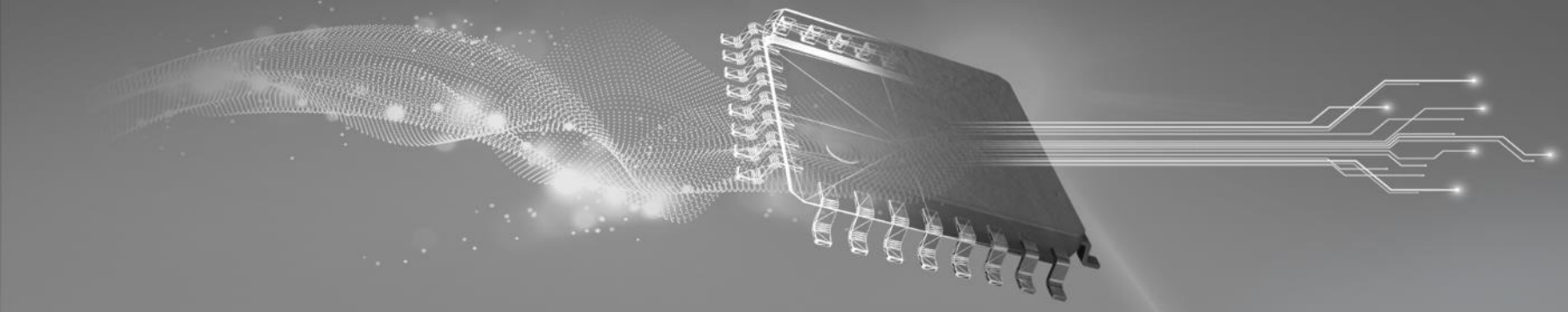
TI TECH DAYS



Demystifying BLDC motor commutation: Trap, Sine, & FOC

Matt Hein

Applications manager, brushless-DC motor drives

Texas Instruments

Agenda

- Introduction
- BLDC motor basics
- Basic commutation (trap)
- Sensored & sensorless
- Advanced commutation (Sine & FOC)
- Summary

Matt Hein introduction

- **Work**
  - Applications engineer in motor drives *(4 months)*
  - Systems engineer in motor drives *(3.5 years)*
  - Product marketing engineer in motor drives (3 years)
  - Product marketing manager in motor drives *(1 year)*
  - Applications manager in motor drives *(1 year)*

- **Personal**
  - Rollerblading
  - Travel (not so much right now)
  - 11-month-old son at home

Some of my writings:

- Seven things that only an analog engineer would understand – e2e.ti.com
- Brushless-DC motor systems for the uninitiated – Planet Analog

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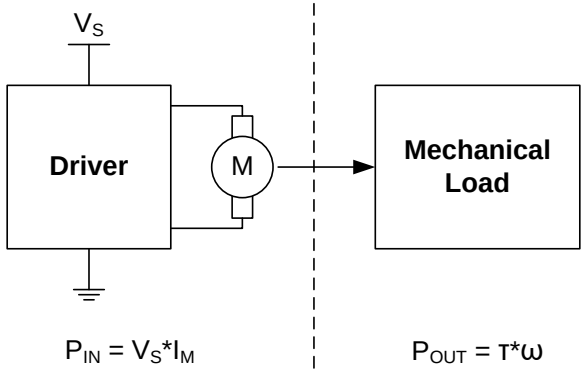
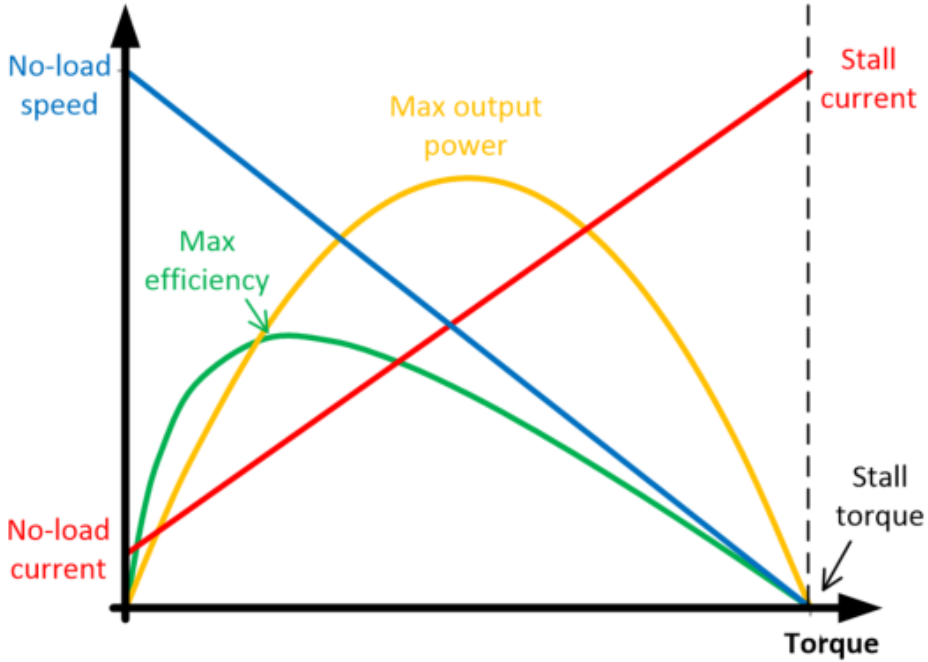
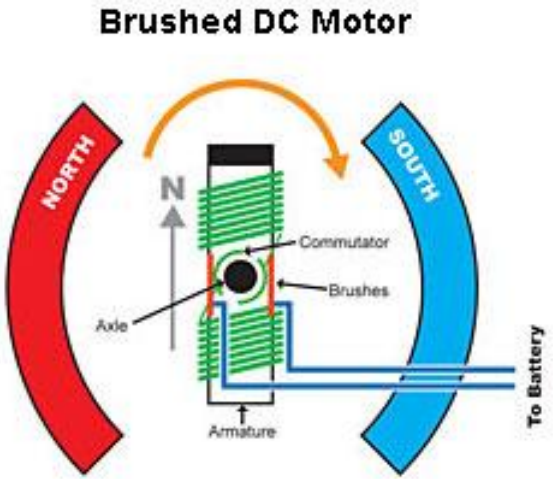
Motor operation

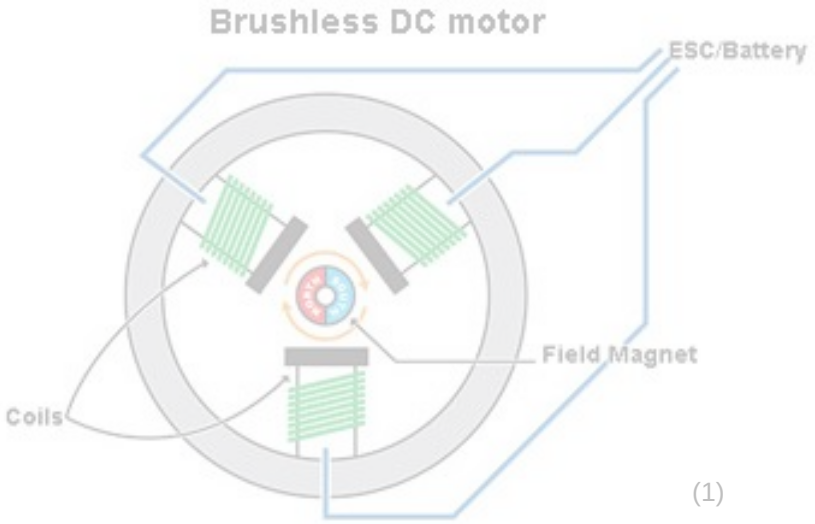


- Electrical power is converted into mechanical power



Motor operation





(1)

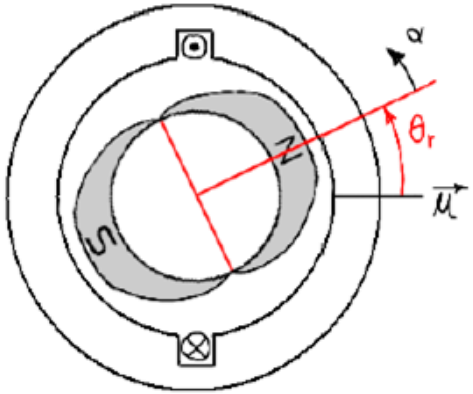
- Commutation is mechanical
- *Advantage:* Easy to drive
- *Downside:* efficiency, power, wear-out, sparking

- Commutation is electrical
- *Advantage:* Efficiency, power
- *Downside:* System needs to apply signal to commutate motor

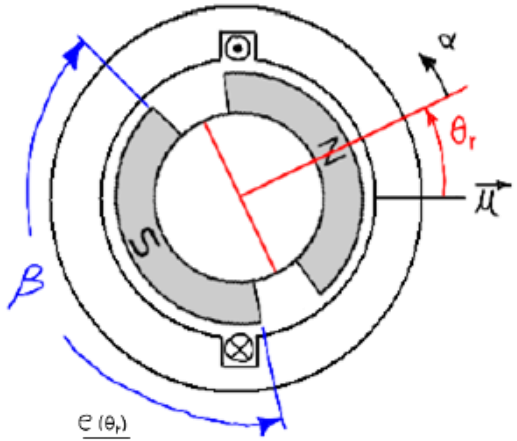
Image credit:
(1) Morai Motion, *Brushed vs Brushless DC Motors*, https://microlinearactuator.com/brushed-vs-brushless-dc-motors/

Motor construction

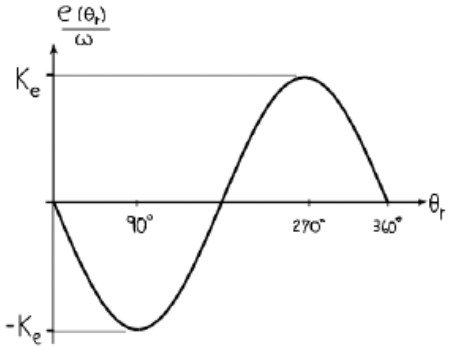
Sinusoidal motors

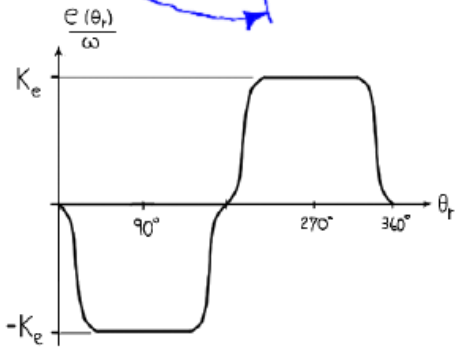


Trapezoidal motors



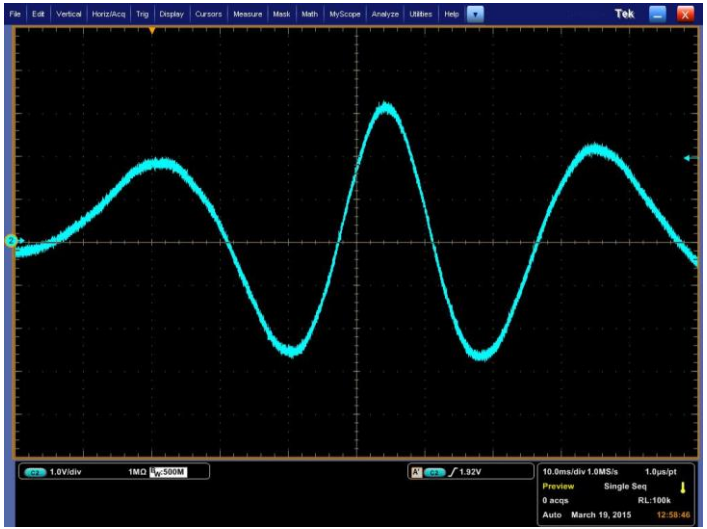
BEMF waveform





Motor construction

Sinusoidal motors

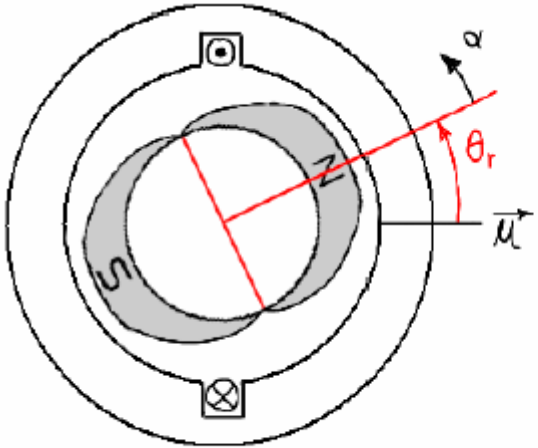


Trapezoidal motors

Need a way to tell them apart? Hook up a scope probe between two outputs and spin it with your fingers!

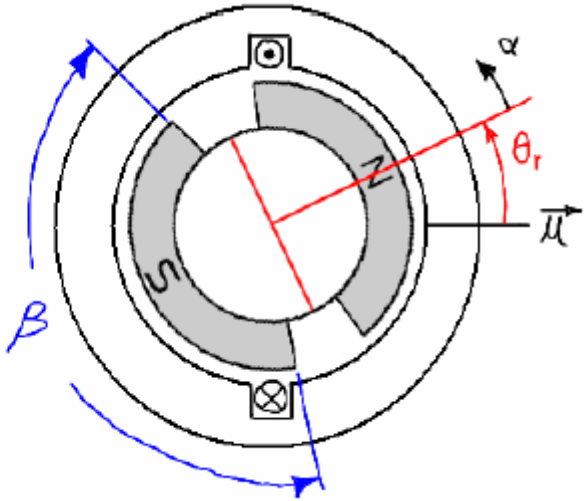
Motor construction

Sinusoidal motors



Ideally driven with a sinusoidal current

Trapezoidal motors



Ideally driven with a trapezoidal current

More on this later!

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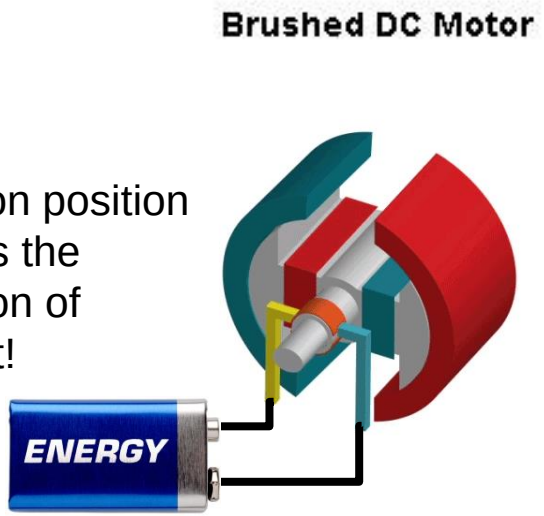
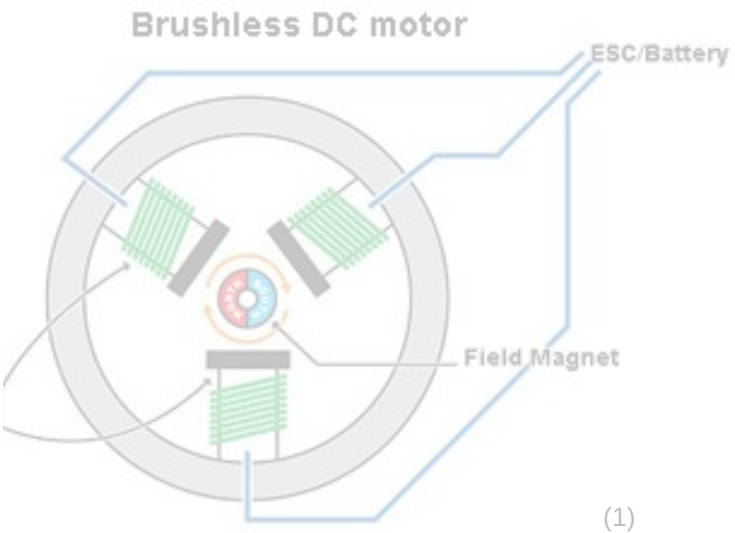


Rotation position defines the direction of current!

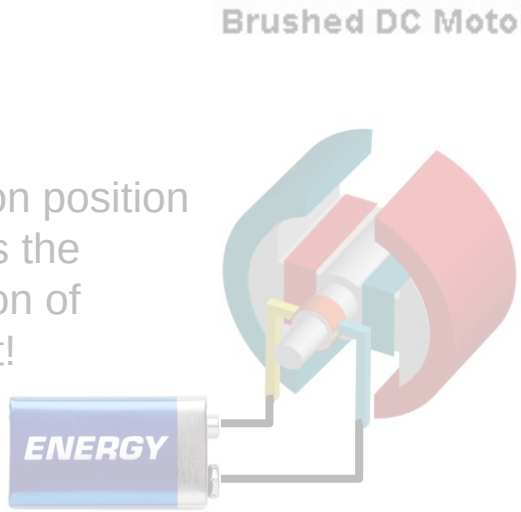


(1)

- Commutator reverses flow of current to make sure that the magnetic field generated on the rotor is always opposed by the field on the stator

Image credit:
(1) Morai Motion, *Brushed vs Brushless DC Motors*, https://microlinearactuator.com/brushed-vs-brushless-dc-motors/

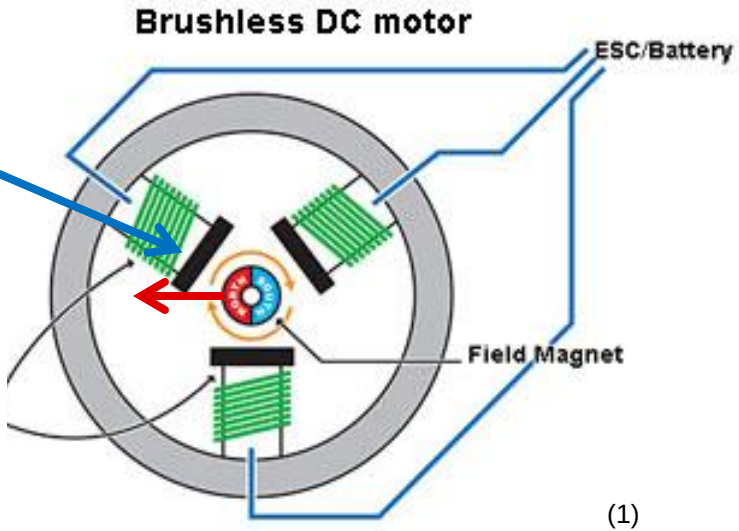
Motor operation



Rotation position defines the direction of current!

- Commutator reverses flow of current to make sure that the magnetic field generated on the rotor is always opposed by the field on the stator

Need to generate a South pole to attract the north pole on the stator



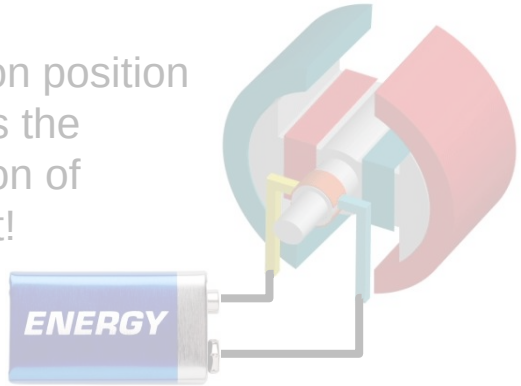
(1)

- Step 1: Figure out where the rotor is
- Step 2: Apply a magnetic field to move the rotor

Image credit:
(1) Morai Motion, *Brushed vs Brushless DC Motors*, https://microlinearactuator.com/brushed-vs-brushless-dc-motors/

Motor operation

Rotation position defines the direction of current!



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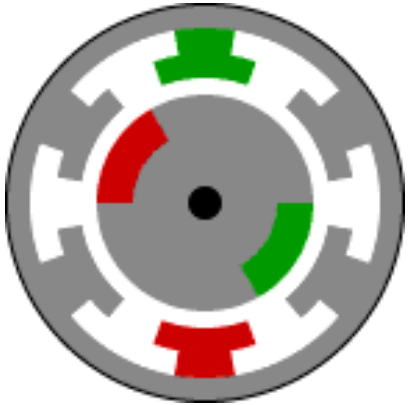
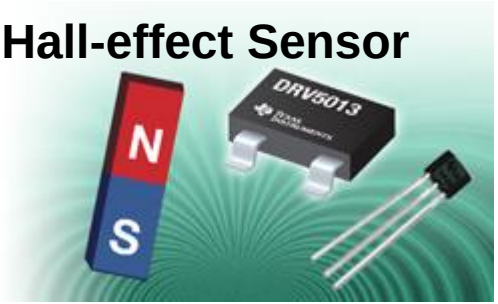


- Step 1: Figure out where the rotor is
- Step 2: Apply a magnetic field to move the rotor

Sensored brushless-DC motor control



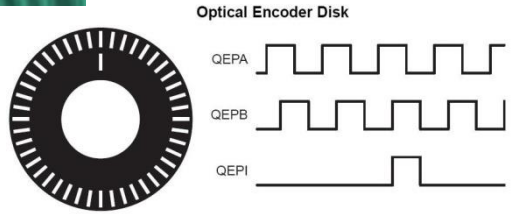
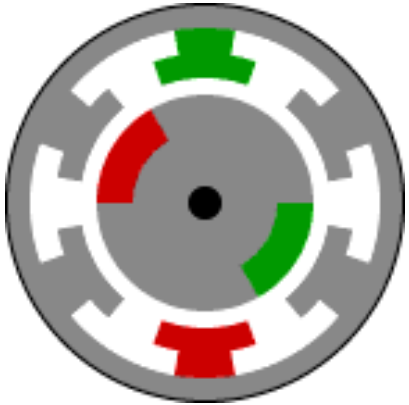


Figure out where the motor is through a position sensor



- Step 1: Figure out where the rotor is
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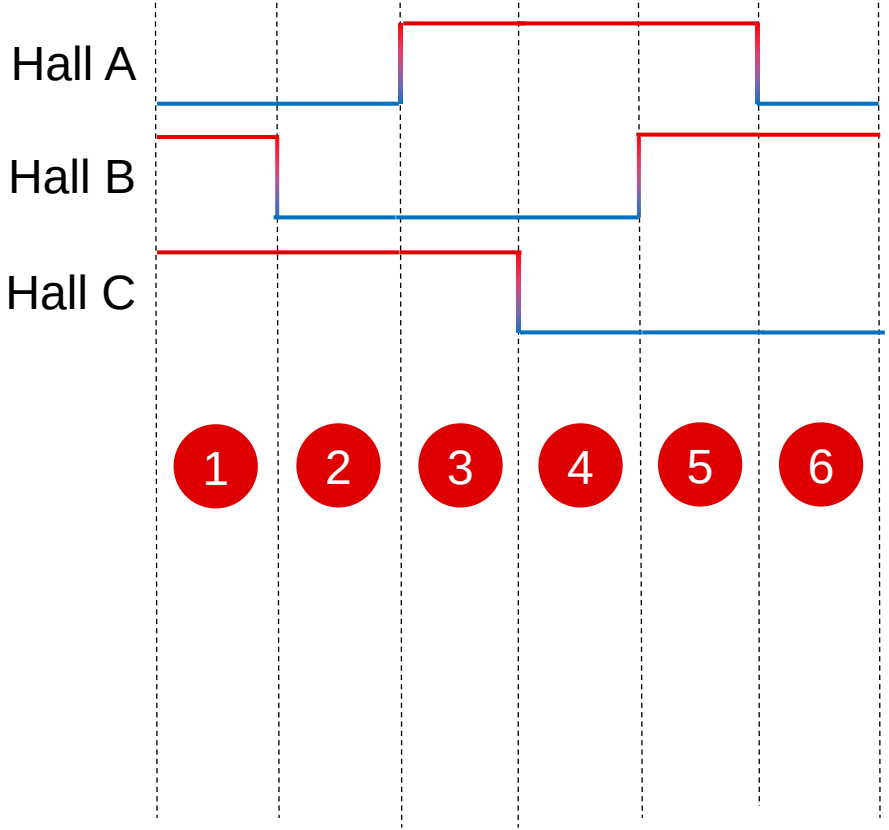
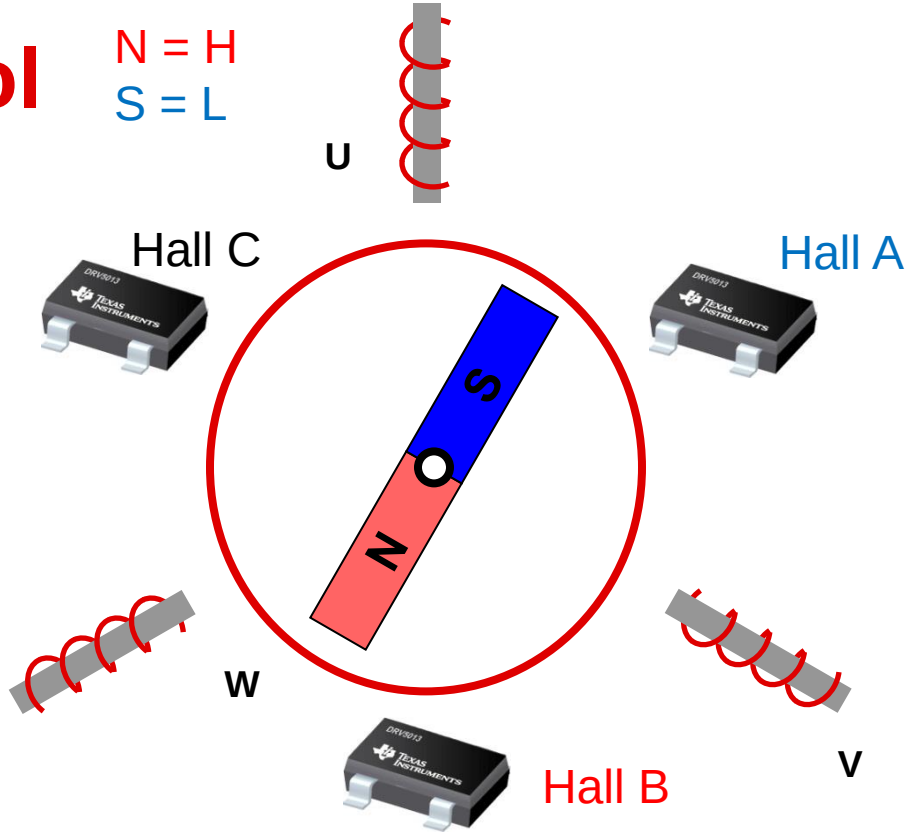
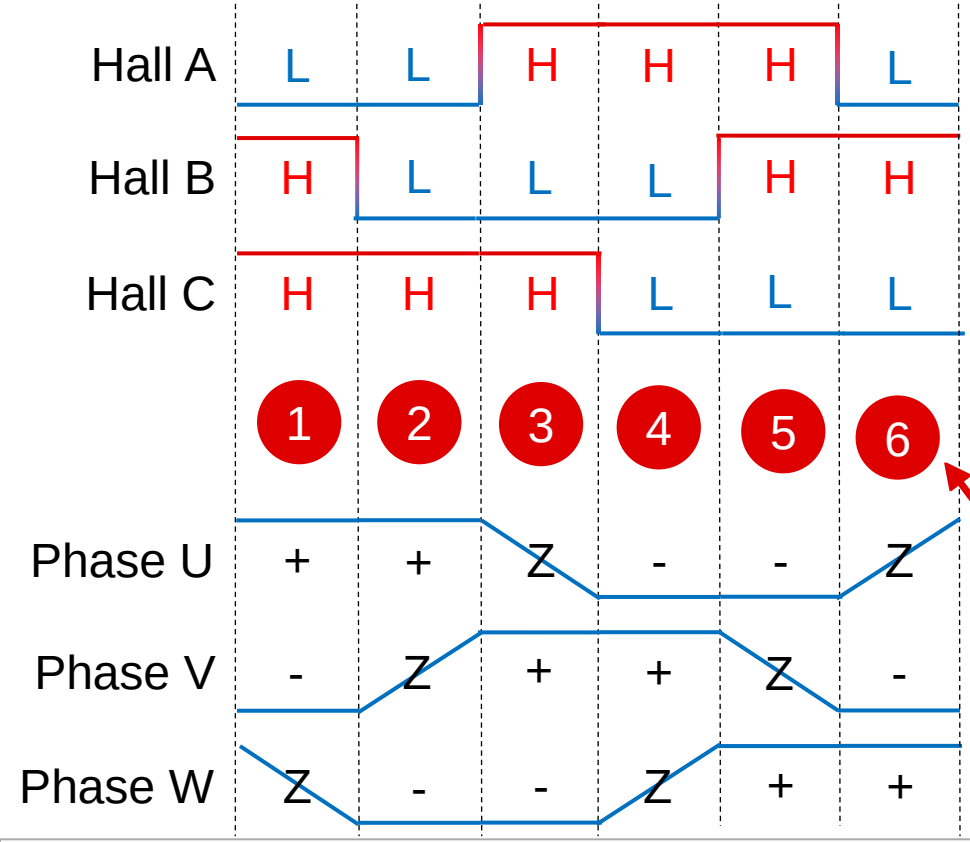
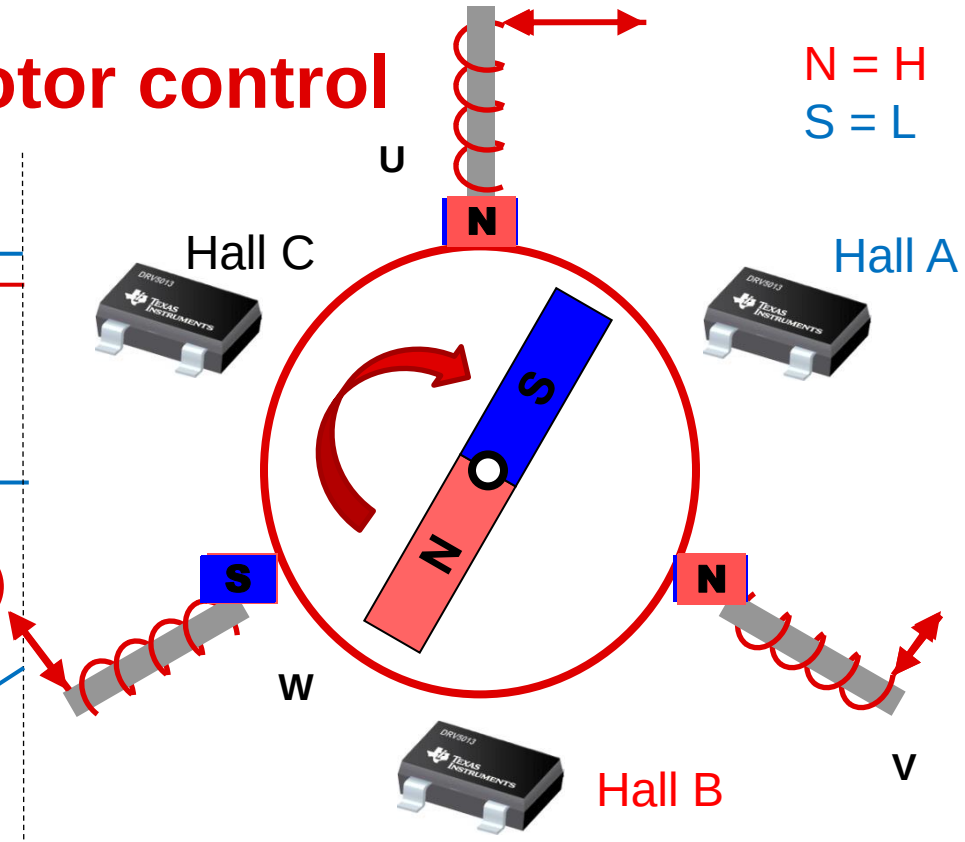
Sensored motor control





Sensored trapezoidal motor control





Trapezoidal control (Trap)

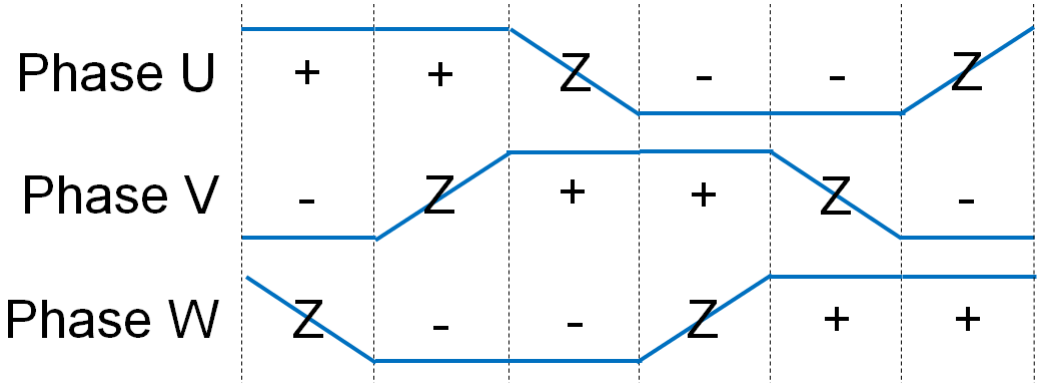
Also called: 6-step, block commutation, 120°, 150°

Advantages

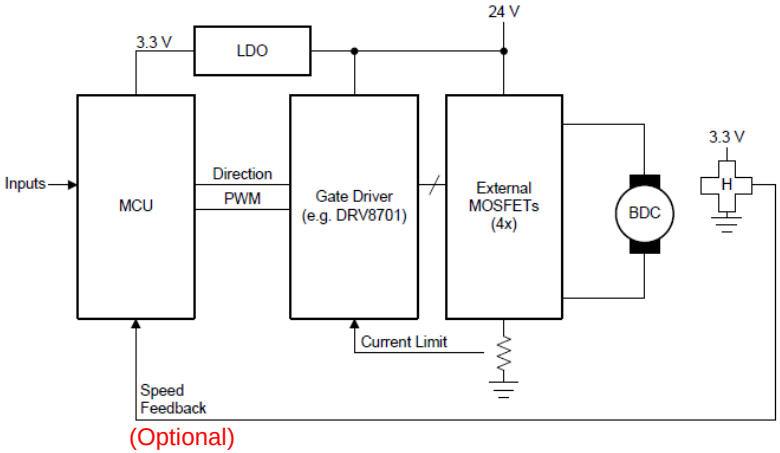
- Highest maximum speed
- Great for delivering maximum torque
- Lowest switching losses
- Easiest implementation

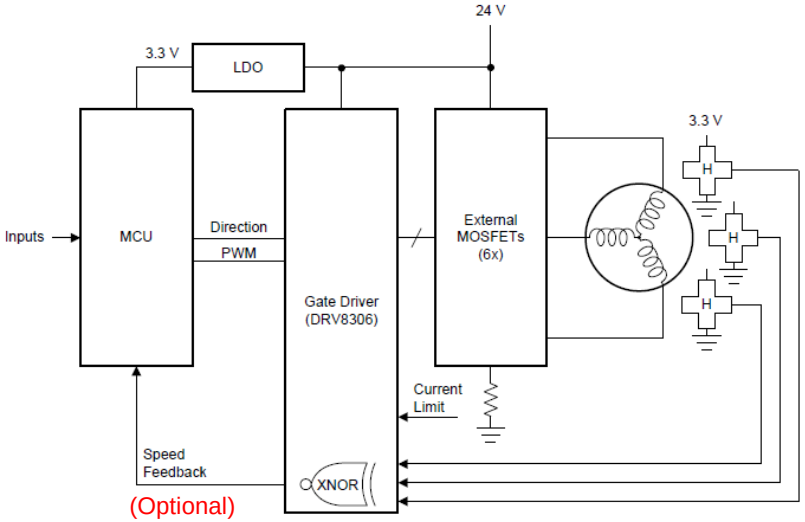
Disadvantages

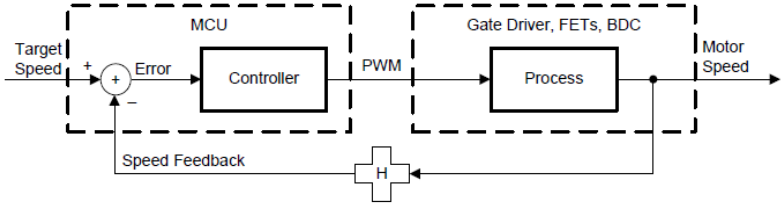
- Not great noise performance
- Efficiency not the best

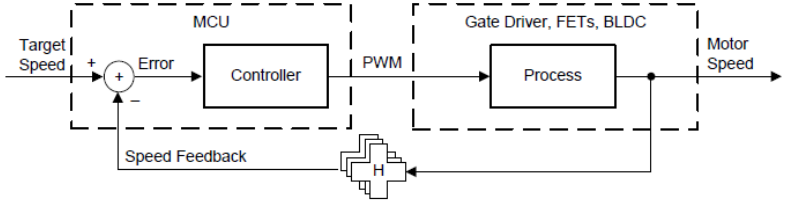


Brushed-DC vs. sensored brushless-DC









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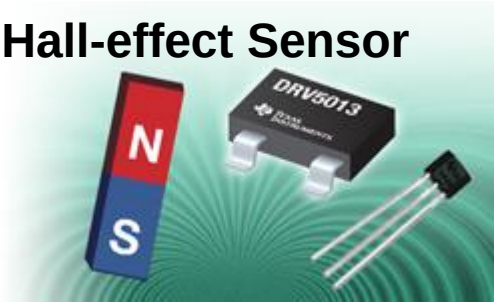
Sensored brushless-DC motor control



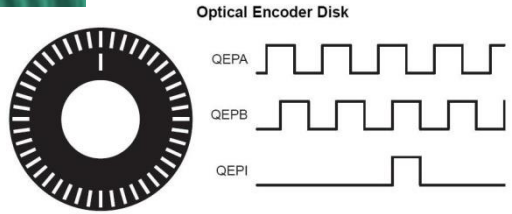
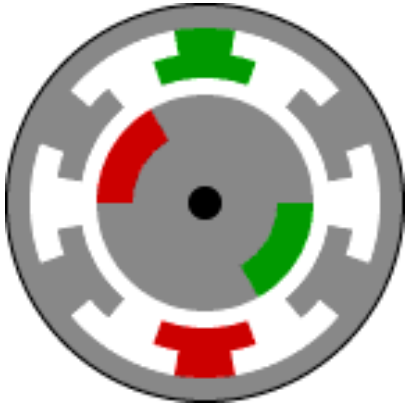


Figure out where the motor is through a position sensor

Disadvantage: increased cost



- Step 1: Figure out where the rotor is
- Step 2: apply a magnetic field to move the rotor

Sensorless brushless-DC motor control

Back-EMF

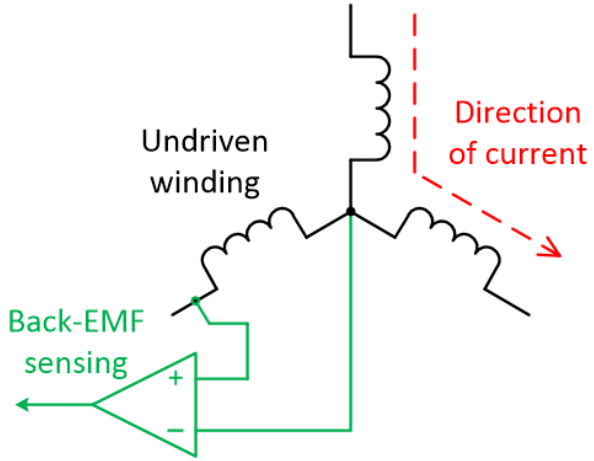
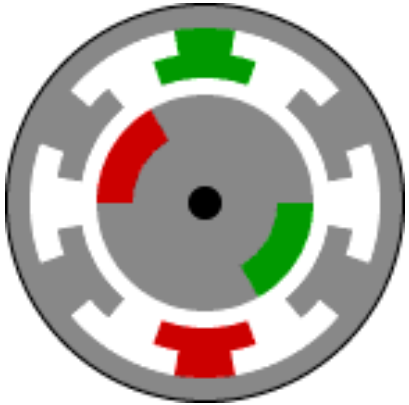


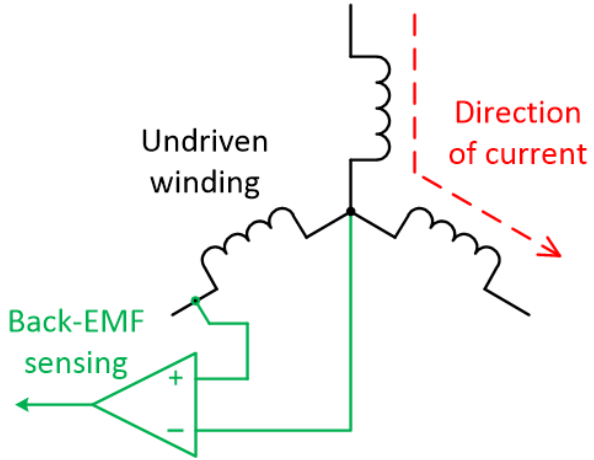
Figure out where the motor is through Back-EMF



- Step 1: Figure out where the rotor is
- Step 2: apply a magnetic field to move the rotor

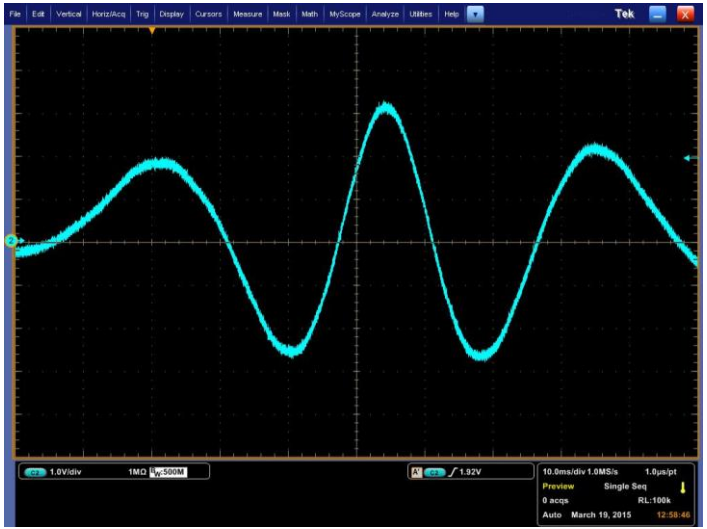
What is Back-EMF?

Back-EMF

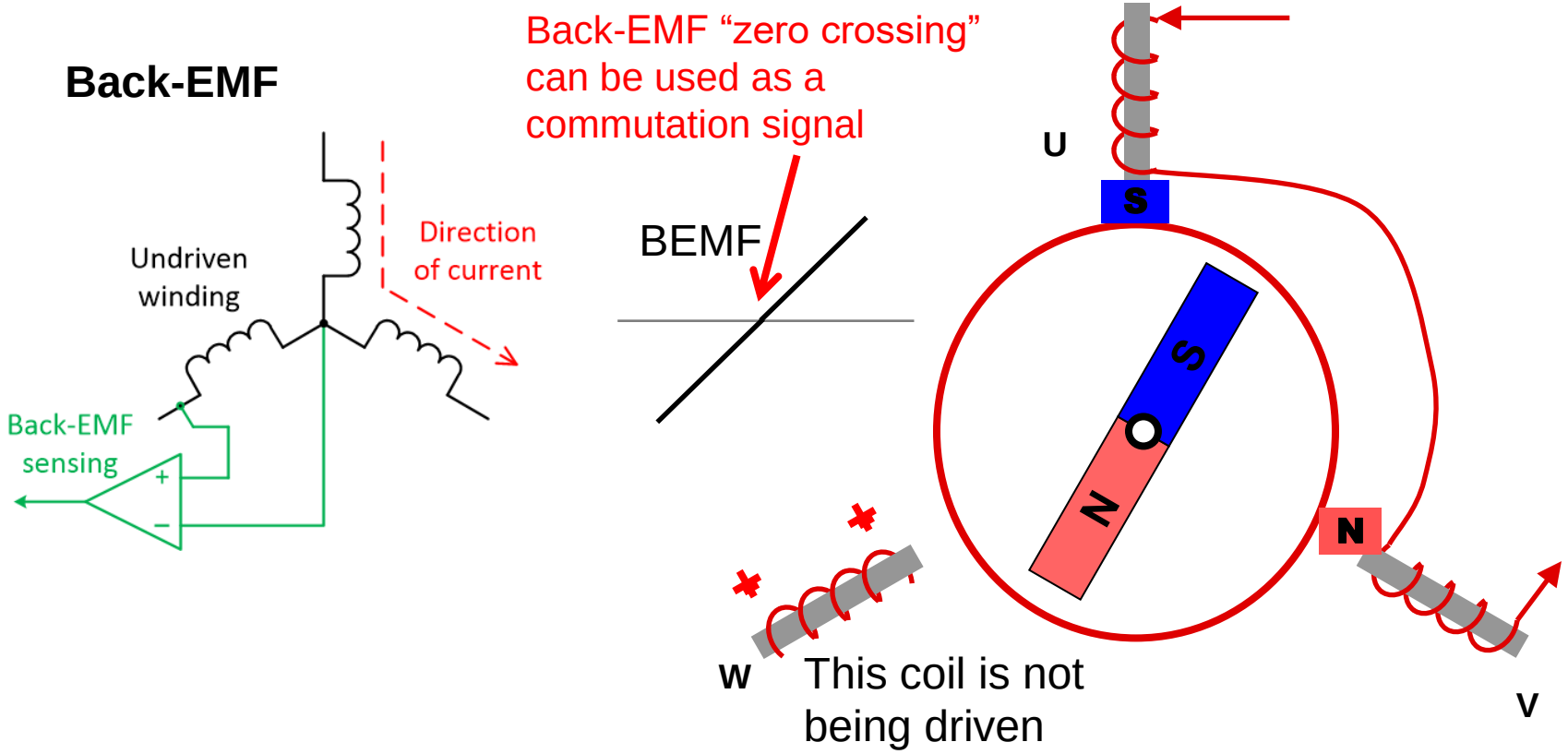


Back-EMF is a sinusoidal or trapezoidal voltage generated on the motor while it is spinning

Spin the motor with your fingers to create a back-EMF signal

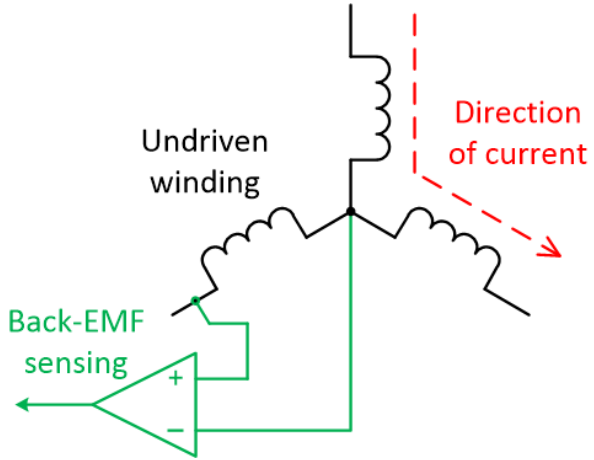


Sensorless brushless-DC motor control



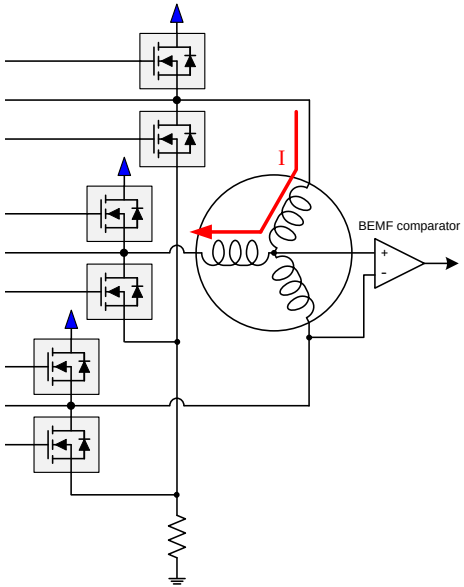
Sensorless brushless-DC motor control

Back-EMF



Detecting Back-EMF:

1) Measurement



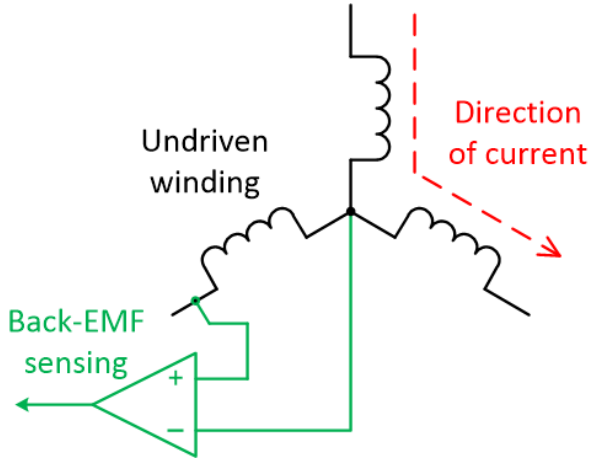
Advantage: Simplicity

Disadvantage: Performance, need to have open window on phase to measure

Back-EMF measurement does not allow for sinusoidal or FOC control

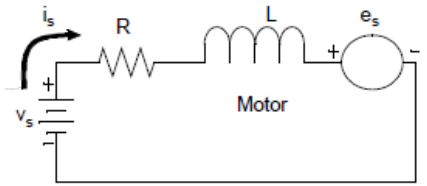
Sensorless brushless-DC motor control

Back-EMF



Detecting Back-EMF:

2) Estimation & Calculation



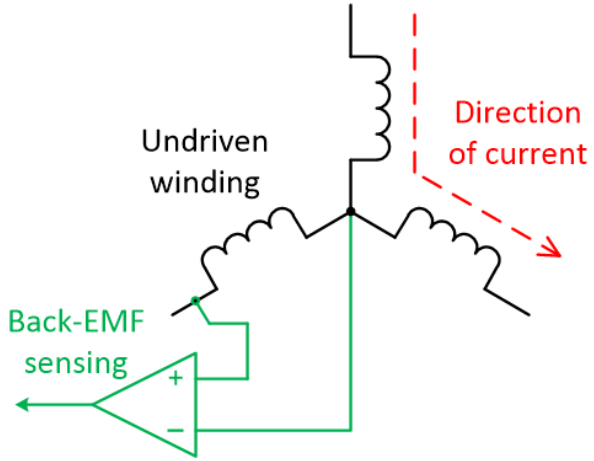
$$v_s = Ri_s + L\frac{d}{dt}i_s + e_s$$

Advantage: Performance, can achieve sine/FOC

Disadvantage: Complexity, calculation, need to know motor parameters

Disadvantages of sensorless?

Back-EMF



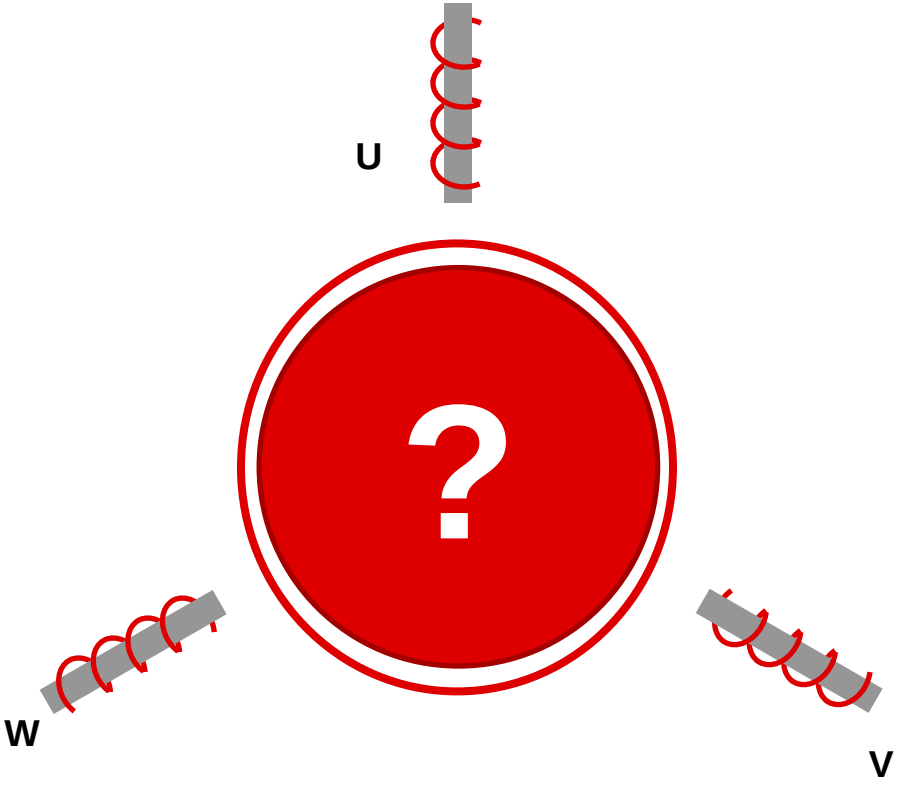
Where is Back-EMF (sensorless techniques) not going to work?

Applications that require torque at zero speed

Servo applications → always sensored!

How do we start a motor sensorlessly*?

*not a real word, but it should be



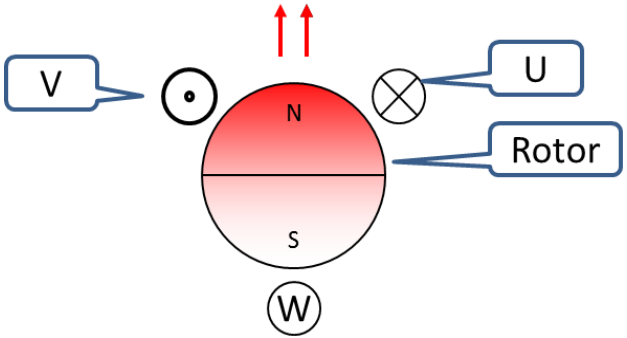
Starting a motor:

- We need to figure out where the rotor is so that we can apply a magnetic field to move it

How do we start a motor sensorlessly*?

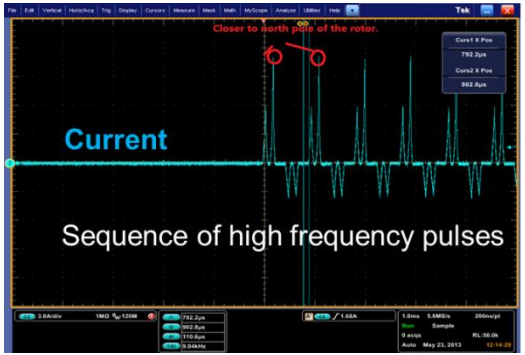
*not a real word, but it should be

Align / Blind Start



- Force a magnetic field on the motor, the motor will align to this field
- The motor may spin backwards

Initial Position / Speed Detect



- Measure position through high frequency pulses or speed through back-EMF detection
- Drive motor given initial condition

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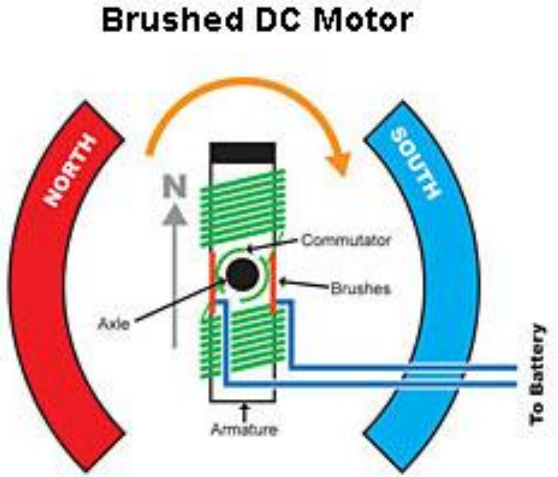
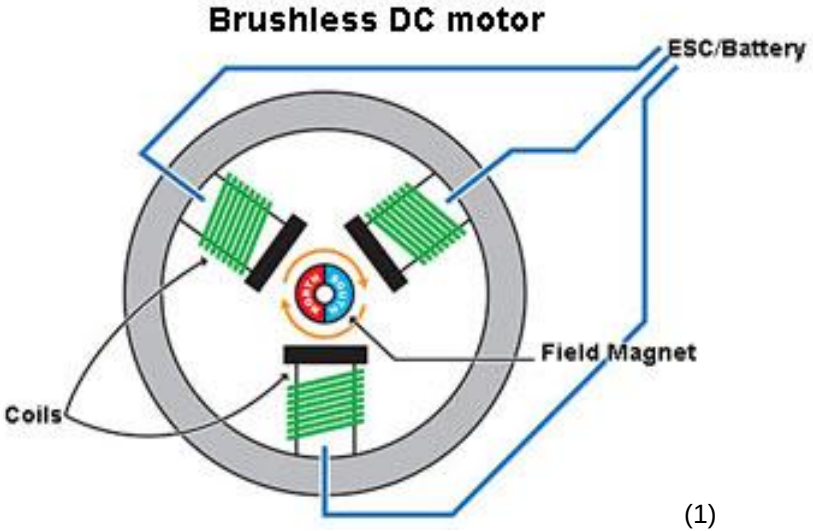
Motor performance





(1)

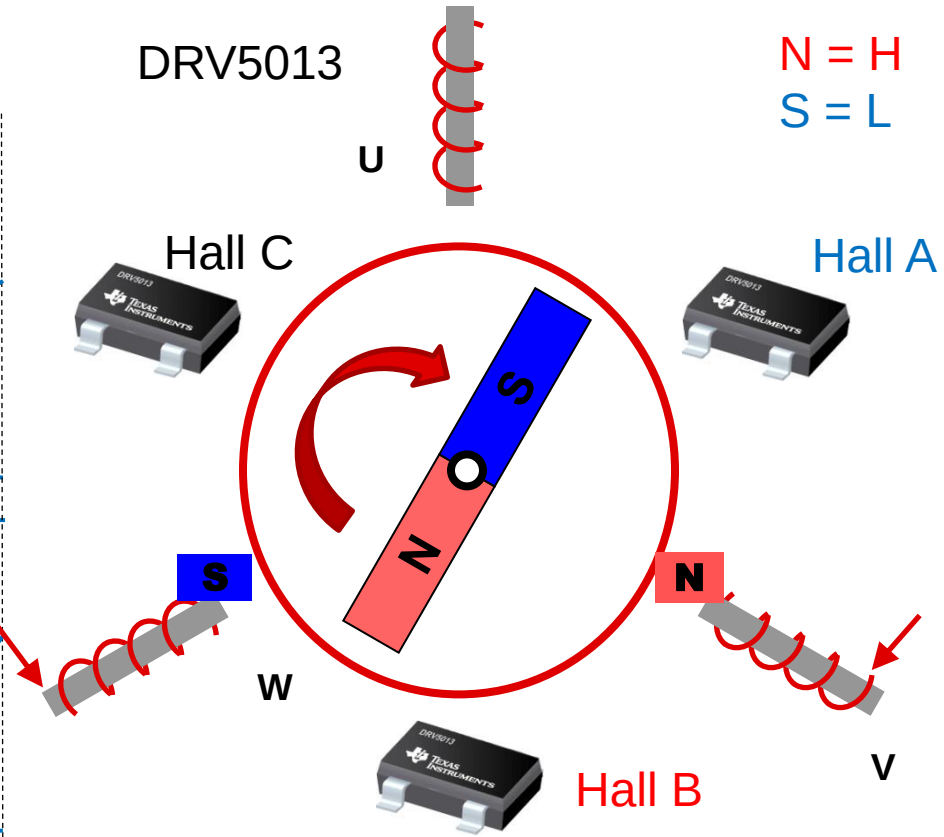
- Commutation is mechanical
- Can’t adjust drive method beyond 100% ON/OFF

- Commutation is electrical
- Can drive motor with trapezoidal (100% ON/OFF) or a smoother sinusoidal waveform

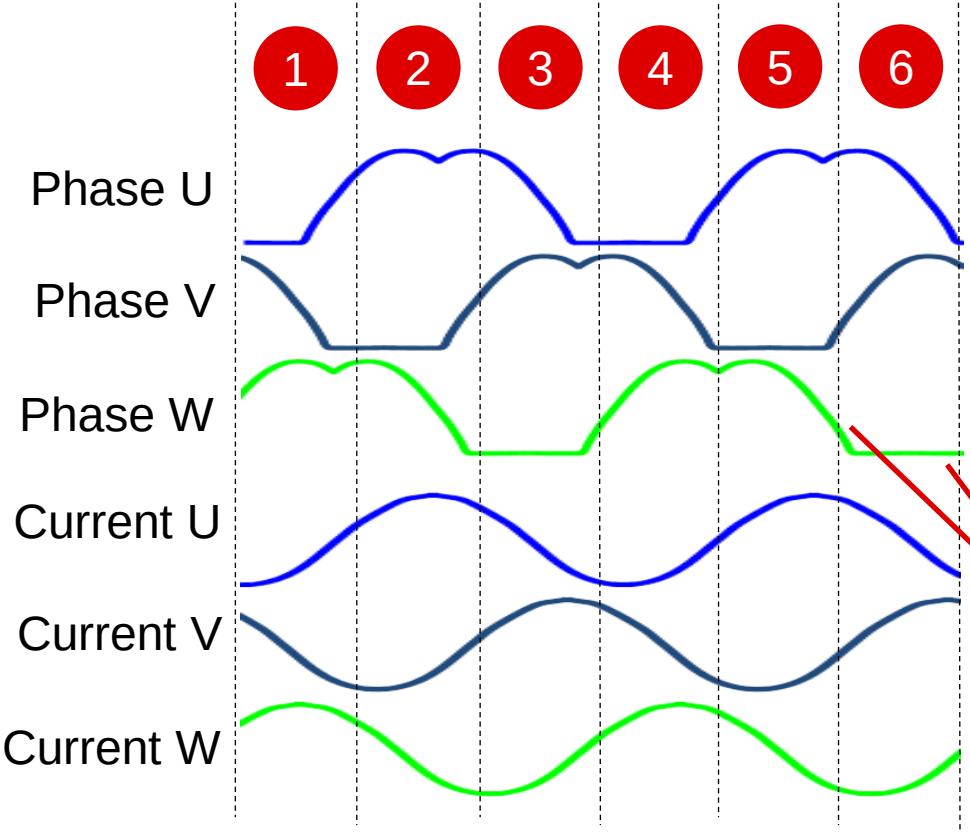
Image credit:
(1) Morai Motion, *Brushed vs Brushless DC Motors*, https://microlinearactuator.com/brushed-vs-brushless-dc-motors/

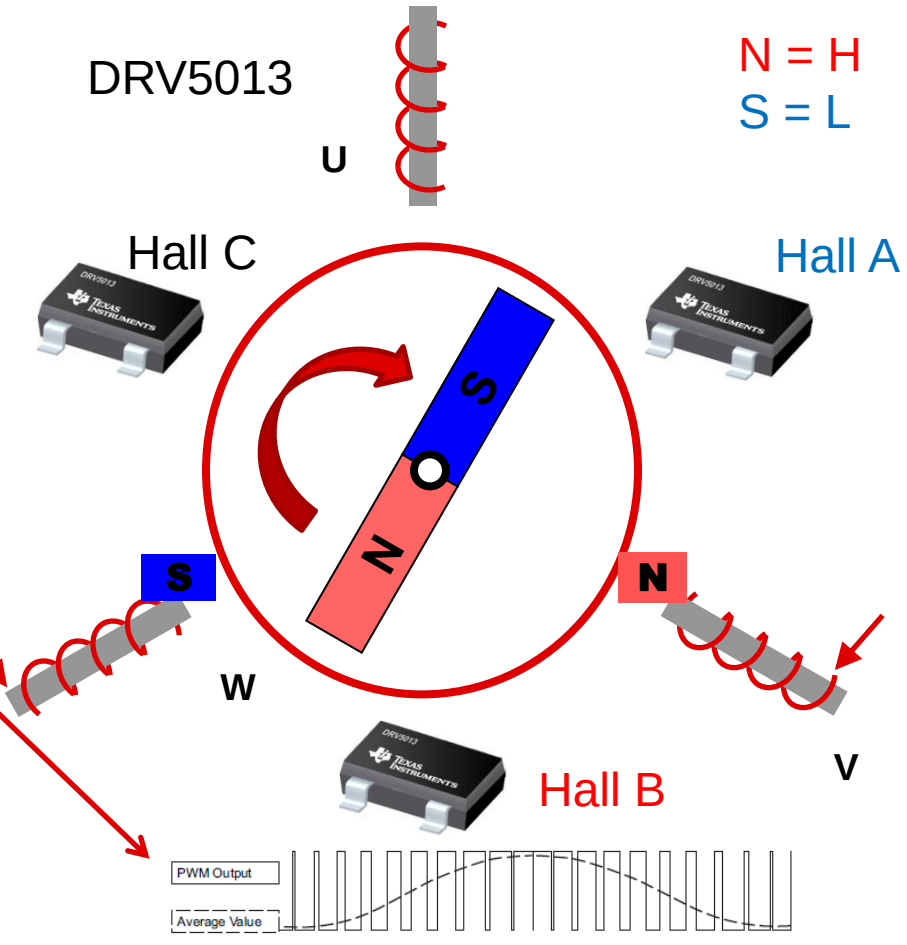
Sensored trapezoidal

	1	2	3	4	5	6
Phase U	+	+	Z	-	-	Z
Phase V	-	Z	+	+	Z	-
Phase W	Z	-	-	Z	+	+
Current U	+	+	Z	-	-	Z
Current V	-	Z	+	+	Z	-
Current W	Z	-	-	Z	+	+



Sensored sinusoidal





Sinusoidal control (Sine)

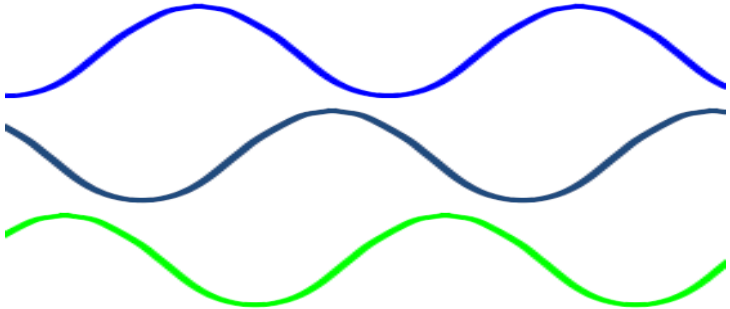
Also called: 180° - *always ask if your sine control is really 180°!*

Advantages

- Low noise
- Easier to implement than FOC

Disadvantages

- Switching losses
- Not great dynamic load performance
- Lower maximum speed



Field-oriented control (FOC)

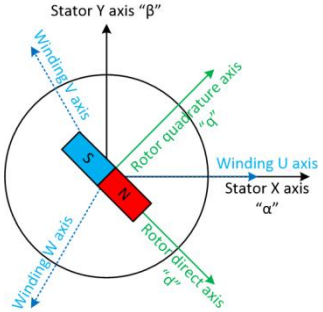
Also called: vector control, “why is this so complicated”

Advantages

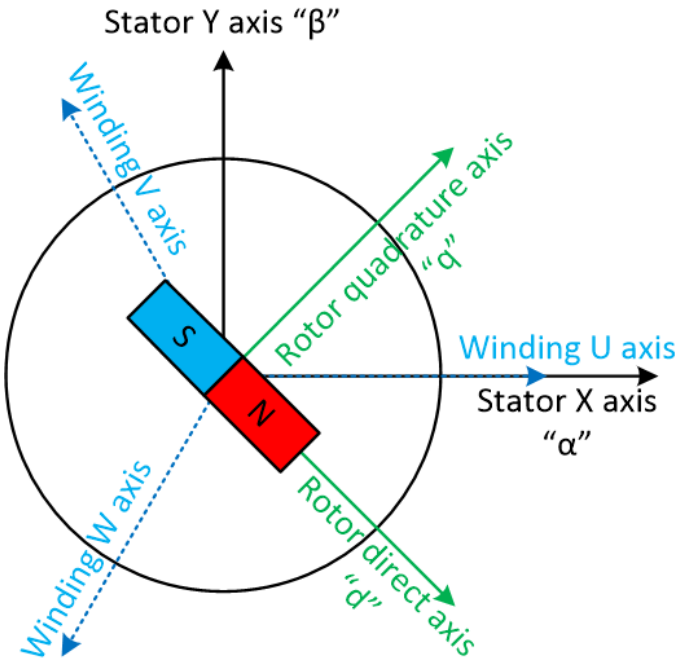
- Highest power output
- Lowest noise
- Best torque ripple
- High motor speed (field weakening)
- Maximum motor efficiency (MTPA)

Disadvantages

- Computation complexity (especially when sensorless)
- Coding experience needed
- Switching losses



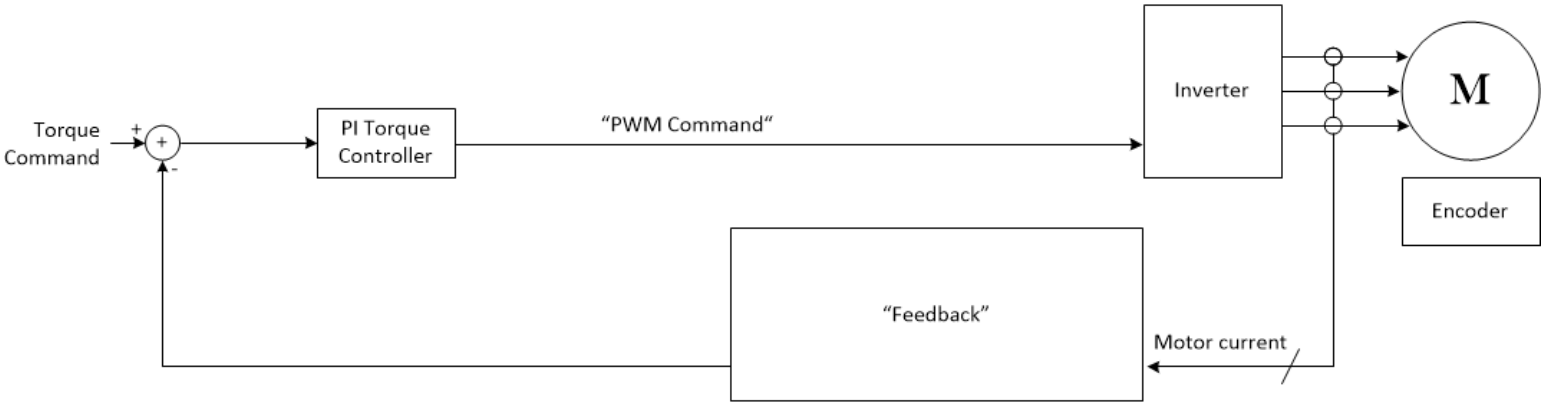
Field-oriented control (FOC)



FOC applies all motor torque perpendicular to the rotor

Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor



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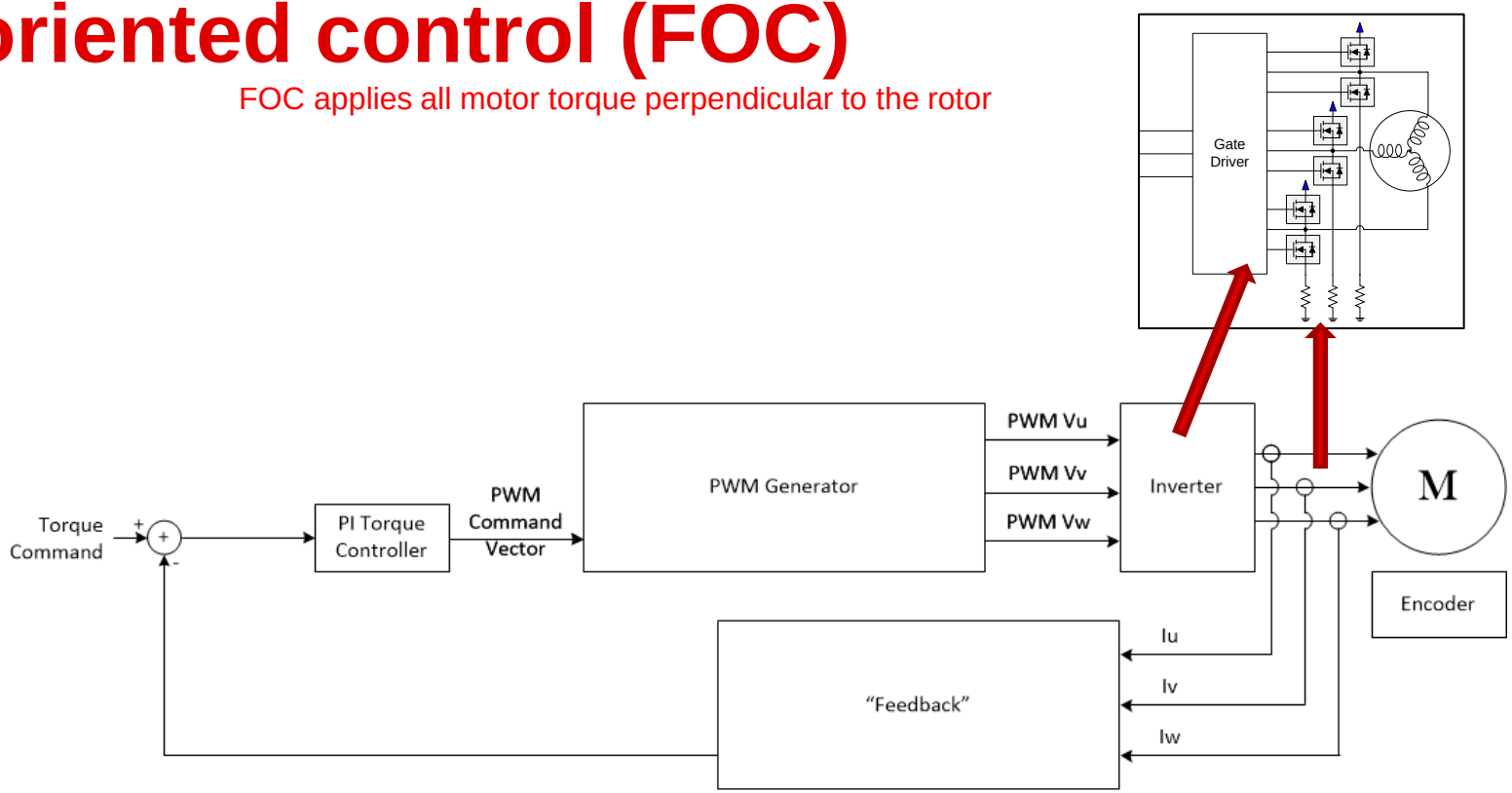

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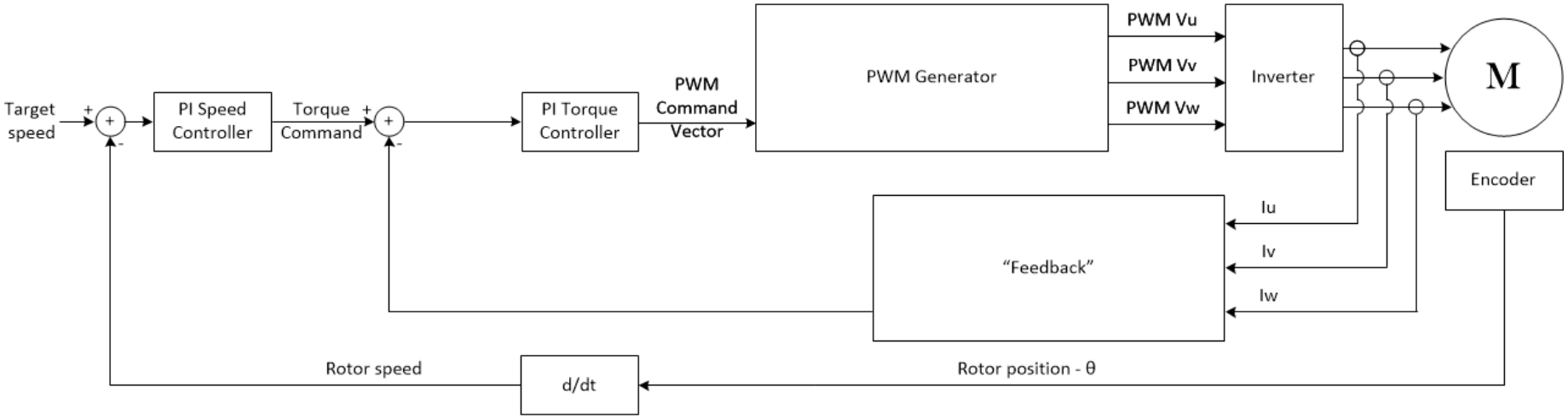

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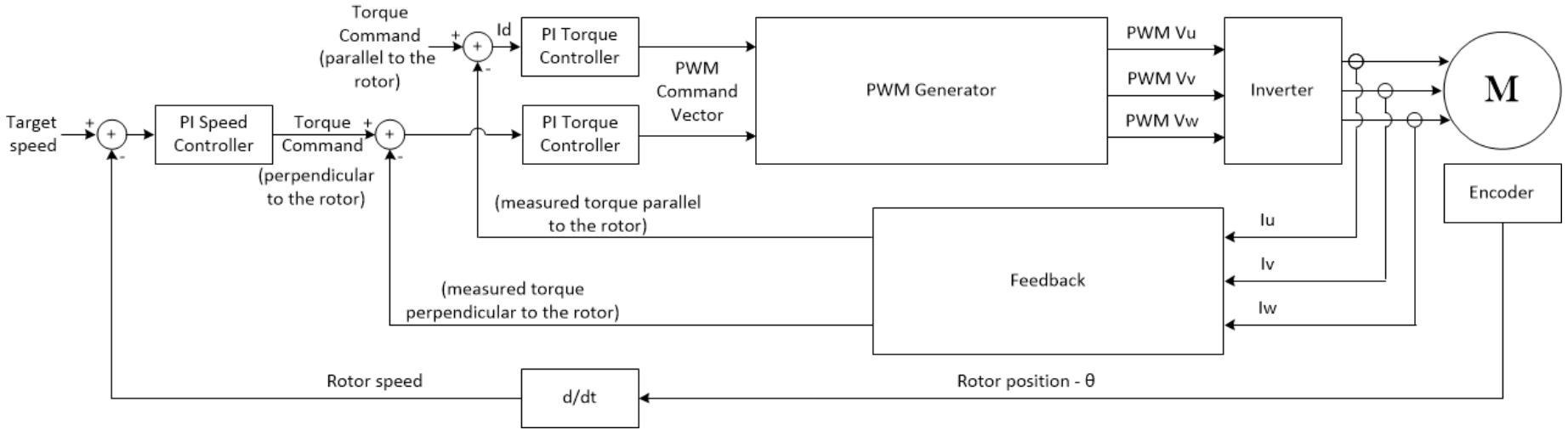

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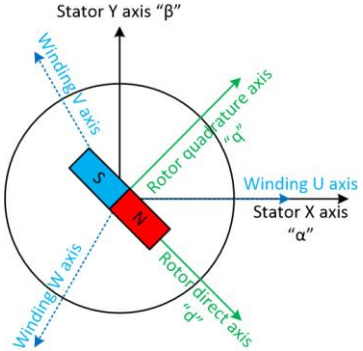

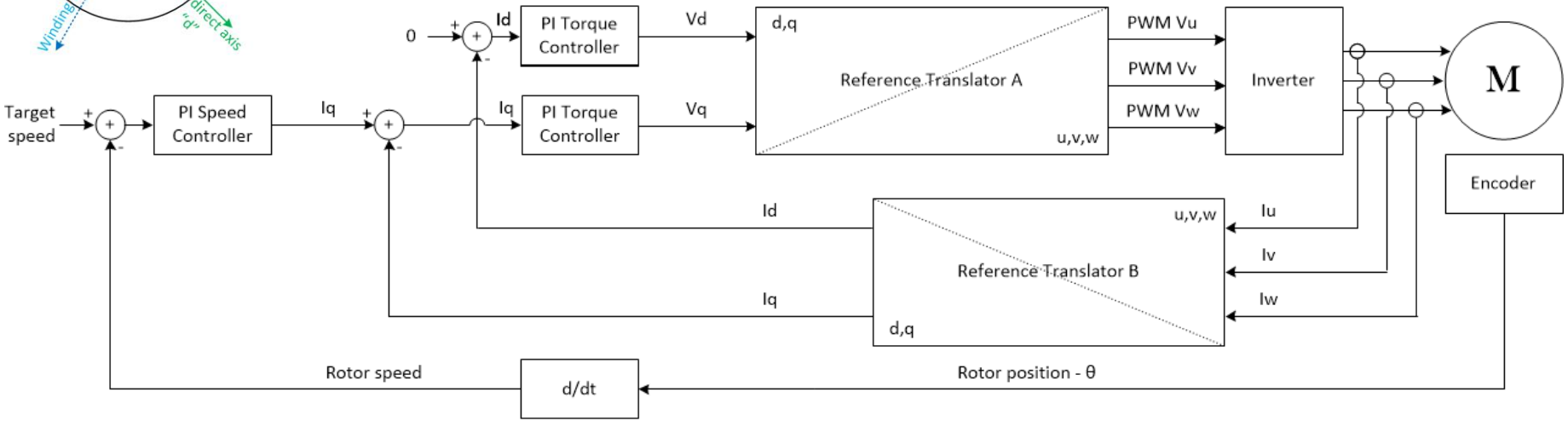

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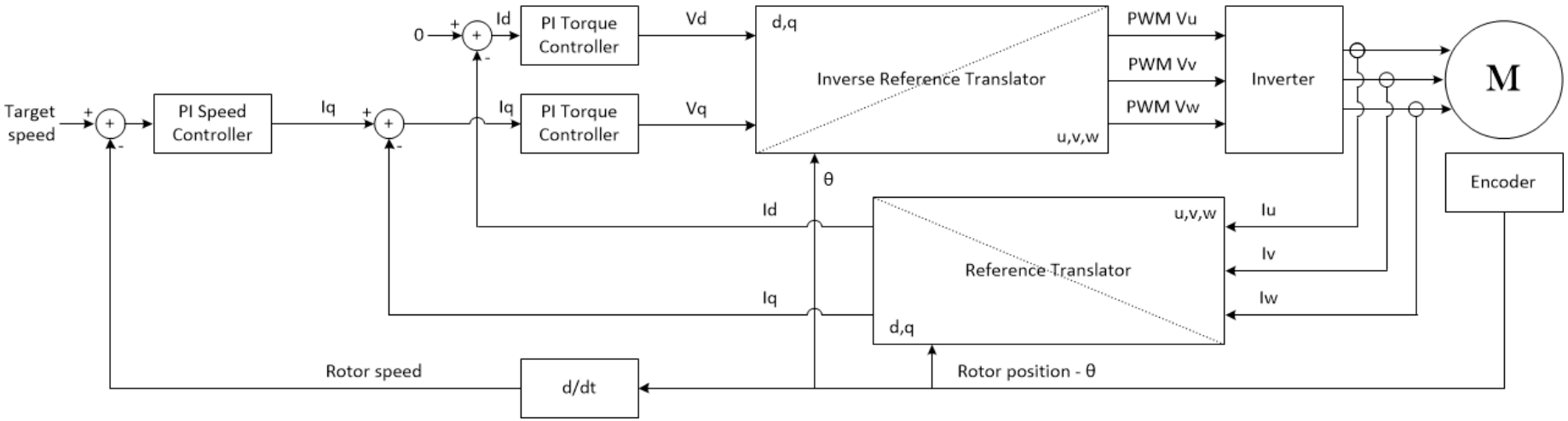

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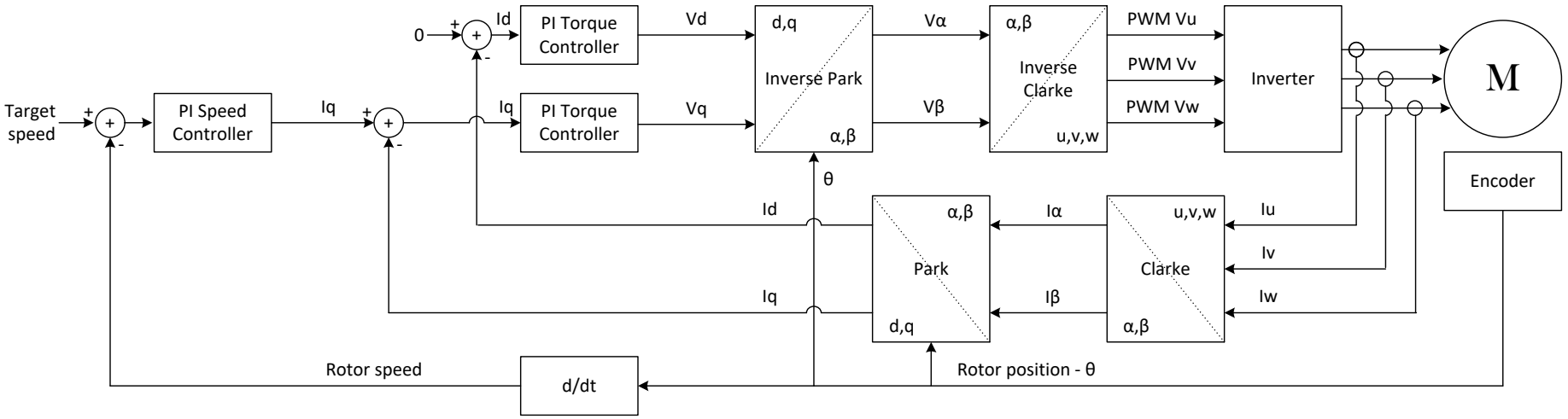
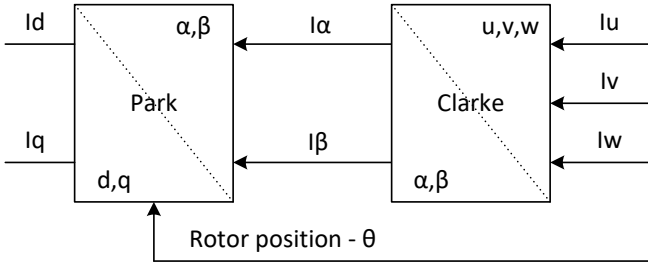
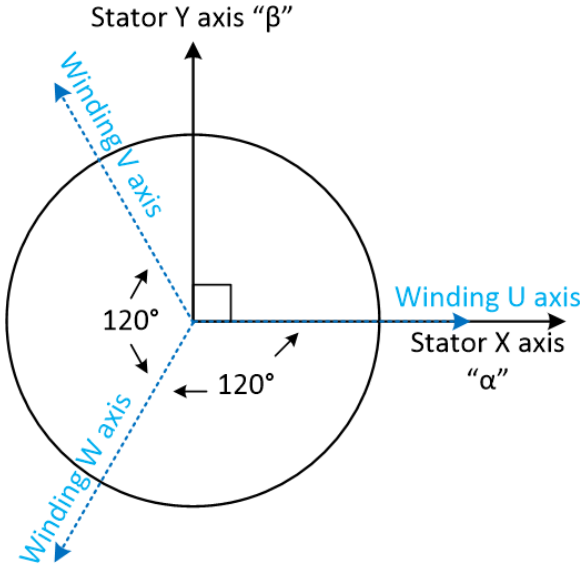


Clarke transform





$$\alpha = U + V_\alpha + W_\alpha$$

$$\alpha = U + V\cos 120° + W\cos 240°$$

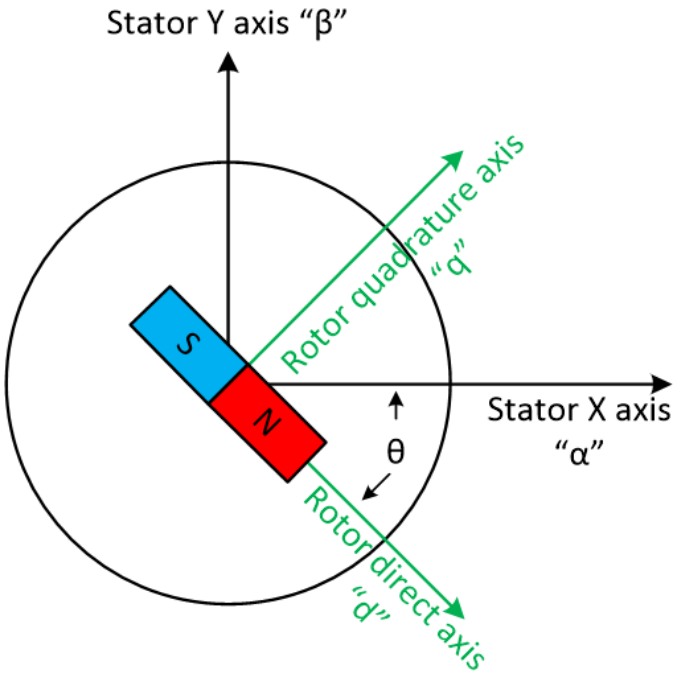
$$\alpha = U - \frac{1}{2}V - \frac{1}{2}W$$

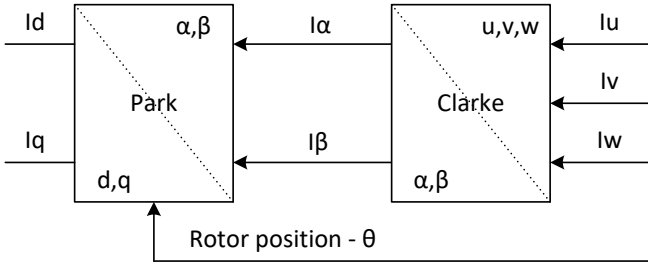
$$\beta = V_\beta + W_\beta$$

$$\beta = V\sin 120° + W\sin 240°$$

$$\beta = \frac{\sqrt{3}}{2}V - \frac{\sqrt{3}}{2}W$$

Park transform



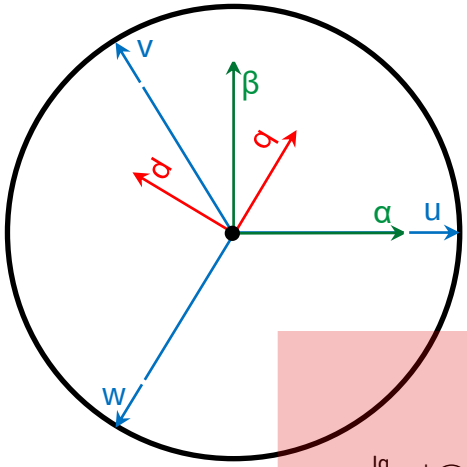


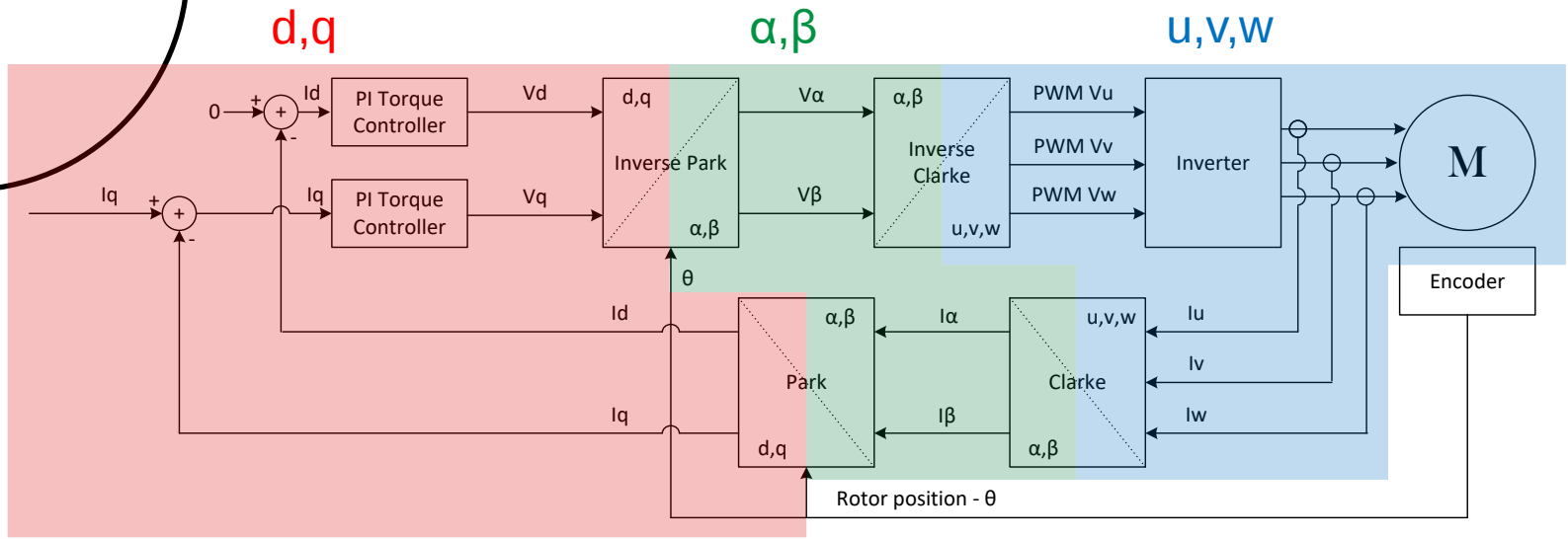
$$\mathrm{d} = \alpha_d + \beta_d$$
$$\mathrm{d} = \alpha\cos\theta + \beta\sin\theta$$

$$q = \alpha_q + \beta_q$$
$$q = -\alpha\sin\theta + q\cos\theta$$

Field-oriented control (FOC)

FOC applies all motor torque perpendicular to the rotor





Agenda

- Introduction
- BLDC motor basics
- Basic commutation (trap)
- Sensored & sensorless
- Advanced commutation (Sine & FOC)
- Summary

Summary

- Think of a brushless-DC motors like a brushed-DC motor without the brushes
  - Brushed-DC motor: mechanical commutation, brushless-DC motor: electrical commutation

- Sensored versus sensorless
  - Sensored requires additional components but control is easier
  - Sensorless requires fewer components but control is harder
  - Don’t ask to do a sensorless servo

- Comparison of commutation methods (Trap, Sine, FOC)

	Implementation	Switching Loss	Audible Noise	Comments
Trap	Easy look-up table	Low	High	Best for high torque or high speed
Sine	Complex look-up table	High	Low	Not the best for dynamic torque
FOC	Complex real-time calculation	High	Lowest	Highest efficiency, dynamics

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