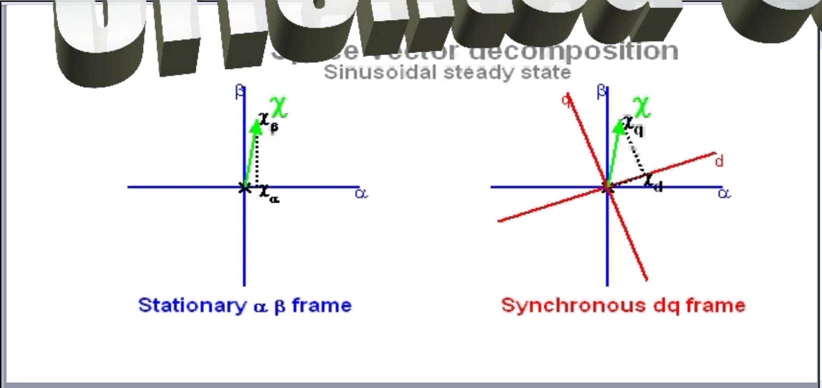
2014 Texas Instruments Motor Control Training Series

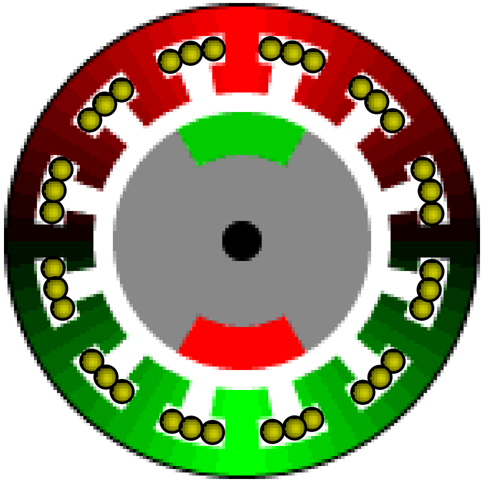
Intro to Field Oriented Control

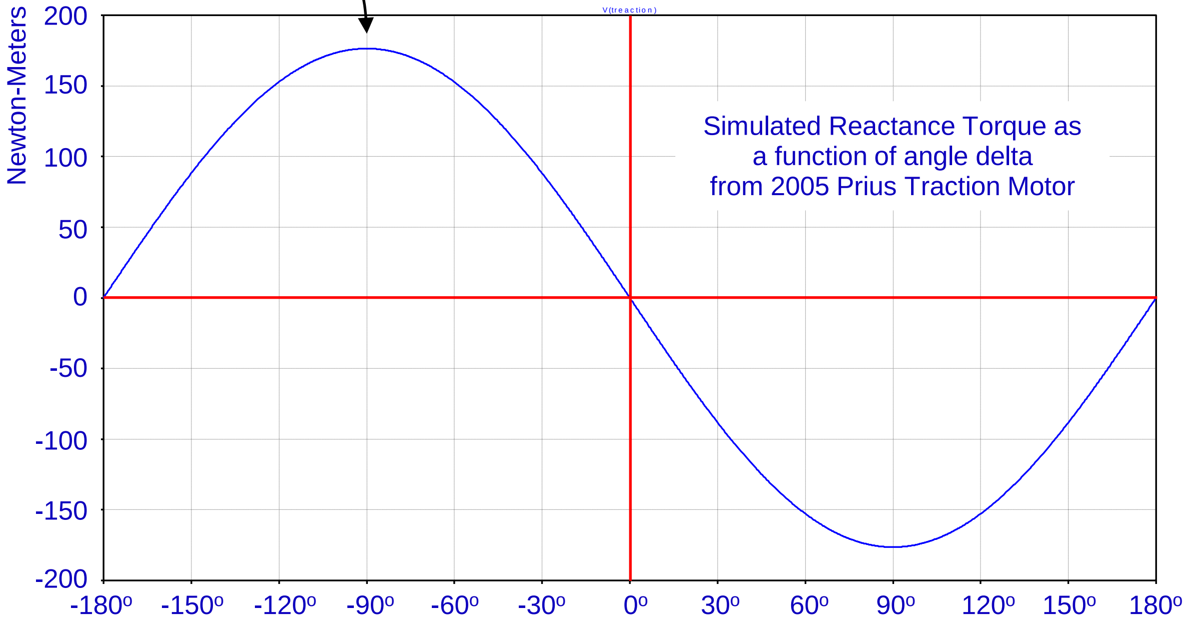


Dave Wilson

Texas Instruments

Maximum Torque Per Amp (MTPA)





Maximum torque per amp (MTPA)

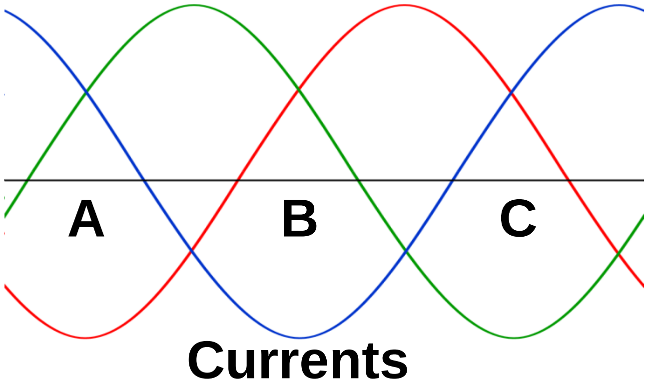
Simulated Reactance Torque as a function of angle delta from 2005 Prius Traction Motor

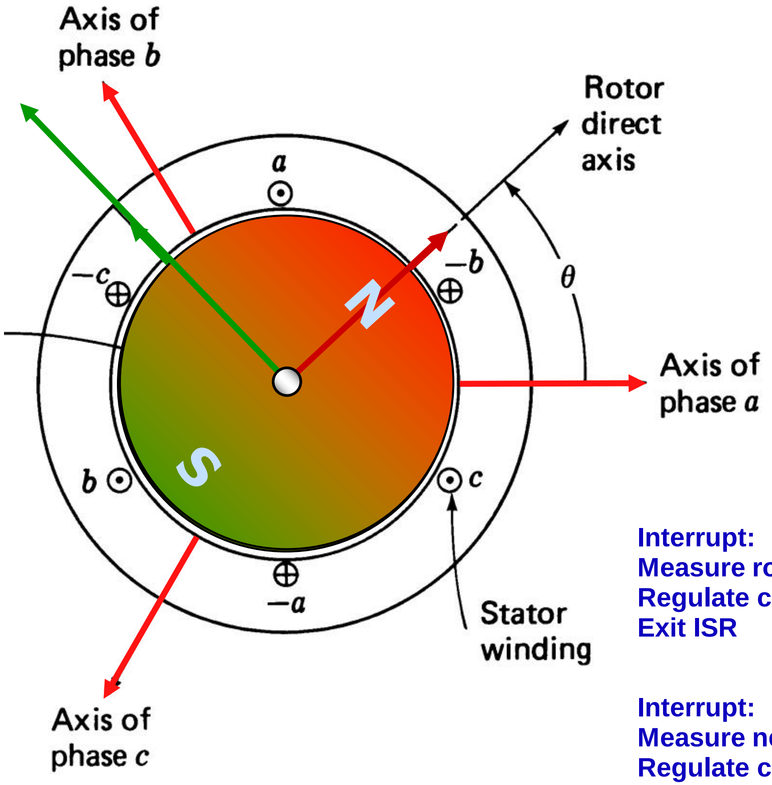
Field Oriented Control in Real Time

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

•
•
•

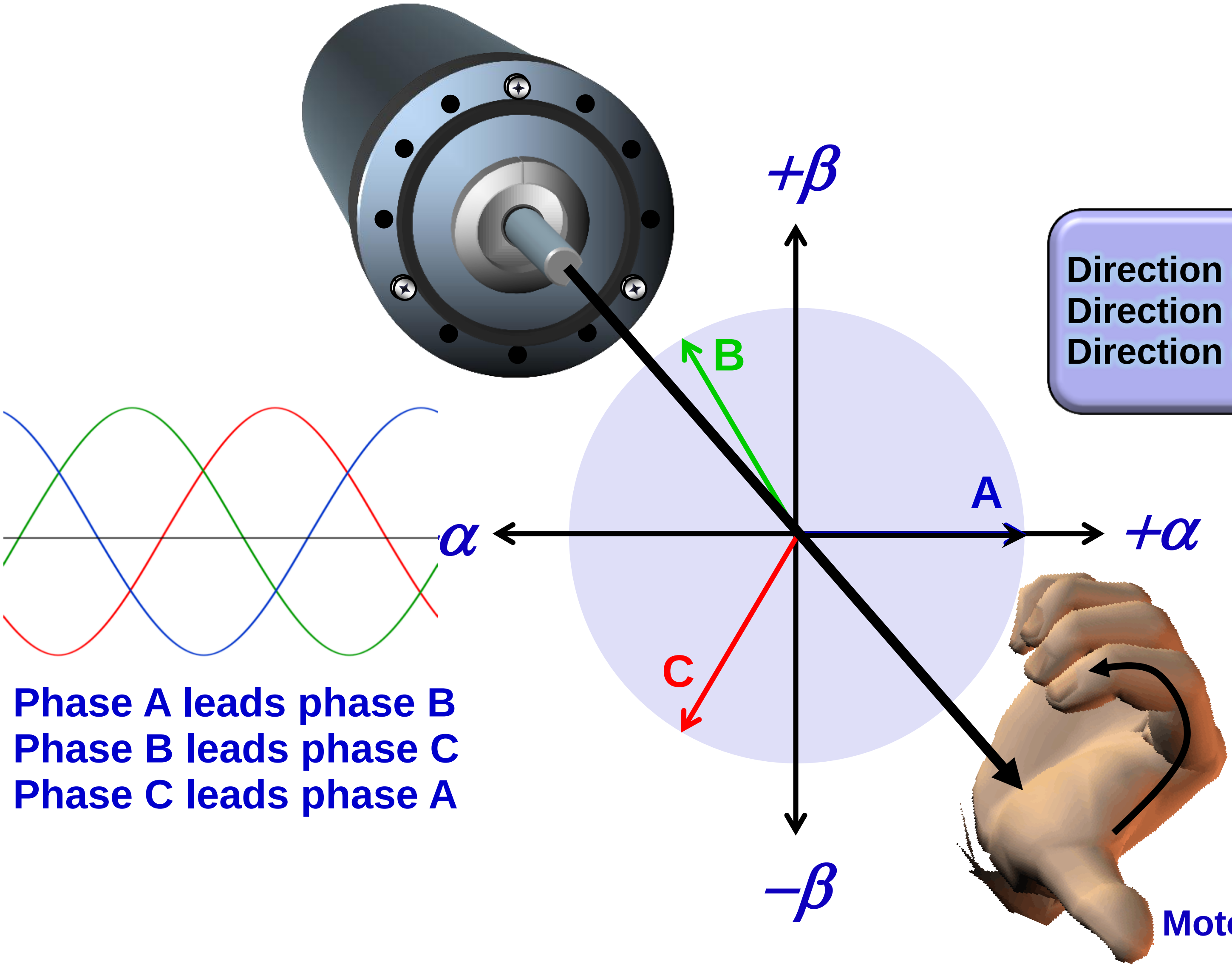
Constant **Constant (for now)**

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

Adjustable

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

Establishing Space Vector Conventions

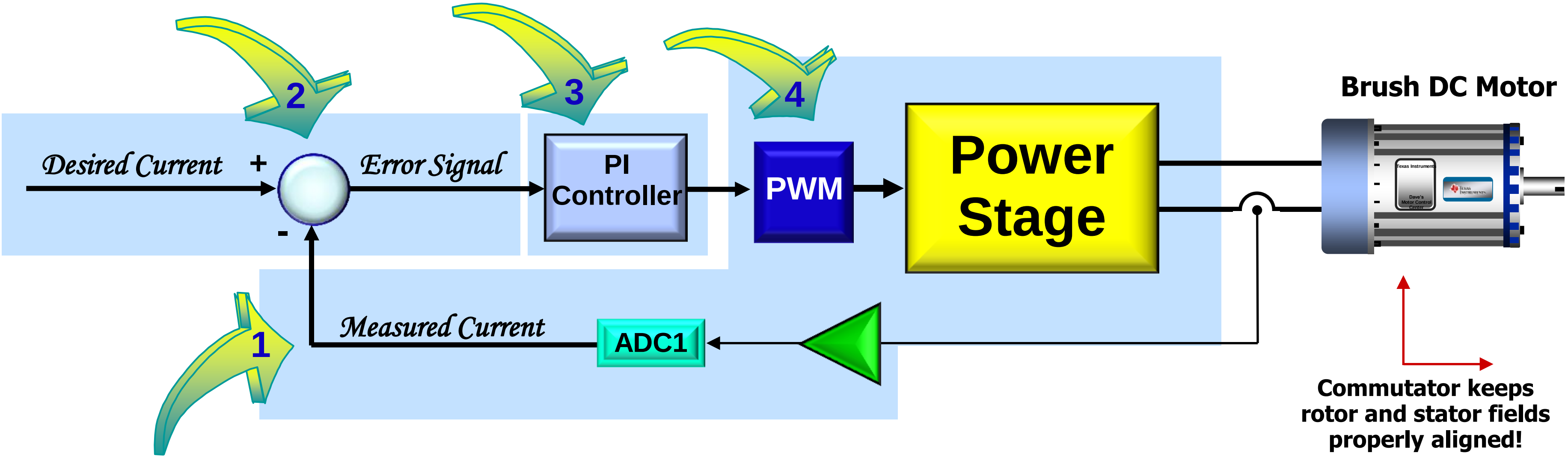


Direction of positive rotation
Direction of positive speed
Direction of positive torque

Phase A leads phase B
Phase B leads phase C
Phase C leads phase A

Motor shaft axis

How Do You Control Torque on a DC Motor?



Commutator keeps rotor and stator fields properly aligned!

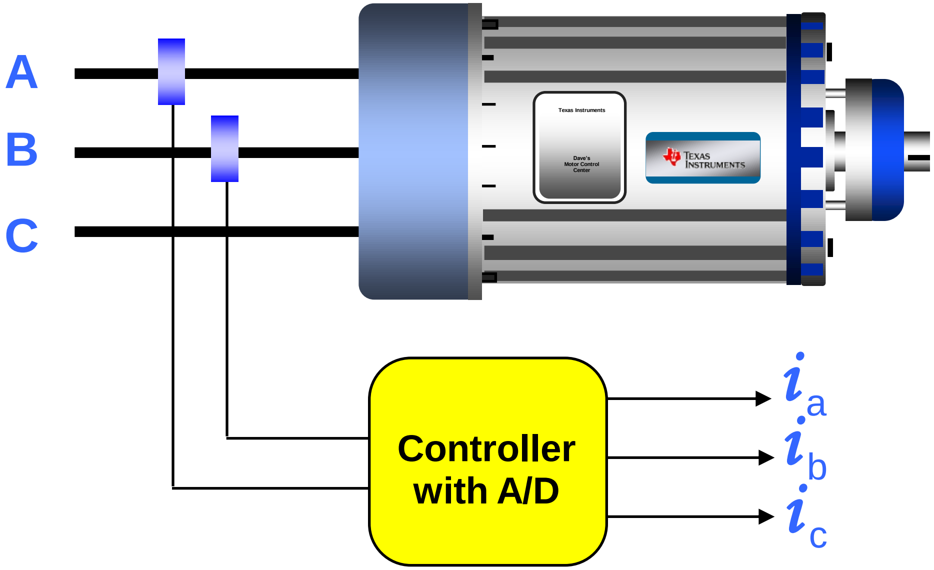
1. *Measure current already flowing in the motor.*
2. *Compare the measured current with the desired current, and generate an error signal.*
3. *Amplify the error signal to generate a correction voltage.*
4. *Modulate the correction voltage onto the motor terminals.*

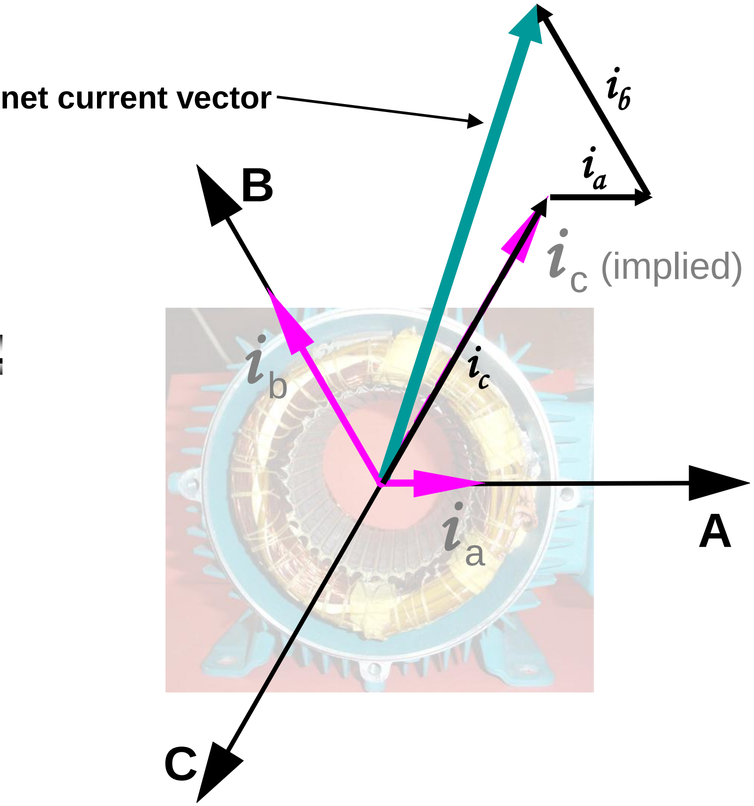
$$Torque = K_a i$$

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”.





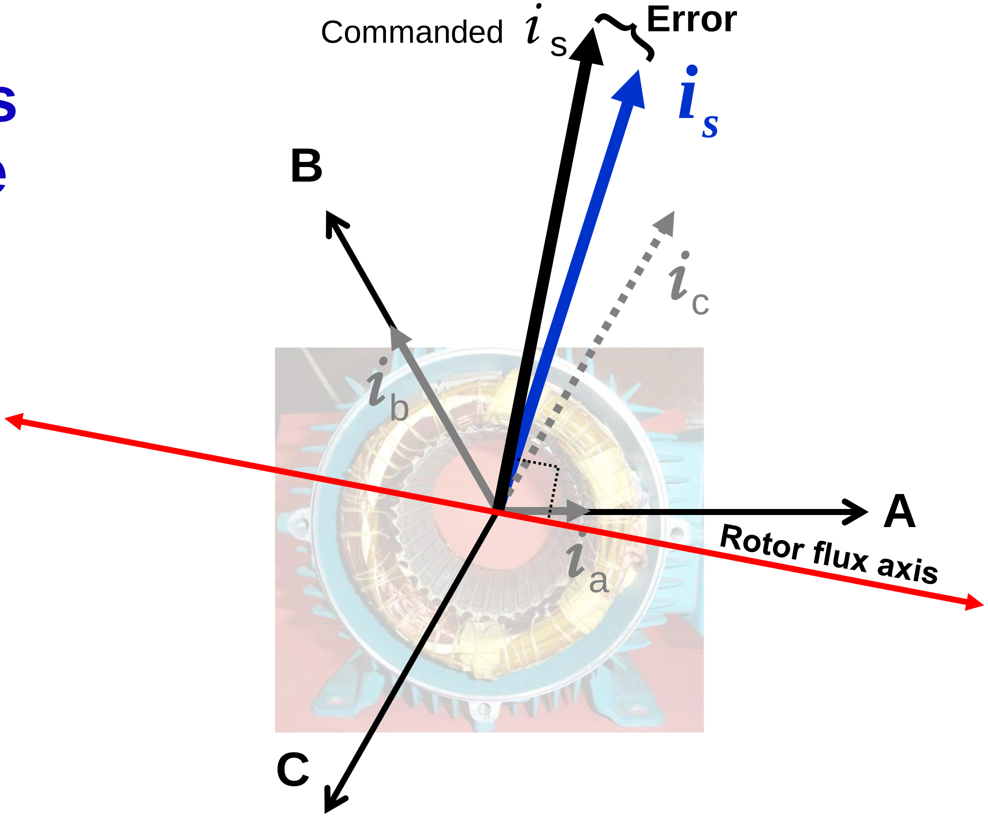
2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

The desired phase currents can be calculated via these equations:

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

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

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

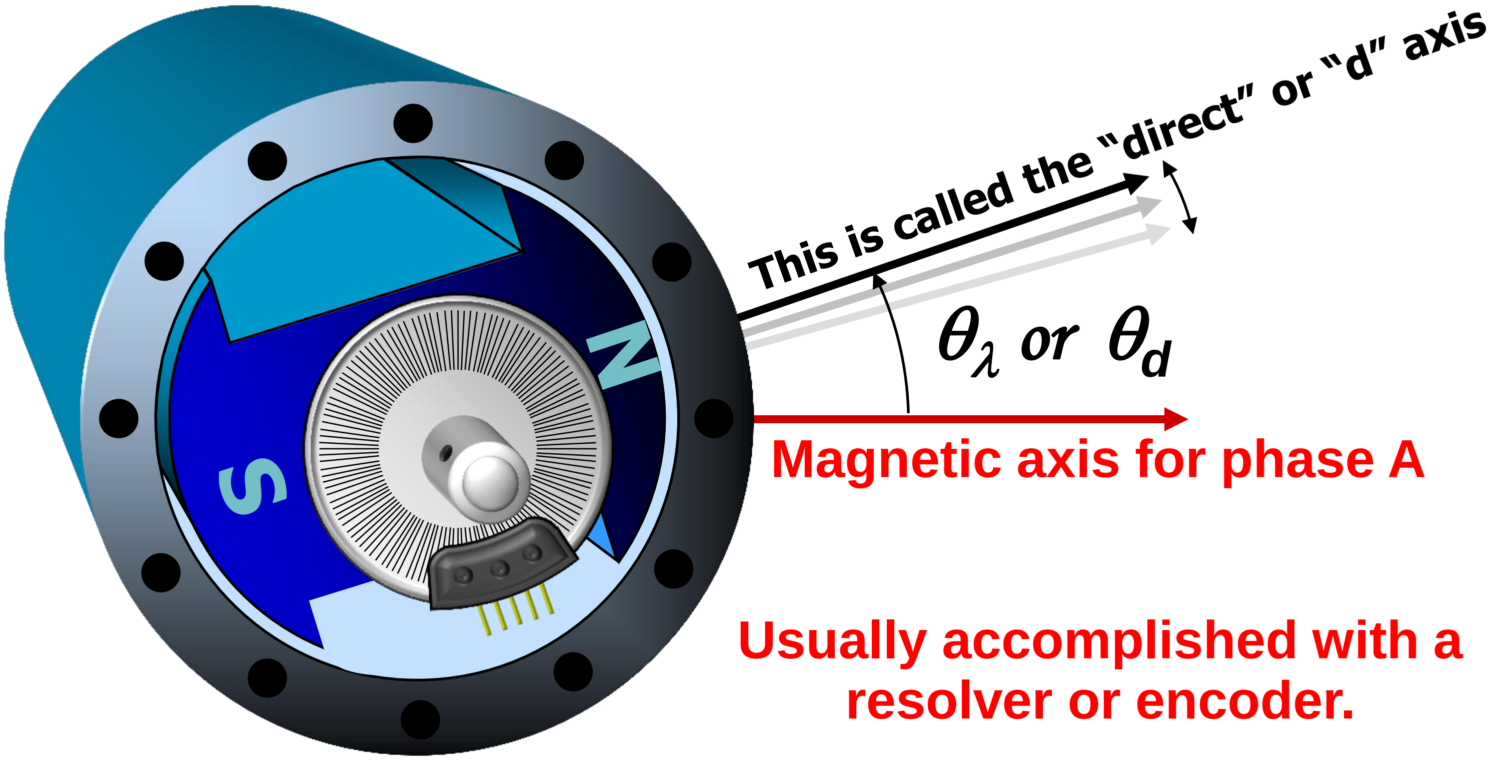


I_m is proportional to motor torque

θ_λ is the angle of the rotor flux

So how do we get the rotor flux angle?

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



This is called the "direct" or "d" axis

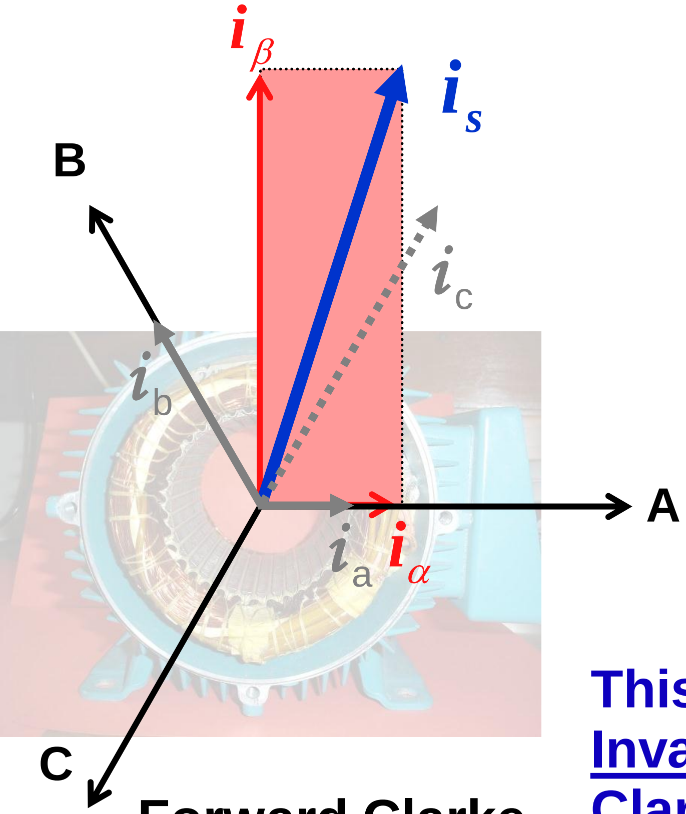
θ_λ or θ_d

Magnetic axis for phase A

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.



Trick #1

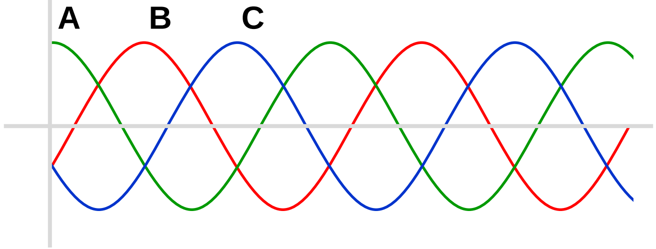
In other words, convert a 3-phase motor into a 2-phase motor.

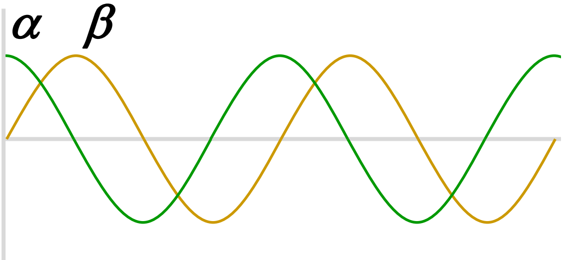
This is the <u>Amplitude Invariant</u> form of the Clarke Transform

Forward Clarke

$$\alpha = A$$

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





Stationary Frame Servo

Tracking a rotating reference signal from a stationary frame is tedious!

Synchronous Frame Servo

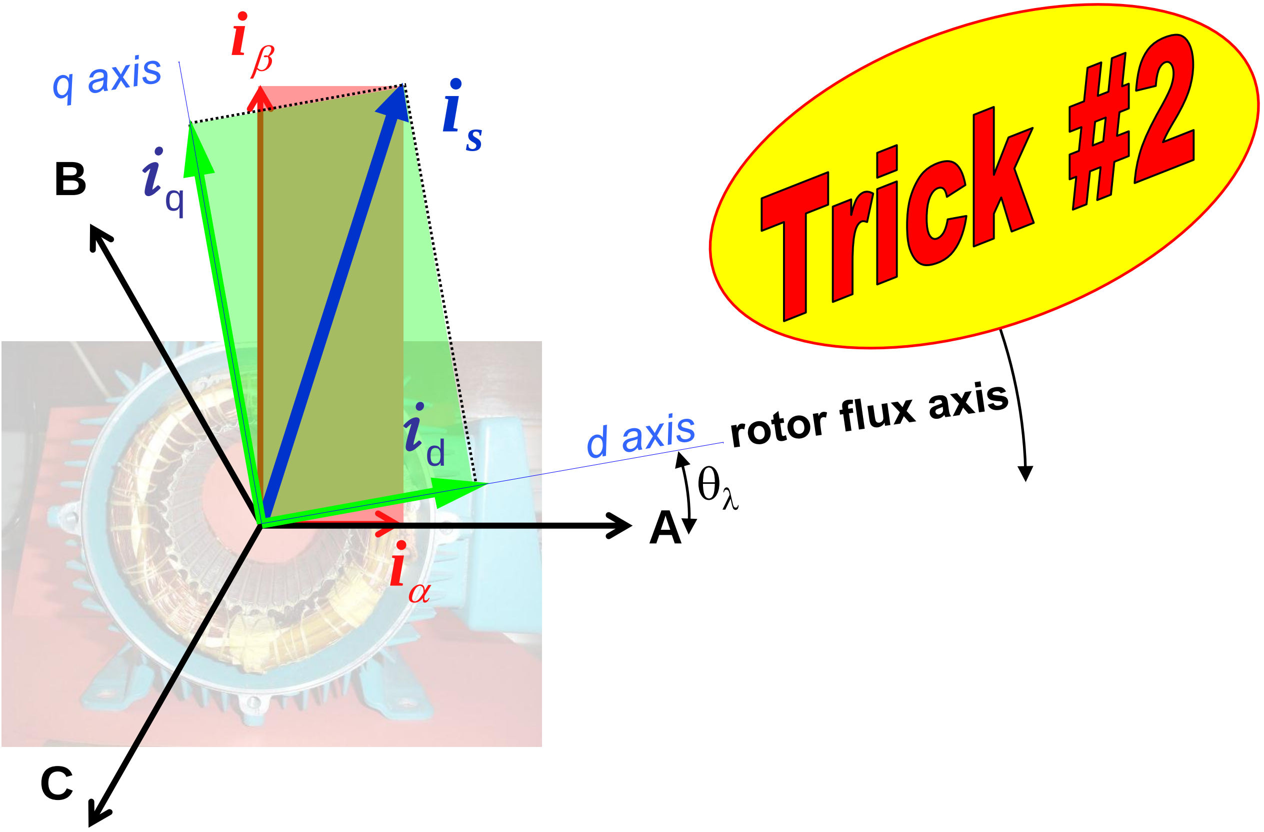
Tracking a rotating reference signal in the same rotating frame is easy!

Take the “Coffee” Test

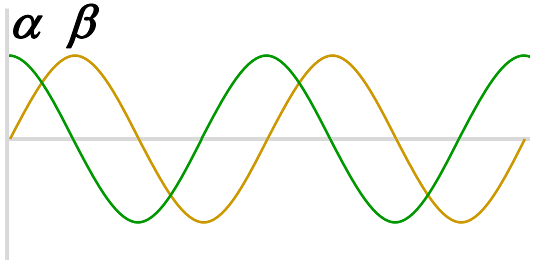
1. Give your coffee a good stir so that bubbles form on the surface.
2. Holding the cup as shown here, spin around in the same direction that you stirred the coffee.
3. As soon as you reach synchronous speed, the bubbles stop spinning. Why?

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.

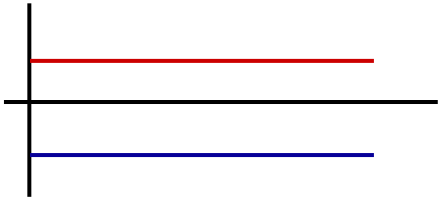


This is called the Park Transform



$$i_d = i_\alpha \cos\theta_\lambda + i_\beta \sin\theta_\lambda$$

$$i_q = -i_\alpha \sin\theta_\lambda + i_\beta \cos\theta_\lambda$$

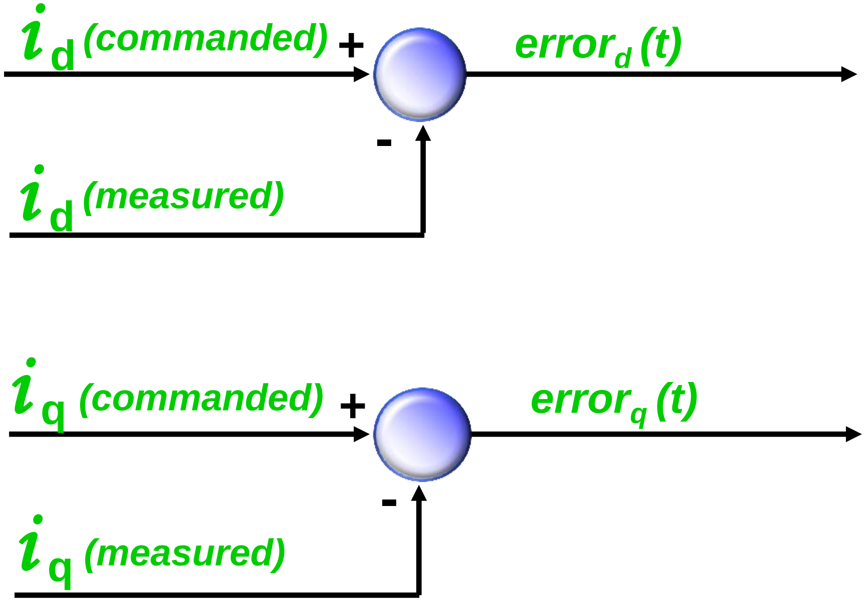


2. Compare the measured current (vector) with the desired current (vector), and generate error signals.

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.

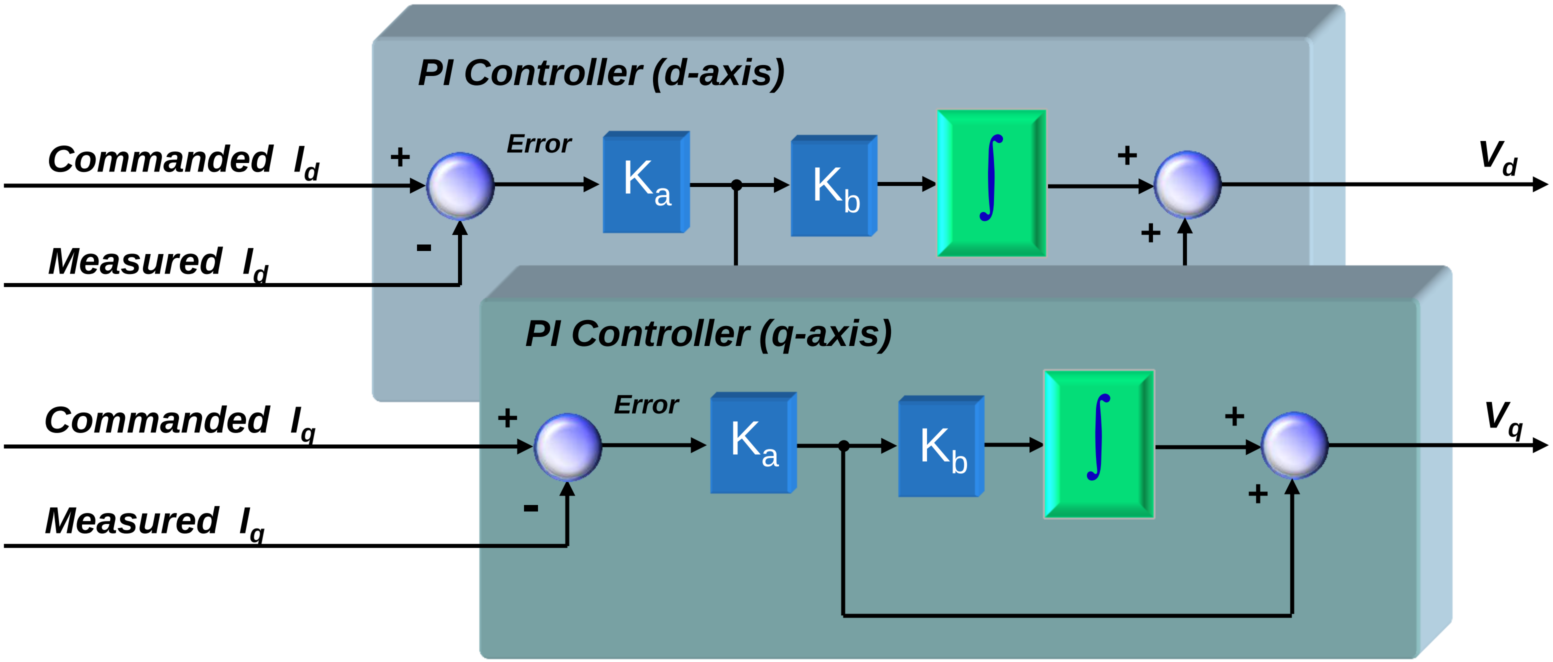
This is how much torque we want!



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.

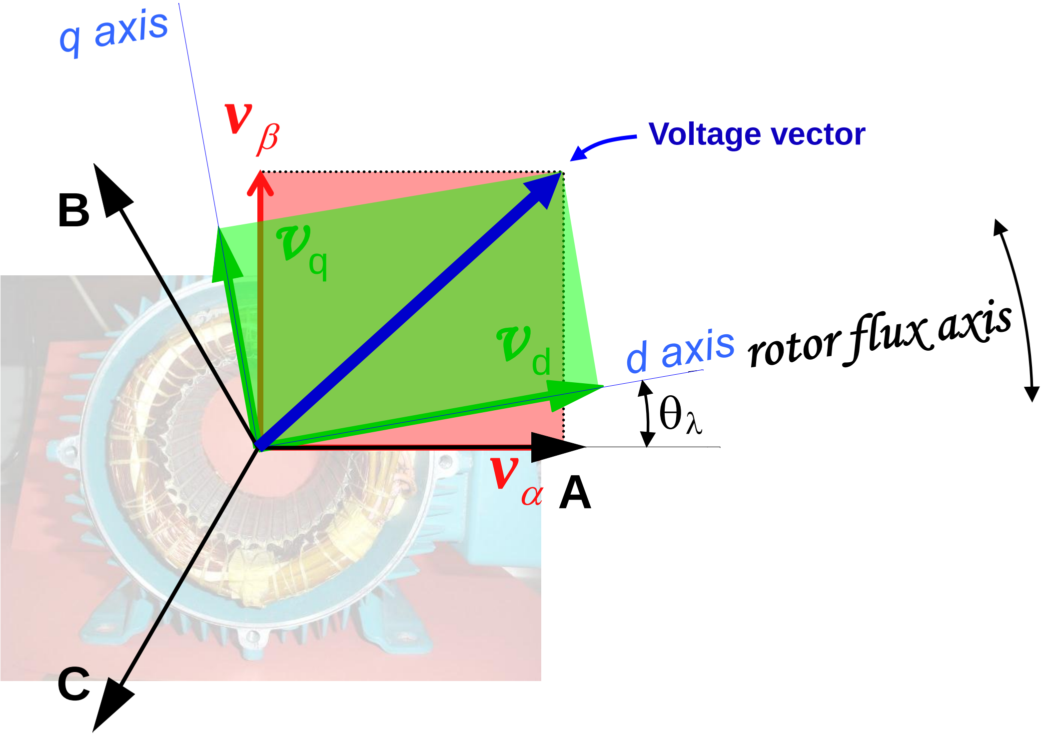


$$K_a = L \cdot Current\ \ Bandwidth\ \ (rad/\sec),\ K_b = R/L$$

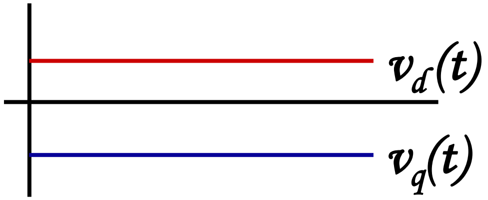
Motor	Rd	Rq	Ld	Lq
PMSM	*Rs*	*Rs*	*Ls*	*Ls*
ACIM	*Rs*	*Rs+Rr*	$L_s\left(1-\frac{L_m{}^2}{L_r L_s}\right)$	$L_s\left(1-\frac{L_m{}^2}{L_r L_s}\right)$
IPM	*Rs*	*Rs*	*Ls_d*	*Ls_q*

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.

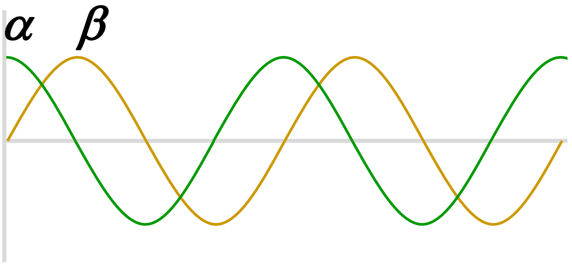


Part A. Transfer the voltage vectors back to the stationary rectangular coordinate system.



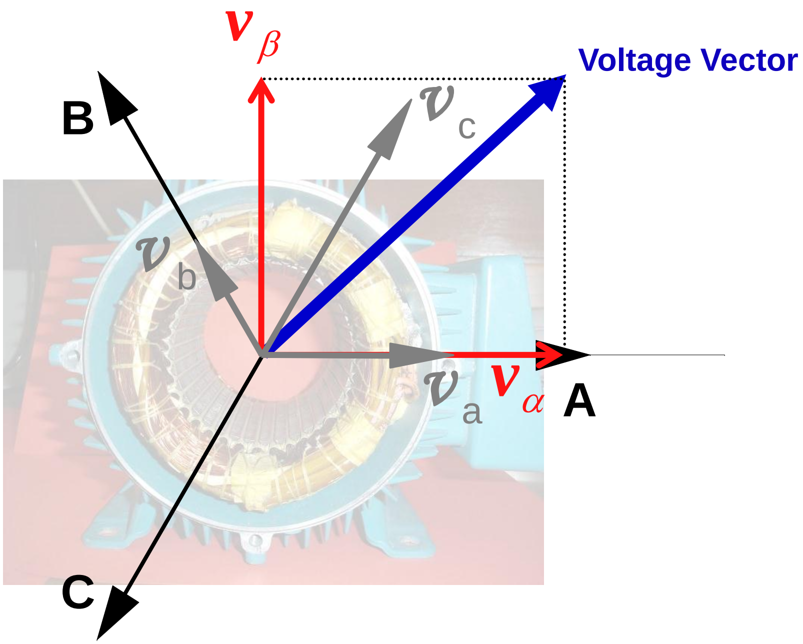
$$v_\alpha = v_d \cos\theta_\lambda - v_q \sin\theta_\lambda$$

$$v_\beta = v_d \sin\theta_\lambda + v_q \cos\theta_\lambda$$

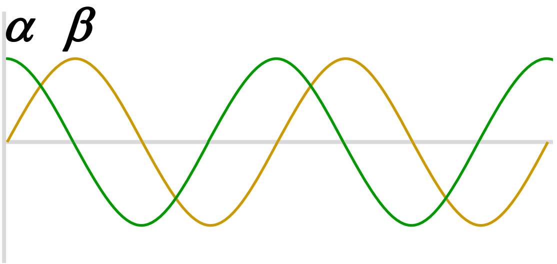


4. Modulate the correction voltages onto the motor terminals.

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



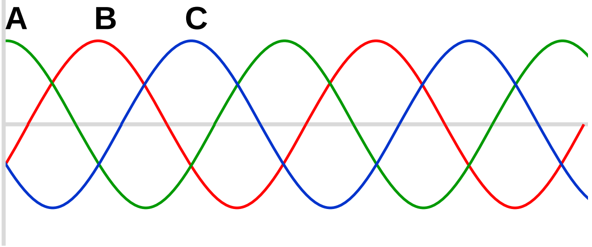
Reverse Clarke Transformation



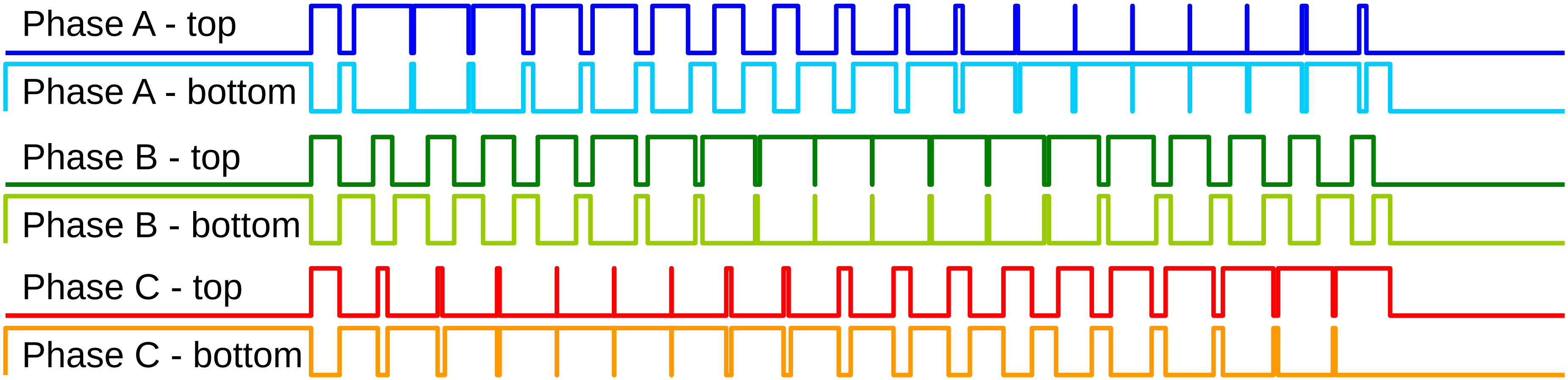
$$A = \alpha$$

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

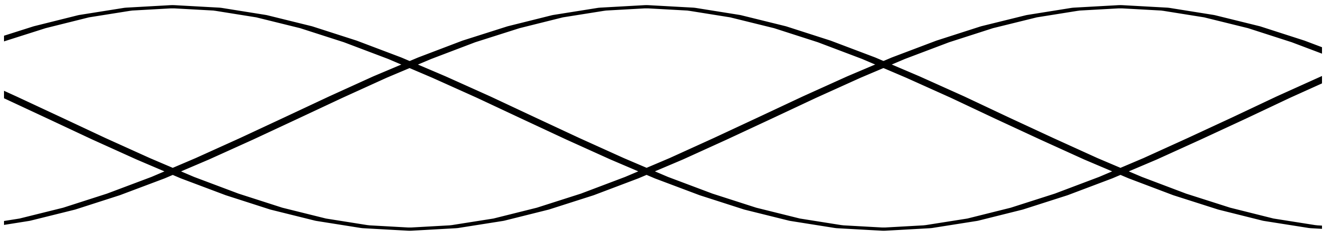
$$C = -\tfrac{1}{2}\alpha - \tfrac{\sqrt{3}}{2}\beta$$



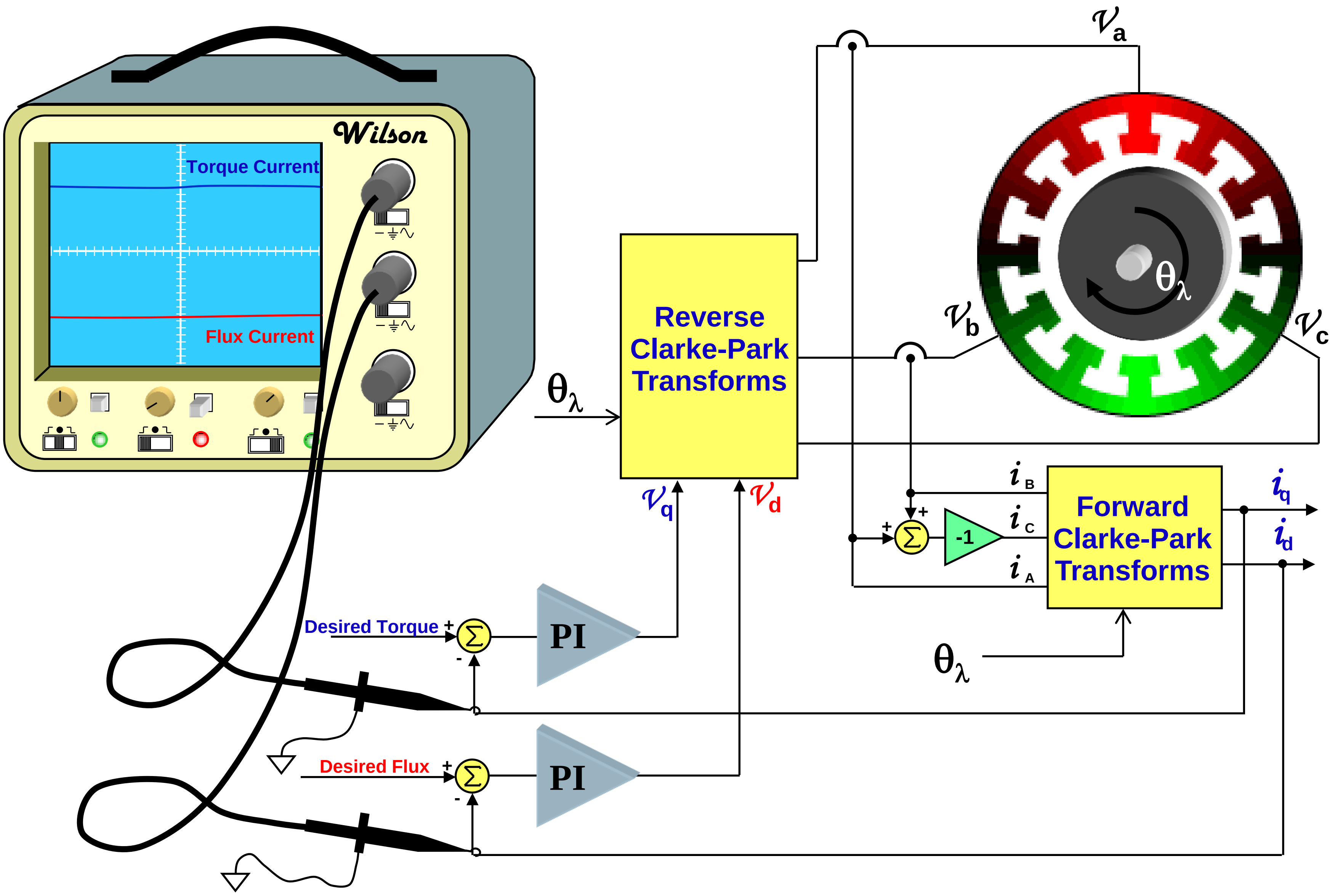
4. Modulate the correction voltages onto the motor terminals.



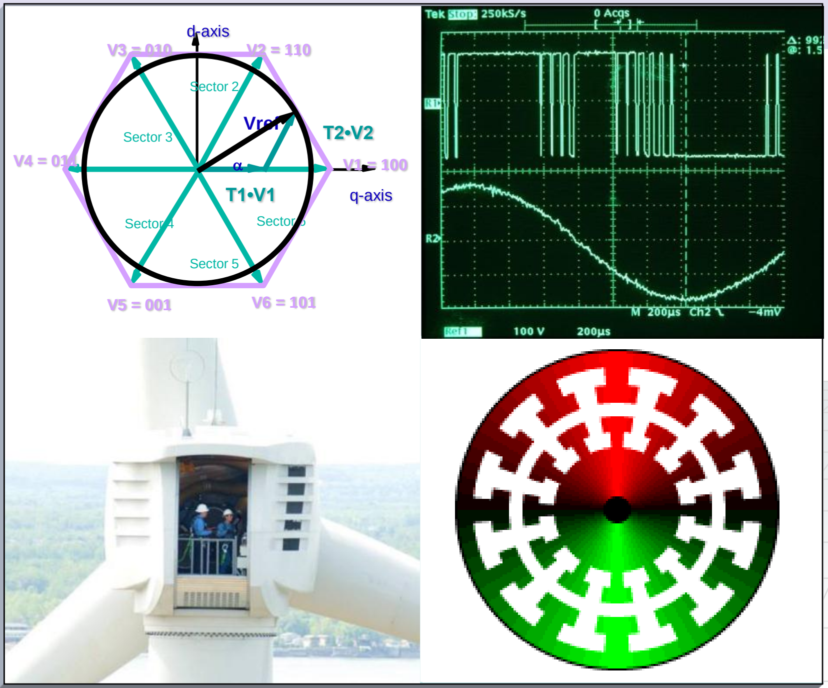
Over time, under steady-state conditions, the correction voltages v_a, v_b, and v_c will be sine waves phase shifted by 120°.



FOC in a Nutshell



Space Vector Modulation



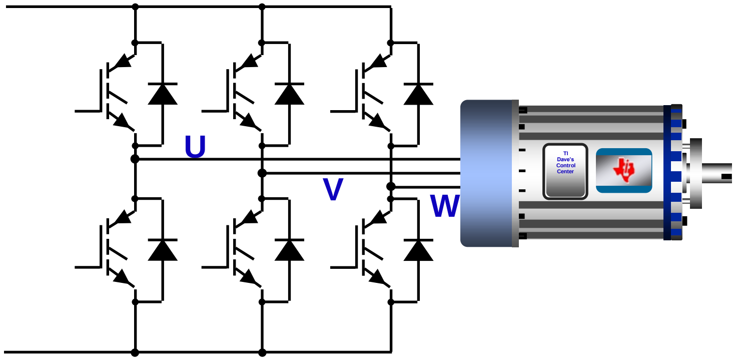
TEXAS
INSTRUMENTS

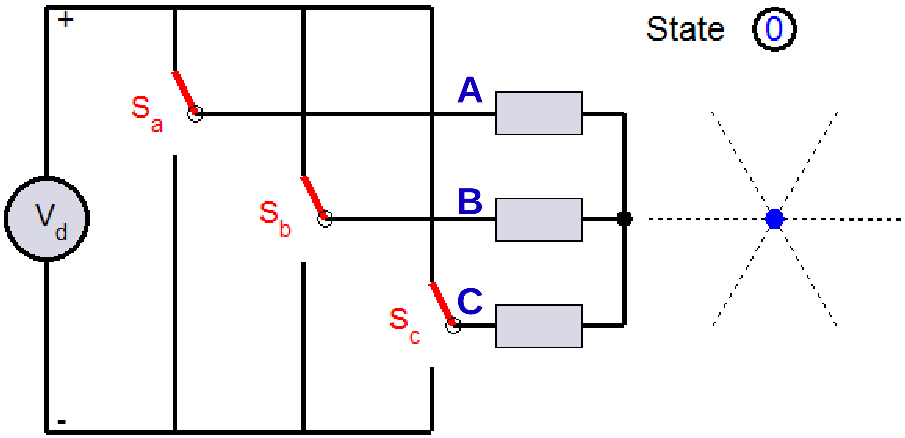
Space Vector Modulation

- PWMs treat each phase individually.

- SVM treats the inverter as ONE unit!!
  - ALL 6 switches affected.

- PWMs control the phase voltages.
  - ➢120° offsets between A, B, and C.
- SVM controls the Voltage Vector.



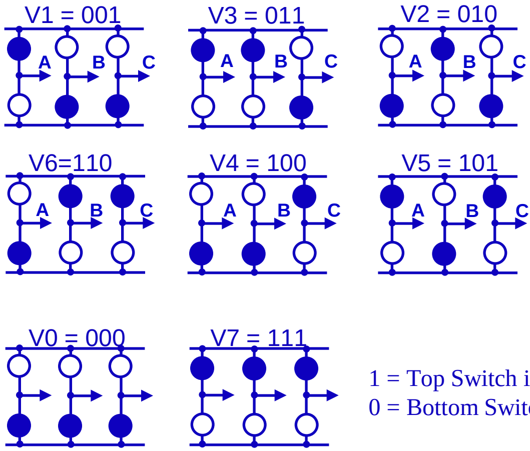


Source: Mahmoud Riaz, Sc.D., Professor of Electrical Engineering, Department of Electrical and Computer Engineering, University of Minnesota

The inverter can be driven to 8 states.

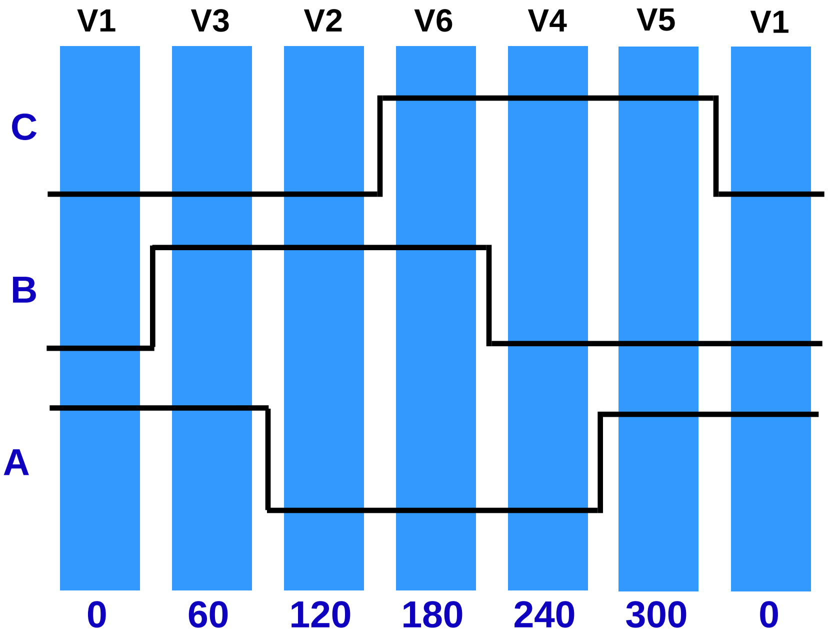
- 6 voltage vectors

- 2 null vectors

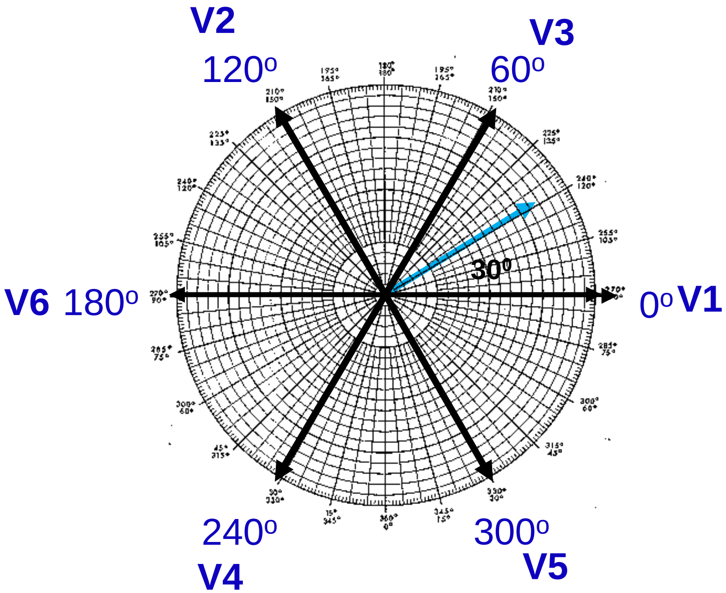


1 = Top Switch is on
0 = Bottom Switch is on

Space Vector Modulation



“6-Step” Voltage Waveforms



Vector Diagram

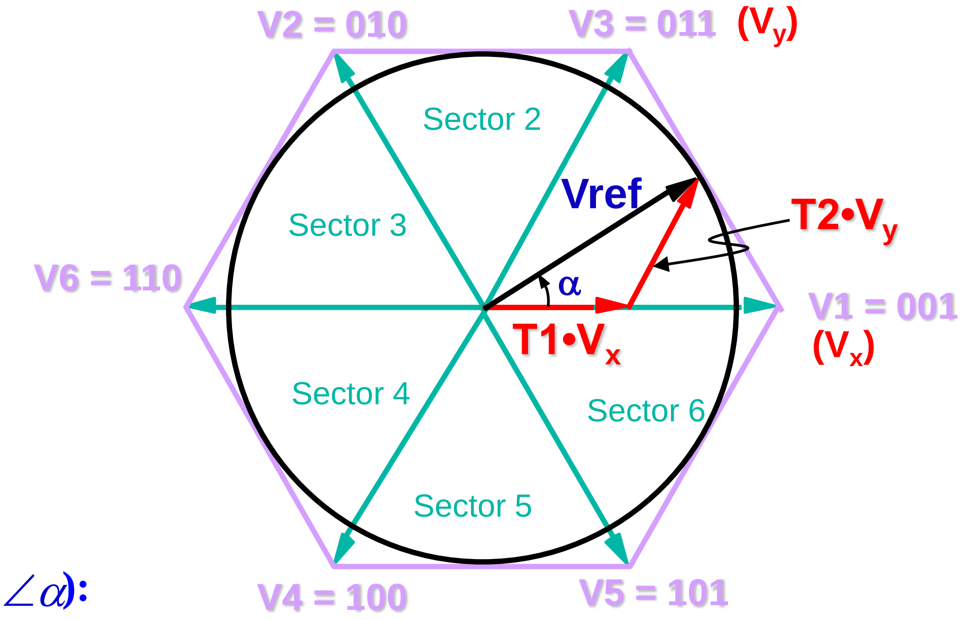
- Output voltage vector created by repeatedly switching between adjacent vectors and the “null” vector (all three phases high or all three phases low).
- Output angle θ determined by relative “on” time between two adjacent vectors.
- Output magnitude determined by relative “on” time between two adjacent vectors **and** the null vector.

SVM Implementation

- Vref, is created by the two adjacent state vectors V_x, V_y, and a null vector in a time averaging fashion:

$$\text{Vref} = V_x \bullet T1 + V_y \bullet T2 + V_{null} \bullet T0$$

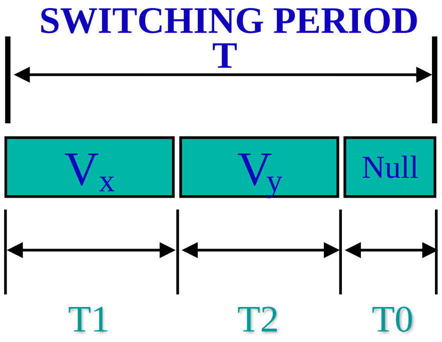
Where: V_x = **lowest angle voltage vector**
V_y = **highest angle voltage vector**



If Vref is represented in POLAR notation ($m\angle\alpha$):

Example vector reconstruction in sector 1.

$T1 = T \bullet m \bullet SIN(60 - \alpha)$
$T2 = T \bullet m \bullet SIN(\alpha)$
$T0 = T - T1 - T2$

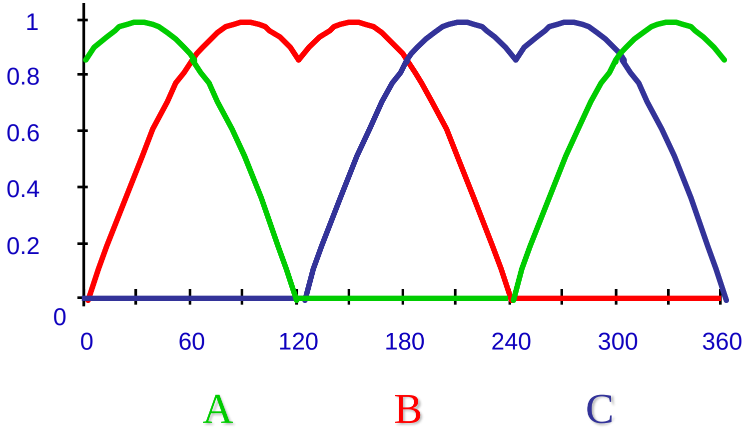


m = vector magnitude (0 to 1)
α = vector angle between Vref and Vx (0 to 60°)
T = switching period

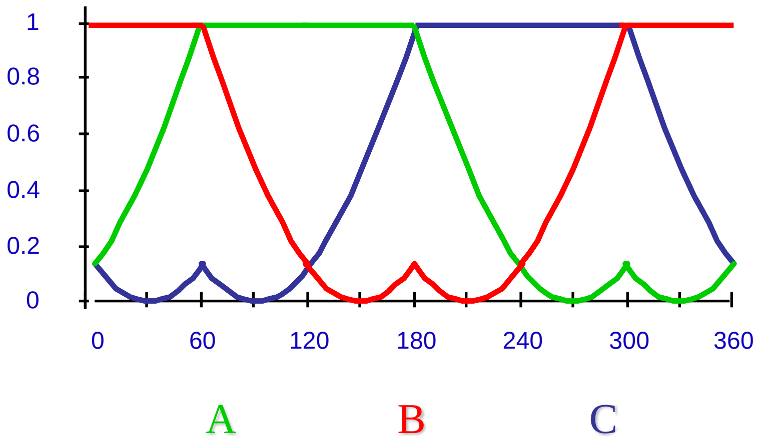
SVM Variations

- Choice of Null vectors effects SVM waveform creation and switching performance but motor still sees sinusoidal waveform at its phases.

NULL=V0



NULL=V7

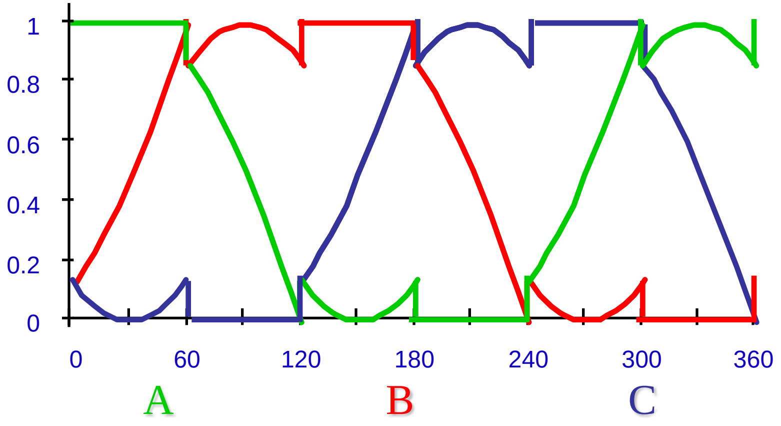


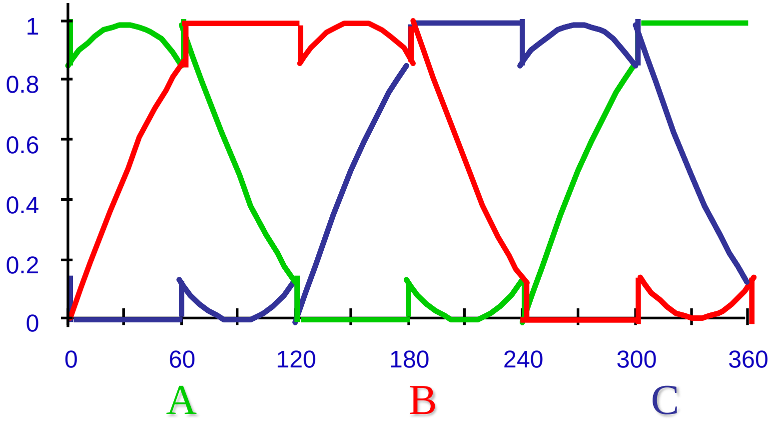
Good choice when reduced switching losses are desired in an inverter with high-side bootstrap circuits.

SVM Variations (continued)

Null = V7 in sectors 1,3,5
Null = V0 in sectors 2,4,6

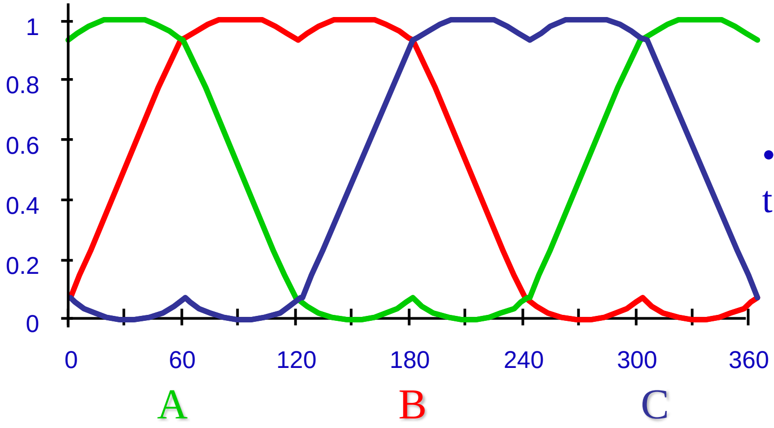
Null = V0 in sectors 1,3,5
Null = V7 in sectors 2,4,6





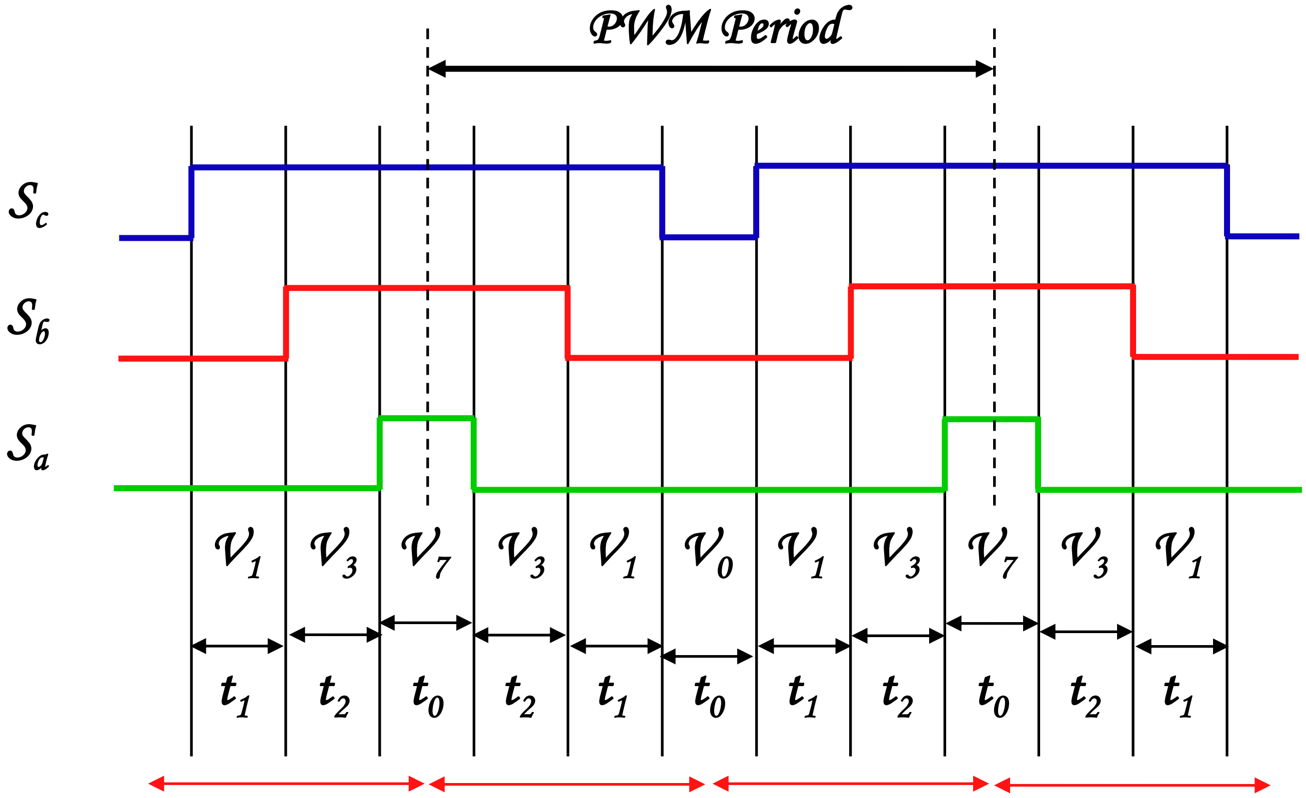
Null = alt-rev
(null alternates every sequence
and sequence reverses.)

Most popular form of SVM



- Similar waveforms to Third Harmonic

SVM Using Center-Aligned PWMs



Alternating-Reversing Sequence

Check out http://www.ipes.ethz.ch/ipes/Raumzeiger/e_RZ4.html for a neat SVM animation!

SVM with PWMs

Procedure for implementing SVM with Center-Aligned PWM Module

1 Check which sector the Vref vector is in. (5 compares)
2 Calculate T1, T2, and T0 from block below. (3 multiples)
3 Adjust PWMs High times based on table below. (1-3 additions)

$T1 = T \cdot m \cdot SIN(60 - \alpha)$
$T2 = T \cdot m \cdot SIN(\alpha)$
$T0 = T - T1 - T2$

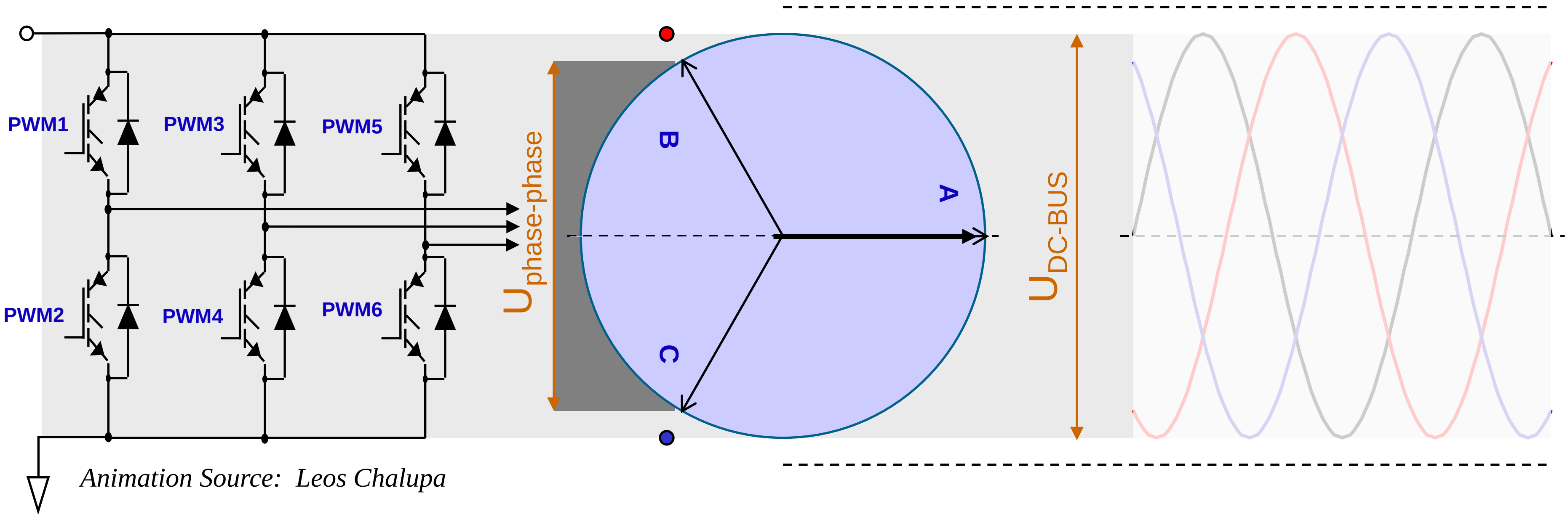
	Null = V0	Null = V7	V7 in 1,3,5 V0 in 2,4,6	V0 in 1,3,5 V7 in 2,4,6	Alternating Reversing Sequencing
Sector 1	U = T1+T2 V = T2 W = 0	U = 100% V = T0+T2 W = T0	U = 100% V = T0+T2 W = T0	U = T1+T2 V = T2 W = 0	U = T1+T2+.5T0 V = T2+.5T0 W = .5T0
Sector 2	U = T1 V = T1+T2 W = 0	U = T0+T1 V = 100% W = T0	U = T1 V = T1+T2 W = 0	U = T0+T1 V = 100% W = T0	U = T1+.5T0 V = T1+T2+.5T0 W = .5T0
Sector 3	U = 0 V = T1+T2 W = T2	U = T0 V = 100% W = T0+T2	U = T0 V = 100% W = T0+T2	U = 0 V = T1+T2 W = T2	U = .5T0 V = T1+T2+.5T0 W = T2+.5T0
Sector 4	U = 0 V = T1 W = T1+T2	U = T0 V = T0+T1 W = 100%	U = 0 V = T1 W = T1+T2	U = T0 V = T0+T1 W = 100%	U = .5T0 V = T1+.5T0 W = T1+T2+.5T0
Sector 5	U = T2 V = 0 W = T1+T2	U = T0+T2 V = T0 W = 100%	U = T0+T2 V = T0 W = 100%	U = T2 V = 0 W = T1+T2	U = T2+.5T0 V = .5T0 W = T1+T2+.5T0
Sector 6	U = T1+T2 V = 0 W = T1	U = 100% V = T0 W = T0+T1	U = T1+T2 V = 0 W = T1	U = 100% V = T0 W = T0+T1	U = T1+T2+.5T0 V = .5T0 W = T1+.5T0

Note: All calculations referenced to top switch

Source: Understanding Space Vector Modulation,
by Peter Pinewski, EDN Products Edition, March 7, 1996

Sinusoidal Modulation - Limited Amplitude

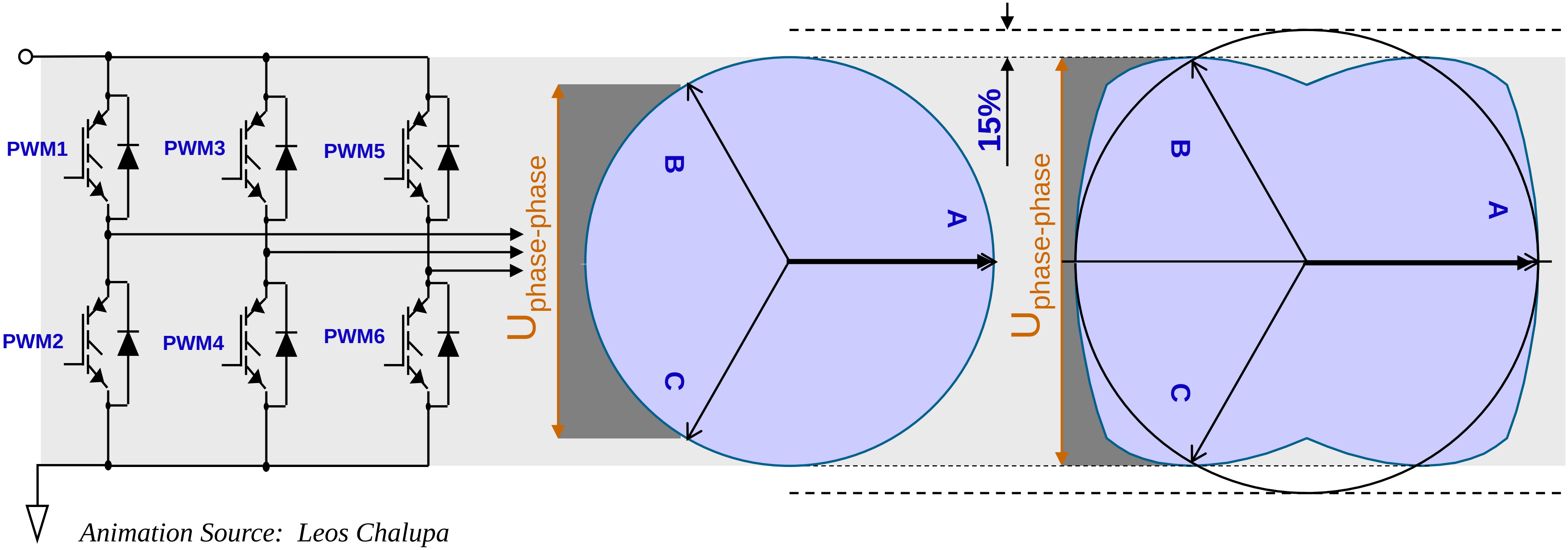
- In sinusoidal modulation the amplitude is limited to half of the DC-bus voltage.
- The phase to phase voltage is then lower then the DC-bus voltage (although such voltage can be generated between the terminals).



Animation Source: Leos Chalupa

Full Phase-to-Phase Voltage Generation

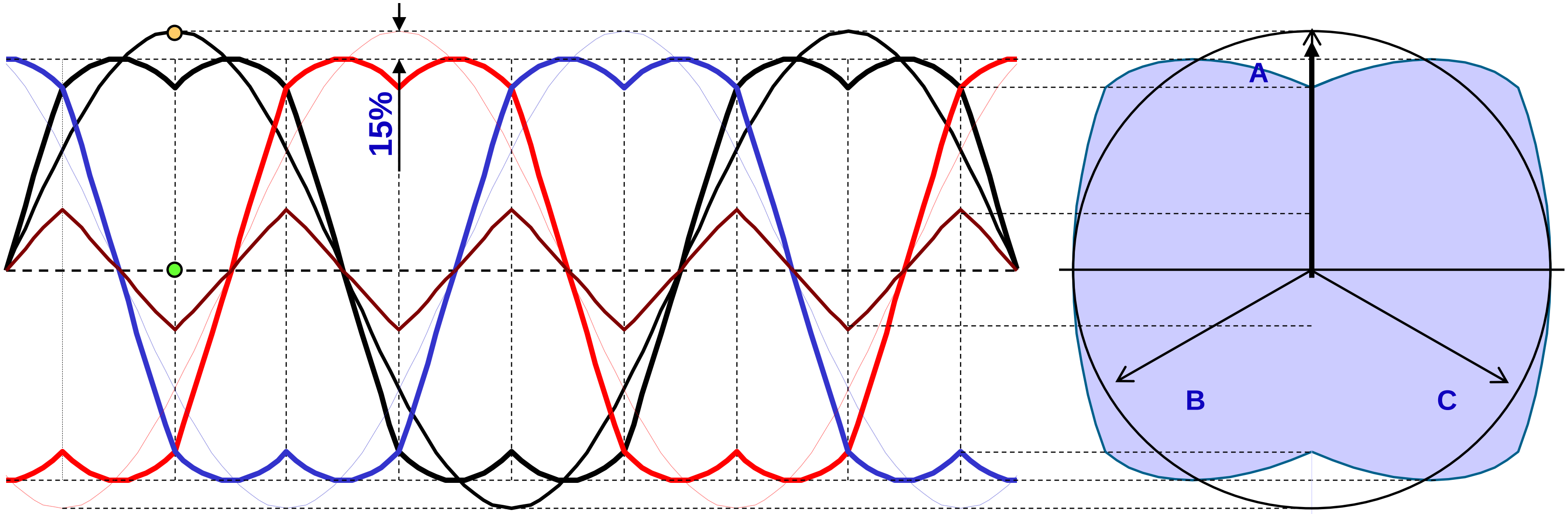
- Full phase-to-phase voltage can be generated by continuously shifting the 3-phase voltage system.
- The amplitude of the first harmonic can be then increased by 15.5%.



Animation Source: Leos Chalupa

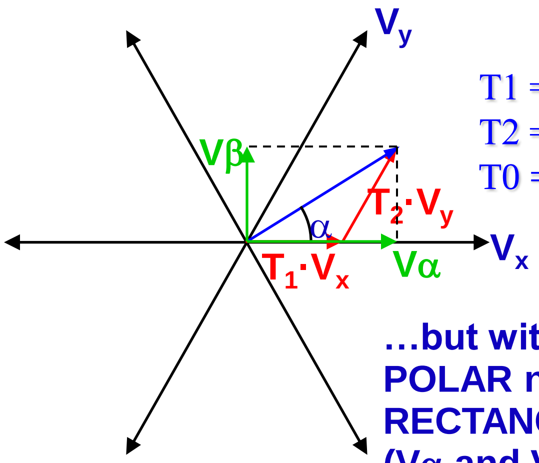
How to Increase Modulation Index

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



Animation Source: Leos Chalupa

SVM with Field Oriented Systems



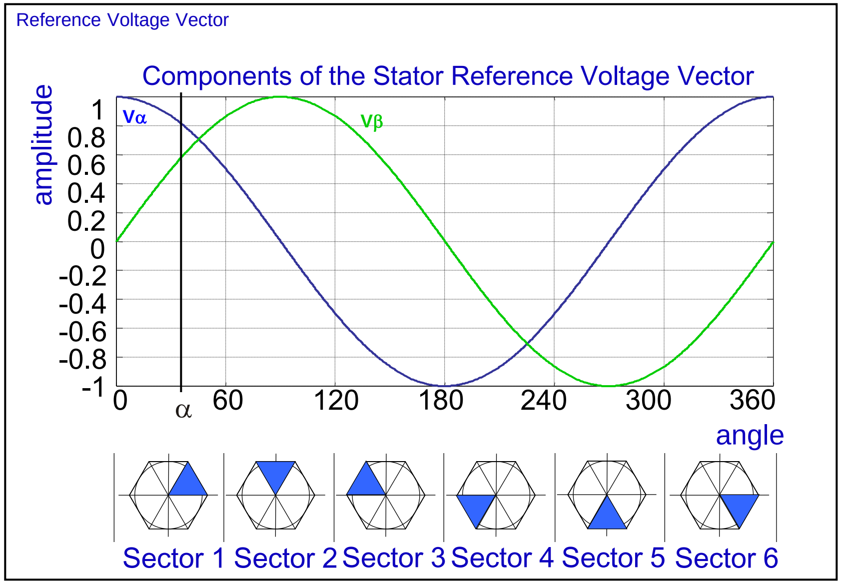
Recall:

$T1 = T \bullet m \bullet SIN(60 - \alpha)$

$T2 = T \bullet m \bullet SIN(\alpha)$

$T0 = T - T1 - T2$

…but with FOC, we don't have POLAR notation. We have RECTANGULAR notation (Vα and Vβ).



We could calculate "m" and "α":

$$m = \sqrt{(V\alpha)^2 + (V\beta)^2}$$

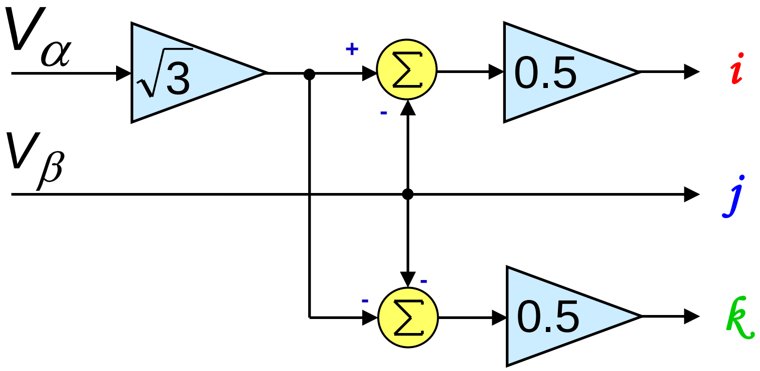
$$\alpha = \tan^{-1}\frac{V\beta}{V\alpha}$$

Or…

We could use a simple procedure designed specifically for RECTANGULAR notation:

1. *Perform modified inverse Clarke-transform on the voltage vector*
2. *Calculate which sector the voltage vector is in*
3. *Determine T1, T2, and T0*
4. *Directly calculate the PWM register values*

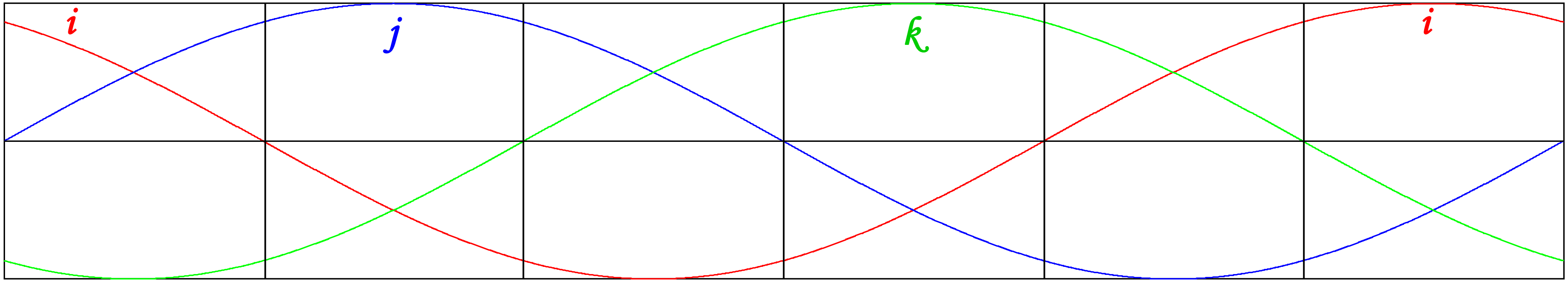
1. Perform Modified Inverse Clarke Transform



$$i = \frac{\sqrt{3}}{2} V_\alpha - \frac{V_\beta}{2}$$

$$j = V_\beta$$

$$k = -\frac{\sqrt{3}}{2} V_\alpha - \frac{V_\beta}{2}$$



2. Identify the correct sector based on i, j, and k variables

a. Calculate the following expression:

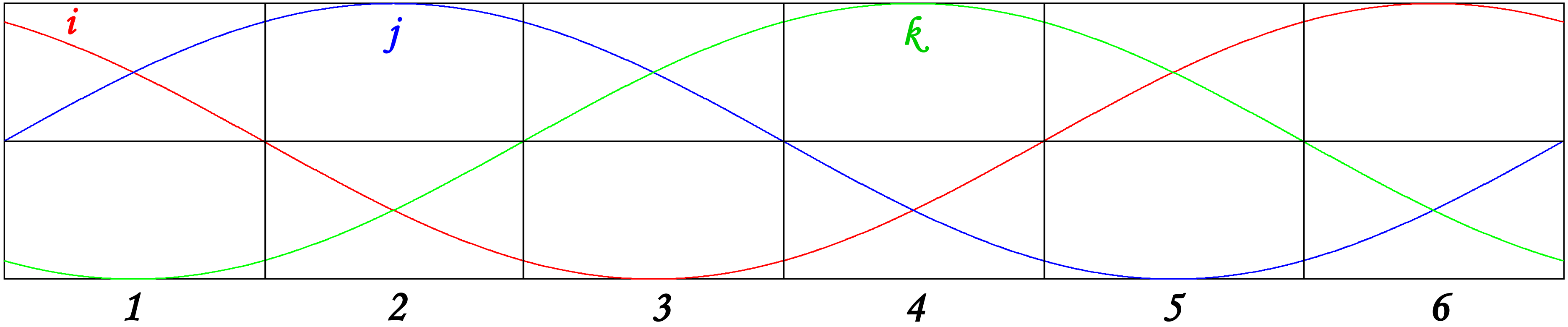
$$N = sign(i) + 2\,sign(j) + 4\,sign(k)$$

$$where\ sign(+) = 1;\ sign(-) = 0$$

b. Use look-up table below to determine the sector from the value of N

N =	1	2	3	4	5	6
Sector =	6	2	1	4	5	3

Alternatively, you can determine the sector by using IF THEN statements to check the polarities of i, j, and k.



3. Based on the sector, determine T1, T2, and T0

Sector→ Bounded by:	1 (U_0-U_{60})	2 (U_{60}-U_{120})	3 (U_{120}-U_{180})	4 (U_{180}-U_{240})	5 (U_{240}-U_{300})	6 (U_{300}-U_0)
T1†	i	$-k$	j	$-i$	k	$-j$
T2†	j	$-i$	k	$-j$	i	$-k$

T0 = 1 – T1 – T2

4. Load the PWM registers based on this table

	Null = V0	Null = V7	V7 in 1,3,5 V0 in 2,4,6	V0 in 1,3,5 V7 in 2,4,6	Alternating Reversing Sequencing
Sector 1	U = T1+T2 V = T2 W = 0	U = 100% V = T0+T2 W = T0	U = 100% V = T0+T2 W = T0	U = T1+T2 V = T2 W = 0	U = T1+T2+.5T0 V = T2+.5T0 W = .5T0
Sector 2	U = T1 V = T1+T2 W = 0	U = T0+T1 V = 100% W = T0	U = T1 V = T1+T2 W = 0	U = T0+T1 V = 100% W = T0	U = T1+.5T0 V = T1+T2+.5T0 W = .5T0
Sector 3	U = 0 V = T1+T2 W = T2	U = T0 V = 100% W = T0+T2	U = T0 V = 100% W = T0+T2	U = 0 V = T1+T2 W = T2	U = .5T0 V = T1+T2+.5T0 W = T2+.5T0
Sector 4	U = 0 V = T1 W = T1+T2	U = T0 V = T0+T1 W = 100%	U = 0 V = T1 W = T1+T2	U = T0 V = T0+T1 W = 100%	U = .5T0 V = T1+.5T0 W = T1+T2+.5T0
Sector 5	U = T2 V = 0 W = T1+T2	U = T0+T2 V = T0 W = 100%	U = T0+T2 V = T0 W = 100%	U = T2 V = 0 W = T1+T2	U = T2+.5T0 V = .5T0 W = T1+T2+.5T0
Sector 6	U = T1+T2 V = 0 W = T1	U = 100% V = T0 W = T0+T1	U = T1+T2 V = 0 W = T1	U = 100% V = T0 W = T0+T1	U = T1+T2+.5T0 V = .5T0 W = T1+.5T0

Note: All calculations referenced to top switch

Source: Understanding Space Vector Modulation,
by Peter Pinewski, EDN Products Edition, March 7, 1996

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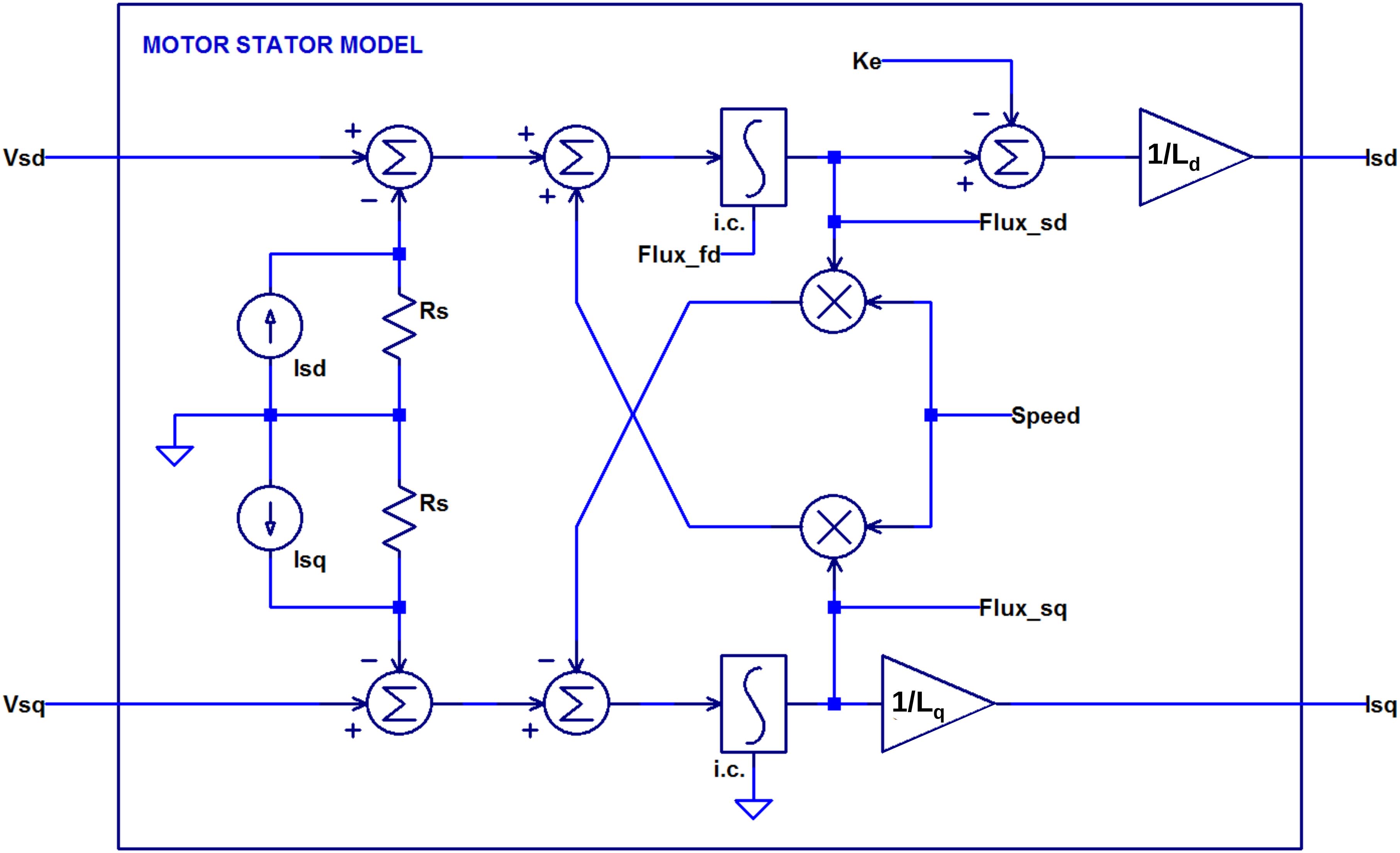
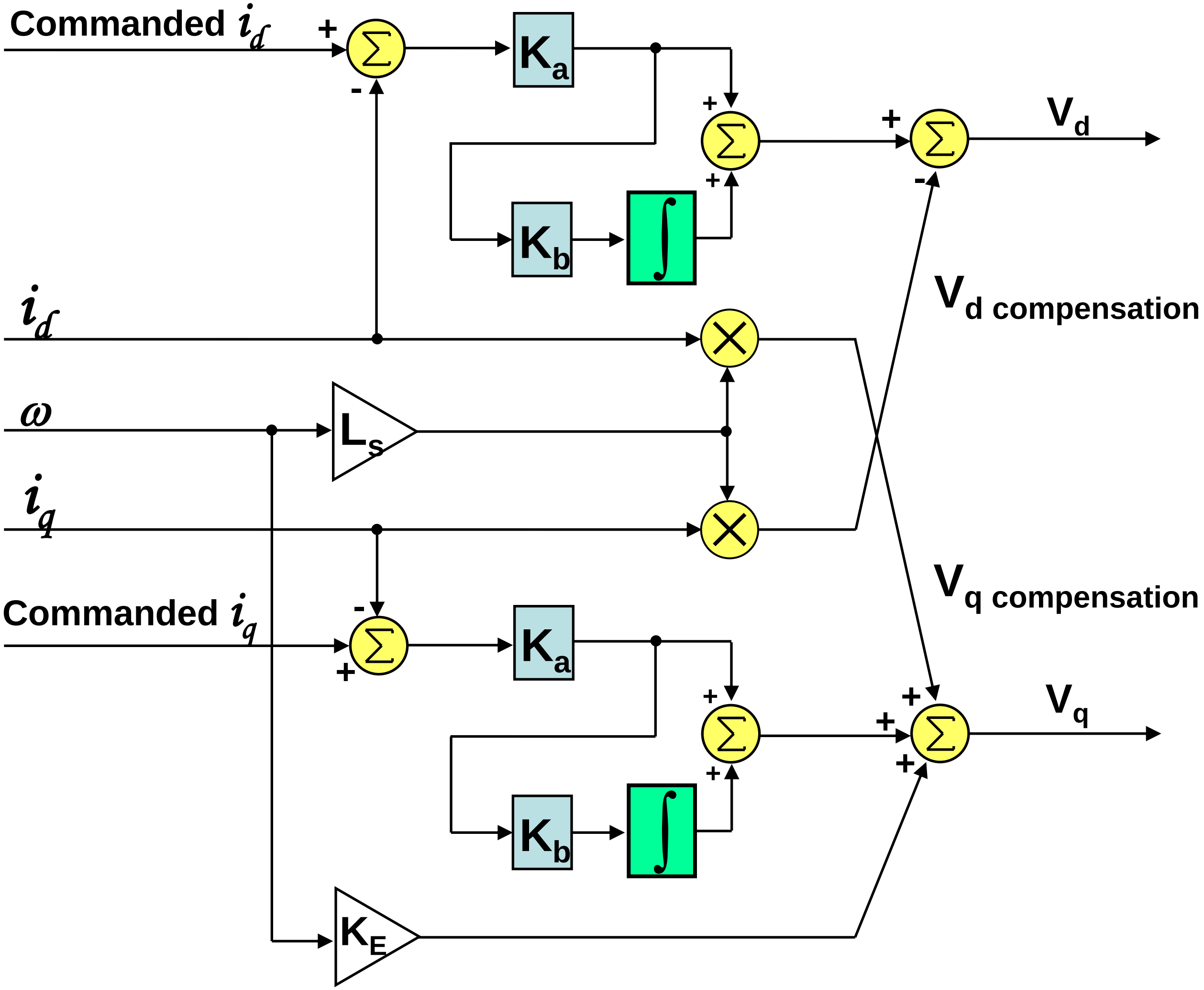
† Recall that T1 always applies to V_x (the most clockwise vector), and T2 applies to V_y (the most counter-clockwise vector) for any given sector.

Axis Coupling



Current Regulator Decoupling

Permanent Magnet Motors



Too Much Flux???

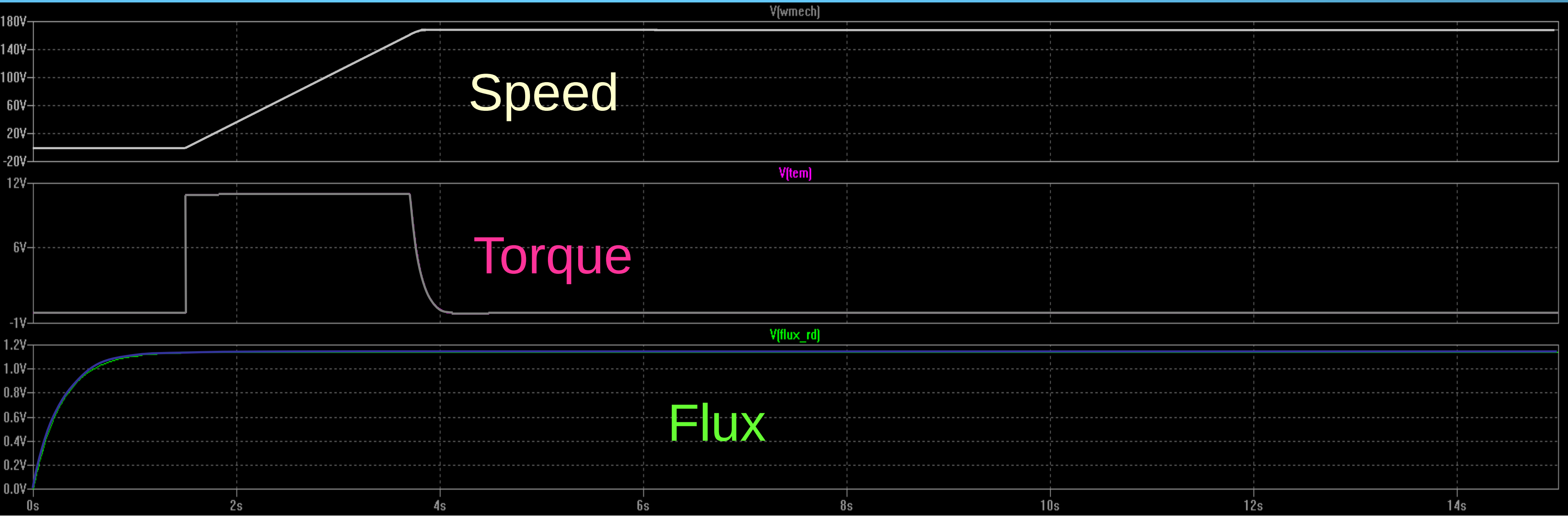
The larger the flux, the higher the dλ/dt is for a given speed.

dλ/dt is voltage, so the back-EMF is higher for a given speed.

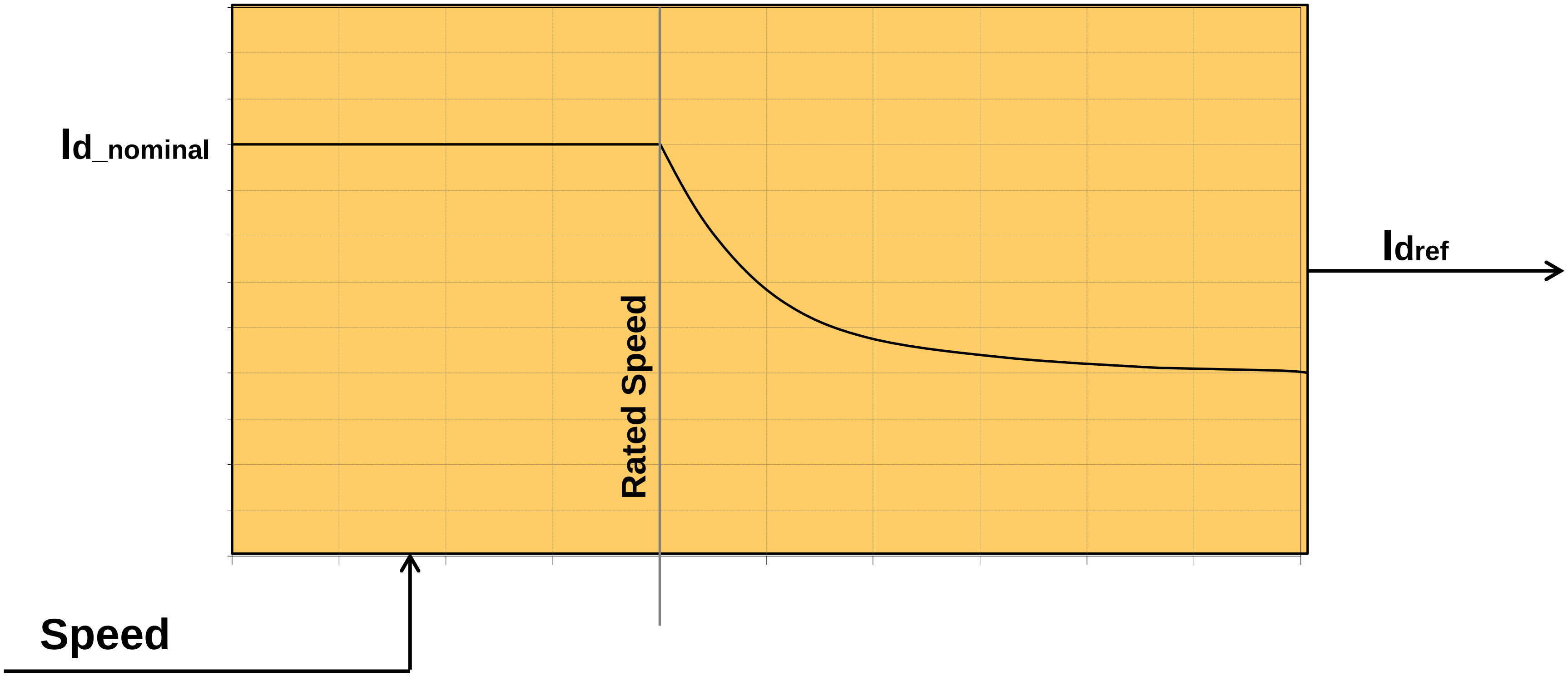
When the back-EMF amplitude reaches the bus voltage, current goes to zero.

When current goes to zero, torque goes to zero.

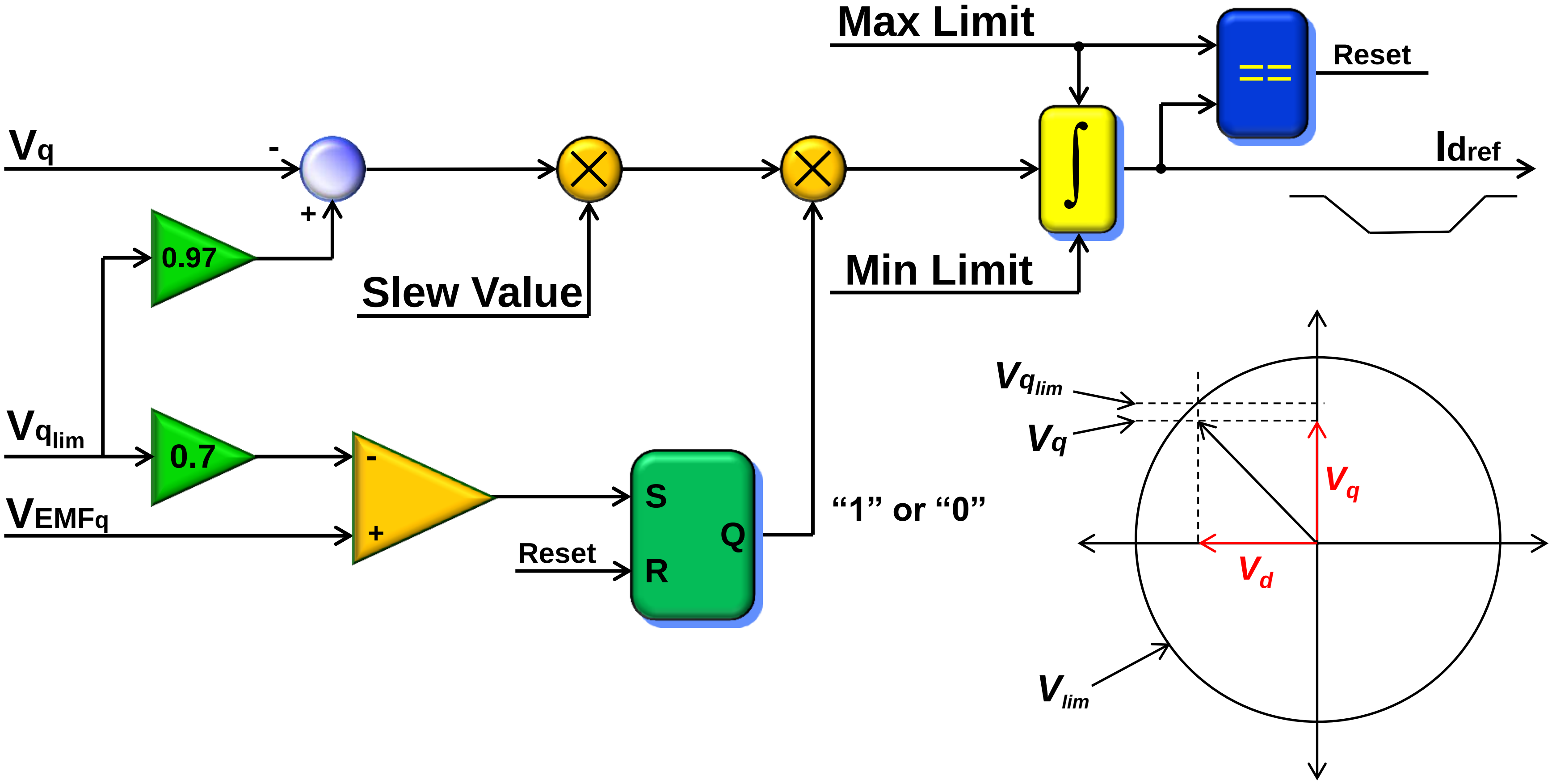
Therefore, the motor cannot go any faster…all because of too much flux.



Weakening the Field…LUT



Weakening the Field…Voltage Limit



Vd is given 1st dibs on available voltage

Less Flux Means More Speed

Observe how the flux is weakened

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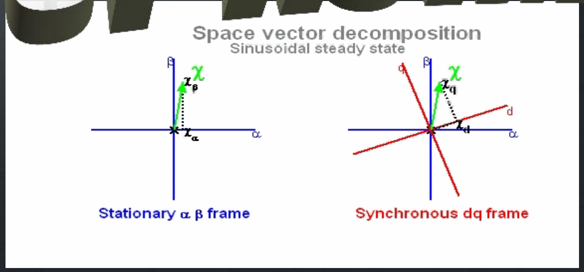
Field Oriented Control of ACIMs

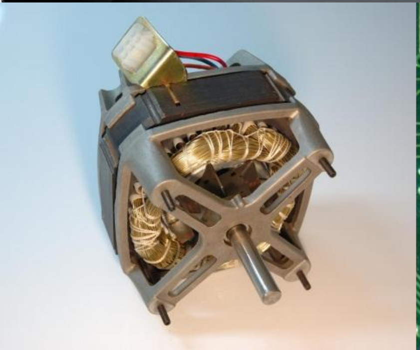


Space vector decomposition

Sinusoidal steady state

Stationary α β frame

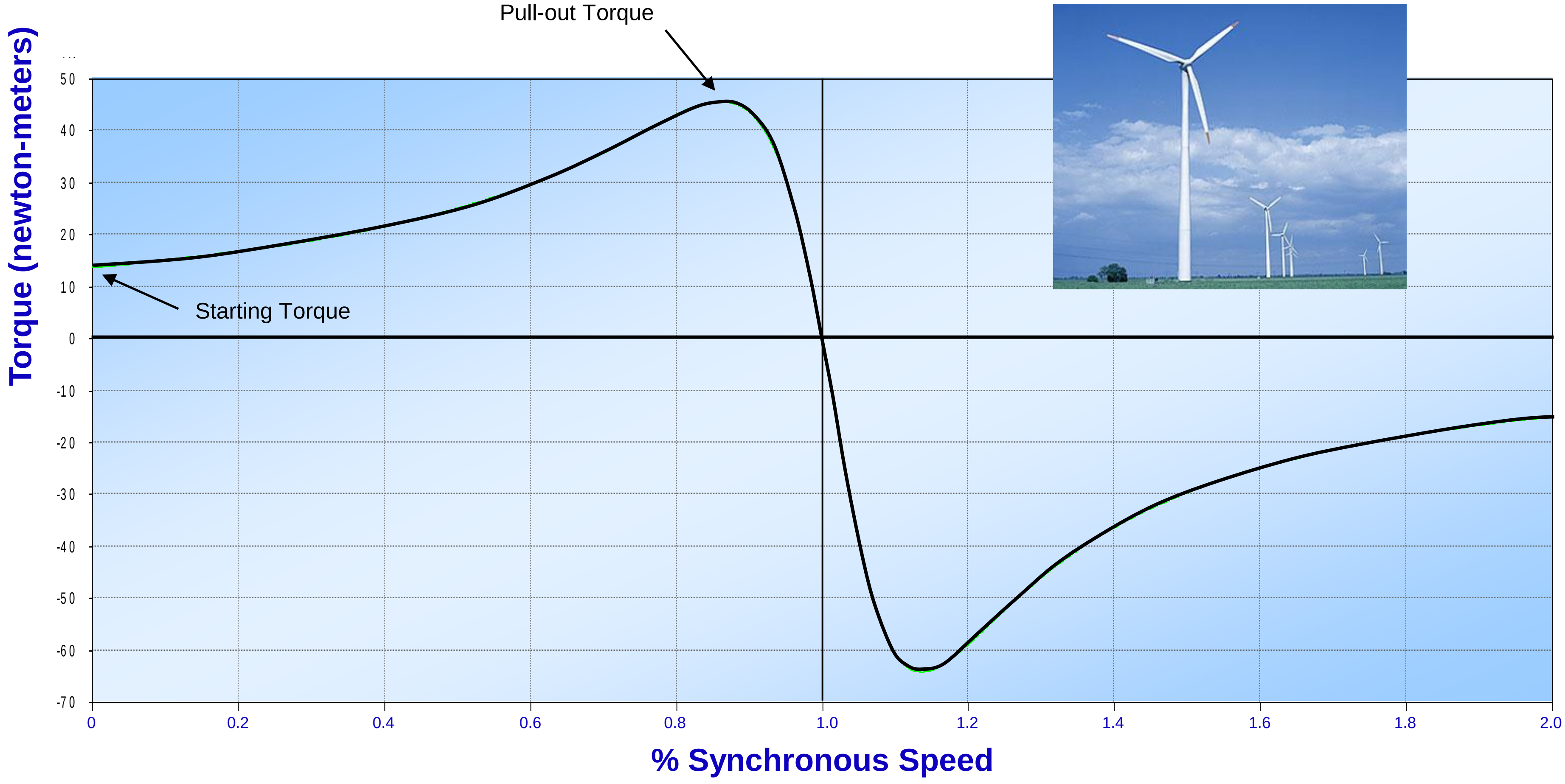
Synchronous dq frame



Dave Wilson

TEXAS INSTRUMENTS

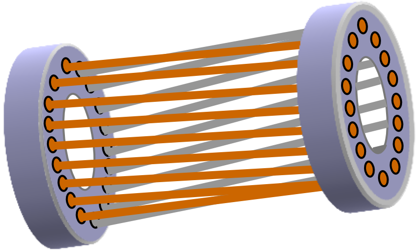
Speed-Torque Performance of Induction Motors

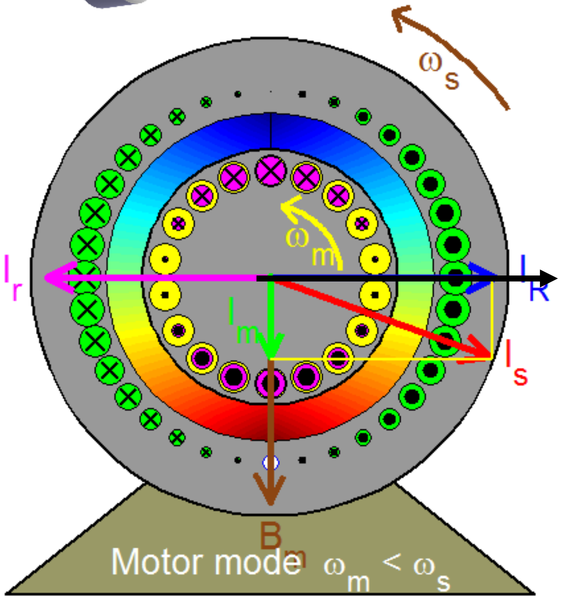


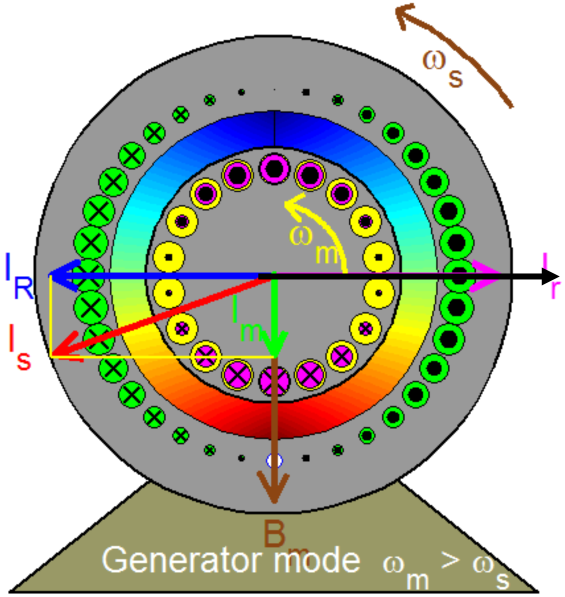
Pull-out Torque

Starting Torque

Stator and Rotor Fields

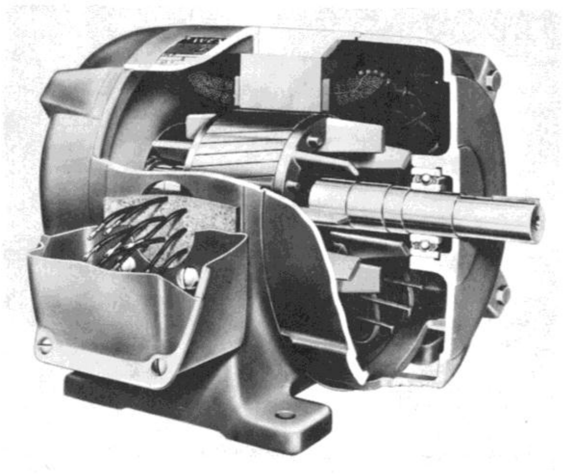


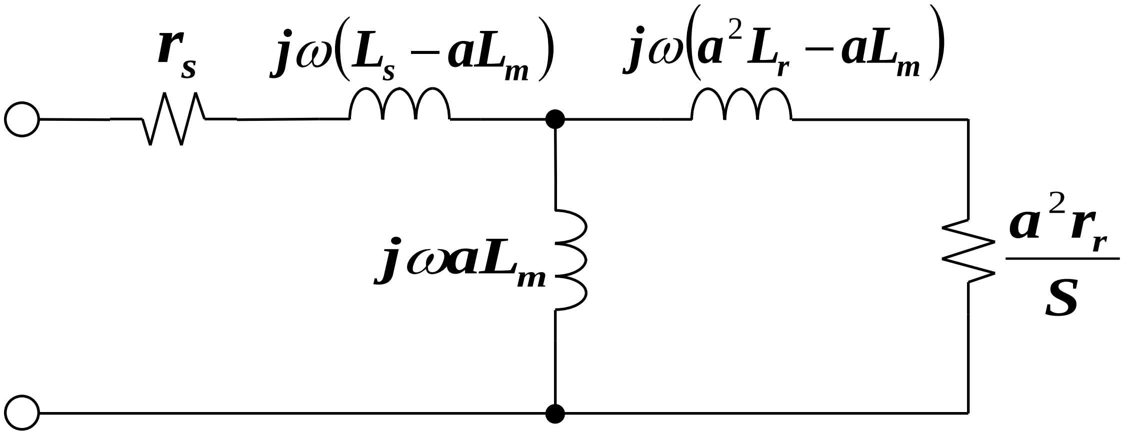




Source: Mahmoud Riaz, Sc.D., Professor of Electrical Engineering, Department of Electrical and Computer Engineering, University of Minnesota

ACIM Circuit Representation with Arbitrary Turns Ratio "a"

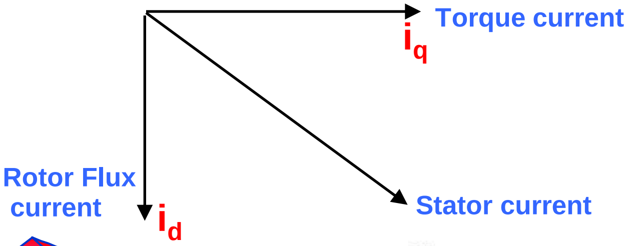




General equivalent circuit showing arbitrary value of referral ratio "a" (a=1 corresponds to a turns ratio of N_s/N_r, which yields the conventional circuit.)

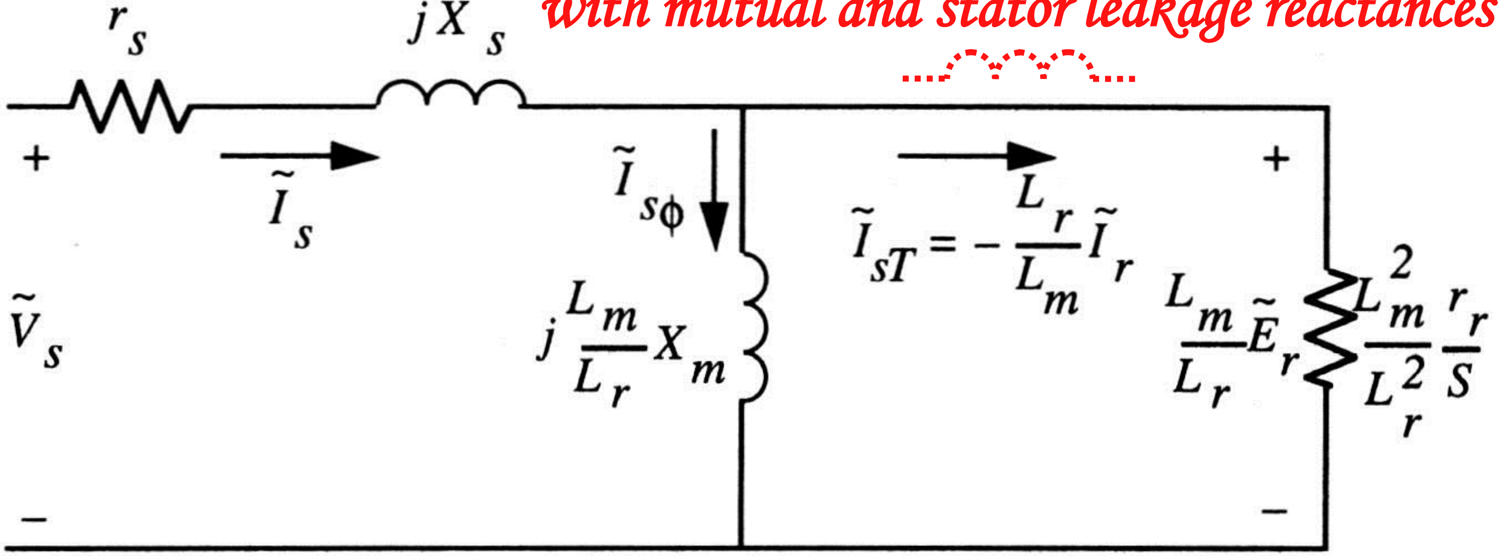
If the actual value of rotor current isn't required, "a" can be any value except zero or infinity, resulting in an infinite number of possible circuits!

ACIM Circuit Representation with Turns Ratio a=Lm/Lr



This implies that a reference frame exists where the stator current can be resolved into torque current and flux current.

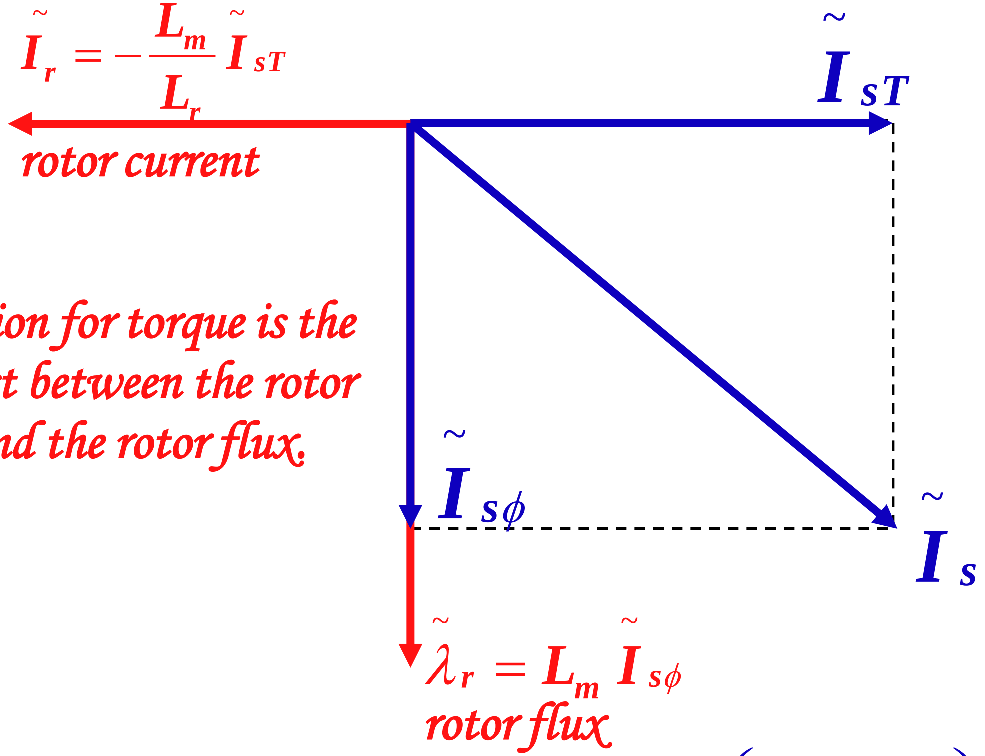
Rotor leakage reactance now lumped with mutual and stator leakage reactances!



Equivalent circuit showing torque component (I_{sT}) and rotor flux component ($I_{s\phi}$) of stator current

Source: Vector Control and Dynamics of AC Drives, by Don Novotny and Tom Lipo, Oxford University Press, 2000

Torque Production in an ACIM



One expression for torque is the cross product between the rotor current and the rotor flux.

Stator current is resolved into flux producing and torque producing components.

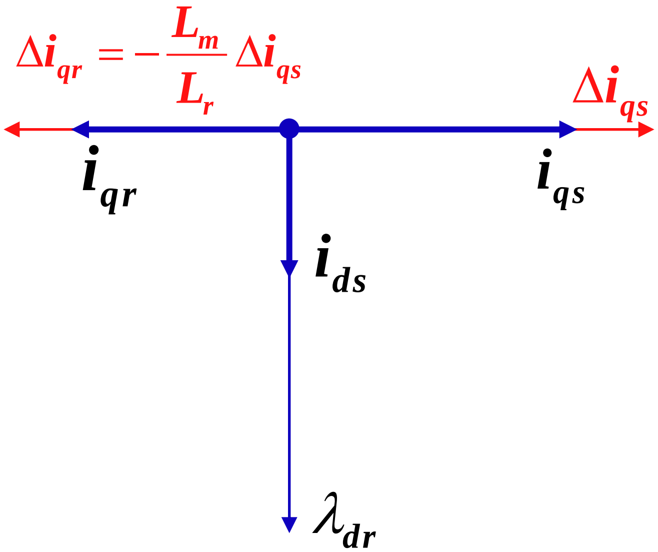
Rotor flux is NOT fixed w.r.t. rotor. It is "asynchronous" to rotor position.

$$T_e = 3\frac{P}{2}\frac{E_r I_r}{2\omega_e} = \frac{3}{4}\frac{P}{\cancel{\omega_e}}\underbrace{\left(\cancel{\omega_e} L_m I_{s\phi}\right)}_{\text{rotor flux}}\underbrace{\left(\frac{L_m}{L_r} I_{sT}\right)}_{\text{rotor current}} = \frac{3}{4}P\frac{L_m^2}{L_r} I_{s\phi} I_{sT}$$

P is the number of poles

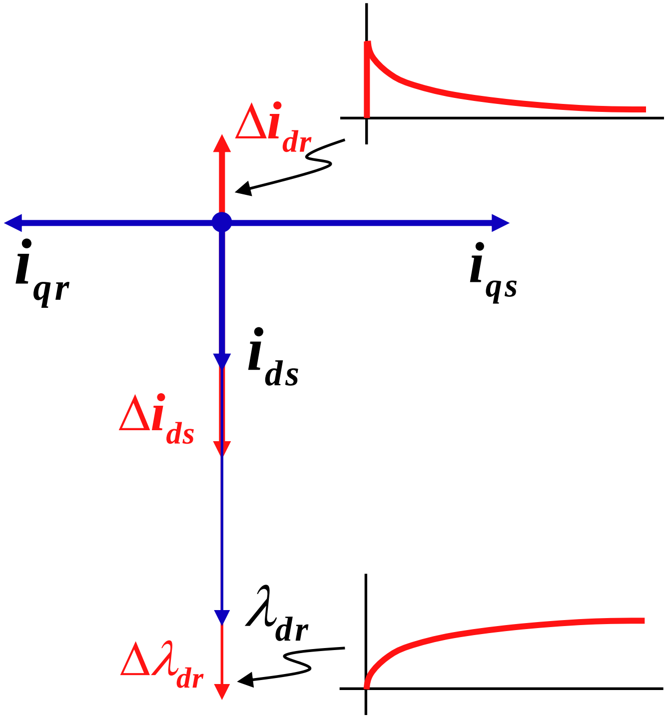
Dynamic Response of Rotor-Referenced FOC

Step change in i_{qs}



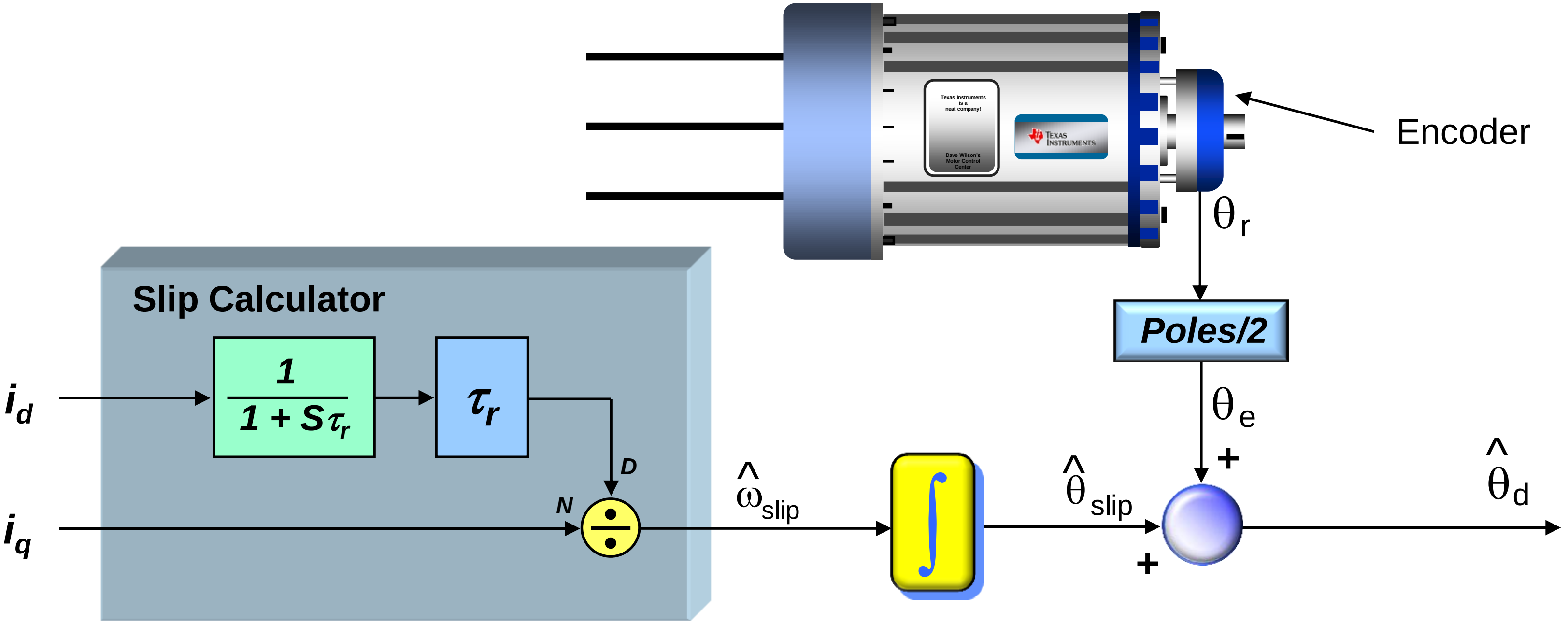
Rotor current (and thus torque) are *instantaneously* changed.

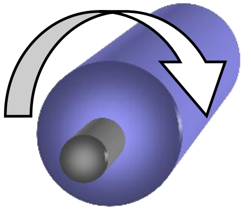
Step change in i_{ds}



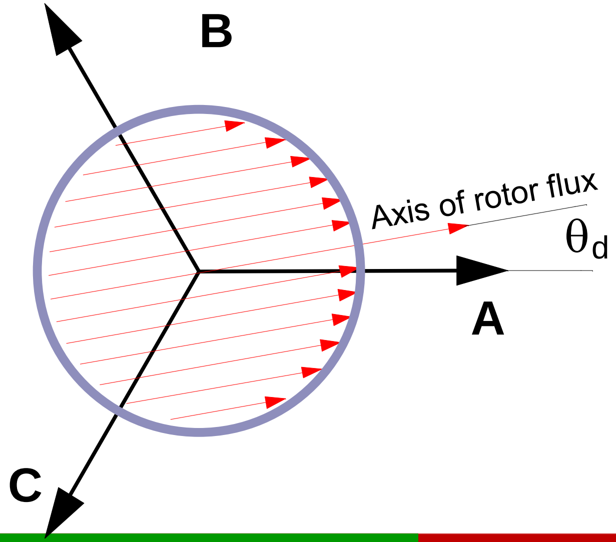
Rotor flux (and thus torque) are *gradually* changed.

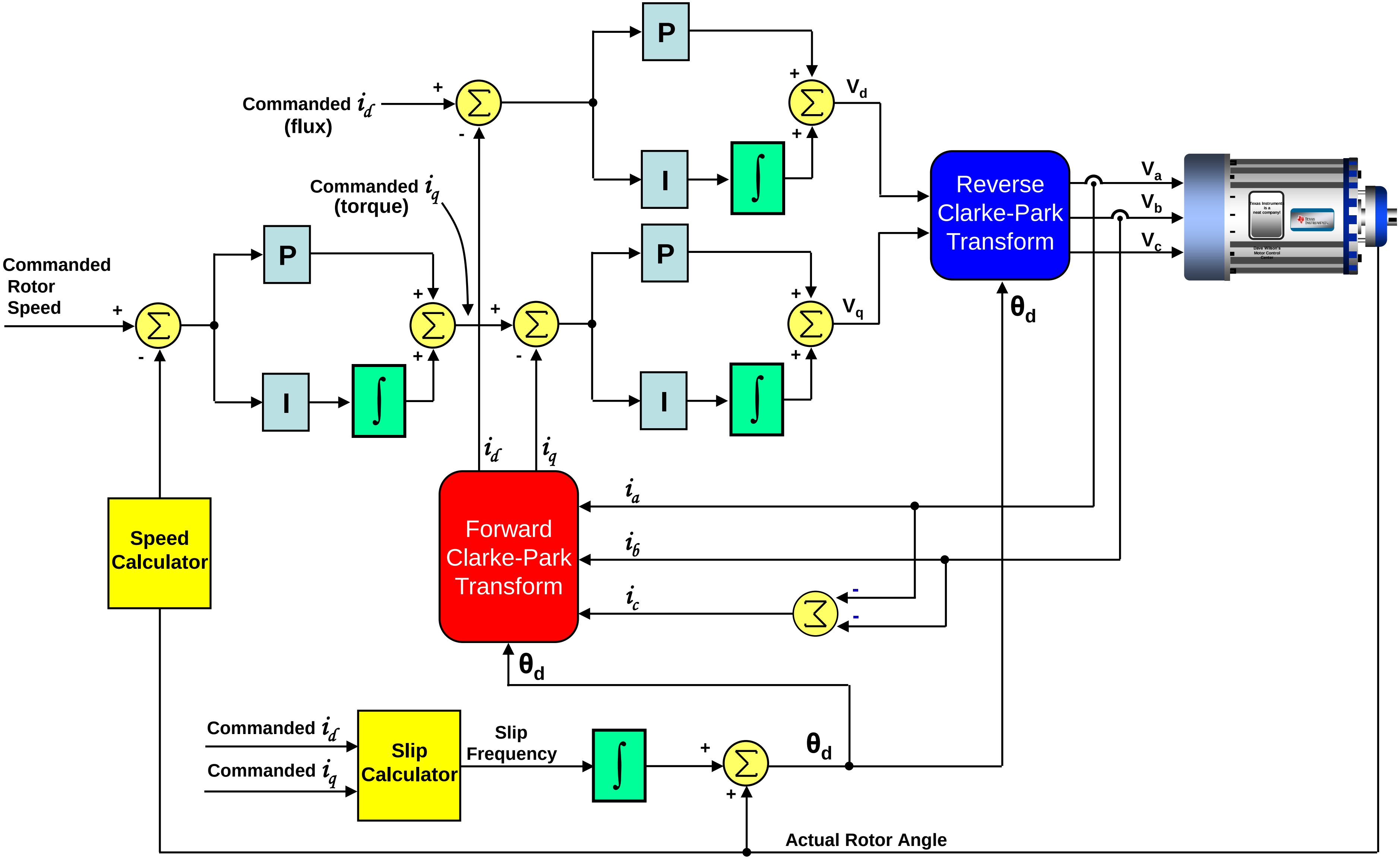
ACIM Slip Frequency Calculation





Recall that the rotor flux sweeps across the surface of the rotor at a speed equal to the slip frequency, i.e., it is "asynchronous" to the rotor.





Control Diagram of an Induction Motor Speed Controller Utilizing Field Oriented Control.

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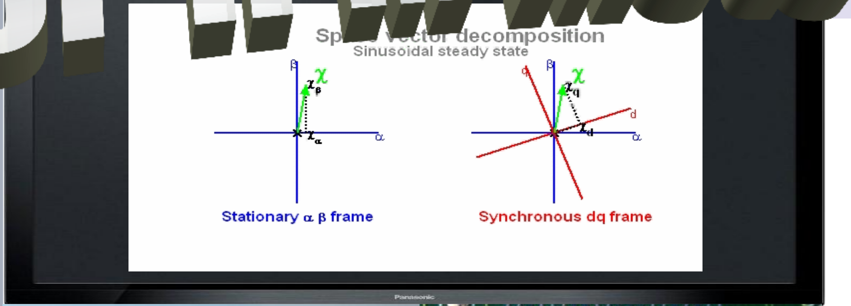
Field Oriented Control of IPM Motors

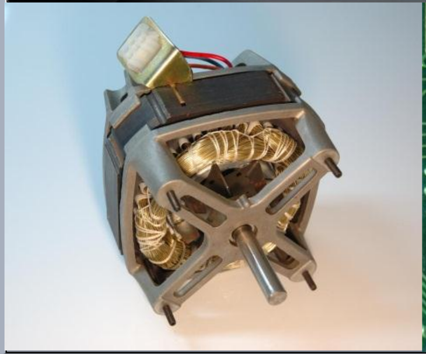


Sp vector decomposition

Sinusoidal steady state

Stationary α β frame

Synchronous dq frame



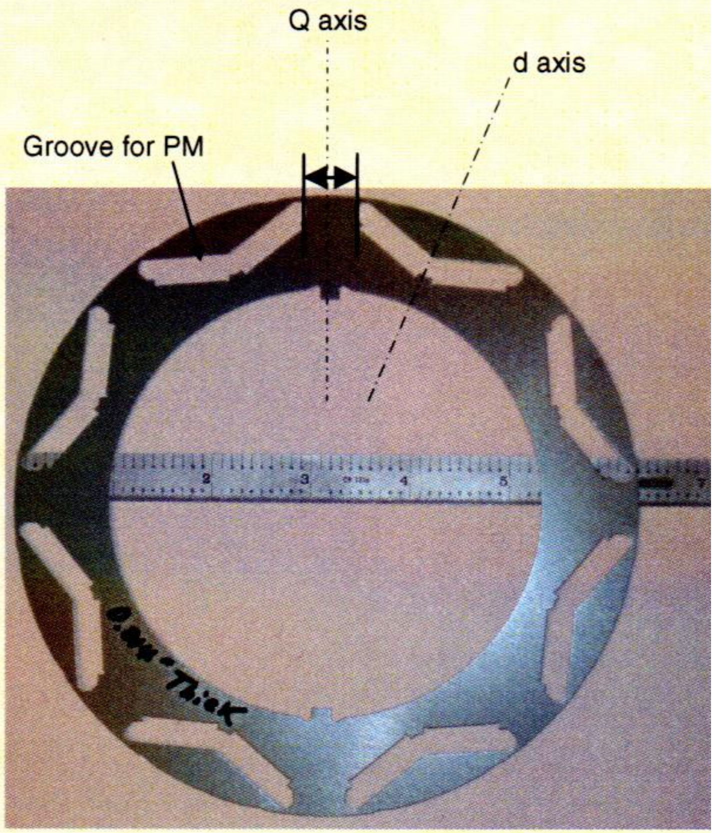
Dave Wilson

TEXAS INSTRUMENTS

Buried Magnets Create NEW Torque

Buried rotor magnets produce different inductances on the *d-q* axes.

This results in a NEW torque component proportional to the difference in these inductances.



Prius 2004 rotor punchings

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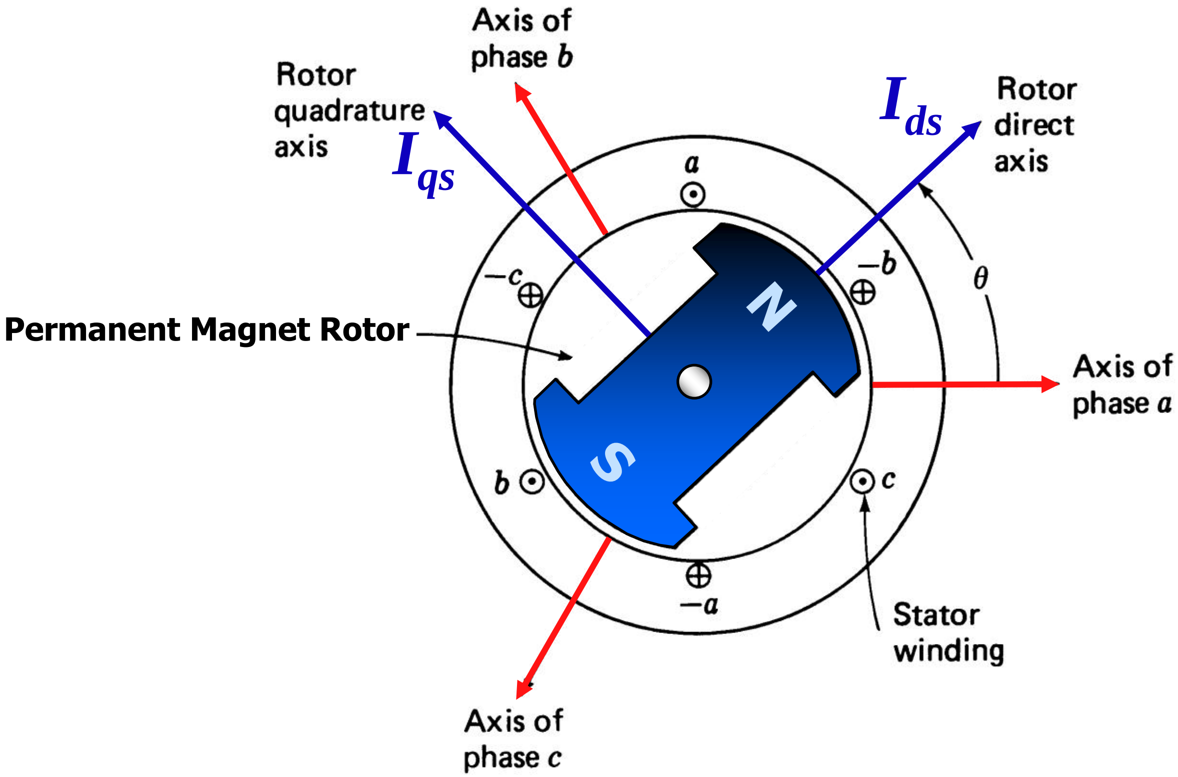
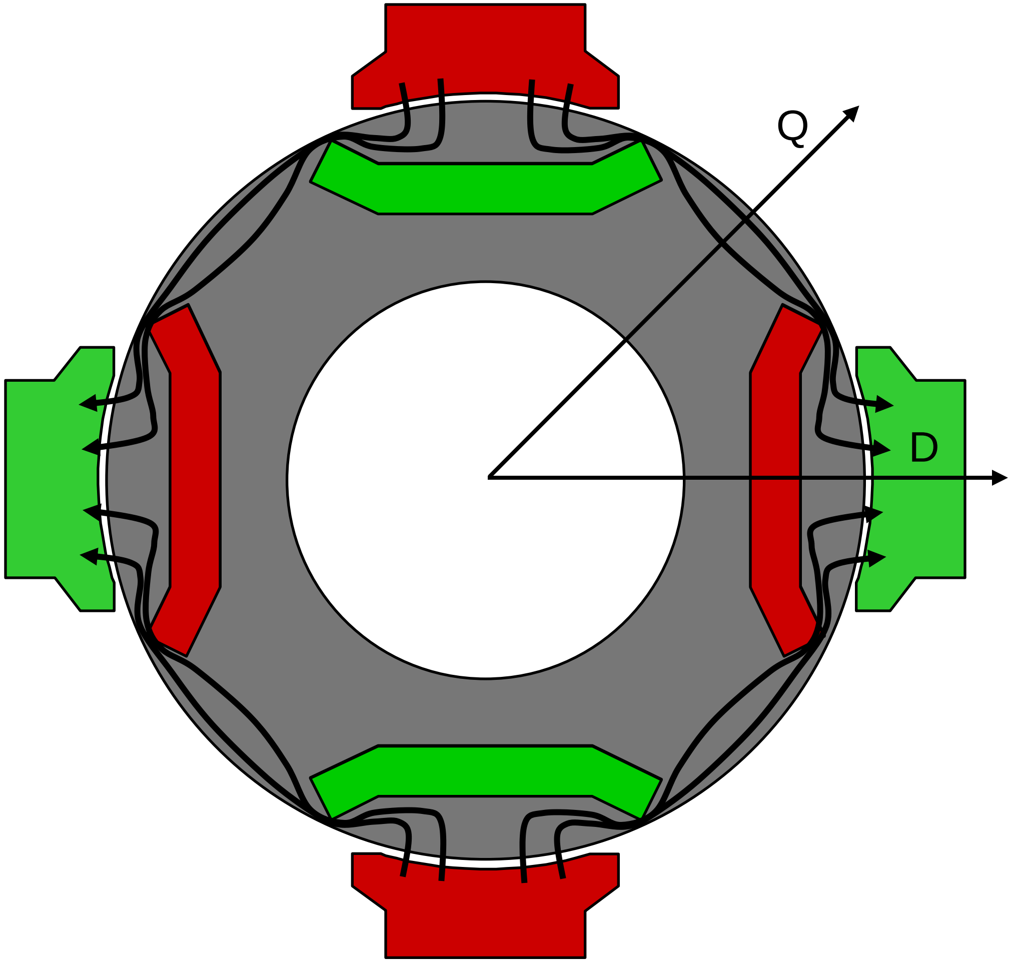
Total Motor Torque



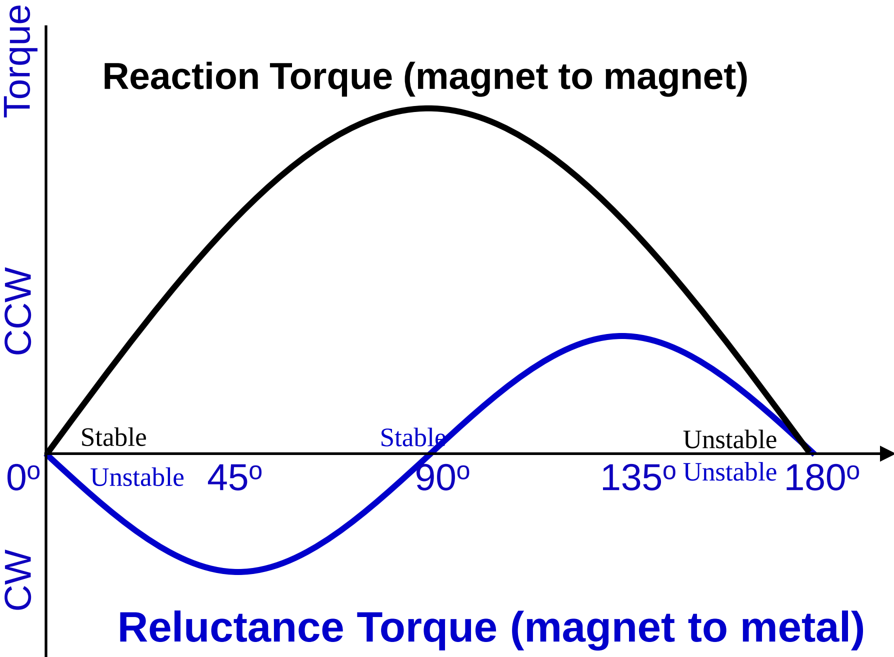
$$Torque=\frac{3}{2}\frac{P}{2}\left[\overbrace{\lambda_{dr}I_{qs}}^{\text{Reaction Torque}}+\overbrace{\left(L_{ds}-L_{qs}\right)I_{ds}I_{qs}}^{\text{Reluctance Torque}}\right]^{\dagger}$$

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

Torque vs. Angle

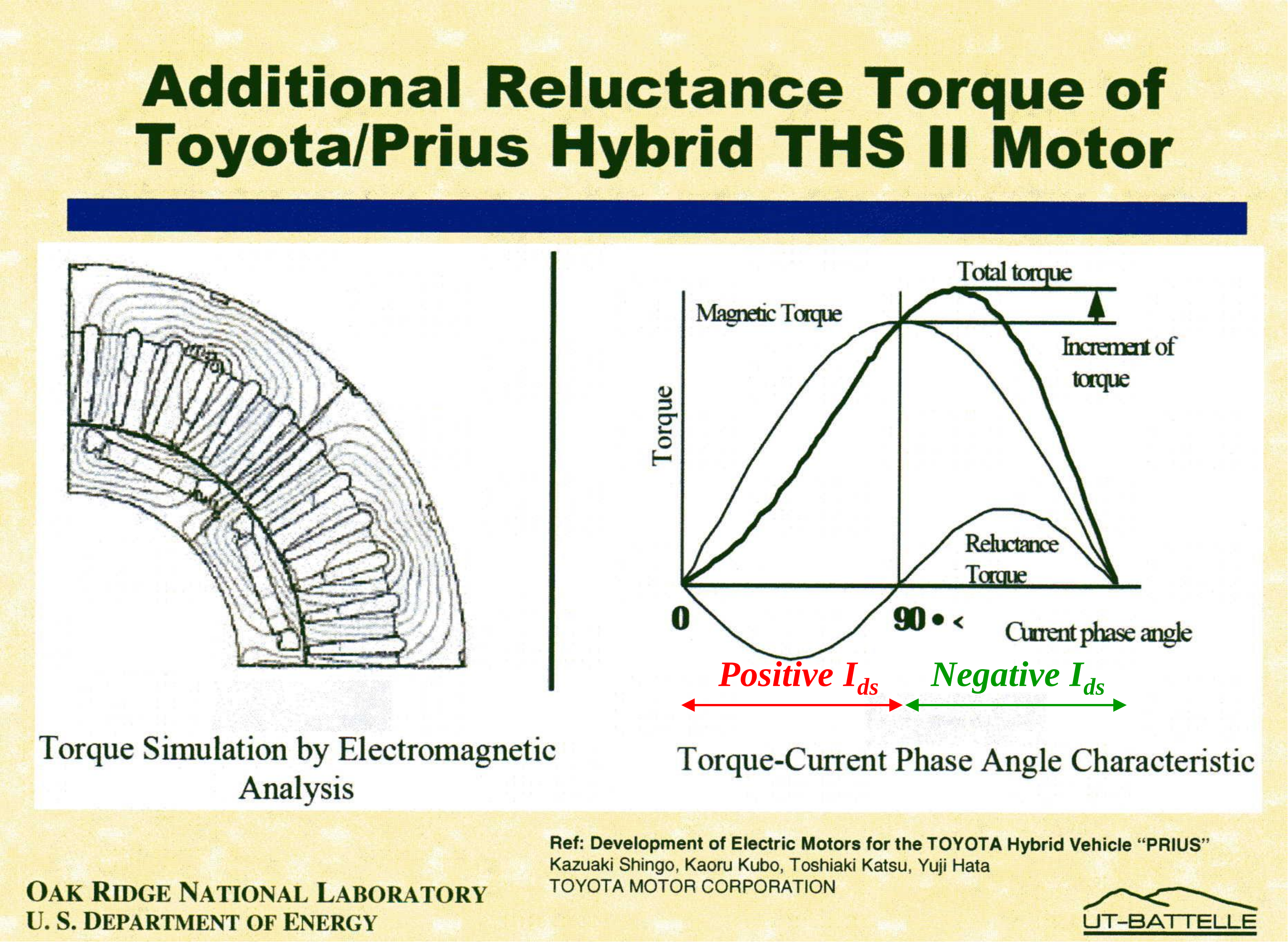


Locked Rotor



The magnets exerts force on the rotor in an effort to minimize the resistance (reluctance) of the flux path.

Effect of Saliency on Optimum Torque Angle



Additional Reluctance Torque of Toyota/Prius Hybrid THS II Motor

Torque Simulation by Electromagnetic Analysis

Torque-Current Phase Angle Characteristic

Ref: Development of Electric Motors for the TOYOTA Hybrid Vehicle "PRIUS"
Kazuaki Shingo, Kaoru Kubo, Toshiaki Katsu, Yuji Hata
TOYOTA MOTOR CORPORATION

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

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MTPA Control of IPM Motors