An introduction to electric motors

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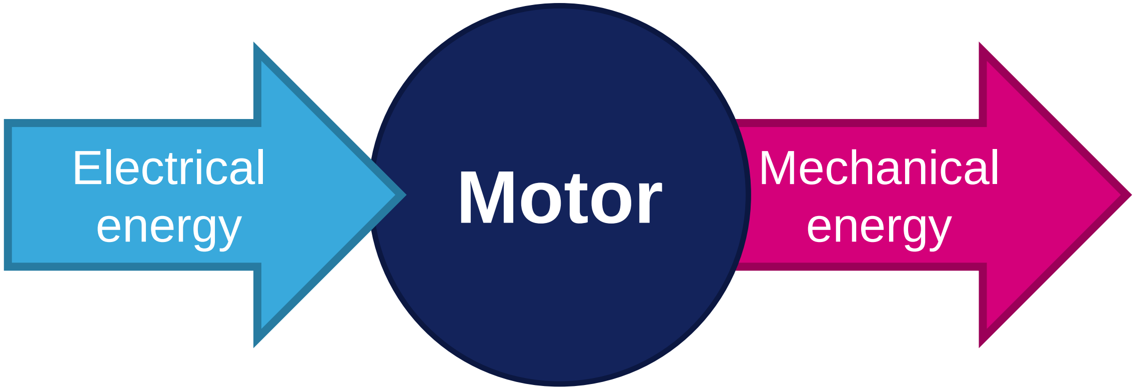
What is an electric motor

An electric motor is a device converting electrical energy into mechanical energy (usually a torque).

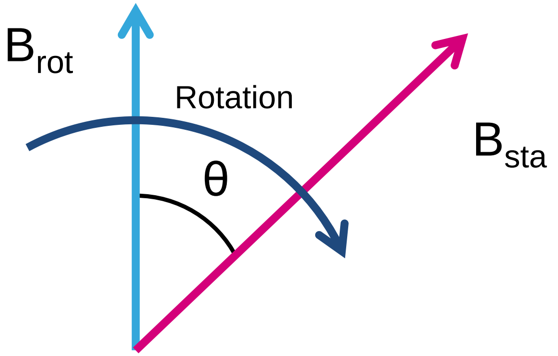
This conversion is usually obtained through the generation of a magnetic field by means of a current flowing into one or more coils.



Rotor and stator magnetic fields

The rotation is obtained thanks to the attractive force between two magnetic fields:

- One field is located on the rotor (the moving part).
- The second magnetic field is located on the stator (the body of the motor).

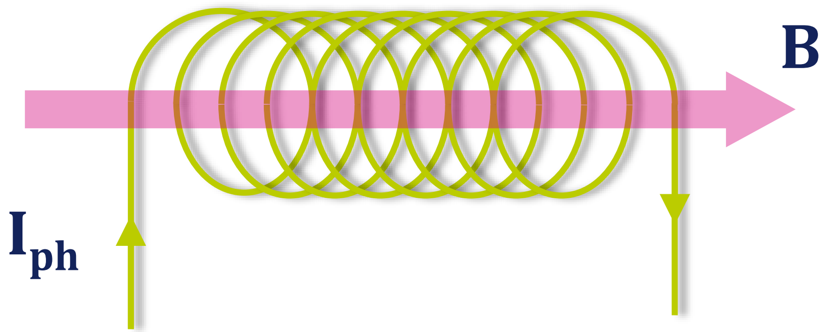


Usually one of the two is generated by a permanent magnet while the other one is generated through an electromagnet (solenoid).

Magnetic field generation

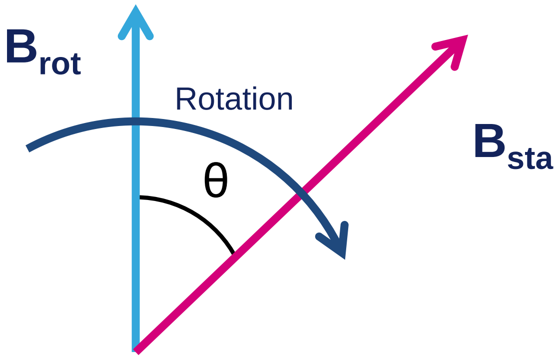
The relation between electrical energy (current) and magnetic field generated by a solenoid (coil) is obtained through the following formula:

$$\boldsymbol{B = kI_{ph}}$$



Torque

The output torque of an electrical motor depends on the intensity of the rotor and stator magnetic fields and on their phase relation:

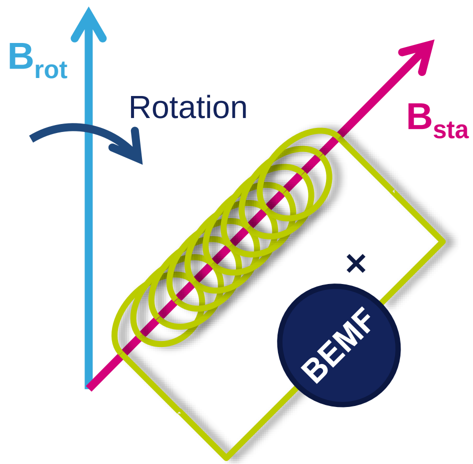


$$Tq \propto B_{rot} \cdot B_{sta} \cdot \sin(\theta) \propto \boldsymbol{I_{ph}} \cdot \mathbf{sin}(\boldsymbol{\theta})$$

The angle θ between the two magnetic field is named **load angle.** The maximum output torque, and then the **maximum efficiency**, is obtained when the **load angle is 90°**.

Back electro-motive force

The rotation of the B_{rot} magnetic field causes a variation of the magnetic flux in the solenoid.



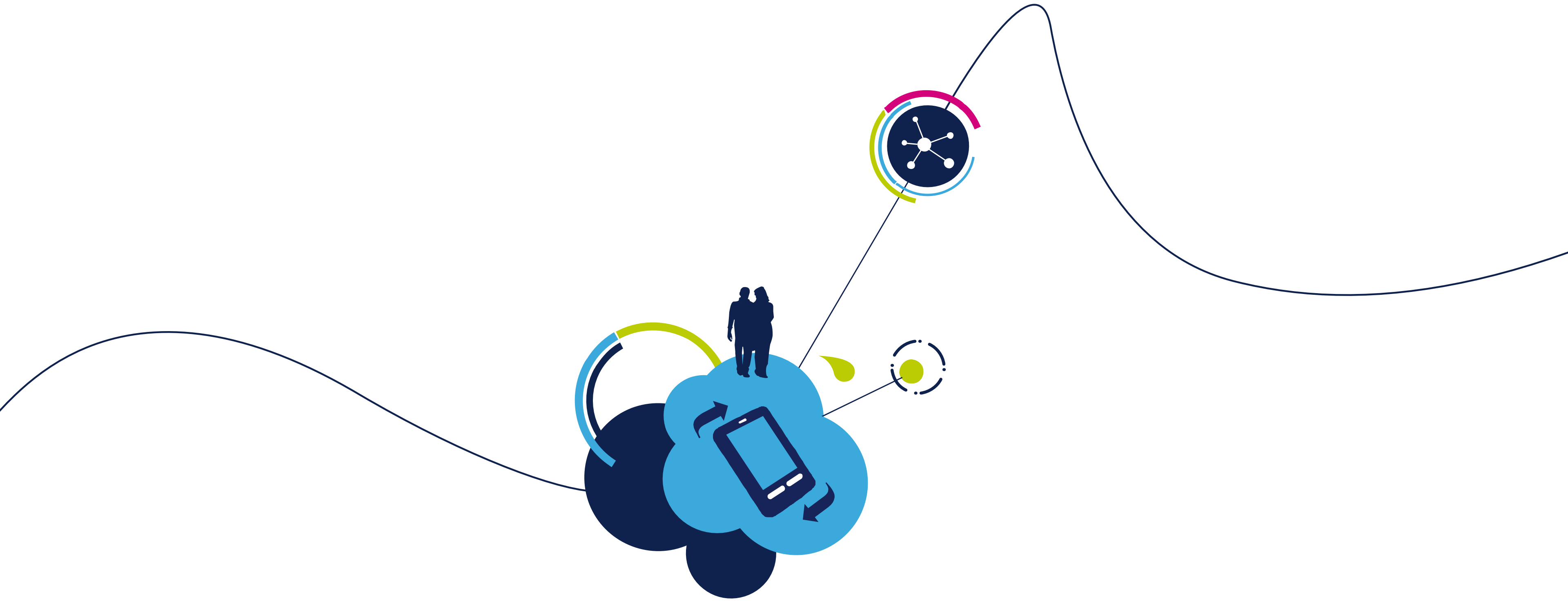
As a consequence, an electro-motive force facing the flux variation is generated (Lenz's law).
This effect is named **back electro-motive force** (**BEMF**) and is proportional to the motor speed according to the formula:

$$V_{BEMF} = \mathrm{k_e} \cdot Speed$$

Basic principle

The electric motor operation is based on the following points:

- At least one of the two magnetic field is generated by a solenoid carrying a current.
- The phase relation between the rotor and stator magnetic field (i.e. the load angle) must be always greater than 0° in order to keep the motor in motion (negative angles reverse the rotation).
- Output torque depends on both the solenoid current and load angle.
- Motor rotation causes a back electro-motive force opposing the motion itself.

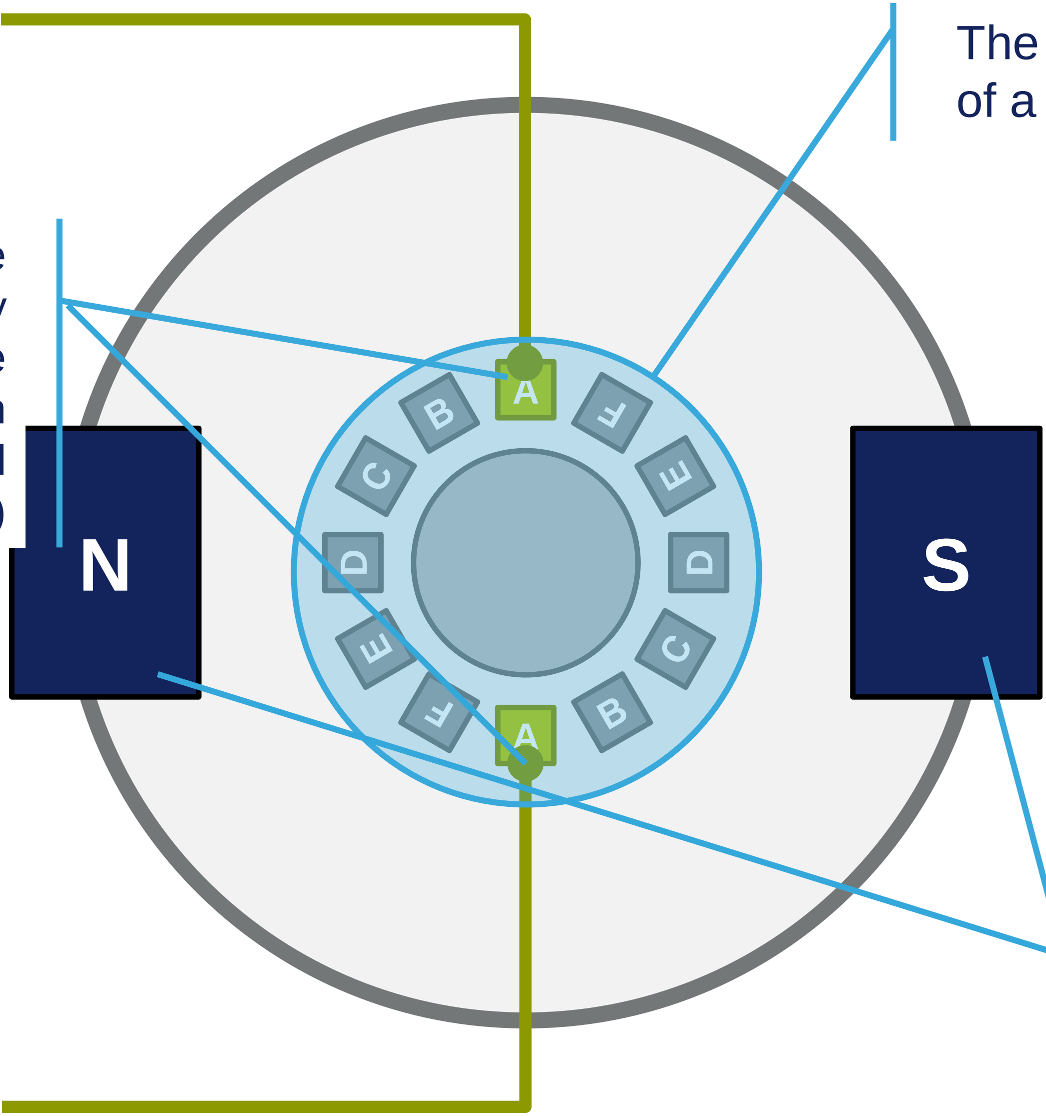


Brush DC motor

Brush DC motor basics

The rotor is composed of a group of coils

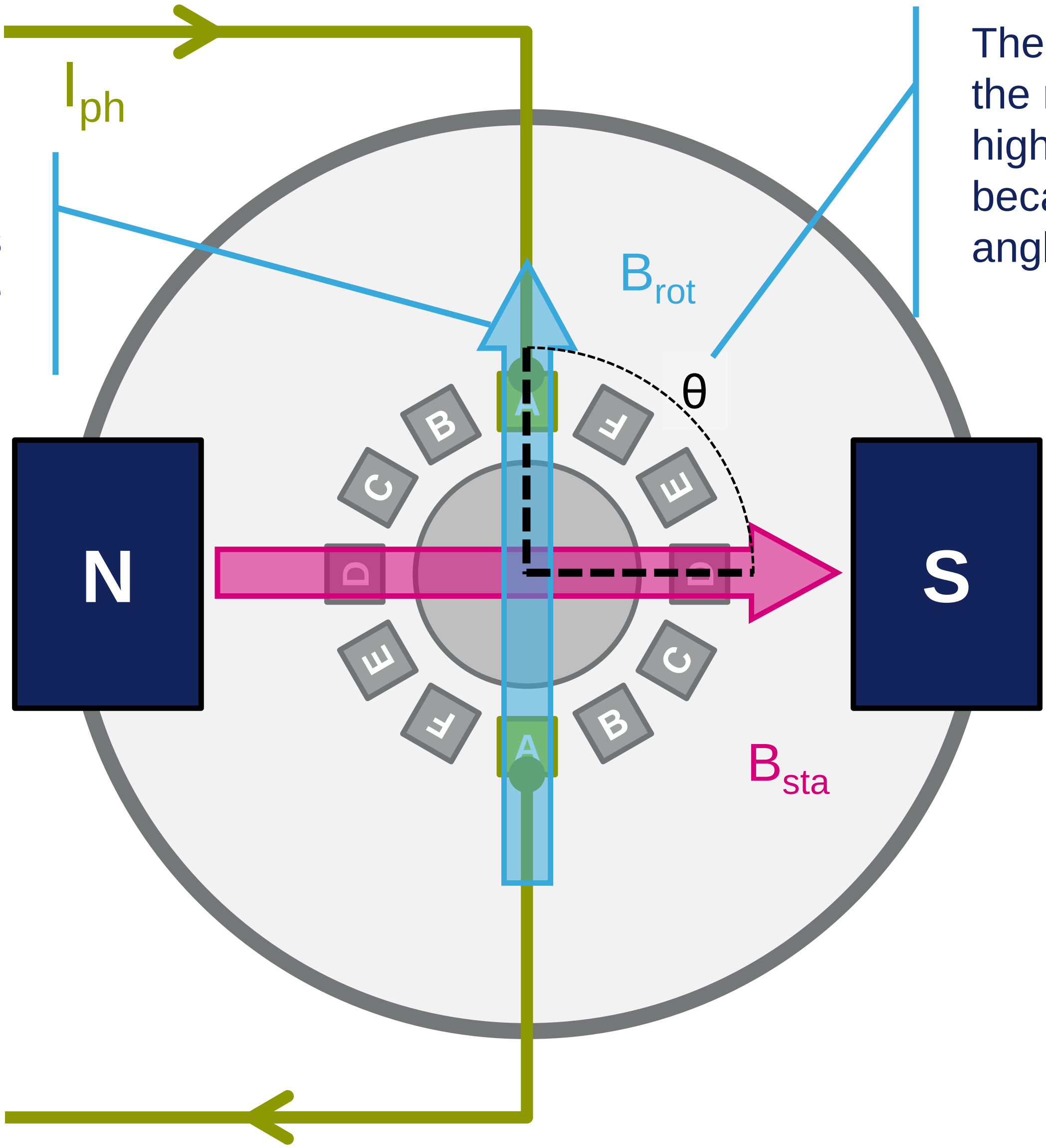
The rotor coils are sequentially connected to the motor leads through mechanical switches (brushes)



The stator magnetic field is generated by a permanent magnet

Brush DC motor basics

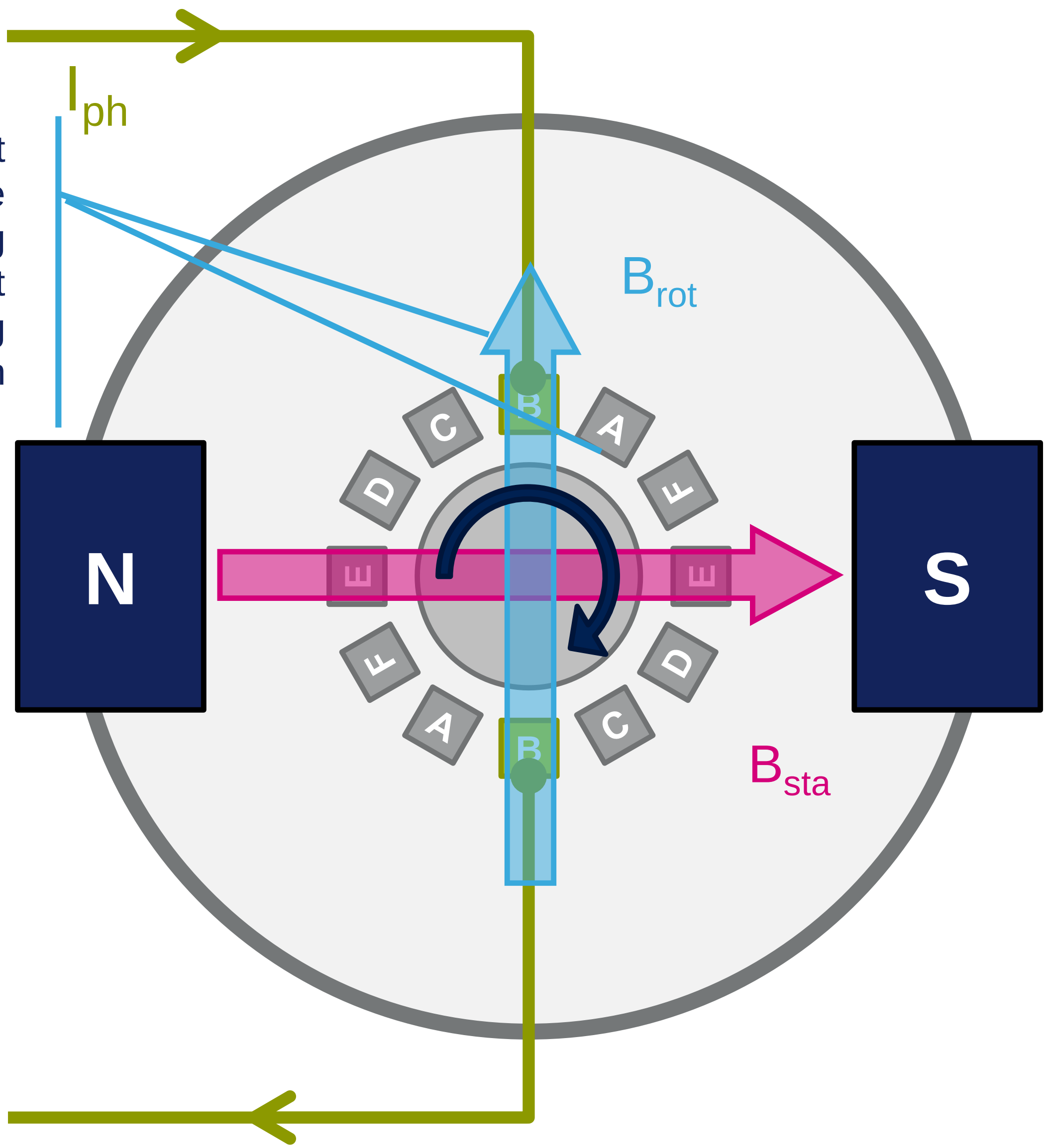
Forcing a current in the motor causes the rotor to generate a magnetic field



The torque applied to the rotor is the highest possible because the load angle (θ) is about 90°

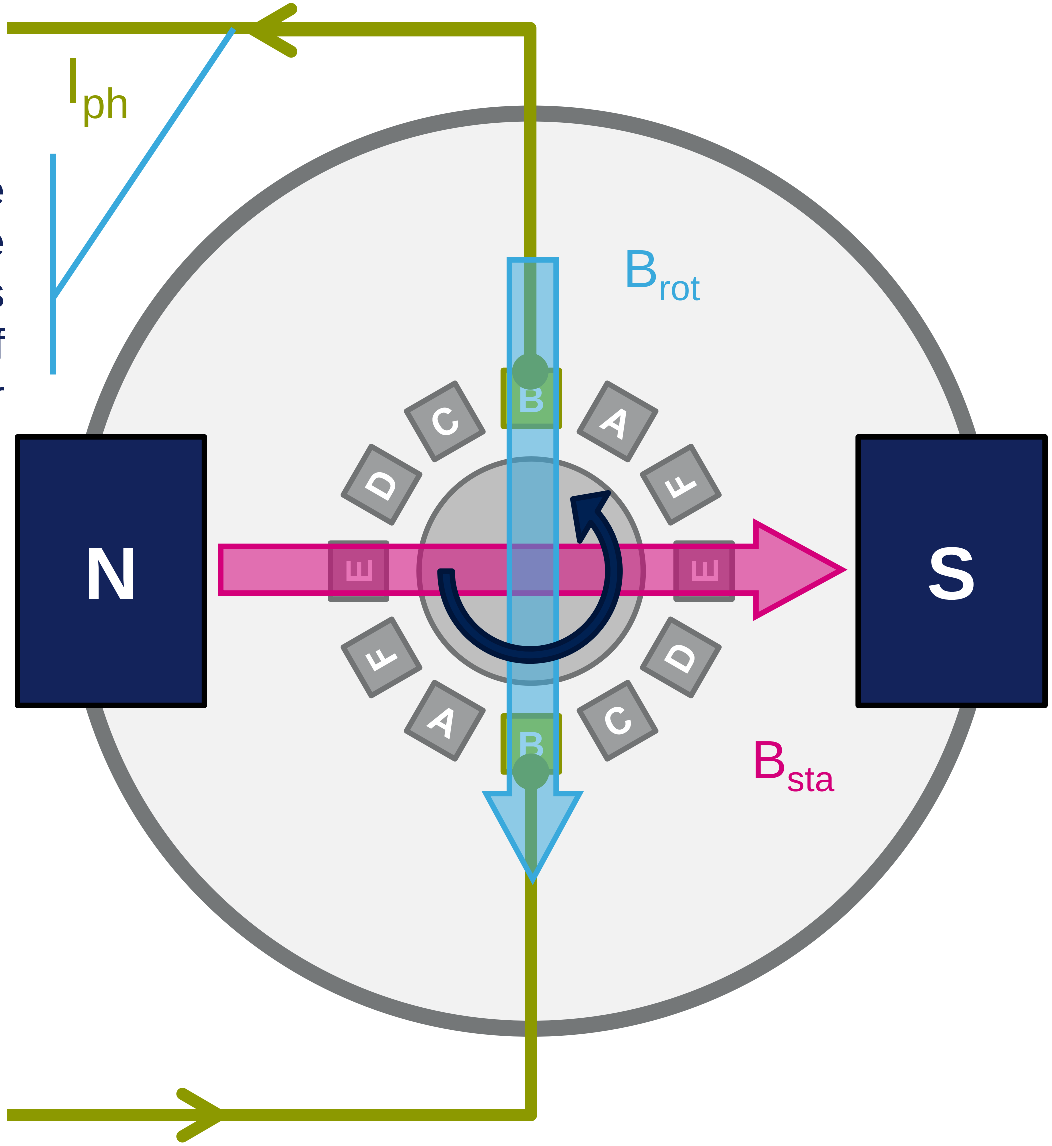
Brush DC motor basics

The brushes connect the motor leads to the next coil **(B),** keeping the load angle almost equal to 90° during rotation



Brush DC motor basics

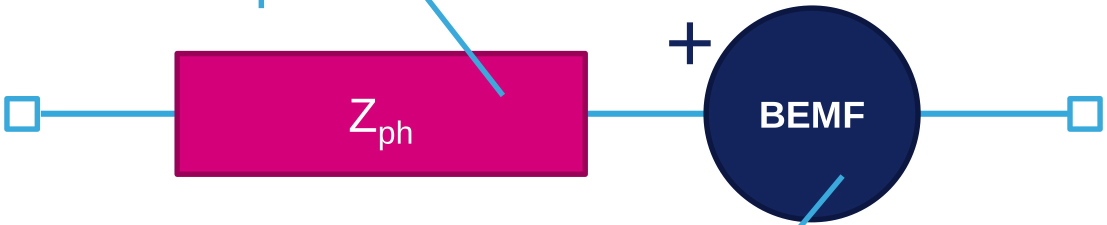
Changing the direction of the current reverses the direction of the motor



Electrical model of a brush DC motor

Phase impedance

$$\mathbf{Z_{ph} = R_{ph} + j\omega L_{ph}}$$



Back electromotive force generator

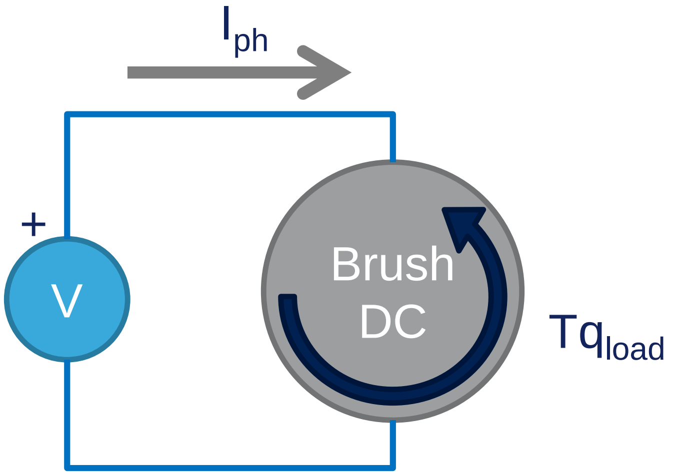
$$\boldsymbol{V_{BEMF} = \mathbf{k_e} \cdot Speed}$$

Voltage mode driving

The brush DC motor is driven by directly applying a voltage to the motor leads.

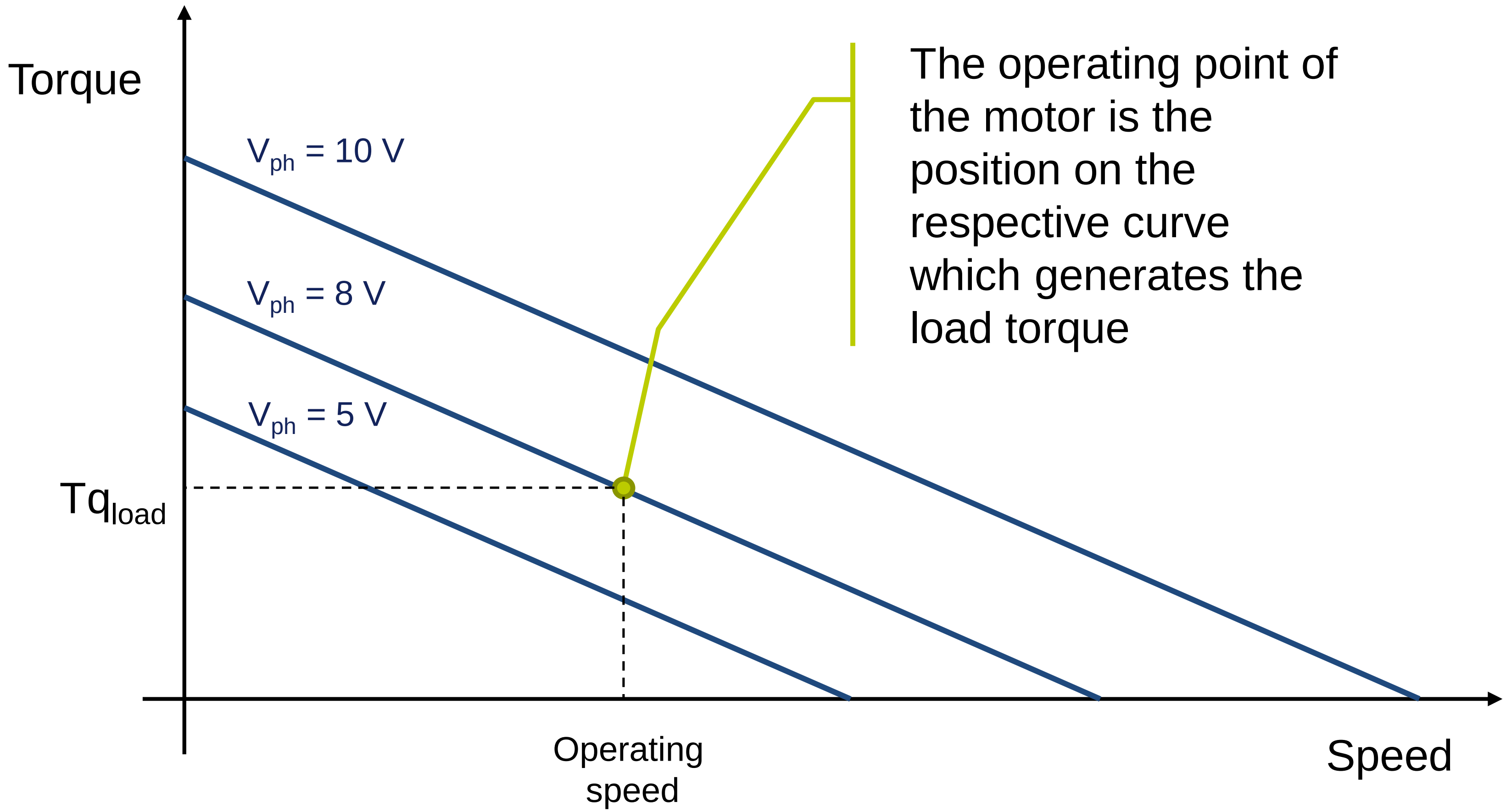
The resulting current and speed depend on:

- The voltage applied on the leads (V_{ph})
- The load torque (Tq_{load})



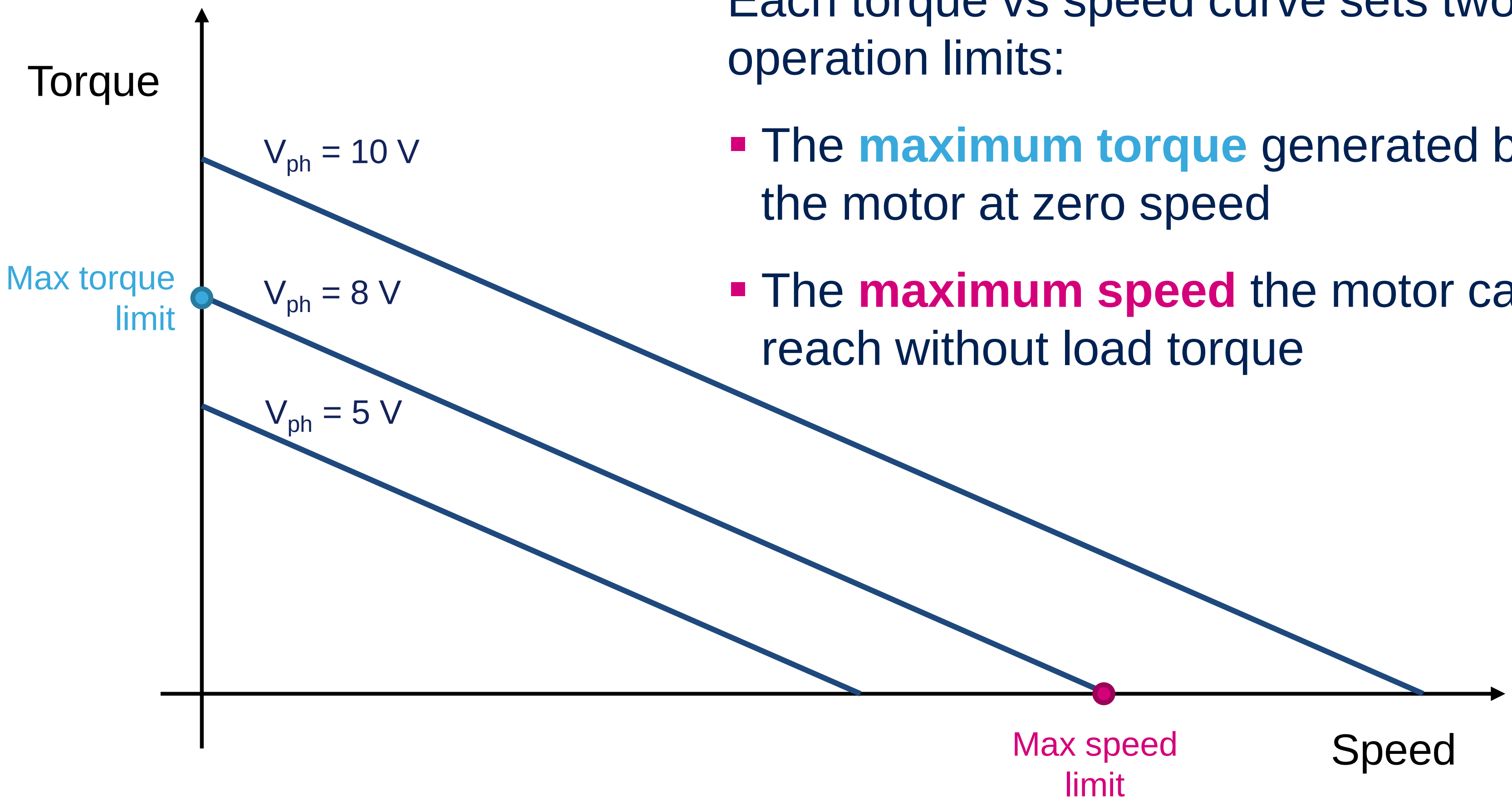
Voltage mode driving

Each phase voltage generates a torque vs. speed relation



The operating point of the motor is the position on the respective curve which generates the load torque

Voltage mode driving



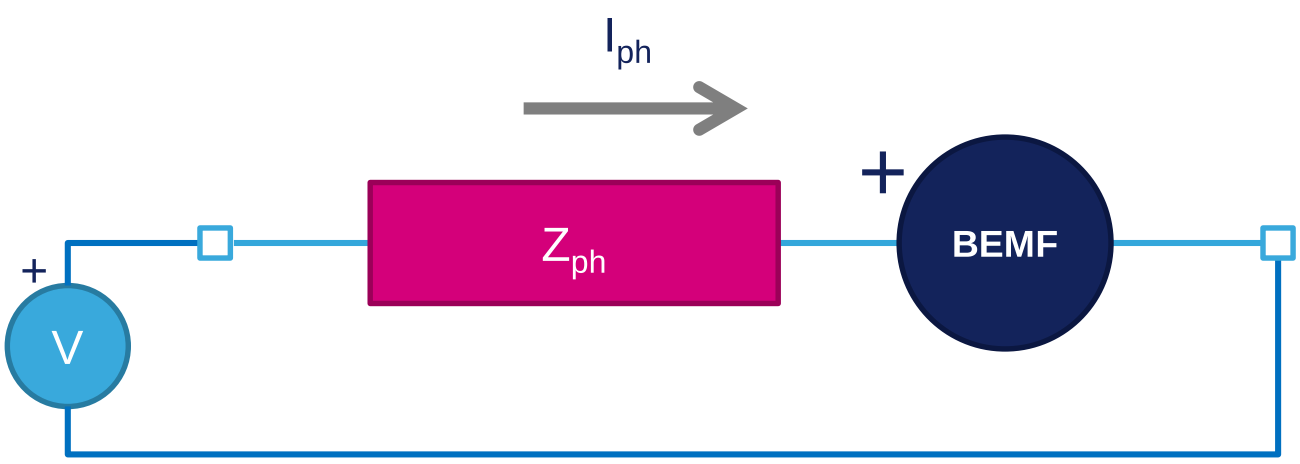
Each torque vs speed curve sets two operation limits:

- The **maximum torque** generated by the motor at zero speed
- The **maximum speed** the motor can reach without load torque

Voltage mode driving

At **maximum torque** limit, the current into the motor is maximum.

The **maximum torque** is limited by the current rating of the motor.



Speed = 0 → BEMF = 0

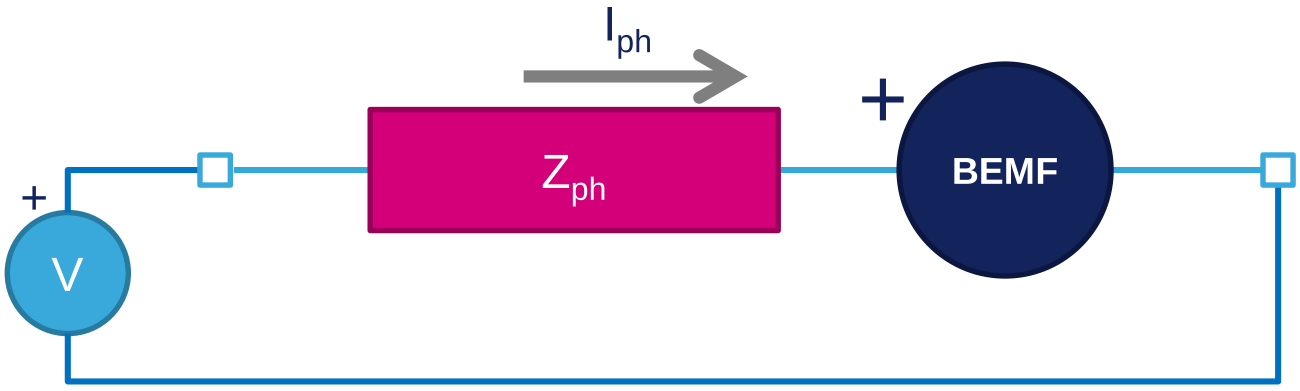
$I_{ph} = V_{ph}/R_{ph}$

Voltage mode driving

At **maximum speed** limit, the current into the motor is minimum
(in theory it is zero)

The **maximum speed** is limited by the supply voltage of the motor driver:

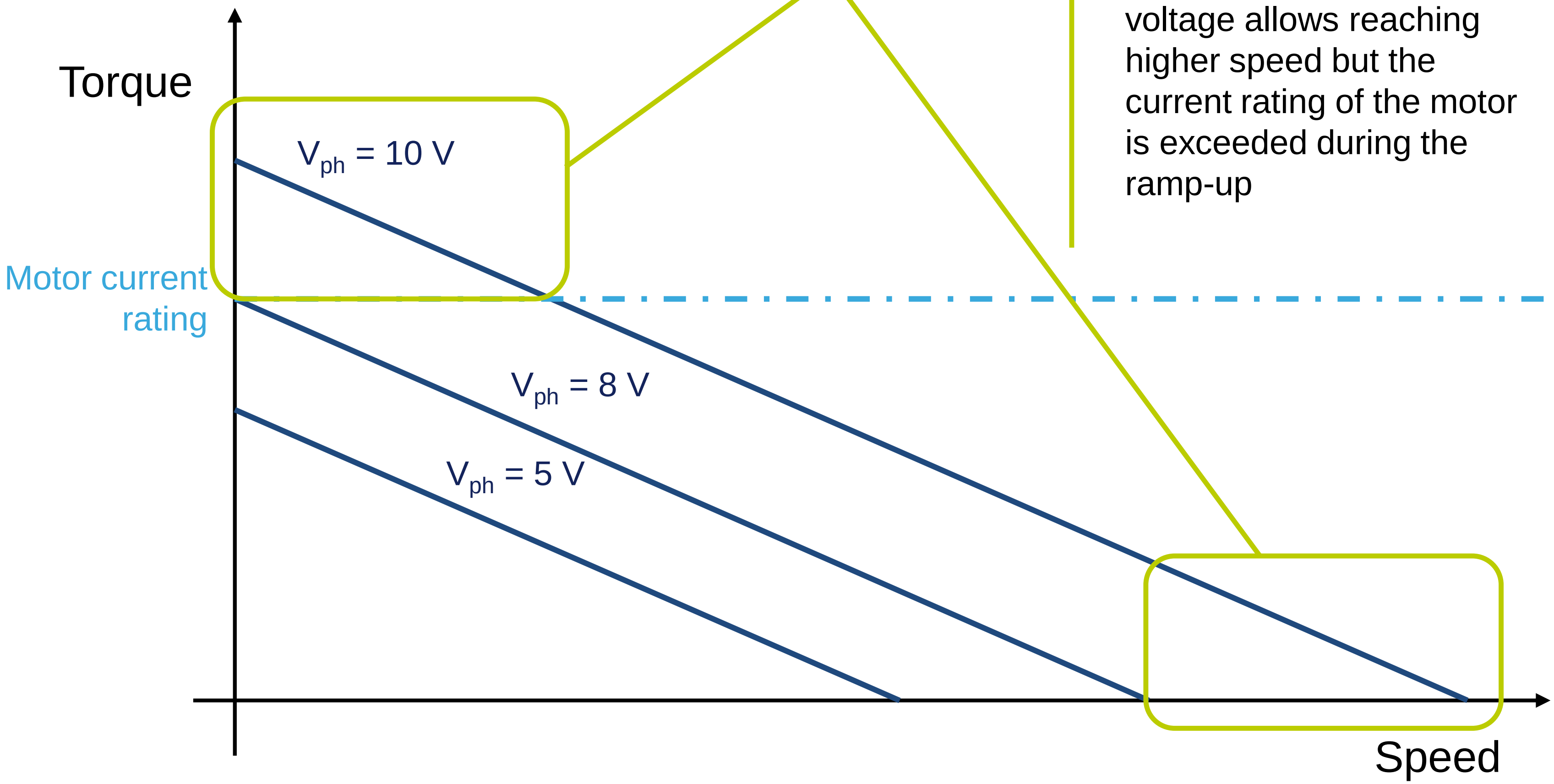
Higher supply voltage → Higher speed



$\mathbf{BEMF = V_{ph}}$

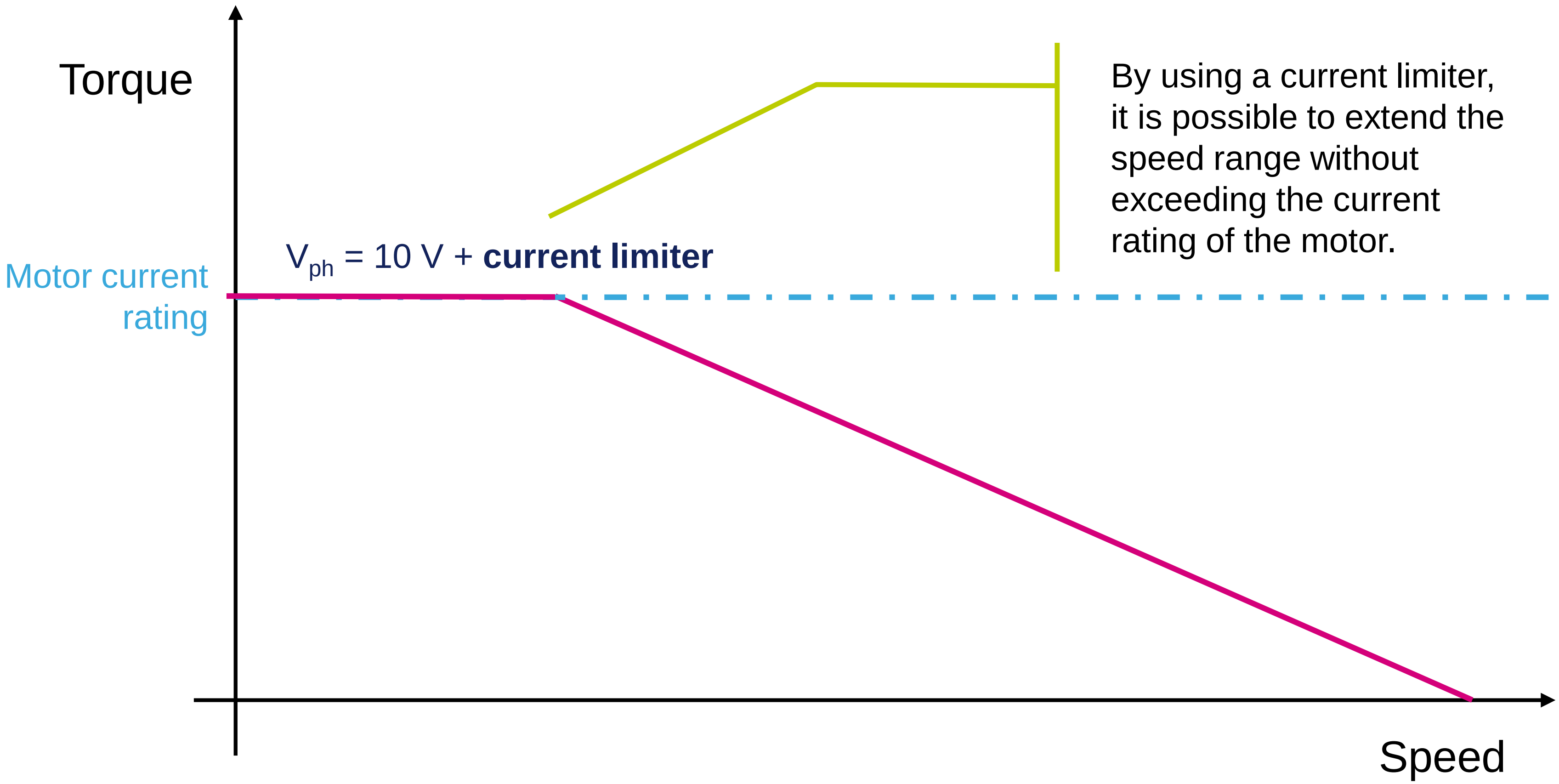
$I_{ph} = (V_{ph} - BEMF)/R_{ph} = 0$

Extending maximum speed



Increasing the supply voltage allows reaching higher speed but the current rating of the motor is exceeded during the ramp-up

Extending maximum speed



Brush DC motor summary

- The magnetic field intensity is proportional to the current forced into the motor leads.
- The magnetic field rotation is automatically obtained commutating the active coil through mechanical switches (brushes).
- The load angle is almost constant and it is about 90° allowing the maximum efficiency (current vs. torque proportion).
- The motor is controlled by applying a voltage to the motor leads. The higher the voltage, the higher the speed. The direction is changed by reversing the polarity on the leads.
- The **maximum torque** is limited by the current rating of the motor and it is obtained at zero speed (start-up).
- The **maximum speed** is limited by the supply voltage and it is obtained when no load torque is present.

Three-phase brushless motor

Brushless motors overview

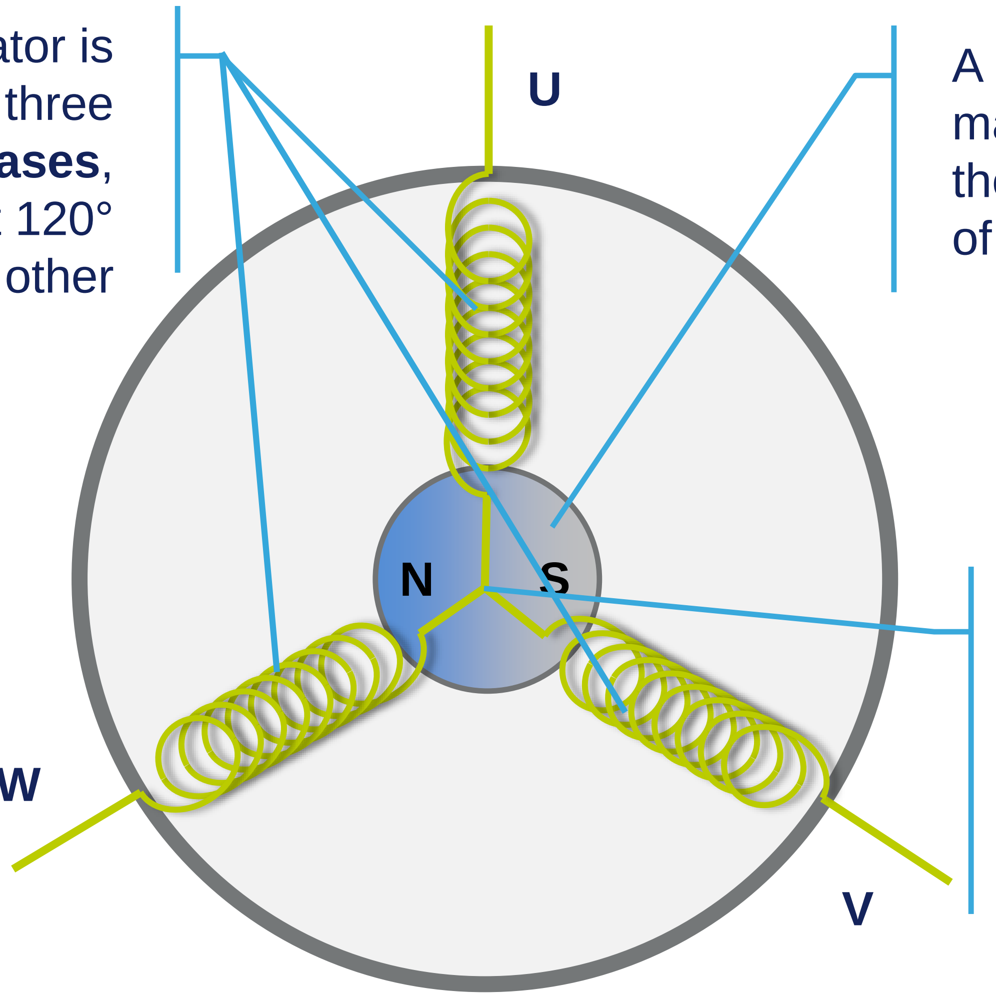
There are different types of brushless motors:

- Single-phase
- Two-phase
- **Three-phase**

The presentation will describe the basics of the **three-phase brushless motor** because it is the most common version.
In most cases, the considerations can be extended to the other types.

Three-phase brushless motor basics

The stator is composed of three coils, named **phases**, positioned at 120° from each other



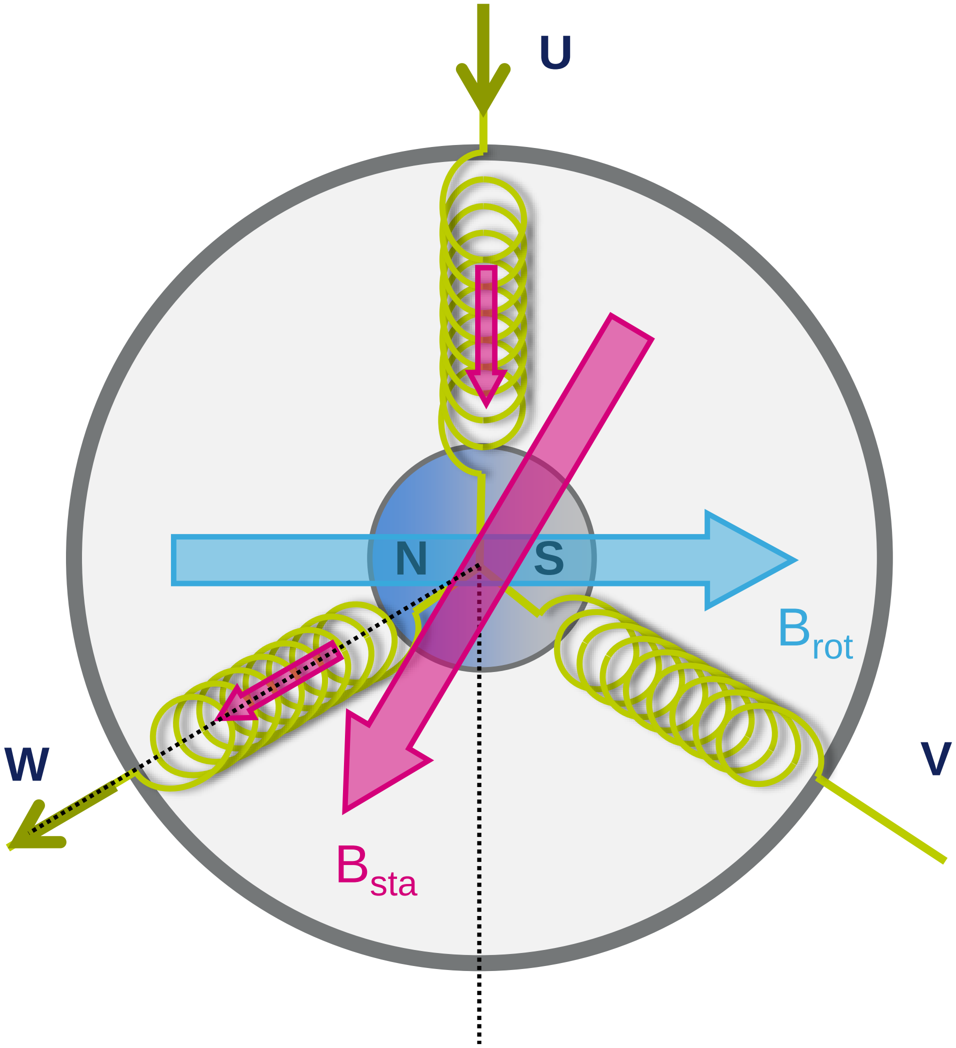
A permanent magnet generates the magnetic field of the rotor

The windings are connected by one of the sides. The sum of the currents is zero.

Three-phase brushless motor basics

The **rotor magnetic field** is always present and it is generated by a permanent magnet.

When a current flows from a motor phase to another one, the magnetic fields are combined generating the **stator field**.

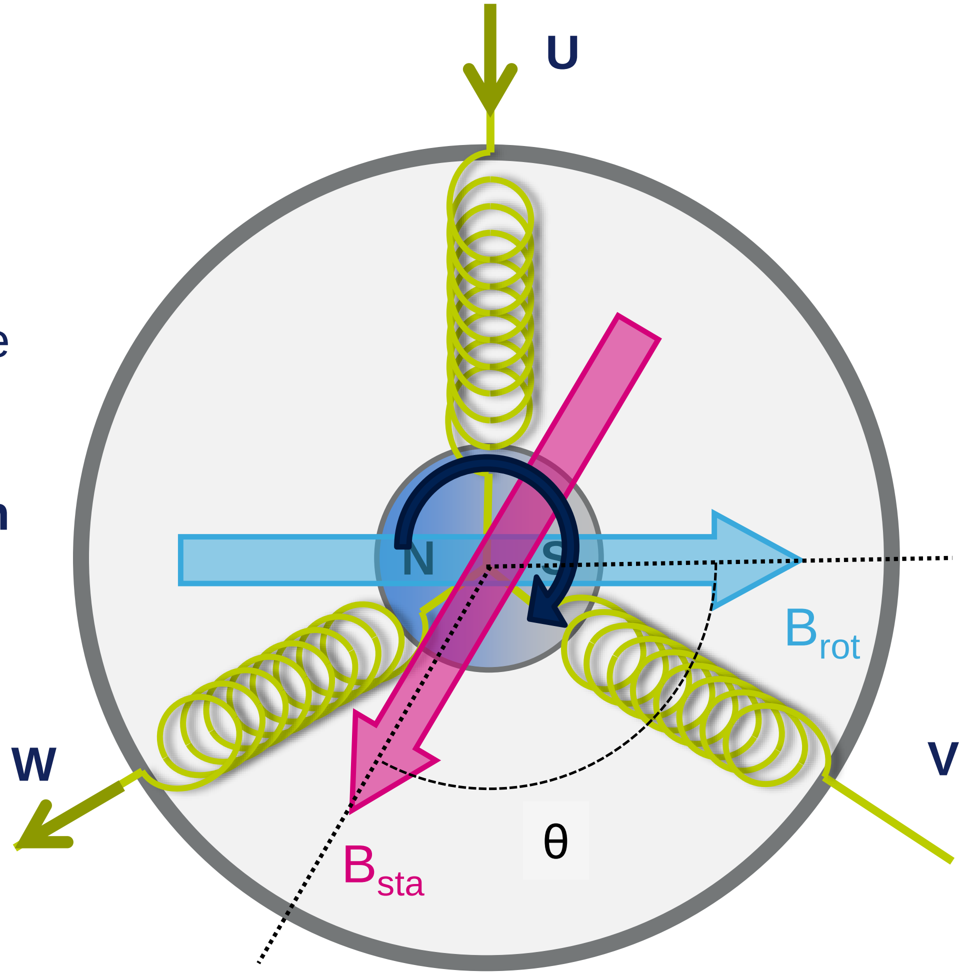


Three-phase brushless motor basics

The torque applied to the motor is proportional to the sine of the load angle (θ).

When the rotor magnetic field approaches the stator one, the torque is reduced.

In order to keep the motor in motion, it is necessary to change the direction of the stator magnetic field.

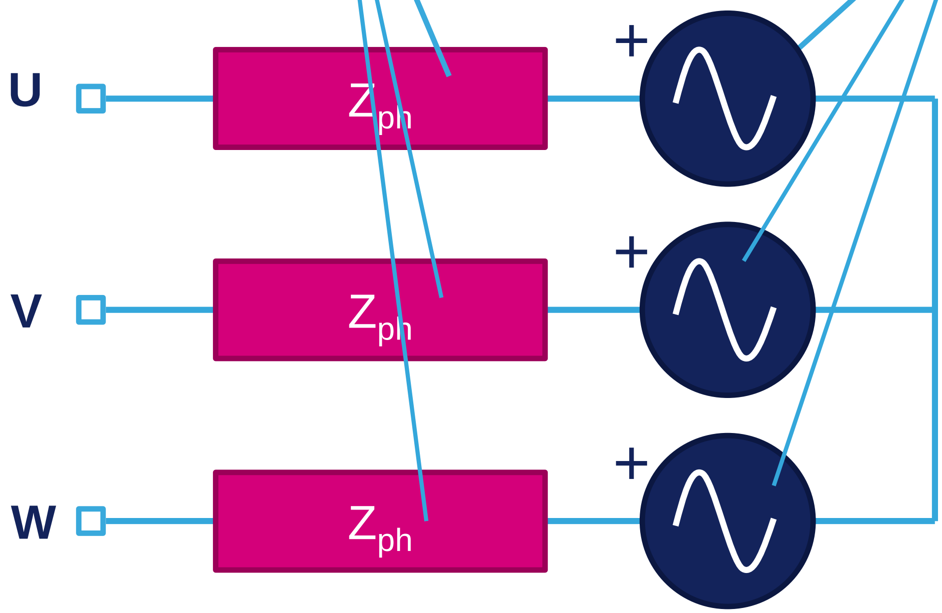


Three-phase brushless motor basics

Electrical model of a 3-ph BLDC motor

Phase impedance

$$\mathbf{Z_{ph} = R_{ph} + j\omega L_{ph}}$$



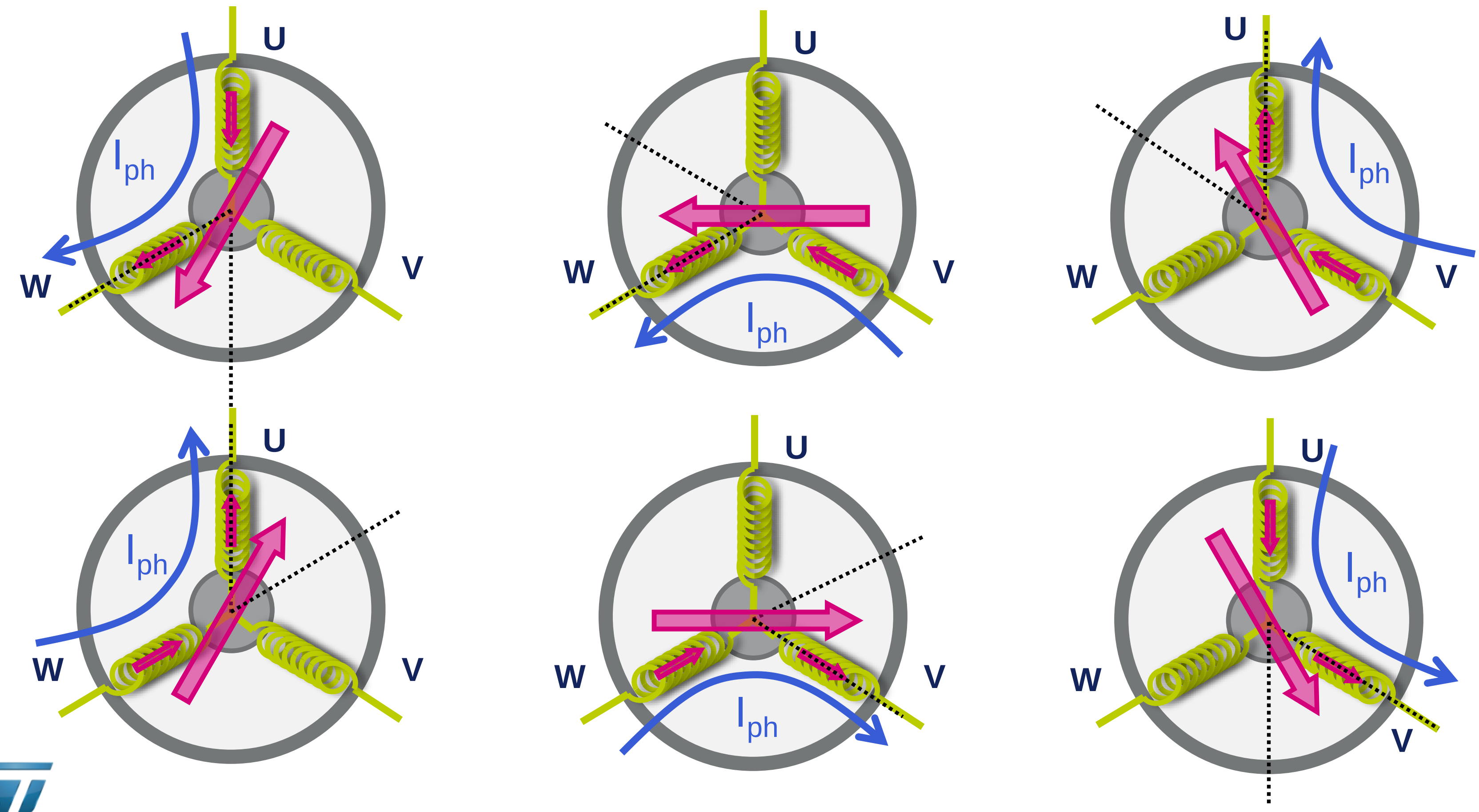
Back electromotive force (BEMF) generators are three sinewave voltages(*) delayed from each other by 120°.
The sinewave amplitude is proportional to the motor speed:

$$\boldsymbol{V_{BEMF} = \mathrm{k_e} \cdot Speed}$$

(*) Some motors have a BEMF with trapezoidal shape instead of sinusoidal

6-step driving

6-step driving imposes a current between two of the three phases leaving the third one floating.
In this way the stator magnetic field can be positioned in **6 discrete directions**.



6-step driving

The scanning of the 6 driving combinations of the six steps is synchronized by the rotor position.

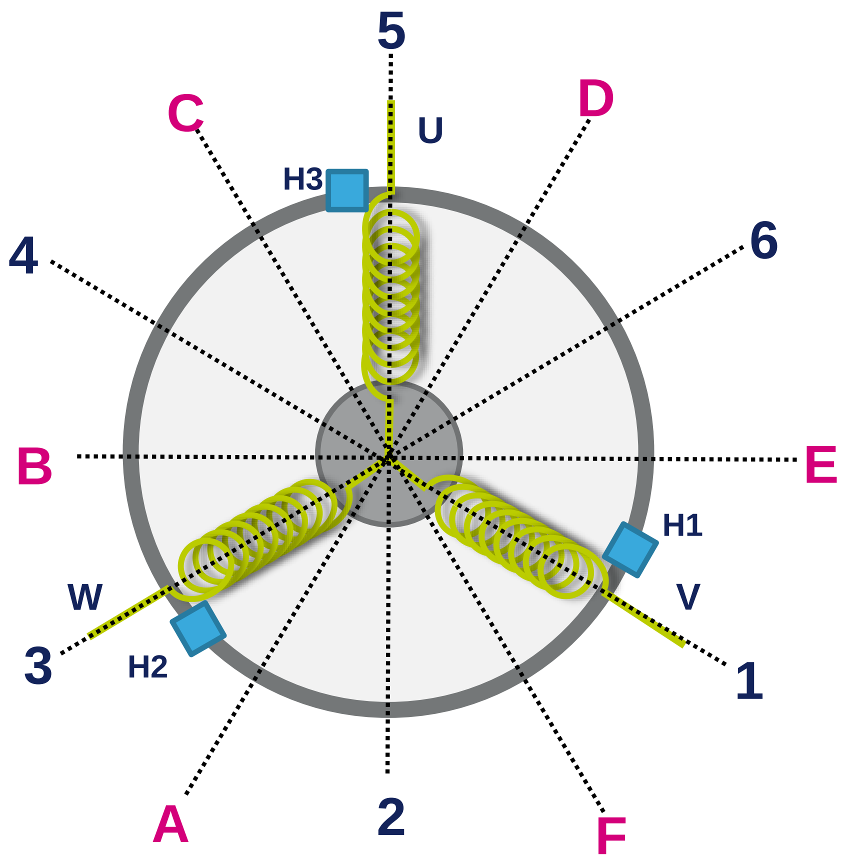
The rotor position can be monitored using Hall sensors or a BEMF sensing technique (sensorless).

6-step driving

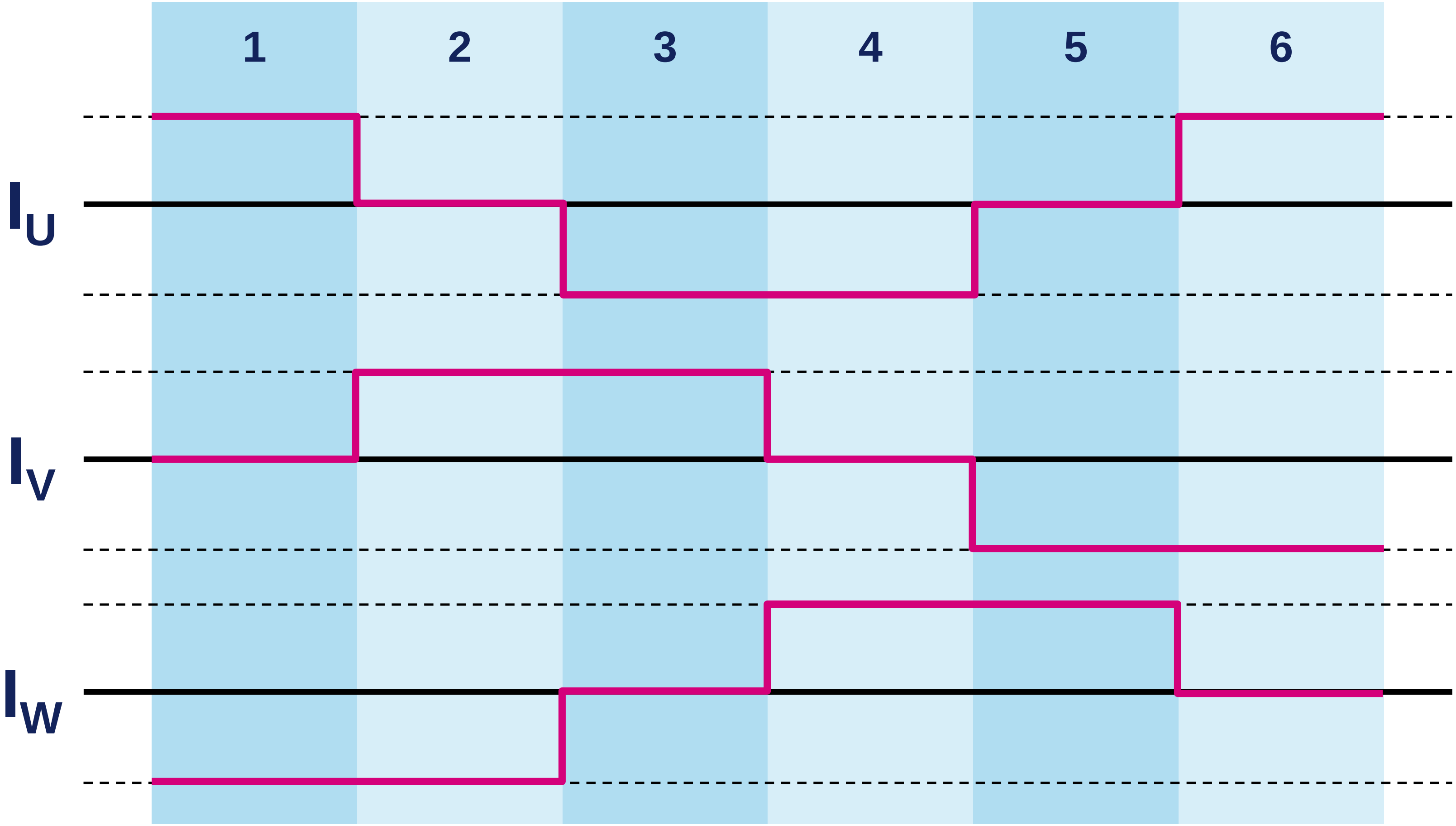
Hall sensors detect the rotor position returning a digital or analog signal. The information is used to move the stator magnetic field in the next position.

Rotor position	Stator position	Current
1	A	U → W
2	B	V → W
3	C	V → U
4	D	W → U
5	E	W → V
6	F	U → V

NOTE: Clockwise rotation

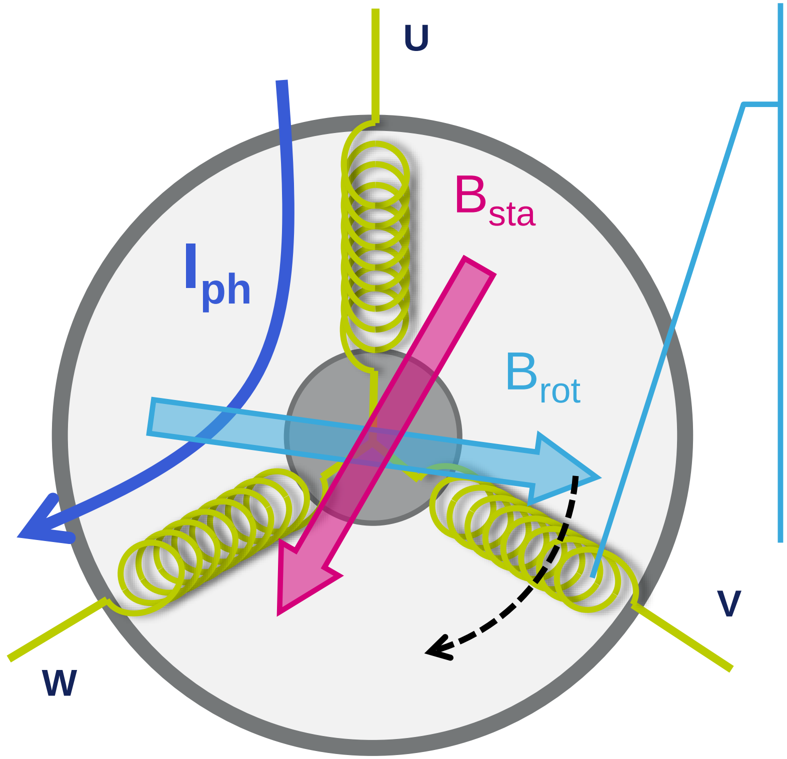


6-step driving



6-step driving

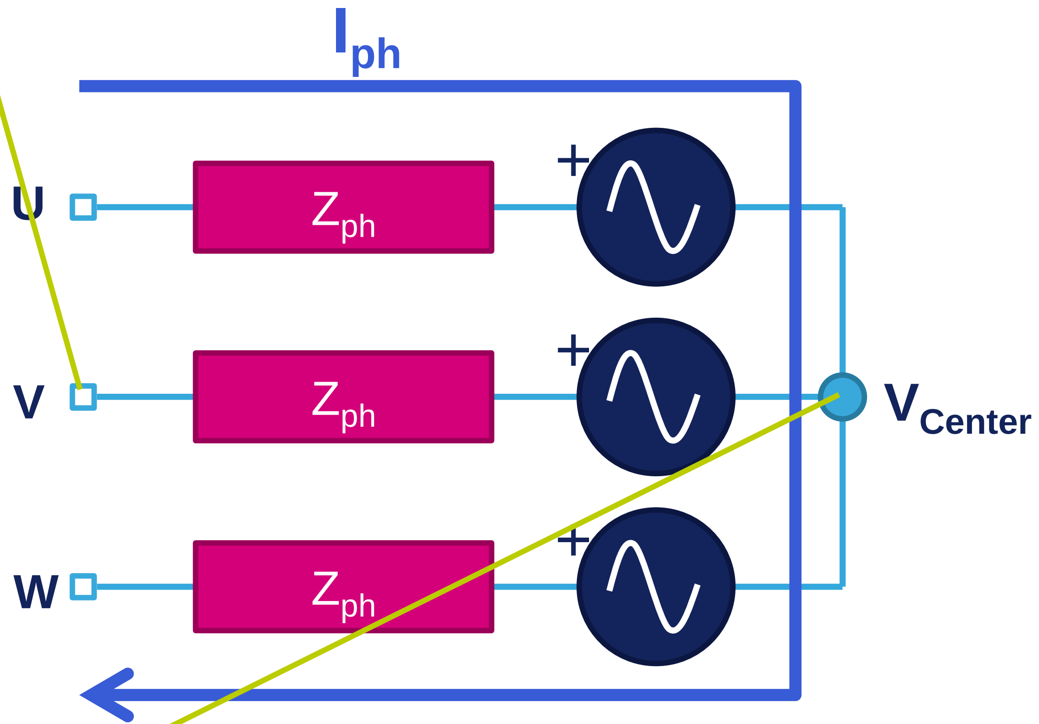
The sensorless driving detects the BEMF zero-crossing measuring the voltage on the floating phase.



When the magnetic field of the rotor crosses the unloaded phase, the respective BEMF voltage changes polarity (zero-crossing)

6-step driving

$$V_V = V_{BEMFV} + V_{Center}$$



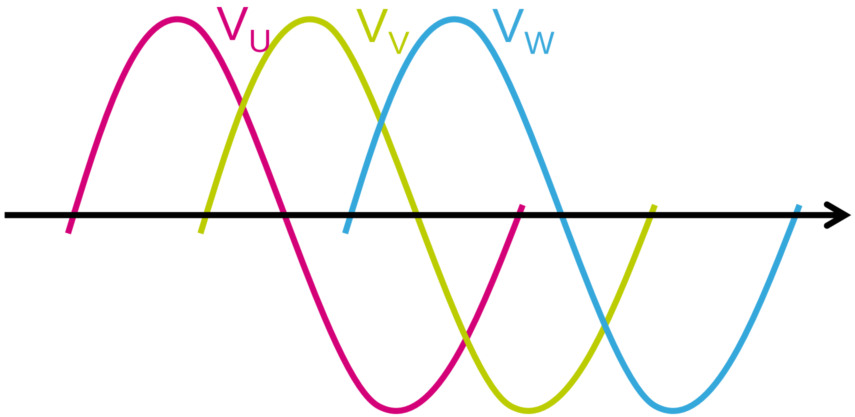
In order to detect the zero-crossing of the BEMF, the center-tap voltage has to be known.
Some motors make the center tap available. In other cases, it can be reconstructed through the phase voltages.

Sinusoidal driving

By applying three sinusoidal voltages with a delay of 120° in the motor phases it is possible to obtain three sinusoidal currents generating a rotating magnetic field.
This method, named **sinusoidal driving**, allows a smoother operation compared to the 6-step method.

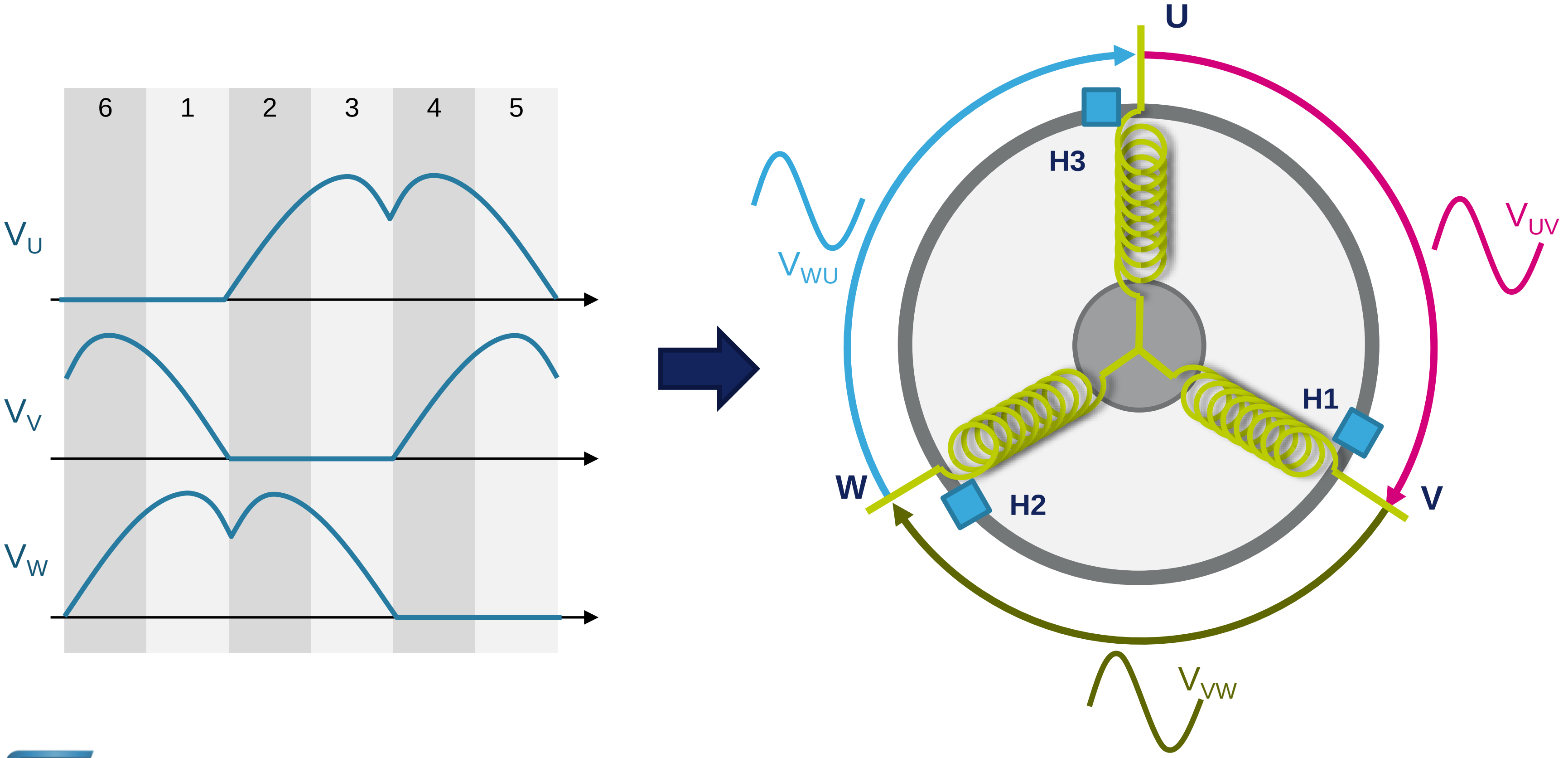
Applying a sinusoidal voltage to each phase could be difficult because the power bridge has to be able to apply both positive and negative voltages (bipolar driving).

Alternatively, the **space vector modulation** can be used.



Sinusoidal driving

The **space vector modulation** imposes a sinusoidal voltage between to adjacent phases applying a non sinusoidal voltage to the motor leads:



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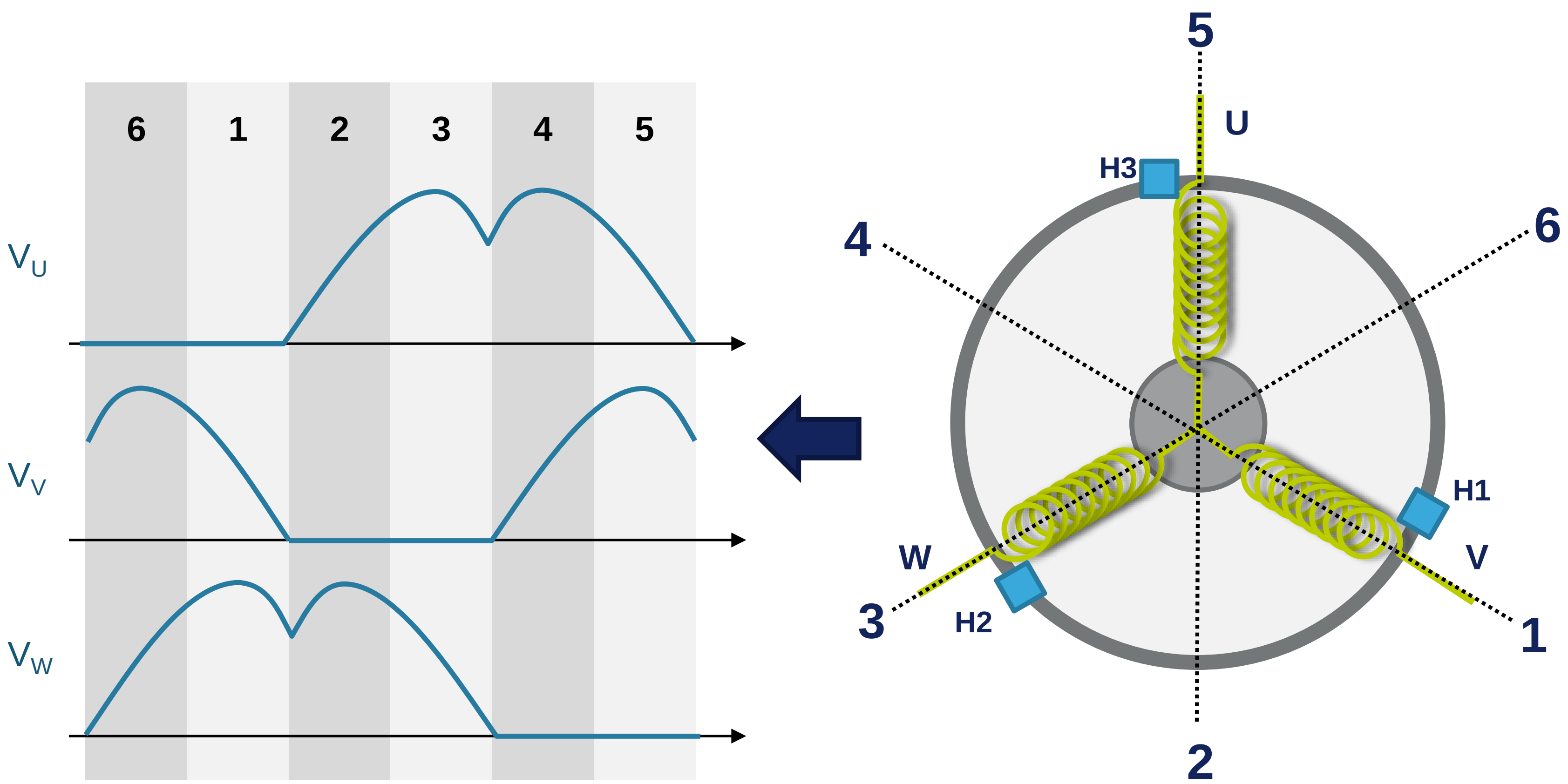
Sinusoidal driving

The generation of the voltages is synchronized through the Hall sensors:



Sinusoidal driving

The sinusoidal driving needs to solve some issues to increase performance:

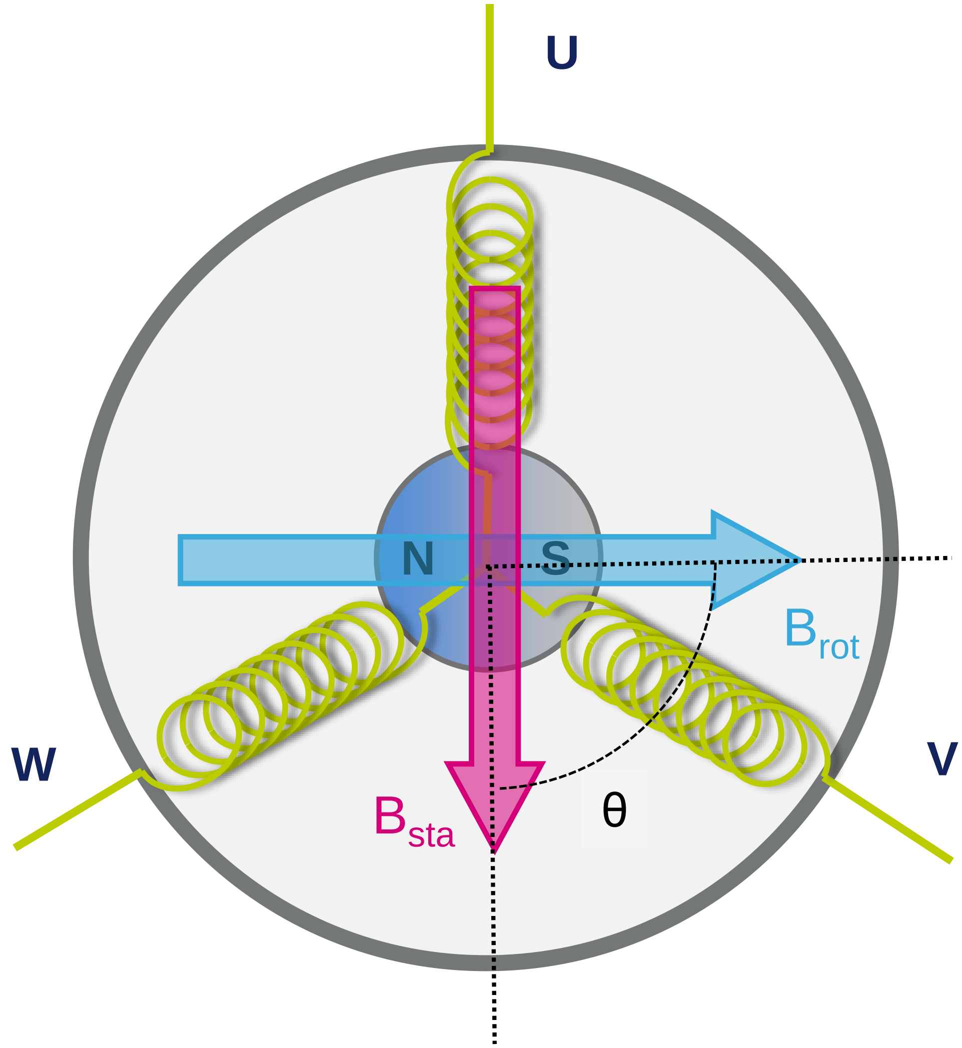
- The BEMF varies with speed
  When the motor accelerates, the BEMF voltage increases, so the voltage applied to the motor must be varied to keep current amplitude (i.e. torque) constant.

- Phase relation between B_{sta} and B_{rot} is unknown
  The load angle, which determines the efficiency of the system, is not directly controlled (<u>no current control</u>).

Field Oriented Control

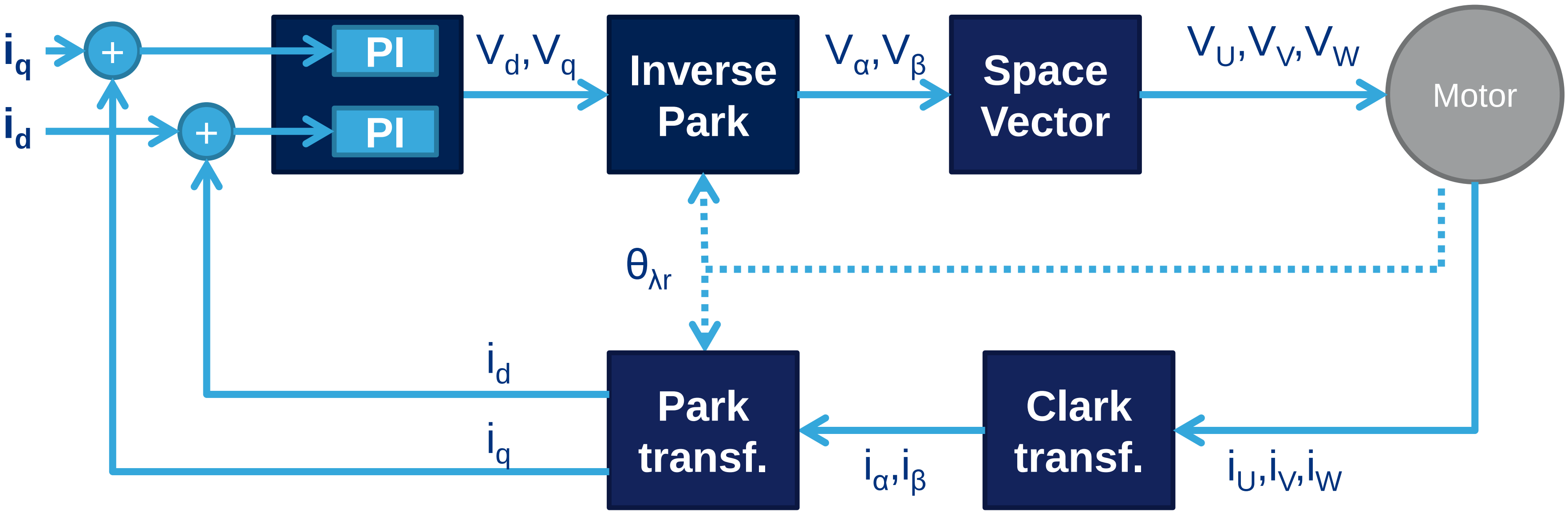
The **Field Oriented Control (FOC)** algorithm allows to obtain the maximum performance from a BLDC motor.

The objective of the algorithm is to control the vector components of the stator magnetic field (i.e. the phase currents) in order to obtain the target **intensity** and **phase relation** with the rotor magnetic field.



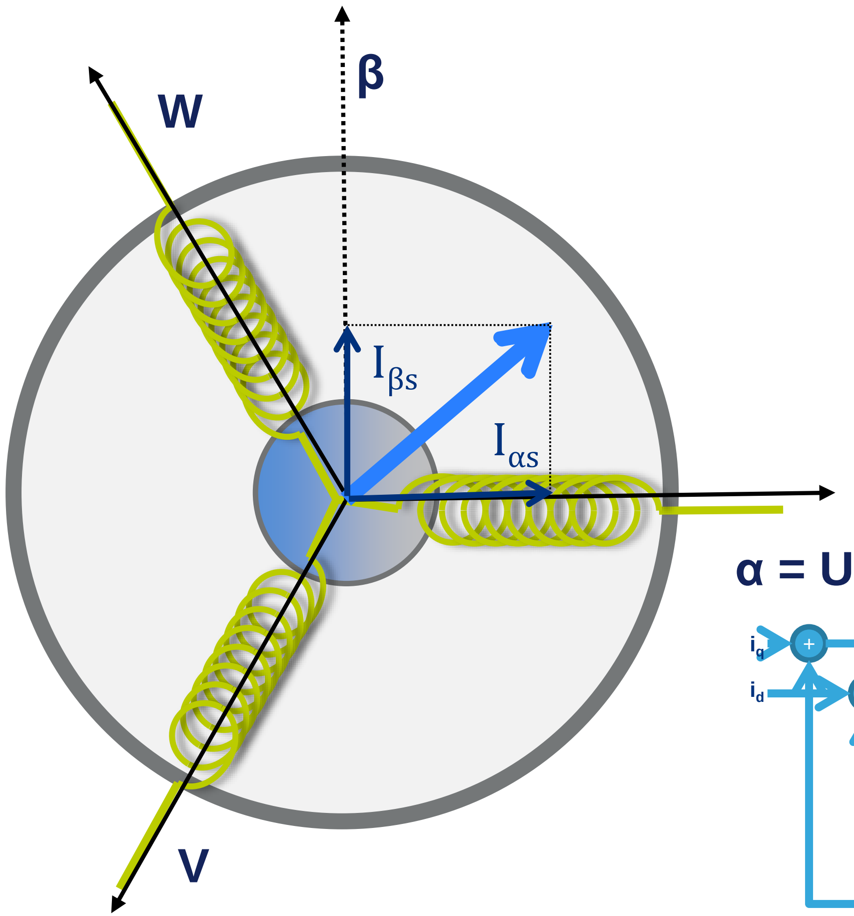
Field Oriented Control

Field Oriented Control (**FOC**) can be represented through this block diagram



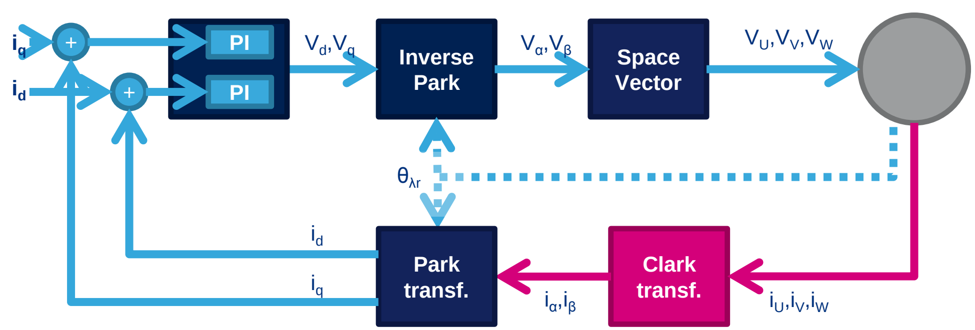
Field Oriented Control

STEP 1) Using the Clark transformation, the currents of the 3-phase system (U,V,W) are projected in an orthogonal system (α,β).



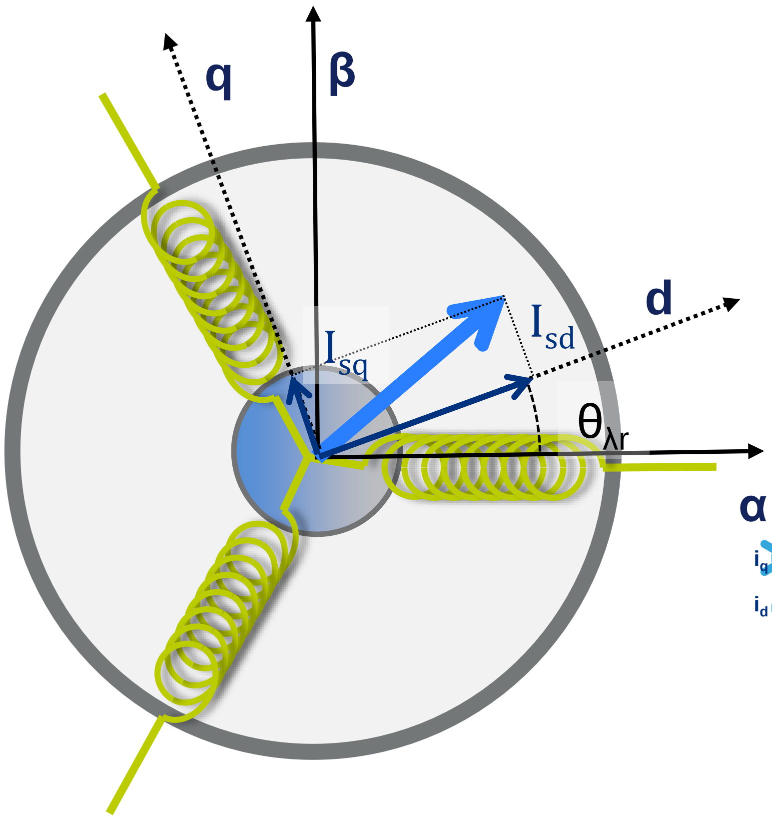
$$
\begin{cases}
i_{\alpha s} = i_U \\
i_{\beta s} = \dfrac{1}{\sqrt{3}} i_U + \dfrac{2}{\sqrt{3}} i_V
\end{cases}
$$

NOTE: Considering $i_U + i_V + i_W = 0$, the projection can be obtained using only two currents



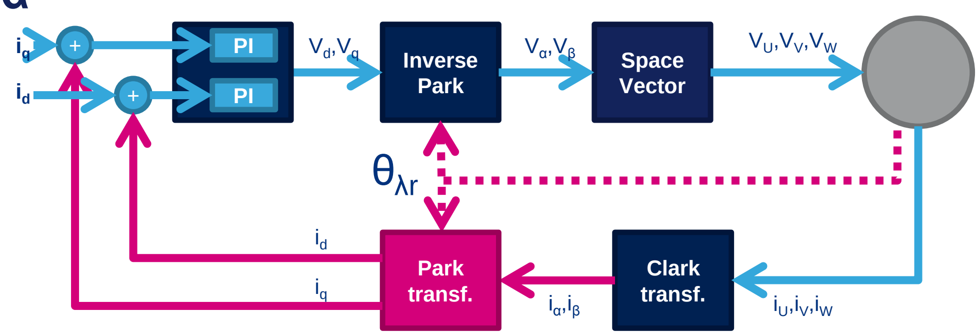
Field Oriented Control

STEP 2) Using the Park transformation, the orthogonal system (α,β) is projected on a rotating system lying on the rotor. The resulting orthogonal system (d,q) allows splitting the stator current into **direct** (d) and **quadrature** (q) components.



$$\begin{cases} i_{ds} = i_{\alpha s}\cos(\theta_{\lambda r}) + i_{\beta s}\sin(\theta_{\lambda r}) \\ i_{qs} = -i_{\alpha s}\sin(\theta_{\lambda r}) + i_{\beta s}\cos(\theta_{\lambda r}) \end{cases}$$

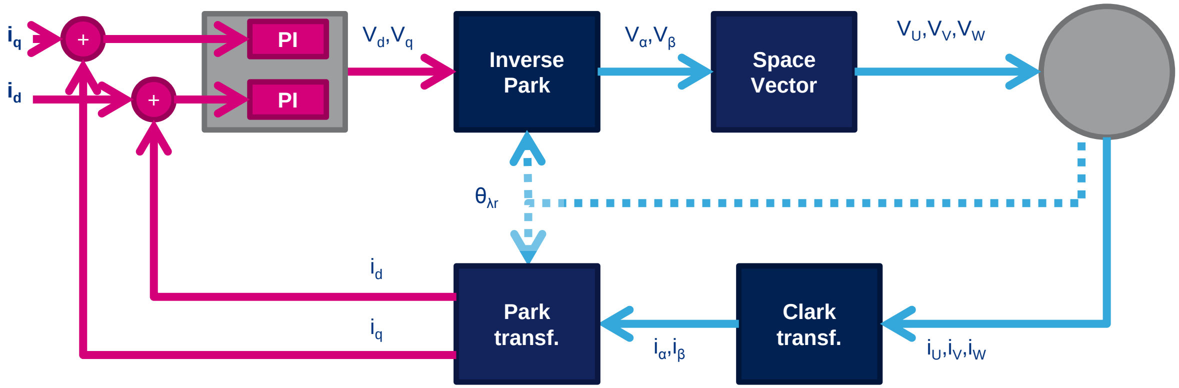
Where $\theta_{\lambda r}$ is the rotor position



Field Oriented Control

STEP 3) The **direct** (d) and **quadrature** (q) components of the current can be controlled using a standard PI system.

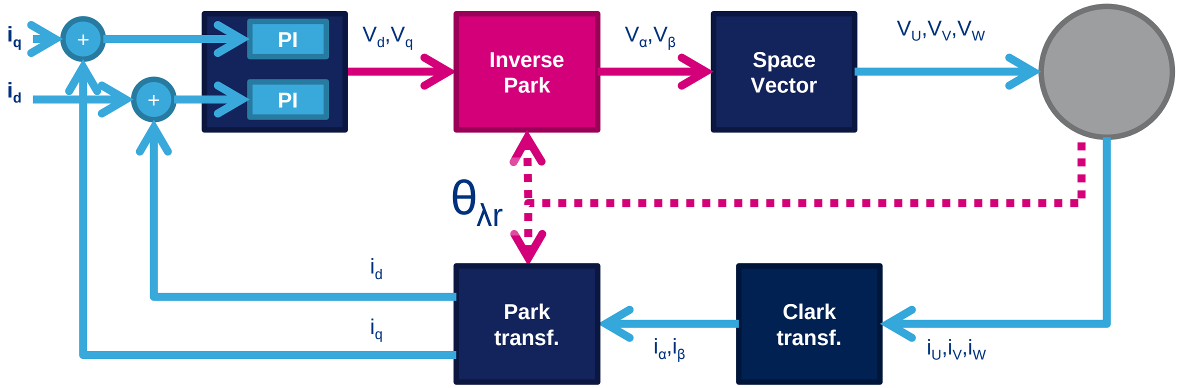
- The direct component gives information about the load angle of the motor. The maximum efficiency is obtained when $i_d = 0$.
- The quadrature component is normally used as torque reference form the regulation of the motor speed (speed loop).



STEP 4) Using the inverse Park transformation, the output of the PI controller, which are the direct and quadrature voltages, are re-projected on the orthogonal system (α,β).

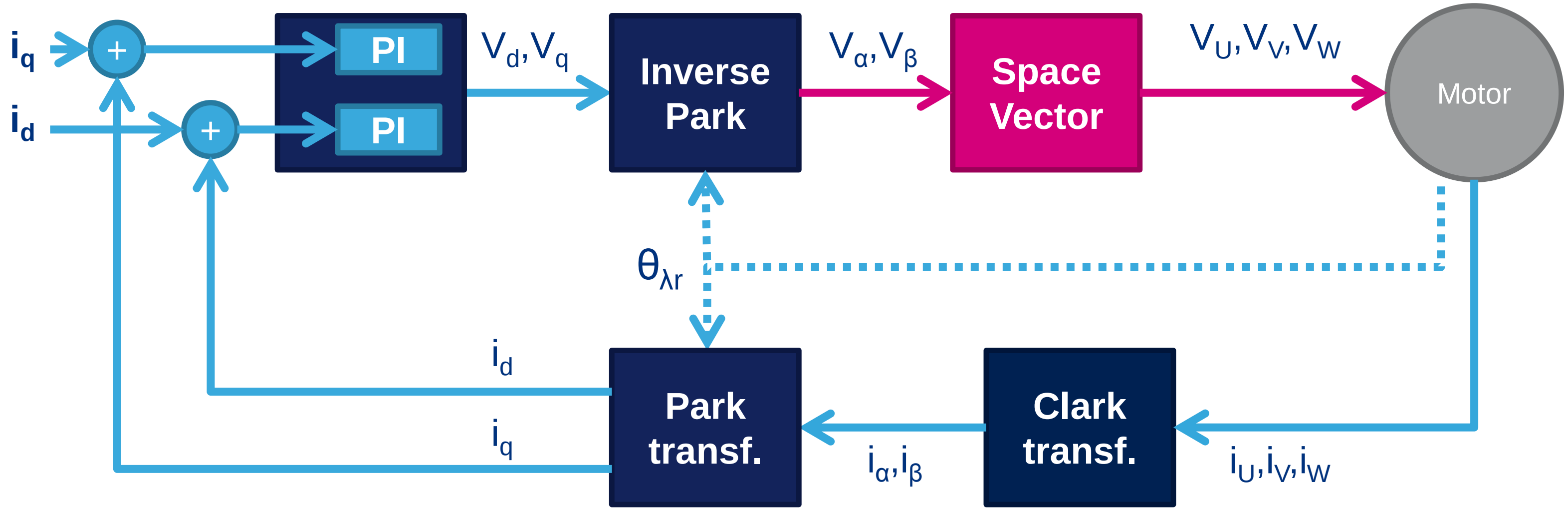
$$\begin{cases} V_{\alpha ref} = V_{dref}\cos(\theta_{\lambda r}) - V_{qref}\sin(\theta_{\lambda r}) \\ V_{\beta ref} = V_{dref}\sin(\theta_{\lambda r}) - V_{qref}\sin(\theta_{\lambda r}) \end{cases}$$

Where $\theta_{\lambda r}$ is the rotor position



Field Oriented Control

STEP 5) The voltages projected on the (α,β) system are converted to (U,V,W) voltages using the space vector modulation.



Field Oriented Control

Pros

- Can control the efficiency of the system imposing a load angle (direct component of the current)
- Smooth operation thanks to the sinusoidal driving

Cons

- Implies complex calculations which cannot be performed by low-level microcontrollers
- Needs the information of the rotor flux (i.e. expensive sensors or more complex calculations)

Three-phase brushless motor summary

- The stator magnetic field is the combination of the magnetic fields generated by the motor phases.
- The magnetic field rotation is obtained driving in the proper way the phases.
- The position of the rotor must be sensed in order to determine the proper driving sequence.

Bipolar stepper motor

Stepper motors overview

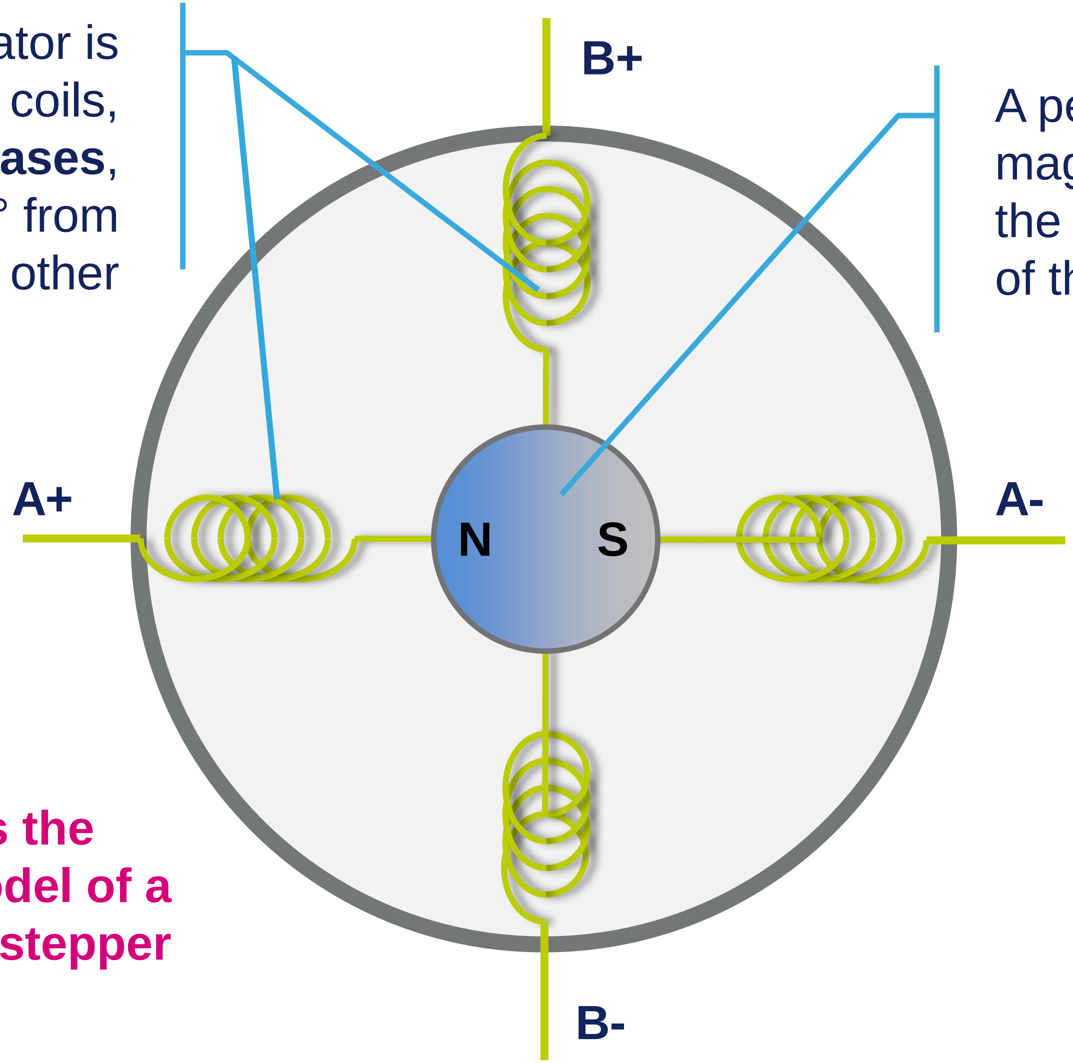
There are different types of stepper motors:

- Unipolar (two phases)
- **Bipolar (two phases)**
- Three-phase
- Five-phase

The presentation will describe the basics of the **bipolar stepper motor** because it is one of the most common versions.
In most cases, the considerations can be extended to the other types.

Bipolar stepper motor basics

The stator is composed of two coils, named **phases**, positioned at 90° from each other



A permanent magnet generates the magnetic field of the rotor

NOTE: This is the simplified model of a 4-step/round stepper motor

Bipolar stepper motor basics

The stepper motors are designed to **keep a target angular position**. This objective is obtained by splitting the rotation of the shaft in small fractions named **steps**.

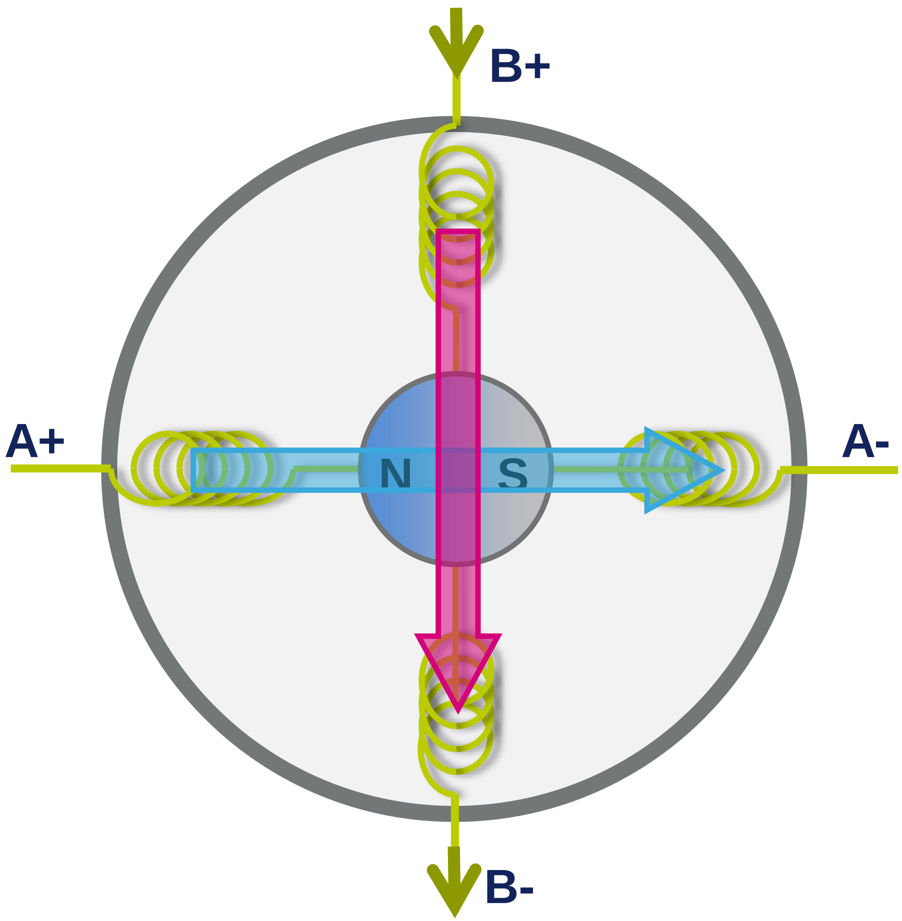
Each step represents a stable position where the motor shaft can be easily kept forcing the proper current into the phases.

Bipolar stepper motor basics

The rotor magnetic field is always present and it is generated by a permanent magnet.

The stator magnetic field is generated by forcing a current in one phase.

The rotor will align to the stator magnetic field: **the target step position is achieved**.



Bipolar stepper motor basics

The phases have always to be driven following the **proper sequence**, otherwise motor rotation cannot be achieved.

The stepper motor is moved by performing a series of small rotations, i.e. **steps**. This way the mechanical position of the shaft is always known without the need for a dedicated position sensor (*).

The motor speed is determined by the frequency at which the sequence is performed and it is expressed in **steps per second** or **pulses per second (pps)**.

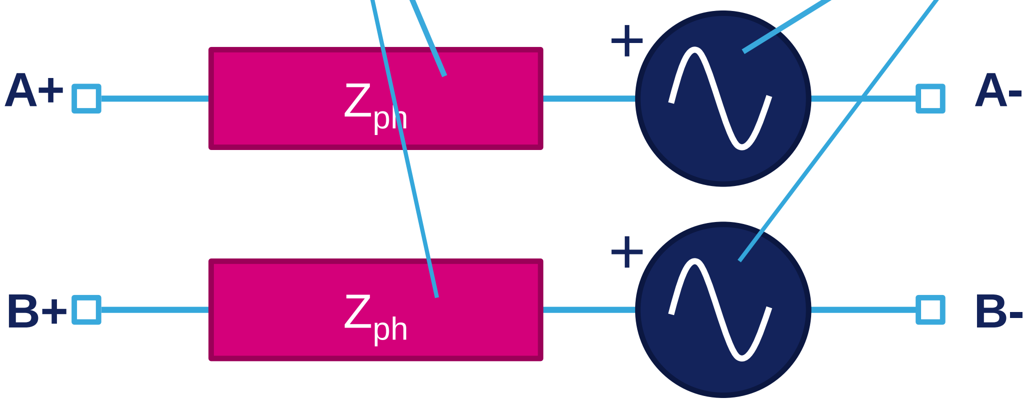
(*) This is true only if the starting position is already known

Bipolar stepper motor basics

Electrical model of a stepper motor

Phase impedance

$$\mathbf{Z_{ph} = R_{ph} + j\omega L_{ph}}$$



Back electromotive force (BEMF) generator are two sinewave voltages(*) delayed from each other by 90°.
The sinewave amplitude is proportional to the motor speed:

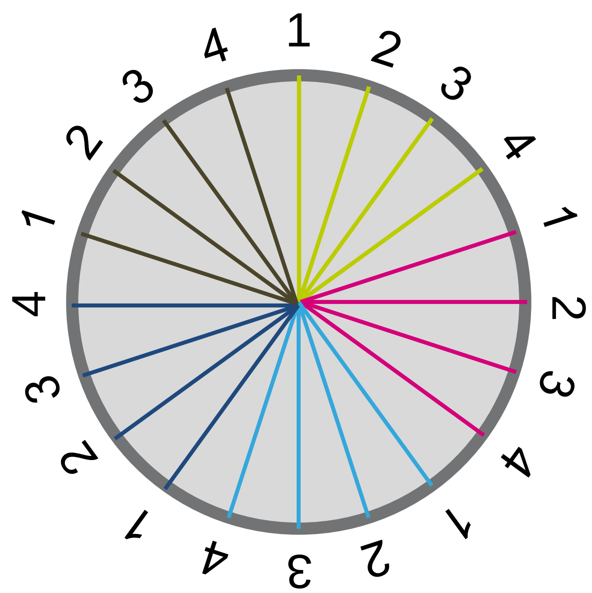
$$V_{BEMF} = \mathrm{k_e} \cdot Speed$$

Step angle

In stepper motors, a complete rotation of the stator magnetic field (i.e. a sequence of **four steps**) does not correspond to a complete mechanical rotation.

This effect is obtained through a proper shaping of the rotor and stator cores: as a consequence, **at each position of the magnetic field, more mechanical positions correspond**.

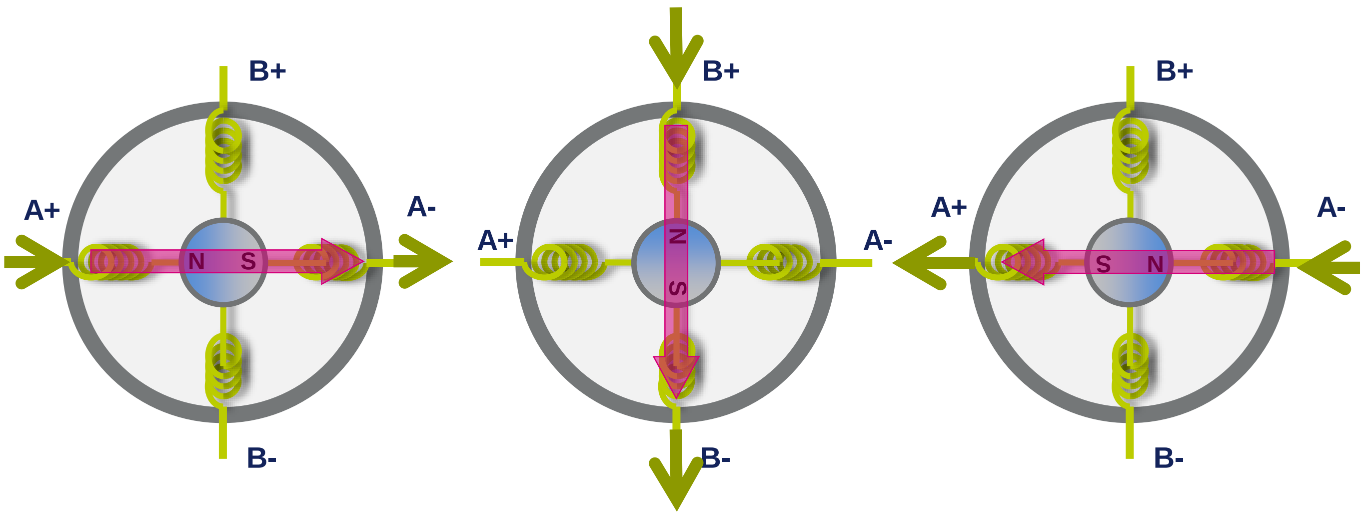
$$Step\ angle = \frac{360}{poles \times phases} = \frac{360}{N_{STEP}}$$



Example: in a 20-step stepper motor, each full step combination (numbered from 1 to 4) can position the rotor at 5 possible angles (colors)

Full step

Forcing the phase currents according to the following sequence, the motor rotates performing one step at a time.
This is named **Full-step 1 phase on driving** or **Full-step wave mode**.



1	2	3	4
I_{phA} = +	I_{phA} = 0	I_{phA} = -	I_{phA} = 0
I_{phB} = 0	I_{phB} = +	I_{phB} = 0	I_{phB} = -

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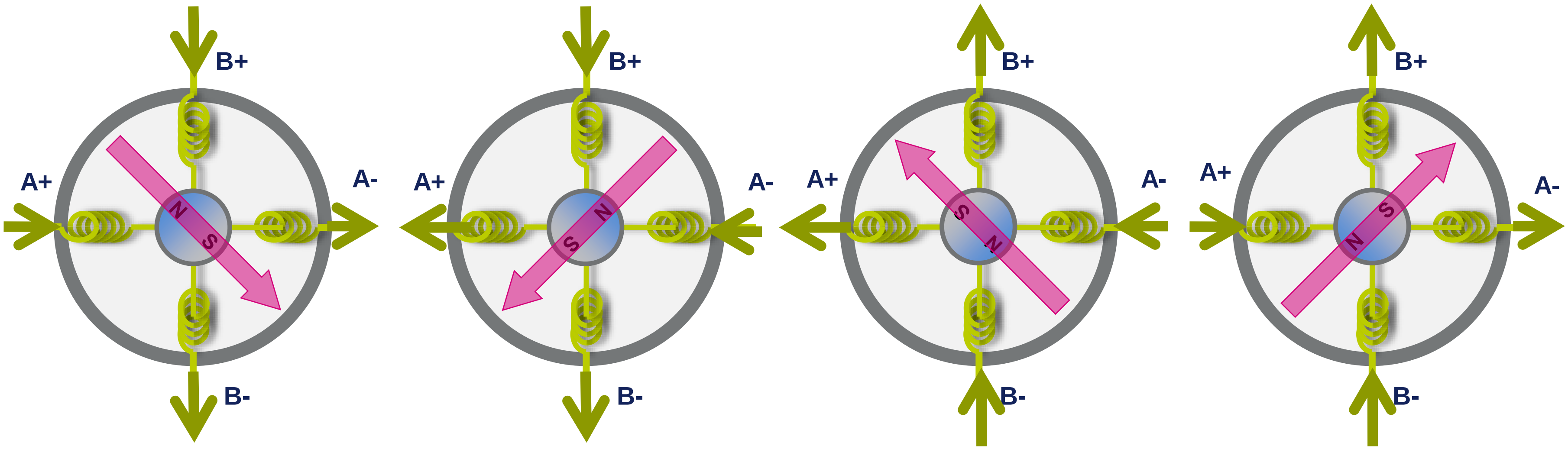
Full step

It is also possible to perform the sequence forcing the same current in both phases. In this case, the stator magnetic field is the geometric sum of two components and is √2 times stronger.
This is named **Full-step 2 phase on driving** or **Full-step normal mode**.



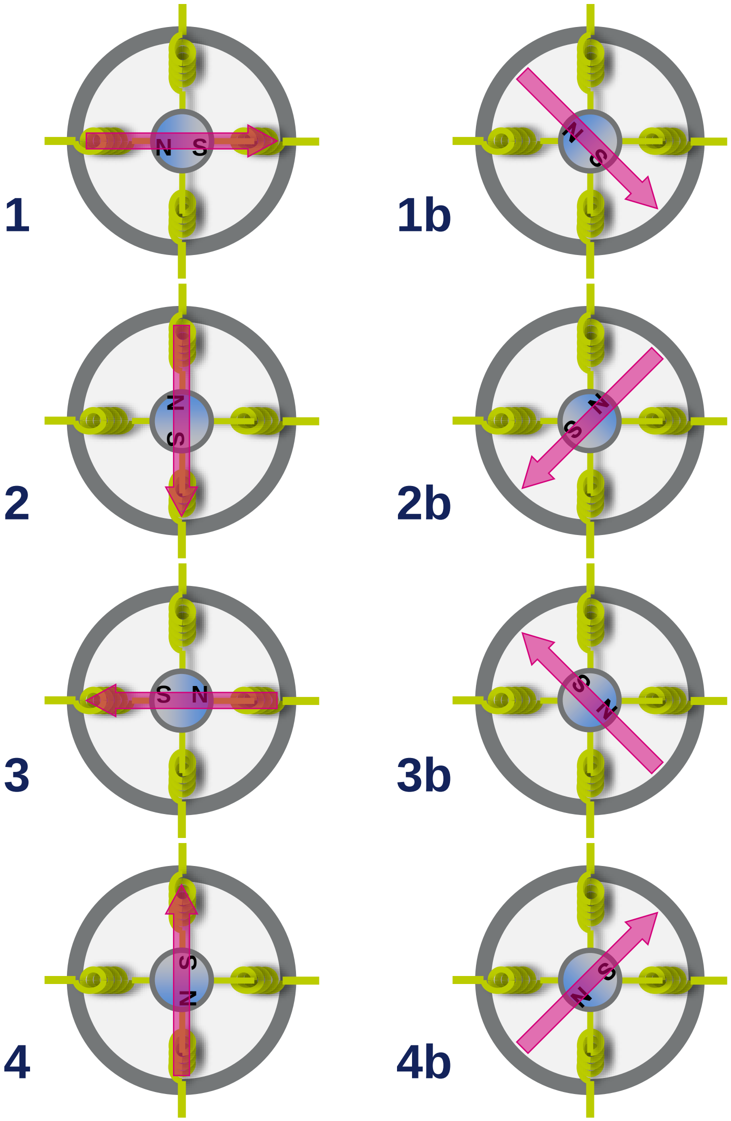
1b	2b	3b	4b
I_{phA} = +	I_{phA} = -	I_{phA} = -	I_{phA} = +
I_{phB} = +	I_{phB} = +	I_{phB} = -	I_{phB} = -

Half step

Combining the two driving methods, it is possible to position the rotor in the middle position between two subsequent steps.
Half-step is performed.

1ph ON	2ph ON	Half-step
1		1
	1b	1b
2		2
	2b	2b
3		3
	3b	3b
4		4
	4b	4b

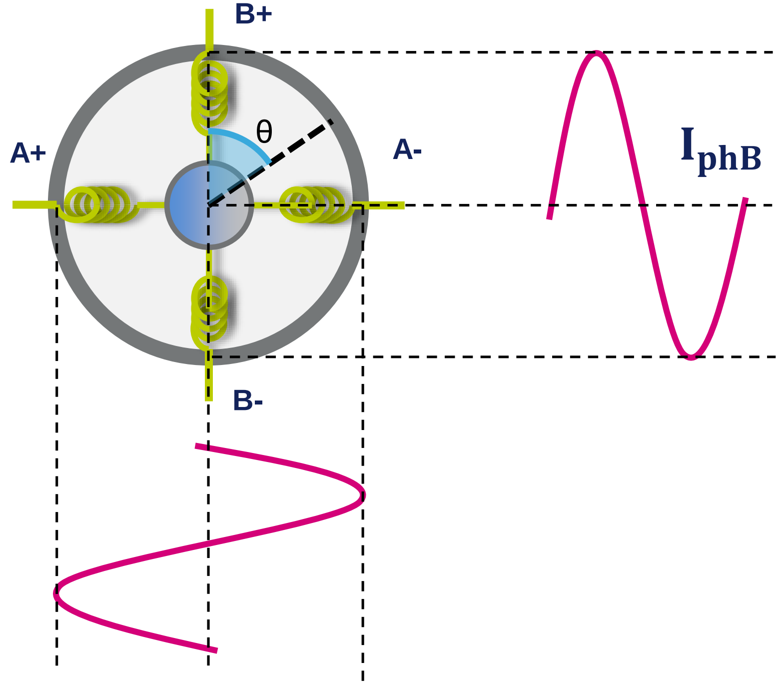
This method doubles the number of mechanical positions achievable by the motor.



Microstepping

Starting from half-step concept, it is possible to further increase the number of stable mechanical positions using the **microstepping** technique.

Each position of the rotor can be achieved by applying the proper pair of currents to the phases.
This pair is determined by the sine and cosine values of the target angle.



$$\mathbf{I_{phB} = I_{peak} \cdot cos\ (\theta)}$$

$$\mathbf{I_{phA} = I_{peak} \cdot sin(\theta)}$$

Microstepping

Microstepping indicates all the driving methods which allow a mechanical resolution higher than the half-step driving.

The pairs of currents which are applied to the phases depends on the number of microsteps in which the step is divided:

$$\mathbf{I_{phA}}(\boldsymbol{n}) = \mathbf{I_{peak}} \cdot \mathbf{sin}\left(\frac{\boldsymbol{\pi}}{\mathbf{2}} \cdot \frac{\boldsymbol{n}}{\boldsymbol{N_{microsteps}}}\right)$$

$$\mathbf{I_{phB}}(\boldsymbol{n}) = \mathbf{I_{peak}} \cdot \mathbf{cos}\left(\frac{\boldsymbol{\pi}}{\mathbf{2}} \cdot \frac{\boldsymbol{n}}{\boldsymbol{N_{microsteps}}}\right)$$

Where $N_{microsteps}$ is the number of microsteps and *n* ranges from 0 to $4 \cdot N_{microsteps}$.

Microstepping

The main advantage of microstepping is the smoother operation compared to the full- or the half-step methods.

The step movement is split into sub-movements (i.e. microsteps) so the resulting rotation is more continuous.

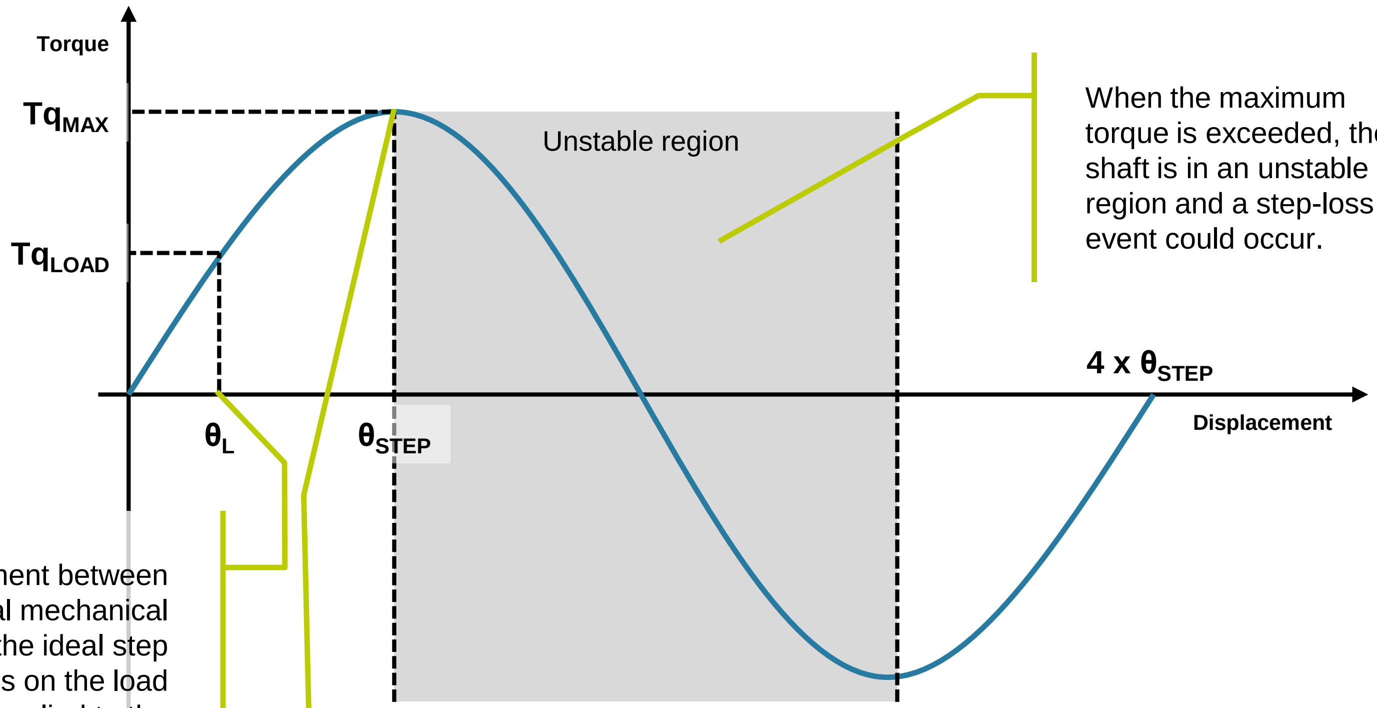
The main drawback is the reduction of the maximum output torque at the same maximum current:

$$Tq_{full-step} = \sqrt{2} \cdot Tq_{microstep}$$

This is because in microstepping the motor phases are driven with the maximum current one at a time (the sine peak corresponds to the cosine zero-crossing and vice-versa), whereas in full-step, both phases can be driven at maximum current at the same time.

Torque vs Angle characteristic

The torque vs displacement angle (i.e. the angle between the ideal step position and the actual rotor position) is sinusoidal:



When the maximum torque is exceeded, the shaft is in an unstable region and a step-loss event could occur.

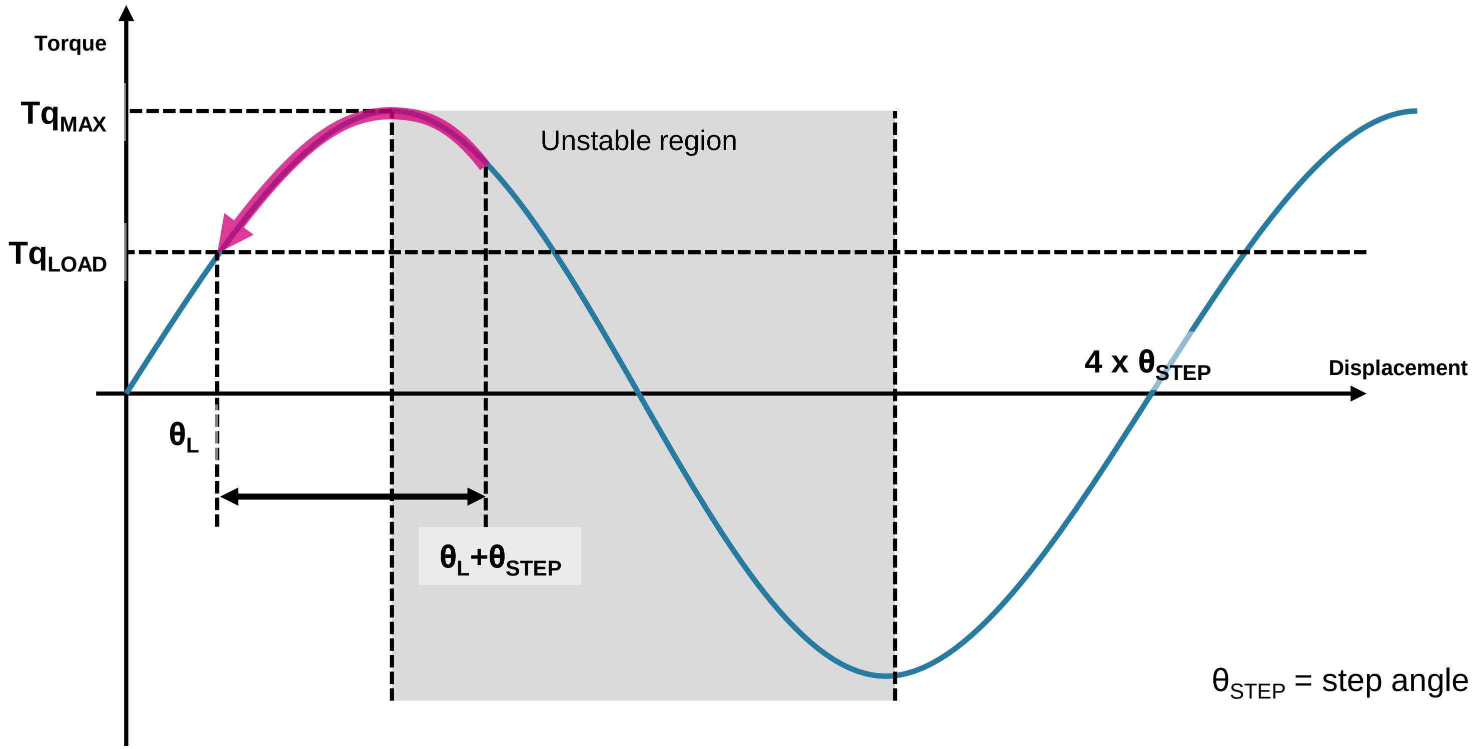
The displacement between the actual mechanical position and the ideal step position depends on the load torque which is applied to the motor shaft

When the displacement is equal to a step angle (rotor an stator magnetic fields are at 90°), the maximum torque is reached.

θ_{STEP} = step angle

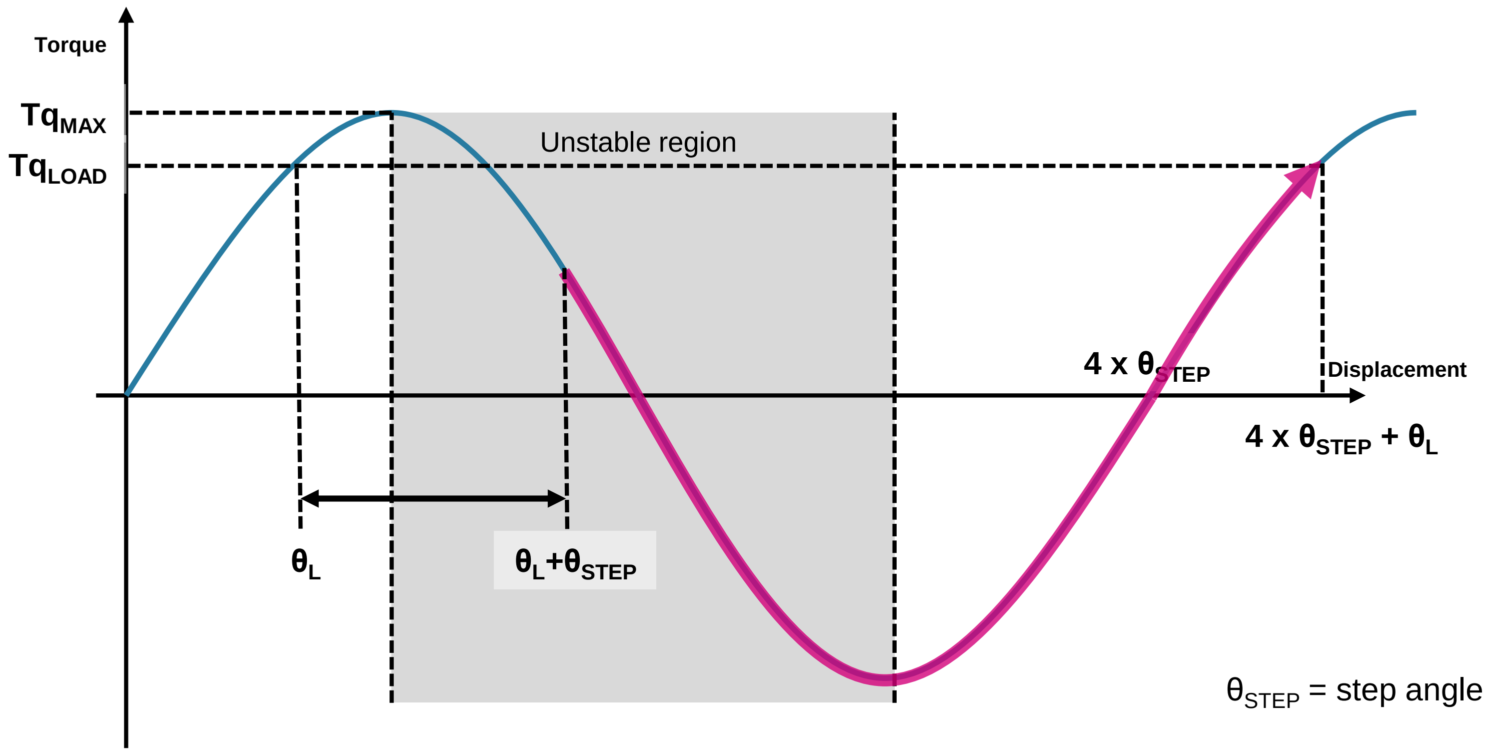
Torque vs Angle characteristic

When a step is performed, the displacement is abruptly increased by 90° because the stator magnetic field moves one step away from the current rotor position.
As a consequence, the torque increases and the rotor moves to the next position.



Torque vs Angle characteristic

If the starting displacement is about one step angle (i.e. the load torque approaches the Tq_{MAX}), the output torque **after the step** could be lower than the load and the new stable position will be a 4-step angle away from the target position.
This is a step-loss condition which could also cause the de-synchronization of the motor (stall).



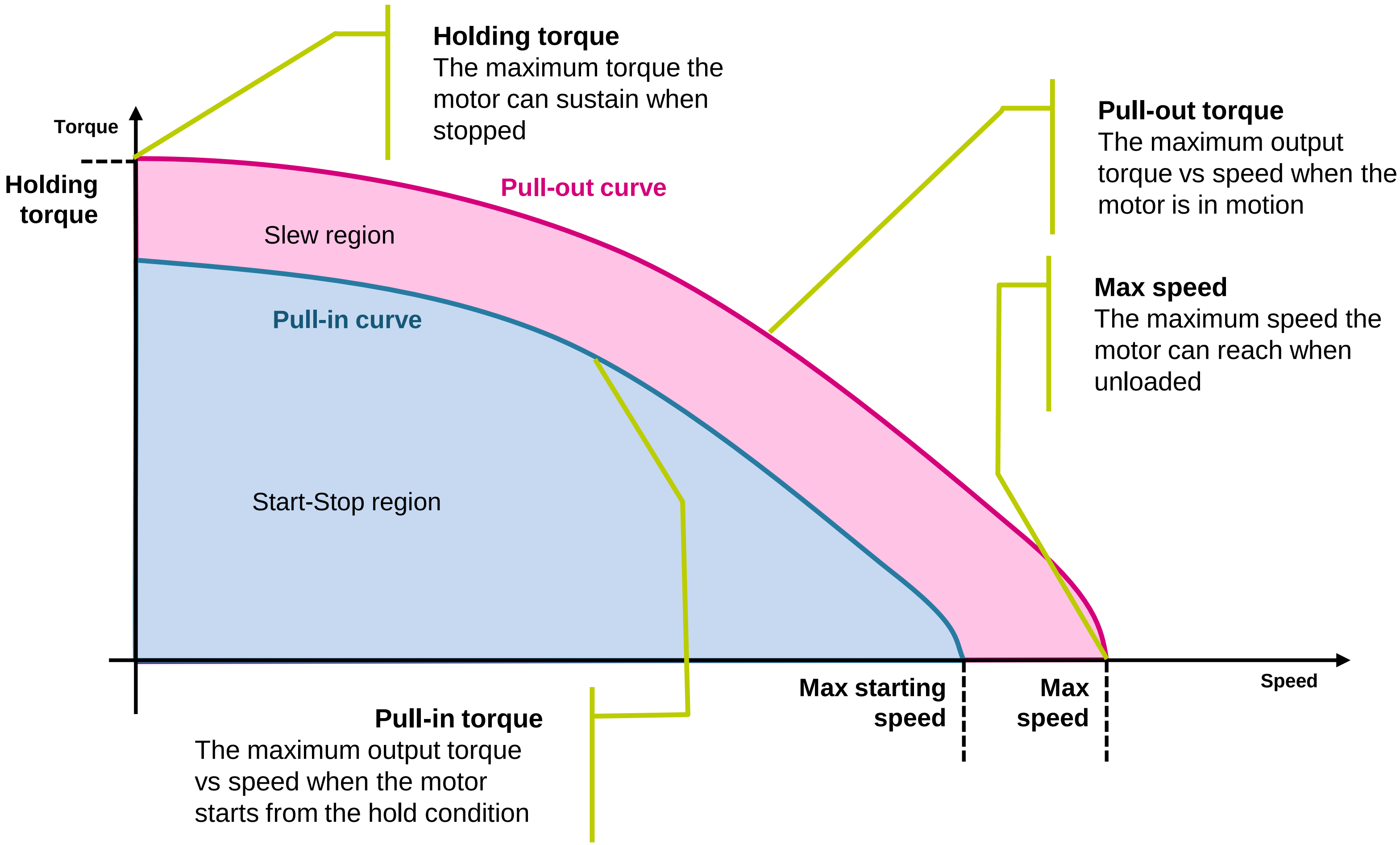
Stall and step-loss

When the stepper motor is loaded with a torque exceeding its torque vs. speed characteristic, a **stall** or a **step-loss** event could occur.

The stepper motor is in **stall** when it completely loses the synchronism.
As result, the rotor is stopped or vibrates, but no rotation is performed.

When a **step-loss** occurs, the motor loses the synchronism for a short period and then resumes.
As result, the rotor continues its rotation, but the actual position is different from the ideal one.

Torque vs. Speed characteristic



NOTE: The curves change with driving method and phase current. Most manufacturers provide the curve @ rated current in full-step.

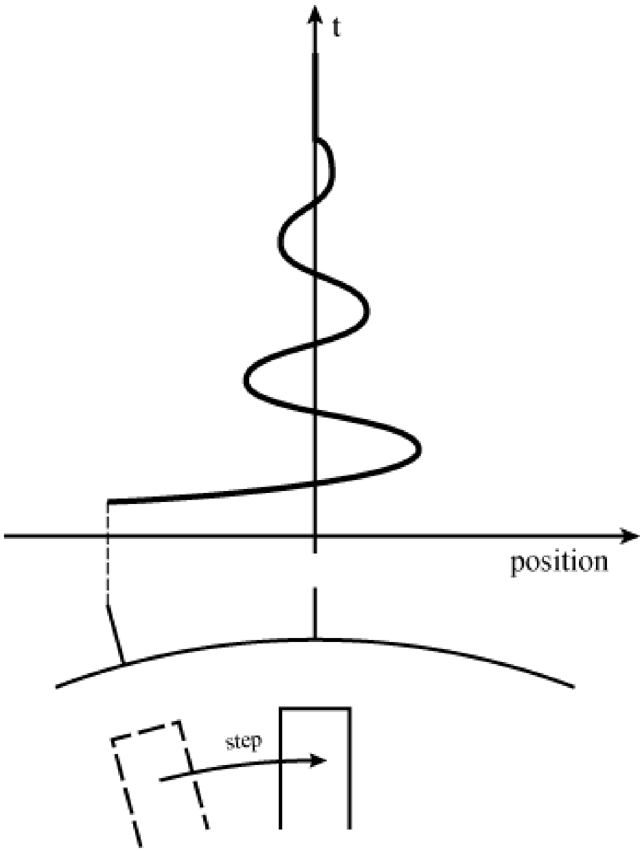
Resonances

Each time a step (or a microstep) is performed, the final position is not immediately asserted, but the rotor vibrates around the target position before stopping.

When the step rate reaches the frequency of this vibration, the mechanic of the motor **resonates**.

This effect is named mid-point resonance.

The stepper motor should not operate in this condition.



Effects of the resonances:

- **Strong vibrations:** the motor is very noisy because the resonances stimulate the internal mechanic.

- **Reduced torque:** the energy is “dissipated” by the resonance (vibrations) so a minor par of the energy is converted into an effective torque.

- **Discontinuous motion:** if vibration are strong enough to move the rotor in the unstable region, step-loss events could occurs.

Bipolar stepper motor summary

- The stepper motor is designed to move the rotor in a target position and keep it.
- The stator magnetic field is the combination of the magnetic fields generated by the motor phases.
- Each combination of currents in the motor phases moves and keeps the motor in a stable position. At each position of the magnetic field, more mechanical positions may correspond.
- The motor rotation is performed through a proper sequence of phase currents.
- The rotation is always performed one step (or microstep) at a time.