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# AN4144
# Application note

## Voltage mode control operation and parameter optimization

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## Introduction

Voltage mode driving is the stepper motor driving method patented by STMicroelectronics® which improves the performance of classic control systems.

This driving method performs smoother operation and higher microstepping resolutions and is the best solution for applications where high precision positioning and low mechanical noise are mandatory.

This application note describes the operating principles of Voltage mode driving and the strategies for the regulation of the control parameters in order to fit the application requirements.

The application note also investigates and provides solutions to one of the most common issues in Voltage mode driving systems: the resonances of the stepper motors.

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# 1 Voltage mode driving

This section describes the basic principles of Voltage mode driving and its implementation in STMicroelectronics devices with a focus on the compensation of:

- The back electromotive force (*Section 1.2 on page 7*)
- The motor supply voltage variation (*Section 1.3 on page 11*)
- The thermal drift of the phase resistance (*Section 1.4 on page 12*).

## 1.1 Basic principles

The classic current mode driving method limits the phase current to a reference value using a comparator and a current sensor (usually an external resistor). This control is the most intuitive but brings with it some drawbacks: the current ripple can be significant and obtaining an acceptable control of the current can be challenging. In trying to solve these problems, current control algorithms were made more and more complex, including techniques such as fast decay and mixed decay. With the introduction of microstepping in stepper motor driving a new current control algorithm limit became evident: the analog circuitry and the control loop should be able to manage lower currents with higher resolution.

Voltage mode totally changes the control approach implementing an open-loop control: a sinusoidal voltage is applied to the motor phases and the electro-mechanical system response with a sinusoidal current.

*Note: Due to its principle of operation, Voltage mode driving is not suited to full step driving. The best performance is always obtained using microstepping operation.*

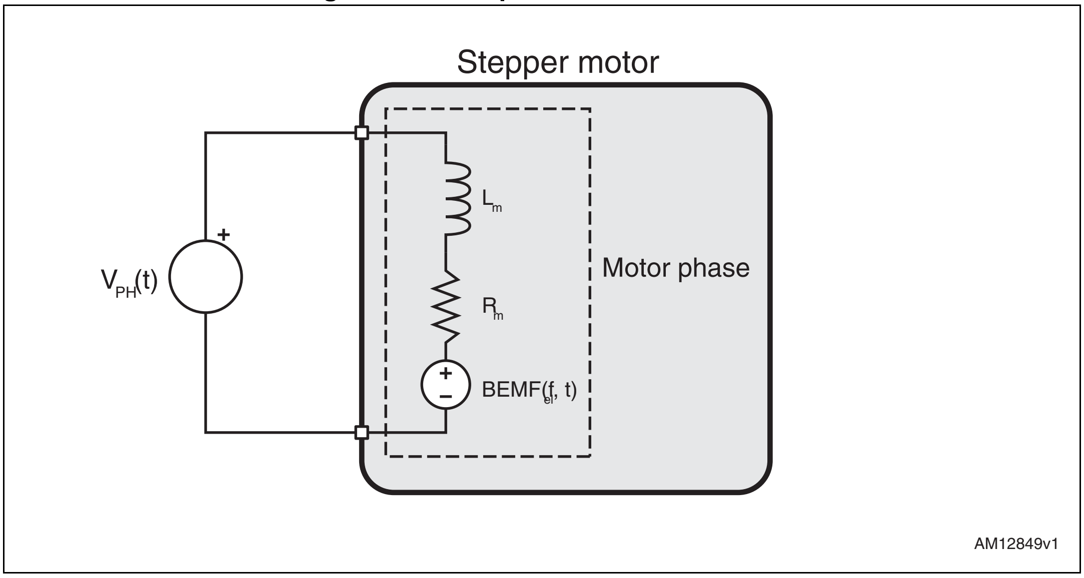
This result can be obtained through the analysis of the stepper motor electrical model.

*Equation 1*, extracted from the model in *Figure 1*, shows how the current of a generic motor phase is related to:

- Phase voltage $V_{PH}$
- Back electromotive force (BEMF)
- Phase resistance ($R_m$) and inductance ($L_m$).

The back electromotive force is typically a sinusoidal voltage with frequency and amplitude proportional to motor rotation speed. The BEMF frequency ($f_{el}$) is equal to one quarter of the rotation speed expressed in steps per second ($f_{STEP}$); this frequency is exactly the same as the hypothetical current sine wave that should be applied to the motor phase in order to make the motor turn at $f_{STEP}$ step rate. The BEMF amplitude is proportional to step frequency through a linear coefficient $k_e$: this parameter depends on motor characteristics and structure (rotor material, coil turns, etc.).

**Figure 1. Motor phase electrical model**



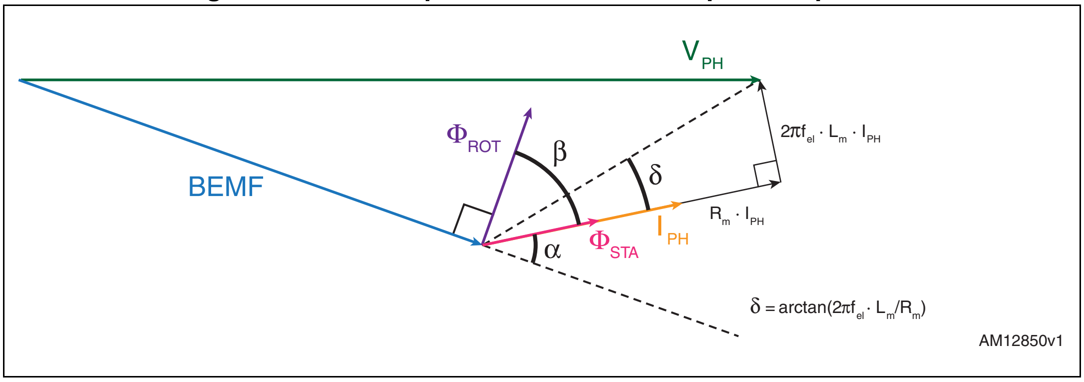

**Equation 1**

$$i_{PH}(t) = \frac{V_{PH}(t) + BEMF(f_{el}, t)}{R_m + i2\pi f_{el} \cdot L_m}$$

Considering all the currents and voltages of the electrical model as sinusoidal, *Equation 1* can be written as a vector equation (*Equation 2*). The resulting vector system, which is shown in *Figure 2*, adds a new variable to the current vs. voltage relationship: the load angle $\beta$ which is the angle between stator and rotor magnetic field vectors. The load angle is in direct relation with the angle $\alpha$ lying between the phase current and BEMF phasors, as shown in *Equation 3*.

The torque (Tq) applied to the motor shaft is proportional to both the phase current and the sine of the load angle, as shown by *Equation 4*, where the $k_t$ parameter is the motor torque constant which is equal to the $k_e$ constant, but expressed in Nm/A instead of V/Hz.

**Figure 2. Phasor representation of motor phase equation**



**Equation 2**

$$I_{PH}(f_{el}) = \frac{V_{PH}(f_{el}) + BEMF(f_{el})}{R_m + i2\pi f_{el} \cdot L_m}$$

**Equation 3**

$$\alpha = \frac{\pi}{2} - \beta$$

**Equation 4**

$$T_q = K_t \cdot |I_{PH}| \cdot \cos(\alpha) = K_t \cdot |I_{PH}| \cdot \cos\left(\frac{\pi}{2} - \beta\right)$$

$$K_t[Nm/A] = K_e[V/Hz]$$

Starting from *Equation 2*, it is possible to obtain the voltage amplitude which, when applied to the motor phase, makes the amplitude of phase current constant. The basic principle of Voltage mode control is based on this relationship. The resulting formula (*Equation 5*) shows how the voltage amplitude is a complex function of phase current, motor parameters and other factors.

**Equation 5**

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

Resolving this equation, to obtain the phase voltage to be applied for various speeds, is very complex and computationally onerous. In addition, the phase relationship between the current and the BEMF phasors ($\alpha$) is difficult to measure or evaluate for a specific application.

The STMicroelectronics control method, starting from this complex model, implements an effective driving strategy that overcomes these issues with the classic current mode control method in most microstepping applications.

## 1.2 Back EMF compensation algorithm

In order to devise a simple but effective compensation method, consider the formulas in *Equation 6*. In this manner, the dependence on the load angle ($\beta$) can be removed, obtaining a formula which allows the evaluation of the $V_{PH}$ voltage that is able to produce a constant $I_{PH}$ current independent of the motor speed (or its equivalent $f_{el}$).

**Equation 6**

$$|V_{PH}| \le |R_m + i2\pi f_{el} \cdot L_m| \cdot |I_{PH}| + |V_{BEMF}(f_{el})|$$

$$|V_{PH}| = \sqrt{R_m{}^2 + (2\pi f_{el})^2 \cdot L_m{}^2} \cdot |I_{PH}| + K_e \cdot (f_{el})$$

Using this formula, a compensation algorithm that gives the phase voltage amplitude ($V_{PH}$) for a target phase current ($I_{PH}$) and motor speed ($f_{el}$) is defined.

The compensation algorithm of *Equation 6* can be further simplified according to the electrical frequency. Two different cases can be considered, when the motor speed is low ($2\pi f_{el} << R/L$) and when it is high ($2\pi f_{el} >> R/L$).

*Equation 7* shows how the formula can be approximated when these two cases are considered.

**Equation 7**

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

The Voltage mode control implemented in STMicroelectronics’ products is based on the simplified model described by *Equation 7*.

In particular, the following parameters are extracted and used to describe the compensation curve:

- $K_{VAL}$ is the voltage applied to the motor phase at zero speed. It is the starting point of the BEMF compensation curve
- Intersect speed is the motor speed that determines the switching from the low-speed compensation factor (starting slope) to the high-speed one (final slope)
- Starting slope is the rate at which the phase voltage is increased in the low-speed range (i.e. motor speed is less than intersect speed)
- Final slope is the rate at which the phase voltage is increased in the high-speed range (i.e. motor speed is greater than intersect speed).

These parameters are listed in *Table 1*.

**Table 1. BEMF compensation parameters**

| Parameter | Description | Formula | Unit |
|---|---|---|---|
| $K_{VAL}$ | Voltage applied to the phase at zero speed in order to obtain the target current value. | $R_m \cdot \|I_{PH\_TARGET}\|$ | $[\Omega] \cdot [A] = [V]$ |
| Intersect speed | Motor speed discriminating the compensation slope that should be used. | $4 \cdot R_m/2\pi L_m$ | $\left[\frac{step}{cycle}\right] \cdot [\Omega]/[H]$ $= \left[\frac{step}{cycle}\right] \cdot [Hz]$ $= step/s$ |
| Starting slope | Compensation slope used when motor speed is lower than intersect speed. | $K_e/4$ | $\left[\frac{V}{Hz}\right]/\left[\frac{step}{cycle}\right] =$ $[V] \cdot s/step$ |
| Final slope | Compensation slope used when motor speed is higher than intersect speed. | $(2\pi \cdot L_m \cdot \|I_{PH\text{-}TARGET}\| + K_e)/4$ | $\left[\frac{V}{Hz}\right]/\left[\frac{step}{cycle}\right] =$ $[V] \cdot s/step$ |

The control system generates the phase voltage using a PWM modulation. The outputs switch between supply voltage $V_{BUS}$ and ground at a fixed frequency. The mean voltage of the resulting square-wave is adjusted through its duty cycle (on time over square-wave period ratio) according to *Equation 8*:

**Equation 8**

$$\overline{V_{PH}} = V_{BUS} \cdot \frac{t_{ON}}{t_{SW}} = V_{BUS} \cdot DutyCycle_{PMW}$$

The duty cycle ranges from 0% (the output is always forced to ground) to 100% (the output is always forced to $V_{BUS}$).

The BEMF compensation curve is implemented adjusting the PWM duty cycle, so all the voltage values must be normalized to the supply voltage of the power stage (*Figure 3*).

**Figure 3. BEMF compensation curve**

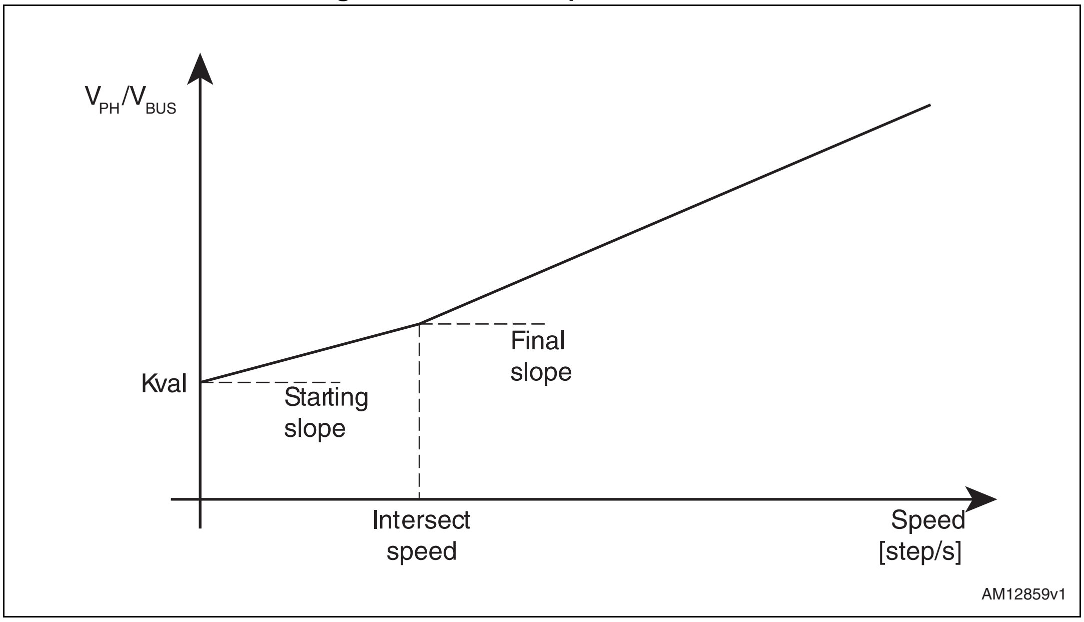
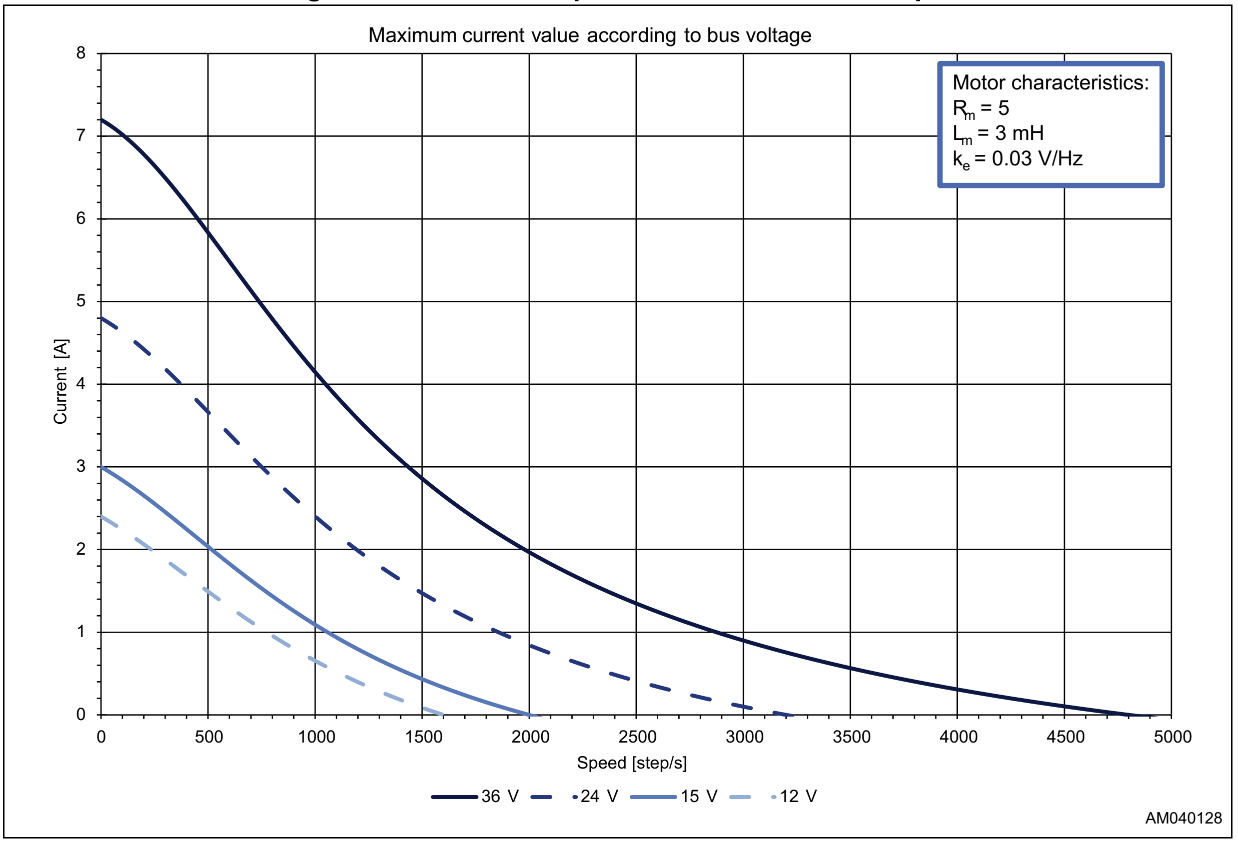


Table 2. BEMF compensation parameters normalized to the supply voltage ($V_{BUS}$)

| Parameter | Formula | Unit |
|---|---|---|
| $K_{VAL}$ | $R_m \cdot \lvert I_{PH\_TARGET} \rvert / V_{BUS}$ | $[\Omega] \cdot [A]/[V] = \%$ |
| Intersect speed | $4 \cdot R_m / 2\pi L_m$ | $\left[\frac{step}{cycle}\right] \cdot [\Omega]/[H]$ $= \left[\frac{step}{cycle}\right] \cdot [Hz]$ $=$ step/s |
| Starting slope | $(K_e/4)/V_{BUS}$ | $\left(\left[\frac{V}{Hz}\right] / \left[\frac{step}{cycle}\right]\right) = /[V] = \% \cdot s/step$ |
| Final slope | $((2\pi \cdot L_m \cdot \lvert I_{PH\text{-}TARGET} \rvert + K_e)/4)/V_{BUS}$ | $\left(\left[\frac{V}{Hz}\right] / \left[\frac{step}{cycle}\right]\right) = /[V] = \% \cdot s/step$ |

The supply voltage of the systems limits the maximum phase current which is a function of the motor speed. If the phase voltage which is needed to obtain the target current is greater than the supply voltage, the phase current cannot reach the expected value (*Figure 4*).

Figure 4. Maximum output current limitation example



## 1.3 Motor supply voltage compensation

The power stage generates the voltage sine waves using a PWM modulation method, so the average output voltage value is proportional to the motor supply voltage ($V_{BUS}$) and power bridge duty cycle (see *Equation 9*). Therefore, perturbations on this voltage cause errors on the output voltage and then on the phase currents.

**Equation 9**

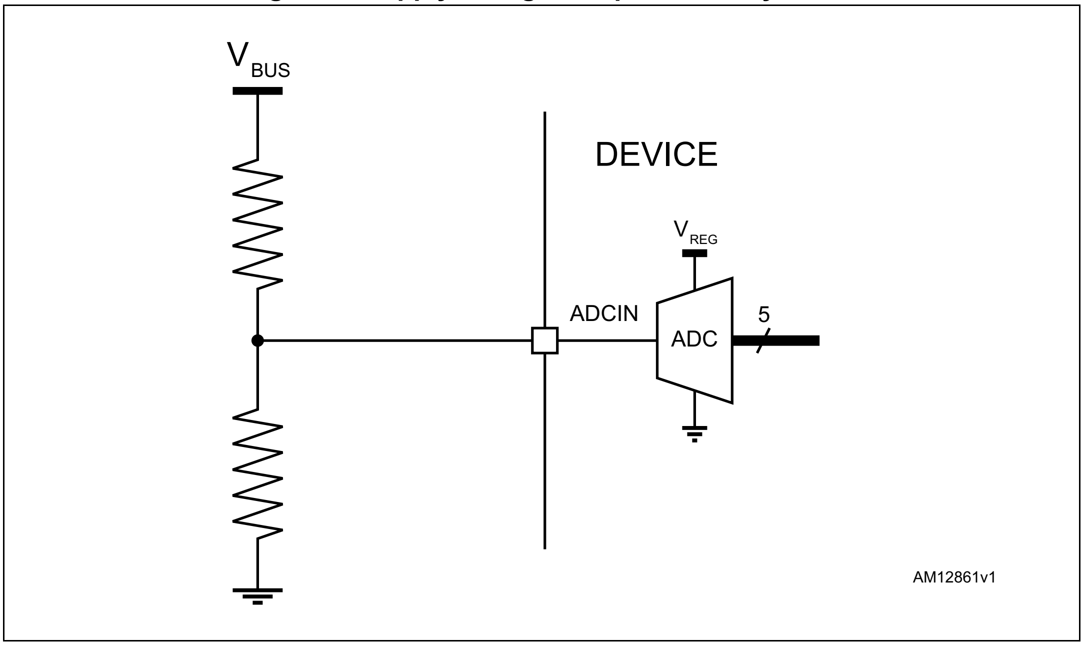
$$\overline{V_{PH}} = V_{BUS} \cdot DutyCycle_{PMW}$$

In most industrial applications, the supply voltage is not well regulated and it may undergo significant voltage fluctuations, due to various factors, e.g.: variations of load conditions.

The Voltage mode algorithm implemented in STMicroelectronics devices provides a compensation system that increases the supply voltage rejection of PWM modulator.

The supply voltage is constantly monitored through a voltage divider and an integrated analog-to-digital converter and the power stage duty cycle is changed in order to compensate for its variations.

**Figure 5. Supply voltage compensation system**




The voltage divider should be sized in order to obtain $V_{REF}/2$ at the ADC input when the supply voltage is at its nominal value. When the supply voltage is perturbed, the same distortion is proportionally applied to the ADC input and the nominal duty cycle is multiplied by a compensation coefficient $k_{\varepsilon}$, as shown in *Equation 10*.

**Equation 10**

$$\overline{V_{PH}} = (V_{BUS} \cdot \varepsilon) \cdot (DutyCycle_{PMW} \cdot K_{\varepsilon}) = V_{BUS} \cdot DutyCycle_{PMW}$$

where $k_{\varepsilon} = 1/\varepsilon$.

In any case, the compensation system is limited by the actual supply voltage: if the compensated duty cycle ($DutyCycle_{PWM} \cdot k_e$) is greater than 100%, the supply voltage is not large enough to obtain the target current (maximum output current limit has been reached) and the compensation algorithm fails.

## 1.4 Compensation of thermal drift of the phase resistance

During operation, the motor dissipates energy and increases its temperature, therefore the phase resistance. The relationship between phase resistance and temperature is shown in *Equation 11*: the change in the phase resistance is proportional to the temperature variation, its nominal value (phase resistance at room temperature $T_0$) and the temperature coefficient ($\sigma$) of the material composing the coil.

**Equation 11**

$$R_m(T) = R_{m,T0} + \Delta R(T) = R_{m,T0} + R_{m,T0} \cdot \delta \cdot (T - T_0)$$

As described in previous paragraphs, the voltage to current relation depends on different motor parameters, including phase resistance ($R_m$ in *Equation 1 on page 6*). In particular, a higher phase resistance reduces the load current at the same applied voltage.

The duty cycle of the PWM output is multiplied by a scalar factor in order to compensate for the resistance variation.

# 2 Tuning of the BEMF compensation parameters

This paragraph describes how the BEMF compensation parameters can be tuned in order to obtain the best results. Setting the correct compensation parameters is fundamental to Voltage mode algorithm performance.

The tuning sequence can be divided into the following steps:

- Collecting the characteristics of the application and motor (*Section 2.1*)
- Obtaining a preliminary set of parameters (*Section 2.2*)
- Tuning the parameters in order to obtain the needed results (*Section 2.3 on page 17*).

## 2.1 Collecting the application characteristics

The compensation system is based on the electrical model of the stepper motor, so its setup is strongly dependent on the motor characteristics.

The required information is:

- Resistance of the motor phase ($R_m$)
- Inductance of the motor phase ($L_m$)
- Electrical constant of the motor ($k_e$).

The $R_m$ and $L_m$ values are usually reported on the motor datasheet. They can also be measured with common measuring instruments.

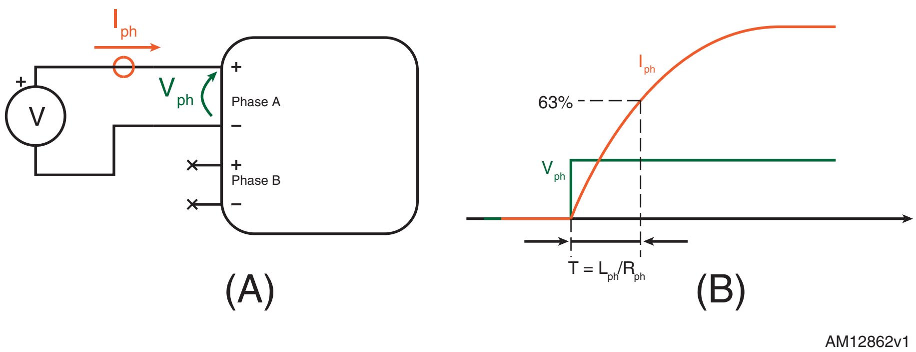
If the user has an RLC meter, they can connect it to one of the motor phases and measure the series R and L at 100 Hz (make sure the motor does not move). The resulting values are considered to be $R_m$ and $L_m$.

If they do not have an RLC meter, the $R_m$ can be measured using a bench multimeter applied to one of the phases.

To measure the $L_m$, use the following procedure:

- Connect a DC voltage at one motor phase and apply the voltage and current probes of the oscilloscope, as shown in *Figure 6* A
- Increase the voltage up to the value where the current equals the nominal value
- For a better measurement, lock the rotor position
- Unplug one terminal of the voltage source cable without switching it off and disable (or set to the max.) the current limitation
- Connect the voltage source rapidly and monitor, on the scope, the voltage and current waveform
- The measurement is good if the voltage trace is similar to a step and the current increases exponentially (*Figure 6* B)
- Measure the time for the current waveform to rise up to 63% of the nominal value (*Figure 6* B)
- This time is equal to the $L_m/R_m$ ratio.

**Figure 6. Phase inductance measurement**




The $k_e$ is the coefficient that relates the motor speed to the BEMF amplitude. This value is not usually present on stepper motor datasheets, but it can be easily measured by means of an oscilloscope:

- Connect one of the motor phases to an oscilloscope channel
- Set the oscilloscope to the trigger value on the rising or falling edge of the channel and set the threshold value close to zero (few mV above or below zero)
- Turn the motor shaft. This can be done by hand or by means of another motor. The most important thing is to obtain a rotation speed as constant as possible
- Set oscilloscope time and voltage scales in order to display a sine wave during the motor rotation.

If the rotor is turned by hand, the operations should be repeated until a good sine wave is obtained. A good sine wave keeps its amplitude constant for at least 2 or 3 cycles (*Figure 7* and *Figure 8*). This operation might require several attempts.

- Measure the peak voltage to frequency ratio of the sine wave. The resulting value is the motor electric constant expressed in V/Hz.

**Figure 7. Bad $k_e$ measurement waveform**

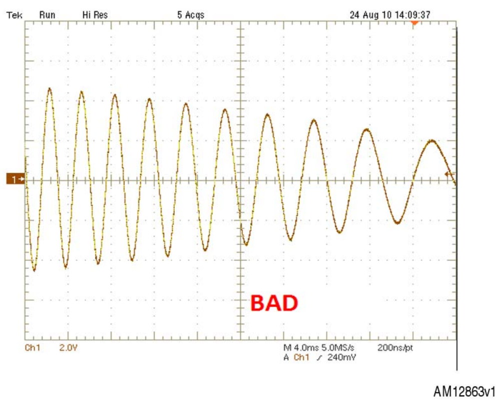
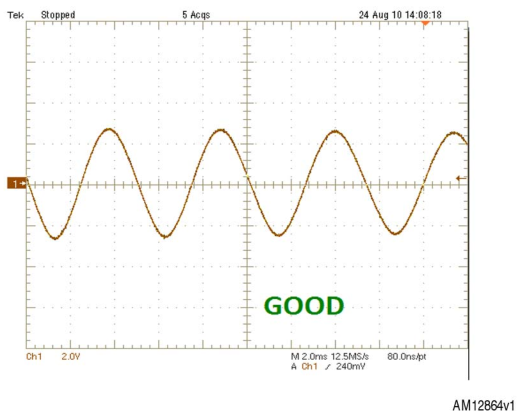



**Figure 8. Good $k_e$ measurement waveform**



## 2.2 First dimensioning

A preliminary set of parameters can be obtained starting from the simplified model of the stepper motor described in *Section 1.1 on page 5*.

Starting from the formulas listed in *Table 2* of *Section 1.2 on page 7*, it is possible to define the BEMF compensation register values as shown in *Table 3*:

**Table 3. BEMF compensation register values according to application parameters**

| Parameter | Register name | Register value |
|---|---|---|
| $K_{VAL}$ | KVAL_HOLD, KVAL_ACC, KVAL_DEC, KVAL_RUN | $R_m \cdot \lvert I_{PH\_TARGET} \rvert / V_{BUS} \cdot 2^8$ |
| Intersect speed | INT_SPEED | $(4 \cdot R_m / 2\pi L_m) \cdot 2^{26} \cdot t_{tick}$<br>where $t_{tick}$ = 250 ns |
| Starting slope | ST_SLP | $((K_e/4)/V_{BUS}) \cdot 2^{16}$ |
| Final slope | FN_SLP_ACC, FN_SLP_DEC | $(((2\pi \cdot L_m \cdot \lvert I_{PH\text{-}TARGET} \rvert + K_e)/4)/V_{BUS}) \cdot 2^{16}$ |

The resulting values are not the optimal compensation values because they are obtained starting from a simplified model of the motor. They can be used as a starting point for further optimization of the control system.

The same result can be easily obtained using the BEMF compensation tool which is integrated into the L6470 evaluation software.

### 2.2.1 Holding, acceleration, deceleration and running currents

The BEMF compensation system allows different current values according to motion status. The different current values are set through a specific set of registers, as shown in *Table 4*.

**Table 4. Motor status and BEMF compensation registers relationship**

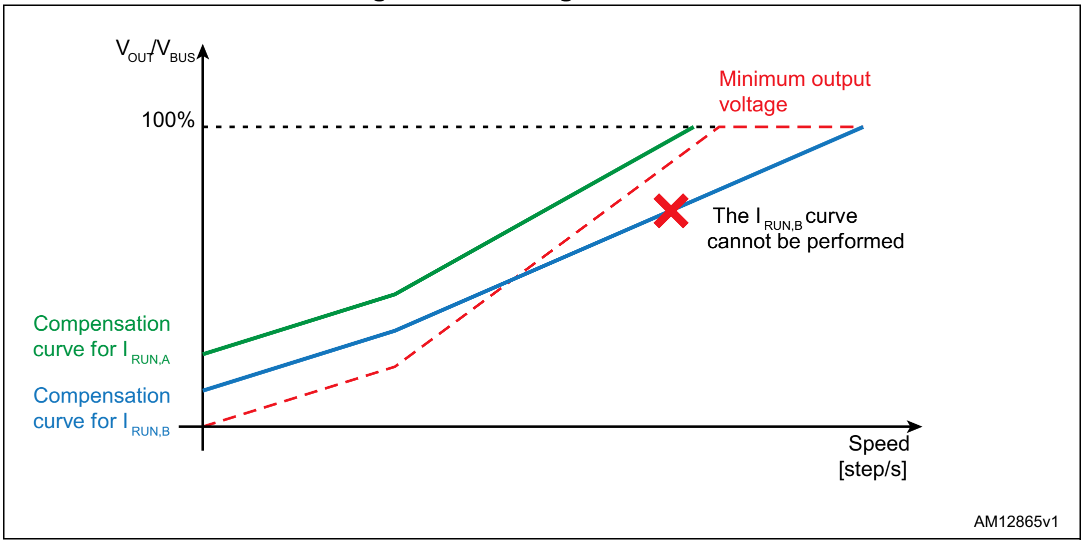
| Motor status | Registers |
|---|---|
| Hold (motor stopped) | KVAL_HOLD |
| Acceleration | KVAL_ACC, INT_SPEED, ST_SLP, FN_SLP_ACC |
| Deceleration | KVAL_DEC, INT_SPEED, ST_SLP, FN_SLP_DEC |
| Constant speed | KVAL_RUN, INT_SPEED, ST_SLP, FN_SLP_ACC |

The holding current generates the magnetic field that keeps the motor in position after the motion is completed. Its value is usually lower than the others because it is not necessary to face the friction and the inertial component of the load torque. In these conditions the BEMF value is zero, so no compensation is needed and the only parameter defining the current is KVAL_HOLD.

During the acceleration phase the current is set through the KVAL_ACC, INT_SPEED, ST_SLP and FN_SLP_ACC parameters.

The constant speed current setup shares most of the parameters with the acceleration setup (INT_SPEED, ST_SLP and FN_SLP_ACC), so the two currents are closely related. The BEMF compensation curve for the acceleration phase (INT_SPEED, ST_SLP and FN_SLP_ACC parameters) defines the minimum output voltage at each speed limiting the minimum constant speed current (*Figure 9*).

**Figure 9. Running current limit**




## 2.2.2 Compensation register values out of range

In some cases the values obtained using the formulas listed in *Table 3* may be out of the range of the respective registers.

If one of the $K_{VAL}$ registers exceeds the maximum limit of 255 (corresponding to a PWM duty cycle close to 100%), the motor supply voltage is not large enough to force the target current into the phase resistance. In this case, the application parameters (supply voltage, target current and motor characteristics) are not consistent and they should be changed.

### Example 1

$V_{BUS}$ = 12 V; $R_m$ = 9 Ω; $I_{PH\ TARGET}$ = 2 A

$K_{VAL} = R_m \cdot |I_{PH\_TARGET}| / V_{BUS} \cdot 2^8 = 384 >$ max. $K_{VAL}$ value (255)

**Target current is not achievable**.

If the intersect speed exceeds the maximum value, the resistive component of the motor phase impedance dominates the inductive component, so the increase of the impedance with speed can be considered negligible and its compensation is unnecessary. In this case, the maximum intersect speed value may be used and during the fine tuning phase particular attention should be paid to the intersect speed region.

### Example 2

$L_m$ = 4 mH; $R_m$ = 1 Ω

$4 \cdot (R_m/2\Pi L_m) \approx 15920$ steps/s -> **maximum value should be used**.

If one or more of the compensation slope parameters (ST_SLP, FN_SLP_ACC and FN_SLP_DEC) exceeds the maximum value, the motor supply voltage is not enough to counteract the BEMF voltage increase.

The maximum compensation rate is 0.004% of the bus voltage at step/s. Considering a starting $K_{VAL}$ value equal to zero, this compensation rate reaches 100% of the bus voltage at a rotation speed of only 250 step/s.

So a high compensation value does not correspond to any real application. The application parameters (supply voltage, target current and motor characteristics) are not consistent and they should be changed.

## 2.3 Fine tuning

In some cases, the results obtained after the first dimensioning of the BEMF parameters (*Section 2.2*) do not fit with the performance required by the application. In these cases the optimal compensation can be obtained by fine tuning the system.

Performing these adjustments requires a current probe that is able to measure the phase currents over the entire operating range of the application.

The following procedure describes how to tune the acceleration parameters of the BEMF compensation system (KVAL_ACC, INT_SPEED, ST_SLP and FN_SLP_ACC). Replacing the KVAL_ACC and FN_SLP_ACC values with the respective deceleration parameters (KVAL_DEC and FN_SLP_DEC), the same procedure can be used to tune the BEMF compensation in the deceleration phase. Intersect speed and starting slope parameters are shared by both the acceleration and deceleration compensation setups (*Section 2.2.1*), so their tuning should be performed one time only.

### 2.3.1 Step 1: verify the phase current during the speed sweep

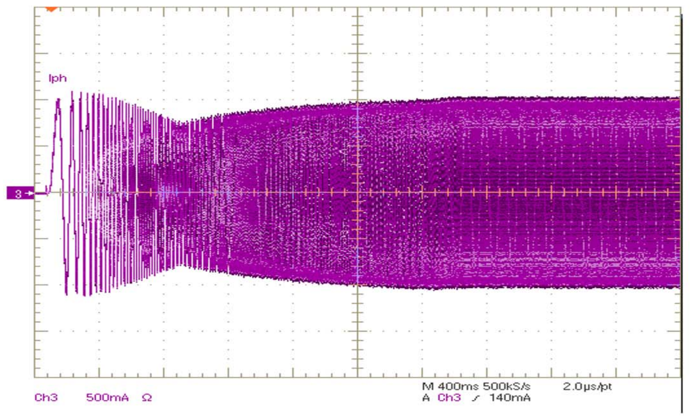
The most important step in the fine tuning of the BEMF compensation system is the analysis of the result obtained through the first dimensioning procedure.

This check can be performed monitoring the phase current of the motor during a slow acceleration (e.g.: 200 - 400 step/$s^2$) up to the maximum speed of the application.

If the amplitude of the phase current is constant during the entire acceleration, the BEMF is well compensated. Otherwise, the BEMF compensation parameters should be tuned.

*Figure 10* shows an example of sub-optimal BEMF compensation obtained using the first dimensioning formulas (target peak current equal to 1 A).

**Figure 10. Speed sweep with first dimensioning parameters**




### 2.3.2 Step 2: adjust the starting amplitude ($K_{VAL}$)

The first value which must be adjusted is the starting amplitude ($K_{VAL}$). The value is tuned using the following method:

1. Copy the first dimensioning value of the parameter into the KVAL_HOLD register.
2. Set the electrical position register EL_POS to one of the full step position values (0x000, 0x080, 0x100 or 0x180).
3. Turn on the device outputs sending a HardStop command to the IC (only one phase of the motor is driven according to the electrical position value as listed in *Table 5*, the other outputs are forced to ground through the low-side MOSFETs).
4. Measure the driving current and adjust the $K_{VAL}$ value in order to obtain the required peak current.

**Table 5. Output current according to the electrical position**

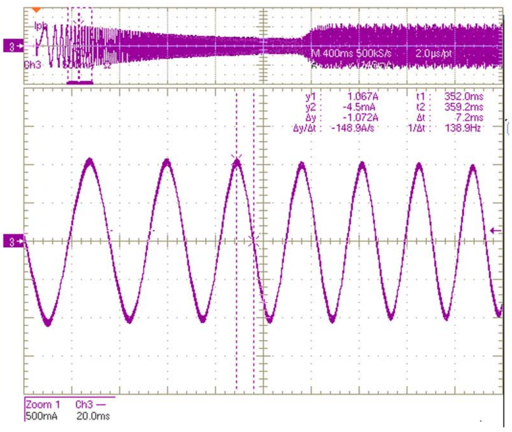
| Electrical position | Output current |
|---|---|
| 0x000 | OUTB1 source, OUTB2 sink.<br>OUTA1 and OUTA2 shorted to ground. |
| 0x080 | OUTA1 source, OUTA2 sink<br>OUTB1 and OUTB2 shorted to ground. |
| 0x100 | OUTB2 source, OUTB1 sink<br>OUTA1 and OUTA2 shorted to ground. |
| 0x180 | OUTA2 source, OUTA1 sink<br>OUTB1 and OUTB2 shorted to ground. |

### 2.3.3 Step 3: adjust the intersect speed value

The most important parameter in the BEMF compensation algorithm is the intersect speed. Its optimal value can be determined by performing a speed sweep (i.e. a slow acceleration as described in *Section 2.3.1*) setting the final slope value equal to the starting slope value which has been obtained during the first dimensioning.

The resulting phase current is almost constant in the first part of the motion and it decreases at higher speed (a motor stall may occur before the maximum speed is reached). The intersect speed value is the motor speed at which the phase current begins decreasing; e.g.: in *Figure 11* the optimal intersect speed value is about 138.9 step/s.

**Figure 11. Evaluation of the optimal intersect speed value**

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### 2.3.4 Step 4: adjust the starting and final slopes

After setting the new value for the intersect speed, the starting and final slopes must be adjusted. It is recommended to change one of the two values at a time; changing both the starting and final slopes simultaneously may make it more difficult to find the optimal combination. As for the intersect speed, the correct values can be obtained by measuring the phase current during a series of speed sweeps.

To tune the starting slope value, the initial part of the acceleration (from zero to the intersect speed) must be considered (*Figure 12*). If the current amplitude increases, the starting slope value must be reduced, otherwise it must be increased.

The same operation must be done for the evaluation of the final slope value, but the final part of the acceleration must be considered (*Figure 13*).

**Figure 12. Tuned starting slope value**

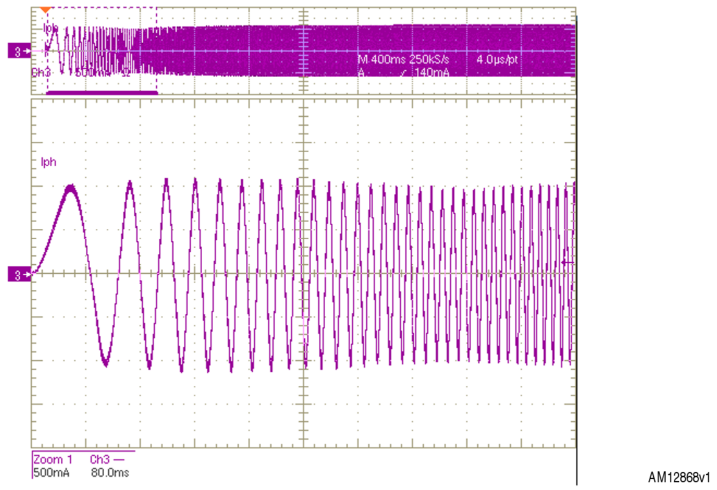
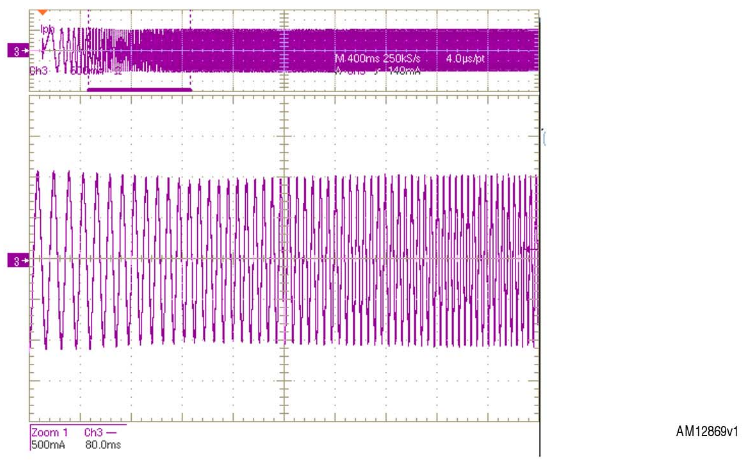


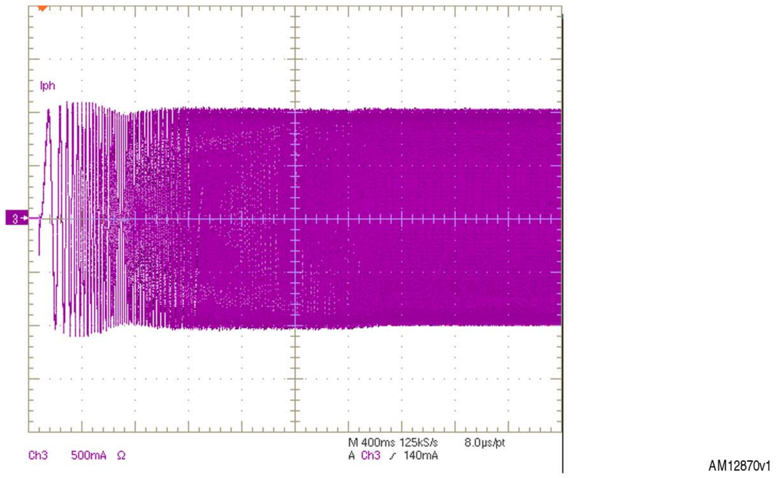

**Figure 13. Tuned final slope value**



### 2.3.5 Step 5: final check

When all the values have been tuned and the optimal compensation is obtained, a final check should be done. Performing a speed sweep the measured current amplitude must be almost constant. According to the oscilloscope characteristics, some artifacts (*Figure 14*) may be displayed when long time acquisitions are performed.

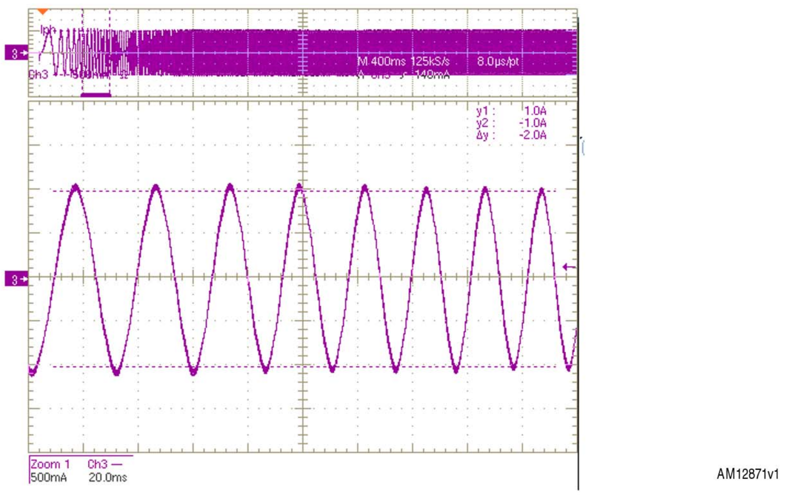
**Figure 14. Final check acquisition showing artifacts**




In order to avoid mistaking artifacts for real compensation errors, the following suggestions should be considered:

- If present, use the ZOOM function of the oscilloscope to magnify the critical areas (*Figure 15*)
- Split the acceleration into more parts.

**Figure 15. Magnified acquisition verifies the presence of artifacts**



# 3 Supply voltage compensation guidelines

The effectiveness of the compensation is strongly dependent on the actual duty cycle value because the system is not able to overcome the maximum duty cycle of 100%. When the variations of the application supply voltage make the use of the compensation system essential, the maximum target current is limited by the lower voltage value which is expected from the power supply output.

For this reason, the application setup, i.e. motor characteristics and phase currents, should be chosen considering the minimum expected supply voltage.

For example, suppose 85% of the 24 V bus is needed in order to reach the target current at 1000 step/s. If the bus voltage is reduced by 20% (i.e. the actual voltage is: 24 V · 0.8 = 19.2 V), the compensation system increases the duty cycle by a factor of 1/0.8 = 1.25. In this case the resulting duty cycle is 106.25%, which is greater than the maximum available value (100%).

**Example 3**

$V_{BUS} = V_{BUS,nom}$ = 24 V -> $DutyCycle_{PWM}$ at 1000 step/s = 85%

$V_{BUS} = 0.8 \cdot V_{BUS,nom}$ = 19.2 V -> $DutyCycle_{PWM}$ at 1000 step/s = 85% / 0.8 = 106.25%.

# 4 Thermal drift compensation guidelines

The compensation of the thermal drift of the phase resistance is not automatically performed by STMicroelectronics devices, but a compensation factor (KTHERM) is made available through a dedicated register.

The thermal compensation factor (KTHERM) is a scalar value between 1 (no compensation) and 1.5, which is applied to the PWM value obtained by the other compensation systems (BEMF compensation and supply voltage compensation).

As shown in *Equation 11* of *Section 1.4 on page 12*, the thermal drift of the resistance is directly proportional to the nominal resistance value ($R_{m,T0}$) and the temperature variation. For this reason the thermal drift compensation becomes more important when the driven motor has a high phase resistance value.

A suggested implementation of the thermal drift compensation is based upon the phase current measurement during the non-operative period of the motor (if present).

The proposed method requires an initial calibration of the system (performed when the motor is cold) and described by the following sequence:

1. The motor is stopped in a specific electrical position.
2. The overcurrent or stall detection threshold is set to a calibration value ($I_{cal}$).
3. The output voltage is increased at a low rate through the KVAL_HOLD parameter.
4. When the calibration current is reached, the respective KVAL_HOLD value must be stored (KCAL) in the MCU memory.

Since the KCAL value is related to the design parameters only, this calibration can also be performed during the design of the application. However, because of the variation of the application characteristics (bus voltage, motor phase resistance, etc.) and the device circuitry (current sensing), it would be useful to perform the calibration sequence on each system instead of defining a single KCAL value during the application design.

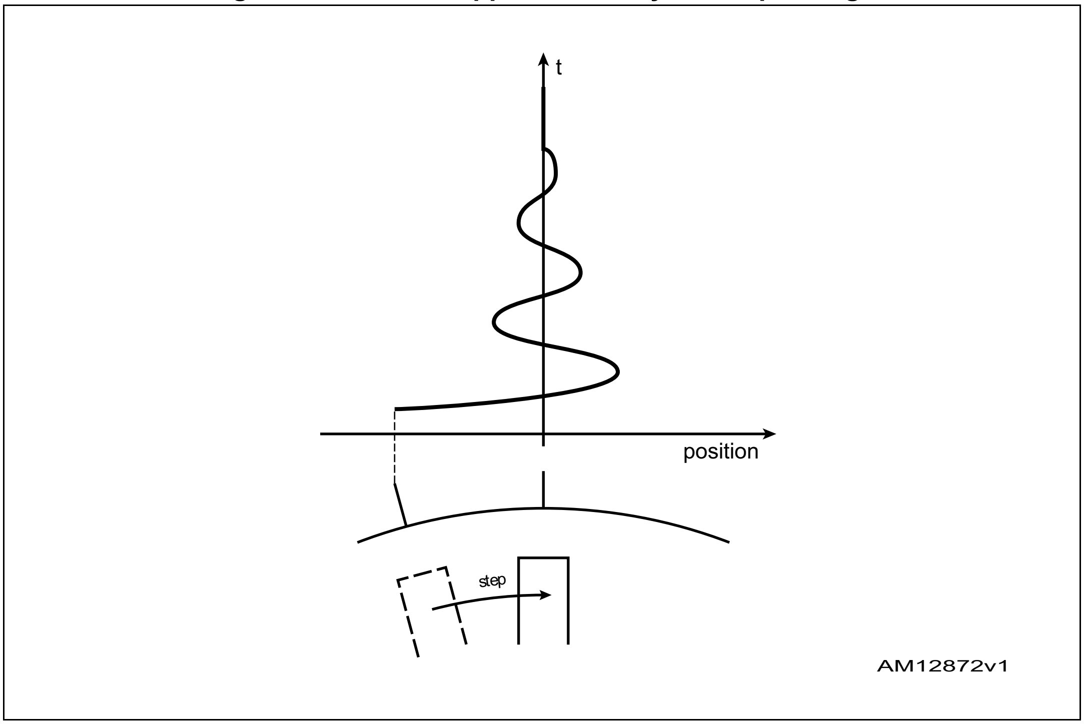
When a significant change of the motor temperature is expected, the following compensation sequence can be performed:

1. The motor is stopped in the same electrical position used during the calibration.
2. The overcurrent or stall detection threshold is set to a calibration value ($I_{cal}$).
3. The KVAL_HOLD value is set to KCAL.
4. The compensation coefficient (K_THERM) is increased or decreased in order to reach the calibration current using the overcurrent/stall information provided by the device.

# 5 Stepper motor resonances

The stepper motors, as in all complex mechanical systems, have one or more resonance points. These resonances are strictly related to the motion performed by the stepper motors: at each step (or microstep) the rotor approaches the new position and it oscillates around this position before stopping (*Figure 16*). When the step rate matches the oscillation frequency, the mechanical resonance is stimulated which results in a jittering motion. In some cases the vibration can be strong enough to cause a step loss or motor stall.

**Figure 16. Position ripple caused by the step change**




The position, and the strength of these resonance points, depends on the relationship between motor characteristics (in particular the inertia and the stiffness of the rotor) and mechanical load connected to the shaft.

## 5.1 The effects of the resonances on Voltage mode driving

The vibrations caused by the motor resonances distort the back electromotive force making the model described in *Section 1.1 on page 5* no longer valid. In fact, if the back EMF is not sinusoidal, applying a sinusoidal voltage to the motor phase results in a distorted current (*Figure 17*).

The distortion of the phase current may amplify the resonances and cause a motor stall (*Figure 18*).

**Figure 17. Phase current distortion**

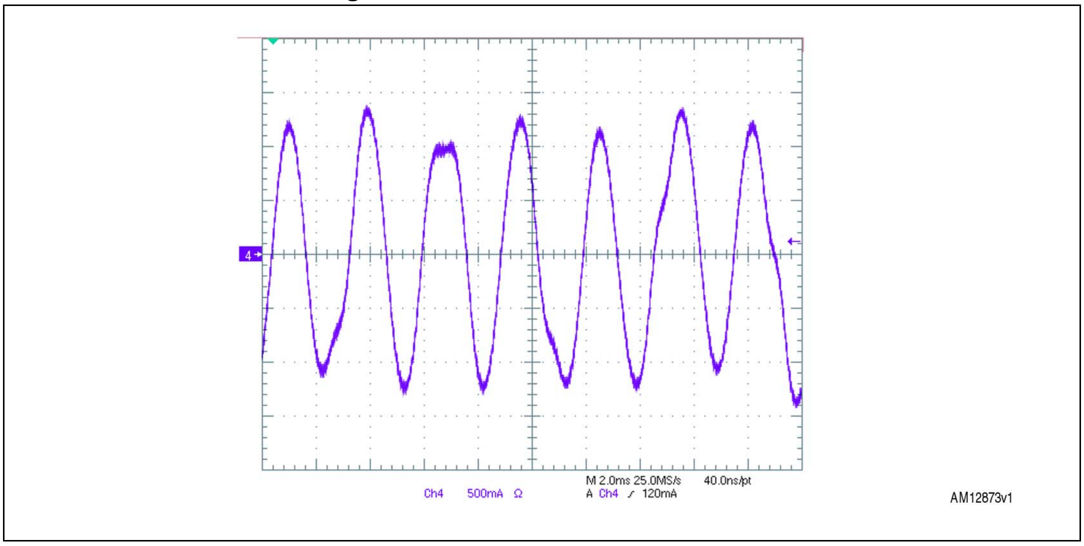
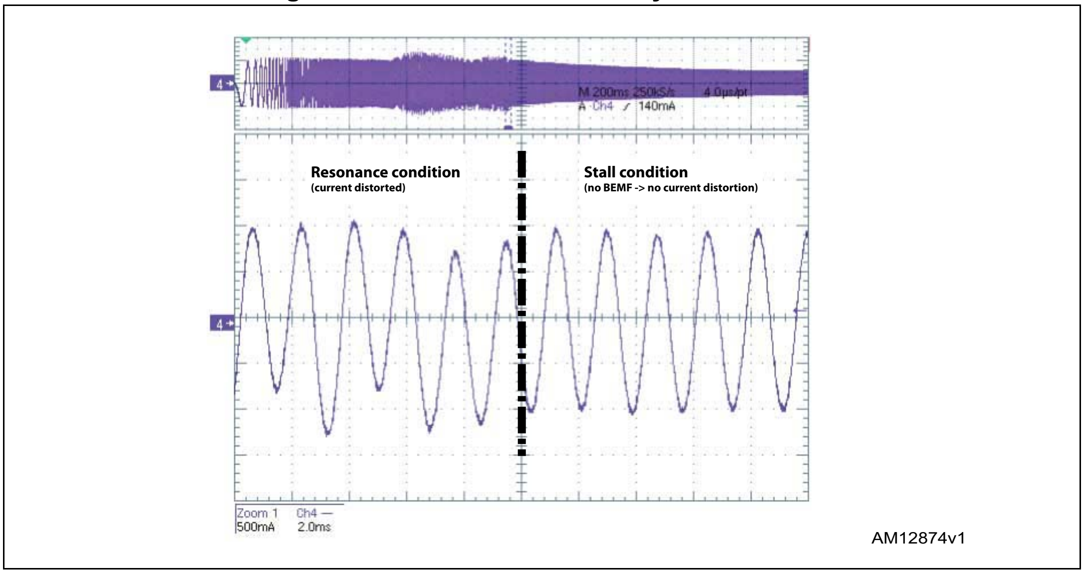



**Figure 18. Motor stall caused by resonances**



## 5.2 Facing resonances

Facing resonances is a critical issue in the development of a stepper motor application. This section lists the most common solutions to reduce or avoid resonance effects.

### 5.2.1 Damping resonances using the mechanical load

The worst condition for stepper motor driving is when the shaft is unloaded. When the shaft remains unloaded, all the energy provided to the motor is dissipated by the rotor itself exciting its resonance points.

Even a small load can dampen the rotor oscillations enough to make the motion smoother. Moreover, the mechanical load adds inertia to the system shifting the resonance points. The stepper motor mounting can also influence the resonance frequencies.

### 5.2.2 Reducing motor current

As previously described, the resonances are caused by the rotor oscillations during a step change. The amplitude of these oscillations is proportional to the intensity of the stimulating magnetic field, i.e. the current value. Reducing the phase current to the minimum required reduces the strength of the resonances.

Many times the resonance points of the stepper motor are represented as a lack of torque on the speed-torque curve. This representation may cause misunderstandings with this issue. The reduced torque is not the root cause of the problem (resonance), but it is the consequence of it. Therefore, increasing the phase current in order to compensate for the torque reduction is usually not a solution.

### 5.2.3 Skipping the resonance points increasing the acceleration

The most common method to avoid resonance points is to quickly accelerate past their positions. Working within the range of the system resonances is never recommended even for a short period of time.

High acceleration values allow the motor to pass through the resonance points faster, reducing the negative effects.

# 6 Revision history

**Table 6. Document revision history**

| Date | Revision | Changes |
|---|---|---|
| 26-Jul-2012 | 1 | Initial release. |
| 14-Feb-2014 | 2 | Updated *Figure 4 on page 10* (updated data).<br>Minor modifications throughout document. |
| 26-Mar-2015 | 3 | Updated *Section 2.2.2 on page 16* (updated *Example 2*, maximum compensation rate).<br>Minor modifications throughout document. |
| 04-Aug-2017 | 4 | Updated *Figure 4 on page 10* (replaced by new figure). |