UM0492
User manual

STM32F103xx permanent-magnet synchronous motor FOC software library V2.0

Introduction

This user manual describes the permanent magnet synchronous motor (PMSM) FOC software library, a field oriented control (FOC) firmware library for 3-phase permanent-magnet motors developed for the STM32F103xx microcontrollers.

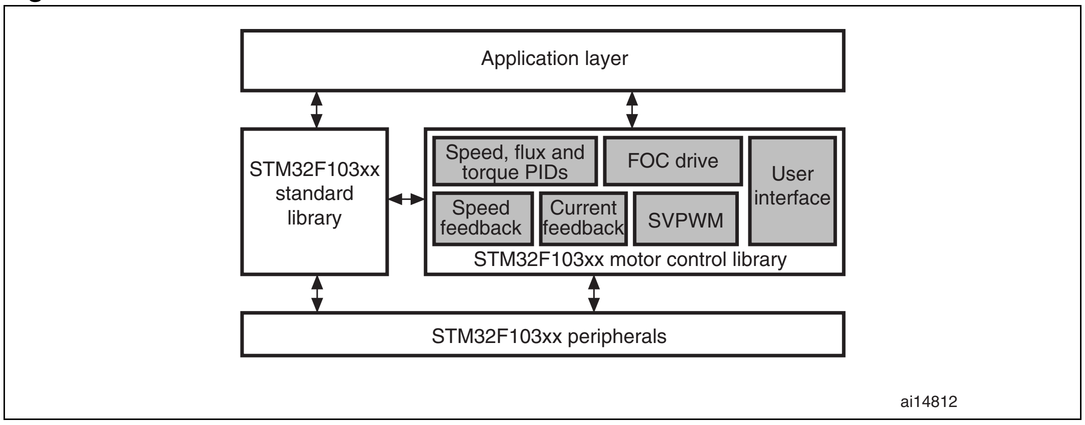
These 32-bit, ARM Cortex™-M3 cored ST microcontrollers (STM32F103xx) come with a set of peripherals that makes it suitable for performing both permanent-magnet and AC induction motor FOC. In particular, this manual describes the STM32F103xx software library developed to control surface-mounted or internal, sinewave-driven permanent-magnet motors in both torque and speed control mode. These motors may be equipped with an encoder, with three Hall sensors or they may be sensorless. The control of an AC induction motor equipped with encoder or tacho generator is described in the UM0483 user manual.

The PMSM FOC library is made of several C modules, and is fitted out with IAR EWARM 5.20, KEIL RealView MDK 3.22a and Green Hills MULTI 5.03 workspaces. It is used to quickly evaluate both the MCU and the available tools. In addition, when used together with the STM32F103xx motor control starter kit (STM3210B-MCKIT) and PM motor, a motor can be made to run in a very short time. It also eliminates the need for time-consuming development of FOC and speed regulation algorithms by providing ready-to-use functions that let the user concentrate on the application layer. Moreover, it is possible to get rid of any speed sensor thanks to the sensorless algorithm for rotor position reconstruction.

A prerequisite for using this library is basic knowledge of C programming, PM motor drives and power inverter hardware. In-depth know-how of STM32F103xx functions is only required for customizing existing modules and for adding new ones for a complete application development.

Figure 1 shows the architecture of the firmware. It uses the STM32F103xx standard library extensively but it also acts directly on hardware peripherals when optimizations in terms of execution speed or code size are required.

Figure 1. Firmware architecture



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PMSM FOC software library V2.0 features (CPU running at 72 MHz)

- Supported speed feedbacks:
  - Sensorless
  - 60° or 120° displaced Hall sensors
  - Quadrature incremental encoder
- Current-sampling method:
  - 2 isolated current sensors (ICS)
  - single, common DC link shunt resistor
  - 3 shunt resistors placed on the bottom of the three inverter lags
- optimized IPMSM & SM-PMSM drive
- field weakening
- feed-forward, high-performance current regulation
- DAC functionality for tracing the most important software variables
- Brake resistor management
- Speed control mode for speed regulation
- Torque control mode for torque regulation
- 16-bit space vector
  - PWM frequency can be easily adjusted
  - Centered PWM pattern type
  - 11-bit resolution at 17.6 kHz
- Rules for the “a priori” determination of all the parameters necessary for firmware customization
- CPU load below 22% in the 3-shunt/sensorless configuration (10 kHz FOC sampling rate)
- Code size in 3-shunt/sensorless configuration is about 12.5 Kbytes plus 11.5 Kbytes for LCD/joystick management

1 Getting started with tools

To develop an application for a PM synchronous motor using the PMSM FOC software library, you must set up a complete development environment, as described in the following sections. A PC running Windows XP is necessary.

1.1 Working environment

The PMSM FOC software library was fully validated using the main hardware boards included in STM3210B-MCKIT starter kit (a complete inverter and control board). The STM3210B-MCKIT starter kit provides an ideal toolset for starting a project and using the library. Therefore, for rapid implementation and evaluation of the software described in this user manual, it is recommended to acquire this starter kit.

This library is provided with IAR EWARM v. 5.20, KEIL RVMDK v. 3.22 and Green Hills MULTI v. 5.0.3 workspaces. Exhaustive validation was performed using IAR, while simple functional validation was done with the other toolchains. You can set up your workspace manually for any other toolchain.

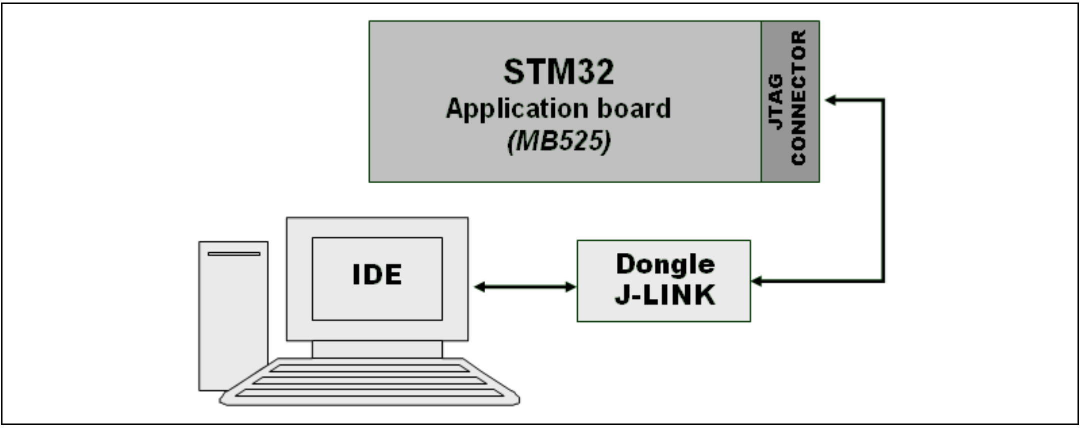
1.2 Software tools

A complete software package consists of:

- A third-party integrated development environment (IDE)
- A third-party C-compiler
- JTAG interface for debugging and programming

  Using the JTAG interface of the MCU you can enter in-circuit debugging session with most of toolchains. Each toolchain can be provided with an interface connected between the PC and the target application.

Figure 2. JTAG interface for debugging and programming



The JTAG interface can also be used for in-circuit programming of the MCU. Other production programmers can be obtained from third-parties.

1.3 Library source code

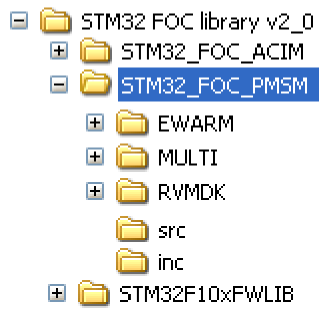
1.3.1 Updates

It is highly recommended to check for the latest releases of the library before starting any new development, and then to verify from time to time all release notes to be aware of any new features that might be of interest for your project. Registration mechanisms are available on ST websites to automatically obtain updates.

1.3.2 File structure

The PMSM FOC software library contains workspaces for the previously mentioned toolchains. Once the files are unzipped, the following library structure appears, as shown in *Figure 3*.

Figure 3. File structure



The **STM32 FOC Firmware Libraries v2.0** folder contains the firmware libraries for running 3-phase (sensored or sensorless) PMSM and sensored AC induction motors.

The **STM32F10xFWLIB** folder contains the standard library for the STM32F103xx.

The **inc** folder contains the header and the **src** folder contains the source files of the motor control library.

Finally, each of the **EWARM**, **RVMDK** and **MULTI** folders contains the configuration files for the respective toolchain plus a **lib** folder that contains the compiled object files of two modules: *MC_State_Observer* and *MC_FOC_Methods.*
The complete source files are available free of charge from ST on request. Do not hesitate to contact your nearest ST sales office or support team.

1.4 Customizing the workspace for your STM32F103xx derivative

The PMSM FOC software library was written for the STM32F103VB6. However, it works equally successfully with all the products in the STM32F103xx performance line family.

Using a different STM32F103xx sales type may require some modifications to the library, according to the available features (some of the I/O ports are not present on low-pin count packages). Refer to the MCU datasheet for further details.

Also, depending on the memory size, the workspace may have to be configured to fit your STM32F103xx MCU derivative.

2 Introduction to the sensorless FOC of PM motors

2.1 Introduction to the PM synchronous motor FOC drive

This software library is designed to achieve the high dynamic performance in AC permanent-magnet synchronous motor (PMSM) control offered by the well-established field oriented control (FOC) strategy.

With this approach, it can be stated that, by controlling the two currents i_{qs} and i_{ds}, which are mathematical transformations of the stator currents, it is possible to offer electromagnetic torque (T_e) regulation and, to some extent, flux weakening capability.

This resembles the favorable condition of a DC motor, where those roles are held by the armature and field currents.

Therefore, it is possible to say that FOC consists in controlling and orienting stator currents in phase and quadrature with the rotor flux; this definition makes clear that a means of measuring stator currents and the rotor angle is needed.

Basic information on the algorithm structure (and then on the library functions) is represented in *Figure 4*.

- the space vector PWM block (CALC SVPWM) implements an advanced modulation method that reduces current harmonics, thus optimizing DC bus exploitation
- the current reading block allows the system to measure stator currents correctly, using either cheap shunt resistors or market-available isolated current Hall sensors (ICS)
- the rotor speed/position feedback block allows the system to handle Hall sensor or incremental encoder signals in order to correctly acquire the rotor angular velocity or position. Moreover, this firmware library provides sensorless detection of rotor speed/position, as described in *Section 2.2*.
- the PID-controller blocks implement proportional, integral and derivative feedback controllers (current regulation)
- the Clarke, Park, Reverse Park & Circle limitation blocks implement the mathematical transformations required by FOC

Figure 4. Basic FOC algorithm structure, torque control

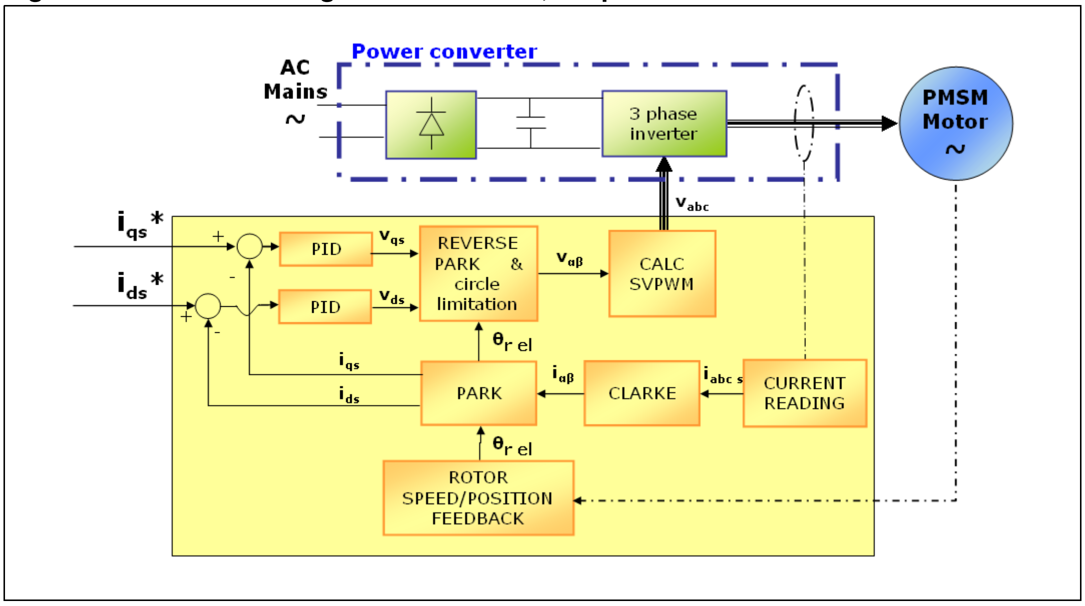
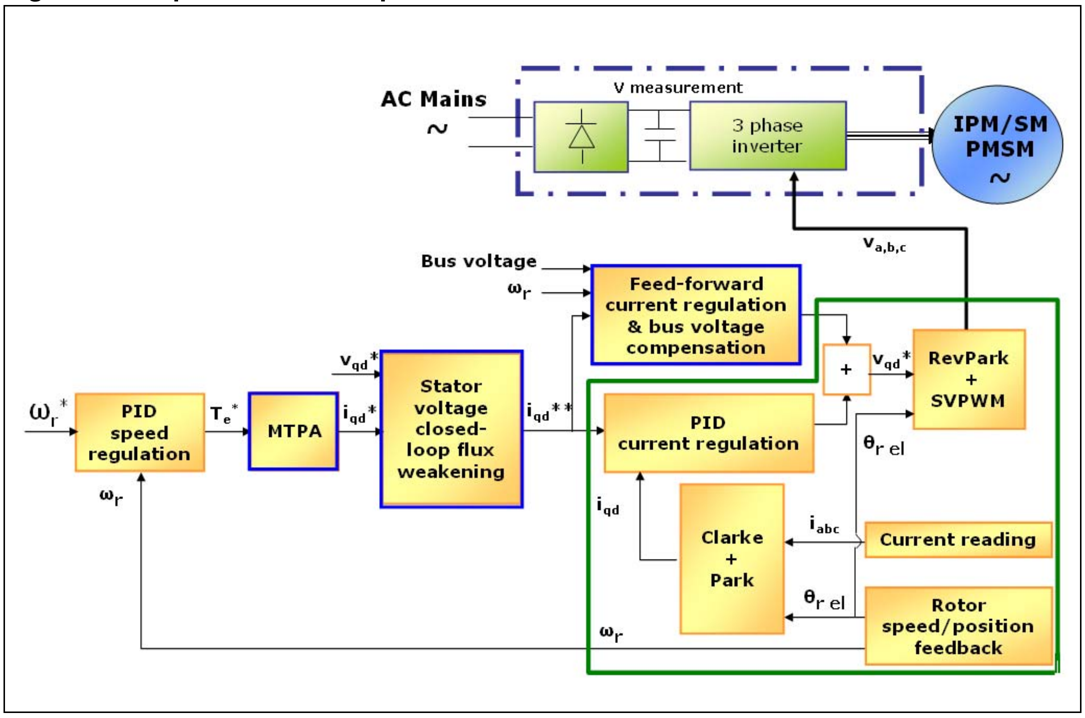


Figure 5. Speed control loop



The i_{qs} and i_{ds} current components can be selected to perform electromagnetic torque and flux control.

On the other hand, *Figure 5* shows the speed control loop as well as the whole set of specific features offered by this motor control library. See *Section 2.1.4*, *Section 2.3* and *Section 2.1.5*. *Section 2.1.4* explains the MTPA (maximum-torque-per-ampere) strategy optimized for IPMSM. *Section 2.3* explains flux-weakening control, and *Section 2.1.5* shows how to take advantage of the feed-forward current regulation.

Each of these features can be set as an option (see *Section 4.1*), according to the motor being used and user needs.

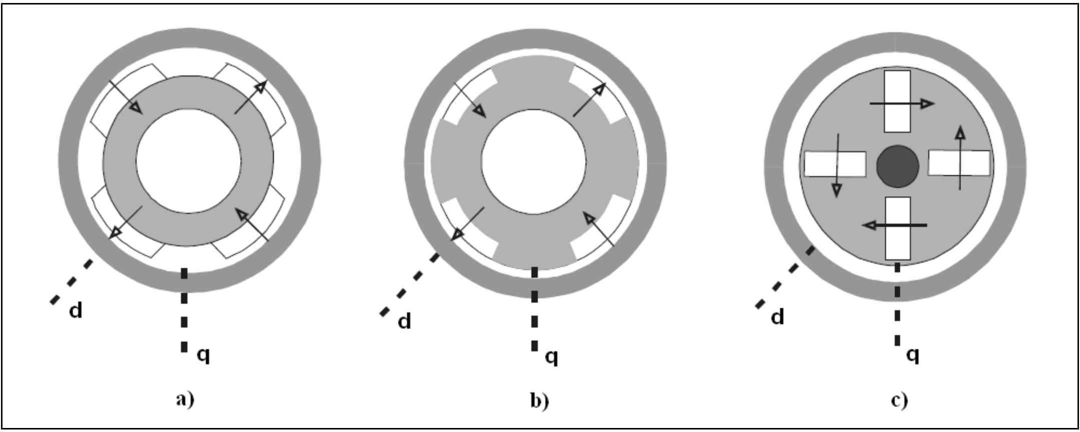
2.1.1 PM motor structures

Mainly, there are two different PM motor constructions available:

a) In the first one, drawing a) in *Figure 6*, the magnets are glued to the surface of the rotor, and this is the reason why it is referred to as SM-PMSM (surface mounted PMSM)

b) in the second one, illustrated by drawings b) and c) in *Figure 6*, the magnets are embedded in the rotor structure. This construction is known as IPMSM (interior PMSM)

Figure 6. Different PM motor constructions



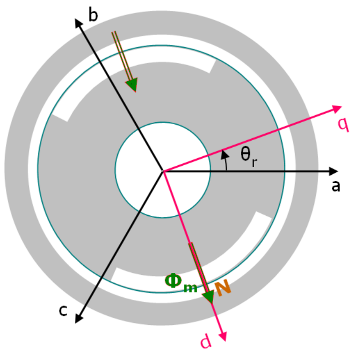
SM-PMSMs inherently have an isotropic structure, that is, the direct and quadrature inductances L_d and L_q are the same. Usually, their mechanical structure allows a wider airgap, which in turn means lower flux weakening capability.

On the other hand, IPMSMs show an anisotropic structure (with $L_d < L_q$, typically), slight in the b) construction (called inset PM motor), strong in the c) configuration (called buried or radial PM motor); this peculiar magnetic structure can be exploited (as explained in *Section 2.1.4*) to produce a greater amount of electromagnetic torque. their fine mechanical structure usually shows a narrow airgap, thus giving good flux weakening capability.

This firmware library is optimized for use in conjunction with SM-PMSMs and IPMSMs. machines.

2.1.2 PMSM fundamental equations

Figure 7. Assumed PMSM reference frame convention



With reference to *Figure 7*, the motor voltage and flux linkage equations of a PMSM (SM-PMSM or IPMSM) are generally expressed as:

$$v_{abc_s} = r_s i_{abc_s} + \frac{d\lambda_{abc_s}}{dt}$$

$$\lambda_{abc_s} = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & L_{ls} + L_{ms} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} & L_{ls} + L_{ms} \end{bmatrix} i_{abc_s} + \begin{bmatrix} \sin\theta_r \\ \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \Phi_m \text{, where:}$$

- r_s is the stator phase winding resistance
- L_{ls} is the stator phase winding leakage inductance
- L_{ms} is the stator phase winding magnetizing inductance; in case of an IPMSM, self and mutual inductances have a second harmonic component L_{2s} proportional to $\cos(2\theta_r + k \times 2\pi/3)$, with $k = 0 \pm 1$, in addition to the constant component L_{ms}(neglecting higher-order harmonics)
- θ_r is the rotor electrical angle
- Φ_m is the flux linkage due to permanent magnets

The complexity of these equations is apparent, as the three stator flux linkages are mutually coupled and, what is more, as they are dependent on the rotor position, which is time-varying and a function of the electromagnetic and load torques.

The reference frame theory simplifies the PM motor equations, by making a change of variables that refers the stator quantities abc (that can be visualized as directed along axes each 120° apart) to qd components, directed along a 90° apart axes, rotating synchronously with the rotor, and vice versa (see *Section 5.5* for more details). The d "direct" axis is aligned with the rotor flux, while the q "quadrature" axis leads at 90 degrees in the positive rolling direction.

The motor voltage and flux equations are simplified to:

$$\begin{cases} v_{qs} = r_s i_{qs} + \dfrac{d\lambda_{qs}}{dt} + \omega_r \lambda_{ds} \\ v_{ds} = r_s i_{ds} + \dfrac{d\lambda_{ds}}{dt} - \omega_r \lambda_{qs} \end{cases}$$

$$\begin{cases} \lambda_{qs} = L_{qs} i_{qs} \\ \lambda_{ds} = L_{ds} i_{ds} + \Phi_m \end{cases}$$

For an SM-PMSM, the inductances of the d- and q- axis circuits are the same (refer to *Section 2.1.1*), that is we have:

$$L_s = L_{qs} = L_{ds} = L_{ls} + \frac{3L_{ms}}{2}$$

On the other hand, IPMSMs show a salient magnetic structure, so their inductances can be written as:

$$L_{qs} = L_{ls} + \frac{3(L_{ms} + L_{2s})}{2}$$
$$L_{ds} = L_{ls} + \frac{3(L_{ms} - L_{2s})}{2}$$

2.1.3 SM-PMSM field-oriented control (FOC)

The equations below describe the electromagnetic torque of an SM-PMSM:

$$T_e = \frac{3}{2}\bar{p}(\lambda_{d_s} i_{q_s} - \lambda_{q_s} i_{d_s}) = \frac{3}{2}\bar{p}(L_s i_{d_s} i_{q_s} + \Phi_m i_{q_s} - L_s i_{q_s} i_{d_s})$$

$$T_e = \frac{3}{2}\bar{p}(\Phi_m i_{q_s})$$

The last equation makes it clear that the quadrature current component i_{qs} has linear control on the torque generation, whereas the current component i_{ds} has no effect on it (as mentioned above, these equations are valid for SM-PMSMs).

Therefore, if I_s is the motor rated current, then its maximum torque is produced for $i_{qs} = I_s$ and $i_{ds} = 0$ (in fact $I_s = \sqrt{i_{q_s}^2 + i_{d_s}^2}$). In any case it is clear that, when using an SM-PMSM, the torque/current ratio is optimized by letting $i_{ds} = 0$. This choice therefore corresponds to the MTPA (maximum-torque-per-ampere) control for isotropic motors. See *Section 4.1* to find out how to set up the library configuration and carry out this strategy.

On the other hand, the magnetic flux can be weakened by acting on the direct axis current i_{ds}; this extends the achievable speed range, but at the cost of a decrease in maximum quadrature current i_{qs}, and hence in the electromagnetic torque supplied to the load (see *Section 2.3* for details about the Flux weakening strategy).

In conclusion, by regulating the motor currents through their components i_{qs} and i_{ds}, FOC manages to regulate the PMSM torque and flux; current regulation is achieved by means of what is usually called a “synchronous frame CR-PWM”.

2.1.4 IPMSM maximum torque per ampere (MTPA) control

The electromagnetic torque equation of an IPMSM is:

$$T_e = \frac{3}{2}\bar{p}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) = \frac{3}{2}\bar{p}(L_{ds} i_{ds} i_{qs} + \Phi_m i_{qs} - L_{qs} i_{qs} i_{ds})$$

$$T_e = \frac{3}{2}\bar{p}\Phi_m i_{qs} + \frac{3}{2}\bar{p}L_{ds} - L_{qs} i_{qs} i_{ds}$$

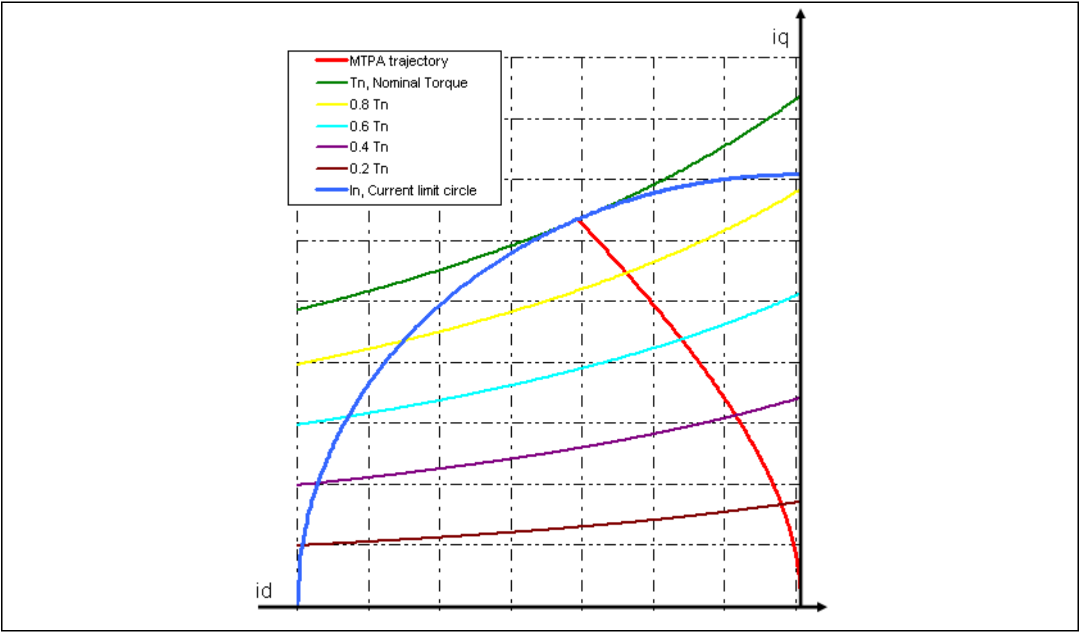
The first term in this expression is the PM excitation torque. The second term is the so-called reluctance torque, which represents an additional component due to the intrinsic salient magnetic structure. Besides, since $L_d < L_q$ typically, reluctance and excitation torques have the same direction only if $i_{ds} < 0$.

Considering the torque equation, it can be pointed out that the current components i_{qs} and i_{ds} both have a direct influence on torque generation.

The aim of the MTPA (maximum-torque-per-ampere) control is to calculate the reference currents (i_{qs}, i_{ds}) which maximize the ratio between produced electromagnetic torque and copper losses (under the condition: $I_s = \sqrt{i_{qs}^2 + i_{ds}^2} \le I_n$).

Therefore, given a set of motor parameters (pole pairs, direct and quadrature inductances L_d and L_q, magnets flux linkage, nominal current) the MTPA trajectory is identified as the locus of (i_{qs}, i_{ds}) pairs that minimizes the current consumption for each required torque (see *Figure 8*).

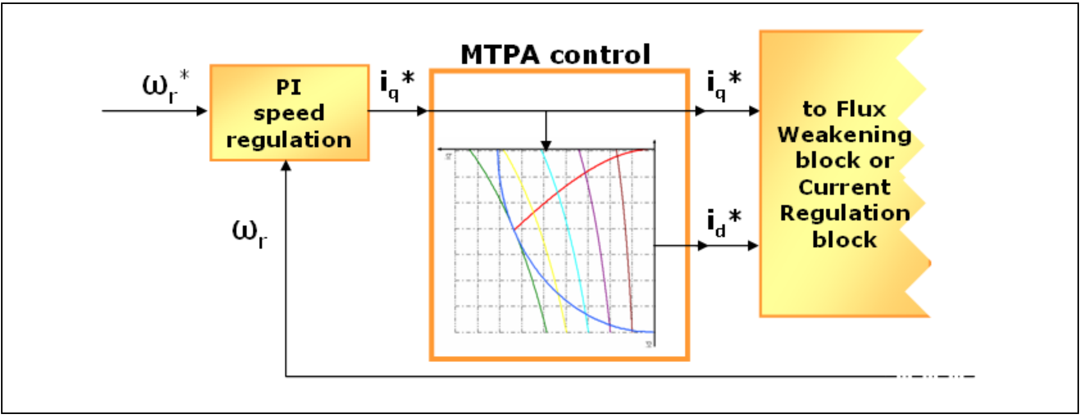
Figure 8. MTPA trajectory



Section 4.1 explains how this feature is activated. By inputting the motor parameters into a spreadsheet included in the firmware library package (the file location is **STM32MC-KIT\design tools\ PMSM_MTPA_FEEDFORWARD.xls**), it is possible to precalculate the MTPA trajectory and insert the result, as coefficients of an 8-interval linear interpolation, into the proper parameter header file (see details in *Section 4.6.4*).

Figure 9 shows an actual implementation. The MTPA strategy is implemented inside a speed-control loop. In that case, i_q* (output of the PI regulator) is fed to the MTPA function, i_d* is chosen by entering the linear interpolated trajectory.

Figure 9. MTPA control



In any case, by acting on the direct axis current i_{ds}, the magnetic flux can be weakened so as to extend the achievable speed range. As a consequence of entering this operating region, the MTPA path is left (see *Section 2.3* for details about the flux-weakening strategy).

In conclusion, by regulating the motor currents through their i_{qs} and i_{ds} components, FOC manages to regulate the PMSM torque and flux. Current regulation is then achieved by means of what is usually called a “synchronous frame CR-PWM”.

2.1.5 Feed-forward current regulation

The feed-forward feature provided by this firmware library aims at improving the performance of the CR-PWM (current-regulated pulse width modulation) part of the motor drive.

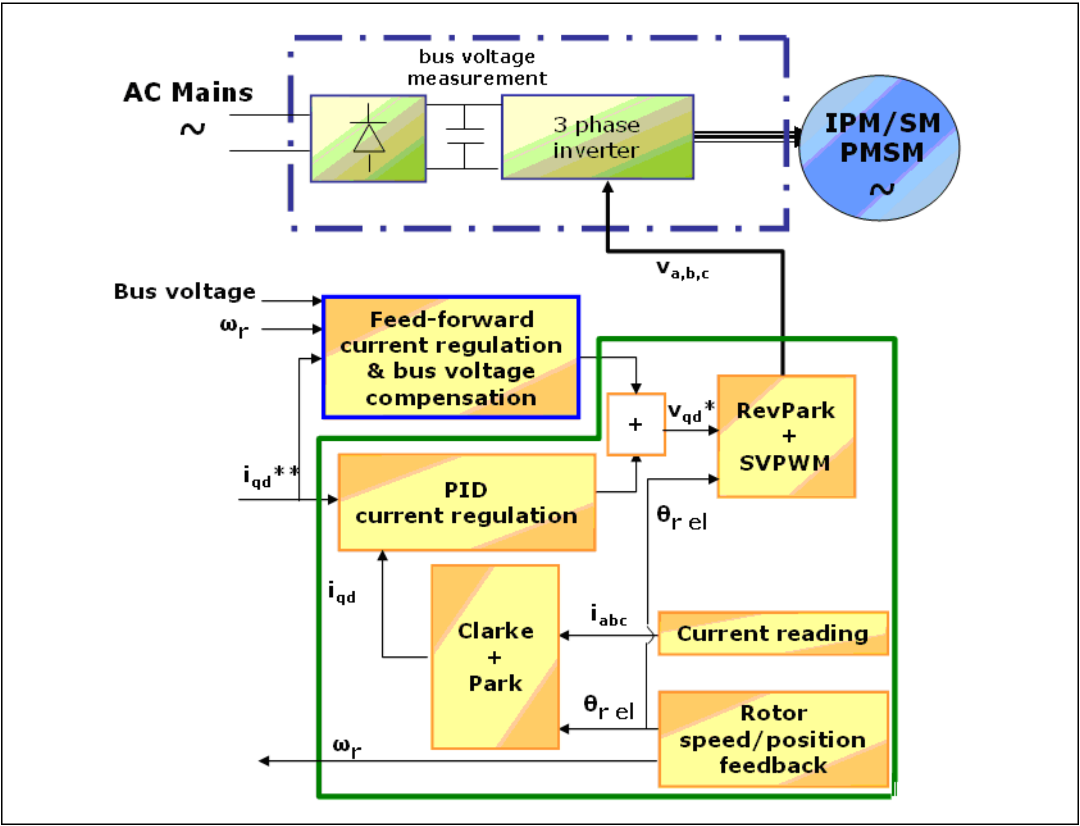
Basically, it calculates in advance the v_q^* and v_d^* stator voltage commands required to feed the motor with the i_q^{**} and i_d^{**} current references. By doing so, it backs up the standard PID current regulation (see *Figure 10*).

The feed-forward feature works in the synchronous reference frame and requires good knowledge of some machine parameters, such as the winding inductances L_d and L_q (or L_s if an SM-PMSM is used) and the motor voltage constant K_e.

The feed-forward algorithm has been designed to compensate for the frequency-dependent back emf's and cross-coupled inductive voltage drops in permanent magnet motors. As a result, the q-axis and d-axis PID current control loops become linear, and a high performance current control is achieved.

As a further effect, since the calculated stator voltage commands v_q^* and v_d^* are compensated according to the present DC voltage measurement, a bus voltage ripple compensation is accomplished.

Figure 10. Feed-forward current regulation



Depending on some overall system parameters, such as the DC bulk capacitor size, electrical frequency required by the application, motor parameters etc., the feed-forward functionality could bring a major or a poor contribution to the motor drive. It is therefore recommended that the user assess the resulting system performance and enable the functionality only if a valuable effect is measured.

See *Section 4.1* for details on activating the feed-forward feature, *Section 4.6* for how to insert the required parameters into the proper header file (by using the *PMSM_MTPA_FEEDFORWARD.xls* spreadsheet provided in **STM32MC-KIT\design tools**) and, *Section 5.4* for the functional description and prototypes of the available functions.

2.2 Introduction to sensorless rotor position / speed feedback

In *Section 2.1* it has been shown that rotor position / speed measurement has a crucial role in PMSM field oriented control. Hall sensors or encoders are broadly used in the control chain for that purpose.

Sensorless algorithms for rotor position / speed feedback are considered very useful and for different reasons: to lower the overall cost of the application, to enhance the reliability by redundancy, etc.

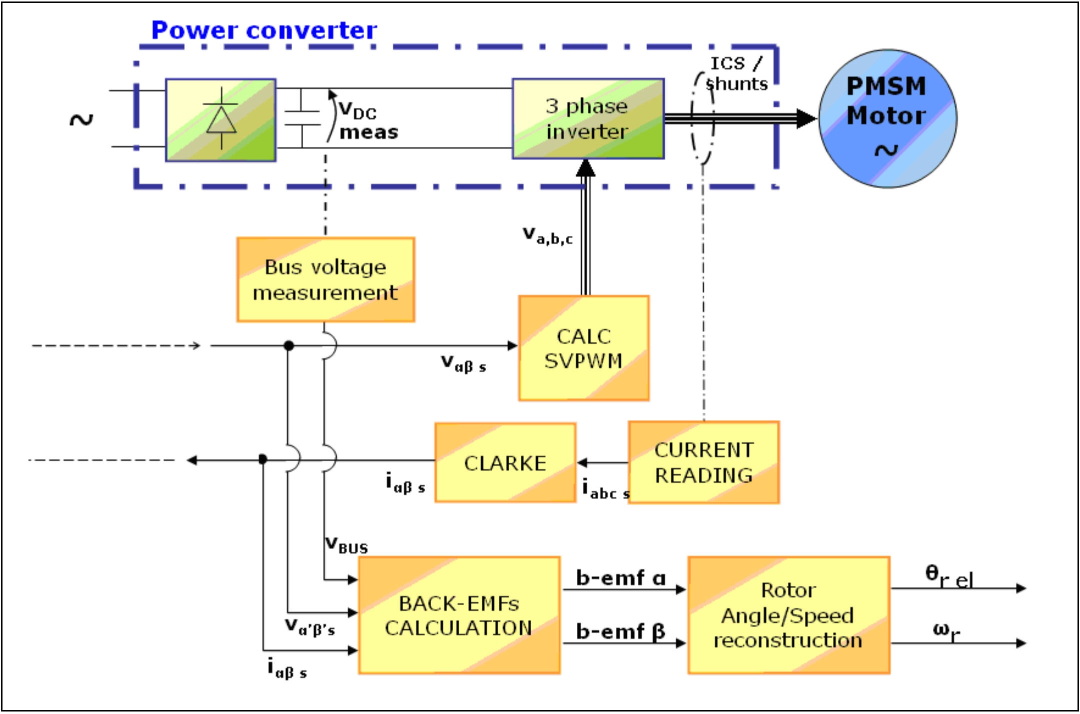
This firmware library provides a complete solution for sensorless detection of rotor position / speed feedback, which is based on the state observer theory. The implemented algorithm is applicable to both SM-PM and IPM synchronous motors, as explained in [5] (Appendix *A.9: References*). A theoretical and experimental comparison between the implemented rotor flux observer and a classical VI estimator [6](Appendix *A.9: References*) has pointed out the observer's advantage, which turns out to be a clearly reduced dependence on the stator resistance variation and an overall robustness in terms of parameter variations.

A state observer, in control theory, is a system that provides an estimation of the internal state of a real system, given its input and output measurement.

In our case, the internal states of the motor are the back-emfs and the phase currents, while the input and output quantities supplied are the phase voltages and measured currents, respectively (see *Figure 11*).

DC bus voltage measurement is used to convert voltage commands into voltage applied to motor phases.

Figure 11. General sensorless algorithm block diagram



In particular, the observed states are compared for consistency with the real system via the phase currents, and the result is used to adjust the model through a gain vector (K1, K2).

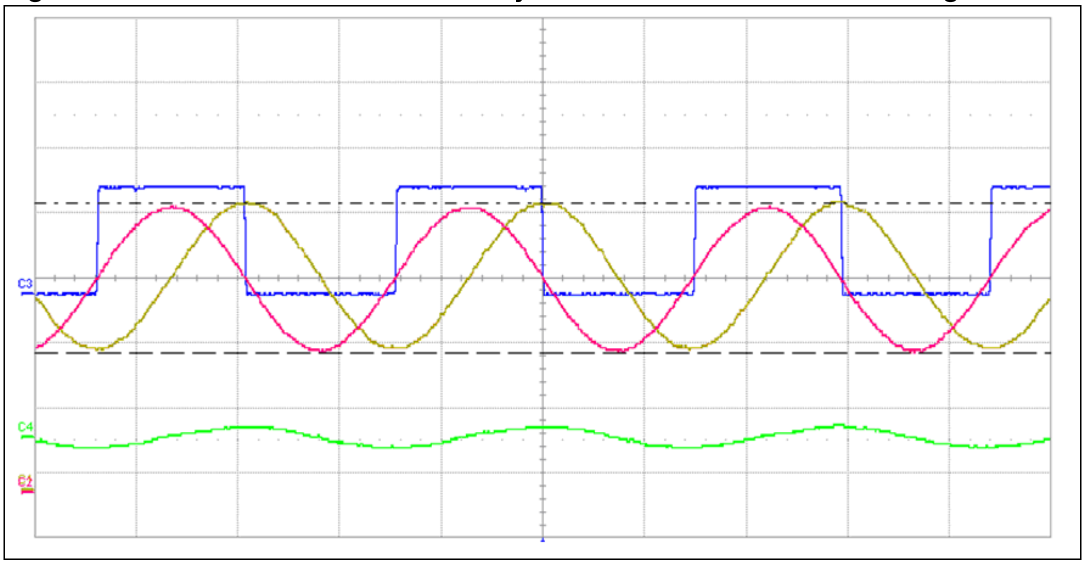
The motor back-emfs are defined as:

$$e_\alpha = \Phi_m p \omega_r \cos(p\omega_r t)$$
$$e_\beta = -\Phi_m p \omega_r \sin(p\omega_r t)$$

As can be seen, they hold information about the rotor angle. Then, back-emfs are fed to a block which, acting as a PLL, is able to reconstruct the rotor electrical angle and speed.

Figure 12 shows a scope capture taken while the motor is running in field oriented control (positive rolling direction); the yellow and the red waveforms (C1,C2) are respectively the observed back-emfs alpha and beta, the blue square wave (C3) is a signal coming from a Hall sensor cell placed on the a-axis, the green sinewave is current i_a (C4).

Figure 12. PMSM back-emfs detected by the sensorless state observer algorithm



More information on how to set parameters to make the firmware suit the user's motor could be found in *Section 4.5*.

2.3 Introduction to flux-weakening control

The purpose of the flux-weakening functionality is to expand the operating limits of a permanent-magnet motor by reaching speeds higher than rated, as many applications require under operating conditions where the load is lower than rated. Here, the rated speed is considered to be the highest speed at which the motor can still deliver maximum torque.

The magnetic flux can be weakened by acting on direct axis current i_d; given a motor rated current I_n, such that $I_n = \sqrt{i_q^2 + i_d^2}$, if we choose to set id $\neq$ 0, then the maximum available quadrature current i_q is reduced. Consequently, in case of an SM-PMSM, as shown in *Section 2.1.3*, the maximum deliverable electromagnetic torque is also reduced. On the other hand, for an IPM motor, acting separately on i_d causes a deviation from the MTPA path (as explained in *Section 2.1.4*).

"Closed-loop" flux weakening has been implemented. Accurate knowledge of machine parameters is not required, which strongly reduces sensitivity to parameter deviation (see [3]-[4] in Appendix *A.9: References*). This scheme is suitable for both IPMSMs and SM-PMSMs.

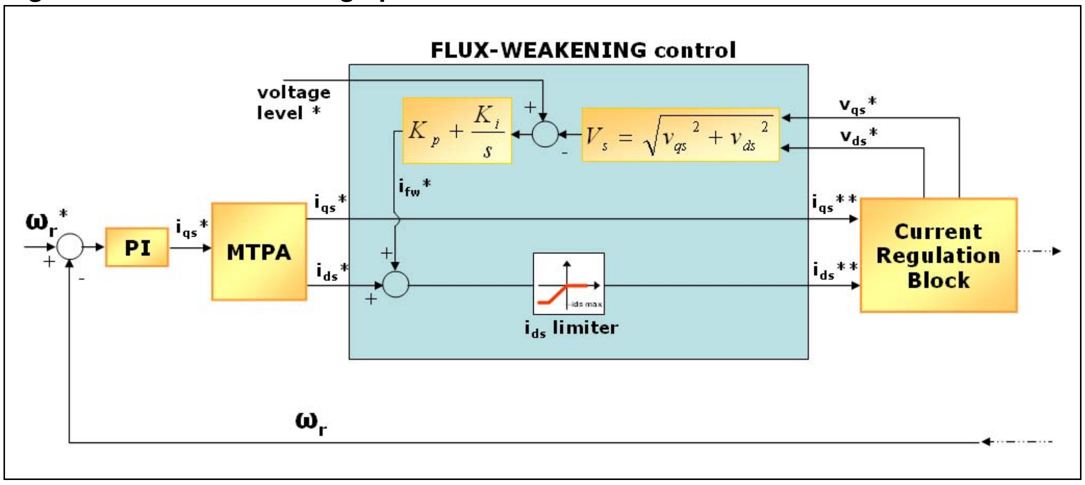
The control loop is based on stator voltage monitoring (*Figure 13* shows the diagram).

The current regulator output V_s is checked against a settled threshold ("voltage level*" parameter). If V_s is beyond that limit, the flux-weakening region is entered automatically by regulating a control signal, i_{fw}*, that is summed up to i_{ds}*, the output of the MTPA controller. This is done by means of a PI regulator (whose gain can be tuned in real time as explained in *Section 3.4*) in order to prevent the saturation of the current regulators. It clearly appears, then, that the higher the voltage level* parameter is settled (by keeping up current regulation), the higher the achieved efficiency and maximum speed.

If V_s is smaller than the settled threshold, then i_{fw} decreases to zero and the MTPA block resumes control.

The current i_{ds}** output from the flux-weakening controller must be checked against i_{ds} max to avoid the demagnetization of the motor.

Figure 13. Flux-weakening operation scheme



See *Section 4.1*, *Section 4.6* and *Section 5.4*, respectively, about the activation of the flux-weakening feature, inserting the required parameters into the proper header file, and the functional description and prototypes of the available functions.

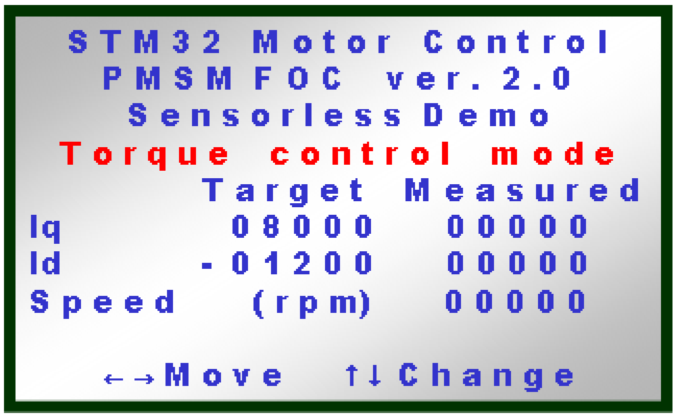
3 Running the demo program

3.1 Torque control mode

Figure 14, *Figure 15* and *Figure 16* show a few LCD menus for setting control parameters when in Torque Control mode. The parameter highlighted in red color is the one that can be set and its value can be modified by acting on the joystick key.

Moving the joystick up/down selects the active control mode (in the example shown in *Figure 14*, it is Torque control). Once the motor Start command has been issued (by pressing the JOY or KEY key), this parameter is no longer accessible. It becomes accessible again when the motor is stopped.

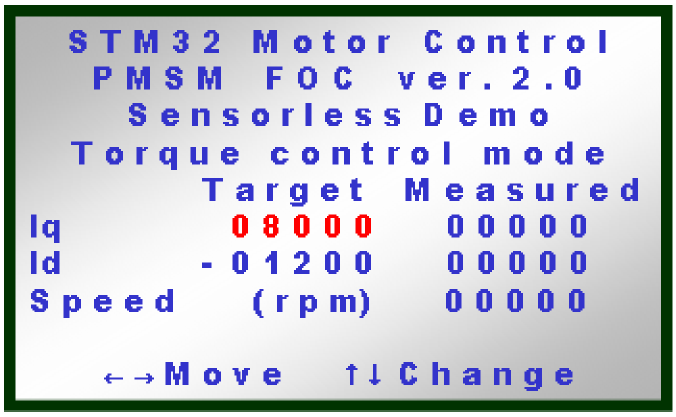
Figure 14. LCD screen for Torque control settings



```
   STM32 Motor Control
     PMSM FOC ver.2.0
      Sensorless Demo
  Torque control mode
            Target  Measured
Iq           08000    00000
Id          -01200    00000
Speed        (rpm)    00000

      ←→Move    ↑↓Change
```

From the previous screen (*Figure 14*), if the joystick is moved to the right, the Target Iq current component becomes highlighted (in red). This parameter can now be modified by moving the joystick up/down. Once the motor Start command has been issued, Target Iq can be changed in runtime while the measured Iq current component is shown in the **Measured** field.

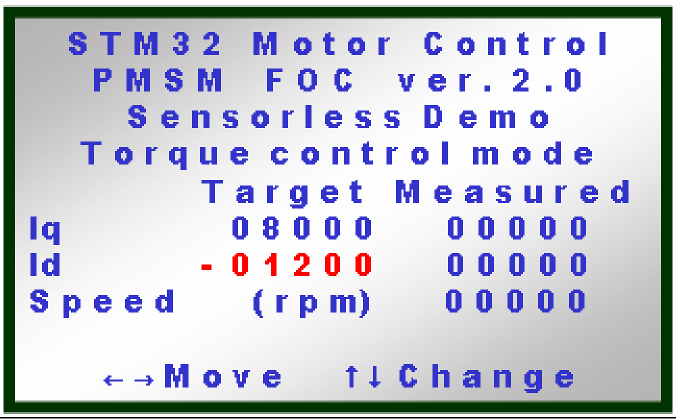
Figure 15. LCD screen for Target Iq settings



```
   STM32 Motor Control
     PMSM FOC ver.2.0
      Sensorless Demo
  Torque control mode
            Target  Measured
Iq           08000    00000
Id          -01200    00000
Speed        (rpm)    00000

      ←→Move    ↑↓Change
```

From the previous screen (*Figure 15*), if the joystick is moved to the right, the Target Id current component becomes highlighted (in red). This parameter can now be modified by moving the joystick up/down. Once the motor Start command has been issued, the Target Id can be changed in runtime while the measured Id current component is shown in the **Measured** field.

Figure 16. LCD screen for Target Id settings



```
STM32 Motor Control
PMSM FOC ver.2.0
Sensorless Demo
Torque control mode
          Target  Measured
Iq         08000   00000
Id        -01200   00000
Speed      (rpm)   00000

←→Move    ↑↓Change
```

The motor is stopped (main state machine moves from Run to Stop state) by pressing either the KEY button or the joystick.

Different motor ramp-up strategies are used in torque control mode depending on the kind of configuration utilized for the speed / position feedback:

- `ENCODER` or `VIEW_ENCODER_FEEDBACK` uncommented in the configuration file *stm32f10x_MCconf.h*. In this case a rotor pre-positioning phase (also called alignment) is necessary in order to make absolute the otherwise relative position information fed back by the quadrature encoder. This alignment phase is performed only at first startup after any detected microcontroller fault event or reset. Refer to *Section 4.3* for a deeper description of this procedure.

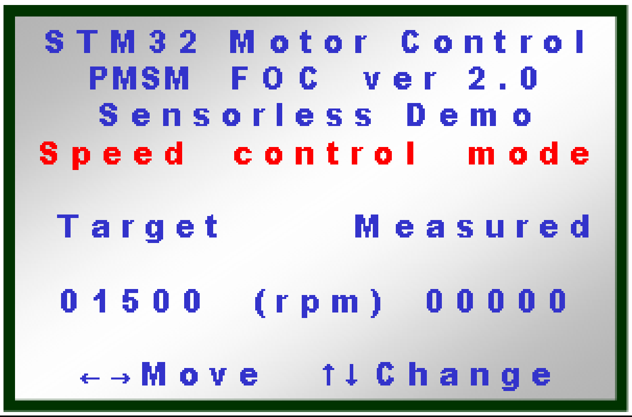
  After the rotor pre-positioning is performed, if `ENCODER` is uncommented, the variables containing the target value of the Iq and Id stator current components (respectively `hTorque_Reference` and `hFlux_Reference`) are initialized with the values `PID_TORQUE_REFERENCE` and `PID_FLUX_REFERENCE` defined in the header file *MC_Control_Param.h;* the main state machine switches from the Start to the Run state. On the other hand, if `VIEW_ENCODER_FEEDBACK` is uncommented, the ramp-up strategy related to the sensorless operation starts just after the end of the pre-positioning.
- `HALL_SENSORS` is uncommented in the *stm32f10x_MCconf.h* configuration file. In this case no rotor pre-positioning is performed and the `hTorque_Reference` software variable is simply initialized with the `PID_TORQUE_REFERENCE` value defined in the *MC_Control_Param.h* header file. The software variable containing the electrical rotor angle is initialized based on the digital value of the three Hall sensor outputs, and the main state machine switches from the Start to the Run state.
- `NO_SPEED_SENSORS` is uncommented in *stm32f10x_MCconf.h*. In case of sensorless motor driving, a particular ramp-up is necessary in order to make the rotor move and the sensorless algorithm converge to the actual rotor position. A deeper description of the ramp-up procedure is described in *Section 4.5*.

3.2 Speed control mode

Figure 17 and *Figure 18* show two LCD menus used to set control parameters when in Speed control mode. The parameter highlighted in red color is the one that can be set and its value can be modified by acting on the joystick key.

From the menu screen shown in *Figure 17*, it is possible to switch from Torque control to Speed control operations (and vice versa) by moving the joystick up/down while the motor is stopped.

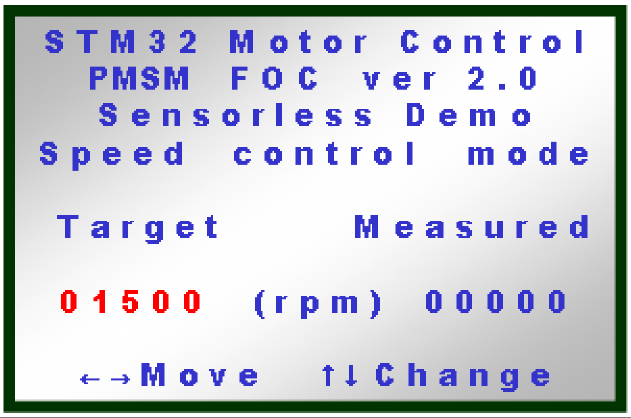
Figure 17. Speed control main settings



```
STM32 Motor Control
 PMSM FOC ver 2.0
 Sensorless Demo
Speed control mode

Target      Measured

01500 (rpm) 00000

←→Move   ↑↓Change
```

From the menu screen shown in *Figure 18*, moving the joystick to the right selects the Target speed (parameter highlighted in red). Once selected, the parameter can be incremented/decremented by moving the joystick up/down. The motor can then be started simply by pressing the joystick. When the motor is on, the target speed can still be modified.

Figure 18. LCD screen for setting Target speed



```
STM32 Motor Control
 PMSM FOC ver 2.0
 Sensorless Demo
Speed control mode

Target      Measured

01500 (rpm) 00000

←→Move   ↑↓Change
```

Like in the torque control mode, the motor is started/stopped by pressing the joystick or the KEY button.

Since in speed control mode, the torque and flux parameters (Target Iq and Target Id) are the outputs of the Torque and flux controller, they cannot be set directly. The PID regulators can however be real-time tuned as explained below.

Different motor ramp-up strategies are used in speed control mode depending on the kind of configuration utilized for the speed / position feedback:

- `ENCODER` or `VIEW_ENCODER_FEEDBACK` uncommented in the *stm32f10x_MCconf.h* configuration file. As already stated in the previous paragraph, a rotor pre-positioning phase (also called alignment) is necessary in this case. Refer to *Section 4.3* for a deeper description of this procedure.

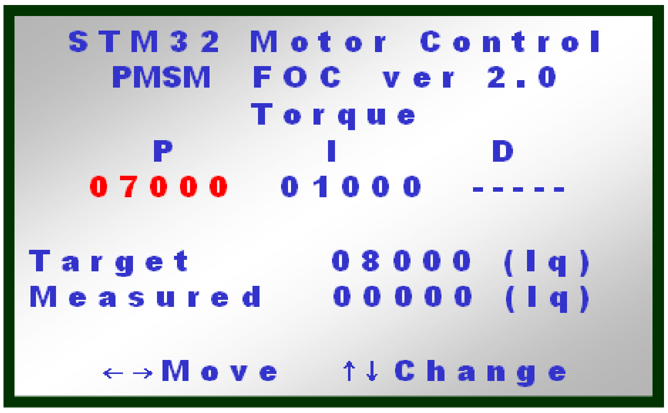
  After the rotor pre-positioning is performed, if `ENCODER` is uncommented the variables containing the target values of the Iq and Id current components (*hTorque_Reference* and `hFlux_Reference`, respectively) are driven by the torque and flux controller block and the main state machine switches from the Start to the Run state. On the other hand, if `VIEW_ENCODER_FEEDBACK` is uncommented, the ramp-up strategy related to the sensorless operation starts just after the end of the pre-positioning.
- `HALL_SENSORS` is uncommented in the *stm32f10x_MCconf.h* configuration file. The *hTorque_Reference* software variable is driven by the flux and torque controller block from the moment the start command is given. The software variable containing the electrical rotor angle is also initialized based on the digital value of the three Hall sensor outputs at that moment. Finally, the main state machine switches from the Start to the Run state.
- `NO_SPEED_SENSORS` is uncommented in *stm32f10x_MCconf.h*. In case of sensorless motor driving, a particular ramp-up is necessary in order to make the rotor move and the sensorless algorithm converge to the actual rotor position. A more detailed description of the ramp-up procedure is described in *Section 4.5*.

3.3 Currents and speed regulator tuning

As already exposed in *Section 2.1*, the Iq and Id currents regulation is achieved by mean of two PID controllers where the derivative action can be optionally disabled by uncommenting the definition of `DIFFERENTIAL_TERM_ENABLED` in *stm32f10x_MCconf.h.* Next figures show the two LCD menus allowing the real-time tuning of the proportional, integral and in case it is present derivative gains:

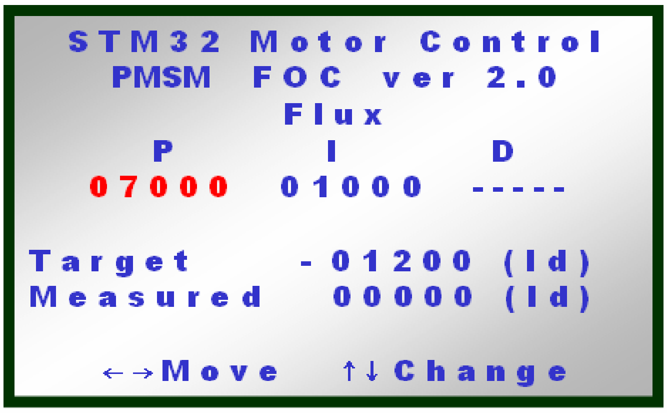
Figure 19 shows the screen used to select either of the torque PID coefficients whereas *Figure 20* shows the screen used to select either of the flux PID coefficients. From both screen, either of the P, I or D (when present) coefficient can be selected (highlighted in red) by moving the joystick to the right/left. Then, each value can be changed (incremented or decremented) by pressing the joystick up/down.

Figure 19. LCD screen for setting the P term of torque PID



```
STM32 Motor Control
PMSM  FOC  ver 2.0
      Torque
   P       I       D
 07000   01000   -----

Target       08000 (Iq)
Measured     00000 (Iq)

←→Move      ↑↓Change
```

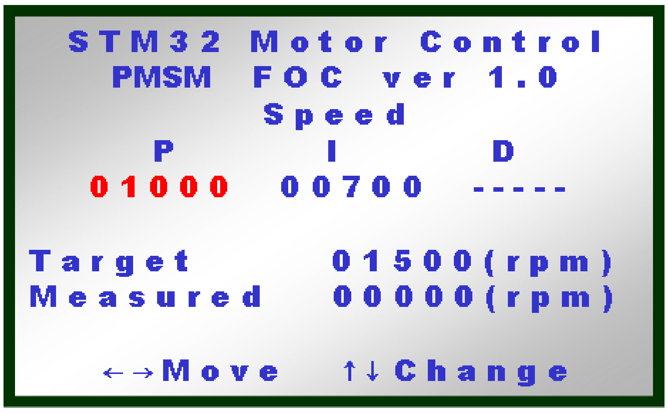
Figure 20. LCD screen for setting the P term of flux PID



```
STM32 Motor Control
 PMSM FOC ver 2.0
       Flux
  P        I        D
07000    01000    -----

Target          -01200 (Id)
Measured         00000 (Id)

  ←→Move    ↑↓Change
```

Moreover, to achieve speed regulation in speed control mode, a PI(D) is also implemented inside the torque and flux controller block. The tuning of its related gains can be done in real time by means of the dedicated LCD menu:

Figure 21. LCD screen for setting the P term of the speed PID



```
STM32 Motor Control
 PMSM FOC ver 1.0
      Speed
  P        I        D
01000    00700    -----

Target          01500(rpm)
Measured        00000(rpm)

  ←→Move    ↑↓Change
```

Like for the previous menus, either of the P, I or D (when present) coefficients can be selected (highlighted in red) by moving the joystick to the right/left. The desired values can then be changed (incremented or decremented) by pressing the joystick up/down.

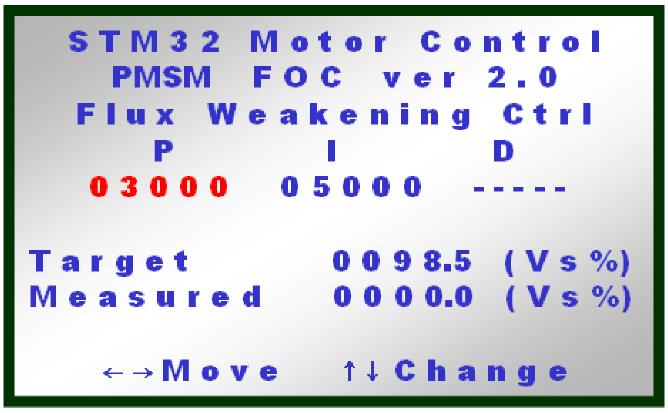
3.4 Flux-weakening PI controller tuning

This menu is available if the flux-weakening functionality has been enabled in the *stm32F10x_MCconf.h* file (see *Section 2.3* and *Section 4.1*).

It is used to real-time tune the proportional and integral gains of the PI regulator used inside the flux-weakening block.

Either of the P coefficient, I coefficient or the target stator voltage V_s can be selected (highlighted in red) by moving the joystick to the right/left. The desired values can then be changed (incremented or decremented) by pressing the joystick up/down. *Figure 22* shows the screen used for the tuning operation.

Figure 22. LCD screen for setting the P term of the flux-weakening PI



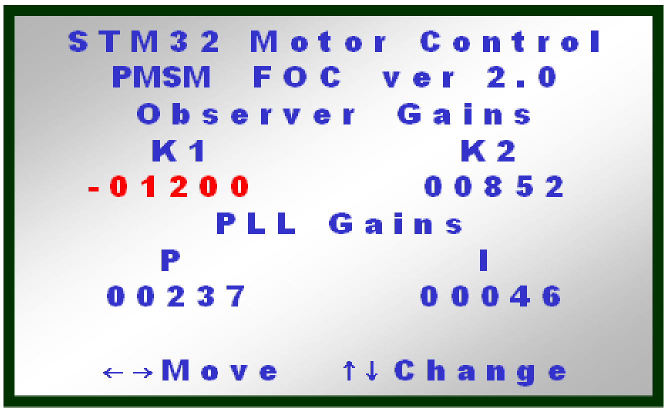
```
STM32 Motor Control
PMSM FOC ver 2.0
Flux Weakening Ctrl
P          I          D
03000      05000      -----

Target       0098.5 (Vs%)
Measured     0000.0 (Vs%)

←→Move    ↑↓Change
```

The target and measured stator voltages ($V_s = \sqrt{v_\alpha^2 + v_\beta^2}$) are shown in the lower part of the screen as a percentage of the maximum available phase voltage.

3.5 Observer and PLL gain tuning

In the default configuration of the firmware library, the tuning of the sensorless algorithm is disabled. Nevertheless, when the `OBSERVER_GAIN_TUNING` definition is not commented in the *stm32F10x_MCconf.h* configuration header file, a dedicated menu is shown on the LCD.

Figure 23. LCD screen for setting the P term of the flux PID



```
STM32 Motor Control
PMSM FOC ver 2.0
Observer Gains
K1            K2
-01200        00852
PLL Gains
P             I
00237         00046

←→Move    ↑↓Change
```

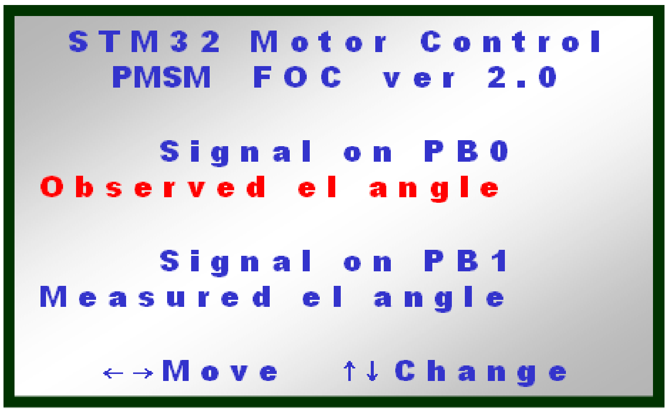
When the menu shown in *Figure 23* is displayed, the joystick can be moved to the right/left to navigate between the different gains. Pressing the joystick up/down will increment/decrement the gain highlighted in red color.

This menu is used to change both the observer and the PLL gains in real time. This feature is particularly useful when used in conjunction with the DAC functionality and with a firmware configuration handling either Hall effect sensors or an encoder. In this way, it is possible to modify the observer and PLL gains by looking for example at both the observed and measured rotor electrical angle and by adjusting the gains so as to cancel any error between the two waveforms.

3.6 DAC functionality

When enabled in the *stm32F10x_MCconf.h*, the DAC functionality is a powerful debug tool which allows the simultaneous tracing of up to two software variables selectable in real time using a dedicated menu.

Figure 24. LCD screen for setting the P term of the flux PID



STM32 Motor Control
PMSM FOC ver 2.0

Signal on PB0
Observed el angle

Signal on PB1
Measured el angle

←→Move ↑↓Change

When the menu shown in *Figure 24* is displayed, the joystick can be moved to the right/left to select the desired microcontroller pin. To change the software variable in output, move the joystick up/down (the list of the available variables depends on the selected firmware configuration). For all other menus, pressing the joystick or the Key button will cause the motor to start/stop.
It is also possible to add two user-defined variables to the default list, by placing the following code lines:

```
...
#include "stm32f10x_MClib.h"
...
MCDAC_Update_Value(USER_1,variable_name1);
MCDAC_Update_Value(USER_2,variable_name2);
...
```

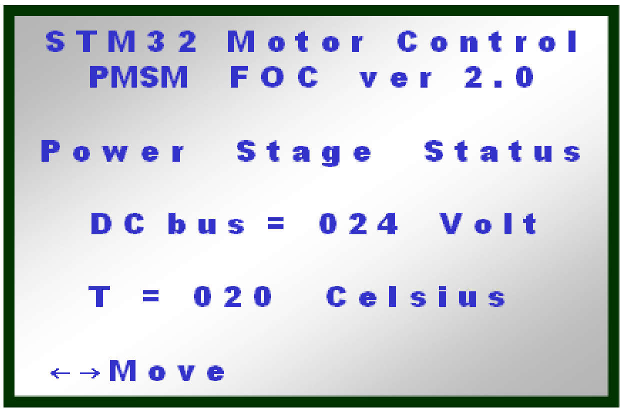
These variables are shown in output if “User 1” or “User 2” are selected on the display. Variable tracing is turned on if the demo program is in the START/RUN states. The variable update frequency is fixed by the sampling rate of the FOC algorithm (see *Section 4.2* for details).

The DAC functionality was implemented in the presented firmware library by using two out of the four TIM3 output compare channels (PB0 and PB1 pins) and by modulating the duty cycle of the generated 30 kHz PWM signal. In order to properly filter the generated signals without introducing important delays on the waveforms, it is suggested to use a proper first-order low-pass filter (e.g. with a 10 kΩ resistor and a 22 nF capacitor). Furthermore, if a High-density performance line (that is an STM32F103xC, STM32F103xD or STM32F103xE derivative) MCU is used, the user can exploit the built-in 2-channel, 12-bit D/A converter by suitably modifying the *stm32f10x_MCdac.c* file.

3.7 Power stage feedbacks

A dedicated menu was designed to show the value in volts of the DC bus voltage and the temperature of the STM3210B-MCKIT power board heat sink:

Figure 25. Power stage status



STM32 Motor Control
PMSM FOC ver 2.0

Power Stage Status

DC bus = 024 Volt

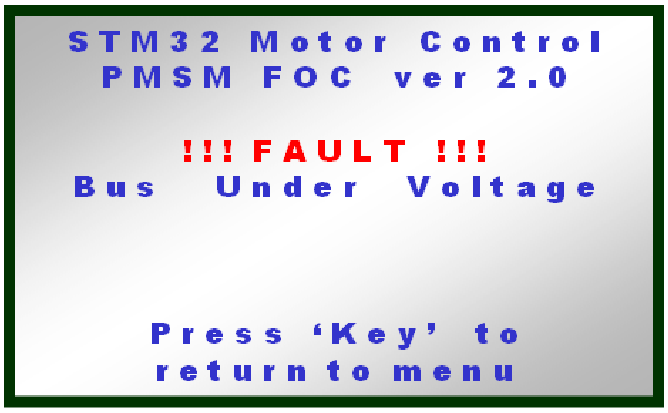
T = 020 Celsius

←→Move

3.8 Fault messages

This section provides a description of all the possible fault messages that can be detected when using the software library together with the STM3210B-MCKIT. *Figure 26* shows a typical error message as displayed on the LCD.

Figure 26. Error message shown in the event of an undervoltage fault



STM32 Motor Control
PMSM FOC ver 2.0

!!! FAULT !!!
Bus Under Voltage

Press 'Key' to
return to menu

The message "Press 'Key' to return to menu" is visible only if the source of the fault has disappeared. In this case, pressing the 'Key' button causes the main state machine to switch from the Fault to the Idle state.

There are six different fault sources when using the firmware library in conjunction with the STM3210B-MCKIT:

3.8.1 Overcurrent

A low level was detected on the PWM-peripheral-dedicated pin (BKIN). If the STM3210B-MCKIT is being used, this means that either the hardware overtemperature protection or the hardware overcurrent protection has been triggered. Refer to the STM3210B-MCKIT user manual for details.

3.8.2 Overheating

An overtemperature was detected on the dedicated analog channel. The intervention threshold (`NTC_THRESHOLD_C`) and the related hysteresis (`NTC_HYSTERESIS_C`) are specified in the *MC_Control_Param.h* header file. Refer to the STM3210B-MCKIT user manual for details.

3.8.3 Bus overvoltage

Available only if the `BRAKE_RESISTOR` definition is commented (default) in *stm32f10x_MCconf.h* configuration header file. It means that an overvoltage was detected on the dedicated analog channel. The intervention threshold (`OVERVOLTAGE_THRESHOLD_V`) is specified in the *MC_Control_Param.h* header file. Refer to STM3210B-MCKIT user manual for details.

Note: If the `BRAKE_RESISTOR` *definition is not commented in stm32f10x_MCconf.h, it is assumed that a resistor with a high power dissipation capability was connected in parallel to the bus capacitors through a switch. In this case the overvoltage does not generate a FAULT event because the resistor is supposedly able to dissipate the excess of voltage across the bus capacitors. For more detailed information on brake resistor management see also Section 3.14.*

3.8.4 Bus undervoltage

The bus voltage is below 20 V DC. This threshold is specified in the *MC_Control_Param.h* header file by the `UNDERVOLTAGE_THRESHOLD_V` parameter. Refer to STM3210B-MCKIT user manual for details.

3.8.5 Startup failed

Available only when `NO_SPEED_SENSORS` is not commended. It signals that no startup output condition was detected during motor ramp-up (`FREQ_START_UP_DURATION` in *MC_State_Observer_param.*h). See also *Section 4.5.2*.

3.8.6 Error on speed fdbck

An error on the speed / position feedback was noticed. Depending on the utilized kind of feedback this could mean that:

- if an encoder is being used, the measured speed was out of the allowed range ([`MINIMUM_MECHANICAL_SPEED_RPM`; `MAXIMUM_MECHANICAL_SPEED_RPM`]) for a consecutive number of times equal to or higher than `MAXIMUM_ERROR_NUMBER` (all these parameters can be found in *MC_encoder_param.h*). For instance, this could mean that the encoder connection was lost. See also *Section 4.3*.
- in case of a Hall sensors configuration, the timer utilized for interfacing with the three Hall effect sensors overflowed for `HALL_MAX_OVERFLOWS` (*MC_hall_param.h*) consecutive times, as mentioned in *Section 4.4* and explained in *Section 5.7*. This

usually indicates that information has been lost (Hall sensor timeout) or that speed is decreasing very sharply.

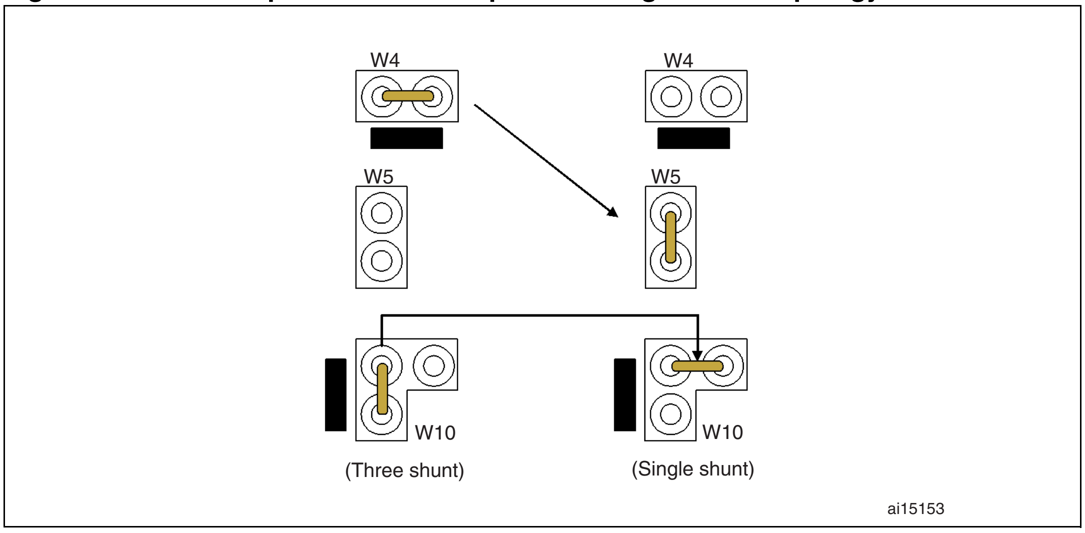
- in case of sensorless operation, the quality of the speed measurement expressed in terms of the distribution around the mean value is not good. This typically means that either the observer is not properly tuned or that the speed is so low that a good observation of the induced B-emf is not possible (e.g. rotor is locked). Refer also to *Section 4.5.3*.

3.9 Setting up the system when in single-shunt topology and using the MB459B power board

To set up the MB459B power board for the single-shunt topology, the only required operation is to move the wires present in the W4, W5 and W10 place holders as shown in *Figure 27*:

- W4 open
- W5 closed
- W10 between 1-2 (unlike in the silkscreen)

Figure 27. MB459B power board setup for the single-shunt topology



3.10 Setting up the system when using ICSs

The default configuration provides for the use of three shunt resistors and no speed sensor. This section gives you information about how to provide the STM32F103xx with ICS feedback signals and to properly customize the firmware.

Caution: When using two ICSs for stator current reading, you must ensure that the conditioned sensors output signal range is compatible with the STM32F103xx supply voltage.

In order for the implemented FOC algorithm to work properly, it is necessary to ensure that the software implementation of the `stm32f10x_svpwm_ics` module and the hardware connections of the two ICSs are consistent.

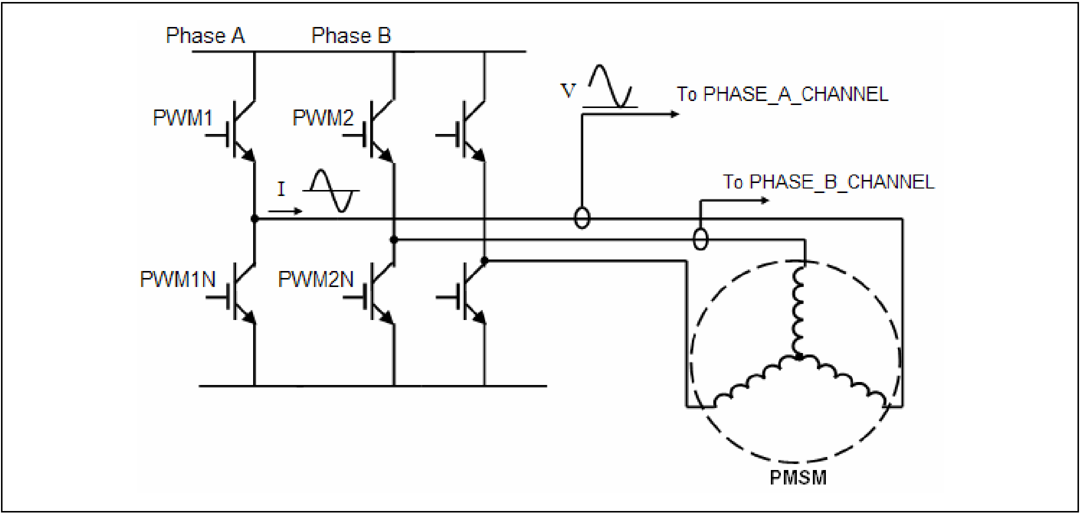
As illustrated in *Figure 28*, the two ICSs must act as transducers on motor phase currents coming out of the inverter legs driven by STM32F103xx PWM signals PWM1 (Phase A) and

PWM2 (Phase B). In particular, the current coming out of inverter Phase A must be read by an ICS whose output has to be sent to the analog channel specified by the PHASE_A_ADC_CHANNEL parameter in `MC_pwm_ics_prm.h`. Likewise, the current coming out of inverter Phase B must be read by the other ICS and its output has to be sent to the analog channel specified by the PHASE_B_ADC_CHANNEL parameter in `MC_pwm_ics_prm.h`.

About the positive current direction convention, a positive half-wave on PHASE_X_ADC_CHANNEL is expected, corresponding to a positive half-wave on the current coming out of the related inverter leg (see direction of I in *Figure 28*).

Note: Firmware support of ICS current measurement is enabled as explained in Section 4.1. Using ICS allows the MMI to be set to 100% (`#define MAX_MODULATION_100_PER_CENT`, see Section 4.2 and Section 5.5.3).

Figure 28. ICS hardware connections



3.10.1 Selecting PHASE_A_ADC_CHANNEL and PHASE_B_ADC_CHANNEL

Default settings for PHASE_A_ADC_ CHANNEL and PHASE_B_ADC_CHANNEL are respectively `ADC_CHANNEL11` and `ADC_CHANNEL12`. You can change the default settings if the hardware requires it by editing the “Current reading parameters” section of the `MC_pwm_ics_prm.h` file.

As an example, in order to convert Phase X (X =A, B) current feedback on ADC channel 0, the related parameters must be edited as shown below:

```
#define PHASE_X_ADC_CHANNEL      ADC_Channel_0

#define PHASE_X_GPIO_PORT           GPIOA

#define PHASE_X_GPIO_PIN              GPIO_Pin_0
```

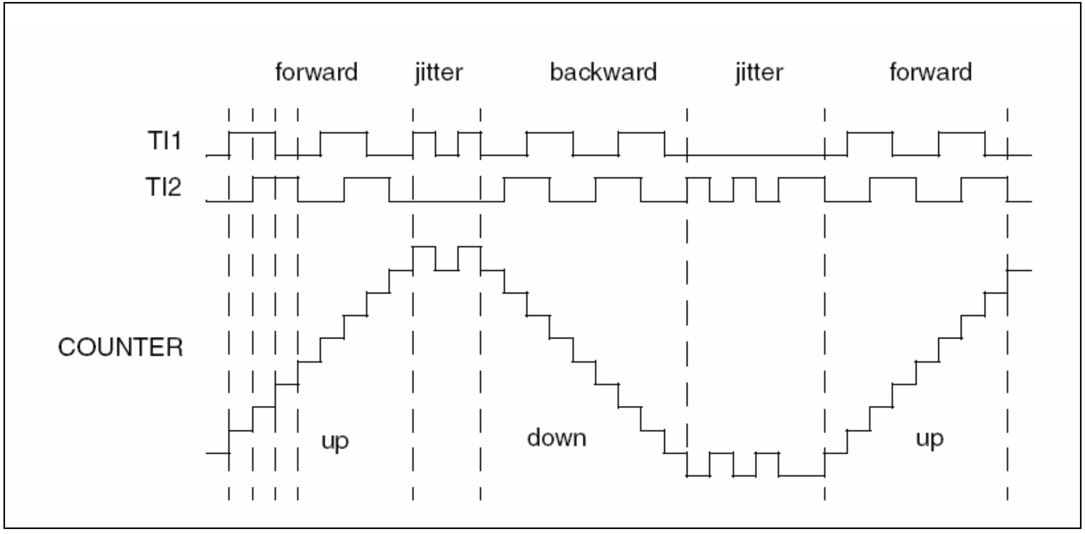
3.11 Setting up the system when using an encoder

Quadrature incremental encoders are widely used to read the rotor position of electric machines.

As the name implies, incremental encoders actually read angular displacements with respect to an initial position: if that position is known, then the rotor absolute angle is known too. For this reason it is always necessary, when processing the encoder feedback (ENCODER or VIEW_ENCODER_FEEDBACK definitions not commented in stm32f10x_MCconf.h), to perform a rotor prepositioning before the first startup after any fault event or microcontroller reset.

Quadrature encoders have two output signals (represented in *Figure 29* as TI1 and TI2). With these, and with the STM32F103xx standard timer in encoder interface mode, it is possible to get information about the rolling direction.

Figure 29. Encoder output signals: counter operation



In addition, the rotor angular velocity can be easily calculated as a time derivative of the angular position.

To set up the PMSM FOC software library for use with an incremental encoder, simply modify the `stm32f10x_MCconf.h` and `MC_encoder_param.h` header files according to the indications given in *Section 4.1* and *Section 4.3*, respectively.

However, some extra care should be taken, concerning what is considered to be the positive rolling direction: this software library assumes that the positive rolling direction is the rolling direction of a machine that is fed with a three-phase system of positive sequence.

Because of this, and because of how the encoder output signals are wired to the microcontroller input pins, it is possible to have a sign discrepancy between the real rolling direction and the direction that is read. To avoid this kind of reading error, apply the following procedure:

1. Turn the rotor by hand in the direction assumed to be positive and look at the B-emf induced on the three motor phases. For this purpose, a neutral point may need to be reconstructed with three resistors if the real one is not available.
2. Connect the motor phases to the hardware respecting the positive sequence (for instance when using the MB459 board, a positive sequence of the motor phases may be connected to J5 2,1 and 3).
3. Run the firmware in encoder configuration and turn by hand the rotor in the direction assumed to be positive. If the measured speed shown on the LCD is positive, the

connection is correct, otherwise, it can be corrected by simply swapping and rewiring the encoder output signals.

If this is not practical, a software setting may be modified instead: in the `stm32f10x_encoder.c` file, replace the code line 164:

```
TIM_ICPolarity_Rising, TIM_ICPolarity_Rising);
```

by

```
TIM_ICPolarity_Rising, TIM_ICPolarity_Falling);
```

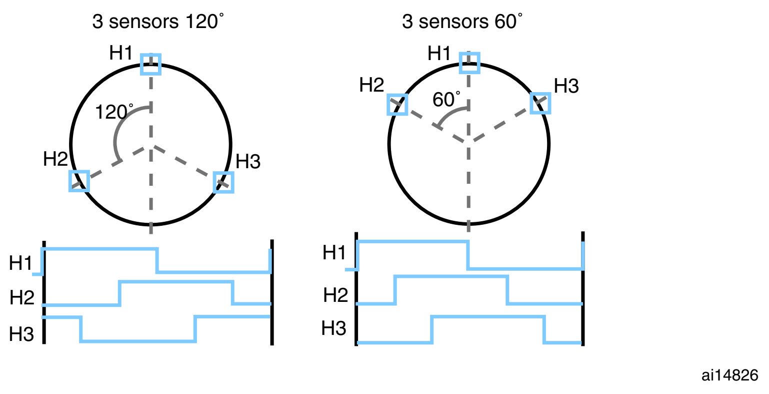
3.12 Setting up the system when using Hall-effect sensors

Hall-effect sensors are devices capable of sensing the polarity of the rotor’s magnetic field; they provide a logic output, which is 0 or 1 depending on the magnetic pole they face and thus, on the rotor position.

Typically, in a three-phase PM motor three Hall-effect sensors are used to feed back the rotor position information. They are usually mechanically displaced by either 120° or 60° and the presented firmware library was designed to support both possibilities. To set up the PMSM FOC software library for use with three Hall sensors, simply modify the *stm32f10x_MCconf.h* and *MC_hall_param.h* header files according to the indications given in *Section 4.1* and *Section 4.4*, respectively.

As shown in *Figure 30*, the typical waveforms can be visualized at the sensor outputs in case of 60° and 120° displaced Hall sensors. More particularly, *Figure 30* refers to an electrical period (i.e. one mechanical revolution in case of one pole pair motor).

Figure 30. 60° and 120° displaced Hall sensor output waveforms



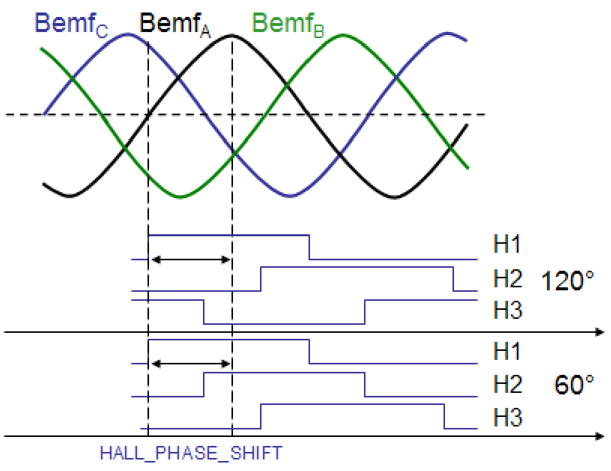
Since the rotor position information they provide is absolute, there is no need for any initial rotor prepositioning. Particular attention must be paid, however, when connecting the sensors to the proper microcontroller inputs.

In fact, as stated in *Section 3.11*, this software library assumes that the positive rolling direction is the rolling direction of a machine that is fed with a three-phase system of positive sequence. In that case to properly work, the software library expects the Hall sensor signal transitions to be in the sequence shown in *Figure 30* for both 60° and 120° displaced Hall sensors.

For these reasons, it is suggested to follow the instructions given below when connecting a Hall-sensor equipped PM motor to your board:

1. Turn the rotor by hand in the direction assumed to be positive and look at the B-emf induced on the three motor phases. For this purpose if the real neutral point is not available, it can be reconstructed by means of three resistors for instance.
2. Connect the motor phases to the hardware respecting the positive sequence. Let “Phase A”, “Phase B” and “Phase C” be the motor phases driven by TIM1_CH1, TIM1_CH2 and TIM1_CH3, respectively (e.g. when using the MB459 board, a positive sequence of the motor phases could be connected to J5 2,1 and 3).
3. Turn the rotor by hand in the direction assumed to be positive, look at the three Hall sensor outputs (H1, H2 and H3) and connect them to the selected timer on channels 1, 2 and 3, respectively, making sure that the sequence shown in *Figure 30* is respected.
4. Measure the delay in electrical degrees between the maximum of the B-emf induced on Phase A and the first rising edge of signal H1. Enter it in the *MC_hall_param.h* header file (`HALL_PHASE_SHIFT`). For your convenience, an example with `HALL_PHASE_SHIFT` equal to –90 °C is illustrated in *Figure 31*.

Figure 31. Determination of Hall electrical phase shift



3.13 Progressive sensorless system development

In order to simplify sensorless development, a process was defined when designing the presented firmware library. This process is a 4-step path that takes the user in a very short time to the final achievement of running the motor without either speed or position feedback sensors.

The defined process is based on the hypothesis that within the development stage of design, the user can count on speed / position rotor information coming from either the Hall sensors or the encoder. If not possible or not convenient in the application, it is anyway sufficient to mechanically couple the shaft of the motor to the one of the motor mounting sensors (e.g. the BLDC motor provided in the STM3210B-MCKIT). This feedback information is actually necessary mainly for the purpose of comparing the rotor position information observed by the sensorless algorithm to the real one. In this way, the sensorless algorithm can be fine tuned.

As mentioned above, the path consists of 4 steps listed and described below:

1. Run the motor in a pure sensor configuration:

   To this purpose, you should:

   – Tune the Iq and Id current loop regulator gains by following the instructions given in appendix A.4 and A.5

   – Comment `FLUX_TORQUE_PIDs_TUNING`, run the motor in speed control and tune the speed PI(D) gains. Derivative action can be enabled / disabled by uncommenting / commenting the `DIFFERENTIAL_TERM_ENABLED` line in *stm32f10x_MCconf.h*.

2. Run the motor in sensor mode and tune the observer gains

   The Clark and Parke transformation blocks and the speed regulator will utilize the rotor position and speed information read by the sensor. The sensorless algorithm will be run in parallel. To this purpose it is necessary to:

   – Precompute initial observer gains following the instructions provided in appendix A.6

   – Uncomment `OBSERVER_GAIN_TUNING` in *stm32f10x_MCconf.h*.

   – Fill in *MC_PMSM_motor_param.h* (see Section 4.6) and *MC_State_Observer_param.h* (startup section not required in this step, see Section 4.5)

   – Real-time tune observer gains by visually comparing (through DAC functionality) the observed and real I_α and I_β (error must be null) and by making sure that the observed B-emf waveforms are as clean and sinusoidal as possible. Real-time tuning of PLL gains should not be required but, in case, proportionally increase Kp and Ki to enlarge the PLL bandwidth (quickness to speed variation) and vice versa

   – Once the 4 gains have been found, write them in *MC_State_Observer_param.h*

3. Run the motor in sensorless mode processing the sensor feedback:

   The transformation blocks and the speed regulator will utilize the rotor position and speed information coming from the sensorless algorithm (“observed value”). The real (measured) information coming from the real sensors are processed for comparison with the observed ones.

   With this aim it is necessary to:

   – Uncomment `NO_SPEED_SENSORS` and a definition between `VIEW_HALL_FEEDBACK` and `VIEW_ENCODER_FEEDBACK` (depending on the sensor you are using)

   – Fill startup section of *MC_State_Observer_param.h* and relax at first statistic parameters if motor cannot start with different current and frequency startup parameters (“Error on speed fdbck” or “Start-up failed” faults)

Note: Be aware that due to the different speed resolution/accuracy, a different setup for speed PID could be necessary.

   – Tune startup parameters performing different ramp-up trials and, if required, further tune observer and PLL gains

4. Congratulations! The motor can now run in pure sensorless mode:

   Depending on the requirements of the used debug feature, on the expected code size and CPU load you could:

   – Comment `VIEW_HALL_FEEDBACK` or `VIEW_ENCODER_FEEDBACK` (depending on which was not commented) in *stm32f10x_MCconf.h*

   – Comment `OBSERVER_GAIN_TUNING` in *stm32f10x_MCconf.h*

   – Comment `DAC_FUNCTIONALITY` in *stm32f10x_MCconf.h*

3.14 Setting up the system when using a brake resistor

Due to its physical construction, a PM synchronous motor is able to transform kinetic energy into electrical energy just like a dynamo.

Under a limited number of conditions this property of PM synchronous motors has to be taken into consideration to avoid possible damage to the hardware system. For instance, a dangerous situation could arise when:

- The six inverter switches are opened and the motor is running at a speed higher than the nominal one. In this case, the amplitude of the line-to-line B-emf generated is higher than the nominal bus voltage
- The control tries to brake, an energy transfer from the load to the board occurs

Unless the used power system has regenerative capabilities, in both of these situations the inverter bulk capacitor is charged. Furthermore, depending on the rotor speed (with reference to the first situation) or on the amount of energy transferred (with reference to the second situation), the voltage across the bulk capacitors could increase to a destructive level.

A strategy for somehow dissipating the generated electrical energy is thus necessary. Different methods could be implemented to do so, but one of them in particular, the utilization of a brake resistor, is supported by the library presented in this user manual.

Caution: If the motor is operated beyond the rated speed, it is mandatory to use a regenerative power converter or a brake resistance to prevent bus overvoltage from damaging your board.

3.14.1 How to configure the FOC software library for brake resistor management

To enable the management of the brake resistor on the STM32F103xx PMSM FOC firmware library, simply uncomment the definition of `BRAKE_RESISTOR` in the *stm32f10x_MCconf.h* header file.

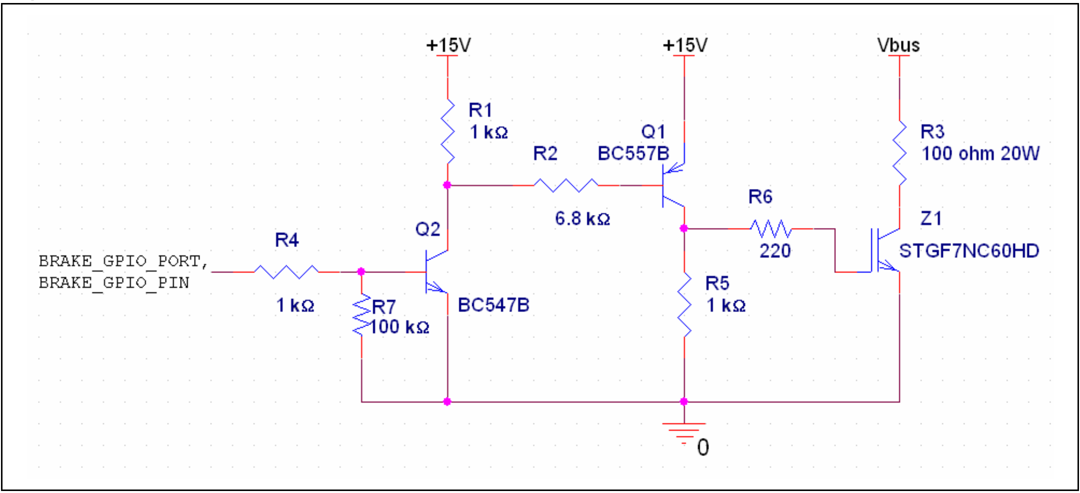
The analog watchdog feature of the STM32F103xx allows to generate an interrupt whenever the bus voltage goes above the `OVERVOLTAGE_THRESHOLD_V` parameter specified in *MC_Control_Param.h* and as a consequence, the `BRAKE_GPIO_PIN` pin of the `BRAKE_GPIO_PORT` port is set to high level (both definitions are in *MC_MotorControl_Layer.c*, default values are GPIOD and GPIO_Pin_13 for compatibility with STM3210B-MCKIT). From then on, a hysteresis control of the bus voltage is performed. Hysteresis can be entered by editing the `BRAKE_HYSTERESIS` parameter in *stm32f10x_it.c.*

3.14.2 How to modify the MB459 board for brake resistor management

In order to make the MB459 board suitable for the management of a brake resistor, it is necessary to solder some additional components on its wrapping area.

Figure 32 gives an example of the circuit to be used for the hardware implementation of the brake.

Figure 32. Brake resistor circuit



Note that the size of the resistor in terms of both resistance and sustainable power should be carefully dimensioned.

When using the PMSM FOC library in conjunction with the STM3210B-MCKIT, note that the pin 23 of the MC connector (J7) that carries the signal for brake implementation is positioned close to the wrapping area.

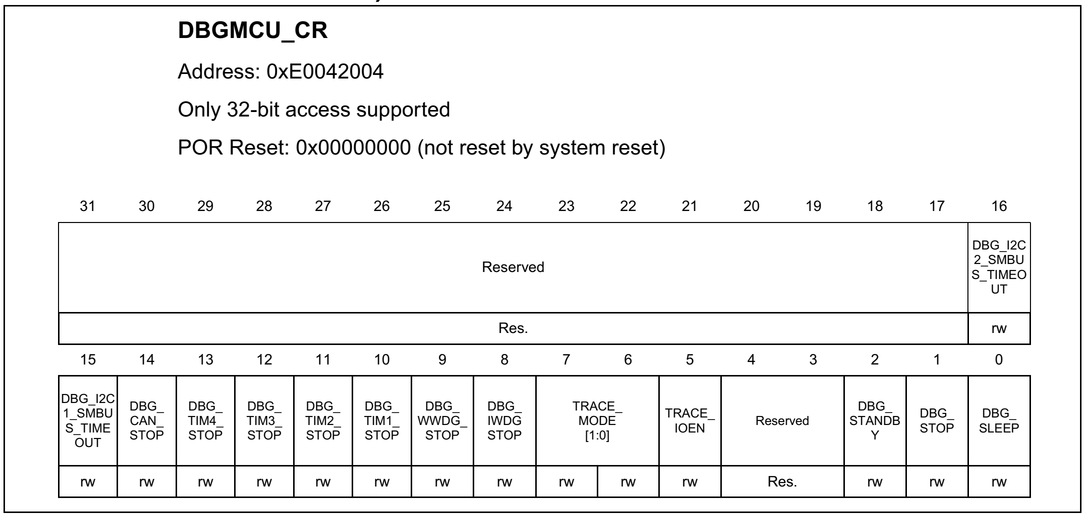
3.15 Note on debugging tools

The third party JTAG interface should always be isolated from the application using the MB535 JTAG opto-isolation board; it provides protection for both the JTAG interface and the PC connected to it.

Caution: During a breakpoint, when using the JTAG interface for the firmware development, the motor control cell clock circuitry should always be disabled; if enabled, a permanent DC current may flow in the motor because the PWM outputs are enabled, which could cause permanent damage to the power stage and/or motor. A dedicated bit in the DBGMCU_SR register, the DBG_TIM1_STOP bit, must be set to 1 (see *Figure 33*).
If the DBG_TIM1_STOP bit is set (Safe mode), the timer is frozen and PWM outputs are shut down. This is a Safe state for the inverter. The timer can still be restarted from where it stopped.
If the DBG_TIM1_STOP bit is reset (Normal mode), the timer continues to operate normally, which may prove dangerous in some cases since a constant duty cycle is applied to the inverter (interrupts not serviced).

In the `main.c` module the `DBGMCU_Config(DBGMCU_TIM1_STOP, ENABLE)` function performs the above described task.

Figure 33. DBG_TIM1_STOP bit in TIM1 control register (extract from STM32 reference manual)



DBGMCU_CR

Address: 0xE0042004

Only 32-bit access supported

POR Reset: 0x00000000 (not reset by system reset)

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved															DBG_I2C2_SMBUS_TIMEOUT
Res.															rw

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
DBG_I2C1_SMBUS_TIMEOUT	DBG_CAN_STOP	DBG_TIM4_STOP	DBG_TIM3_STOP	DBG_TIM2_STOP	DBG_TIM1_STOP	DBG_WWDG_STOP	DBG_IWDG STOP	TRACE_MODE [1:0]		TRACE_IOEN	Reserved		DBG_STANDBY	DBG_STOP	DBG_SLEEP
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	Res.		rw	rw	rw

4 Getting started with the library

It is quite easy to set up an operational evaluation platform with a drive system that includes the STM3210B-MCKIT (featuring the STM32F103xx microcontroller, where this software runs) and a permanent-magnet motor.

This section explains how to quickly configure your system and, if necessary, customize the library accordingly.

Follow these steps to accomplish this task:

1. Gather all the information that is needed regarding the hardware in use (motor parameters, power devices features, speed/position sensor parameters, current sensors transconductance);
2. Edit, using an IDE, the `stm32f10x_MCconf.h` configuration header file (as explained in more detail in *Section 4.1*), and the following parameter header files,
   - `MC_Control_Param.h` (see *Section 4.2*),
   - `MC_encoder_param.h` (see *Section 4.3*) or `MC_hall_prm.h` (see *Section 4.4*),
   - `MC_State_Observer_param.h` (see *Section 4.5*)
   - `MC_PMSM_motor_param.h` (see *Section 4.6*);
3. Re-build the project and download it on the STM32F103xx microcontroller.

Please be aware that this procedure should also be followed when the final target is a sensorless drive. In fact, receiving speed/position information from any kind of sensor makes it possible to achieve a more precise customization, and to tune the algorithm utilized for sensorless rotor position reconstruction.

4.1 Library configuration file: `stm32f10x_MCconf.h`

The purpose of this file is to declare the compiler conditional compilation keys that are used throughout the entire library compilation process to:

- Select which current measurement technique is actually in use (the choice is between single-shunt, three-shunt or ICS sensors, according to availability)
- Select which speed/position sensor is actually used (here the choice is between Hall sensors, quadrature incremental encoder or no speed sensors, depending on the requirements). When in sensorless mode, it is also possible to set up the driver to perform a rotor alignment before every motor startup
- Enable or disable the optimized drive for internal permanent magnet motors (IPMSMs)
- Enable or disable the flux-weakening functionality used to achieve motor speeds higher than rated
- Enable or disable the feed-forward current regulation functionality
- Enable or disable the derivative action in the PID controllers in accordance with expected performance and code size.
- Enable or disable the brake resistor management depending on requirements on brake performance and on maximum speed
- Enable or disable a virtual 2-channel DAC for real-time tracing of the most important software variables. For the best debug support, user should keep this feature enabled

- Enable or disable the execution of a specific software dedicated to the tuning of current PIDs
- Enable or disable the tuning of the State Observer and PLL gains
- In case of "no speed sensor" it is still possible to acquire signals coming from Hall sensors or encoder and evaluate whether the sensorless algorithm is working properly, using the DAC functionality. Those signal will not be used in the FOC algorithm; the choice here is between Hall sensors, quadrature incremental encoder or none.

If this header file is not edited appropriately (no choice or undefined choice), you will receive an error message when building the project. Note that you will not receive an error message if the configuration described in this header file does not match the hardware that is actually in use, or in case of wrong wiring.

More specifically:

- `#define ICS_SENSORS`

  To be uncommented when current sampling is done using isolated current sensors.
- `#define THREE_SHUNT`

  To be uncommented when current sampling is performed via three shunt resistors (default).
- `#define SINGLE_SHUNT`

  To be uncommented when current sampling is performed via a single shunt resistor (it is also required to set up the MB459B power board as described in *Section 3.9: Setting up the system when in single-shunt topology and using the MB459B power board on page 34*)
- `#define ENCODER`

  To be uncommented when an incremental encoder is connected to the starter kit for position sensing; in parallel, fill out MC_encoder_param.h (as explained in *Section 4.3*)
- `#define HALL_SENSORS`

  To be uncommented when three Hall sensors (60° or 120° displaced) are in use to detect rotor speed; in parallel, fill out MC_hall_prm.h (as explained in *Section 4.4*)
- `#define NO_SPEED_SENSORS`

  To be uncommented to use the rotor position information inside the FOC algorithm (rotor position information is provided by a state observer) (default). In this case, the user should fill MC_State_Observer_param.h and MC_PMSM_motor_param.h in parallel (as explained in *Section 4.5* and *Section 4.6*, respectively)
- `#define VIEW_HALL_FEEDBACK`

  To be uncommented only in conjunction with `NO_SPEED_SENSORS`. It is used to process the information that comes from three Hall sensors, to be displayed through the DAC functionality (and compared with the information coming from the sensorless rotor position reconstruction algorithm)
- `#define VIEW_ENCODER_FEEDBACK`

  To be uncommented only in conjunction with `NO_SPEED_SENSORS`. It is used to process the information coming from an incremental encoder, to be displayed through the DAC functionality (and compared with the information coming from the sensorless rotor position reconstruction algorithm) (default)

- `#define NO_SPEED_SENSORS_ALIGNMENT`

  To be uncommented only in conjunction with `NO_SPEED_SENSORS`. It sets up the driver to perform a rotor alignment before every motor startup. In this case, the user also has to fill a section of *MC_State_Observer_param.h* (as explained in *Section 4.5*)
- `#define IPMSM_MTPA`

  To be uncommented to take advantage of the optimized MTPA (maximum torque per ampere) drive designed for internal permanent magnet synchronous motors (IPMSMs). In this case, the user also has to fill a section of *MC_PMSM_Motor_param.h* (see *Section 2.1.4* and *Section 4.6*). Leaving this `#define` commented (default) implies that the demo program optimizes vector control as needed by a PMSM (as explained in *Section 2.1.3*)
- `#define FLUX_WEAKENING`

  To be uncommented if the user's application requires to operate the motor beyond its nominal speed (default). In parallel, fill *MC_PMSM_Motor_param.h* (as explained in *Section 4.6*); see *Section 3.13* about the precautions to be taken when using the flux-weakening feature
- `#define FEED_FORWARD_CURRENT_REGULATION`

  To be uncommented in order to back up the standard PID current regulation with a feed-forward calculation. In parallel, the user should fill the corresponding section in *MC_PMSM_Motor_param.h* (as explained in *Section 4.6*)
- `#define BRAKE_RESISTOR`

  To be uncommented to enable the software management of a resistive brake (refer to *Section 3.14.2* for more information about the hardware modifications to be applied to the MB459 board)

Caution: In order to avoid any damage to the power stage, it is mandatory to utilize the brake resistor feature for operation above the nominal speed.

- `#define DIFFERENTIAL_TERM_ENABLED`

  To be uncommented to enable the differential term in the PID regulator function in the MC_PID_regulators library module (see *Section 5.9*)
- `#define FLUX_TORQUE_PIDs_TUNING`

  To be uncommented when a rotor position sensor is utilized. It generates a software dedicated to torque and flux PID gain tuning. Fill `MC_Control_Param.h` in parallel
- `#define OBSERVER_GAIN_TUNING`

  If uncommented, it enables the visualization on LCD of a menu dedicated to state observer and PLL gain tuning
- `#define DAC_FUNCTIONALITY`

  To be uncommented to enable the DAC functionality. Refer to *Section 3.6* for more detailed information about this feature.

Once these settings have been done, only the required blocks will be linked in the project; this means that you do not need to exclude .c files from the build.

Caution: When using shunt resistors for current measurement, ensure that the `REP_RATE` parameter (in `MC_Control_Param.h`) is set properly (see *Section 4.2* and *Section A.2: Selecting the update repetition rate based on the PWM frequency for single- or three-shunt resistor configuration on page 136* for details).

4.2 Drive control parameters: `MC_Control_Param.h`

The `MC_Control_Param.h` header file gathers parameters related to:

- *Power device parameters on page 46*
- *Current regulation parameters on page 46*
- *Power board protection thresholds on page 46*
- *Speed loop sampling time on page 47*
- *Speed PID-controller init values on page 48*
- *Quadrature current PID-controller init values on page 49*
- *Linear variation of PID constants according to mechanical speed. on page 49*

Power device parameters

- `#define PWM_FREQ`

  Define here, in Hz, the switching frequency; in parallel, uncomment the maximum allowed modulation index definition (`MAX_MODULATION_XX_PER_CENT`) corresponding to the PWM frequency selection.

  Note that if ICSs are used, the 100% modulation index is allowed regardless of the selected PWM frequency.
- `#define DEADTIME_NS`

  Define here, in ns, the dead time, in order to avoid shoot-through conditions.

Current regulation parameters

- `#define REP_RATE`

  Stator currents sampling frequency and consequently flux and torque PID regulators sampling rate, are defined according to the following equation:

$$\text{Flux and torque PID sampling rate} = \frac{2 \cdot \text{PWM\_FREQ}}{\text{REP\_RATE} + 1}$$

In fact, because there is no reason for either executing the FOC algorithm without updating the stator currents values or for performing stator current conversions without running the FOC algorithm, in the proposed implementation the stator current sampling frequency and the FOC algorithm execution rate coincide.

Note: REP_RATE must be an odd number if currents are measured by shunt resistors (see Section A.2: Selecting the update repetition rate based on the PWM frequency for single- or three-shunt resistor configuration on page 136 for details); its value is 8-bit long;

Power board protection thresholds

- `#define NTC_THRESHOLD_C`
- `#define NTC_HYSTERIS_C`

  These two values (expressed in °C) are used to set the operating temperature range of the power devices (measured at heat sink) when the software library is used with the MB459 board. In particular, if the measured temperature exceeds `NTC_THRESHOLD_C`, a fault event is generated that is kept as long as the measured temperature remains below `NTC_THRESHOLD_C - NTC_HYSTERESIS_C`.

- `#define  OVERVOLTAGE_THRESHOLD_V`
- `#define  UNDERVOLTAGE_THRESHOLD_V`

  These two values (expressed in volt) set the minimum and maximum acceptable bus DC voltage when the software library is utilized with the MB459 board. If the bus voltage exceeds `OVERVOLTAGE_THRESHOLD_V` or is below `UNDERVOLTAGE_THRESHOLD_V`, a fault event is generated that is kept as long as the bus voltage remains outside the allowed range.
- `#define BUS_ADC_CONV_RATIO`

  Defines the ratio between the ADC input voltage and the corresponding DC bus voltage.

Speed loop sampling time

```
#define PID_SPEED_SAMPLING_TIME
```

The speed regulation loop frequency is selected by assigning one of the defines below:

```
#define PID_SPEED_SAMPLING_500µs  0   //min 500µs
#define PID_SPEED_SAMPLING_1ms    1
#define PID_SPEED_SAMPLING_2ms    3   //(4-1)*500µs=2ms
#define PID_SPEED_SAMPLING_5ms  9
#define PID_SPEED_SAMPLING_10ms   19
#define PID_SPEED_SAMPLING_20ms 39
#define PID_SPEED_SAMPLING_127ms  255 //max(255-1)*500µs=127ms
```

Note: Please note that the speed regulation loop frequency in the demo program also coincides with the control frequency of the flux-weakening and feed-forward functionalities (if they are enabled).

Speed PID-controller init values

- `#define PID_SPEED_REFERENCE_RPM`
  Define here, in rpm, the mechanical rotor speed setpoint at startup in closed loop mode;
- `#define PID_SPEED_KP_DEFAULT`
  The proportional constant of the speed loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_SPEED_KI_DEFAULT`
  The integral constant of the speed loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_SPEED_KD_DEFAULT`
  The derivative constant of the speed loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define SP_KPDIV`
  The scaling factor of the proportional gain for the speed regulation loop (unsigned 16-bit power-of-two value);
- `#define SP_KIDIV`
  The scaling factor of the integral gain for the speed regulation loop (unsigned 16-bit power-of-two value);
- `#define SP_KDDIV`
  The scaling factor of the differential gain for the speed regulation loop (unsigned 16-bit power-of-two value)

Quadrature current PID-controller init values

See Appendix *A.4*, which illustrates the method to be followed for computing initial PI constants, starting from motor parameters and required control bandwidth.

- `#define PID_TORQUE_REFERENCE`
  The torque (Iq) reference value, in torque control mode, at startup (signed 16-bit value);
- `#define PID_TORQUE_KP_DEFAULT`
  The proportional constant of the torque loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_TORQUE_KI_DEFAULT`
  The integral constant of the torque loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_TORQUE_KD_DEFAULT`
  The derivative constant of the torque loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_FLUX_REFERENCE`
  The flux (I_d) reference value, in torque control mode, at startup (signed 16-bit value); default value is 0;
- `#define PID_FLUX_KP_DEFAULT`
  The proportional constant of the flux loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_FLUX_KI_DEFAULT`
  The integral constant of the flux loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define PID_FLUX_KD_DEFAULT`
  The derivative constant of the flux loop regulation (signed 16-bit value, adjustable from 0 to 32767);
- `#define SQUARE_WAVE_PERIOD`
  The period (in ms) of the square wave reference torque generated when `FLUX_TORQUE_PIDs_TUNING` is uncommented in `stm32f10x_MCconf.h`
- `#define TF_KPDIV`
  The scaling factor of the proportional gains used in the current regulation loops (unsigned 16-bit power-of-two value). This scaling divider corresponds to the KpDIV parameter in Appendix *A.4*;
- `#define TF_KIDIV`
  The scaling factor of the integral gains used in the current regulation loops (unsigned 16-bit power-of-two value). This scaling divider corresponds to the KiDIV parameter in Appendix *A.4*;
- `#define TF_KDDIV`
  The scaling factor of the differential gains used in the current regulation loops (unsigned 16-bit power-of-two value).

Linear variation of PID constants according to mechanical speed.

Refer to *Section 5.9.4: Adjusting speed regulation loop Ki, Kp and Kd vs. motor frequency on page 123*.

4.3 Incremental encoder parameters: `MC_encoder_param.h`

The `MC_encoder_parameter.h` header file is to be filled if position/speed sensing is performed by means of a quadrature, square wave, relative rotary encoder (`ENCODER` or `VIEW_ENCODER_FEEDBACK` defined in `stm32f10x_MCconf.h`).

- `#define TIMER2_HANDLES_ENCODER`

  To be uncommented if the two sensor output signals are wired to TIMER2 input pins (default; required when using STM3210B-MCKIT);
- #define TIMER3_HANDLES_ENCODER

  To be uncommented if the two sensor output signals are wired to TIMER3 input pins;
- #define TIMER4_HANDLES_ENCODER

  To be uncommented if the two sensor output signals are wired to TIMER4 input pins.
- #define ENCODER_PPR

  Defines the number of pulses generated by a single channel, for one shaft revolution (actual resolution will be 4x);
- #define MINIMUM_MECHANICAL_SPEED_RPM

  Defines in rpm, the minimum speed below which the speed measurement is either not realistic or not safe in the application; an error counter is increased every time the measured speed is below the specified value. In order to disable this check and control the motor down to zero speed, the user can set this parameter to zero: a warning message "pointless comparison of unsigned integer with zero" will be issued at compilation time.
- #define MAXIMUM_MECHANICAL_SPEED_RPM

  Defines in rpm, the maximum speed above which the speed measurement is either not realistic or not safe in the application; an error counter is increased every time the measured speed is above the specified value.
- #define MAXIMUM_ERROR_NUMBER

  Defines the number of consecutive errors on speed measurements to be detected before a fault event is generated (check rate is specified by `SPEED_MEAS_TIMEBASE` in `stm32f10x_Timebase.c`).
- #define SPEED_BUFFER_SIZE

  Defines the buffer size utilized for averaging speed measurement. Power of two is desirable for ease the computation.

Alignment settings:

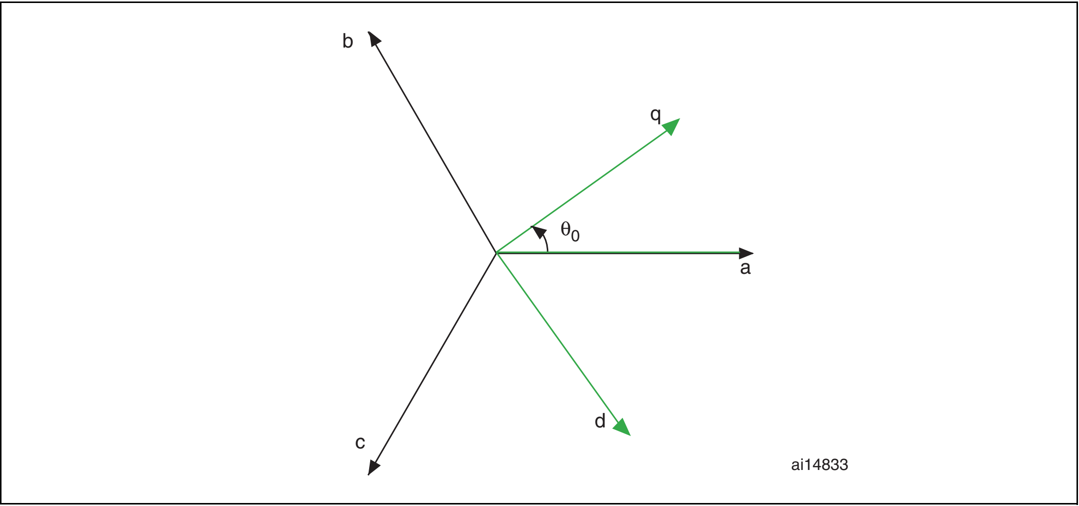
Quadrature encoder is a relative position sensor. Considering that absolute information is required for performing field oriented control, it is necessary to somehow establish a 0° position. This task is performed by means of an alignment phase, and is carried out at first motor startup and after any fault event. It basically consists in imposing a null reference torque (Iq) and a reference flux (Id) with a linearly increasing magnitude and a constant orientation.

If properly configured, at the end of this phase, the rotor is locked in a well-known position and the encoder timer counter is initialized accordingly.

The following parameters are used to customize the alignment phase depending on the motor inertia and load conditions:

- `T_ALIGNMENT` in milliseconds defines the desired duration of the alignment phase
- `ALIGNMENT_ANGLE` specifies the vector orientation (angle θ in the below diagram)

Figure 34. Alignment angle



- `I_ALIGNMENT` (in digits) defines the final value of the reference Id magnitude. With STM3210B-MCKIT and with `ALIGNMENT_ANGLE` set to 90° (default), the final phase A current value can be computed by using the formula:

  Alignment final phase A current = (`I_ALIGNMENT` * 0.64)/(32767*R_{shunt})

4.4 Hall sensor parameters: `MC_hall_prm.h`

The `MC_hall_prm.h` header file is to be filled if a position/speed sensing is performed by means of three Hall sensors (`HALL_SENSORS` or `VIEW_HALL_FEEDBACK` defined in `stm32f10x_MCconf.h`).

- `#define TIMER2_HANDLES_HALL`

  To be uncommented if the three sensor output signals are wired to TIMER2 input pins (default; required if using STM3210B-MCKIT);
- `#define TIMER3_HANDLES_HALL`

  To be uncommented if the three sensor output signals are wired to TIMER3 input pins;
- `#define TIMER4_HANDLES_HALL`

  To be uncommented if the three sensor output signals are wired to TIMER4 input pins.
- `#define HALL_SENSORS_PLACEMENT`

  Defines the electrical displacement between the Hall sensors expressed in degrees (physical displacement × number of pole pairs). The choice is between 120 (`DEGREES_120`) and 60 degrees (`DEGREES_60`).
- `#define HALL_PHASE_SHIFT`

  Defines the electrical phase shift (degrees) between the 0° angle, with the convention utilized in the firmware, and the first rising edge on TIMx_CH1 (H1 signal with STM3210B-MCKIT).

  Refer to *Section 3.12* for a detailed explanation on how to determine this parameter.
- `#define HALL_MAX_SPEED_FDBK_RPM`

  Defines the rotor mechanical frequency (rpm) above which speed feedback is not realistic in the application: used to discriminate glitches for instance.
- `#define HALL_MAX_SPEED`

  This parameter is the value returned by the `HALL_GetSpeed` function (0.1 Hz unit) if measured speed is greater than `HALL_MAX_SPEED_FDBK_RPM`. The default value is 500 Hz, but it can be 0 or FFFF depending on how this value is managed by the upper layer software.
- `#define HALL_MAX_PSEUDO_SPEED`

  This parameter is the value returned by the `HALL_GetRotorFreq` function if measured speed is greater than `MAX_SPEED_FDBK`. The unit is ddp. See Appendix *A.7* for more details about how to convert Hertz into pseudofrequency.
- `#define HALL_MIN_SPEED_FDBK_RPM`

  Defines the rotor mechanical frequency below which speed feedback is not realistic in the application.
- `#define HALL_MAX_RATIO`
  - It defines the lowest speed that can be measured (when counter = 0xFFFF)
  - It also prevents the clock prescaler from decreasing excessively when the motor is stopped. (This prescaler is automatically adjusted during each capture interrupt to optimize the timing resolution.)

- `#define HALL_MAX_OVERFLOWS`

  This is the maximum number of consecutive timer overflows taken into account. It is set by default to 2: if the timer overflows more than twice (meaning that the Hall sensor period has been increased by a factor of at least two between two consecutive valid edges), the number of overflows is not counted anymore. This usually indicates that information has been lost (Hall sensor timeout) or that speed is decreasing very sharply. The corresponding timeout delay depends on the selected timer prescaler, which is variable; the higher the prescaler (low speed), the longer the timeout period (see also *Section 5.7*)
- `#define HALL_SPEED_FIFO_SIZE`

  This is the length of the software FIFO in which the latest speed measurements are stored. This stack is necessary to compute rolling averages on several consecutive pieces of data.

4.5 State observer parameters: `MC_State_Observer_param.h`

The `MC_State_Observer_param.h` is to be filled if the user wants to take advantage of or evaluate the implemented sensorless algorithm for rotor position / speed detection. In that case, the `MC_PMSM_motor_param.h` header file also has to be configured accordingly (see *Section 4.6*).

See also *Section 3.13*, which guides you progressively through the steps that make a sensorless system up and running.

The gathered parameters are related to the:
- state observer
- startup
- measurement statistics and reliability

4.5.1 State observer parameters

- `#define MAX_CURRENT`

  In Amperes, defines the current value equivalent to an ADC conversion equal to 32767 (signed 16 bits max). If the current is measured by using shunt resistors then:

  $$\text{MAX\_CURRENT} = \frac{3.3}{2 \cdot R_{shunt} \cdot A_V}, \text{ where:}$$

  – A_V is the gain of the amplifying network ($A_V = 2.57$ on the MB459B kit board)

  – R_{shunt} is the shunt resistance (in Ohms)
- `#define K1`

  K1 (signed 32-bit value) is an element of the gain vector of the implemented state observer (as described in *Section 2.2*). An “a priori” determination of K1 can be made using the formulas given in *Section A.5*. When the motor is running, this initial value can then be tuned using the LCD interface and evaluating the results. In that case, the value of K1 read on the display is 10 times smaller.
- `#define K2`

  K2 (signed 32-bit value) is an element of the gain vector of the implemented state observer (as described in *Section 2.2*). An “a priori” determination of K2 can be made using the formulas given in *Section A.5*. When the motor is running, this initial value can then be tuned using the LCD interface and evaluating the results. In that case, the value of K2 read on the display is 100 times smaller.

- `#define PLL_KP_GAIN`

  The default formula provides an "a priori" determination of the phase detector gain of the PLL. Nonetheless, this (signed 16-bit) value can be tuned when the motor is running, by using the LCD interface and evaluating the results. If necessary, the default value can be overwritten with a more suitable one.
- `#define PLL_KI_GAIN`

  The default formula provides an "a priori" determination of the loop filter gain of the PLL. Nonetheless, this (signed 16-bit) value can be tuned when the motor is running by using the LCD interface and evaluating the results. If necessary, the default value can be overwritten with a more suitable one.
- `#define F1, #define F2`

  These coefficients (signed 16-bit values) help amplify the observer equations, so that motor winding resistance and inductance can give a valuable contribution.

  Maximum value is 2^{15} = 32768

Note: Depending on several system parameters (motor parameters, state observer parameters, sampling frequency, current and voltage conversion parameters), compilation errors [Pe068] or/and [Pe069] may occur in the `MC_State_Observer_Interface.c` source file. In that case, the user should follow the procedure below to solve the problem:

1. *Jump to the code line where the error was reported and see which Cx factor (x=1..5) caused the issue.*
2. *Go to the definition of that Cx factor (in `MC_State_Observer_param.h`) and assess whether F1 or F2 is involved.*
3. *Decrease F1 or F2 accordingly, always choosing positive powers of two.*

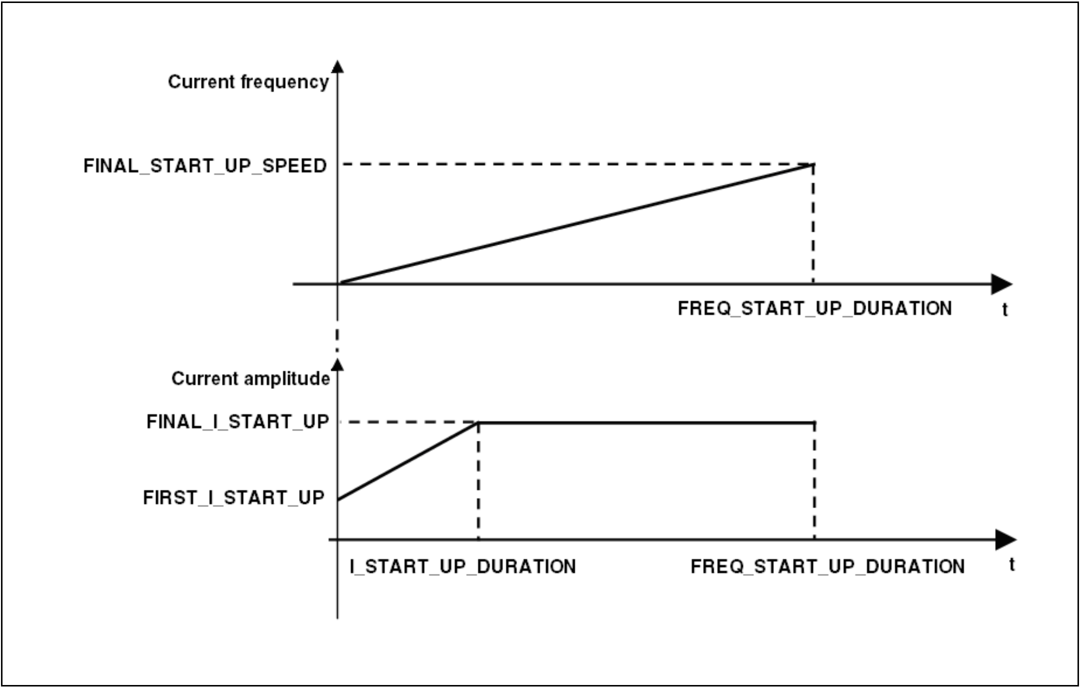
4.5.2 Startup parameters

Rotor position reconstruction is based on the observation of the back-emfs generated when the rotor is running. Therefore, a startup procedure has been implemented in order to spin the motor when starting from standstill: a rotating stator flux is generated by a three-phase symmetrical current, thus causing the rotor to follow.

The startup procedure has assumedly ended successfully when the observation of the back-emfs becomes reliable, according to the parameters explained in Section 4.5.3 (and the main state machine switches from Start to Run) otherwise a timeout occurs (in that case the main state machine switches from Start to Fault).

The parameters described in this section are used to adapt the startup to the application by customizing the amplitude and frequency profiles (see Figure 35) of the three-phase current system.

Figure 35. Startup current system frequency and amplitude profile



- `#define FREQ_START_UP_DURATION`
  In milliseconds, defines the overall time allowed for startup.
- `#define FINAL_START_UP_SPEED`
  In RPM, defines the speed of the rotating stator flux, and hence of the rotor, at the end of the overall time allowed for startup (this parameter sets the slope of the frequency linear ramp-up).
- `#define FIRST_I_STARTUP`
  In digits, defines the initial amplitude of the three-phase current system according to the formula below:

$$I(digit) = \frac{I(Amps) \cdot R_{shunt} \cdot A_v \cdot 65536}{3.3}$$

- `#define FINAL_I_STARTUP`
  In digits, defines the final amplitude of the three-phase current system according to the above formula. This amplitude should be chosen to generate an electromagnetic torque T_e that matches the estimated load applied.
- `#define I_STARTUP_DURATION`
  In milliseconds, defines the time allowed to increase current amplitude linearly from initial to final amplitude.
- `#define MINIMUM_SPEED_RPM`
  In RPM, defines the minimum speed at which the startup procedure may end (if the rotor speed / position detection is considered reliable) to make way for normal operations.
  Depending on the user's application requirements, a rotor alignment or pre-positioning

phase can be performed before each motor startup. This additional feature is activated as an option by properly configuring *stm32f10x_MCconf.h* (see *Section 4.1*).

In this case, the following parameters should be selected to achieve the expected behavior:

– `#define SLESS_T_ALIGNMENT`

  In milliseconds, defines the desired duration of the alignment phase.

– `#define SLESS_ALIGNMENT_ANGLE`

  specifies the vector orientation (angle θ in *Figure 34*)

– `#define SLESS_I_ALIGNMENT`

  Defines (in digits) the final value of the reference I_d magnitude. With STM3210B-MCKIT and with `SLESS_ALIGNMENT_ANGLE` set to 90° (default), the final phase A current value can be computed by using the formula:

Alignment final phase A current = (`SLESS_I_ALIGNMENT` × 0.64)/(32767 × R_{shunt})

4.5.3 Statistics parameters

State observer output results are continuously monitored to statistically assess the reliability of the rotor speed / position information supplied. Since this technique is used as a fault detection system, the parameters described in this section are used to set the desired safety level.

- `#define VARIANCE_THRESHOLD`

  This parameter sets the threshold for the speed measurement variance. The sensorless algorithm calculation is not considered reliable if the variance of the observed speed is greater than the desired percentage of the mean value, according to the formula: $\sigma^2 \geq \mu^2 \cdot$ `VARIANCE_THRESHOLD`, where σ and μ are the variance and the mean value of the observed speed, respectively (for instance, a `VARIANCE_THRESHOLD` of 0.0625 leads to a percentage of the mean value equal to 25%).

  The lower the `VARIANCE_THRESHOLD` parameter, the more strict (and hence the higher the safety level) of this fault detection algorithm, and vice versa.

- `#define RELIABILITY_HYSTERESIS`

  This (unsigned 8-bit) parameter defines the number of consecutive times the speed measurement variance should be found higher than the `VARIANCE_THRESHOLD` threshold before the rotor speed / position detection algorithm is declared nonreliable.

  In this case, the main state machine switches from Run to Fault (see *Section 3.8* about the fault messages and *Section 5.8* about the functions that implement this method).

- `#define NB_CONSECUTIVE_TESTS`

  Defines the number of consecutive times the speed measurement variance should be found lower than the `VARIANCE_THRESHOLD` threshold before the startup procedure is declared to have successfully completed. In this case, the main state machine switches from Start to Run (see *Section 3.8* about the fault messages).

4.6 Permanent-magnet synchronous motor parameters: `MC_PMSM_motor_param.h`

The `MC_PMSM_motor_param.h` is to be filled with the motor parameters. Three different sections can be distinguished:

- Parameters needed to carry out the FOC
- Parameters needed to perform sensorless rotor speed / position detection
- Parameters needed to perform the flux weakening functionality
- Parameters needed to optimize the drive of an IPMSM (MTPA)
- Parameters needed to carry out feed-forward current regulation

4.6.1 Basic motor parameters

This is the minimum set of motor parameters to be known in order to carry out FOC:

- `#define POLE_PAIR_NUM`

  Defines the number of magnetic pole pairs.
- `#define NOMINAL_CURRENT`

  In digits, defines the motor nominal current (0 to peak) according to the formula:

  $$I(\text{digit}) = \frac{I(\text{Amps}) \cdot R_{shunt} \cdot A_v \cdot 65536}{3.3}.$$

  Of course, these data are to be matched with inverter current rating.
- `#define MOTOR_MAX_SPEED_RPM`

  In RPM, defines the maximum motor speed required by the application. This parameter could be set depending on the application specification, on account of load profiles and on account of the mechanical construction of the motor.

  If the mechanical load is lower than rated, a speed higher than rated could be achieved by activating the flux-weakening functionality (see *Section 2.3*, *Section 3.4* and *Section 4.1*).
- `#define ID_DEMAG`

  In digit (negative 16-bit signed value), defines the maximum reference current i_d* that does NOT demagnetize the motor magnets. At most, this parameter could be equal to –`NOMINAL_CURRENT` (default)
  Note that if neither the IPMSM MTPA nor the flux-weakening functionality is enabled, the `#define ID_DEMAG` parameter does not need specifying (leave it unchanged at the default value).

4.6.2 Motor parameters for sensorless FOC

These parameters are used by the state observer algorithm to detect the rotor speed and position (see also Section 4.5):

– `#define RS`

Defines the motor winding resistance (phase) in Ohms.

– `#define LS`

Defines the motor winding inductance (phase) in Henry.
Note that if the motor being used is an IPMSM, then $L_d \neq L_q$and the synchronous inductance L_s may be set equal to L_q (see [5] in *A.9: References*).

– `#define MOTOR_VOLTAGE_CONSTANT`

Defines the motor voltage constant K_e (V/krpm RMS phase to phase) in Volts.

4.6.3 Additional parameters for flux weakening operation

This section has to be filled if, depending on the application specifics, the drive has to operate the motor beyond its rated speed (here, rated speed is considered to be the highest speed at which the motor can deliver maximum torque).

The mechanical limit of the motor must *not* be exceeded in any case. Moreover, if the motor is being operated beyond the rated speed, it is mandatory to have a regenerative power converter or a brake resistance (see *Section 3.14*).

See *Section 2.3* about the strategy implemented for flux weakening control.

- `#define FW_VOLTAGE_REF`

  Defines (in tenths of percent of the maximum available voltage) the stator voltage amplitude reference level to be kept constant during flux-weakening operations. The higher this parameter (close to 1000), the more effective the exploitation of the DC bus voltage.
- `#define FW_KP_GAIN`

  Defines (as a positive digit) the proportional gain of the PI regulator acting inside the flux-weakening module (see block diagram illustrated in *Figure 13: Flux-weakening operation scheme*.
- `#define FW_KI_GAIN`

  Defines (as a positive digit) the integral gain of the PI regulator acting inside the flux-weakening module (see block diagram depicted in illustrated in *Figure 13: Flux-weakening operation scheme*.

4.6.4 Additional parameters for IPMSM drive optimization (MTPA)

To edit the parameters related to MTPA, it is required to fill the annexed spreadsheet with the information below:

- Motor rated current, 0-to-peak Amperes, cell B2. These data must be matched with inverter current rating.
- Motor winding L_d inductance, H, cell B3
- Motor winding L_q inductance, H, cell B4
- Motor voltage constant K_e, Volts RMS/krpm, phase-to-phase, cell B5
- Motor winding resistance, Ohms, cell B6
- Number of magnetic pole pairs, cell B7
- Shunt resistance, Ohms, cell B9
- Amplification network gain (shunt current reading), cell B10

As a result of data processing, the following information can be obtained from the spreadsheet:

- `#define IQMAX`
  The user can copy it from cell B19
- `#define SEGDIV`
  The user can copy it from cell B20
- `#define ANGC`
  The user can copy it from cell B21
- `#define OFST`
  The user can copy it from cell B22

4.6.5 Additional parameters for feed-forward, high performance current regulation

To edit the parameters related to feed forward, it is required to fill the annexed spreadsheet with the information below:

- Motor winding L_d inductance, H, cell B3
- Motor winding L_q inductance, H, cell B4
  Note that if the motor in use is an SM-PMSM, then L_d should be set equal to L_q.
- Motor voltage constant K_e, Volts RMS/krpm, phase-to-phase, cell B5
- Shunt resistance, Ohms, cell B9
- Amplification network gain (shunt current reading), cell B10
- `SAMPLING_FREQ` (is the FOC sampling rate automatically computed in precompilation phase starting from `REP_RATE` and `PWM_FREQ`, according to the following equation:
  $$\text{Flux and torque PID sampling rate} = \frac{2 \cdot \text{PWM\_FREQ}}{\text{REP\_RATE} + 1}, \text{ kHz, cell B11}$$
- DC bus to ADC conversion factor; it defines the ratio between the ADC input voltage and the corresponding DC bus voltage, cell B12

As a result of data processing, the following information can be obtained from the spreadsheet:

- `#define CONSTANT1_Q`
  The user can copy it from cell B25
- `#define CONSTANT1_D`
  The user can copy it from cell B26
- `#define CONSTANT2`
  The user can copy it from cell B27

5 Library functions

Functions are described in the format given below:

Synopsis	Lists the prototype declarations.
Description	Describes the functions specifically with a brief explanation of how they are executed.
Input	Gives the format and units.
Returns	Gives the value returned by the function, including when an input value is out of range or an error code is returned.
Note	Indicates the limits of the function or specific requirements that must be taken into account before implementation.
Caution	Indicates important points that must be taken into account to prevent hardware failures.
Functions called	Lists called functions. Useful to prevent conflicts due to the simultaneous use of resources.
Code example	Indicates the proper way to use the function, and if there are certain prerequisites (interrupt enabled, etc.).

Some of these sections may not be included if not applicable (for example, no parameters or obvious use).

5.1 Current reading in three shunt resistor topology and space vector PWM generation: `stm32f10x_svpwm_3shunt` module

Two important tasks are performed in the `stm32f10x_svpwm_3shunt` module:

- Space vector pulse width modulation (SVPWM)
- Current reading in three shunt resistor topology

In order to reconstruct the currents flowing through a three-phase load with the required accuracy using three shunt resistors, it is necessary to properly synchronize A/D conversions with the generated PWM signals. This is why the two tasks are included in a single software module.

5.1.1 List of available functions

The following is a list of available functions as listed in the stm32f10x_svpwm_3shunt.h header file:

- *SVPWM_3ShuntInit on page 62*
- *SVPWM_3ShuntCurrentReadingCalibration on page 63*
- *SVPWM_3ShuntGetPhaseCurrentValues on page 63*
- *SVPWMEOCEvent on page 64*
- *SVPWMUpdateEvent on page 64*
- *SVPWM_3ShuntCalcDutyCycles on page 64*
- *SVPWM_3ShuntAdvCurrentReading on page 65*

SVPWM_3ShuntInit

Synopsis	void SVPWM_3ShuntInit(void);
Description	The purpose of this function is to set-up microcontroller peripherals for performing 3 shunt resistor topology current reading and center aligned PWM generation. The function initializes NVIC, ADC, GPIO, TIM1 peripherals. In particular, the ADC and TIM1 peripherals are configured to perform two simultaneous A/D conversions per PWM switching period. Refer to *Section 5.1.3* for further information.
Input	None.
Returns	None.
Note	It must be called at main level.
Functions called	**Standard library:** RCC_ADCCLKConfig, RCC_AHBPeriphClockCmd, RCC_APB2PeriphClockCmd, GPIO_StructInit, GPIO_Init, GPIO_PinLockConfig,GPIO_PinRemapConfig, TIM1_DeInit, TIM1_TimeBaseStructInit, TIM1_TimeBaseInit, TIM1_OCStructInit, TIM1_OC1Init, TIM1_OC2Init, TIM1_OC3Init, TIM1_OC4Init, TIM1_OC1PreloadConfig, TIM1_OC2PreloadConfig, TIM1_OC3PreloadConfig, TIM1_OC4PreloadConfig, TIM1_BDTRConfig, TIM1_SelectOutputTrigger, TIM1_ClearITPendingBit, TIM1_ITConfig, TIM1_Cmd,TIM1_GenerateEvent, TIM1_ClearFlag, ADC_DeInit, ADC_Cmd, ADC_StructInit, ADC_Init, ADC_StartCalibration, ADC_GetCalibrationStatus, ADC_RegularChannelConfig, ADC_InjectedSequencerLengthConfig, ADC_InjectedChannelConfig, NVIC_PriorityGroupConfig, NVIC_StructInit, NVIC_Init. **Motor control library:** SVPWM_3ShuntCurrentReadingCalibration

`SVPWM_3ShuntCurrentReadingCalibration`

Synopsis	void SVPWM_3ShuntCurrentReadingCalibration(void);
Description	The purpose of this function is to store the three analog voltages corresponding to zero current values for compensating the offset introduced by the amplification network.
Input	None.
Returns	None.
Note	This function reads the analog voltage on the ADC channels used for current reading. For this reason it must be called before the PWM outputs are enabled so that the current flowing through the inverter is zero. Those values are then stored into `Phase_x_Offset` variables.
Functions called	**Standard library:** ADC_ITConfig, ADC_ExternalTrigInjectedConvConfig, ADC_ExternalTrigInjectedConvCmd, ADC_InjectedSequencerLengthConfig, ADC_InjectedChannelConfig, ADC_ClearFlag, ADC_SoftwareStartInjectedConvCmd, ADC_GetFlagStatus, ADC_GetInjectedConversionValue, ADC_SoftwareStartInjectedConvCmd **Motor control library:** SVPWM_InjectedConvConfig

`SVPWM_3ShuntGetPhaseCurrentValues`

Synopsis	Curr_Components SVPWM_3ShuntGetPhaseCurrentValues(void);
Description	This function computes current values of Phase A and Phase B in q1.15 format starting from values acquired from the A/D Converter peripheral.
Input	None.
Returns	Curr_Components type variable.
Note	In order to have a q1.15 format for the current values, the digital value corresponding to the offset must be subtracted when reading phase current A/D converted values. Therefore, the function must be called after SVPWM_3ShuntCurrentReadingCalibration.
Functions called	None.

SVPWMEOCEvent

Synopsis	void SVPWMEOCEvent();
Description	Routine to be performed inside the end of conversion ISR. It computes the bus voltage and temperature sensor sampling and disables external ADC triggering.
Input	None.
Returns	Always true.
Note	None.
Functions called	ADC_GetInjectedConversionValue.

SVPWMUpdateEvent

Synopsis	void SVPWMUpdateEvent(void);
Description	Routine to be performed inside the update event ISR. It re-enables external ADC triggering.
Input	None.
Returns	None.
Note	None.
Functions called	ADC_ClearFlag.

SVPWM_3ShuntCalcDutyCycles

Synopsis	void SVPWM_3ShuntCalcDutyCycles (Volt_Components Stat_Volt_Input);
Description	After executing the FOC algorithm, new stator voltage components V_α and V_β are computed. The purpose of this function is to calculate exactly the three duty cycles to be applied to the inverter legs starting from the values of these voltage components. Moreover, once the three duty cycles to be applied in the next PWM period are known, this function sets the Channel 4 output compare register used to set the sampling point for the next current reading. In particular, depending on the duty cycle values, the sampling point is computed (see *Section 5.1.3*). Refer to *Section 5.1.2* for information on the theoretical approach of SVPWM.
Input	V_α and V_β
Returns	None.
Note	None.
Functions called	None.

`SVPWM_3ShuntAdvCurrentReading`

Synopsis	void SVPWM_3ShuntAdvCurrentReading(FunctionalState cmd);
Description	It is used to enable or disable advanced current reading. If advanced current reading is disabled, current reading is performed in conjunction with the update event.
Input	cmd (ENABLE or DISABLE)
Returns	None.
Note	None.
Functions called	TIM1_ClearFlag, TIM1_ITConfig

5.1.2 Space vector PWM implementation

Figure 36 shows the stator voltage components V_α and V_β while *Figure 37* illustrates the corresponding PWM for each of the six space vector sectors.

Figure 36. V_α and V_β stator voltage components

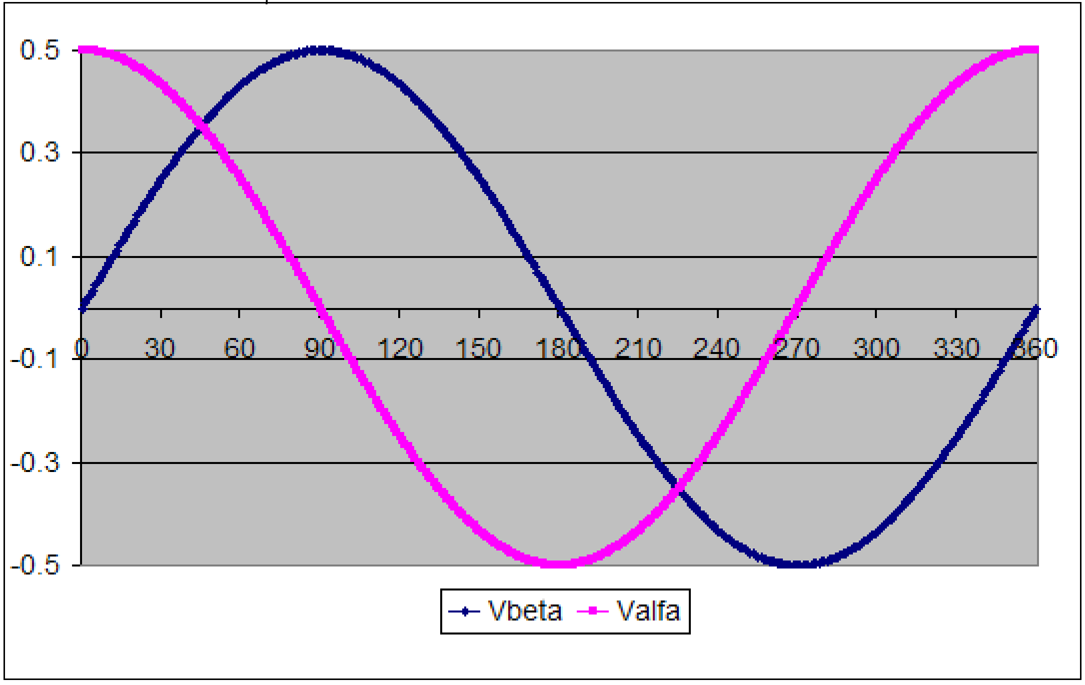
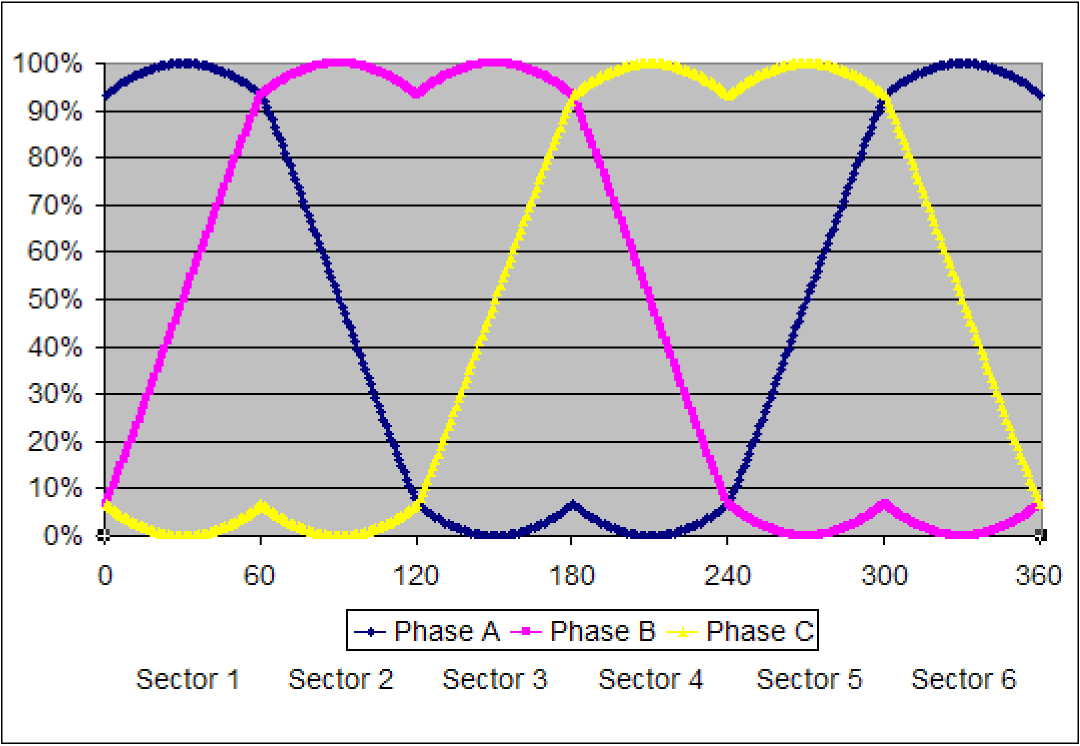


Figure 37. SVPWM phase voltage waveforms



With the following definitions for: $U_\alpha = \sqrt{3} \times T \times V_\alpha$, $U_\beta = -T \times V_\beta$ and $X = U_\beta$,

$Y = \frac{U_\alpha + U_\beta}{2}$ and $Z = \frac{U_\beta - U_\alpha}{2}$.

literature demonstrates that the space vector sector is identified by the conditions shown in *Table 1*.

Table 1. Sector identification

	Y < 0			**Y ≥ 0**		
	Z < 0	**Z ≥ 0**		**Z < 0**		**Z ≥ 0**
		X ≤ 0	**X > 0**	**X ≤ 0**	**X > 0**	
Sector	V	IV	III	VI	I	II

The duration of the positive pulse widths for the PWM applied on Phase A, B and C are respectively computed by the following relationships:

Sector I, IV: $t_A = \frac{T + X - Z}{2}$, $t_B = t_A + Z$, $t_C = t_B - X$

Sector II, V: $t_A = \frac{T + Y - Z}{2}$, $t_B = t_A + Z$, $t_C = t_A - Y$

Sector III, VI: $t_A = \frac{T - X + Y}{2}$, $t_B = t_C + X$, $t_C = t_A - Y$, where T is the PWM period.

Now, considering that the PWM pattern is center aligned and that the phase voltages must be centered at 50% of duty cycle, it follows that the values to be loaded into the PWM output compare registers are given respectively by:

Sector I, IV: $\mathrm{TimePhA} = \frac{T}{4} + \frac{T/2 + X - Z}{2}$, $\mathrm{TimePhB} = \mathrm{TimePhA} + Z$, $\mathrm{TimePhC} = \mathrm{TimePhB} - X$

Sector II, V: $\mathrm{TimePhA} = \frac{T}{4} + \frac{T/2 + Y - Z}{2}$, $\mathrm{TimePhB} = \mathrm{TimePhA} + Z$, $\mathrm{TimePhC} = \mathrm{TimePhA} - Y$

Sector III,VI: $\mathrm{TimePhA} = \frac{T}{4} + \frac{T/2 + Y - X}{2}$, $\mathrm{TimePhB} = \mathrm{TimePhC} + X$, $\mathrm{TimePhC} = \mathrm{TimePhA} - Y$

5.1.3 Current sampling in three shunt topology and general purpose A/D conversions

The three currents I_1, I_2, and I_3 flowing through a three-phase system follow the mathematical relation:

$$I_1 + I_2 + I_3 = 0$$

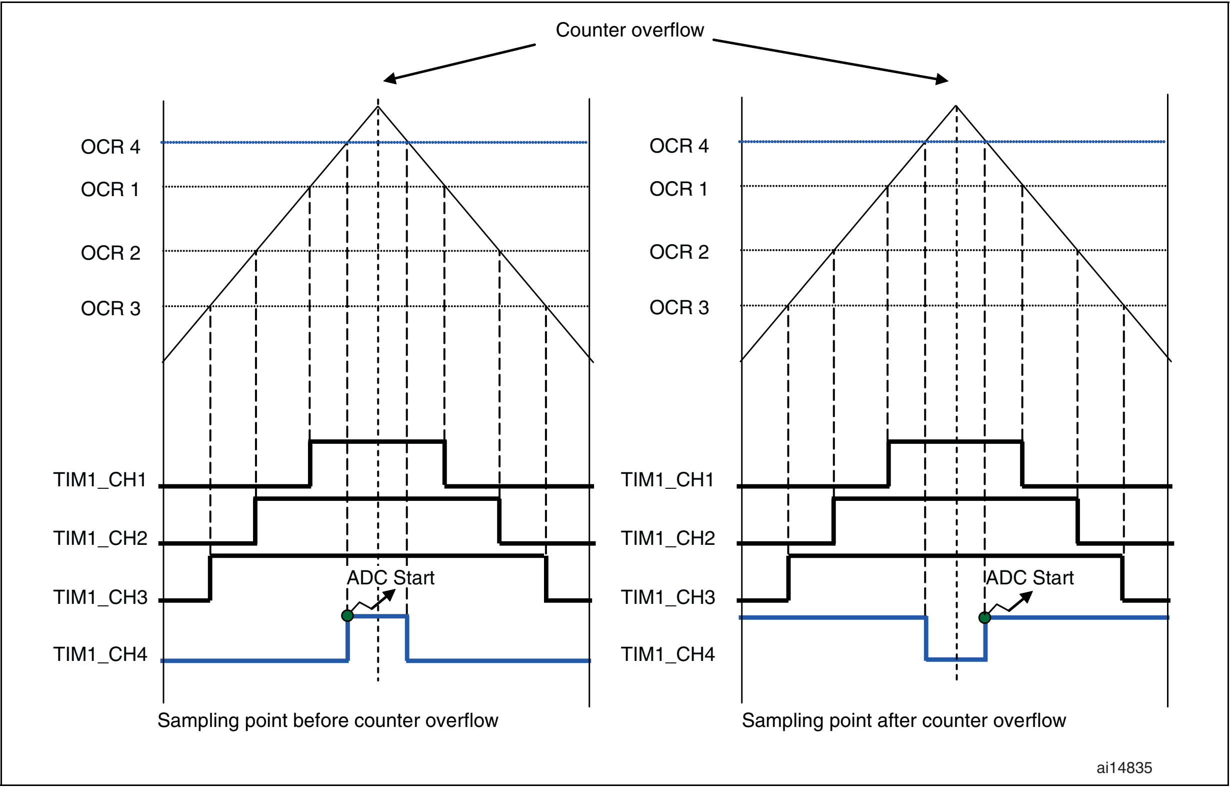
For this reason, to reconstruct the currents flowing through a generic three-phase load, it is sufficient to sample only two out of the three currents while the third one can be computed by using the above relation.

The flexibility of the STM32F103xx A/D converter makes it possible to synchronously sample the two A/D conversions needed for reconstructing the current flowing through the motor. The ADC can also be used to synchronize the current sampling point with the PWM output using the external triggering capability of the peripheral. Owing to this, current conversions can be performed at any given time during the PWM period. To do this, the control algorithm uses the fourth PWM channel of TIM1 to synchronize the start of the conversions.

Injected conversions, as described above, are used for current-reading purposes whereas regular conversions are reserved for the user. As soon as the injected A/D conversions for current-reading purposes have completed, bus voltage and temperature sensing are also simultaneously converted by the dual A/D.

Figure 38 shows the synchronization strategy between the TIM1 PWM output and the ADC. The A/D converter peripheral is configured so that it is triggered by the rising edge of TIM1_CH4.

Figure 38. PWM and ADC synchronization



In this way, supposing that the sampling point must be set before the counter overflow, that is, when the TIM1 counter value matches the OCR4 register value during the upcounting, the A/D conversions for current sampling are started. If the sampling point must be set after the counter overflow, the PWM 4 output has to be inverted by modifying the CC4P bit in the TIM1_CCER register. In so doing, when the TIM1 counter matches the OCR4 register value during the downcounting, the A/D samplings are started.

After the first two simultaneous conversions other two simultaneous conversions are started, one for the bus voltage and the other for the temperature sensing. At the end of the second conversion, the three-phase load current has been updated and the FOC algorithm can then be executed in the A/D end of injected conversion interrupt service routine (JEOC ISR).

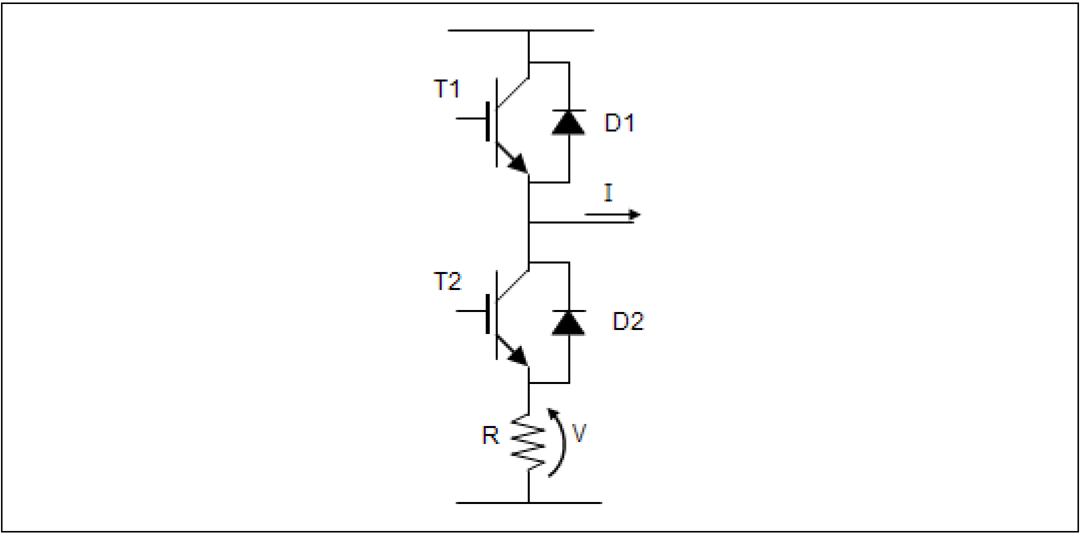
After execution of the FOC algorithm, the value to be loaded into the OCR4 register is calculated to set the sampling point for the next PWM period, and the A/D converter is configured to sample the correct channels.

Regular conversions are reserved for user purposes and must be configured manually (See also firmware standard library user manual UM0427).

5.1.4 Tuning delay parameters and sampling stator currents in three shunt resistor topology

Figure 39 shows one of the three inverter legs with the related shunt resistor:

Figure 39. Inverter leg and shunt resistor position



To indirectly measure the phase current I, it is possible to read the voltage V providing that the current flows through the shunt resistor R.

It is possible to demonstrate that, whatever the direction of current I, it always flows through the resistor R if transistor T2 is switched on and T1 is switched off. This implies that in order to properly reconstruct the current flowing through one of the inverter legs, it is necessary to properly synchronize the conversion start with the generated PWM signals. This also means that current reading cannot be performed on a phase where the duty cycle applied to the low side transistor is either null or very short.

Fortunately, as discussed in *Section 5.1.3*,to reconstruct the currents flowing through a generic three-phase load, it is sufficient to simultaneously sample only two out of three currents, the third one being computed from the relation given in *Section 5.1.3*. Thus, depending on the space vector sector, the A/D conversion of voltage V will be performed only on the two phases where the duty cycles applied to the low side switches are the highest. In particular, by looking at *Figure 37*, you can deduct that in sectors 1 and 6, the voltage on the Phase A shunt resistor can be discarded; likewise, in sectors 2 and 3 for Phase B, and finally in sectors 4 and 5 for Phase C.

Moreover, in order to properly synchronize the two stator current reading A/D conversions, it is necessary to distinguish between the different situations that can occur depending on PWM frequency and applied duty cycles.

Note: The explanations below refer to space vector sector 4. They can be applied in the same manner to the other sectors.

Case 1: Duty cycle applied to Phase A low side switch is larger than DT+T_N

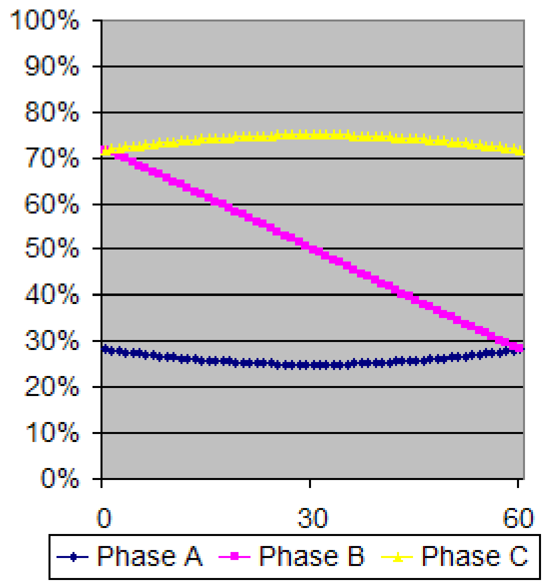
Where:

- DT is dead time.
- T_N is the duration of the noise induced on the shunt resistor voltage of a phase by the commutation of a switch belonging to another phase.
- T_S is the sampling time of the STM32F103xx A/D converter (the following consideration is made under the hypothesis that $T_S < DT + T_N$). Refer to the STM32F103xx reference manual for more detailed information.

This case typically occurs when SVPWM with low (<60%) modulation index is generated (see *Figure 40*). The modulation index is the applied phase voltage magnitude expressed as a percentage of the maximum applicable phase voltage (the duty cycle ranges from 0% to 100%).

Figure 41 offers a reconstruction of the PWM signals applied to low side switches of Phase A and B in these conditions plus a view of the analog voltages measured on the STM32F103xx A/D converter pins for both Phase B and C (the time base is lower than the PWM period).

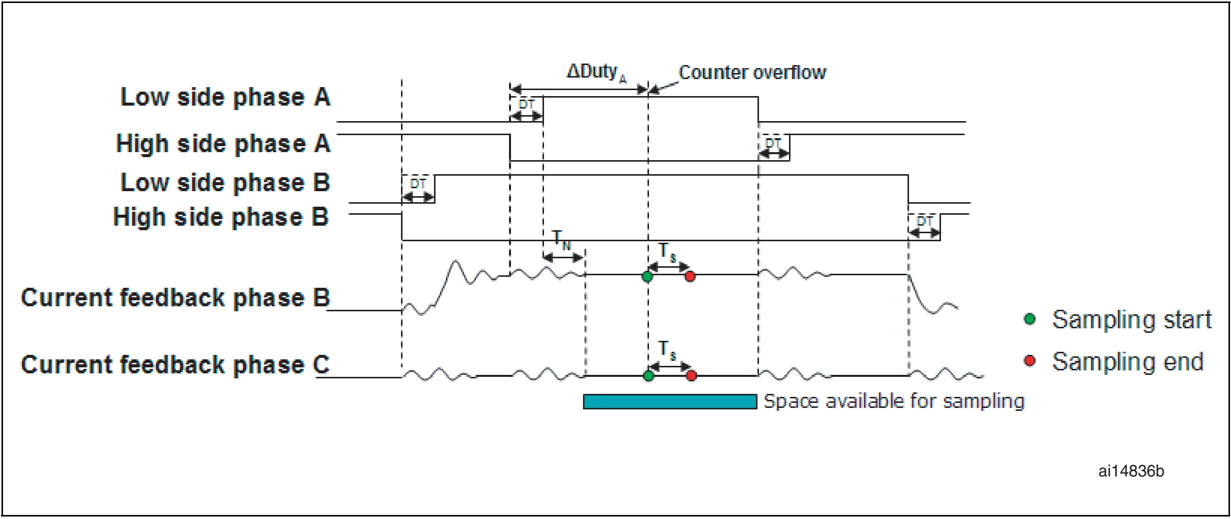
Figure 40. Low-side switch gate signals (low modulation indexes)



Note that these current feedbacks are constant in the view in *Figure 41* because it is assumed that commutations on Phase B and C have occurred out of the visualized time window.

Moreover, it can be observed that in this case the two stator current sampling conversions can be performed synchronized with the counter overflow, as shown in *Figure 41*.

Figure 41. Low side Phase A duty cycle > $DT+T_N$



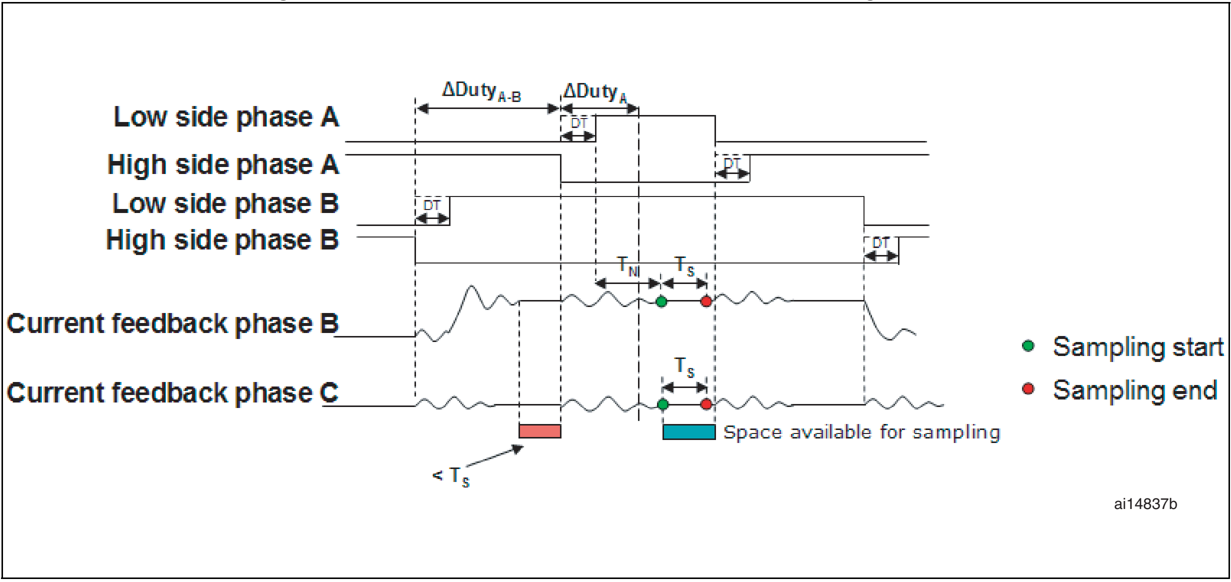
Case 2: $(DT+T_N+T_S)/2 < \Delta Duty_A < D_T+T_N$ and $\Delta Duty_{AB} < D_T+T_R+T_S$

With the increase in modulation index, $\Delta Duty_A$ can have values smaller than D_T+T_N. Sampling synchronized with the counter overflow could be impossible.

In this case, the two currents can still be sampled between the two Phase A low side commutations, but only after the counter overflow.

Consider that in order to avoid the acquisition of the noise induced on the phase B current feedback by phase A switch commutations, it is required to wait for the noise to be over (T_N). See *Figure 42*.

Figure 42. $(DT+T_N+T_S)/2 < \Delta Duty_A < D_T+T_N$ and $\Delta Duty_{AB} < D_T+T_R+T_S$

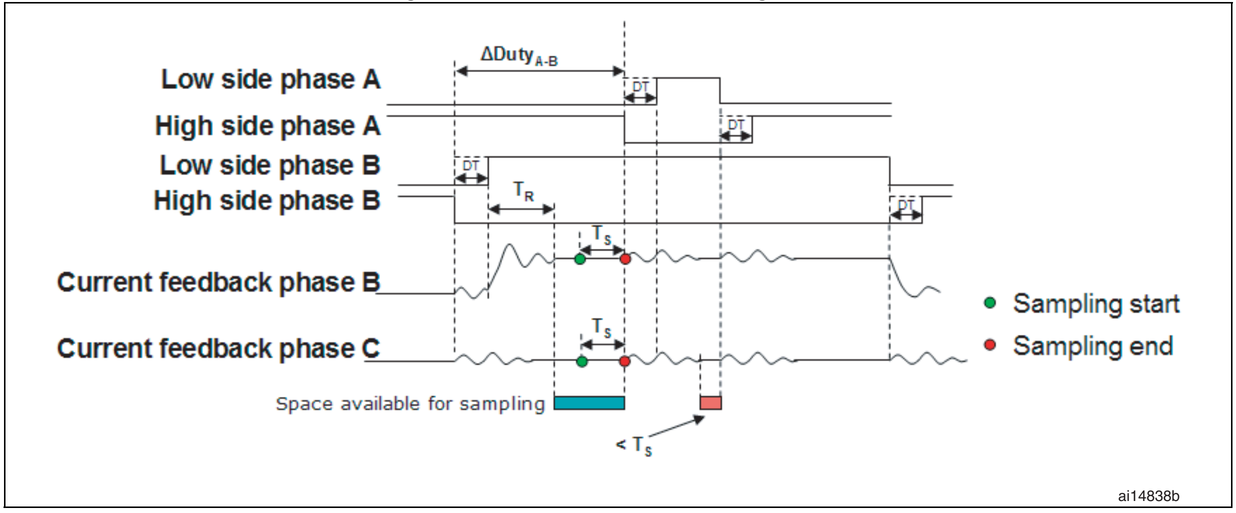


Case 3: $\Delta DutyA < (DT+T_N+T_S)/2$ and $\Delta Duty_{A-B} > DT+T_R+T_S$

In this case, it is no more possible to sample the currents during Phase A low-side switch-on. Anyway, the two currents can be sampled between Phase B low-side switch-on and

Phase A high-side switch-off. The choice was therefore made to sample the currents T_S µs before of phase A high-side switch-off (see *Figure 43*).

Figure 43. ΔDutyA < $(DT+T_N+T_S)/2$ and $\Delta Duty_{A-B}>DT+T_R+T_S$



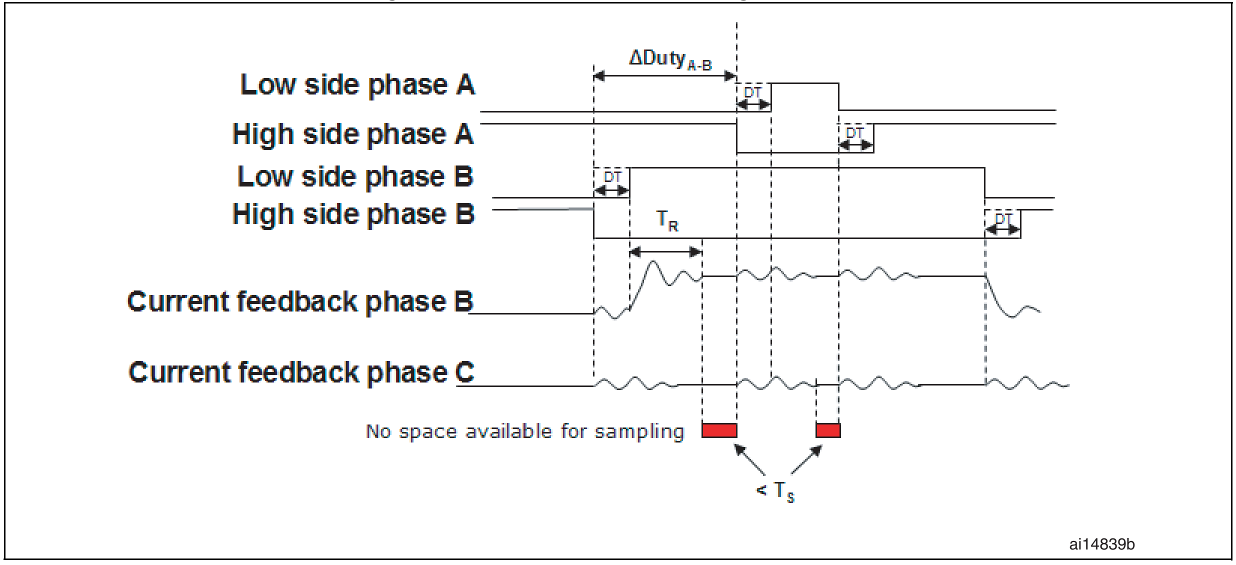
Case 4: $\Delta Duty_A<(DT+T_N+T_S)/2$ and $\Delta Duty_{A-B}<DT+T_R+T_S$

In this case, the duty cycle applied to Phase A is so short that no current sampling can be performed between the two low-side commutations.

Furthermore if the difference in duty cycles between Phases B and A is not long enough to allow the A/D conversions to be performed between Phase B low-side switch-on and Phase A high-side switch-off, it is impossible to sample the currents (See *Figure 44*).

To avoid this condition, it is necessary to reduce the maximum modulation index or decrease the PWM frequency.

Figure 44. $\Delta Duty_A<(DT+T_N+T_S)/2$ and $\Delta Duty_{A-B}<DT+T_R+T_S$



The following parameters have been set as default in the firmware. They are related to the MB459 board:

- DT = 0.8 µs
- T_N = 2.55 µs
- T_S = 0.7 µs
- T_R = 2.55 µs

The maximum applicable duty cycles are listed in *Table 2* as a function of the PWM frequency.
The values in *Table 2* are measured using the MB459 board. This evaluation platform is designed to support several motor driving topologies (PMSM and AC induction) and current reading strategies (single- and three-shunt resistor). Therefore, the figures provided in *Table 2* should be understood as a starting point and not as a best case.

Table 2. PWM frequency vs. maximum duty cycle relationship for three-shunt topology

PWM frequency	Max duty cycle	Max modulation Index
Up to 11.4 kHz	100%	100%
12.2 kHz	99%	98%
12.9 kHz	98.5%	97%
13.7 kHz	98%	96%
14.4 kHz	98%	96%
15.2 kHz	97%	94%
16 kHz	96.5%	93%
16.7 kHz	96.5%	93%
17.5 kHz	95.5%	91%

It is possible to adjust the noise parameters based on customized hardware by editing the following definitions in the `MC_pwm_3shunt_prm.h` header file:

```
#define SAMPLING_TIME_NS 700 //0.7usec
#define TNOISE_NS 2550 //2.55usec
#define TRISE_NS 2550 //2.55usec
```

Changing the noise parameters, sampling time and dead time affects the values provided in *Table 2*.

5.2 Current reading in single shunt resistor topology and space vector PWM generation: `stm32f10x_svpwm_1shunt` module

Two major tasks are performed in the `stm32f10x_svpwm_1shunt` module:

- space-vector pulse-width modulation (SVPWM)
- current reading in single-shunt-resistor topology

In order to reconstruct the currents flowing through a three-phase load with the required accuracy using a single shunt resistor, it is necessary to properly synchronize A/D conversions with the generated PWM signals. This is why the two tasks are included in a single software module.

5.2.1 List of available functions

The following is the list of available functions as listed in the `stm32f10x_svpwm_1shunt.h` header file:

- *`SVPWM_1ShuntInit` on page 74*
- *`SVPWM_1ShuntCurrentReadingCalibration` on page 75*
- *`SVPWM_1ShuntGetPhaseCurrentValues` on page 75*
- *`SVPWM_1ShuntCalcDutyCycles` on page 76*
- *SVPWM_1ShuntAdvCurrentReading on page 77*
- *SVPWMEOCEvent on page 77*
- *SVPWMUpdateEvent on page 77*

`SVPWM_1ShuntInit`

Synopsis	void SVPWM_1ShuntInit(void);
Description	The purpose of this function is to set up the microcontroller peripherals so as to perform single-shunt-resistor topology current reading and center aligned PWM generation. The function initializes the NVIC, ADC, GPIO, TIM1 and DMA peripherals. More particularly, the ADC and TIM1 peripherals are configured to perform two A/D conversions per PWM switching period. Refer to *Section 5.2.3* for further information.
Input	None.
Returns	None.
Note	It must be called at main level.
Functions called	**Standard library:** RCC_ADCCLKConfig, RCC_AHBPeriphClockCmd, RCC_APB2PeriphClockCmd, GPIO_StructInit, GPIO_Init, GPIO_PinLockConfig,GPIO_PinRemapConfig, TIM1_DeInit, TIM1_TimeBaseStructInit, TIM1_TimeBaseInit, TIM1_OCStructInit, TIM1_OC1Init, TIM1_OC2Init, TIM1_OC3Init, TIM1_OC4Init, TIM1_OC1PreloadConfig, TIM1_OC2PreloadConfig, TIM1_OC3PreloadConfig, TIM1_OC4PreloadConfig, TIM1_BDTRConfig, TIM1_SelectOutputTrigger, TIM1_ClearITPendingBit, TIM1_ITConfig, TIM1_Cmd,TIM1_GenerateEvent, TIM1_ClearFlag, TIM1_DMACmd, TIM1_DMAConfig, ADC_DeInit, ADC_Cmd, ADC_StructInit, ADC_Init, ADC_StartCalibration, ADC_GetCalibrationStatus, ADC_RegularChannelConfig, ADC_InjectedSequencerLengthConfig, ADC_InjectedChannelConfig, NVIC_PriorityGroupConfig, NVIC_StructInit, NVIC_Init. DMA_DeInit, DMA_Init, DMA_Cmd **Motor control library:** SVPWM_1ShuntCurrentReadingCalibration

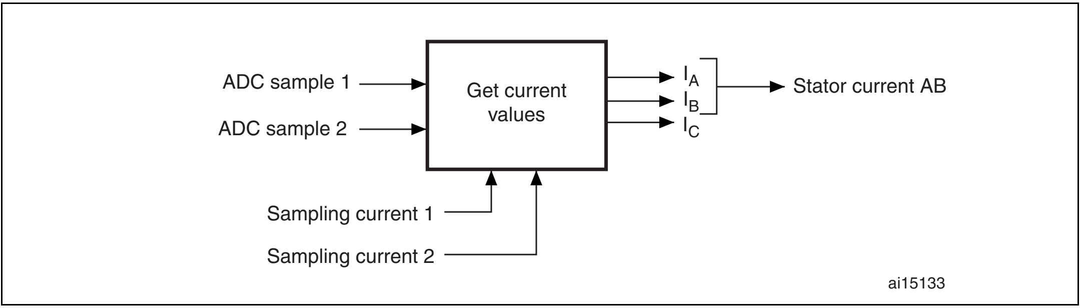
`SVPWM_1ShuntCurrentReadingCalibration`

Synopsis	void SVPWM_1ShuntCurrentReadingCalibration(void);
Description	The purpose of this function is to store the analog voltages corresponding to zero-current values in order to compensate for the offset introduced by the amplification circuit.
Input	None.
Returns	None.
Note	This function reads the analog voltage on the ADC channels used for current reading. For this reason it must be called before the PWM outputs are enabled so that the current flowing through the inverter is zero. Those values are then stored into the `hPhaseOffset` variable.
Functions called	**Standard library:** ADC_ITConfig, ADC_ExternalTrigInjectedConvConfig, ADC_ExternalTrigInjectedConvCmd, ADC_InjectedSequencerLengthConfig, ADC_InjectedChannelConfig, ADC_ClearFlag, ADC_SoftwareStartInjectedConvCmd, ADC_GetFlagStatus, ADC_GetInjectedConversionValue, ADC_SoftwareStartInjectedConvCmd **Motor control library:** SVPWM_InjectedConvConfig

`SVPWM_1ShuntGetPhaseCurrentValues`

Synopsis	Curr_Components SVPWM_1ShuntGetPhaseCurrentValues(void);
Description	This function computes current values of Phase A and Phase B in q1.15 format starting from values acquired from the A/D converter peripheral. See *Figure 45*.
Input	None.
Returns	`Curr_Components` type variable.
Note	In order to have a q1.15 format for the current values, the digital value corresponding to the offset must be subtracted when reading phase current A/D converted values. Therefore, the function must be called after SVPWM_1ShuntCurrentReadingCalibration.
Functions called	None.

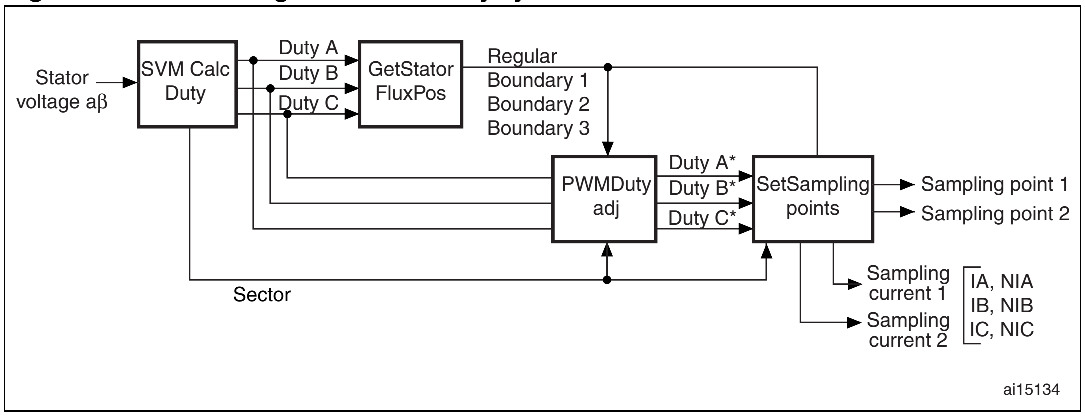
Figure 45. Block diagram of GetPhaseCurrentValues



`SVPWM_1ShuntCalcDutyCycles`

Synopsis	void SVPWM_1ShuntCalcDutyCycles (Volt_Components Stat_Volt_Input);
Description	After executing the FOC algorithm, the new stator voltage components, V_α and V_β, are computed. The purpose of this function is to calculate the three exact duty cycles to be applied to the inverter legs, starting from the values of these voltage components. Moreover, once the three duty cycles to be applied during the next PWM period are known, this function performs the following tasks: ● Gets stator flux position (regular or boundary zone 1, 2 or 3) ● Computes the PWM channel that must be distorted and updates the value of duty cycle registers ● Computes the sampling point and the related sampled phase ● Sets the preload variables for PWM mode Ch 1,2,3,4. See *Figure 46*. Refer to *Section 5.2.2* for information on the theoretical approach to single-shunt current reading.
Input	V_α and V_β.
Returns	None.
Note	None.
Functions called	None.

Figure 46. Block diagram of CalcDutyCycles



`SVPWM_1ShuntAdvCurrentReading`

Synopsis	void SVPWM_1ShuntAdvCurrentReading(FunctionalState cmd);
Description	It is used to enable or disable current reading. If current reading is disabled, the bus voltage and temperature sensor are still sampled in conjunction with the update event.
Input	cmd (ENABLE or DISABLE)
Returns	None.
Note	None.
Functions called	TIM1_ClearFlag, TIM1_ITConfig

`SVPWMEOCEvent`

Synopsis	void SVPWMEOCEvent();
Description	Routine to be performed inside the end-of-conversion ISR. For single-shunt current reading, it is called twice. The first time, to store the first sampled value. It returns a “false”. The second time, it returns a “true” to indicate the execution of the FOC cycle. It computes the bus voltage and temperature sensor sampling, and disables external ADC triggering.
Input	None.
Returns	False the first time it is entered, True the second time.
Note	None.
Functions called	ADC_GetInjectedConversionValue, ADC_ITConfig.

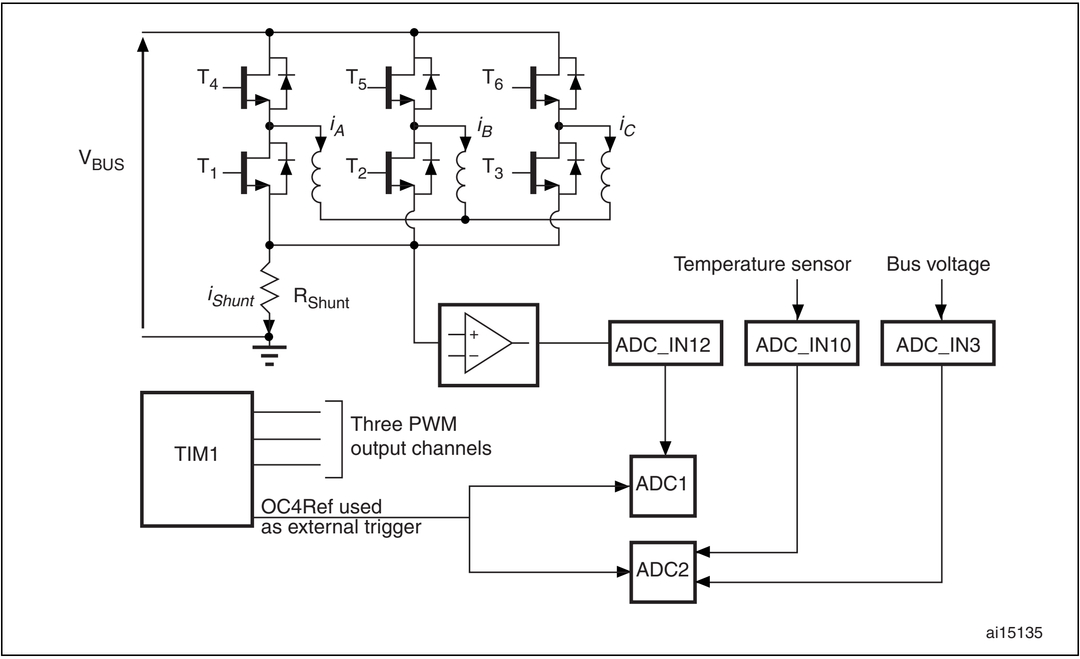
`SVPWMUpdateEvent`

Synopsis	void SVPWMUpdateEvent(void);
Description	Routine to be performed inside the update event ISR. It sets the PWM output mode of the four channels (Toggle or PWM), enables or disables the DMA event for each channel, updates the DMA buffers and DMA length and, finally, it re-enables external ADC triggering.
Input	None.
Returns	None.
Note	None.
Functions called	ADC_ClearFlag,ADC_ITConfig.

5.2.2 Current sampling in single-shunt topology

Figure 47 illustrated the single-shunt hardware architecture.

Figure 47. Single-shunt hardware architecture



It is possible to demonstrate that for each configuration of the low-side switches, the current through the shunt resistor is given in *Table 3*. T_4, T_5 and T_6 assume the complementary values of T_1, T_2 and T_3, respectively.

In *Table 3*, the value “0” means that the switch is open whereas the value “1” means that the switch is closed.

Table 3. Current through the shunt resistor

T_1	T_2	T_3	I_{Shunt}
0	0	0	0
0	1	1	i_A
0	0	1	$-i_C$
1	0	1	i_B
1	0	0	$-i_A$
1	1	0	i_C
0	1	0	$-i_B$
1	1	1	0

Using the centered-aligned pattern, each PWM period is subdivided into 7 subperiods (see *Figure 48*). During three subperiods (I, IV, VII) the current through the shunt resistor is zero. During the other subperiods, the current through the shunt resistor is symmetrical with respect to the center of the PWM.

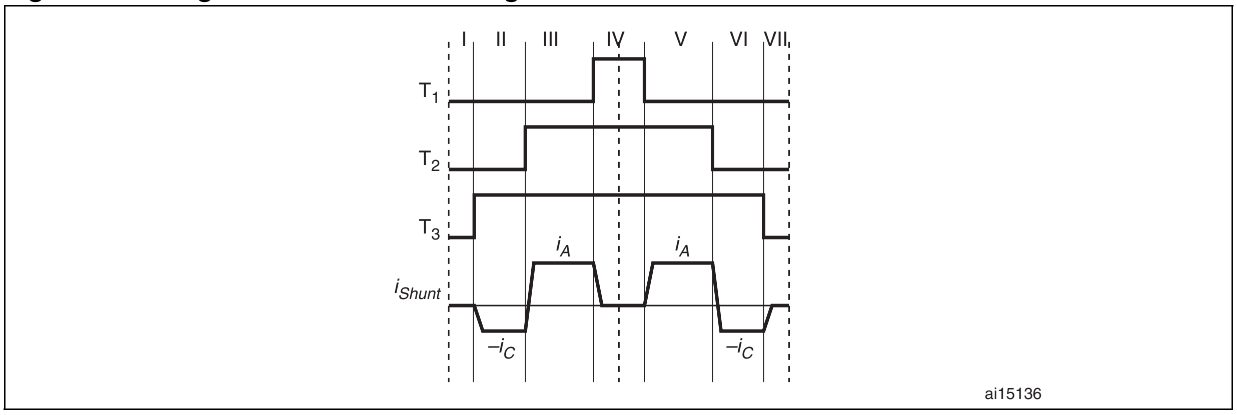
For the conditions showed in *Figure 48*, there are two pairs:

- subperiods II and VI, during which i_{Shunt} is equal to $-i_C$
- subperiods III and V, during which i_{Shunt} is equal to i_A

So under these conditions, it is possible to reconstruct the three-phase current through the motor from the sampled values:

- i_A is i_{Shunt} measured during subperiod III or V
- i_C is $-i_{Shunt}$ measured during subperiod II or VI
- $i_B = -i_A - i_C$

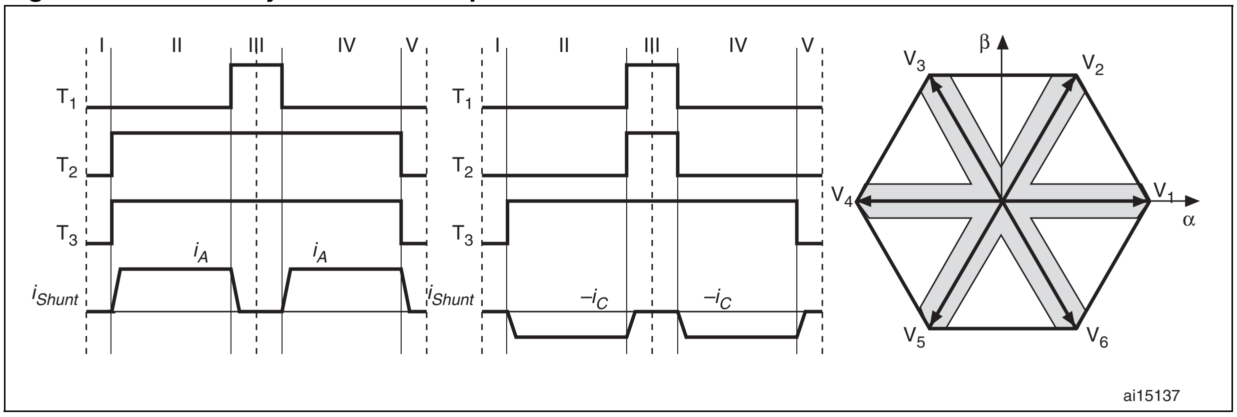
Figure 48. Single-shunt current reading



But if the stator-voltage demand vector lies in the boundary space between two space vector sectors, two out of the three duty cycles will assume approximately the same value. In this case, the seven subperiods are reduced to five subperiods.

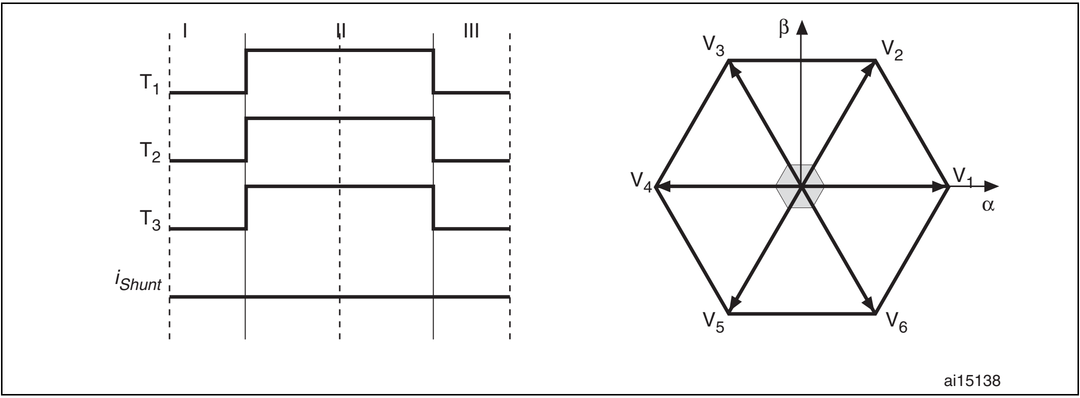
Under these conditions, only one current can be sampled, the other two cannot be reconstructed. This means that it is not possible to sense both currents during the same PWM period, when the imposed voltage demand vector falls in the gray area of the space vector diagram represented in *Figure 49*.

Figure 49. Boundary between two space-vector sectors



Similarly, for a low modulation index, the three duty cycles assume approximately the same value. In this case, the seven subperiods are reduced to three subperiods. During all three subperiods, the current through the shunt resistor is zero. This means that it is not possible to sense any current when the imposed voltage vector falls in the gray area of the space-vector diagram represented in *Figure 50*.

Figure 50. Low modulation index



5.2.3 Definition of the noise parameter and boundary zone

T_{Rise} is the time required for the data to become stable in the ADC channel after the power device has been switched on or off.

The duration of the ADC sampling is called the sampling time.

T_{MIN} is the minimum time required to perform the sampling, and

$$T_{MIN} = T_{Rise} + \text{sampling time} + \text{dead time}$$

D_{MIN} is the value of T_{MIN} expressed in duty cycle percent. It is related to the PWM frequency as follows:

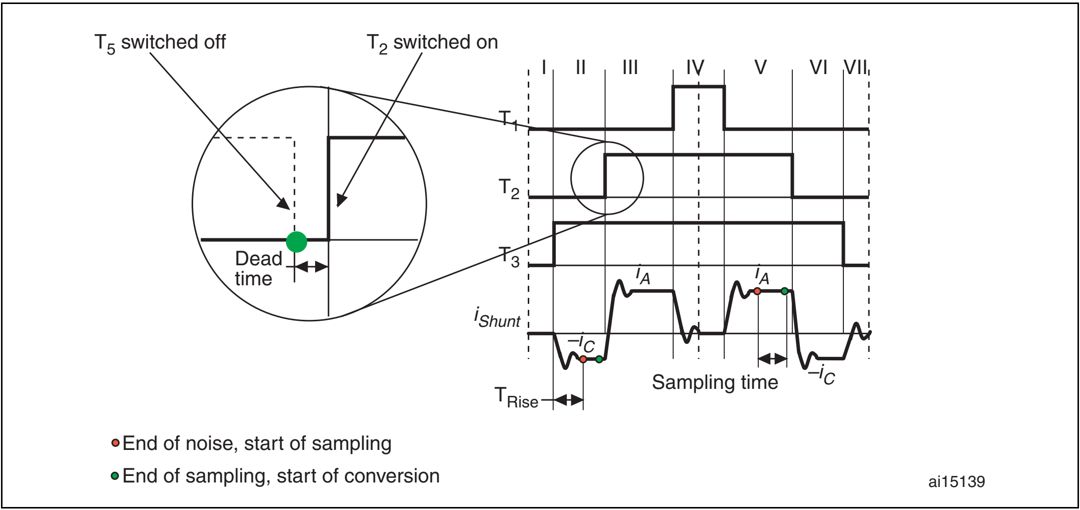
$$D_{MIN} = (T_{MIN} \times F_{PWM}) \times 100$$

It is possible to adjust the noise parameters based on customized hardware by editing the following definitions in the *MC_pwm_1shunt_prm.h* header file:

- `#define SAMPLING_TIME_NS 700 //0.7usec`
- `#define TRISE_NS 2550 //2.55usec`

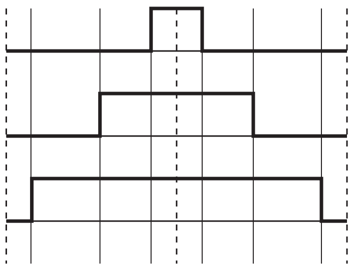
Changing the noise parameters, sampling time and dead time affects the values provided in *Table 4*.

Figure 51. Definition of noise parameters



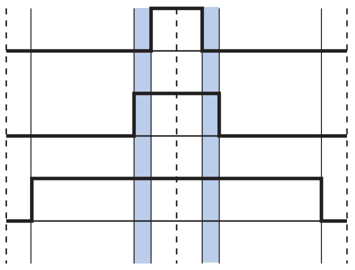
The voltage-demand vector lies in a region called the Regular region when the three duty cycles (calculated by space vector modulation) inside a PWM pattern differ from each other by more than D_{MIN}. This is represented in *Figure 52*.

Figure 52. Regular region



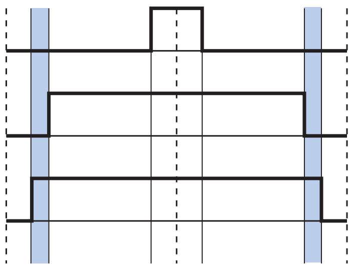
The voltage-demand vector lies in a region called Boundary 1 when two of the duty cycles differ from each other by less than D_{MIN}, and the third is greater than the other two and differs from them by more than D_{MIN}. This is represented in *Figure 53*.

Figure 53. Boundary 1



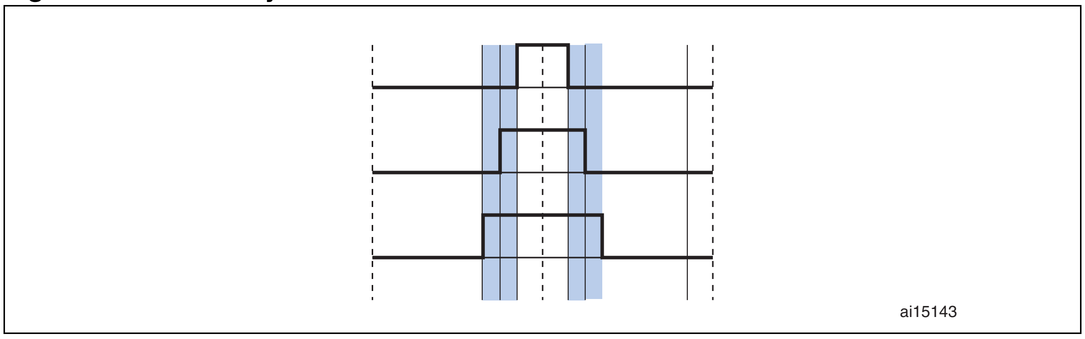
The voltage-demand vector lies in a region called Boundary 2 when two duty cycles differ from each other by less than D_{MIN}, and the third is smaller than the other two and differs from them by more than D_{MIN}. This is represented in *Figure 54*.

Figure 54. Boundary 2



The voltage-demand vector lies in a region called Boundary 3 when the three PWM signals differ from each other by less than D_{MIN}. This is represented in *Figure 55*.

Figure 55. **Boundary 3**



If the voltage-demand vector lies in Boundary 1 or Boundary 2 region, a distortion must be introduced in the related PWM signal phases to sample the motor phase current.

An ST patented technique for current sampling in the “Boundary” regions has been implemented in the firmware. Please contact your nearest ST sales office or support team for further information about this technique.

Note: *The current-compensation technique implemented by default can lead to bad current sampling if a motor with a high stator inductance is driven at a high electrical speed. In this case, it may be useful to exclude the default current-compensation technique by commenting the following define in the MC_pwm_1shunt_prm.h header file:*

```
#define CURRENT_COMPENSATION
```

5.2.4 Performance

The following parameters have been set as default in the firmware. They are related to the MB459 board:

- DT = 0.8 µs
- T_R = 1.5 µs
- T_S = 0.7 µs

The maximum applicable duty cycles are listed in *Table 4* as a function of the PWM frequency.

Table 4. **PWM frequency vs. maximum duty cycle relationship for single-shunt topology**

PWM frequency	Max duty cycle	Max modulation index	Min REP_RATE
Up to 11.4 kHz	100%	100%	1
12.2 kHz	100%	100%	
12.9 kHz	100%	100%	
13.7 kHz	100%	100%	
14.4 kHz	100%	100%	
15.2 kHz	100%	100%	3
16 kHz	99.5%	99%	
16.7 kHz	99%	98%	
17.5 kHz	99%	98%	

5.3 Isolated current sensor reading and space vector PWM generation: `stm32f10x_svpwm_ics module`

Two important tasks are performed in the `stm32f10x_svpwm_ics` module.

- Space vector pulse width modulation (SVPWM),
- Three-phase current reading when two isolated current sensors (ICS) are used.

In order to reconstruct the currents flowing through a three phase load with the required accuracy using two ICSs, it is necessary to properly synchronize A/D conversions with the generated PWM signals. This is why the two tasks are included in a single software module.

5.3.1 List of available functions and interrupt service routines

The following is a list of available functions as listed in the `stm32f10x_svpwm_ics.h` header file:

- *`SVPWM_IcsInit` on page 84*
- *`SVPWM_IcsCurrentReadingCalibration` on page 84*
- *`SVPWM_IcsGetPhaseCurrentValues` on page 85*
- *`SVPWM_IcsCalcDutyCycles` on page 85*
- *`SVPWMEOCEvent` on page 86*
- *`SVPWMUpdateEvent` on page 86*

`SVPWM_IcsInit`

Synopsis	void SVPWM_IcsInit(void);
Description	The purpose of this function is to set-up microcontroller peripherals for performing ICS reading and center aligned PWM generation. The function initializes NVIC, ADC, GPIO, and TIM1 peripherals. In particular, the ADC and TIM1 peripherals are configured to perform two pairs of simultaneous injected A/D conversions every time the PWM registers are updated (event called U event). The first pair of conversions read the current values whereas the second pair acquires the bus voltage and the voltage at the temperature sensor. Refer to *Section 5.3.2* for further information on A/D conversion triggering in ICS configuration.
Input	None.
Returns	None.
Note	It must be called at main level.
Functions called	**Standard library:** RCC_ADCCLKConfig, RCC_AHBPeriphClockCmd, RCC_APB2PeriphClockCmd, GPIO_StructInit, GPIO_Init, GPIO_PinLockConfig, GPIO_PinRemapConfig, TIM1_DeInit, TIM1_TimeBaseStructInit, TIM1_TimeBaseInit, TIM1_OCStructInit, TIM1_OC1Init, TIM1_OC2Init, TIM1_OC3Init, TIM1_BDTRConfig, TIM1_SelectOutputTrigger, TIM1_ClearITPendingBit, TIM1_ITConfig, TIM1_Cmd, ADC_DeInit, ADC_Cmd, ADC_StructInit, ADC_Init, ADC_StartCalibration, ADC_GetCalibrationStatus, ADC_InjectedSequencerLengthConfig, ADC_InjectedChannelConfig, ADC_ExternalTrigInjectedConvCmd, NVIC_PriorityGroupConfig, NVIC_StructInit, NVIC_Init. **Motor control library:** SVPWM_IcsCurrentReadingCalibration

`SVPWM_IcsCurrentReadingCalibration`

Synopsis	void SVPWM_IcsCurrentReadingCalibration(void);
Description	The purpose of this function is to store the two analog voltages corresponding to zero current values for compensating the offset introduced by both ICS and amplification network.
Input	None.
Returns	None.
Note	This function is called by MCL_Init which is executed at every motor startup. It reads the analog voltage on the A/D channels used for current reading before the PWM outputs are enabled so that the current flowing through the inverter is zero.

Functions called	**Standard Library:** ADC_ITConfig, ADC_ExternalTrigInjectedConvConfig, ADC_ExternalTrigInjectedConvCmd, ADC_InjectedChannelConfig, ADC_ClearFlag, ADC_SoftwareStartInjectedConvCmd, ADC_GetFlagStatus, ADC_GetInjectedConversionValue, SVPWM_IcsInjectedConvConfig **Motor Control library:** SVPWM_IcsInjectedConvConfig

SVPWM_IcsGetPhaseCurrentValues

Synopsis	Curr_Components SVPWM_IcsGetPhaseCurrentValues(void);
Description	This function computes current values of Phase A and Phase B in q1.15 format from the values acquired from the A/D converter.
Input	None.
Returns	Curr_Components type variable
Note	In order to have a q1.15 format for the current values, the digital value corresponding to the offset must be subtracted when reading phase current A/D converted values. Thus, the function must be called after SVPWM_IcsCurrentReadingCalibration.
Functions called	None.

SVPWM_IcsCalcDutyCycles

Synopsis	void SVPWM_IcsCalcDutyCycles (Volt_Components Stat_Volt_Input);
Description	After execution of the FOC algorithm, new stator voltages component V_{α} and V_{β} are computed. The purpose of this function is to calculate exactly the three duty cycles to be applied to the three inverter legs starting from the values of these voltage components. Refer to *Section 5.1.2* for details about the theoretical approach of SVPWM and its implementation.
Input	V_{α} and V_{β}
Returns	None.
Note	None.
Functions called	None.

`SVPWMEOCEvent`

Synopsis	void SVPWMEOCEvent();
Description	Routine to be performed inside the end of conversion ISR. It computes the bus voltage and temperature sensor sampling.
Input	None.
Returns	Always true.
Note	None.
Functions called	ADC_GetInjectedConversionValue

`SVPWMUpdateEvent`

Synopsis	void SVPWMUpdateEvent(void);
Description	Routine to be performed inside the update event ISR. Nothing is performed.
Input	None
Returns	None.
Note	None.
Functions called	None.

5.3.2 Current sampling in isolated current sensor topology and integrating general-purpose A/D conversions

The three currents I_1, I_2, and I_3 flowing through a three-phase system follow the mathematical relationship:

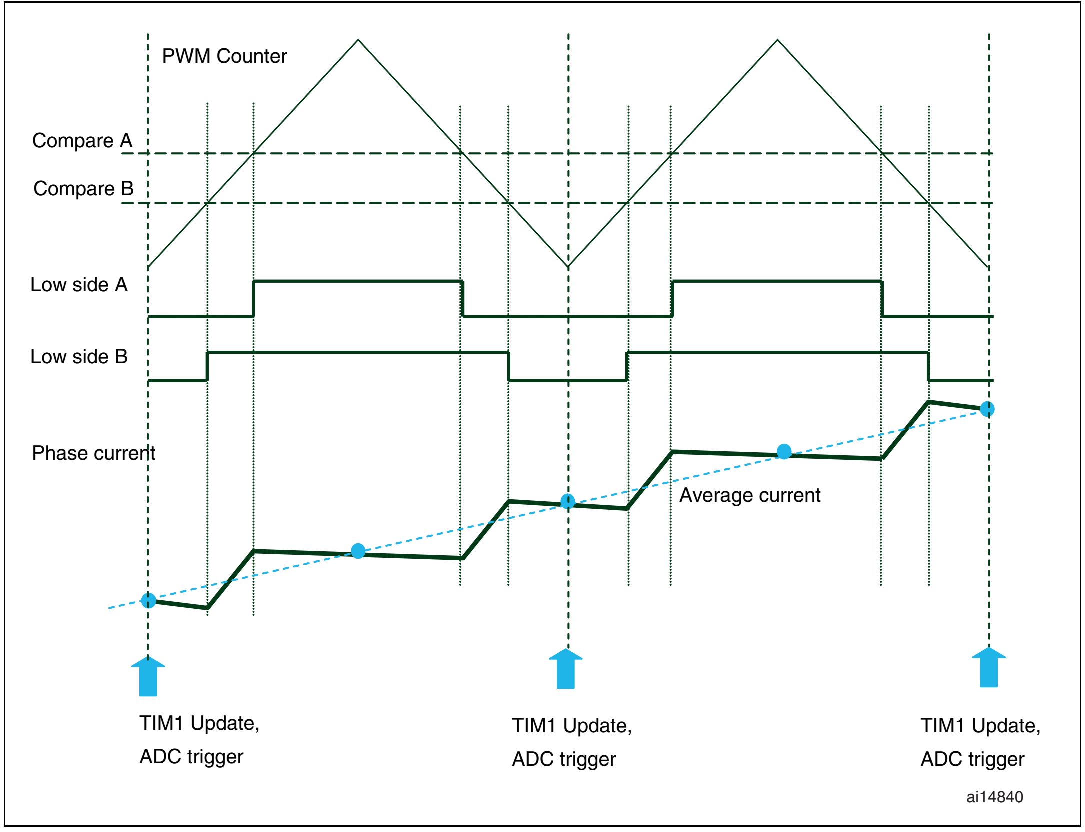
$$I_1 + I_2 + I_3 = 0$$

Therefore, to reconstruct the currents flowing through a generic three-phase load, it is sufficient to sample only two out of the three currents while the third one can be computed by using the above relationship.

The flexibility of the STM32F103xx A/D converter trigger makes it possible to synchronize the two A/D conversions necessary for reconstructing the stator currents flowing through the motor with the PWM reload register updates. The update rate can be adjusted using the repetition counter. This is important because, as shown in *Figure 56*, it is precisely during counter overflow and underflow that the average level of current is equal to the sampled current. Refer to the STM32F103xx reference manual to learn more about A/D conversion triggering and the repetition counter.

Note: Regular conversions are reserved for the user and must be configured manually (See also firmware standard library user manual UM0427).

Figure 56. Stator currents sampling in ICS configuration (`REP_RATE=1`)



5.4 PMSM (SM-PMSM / IPMSM) field-oriented control: `MC_FOC_Drive` and `MC_FOC_Methods` modules

The `MC_FOC_Drive` and `MC_FOC_Methods` modules, designed for surface-mounted or internal permanent-magnet synchronous motors, provides, at the core, decoupled electromagnetic torque (T_e) regulation and, to some extent, flux weakening capability. In addition, it provides speed regulation by PID feedback control.

To operate, it requires no adjustment with all of the selectable current or speed sensing configurations (in accordance with the settings in the `stm32f10x_MCconf.h` file):

- isolated current sensing (ICS)
- three-shunt resistor current sensing
- DC link single-shunt resistor
- encoder position and speed sensing
- Hall sensor position and speed sensing
- sensorless position and speed detection

The `MC_FOC_Drive` module handles several functions of other modules, and has no direct access to the microcontroller peripheral registers.

5.4.1 List of available C functions

FOC_Init

Synopsis	void FOC_Init (void)
Description	It initializes to proper values all the variables related to the field-oriented control algorithm. To be called once prior to every motor startup.
Input	None
Output	None

Functions called	**if FLUX_WEAKENING is enabled (library configuration file):** FOC_FluxRegulator_Init
	if IPMSM_MTPA is enabled: FOC_MTPA_Init
	if FEED_FORWARD_CURRENT_REGULATION is enabled: FOC_FF_CurrReg_Init

Note	In the demo program, it's called during the INIT state.

`FOC_Model`

Synopsis void FOC_Model (void)

Description The purpose of this function is to perform PMSM torque and flux regulation, implementing the FOC algorithm.

Current commands i_{qs}** and i_{ds}** (which, under field oriented conditions, can control machine torque and flux respectively) are defined outside this function (in Speed control mode they are provided, by means of speed and flux regulators, by the `FOC_CalcFluxTorqueRef` function, while in Torque control mode they are provided by the `FOC_TorqueCtrl` function as set by the user via the LCD menus, as explained in *Section 3.1*).

Therefore, as a current source is required, the function has to run the power converter as a CR-PWM. For this purpose, it implements an high performance synchronous (d, q) frame current regulator, whose operating frequency is defined, as explained in *Section 4.2*, by the parameter REP_RATE (in conjunction with PWM_FREQ).

Triggered by ADC JEOC ISR, the function loads stator currents (read by ICS or shunt resistors) and carries out Clark and Park transformations, converting them to i_{qs} and i_{ds} (see *Figure 4*).

Then, these currents are fed to PID regulators together with reference values i_{qs}** and i_{ds}**. At this point, if `FEED_FORWARD_CURRENT_REGULATION` is enabled in the library configuration, the PID regulator output voltages, v_{qs} and v_{ds}, are added up to the output voltages of the feed-forward block. They are then transformed back to a stator frame (through Reverse Park conversion), and finally drive the power stage.

In order to correctly perform Park and Reverse Park transformation, it is essential to know the rotor position ($\theta_{r\ el}$) (because currents have to be oriented in phase and in quadrature with the rotor flux). To manage this task, depending on the configuration (set in `stm32f10x_MCconf.h`), the function can read the rotor angle measurement from encoders, Hall sensors, or the provided sensorless algorithm.

Input None.

Returns None.

Functions called	Clarke, Park, RevPark_Circle_Limitation; PID_Regulator, Rev_Park;
	If working with encoder: ENC_Get_Electrical_Angle;
	if Working with Hall sensors: HALL_GetElectricalAngle;
	if working in sensorless mode: STO_Get_Electrical_Angle;
	if working with ‘ICS’: SVPWM_IcsGetPhaseCurrentValues, SVPWM_IcsCalcDutyCycles;
	if working with ‘three shunt’: SVPWM_3ShuntGetPhaseCurrentValues, SVPWM_3ShuntCalcDutyCycles;
	If working with ‘single shunt’: SVPWM_1ShuntGetPhaseCurrentValues, SVPWM_1ShuntCalcDutyCycles.

`FOC_CalcFluxTorqueRef`

Synopsis	void FOC_CalcFluxTorqueRef (void)
Description	In Speed-control mode, this function provides current components iqs** and ids** to be used as reference values (by the `FOC_Model` function) (see “Speed closed-loop control” in *Figure 5*). Speed setpoint and actual rotor speed ω_r are compared in a PID control loop whose output is iqs*. Then, if an IPMSM motor is used and the user has enabled the related torque optimization algorithm, this reference is given to the MTPA block which returns the most suitable i_{ds}* reference. Otherwise, i_{ds}* is set to zero. At this point, i_{qs}* and i_{ds}* are passed to the flux-weakening block (if it has been activated) to get the final current references, i_{qs}** and i_ds**, and feed the motor through the synchronous frame PID regulators and feed-forward block (if enabled).
Input	None.
Returns	None.

Functions called	PID_Regulator;
	if working with encoder:
	ENC_Get_Mechanical_Speed;
	if working with Hall sensors:
	HALL_GetSpeed;
	if working in sensorless mode:
	STO_Get_Speed_Hz;
	If `FLUX_WEAKENING` is enabled (library configuration file):
	FOC_FluxRegulator;
	FOC_FluxRegulator_Update;
	If `IPMSM_MTPA` is enabled:
	FOC_MTPA;
	if `FEED_FORWARD_CURRENT_REGULATION` is enabled:
	FOC_FF_CurrReg.

`FOC_TorqueCtrl`

Synopsis	void FOC_TorqueCtrl(void)
Description	When in Torque control mode, the demo program, via the LCD menus, allows the user to change the stator reference currents acting on the `hTorque_Reference` and `hFlux_Reference` variables. The purpose of this function is to copy the value of those variables in the i_q** and i_d** current references, which are then fed to the motor using the `FOC_Model` function.
Input	None
Output	None
Functions called	**If FEED_FORWARD_CURRENT_REGULATION is enabled:** FOC_FF_CurrReg
Note	The demo program executes this function with the speed regulation loop frequency (see *Section 5.10.1: List of available functions and interrupt service routines*)

FOC_MTPA

Synopsis	s16 FOC_MTPA(s16 hIqRef)
Description	This function implements the IPMSM MTPA optimized drive, described in *Section 2.1.4*: i_q* (which, in speed control mode, is the output of the PI regulator) is the input to the function, the i_d* output is chosen by entering the linear, interpolated MTPA trajectory.
Input	Reference current i_q* (signed, 16 bits)
Output	Reference current i_d* (signed, 16 bits)
Functions called	None
Note	As a preliminary step, the MTPA section of the header file *MC_PMSM_motor_param.h* should be customized according to the motor in use (see *Section 4.2* for details on how to do this). The `FOC_MTPAInterface_Init` Function must be called at least once before the first motor startup. In the demo program, the MTPA functionality is enabled through the library configuration file (see *Section 4.1*)
See also	*Figure 9: MTPA control on page 19* shows the block diagram; `FOC_MTPAInterface_Init`, `FOC_MTPA_Init` functions

FOC_FluxRegulator

Synopsis	Curr_Components FOC_FluxRegulator (Curr_Components Stat_Curr_qd_ref, Volt_Components Stat_Volt_qd, s16 hVoltLevel)
Description	This function implements the flux-weakening functionality as described in *Section 2.3*.
Input	Reference currents i_q*i_d* (Curr_Components structure), reference stator voltages v_q*v_d* (Volt_Components structure), stator voltage amplitudes to be kept as reference levels during operations (positive signed, 16 bits).
Output	Reference current i_{qsat}**i_d** (Curr_Components structure)
Functions called	PID_Regulator
Note	As a preliminary step, the flux-weakening section of the *MC_PMSM_motor_param.h* header file should be customized according to the motor in use (see *Section 4.2* for details on how to do this). The `FOC_FluxRegulatorInterface_Init` function must be called before every motor startup. In the demo program, this functionality is enabled through the library configuration file (see *Section 4.1*)
See also	*Figure 13: Flux-weakening operation scheme on page 24*; `FOC_FluxRegulatorInterface_Init`, `FOC_FluxRegulator_Init`, `FOC_FluxRegulator_update` functions

`FOC_FF_CurrReg`

Synopsis	Volt_Components FOC_FF_CurrReg(Curr_Components Stat_Curr_qdref, Volt_Components Stat_Volt_qd, s16 hspeed, s16 hvbus)
Description	This function implements the feed-forward current regulation functionality, as described in *Section 2.1.5*.
Input	Reference currents i_q**i_d** (Curr_Components structure), reference stator voltages v_q*v_d* (Volt_Components structure), rotor electrical speed (dpp), DC bus voltage (positive signed, 16 bits)
Output	Reference voltages v_q*v_d* (Volt_Components structure)
Functions called	None
Note	As a preliminary step, the feed-forward section of the *MC_PMSM_motor_param.h* header file should be customized according to the motor in use (see *Section 4.2* for details on how to do this). The `FOC_FF_CurrReg_Init` function must be called at least once before the first motor startup. In the demo program, this functionality is enabled through the library configuration file (see *Section 4.1*).
See also	*Figure 10: Feed-forward current regulation on page 20*; `FOC_FF_CurrReg_Init` function

`FOC_MTPAInterface_Init`

Synopsis	void FOC_MTPAInterface_Init(void)
Description	According to the used motor and to the parameters written in the MTPA section of *MC_PMSM_motor_param.h*, it initializes all the variables related to the MTPA trajectory generator to proper values (`FOC_MTPA` function). It has to be called at least once before the first motor startup.
Input	None (reads parameters from *MC_PMSM_motor_param.h*)
Output	None
Functions called	FOC_MTPA_Init
Note	None
See also	*MC_type.h* for structure declarations; `FOC_ Init`, `FOC_MTPA` functions

`FOC_MTPA_Init`

Synopsis	void FOC_MTPA_Init(MTPA_Const MTPA_InitStructure_in, s16 hIdDemag_in)
Description	This function is called by `FOC_MTPAInterface_Init` to initialize the MTPA algorithm according to default parameters defined in *MC_PMSM_motor_param.h*
Input	MTPA initialization structure (MTPA_Const structure), maximum allowed reference current i_d* (positive signed, 16 bits)
Output	None
Functions called	None
Note	None
See also	*MC_type.h* for structure declarations; `FOC_MTPAInterface_Init` function

`FOC_FluxRegulatorInterface_Init`

Synopsis	void FOC_FluxRegulatorInterface_Init(void)
Description	According to the used motor and to the parameters written in the flux-weakening section of *MC_PMSM_motor_param.h,* it initializes all the variables related to flux-weakening operations to proper values (`FOC_Flux_Regulator` function). It has to be called before every motor startup.
Input	None (reads parameters from *MC_PMSM_motor_param.h*)
Output	None
Functions called	FOC_FluxRegulator_Init
Note	None
See also	*MC_type.h* for structure declarations; `FOC_ Init`, `FOC_FluxRegulator` functions

`FOC_FluxRegulator_Init`

Synopsis	void FOC_FluxRegulator_Init(PID_Struct_t *PI_Stat_Volt_InitStructure_in, s16 hNominalCurrent_in)
Description	This function is called by `FOC_FluxRegulatorInterface_Init` to initialize the flux-weakening algorithm according to default parameters defined in *MC_PMSM_motor_param.h*
Input	Pointer to a PID instance structure (PID_Struct_t structure), motor nominal current (positive signed 16 bits)
Output	None
Functions called	None
Note	None

See also	*MC_type.h* for structure declarations; `FOC_FluxRegulatorInterface_Init` function

`FOC_FluxRegulator_Update`

Synopsis	s16 FOC_FluxRegulator_Update(s16 hKpGain, s16 hKiGain)
Description	According to the user input, it modifies the proportional and integral gains of the PI regulator implemented in the flux-weakening block (see *Figure 13: Flux-weakening operation scheme on page 24*)
Input	Proportional gain (positive signed 16 bits), integral gain (positive signed 16 bits)
Output	Stator voltage amplitude (positive signed 16 bits)
Functions called	None
Note	None
See also	None

`FOC_FF_CurrReg_Init`

Synopsis	void FOC_FF_CurrReg_Init(s32 wConstant1Q, s32 wConstant1D, s32 wConstant2)
Description	According to the used motor and to the parameters written in the feed-forward section of *MC_PMSM_motor_param.h*, It initializes all the variables related to feed-forward operations to proper values (`FOC_FF_CurrReg` function). It has to be called at least once before the first motor startup.
Input	Signed 32 bits parameters from the related section in MC_PMSM_motor_param.h
Output	None
Functions called	None
Note	See also Function FOC_ Init, FOC_FF_CurrReg

5.5 Reference frame transformations: `MC_Clarke_Park` module

This module, intended for AC machines (induction, synchronous and PMSM), is designed to perform transformations of electric quantities between frames of reference that rotate at different speeds.

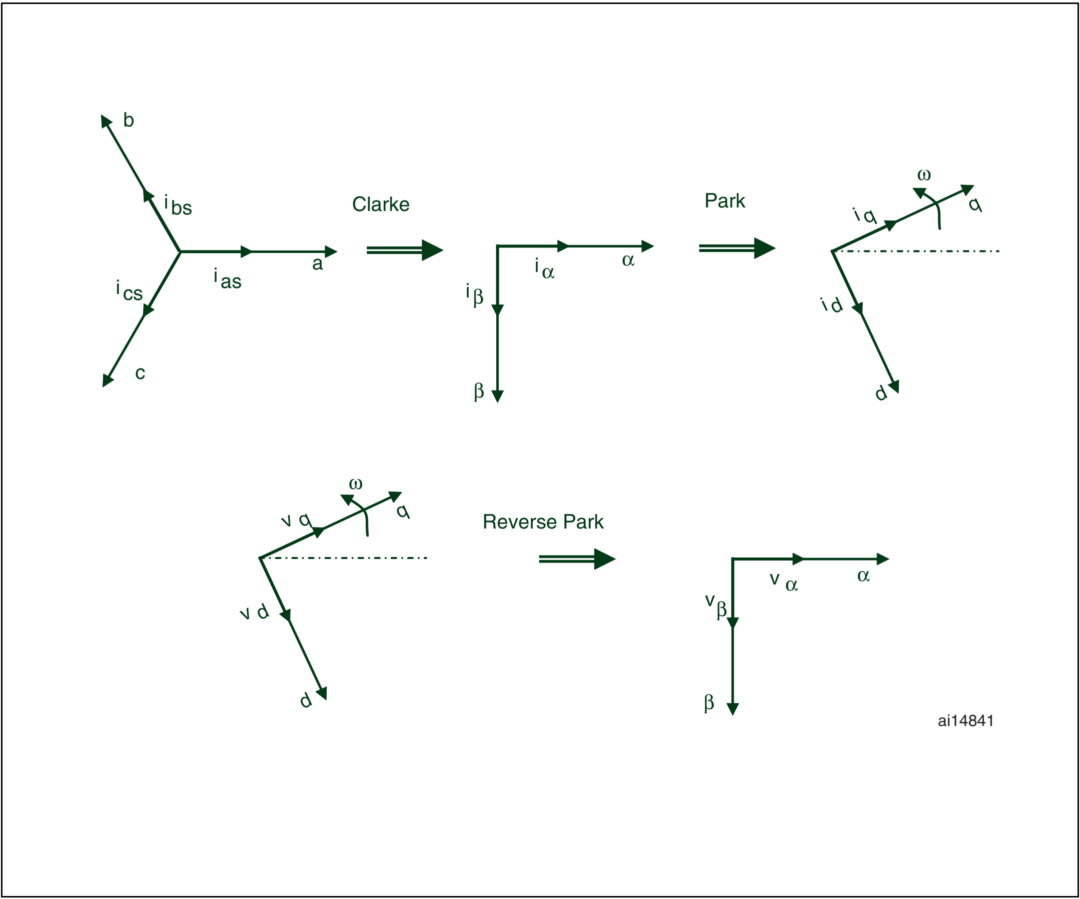
Based on the arbitrary reference frame theory, the module provides three functions, named after two pioneers of electric machine analysis, E. Clarke and R.H. Park.

These functions implement three variable changes that are required to carry out field-oriented control (FOC):

- Clarke transforms stator currents to a stationary orthogonal reference frame (named $\alpha\beta$ frame, see *Figure 57*);
- then, from that arrangement, Park transforms currents to a frame that rotates at an arbitrary speed (which, in PMSM field-oriented control, is synchronous with the rotor);
- Reverse Park transformation brings back stator voltages from a rotating frame (*q, d)* to a stationary one.

The module also includes a function to calculate trigonometric functions (sine and cosine), and a function to correct the voltage vector command (the so-called “Circle limitation”).

Figure 57. Clarke, Park, and reverse Park transformations



5.5.1 List of available C functions

- *Clarke on page 97*
- *Park on page 97*
- *Rev_Park on page 97*
- *Rev_Park_Circle_Limitation on page 98*
- *Trig_Functions on page 98*

`Clarke`

Synopsis	Curr_Components Clarke (Curr_Components Curr_Input)
Description	This function transforms stator currents i_{as} and i_{bs} (which are directed along axes each displaced by 120 degrees) into currents i_α and i_β in a stationary (α β) reference frame; $\alpha\beta$ axes are directed along paths orthogonal to each other. See *Section 5.5.2* for the details.
Input	Stator currents i_{as} and i_{bs} (in q1.15 format) as members of the variable Curr_Input, which is a structure of type Curr_Components.
Returns	Stator currents i_α and i_β (in q1.15 format) as members of a structure of type Curr_Components.
Functions called	None

`Park`

Synopsis	Curr_Components Park (Curr_Components Curr_Input, s16 Theta)
Description	The purpose of this function is to transform stator currents i_α and i_β, which belong to a stationary (α β) reference frame, to a reference frame synchronous with the rotor and properly oriented, so as to obtain i_{qs} and i_{ds}. See *Section 5.5.2* for details.
Input	Stator currents i_α and i_β (in q1.15 format) as members of the variable Curr_Input, which is a structure of type Curr_Components; rotor angle $\theta_{r\ el}$ (65536 pulses per revolution).
Returns	Stator currents i_{qs} and i_{ds} (in q1.15 format) as members of a structure of type Curr_Components.
Functions called	Trig_Functions

`Rev_Park`

Synopsis	Volt_Components Rev_Park (Volt_Components Volt_Input)
Description	This function transforms stator voltage v_q and v_d, belonging to a rotating frame synchronous with the rotor, to a stationary reference frame, so as to obtain v_α and v_β. See *Section 5.5.2* for details.
Input	Stator voltages v_{qs} and v_{ds} (in q1.15 format) as members of the variable Volt_Input, which is a structure of type Volt_Components.
Returns	Stator voltages v_α and v_β (in q1.15 format) as members of a structure of type Volt_Components.
Functions called	None

`Rev_Park_Circle_Limitation`

Synopsis	void RevPark_Circle_Limitation(void)
Description	After the two new values (v_d and v_q) of the stator voltage producing flux and torque components of the stator current, have been independently computed by flux and torque PIDs, it is necessary to saturate the magnitude of the resulting vector, equal to $\sqrt{v_d^2 + v_q^2}$ before passing them to the Rev_Park function. The purpose of this routine is to perform the saturation. Refer to *Section 5.5.3: Circle limitation on page 101* for more detailed information
Input	None.
Returns	None.
Note	The limitation of the stator voltage vector must be done in accordance with the PWM frequency as shown in *Table 2: PWM frequency vs. maximum duty cycle relationship for three-shunt topology on page 73*.
Functions called	None.

`Trig_Functions`

Synopsis	Trig_Components Trig_Functions(s16 hAngle)
Description	This function returns trigonometric cosine and sine functions of the input angle.
Input	An angle, in s16 format (correspondence with radians is illustrated in *Figure 58*)
Returns	Cosine and sine of the input angle, in s16 format (see *Figure 59*) as members of a structure of the Trig_Components type.
Functions called	None

Figure 58. Radians versus s16

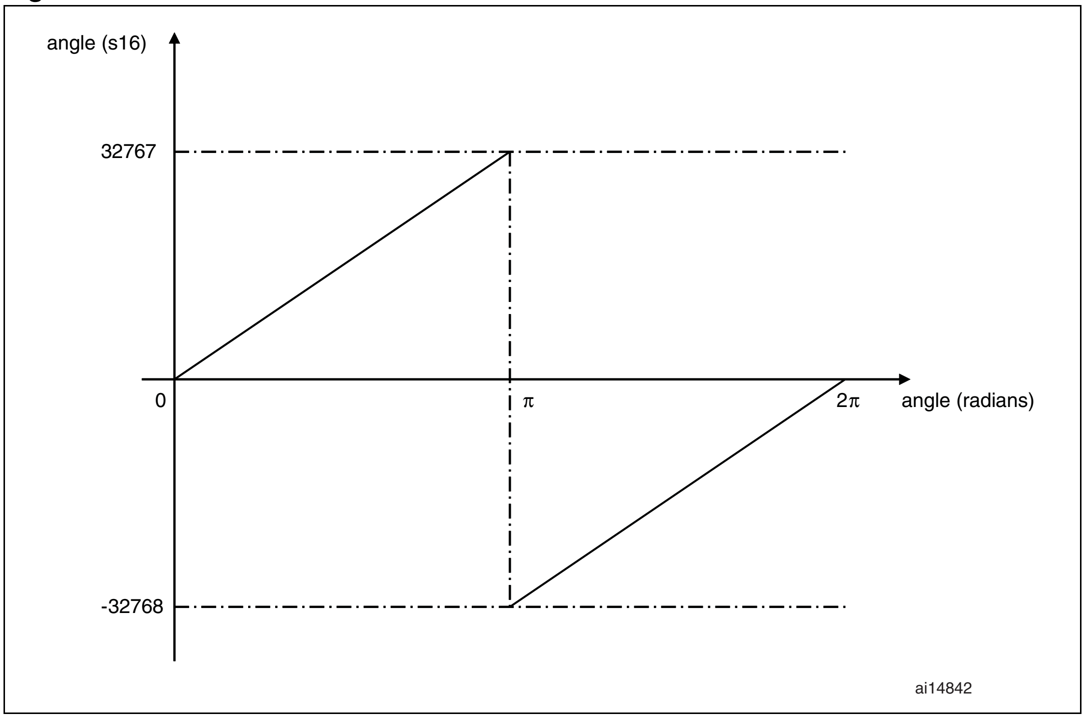
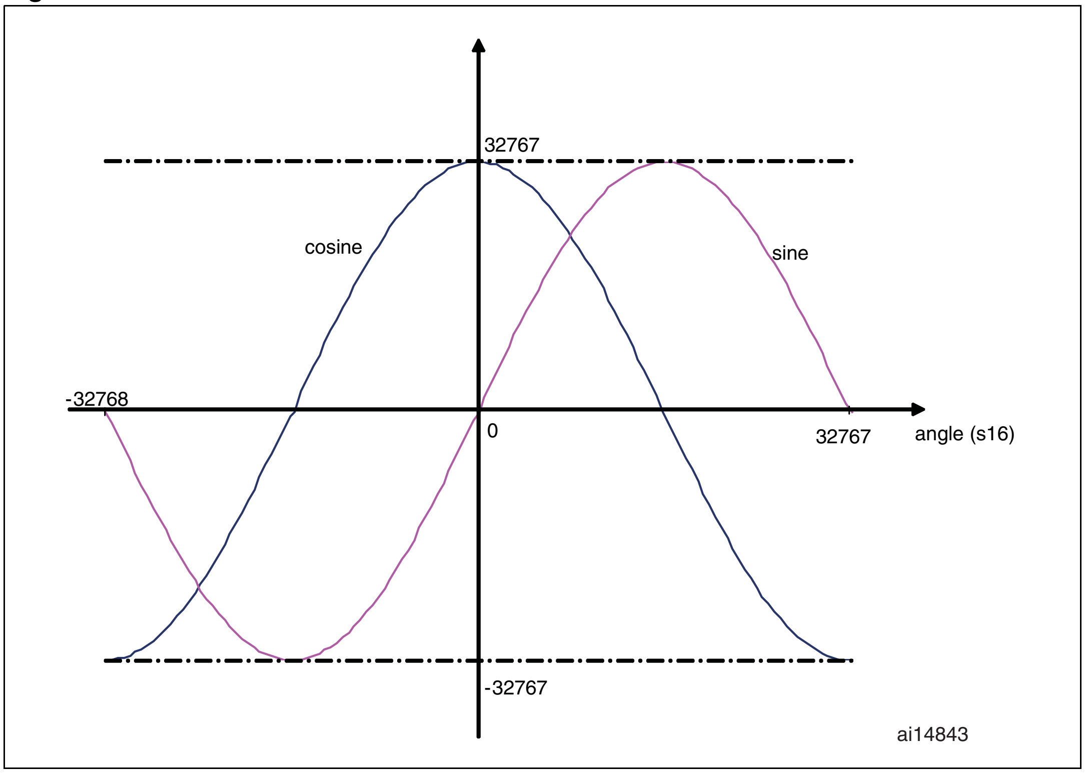


Figure 59. s16 versus sine and cosine



5.5.2 Detailed explanation about reference frame transformations

PM synchronous motors show very complex and time-varying voltage equations.

By making a change of variables that refers stator quantities to a frame of reference synchronous with the rotor, it is possible to reduce the complexity of these equations.

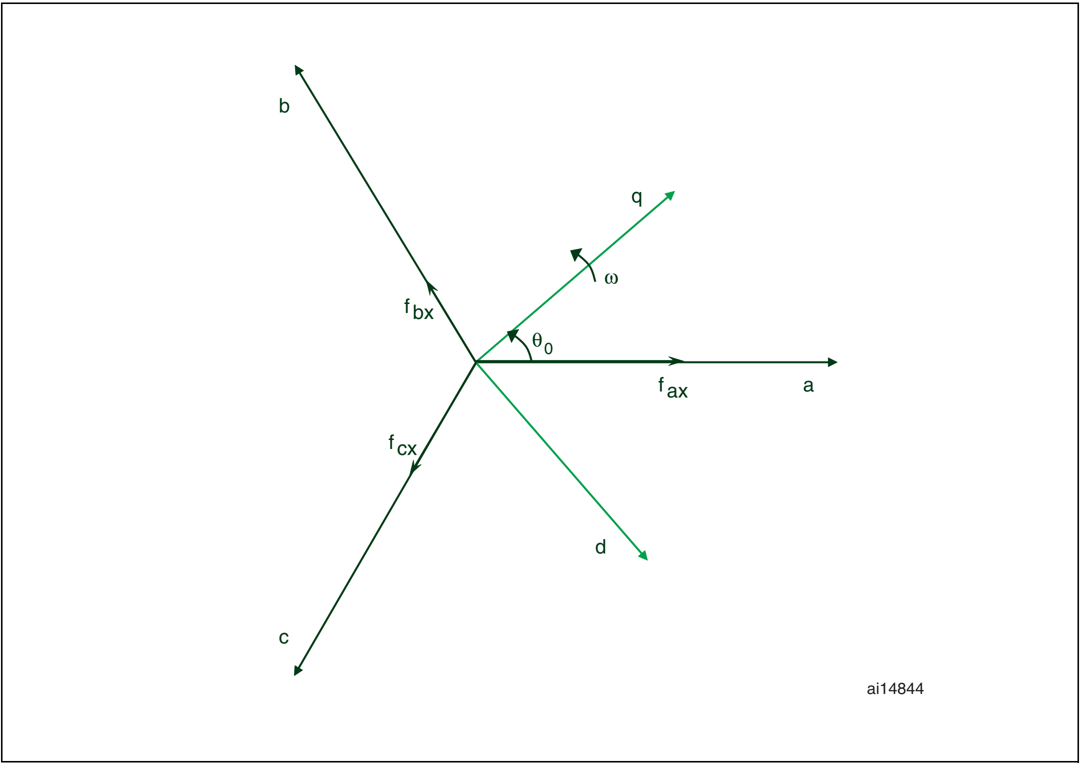
This strategy is often referred to as the Reference-Frame theory [1].

Supposing f_{ax}, f_{bx}, f_{cx} are three-phase instantaneous quantities directed along axis each displaced by 120 degrees, where x can be replaced with s or r to treat stator or rotor quantities (see *Figure 60*); supposing f_{qx}, f_{dx}, f_{0x} are their transformations, directed along paths orthogonal to each other; the equations of transformation to a reference frame (rotating at an arbitrary angular velocity ω) can be expressed as:

$$f_{qdox} = \begin{bmatrix} f_{qx} \\ f_{dx} \\ f_{0x} \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} f_{ax} \\ f_{bx} \\ f_{cx} \end{bmatrix}$$

where θ is the angular displacement of the (q, d) reference frame at the time of observation, and θ_0 that displacement at t=0 (see *Figure 60*).

Figure 60. Transformation from an *abc* stationary frame to a rotating frame (q, d)



With Clark's transformation, stator currents i_{as} and i_{bs} (which are directed along axes each displaced by 120 degrees) are resolved into currents $i\alpha$ and $i\beta$ on a stationary reference frame (α β).

Appropriate substitution into the general equations (given above) yields:

$$i_\alpha = i_{as}$$

$$i_\beta = -\frac{i_{as} + 2i_{bs}}{\sqrt{3}}$$

In Park's change of variables, stator currents i_α and i_β, which belong to a stationary reference frame (α β), are resolved to a reference frame synchronous with the rotor and oriented so that the d-axis is aligned with the permanent magnets flux, so as to obtain i_{qs} and i_{ds}.

Consequently, with this choice of reference, we have:

$$i_{qs} = i_\alpha \cos\theta_r - i_\beta \sin\theta_r$$
$$i_{ds} = i_\alpha \sin\theta_r + i_\beta \cos\theta_r$$

On the other hand, reverse Park transformation takes back stator voltage v_q and v_d, belonging to a rotating frame synchronous and properly oriented with the rotor, to a stationary reference frame, so as to obtain v_α and v_β:

$$v_\alpha = v_{qs} \cos\theta_r + v_{ds} \sin\theta_r$$
$$v_\beta = -v_{qs} \sin\theta_r + v_{ds} \cos\theta_r$$

5.5.3 Circle limitation

As discussed above, FOC allows to separately control the torque and the flux of a 3-phase permanent magnet motor. After the two new values(v_d^* and v_q^*) of the stator voltage producing flux and torque components of the stator current, have been independently computed by flux and torque PIDs, it is necessary to saturate the magnitude of the resulting vector ($|\vec{v}^*|$) before passing them to the Reverse Park transformation and, finally, to the SVPWM block.

The saturation boundary is normally given by the value (S16_MAX=32767) which produces the maximum output voltage magnitude (corresponding to a duty cycle going from 0% to 100%).

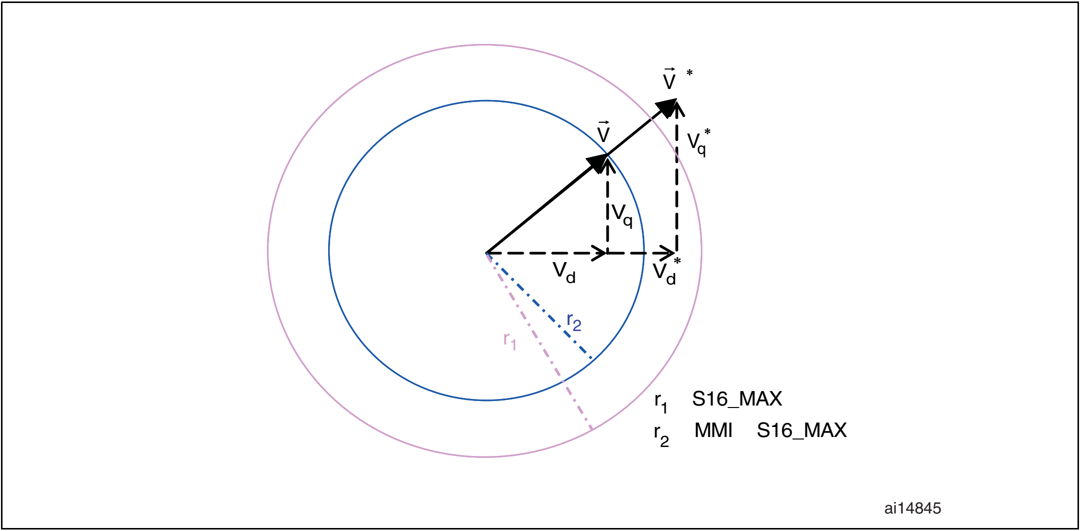
Nevertheless, when using a single-shunt or three-shunt resistor configuration and depending on PWM frequency, it might be necessary to limit the maximum PWM duty cycle to guarantee the proper functioning of the stator currents reading block.

For this reason, the saturation boundary could be a value slightly lower than S16_MAX depending on PWM switching frequency when using a single-shunt or three-shunt resistor configuration.

Table 2 on page 73 and *Table 4 on page 82* show the maximum applicable modulation index as a function of the PWM switching frequency when using the STM3210B-MCKIT in three- and single-shunt topology, respectively. Appendix *A.8: MMI (maximum modulation index): automatic calculation* explains how to calculate the MMI (maximum modulation index) for given PWM frequency and noise parameters.

The `RevPark_Circle_Limitation` function performs the discussed stator voltage components saturation, as illustrated in *Figure 61*.

Figure 61. Circle limitation working principle



V_d and V_q represent the saturated stator voltage components to be passed to the Reverse Park transformation function, while V_d* and V_q*are the outputs of the PID current controllers. From geometrical considerations, it is possible to draw the following relationship:

$$V_d = \frac{V_d^* \cdot \text{ MMI} \cdot \text{ S16\_MAX}}{|\vec{V}^*|}$$

$$V_q = \frac{V_q^* \cdot \text{ MMI} \cdot \text{ S16\_MAX}}{|\vec{V}^*|}$$

In order to speed up the computation of the above equations while keeping an adequate resolution, the value

$$\frac{\text{MMI} \cdot \text{ S16\_MAX}^2}{|\vec{V}^*|}$$

is computed and stored in a look-up table for different values of $|\vec{V}^*|$. Furthermore, considering that MMI depends on the selected PWM frequency, a number of look-up tables are stored in `MC_Clarke_Park.c` (with MMI ranging from 91 to 100).

Once you have selected the required PWM switching frequency, you should uncomment the Max Modulation Index definition corresponding to the selected PWM frequency in the `MC_Control_Param.h` definition list shown below.

```
//#define MAX_MODULATION_100_PER_CENT    // up to 11.4 kHz PWM frequency
//#define MAX_MODULATION_99_PER_CENT      // up to 11.8 kHz PWM frequency
//#define MAX_MODULATION_98_PER_CENT      // up to 12.2 kHz PWM frequency
//#define MAX_MODULATION_97_PER_CENT      // up to 12.9 kHz PWM frequency
//#define MAX_MODULATION_96_PER_CENT      // up to 14.4 kHz PWM frequency
//#define MAX_MODULATION_95_PER_CENT      // up to 14.8 kHz PWM frequency
//#define MAX_MODULATION_94_PER_CENT      // up to 15.2 kHz PWM frequency
//#define MAX_MODULATION_93_PER_CENT      // up to 16.7 kHz PWM frequency
//#define MAX_MODULATION_92_PER_CENT      // up to 17.1 kHz PWM frequency
//#define MAX_MODULATION_91_PER_CENT      // up to 17.5 kHz PWM frequency
```

For information on selecting the PWM switching frequency, you will find advice in *Section A.2 on page 136*. To determine the max modulation index corresponding to the PWM switching frequency, refer to *Table 2 on page 73* and *Table 4 on page 82*. As said before, if ICSs are used, it is allowed to select a 100% MMI, regardless of the chosen PWM frequency.

5.6 Encoder feedback processing: `stm32f10x_encoder` module

5.6.1 List of available functions and interrupt service routines

The following is a list of available functions as listed in the `stm32f10x_encoder.h` header file:

- *ENC_Init on page 103*
- *ENC_Get_Electrical_Angle on page 103*
- *ENC_Get_Mechanical_Angle on page 104*
- *ENC_ResetEncoder on page 104*
- *ENC_Clear_Speed_Buffer on page 104*
- *ENC_Get_Mechanical_Speed on page 104*
- *ENC_Calc_Average_Speed on page 105*
- *ENC_ErrorOnFeedback on page 105*
- *ENC_Start_Up on page 105*

`ENC_Init`

Synopsis	void ENC_Init(void)
Description	The purpose of this function is to initialize the encoder timer. The peripheral clock, input pins and update interrupt are enabled. The peripheral is configured in 4X mode, which means that the counter is incremented/decremented on the rising/falling edges of both timer input 1 and 2 (TIMx_CH1 and TIMx_CH2 pins).
Functions called	RCC_APB1PeriphClockCmd, RCC_APB2PeriphClockCmd, GPIO_StructInit, GPIO_Init, NVIC_Init, TIM_DeInit, TIM_TimeBaseStructInit, TIM_TimeBaseInit, TIM_EncoderInterfaceConfig, TIM_ICInit, TIM_ClearFlag, TIM_ITConfig, TIM_Cmd
See also	STM32F103xx reference manual: TIMx in encoder interface mode

`ENC_Get_Electrical_Angle`

Synopsis	s16 ENC_Get_Electrical_Angle(void)
Description	This function returns the electrical angle in signed 16-bit format. This routine returns: 0 for 0 degrees, -32768 (S16_MIN) for -180 degrees, +32767 (S16_MAX) for +180 degrees.
Input	None
Output	Signed 16 bits
Functions called	None

ENC_Get_Mechanical_Angle

Synopsis	s16 ENC_Get_Mechanical_Angle(void)
Description	This function returns the mechanical angle in signed 16-bit format. This routine returns: 0 for 0 degrees, -32768 (S16_MIN) for -180 degrees, +32767 (S16_MAX) for +180 degrees.
Input	None
Output	Signed 16 bits
Functions called	None
Note	Link between Electrical/Mechanical frequency/RPM: Electrical frequency = number of pair poles x mechanical frequency RPM speed = 60 x Mechanical frequency (RPM: revolutions per minute) **Example**: electrical frequency = 100 Hz, motor with 8 pair poles: *100Hz electrical <-> 100/8 =12.5Hz mechanical <-> 12.5 x 60=750 RPM*

ENC_ResetEncoder

Synopsis	void ENC_resetEncoder(void)
Description	This function writes into the encoder timer register the value corresponding to the alignment angle set in MC_encoder_param.h. It is called at the end of any alignment phase.
Functions called	None

ENC_Clear_Speed_Buffer

Synopsis	void ENC_Clear_Speed_Buffer(void)
Description	This function resets the buffer used for speed averaging.
Functions called	None

ENC_Get_Mechanical_Speed

Synopsis	s16 ENC_Get_Mechanical_Speed(void)
Description	This function returns the rotor speed in Hz. The value returned is given with 0.1Hz resolution, which means that 1234 is equal to 123.4 Hz.
Input	None
Output	Signed 16 bits
Functions called	None
Note	This routine returns the mechanical frequency of the rotor. To find the electrical speed, use the following conversion: *electrical frequency = number of pole pairs * mechanical frequency*

`ENC_Calc_Average_Speed`

Synopsis	void ENC_Calc_Average_Speed(void)
Description	This function must be called every `SPEED_MEAS_TIMEBASE` ms; it computes the latest speed measurement, if it is out of the range specified in `MC_encoder_param.h`, then the error counter is incremented and the speed is saturated. Furthermore, if the error counter is higher than `MAXIMUM_ERROR_NUMBER`, the boolean variable storing the error status is set. Finally, the new average value is computed based on the latest `SPEED_BUFFER_SIZE` speed measurement. The user can disregard the warning message ‘pointless comparison of unsigned integer with zero’ that is issued by the compiler if MINIMUM_MECHANICAL_SPEED_RPM has been set to zero.
Functions called	ENC_Calc_Rot_Speed
Input	None
Returns	None

`ENC_ErrorOnFeedback`

Synopsis	bool ENC_ErrorOnFeedback(void)
Description	This function simply returns the status of the boolean variable containing the speed measurement error status which is updated every `SPEED_MEAS_TIMEBASE` ms by the `ENC_Calc_Average_Speed` function. In the proposed firmware library this function is called in Run state by the main to check for possible faults of the speed feedback (such as disconnected encoder wires).
Functions called	None
Input	None
Returns	boolean, TRUE if an error occurred, FALSE otherwise.

`ENC_Start_Up`

Synopsis	void ENC_Start_Up (void)
Description	The purpose of this function is to perform the regulation of torque and flux stator current component (Iq and Id) during the alignment phase of the PMSM. The function also updates the main state machine (from Start to Run) at the end of the alignment.
Functions called	SVPWM_3ShuntGetPhaseCurrentValues or SVPWM_IcsGetPhaseCurrentValues, Clarke, Park, PID_Regulator, RevPark_Circle_Limitation, SVPWM_IcsCalcDutyCycles or SVPWM_3ShuntCalcDutyCycles, ENC_ResetEncoder, ENC_Clear_Speed_Buffer
Input	None
Returns	None

5.7 Hall sensor feedback processing: `stm32f10x_hall` module

5.7.1 List of available functions

The following is a list of available functions as listed in the `stm32f10x_hall.h` header file:

- *HALL_HallTimerInit on page 106*
- *HALL_GetRotorFreq on page 107*
- *HALL_GetSpeed on page 107*
- *HALL_InitHallMeasure on page 108*
- *HALL_IsTimedOut on page 108*
- *HALL_GetElectricalAngle on page 108*
- *HALL_IncElectricalAngle on page 109*
- *HALL_Init_Electrical_Angle on page 109*
- *HALL_ClrTimeOut on page 109*

HALL_HallTimerInit

Synopsis	void HALL_HallTimerInit(void)
Description	The purpose of this function is to initialize the peripherals involved in Hall sensor feedback processing. In particular, GPIO input pins connected to the Hall sensors are initialized as floating inputs, timer TIMx is configured in “clear on capture” mode and its XOR input function is enabled, the prescaler is initialized with HALL_MAX_RATIO. Finally TIMx input capture (on negative edge of the XORed signal) and overflow (Update) event interrupts are enabled.
Functions called	RCC_APB1PeriphClockCmd, RCC_APB2PeriphClockCmd, GPIO_StructInit, GPIO_Init, TIM_DeInit, TIM_TimeBaseStructInit, TIM_TimeBaseInit, TIM_ICStructInit, TIM_ICInit, TIM_PrescalerConfig, TIM_InternalClockConfig, TIM_SelectHallSensor, TIM_SelectInputTrigger, TIM_SelectSlaveMode, TIM_UpdateRequestConfig, NVIC_Init, TIM_ClearFlag, TIM_ITConfig, TIM_SetCounter, TIM_Cmd
See also	STM32F103xx reference manual, section “Interfacing with Hall sensors”

`HALL_GetRotorFreq`

Synopsis s16 HALL_GetRotorFreq (void)

Description This routine computes the rotor electrical frequency in dpp format starting from the array storing the latest period measurements and according to the following formula:

$$\omega_{dpp} = \frac{CKTIM \cdot 2^{16}}{3 \cdot SAMPLING\_FREQ \cdot \text{captured value} \cdot \text{prescaler value}}$$

where CKTIM is the timer peripheral clock and `SAMPLING_FREQ` is the sampling rate of the FOC algorithm. Be aware that speed is assumed to be zero if either the prescaler is equal to the maximum or a timeout occurred. Please refer to *Section 5.7.2* for more detailed explanation of the operating principle utilized for speed measuring.

Functions called GetAvrgHallPeriod or GetLastHallPeriod.

Input None

Returns It returns the electrical frequency in dpp unit. Format is s16.

See also Appendix *A.7: Speed formats* for more information about dpp unit

`HALL_GetSpeed`

Synopsis s16 HALL_GetSpeed (void)

Description This routine computes the rotor mechanical frequency in 0.1 Hz format starting from the array storing the latest period measurements and according to the following formula:

$$\omega_{dpp} = \frac{CKTIM \cdot 10}{3 \cdot POLE\_PAIR\_NUM \cdot \text{captured value} \cdot \text{prescaler value}}$$

Where CKTIM is the timer peripheral clock and POLE_PAIR_NUM is the number of pole pairs. Be aware that returned value is zero if the prescaler is equal to the maximum or a timeout occurred, and that excessive speed (or high frequency glitches) will result in a predefined value being returned (HALL_MAX_SPEED).

Functions called GetAvrgHallPeriod or GetLastHallPeriod.

Input None

Returns It returns the mechanical speed in 0.1Hz unit. Format is s16

`HALL_InitHallMeasure`

Synopsis	void HALL_InitHallMeasure(void)
Description	It clears software FIFO where latest speed information is "pushed". This function must be called before starting the motor to initialize the speed measurement process.
Functions called	HALL_ClrCaptCounter, TIM_SetCounter, TIM_Cmd, TIM_ITConfig
Input	None
Returns	None
See also	*Section A.7* for more information about dpp unit

`HALL_IsTimedOut`

Synopsis	bool HALL_IsTimedOut(void)
Description	This function simply returns the status of the boolean variable containing the speed measurement timeout status. In the proposed firmware library this function is called in Run state by the main.c to check for possible faults of the speed feedback (such as disconnected wires).
Functions called	None
Input	None
Returns	boolean, TRUE a timeout occurred, FALSE otherwise

`HALL_GetElectricalAngle`

Synopsis	s16 HALL_GetElectricalAngle(void)
Description	This function exports the private variable containing the rotor electrical angle information. In the present library, this function is called by FOC algorithm since the rotor electrical angle is indispensable for performing Park transformation of stator currents
Functions called	None
Input	None
Returns	electrical angle, s16 format
See also	*Section 5.5.3* for detailed explanation about reference frame transformations

`HALL_IncElectricalAngle`

Synopsis	void HALL_IncElectricalAngle(void)
Description	As will be discussed later, the software variable containing the rotor electrical angle information is synchronized with the feedback coming from the motor at each valid transition of the XOR of the three Hall sensor output. In addition, in order to increase the accuracy between two successive valid transitions, the rotor electrical angle information is incremented each time the FOC algorithm is executed (FOC_Module routine) by accumulating the latest speed measurement (dpp format). The HALL_IncElectricalAngle function performs the accumulation of the speed and must consequently be called with the same sampling rate than the FOC algorithm.
Functions called	None
Input	None
Returns	None

`HALL_Init_Electrical_Angle`

Synopsis	void HALL_Init_Electrical_Angle(void)
Description	Hall effect sensors are “absolute” and it is thus possible to reconstruct the rotor position by simply reading the set of their outputs. This operating principle is utilized in this software function to initialize the software variable containing the present electrical angle before any motor startup. The function acts by reading the state of H3, H2 and H1 signal (task performed by private function ReadHallState) and consequently initializing the software variable. The maximum obtainable accuracy is ±30 electrical degrees (that is 30/POLE_PAIR_NUM mechanical degrees).
Input	None
Returns	None

`HALL_ClrTimeOut`

Synopsis	HALL_ClrTimeOut
Description	This function sets to FALSE the boolean variable containing the timeout error flag indicating that information was lost, or speed is decreasing sharply.
Functions called	None
Input	None
Returns	None

5.7.2 Speed measurement implementation

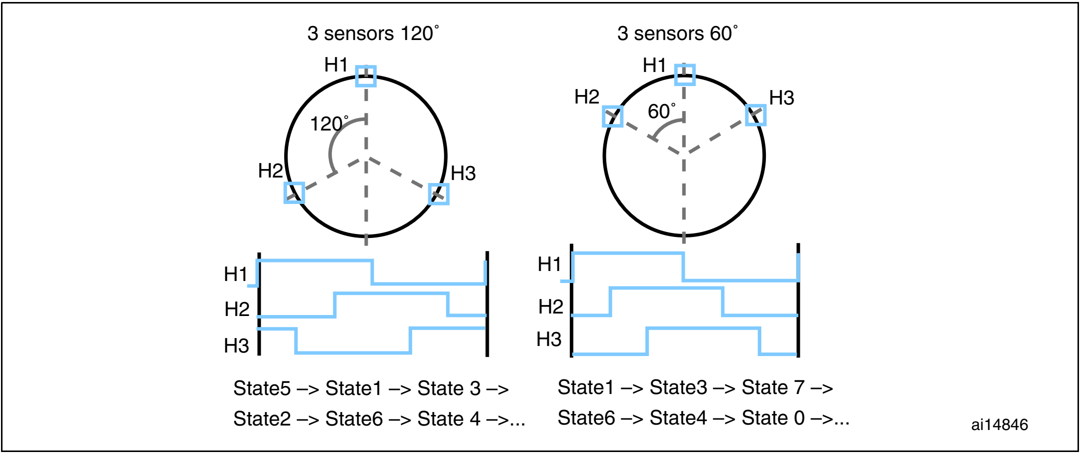
Thanks to the STM32F103xx general-purpose timer (TIMx) features, it is very simple to interface the microcontroller with three Hall sensors. In fact, when the TI1S bit in the TIMx_CR2 register is set, the three signals on the TIMx_CH1, TIMx_CH2 and TIMx_CH3 pins are XORed and the resulting signal is input to the logic performing TIMx input capture.

In this way, the speed measurement is converted into the period measurement of a square wave having a frequency three times higher than the real electrical frequency. The only exception is that the rolling direction, which is not extractable from the XORed signal, is on the contrary performed by directly accessing the three Hall sensor output.

Rolling direction identification

As shown in *Figure 62* it is possible to associate any of Hall sensor output combinations with a state whose number is obtainable by considering H3-H2-H1 as a three-digit binary number (H3 is the most significant bit).

Figure 62. Hall sensors, output-state correspondence


3 sensors 120˚
H1
120˚
H2
H3
H1
H2
H3
State5 –> State1 –> State 3 –>
State2 –> State6 –> State 4 –>...
3 sensors 60˚
H1
H2
60˚
H3
H1
H2
H3
State1 –> State3 –> State 7 –>
State6 –> State4 –> State 0 –>...
ai14846

Consequently, it is possible to reconstruct the rolling direction of the rotor by comparing the present state with the previous one, and considering that in presence of a positive speed, the sequence must be the one illustrated in *Figure 62*.

Period measurement

Although the principle for measuring a period with a timer is quite simple, it is important to keep the best resolution, in particular for signals, such as the one under consideration, that can vary with a ratio that can easily reach 1:1000.

In order to always have the best resolution, the timer clock prescaler is constantly adjusted in the current implementation.

The basic principle is to speed up the timer if the captured values are too low (for an example of short periods, see *Figure 63*), and to slow it down when the timer overflows between two consecutive captures (see example of large periods in *Figure 64*).

Figure 63. Hall sensor timer interface prescaler decrease

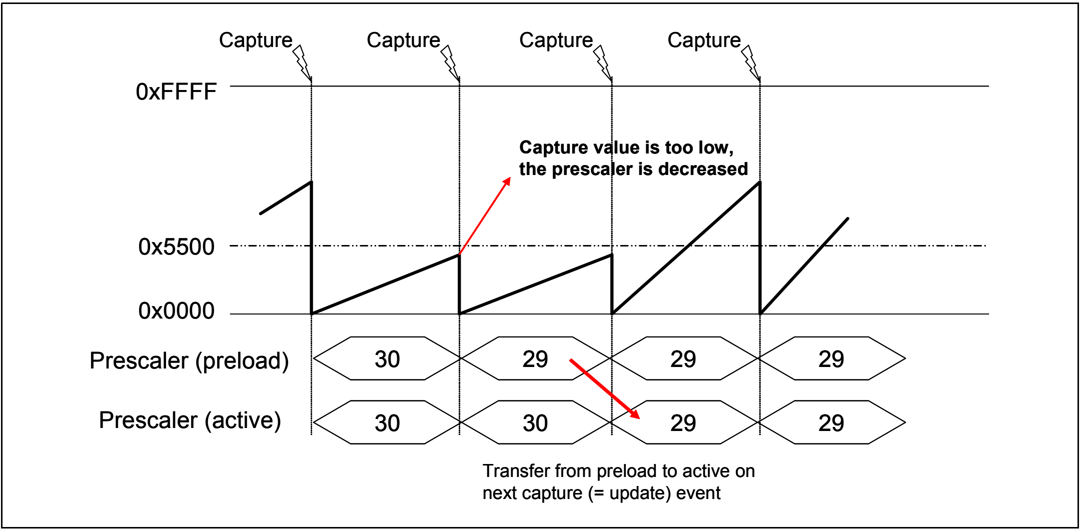
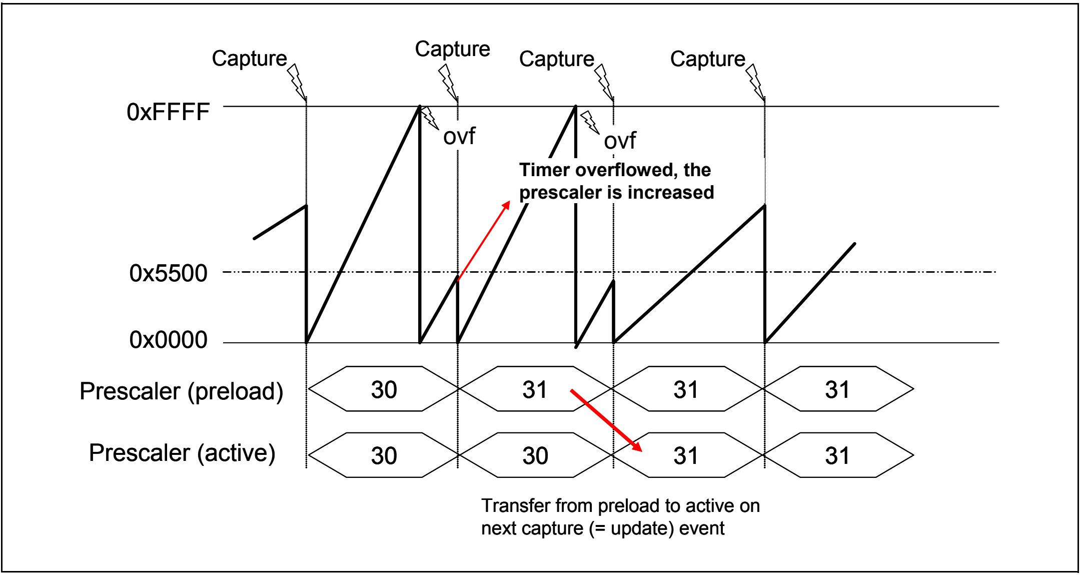

Capture
Capture
Capture
Capture
0xFFFF
Capture value is too low, the prescaler is decreased
0x5500
0x0000
Prescaler (preload)
30
29
29
29
Prescaler (active)
30
30
29
29
Transfer from preload to active on next capture (= update) event

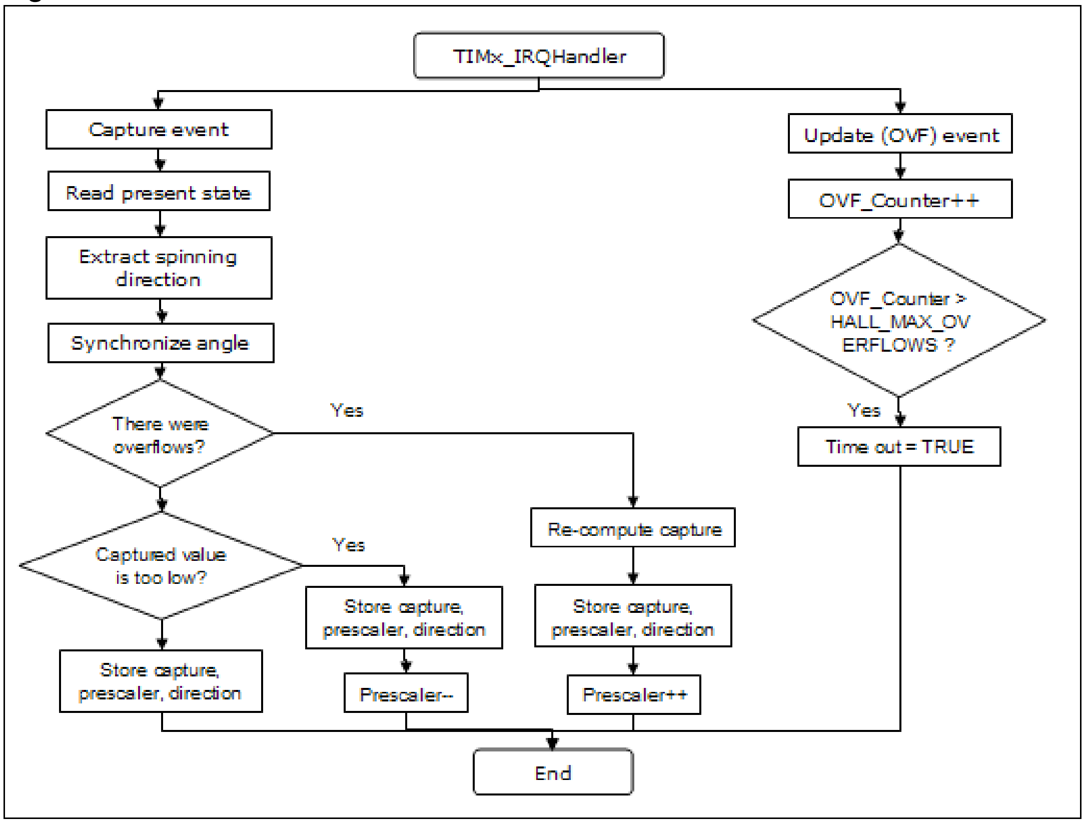
Figure 64. Hall sensor timer interface prescaler increase


Capture
Capture
Capture
Capture
0xFFFF
ovf
ovf
Timer overflowed, the prescaler is increased
0x5500
0x0000
Prescaler (preload)
30
31
31
31
Prescaler (active)
30
30
31
31
Transfer from preload to active on next capture (= update) event

The prescaler modification is done in the capture interrupt, taking advantage of the buffered registers: the new prescaler value is taken into account only on the next capture event, by the hardware, without disturbing the measurement.

Further details are provided in the flowchart shown in *Figure 65*, which summarizes the actions taken into the TIMx_IRQHandler.

Figure 65. TIMx_IRQHandler flowchart

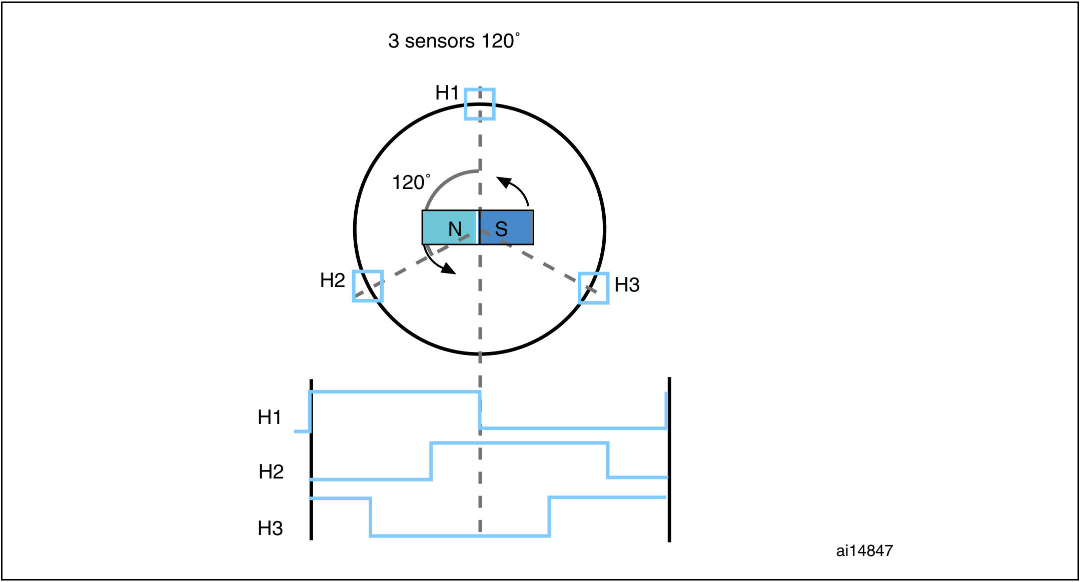

TIMx_IRQHandler
Capture event
Read present state
Extract spinning direction
Synchronize angle
There were overflows?
Yes
Captured value is too low?
Yes
Store capture, prescaler, direction
Store capture, prescaler, direction
Prescaler--
Re-compute capture
Store capture, prescaler, direction
Prescaler++
Update (OVF) event
OVF_Counter++
OVF_Counter > HALL_MAX_OVERFLOWS ?
Yes
Time out = TRUE
End

5.7.3 Electrical angle extrapolation implementation

As shown in *Figure 65*, the speed measurement is not the only task performed in TIMx_IRQHandler. Beside the speed measurement, the high-to-low transition of the XORed signal also gives the possibility of synchronizing the software variable containing the present electrical angle.

In fact, as can be seen in *Figure 66* any Hall sensor transition gives very precise information about rotor position.

Figure 66. Hall sensor output transitions



For this reason, in the proposed solution, the electrical angle is synchronized every time an IC occurs with an angle depending on the present state on the Hall sensor output, spinning direction and `PHASE_SHIFT` (see also *Section 3.12* for indications on how to measure it).

Furthermore, the utilization of the FOC algorithm implies the need for a good and constant rotor position accuracy, including between two consecutive falling edges of the XORed signal (which occurs each 120 electrical degrees). For this reason it is clearly necessary to somehow interpolate rotor electrical angle information. For this purpose, the latest available speed measurement in dpp format is added to the present electrical angle software variable value any time the FOC algorithm is executed.

5.8 Sensorless speed / position detection: `MC_State_Observer` and `MC_State_Observer_Interface` modules

The `MC_State_Observer` module, designed for permanent-magnet synchronous motors, implements a back-emf state observer and a phase-locked loop (PLL). It is able to detect rotor angular position and speed.

In addition, the module processes the output data and, by doing so, implements a safety feature that detects locked-rotor condition or malfunctioning.

The `MC_State_Observer_Interface` module acts as an interface with the first, providing motor parameters and state observer default gains.

The `MC_State_Observer` module, which is the engine of the sensorless algorithm, is provided as a compiled object file; the source code is available free of charge from ST on request: please, contact your nearest ST sales office.

5.8.1 List of available C functions

The following is a list of available functions as listed in the `MC_State_Observer_Interface.h` and `MC_State_Observer.h` header files:

- *STO_Init on page 114*
- *STO_StateObserverInterface_Init on page 115*
- *STO_Obs_Gains_Update on page 115*
- *STO_Calc_Rotor_Angle on page 115*
- *STO_Calc_Speed on page 116*
- *STO_InitSpeedBuffer on page 116*
- *STO_Get_Electrical_Angle on page 116*
- *STO_Get_Mechanical_Angle on page 116*
- *STO_Get_Speed on page 117*
- *STO_Get_Speed_Hz on page 117*
- *STO_IsSpeed_Reliable on page 117*
- *STO_Check_Speed_Reliability on page 117*
- *STO_Start_Up on page 118*
- *STO_Get_wIalfa_est on page 118*
- *STO_Get_wIbeta_est on page 118*
- *STO_Get_wBemf_alfa_est on page 118*
- *STO_Get_wBemf_beta_est on page 119*
- *STO_Gains_Init on page 119*
- *STO_Gains_Update on page 119*

STO_Init

Synopsis	void STO_Init(void)
Description	It initializes to proper values all the variables related to the state observer. To be called once before every motor startup.
Input	None
Returns	None
Note	In the demo program, it is called during the INIT state.

`STO_StateObserverInterface_Init`

Synopsis	void STO_StateObserverInterface_Init(void)
Description	This function initializes the Sensorless algorithm according to motor parameters, default state observer gain vector (K1,K2) and PLL gains; data are retrieved in the MC_State_Observer_param.h, MC_PMSM_motor_param.h header files.
Input	None
Returns	None
Note	During runtime, using the `STO_Obs_Gains_Update` function, it is possible, at any time, to overwrite these initial settings, modifying observer and PLL gains.

`STO_Obs_Gains_Update`

Synopsis	void STO_Obs_Gains_Update(void)
Description	The purpose of this function is to modify the state observer and PLL gains, previously set by STO_StateObserverInterface_Init.
Input	None
Returns	None
Note	In the demo program, by uncommenting `OBSERVER_GAIN_TUNING` in stm32f10xMCconf.h, it is possible (through `STO_Obs_Gains_Update`) to fine tune the sensorless algorithm.

`STO_Calc_Rotor_Angle`

Synopsis	void STO_Calc_Rotor_Angle(Volt_Components Stat_Volt_alfa_beta, Curr_Components Stat_Curr_alfa_beta, s16 hBusVoltage)
Description	It is the core of the module as it implements the State observer; this function has to be called with the same periodicity of stator current sampling (in the demo program, since that periodicity coincides with the FOC execution rate, as discussed in *Section 4.2*, it is called from inside the FOC routine). It gets the measured stator currents (Stat_Curr_alfa_beta), the applied voltage commands (Stat_Volt_alfa_beta), and the measured DC bus voltage (hBusVoltage) as inputs at step k; as a result, it carries out step k+1 of the discretized state observer equations, thus achieving estimation of the motor back-emf (e_α and e_β). Consequently, by means of a numerical PLL, back-emfs are processed to calculate rotor speed and angle. Observed back-emfs, observed rotor angle and speed are written into module private variables.
Input	Stator voltage commands v_α and v_β (s16 format), measured stator currents i_α and i_β (s16 format), DC bus voltage (s16 format). See MC_type.h for structure declarations.
Returns	None
Note	See *Section 2.2* for more information about the sensorless algorithm.

`STO_Calc_Speed`

Synopsis	void STO_Calc_Speed(void)
Description	This function has to be called with the timing of the speed loop control (in the demo program it is fixed by the PID_SPEED_SAMPLING_TIME parameter). It undertakes two actions: ● it averages the buffered values of observed speed, storing the result in a module private variable; ● it calculates the population variance of that speed buffer: if the variance is higher than the threshold settled by VARIANCE_THRESHOLD (see *Section 4.5.3*), then speed estimation is declared “not reliable” and a module private flag is raised.
Input	None
Returns	None
Note	None

`STO_InitSpeedBuffer`

Synopsis	void STO_InitSpeedBuffer(void)
Description	This function initializes the buffer used by STO_Calc_Speed to store observed rotor speed. To be called once before every motor startup.
Input	None
Returns	None
Note	In the demo program, it is called during the WAIT and FAULT states.

`STO_Get_Electrical_Angle`

Synopsis	s16 STO_Get_Electrical_Angle(void)
Description	It returns the rotor electrical angle at step k+1, as STO_Calc_Rotor_Angle calculated and stored in a module private variable at time k.
Input	None
Returns	Observed rotor electrical angle (s16 format)
Note	None

`STO_Get_Mechanical_Angle`

Synopsis	s16 STO_Get_Mechanical_Angle(void)
Description	It returns the rotor mechanical angle at step k+1.
Input	None
Returns	Observed rotor mechanical angle (s16 format)
Note	This function relies on STO_Get_Electrical_Angle.

`STO_Get_Speed`

Synopsis	s16 STO_Get_Speed(void)
Description	It returns the rotor electrical speed, as STO_Calc_Speed calculated by averaging the buffered values of observed speed.
Input	None
Returns	Observed rotor electrical speed (dpp format)
Note	See *Section A.7* about the speed format

`STO_Get_Speed_Hz`

Synopsis	s16 STO_Get_Speed_Hz(void)
Description	It returns the rotor mechanical speed.
Input	None
Returns	Observed rotor mechanical speed (Hz*10).
Note	This function relies on `STO_Get_Speed`.

`STO_IsSpeed_Reliable`

Synopsis	bool STO_IsSpeed_Reliable(void)
Description	This routine indicates if the information provided by the sensorless algorithm is reliable. To do so, it checks the module private flag managed by `STO_Calc_Speed`. A FALSE statement is an indication of a malfunctioning in the rotor position reconstruction due, for example, to an improper choice of the observer and/or PLL gains or to a locked-rotor condition.
Input	None
Returns	Boolean, TRUE if the observer provides reliable data.
Note	None

`STO_Check_Speed_Reliability`

Synopsis	bool STO_Check_Speed_Reliability(void)
Description	This routine indicates if the information provided by the sensorless algorithm has remained reliable over time. It should be called with the same speed sampling time periodicity. STO_IsSpeed_Reliable is called: if that function returns FALSE for `RELIABILITY_HYSTERESYS` (MC_State_Observer_param.h) times, then the rotor speed / position detection algorithm is declared not reliable.
Input	None
Returns	Boolean, TRUE if the observer provides reliable data.
Note	This function relies on `STO_IsSpeed_Reliable`.

`STO_Start_Up`

Synopsis	void STO_Start_Up(void)
Description	This function implements a startup procedure to be used to spin the motor when starting from standstill; it has to be called with the same stator currents sampling periodicity. As a result, according to parameters set in MC_State_Observer_param.h (see *Section 4.5.2*), a rotating stator flux is generated by a three-phase symmetrical current, thus causing the rotor to follow. During these operations, the STO_Calc_Rotor_Angle function is called: if the reliability of the observer is within the limits fixed in MC_State_Observer_param.h (see *Section 4.5.3*), the main state machine is allowed to switch to Run.
Input	None
Returns	None
Note	None

`STO_Get_wIalfa_est`

Synopsis	s16 STO_Get_wIalfa_est(void),
Description	This function returns the observed currents i_{α}, as computed at step k by function STO_Calc_Rotor_Angle
Input	None
Returns	Observed currents i_{α} (s16 format).
Note	In the demo program, this function is used only to display the variable of interest through DAC functionality (if enabled in stm32f10xMCConf.h)

`STO_Get_wIbeta_est`

Synopsis	s16 STO_Get_wIbeta_est(void)
Description	This function returns the observed currents i_{β}, as computed at step k by function STO_Calc_Rotor_Angle
Input	None
Returns	Observed currents i_{β} (s16 format).
Note	In the demo program, this function is used only to display the variable of interest through DAC functionality (if enabled in stm32f10xMCConf.h)

`STO_Get_wBemf_alfa_est`

Synopsis	s16 STO_Get_wBemf_alfa_est(void)
Description	This function returns the observed back-emf e_{α}, as computed at step k by function STO_Calc_Rotor_Angle
Input	None
Returns	Observed back-emf e_{α} (s16 format).
Note	In the demo program, this function is used only to display the variable of interest through DAC functionality (if enabled in stm32f10xMCConf.h)

`STO_Get_wBemf_beta_est`

Synopsis	s16 STO_Get_wBemf_beta_est(void)
Description	This function returns the back-emf e_β, as computed at step k by function STO_Calc_Rotor_Angle
Input	None
Returns	Observed back-emf e_β (s16 format)
Note	In the demo program, this function is used only to display the variable of interest through DAC functionality (if enabled in stm32f10xMCConf.h)

`STO_Gains_Init`

Synopsis	void STO_Gains_Init(StateObserver_Const* StateObserver_ConstStruct)
Description	This function is called by `STO_StateObserverInterface_Init` to initialize the Sensorless algorithm according to default parameters defined in MC_State_Observer_param.h
Returns	None
Note	None

`STO_Gains_Update`

Synopsis	void STO_Gains_Update(StateObserver_GainsUpdate* STO_GainsUpdateStruct)
Description	This function is called by `STO_Obs_Gains_Update` to modify state observer and PLL gains.
Returns	None
Note	None

5.9 PID regulators: `MC_PID_regulators` module

The `MC_PID_regulators` module contains all the functions required to implement as many instances of a PID regulator as required by the application, to control currents I_{QS} and I_{DS}, motor speed (in case of Speed control mode) or stator voltages (by means of flux weakening for speeds higher than rated).

Note: The differential terms are calculated as an option by uncommenting `DIFFERENTIAL_TERM_ENABLED` in the library configuration file (Section 4.1).

An instance of a PID regulator is created by declaring and initializing a static variable that is a structure of the PID_Struct_t type (see *MC_type.h* for structure declaration).

5.9.1 List of available functions

The following is a list of available functions in the `MC_PID_regulators` module:

- *PID_Init on page 120*
- *PID_Regulator on page 120*
- *PID_Speed_Coefficients_update on page 121*

`PID_Init`

Synopsis	void PID_Init (PID_Struct_t *PID_Torque, PID_Struct_t *PID_Flux, PID_Struct_t *PID_Speed)
Description	The purpose of this function is to initialize the PIDs for current and speed regulation. For each, a set of default values is loaded: target (speed or current, proportional, integral and derivative gains, lower and upper limiting values for the output.
Input	PID_Struct_t *, PID_Struct_t *, PID_Struct_t * (see *MC_type.h* for structure declarations)
Functions called	None
Note	Default values for PID regulators are declared and can be modified in the MC_Control_Param.h file (see *Section 4.2 on page 46*).

`PID_Regulator`

Synopsis	s16 PID_Regulator(s16 hReference, s16 hPresentFeedback, PID_Struct_t *PID_Struct)
Description	The purpose of this function is, at a certain step K, to compute the output of a PID regulator instance, sum of its proportional, integral and derivative terms (the latter is computed if the `DIFFERENTIAL_TERM_ENABLED` option is uncommented, see *Section 4.1*).
Input	hReference (the desired setpoint), hPresentFeedback (the measured output of the controlled system), PID_Struct_t *PID_Struct (pointer to a PID_Struct_t variable which is the regulator instance itself, as it retains its gains, internal states, integral sum limits and output limits (see *MC_type.h* for structure declarations).
Output	The controller output (signed 16 bits)
Functions called	None
Note	The demo program has several “instances” of this PID regulator; default values for the PID regulation of currents and speed can be modified in the *MC_Control_Param.h* file (see *Section 4.2 on page 46*). The `PID_Regulator` function updates the internal states of the PID regulator instance (integral sum, previous error) through the input pointer to the `PID_Struct_t` variable.

`PID_Speed_Coefficients_update`

Synopsis	void PID_Speed_coefficients_update(s16 motor_speed)
Description	This function automatically computes the proportional, integral and derivative gain for the speed PID regulator according to the actual motor speed. The computation is done following a linear curve based on 4 set points. See *Section 5.9.4 on page 123* for more information.
Functions called	None
Caution	Default values for the four set points are declared and can be modified in the MC_Control_Param.h file (see *Section 4.2 on page 46*).

5.9.2 PID regulator theoretical background

The regulators implemented for Torque, Flux and Speed are actually Proportional Integral Derivative (PID) regulators (see note below regarding the derivative term). PID regulator theory and tuning methods are subjects which have been extensively discussed in technical literature. This section provides a basic reminder of the theory.

PID regulators are useful to maintain a level of torque, flux or speed according to a desired target.

Figure 67. PID general equation

$$\left.\begin{aligned} \text{torque} &= f(\text{rotor position}) \\ \text{flux} &= f(\text{rotor position}) \end{aligned}\right\} \text{torque and flux regulation for maximum system efficiency}$$

$$\text{torque} = f(\text{rotor speed}) \Big\} \text{ torque regulation for speed regulation of the system}$$

Where: $Error_{sys_T}$ Error of the system observed at time t = T

$Error_{sys_{T-1}}$ Error of the system observed at time t = T - Tsampling

$$f(X_T) = K_p \times Error_{sys_T} + K_i \times \sum_{0}^{T} Error_{sys_t} + K_d \times \underbrace{(Error_{sys_T} - Error_{sys_{T-1}})}_{\textit{Derivative term can be disabled}} \quad (1)$$

Equation 1 corresponds to a classical PID implementation, where:

- K_p is the proportional coefficient,
- K_i is the integral coefficient.
- K_d is the differential coefficient.

Note: As mentioned in Figure 67, the derivative term of the PIDs can be disabled (through a compiler option, see `stm32f10x_MCconf.h` file).

5.9.3 Regulator sampling time setting

The sampling time needs to be modified to adjust the regulation bandwidth. As an accumulative term (the integral term) is used in the algorithm, increasing the loop time decreases its effects (accumulation is slower and the integral action on the output is delayed). Inversely, decreasing the loop time increases its effects (accumulation is faster and the integral action on the output is increased). This is why this parameter has to be adjusted prior to setting up any coefficient of the PID regulator.

In order to keep the CPU load as low as possible and as shown in equation (1) in *Figure 67*, the sampling time is directly part of the integral coefficient, thus avoiding an extra multiplication. *Figure 68* describes the link between the time domain and the discrete system.

Figure 68. Time domain to discrete PID equations

Time domain

$$f(t) = K_p \times \mathrm{Error}_{sys}(t) + K_i \times \int_0^t \mathrm{Error}_{sys}(t)dt + K_d \times \frac{d}{dt}(\mathrm{Error}_{sys}(t))$$

$$\Updownarrow$$

Discrete domain

$$f(X_T) = K_p \times \mathrm{Error}_{sys_T} + \boxed{k_i \times T_s} \sum_0^T \mathrm{Error}_{sys_t} + K_d \times (\mathrm{Error}_{sys_T} - \mathrm{Error}_{sys_{T-1}})$$

(sampling done at Fs = 1/Ts frequency)

$$\hookrightarrow k_i \times T_s = K_i$$

In theory, the higher the sampling rate, the better the regulation. In practice, you must keep in mind that:

- The related CPU load will grow accordingly.
- For speed regulation, there is absolutely no need to have a sampling time lower than the refresh rate of the speed information fed back by the external sensors; this becomes especially true when Hall sensors are used while driving the motor at low speed.

As discussed in *Section 4.2 on page 46*, the speed regulation loop sampling time can be customized by editing the `PID_SPEED_SAMPLING_TIME` parameter in the `MC_Control_Param.h` header file. The flux and torque PID regulator sampling rates are given by the relationship

$$\text{Flux and torque PID sampling rate} = \frac{2 \cdot \text{PWM\_FREQ}}{\text{REP\_RATE} + 1}$$

Note: *`REP_RATE` must be an odd number if currents are measured by shunt resistors (see also Section A.2 on page 136); its value is 8-bit long.*

5.9.4 Adjusting speed regulation loop Ki, Kp and Kd vs. motor frequency

Depending on the motor frequency, it might be necessary to use different values of Kp, Ki and Kd.

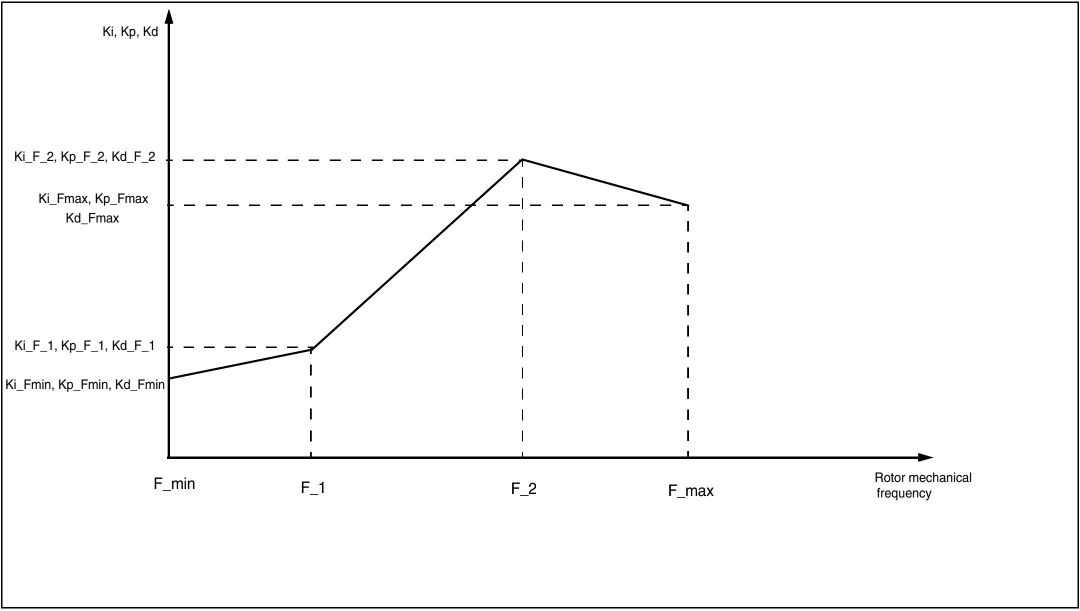
These values have to be input in the code to feed the regulation loop algorithm. A function performing linear interpolation between four set-points (`PID_Speed_Coefficient_update`) is provided as an example in the software library (see `MC_PID_regulators.c`) and can be used in most cases, as long as the coefficient values can be linearized. If that is not possible, a function with a larger number of set-points or a look-up table may be necessary.

To enter the four set-points, once the data are collected, edit the `MC_Control_param.h` file and fill in the field dedicated to the Ki, Kp and Kd coefficient calculation as shown below.

```
//Settings for min frequency
#define Freq_Min   10      // 1 Hz mechanical
#define Ki_Fmin    1000    // Frequency min coefficient settings
#define Kp_Fmin    2000
#define Kd_Fmin    3000

//Settings for intermediate frequency 1
#define F_1                 50 // 5 Hz mechanical
#define Ki_F_1     2000    // Intermediate frequency 1 coefficient settings
#define Kp_F_1     1000
#define Kd_F_1     2500

//Settings for intermediate frequency 2
#define F_2                 200 // 20 Hz mechanical
#define Ki_F_2     1000     // Intermediate frequency 2 coefficient settings
#define Kp_F_2     750
#define Kd_F_2     1200

//Settings for max frequency
#define Freq_Max   500     // 50 Hz mechanical
#define Ki_Fmax    500     // Frequency max coefficient settings
#define Kp_Fmax    500
#define Kd_Fmax    500
```

Once the motor is running, integer, proportional and derivative coefficients are computed following a linear curve between F_min and F_1, F_1 and F_2, F_2 and F_max (see *Figure 69*). Note that F_min, F_1, F_2, F_max are mechanical frequencies, with 0.1 Hz resolution (for example F_1 = 1234 means F_1 = 123.4Hz).

Figure 69. Linear curve for coefficient computation



Disabling the linear curve computation routine, `stm32f10x_Timebase` module

If you want to disable the linear curve computation, you must comment out the `PID_Speed_Coefficients_update(..)` routine. In this case, the default values for Ki, Kp, Kd for torque, flux and speed regulation are used. See `PID_TORQUE_Kx_DEFAULT`, `PID_FLUX_Kx_DEFAULT`, `PID_SPEED_Kx_DEFAULT`, in the `MC_control_Param.h` file.

To disable the linear curve computation routine in `stm32f10x_Timebase.c`:

```
void SysTickHandler(void)
{
    […]
    if ((wGlobal_Flags & SPEED_CONTROL) == SPEED_CONTROL)
    {
      if (State == RUN)
      {
        //PID_Speed_Coefficients_update(XXX_Get_Speed());//to be commented
        […]
      }
    }
    […]
}
```

5.10 General purpose time base: `stm32f10x_Timebase` module

The purpose of the `stm32f10x_Timebase` module is to generate a time base that can be used by the other modules of the applications.

5.10.1 List of available functions and interrupt service routines

The following is a list of available functions as listed in the `stm32f10x_Timebase.h` header file:

- *TB_Init on page 126*
- *TB_Wait on page 126*
- *TB_StartUp_Timeout_IsElapsed, TB_Delay_IsElapsed, TB_DisplayDelay_IsElapsed, TB_DebounceDelay_IsElapsed on page 127*
- *TB_Set_Delay_500us, TB_Set_DisplayDelay_500us, TB_Set_StartUp_Timeout, TB_Set_DebounceDelay_500us on page 126*
- *SysTickHandler on page 127*

`TB_Init`

Synopsis	void TB_Init(void)
Description	The purpose of this function is to initialize the STM32 system tick timer to generate an interrupt every 500 µs, thus providing a general purpose timebase.
Input	None
Returns	None
Functions called	SysTick_CLKSourceConfig, SysTick_SetReload, SysTick_CounterCmd, NVIC_SystemHandlerPriorityConfig, SysTick_ITConfig

`TB_Wait`

Synopsis	void TB_Wait(u16 time)
Description	This function produces a programmable delay equal to variable ‘time’ multiplied by 500µs.
Input	Unsigned 16 bit
Returns	None
Functions called	None
Caution	This routine exits only after the programmed delay has elapsed. Meanwhile, the code execution remains frozen in a waiting loop. Care should be taken when this routine is called at main/interrupt level: a call from an interrupt routine with a higher priority than the timebase interrupt will freeze code execution.

`TB_Set_Delay_500us, TB_Set_DisplayDelay_500us, TB_Set_StartUp_Timeout, TB_Set_DebounceDelay_500us`

Synopsis	void TB_Set_Delay_500us(u16) void TB_Set_DisplayDelay_500us(u16) void TB_Set_StartUp_Timeout(u16) void TB_Set_DebounceDelay_500us
Description	These functions are used to respectively update the values of the hTimebase_500us, hTimebase_display_500us, hStart_Up_TimeBase_500us and hKey_debounce_500us variables. They are used to maintain the main state machine in Fault state, to set the refresh rate of the LCD, the Startup timeout and, to filter the user key bouncing.
Input	Unsigned 16 bits
Returns	None
Functions called	None

`TB_StartUp_Timeout_IsElapsed, TB_Delay_IsElapsed, TB_DisplayDelay_IsElapsed, TB_DebounceDelay_IsElapsed`

Synopsis	bool TB_StartUp_Timeout_IsElapsed(void) bool TB_Delay_IsElapsed(void) bool TB_DisplayDelay_IsElapsed(void) bool TB_DebounceDelay_IsElapsed(void)
Description	These functions return TRUE if the related delay is elapsed, FALSE otherwise.
Input	None
Returns	Boolean
Functions called	None

`SysTickHandler`

Synopsis	void SysTickHandler(void)
Description	This is the System Tick timer interrupt routine. It is executed every 500µs, as determined by TB_Init and is used to refresh various variables used mainly as counters (for example, PID sampling time). Moreover, if `FLUX_TORQUE_PIDs_TUNING` is uncommented in stm32f10xMCConf, it controls the current component reference iq* to generate a square wave of defined period (see *Section 4.1* and Appendix *A.5*).
Input	None
Returns	None
Functions called	**If in speed control mode:** FOC_CalcFluxTorqueRef, (PID_Speed_Coefficients_update) **If in torque control mode:** FOC_TorqueCtrl **If Encoder is used:** ENC_Calc_Average_Speed (if using DAC, ENC_Get_Mechanical_Speed) **If Hall sensors are used:** (if using DAC, HALL_GetSpeed) **if using the sensorless algorithm:** STO_Calc_Speed, STO_Check_Speed_Reliability, MCL_SetFault, STO_Obs_Gains_Update (if using DAC, STO_Get_Speed)
Note	This is an interrupt routine

5.11 Power stage check-up: `MC_MotorControl_Layer` module

5.11.1 List of available functions

The following is a list of available functions as listed in `the MC_MotorControl_Layer.h` header file:

- *MCL_Init on page 128*
- *MCL_ChkPowerStage on page 129*
- *MCL_ClearFault on page 129*
- *MCL_SetFault on page 129*
- *MCL_Chk_OverTemp on page 130*
- *MCL_Chk_BusVolt on page 130*
- *MCL_Compute_BusVolt on page 130*
- *MCL_Compute_Temp on page 130*
- *MCL_Calc_BusVolt on page 131*
- *MCL_Calc_BusVolt on page 131*
- *MCL_Init_Arrays on page 131*
- *MCL_Brake_Init on page 131*
- *MCL_Set_Brake_On on page 132*
- *MCL_Set_Brake_Off on page 132*

`MCL_Init`

Synopsis	void MCL_Init(void)
Description	This function implements the motor control initializations to be performed at each motor start-up; it affects PID regulators, current reading calibration, speed sensors and high side driver boot capacitors initializations.
Functions called	ENC_Clear_Speed_Buffer or HALL_InitHallMeasure and HALL_Init_Electrical_Angle or STO_Init depending on the speed feedback configured, TB_Set_StartUp_Timeout, TIM1_CtrlPWMOutputs, TB_StartUp_Timeout_IsElapsed, SVPWM_3ShuntCurrentReadingCalibration or SVPWM_IcsCurrentReadingCalibration depending on the current feedback configuration, SVPWM_3ShuntCalcDutyCycles or SVPWM_IcsCalcDutyCycles depending on the current feedback configuration
Input	None
Returns	None

`MCL_ChkPowerStage`

Synopsis	void MCL_ChkPowerStage(void)
Description	This function performs checks of the power stage working conditions (only for temperature and bus voltage) and, when required, generates a FAULT event
Functions called	MCL_Chk_OverTemp, MCL_Chk_BusVolt, MCL_SetFault,
Input	None
Returns	None

`MCL_ClearFault`

Synopsis	bool MCL_ClearFault(void)
Description	This function checks if the cause of the fault event is over. In the positive, and if the ‘Key’ button has been pressed, the related flag is cleared and a TRUE is returned. Otherwise a FALSE is returned.
Functions called	TB_Delay_IsElapsed, MCL_Chk_BusVolt, MCL_Chk_OverTemp, GPIO_ReadInputDataBit, KEYS_ExportbKey
Input	None
Returns	TRUE if all the fault flags are cleared and the ‘Key’ button has been pressed by the user, FALSE otherwise.
See also	*Section 3.8: Fault messages*.

`MCL_SetFault`

Synopsis	void MCL_SetFault (u16)
Description	On occurrence of a fault event, this function puts the main state machine in Fault state and disables the motor control outputs of Advanced Control Timer TIM1 (PWM timer).
Functions called	TB_Set_Delay_500us, TIM1_CtrlPWMOutputs, SVPWM_3ShuntAdvCurrentReading in case of three shunt current reading configuration
Input	Source of fault event as defined in MC_const.h.
Returns	None
See also	*Section 3.8: Fault messages*.

`MCL_Chk_OverTemp`

Synopsis	bool MCL_Chk_OverTemp(void)
Description	This function performs the averaging of the latest temperature acquired value by means of the following formula: `XAV(K) = (XAV(K-1)* (T_AV_ARRAY_SIZE-1)+ X(K) )/ T_AV_ARRAY_SIZE`, where X_{AV}(K) is the average at step K, and X(K), the latest measurement at step K. Once the average has been performed, the function checks whether the acquired temperature is within the admitted range or not. The intervention threshold and hysteresis values can be adjusted in MC_Control_Param.h (only for MB459 board).
Input	None
Returns	Returns TRUE if the software-averaged voltage on the thermal resistor connected to ADC channel ADC_IN10 has reached the threshold level (or if it has not yet returned to the threshold level minus the hysteresis value after an overheat detection). Returns FALSE otherwise.

`MCL_Chk_BusVolt`

Synopsis	BusV_t MCL_Chk_BusVolt(void)
Description	This function checks for over and under voltage faults on inverter DC bus. The intervention thresholds can be defined in MC_Control_Param.h (only for MB459 board).
Functions called	None
Input	None
Returns	It returns a BusV_t type variable reporting the fault value

`MCL_Compute_BusVolt`

Synopsis	u16 MCL_Compute_BusVolt(void)
Description	This function computes the DC bus voltage in volt units. In the proposed firmware library this function is utilized for user interfacing.
Input	None
Returns	Bus voltage in volt units

`MCL_Compute_Temp`

Synopsis	u8 MCL_Compute_Temp(void)
Description	This function computes the power stage heat-sink temperature in Celsius degrees (only for MB459 board). In the proposed firmware library this function is utilized for user interfacing.
Input	None
Returns	An integer representing a temperature value expressed in Celsius degrees.

`MCL_Calc_BusVolt`

Synopsis	void MCL_Calc_BusVolt(void)
Description	This function performs the averaging of the latest BUS_AV_ARRAY_SIZE temperature measurement by means of the following formula: $X_{AV}(K) = (X_{AV}(K-1)^{*}$ (`BUS_AV_ARRAY_SIZE-1`) + X(K))/ `BUS_AV_ARRAY_SIZE`, where $X_{AV}(K)$ is the average at step K, and X(K), the latest measurement at step K.
Input	None
Returns	None, the averaged value is written into a module private variable

`MCL_Calc_BusVolt`

Synopsis	s16 MCL_Get_BusVolt(void)
Description	This function simply exports the averaged value of the bus voltage private variable.
Input	None
Returns	Bus voltage in digit**s.**

`MCL_Init_Arrays`

Synopsis	void MCL_Init_Arrays(void)
Description	This function initializes the averaged values of both voltage and temperature. To be called after a MCU reset.
Input	None
Returns	None

`MCL_Brake_Init`

Synopsis	void MCL_Brake_Init(void)
Description	Declared and defined only if the brake resistor feature has been enabled in stm32_MCconf.h, this function initializes the GPIO pin driving the switch for resistive brake implementation (BRAKE_GPIO_PORT, BRAKE_GPIO_PIN are defined in MC_MotorControl_Layer.c). To be called after MCU reset.
Input	None
Returns	None
See also	*Section 3.14* for more detailed information on how to set up your system when using brake resistor**.**

`MCL_Set_Brake_On`

Synopsis	void MCL_Set_Brake_On(void)
Description	Declared and defined only if the brake resistor feature has been enabled in stm32_MCconf.h, it switches on the brake resistor by setting the BRAKE_GPIO_PIN pin of the BRAKE_GPIO_PORT port. The function is called in ADC_IRQHandler every time an analog watchdog interrupt occurs.
Input	None
Returns	None
See also	*Section 3.14* for more detailed information on how to set up your system when using brake resistor.

`MCL_Set_Brake_Off`

Synopsis	void MCL_Set_Brake_Off(void)
Description	Declared and defined only if the brake resistor feature has been enabled in stm32_MCconf.h, this switch off the brake resistor by setting to zero the pin BRAKE_GPIO_PIN of port BRAKE_GPIO_PORT. The function is called in ADC_IRQHandler if both the brake was turned on and the bus voltage went down the threshold specified by BRAKE_HYSTERESIS.
Note	`BRAKE_HYSTERESIS` is defined in stm32f10x_it.c and its default value is 15/16 the over-voltage intervention threshold
Input	None
Returns	None
See also	*Section 3.14* for more detailed information on how to set up your system when using brake resistor.

5.12 Main interrupt service routines: `stm32f10x_it` module

The `stm32f10x_it` module can be used to describe all the exception subroutines that might occur within your application. When an interrupt happens, the software will automatically branch to the corresponding routine accordingly with the interrupt vector table.

With the exception of the ADC, TIM1 Break Input and TIM1 update (if in shunt current reading mode) interrupt requests, all the routines are empty, so that you can write your own code for exception handlers and peripheral interrupt requests.

5.12.1 List of non-empty interrupt service routines

As mentioned above only three interrupts are managed by motor control tasks:

- *TIM1_BRK_IRQHandler on page 133*
- *TIM1_UP_IRQHandler on page 133*
- *ADC1_2_IRQHandler on page 134*

`TIM1_BRK_IRQHandler`

Synopsis	void TIM1_BRK_IRQHandler(void)
Description	The purpose of this function is to manage a break event on the dedicated BREAK pin. In particular, TIM1 outputs are disabled, the main state machine is put into FAULT state.
Input	None.
Returns	None.
Functions called	MCL_SetFault, TIM1_ClearPendingBit
See also	Advanced control timer (TIM1) in STM32F103xx reference manual

`TIM1_UP_IRQHandler`

Synopsis	void TIM1_UP_IRQHandler(void)
Description	This interrupt handler is executed after an update event when an underflow of the TIM1 counter occurs. Inside this handler, the specific SVPWMUpdateEvent routine related to the selected current sampling method (single-shunt, three-shunt or ICS) is called.
Input	None.
Returns	None.
Functions called	ADC_ClearFlag, TIM1_ClearFlag, SVPWMUpdateEvent

`ADC1_2_IRQHandler`

Synopsis	void ADC1_2_IRQHandler(void)
Description	The purpose of this function is to handle the ADC global interrupt request. Two different possible interrupt sources are managed: JEOC (end of conversion injected group), AWD (analog watchdog). JEOC: if the main state machine is in the Start state, it triggers the motor startup procedure (which depends upon the system configuration, see *Section 4.1*); otherwise, if the state is Run, it triggers the execution of the FOC algorithm. If the system configuration includes the brake resistor (see *Section 3.14*), it manages its hysteresis switching (in case of overvoltage). If the DAC functionality is enabled (see *Section 3.6*), it updates the value of the variables of interest. AWD: in the event of an overvoltage, it switches on the brake resistor or generates a fault (OVER_VOLTAGE) depending on whether `BRAKE_RESISTOR` is commented in stm32f10x_MCconf.h, see *Section 4.1* and *Section 3.14*). Inside the handler, the specific SVPWMEOCEvent routine related to the current sampling method (single-shunt, three-shunt or ICS) is called. This routine returns true if the current sampling has completed for this PWM period, so that the FOC-related routines can be executed.
Input	None.
Returns	None.

Functions called	SVPWMEOCEvent, FOC_Model, ADC_GetITStatus, ADC_ClearFlag, MCL_Calc_BusVolt, MCL_SetFault;
	
	if using a brake resistor:
	
	ADC_GetInjectedConversionValue, MCL_Set_Brake_On, MCL_Set_Brake_Off;
	
	if enabling the DAC functionality:
	
	MCDAC_Update_Value, MCDAC_Update_Output;
	
	if using an encoder:
	
	ENC_Start_Up (and, if using DAC, ENC_Get_Electrical_Angle);
	
	if using Hall sensors:
	
	(if using DAC, HALL_IncElectricalAngle, HALL_GetElectricalAngle);
	
	if using the sensorless algorithm:
	
	STO_Start_Up, STO_Calc_Rotor_Angle, MCL_Get_BusVolt (and, if using DAC, STO_Get_Electrical_Angle, STO_Get_wIalfa_est, STO_Get_wIbeta_est, STO_Get_wBemf_alfa_est, STO_Get_wBemf_beta_est)

See also	*Section 5.1* and *Section 5.3* for more details.

Appendix A Additional information

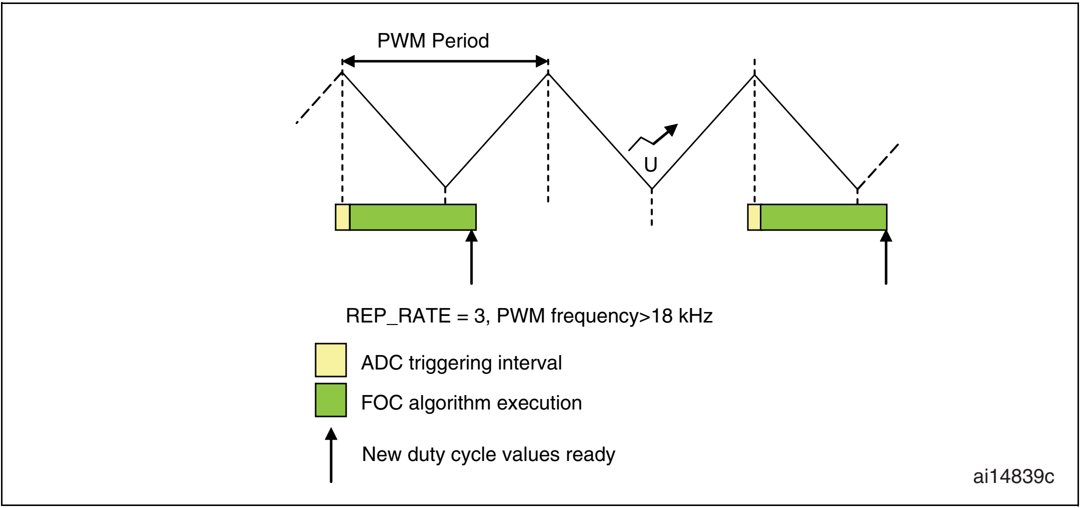
A.1 Adjusting CPU load related to FOC algorithm execution

The advanced control timer (TIM1) peripheral has the built-in capability of updating PWM registers only after a given number of PWM semi-periods. This feature is handled by a programmable repetition counter. It is particularly useful to adjust the CPU load related to FOC algorithm execution for a given PWM frequency (refer to STM32F103xx reference manual for more information on programmable repetition counter).

When using ICS, the injected chain of conversions for current reading is directly triggered by a PWM register update event. Moreover, since the FOC algorithm is executed at the end of the injected chain of conversions in the related ISR, changing repetition counter has a direct impact on FOC refresh rate and thus on CPU load.

However, in the case of single- or three-shunt topology current reading, to ensure that the FOC algorithm is executed once for each PWM register update, it is necessary to keep the synchronization between current conversions triggering and PWM register update. In the proposed software library, this is automatically performed, so that you can reduce the frequency of execution of the FOC algorithm by simply changing the default value of the repetition counter (the `REP_RATE` parameter in the `MC_Control_Param.h` header file). *Figure 70* shows current sampling triggering, and FOC algorithm execution with respect to PWM period when `REP_RATE` is set to 3.

Figure 70. AD conversions for three shunt topology stator currents reading and FOC algorithm execution when REP_RATE=3 and PWM frequency>18 kHz



Note: *Because three shunt resistor topology requires low side switches to be on when performing current reading A/D conversions, the REP_RATE parameter must be an* ***odd*** *number in this case.*

Considering that the raw FOC algorithm execution time is about **20 µs in sensorless and three shunt resistor current reading configuration**, the related contribution to CPU load can be computed as follows:

$$\text{CPU Load}_{\%} = \frac{F_{PWM}}{\text{Refresh\_Rate}} \cdot 20 \cdot 10^{-6} \cdot 100 = \frac{F_{PWM}}{(\text{REP\_RATE} + 1)/2} \cdot 20 \cdot 10^{-6} \cdot 100$$

A.2 Selecting the update repetition rate based on the PWM frequency for single- or three-shunt resistor configuration

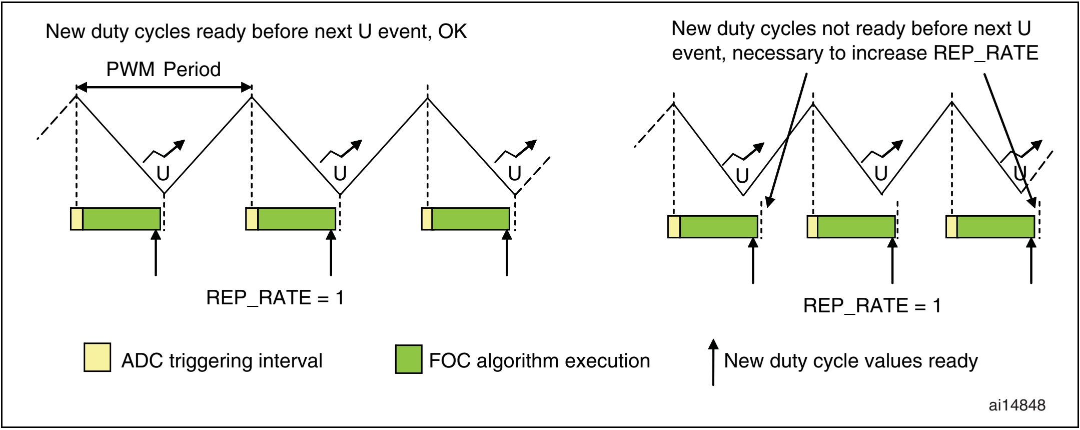
Beyond the well known trade-off between acoustical noise and power dissipation, consideration should be given to selecting the PWM switching frequency using the PMSM FOC software library.

As discussed in *Section 5.1.4 on page 69* and *Section 5.2.4 on page 82*, depending on the PWM switching frequency, a limitation on the maximum applicable duty cycle could occur if using single- or three-shunt resistor configuration for current reading. *Table 2: PWM frequency vs. maximum duty cycle relationship for three-shunt topology on page 73* and *Table 4: PWM frequency vs. maximum duty cycle relationship for single-shunt topology on page 82* summarize the performance of the system when the software library is used in conjunction with STM3210B-MCKIT hardware.

Note: *The MB459 board is an evaluation platform; it is designed to support different motor driving topologies (PMSM and AC induction) and current reading strategies (single and three shunt resistors). Therefore, the figures given in Table 2 on page 73 and Table 4 on page 82 should be understood as a starting point and not as a best case.*

Moreover, in order to guarantee the proper working of the algorithm and be sure that the new computed duty cycles will be applied in the next PWM period, it is always necessary to finish executing the FOC algorithm before the next PWM U event begins as shown in *Figure 71*.

Figure 71. AD conversions for three shunt topology stator currents reading and FOC algorithm execution


New duty cycles ready before next U event, OK
PWM Period
U
U
U
REP_RATE = 1
New duty cycles not ready before next U event, necessary to increase REP_RATE
U
U
U
REP_RATE = 1
ADC triggering interval
FOC algorithm execution
New duty cycle values ready
ai14848

In the three-shunt resistor configuration, considering that as seen in *Section 5.1.4*, the ADC conversions are triggered latest (DT+TN-TS)/2 after the TIM1 counter overflow, and considering the time required for the A/D converter to perform injected conversions, it can been stated that the FOC algorithm is started about 5 µs after the TIM1 counter overflow (worst case). Furthermore, given that the execution time of the FOC algorithm is around 20 µs, in sensorless configuration, to compute the new duty cycle values before the next update event, it is necessary to guarantee a minimum duty cycle period of about (5 + 20) × 2 µs, that is, a maximum achievable FOC execution rate of about 20 kHz. The repetition counter (REP_RATE) can therefore be set to 1.

For PWM frequencies higher than 20 kHz, the repetition counter must be set to 3 (REP_RATE= 3). If PWM frequencies higher than 17.5 kHz are used, please see *Section 5.5.3* to calculate a suitable MMI for *MC_Control_Param.h*.

For single-shunt current reading, see *Table 4: PWM frequency vs. maximum duty cycle relationship for single-shunt topology on page 82* for the minimum repetition rate (*A.8: MMI (maximum modulation index): automatic calculation* explains how to calculate the MMI (maximum modulation index) for given PWM frequency and noise parameters.).

A.3 Fixed-point numerical representation

The PMSM FOC software library uses fixed-point representation of fractional signed values. Thus, a number *n* is expressed as $n = m \cdot f$, where *m* is the integer part (magnitude) and *f* the fractional part, and both *m* and *f* have fixed numbers of digits.

In terms of two's complement binary representation, if a variable *n* requires QI bits to express - as powers of two - its magnitude (of which 1 bit is needed for the sign), QF bits – as inverse powers of two - for its fractional part, then we have to allocate QI + QF bits for that variable.

Therefore, given a choice of QI and QF, the variable representation has the following features:

- Range: $-2^{(QI-1)} < n < 2^{(QI-1)} - 2^{(-QF)}$;
- Resolution: $= 1 / 2^{QF}$.

The equation below converts a fractional quantity *q* to fixed-point representation *n*:
$n = \mathrm{floor}(q \cdot 2^{QF})$

A common way to express the choice that has been made is the "q QI.QF" notation.

So, if a variable is stored in q3.5 format, it means that 3 bits are reserved for the magnitude, 5 bits for the resolution; the expressible range is from -4 to 3.96875, the resolution is 0.03125, the bit weighting is:

bit n.	7	6	5	4	3	2	1	0
value	-4	2	1	1/2	1/4	1/8	1/16	1/32

This software library uses the PU ("Per Unit") system to express current values. They are always referred to a base quantity that is the maximum measurable current I_{max} (which, for the proposed hardware, can be estimated approximately at $I_{max} = 0.6 / R_{shunt}$); so, the "per unit" current value is obtained by dividing the physical value by that base:

$$i_{PU} = \frac{i_{S.I.}}{I_{\max}}$$

In this way, i_{pu} is always in the range from -1 to +1. Therefore, the q1.15 format, which ranges from -1 to 0.999969482421875, with a resolution of 0.000030517578125, is perfectly suitable (taking care of the overflow value (-1)·(-1)=1) and thus extensively used.

Thus, the complete transformation equation from SI units is:

$$i_{q1.15} = \mathrm{floor}\left(\frac{i_{S.I.}}{I_{max}} \cdot 2^{QF}\right)$$

A.4 A priori determination of flux and torque current PI gains

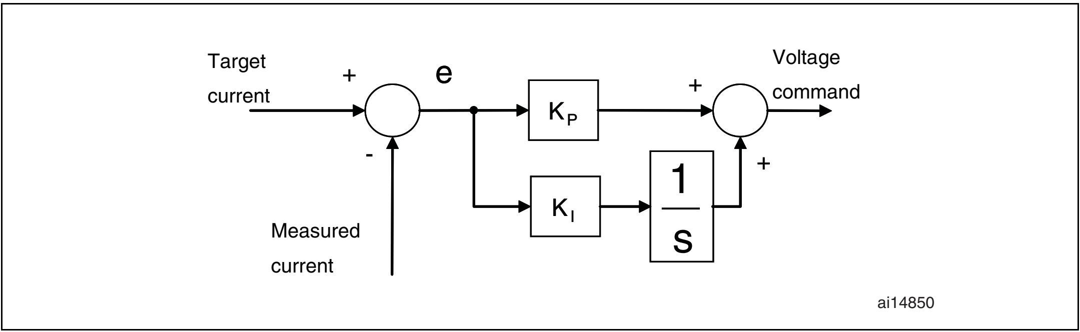
The aim of this appendix is to provide a criterion for the computation of the initial values of the torque/flux PI parameters (K_I and K_P). Appendix *A.5* discusses the way of fine-tuning them.

To calculate these starting values, it is required to know the electrical characteristics of the motor: stator resistance R_s and inductance L_s and the electrical characteristics of the hardware: shunt resistor R_{Shunt}, current sense amplification network A_{Op} and the direct current bus voltage $V_{Bus}DC$.

The derivative action of the controller is not considered using this method.

Figure 72 shows the PI controller block diagram used for torque or flux regulation.

Figure 72. Block diagram of PI controller

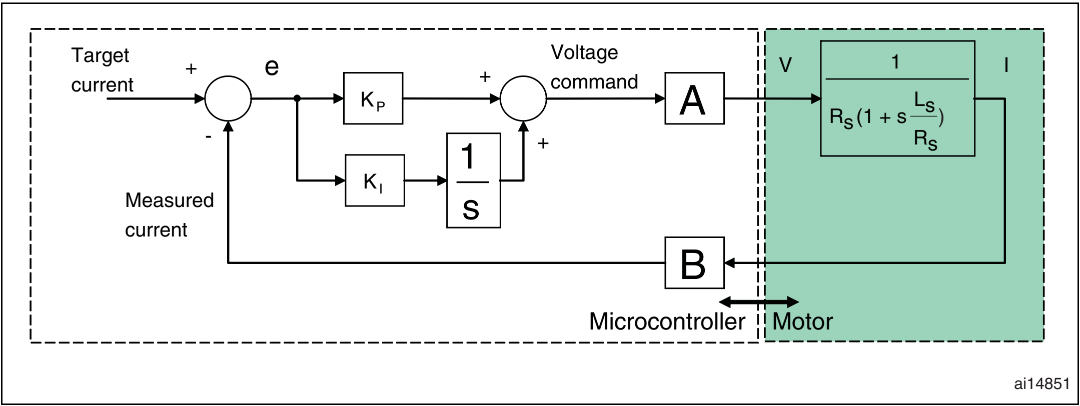


For this analysis, the motor electrical characteristics are assumed to be isotropic with respect to the q and d axes. So, it is assumed that the torque and flux regulators have the same starting value of K_P, and that they also have the same K_I value.

Figure 73 shows the closed loop system in which the motor phase is modelled using the resistor-inductance equivalent circuit in the “locked-rotor” condition.

Block “A” is the proportionality constant between the software variable storing the voltage command (expressed in digit) and the real voltage applied to the motor phase (expressed in Volt). Likewise, block “B” is the is the proportionality constant between the real current (expressed in Ampere) and the software variable storing the phase current (expressed in digit).

Figure 73. Closed loop block diagram

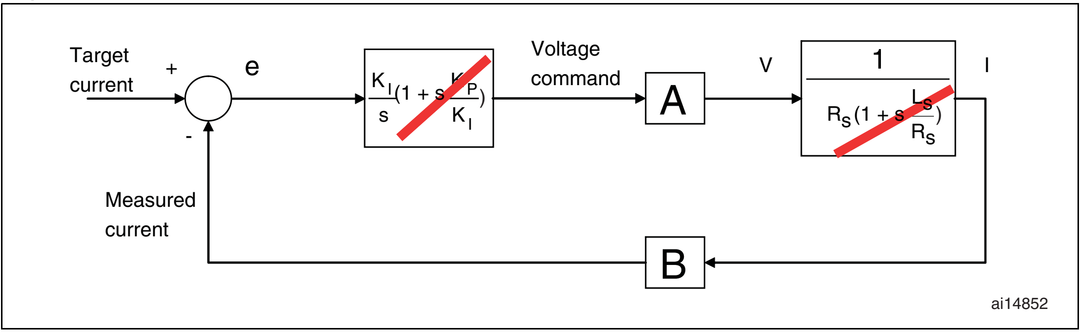


The transfer functions of the two blocks “A” and “B” are expressed by the following formulas:

$A = \frac{V_{Bus}DC}{2^{16}}$ and $B = \frac{R_{shunt}A_{op}2^{16}}{3.3}$, respectively.

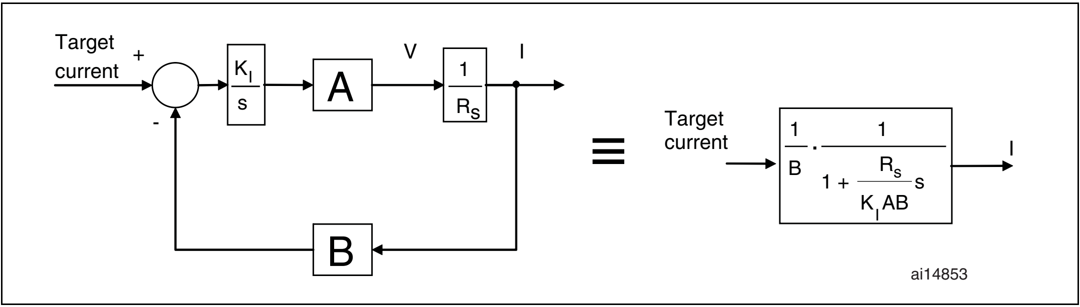
By putting $K_P/K_I = L_S/R_S$, it is possible to perform pole-zero cancellation as described in *Figure 74*.

Figure 74. Pole-zero cancellation



In this condition, the closed loop system is brought back to a first-order system and the dynamics of the system can be assigned using a proper value of K_I. See *Figure 75*.

Figure 75. Block diagram of closed loop system after pole-zero cancellation



It is important to note that the K_I and K_P parameters used inside the PI algorithms will be scaled using the proper divider. The K_PDIV and K_iDIV dividers are defined in *MC_Control_Param.h* (like TF_KPDIV, TF_KIDIV, TF_KDDIV) so the computed values of K_P and K_I must be multiplied by these factors.

Moreover the PI algorithm does not include the PI sampling time (T) in the computation of the integral part. See the following formula:

$$k_i\int_0^t e(\tau)d\tau = k_iT\sum_{k=1}^{n} e(kT) = K_i\sum_{k=1}^{n} e(kT)$$

Since the integral part of the controller is computed as a sum of successive errors, it is required to include T in the K_I computation.

So the final formula can be expressed as: $K_P = L_S\frac{\omega_C}{AB}K_P DIV$

$$K_i = \frac{R_S \cdot \omega_C \cdot K_i DIV}{AB} \cdot T$$

$$AB = \frac{V_{Bus}DC \cdot R_{shunt} \cdot A_{op}}{3.3}$$

Usually, it is possible to set ω_C (the bandwidth of the closed loop system) to 1500 rad/s, to obtain a good trade-off between dynamic response and sensitivity to the measurement noise.

The A_{op} measured for the MB459 is 2.57. It is then possible to compute the values of the parameters knowing the motor parameters (R_S, L_S), $V_{BUS}DC$ and R_{Shunt}.

A.5 Current regulators fine tuning

To fine-tune the current regulator, it is required to start with the parameters (K_I and K_P) computed following the instruction of appendix *A.4: A priori determination of flux and torque current PI gains*.

Then, starting from the default configuration of stm32f10x_MCconf.h, follow the following steps:

- Fill the "power devices parameters", "current regulation parameters", "power board protections thresholds", and "speed loop sampling time" sections of MC_Control_Param.h as described in *Section 4.2*.
- In stm32f10x_MCconf.h, select the kind of sensor to be used during the development stage of your design and fill the related header file (MC_encoder_param.h or MC_hall_param.h) as described in *Section 4.3* or *Section 4.4*. The tuning of the current regulators is not supported in sensorless configuration.
- Fill in `NOMINAL_CURRENT` and `POLE_PAIRS` in MC_PMSM_motor_param.h.
- Uncomment `FLUX_TORQUE_PIDs_TUNING`. A firmware generating a square-wave-shaped reference torque will be generated.

Note: The firmware generated when `FLUX_TORQUE_PIDs_TUNING` is not commented must be run only in Torque control mode.

A square-wave amplitude and period can be selected by editing `PID_TORQUE_REFERENCE` and `SQUARE_WAVE_PERIOD` parameters in MC_Control_Param.h.

The goal is to tune the torque and flux current components PIDs in real time. For this purpose, the user can for instance look at the real and measured Iq current using DAC functionality, and slightly change the torque PI(D) gains with respect to the default values in order to have a quick response to a step of target Iq without overshoots. The same PI(D) gains could then also be used in the flux loop.

Figure 76 and *Figure 77* show two oscilloscope acquisition. In both acquisitions, the C1 channel is the PB0 pin output and the C2 channel is the PB1 pin output.

The DAC functionality was used to output two internal variables; in this case PB0 is the reference Iq and PB1 is the measured Iq.

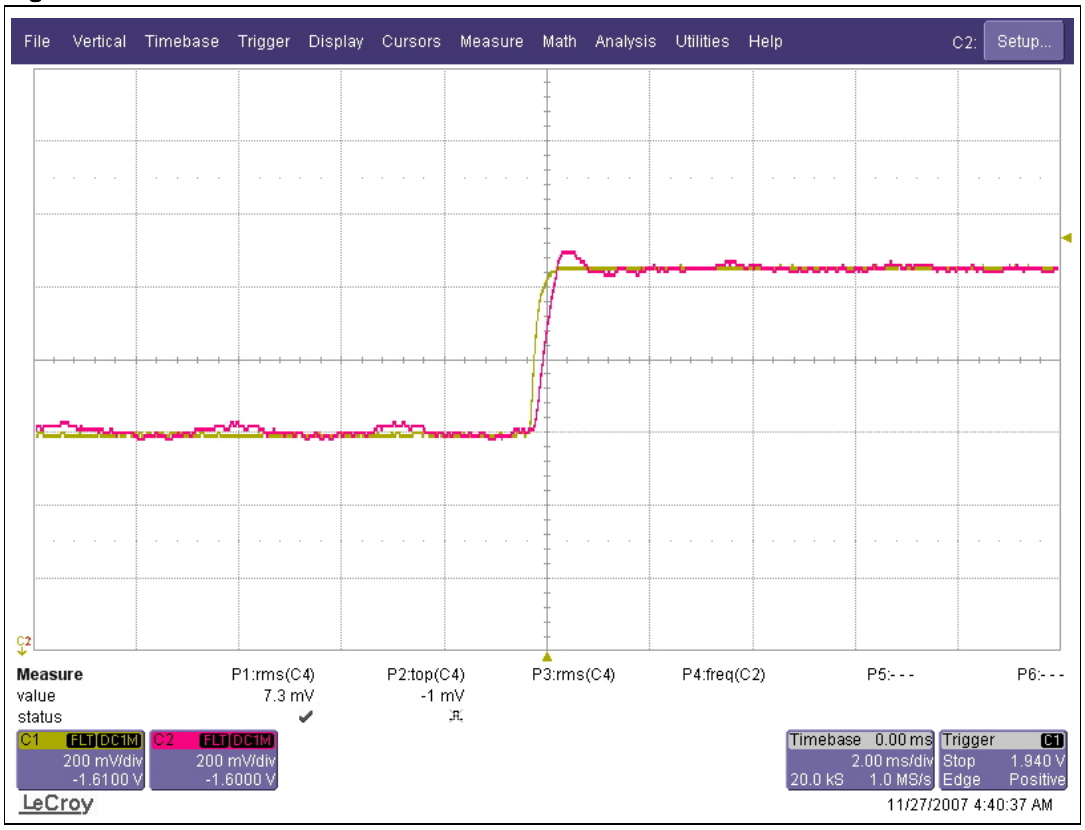
Note: The PB0 and PB1 signals were analog- and digital-filtered.

It is possible to see in *Figure 76* that the measured Iq has an overshoot with respect to the reference Iq. In this case, the PI parameter was set to KP = 8000 and KI = 2000.

To reduce this overshoot it is required to decrease KI while keeping KP constant. This is how the condition of *Figure 77* with KP = 8000 and KI = 1000 is obtained.

It is possible to see that in *Figure 77* the response of the current control is slower than in *Figure 77*. So it is possible to increase the speed of the system by increasing KP and KI and keeping the ratio constant.

Figure 76. KP = 8000 and KI = 2000



Measure	P1:rms(C4)	P2:top(C4)	P3:rms(C4)	P4:freq(C2)	P5:- - -	P6:- - -
value	7.3 mV	-1 mV				
status	✓					

C1 FLT DC1M 200 mV/div -1.6100 V

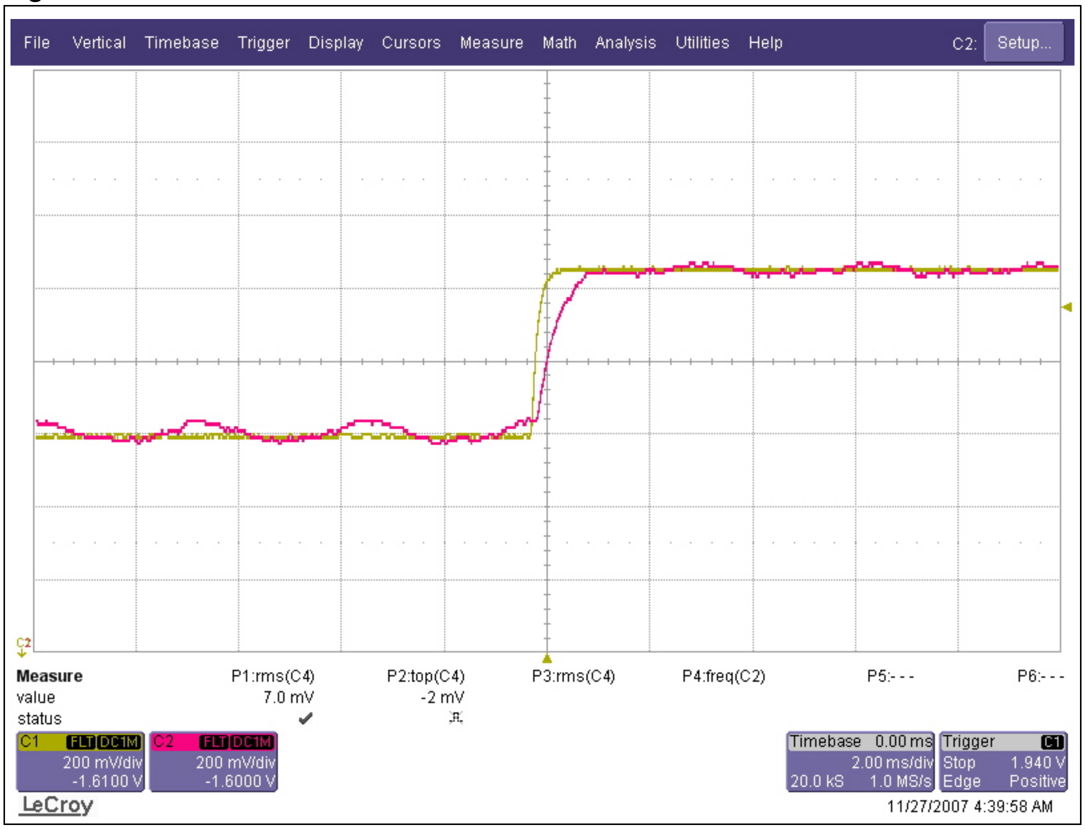
C2 FLT DC1M 200 mV/div -1.6000 V

Timebase 0.00 ms 2.00 ms/div 20.0 kS 1.0 MS/s

Trigger C1 Stop 1.940 V Edge Positive

11/27/2007 4:40:37 AM

Figure 77. KP = 8000 and KI = 1000



```
Measure   P1:rms(C4)   P2:top(C4)   P3:rms(C4)   P4:freq(C2)   P5:- - -   P6:- - -
value     7.0 mV       -2 mV
status    ✓
C1 FLT DC1M   200 mV/div   -1.6100 V
C2 FLT DC1M   200 mV/div   -1.6000 V
Timebase 0.00 ms   2.00 ms/div   20.0 kS   1.0 MS/s
Trigger C1   Stop 1.940 V   Edge Positive
11/27/2007 4:39:58 AM
```

A.6 A priori determination of state observer gains

In order to speed up the sensorless system development, the user can follow the procedure described in this appendix to calculate the initial values of the state observer gains, K1 and K2. Furthermore, thanks to the implemented progressive system development described in *Section 3.13*, it is possible to get the best possible tuning for K1 and K2.

The computation of the initial values of K1 and K2 is based on the placement of the state observer eigenvalues. The required motor parameters are r_s (motor winding resistance), L_s (motor winding inductance), T (sampling time of the sensorless algorithm, which coincides with FOC and stator currents sampling, as discussed in *Section 4.2*).

The motor model eigenvalues could be calculated as:

$$e_1 = 1 - \frac{r_s T}{L_s}$$

$$e_2 = 1$$

The observer eigenvalues are placed with:

$$e_{1obs} = \frac{e_1}{f}$$

$$e_{2obs} = \frac{e_2}{f}$$

Typically, by rule of the thumb, the user can set $f = 4$;

Then, the initial values of K1 and K2 could be calculated as:

$$K_1 = \frac{e_{1obs} + e_{2obs} - 2}{T} + \frac{r_s}{L_s}$$

$$K_2 = \frac{L_s(1 - e_{1obs} - e_{2obs} + e_{1obs}e_{2obs})}{T^2}$$

Finally, K1 and K2 could be used to fill in MC_State_Observer_param.h (see *Section 4.5.1*).

A.7 Speed formats

Two speed formats are commonly utilized in the PMSM FOC firmware library:

- 0.1 Hz: this format is normally utilized by the speed regulators and by the highest layer of the software (for user interfacing for instance).
- digit per PWM (dpp): the dpp format expresses the speed as the variation of the electrical angle (expressed in s16 format) within a PWM period. This format is particularly convenient since the rotor angular position can be easily determined by accumulating the rotor speed information every time the control loop is executed (for example, during PWM update interrupt service routine). Providing that 2n = 0xFFFF (so that angle roll-overs do not need to be managed), the frequency with 0.1 Hz unit can easily be converted into dpp format using the following formula:

  $$\omega_{dpp} = \omega_{0.1\,Hz} \cdot \frac{65536}{10 \cdot \mathrm{SAMPLING\_FREQ}}, \text{ where:}$$

  – SAMPLING_FREQ is the FOC sampling rate (automatically computed in pre-compilation phase starting from REP_RATE and PWM_FREQ)

A.8 MMI (maximum modulation index): automatic calculation

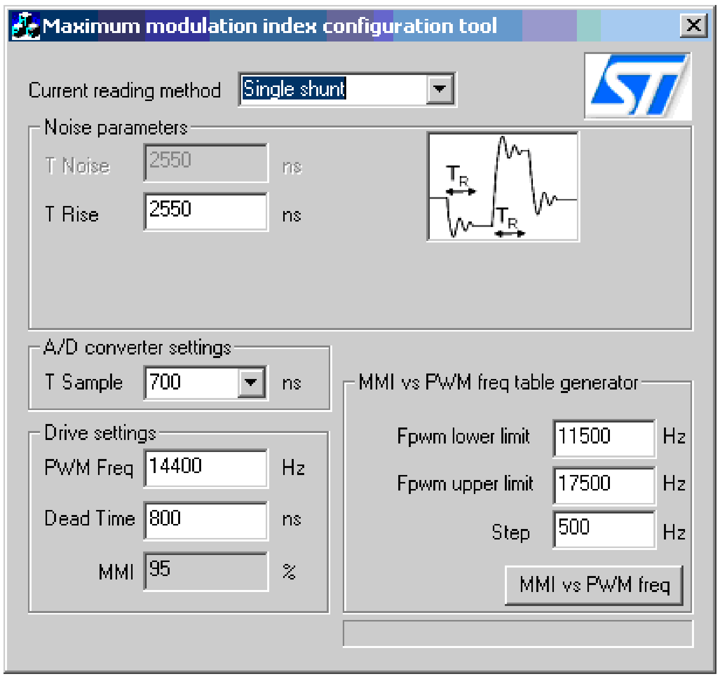
It is possible to customize the maximum modulation index versus PWM frequency table using the provided tool.

To do so, open the *MMIvsPWMFreq.exe* file (the file location is **STM32MC-KIT\design tools**).

Then, set the desired current-reading method: Single-shunt or Three-shunt, and fill the required fields with the customized parameters as shown in *Figure 78*.

The **MMI** field will then indicate the maximum modulation index allowable for the selected PWM frequency (**PWM Freq** field) based on the given noise parameter values (**T Noise**, **T Rise**), **A/D converter settings** and **Dead Time** value.

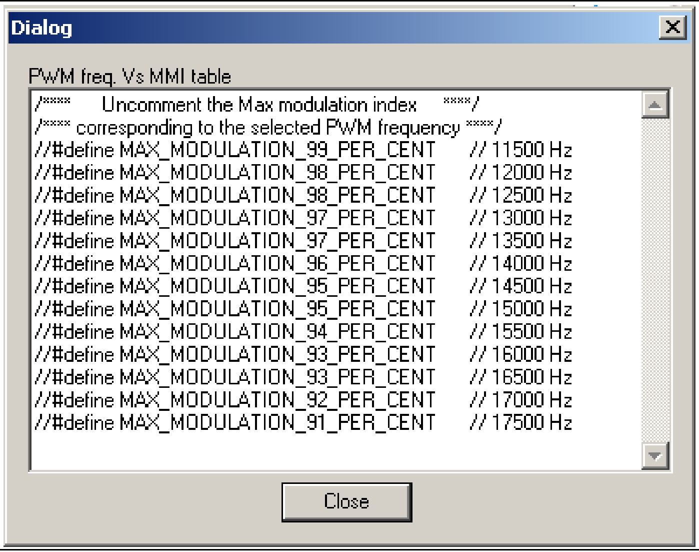
Figure 78. Maximum modulation index configuration tool



It is then possible to generate the new MMI vs. PWM frequency table.

To do so, in the Maximum modulation index configuration tool window (*Figure 78*), set the minimum PWM frequency of the table in the **Fpwm lower limit** field, set the maximum PWM frequency of the table in the **Fpwm upper limit** field and set the frequency step used to calculate the table in the **Step** field. Then press the **MMI vs. PWM freq** button and the dialog box shown in *Figure 79* will appear.

Figure 79. MMI vs. PWM freq. define table



```
/****     Uncomment the Max modulation index      ****/
/**** corresponding to the selected PWM frequency ****/
//#define MAX_MODULATION_99_PER_CENT    // 11500 Hz
//#define MAX_MODULATION_98_PER_CENT    // 12000 Hz
//#define MAX_MODULATION_98_PER_CENT    // 12500 Hz
//#define MAX_MODULATION_97_PER_CENT    // 13000 Hz
//#define MAX_MODULATION_97_PER_CENT    // 13500 Hz
//#define MAX_MODULATION_96_PER_CENT    // 14000 Hz
//#define MAX_MODULATION_95_PER_CENT    // 14500 Hz
//#define MAX_MODULATION_95_PER_CENT    // 15000 Hz
//#define MAX_MODULATION_94_PER_CENT    // 15500 Hz
//#define MAX_MODULATION_93_PER_CENT    // 16000 Hz
//#define MAX_MODULATION_93_PER_CENT    // 16500 Hz
//#define MAX_MODULATION_92_PER_CENT    // 17000 Hz
//#define MAX_MODULATION_91_PER_CENT    // 17500 Hz
```

The generated values can be copied and pasted into the *MC_Control_Param.h* file. The selected PWM frequency must then be uncommented.

A.9 References

- [1] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, Analysis of Electric Machinery and Drive Systems, Wiley-IEEE Press, 2002.
- [2] T. A. Lipo and D. W. Novotny, Vector Control and Dynamics of AC Drives, Oxford University Press, 1996.
- [3] S. Morimoto, Y. Takeda, T. Hirasa, K. Taniguchi, “Expansion of Operating Limits for Permanent Magnet Motor by Optimum Flux-Weakening”, Conference Record of the 1989 IEEE, pp. 51-56 (1989).
- [4] J. Kim, S. Sul, “Speed control of Interior PM Synchronous Motor Drive for the Flux-Weakening Operation”, IEEE Trans. on Industry Applications, 33, pp. 43-48 (1997).
- [5] M. Tursini, A. Scafati, A. Guerriero, R. Petrella, “Extended torque-speed region sensor-less control of interior permanent magnet synchronous motors”, ACEMP'07, pp. 647 - 652 (2007).
- [6] M. Cacciato, G. Scarcella, G. Scelba, S.M. Billè, D. Costanzo, A. Cucuccio, “Comparison of Low-Cost-Implementation Sensorless Schemes in Vector Controlled Adjustable Speed Drives”, SPEEDAM '08, Applied Power Electronics Conference and Exposition (2008).

Revision history

Table 5. Document revision history

Date	Revision	Changes
08-Jan-2008	1	Initial release.

Table 5. Document revision history (continued)

Date	Revision	Changes
21-Aug-2008	2	Permanent-magnet synchronous motor FOC software library updated to revision 2.0 (see *PMSM FOC software library V2.0 features (CPU running at 72 MHz) on page 9*). Updated sections: – *Section 1: Getting started with tools* – *Section 2: Introduction to the sensorless FOC of PM motors* – *Section 3: Running the demo program* – *Power device parameters*, *Speed PID-controller init values*, *Quadrature current PID-controller init values* – *Section 4.5: State observer parameters: MC_State_Observer_param.h* – *Section 4.6: Permanent-magnet synchronous motor parameters: MC_PMSM_motor_param.h* – *Section 5.2: Current reading in single shunt resistor topology and space vector PWM generation: stm32f10x_svpwm_1shunt module* – *Section 5.4: PMSM (SM-PMSM / IPMSM) field-oriented control: MC_FOC_Drive and MC_FOC_Methods modules* – *ENC_Start_Up on page 105* – *Section 5.9.1: List of available functions on page 120* – *SysTickHandler on page 127* – *MCL_Init on page 128* – *Section 5.12: Main interrupt service routines: stm32f10x_it module* – *A.2: Selecting the update repetition rate based on the PWM frequency for single- or three-shunt resistor configuration on page 136* – *A.4: A priori determination of flux and torque current PI gains*, *A.9: References on page 145* Added sections: *Section 3.4: Flux-weakening PI controller tuning*, *Section 4.6.4: Additional parameters for IPMSM drive optimization (MTPA)*, *Section 4.6.5: Additional parameters for feed-forward, high performance current regulation*, *Section 2.1.5: Feed-forward current regulation* and *A.8: MMI (maximum modulation index): automatic calculation*. Single-shunt resistor configuration added: – *Table 4.1: Library configuration file: stm32f10x_MCconf.h on page 43* updated – *SVPWMEOCEvent* and *SVPWMUpdateEvent on page 64* added – *Section 5.2: Current reading in single shunt resistor topology and space vector PWM generation: stm32f10x_svpwm_1shunt module on page 73* added – *SVPWMEOCEvent* and *SVPWMUpdateEvent on page 77* added – *SVPWMEOCEvent* and *SVPWMUpdateEvent on page 86* added – *TIM1_UP_IRQHandler on page 133* updated – *ADC1_2_IRQHandler on page 134* updated – *Appendix A: Additional information on page 135* updated Small text changes.