The mysteries with the apparently simple control of an electric motor

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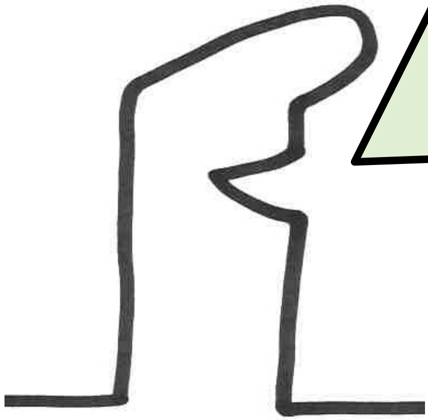
Unjo in brief

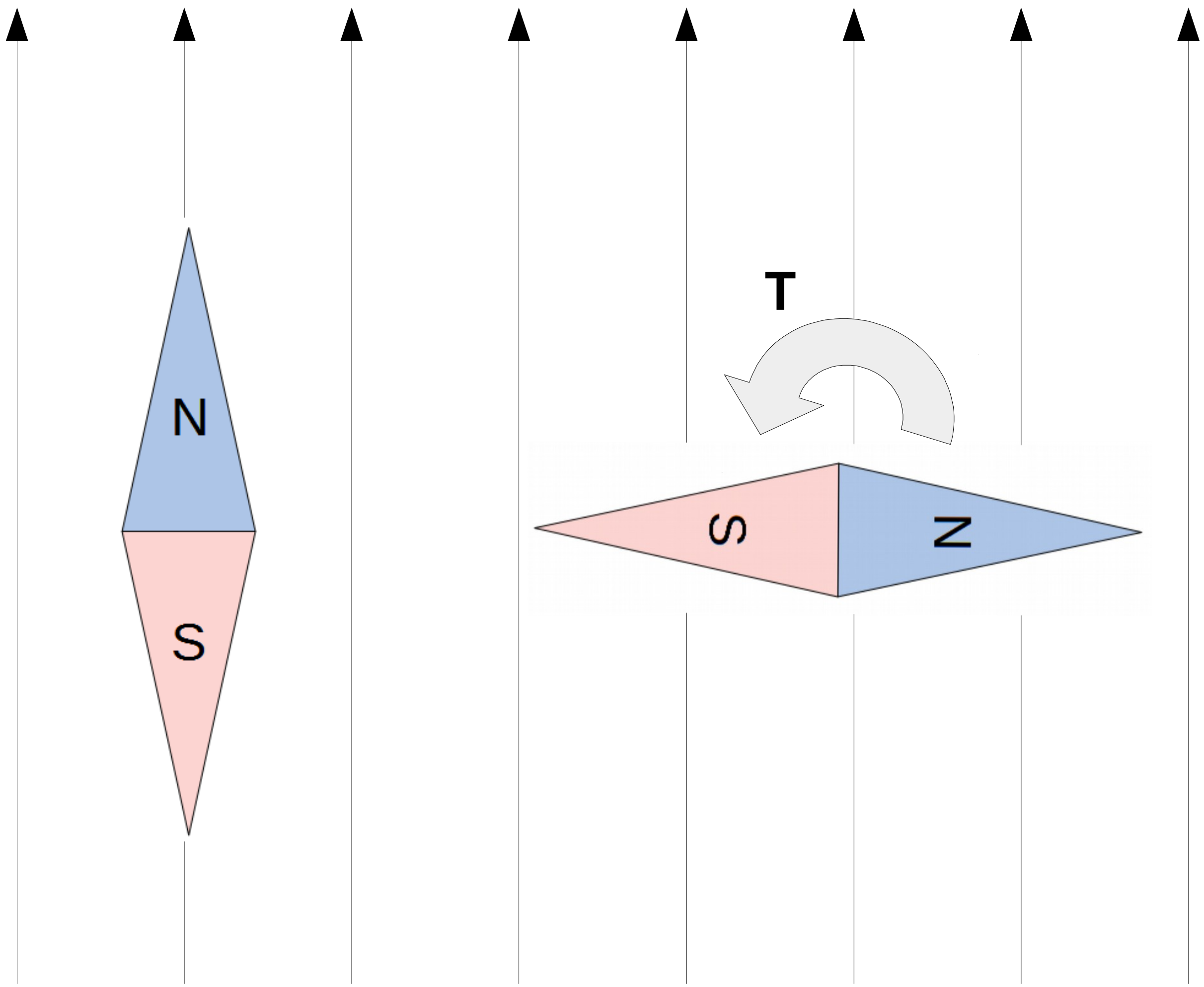
- Founded in 1996 by Undine Jänes and Jonas Hemming
- Provides customized motor control solutions, no standard products
- Headquarter in Mölndal, manufacturing in Sweden and Poland
- 16 R&D motor control engineers

Agenda



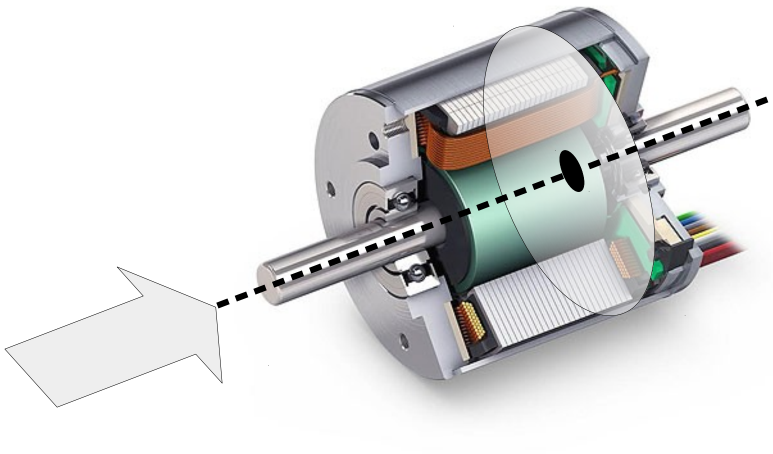
- The synchronous motor
- Motor control basics
- The motor constant
- More control details and trajectory
- The drive electronics
- Brake energy handling
- Sensorless
- Field weakening

A simple example

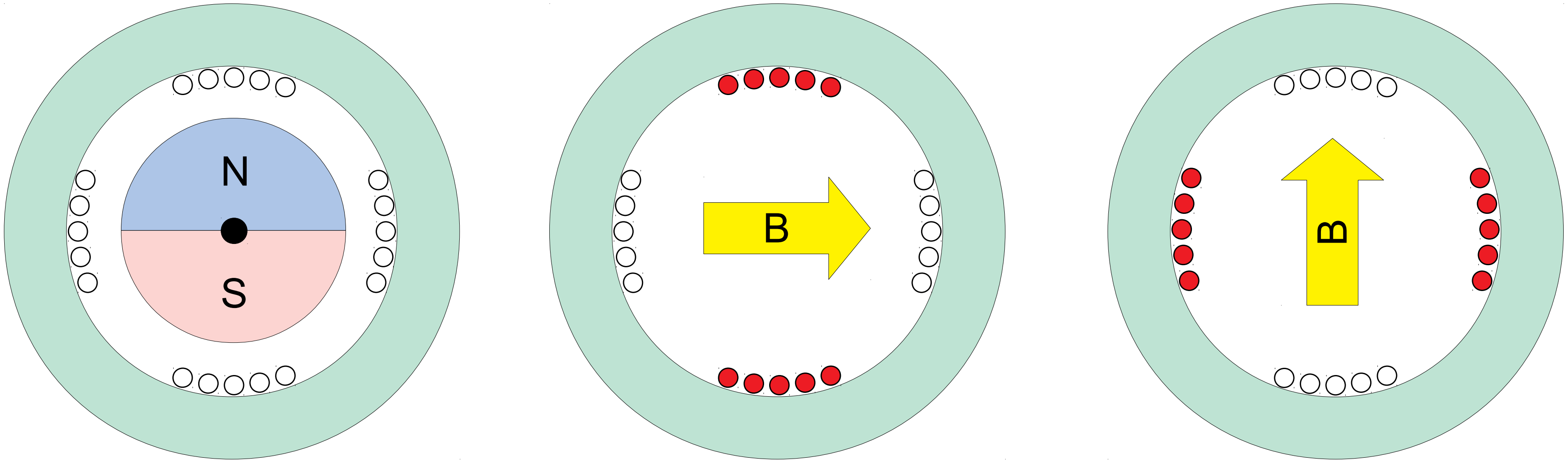


- A compass needle aligns with a magnetic field and stays there. I.e. there is no force or torque on it in this position.
- When it is turned from the equilibrium, a torque develops that tries to turn the needle back.
- The torque is proportional to the magnetic field, and is highest at 90º angle

The synchronous motor

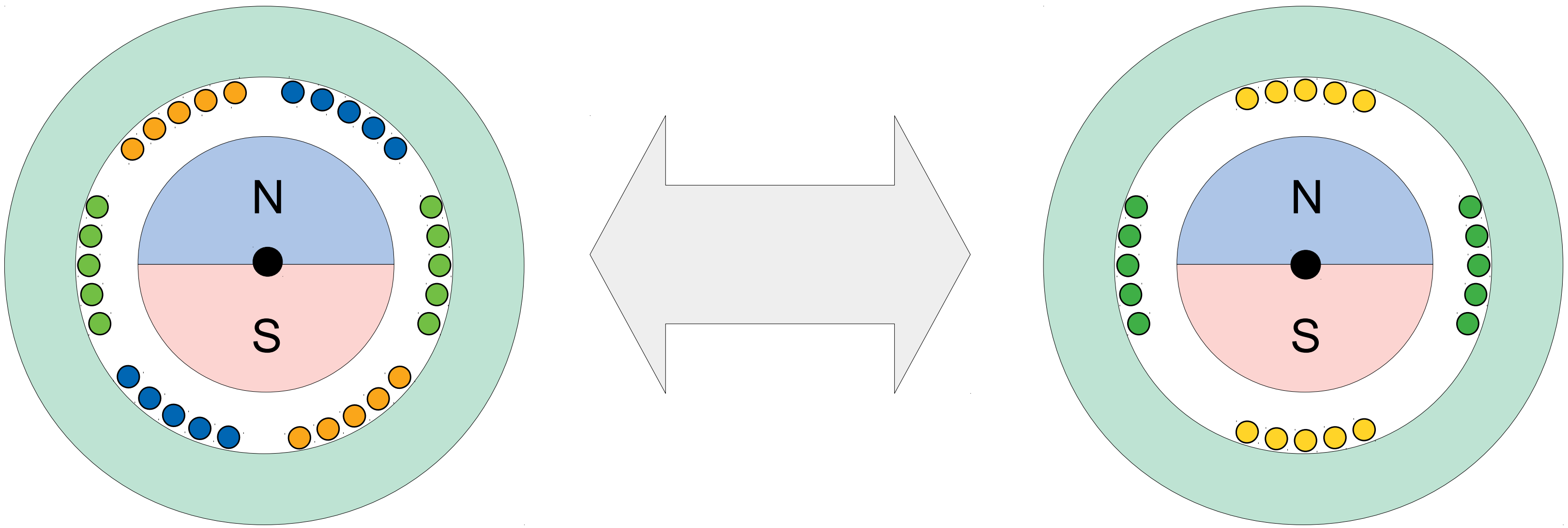


- Looking along the axis, the motor is composed of an outer iron shell, a magnet with an axle through it (the ”rotor”) and several copper windings between the two. The iron shell + windings is called the “stator”.
- The windings can create a magnetic field of arbitrary strength and angle



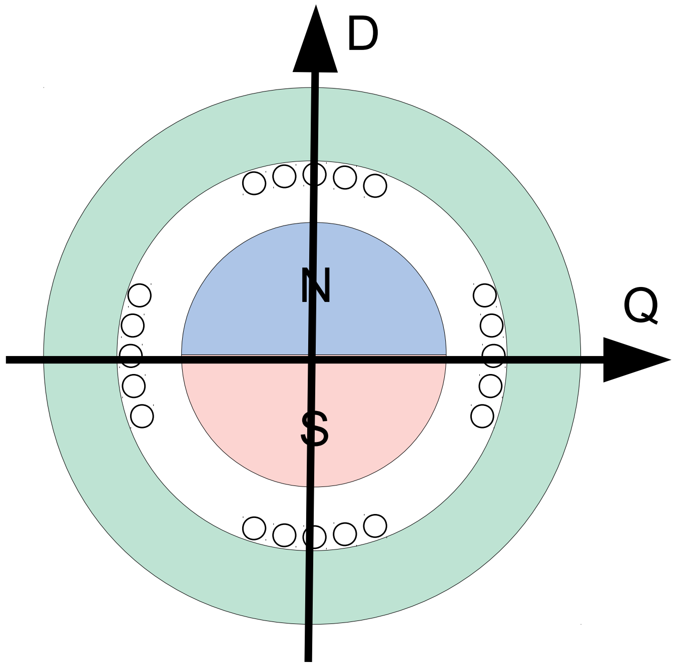
The synchronous motor

- In reality, the motor normally has three windings for a number of practical reasons.
- The two arrangements can produce the same rotating magnetic field, and the winding currents to create a given field can be translated between the two.
- Since it is much easier to describe the motor with two windings, we stick with that for now.

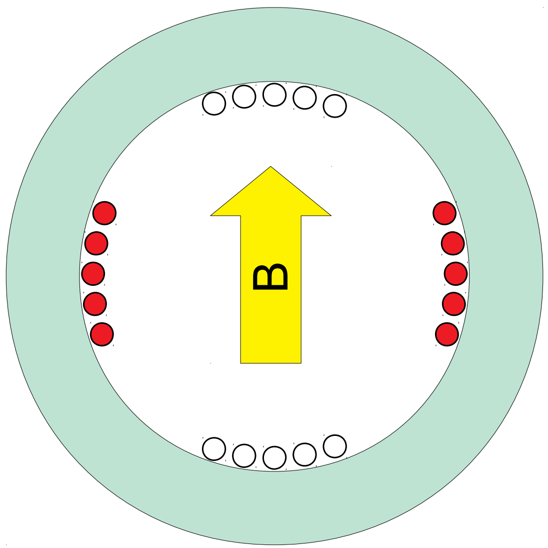


The synchronous motor

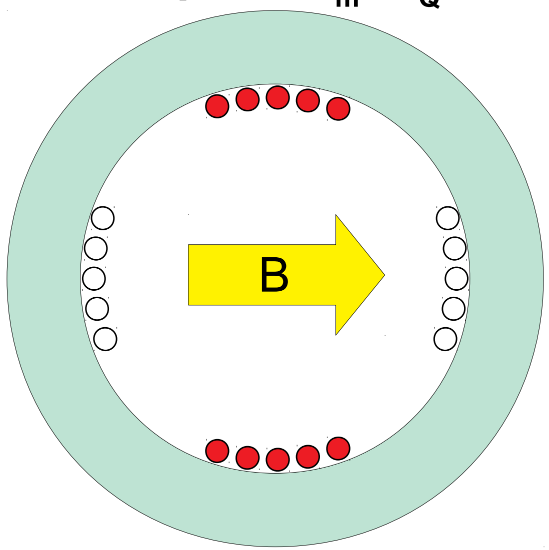
- To describe the relation between the winding currents and the torque, a coordinate system D-Q is defined, these coordinates are attached to the rotor.
- Applying field along the magnet ("D-direction") produces no torque, only power losses.
- Applying field perpendicular to the magnet ("Q-direction") produces a torque proportional to the field. This is what we want to use and control.



D-direction, I_D
No torque produced

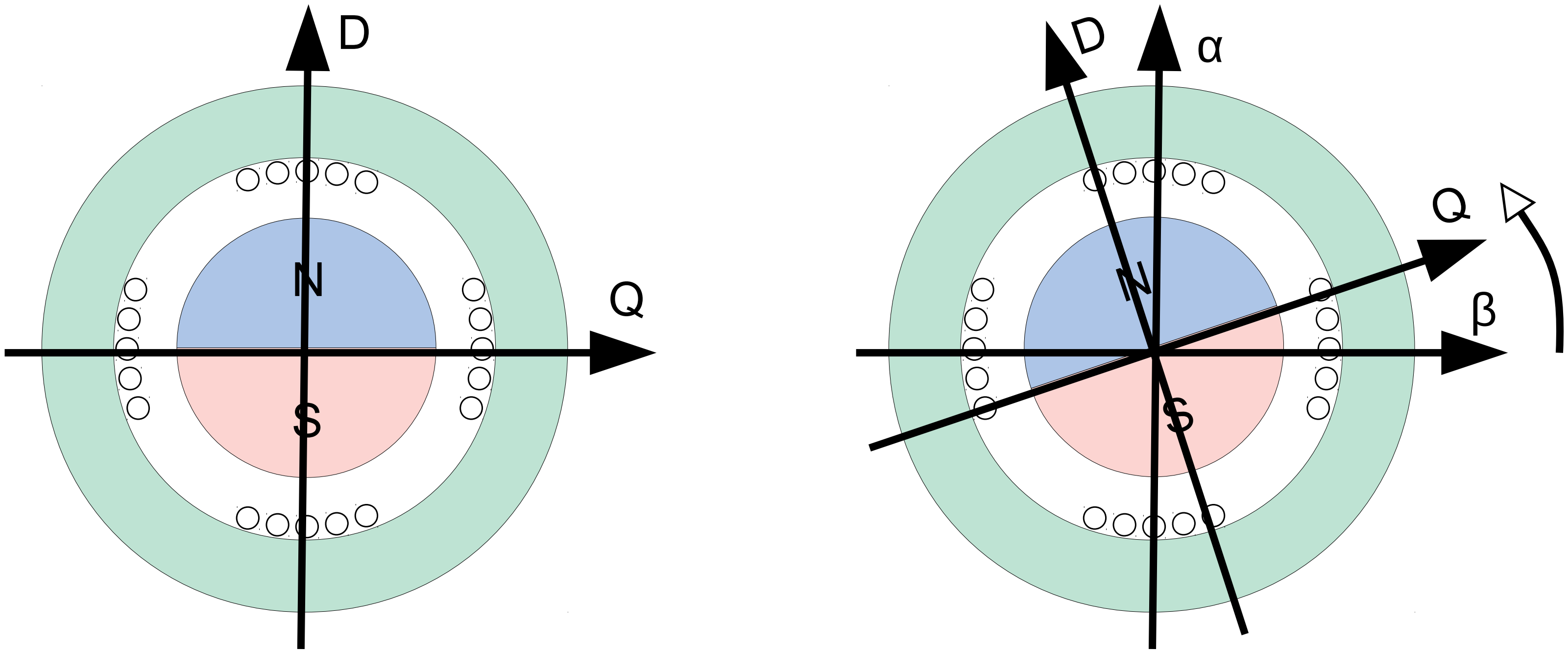


Q-direction, I_Q
Torque = K_m * I_Q



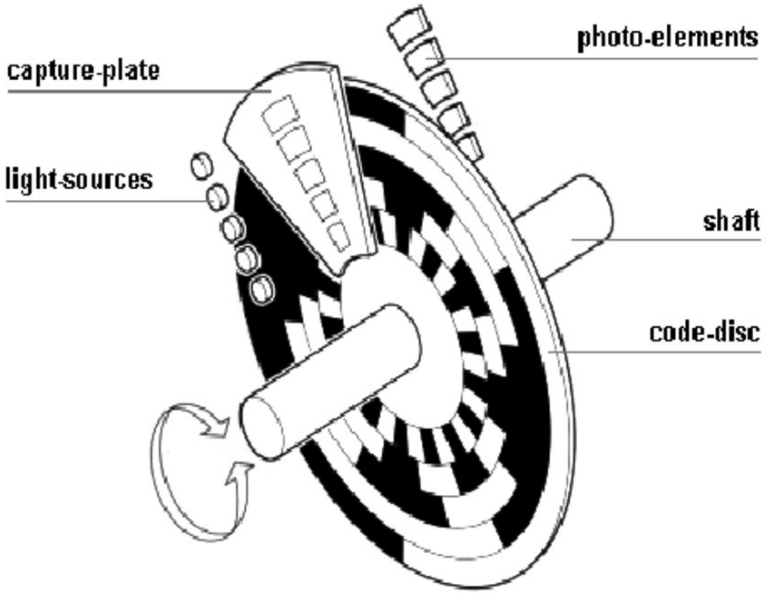
The synchronous motor

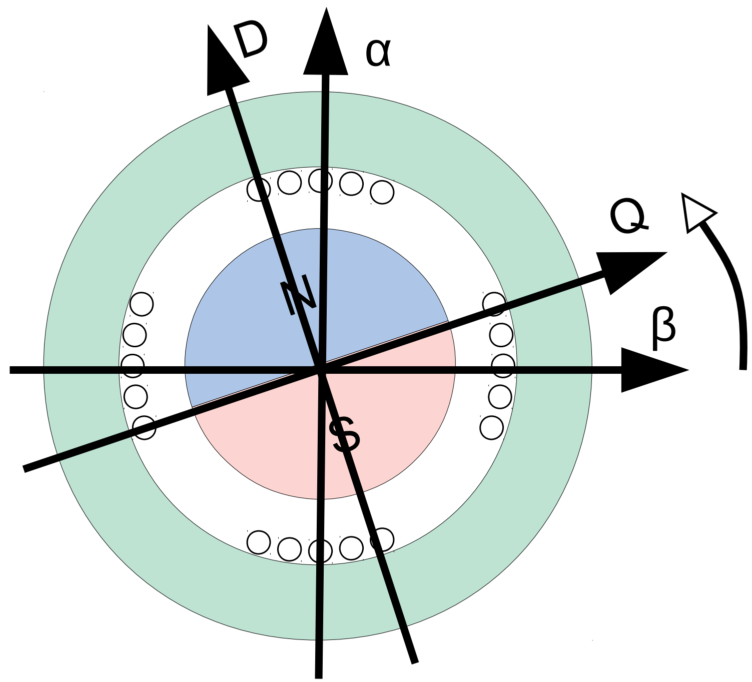
- When the rotor turns, the D-Q axes follow. It is the field along these axes (the Q-axis in particular) that define the torque.The stator windings that produce the field remain stationary, so we need another set of coordinates for them (α-β).
- The field (or current-) vector we want in D-Q coordinates therefore has to be translated to α-β coordinates to give the real winding currents.



The synchronous motor

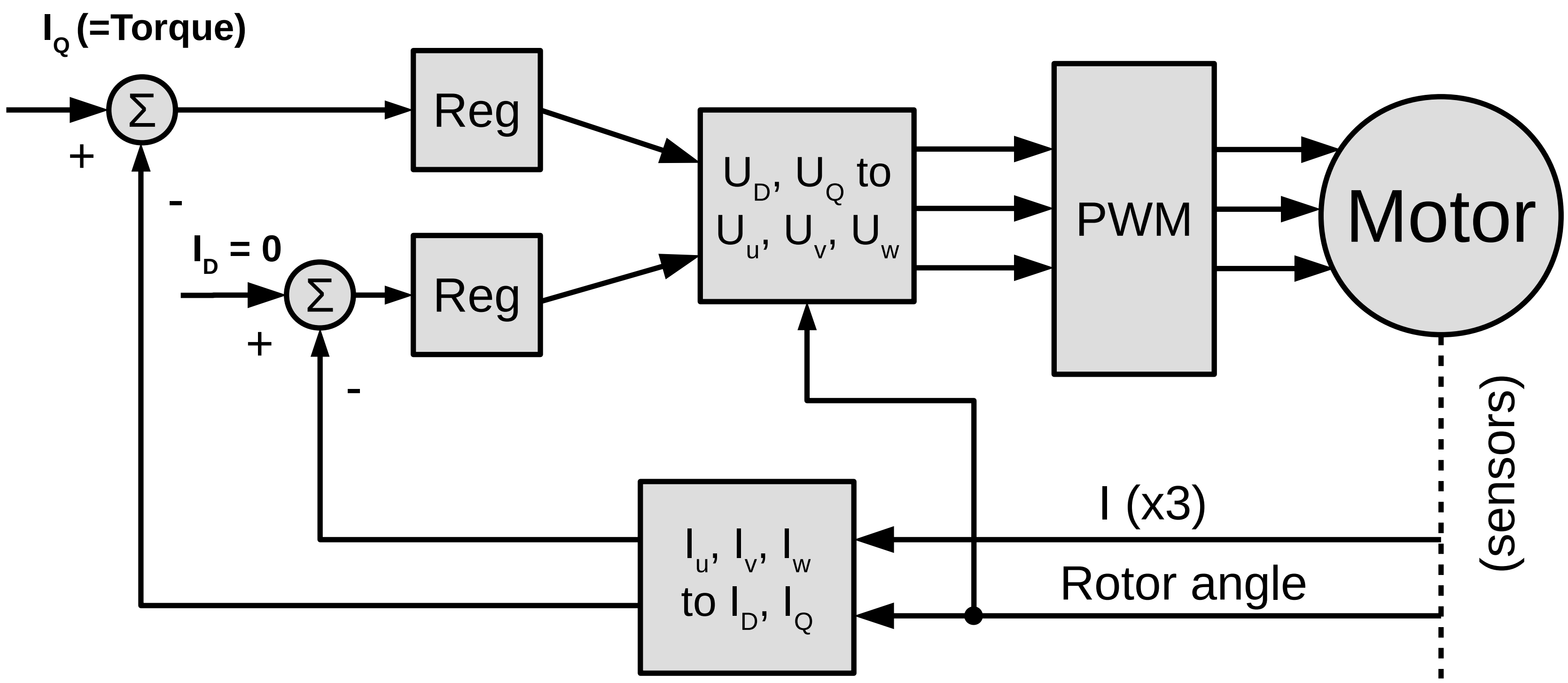
- Since the rotor angle has to be known to apply the field vector in the correct direction, an angular sensor is normally used. There are many types available and all of them have different pros and cons.
- It is however possible to deduce the rotor angle without the use of any sensor at all. This is called ”sensorless”.





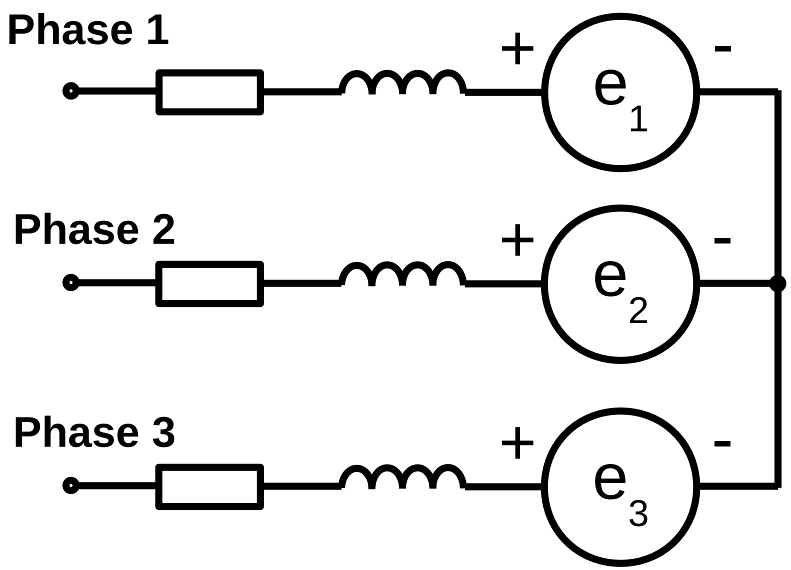
Field Oriented Control

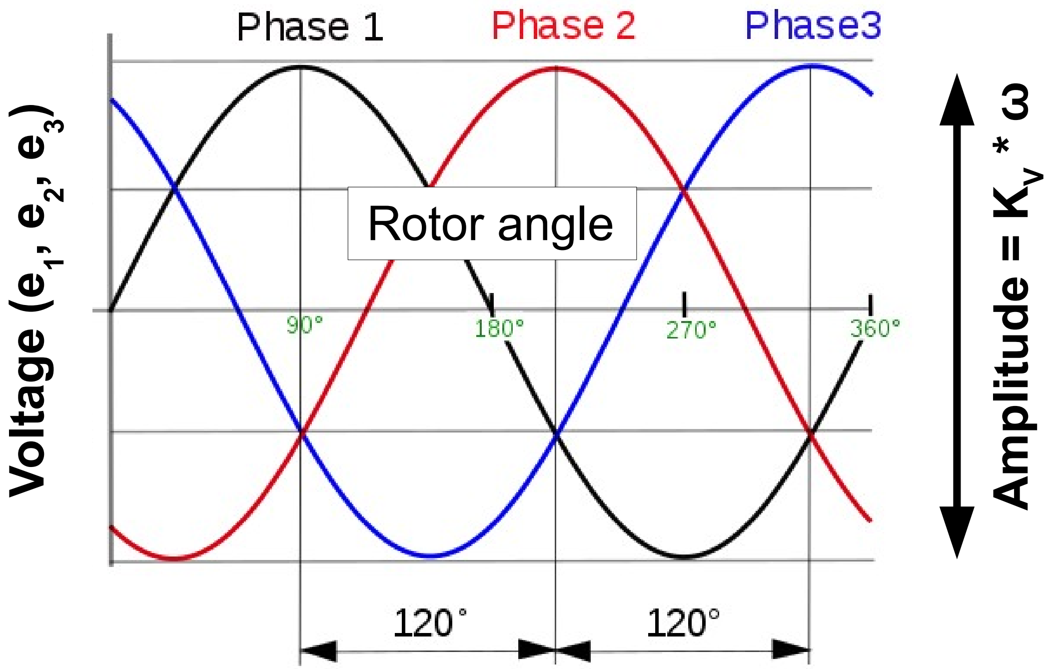
- With the description of the motor with the D-Q coordinates and the related coordinate transformations we have arrived to a method that directly controls the the torque via I_Q. Note that I_D also has to be controlled and set to zero.
- This control method is called Field Oriented Control (FOC)



Back-emf

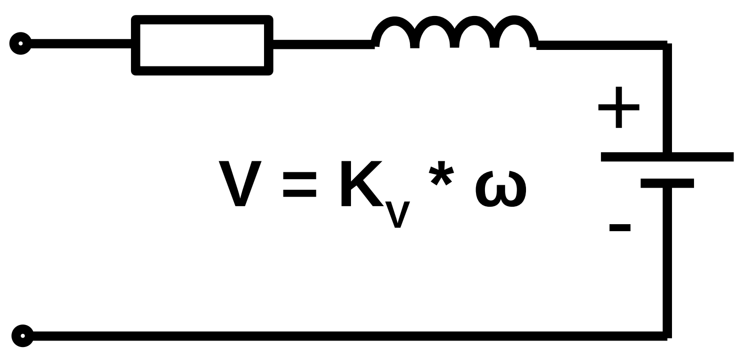
- When the rotor turns it produces a voltage across the windings that is proportional to the angular speed **ω** via a constant called K_V. This voltage is called ”back emf” [emf = electro-motive force].
- The three voltages contain information about the rotor angle as long as the speed is high enough. This can be used for ”sensorless control”

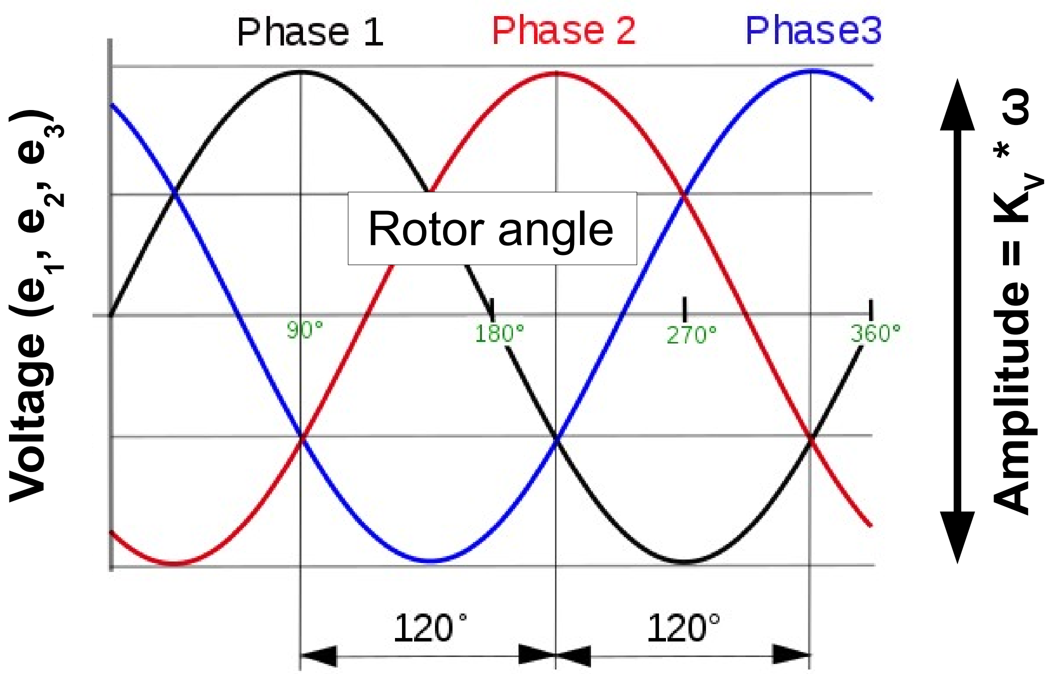




Back-emf

- A popular simplified model of the back-emf is to replace the three voltages with a single DC voltage. This model is linked to the D-Q description presented earlier, and also makes the motor look like the classic brushed motor or ”DC-motor”.
- It is clear from both models that any power source driving the motor will have to produce at least the voltage $K_V * \omega$.

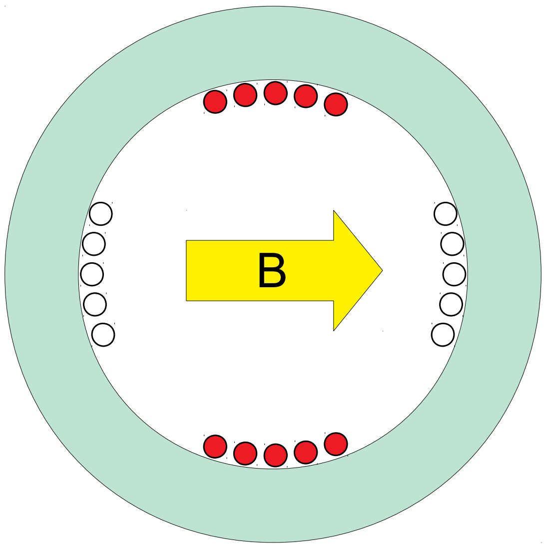


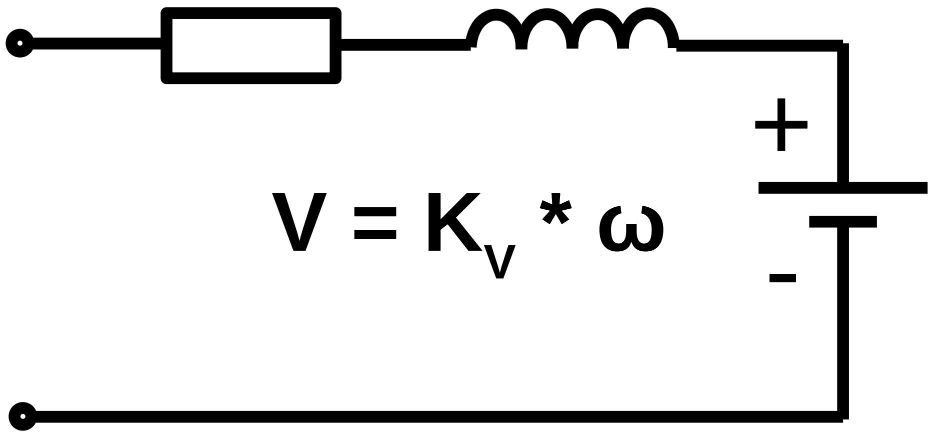


The motor constant

- So far we have come across two ”motor constants”, one that relates current to torque called $\mathbf{K_m}$ and one relating speed to voltage $\mathbf{K_V}$.
- Since both torque and voltage are created by the same magnetic field, they should be related somehow...

Q-direction, I_Q
Torque = $K_m * I_Q$

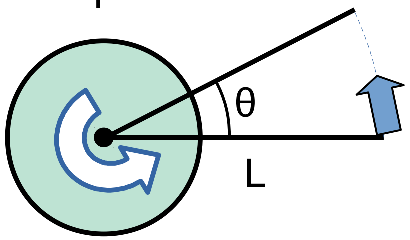




The motor constant

- It can be shown that the two motor constants are the same, and even though the units seem different they are of course the same too.

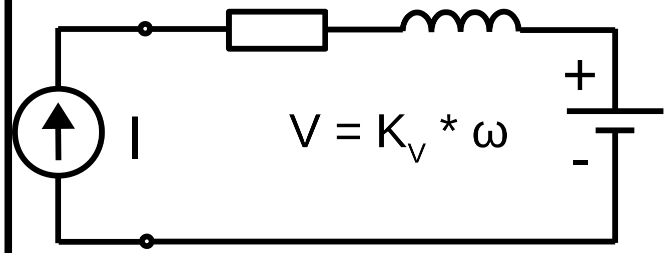
Torque = T



S = L * θ
F = T / L

$E = F * S = (T/L) \ * L * \theta$

i.e. $\mathbf{E = T * \theta}$



$E = I * V * t = I * K_V * \omega * t$

$\omega * t = \theta$, $\mathbf{E = I * K_V * \theta}$

Energy is conserved, so: $T * \theta = I * K_V * \theta$

i.e. $\mathbf{T = K_V * I}$, implying that $\mathbf{K_V = K_M}$

Unit check:

$[K_V]$ = V/(rad/s) = Vs

$[K_M]$ = Nm/A = J/A = VAs/A = Vs

The motor constant

- In most datasheets two motor constants are presented as if they were two different things, sometimes with inverse/non-SI units. This often leads to the misconception that they can be chosen independently.
- Also, it is often not stated if the voltages and currents refer to amplitude, rms or peak-peak values causing even more confusion.

Characteristics

Terminal resistance	13.1 Ω
Terminal inductance	0.729 mH
Torque constant	34.8 mNm/A
Speed constant	274 rpm/V
Speed / torque gradient	103 rpm/mNm
Mechanical time constant	4.82 ms
Rotor inertia	4.45 gcm^2

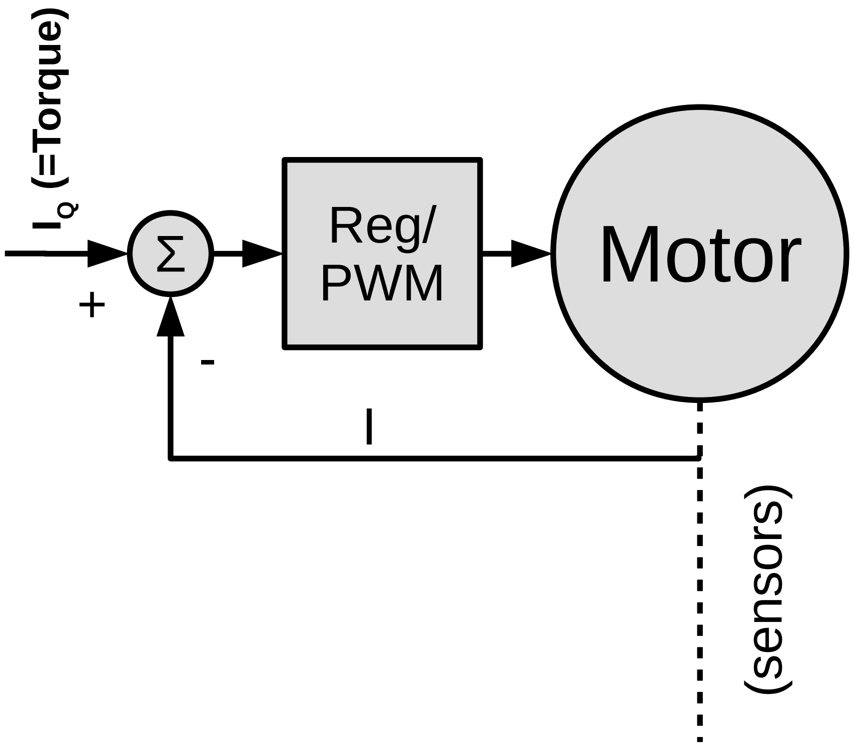
Motor ”voltage rating”

- The same motor often comes with several different ”nominal voltages”. The difference is the number of turns in the windings. A common misconception is that e.g. a ”12V” motor must be used if the motor drive has 12V supply.
- This is not true, your application may be better off with e.g. a ”24V” motor if you don’t need the maximum speed. If so, the design would require lower current and can use cheaper drive electronics due to the lower current needed.

Motor Data		283856	283857	283858	283859	283860
Values at nominal voltage						
1 Nominal voltage	V	12	18	24	36	48
2 No load speed	rpm	12400	12900	12900	12200	12900
3 No load current	mA	226	161	121	73.5	60.4
4 Nominal speed	rpm	9800	10300	10400	9630	10500
5 Nominal torque (max. continuous torque)	mNm	23	21.8	22.7	22.5	23.2
6 Nominal current (max. continuous current)	A	2.71	1.8	1.4	0.872	0.716
7 Stall torque	mNm	114	112	121	111	127
8 Stall current	A	12.6	8.55	6.97	4	3.66
9 Max. efficiency	%	76	75	76	75	77
Characteristics						
10 Terminal resistance phase to phase	Ω	0.955	2.1	3.44	9.01	13.1
11 Terminal inductance phase to phase	mH	0.05	0.103	0.182	0.462	0.729
12 Torque constant	mNm/A	9.1	13	17.4	27.7	34.8
13 Speed constant	rpm/V	1050	732	549	345	274
14 Speed/torque gradient	rpm/mNm	110	118	109	112	103
15 Mechanical time constant	ms	5.14	5.5	5.06	5.23	4.82
16 Rotor inertia	gcm^2	4.45	4.45	4.45	4.45	4.45

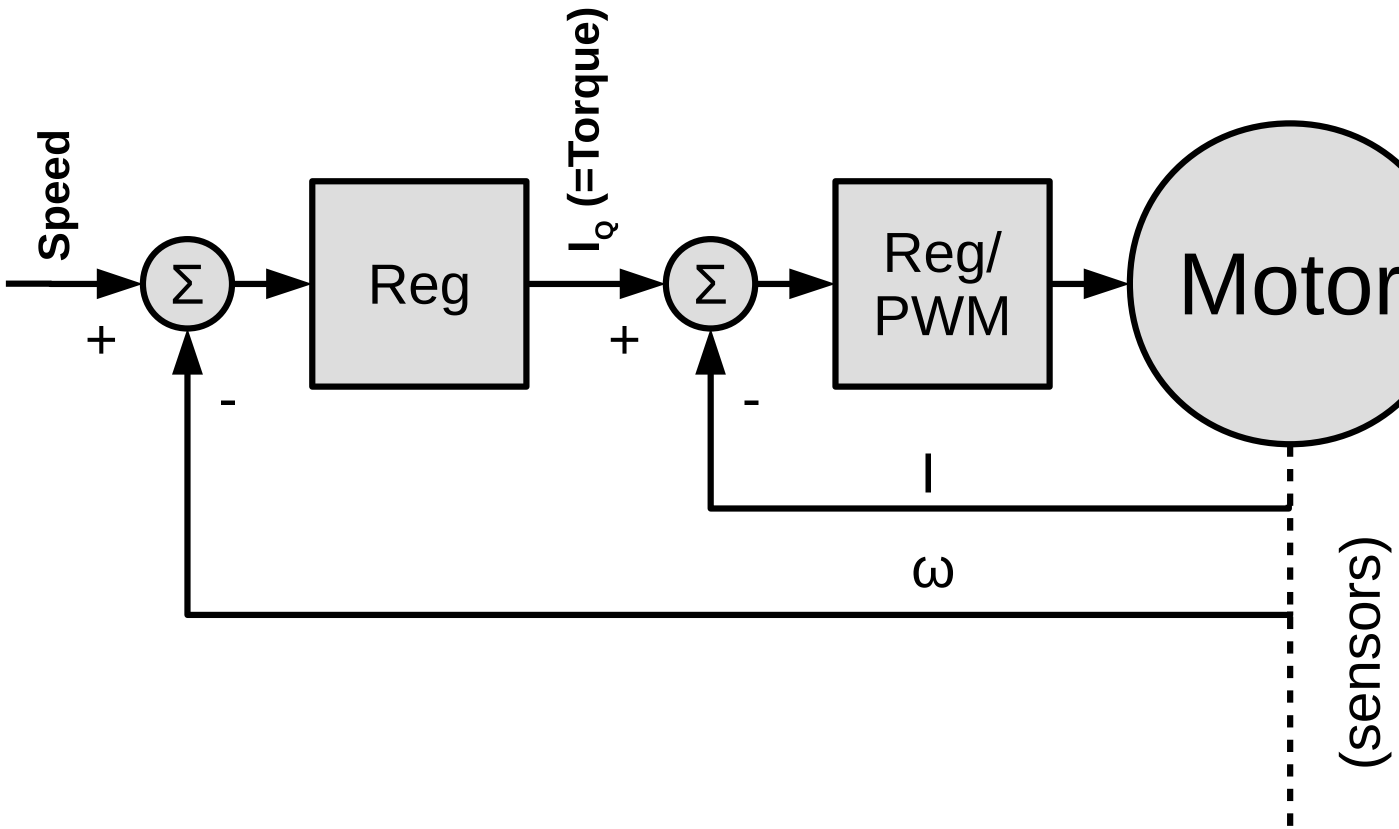
Control loops

- The field oriented control shown earlier (simplified below) controls the motor torque directly, but we may want to control other aspects...



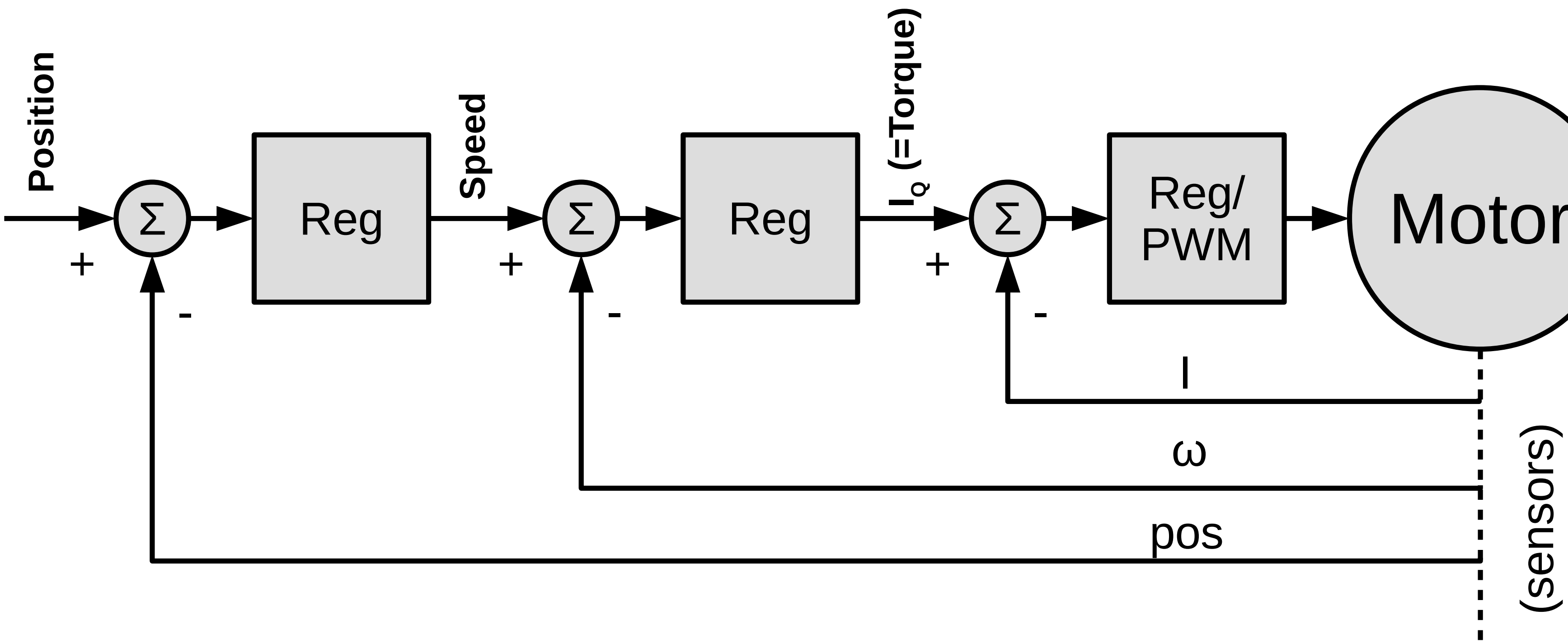
Control loops

- To control speed, we simply add one more loop that measures speed and commands the torque setpoint.

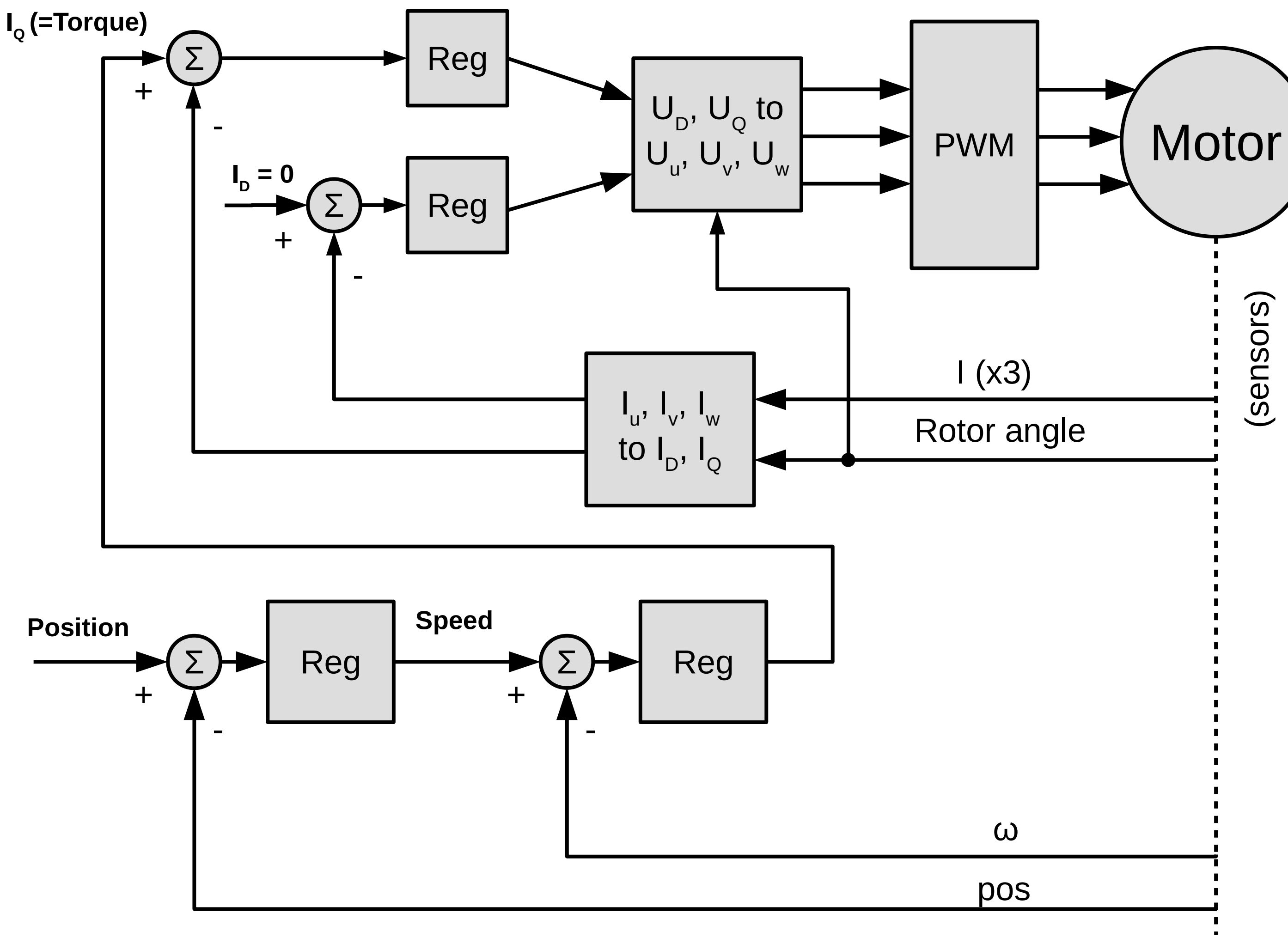


Control loops

- To control position, add yet another control loop commanding the speed setpoint.
- All control loops have to be stable, and the control parameters need to be limited for practical resons (e.g. max current or speed).
- When a control parameter is limited, integrator windup has to be handled to avoid overshoots and related issues.

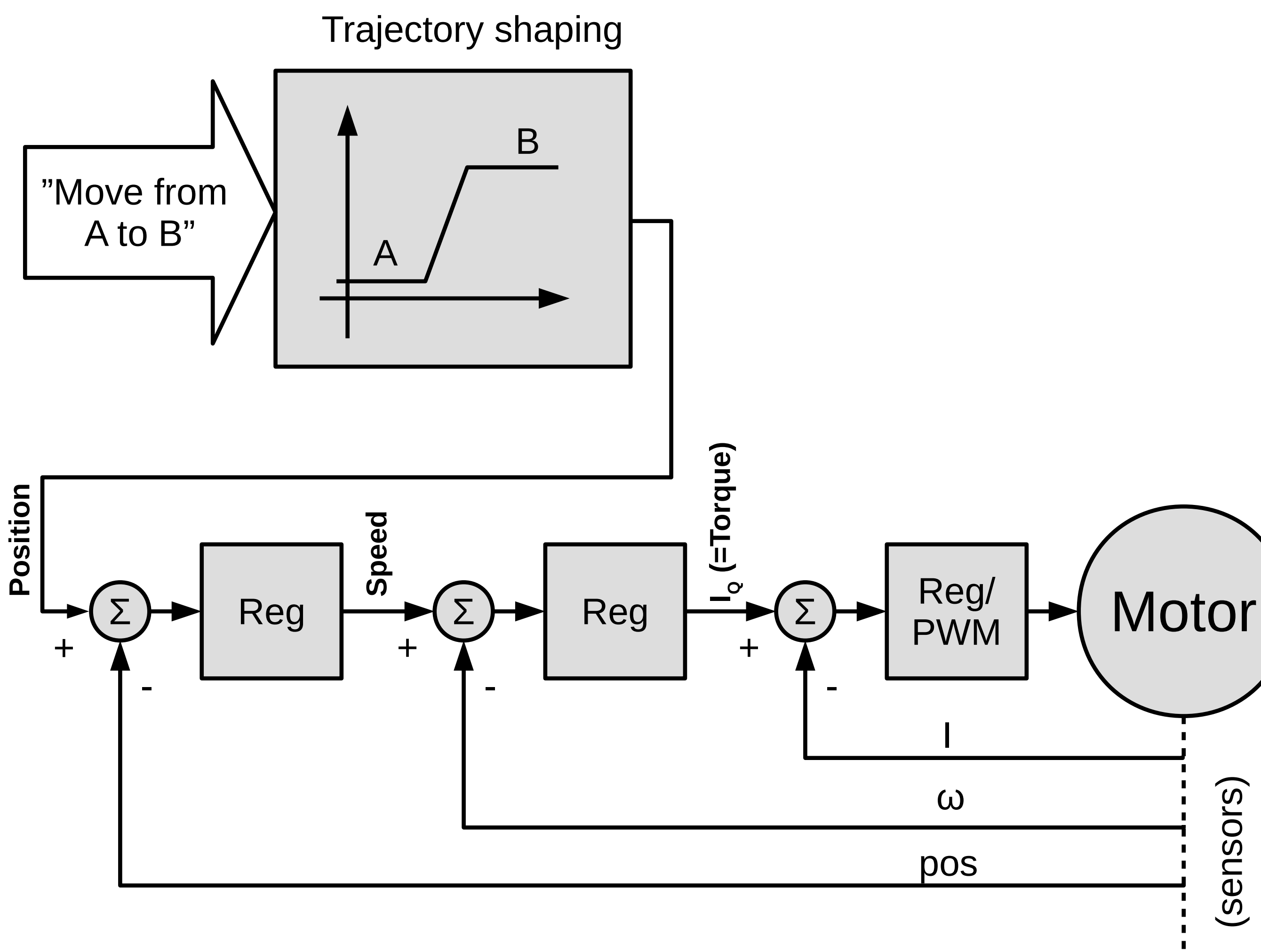


Control loops



- The complete FOC (limiters and windup protection not shown) looks something like this.
- Although it starts out simple, a practical controller gets a bit complex.

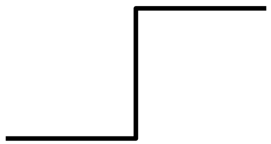
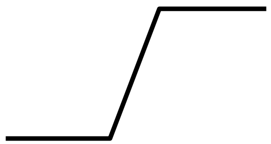
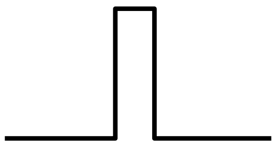
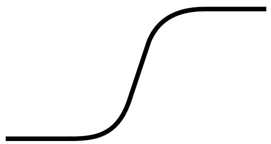
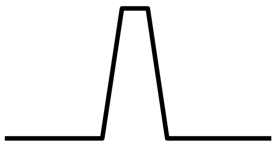
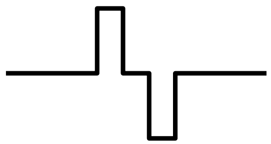
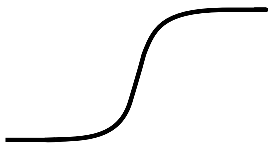
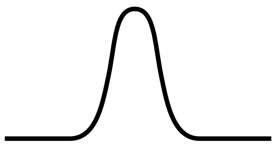
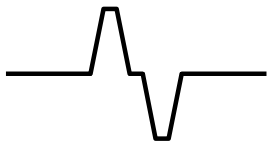
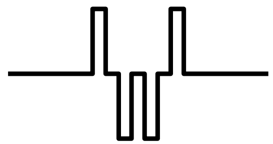
Trajectory shaping



- If we suddenly change e.g. the position setpoint, the controller would try to reach that setpoint "as fast as it can". This is often not desirable.
- A better solution is to shape the setpoint to get smooth movements. This is called trajectory shaping.

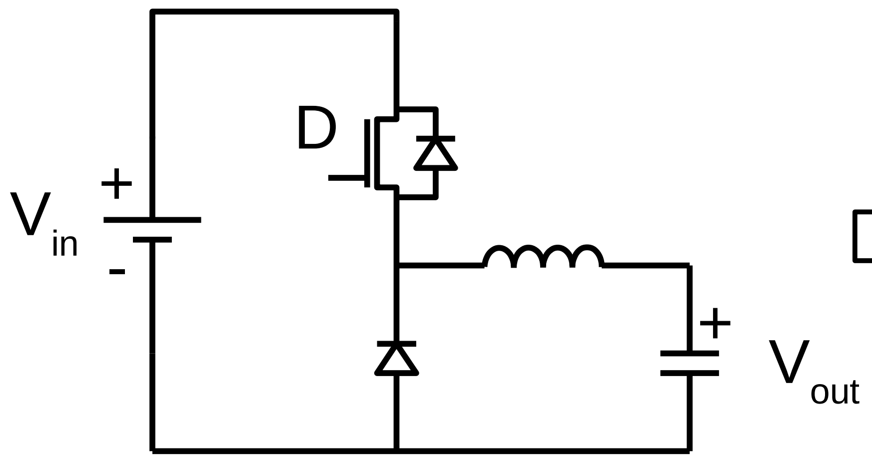
Trajectory shaping

- The trajectory is often shaped with polynomials. With increasing order of the polynomials, more derivatives of the controlled parameter can be limited for increasingly smooth control.

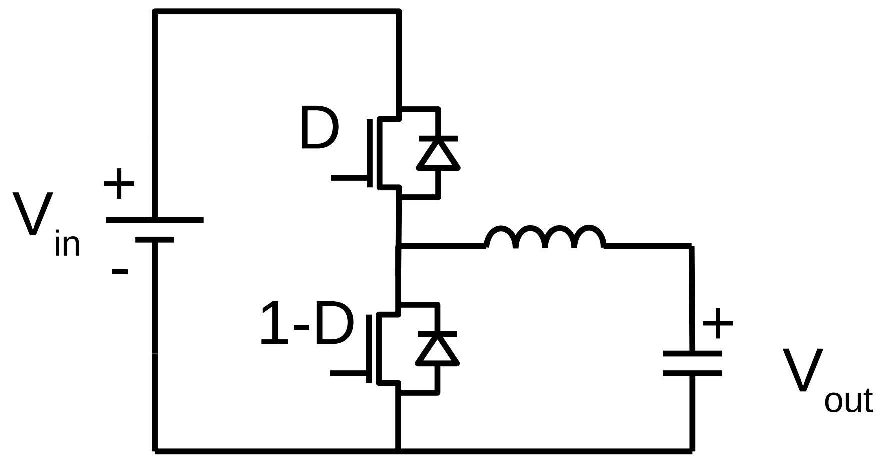
Order	**Position**	**Velocity**	**Acceleration**	**”Jerk”**
0		”∞”	”∞”	”∞”
1			”∞”	”∞”
2				”∞”
3				

Drive stage

- The most common drive stage for motors is closely related to the well-known buck converter (left).
- First, a synchronous rectifier is added (right). This does not change the output voltage relation, but crucially makes the converter bi-directional i.e. power can flow both V_{in} to V_{out} and vice versa



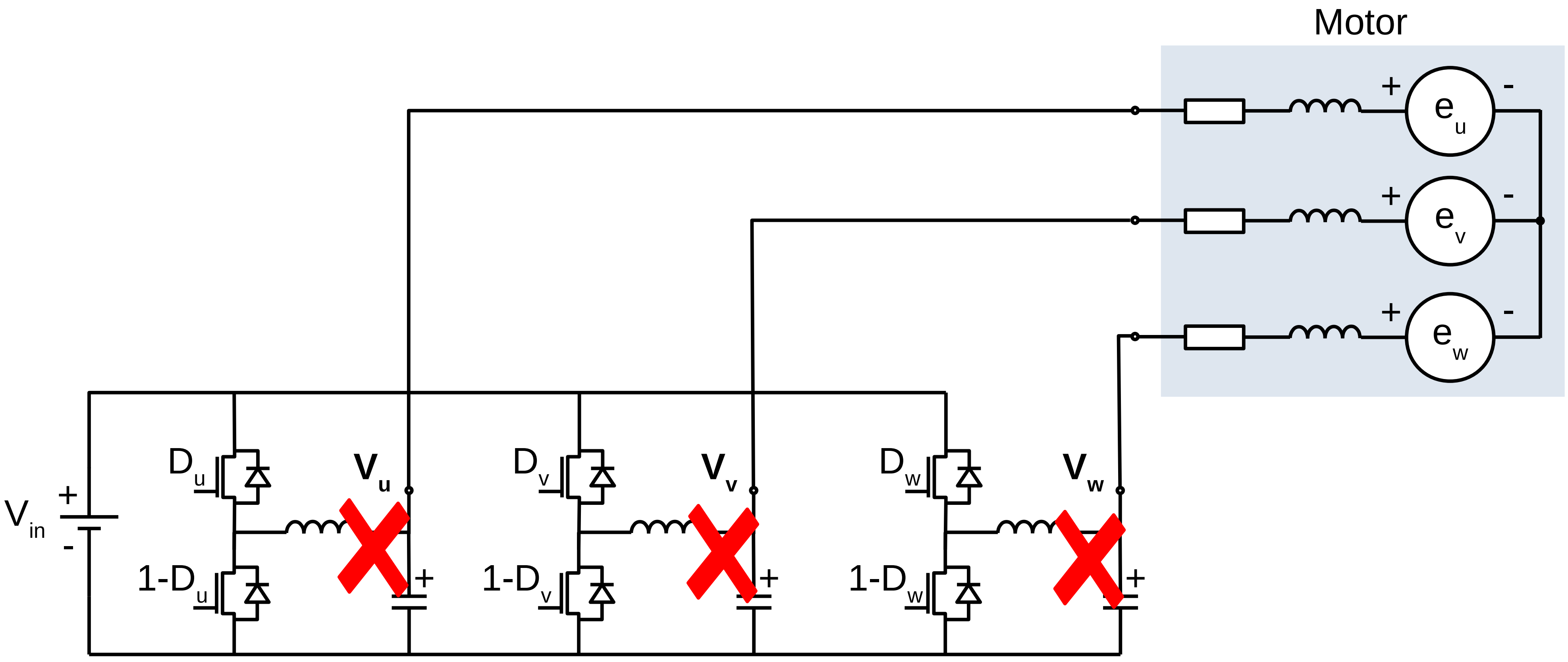
$V_{out} = D * V_{in}$



$V_{out} = D * V_{in}$

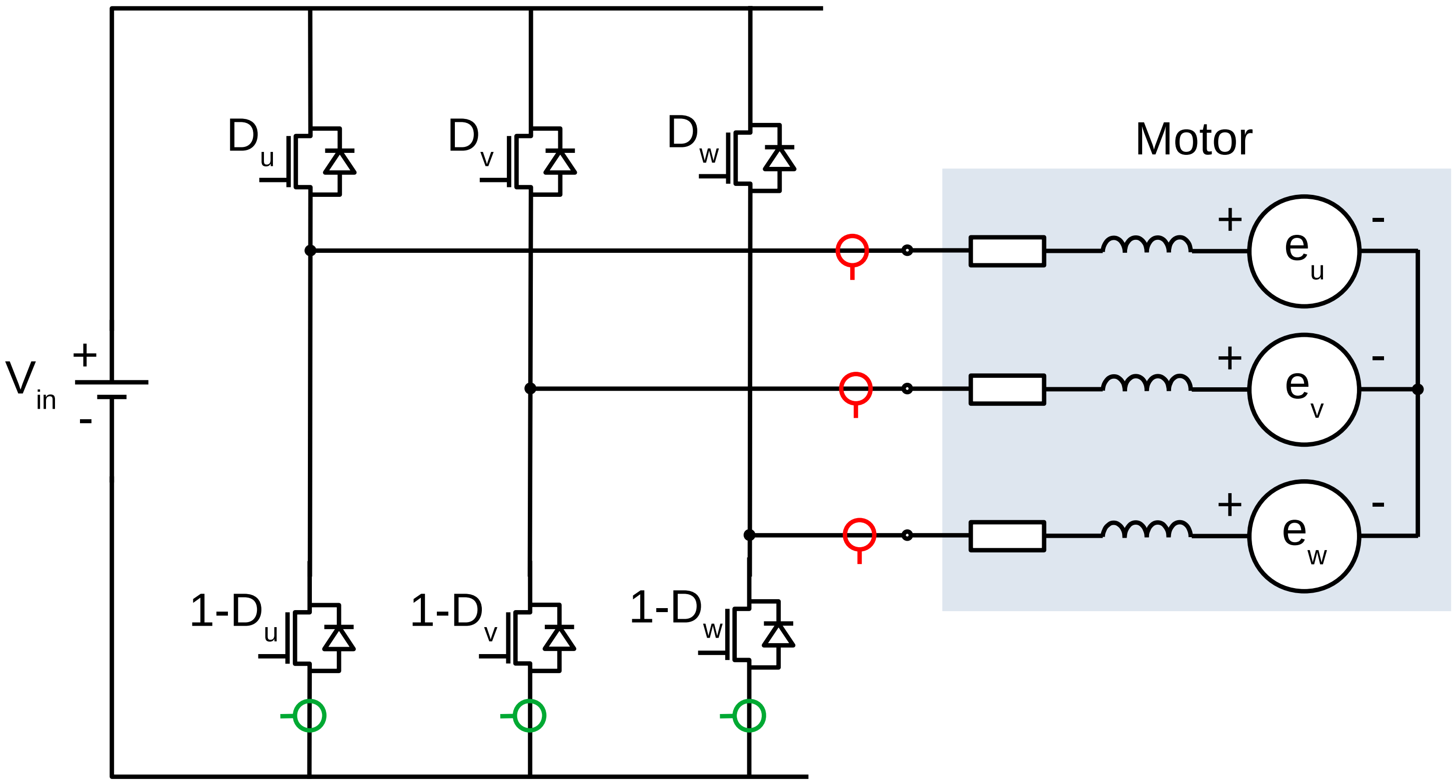
Drive stage

- Three of these buck-converter are connected to one motor phase each.
- The inductor and capacitor on the outputs can be removed, since the motor already has inductances and only the phase current decides the motor torque.



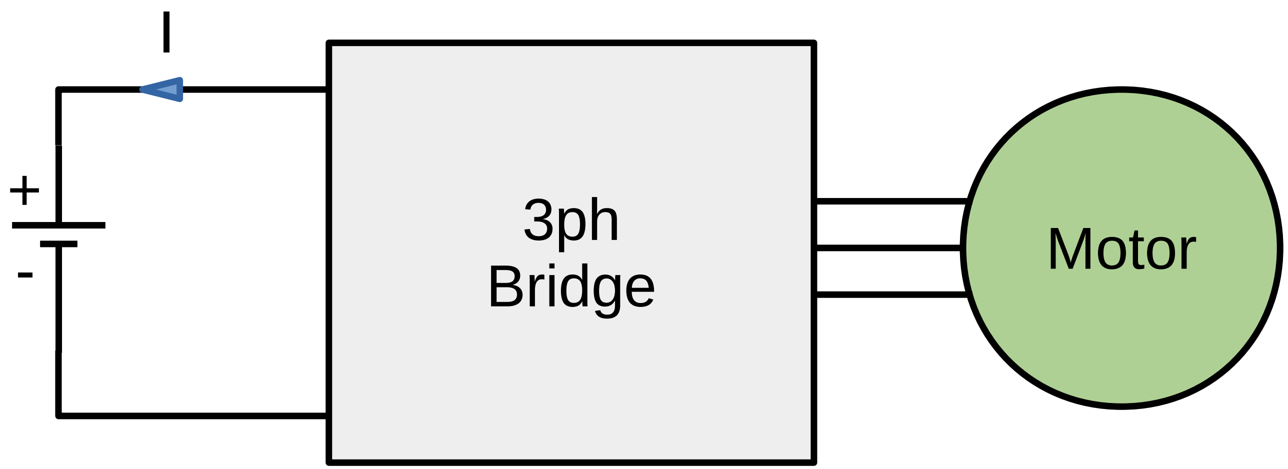
Drive stage

- Redrawn, the motor stage looks like this, commonly called a ”three phase bridge”.
- Motor currents needed for the controller can be measured either in the motor phases (red) or in the bridge (green). Only two sensors are needed if measurements are made in the motor phases (unless ”S/C to chassis” failure has to be detected).



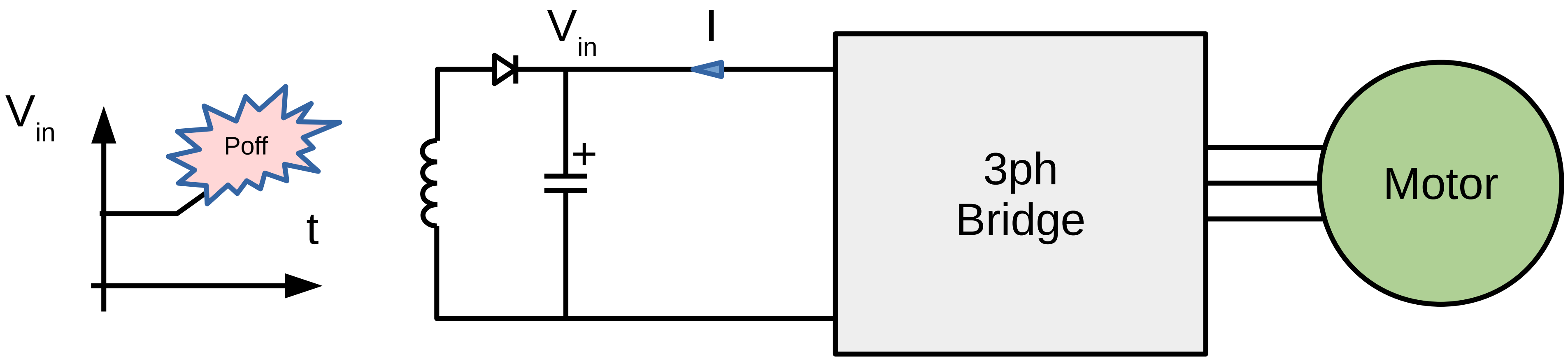
Brake energy

- Since the three phase bridge is bi-directional, power can flow both to and from the motor. Typically power ”comes back” when the motor is decelerated and the kinetic energy in the moving parts is converted back to electrical energy i.e. the motor acts as a generator.
- If the power source is a battery, the returned energy may be fed back to the battery and some of the energy can be re-used later.



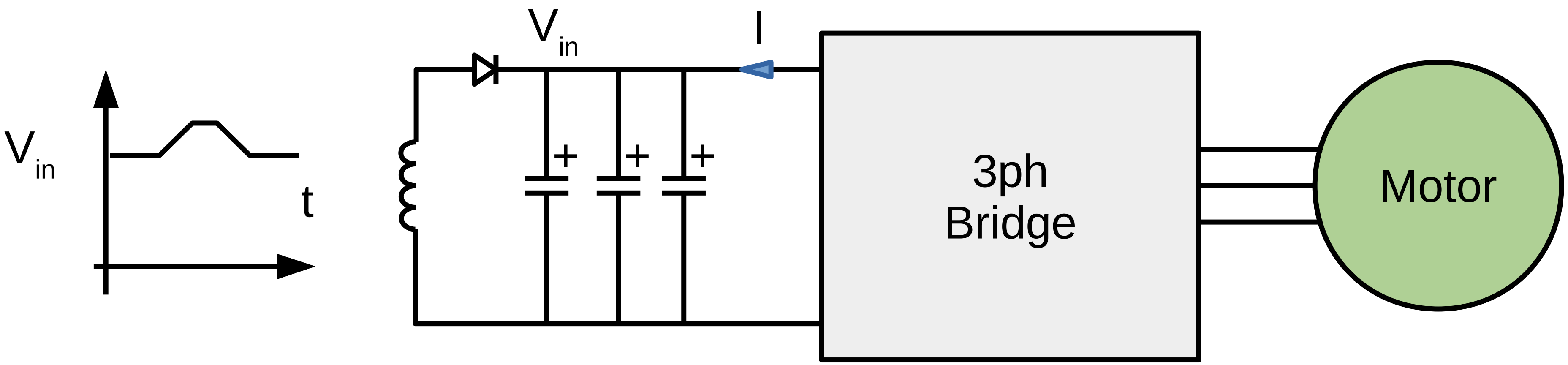
Brake energy

- If the power source is a power converter that is not bi-directional, the returned energy may charge the V_{in} node to a very high voltage and cause damage to the converter and/or the motor drive stage.



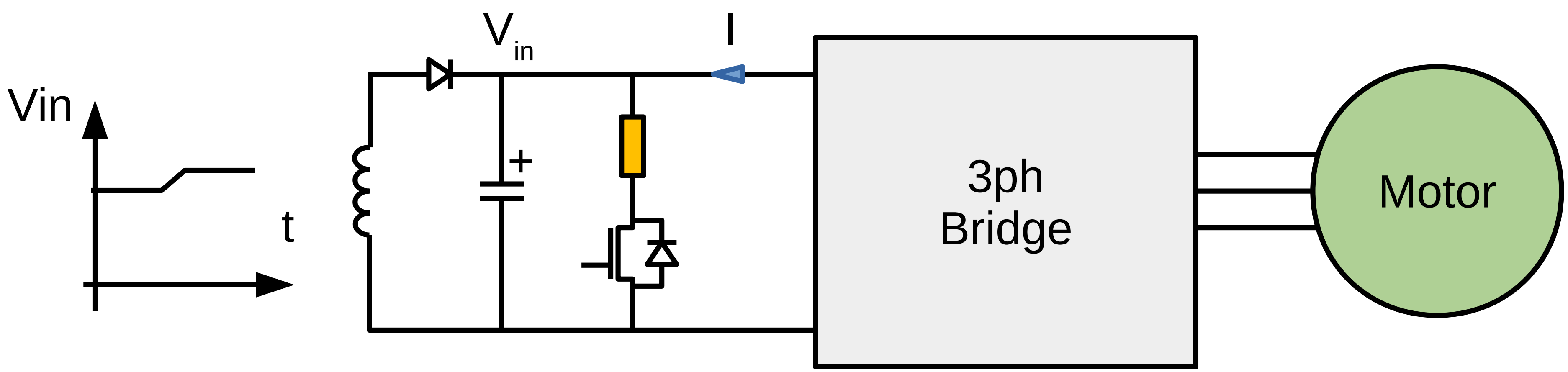
Brake energy

- By adding more capacitors to the V_{in} node, the voltage increase can be limited to some acceptable value depending on the amount of energy that comes back. The energy recovered can be re-used later as for the battery case, but with a much more limited energy capability.



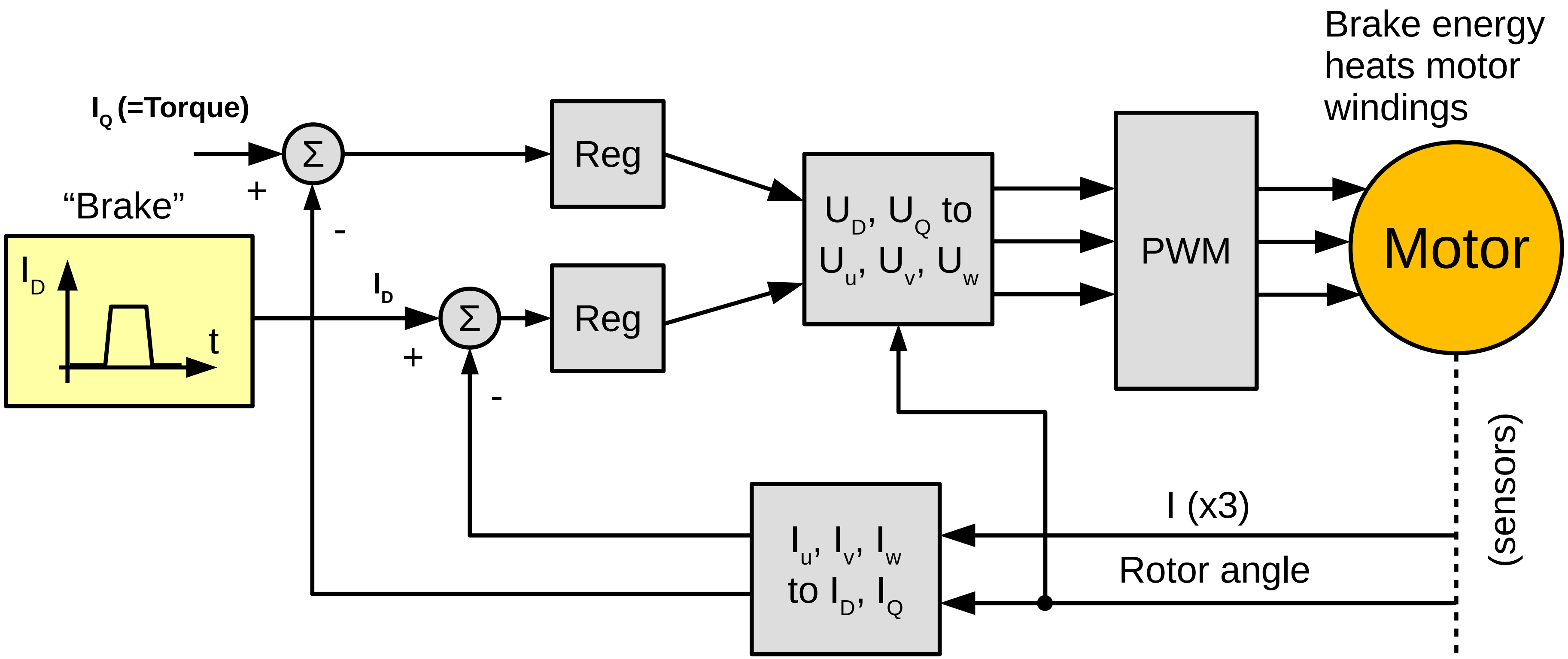
Brake energy (classic solution)

- If the brake energy is too high to recover in capacitors, or if the capacitors needed would be unrealistic due to cost or size constraints, the brake energy can be simply dissipated in a resistor (orange in picture).
- This resistor will become hot and may not be practical to integrate into the motor controller. Therefore, standard drives often provide the controlling transistor, and two connectors for an external brake resistor.



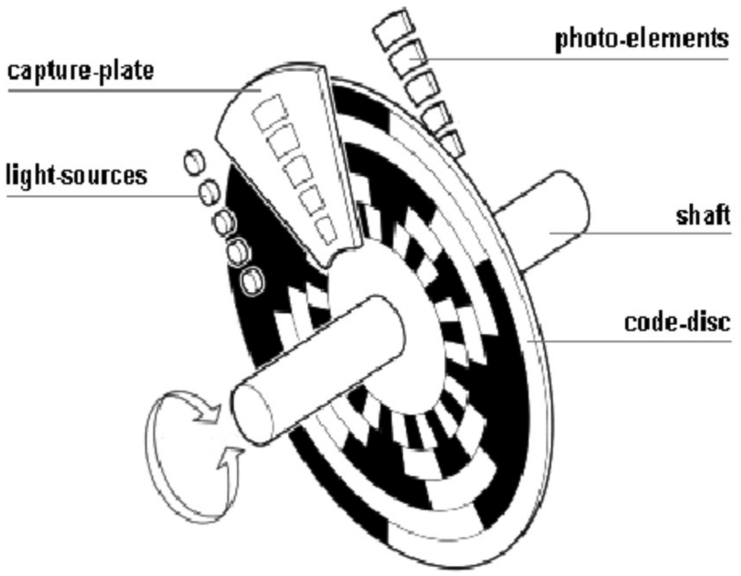
Brake energy

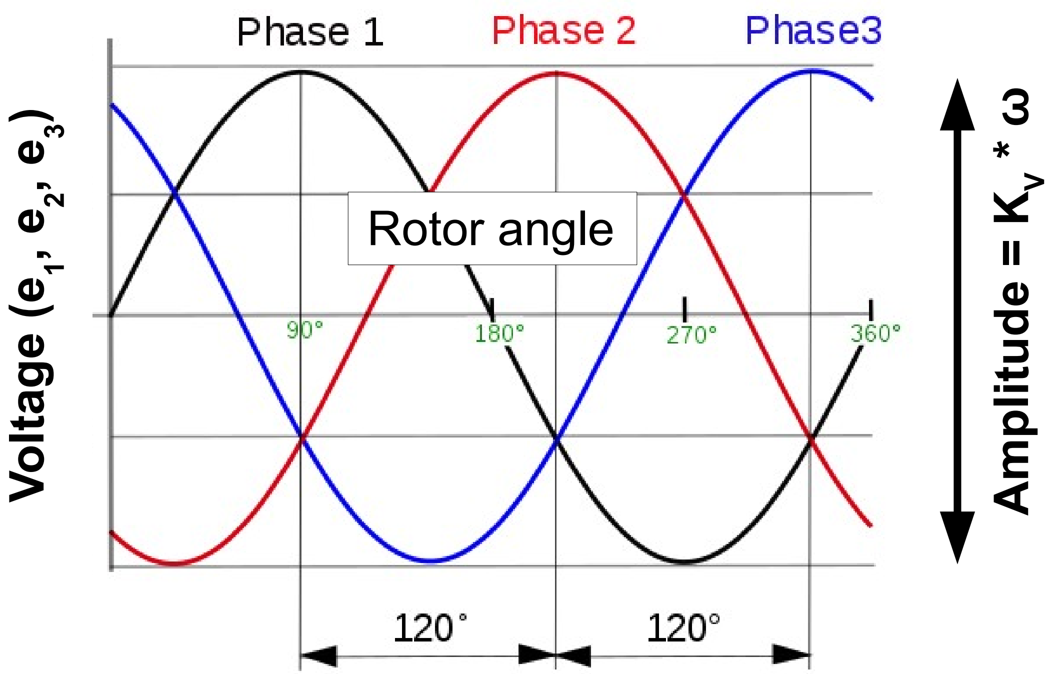
- It is also possible to dissipate the brake energy inside the motor itself. The current called I_D does not produce any torque and increases winding power loss. Energy can be ”dumped” in the motor by temporarily increasing I_D, and this can be done without affecting the motor control performance.



Sensorless

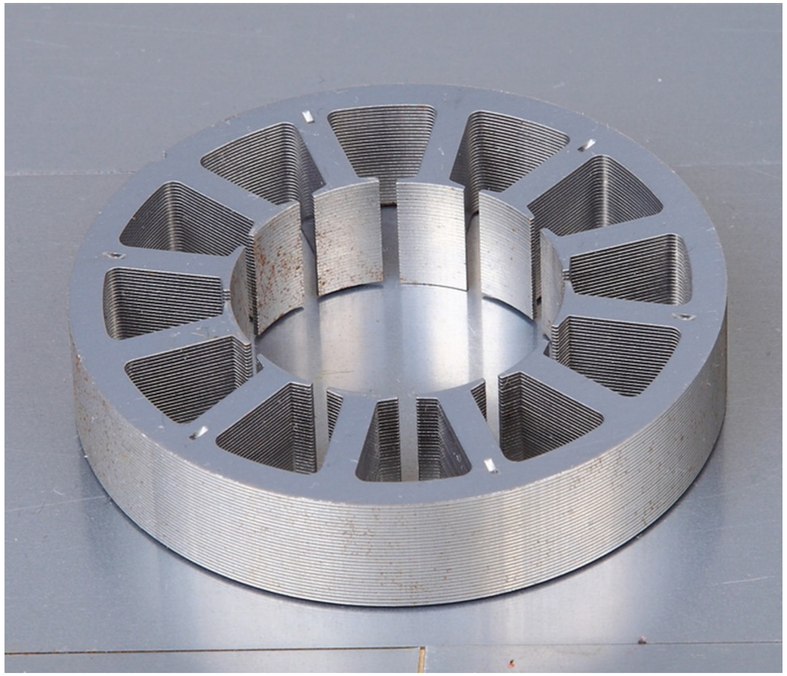
- Knowing the rotor angle is necessary to apply the magnetic field in the correct direction (perpendicular to the rotor magnet). The most obvious way to get the rotor position is to use a sensor of some sort.
- When the rotor is spinning, the back-emf can be measured to get the rotor angle. But if the rotor stands still, this is not possible to use. But there are other ways...

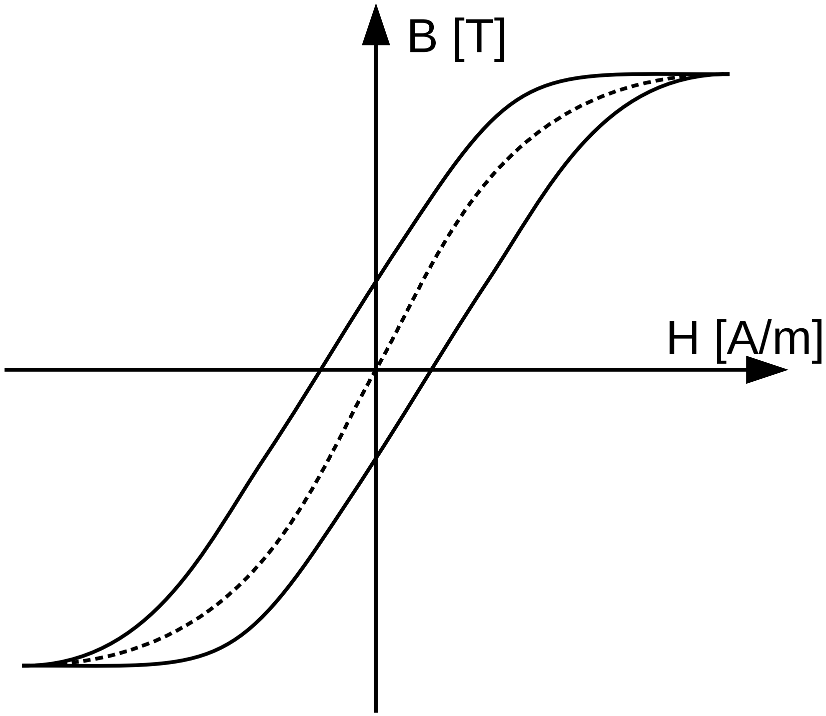




Sensorless

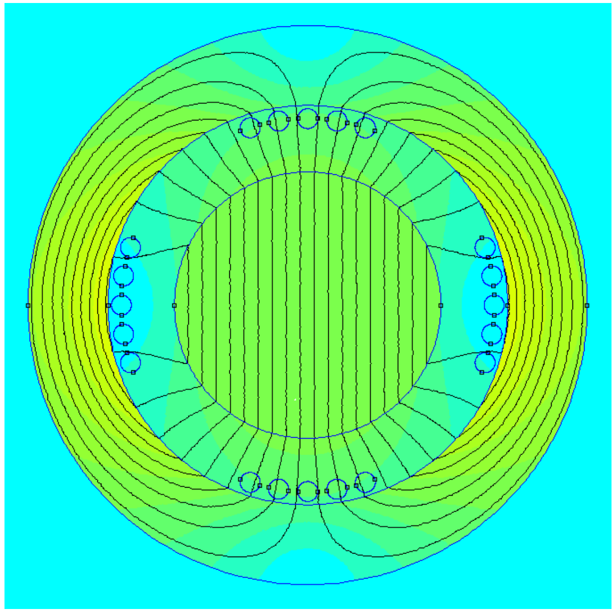
- The stator is typically made of laminated iron or other ferromagnetic material. All magnetic materials are non-linear, and will eventually be saturated if magnetized hard enough.
- This non-linear behaviour can be used to determine the rotor angle



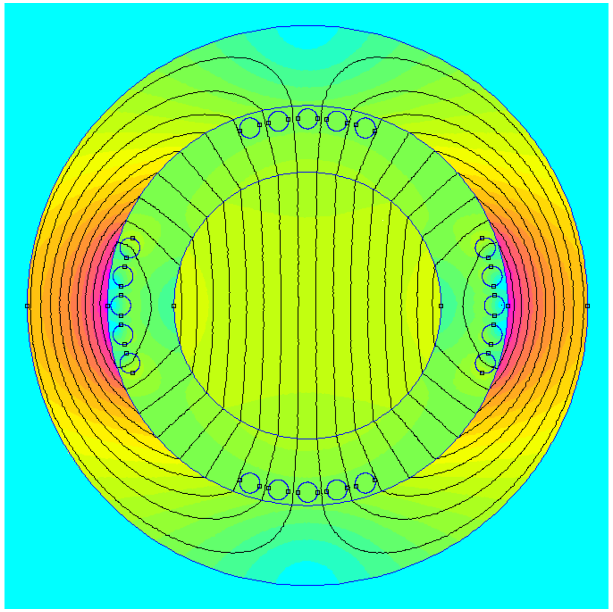


Sensorless

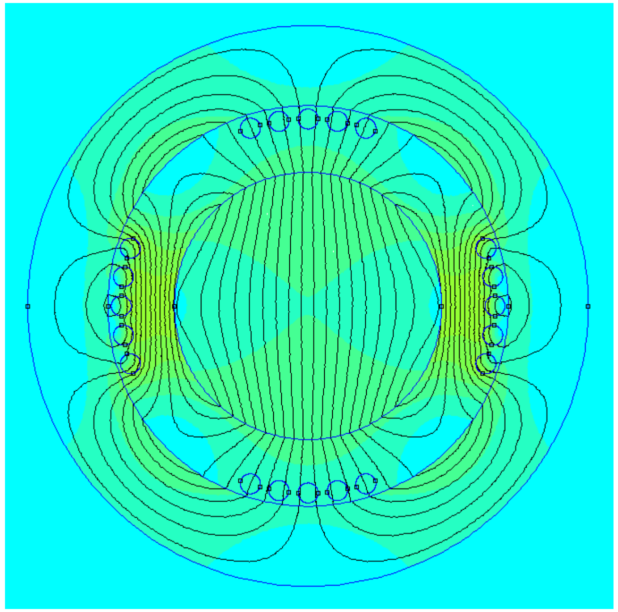
- Applying a current in the D-direction (along the rotor magnet) will either increase or decrease the magnetization of the entire stator.



Rotor magnet only, no current



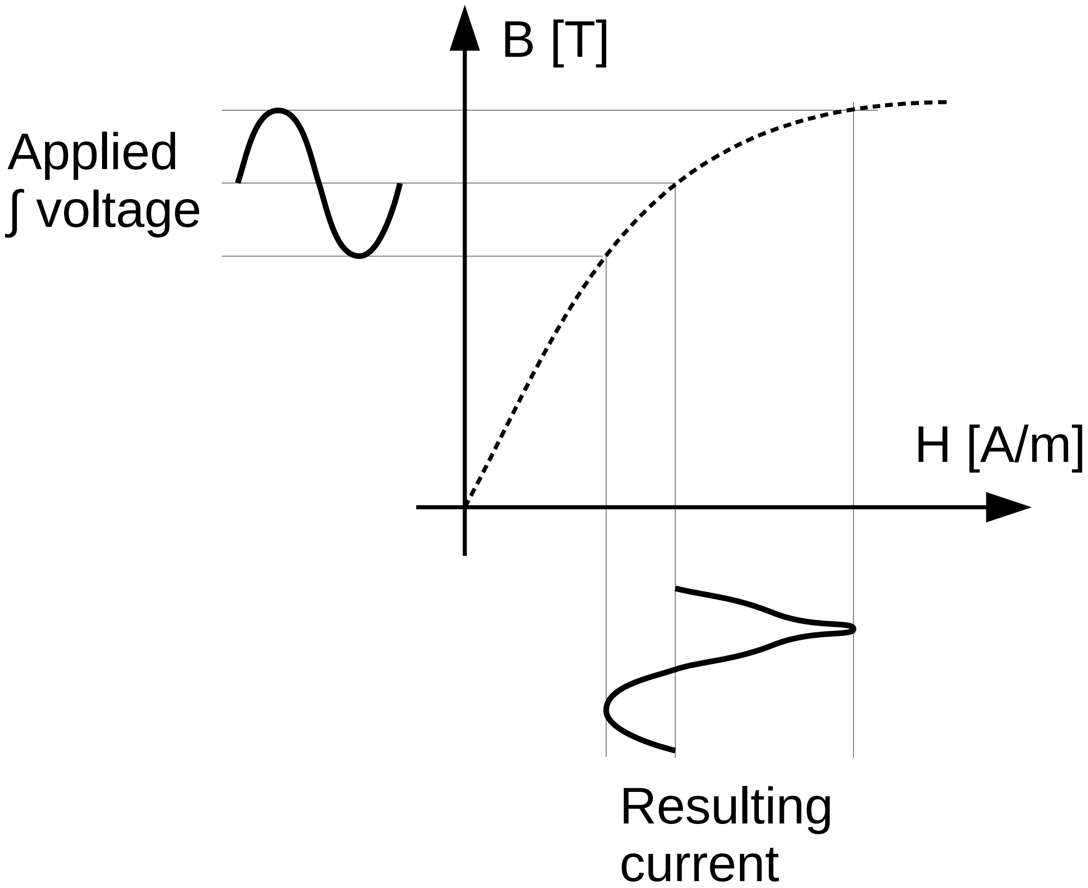
I_D positive



I_D negative

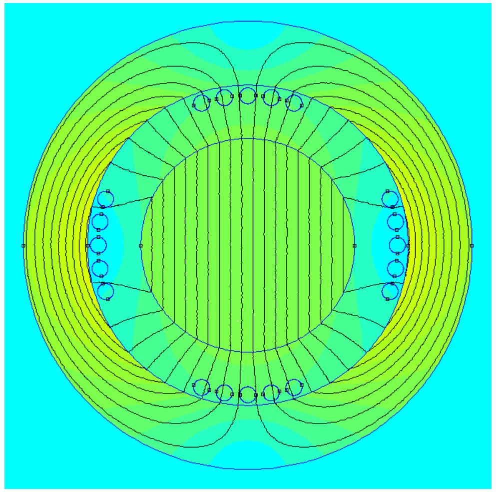
Sensorless

- The saturation effect will cause the resulting current seen in the windings to be non-linear and ”peak” when the applied field drives the stator material closer to saturation. The waveform is asymmetric.

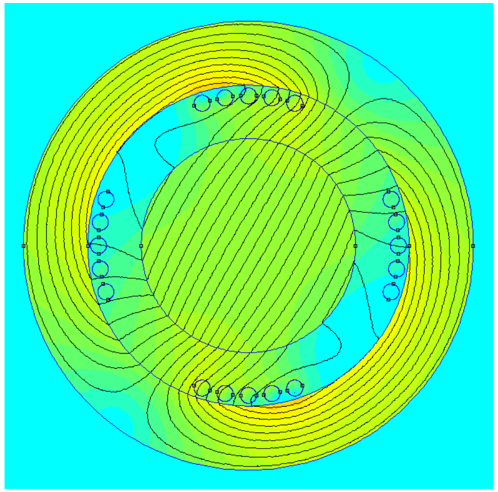


Sensorless

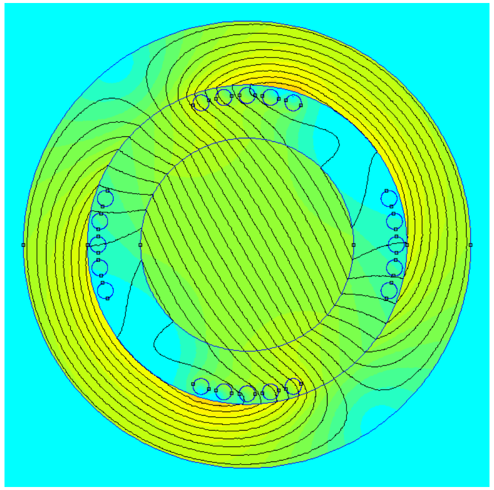
- Applying a current in the Q-direction (perpendicular to the rotor magnet) creates another pattern where some regions a magnetized higher and some regions lower. The resulting current is also non-linear, but this time symmetric.



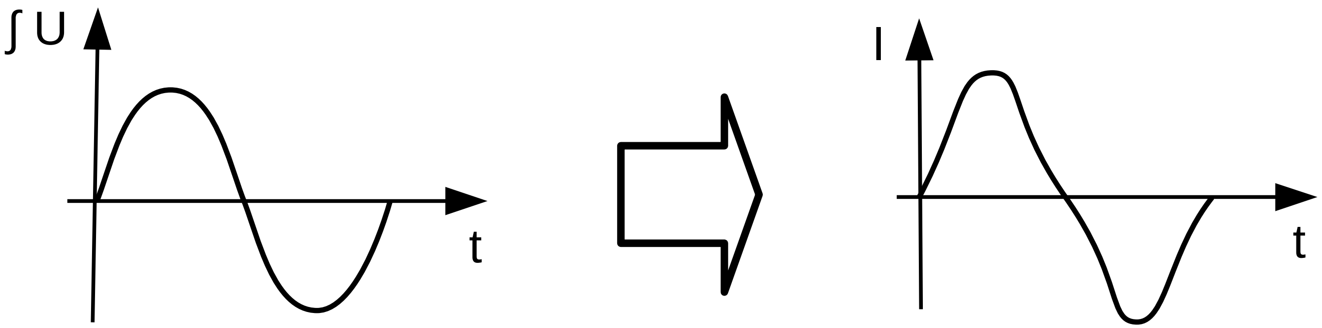
Rotor magnet only, no current



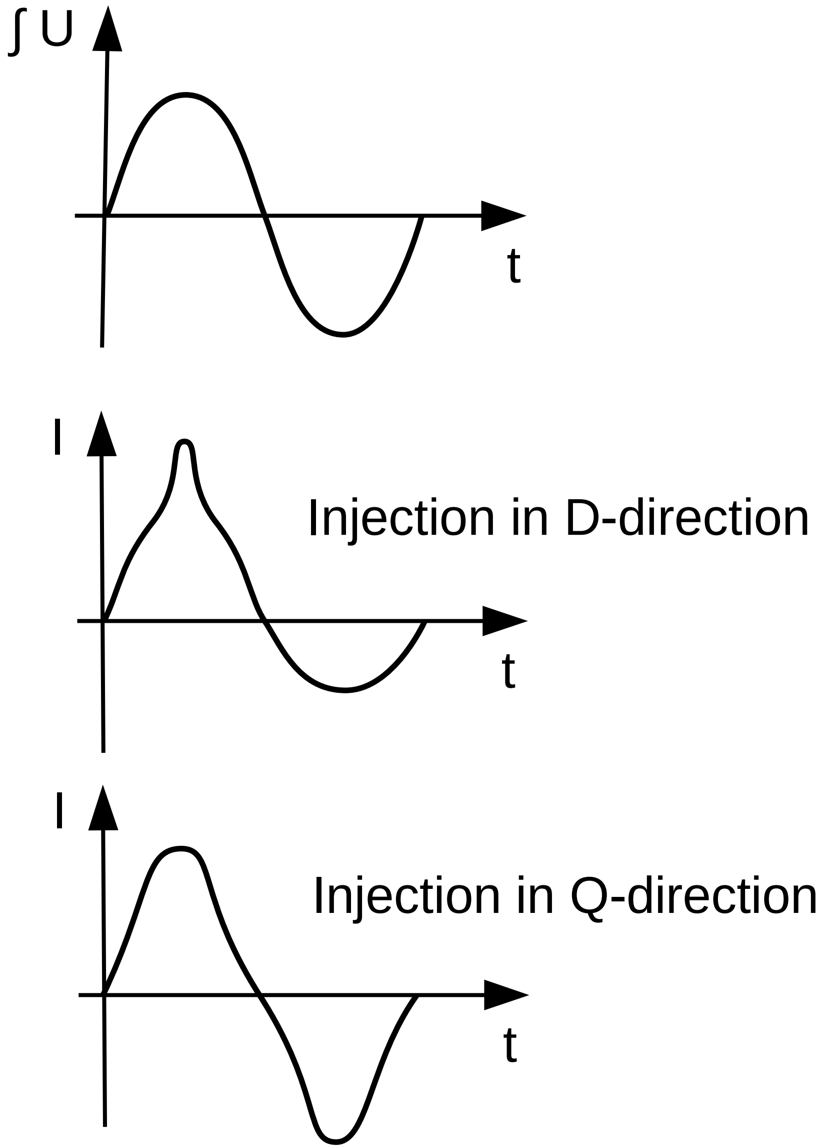
I_Q positive



I_Q negative



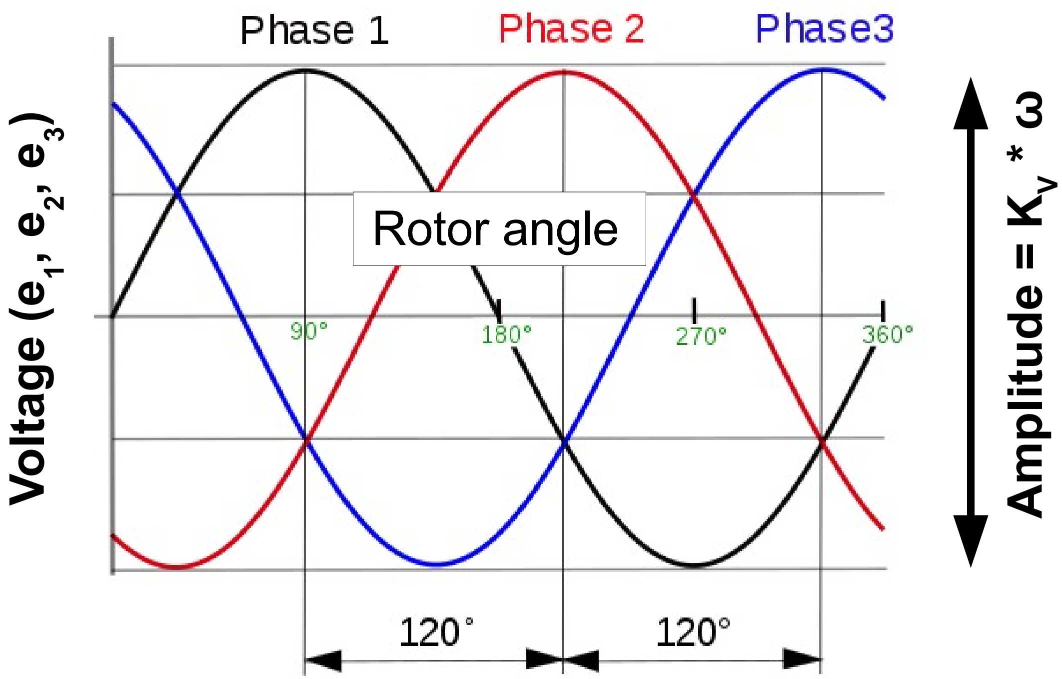
Sensorless

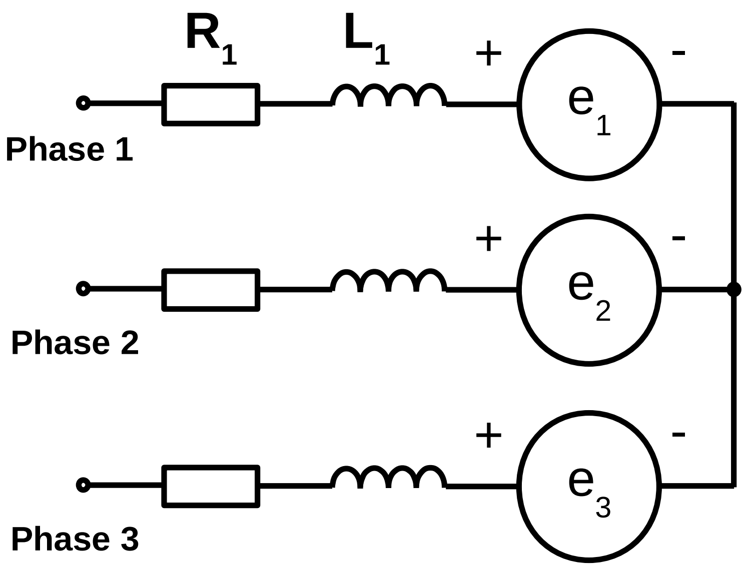


- The difference between the two current waveforms tells whether the injected signal is in the D- or Q-direction.
- There are several ways to implement the same idea, either a ”pulse” signal is applied, or a high frequency sine signal is applied.
- When using sine injection, a fourier transform is used to extract 2nd and 3rd harmonics that in turn are analyzed to give the rotor angle.
- Sine injection is often called ”HFI” (high frequency injection)
- There are several other ways to get rotor angle information via HFI (e.g. from reluctance variation vs. angle)

Field weakening

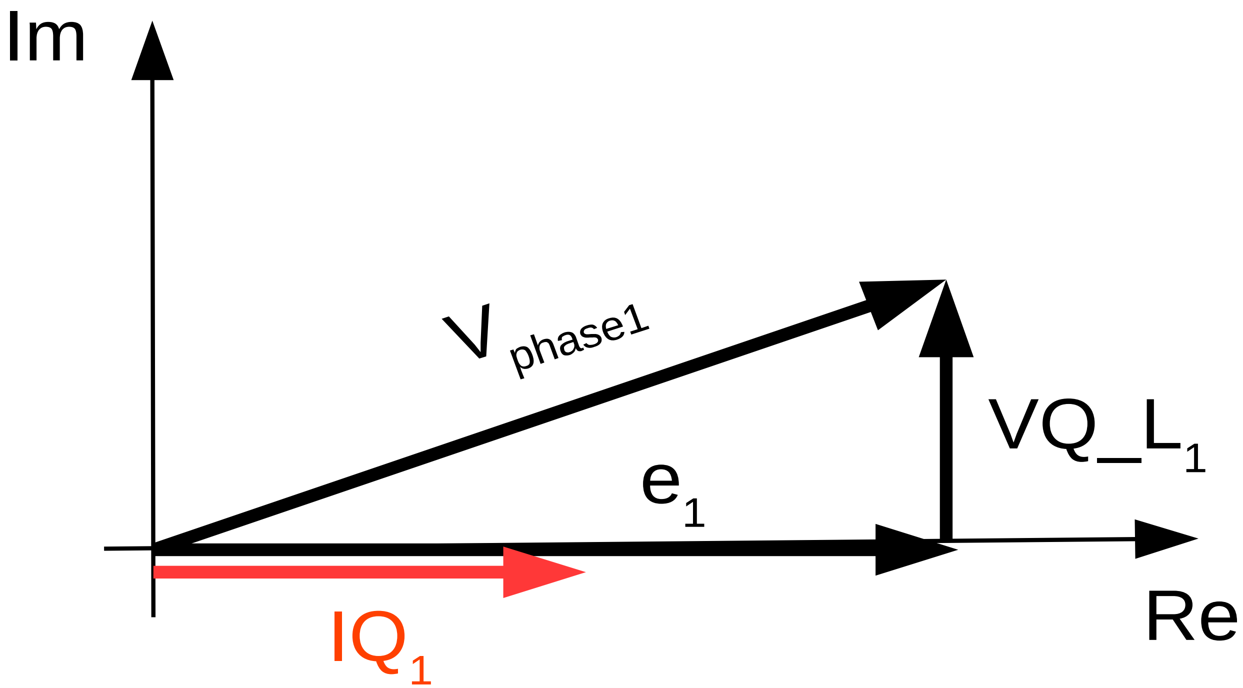
- As motor speed increases, a point is reached where the back-emf is equal to the available voltage from the motor drive. The speed cannot be increased unless the phase voltages are reduced somehow.
- Note that the back-emf is not the actual voltage seen from outside, there are voltage drops across the resistance and inductance that adds a little voltage.





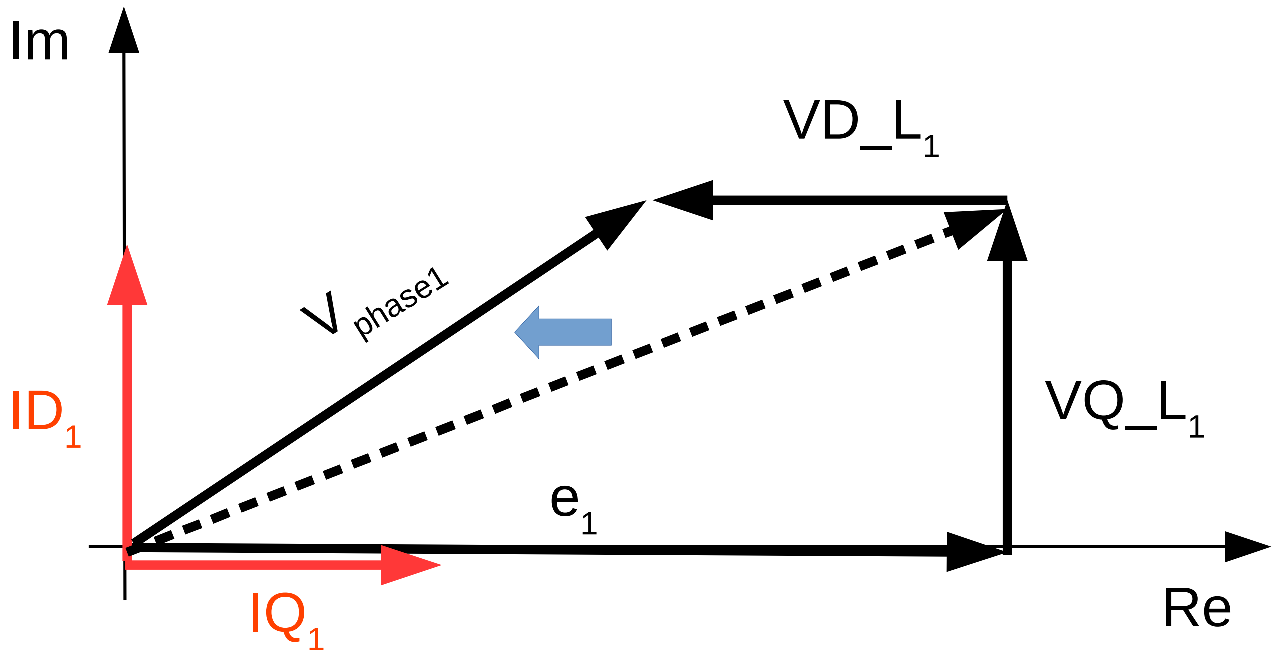
Field weakening

- Looking at the total voltage seen on one of the phases, and neglecting the resistive component we get the diagram below. Note that the diagram shows amplitude and phase angle of the voltage waveforms (sine).
- The current IQ_1 is in phase with the voltage e_1. The voltage drop over L_1 is 90º phase shifted from IQ_1 since it is an inductive voltage drop. The sum of the two gives the voltage V_{phase1}.



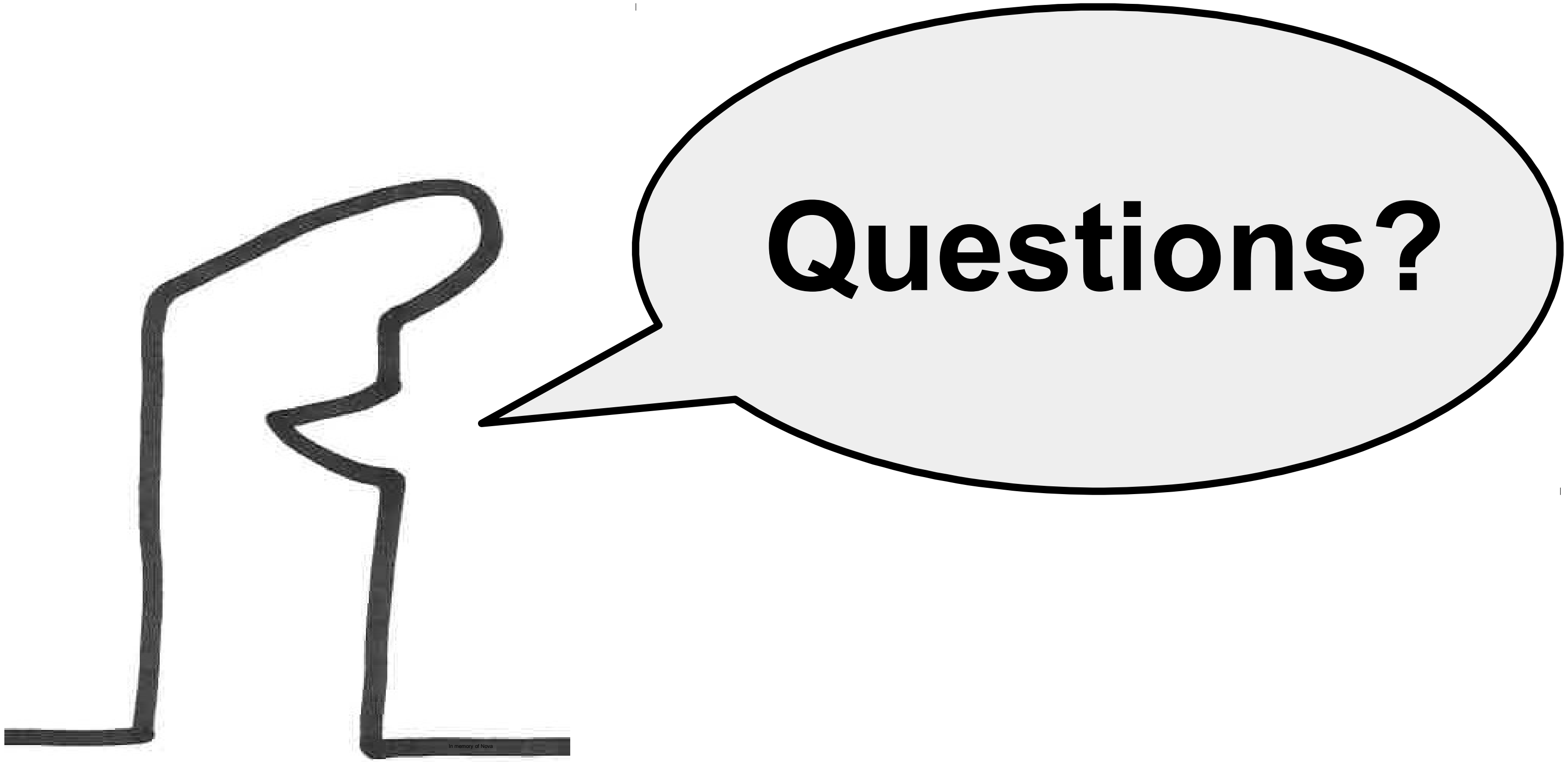
Field weakening

- If we add a current in the D-direction (that will not affect the motor torque), it means that we add a current component that is 90º phase shifted from IQ_1.
- The result is that we can lower the V_{phase1} voltage (not the back-emf though).
- At the cost of increased winding losses, we can now run the motor faster than the back-emf would otherwise allow. This is called field- or flux weakening.



Summary

- The synchronous motor – Apply field perpendicular to magnet to get torque
- Motor control basics – Field Oriented Control
- The motor constant – A sometimes overlooked degree of freedom
- More control details and trajectory – Smooth movements
- The drive electronics – Three buck converters, bidirectional power flow possible
- Brake energy handling – Several options, possible to dump energy in the motor windings
- Sensorless control – Possible even at standstill, one HFI example
- Field weakening – The hidden warp drive


Questions?