Motor Control

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MINDA R&D

Forever Evolving

Outline of the Presentation

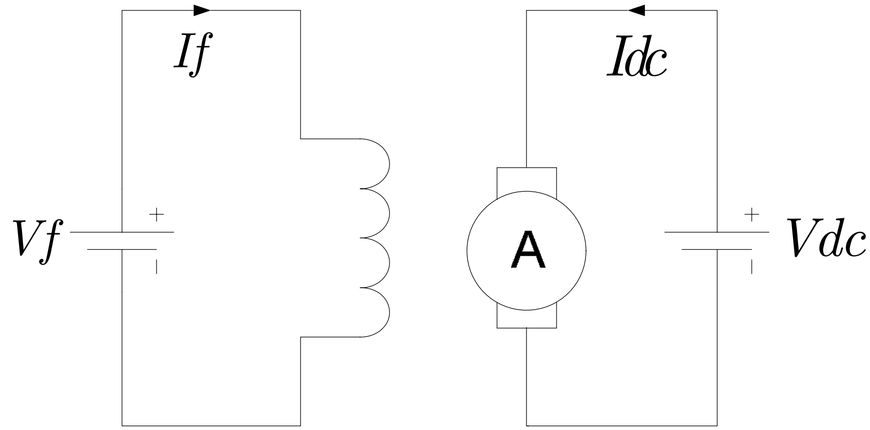
- DC Motor Basics & Control
- Stepper Motor Basics & Control
- Induction Motor Control
- BLDC Motor Control
- PMSM Motor Control

DC Motor Basics & Control

- Types of DC Motors
  - Separately Excited DC Motor
  - Series Excited DC Motor
  - Shunt Excited DC Motor
  - Cumulatively Compound
- Speed Control of DC Motor
  - Fundamentals
  - Rectifier Controlled
  - Chopper Controlled

Separately Excited DC Motor

$$Eb = Ke \cdot \phi \cdot \omega m$$
$$Vdc = Eb + Ia \cdot Ra$$
$$Te = Ke \cdot \phi \cdot Ia$$

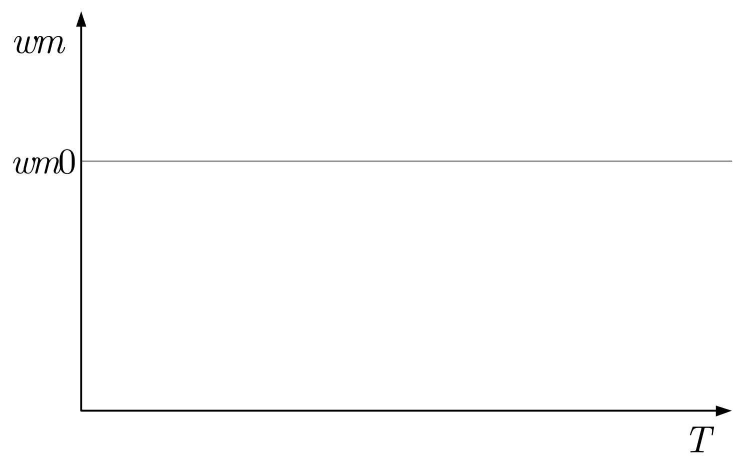


Eb Motor Back EMF

Ke Motor Constant

ϕ Flux per pole

Te Electromagnetic Torque Developed By the Motor

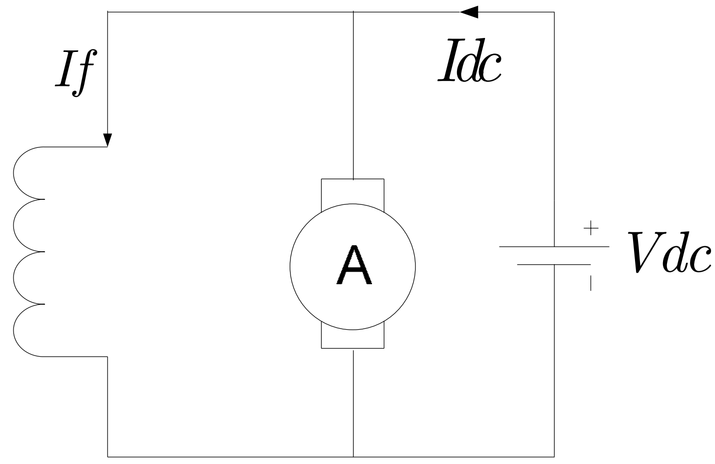


Shunt DC Motor

$$Eb = Ke \cdot \phi \cdot \omega m$$

$$Vdc = Eb + Ia \cdot Ra$$

$$Te = Ke \cdot \phi \cdot Ia$$

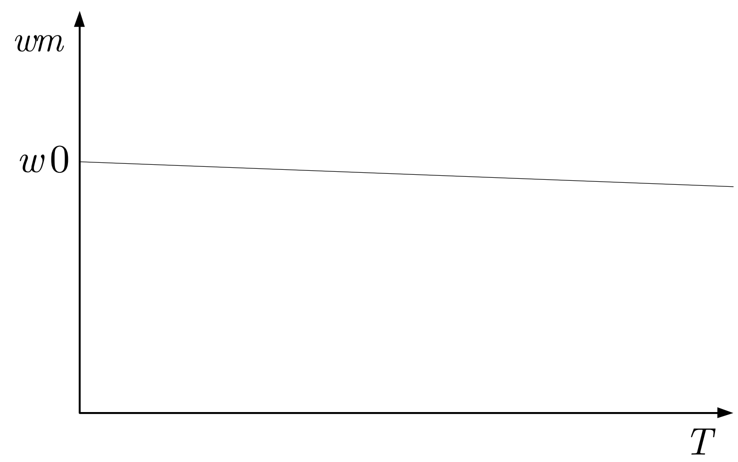


Eb Motor Back EMF

Ke Motor Constant

ϕ Flux per pole

Te Electromagnetic Torque Developed By the Motor

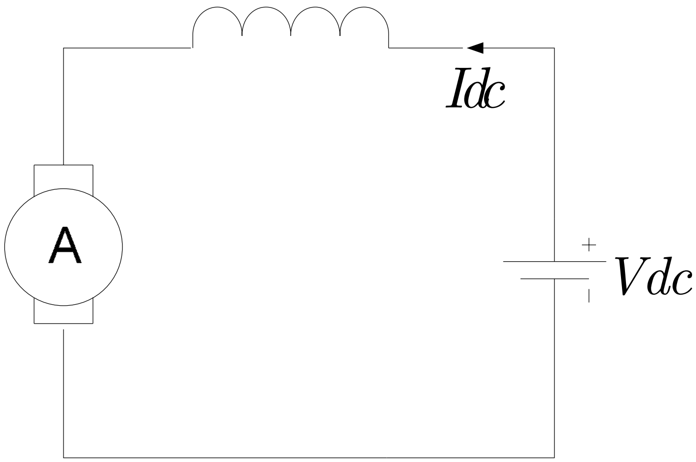


Series DC Motor

$$Eb = Ke \cdot \phi \cdot \omega m$$

$$Vdc = Eb + Ia \cdot Ra$$

$$Te = Ke \cdot \phi \cdot Ia$$

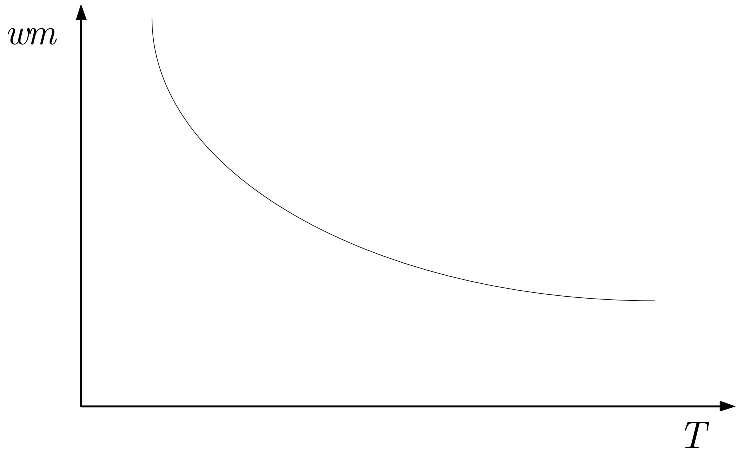


Eb Motor Back EMF

Ke Motor Constant

ϕ Flux per pole

Te Electromagnetic Torque Developed By the Motor



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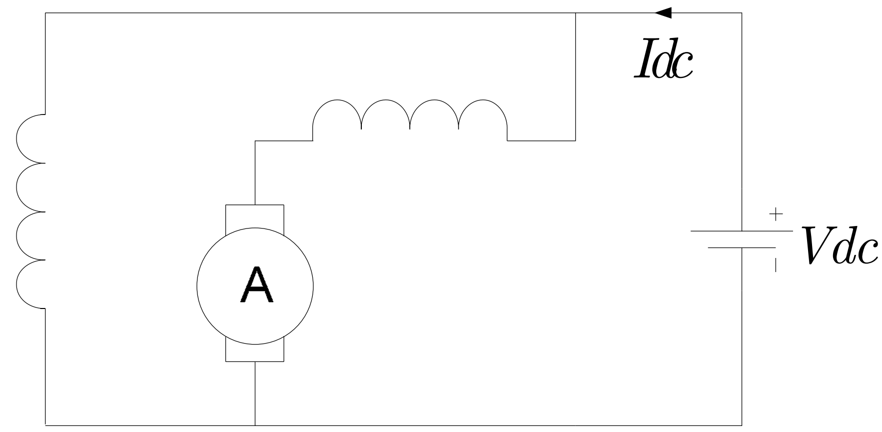
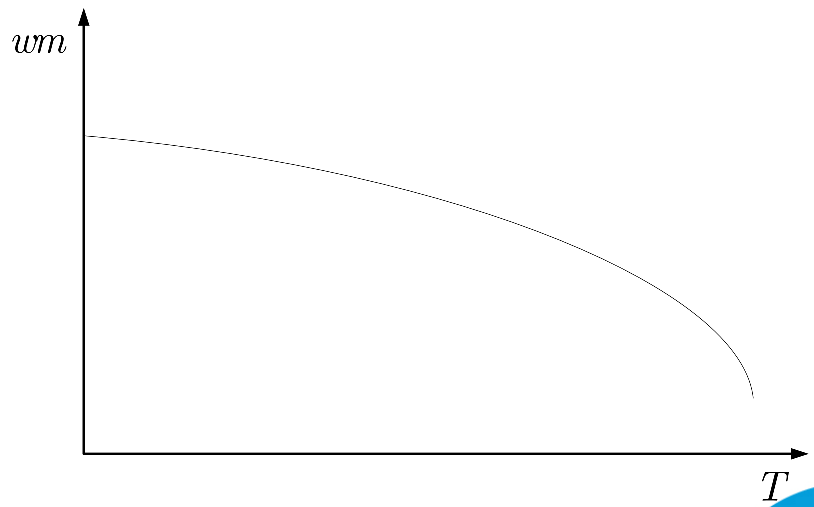
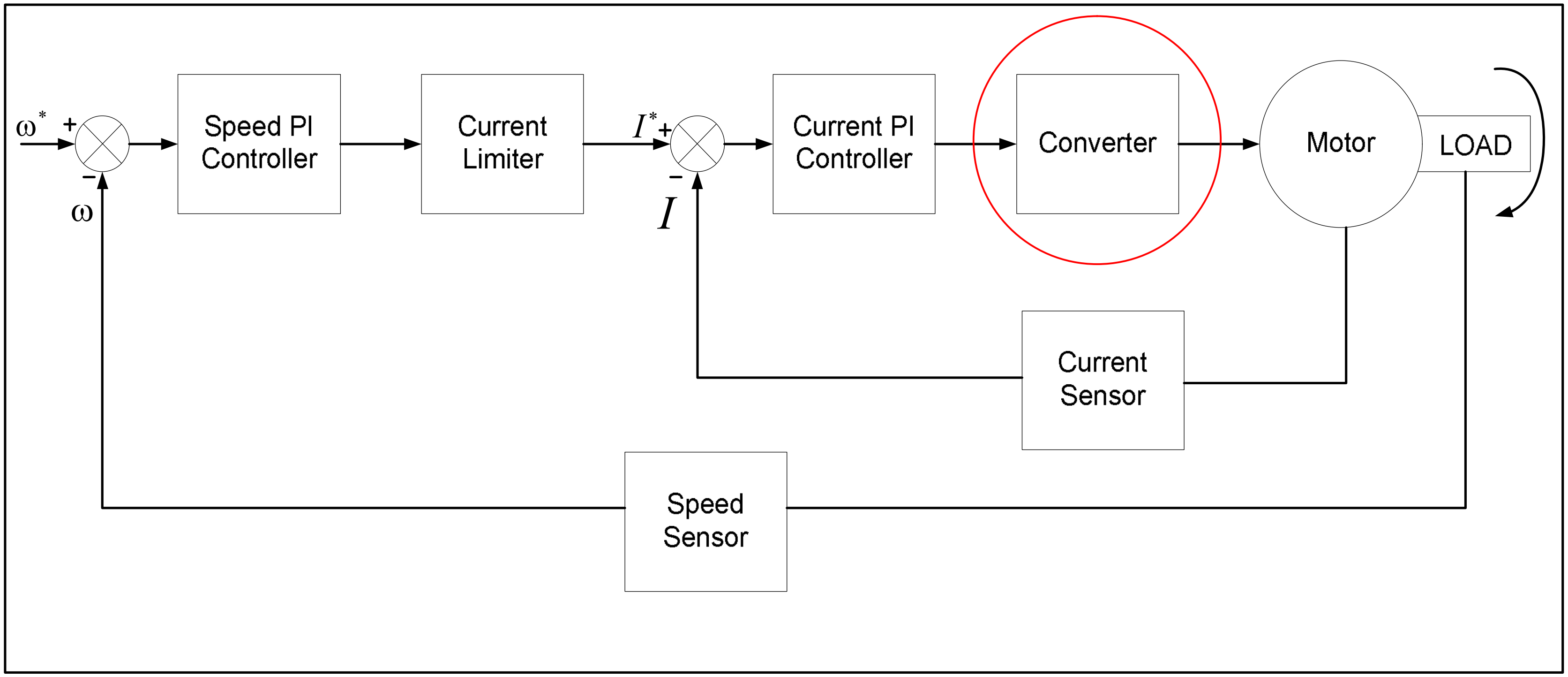
Compound DC Motor

- No load speed is depends upon strength of shunt field and slope of characteristic is depends on series field
- Used in applications where high starting torque is needed and also the no load speed will remain in safe zones
- Pressing machines are typical examples of the application





DC Motor Control Fundamentals



Error	Target
$E_\omega = \omega^* - \omega$	$E_\omega \to 0$
$E_I = I^* - I$	$E_I \to 0$

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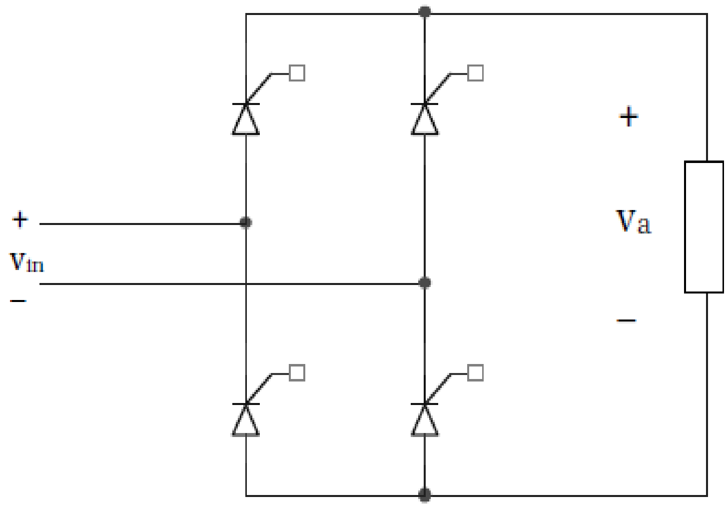
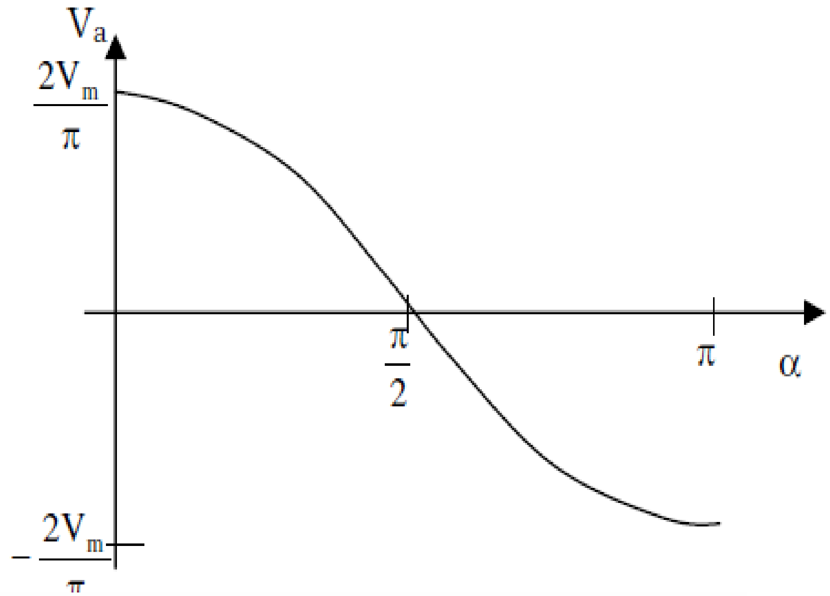
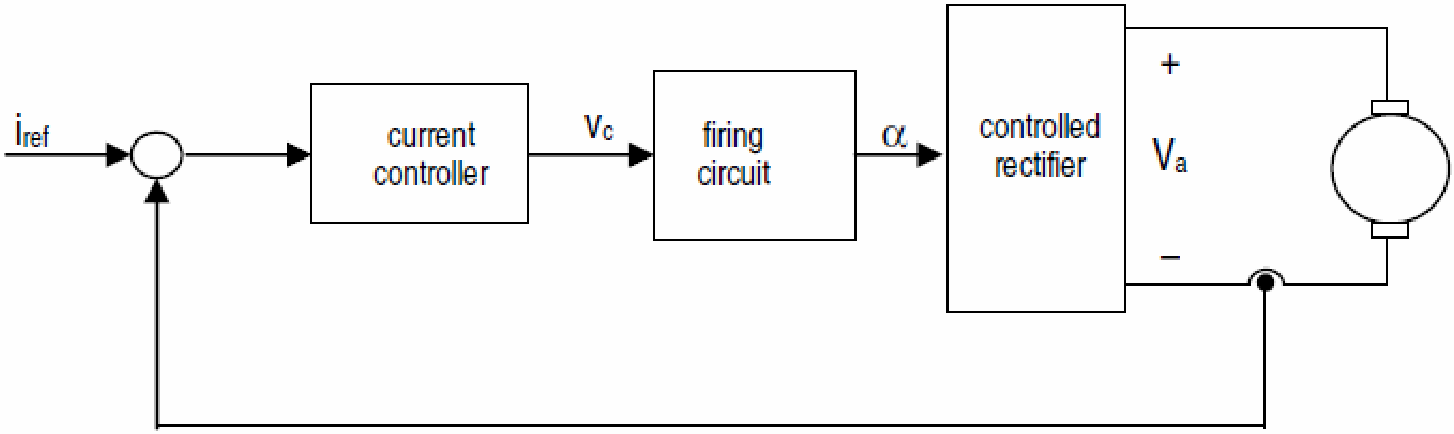
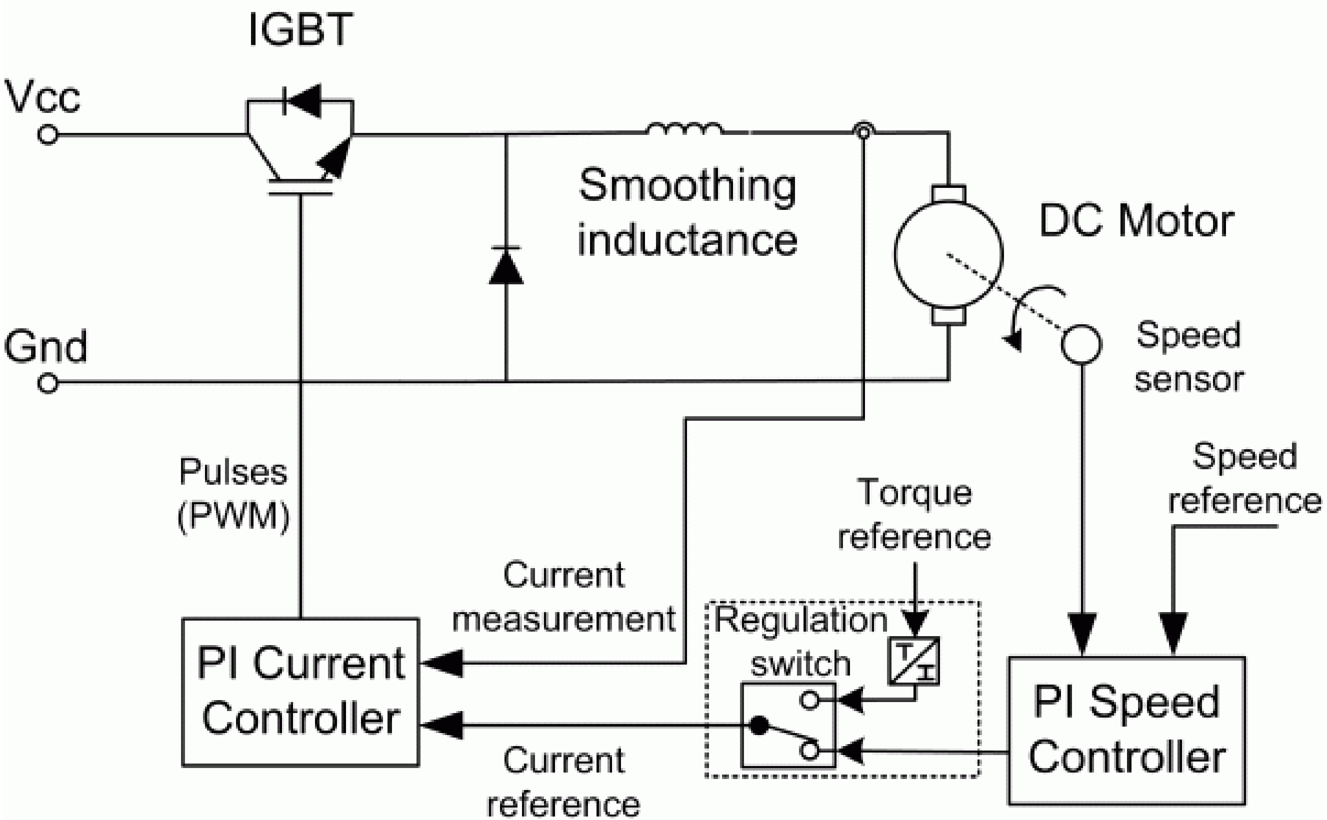
Rectifier Controlled DC Motor







Chopper Controlled DC Motor



- Buck converter can be used as single quadrant converter for DC motor control.
- For multi-quadrant converter bridge converters are being used

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Stepper Motor Fundamentals

- A stepper motor is an electric machine that rotates in discrete angular increments or steps when applied a current pulse.
- Each pulse applied to the motor causes its shaft to move a certain angle of rotation, called a stepping angle.
- The stepper motor has salient poles on both the stator and the rotor, and normally only the stator poles hold the poly-phase windings called the control windings.
- Types of Stepper Motors
  - Permanent Magnet Rotor
  - Reluctance type Rotor
  - Hybrid type

Stepper Motor Fundamentals

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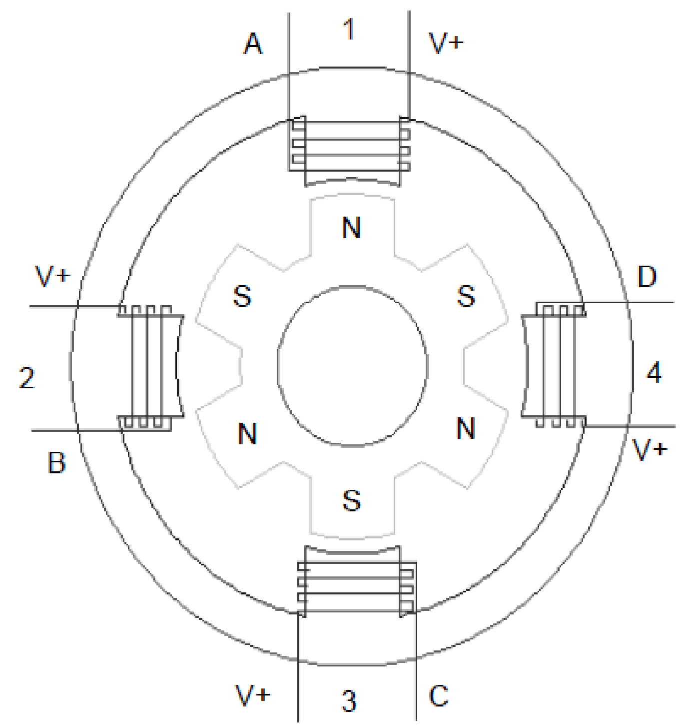
Operating Principal of Hybrid Stepper Motor

- The operation of the stepper motor relies on the simple principle of magnetic attraction.
- This principle states that opposite magnetic poles attract while like poles repel each other.
- Fig shows construction of 4 phase 6 pole stepper hybrid motor
- If winding A or C is excited, pole 1 or pole 3 is energized as south.
- If winding B or D is excited, pole 2 or pole 4 is energized as north.



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Stepper Motor Driving Topology

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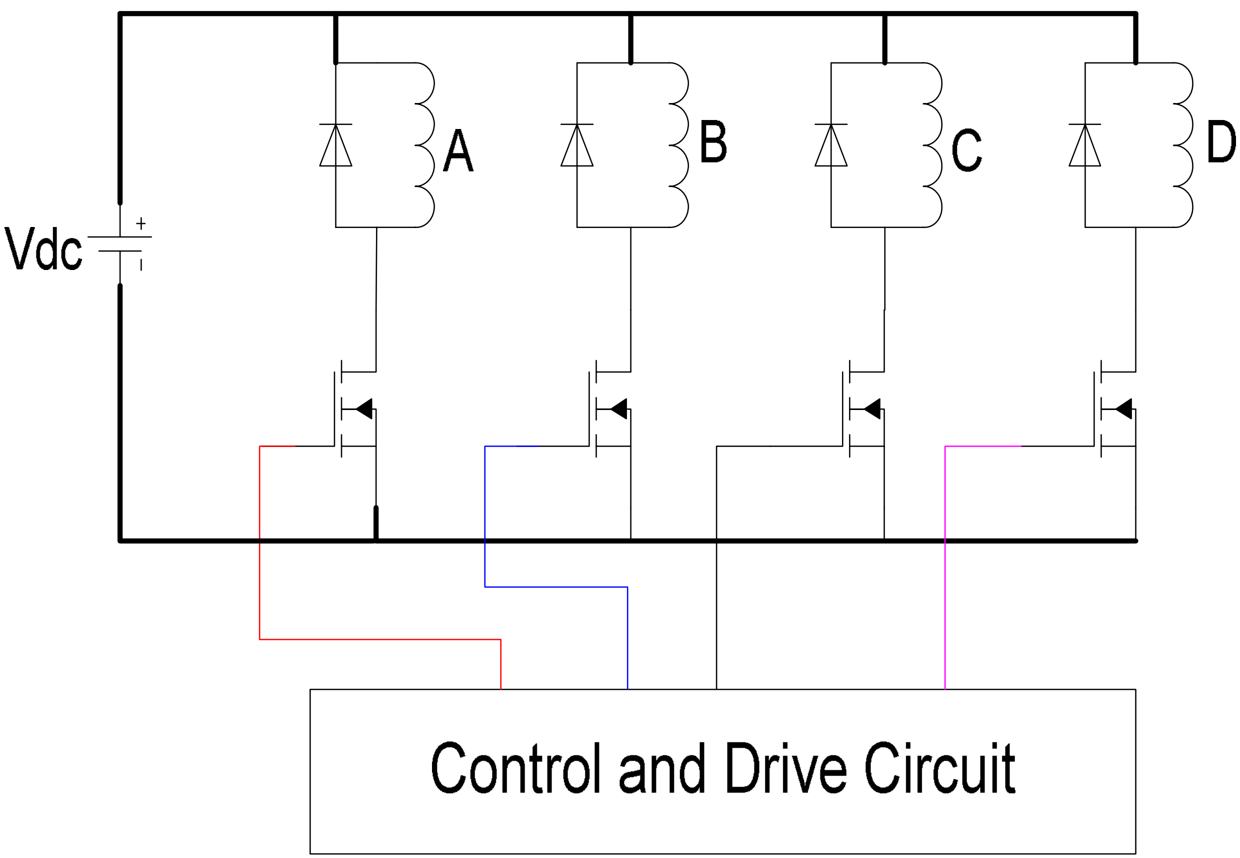
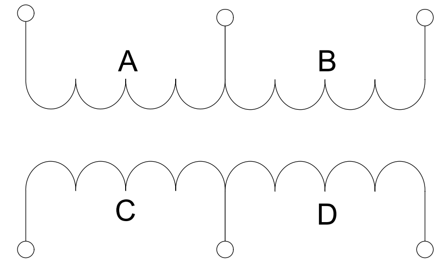
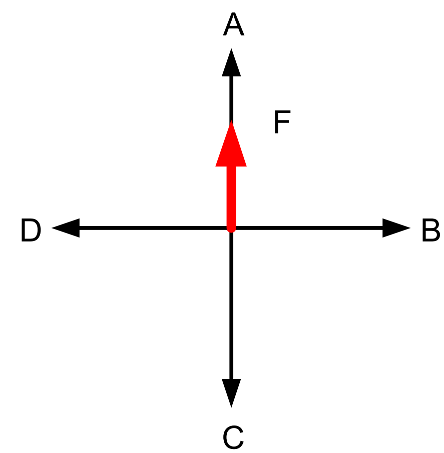
Unipolar Drive





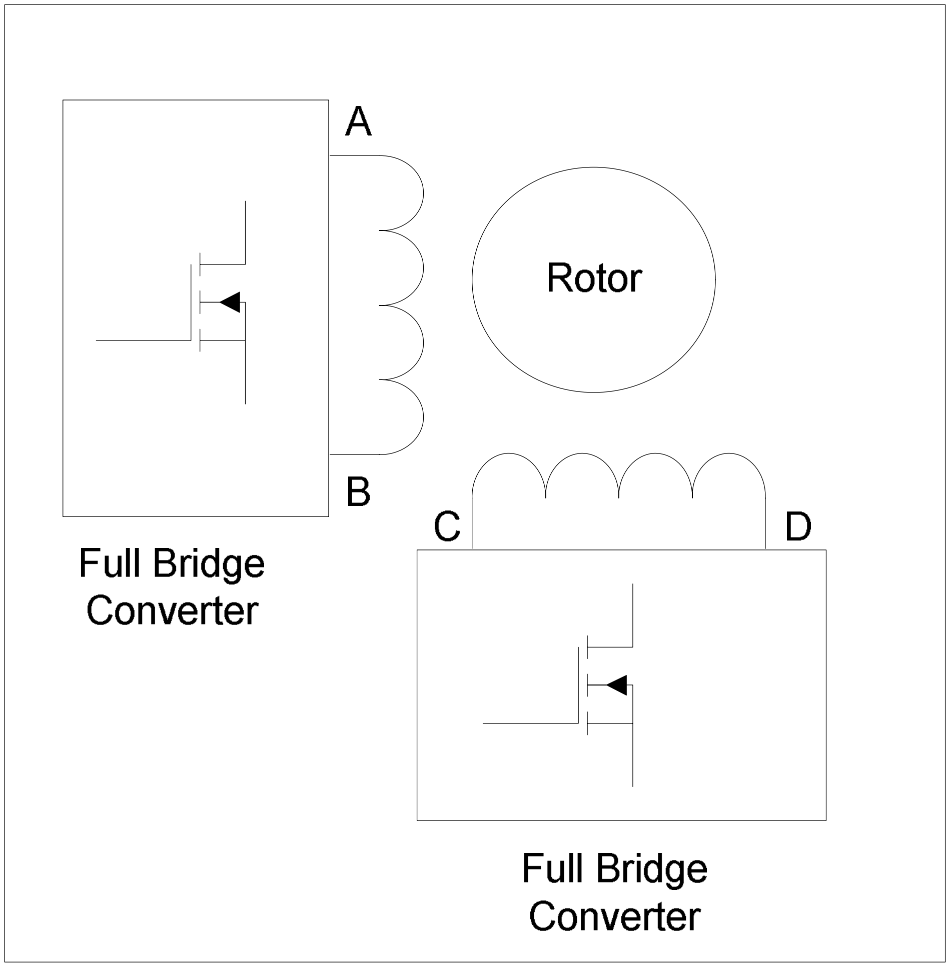
Motor Windings

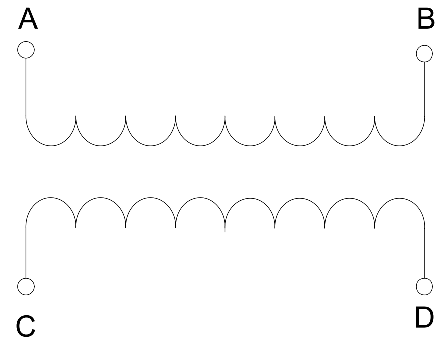


Vector Diagram

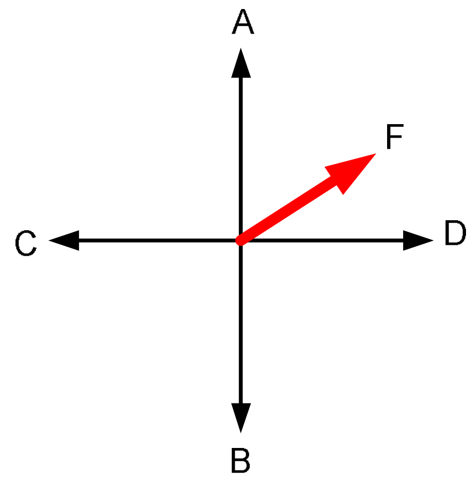
Stepper Motor Driving Topology

Bipolar Drive





Motor Windings



Vector Diagram

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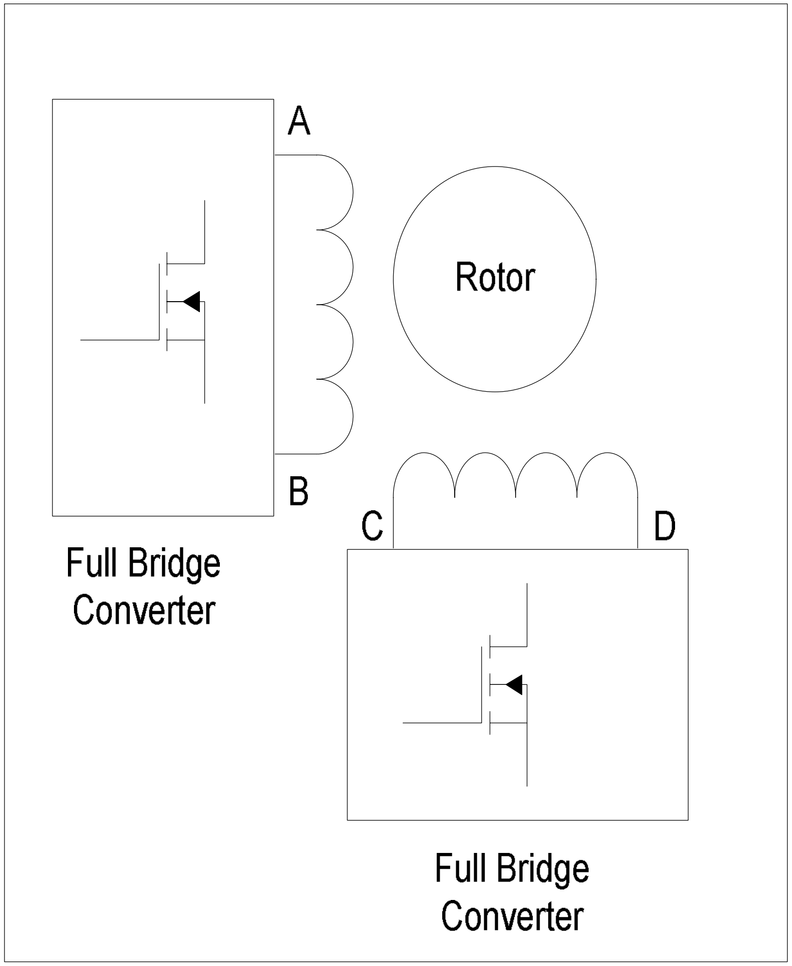
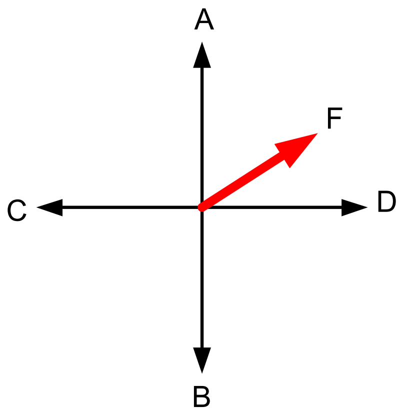
Stepper Motor Driving Mode

Full Step Driving Mode



	A	B	C	D	Rotor
Mode 1	1	0	0	1	θ
Mode 2	0	1	0	1	2θ
Mode 3	0	1	1	0	3θ
Mode 4	1	0	1	0	4θ



Vector Diagram

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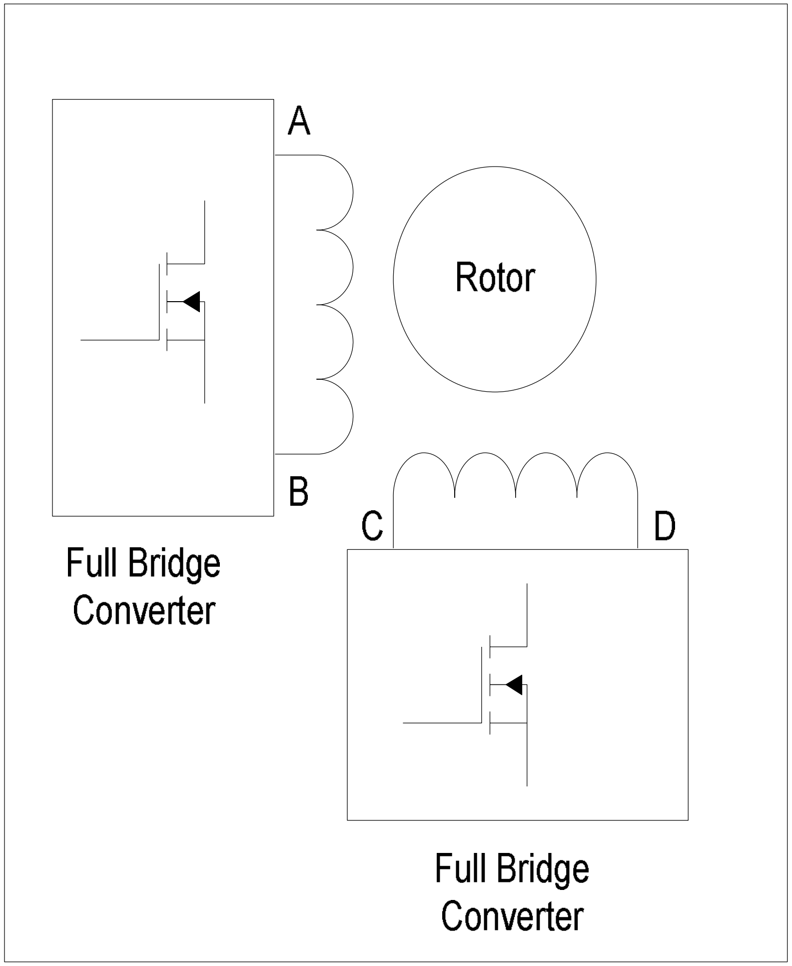
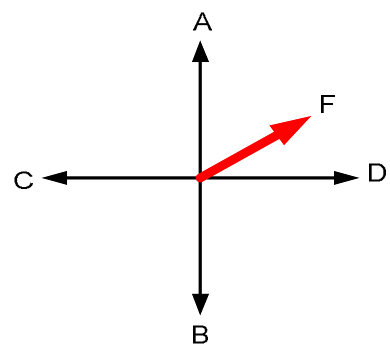
Stepper Motor Driving Mode

Half Step Driving Mode



	A	B	C	D	Rotor
Mode 1	1	0	0	0	0
Mode 2	1	0	0	1	$\theta / 2$
Mode 3	0	0	0	1	θ
Mode 4	0	1	0	1	$3\theta / 2$
Mode 5	0	1	0	0	2θ
Mode 6	0	1	1	0	$5\theta / 2$
Mode 7	0	0	1	0	3θ
Mode 8	1	0	1	0	$7\theta / 2$



Vector Diagram

Stepper Motor Driving Mode

Micro Stepping Driving Mode

- In full step and half step mode, the same amount of current flows through the energized stator windings.
- However, if the currents are not equal, the rotor will be shifted toward the stator pole with the higher current.
- The amount of deviation is proportionate to the values of the currents in each winding.
- Refer ZaberWiki for further understanding

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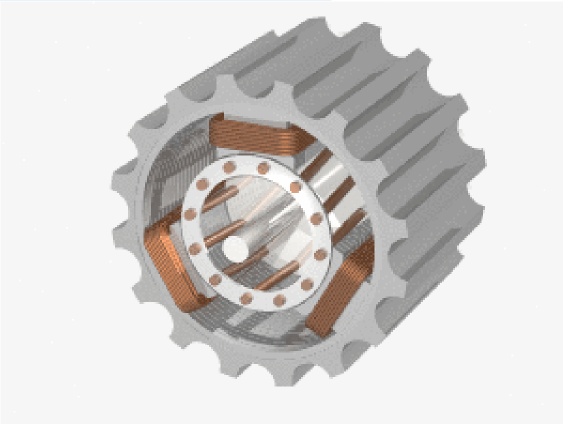
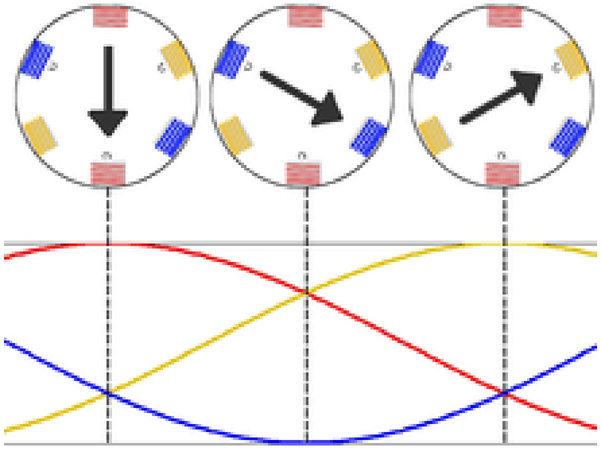
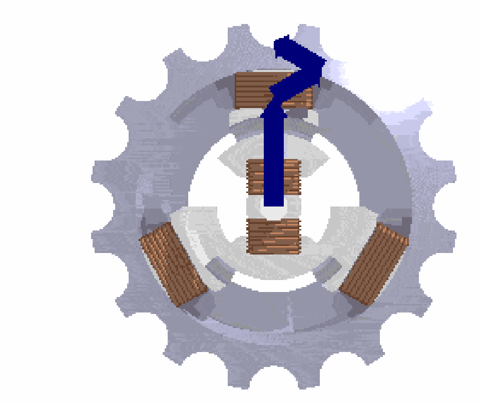
Induction Motor Fundamentals

- Stator has 3 phase sinusoidaly distributed winding.
- Rotor consists of 3 phase windings with shorted copper bars at the end
- Rotating magnetic field is generated in the stator if 3 phase balance supply is applied to the stator
- This rotating magnetic field induces voltage in the rotor by transforming action
- The rotor current produces the rotor magnetic field which rotates with relative angular velocity which is called as slip (S) velocity

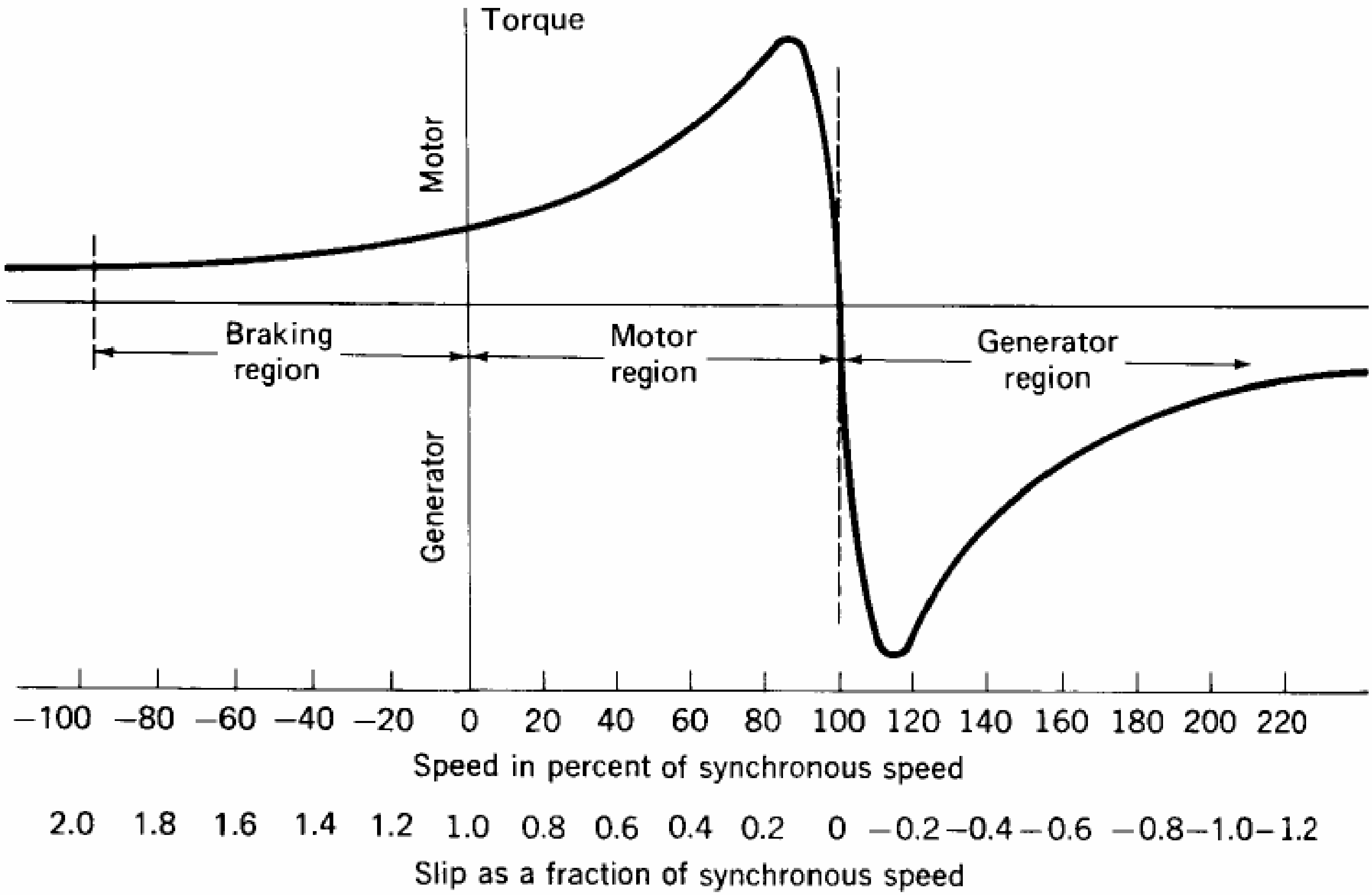






Induction Motor Fundamentals

Induction Motor Speed-Torque Characteristics



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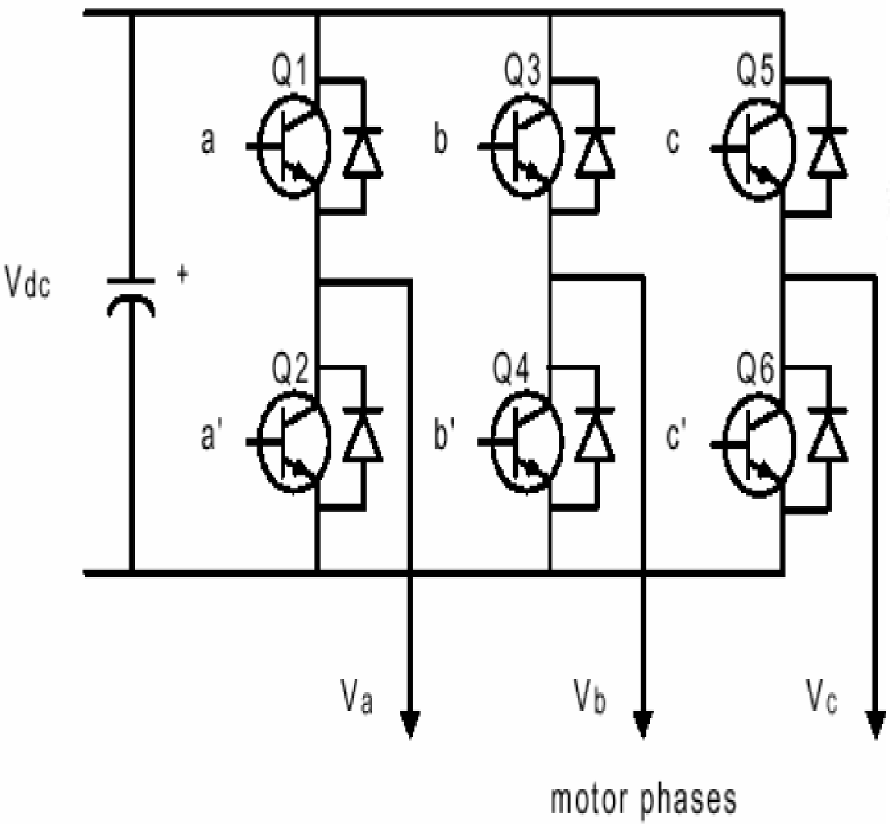
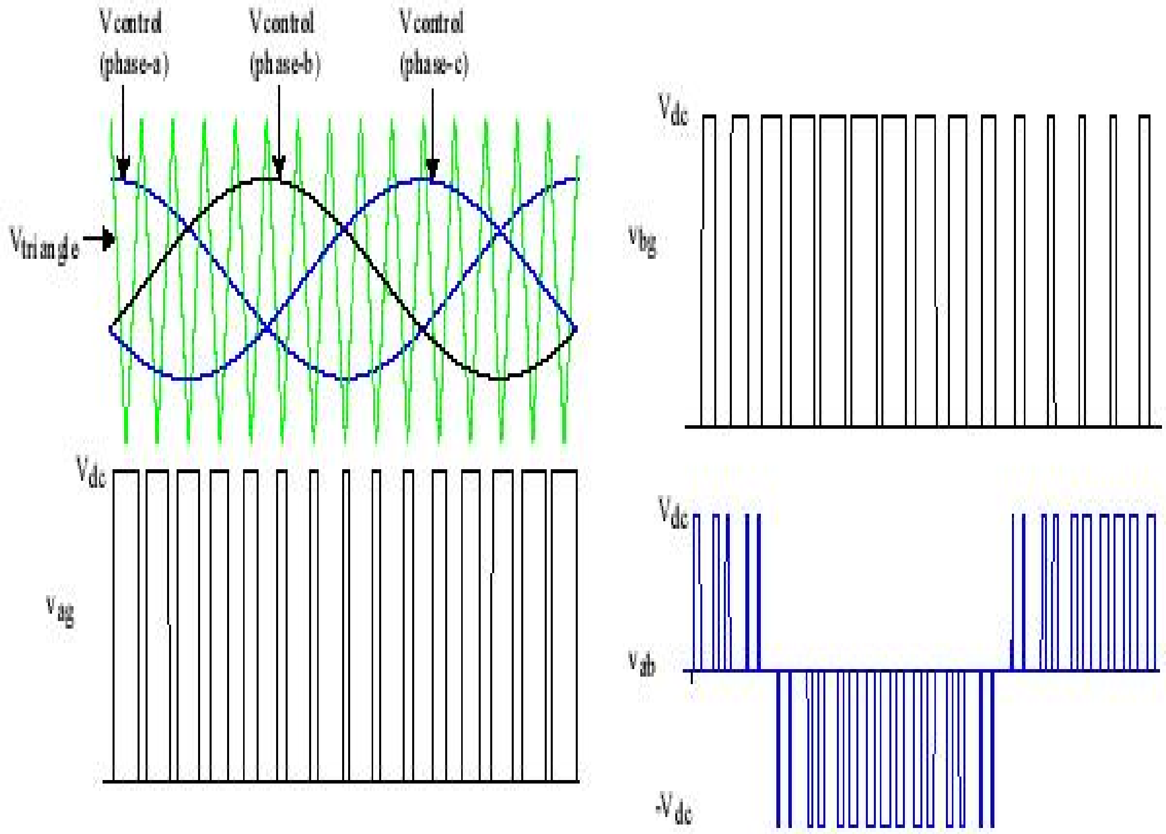
Induction Motor Control

Sine-Triangle PWM Control





- Modulation Index
- DC Bus utilization is 78%

$$m = V_S / V_T$$

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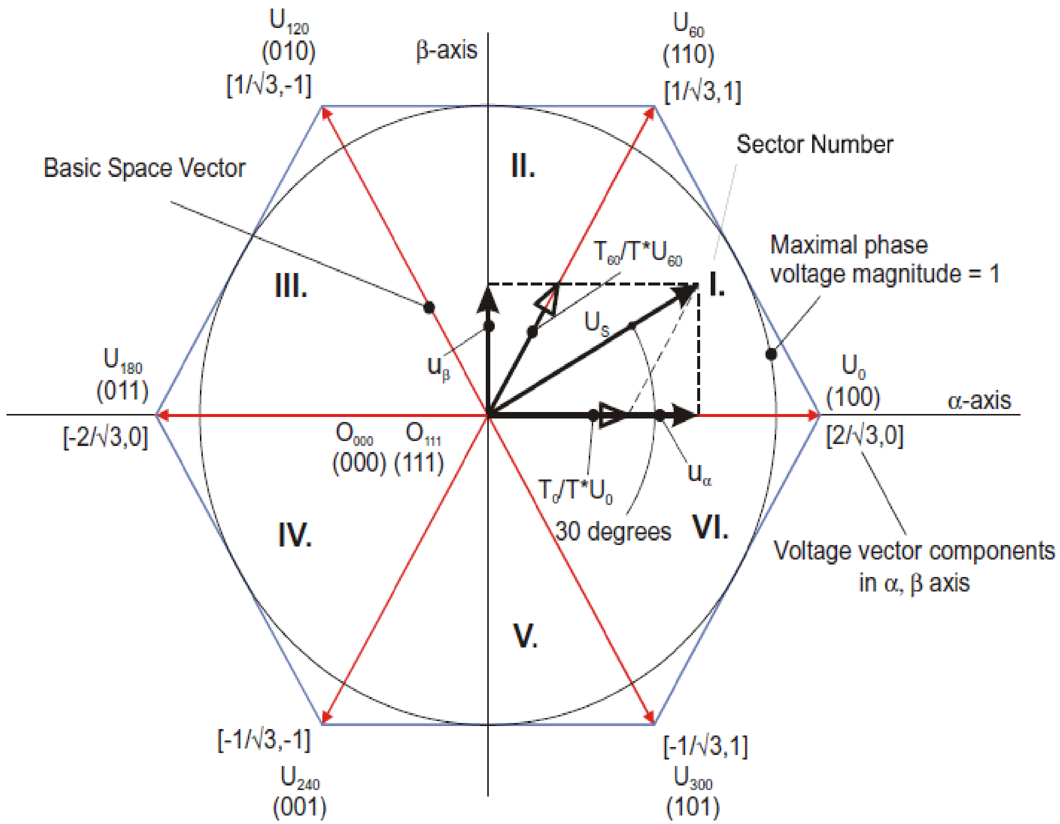
Induction Motor Control

Space Vector PWM Control

Vector	c	b	a	U_{AB}	U_{BC}	U_{CA}
U_{000}	0	0	0	0	0	0
U_{0}	0	0	1	U_{DC}	0	$-U_{DC}$
U_{60}	0	1	1	0	U_{DC}	$-U_{DC}$
U_{120}	0	1	0	$-U_{DC}$	U_{DC}	0
U_{180}	1	1	1	$-U_{DC}$	0	U_{DC}
U_{240}	1	0	0	0	$-U_{DC}$	U_{DC}
U_{300}	1	0	1	U_{DC}	$-U_{DC}$	0
U_{111}	1	1	1	0	0	0



Induction Motor Control

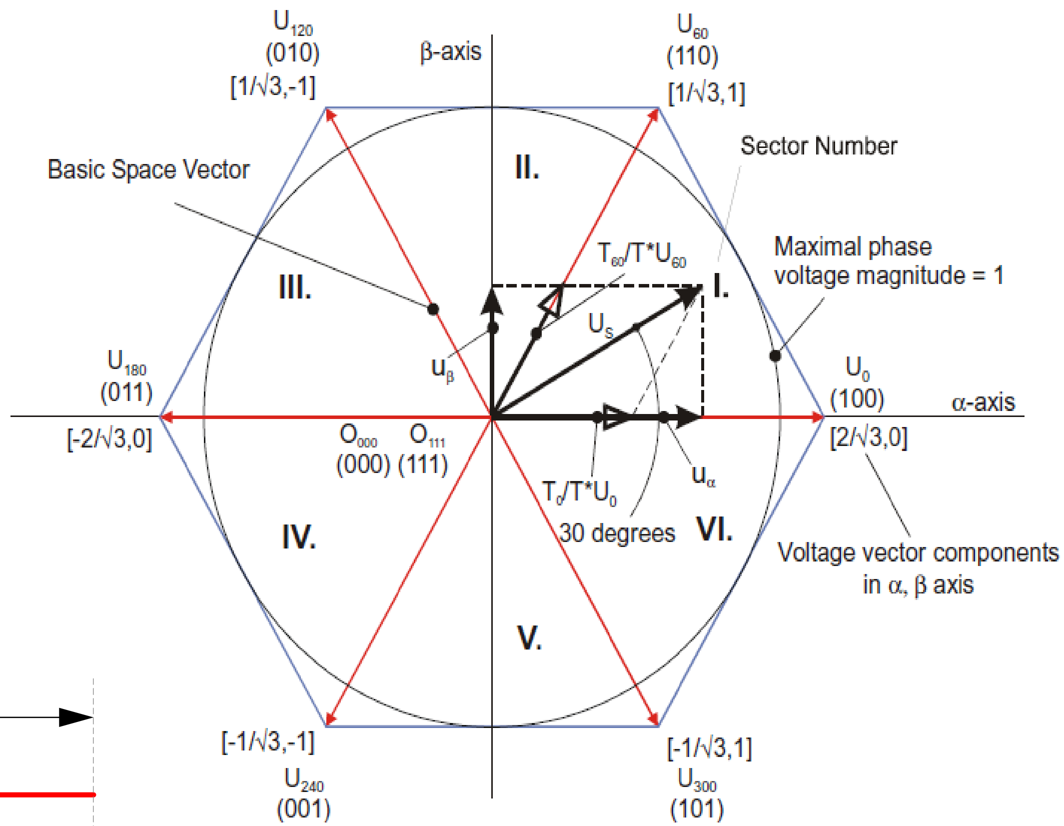
Space Vector PWM Control

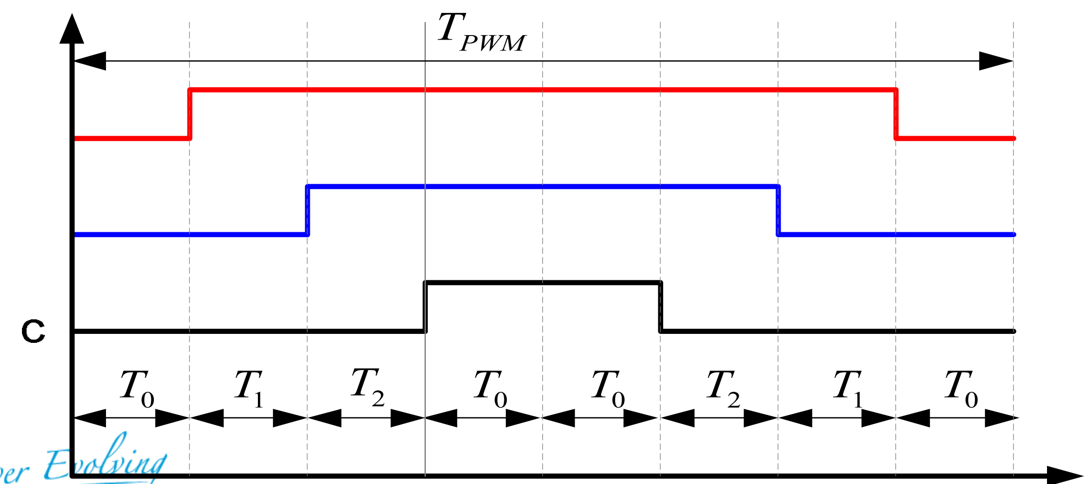
- Works on the constant volt-seconds principal

$$T_1 = m_a \cdot T_{PWM} \cdot \sin\left(\frac{\pi}{3} - \alpha\right)$$

$$T_2 = m_a \cdot T_{PWM} \cdot \sin\alpha$$

$$T_0 = T_{PWM} - (T_1 + T_2)$$

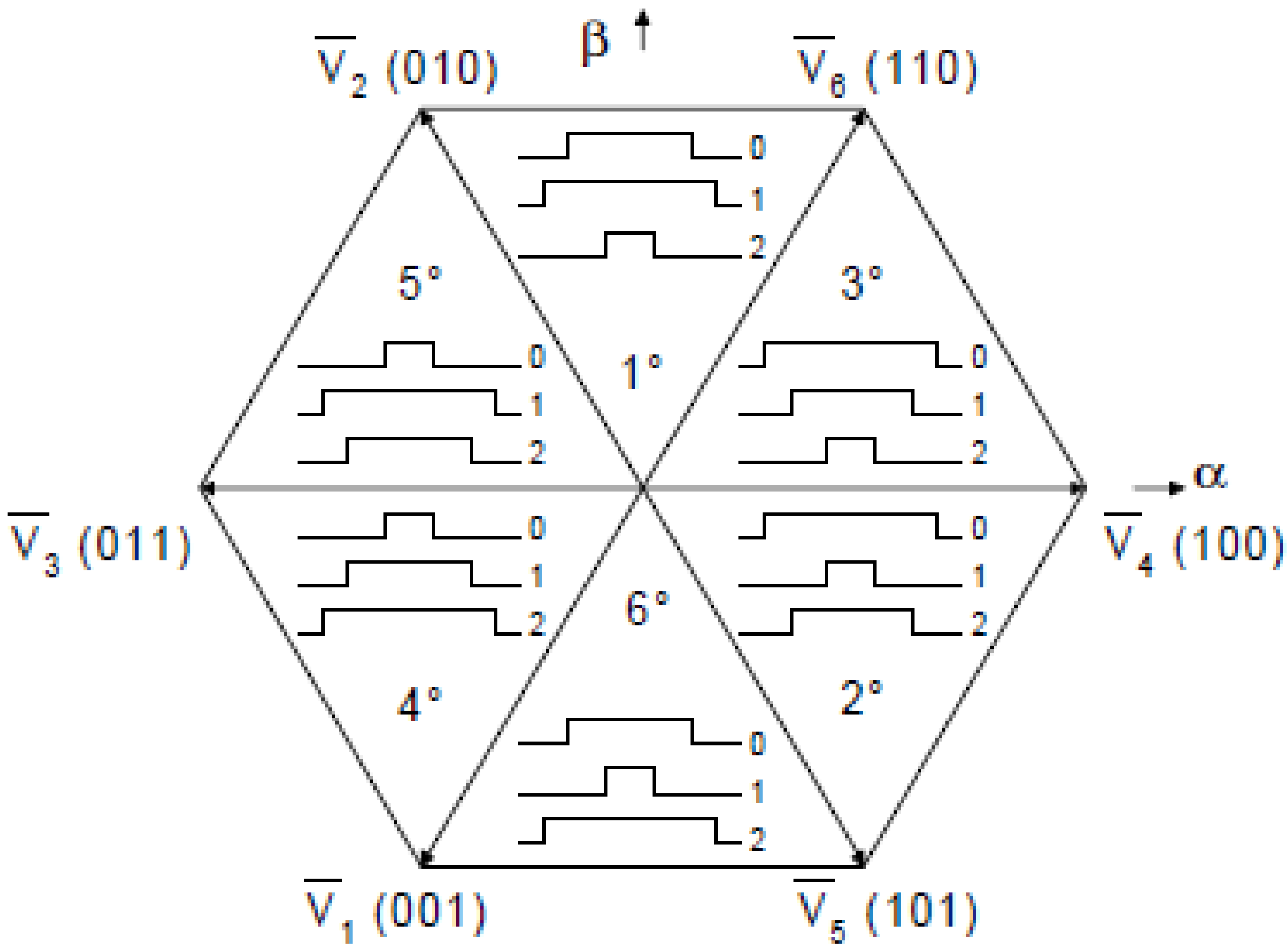




m_a = **Modulation Index**

Induction Motor Control

Space Vector PWM Control



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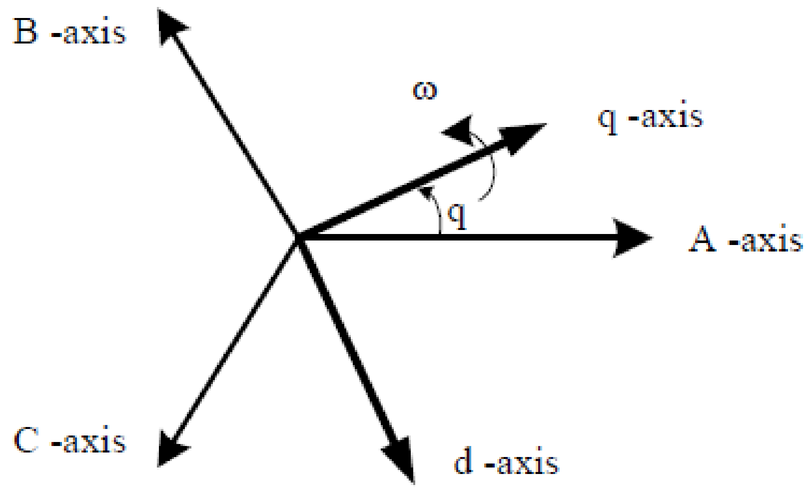
Reference Frame Theory

- The inductances of the rotating machines are time varying quantities and depends on the speed of the motor
- All time varying inductances can be eliminated by referring stator and rotor variables to a frame of reference which may rotate at any angular velocity called arbitrary reference frame (w)
- When w = 0; the reference frame is stationary
- When w = we; the reference frame is synchronously rotating reference frame and the transformation is known is as Park's Transformation
- When w = wr; the reference frame is fixed in the rotor

Reference Frame Theory



$$\left[f_{qd0s}\right] = T_{qd0}(\theta)\left[f_{abcs}\right]$$

where

$$T_{qd0s}(\theta) = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\left[f_{qd0s}\right] = \left[f_{qs} \quad f_{ds} \quad f_{0s}\right]^T$$

and $\left[f_{abcs}\right] = \left[f_{as} \quad f_{bs} \quad f_{cs}\right]^T$

$$\theta = \int_0^t \omega(\zeta)\,d\zeta + \theta(0)$$

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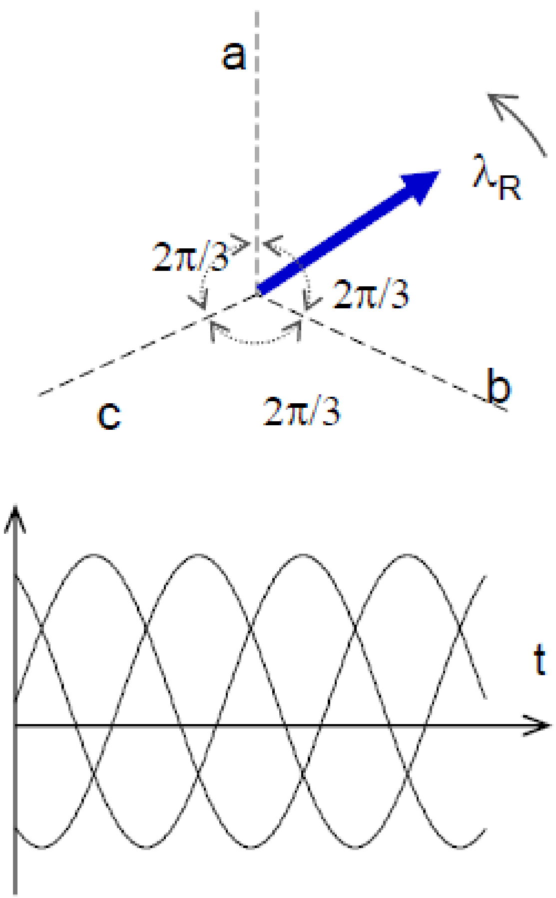
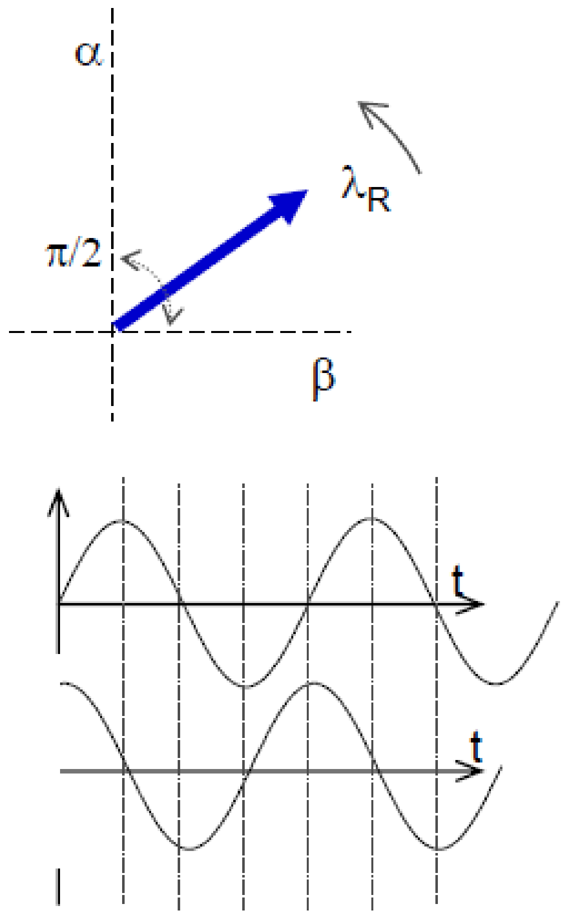
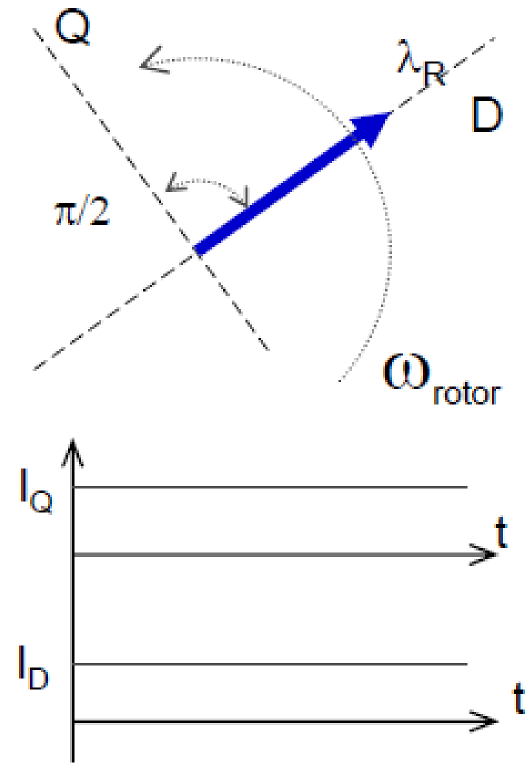
Reference Frame Theory



Three phase reference frame



Two phase orthogonal reference frame



Rotating Orthogonal Reference Frame

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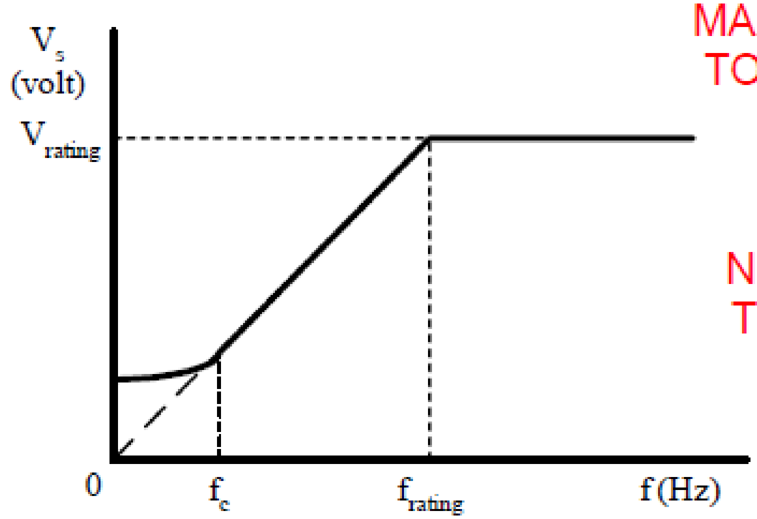
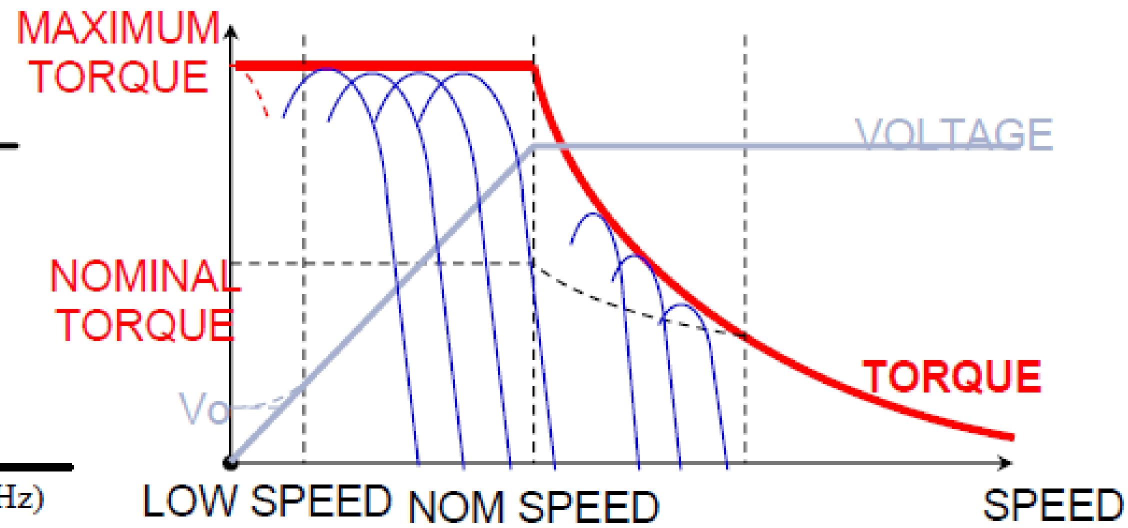
Scalar V/F Control of Induction Motor





- Simple implementation : Just need a 3 sine modulated PWM applied to VSI (Voltage Source Inverter)
- No Position Information is needed
- Doesn't deliver a good dynamic response

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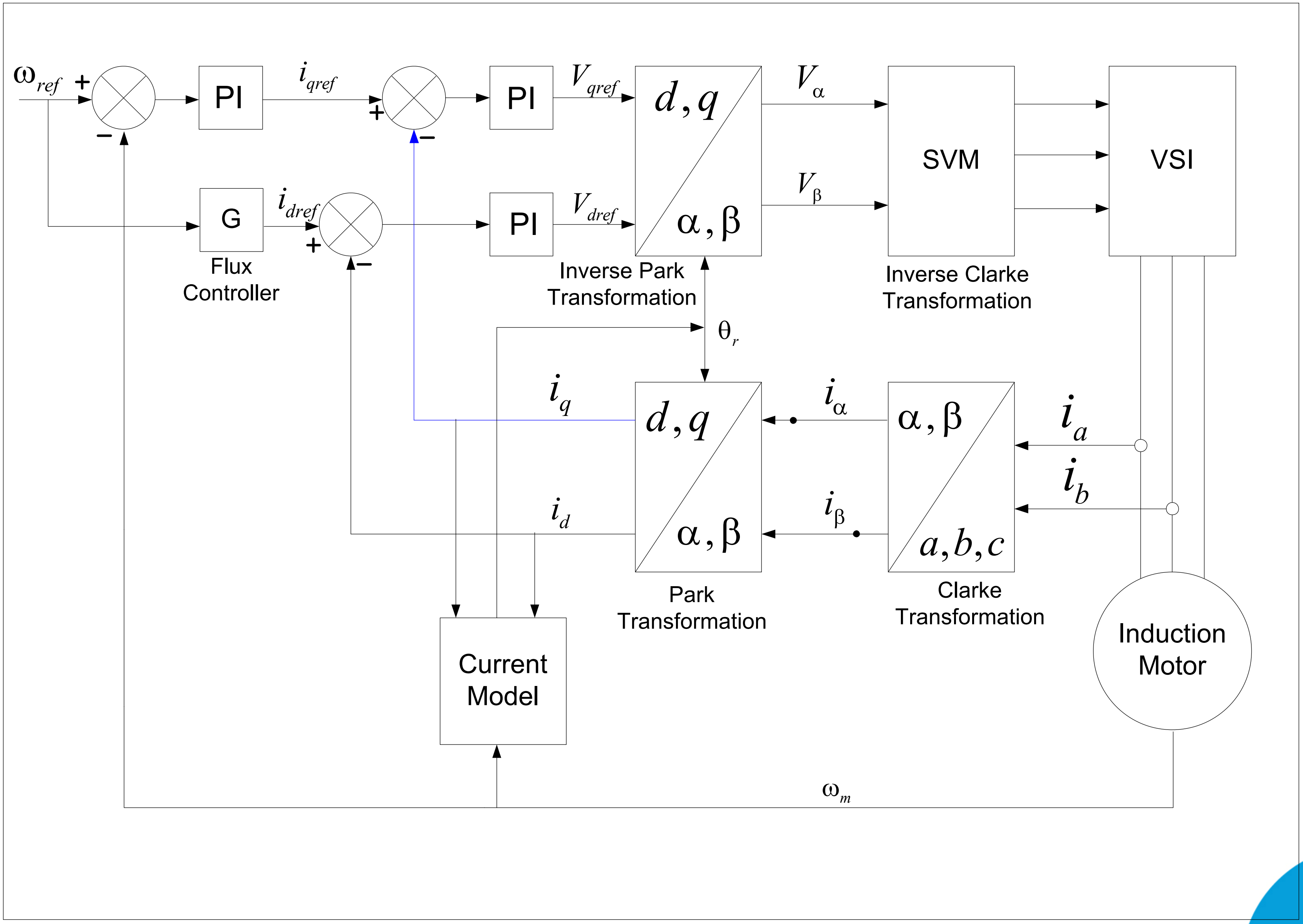
Vector Control of Induction Motor

- FOC or Vector Control involves controlling the components of the motor stator currents, represented by a vector, in a rotating reference frame (with a d-q coordinate system)
- In a arbitrary reference frame the electromagnetic torque is similar to the torque expression of the separately excited DC motor
- Torque and Speed are decoupled using FOC algorithm
- Gives better dynamic response compare to scalar control

Vector Control of Induction Motor



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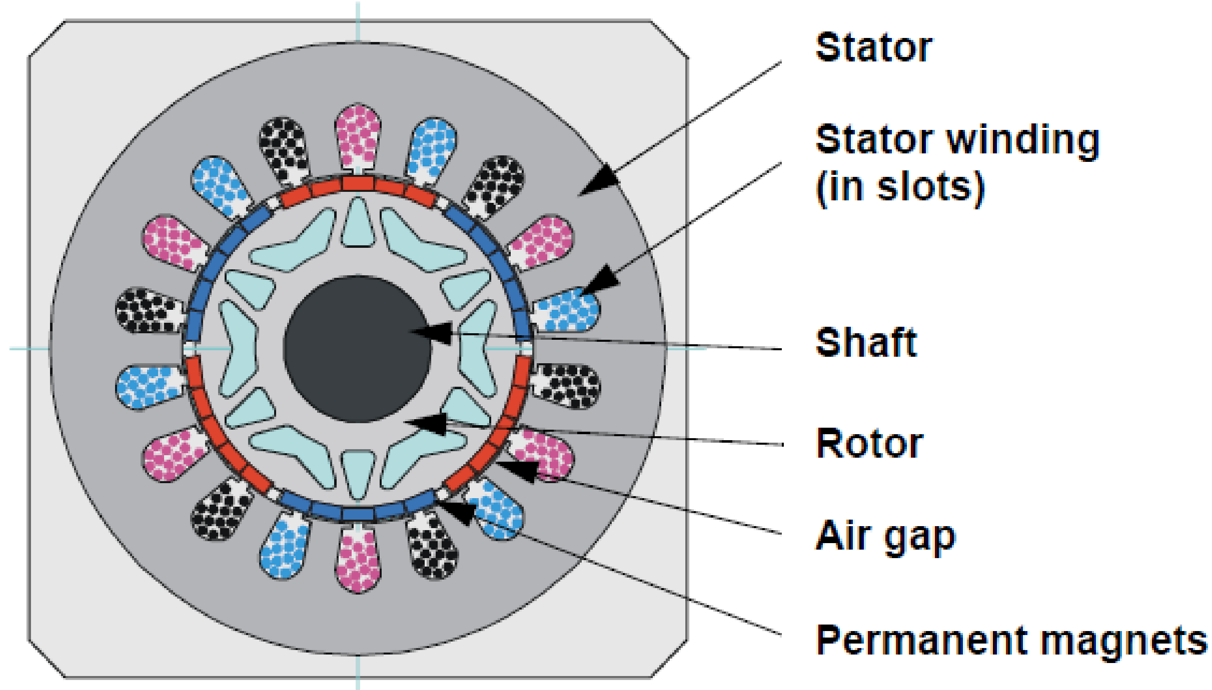
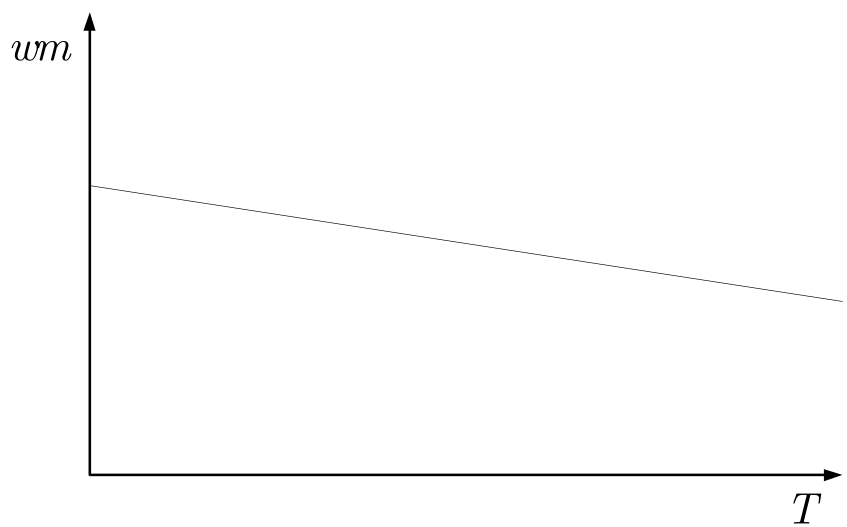
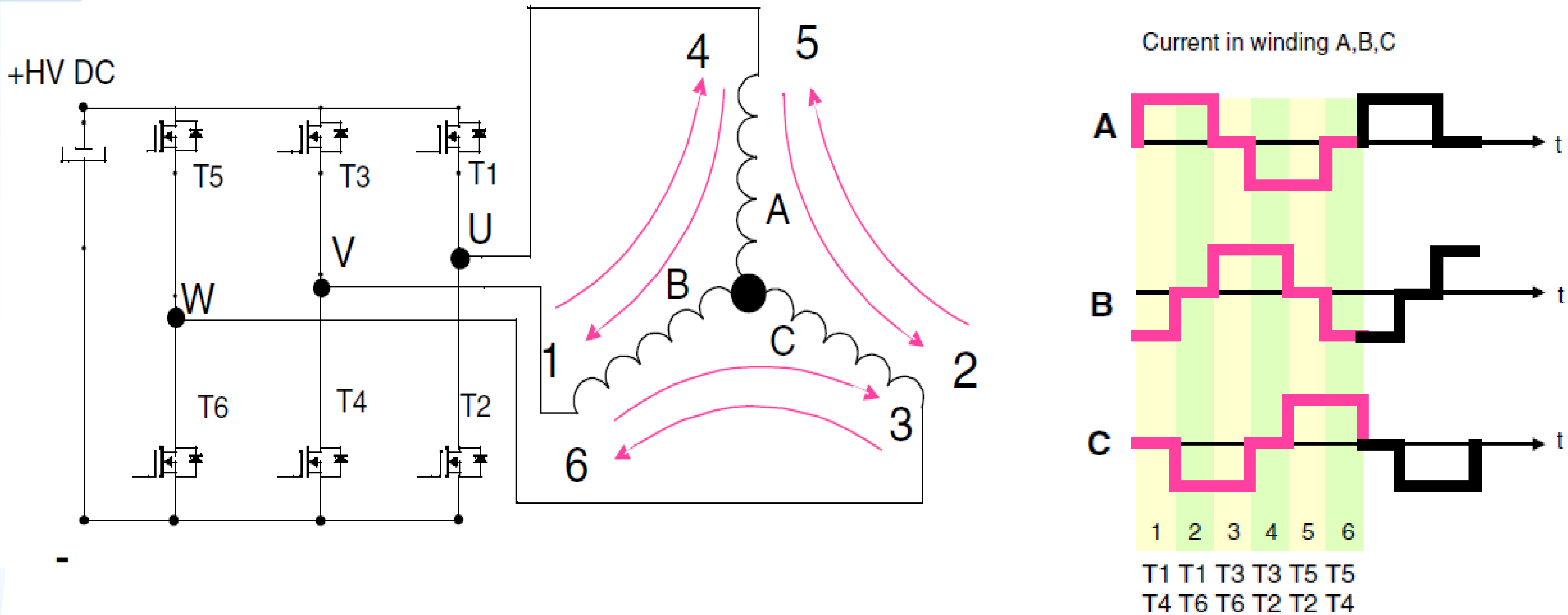
BLDC Motor Control Fundamentals

- Stator has 3 phase uniformly distributed winding.
- Rotor consists of permanent magnets
- Torque speed curve is similar to DC shunt motor hence BLDC motor essentially is constant torque machine





Sensor based BLDC Control



- Upper or Lower switches can be controlled by PWM
- Generally Upper switches are controlled by PWM due to the limited bootstrapping time

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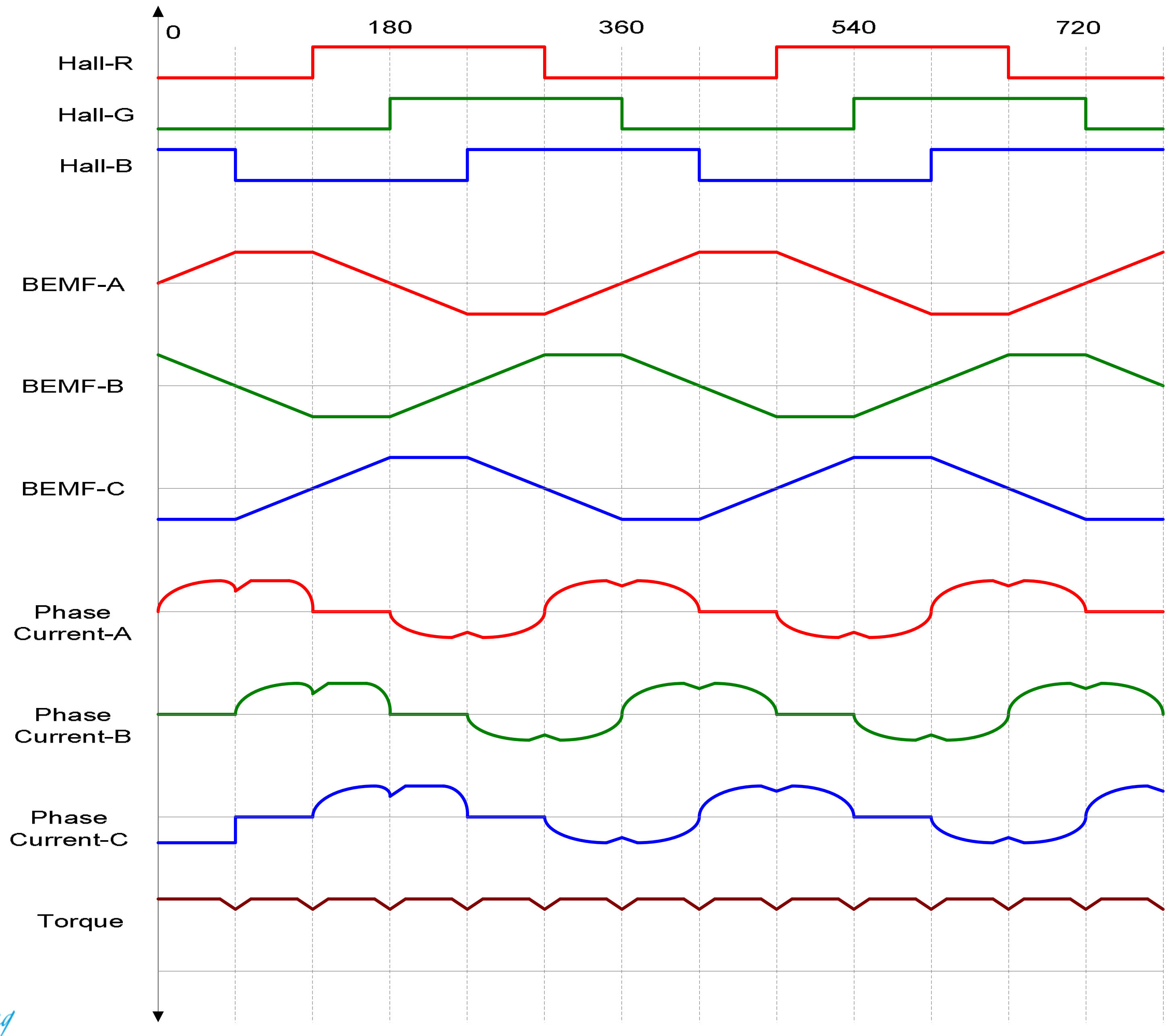
Sensor based BLDC Control



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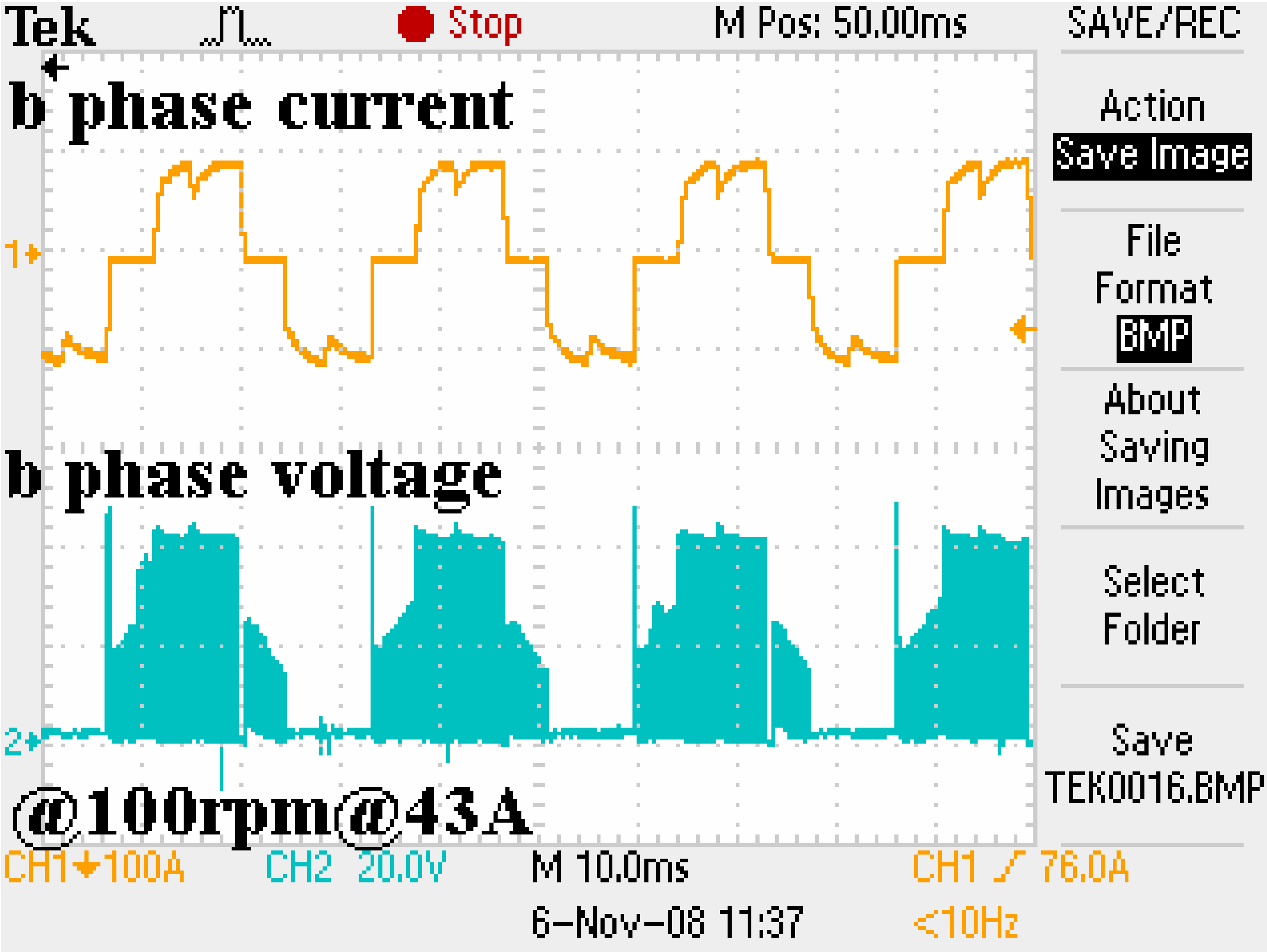
Sensor based BLDC Control



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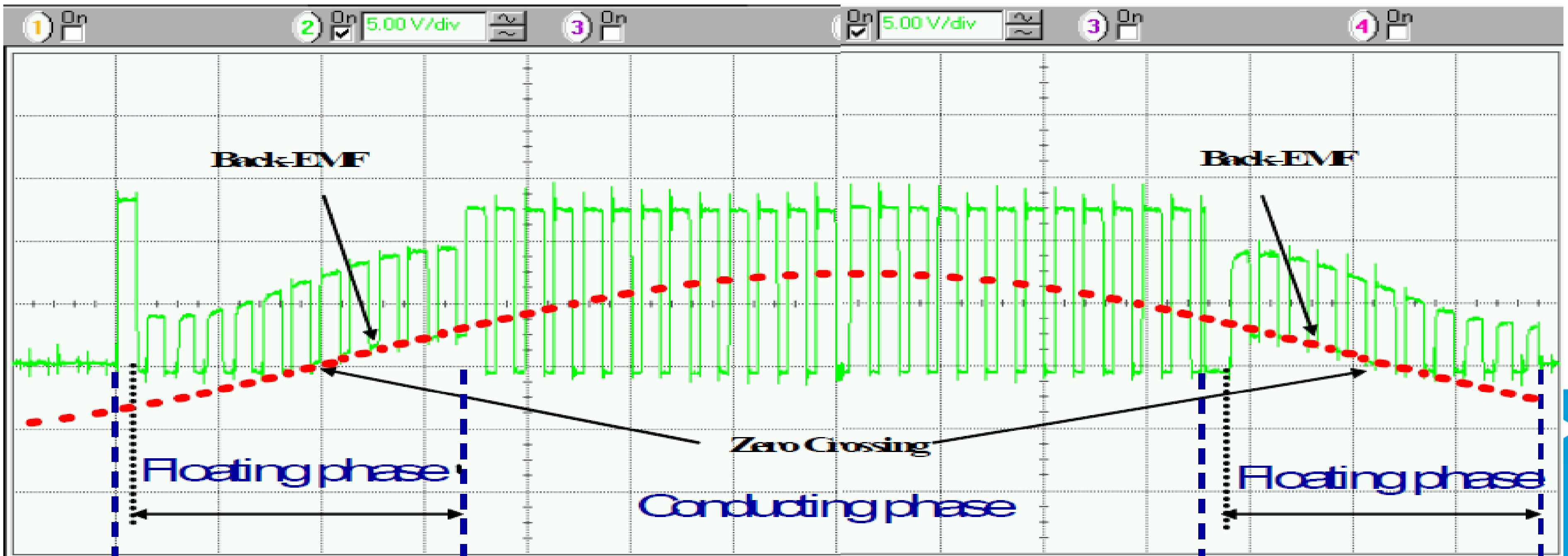
Sensorless BLDC Control

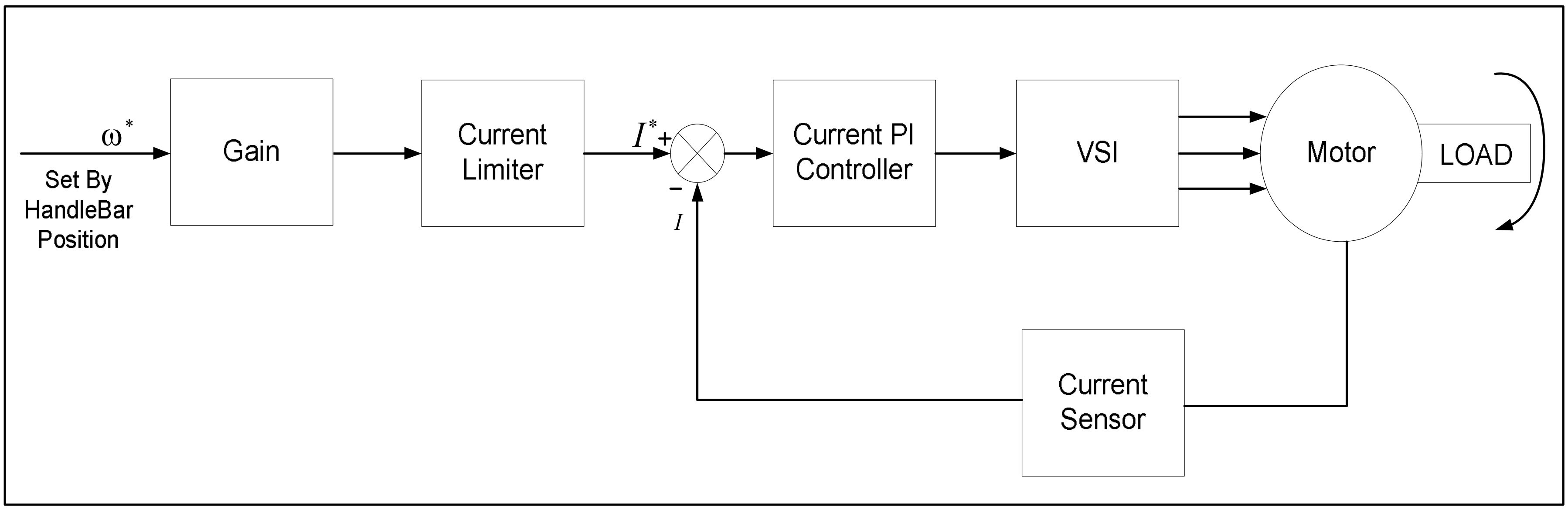
- Current commutation is done without Hall Sensors
- Calculate an appropriate point at which the next vector applied
- The switching point can be find out where the Back-EMF of the phase crosses zero potential



Forever

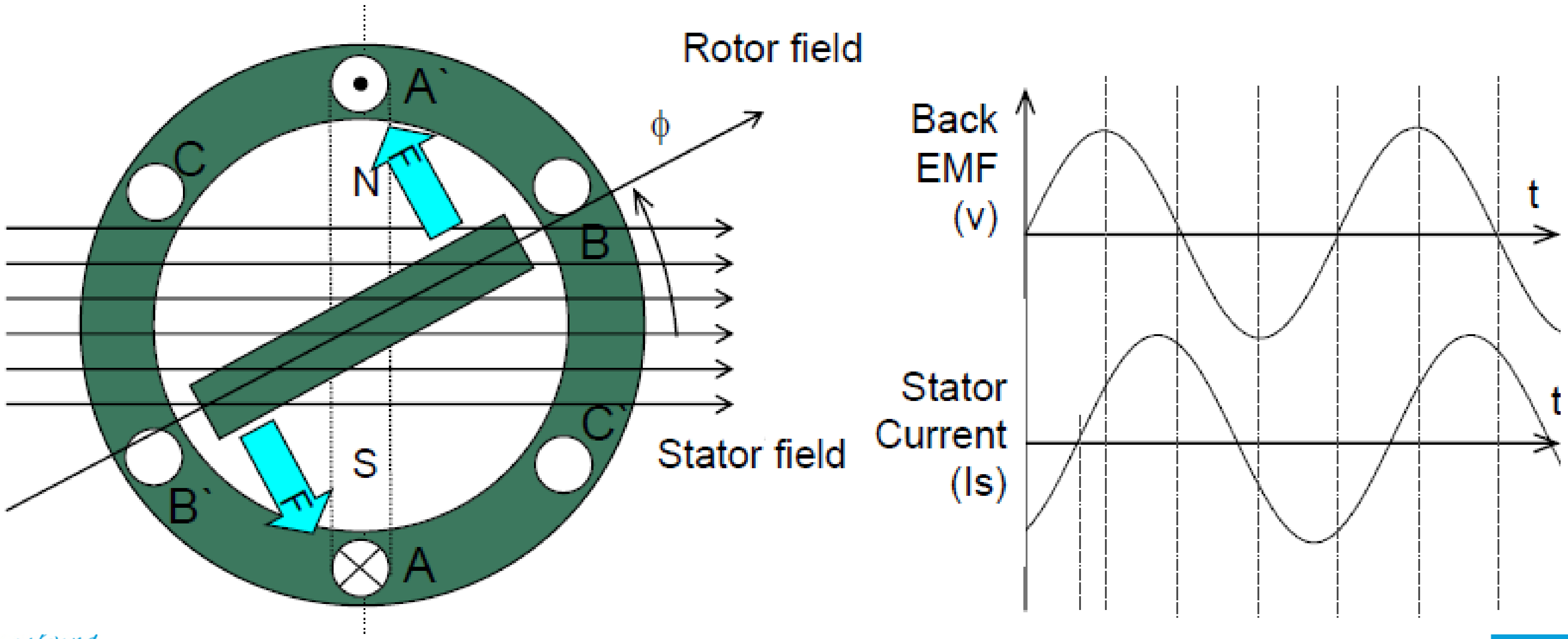
BLDC Controller for E-Bike

- BLDC Hub type motor is being used in E-bike application
- Main aim to maintain torque from rated speed to zero speed



PMSM Motor Control Fundamentals

- A PMSM rotates at a fixed speed in synchronization with the frequency of the power source independent of the load, provided an adequate field current is applied on the motor windings.



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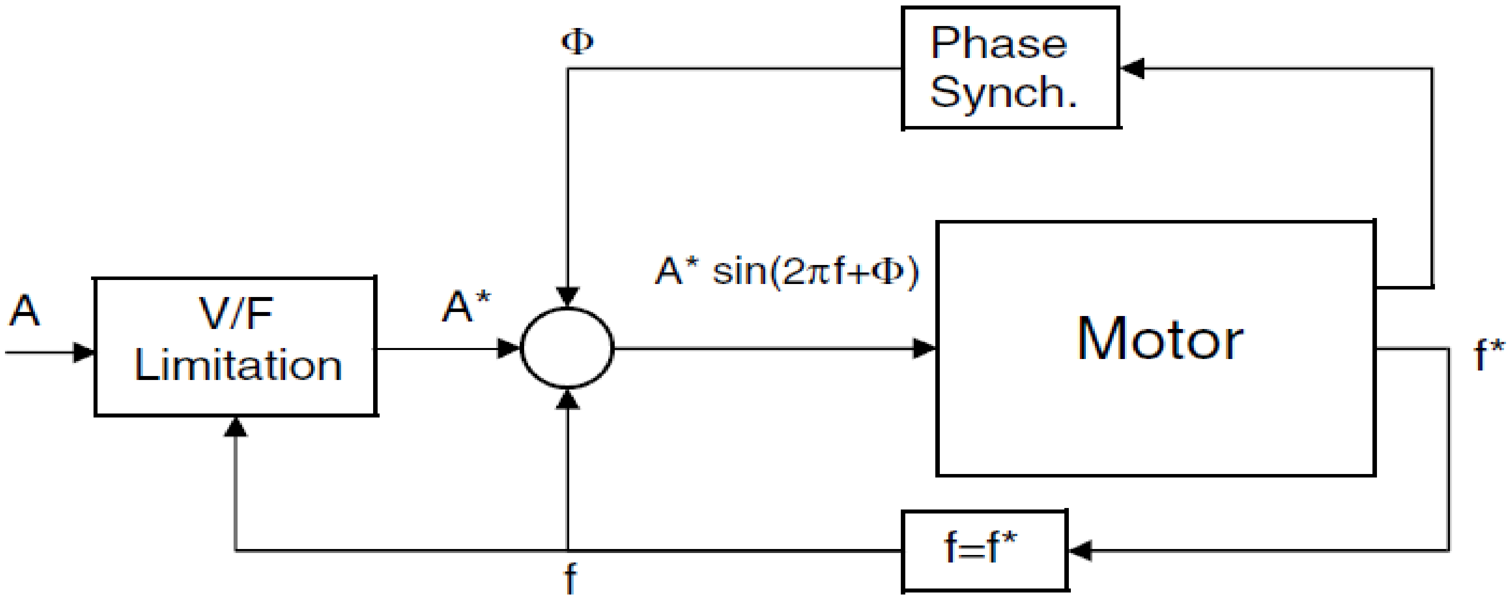
PMSM Motor Control Fundamentals

- A PMSM and a BLDC motor have no intrinsic differences. The winding function of the BLDC motor is trapezoidal (uniformly distributed) while the winding function of the PMSM is sinusoidal (sinusoidaly distributed)

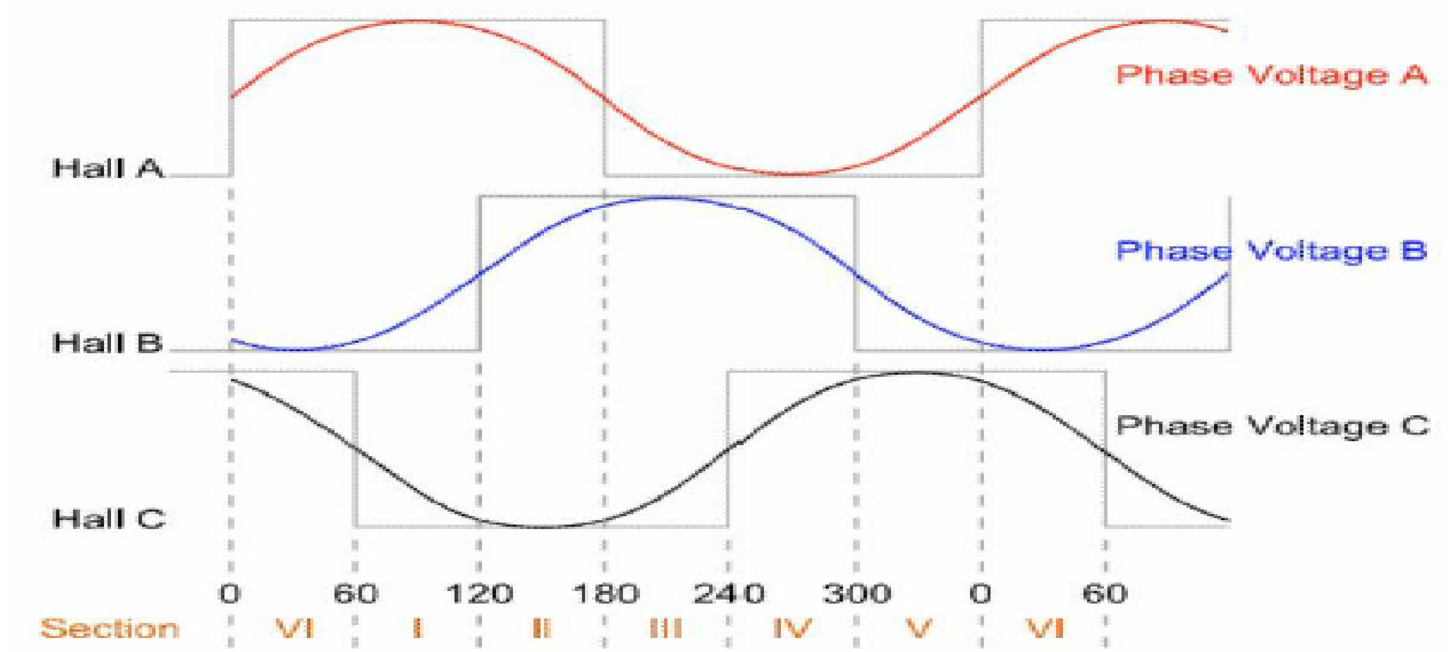
	BLDC motor	PMAC motor
Phase Voltage and Phase Current	rectangular	sinusoidal
Current Peak Value	high	low
Torque	with commutation ripples	smooth
Noise	high	low
Core Power Loss	high	low
Switching Power Loss	low in inverter	high in inverter
Implementation	simple	relatively complicated

PMSM Motor Scalar Control



- The PMSM Motor operating frequency f and amplitude A is controlled using the V/F curve.
- The phase is synchronized by the hall sensors
- Actually hall sensor gives the sector information for V/F curve

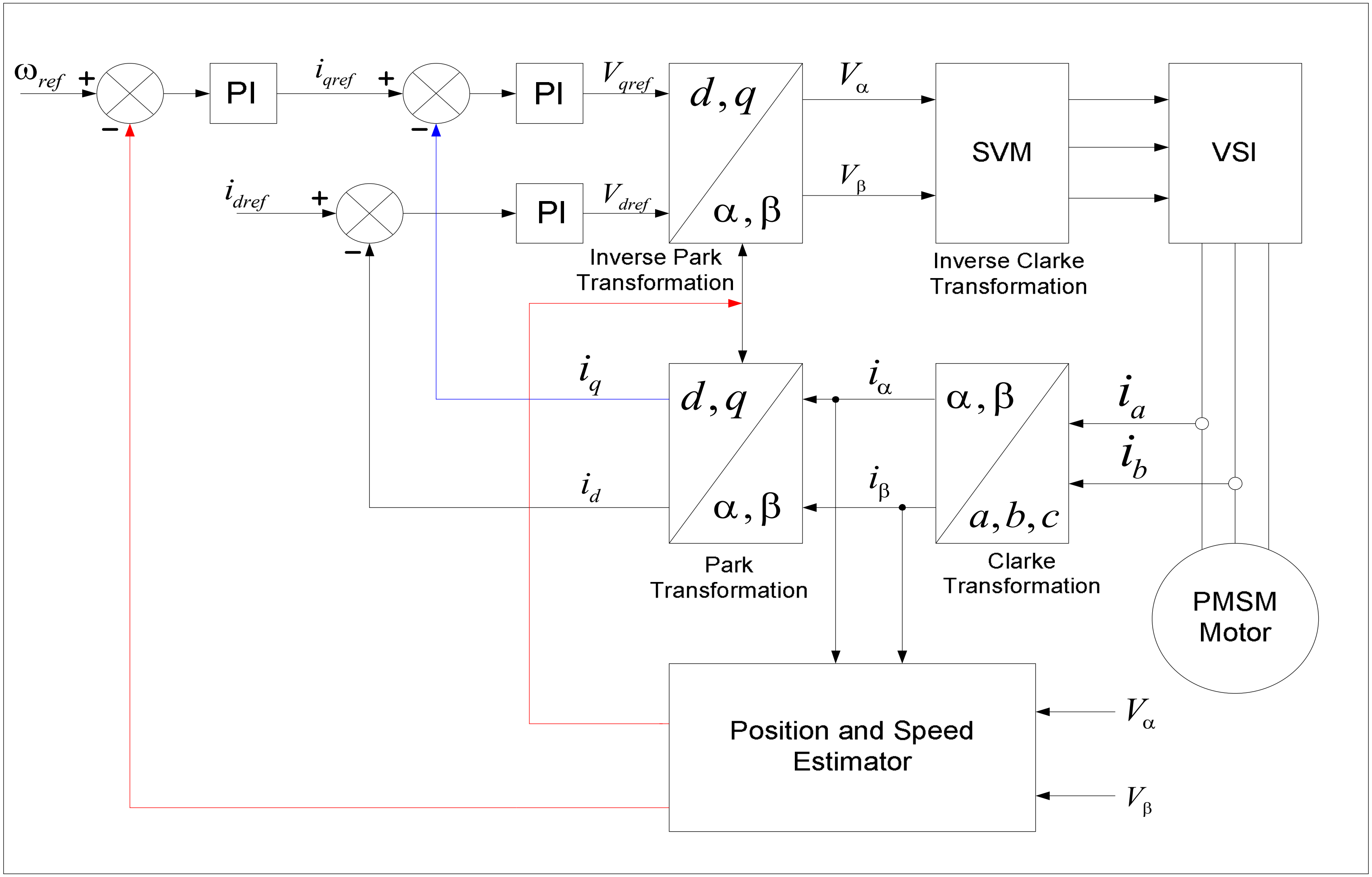
PMSM Motor Scalar Control



- The PMSM Motor operating frequency f and amplitude A is controlled using the V/F curve.
- The phase is synchronized by the hall sensors
- Actually hall sensor gives the sector information for V/F curve

Forever Evolving

PMSM Motor Field Oriented Control



$$i_{dref} = 0$$

$$\tilde{I} = I_q - jI_d$$

Forever Evolving

Thank You

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