# Motors and Motor Controllers

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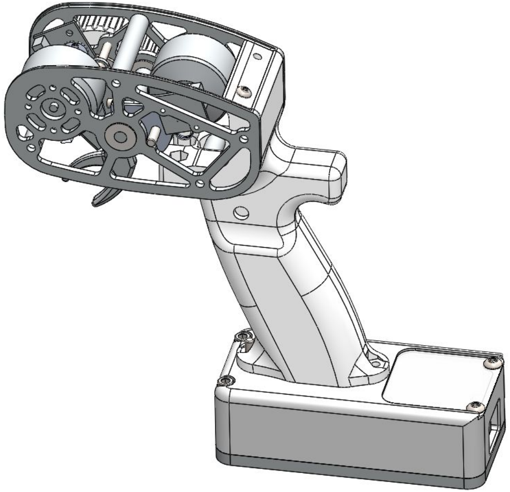
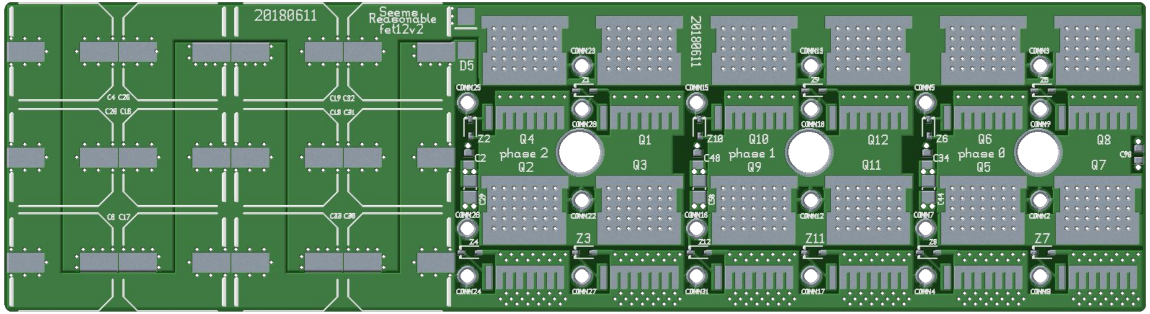
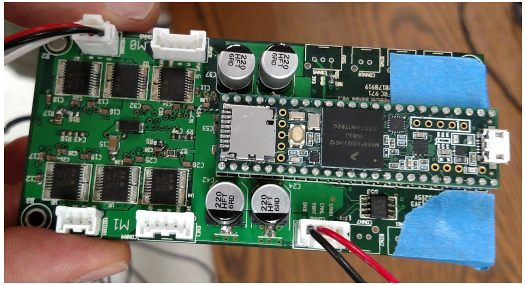
Spartan Series 2018

# Why I'm interested in this stuff







# What is a motor?

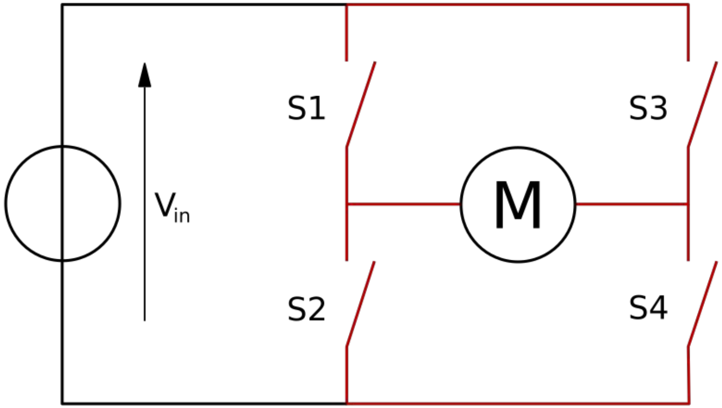
- Device that converts electrical power to mechanical
  - Reversible too (motors and generators are the same)
- General idea is to have two magnetic fields on the rotor (rotating part) and stator (stationary part) which are kept rotationally separated to produce torque
- At least one of them has to be produced from an electromagnetic coil
  - Otherwise, can't change it, so then motor can't rotate continuously
- Many permutations of how to implement it, with various tradeoffs:
  - Permanent magnets on rotor or stator
  - Two coils connected in series or parallel or separately
  - How to power coils in rotor
  - How to commutate (keep the fields separated, because as it rotates the fields will align eventually if one/both doesn’t keep moving)

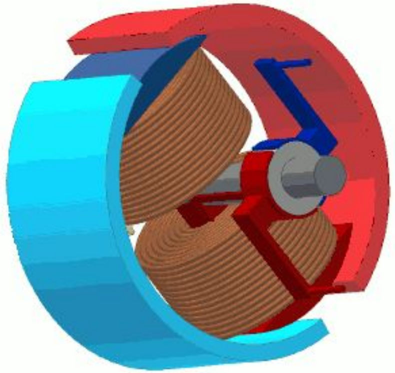
# Electricity basics

- Voltage, current, resistance, and power
- Simple analogy to water in pipes (hydraulic analogy)
  - Water has no mass, turbulence, it always stays in the pipes, etc
  - Have to be careful taking it too far
- Voltage is pressure, and current is velocity
  - Ohm's law: $V = I * R$, aka pressure difference = velocity * resistance to flow
- Resistance to electricity is like resistance to flow (constriction in pipe)
  - All pipes restrict flow to some extent, just like all wires
- Power is energy moved per unit time
  - $P = I * V = I^2 * R$

# Brushed permanent magnet motor

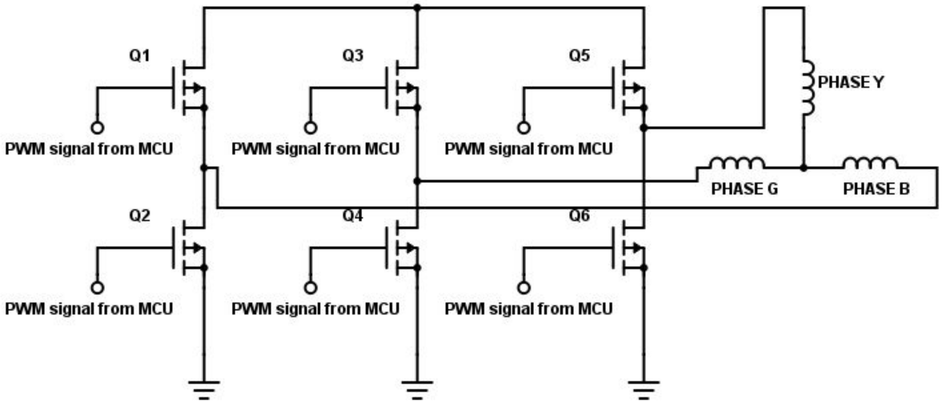
- Common for a while in low power applications
- Brushes commutate mechanically so it spins when you apply DC voltage
  - But brushes wear out, and aren't too efficient, and spark
- Simple to control, especially with fairly simple power electronics (switch power on/off quickly, voltage averages out, also allows reversing easily)



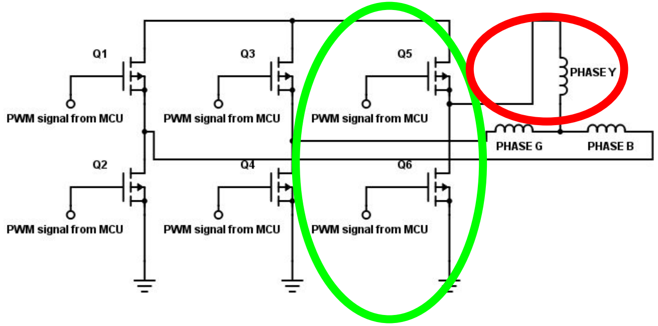
# Permanent magnet synchronous motor (PMSM)

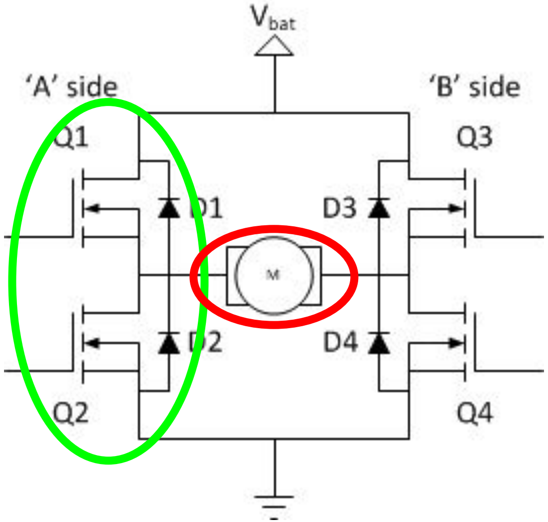
- Currently used in high performance low to medium power applications (toothbrushes to trains, but not power plants)
- Rotor has permanent magnets so no need to connect to it electrically
- Requires more sophisticated control electronics
  - Similar to induction motors, which are also used in similar applications
- Commonly called “brushless motors”

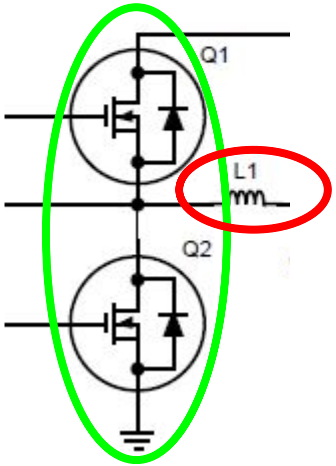



# Motor controllers

- Need to control the current going through the motor
- Same component structure for brushed motors, three-phase motors, inverters, DC mains supplies (opposite of an inverter), and DC-DC converters

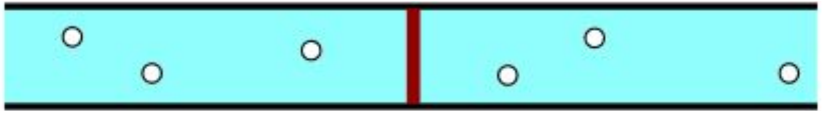


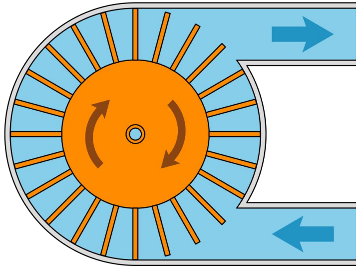



# More electricity concepts

- Capacitance: resistance to change in voltage
  - Batteries have a lot
  - Flexible diaphragm in pipe
  - If you try changing the voltage across it, a capacitor will change current through itself to oppose the change

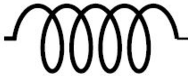


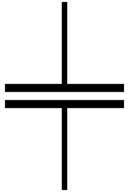
- Inductance: resistance to change in current
  - Inductor is basically a big coil of wire (like an electromagnet, in a motor or solenoid)
  - Heavy paddlewheel
  - If you try changing the current through it, an inductor will change the voltage across itself to oppose the change



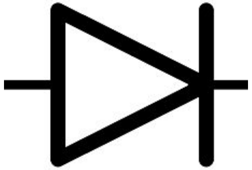
# Electronic components

- Anything that electricity flows through is (at least) a resistor, capacitor, and inductor (some are mostly just one, but all have some parasitics)
- Inductor is literally just a coil of wire

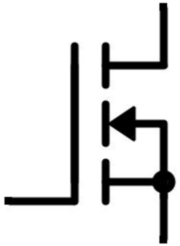




- Capacitor is parallel plates that are close together
    - Different materials and different ways of packing lots of surface area into a small volume
- Diode lets current flow one direction but not the other
    - Open circuit with voltage one way, constant voltage drop the other

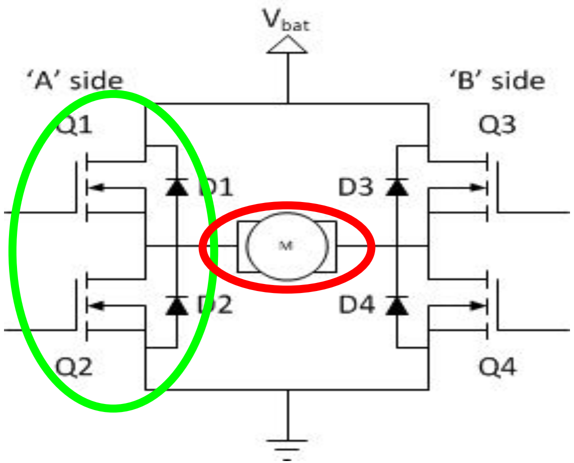


- MOSFET is either a diode or a resistor
    - Like a switch, allows turning things on and off
    - Switches quickly because no physical moving parts



# Half-bridges

- Each phase is driven high or low
- However, need some dead time to avoid shoot through
    - If they're both on for any amount of time, lots of current flows really fast because no inductor to slow it down
- Switching is actually a fairly complicated process



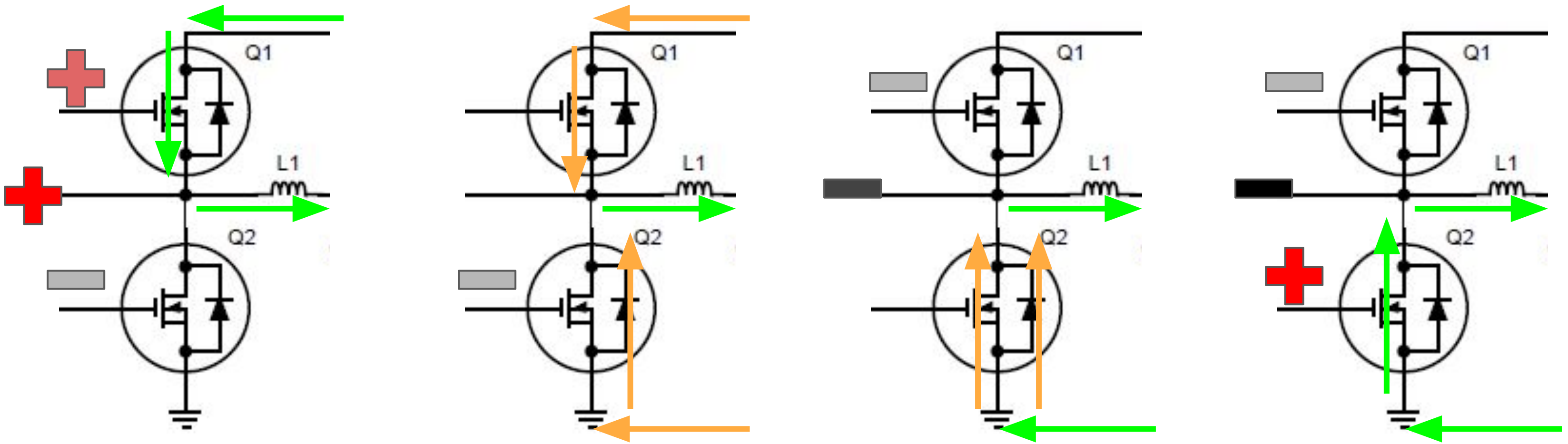
# Switching

2: High side turning off

4: Low side on

1: High side on

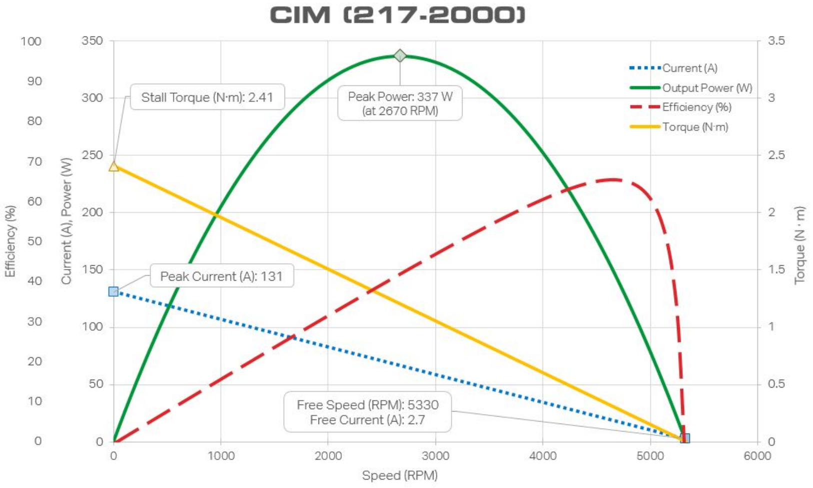
3: Low side turning on



# Flux linkage

- Flux linkage is integral of how much force is exerted per unit of current between a coil and a magnet (force is change in flux linkage)
- Equivalently, how much magnetic flux (how many magnetic field lines) from the magnet go through turns of the coil
- Proportional to the voltage induced in the coil from moving the magnet
- In a PMSM, can write rotor-stator flux linkage (the interesting one) as $\lambda(\theta) = L * i + \Psi_R(\theta)$
    - First term based on varying reluctance (varying air gap, which creates cogging)
    - Second term is an arbitrary function of the position

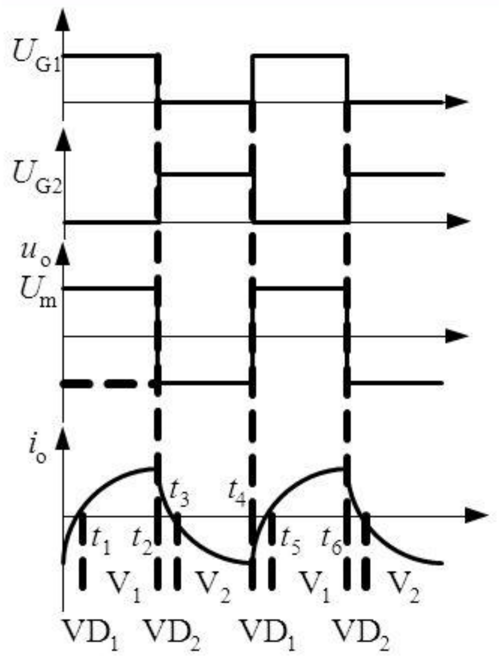
# Motor equations and curves

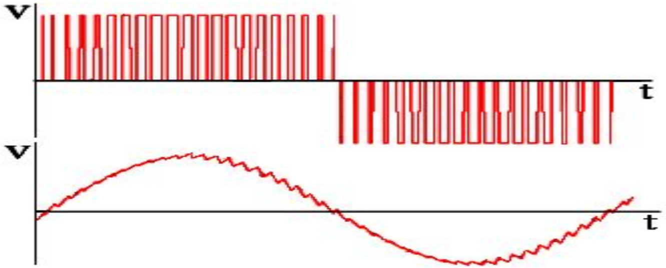



- Standard equations:
  - Torque = stall torque * (speed / free speed)
  - Current = stall current * (speed / free speed)
  - Stall current = voltage / resistance
    - V = I * R
  - No torque or current at free speed (no force)
- Voltage across motor at a given speed is called “back-EMF voltage”
  - Proportional to speed
  - You can measure it with a voltmeter
  - Magnets are moving by coils
- Torque is proportional to the current through the motor
  - Coils are exerting force on the magnets

# Current ripple

- Current ramps up and down at switching frequency
  - 20kHz typical for motor controllers, ~10MHz for power supplies
  - Exponential decay, but usually fast enough relative to the inductance it looks like triangles
- Rapidly varying current -> rapidly varying magnetic fields
  - Also means moving lots of energy in and out of the magnetic fields constantly
- Need input capacitors



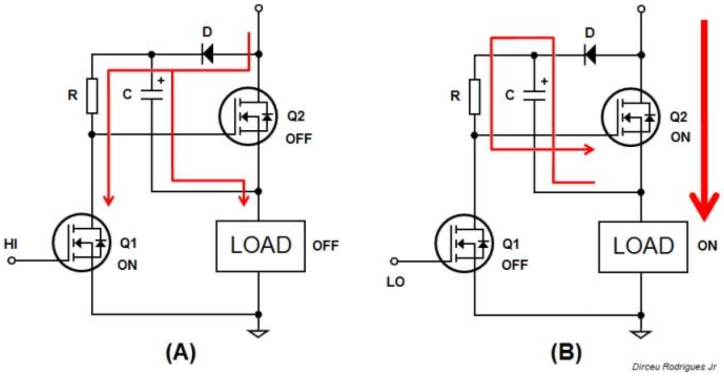



# Input capacitors

- Quickly changing currents cause lots of problems
  - Magnetic interference
  - Parasitic inductance in the power supply means they actually don't in practice
- Use capacitors near the half bridge (physically) to help
  - Boost DC-DC and inverter it's actually the output side
- Large ripple current means they produce heat
  - Ripple energy is constantly being moved in and out

# Bootstrap circuit

- N-channel MOSFET needs gate voltage higher than source
  - Could also use P-channel which needs lower than source which connects to power, but N-channel more efficient so for large amounts of power makes more sense
- Easy for low side: drop down from input voltage
- Hard for high side: need a voltage higher than the input
- Solution: bootstrap circuit
  - Capacitor charges while low side on
    - Through diode
  - As low side turns off, load voltage rises
  - Capacitor resists change in voltage
    - Diode turns off
    - High side of cap rises above input
  - Limits maximum on-time as capacitor discharges, but need enough voltage to turn on



# Controlling a half bridge

- Simplest is fixed-frequency PWM
  - Vary the duty cycle based on the control output
  - More complicated ways that decide each switching point in some way too
- Use a control loop to vary the duty cycle based on feedback
  - Motors it's commonly measured current
  - Simple motor controllers also just drive a fixed duty cycle as a proxy for voltage and rely on something external to command an appropriate voltage
  - DC-DCs have a measurement of the output voltage

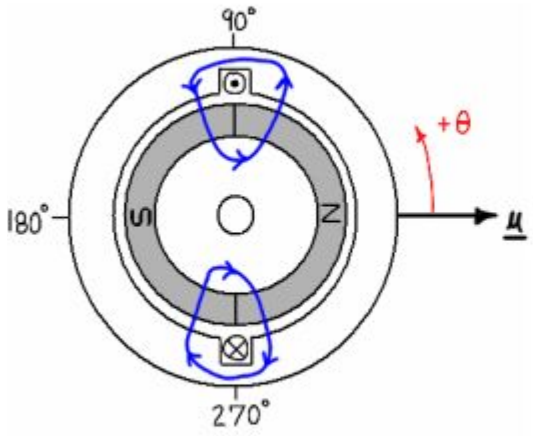
# Cool links

- http://krex.k-state.edu/dspace/bitstream/handle/2097/1507/JamesMevey2009.pdf
- http://www.ti.com/lit/ml/slua618/slua618.pdf

# Complicated math follows...

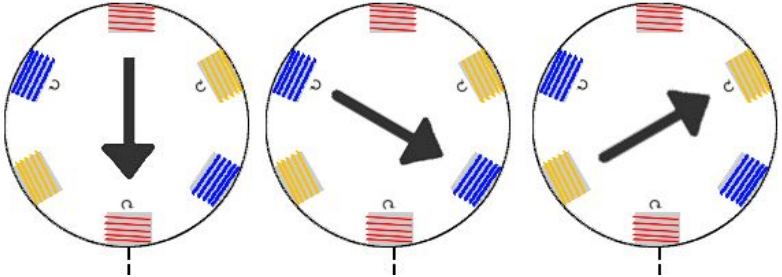
# Torque

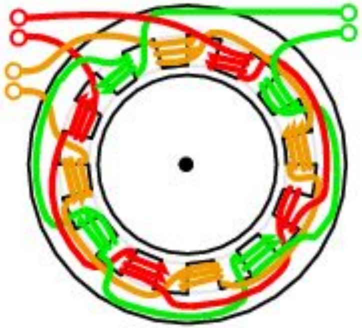
- Lorentz force (magnetic part only, velocity ⊥ magnetic field): F = q * v * B
  - For each of the phases independently
- If the magnetic fields aren't ⊥, effective field in the direction that matters goes down as sin(θ) (rest of it just pushes on the motor bearings)
- Alternative approach: conservation of energy
  - Electrical power in = mechanical power out
  - Electrical power = I * V
  - Faraday's law: e = d/dt φ
  - This works out to the same numbers



# Controlling a PMSM

- Basic idea is current in the three coils combines to form a magnetic field facing in any direction, and the control system keeps that 90° ahead of the stator
- Three phases is common
  - Two can't self-start
  - Same reasons as three phase power: three is 2x as much capacity for 1.5x as much wire, but 4 is only 3x as much for 2x as much wire and so on
  - More is harder to make compact
- Also common to duplicate the three phases multiple times, which doesn't really change anything





# Controlling a PMSM continued

- For a simple motor with sinusoidal flux linkage, you want the current to be matching sine waves to get maximum ripple-free torque
  - $\sin^2(\Theta) + \sin^2(\Theta + 120°) + \sin^2(\Theta - 120°) = \text{constant}$
  - This is constant mechanical power and also constant electrical power
- When you add harmonics, it gets complicated
  - If flux linkage is $\sin(\Theta) + ½\sin(5\Theta)$, need to drive $\sin(\Theta) - ½\sin(5\Theta)$ (FOIL and it comes out the same)