lecture X - MOTORS 101

How does a motor spin? And how do we *design circuits* that can make them spin using PCBs?

Outline for Today

- Modeling motors (4-magnet model)
- Brushed vs brushless motors
- Circuit model of a motor, brushed + brushless models
- 3-coil version of BLDC motors
- Field-Oriented Control (visually), Clarke+Park transforms

(Our goal is to teach you Field-Oriented Control today which is a technique for controlling three-phase, brushless motors)

Designing a Motor Controller.

https://dspace.mit.edu/handle/1721.1/118671

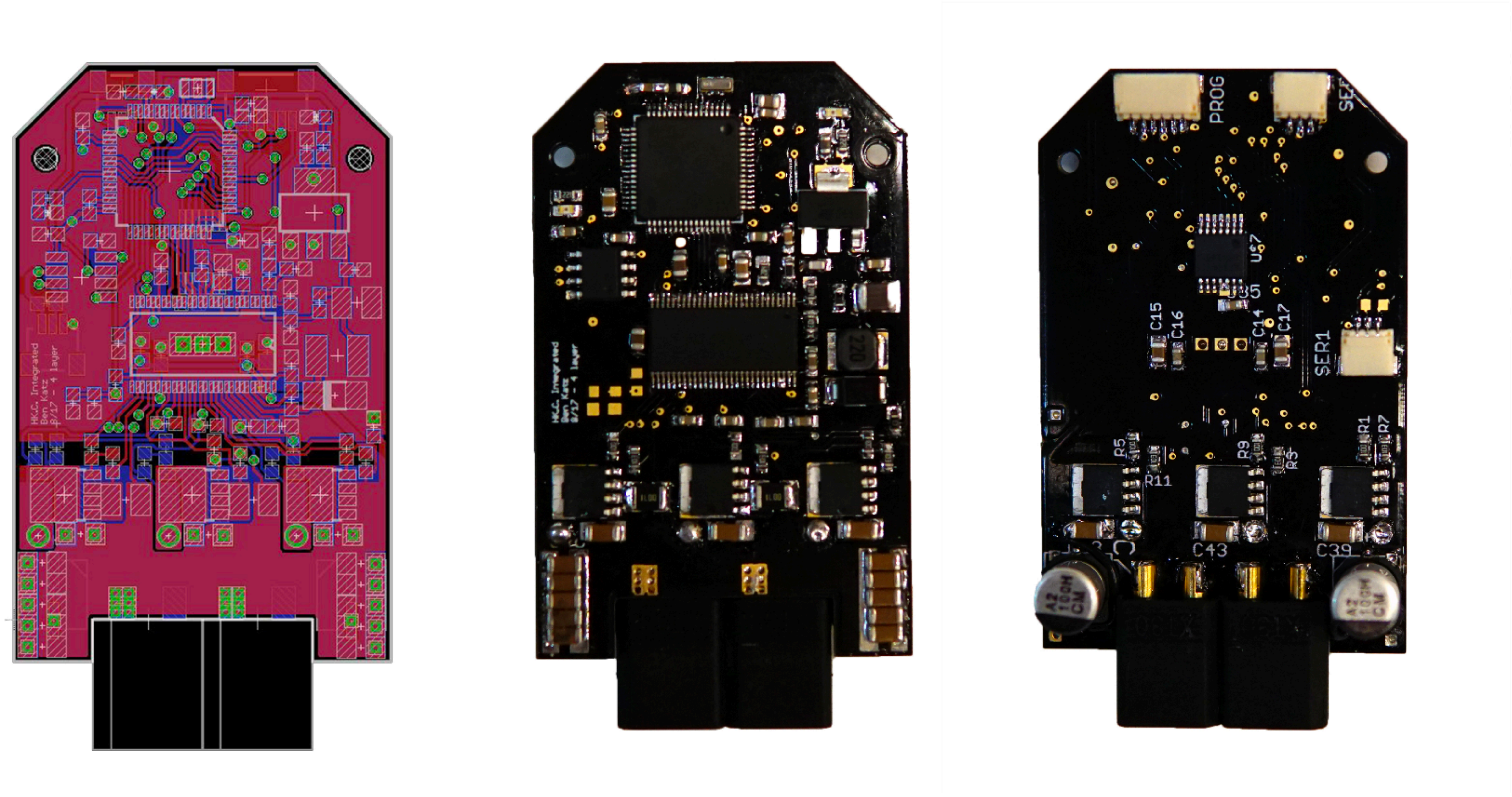
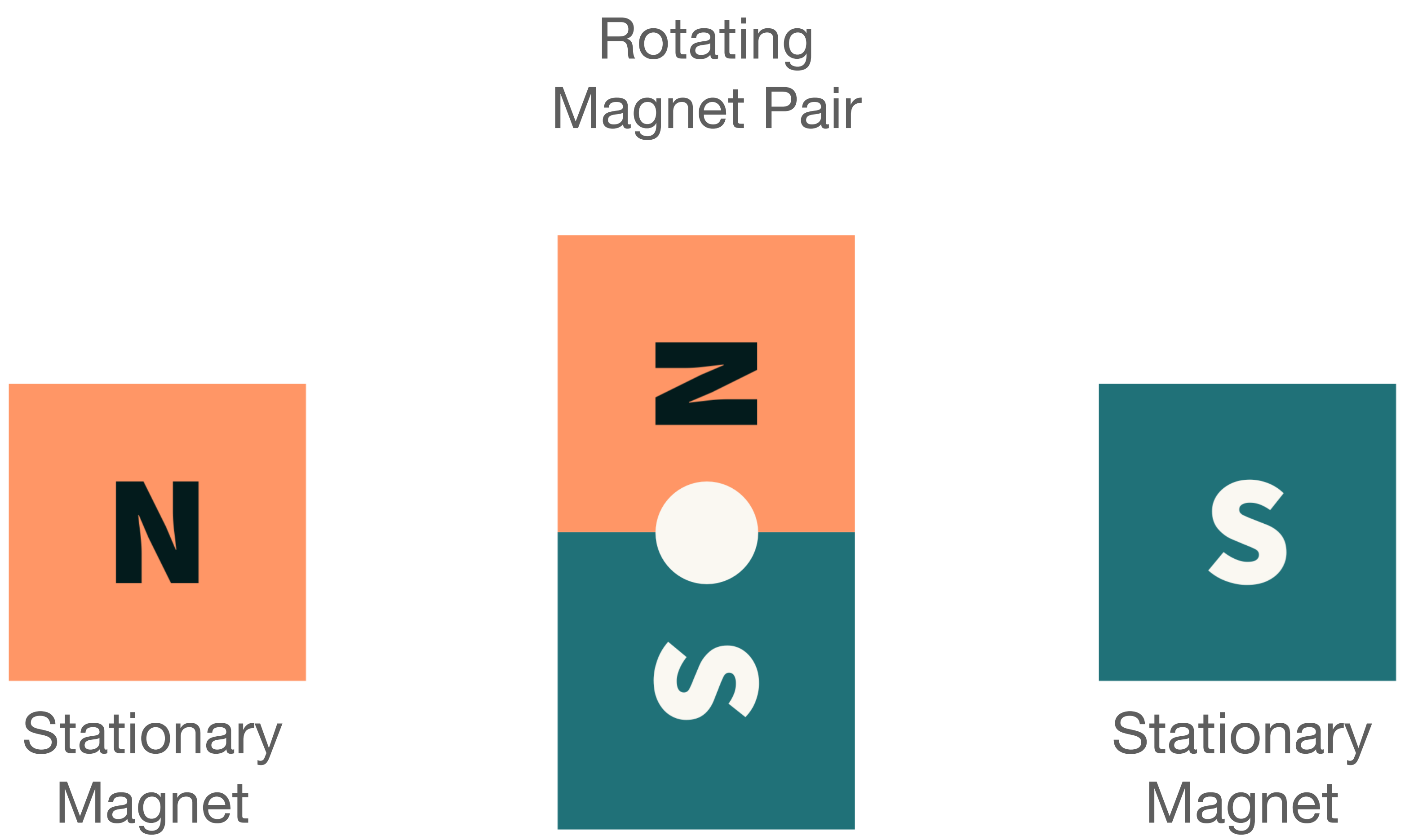


Figure 2-10: PCB layout, front, and back of the inverter.

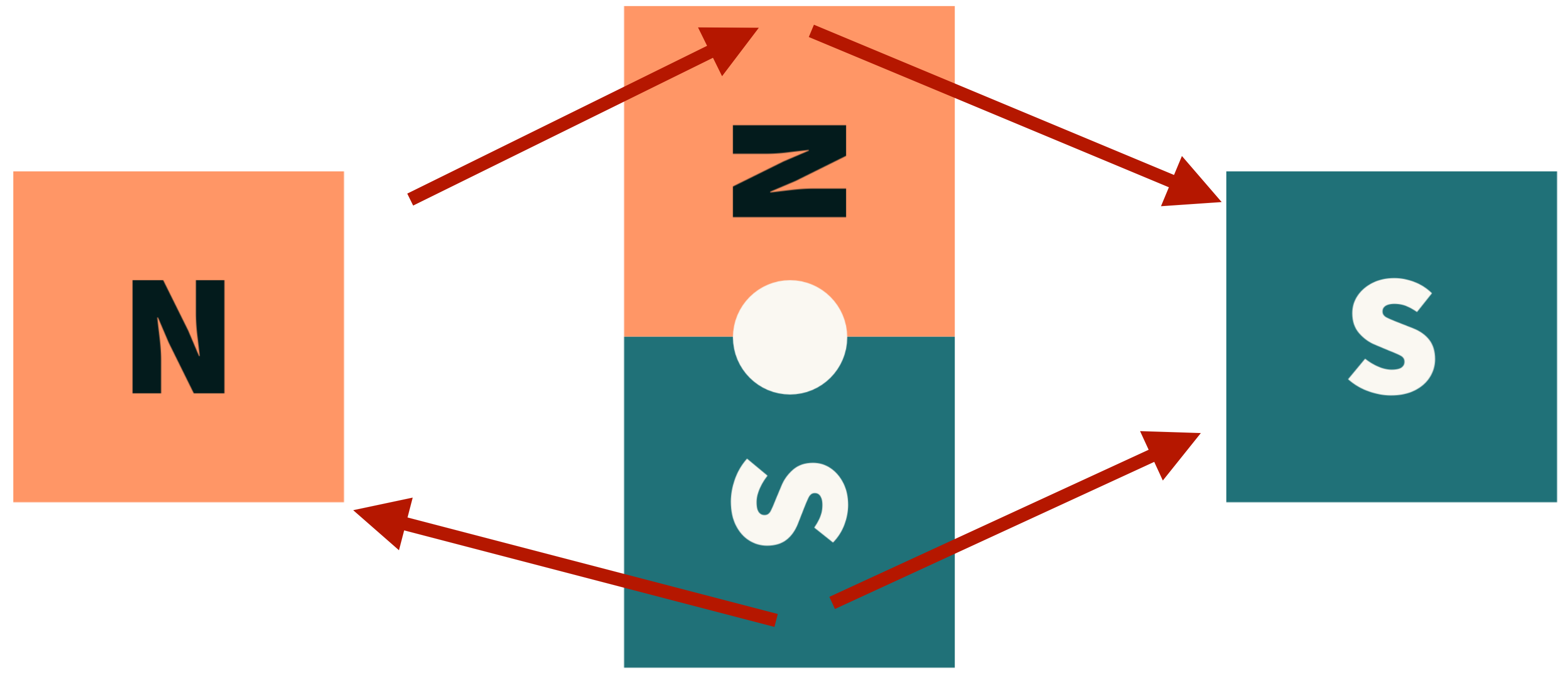
https://dspace.mit.edu/handle/1721.1/118671

DEMOS!!!

4-magnet model of a motor

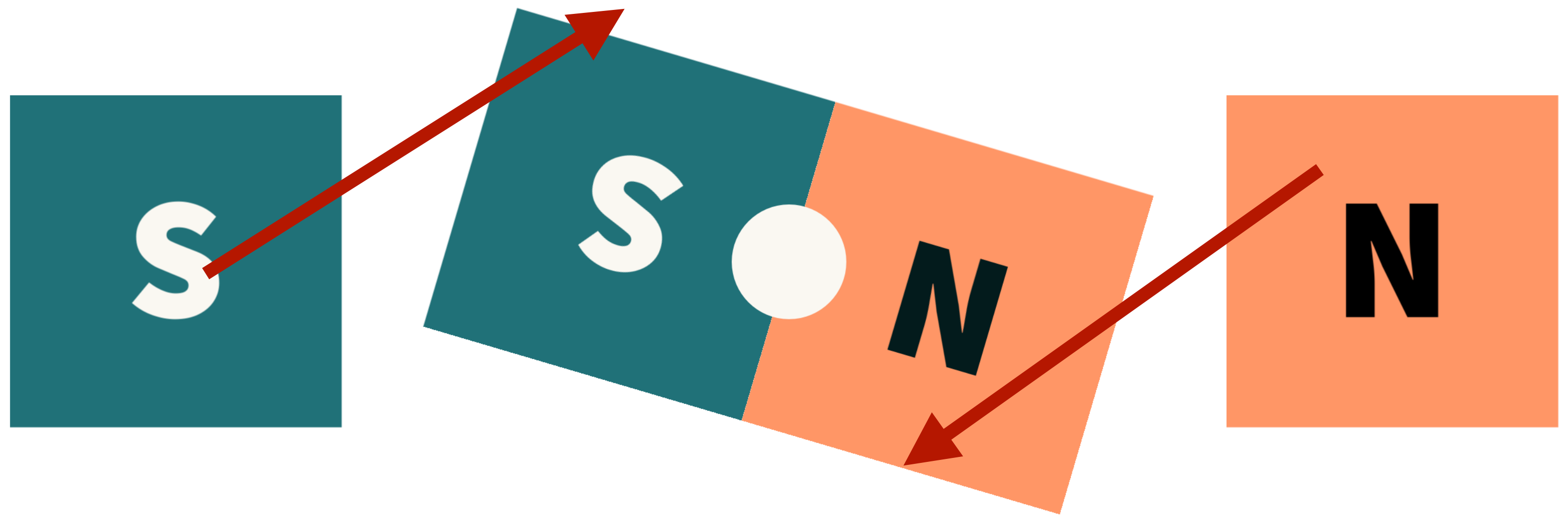


Forces between magnets produces a torque



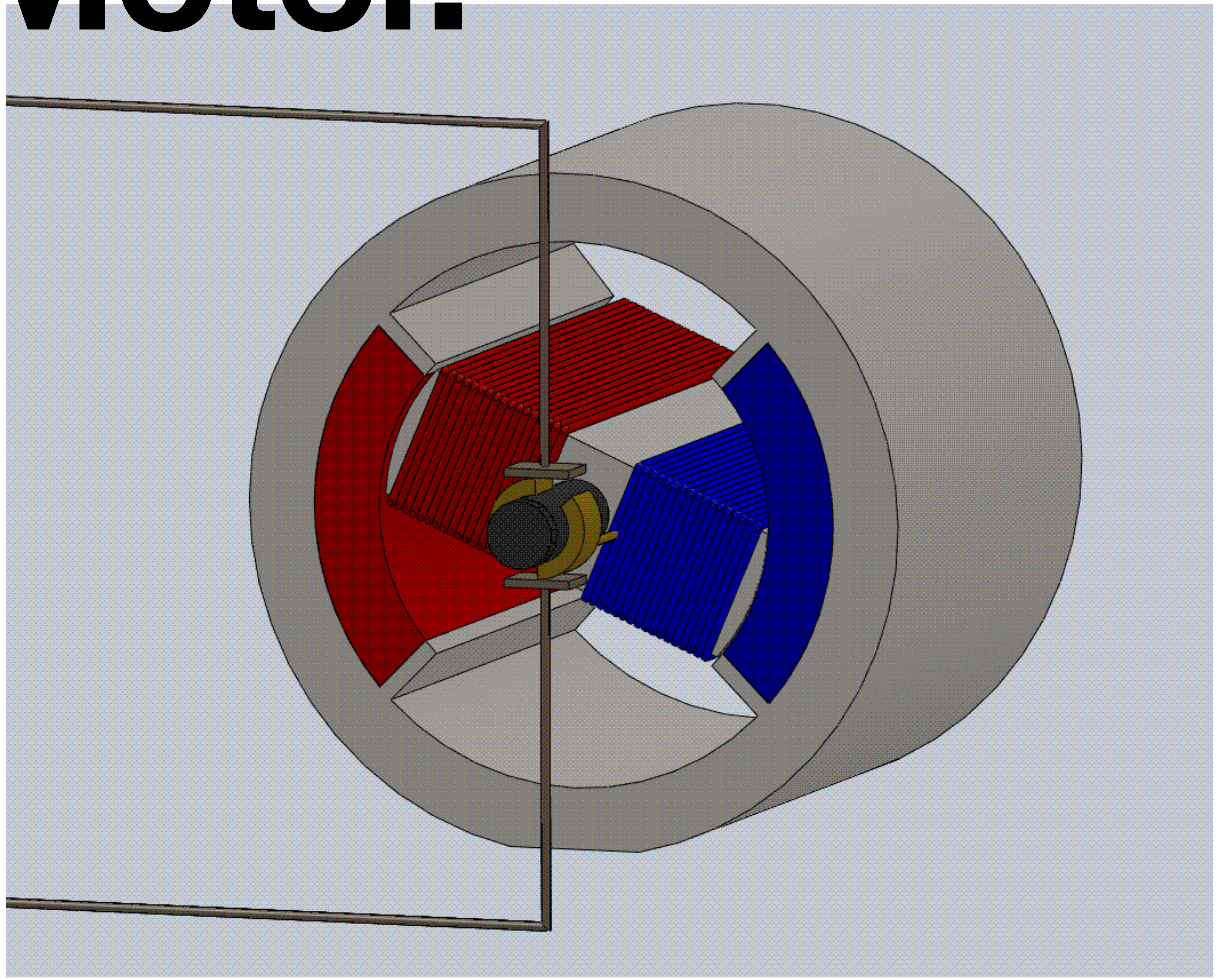
As the magnet rotates the force becomes more horizontal, when the force is horizontal the magnet would stop moving if we left it like this. Imagine the forces as strings pulling the magnet, the magnet would stop.

But if we SWITCH the magnets, S now repels S, N repels N, and the motor can keep spinning!



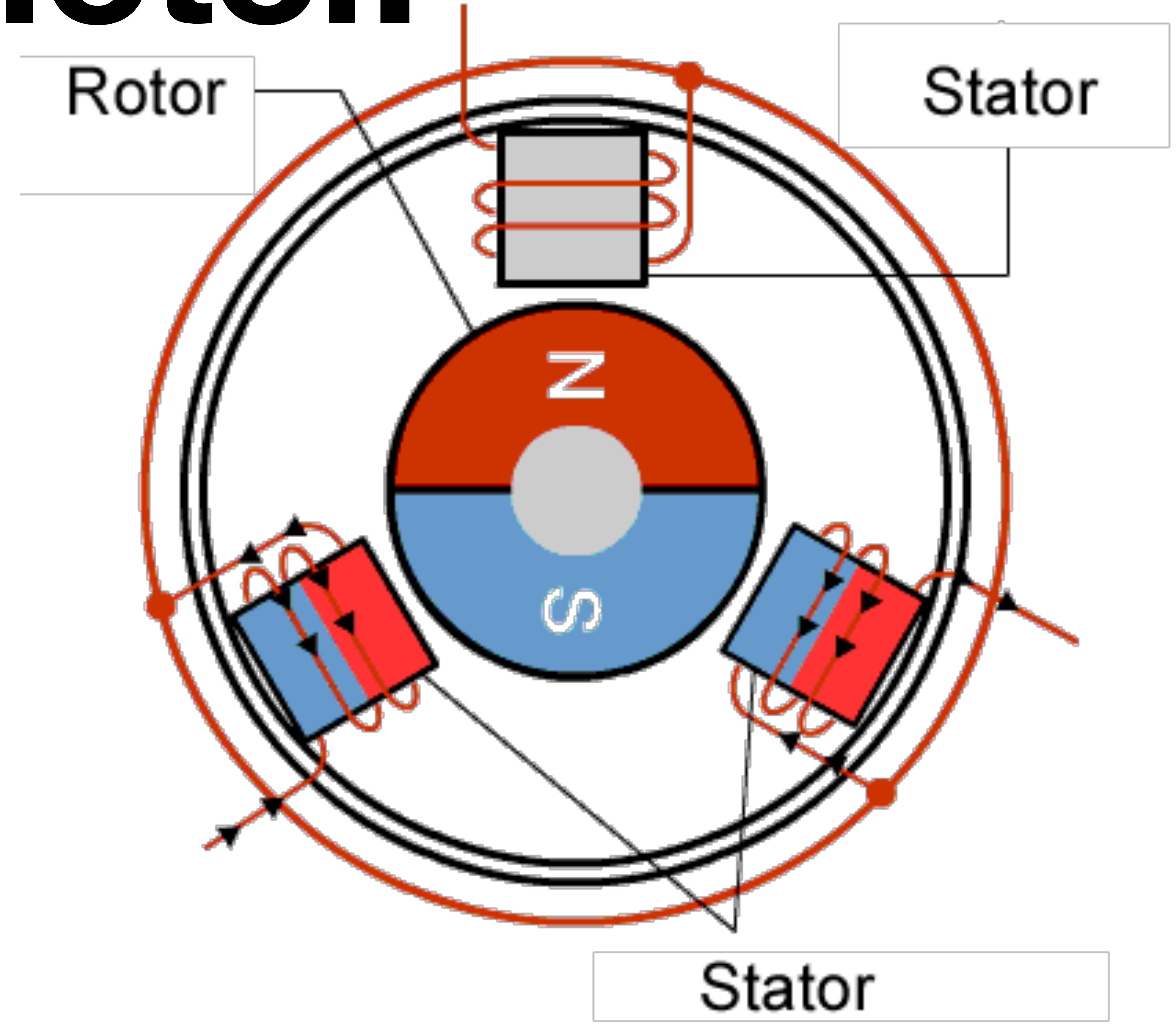
Ok but like, how do we do**?**

Brushed Motor.



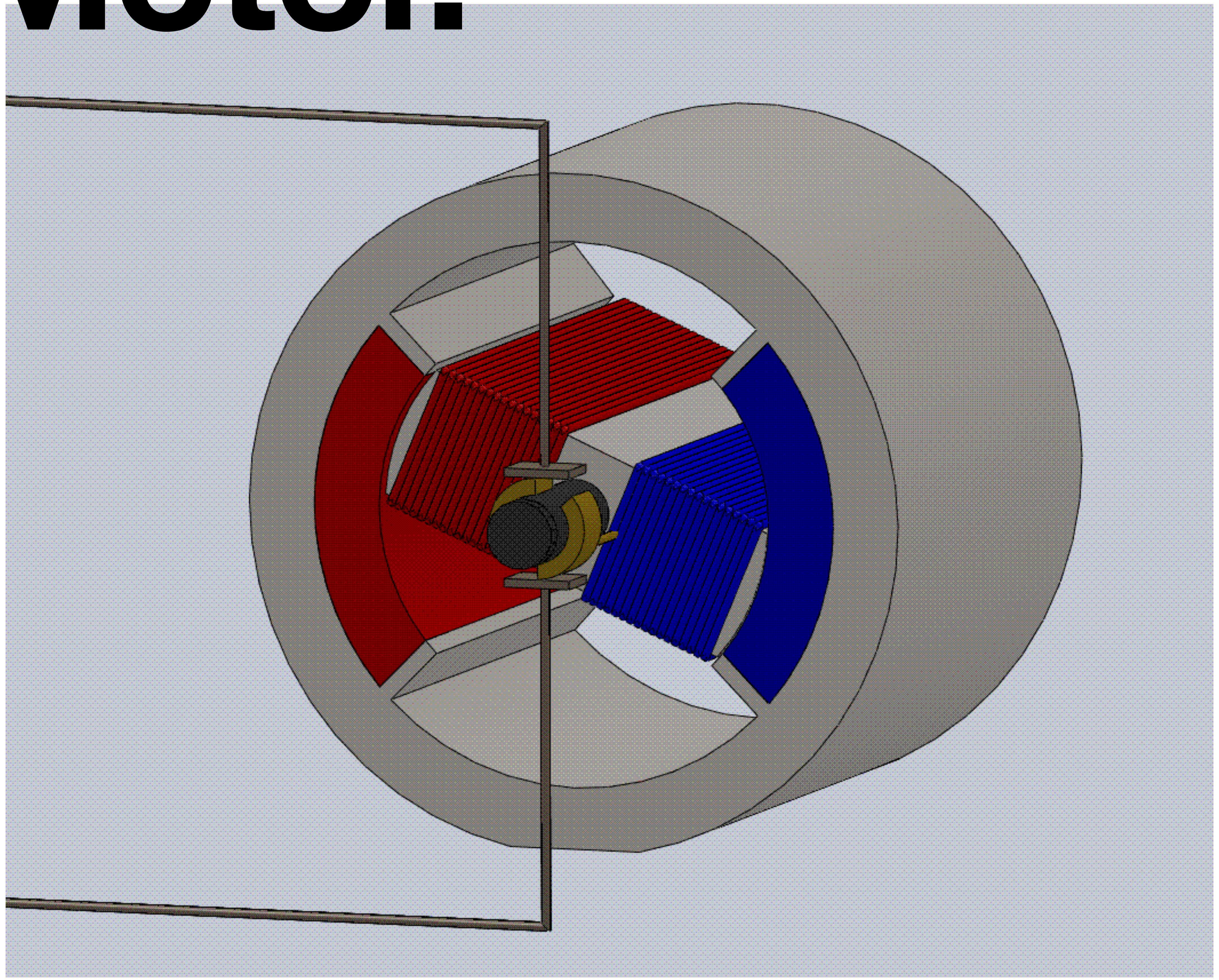
[(https://cecas.clemson.edu/cvel/auto/actuators/motors-dc-brushed.html)](https://cecas.clemson.edu/cvel/auto/actuators/motors-dc-brushed.html)

Brushless Motor.



[(https://www.renesas.com/us/en/support/engineer-school/brushless-dc-motor-01-overview)](https://www.renesas.com/us/en/support/engineer-school/brushless-dc-motor-01-overview)

Brushed Motor.



(https://cecas.clemson.edu/cvel/auto/actuators/motors-dc-brushed.html)

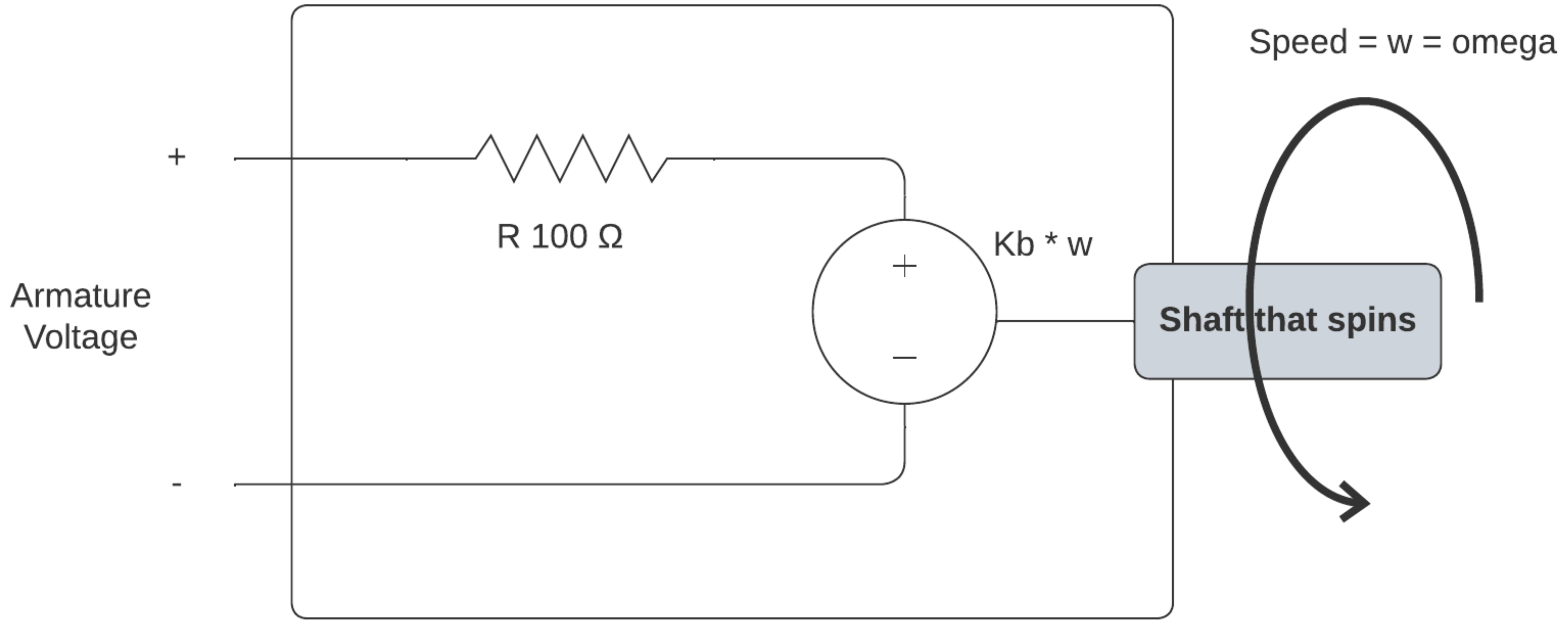
Brushless

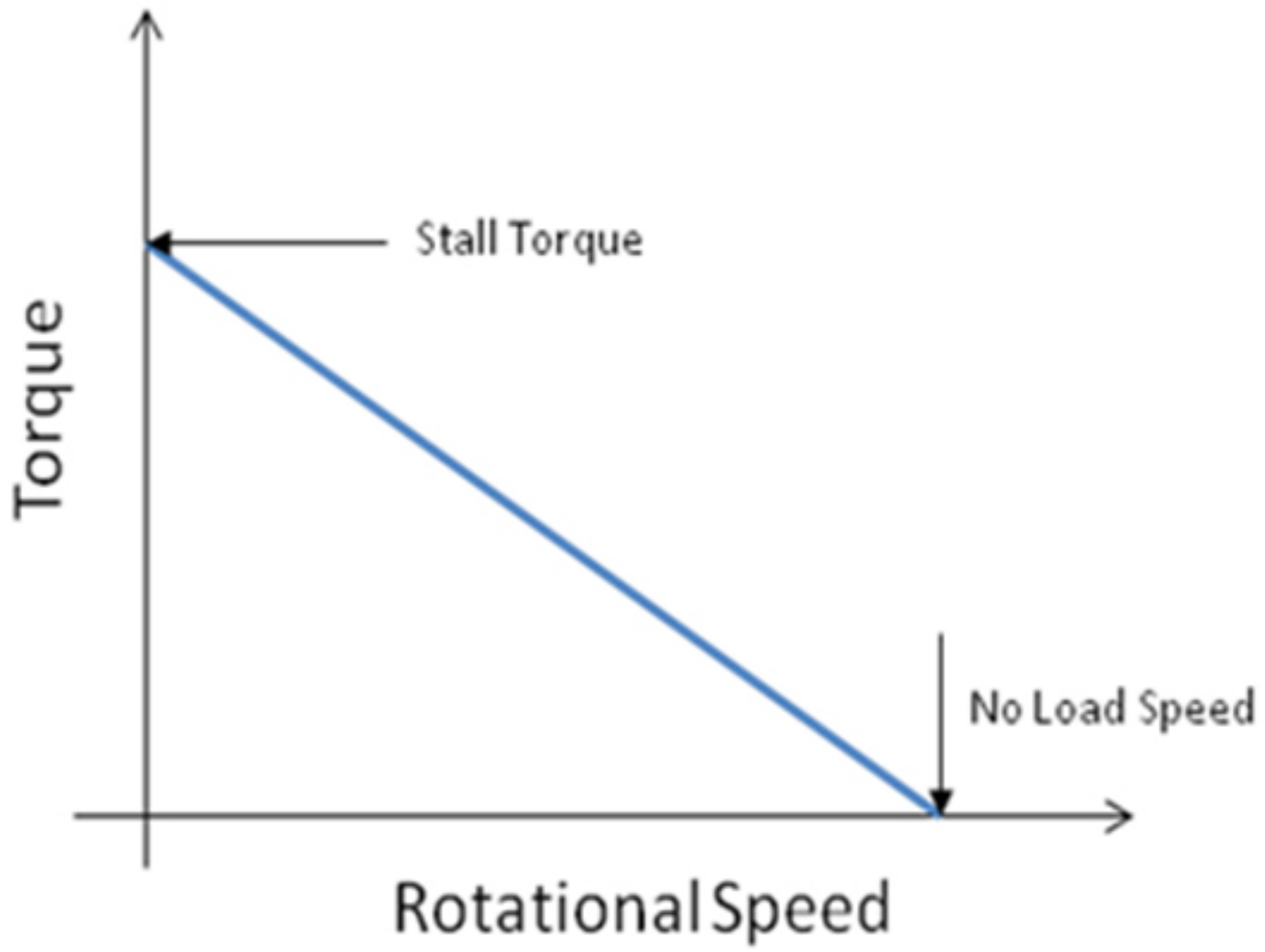
(https://www.hobbytown.com/spektrum-rc-firma-130-amp-sensorless-brushless-smart-esc-motor-combo-1900kv-spmxsemc04/p1222229)

Circuit Model of a Motor.

V = k_b * w

T = k_t * I





https://www.motioncontroltips.com/torque-equation/

(Note how the max speed depends on the armature voltage)

Practical Aside.

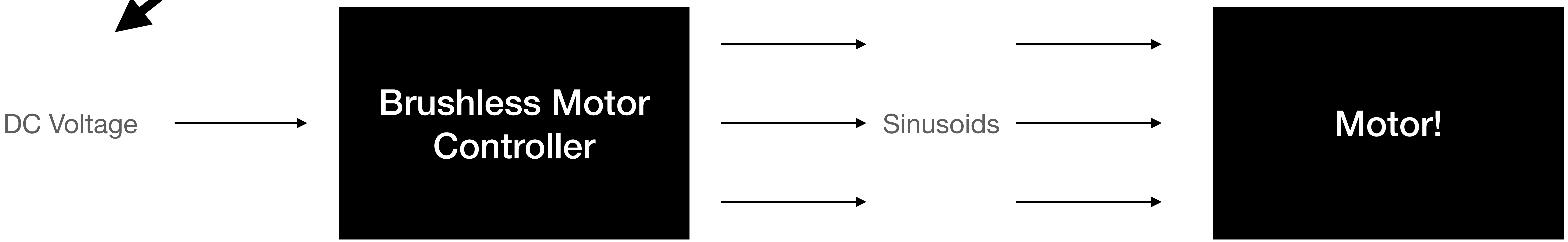
(Brushed motors also have motor controllers that allow you to control the speed of the motor)

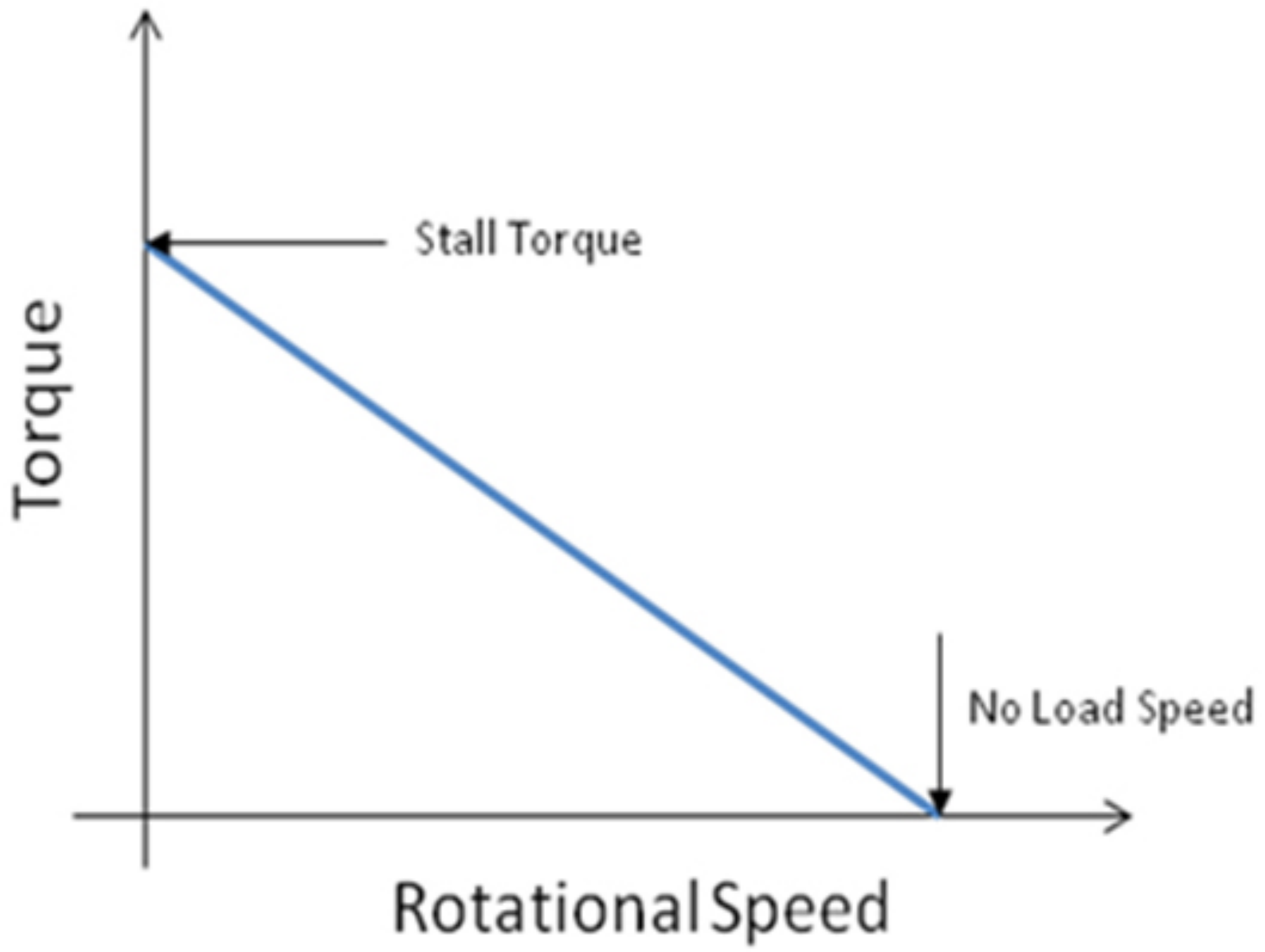
(These work by taking in a DC voltage from a source, and then varying the armature voltage)

(Then, the torque-speed max speed point is dependent on the DC input voltage)

Modeling Brushless Motors.

(Same model but it’s THIS V and I)





V = k_b * w

T = k_t * I

Field-Oriented-Control, of brushless motors!

@ MIT

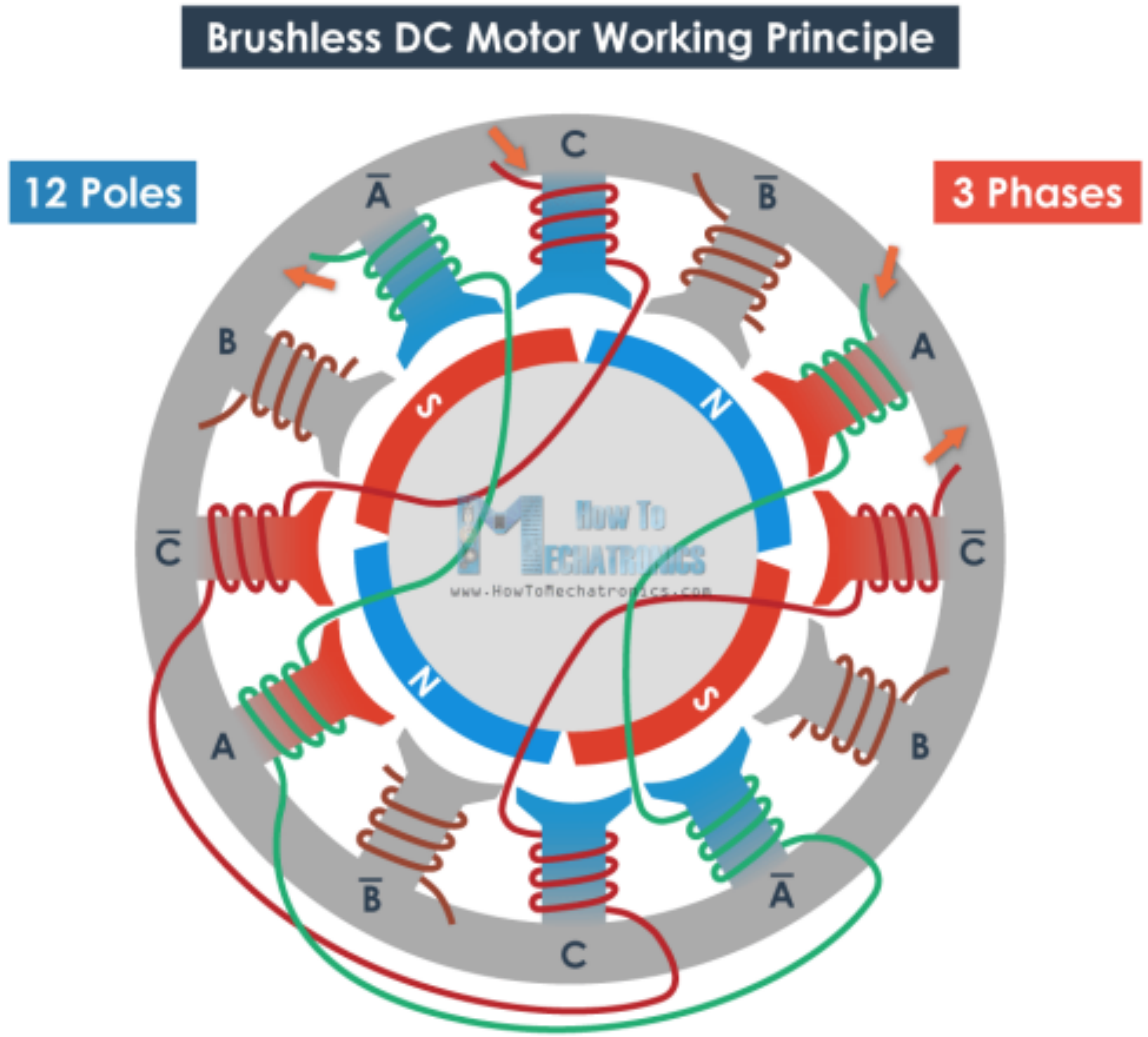
This is a Brushless Motor.

T-Motor U15

(pole pairs is the number of pairs of magnets on the rotor)

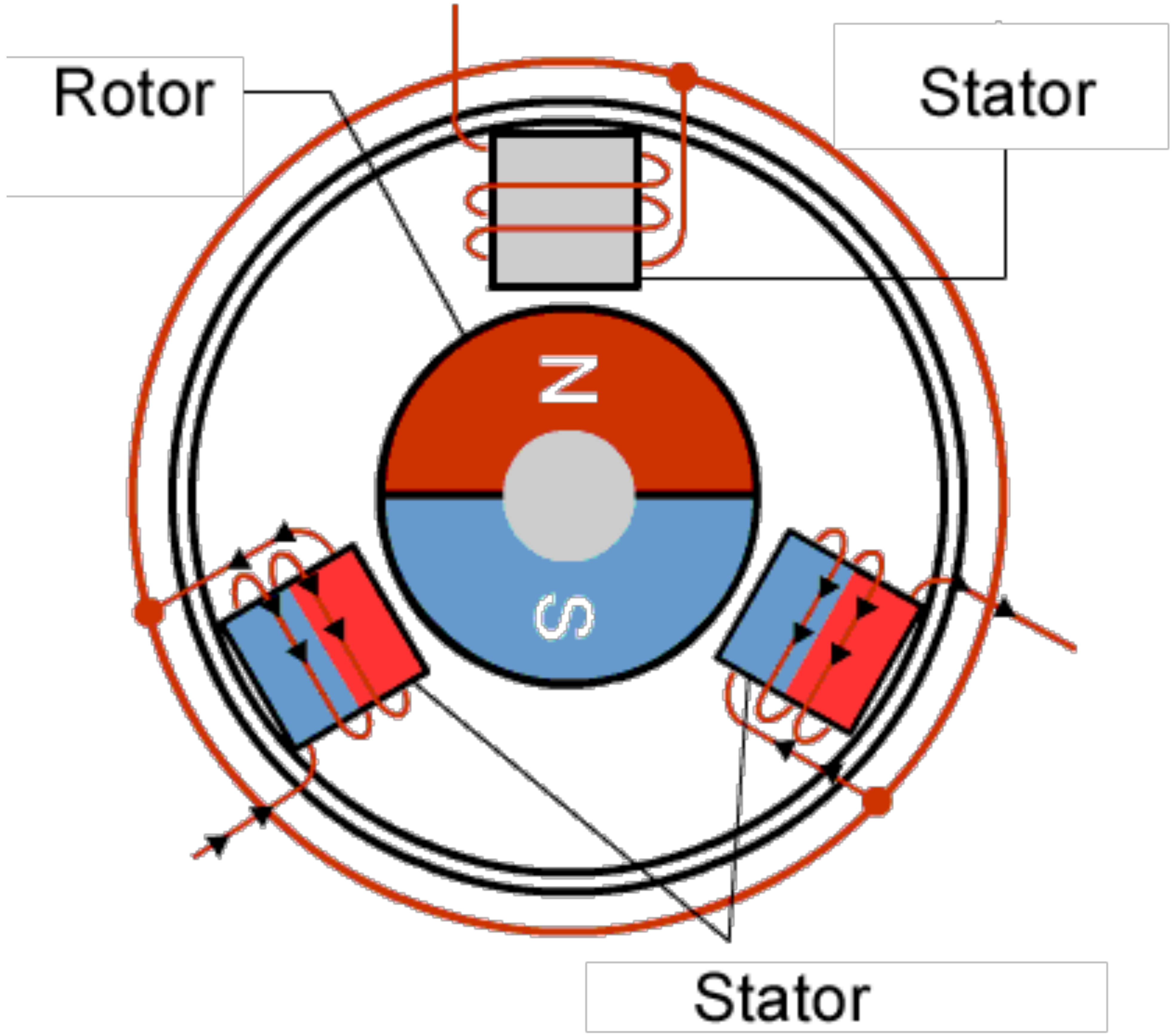
(Slots is the number of coils in the stator)

This is a Brushless Motor.



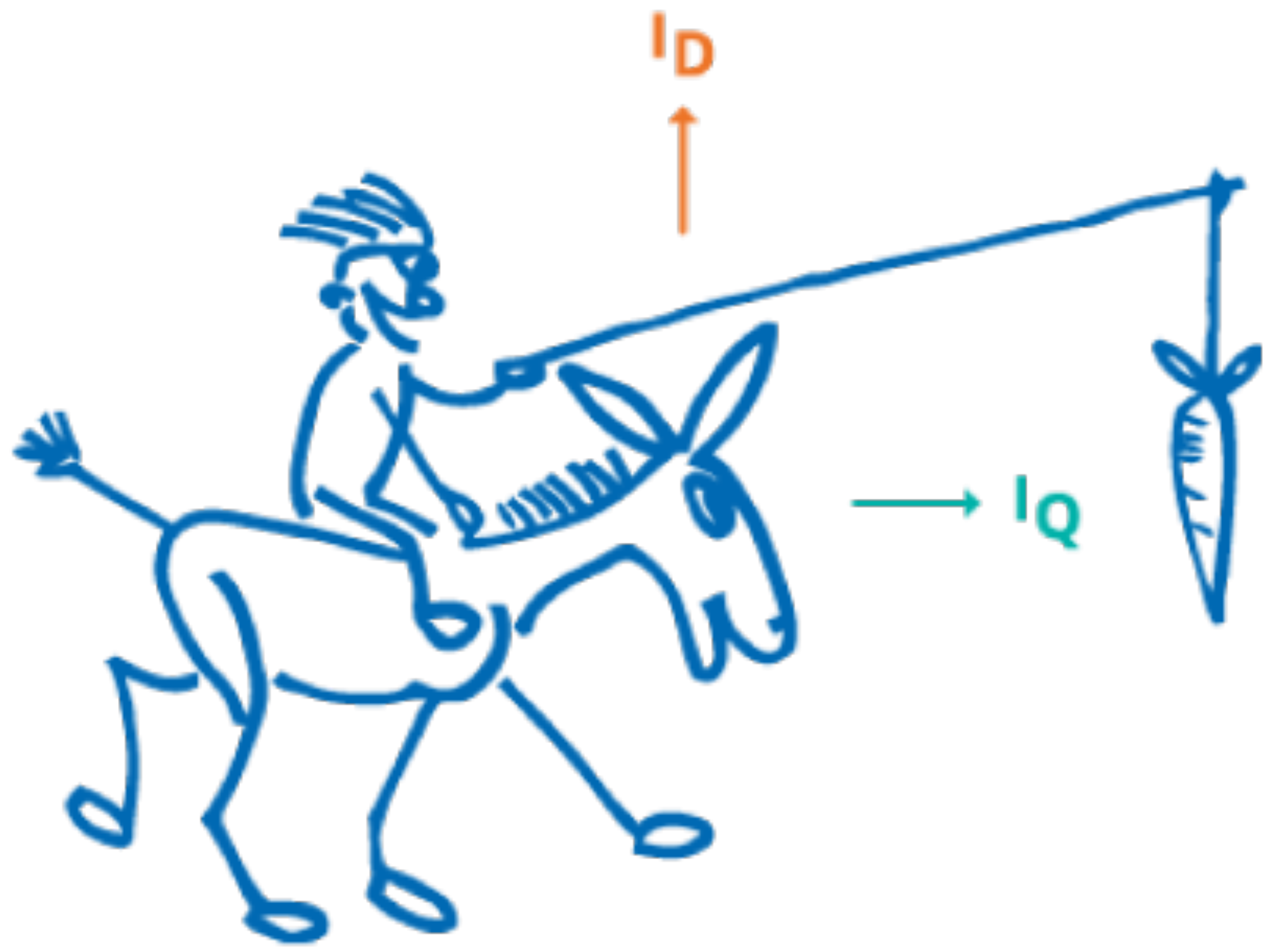
https://futurelab3d.com/how-brushless-motor-and-esc-work/

(Phases have a pattern, and they alternate, this depends on motor design)

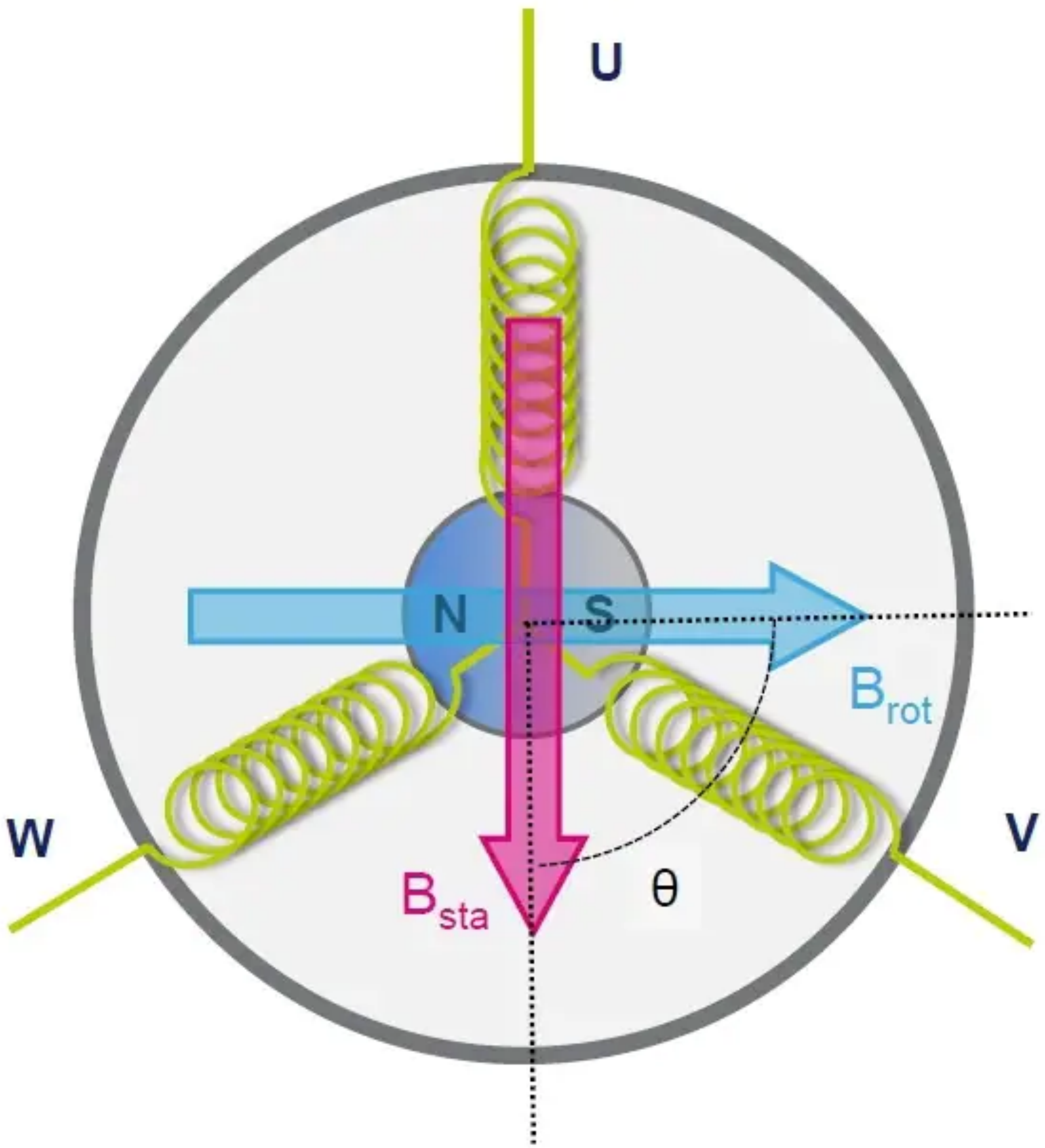


(But ALL motors can be simplified into this model)

Field-Oriented Control.

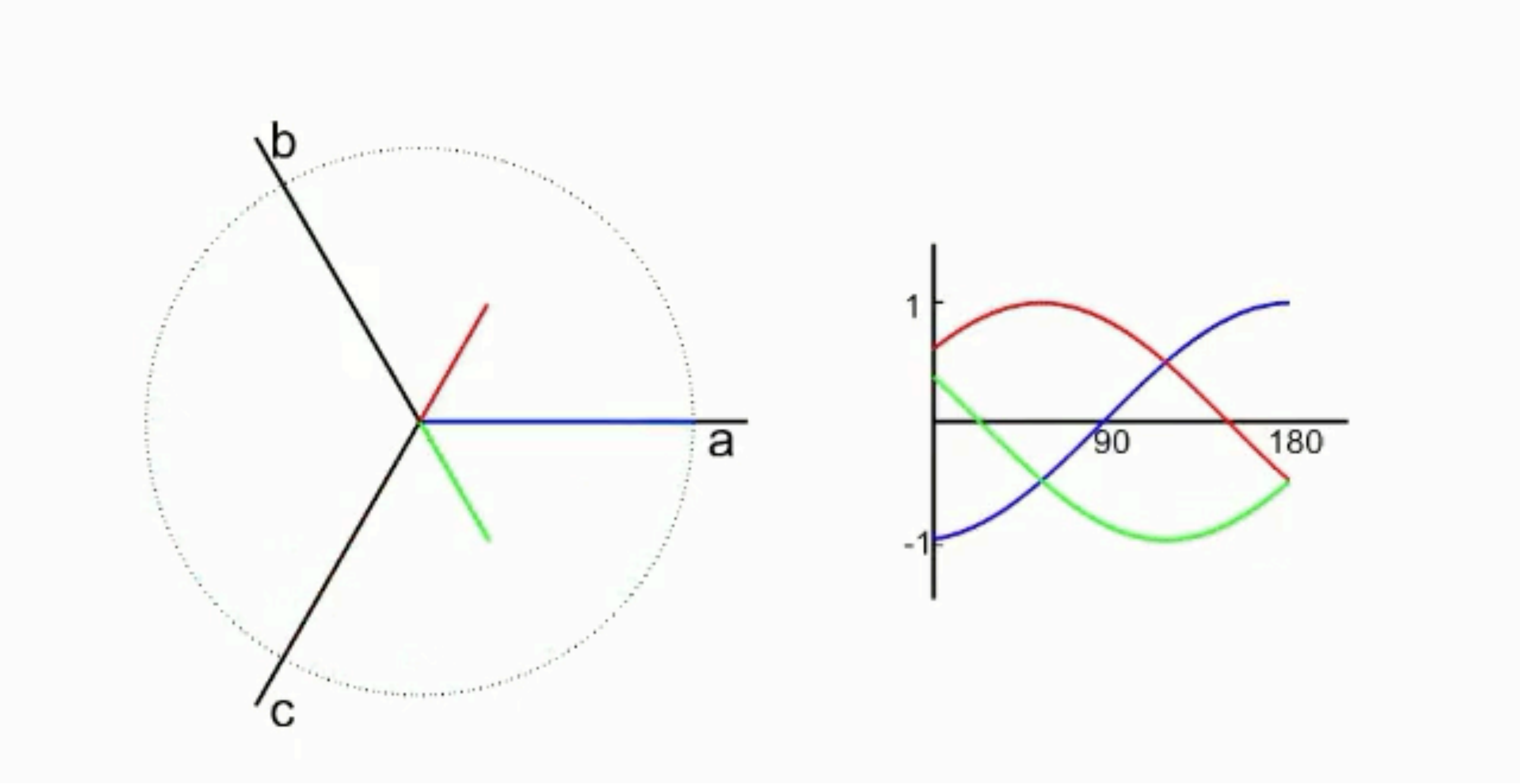


https://www.trinamic.com/technology/motor-control-technology/field-oriented-control/



https://www.st.com/en/applications/industrial-motor-control/3-phase-field-oriented-control-foc.html

Field-Oriented Control.

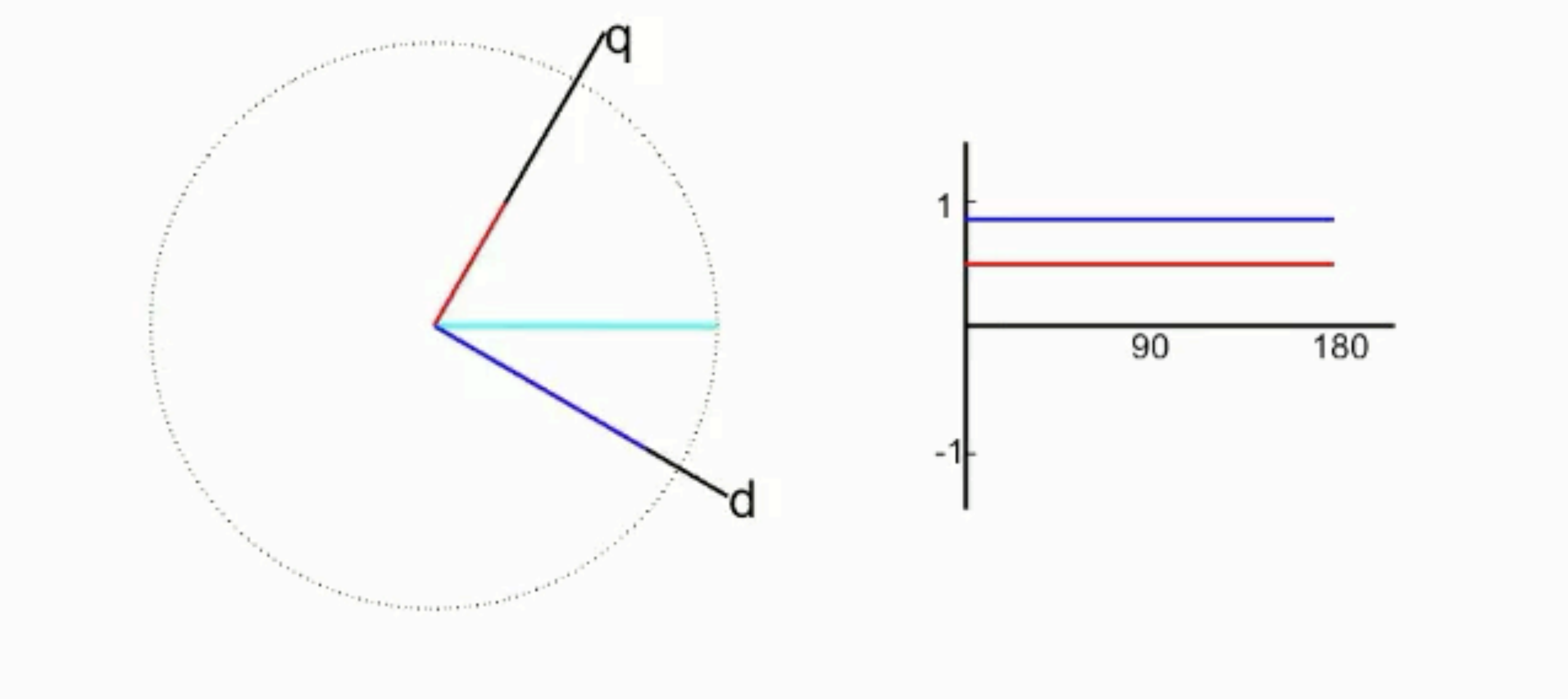


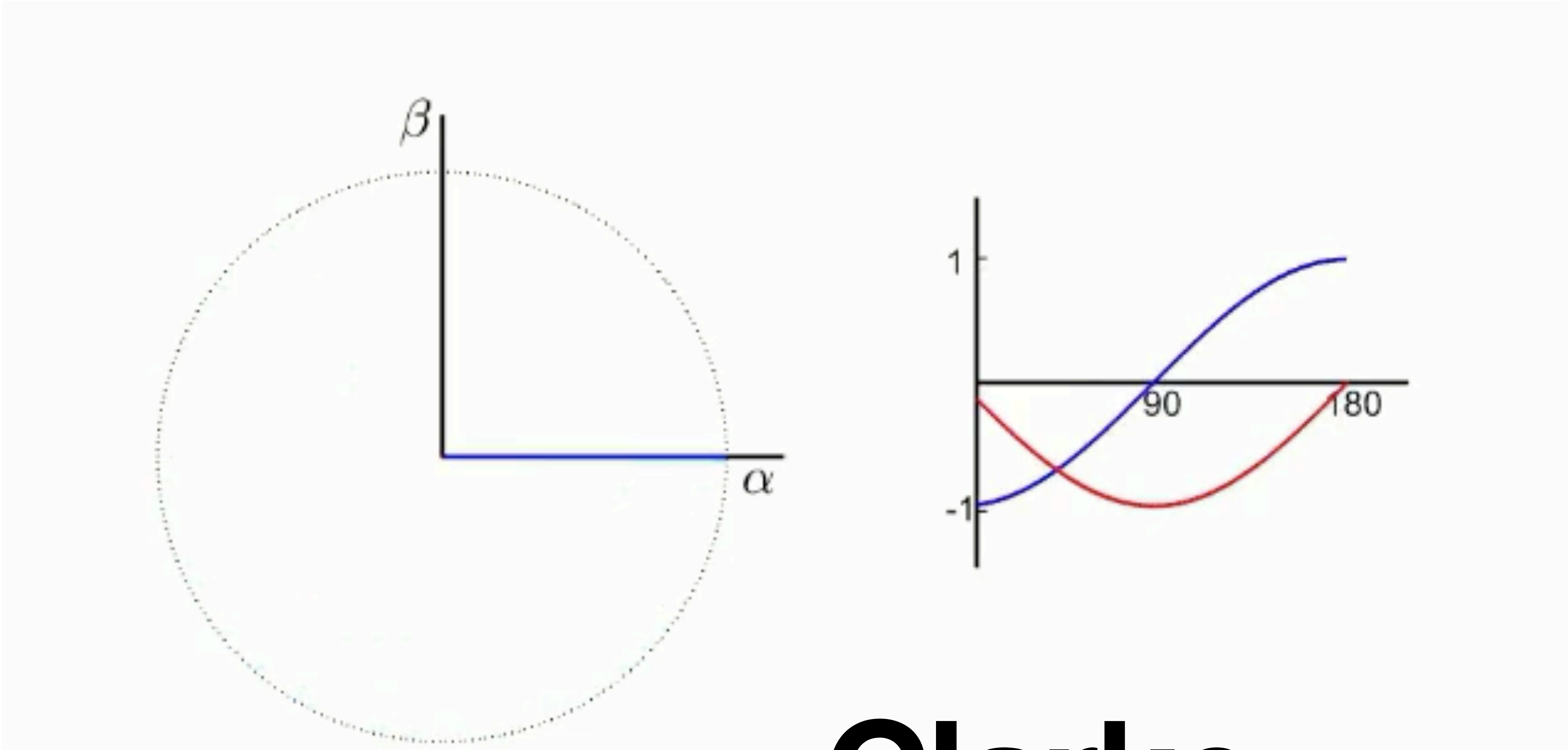
-Mathworks

Clarke + Park Transform.

-Mathworks

Park





Clarke

(Edith Clarke was the first woman to deliver a paper at the American Institute of Electrical Engineers, the first female engineer whose professional standing was recognized by Tau Beta Pi, and the first woman named as a Fellow of the American Institute of Electrical Engineers.) - AND SHES FROM MIT!

-Wikipedia

Clarke + Park Transform.

-Texas Instruments

3.1 Mathematical Clarke transform.

The mathematical transformation called Clarke transform modifies a three-phase system to a two-phase orthogonal system:

$$i_\alpha = \frac{2}{3} \cdot i_a - \frac{1}{3}(i_b - i_c)$$

$$i_\beta = \frac{2}{\sqrt{3}}(i_b - i_c)$$

$$i_o = \frac{2}{3}(i_a + i_b + i_c)$$

STAR NODE —> Kirchoff's Current Law

with i_α and i_β components in an orthogonal reference frame and i_o the homopolar component of the system.

3.2 Mathematical Park transform.

The two phases α, β frame representation calculated with the Clarke transform is then fed to a vector rotation block where it is rotated over an angle θ to follow the frame d,q attached to the rotor flux.

The rotation over an angle θ is done according to the formulas:

$$i_{sd} = i_\alpha \cdot \cos(\theta) + i_\beta \cdot \sin(\theta)$$

$$i_{sq} = -i_\alpha \cdot \sin(\theta) + i_\beta \cdot \cos(\theta)$$

Clarke

Park

Clarke + Park Transform.

-Texas Instruments

3.3 Mathematical Inverse Park and Clarke transforms.

The vector in the d, q frame is transformed from d, q frame to the two phases α, β frame representation calculated with a rotation over an angle θ according to the formulas:

$$i_\alpha = i_{sd} \cdot \cos(\theta) - i_{sq} \cdot \sin(\theta)$$
$$i_\beta = i_{sd} \cdot \sin(\theta) + i_q \cdot \cos(\theta)$$

The modification from a two-phase orthogonal α, β frame to a three-phase system is done by the following equations:

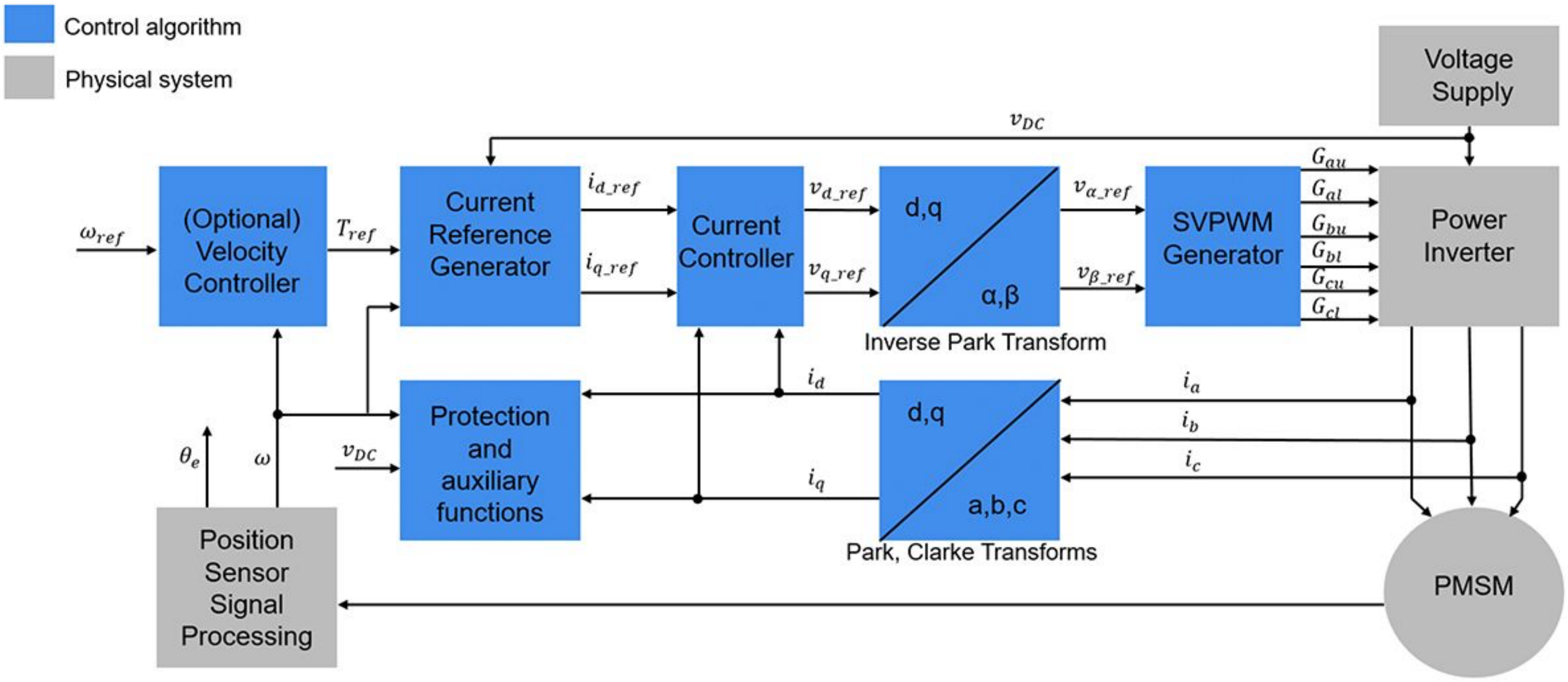
$$i_a = i_\alpha$$
$$i_b = -\frac{1}{2} \cdot i_\alpha + \frac{\sqrt{3}}{2} \cdot i_\beta$$
$$i_c = -\frac{1}{2} \cdot i_\alpha - \frac{\sqrt{3}}{2} \cdot i_\beta$$

3.4 Transforms summary.

Park	Inverse Park
a, b, c -> α, β	**d, q -> α, β**
$i_\alpha = \frac{2}{3} \cdot i_a - \frac{1}{3}(i_b - i_c)$ $i_\beta = \frac{2}{\sqrt{3}}(i_b - i_c)$ $i_o = \frac{2}{3}(i_a + i_b + i_c)$ $\Rightarrow$ $i_\alpha = i_a$ $i_\beta = \frac{1}{\sqrt{3}} \cdot i_a + \frac{2}{\sqrt{3}} i_b$ $i_a + i_b + i_c = 0$	$i_\alpha = i_{sd} \cdot \cos(\theta) - i_{sq} \cdot \sin(\theta)$ $i_\beta = i_{sd} \cdot \sin(\theta) + i_q \cdot \cos(\theta)$
α, β -> d, q	**α, β -> a, b, c**
$i_{sd} = i_\alpha \cdot \cos(\theta) + i_\beta \cdot \sin(\theta)$ $i_{sq} = -i_\alpha \cdot \sin(\theta) + i_\beta \cdot \cos(\theta)$	$i_a = i_\alpha$ $i_b = -\frac{1}{2} \cdot i_\alpha + \frac{\sqrt{3}}{2} \cdot i_\beta$ $ic = -\frac{1}{2} \cdot i_\alpha - \frac{\sqrt{3}}{2} \cdot i_\beta$

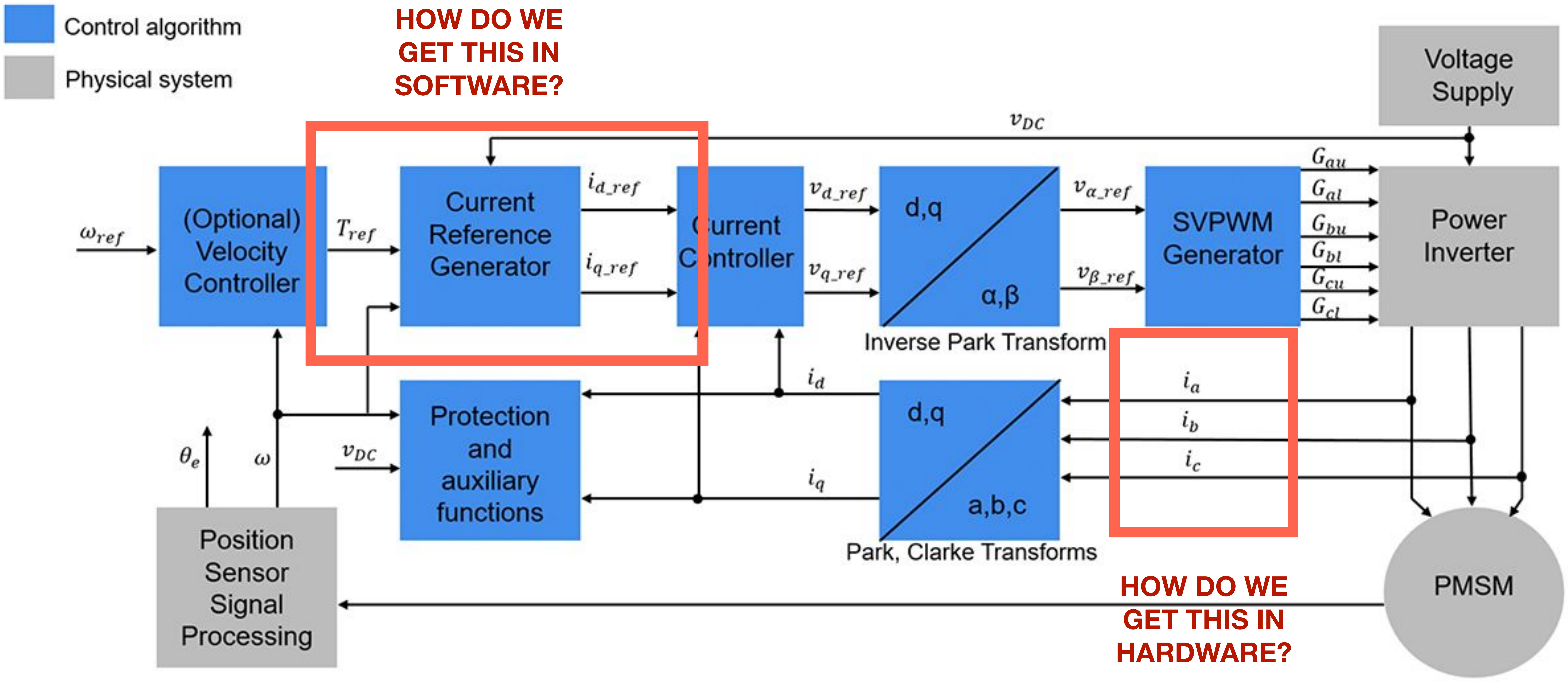
FOC as a block-set.

-Mathworks



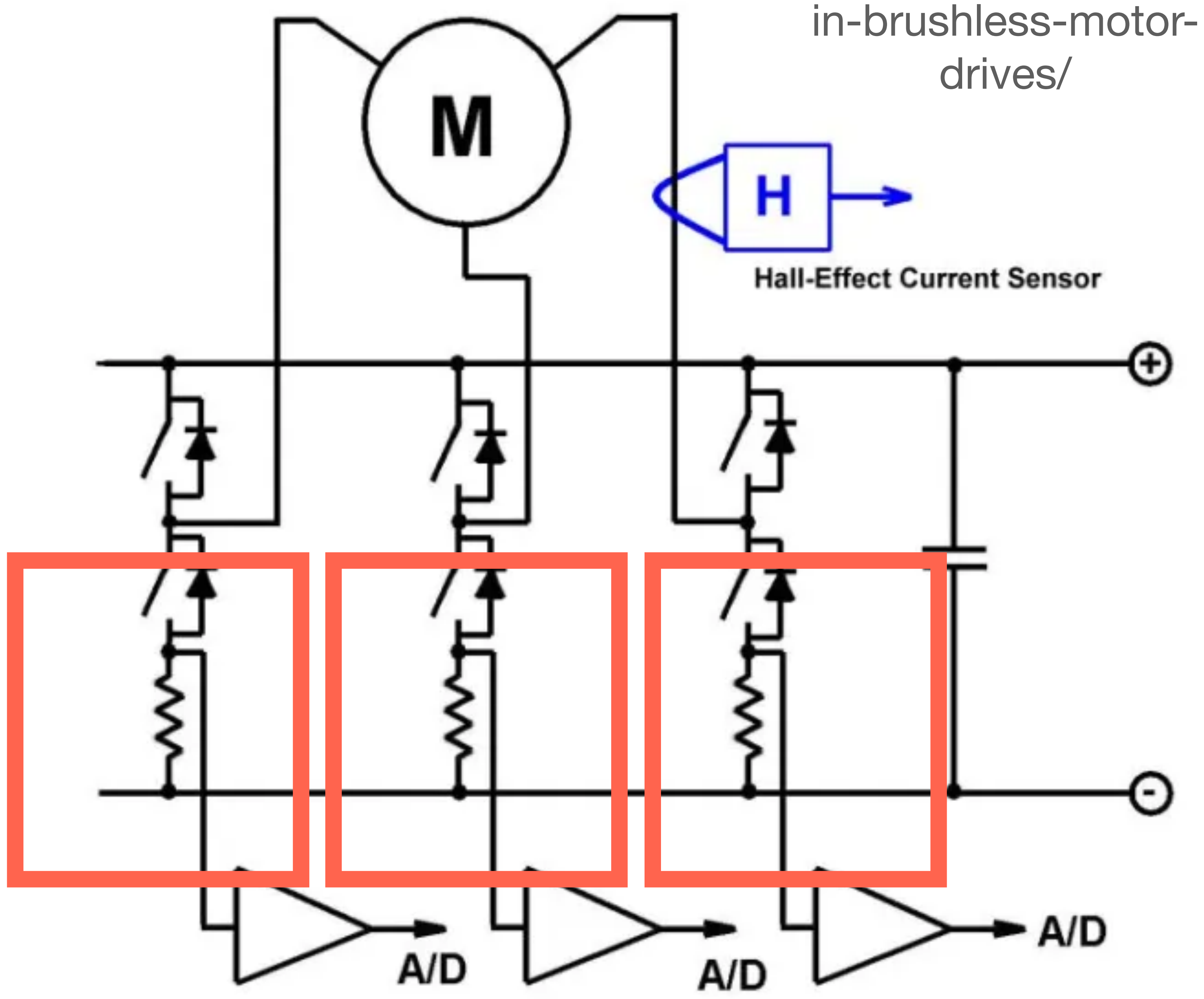
FOC as a block-set.

-Mathworks



Phase Current Measurement + The DRV Chip.

https://www.powerelectronicsnews.com/current-sensing-in-brushless-motor-drives/



8.2 Functional Block Diagram

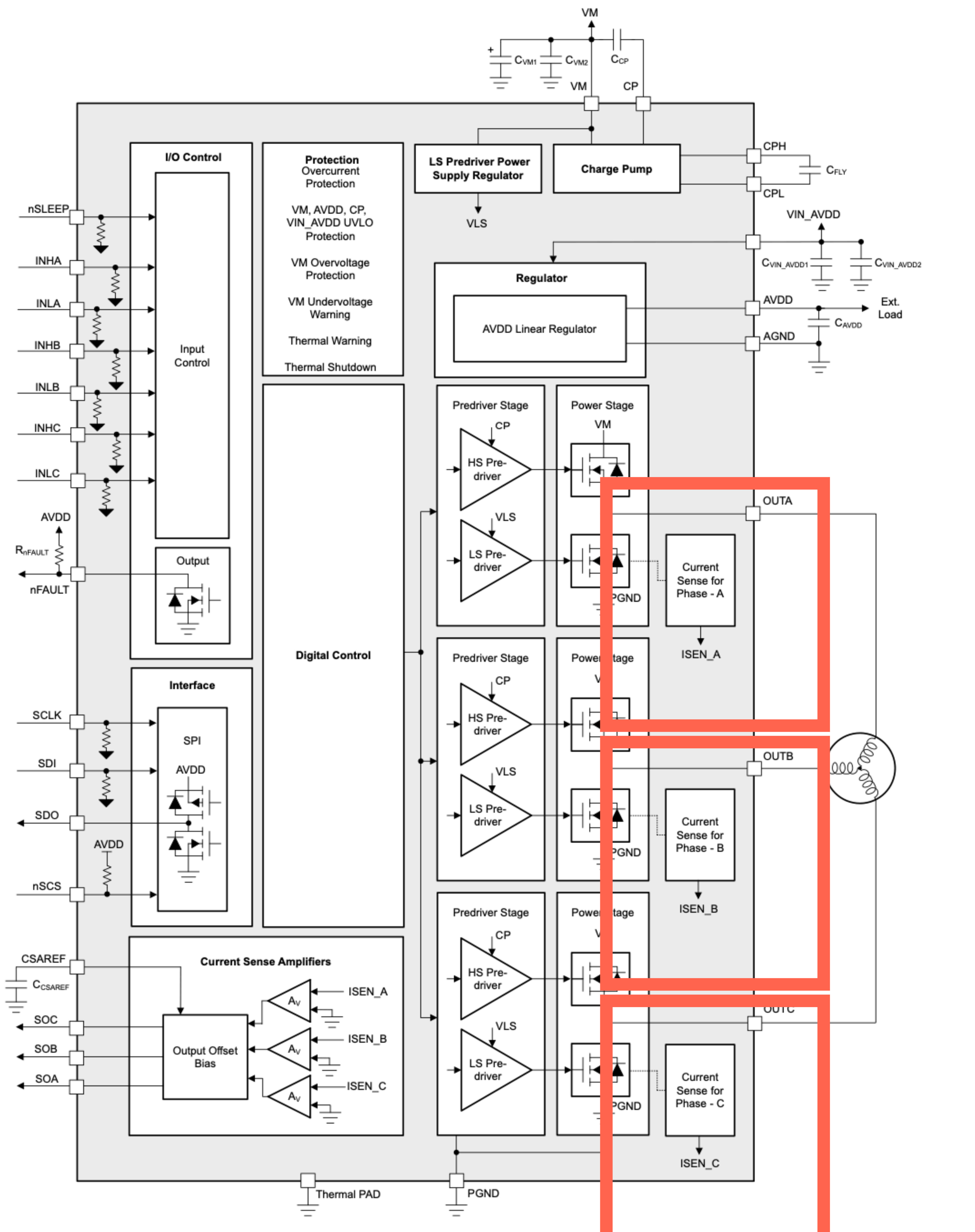


Figure 8-1. DRV8317S Functional Block

(A good alternative is the trinamic series)

How to get id? And iq?

(Remember iq is the torque-producing current)

https://www.mathworks.com/help/sps/ref/pmsmcurrentreferencegenerator.html

https://www.mathworks.com/help/sps/ref/pmsm.html

For the ZDAC method, the block sets the *d*-axis current reference i_d^{ref} to zero and determines the *q*-axis current reference i_q^{ref} using the torque equation:

$$i_d^{ref} = 0,$$

and

$$i_q^{ref} = \frac{2T_{ref}}{3p\psi_m},$$

where:

- T_{ref} is the reference torque input.
- p is the number of pole pairs.
- ψ_m is the permanent magnet flux linkage.

(Comes from data sheet, motor testing, calculating, it can also be estimated).

$$k_e = N\psi_m. \qquad k_t = N\psi_m.$$

(We can get Kt and Kb from motor testing!)

(Comes from motor testing and desired torque).

VESC Schematic. PDF

(https://vesc-project.com/sites/default/files/Benjamin%20Posts/VESC_6.pdf)

FOC as a block-set.

-Mathworks