Voltage mode stepper motor control

Smooth stepper motor driving

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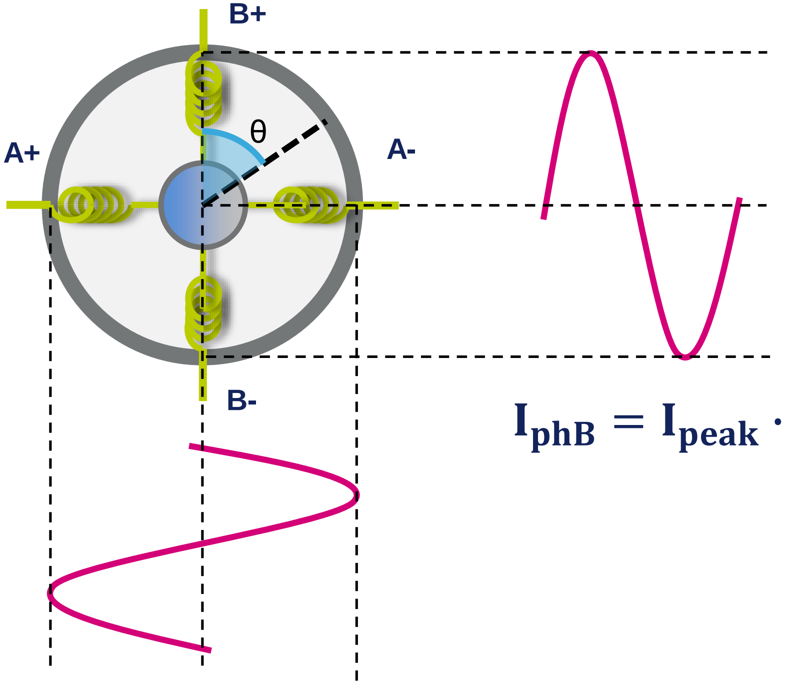
Microstepping in stepper motors

The microstepping driving of the stepper motors is based on the following principle:

Appling two sinusoidal currents at the motor phases with a phase relation of 90° (sine and cosine), it is possible to align the stator magnetic field in any possible direction.

The voltage mode driving is designed to achieve this with the maximum effectiveness.



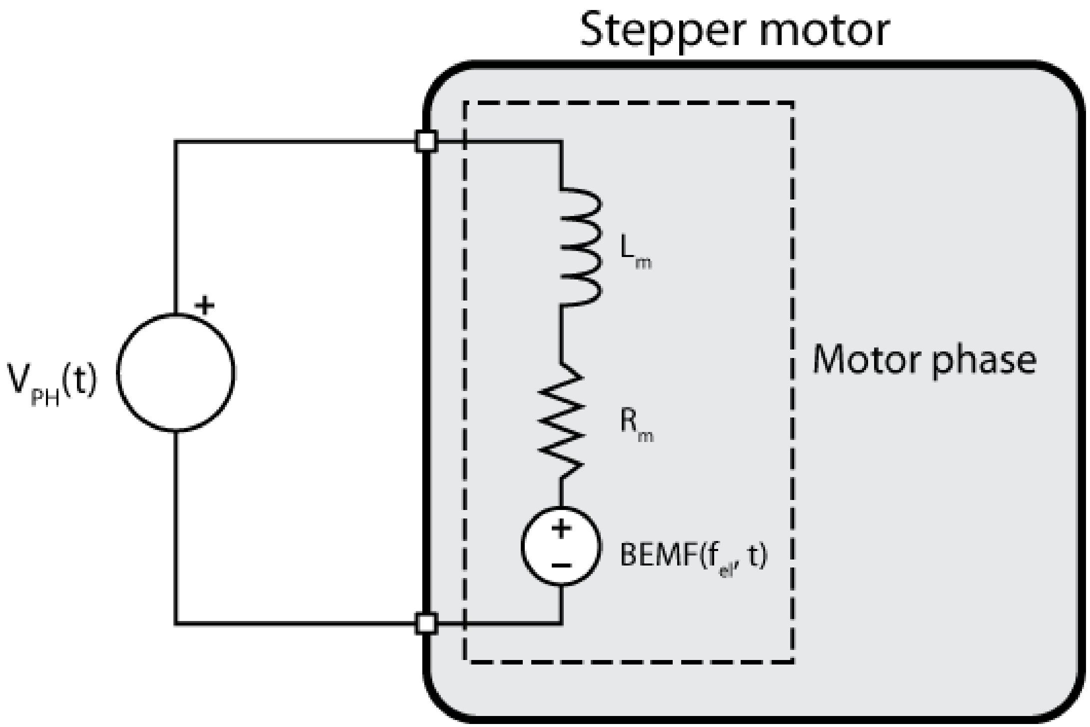
$$I_{phB} = I_{peak} \cdot \cos(\theta)$$

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

Voltage mode basics

Voltage mode is based on the linear model of stepper motors.

If a voltage sinewave is applied to a stepper motor phase the resulting current is sinusoidal too.



Voltage mode vs. Current mode

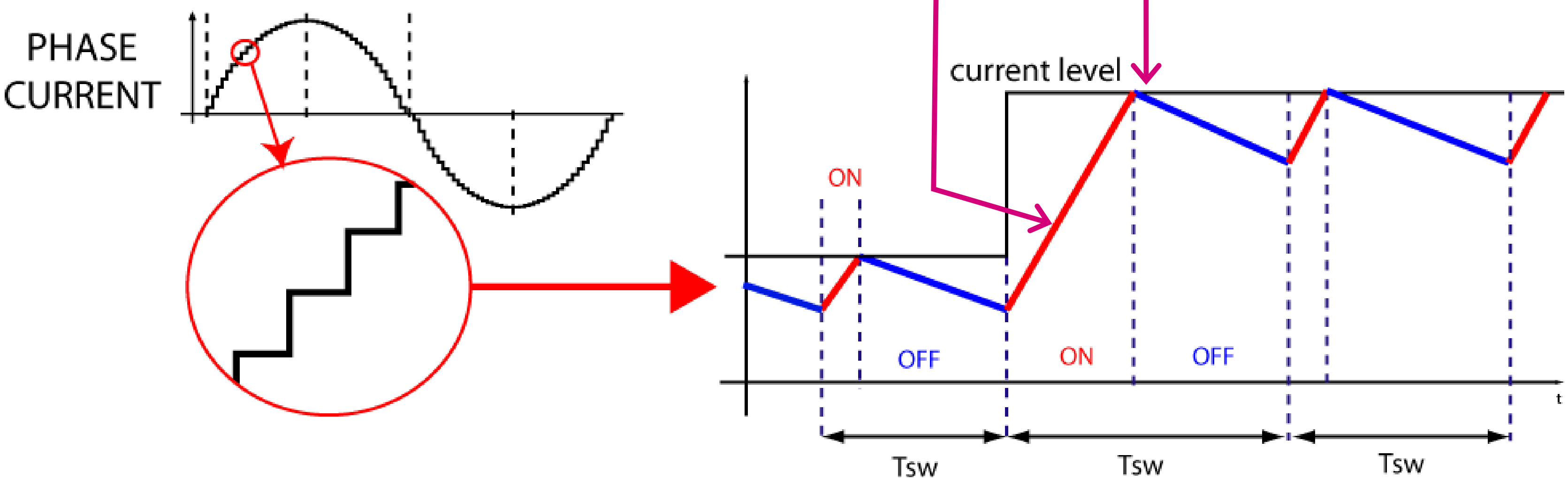
Current mode driving

Abrupt current changes cause strong mechanical vibrations.
Current mode tries to follow even non idealities
(reference quantization and sampling)

Noisy and jerky motion.

Peak current is controlled.
Average current value is
different from target one.

Inaccurate positioning



Non-constant switching freq.

Torque ripple is difficult to control.

Voltage mode vs. Current mode

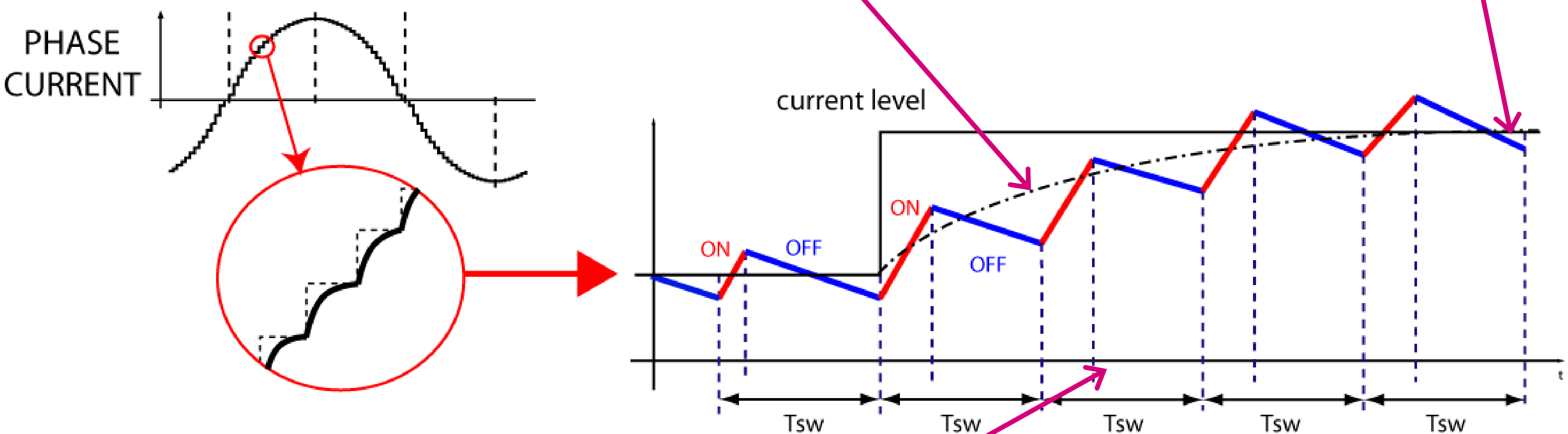
Voltage mode driving

Smooth current transient reduces mechanical vibrations.

Motor movement is soft and silent.

Average current is controlled.

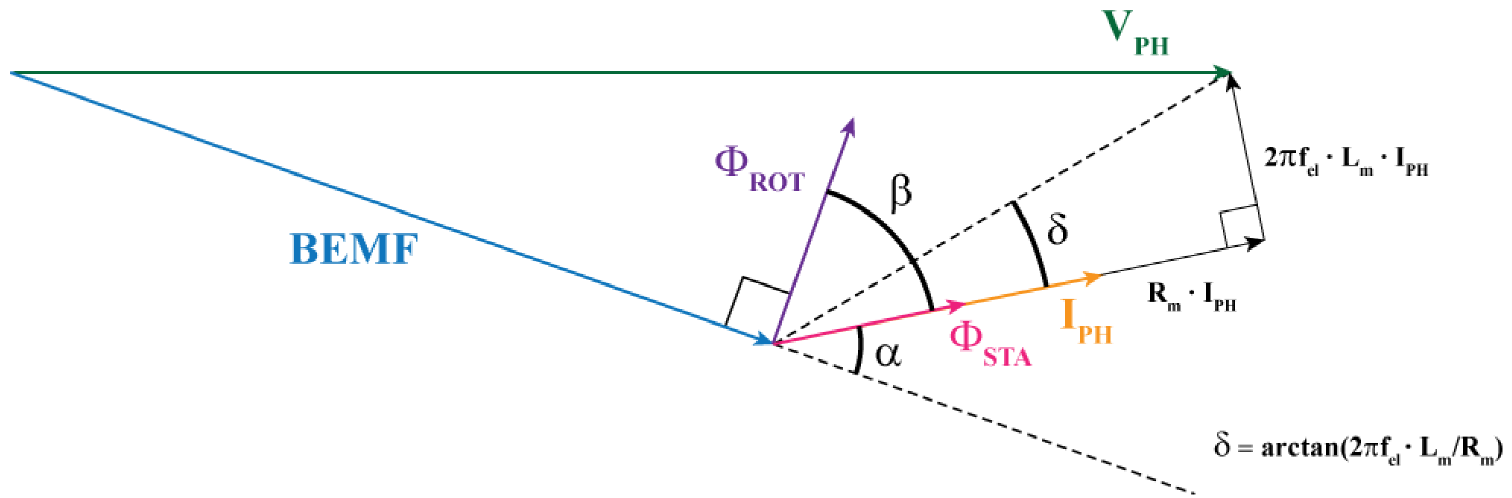
Accurate positioning.



Constant switching freq.

Torque ripple is under control.

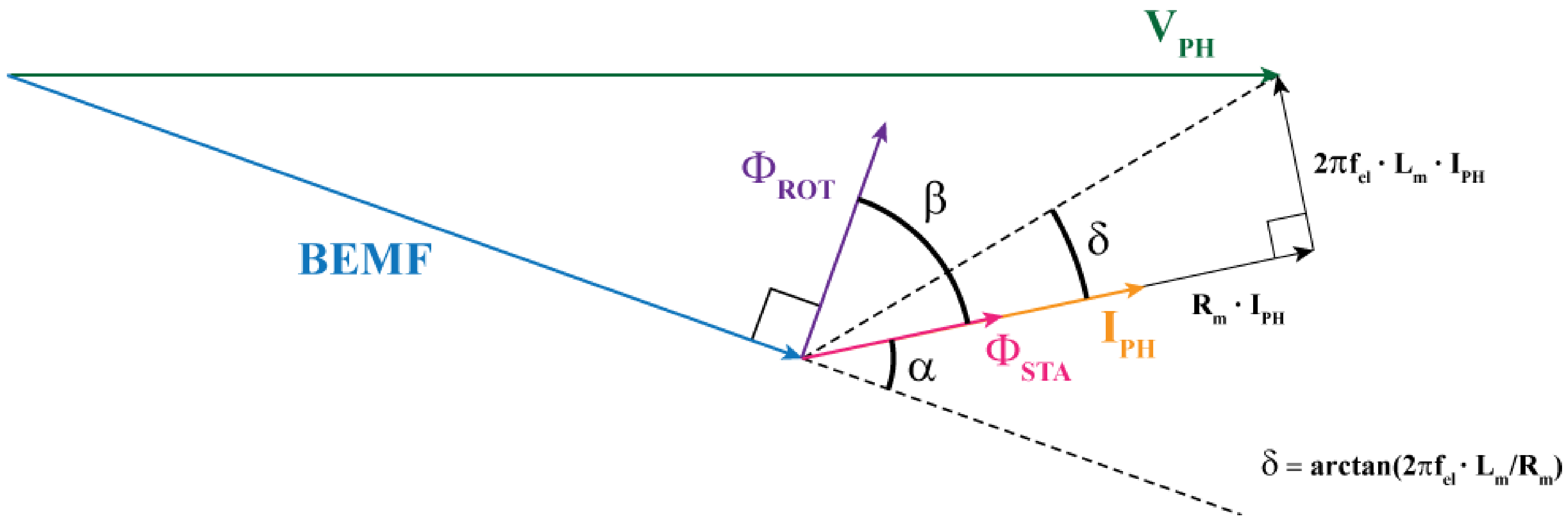
Voltage mode basics



When a voltage sinewave with amplitude V_{PH} is applied to the motor, the amplitude of the resulting current (I_{PH}) depends on:

- Motor electrical parameter
- **BEMF voltage**
- **Sinewave frequency** (i.e. the motor speed)
- The phase relation between rotor and stator magnetic field (i.e. the torque)

Voltage mode basics



The equation that relates the phase voltage and the phase is complex:

$$|V_{PH}|^2 = (R_m^2 + (2\pi f_{el})^2 \cdot L_m^2) \cdot |I_{PH}|^2 + (k_e \cdot f_{el})^2 +$$
$$-2\cos(\pi - \alpha - \arctan(2\pi f_{el} \cdot L_m / R_m)) \cdot |I_{PH}| \cdot (k_e \cdot f_{el}) \cdot \sqrt{R_m^2 + (2\pi f_{el})^2 \cdot L_m^2}$$

Voltage mode basics

ST's patent simplifies the relation allowing a practical implementation of the algorithm.

The system discriminates two cases:

1. When the motor speed (proportional to f_{el}) is low
2. When the motor speed (proportional to f_{el}) is high

$$|V_{PH}| = \begin{cases} R_m \cdot |I_{PH}| + k_e \cdot f_{el} & \text{for } 2\pi f_{el} \ll R_m/L_m \\ 2\pi f_{el} \cdot L_m \cdot |I_{PH}| + k_e \cdot f_{el} & \text{for } 2\pi f_{el} \gg R_m/L_m \end{cases}$$

Voltage mode basics

The control algorithm can be defined through 4 parameters:

$$|V_{PH}| = \begin{cases} \mathbf{KVAL} + \mathbf{StSlp} \cdot \text{Speed} & \text{for Speed} \leq \mathbf{IntSpeed} \\ \mathbf{FnSlp} \cdot \text{Speed} & \text{for Speed} > \mathbf{IntSpeed} \end{cases}$$

Par	Description	Formula	Unit
KVAL	Voltage applied at zero speed	$R_m \cdot \lvert I_{PH} \rvert$	V
IntSpeed	Motor speed discriminating the slow and the fast region	$4 \cdot R_m / 2\pi L_m$	steps/s
StSlp	Compensation slope used in the slow region	$\frac{k_e}{4}$	V/(steps/s)
FnSlp	Compensation slope used in the fast region	$\frac{2\pi L_m \cdot \lvert I_{PH} \rvert + k_e}{4}$	V/(steps/s)

Voltage mode basics

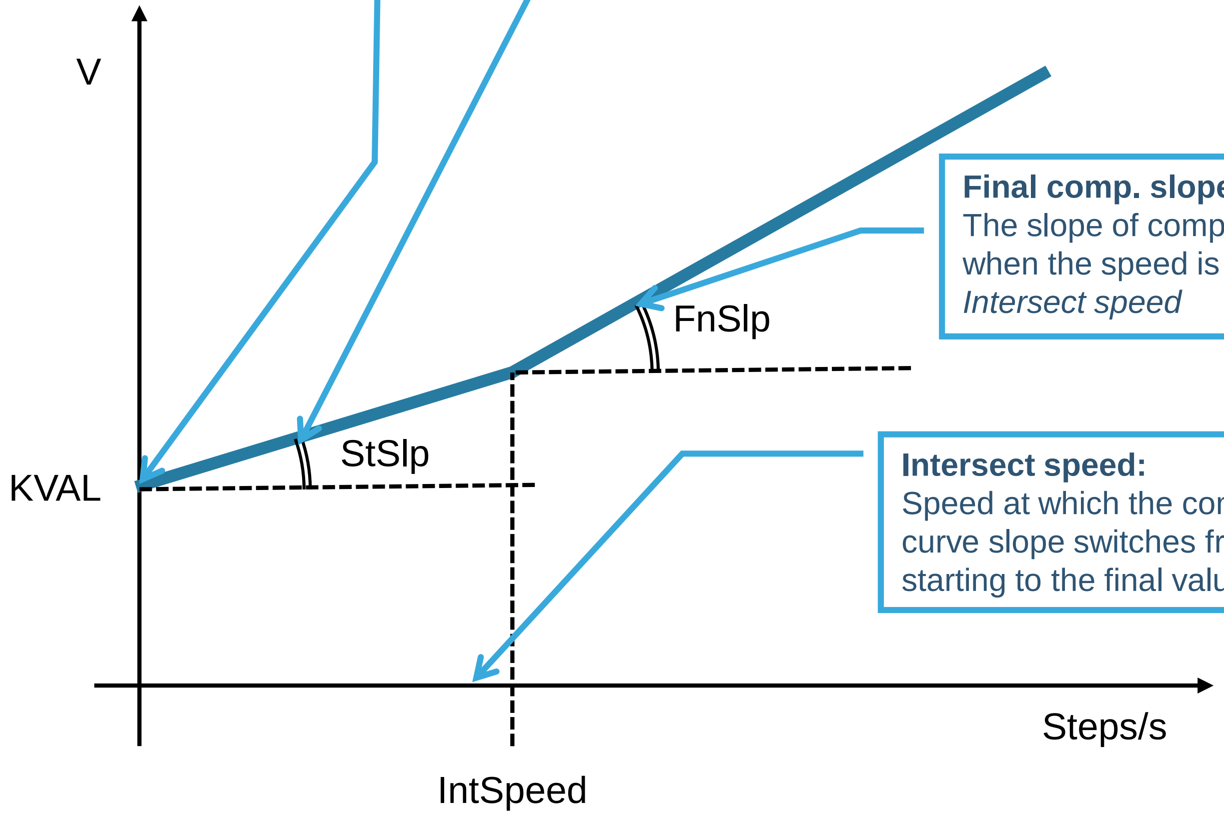
The resulting driving curve is:

Starting amplitude:
The "zero speed" amplitude of the output sinewave

Starting comp. slope:
The slope of the compensation curve when the speed is lower than the *Intersect speed*

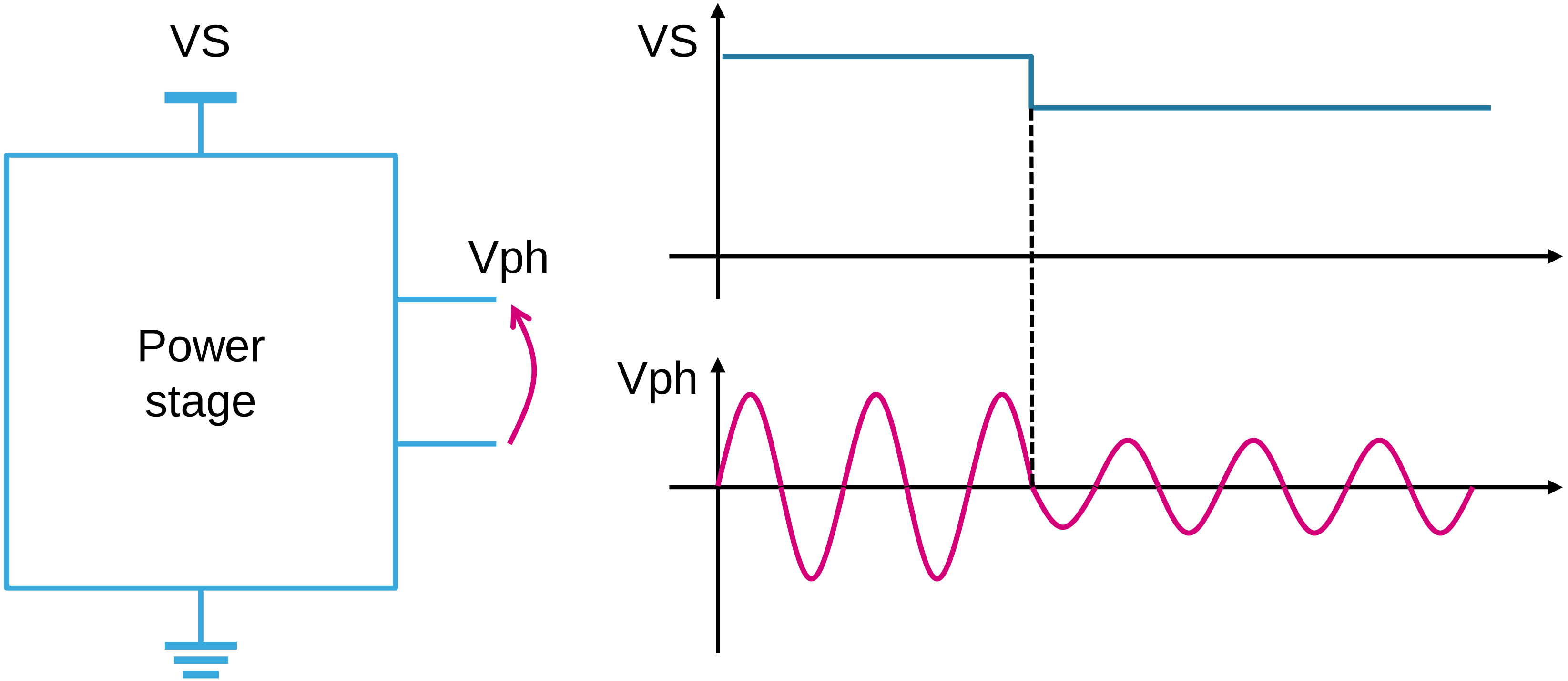
Final comp. slope:
The slope of compensation curve when the speed is greater than the *Intersect speed*

Intersect speed:
Speed at which the compensation curve slope switches from the starting to the final value

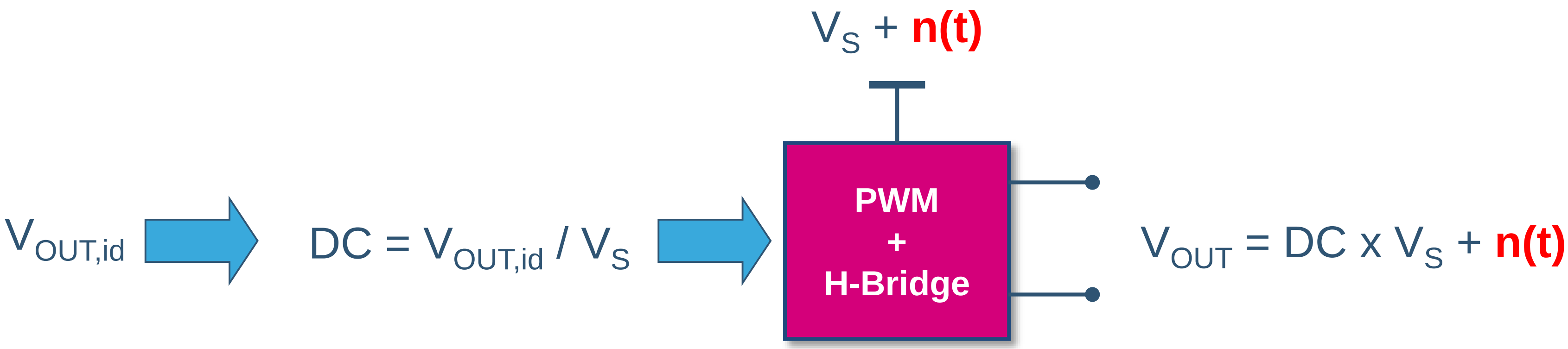


Supply voltage compensation

The voltage sinewaves are generated through a PWM modulation. As a consequence, the actual phase voltage depends on the supply voltage of the power stage.



Supply voltage compensation



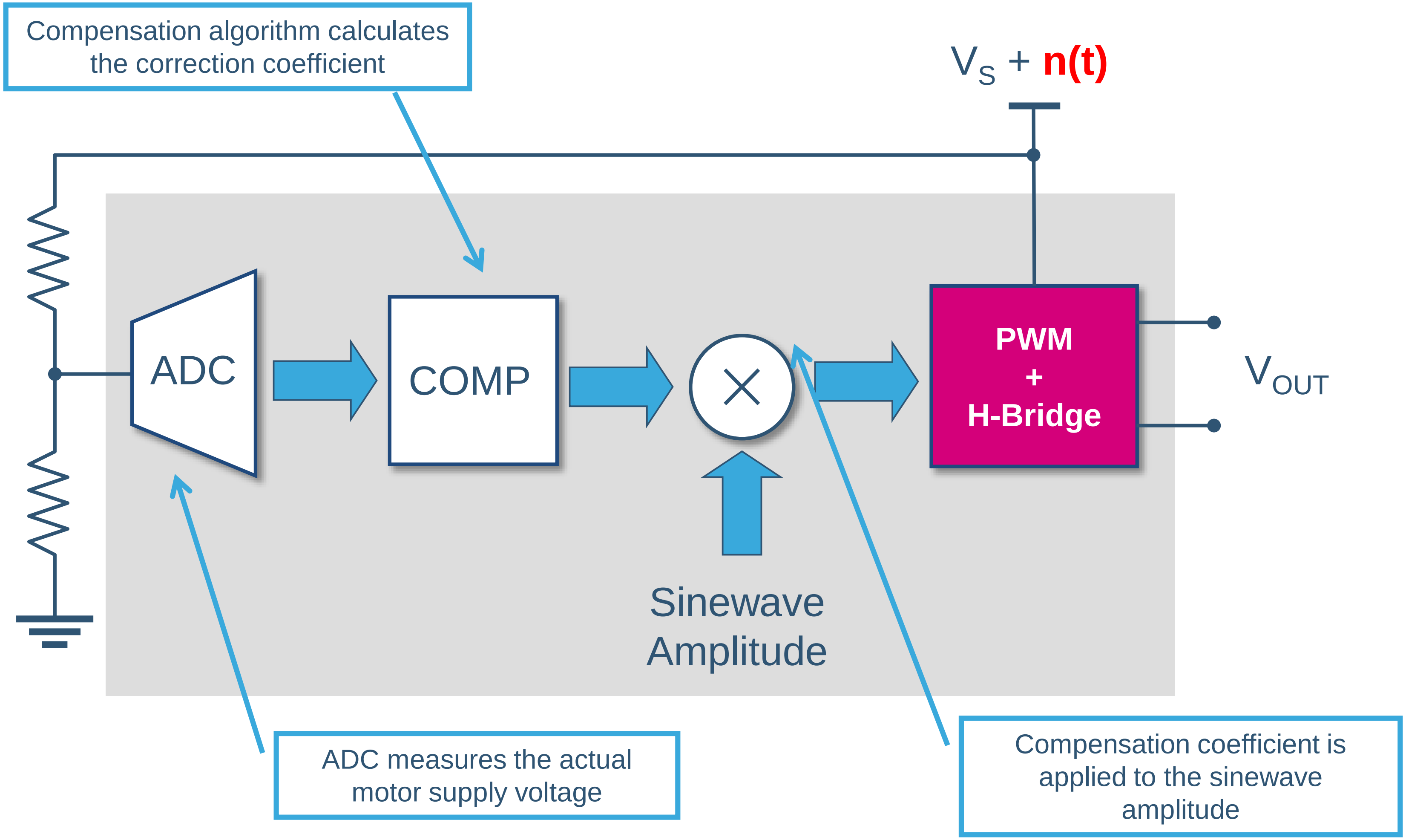
The equation can also be written in this form:

$V_S + n(t) = V_S \times (1 + n(t) / V_S) \rightarrow V_{OUT} = DC \times V_S \times \underline{(1 + n(t) / V_S)} = DC \times V_S \times \varepsilon$

If a compensation factor is applied to the Duty Cycle, the error can be canceled:

$V_{OUT} = DC \times \underline{1/\varepsilon} \times V_S \times \varepsilon = \mathbf{V_{OUT,id}}$

Supply voltage compensation



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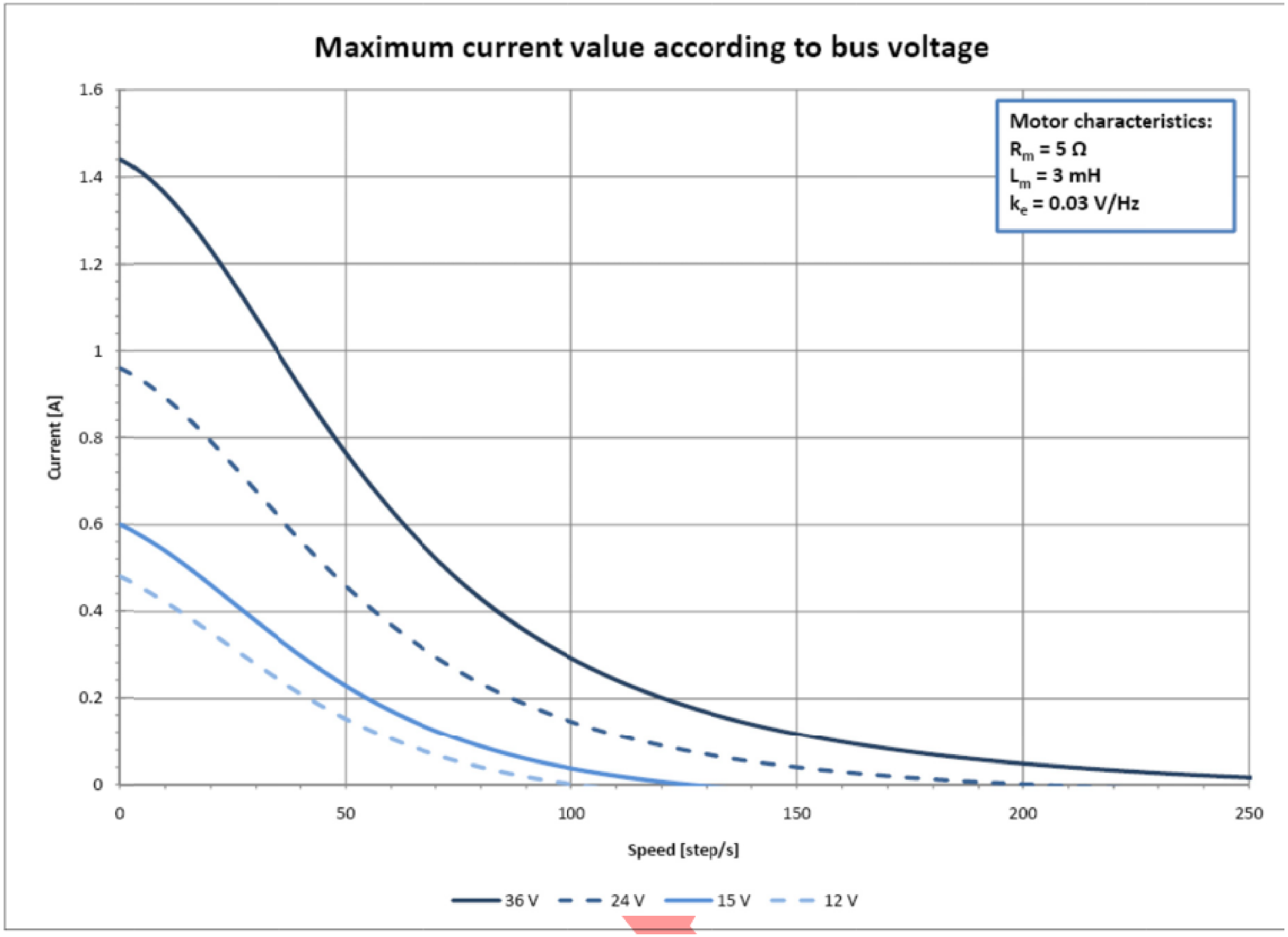
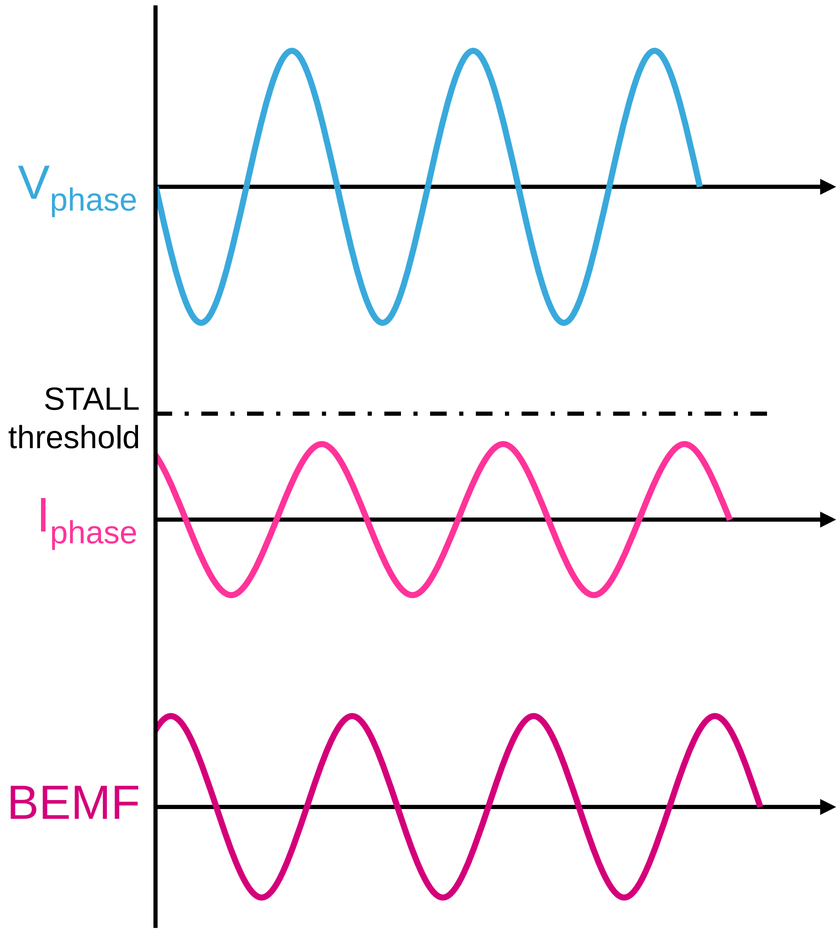
Maximum output current vs supply voltage

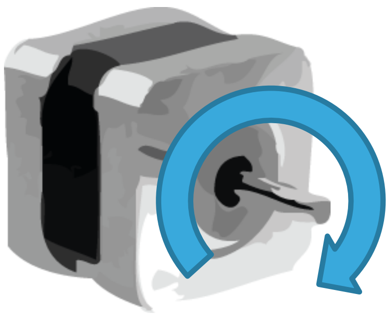


Sensorless stall detection

The voltage mode driving makes the detection of the **stall** condition easier.

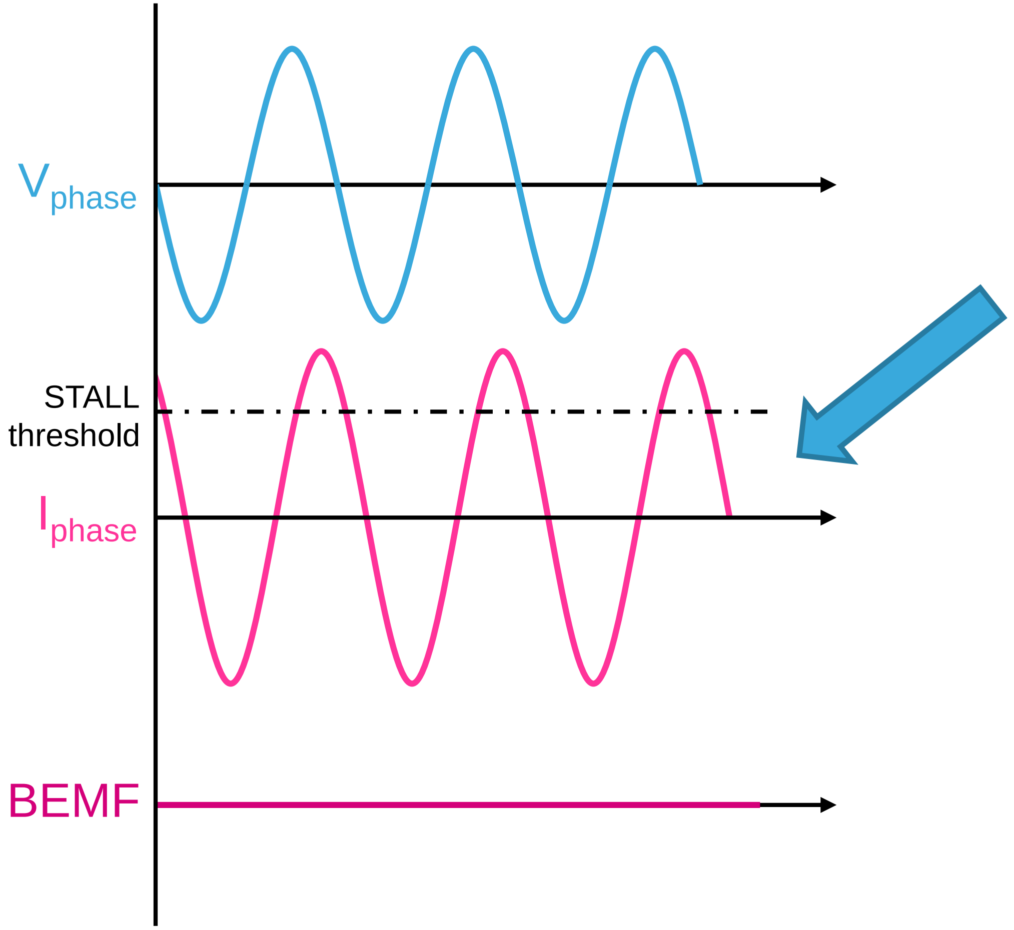


Normal operation

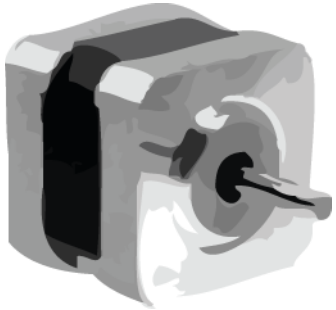


Sensorless stall detection

By measuring the phase current, it is possible to determine the stall condition of the motor:



STALL!
BEMF is null and current is suddenly increased



Sensorless stall detection limitations

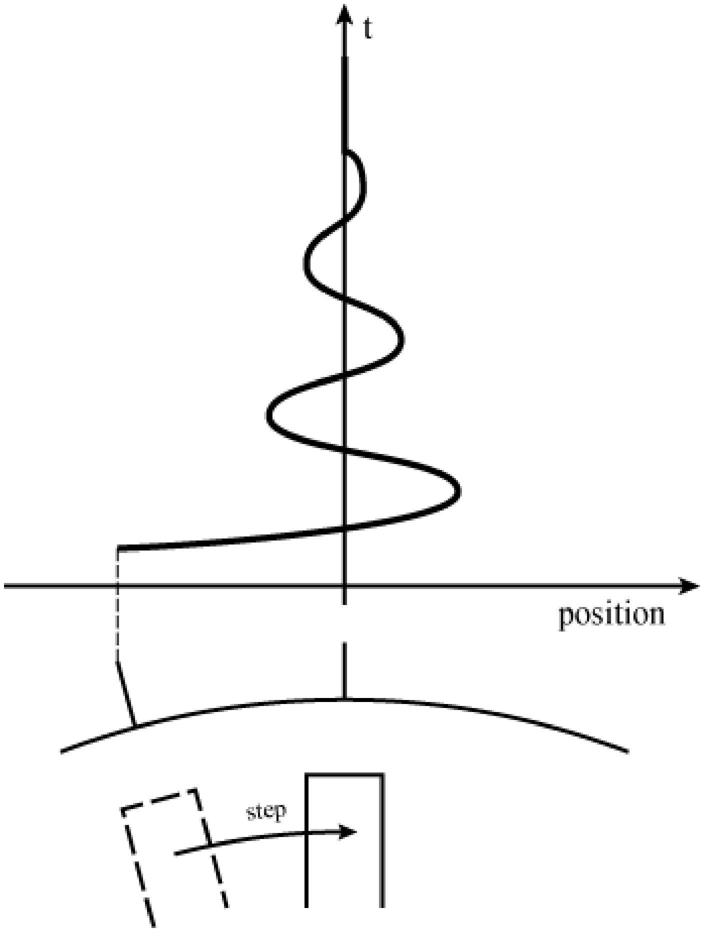
Stall detection performances can be reduced in the following conditions:

- Low speed
  (negligible BEMF value)
- High speed
  (current can be low because the low-pass filtering effect of the inductor)

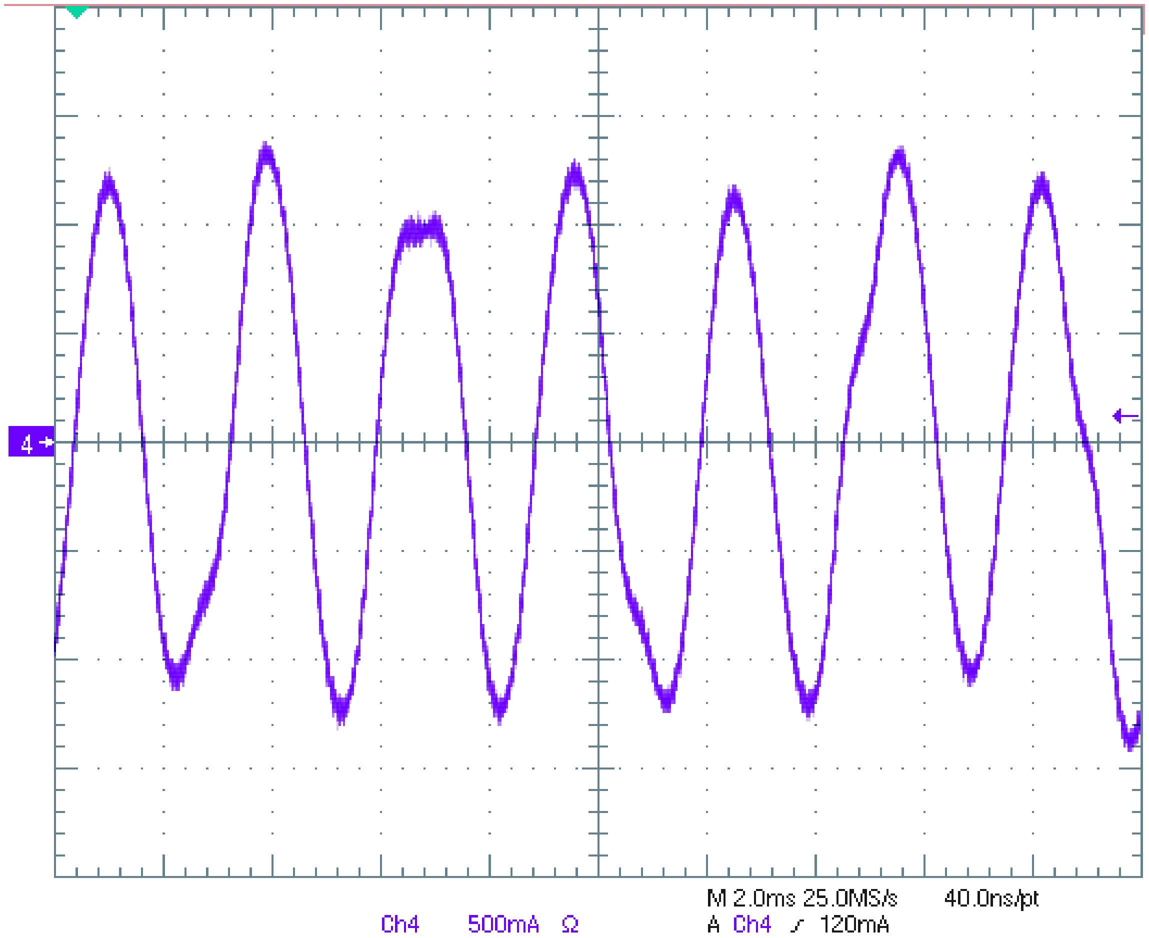
Voltage mode and motor resonances

Stepper motor motion is not uniform and this behavior can make the mechanics resonate.

When this occurs, the **BEMF voltage is no longer sinusoidal** causing issues in the control algorithm.



Voltage mode and motor resonances



Voltage mode and motor resonances

Motor resonances can be avoided by using following strategies:

1. **Appling a mechanical load to the motor**
   The load shifts the resonance spot of the system.

2. **Increasing acceleration to skip resonance spot**
   If the resonance speed is a limited range of the motor, you can skip it using the motor inertia and higher acceleration values.

Voltage mode advantages summary

The main **advantages** of the voltage mode are:

- Extreme smoothness
- Precise positioning (control of the average current)
- Controlled current ripple
- Stall condition is easy to detect

Main **drawbacks** are:

- Algorithm must be tuned according to motor characteristics
- Sensitive to the motor resonances