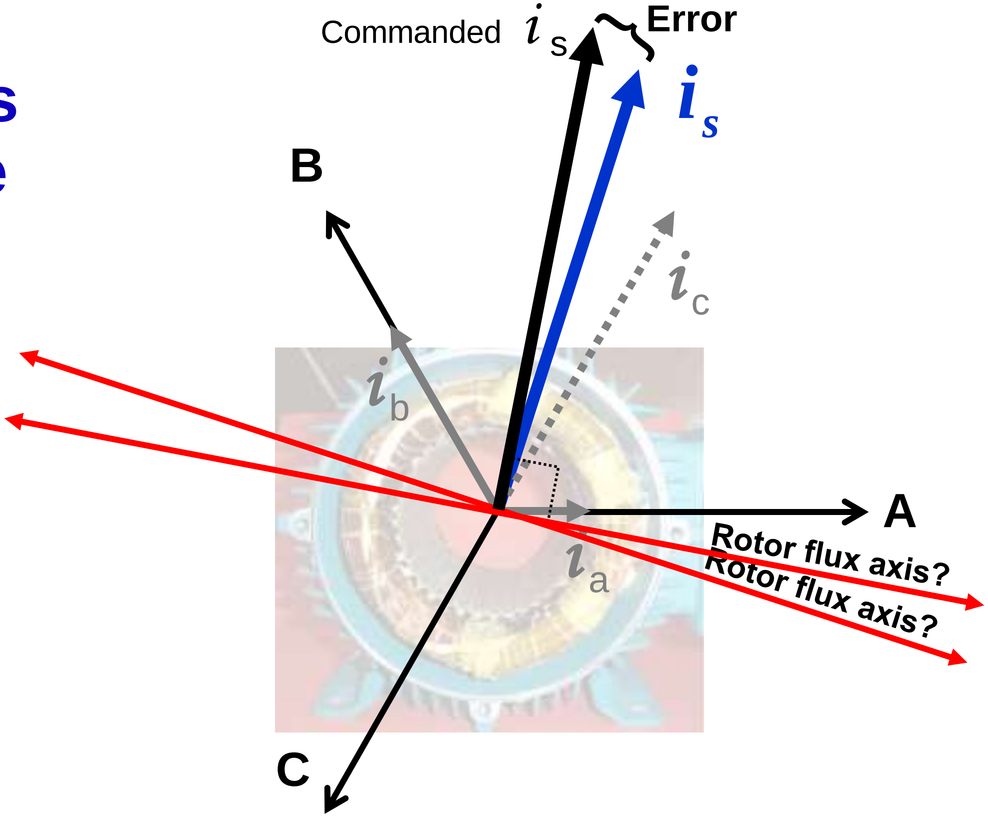
2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

The desired phase currents can be calculated via these equations:

$$i_a = -I_m \sin(\theta_\lambda)$$

$$i_b = -I_m \sin(\theta_\lambda - 120^o)$$

$$i_c = -I_m \sin(\theta_\lambda - 240^o)$$



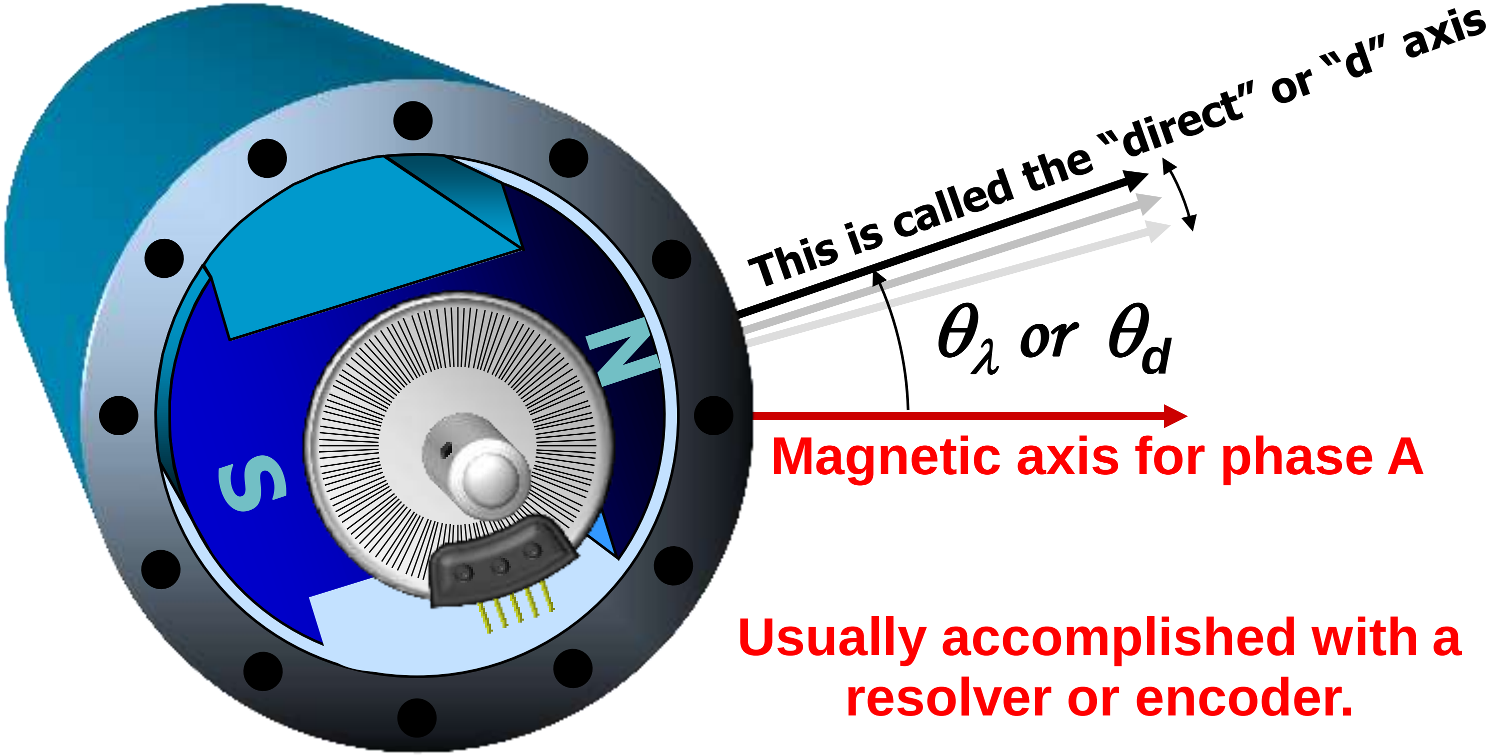
I_m is proportional to motor torque

θ_λ is the angle of the rotor flux

So how can we accomplish this?

2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

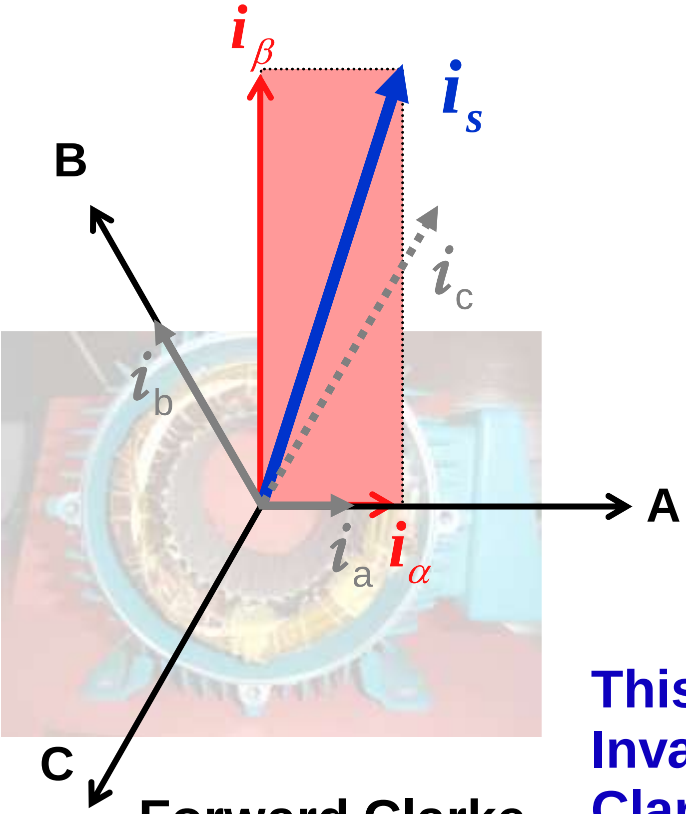
First, we need the angle of the rotor flux.



Usually accomplished with a resolver or encoder.

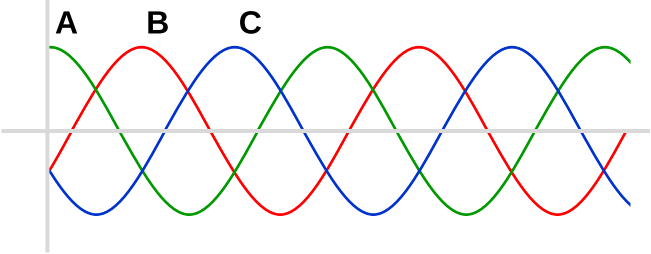
2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

The CLARKE transform allows us to convert three vectors into two orthogonal vectors that produce the same net vector.



In other words, convert a 3-phase motor into a 2-phase motor.

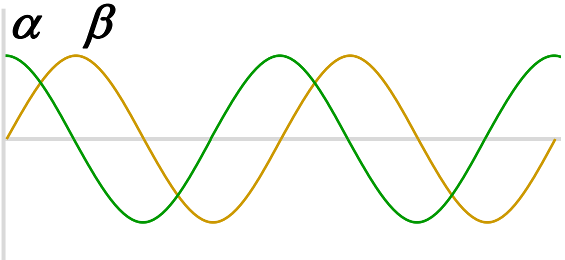
This is the Amplitude Invariant form of the Clarke Transform



Forward Clarke

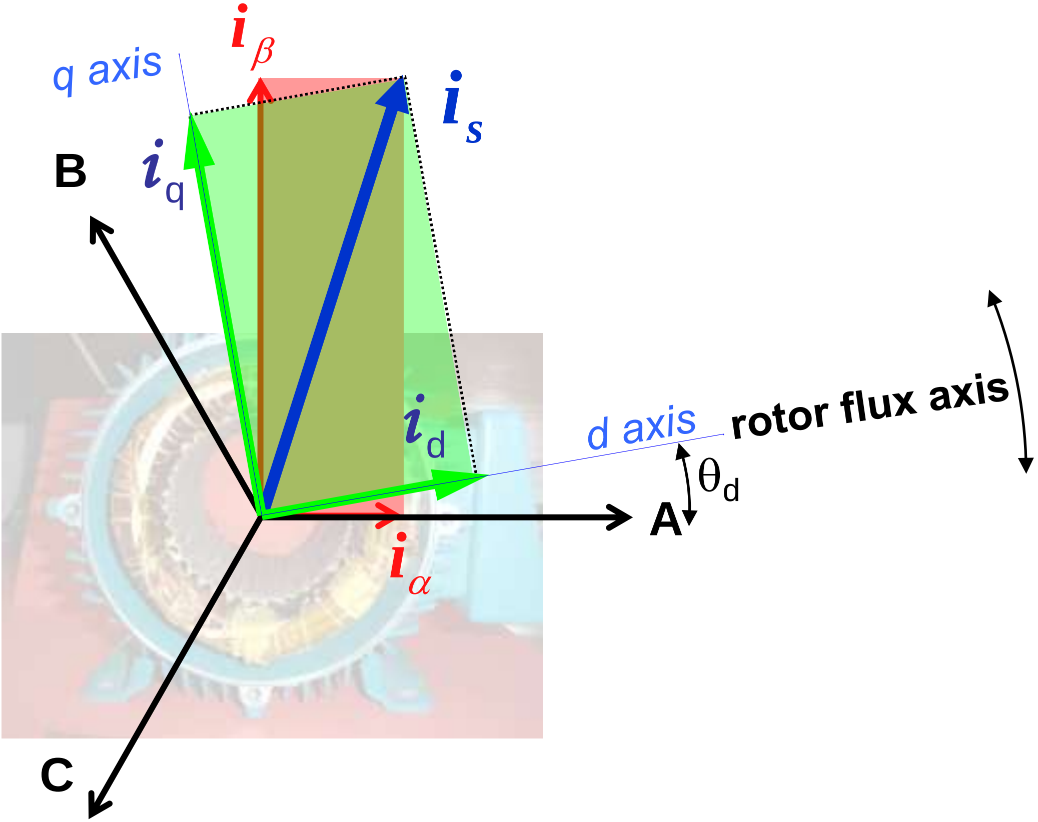
$$\alpha = A$$

$$\beta = \frac{(B-C)}{\sqrt{3}}$$

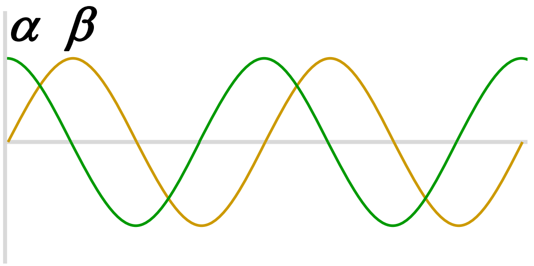


2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

Jump up on the rotating reference frame, whose x-axis is the rotor flux axis.

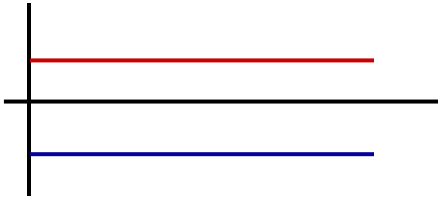


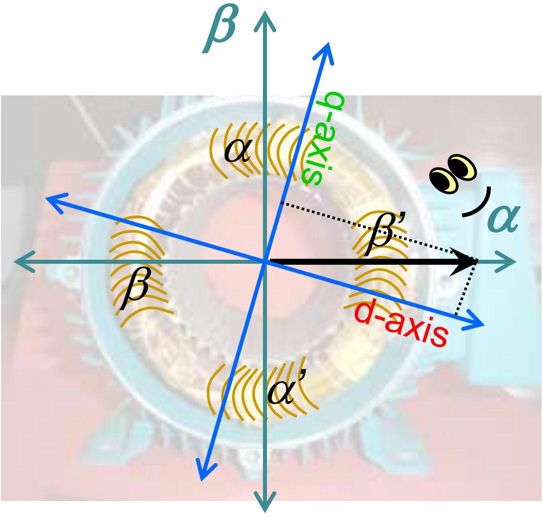
This is called the Park Transform

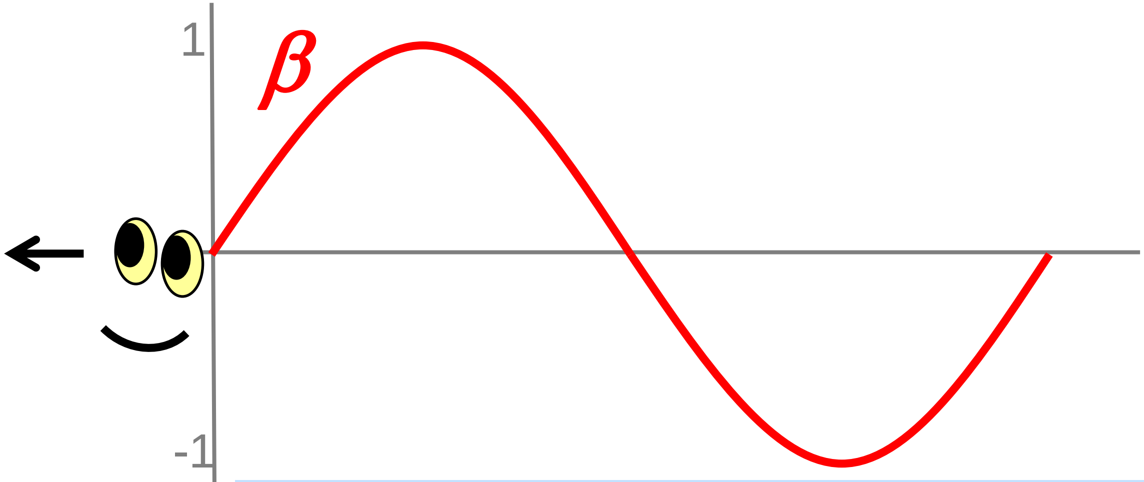


$$i_d = i_\alpha \cos\theta_d + i_\beta \sin\theta_d$$

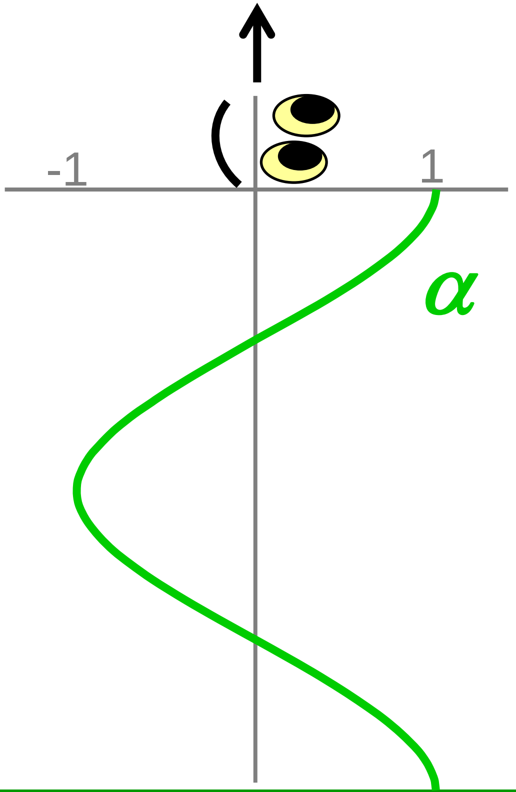
$$i_q = -i_\alpha \sin\theta_d + i_\beta \cos\theta_d$$







Pictorial Example of the Park Transform (Still on Step 2!)



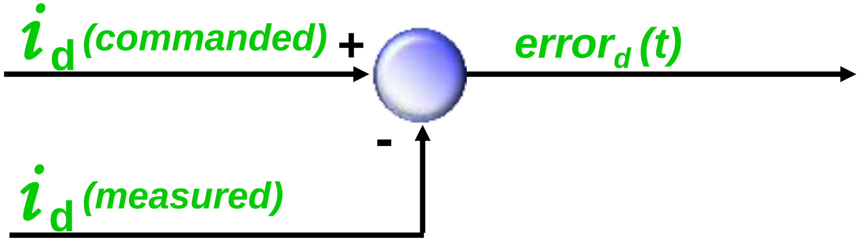
Synchronous Frame

Stationary Frame

2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

i_d and i_q are handled independently. Since the comparison is performed in the synchronous frame, motor AC frequency is not seen. Thus, they are DC quantities!

Under normal conditions, we have all the flux we need supplied by the permanent magnets on the rotor. So commanded i_d is set to zero.



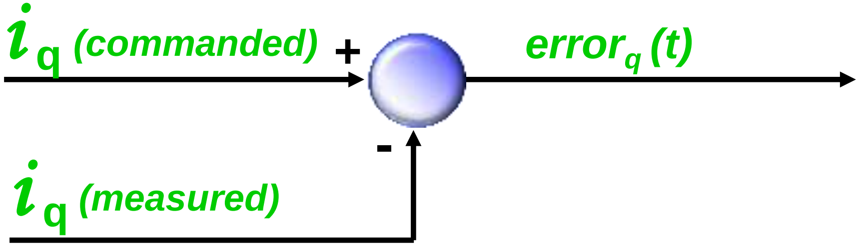
i_d *(commanded)* +

error$_d$ *(t)*

-

i_d *(measured)*

This is how much torque we want!



i_q *(commanded)* +

error$_q$ *(t)*

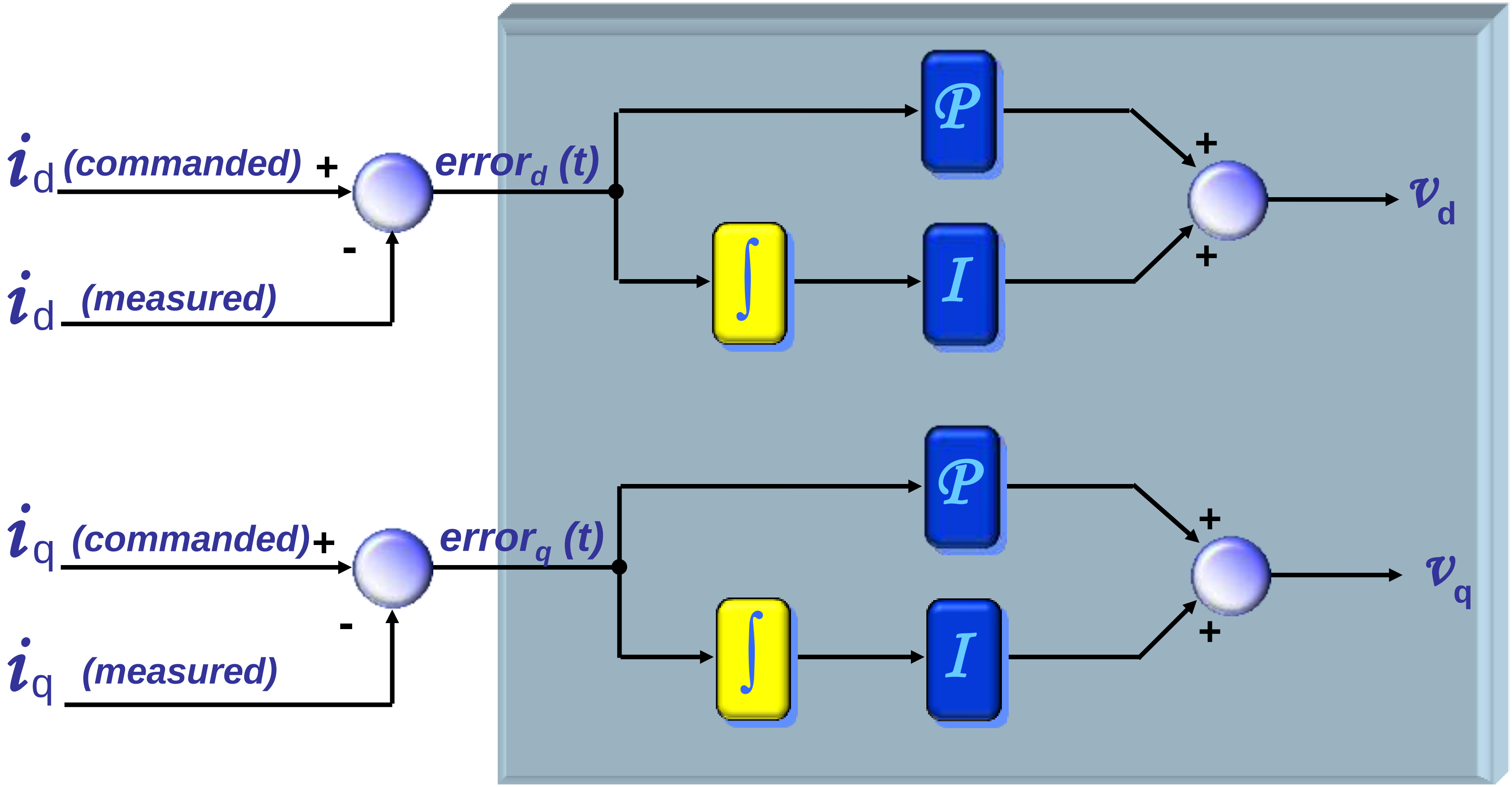
-

i_q *(measured)*

i_d can be used to weaken the field of the machine.

i_q controls the amount of torque generated by the motor

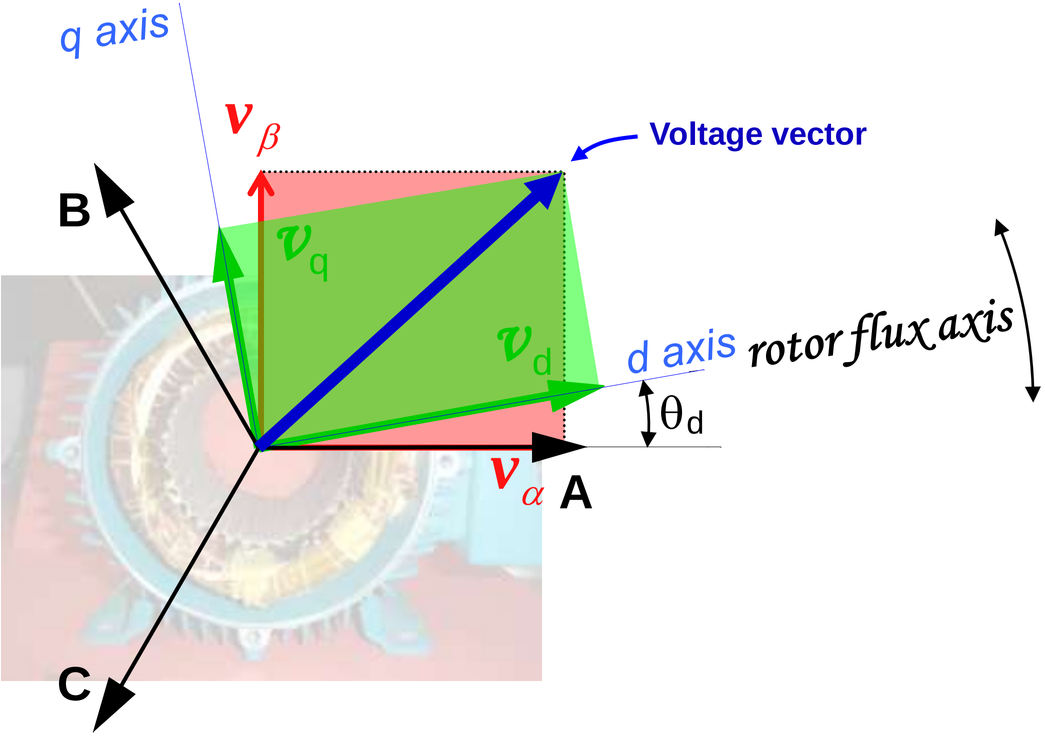
3. (Finally!) Amplify the error signals to generate correction voltages.



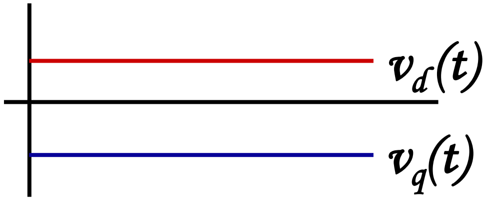
The PI regulator is a good choice for current regulation

4. Modulate the correction voltages onto the motor terminals.

Before we can apply the voltages to the motor windings, we must first jump off of the rotating reference frame.

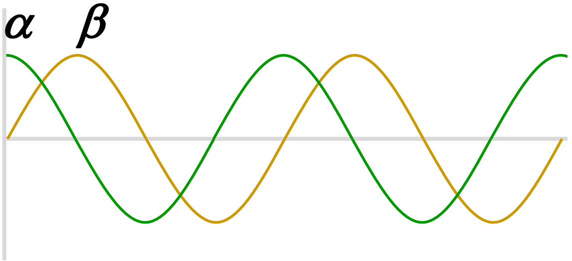


Part A. Transfer the voltage vectors back to the stationary rectangular coordinate system.



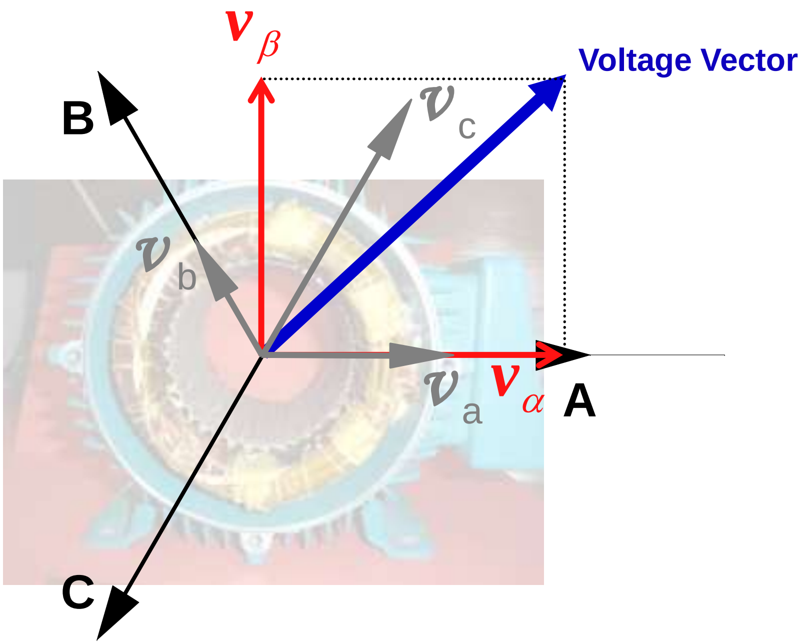
$$v_\alpha = v_d \cos\theta_d - v_q \sin\theta_d$$

$$v_\beta = v_d \sin\theta_d + v_q \cos\theta_d$$

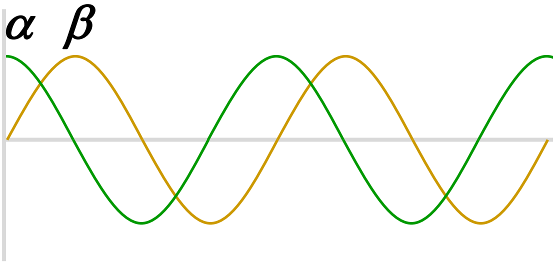


4. Modulate the correction voltages onto the motor terminals.

Part B. Next, we transform the voltage vectors from the rectangular coordinate system to three phase vectors.



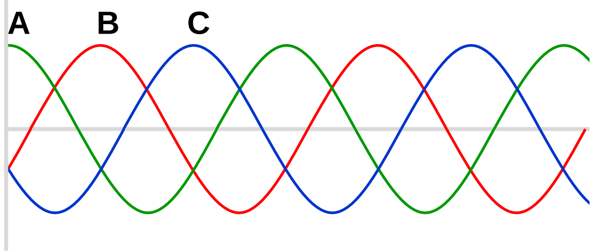
Reverse Clarke Transformation



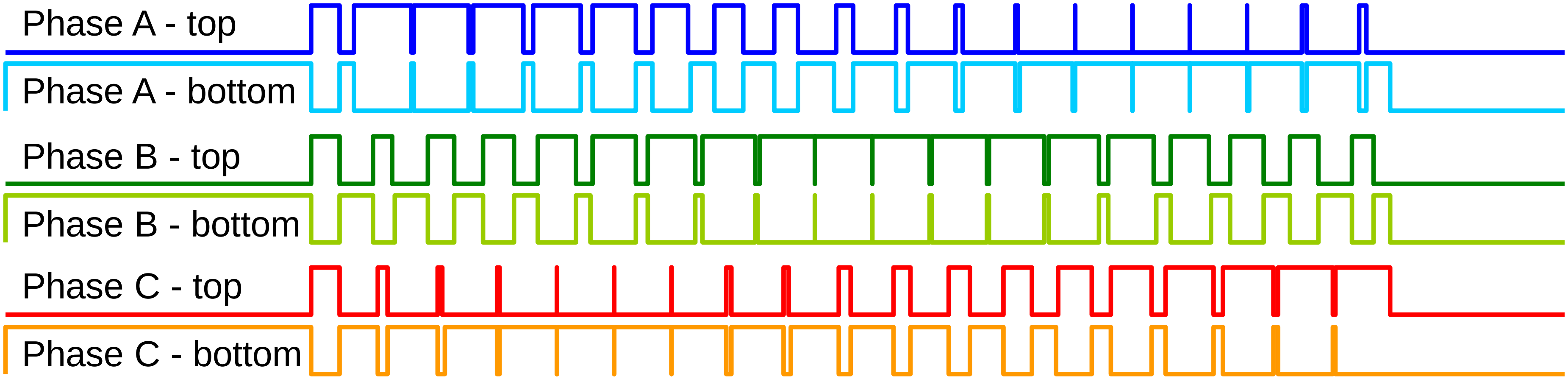
$$A = \alpha$$

$$B = -\frac{1}{2}\alpha + \frac{\sqrt{3}}{2}\beta$$

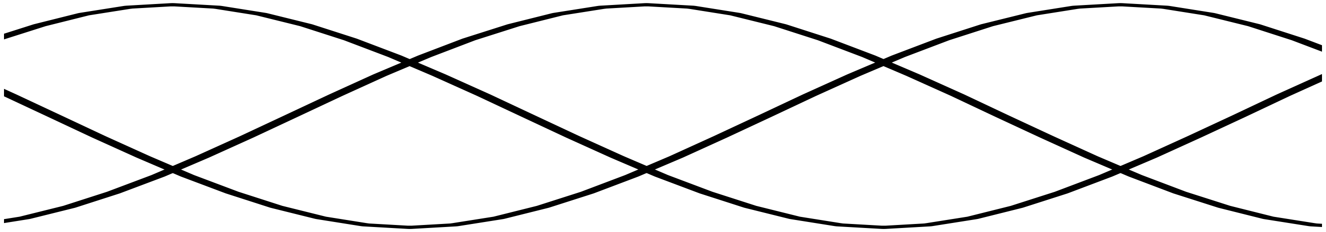
$$C = -\frac{1}{2}\alpha - \frac{\sqrt{3}}{2}\beta$$



4. Modulate the correction voltages onto the motor terminals.



Over time, under steady-state conditions, the correction voltages v_a, v_b, and v_c will be sine waves phase shifted by 120°.



Facts about Field Oriented Control

1. F.O.C. was first proposed in the late 60's by Felix Blaschke, a researcher at Siemens who demonstrated F.O.C. on an AC induction motor. He used magnetic sensors in the airgap of the machine to determine the rotor flux angle.

2. F.O.C. is a TORQUE control algorithm. Notice that at no time did speed enter into the calculations in the previous slides. However, you can wrap a speed loop around an F.O.C. loop to do speed control if you want. The output of the speed control section feeds directly into the commanded q-axis current variable.

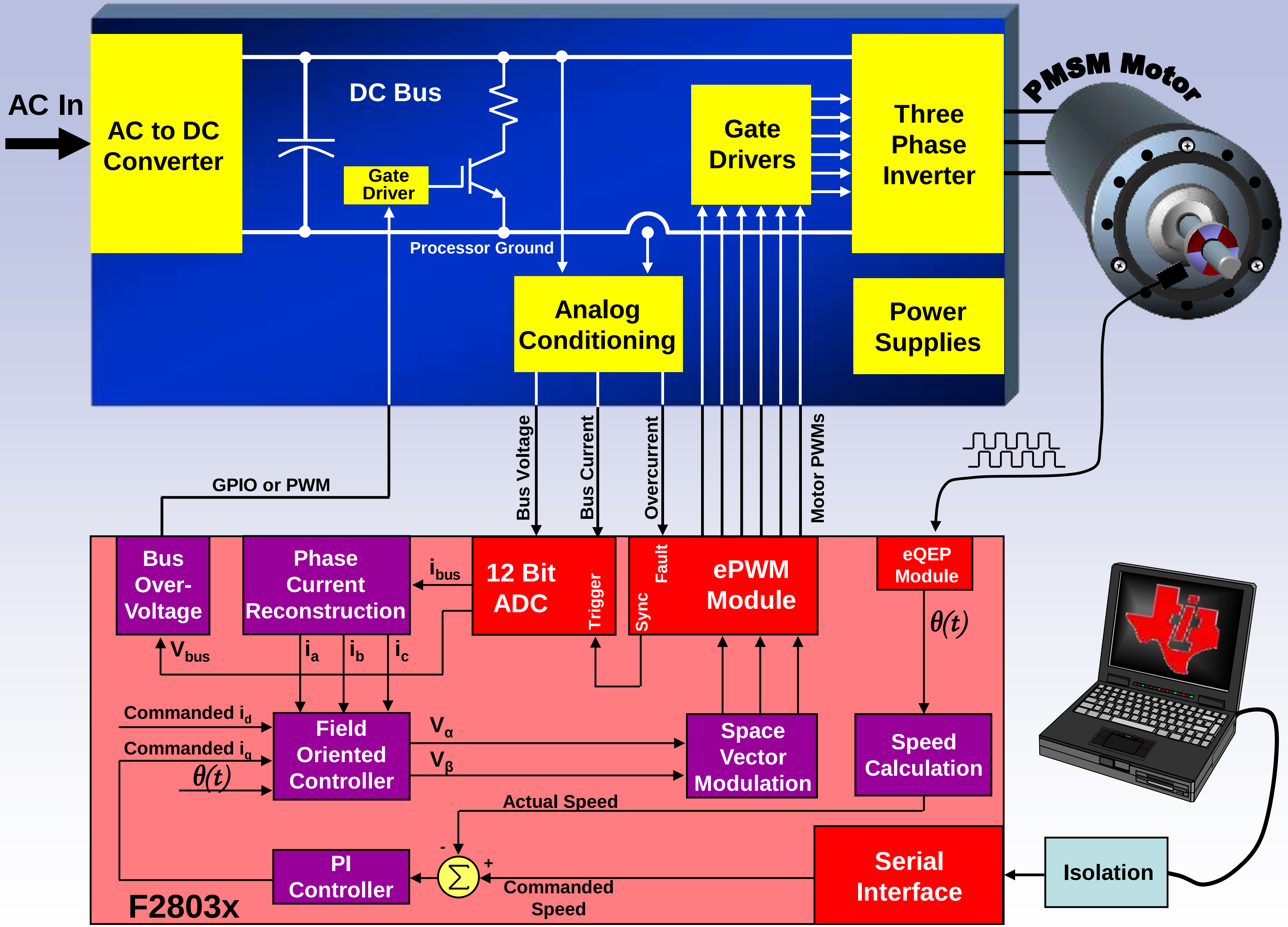
3. F.O.C. works best on motors which exhibit a sinusoidal back-EMF waveform. This includes AC induction motors, Permanent Magnet Synchronous Motors, and many BLDC motors.

4. Since the voltage and current waveforms are sinusoidal, F.O.C. exhibits the lowest torque ripple of any motor control topology. Low torque ripple in turn results in low audible noise.

5. Since F.O.C. requires all of the motor phases be continuously driven, sensorless techniques used with BLDC motors (which require that one phase be unpowered to read the back-EMF signal) will not work with F.O.C. Fortunately, TI has developed other algorithms that will read the motor flux angle with high accuracy (a few degrees) without requiring a shaft sensor OR having an unpowered phase.

6. A typical F.O.C. implementation with a shaft sensor takes about 15uS on an 90 MHz F2806x processor. However, to do sensorless F.O.C. without a shaft sensor requires 2 to 3 times as many calculations. Most of the time is used to calculate the rotor flux angle.

7. The integrity of the current measurement process is critical to F.O.C. performance. 10-bit ADCs are adequate, but 12-bit converters are preferred.



AC In

AC to DC Converter

DC Bus

Gate Driver

Processor Ground

Gate Drivers

Three Phase Inverter

PMSM Motor

Analog Conditioning

Power Supplies

GPIO or PWM

Bus Voltage

Bus Current

Overcurrent

Motor PWMs

Bus Over-Voltage

Phase Current Reconstruction

i_{bus}

12 Bit ADC

Trigger

Fault

Sync

ePWM Module

eQEP Module

$\theta(t)$

V_{bus}

i_a

i_b

i_c

Commanded i_d

Commanded i_q

$\theta(t)$

Field Oriented Controller

V_α

V_β

Space Vector Modulation

Speed Calculation

Actual Speed

-

+

$\sum$

PI Controller

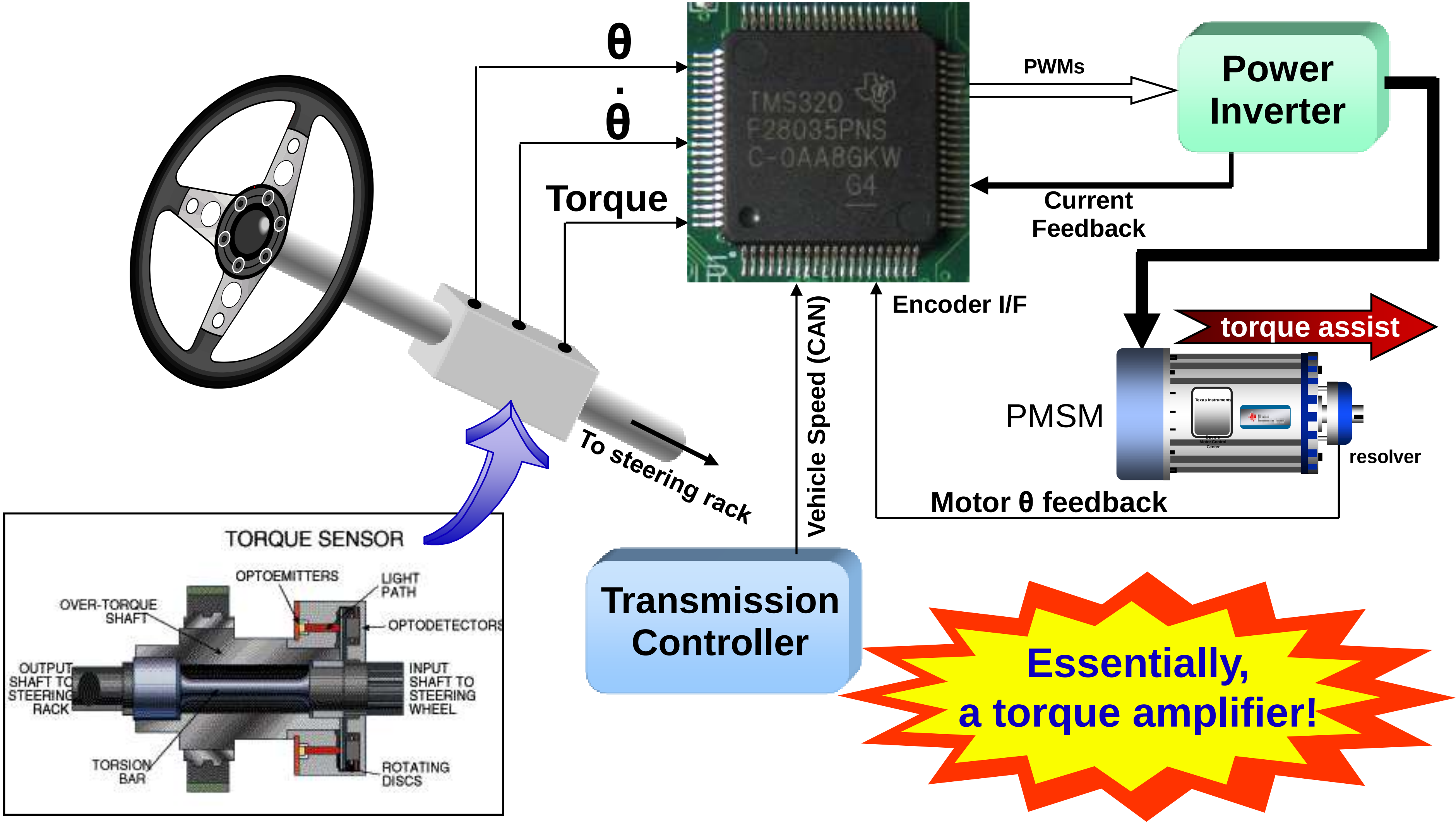
Commanded Speed

Serial Interface

Isolation

F2803x

FOC in Electric Power Steering



PWMs

Power Inverter

Current Feedback

Encoder I/F

torque assist

PMSM

Motor θ feedback

Vehicle Speed (CAN)

Transmission Controller

Essentially, a torque amplifier!