

MCUXpresso SDK Field-Oriented Control (FOC) of 3-Phase PMSM and BLDC motors



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Chapter 1

Introduction

This user's guide describes the implementation of the sensorless motor-control software for a 3-phase Permanent Magnet Synchronous Motor (PMSM). The software is intended for PMSM with sinusoidal Back Electromotive Force (back-EMF) but is also very well usable for brushless motors (BLDC) with trapezoidal back-EMF.

The software also includes the motor parameters identification algorithm, on NXP 32-bit Kinetis V and Kinetis E series MCUs. The sensorless control software itself and the PMSM control theory, in general, are described in [DRM148: Sensorless PMSM Field-Oriented Control](#).

The Freedom (FRDM-MC-LVPMSM) and High Voltage (HVP-MC3PH) power stages are used as hardware platforms for the PMSM control reference solution.

The hardware-dependent part of the sensorless control software, including a detailed peripheral setup and the Motor Control (MC) peripheral drivers, is described as well.

The motor parameters identification theory and algorithms are described in this document.

The last part of the document introduces and explains the user interface represented by the Motor Control Application Tuning (MCAT) page based on the FreeMASTER run-time debugging tool. These tools present a simple and user-friendly way for motor parameter identification, algorithm tuning, software control, debugging, and diagnostics.

Chapter 2

Supported development boards for KV

There are development boards for the Kinetis KV MCUs for motor-control applications. The development boards and supported MCUs are shown in [Table 1](#). The Freedom development platform (FRDM) is targeted for low-voltage and low-power applications with the PMSM control type. The High-Voltage Platform (HVP) is designed to drive high-voltage (115/220 V) applications with up to 1 kW of power.

Table 1. Supported development boards

	Platform	
	FRDM	HVP
MCU / Power Stage	FRDM-MC-LVPMSM	HVP-MC3PH
KV11	FRDM-KV11Z	HVP-KV11Z75

Chapter 3

Motor control vs. SDK peripheral drivers

The motor-control examples use the MCUXpresso SDK peripheral drivers to configure the general peripherals (such as clocks, SPI, SIM, and ports). However, motor control requires critical application timing because most control algorithms run in a 100- μ s loop. To optimize the CPU load, most peripheral hardware features are implemented for the PWM signal generation, analog signal sampling, and synchronization between the PWM and ADC units.

The standard SDK peripheral drivers do not support the configuration and handling of all required features. The motor-control drivers are designed to configure the critical MC peripherals (eflexPWM, FTM, ADC, and LPIT).

It is highly recommended not to modify the default configuration of the allocated MC peripherals due to a possible application-timing conflict. The *mc_periph_init.c* source file contains configuration functions of allocated peripherals.

Chapter 4

Hardware setup

The PMSM sensorless application runs on Tower, Freedom, or EVK development platforms with the 24-V Linix Motor in the default configuration. The HVP platform runs with the default configuration for the MIGE 60CST-MO1330 motor.

4.1 Linix 45ZWN24-40 motor

The Linix 45ZWN24-40 motor is a low-voltage 3-phase permanent-magnet motor with hall sensor used in PMSM applications. The motor parameters are listed in [Table 2](#).

Table 2. Linix 45ZWN24-40 motor parameters

Characteristic	Symbol	Value	Units
Rated voltage	Vt	24	V
Rated speed	-	4000	RPM
Rated torque	T	0.0924	Nm
Rated power	P	40	W
Continuous current	Ics	2.34	A
Number of pole-pairs	pp	2	-



Figure 1. Linix 45ZWN24-40 permanent magnet synchronous motor

The motor has two types of connectors (cables). The first cable has three wires and is designated to power the motor. The second cable has five wires and is designated for the hall sensors' signal sensing. For the PMSM sensorless application, only the power input wires are needed.

4.2 MIGE 60CST-MO1330 motor

The MIGE 60CST-MO1330 motor (described in [Table 3](#)) is used by the PMSM sensorless application. You can also adapt the application to other motors just by defining and changing the motor-related parameters. The motor is connected directly to the high-voltage development board via a flexible cable connected to the three-wire development board connector.

Table 3. MIGE 60CST-MO1330 motor parameters

Characteristic	Symbol	Value	Units
Rated voltage	Vt	220	V
Rated speed	-	3000	rpm
Rated power	P	400	W
Number of pole-pairs	Pp	4	-



Figure 2. MIGE 60CST-MO1330 motor

4.3 Running PMSM application on Freedom development platform

To run the PMSM application using the NXP Freedom development platform, you need these Freedom boards:

- Freedom board with a Kinetis V series MCU (FRDM-KV11Z or FRDM-KV31F).
- 3-phase low-voltage power Freedom shield (FRDM-MC-LVPMSM) with included Linux motor.

You can order all Freedom modules from www.nxp.com or from distributors to easily build the hardware platform for the target application.

4.3.1 FRDM-MC-LVPMSM

This evaluation board, in a shield form factor, effectively turns an NXP Freedom development board or an evaluation board into a complete motor-control reference design, compatible with existing NXP Freedom development boards and evaluation boards. The Freedom motor-control headers are compatible with the Arduino™ R3 pin layout.

The FRDM-MC-LVPMSM low-voltage, 3-phase Permanent Magnet Synchronous Motor (PMSM) Freedom development platform board has the power supply input voltage of 24-48 VDC with a reverse polarity protection circuitry. The auxiliary power supply of 5.5 VDC is created to supply the FRDM MCU boards. The output current is up to 5 A RMS. The inverter itself is realized by a 3-phase bridge inverter (six MOSFETs) and a 3-phase MOSFET gate driver. The analog quantities (such as the 3-phase motor currents, DC-bus voltage, and DC-bus current) are sensed on this board. There is also an interface for speed and position sensors (encoder, hall). The block diagram of this complete NXP motor-control development kit is shown in Figure 3.

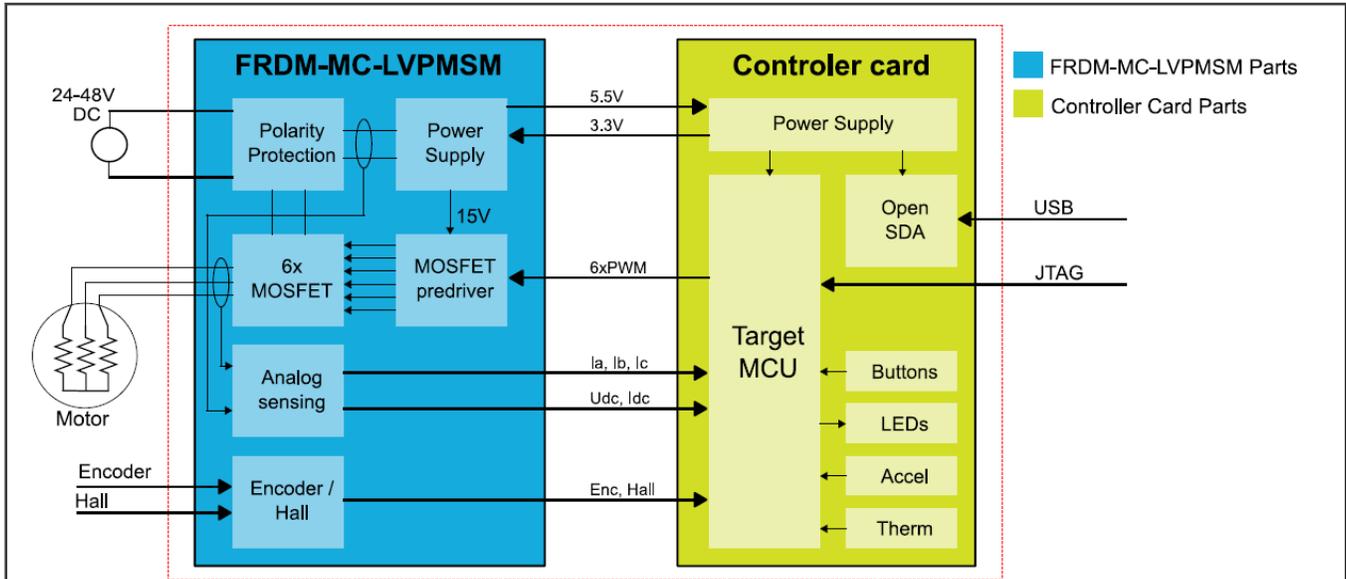


Figure 3. Motor-control development platform block diagram

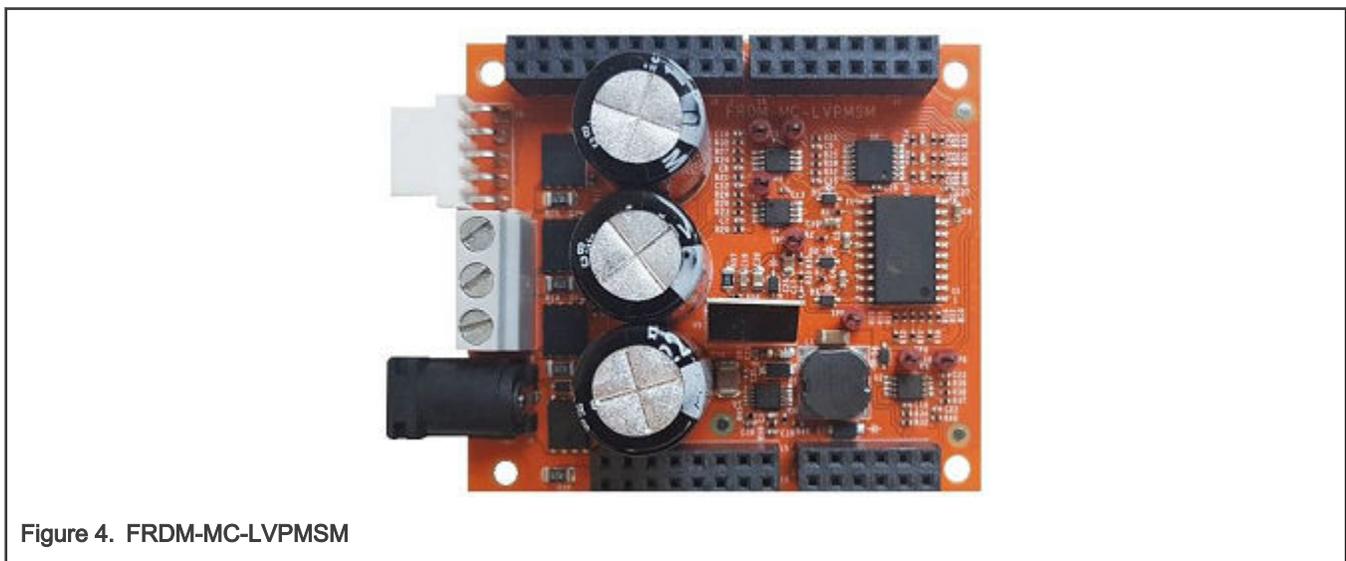


Figure 4. FRDM-MC-LVPMSM

The FRDM-MC-LVPMSM board does not require a complicated setup. For more information about the Freedom development platform, see www.nxp.com.

4.3.2 FRDM-KV11Z board

The FRDM-KV11Z board is a low-cost development tool for the Kinetis V series KV1x MCU family built upon the Arm Cortex-M0+ processor. The FRDM-KV11Z board hardware is form-factor compatible with the Arduino R3 pin layout, providing a broad range of expansion board options. The FRDM-KV11Z platform features OpenSDA, the open-source hardware embedded serial and debug adapter running an open-source bootloader.

To begin, configure the jumpers on the FRDM-KV11Z Freedom System module properly. [Table 4](#) lists the specific jumpers and their settings for the FRDM-KV11Z Freedom System module.

Table 4. FRDM-K11Z jumper settings

Jumper	Setting
J10	1-2

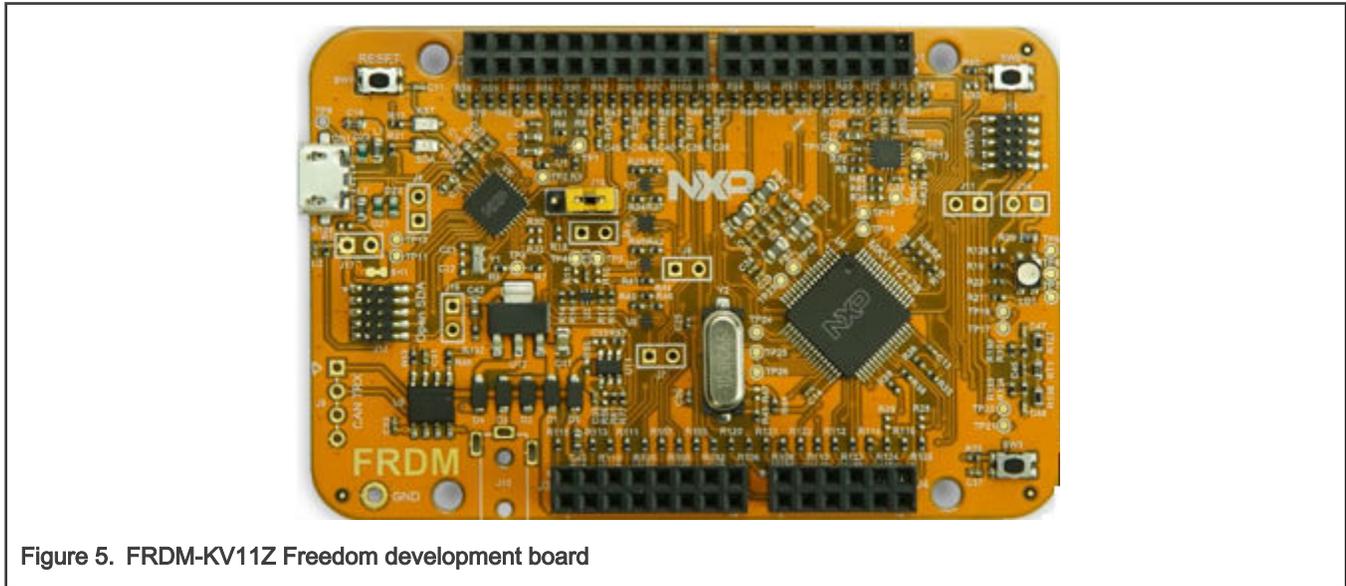


Figure 5. FRDM-KV11Z Freedom development board

4.3.3 Freedom system assembling

1. Connect the FRDM-MC-LVPMSM shield on top of the FRDM-Kxxxx board (there is only one possible option).
2. Connect the Linux motor 3-phase wires to the screw terminals on the board.
3. Plug the USB cable from the USB host to the OpenSDA micro USB connector.
4. Plug the 24-V DC power supply to the DC power connector.

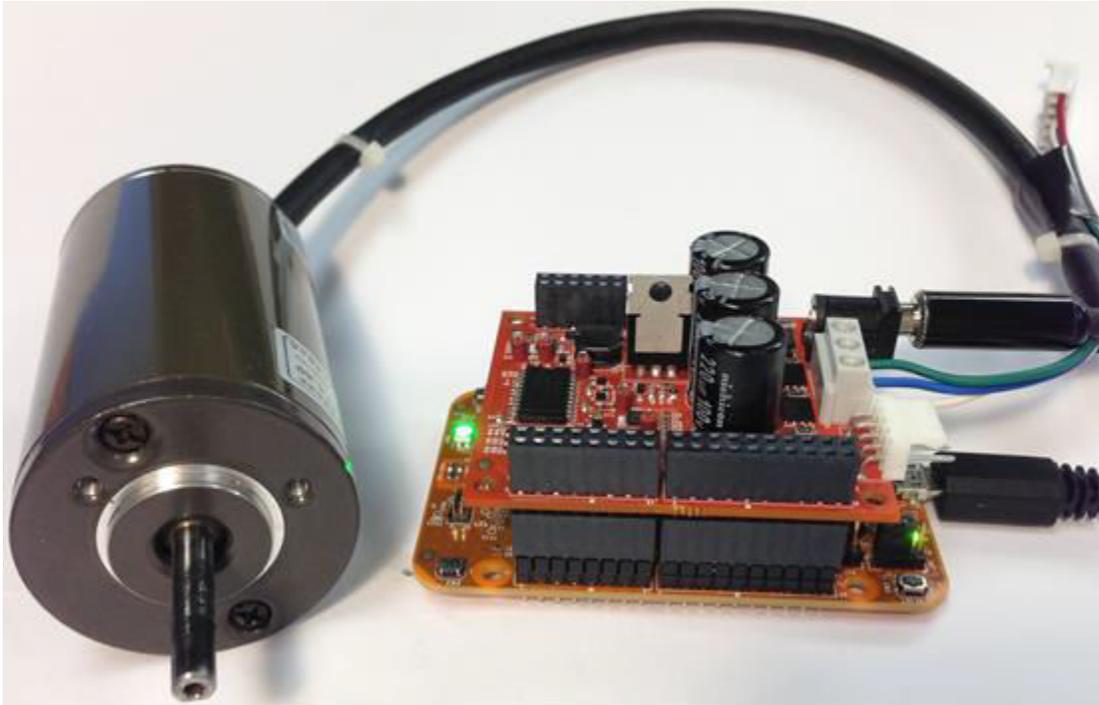


Figure 6. Assembled Freedom system

4.4 Running PMSM application on High-Voltage Platform

To run the PMSM application within the NXP High-Voltage Platform, you need these components:

- HVP daughter card with a Kinetis V series MCU ([HVP-KV11Z75M](#) or [HVP-KV31F120M](#)).
- High-Voltage Platform power stage ([HVP-MC3PH](#)) (motor not included).

You can order all the modules of the High-Voltage Platform from www.nxp.com or from distributors, and easily build the hardware platform for the target application.

4.4.1 HVP-MC3PH

The NXP High-Voltage Platform (HVP) is an evaluation and development solution for Kinetis V and E series MCUs. This platform enables the development of three-phase PMSM, BLDC, and ACIM motor-control and power-factor-correction solutions in a safe high-voltage environment. The HVP is a 115/230-V, 1-kW power stage that is an integral part of the NXP embedded motion control series of development tools. It is supplied in the HVP-MC3PH kit in combination with an HVP daughter card and provides a ready-made software development platform. The block diagram of a complete high-voltage motor-control development kit is in [Figure 7](#).

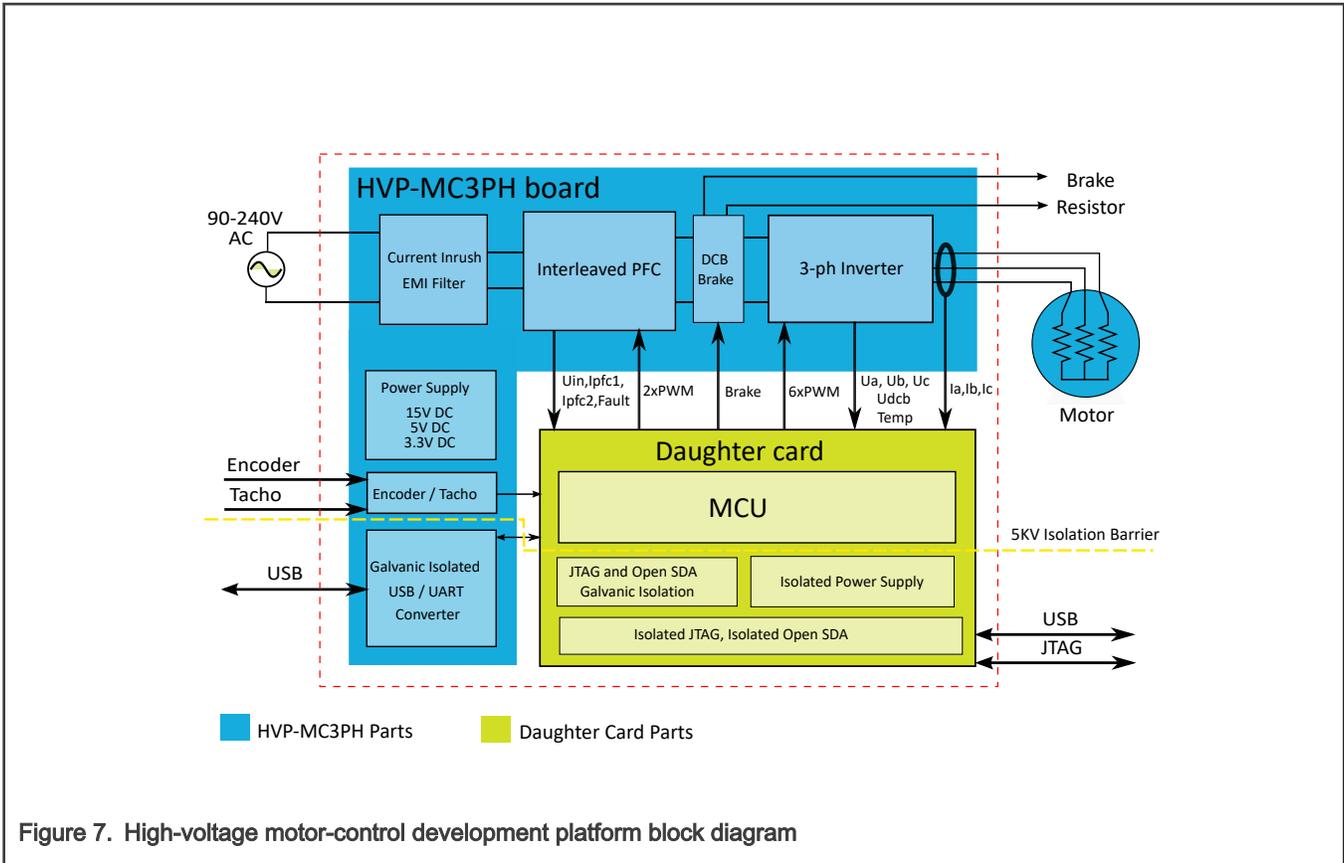


Figure 7. High-voltage motor-control development platform block diagram

The HVP-MC3PH power stage does not require a complicated setup and there is only one way to connect a daughter card to the HVP. The board works in the default configuration, and you don't have to set any jumpers to run the attached application. It is strongly recommended to read the complete *High-Voltage Motor Control Platform User's Guide* (document [HVPMC3PHUG](#)). Note that due to high-voltage, the HVP platform may represent safety risk when not handled correctly. For more information about the NXP high-voltage motor-control development platform, see [nxp.com](#).



Figure 8. HVP-MC3PH high-voltage platform

4.4.2 HVP-KV11Z75M daughter card

The HVP-KV11Z75M MCU daughter card contains a Kinetis KV1x family MCU built around the Arm® Cortex®-M0+ core running at 75 MHz and containing up to 128 KB of flash memory. This daughter card is developed for use in motor-control applications, together with the High-Voltage Platform power stage. This daughter card features OpenSDA, the NXP open-source hardware embedded serial and debug adapter running an open-source bootloader.

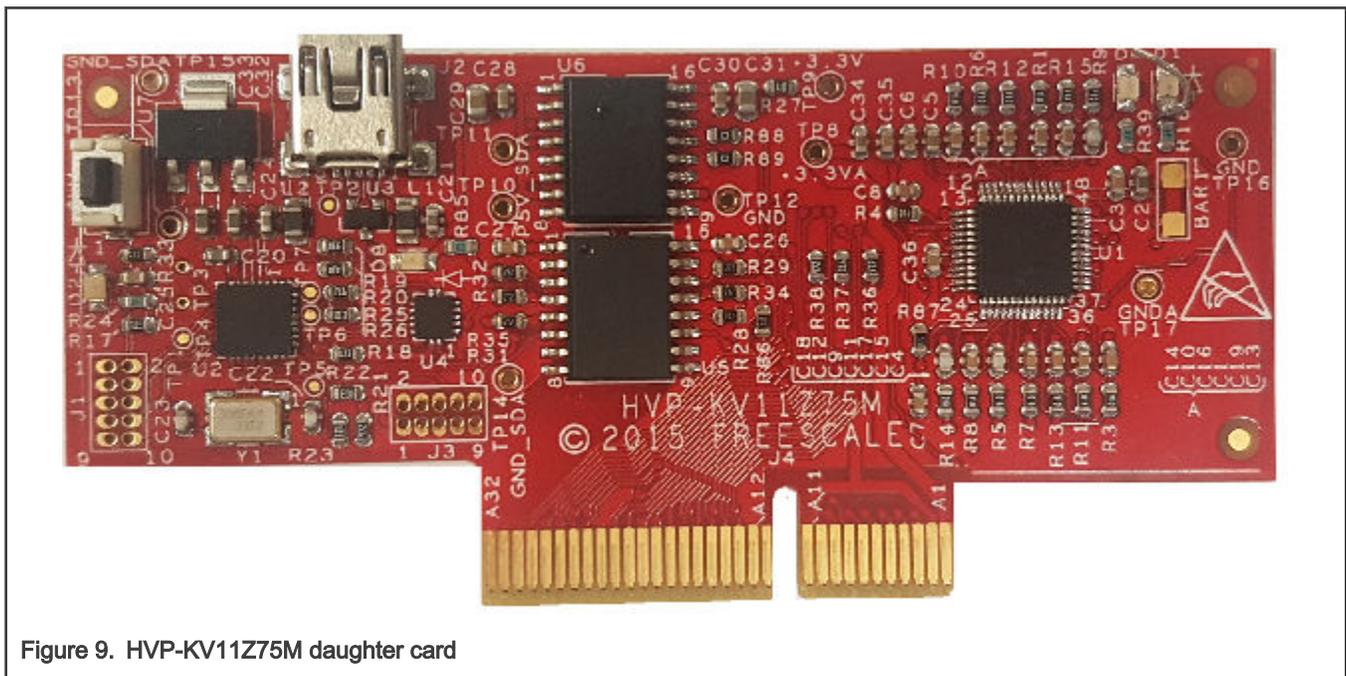


Figure 9. HVP-KV11Z75M daughter card

4.4.3 HVP assembling

1. Check whether the HVP-MC3PH main board is unplugged from the voltage source.

2. Insert the HVP-KVxxx daughter board to the HVP-MC3PH main board (connector J11 is the only option).
3. Connect the PMSM motor three-phase wires into the screw terminals J13 on the board. The order of phases only affects the rotor spinning direction.
4. Plug the USB cable from the USB host to the OpenSDA micro USB connector on the daughter board.
5. Plug a 230-V power supply to the power connector and switch it on.

Chapter 5

MCU features and peripheral settings

The peripherals used for motor control differ among different Kinetis MCUs. The peripheral settings and application timings for each MCU are described in the following sections.

5.1 KV1x family

The KV10Z and KV11Z MCU families are highly scalable members of the Kinetis V series and provide a cost-competitive motor-control solution. Built on the Arm Cortex-M0 core running at 75 MHz with up to 128 KB of flash and up to 16 KB of RAM, it delivers a platform enabling customers to build a scalable solution portfolio. Additional features include dual 16-bit ADCs sampling at up to 1.2 MS/s in a 12-bit mode and 20 channels of flexible motor-control timers (PWMs) across six independent time bases. For more information, see *KV11F Sub-Family Reference Manual* (document [KV11P64M75RM](#)).

Hardware timing and synchronization

Correct and precise timing is crucial for motor-control applications. Therefore, the motor-control-dedicated peripherals take care about the timing and synchronization on the hardware layer. It is also possible to set the PWM frequency as a multiple of the ADC interrupt (FOC calculation) frequency, in this case $FOC_{freq} = PWM_{freq}/2$. The timing diagram is in [Figure 10](#).

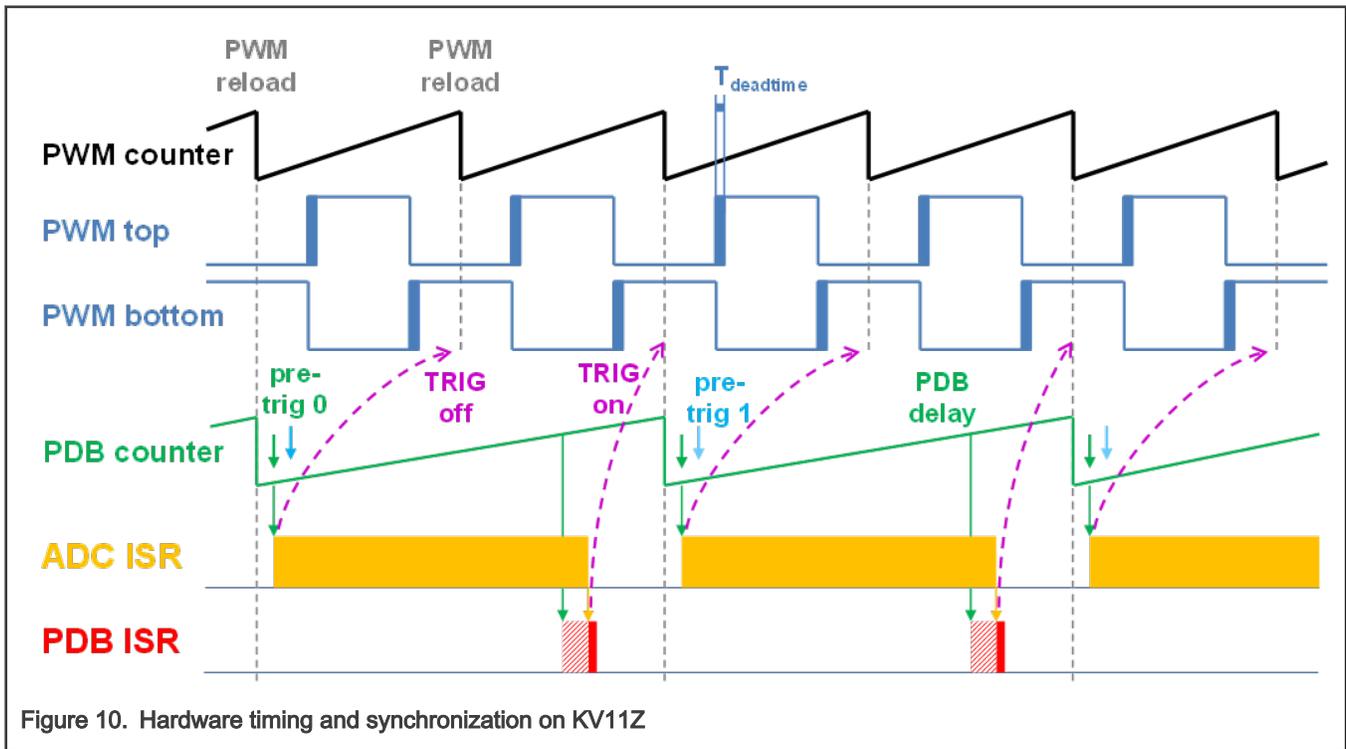


Figure 10. Hardware timing and synchronization on KV11Z

- The top signal (**PWM counter**) shows the FTM counter reloads. At the **PWM top** and **PWM bottom** signals, the dead time is emphasized. The **FTM_TRIG** is generated on the **PWM reload**, which triggers the PDB (resets the **PDB counter**).
- The PDB generates the first pre-trigger for the first ADC (phase current) sample with approximately $T_{deadtime}/2$ delay. This delay ensures correct current sampling at duty cycles close to 100 %.
- When the conversion of the first ADC sample (phase current) is completed, the **ADC ISR** is entered. Firstly, the next **FTM_TRIG** is disabled (**TRIG off**). This ensures that the **PDB counter** does not reset at the next **PWM reload**. Then the FOC is calculated.

- In the middle of the next PWM period (**PDB delay**), the **PDB ISR** is called. This interrupt only enables the **FTM_TRIG (TRIG on)** in the next **PWM reload**. The **PDB ISR** has lower priority than the **ADC ISR**. The **PDB delay** length determines the ratio between the PWM and FOC frequencies.
- The PDB uses the back-to-back mode to automatically generate the **pre-trig 1** (for the DC-bus voltage measurement) immediately after the first conversion is completed.

Peripheral settings

This chapter describes only the peripherals used for motor control. On KV11Z, a 6-channel FlexTimer (FTM) is used for 6-channel PWM generation and two 16-bit SAR ADCs are used for the phase currents and DC-bus voltage measurement. The FTM and ADC are synchronized via the Programmable Delay Block (PDB). There is also one channel from another independent FTM used for the slow loop interrupt generation.

PWM generation - FTM0

- The FTM is clocked from the 75-MHz System clock.
- Only six channels are used, the other two are masked in the OUTMASK register.
- Channels 0+1, 2+3, and 4+5 are combined in pairs running in a complementary mode (each).
- The fault mode is enabled at each combined pair with automatic fault clearing (PWM outputs are re-enabled the first PWM reload after the fault input returns to zero).
- The PWM period (frequency) is determined as how long it takes the FTM to count from CNTIN to MOD. By default CNTIN = -MODULO/2 = -3750 and MOD = MODULO/2 - 1 = 3749. The FTM is clocked from the System clock (75 MHz) so it takes 0.0001 s (10 KHz).
- Dead-time insertion is enabled at each combined pair. The dead-time length is calculated as System clock 75 MHz * T_{deadtime}. The dead-time varies among platforms.
- The FTM generates a trigger to the PDB on counter initialization.
- The FTM fault input is enabled but its polarity and source varies among platforms.

Analog sensing – ADC0, ADC1

- The ADCs operate as 12-bit, single-ended converters.
- The clock source for both ADCs is the 25-MHz Bus clock divided by 2 = 12.5 MHz.
- For ADC calibration purposes, the ADC clock is 3.125 MHz and continues the conversion and averaging with 32 samples enabled in the SC3 register. After the calibration is done, the SC register is filled with its default values and the clock is set back to 12.5 MHz.
- Both ADCs are triggered from the PDB pre-triggers.
- There is an interrupt that serves the FOC fast-loop algorithm generated after the first conversion is completed.

PWM and ADC synchronization – PDB0

- Unlike the FTM, the PDB is clocked from the Bus clock which is three times slower than the System clock (used for FTM). Therefore, the modulo value at PDB is divided by three.
- The PDB is triggered from the FTM0_TRIG.
- The pre-trigger 0 at each channel is generated $0.5 * T_{\text{deadtime}}$ after the FTM0_TRIG.
- The pre-trigger 1 at each channel is generated immediately after the first conversion is completed using the back-to-back mode.
- The PDB Sequence Error interrupt is enabled. This interrupt is generated if a certain result register is not read and the same pre-trigger occurs at this ADC.

- The PDB Delay interrupt is enabled. This interrupt is generated when the PDB_IDLY is reached. This interrupt enables the FTM_TRIG.
- The PDB Sequence Error and PDB Delay interrupts have a common interrupt vector. Which event generated the interrupt is determined at the beginning of the interrupt according to the ERR flag.

Over-current detection at FRDM platform – CMP1

- The plus input to the CMP is taken from the analog pin.
- The minus input to the CMP is taken from the 6-bit DAC0 reference. The DAC reference is set to 3.197 V (62/64*VDD) which corresponds to 7.73 A (for the 8.25 A scale).
- The CMP filter is enabled and four consecutive samples must agree.

Slow loop interrupt generation – FTM2

- The FTM2 is clocked from the System clock / 16, because the slow loop is usually ten times slower than the fast loop, so its modulo value can be kept reasonably low.
- The FTM counts from CNTIN = 0 to MOD = MODULO/16 * 10.
- An interrupt is enabled and generated at the counter reload and it serves the slow loop.

Communication with MC33937 MOSFET driver – SPI

- The SPI runs in the master mode.
- The SPI chip select 1 signal is active in logic high.
- The baud rate is 3.12 MHz.

Peripheral settings differences among platforms

There are some differences in peripheral settings among different platforms. [Table 5](#) summarizes these differences.

Table 5. KV11 platform differences

Peripheral	Feature	Platform		
		FRDM	Tower	HVP
FTM0	PWM polarity	high sides active high low sides active high	high sides active low low sides active high	high sides active high low sides active high
	Fault source	FLT0, CMP1 out	FLT1, input pin	FLT0, input pin
	Fault polarity	Active high	Active high	Active low
	Dead-time	0.5 us	0.5 us	1.5 us
SPI	Driver on SPI	No	Yes	No
PDB	Pre-trigger 0 delay	0.25 us	0.25 us	0.75 us

CPU load and memory usage

The following information apply to the *demo* application built with IAR IDE. [Table 6](#) shows the memory usage and the CPU load. The memory usage is calculated from the *.map* linker file, including the 2-KB FreeMASTER recorder buffer (allocated in RAM). The CPU load is measured using the *SysTick* timer. The CPU load is dependent on the fast-loop (FOC calculation) and slow-loop (speed loop) frequencies. In this case, it applies for the fast loop of 10 KHz and the slow loop of 1 KHz. The total CPU load is calculated according to the following equations.

$$CPU_{fast} = cycles_{fast} \frac{f_{fast}}{f_{CPU}} 100 [\%]$$

$$CPU_{slow} = cycles_{slow} \frac{f_{slow}}{f_{CPU}} 100 [\%]$$

$$CPU_{total} = CPU_{fast} + CPU_{slow} [\%]$$

Where:

CPU_{fast} - the CPU load taken by the fast loop.

$cycles_{fast}$ - the number of cycles consumed by the fast loop.

f_{fast} - the frequency of the fast-loop calculation (10 KHz).

f_{CPU} - the CPU frequency.

CPU_{slow} - the CPU load taken by the slow loop.

$cycles_{slow}$ - the number of cycles consumed by the slow loop.

f_{slow} - the frequency of the slow-loop calculation (1 KHz).

CPU_{total} - the total CPU load consumed by the motor control.

Table 6. KV11 CPU load and memory usage

	MKV11Z
CPU load [%]	59.3
Flash usage [B]	14 081
RAM usage [B]	3 091

NOTE

Memory usage and maximum CPU load can differ depending on the used IDEs and settings.

Chapter 6

Project file and IDE workspace structure

All the necessary files are included in one package, which simplifies the distribution and decreases the size of the final package. The directory structure of this package is simple, easy to use, and organized in a logical manner. The folder structure used in the IDE is different from the structure of the PMSM package installation, but it uses the same files. The different organization is chosen due to a better manipulation with folders and files in workplaces and due to the possibility to add or remove files and directories. The “*pack_motor_board*” project includes all the available functions and routines, MID functions, scalar and vector control of the motor, FOC control, and FreeMASTER MCAT project. This project serves for development and testing purposes.

6.1 PMSM project structure

The directory tree of the PMSM project is shown in [Figure 11](#).

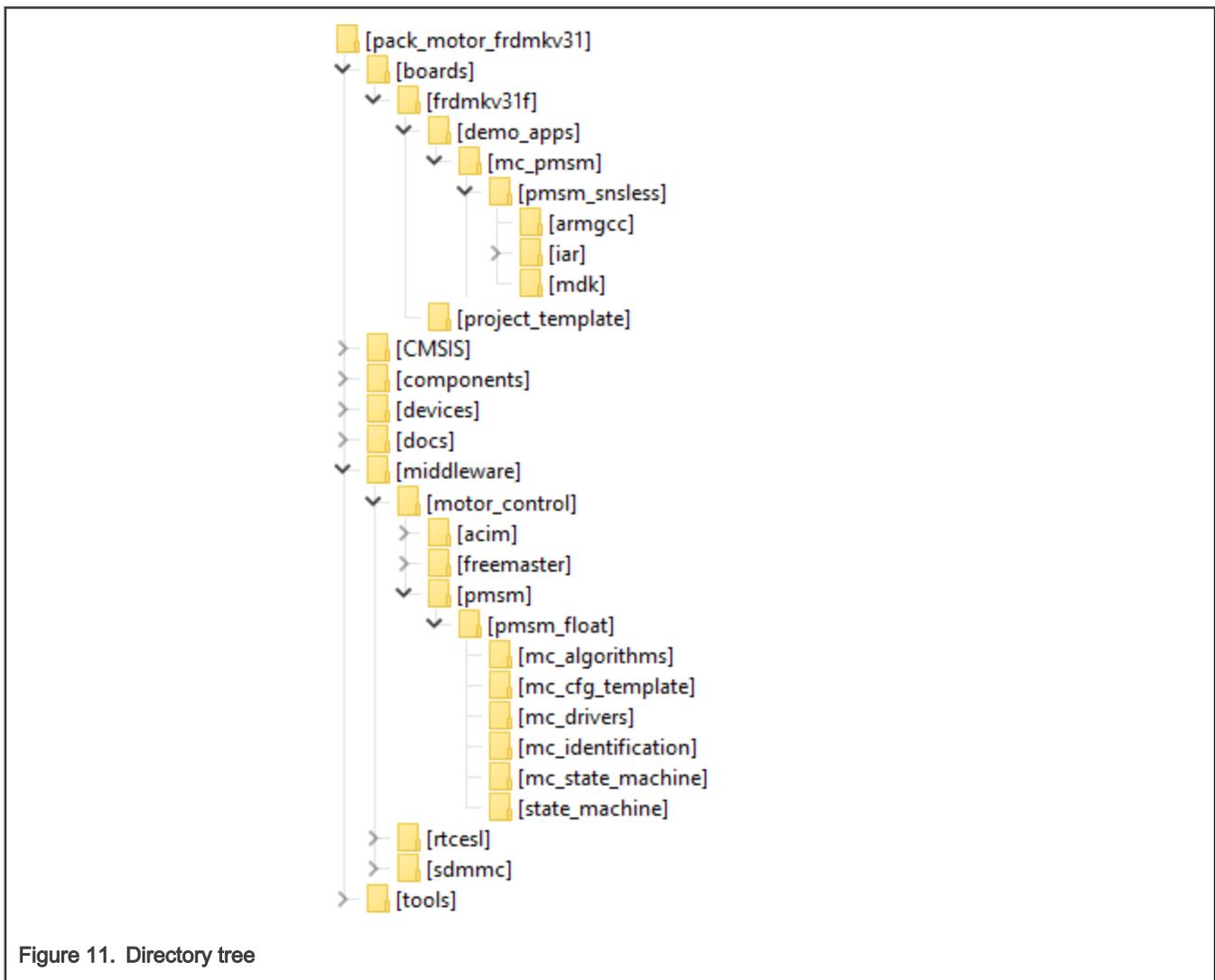


Figure 11. Directory tree

In the motor control project are located two examples. The main project folder in the first example is located in *pack_motor_xkxxx\boards\kxxx\demo_apps\mc_pmsm\pmsm_snsless!*. The example has motor control peripherals set using MC_PMSM middleware component in [MCUXpresso Config Tool](#). The main project folder in the second example is located in *pack_motor_xkxxx\boards\kxxx\demo_apps\mc_pmsm\pmsm_snsless_reg_init!*. The example has motor control peripherals set

using Register Initialization component in MCUXpresso Config Tool. In both examples the main project folder contains these folders and files:

- *iar*—for the IAR Embedded Workbench IDE.
- *armgcc*—for the GNU Arm IDE.
- *mdk*—for the uVision Keil IDE.
- *m1_pmsm_appconfig.h*—contains the definitions of constants for the application control processes, parameters of the motor and regulators, and the constants for other vector-control-related algorithms. When you tailor the application for a different motor using the Motor Control Application Tuning (MCAT) tool, the tool generates this file at the end of the tuning process.
- *main.c*—contains the basic application initialization (enabling interrupts), subroutines for accessing the MCU peripherals, and interrupt service routines. The FreeMASTER communication is performed in the background infinite loop.
- *board.c*—contains the functions for the UART, GPIO, and SysTick initialization.
- *board.h*—contains the definitions of the board LEDs, buttons, UART instance used for FreeMASTER, and so on.
- *clock_config.c and .h*—contains the CPU clock setup functions. These files are going to be generated by the clock tool in the future.
- *mc_periph_init.c*—contains the motor-control driver peripherals initialization functions that are specific for the board and MCU used.
- *mc_periph_init.h*—header file for *mc_periph_init.c*. This file contains the macros for changing the PWM period and the ADC channels assigned to the phase currents and board voltage.
- *freemaster_cfg.h*—the FreeMASTER configuration file containing the FreeMASTER communication and features setup.
- *pin_mux.c and .h*—port configuration files. It is recommended to generate these files in the pin tool.
- *peripherals.c and .h*—MCUXpresso Config Tool configuration files.

The main motor-control folder *pack_motor_xkxxx\middleware\motor_control* contains these subfolders:

- *pmsm*—contains main pmsm motor-control functions.
- *freemaster*—contains the FreeMASTER project file *pmsm_float.pmp* (*pmsm_frac.pmp* for the fraction version of the MCU). Open this file in the FreeMASTER tool and use it to control the application. The folder also contains the auxiliary files for the MCAT tool.

The *pack_motor_xkxxx\middleware\motor_control\pmsm\pmsm_float* folder contains these subfolders common to the other motor-control projects:

(*pack_motor_xkxxx\middleware\motor_control\pmsm\pmsm_frac* for the fraction version of the MCU)

- *mc_algorithms*—contains the main control algorithms used to control the FOC and speed control loop.
- *mc_cfg_template*—contains templates for MCUXpresso Config Tool components.
- *mc_drivers*—contains the source and header files used to initialize and run motor-control applications.
- *mc_identification*—contains the source code for the automated parameter-identification routines of the motor.
- *mc_state_machine*—contains the software routines that are executed when the application is in a particular state or state transition.
- *state_machine*—contains the state machine functions for the FAULT, INITIALIZATION, STOP, and RUN states.

Chapter 7

Tools

Install the [FreeMASTER Run-Time Debugging Tool 3.1.2](#) and one of the following IDEs on your PC to run and control the PMSM application properly:

- [IAR Embedded Workbench IDE v9.20.2](#) or higher
- [MCUXpresso v11.5.0](#)
- [ARM-MDK - Keil µVision version 5.36](#)

For `pin_mux.c`, `clock_config.c` or `peripherals.c` modifications is recommended use [MCUXpresso Configuration Tool v11](#) or higher.

NOTE

For information on how to build and run the application in your IDE, see the *Getting Started with MCUXpresso SDK* document located in the `pack_motor_<board>/docs` folder or find the related documentation at [MCUXpresso SDK builder](#).

7.1 Compiler warnings

Warnings are diagnostic messages that report constructions that are not inherently erroneous and warn about potential runtime, logic, and performance errors. In some cases, warnings can be suspended and these warnings do not show during the compiling process. One of such special cases is the “unused function” warning, where the function is implemented in the source code with its body, but this function is not used. This case occurs when you implement the function as a supporting function for better usability, but you do not use the function for any special purposes for a while.

The IAR Embedded Workbench IDE suppresses these warnings:

- Pa082 - undefined behavior; the order of volatile accesses is not defined in this statement.
- Pa050 - non-native end of line sequence detected.

The Arm-MDK Keil µVision IDE suppresses these warnings:

- 6314 - No section matches pattern xxx.o (yy).

By default, there are no other warnings shown during the compiling process.

Chapter 8

Motor-control peripheral initialization

The motor-control peripherals are initialized by calling the *MCDRV_Init_M1()* function during MCU startup and before the peripherals are used. All initialization functions are in the *mc_periph_init.c* source file and the *mc_periph_init.h* header file. The definitions specified by the user are also in these files. The features provided by the functions are the 3-phase PWM generation and 3-phase current measurement, as well as the DC-bus voltage and auxiliary quantity measurement. The principles of both the 3-phase current measurement and the PWM generation using the Space Vector Modulation (SVM) technique are described in *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)).

The motor control project includes two types of examples. The first example **mc_pmsm** has motor control peripherals initialized using **MC_PMSM** middleware component in **MCUXpresso Config Tool**. The second example **mc_pmsm_reg_init** has motor control peripherals initialized using Register Initialization component in MCUXpresso Config Tool. Therefore, motor control peripheral initialization files *mc_periph_init.c* and *h* differ for both examples.

mc_pmsm example:

The *mc_periph_init.h* header file provides several macros that configure motor control low-level driver. It is recommended to modify this file using MCUXpresso Config Tools and MC_PMSM component. Manual modification is possible but some of the driver rules are checked only when file is generated using MCUXpresso Config Tools.

- *M1_PWM_TIMER, M1_PWM_TIMER_FTM0*—PWM generation timer instance.
- *M1_PWM_FREQ*—the value of this definition sets the PWM frequency.
- *M1_PWM_MODULO*—the value of PWM modulo must correspond with *M1_PWM_FREQ*.
- *M1_FOC_FREQ_VS_PWM_FREQ*—enables you to call the fast loop interrupt at every first, second, third, or nth PWM reload. This is convenient when the PWM frequency must be higher than the maximal fast loop interrupt.
- *M1_FAST_LOOP_FREQ*—the value of this definition sets the speed loop frequency.
- *M1_SLOW_LOOP_FREQ*—the value of this definition sets the slow loop frequency.
- *M1_PWM_MODULO*—the value of slow loop modulo must correspond with *M1_SLOW_LOOP_FREQ*.
- *M1_FAST_LOOP_TS*—the value of fast loop period must correspond with *M1_FAST_LOOP_FREQ*.
- *M1_SLOW_LOOP_TS*—the value of slow loop period must correspond with *M1_SLOW_LOOP_FREQ*.
- *M1_PWM_PAIR_PH[A..C]*—these macros enable a simple assignment of the physical motor phases to the PWM periphery channels (or submodules). Change the order of the motor phases this way.
- *M1_PWM_DEADTIME_ENABLE*—enables PWM dead time insertion.
- *M1_PWM_DEADTIME_LENGTH_DTPS*—PWM dead time length (prescaler part).
- *M1_PWM_DEADTIME_LENGTH_DTVAL*—PWM dead time length (value part).
- *M1_FAULT_ENABLE*—enables PWM fault input.
- *M1_FAULT_NUM*—PWM fault input number.
- *M1_FAULT_POL*—PWM fault input polarity (0 = active high).
- *M1_FAULT_CMP_ENABLE*—PWM fault input taken from CMP output.
- *M1_FAULT_CMP_INSTANCE*—CMP instance used for fault detection.
- *M1_FAULT_CMP_THRESHOLD*—CMP instance used for fault detection.
- *M1_BRAKE_SET, M1_BRAKE_CLEAR*—macros that control the braking resistor GPIO.
- *M1_PWM_POL_TOP, M1_PWM_POL_BOTTOM*—inverter high-side and low-side polarity.

- *M1_SEC[1-6]_PH_[A..C]_[BASE, CHANNEL]*—these macros are used to assign the ADC channels for the phase current measurement. The general rule is that at least one of the phase currents must be measurable on both ADC converters and the two remaining phase currents must be measurable on different ADC converters. The reason for this is that the selection of the phase current pair to measure depends on the current SVM sector. For more information about the 3-phase current measurement, see *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)).
- *M1_[UDCB, AUX]_[BASE, CHANNEL]*—these macros are used to assign the ADC channels for the DC bus voltage and Auxiliary channel assignment. The general rule is that each quantity must be measured on different ADC instance.
- *ADC0_MUXSEL, ADC1_MUXSEL*—switches ADC muxed channels.
- *ADC_OFFSET_WINDOW*—ADC filter window during phase current offset calibration.
- *PDB_PRETRIG_DELAY*—PDB pre-trigger delay, should be set to half of the PWM dead time value.
- *M1_INRUSH_ENABLE*—enables inrush relay .
- *M1_INRUSH_DELAY*—inrush relay switch delay.
- *M1_INRUSH_SET(), M1_INRUSH_CLEAR()*—macros that control the inrush relay GPIO.

In the `mc_pmsm` example, these API-serving ADC and PWM peripherals are available:

- The available APIs for the ADC are:
 - *void M1_MCDRV_CURR_3PH_CHAN_ASSIGN(mcdrv_adc_t*)*—this function assigns ADC instances and channels to the phase-currents and prepares for next measurement.
 - *void M1_MCDRV_CURR_3PH_CALIB_INIT(mcdrv_adc_t*)*—this function initializes the phase-current channel-offset measurement.
 - *void M1_MCDRV_CURR_3PH_CALIB(mcdrv_adc_t*)*—this function reads the current information from the unpowered phases of a stand-still motor and filters them using moving average filters. The goal is to obtain the value of the measurement offset. The length of the window for moving the average filters is set to eight samples by default.
 - *void M1_MCDRV_CURR_3PH_CALIB_SET(mcdrv_adc_t*)*—this function asserts the phase-current measurement offset values to the internal registers. Call this function after a sufficient number of *M1_MCDRV_CURR_3PH_CALIB()* calls.
 - *void M1_MCDRV_ADC_GET(mcdrv_adc_t*)*—this function reads and calculates the actual values of the 3-phase currents, DC-bus voltage, and auxiliary quantity.
- The available APIs for the PWM are:
 - *mcdrv_pwm3ph_t*—MCDRV PWM structure data type.
 - *void M1_MCDRV_PWM3PH_SET(mcdrv_pwm3ph_t*)*—this function updates the PWM phase duty cycles.
 - *void M1_MCDRV_PWM3PH_EN(mcdrv_pwm3ph_t*)*—calling this function enables all PWM channels.
 - *void M1_MCDRV_PWM3PH_DIS (mcdrv_pwm3ph_t*)*—calling this function disables all PWM channels.
 - *void M1_MCDRV_PWM3PH_FLT_GET(mcdrv_pwm3ph_t*)*—this function returns the state of the over-current fault flags and automatically clears the flags (if set). This function returns true when an over-current event occurs. Otherwise, it returns false.

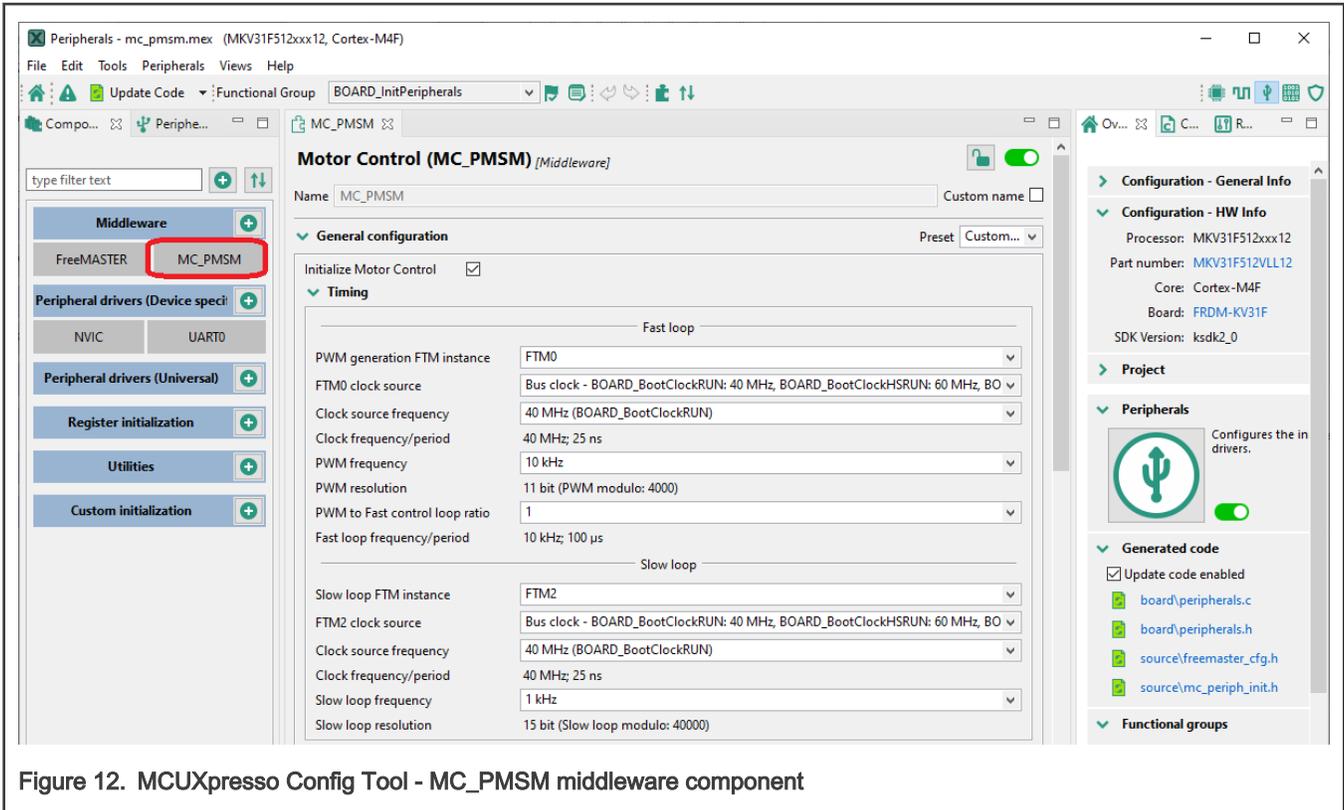


Figure 12. MCUXpresso Config Tool - MC_PMSM middleware component

mc_pmsm_reg_init example:

The *mc_periph_init.h* header file provides several macros that must be modified by user according to actual MC peripheral setting:

- *M1_PWM_FREQ*—the value of this definition sets the PWM frequency.
- *M1_FOC_FREQ_VS_PWM_FREQ*—enables you to call the fast loop interrupt at every first, second, third, or *n*th PWM reload. This is convenient when the PWM frequency must be higher than the maximal fast loop interrupt.
- *M1_FAST_LOOP_FREQ*—the value of this definition sets the speed loop frequency.
- *M1_SLOW_LOOP_FREQ*—the value of this definition sets the slow loop frequency.
- *M1_PWM_PAIR_PH[A..C]*—these macros enable a simple assignment of the physical motor phases to the PWM periphery channels (or submodules). Change the order of the motor phases this way.
- *M1_INRUSH_SET()*, *M1_INRUSH_CLEAR()*—macros that control the inrush relay GPIO.
- *M1_FAULT_NUM*—PWM fault input number.
- *M1_ADC[1,2]_PH[A..C]*—these macros are used to assign the ADC channels for the phase current measurement. The general rule is that at least one of the phase currents must be measurable on both ADC converters and the two remaining phase currents must be measurable on different ADC converters. The reason for this is that the selection of the phase current pair to measure depends on the current SVM sector. If this rule is broken, a preprocessor error is issued. For more information about the 3-phase current measurement, see *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)).
- *M1_ADC[1,2]_UDCB*—this define is used to select the ADC channel for the measurement of the DC-bus voltage.
- *ADC_OFFSET_WINDOW*—ADC filter window during phase current offset calibration.

In the *mc_pmsm* example, these API-serving ADC and PWM peripherals are available:

- The available APIs for the ADC are:
 - *mcdrv_adc_t*—MCDRV ADC structure data type.

- *void M1_MCDRV_ADC_PERIPH_INIT()*—this function is by default called during the ADC peripheral initialization procedure invoked by the *MCDRV_Init_M1()* function and should not be called again after the peripheral initialization is done.
- *void M1_MCDRV_CURR_3PH_CALIB_INIT(mcdrv_adc_t*)*—this function initializes the phase-current channel-offset measurement. This function always returns true.
- *void M1_MCDRV_CURR_3PH_CALIB(mcdrv_adc_t*)*—this function reads the current information from the unpowered phases of a stand-still motor and filters them using moving average filters. The goal is to obtain the value of the measurement offset. The length of the window for moving the average filters is set to eight samples by default. This function always returns true.
- *void M1_MCDRV_CURR_3PH_CALIB_SET(mcdrv_adc_t*)*—this function asserts the phase-current measurement offset values to the internal registers. Call this function after a sufficient number of *M1_MCDRV_CURR_3PH_CALIB()* calls. This function always returns true.
- *void M1_MCDRV_ADC_GET(mcdrv_adc_t*)*—this function reads and calculates the actual values of the 3-phase currents, DC-bus voltage, and auxiliary quantity. This function always returns true.
- The available APIs for the PWM are:
 - *mcdrv_pwm3ph_t*—MCDRV PWM structure data type.
 - *void M1_MCDRV_PWM3PH_SET(mcdrv_pwm3ph_t*)*—this function updates the PWM phase duty cycles. This function always returns true.
 - *void M1_MCDRV_PWM3PH_EN(mcdrv_pwm3ph_t*)*—calling this function enables all PWM channels. This function always returns true.
 - *void M1_MCDRV_PWM3PH_DIS (mcdrv_pwm3ph_t*)*—calling this function disables all PWM channels. This function always returns true.
 - *void M1_MCDRV_PWM3PH_FLT_GET(mcdrv_pwm3ph_t*)*—this function returns the state of the over-current fault flags and automatically clears the flags (if set). This function returns true when an over-current event occurs. Otherwise, it returns false.

Chapter 9

User interface

The application contains the demo mode to demonstrate motor rotation. You can operate it either using the user button or using FreeMASTER. The NXP EVK boards include a user button associated with a port interrupt (generated whenever one of the buttons is pressed). At the beginning of the ISR, a simple logic executes and the interrupt flag clears. When you press the button, the demo mode starts. When you press the same button again, the application stops and transitions back to the STOP state.

The other way to interact with the demo mode is to use the FreeMASTER tool. The FreeMASTER application consists of two parts: the PC application used for variable visualization and the set of software drivers running in the embedded application. Data is transferred between the PC and the embedded application via the serial interface. This interface is provided by the OpenSDA debugger included in the boards.

The application can be controlled the using these two interfaces:

- The button on the development board (controlling the demo mode):

Table 7. Control button assignment

Board	Control button	LED state indication
FRDM-KV11Z	SW2	D4
HVP-KV11Z	-	D20

- Remote control using FreeMASTER (chapter [Remote control using FreeMASTER](#)):
 - Using the Motor Control Application Tuning (MCAT) interface in the “Control Structure” tab or the “Application control” tab (controlling the demo mode).
 - Setting a variable in the FreeMASTER Variable Watch.

Chapter 10

Remote control using FreeMASTER

This section provides information about the tools and recommended procedures to control the sensor/sensorless PMSM Field-Oriented Control (FOC) application using FreeMASTER. The application contains the embedded-side driver of the FreeMASTER real-time debug monitor and data visualization tool for communication with the PC. It supports non-intrusive monitoring, as well as the modification of target variables in real time, which is very useful for algorithm tuning. Besides the target-side driver, the FreeMASTER tool requires the installation of the PC application as well. You can download FreeMASTER 3.0 at www.nxp.com/freemaster. To run the FreeMASTER application including the MCAT tool, double-click the *pmsm_float.pmp* (for fraction version *pmsm_frac.pmp*) file located in the *pack_motor_xkxxx\middleware\motor_control\freemaster*. The FreeMASTER application starts and the environment is created automatically, as defined in the **.pmp* file.

NOTE

In MCUXpresso can be FreeMASTER application run directly from IDE in *motor_control/freemaster* folder

10.1 Establishing FreeMASTER communication

The remote operation is provided by FreeMASTER via the USB interface. Perform the following steps to control a PMSM motor using FreeMASTER:

1. Download the project from your chosen IDE to the MCU and run it.
2. Open the FreeMASTER file *pmsm_x.pmp*. The PMSM project uses the TSA by default, so it is not necessary to select a symbol file for FreeMASTER.
3. Click the communication button (the red “STOP” button in the top left-hand corner) to establish the communication.



Figure 13. Red “STOP” button placed in top left-hand corner

4. If the communication is established successfully, the FreeMASTER communication status in the bottom right-hand corner changes from “Not connected” to “RS232 UART Communication; COMxx; speed=19200”. Otherwise, the FreeMASTER warning popup window appears.



Figure 14. FreeMASTER—communication is established successfully

5. Press *F5* to reload the MCAT HTML page and check the App ID.
6. Control the PMSM motor using the MCAT “Control structure” tab, the MCAT “Application demo control” tab, or by directly writing to a variable in a variable watch.
7. If you rebuild and download the new code to the target, turn the FreeMASTER application off and on.

If the communication is not established successfully, perform the following steps:

1. Go to the “Project -> Options -> Comm” tab and make sure that the correct COM port is selected and the communication speed is set to 19200 bps.

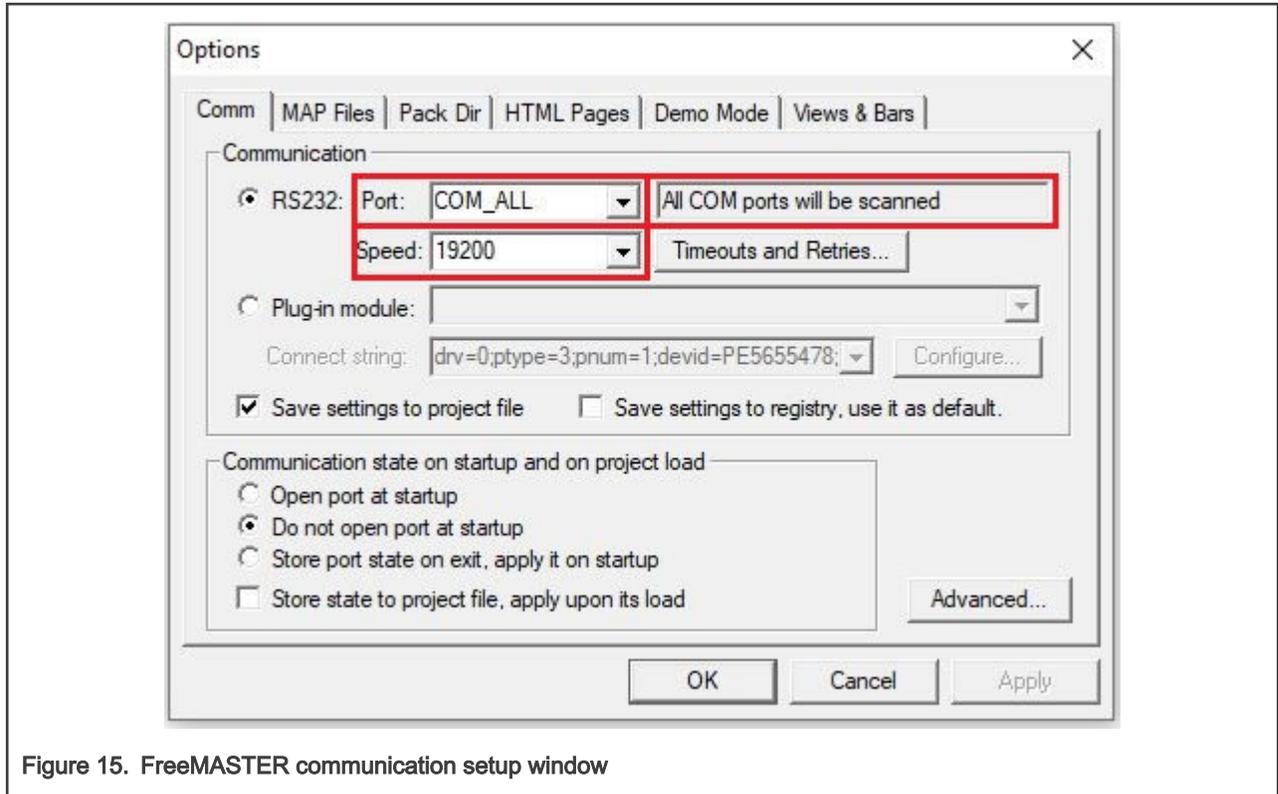


Figure 15. FreeMASTER communication setup window

- If "OpenSDA-CDC Serial Port" is not printed out in the message box next to the "Port" drop-down menu, unplug and then plug in the USB cable and reopen the FreeMASTER project.

Make sure to supply your development board from a sufficient energy source. Sometimes the PC USB port is not sufficient to supply the development board.

10.2 MCAT FreeMASTER interface (Motor Control Application Tuning)

The PMSM sensor/sensorless FOC application can be easily controlled and tuned using the Motor Control Application Tuning (MCAT) plug-in for PMSM. The MCAT for PMSM is a user-friendly modular page, which runs within FreeMASTER. The tool consists of the tab menu, tuning mode selector, and workspace shown in Figure 16. Each tab from the tab menu represents one sub-module which enables you to tune or control different aspects of the application. Besides the MCAT page for PMSM, several scopes, recorders, and variables in the project tree are predefined in the FreeMASTER project file to further simplify the motor parameter tuning and debugging. When the FreeMASTER is not connected to the target, the "App ID" line shows "offline". When the communication with the target MCU is established using a correct software, the "App ID" line displays the board name "pmsm_used_board" and all stored parameters for the given MCU are loaded. If the connection is established and the board ID is not shown, press *F5* to reload the MCAT HTML page.

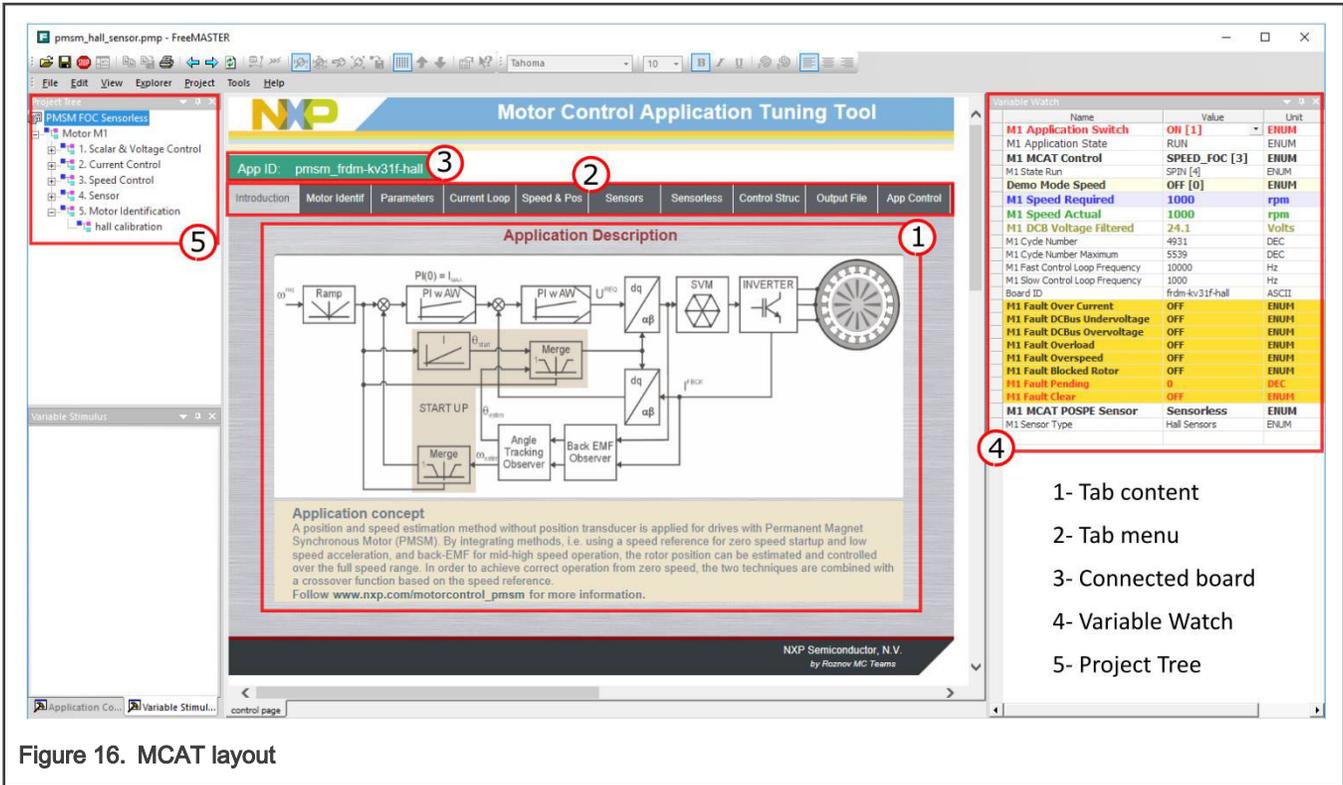


Figure 16. MCAT layout

In the default configuration, the following tabs are available:

- “Introduction”—welcome page with the PMSM sensor/sensorless FOC diagram and a short description of the application.
- “Motor Identif”—PMSM semi-automated parameter measurement control page. The PMSM parameter identification is more closely described further on in this document.
- “Parameters”—this page enables you to modify the motor parameters, specification of hardware and application scales, alignment, and fault limits.
- “Current Loop”—current loop PI controller gains and output limits.
- “Speed & Pos”—this tab contains fields for the specification of the speed controller proportional and integral gains, as well as the output limits and parameters of the speed ramp. The position proportional controller constant is also set here.
- “Sensors”—this page contains the encoder parameters and position observer parameters.
- “Sensorless”—this page enables you to tune the parameters of the BEMF observer, tracking observer, and open-loop startup.
- “Control Struc”—this application control page enables you to select and control the PMSM using different techniques (scalar—Volt/Hertz control, voltage FOC, current FOC, speed FOC, and position FOC). The application state is also shown in this tab.
- “Output file”—this tab shows all the calculated constants that are required by the PMSM sensor/sensorless FOC application. It is also possible to generate the *m1_acim_appconfig.h* file, which is then used to preset all application parameters permanently at the project rebuild.
- “App page”—this tab contains the graphical elements like the speed gauge, DC-bus voltage measurement bar, and variety of switches which enable a simple, quick, and user-friendly application control. The fault clearing and the demo mode (which sets various predefined required speeds and positions over time) can be also controlled from here.

Most tabs offer the possibility to immediately load the parameters specified in the MCAT into the target using the “Update target” button and save (or restore) them from the hard drive file using the “Reload Data” and “Store Data” buttons.

The following sections provide simple instructions on how to identify the parameters of a connected PMSM motor and how to appropriately tune the application.

Control structure—“Control Struc” tab

The application can be controlled through the “Control Struc” tab, which is shown in [Figure 17](#). The state control area on the left side of the screen shows the current application state and enables you to turn the main application switch on or off (turning a running application off disables all PWM outputs). The “Cascade Control Structure” area is placed in the right-hand side of the screen. Here you can choose between the scalar control and the FOC control using the appropriate buttons. The selected parts of the FOC cascade structure can be enabled by selecting “Voltage FOC”, “Current FOC”, and “Speed FOC” (sensor/sensorless). This is useful for application tuning and debugging.

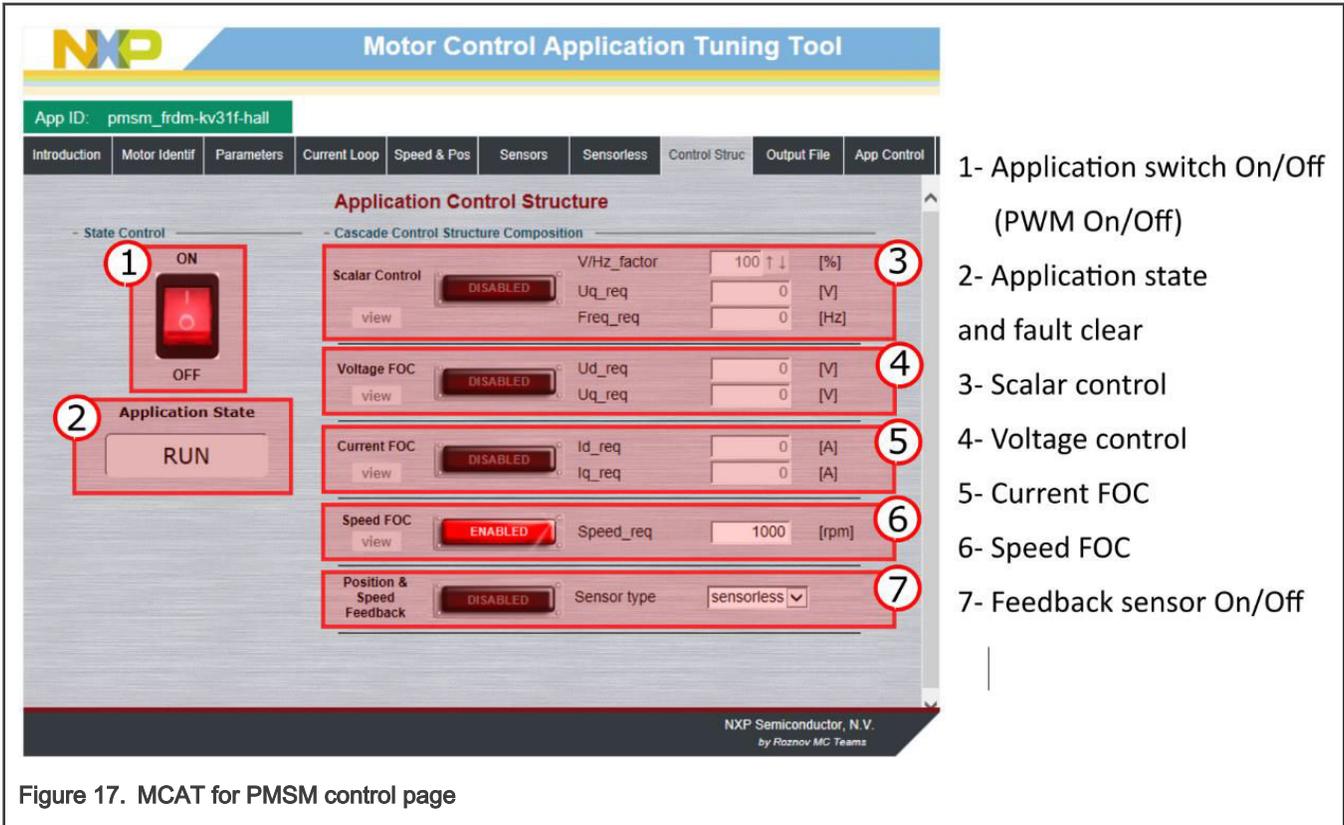


Figure 17. MCAT for PMSM control page

The scalar control diagram is shown in [Figure 18](#). It is the simplest type of motor-control techniques. The ratio between the magnitude of the stator voltage and the frequency must be kept at the nominal value. Hence, the control method is sometimes called Volt per Hertz (or V/Hz). The position estimation BEMF observer and tracking observer algorithms (see Sensorless PMSM Field-Oriented Control ([document DRM148](#)) for more information) run in the background, even if the estimated position information is not directly used. This is useful for the BEMF observer tuning.

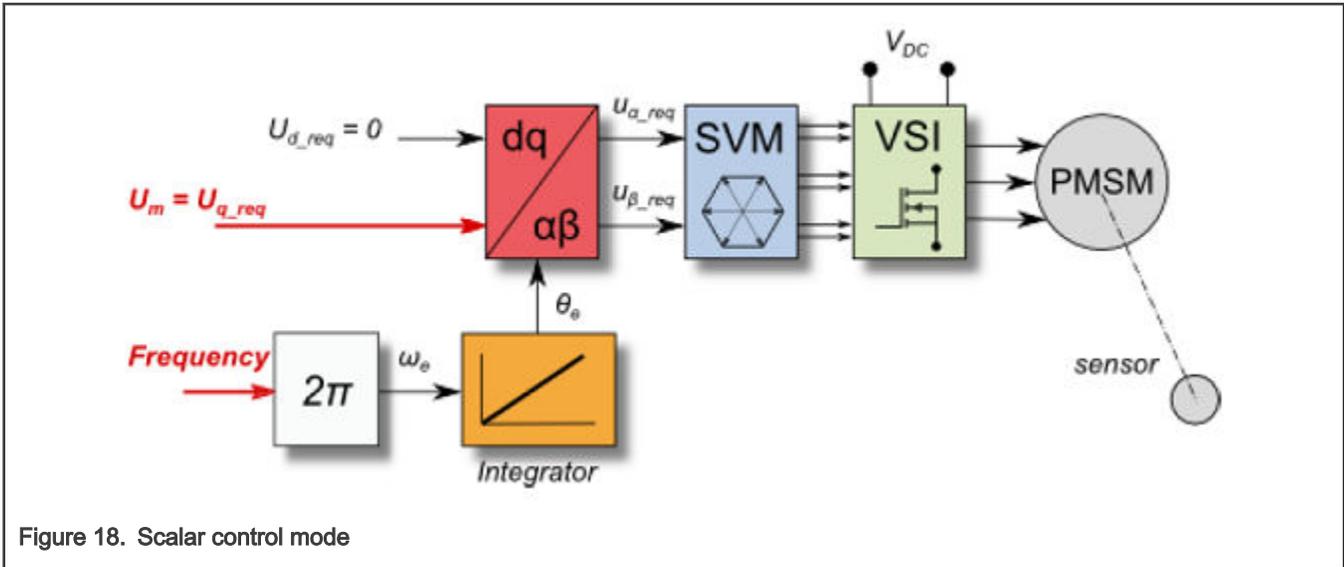


Figure 18. Scalar control mode

The block diagram of the voltage FOC is in Figure 19. Unlike the scalar control, the position feedback is closed using the BEMF observer and the stator voltage magnitude is not dependent on the motor speed. Both the d-axis and q-axis stator voltages can be specified in the “Ud_req” and “Uq_req” fields. This control method is useful for the BEMF observer functionality check.

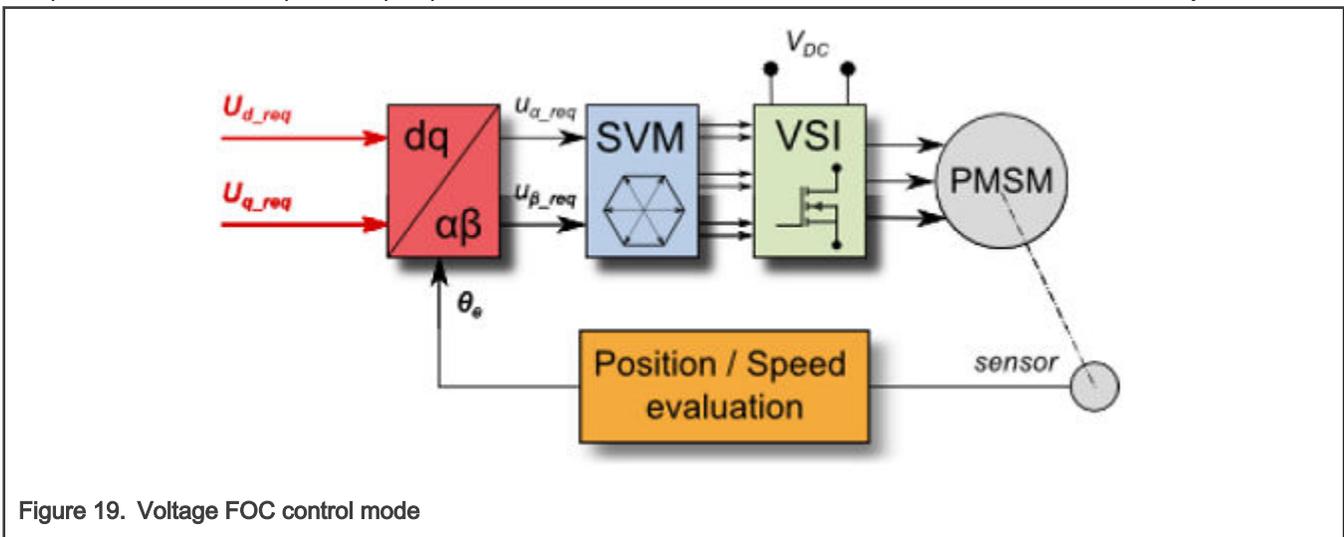


Figure 19. Voltage FOC control mode

The current FOC (or torque) control requires the rotor position feedback and the currents transformed into a d-q reference frame. There are two reference variables (“Id_req” and “Iq_req”) available for the motor control, as shown in the block diagram in Figure 20. The d-axis current component “isd_req” is responsible for the rotor flux control. The q-axis current component of the current “isq_req” generates torque and, by its application, the motor starts running. By changing the polarity of the current “isq_req”, the motor changes the direction of rotation. Supposing that the BEMF observer is tuned correctly, the current PI controllers can be tuned using the current FOC control structure.

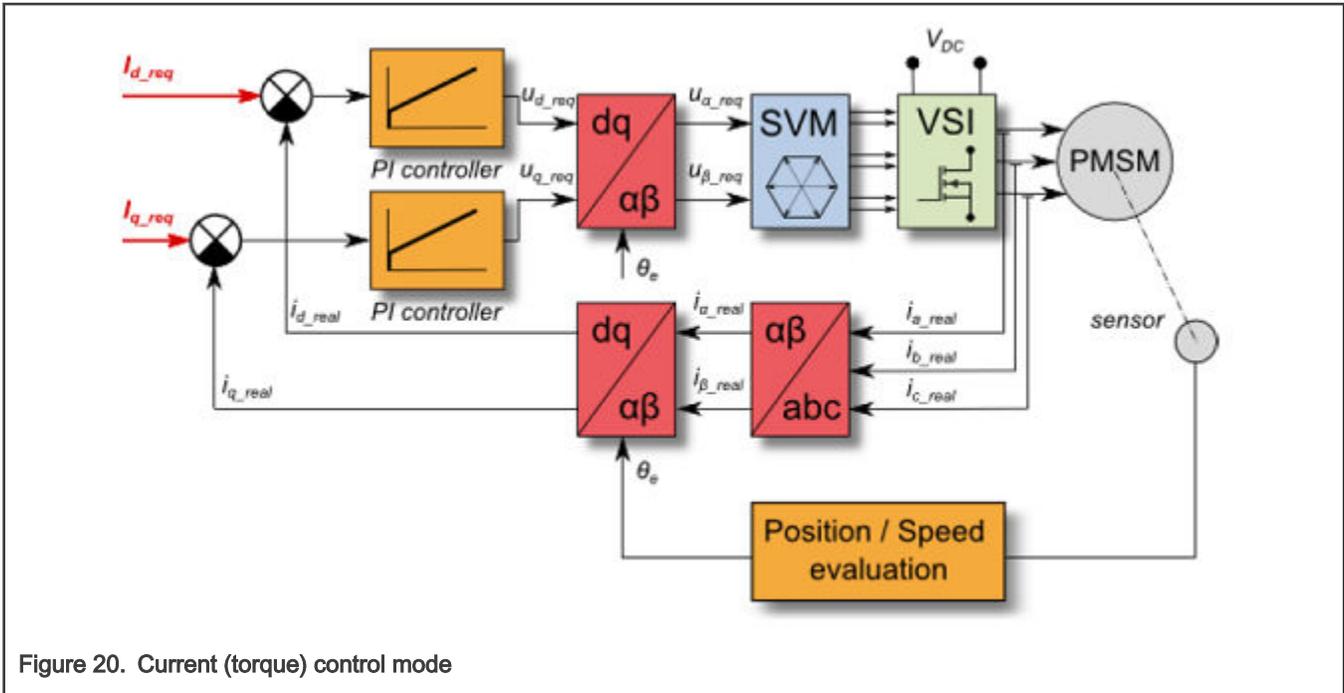


Figure 20. Current (torque) control mode

The speed PMSM sensor/sensorless FOC (its diagram is shown in Figure 21) is activated by enabling the speed FOC control structure. Enter the required speed into the “Speed_req” field. The d-axis current reference is held at 0 during the entire FOC operation.

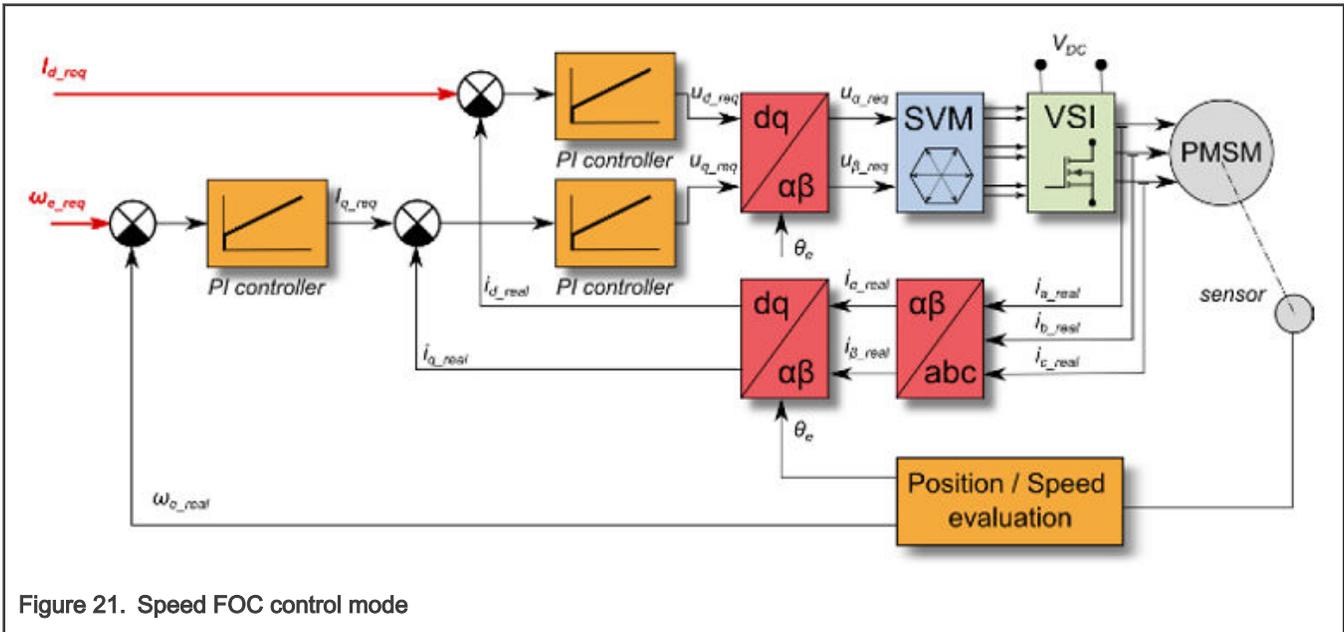


Figure 21. Speed FOC control mode

The position PMSM sensor FOC is shown in Figure 22 (Not available for all devices). The position control using the P controller can be tuned in the “Speed & Pos” menu tab. An encoder sensor is required for the feedback. Without the sensor, the position control does not work. A braking resistor is missing on the FRDM-MC-LVPMSM board. Therefore, it is needed to set a soft speed ramp (in the “Speed & Pos” menu tab) because the voltage on the DC-bus can rise when braking the quickly spinning shaft. It may cause the overvoltage fault.

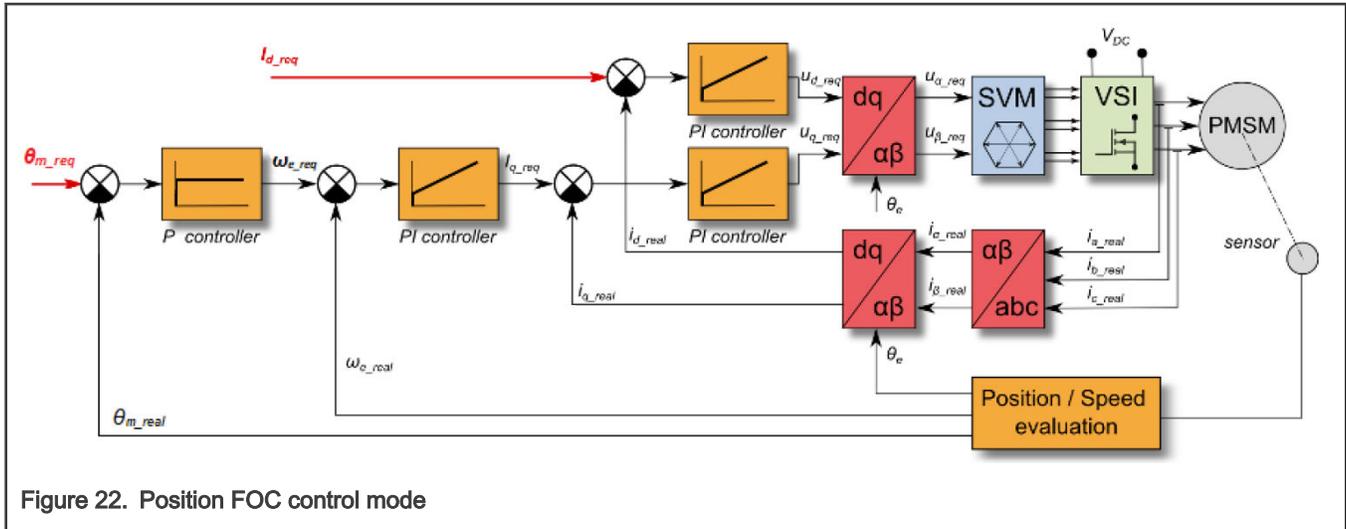


Figure 22. Position FOC control mode

Application demo control—“App control” tab

After launching the application and performing all necessary settings, you can control the PMSM motor using the FreeMASTER application demo control page. This page contains:

- Speed gauge—shows the actual and required speeds.
- Required speed slider—sets up the required speed.
- DC-bus voltage—shows the actual DC-bus voltage.
- Current i_q —shows the actual torque-producing current.
- Current limitation—sets up the torque-producing current limit.
- Demo mode on/off button—turns the demonstration mode on/off.
- RUN/STOP PWM button—runs/stops the whole application (sets the PWM on and off).
- Notification—shows the notification about the actual application state (or faults).

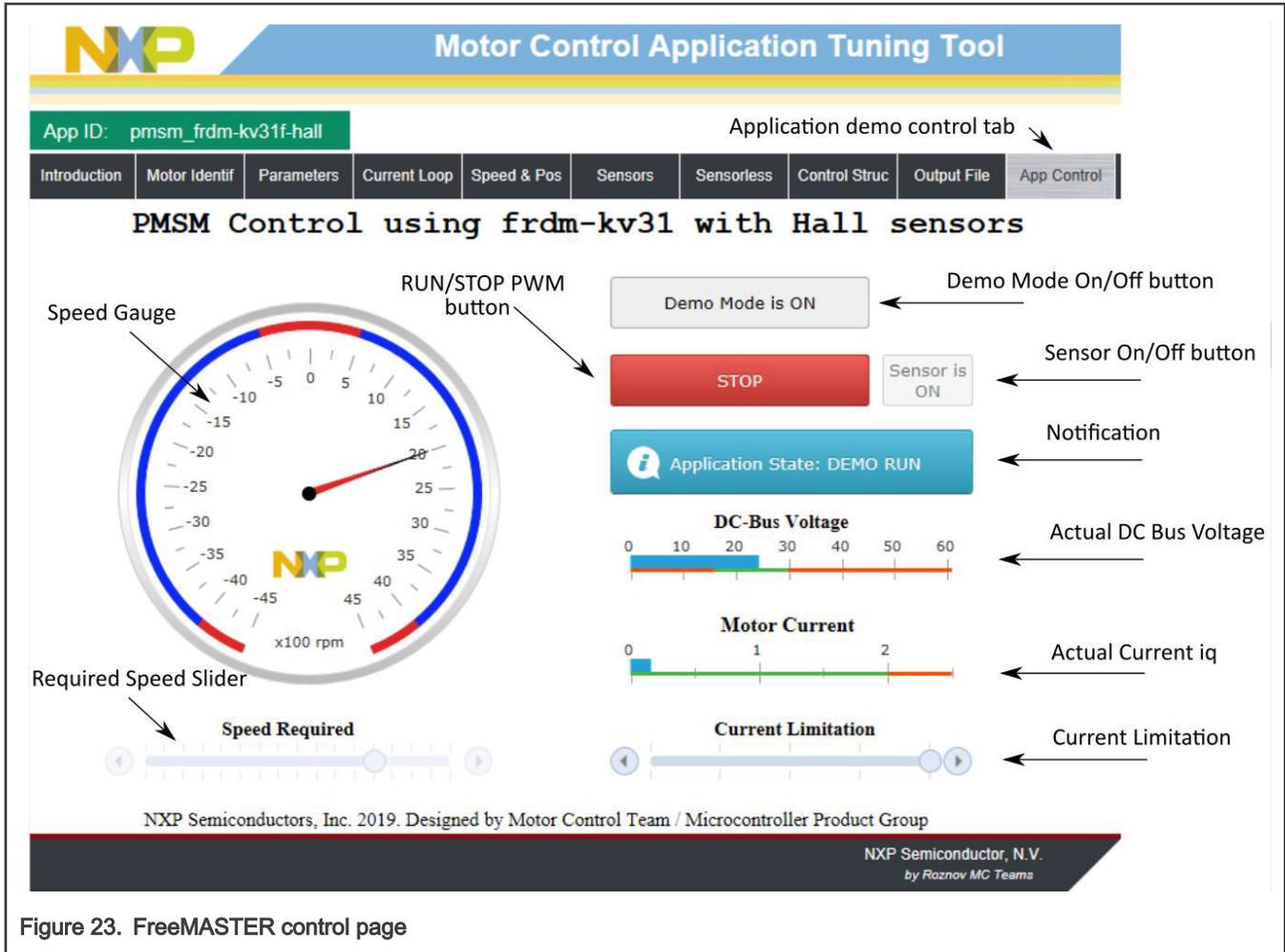


Figure 23. FreeMASTER control page

The following are the basic instructions for controlling a motor:

- To start the motor, set the required speed using the speed slider.
- In case of a fault, click on the fault notification to clear the fault.
- Click the “Demo Mode On/Off” button to turn the demonstration mode on/off.
- Click the “RUN/STOP” button to stop the motor.

Chapter 11

Identifying parameters of user motor using MCAT

This section provides a guide on how to run your own motor or tune the default motor in several steps. It is highly recommended to go through all the steps carefully to eliminate any possible issues during the tuning process. The state diagram in [Figure 24](#) shows a typical PMSM sensor/sensorless control tuning process.

Because the model-based control methods of the PMSM drives are the most effective and usable, obtaining an accurate model of a motor is an important part of the drive design and control. For the implemented FOC algorithms, it is necessary to know the value of the stator resistance R_s , direct inductance L_d , quadrature inductance L_q , and BEMF constant K_e . If your connected PMSM motor is not the default Teknik or Linix motor described in the previous sections, identify the parameters of your motor first. Each tuning phase is described in more detail in the following sections.

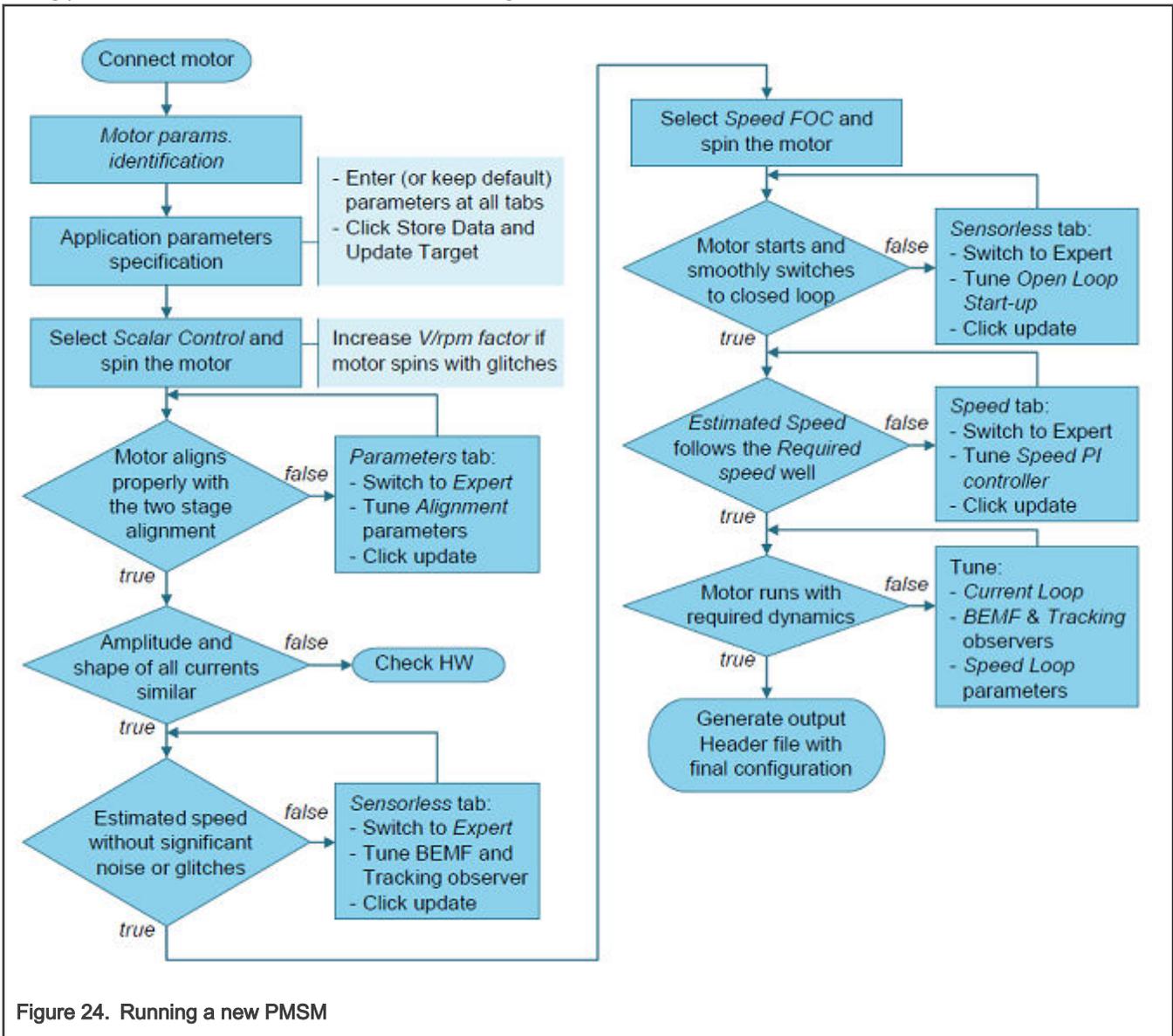


Figure 24. Running a new PMSM

Power stage characterization

Each inverter introduces the total error voltage U_{error} , which is caused by the dead time, current clamping effect, and transistor voltage drop. The total error voltage U_{error} depends on the phase current i_s and this dependency is measured during the power stage characterization process. An example of the inverter error characteristic is shown in Figure 25. The power stage characterization is a part of the MCAT and it can be controlled from the “Motor Identif” tab. To perform the characterization, connect the motor with a known stator resistance R_s and enter this value into the “Calib Rs” field. Then specify the “Calibration Range”, which is the range of the stator current i_s , in which the measurement of U_{error} is performed. Start the characterization by pressing the “Calibrate” button. The characterization gradually performs 65 i_{sd} current steps (from $i_s = -I_{s,calib}$ to $i_s = I_{s,calib}$) with each taking 300 ms, so be aware that the process takes about 20 seconds and the motor must withstand this load. The acquired characterization data is saved to a file and used later for the phase voltage correction during the R_s measurement process. The following R_s measurement can be done with the $I_{s,calib}$ maximum current. It is recommended to use a motor with a low R_s for characterization purposes.

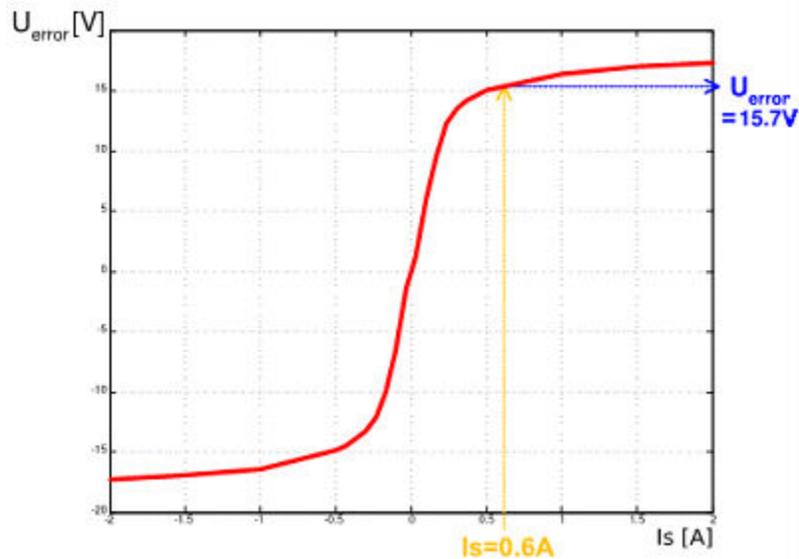


Figure 25. Example power stage characteristic

The power stage characterization is necessary only for the user hardware board. When the NXP power stages (TWR, FRDM, or HVP) are used with the application, the characterization process can be omitted. The acquired characterization data is saved into a file, so it is necessary to do it only once for a given hardware.

Stator resistance measurement

The stator resistance R_s is measured using the DC current I_{phN} value, which is applied to the motor for 1200 ms. The DC voltage U_{DC} is held using current controllers. Their parameters are selected conservatively to ensure stability. The stator resistance R_s is calculated using the Ohm’s law as:

$$R_s = \frac{U_{DC} - U_{error}}{I_{phN}} \text{ [}\Omega\text{]}$$

Stator inductance

For the stator inductance (L_s) identification purposes, a sinusoidal measurement voltage is applied to the motor. During the L_s measurement, the voltage control is enabled. The frequency and amplitude of the sinusoidal voltage are obtained before the actual measurement, during the tuning process. The tuning process begins with a 0-V amplitude and the F_{start} frequency, which are

applied to the motor. The amplitude is gradually increased by $U_d\ inc$ up to a half of the DC-bus voltage ($DCbus/2$), until $I_d\ ampl$ is reached. If $I_d\ ampl$ is not reached even with the $DCbus/2$ and $F\ start$, the frequency of the measuring signal is gradually decreased by $F\ dec$ down to $F\ min$ again, until $I_d\ ampl$ is reached. If $I_d\ ampl$ is still not reached, the measurement continues with $DCbus/2$ and $F\ min$. The tuning process is shown in Figure 26.

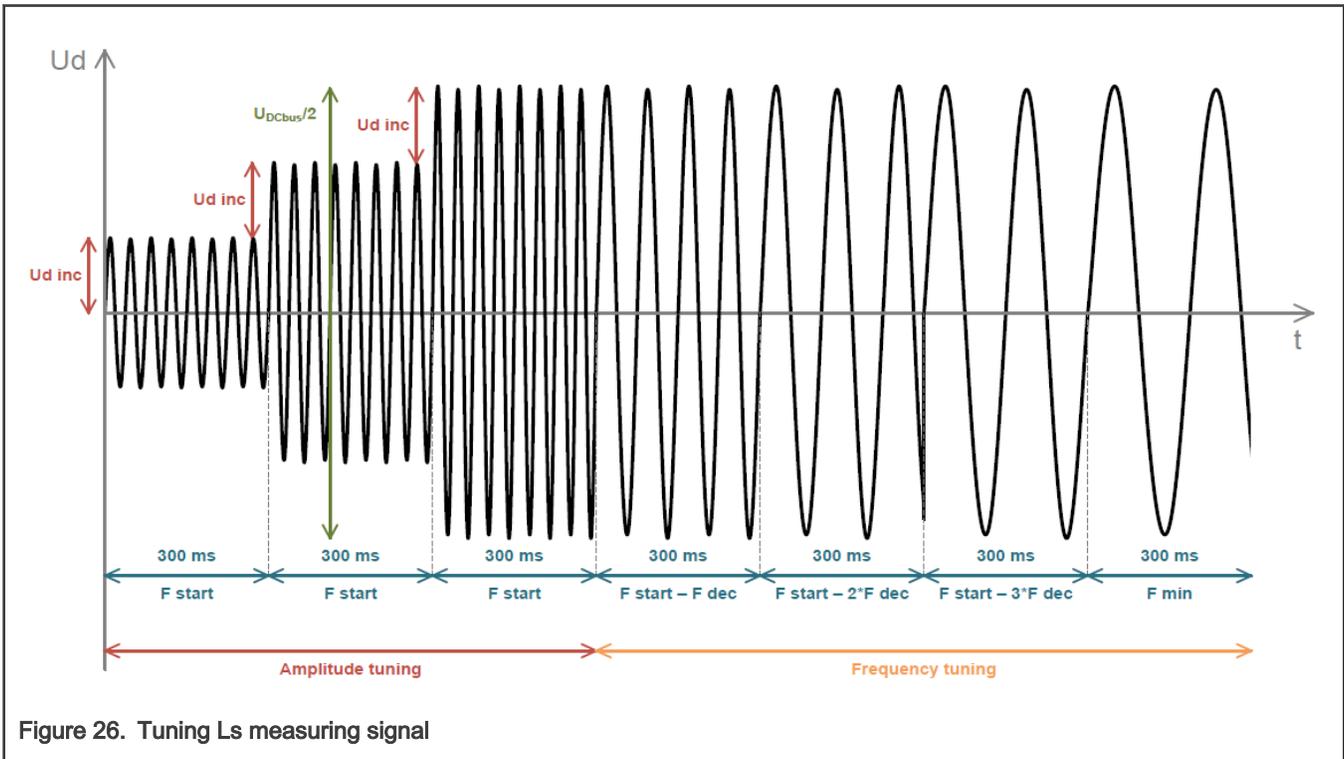


Figure 26. Tuning L_s measuring signal

When the tuning process is complete, the sinusoidal measurement signal (with the amplitude and frequency obtained during the tuning process) is applied to the motor. The total impedance of the RL circuit is then calculated from the voltage and current amplitudes and L_s is calculated from the total impedance of the RL circuit.

$$Z_{RL} = \frac{U_d}{I_d\ ampl} \text{ [}\Omega\text{]}$$

$$X_{Ls} = \sqrt{Z_{RL}^2 - R_s^2} \text{ [}\Omega\text{]}$$

$$L_s = \frac{X_{Ls}}{2\pi f} \text{ [}\Omega\text{]}$$

The direct inductance L_d and quadrature inductance L_q measurements are made in the same way as L_s . Before the L_d and L_q measurement is made, DC current is applied to the D-axis, which aligns the rotor. For the L_d measurement, the sinusoidal voltage is applied in the D-axis. For the L_q measurement, the sinusoidal voltage is applied in the Q-axis.

BEMF constant measurement

Before the actual BEMF constant (K_e) measurement, the MCAT tool calculates the current controllers and BEMF observer constants from the previously measured R_s , L_d , and L_q . To measure K_e , the motor must spin. I_d is controlled through $I_d\ meas$ and the electrical open-loop position is generated by integrating the required speed, which is derived from N_{nom} . When the motor reaches the required speed, the BEMF voltages obtained by the BEMF observer are filtered and K_e is calculated:

$$K_e = \frac{U_{BEMF}}{\omega_{el}} [\Omega]$$

When K_e is being measured, you have to visually check to determine whether the motor is spinning properly. If the motor is not spinning properly, perform these steps:

- Ensure that the number of pp is correct. The required speed for the K_e measurement is also calculated from pp . Therefore, inaccuracy in pp causes inaccuracy in the resulting K_e .
- Increase $I_{d\,meas}$ to produce higher torque when spinning during the open loop.
- Decrease N_{nom} to decrease the required speed for the K_e measurement.

Number of pole-pair assistant

The number of pole-pairs cannot be measured without a position sensor. However, there is a simple assistant to determine the number of pole-pairs (pp). The number of the pp assistant performs one electrical revolution, stops for a few seconds, and then repeats it. Because the pp value is the ratio between the electrical and mechanical speeds, it can be determined as the number of stops per one mechanical revolution. It is recommended not to count the stops during the first mechanical revolution because the alignment occurs during the first revolution and affects the number of stops. During the pp measurement, the current loop is enabled and the I_d current is controlled to $I_{d\,meas}$. The electrical position is generated by integrating the open-loop speed. If the rotor does not move after the start of the number of pp assistant, stop the assistant, increase $I_{d\,meas}$, and restart the assistant.

Mechanical parameters measurement

The moment of inertia J and the viscous friction B can be identified using a test with the known generated torque T and the loading torque T_{load} .

$$\frac{d\omega_m}{dt} = \frac{1}{J} (T - T_{load} - B\omega_m) [rad/s^2]$$

The ω_m character in the equation is the mechanical speed. The mechanical parameter identification software uses the torque profile. The loading torque is (for simplicity reasons) said to be 0 during the whole measurement. Only the friction and the motor-generated torque are considered. During the first phase of measurement, the constant torque T_{meas} is applied and the motor accelerates to 50 % of its nominal speed in time t_f . These integrals are calculated during the period from t_0 (the speed estimation is accurate enough) to t_f :

$$T_{int} = \int_{t_0}^{t_1} T dt [Nms] \quad \omega_{int} = \int_{t_0}^{t_1} \omega_m dt [rad/s]$$

During the second phase, the rotor decelerates freely with no generated torque, only by friction. This enables you to simply measure the mechanical time constant $\tau_m = J/B$ as the time in which the rotor decelerates from its original value by 63 %.

The final mechanical parameter estimation can be calculated by integrating:

$$\omega_m(t_1) = \frac{1}{J} T_{int} - \frac{B}{J} \omega_{int} + \omega_m(t_0) [rad/s]$$

The moment of inertia is:

$$J = \frac{\tau_m T_{int}}{\tau_m [\omega_m(t_1) - \omega_m(t_0)] + \omega_{int}} [kgm^2]$$

The viscous friction is then derived from the relation between the mechanical time constant and the moment of inertia. To use the mechanical parameters measurement, the current control loop bandwidth $f_{0,Current}$, the speed control loop bandwidth $f_{0,Speed}$, and the mechanical parameters measurement torque Trq_m must be set.

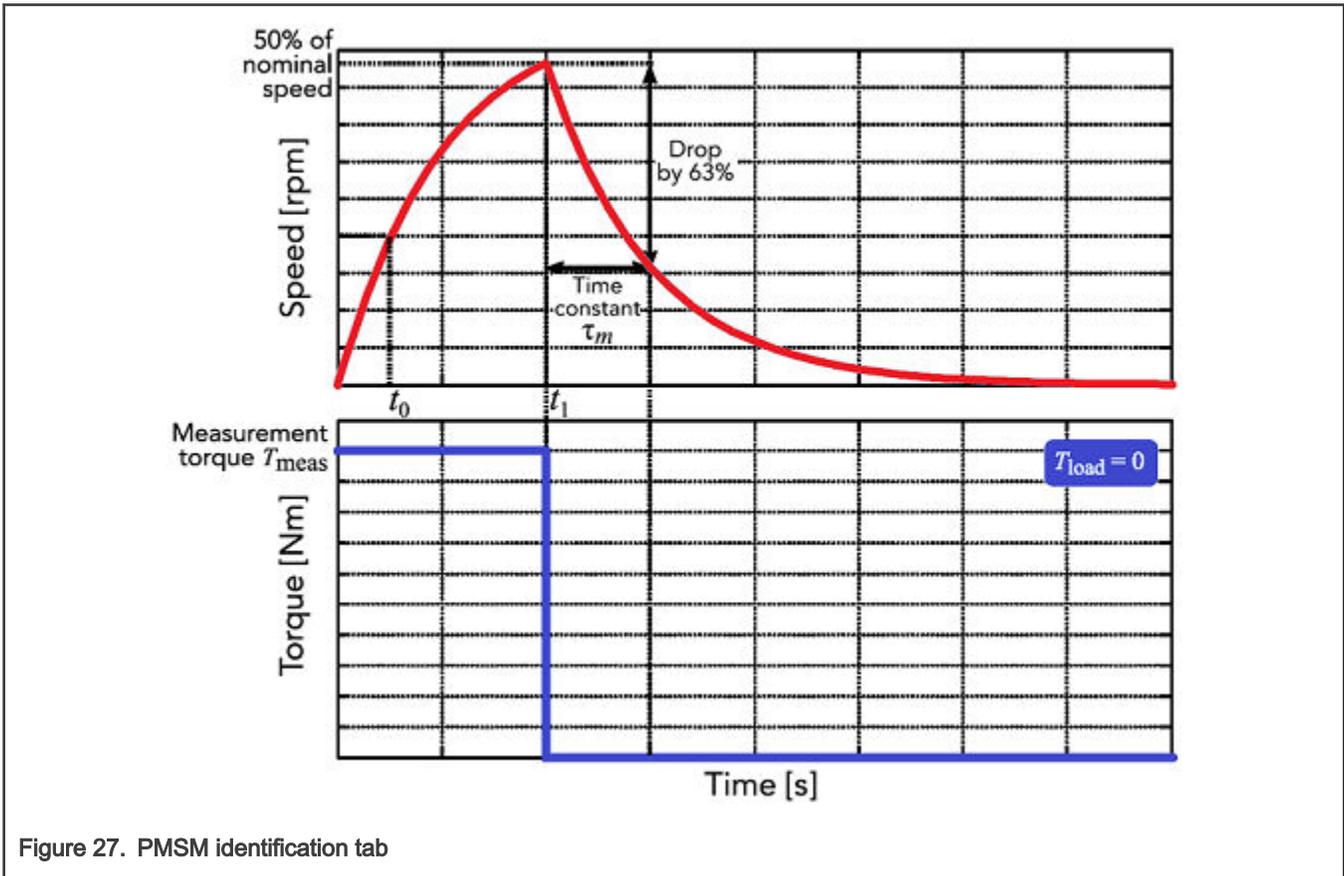


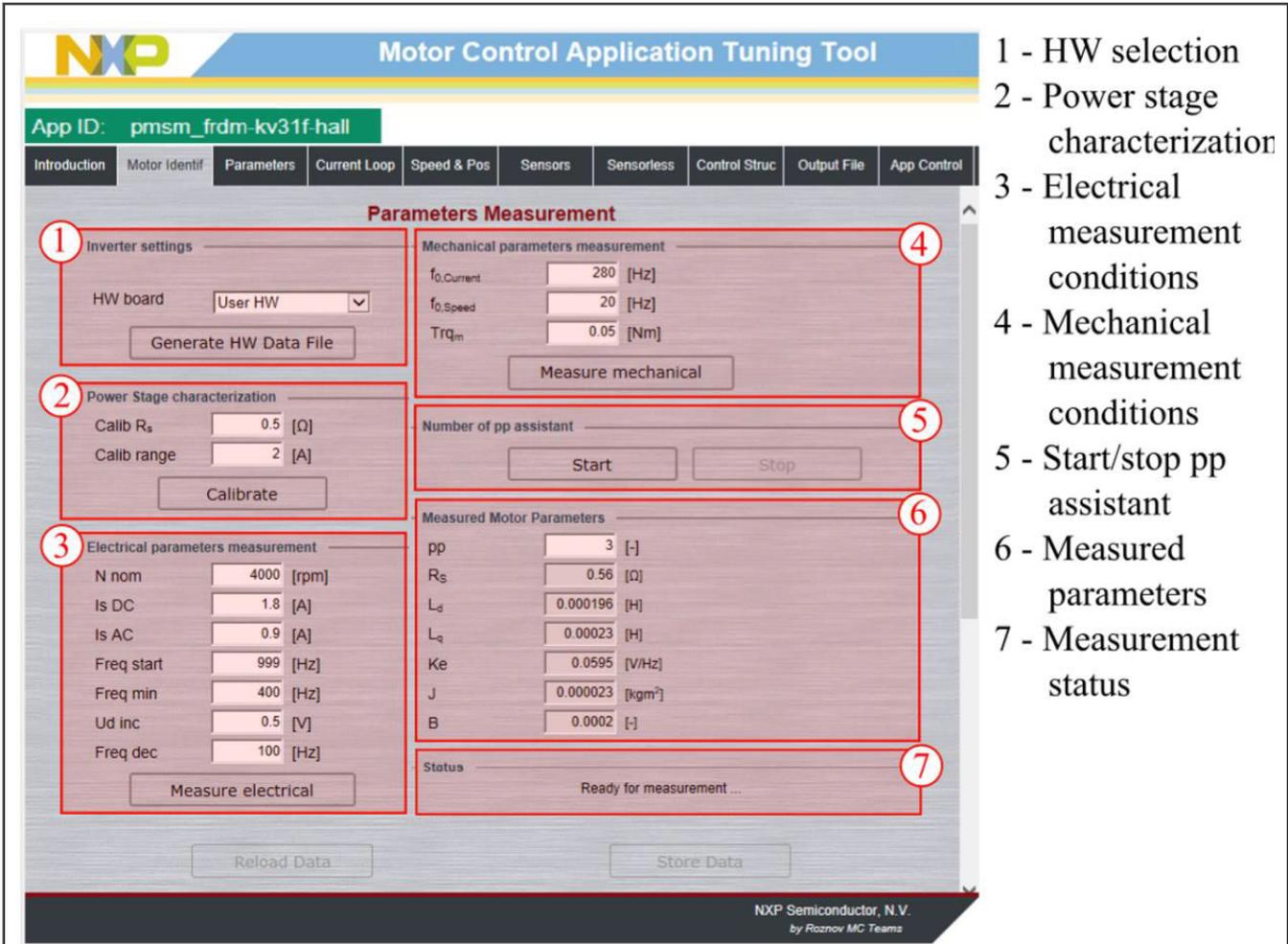
Figure 27. PMSM identification tab

11.1 PMSM electrical and mechanical parameters measurement process

If the parameters of your own motor are known from the datasheet, you can enter them in the "Parameters" tab. If you don't know the parameters of your motor, you have to use automatic parameter identification.

The motor identification process can be controlled and set up in the MCAT "Motor Identif" tab, which is shown in Figure 28. To measure your own motor, follow these steps:

- Select your hardware board. Choose between the standard NXP hardware or use your own. If you use your own hardware, specify its scales ("I max" and "U DCB max" in the "Parameters" menu tab).
- If you don't know the number of motor's pole-pairs, use the number of pole-pair assistant and compute the number of motor rotor stops in one turn.
- If you use your own hardware for the first time (other than NXP boards), perform the power stage characterization.
- Enter the motor measurement parameters and start the measurement by pressing the "Measure electrical" or "Measure mechanical" buttons. You can observe which parameter is being measured in the "Status" bar.



- 1 - HW selection
- 2 - Power stage characterization
- 3 - Electrical measurement conditions
- 4 - Mechanical measurement conditions
- 5 - Start/stop pp assistant
- 6 - Measured parameters
- 7 - Measurement status

Figure 28. PMSM identification tab

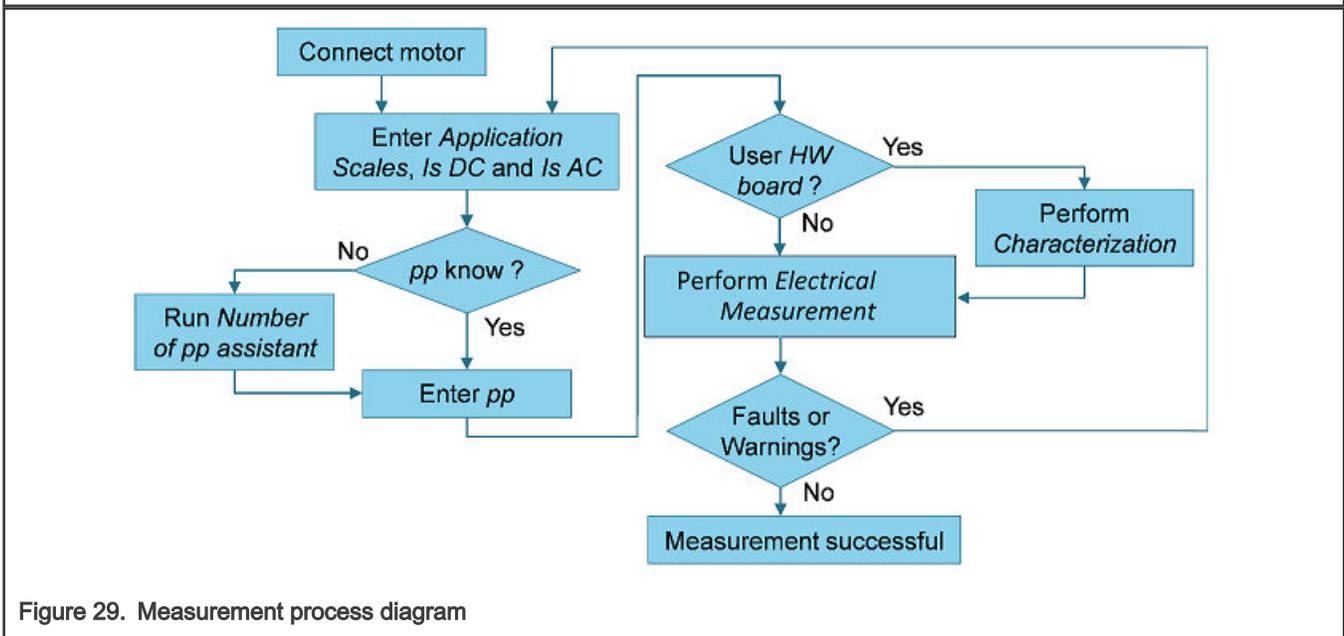


Figure 29. Measurement process diagram

During the measurement, faults and warnings may occur. Do not confuse these faults for the application faults, such as overcurrent, undervoltage, and so on. The list of these faults with their description and possible troubleshooting is shown in [Table 8](#).

Table 8. Measurement faults and warnings

Fault no.	Fault description	Fault reason	Troubleshooting
1	Motor not connected	$I_d > 50$ mA cannot be reached with the available DC-bus voltage.	Check that the motor is connected.
2	R_s too high for calibration	The calibration cannot be reached with the available DC-bus voltage.	Use a motor with a lower R_s for the power stage characterization.
3	Current measurement I_s DC not reached	The user-defined I_s DC was not reached, so the measurement was taken with a lower I_s DC.	Raise the DC-bus voltage to reach the I_s DC or lower the I_s DC to avoid this warning.
4	Current amplitude measurement I_s AC not reached	The user-defined I_s AC was not reached, so the measurement was taken with a lower I_s AC.	Raise the DC-bus voltage or lower the F_{min} to reach the I_s AC or lower the I_s AC to avoid this warning.
5	Wrong characteristic data	The characteristic data, which is used for the voltage correction, does not correspond to the actual power stage.	Select the user hardware and perform the calibration.
6	Mechanical measurement timeout	The mechanical measurement takes too long.	Repeat the measurement process with a different setup.

11.2 Initial configuration setting and update

1. Open the PMSM control application FreeMASTER project containing the dedicated MCAT plug-in module.
2. Select the "Parameters" tab.
3. Leave the measured motor parameters or specify the parameters manually. The motor parameters can be obtained from the motor data sheet or using the PMSM parameters measurement procedure described in *PMSM Electrical Parameters Measurement* (document [AN4680](#)). All parameters provided in [Table 9](#) are accessible. The motor inertia J expresses the overall system inertia and can be obtained using a mechanical measurement. The J parameter is used to calculate the speed controller constant. However, the manual controller tuning can also be used to calculate this constant.

Table 9. MCAT motor parameters

Parameter	Units	Description	Typical range
pp	[-]	Motor pole pairs	1-10
R_s	[Ω]	1-phase stator resistance	0.3-50
L_d	[H]	1-phase direct inductance	0.00001-0.1
L_q	[H]	1-phase quadrature inductance	0.00001-0.1

Table continues on the next page...

Table 9. MCAT motor parameters (continued)

Parameter	Units	Description	Typical range
Ke	[V.sec/rad]	BEMF constant	0.001-1
J	[kg.m ²]	System inertia	0.00001-0.1
I _{ph nom}	[A]	Motor nominal phase current	0.5-8
U _{ph nom}	[V]	Motor nominal phase voltage	10-300
N _{nom}	[rpm]	Motor nominal speed	1000-2000

4. Set the hardware scales—the modification of these two fields is not required when a reference to the standard power stage board is used. These scales express the maximum measurable current and voltage analog quantities.
5. Check the fault limits—these fields are calculated using the motor parameters and hardware scales (see [Table 10](#)).

Table 10. Fault limits

Parameter	Units	Description	Typical range
U DCB trip	[V]	Voltage value at which the external braking resistor switch turns on	U DCB Over ~ U DCB max
U DCB under	[V]	Trigger value at which the undervoltage fault is detected	0 ~ U DCB Over
U DCB over	[V]	Trigger value at which the overvoltage fault is detected	U DCB Under ~ U max
N over	[rpm]	Trigger value at which the overspeed fault is detected	N _{nom} ~ N _{max}
N min	[rpm]	Minimal actual speed value for the sensorless control	(0.05~0.2) * N _{max}

6. Check the application scales—these fields are calculated using the motor parameters and hardware scales.

Table 11. Application scales

Parameter	Units	Description	Typical range
N _{max}	[rpm]	Speed scale	>1.1 * N _{nom}
E _{block}	[V]	BEMF scale	ke * N _{max}
kt	[Nm/A]	Motor torque constant	-

7. Check the alignment parameters—these fields are calculated using the motor parameters and hardware scales. The parameters express the required voltage value applied to the motor during the rotor alignment and its duration.
8. Click the “Store data” button to save the modified parameters into the inner file.

11.3 Control structure modes

1. Select the scalar control by clicking the “DISABLED” button in the “Scalar Control” section. The button color changes to red and the text changes to “ENABLED”.
2. Turn the application switch on. The application state changes to “RUN”.
3. Set the required frequency value in the “Freq_{req}” field; for example, 15 Hz in the “Scalar Control” section. The motor starts running ([Figure 30](#)).

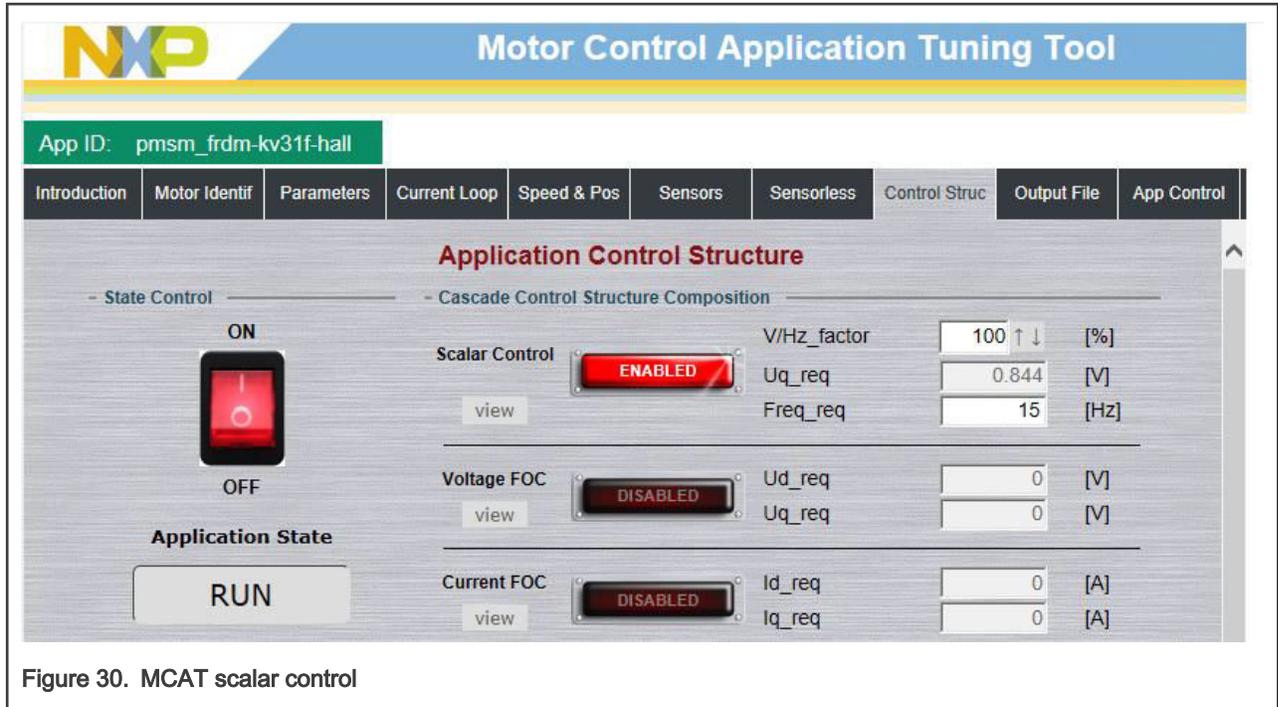


Figure 30. MCAT scalar control

4. Select the “Phase Currents” recorder from the “Scalar & Voltage Control” FreeMASTER project tree.
5. The optimal ratio for the V/Hz profile can be found by changing the V/Hz factor directly or using the “UP/DOWN” buttons. The shape of the motor currents should be close to a sinusoidal shape (Figure 31).

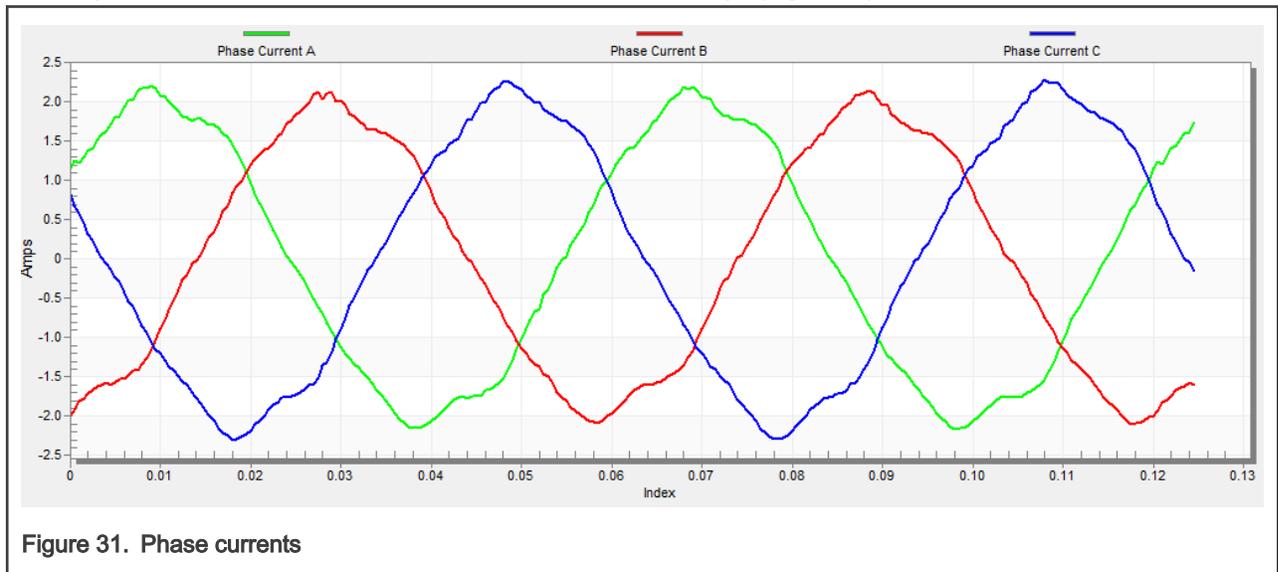


Figure 31. Phase currents

6. Select the “Position” recorder to check the observer functionality. The difference between the “Position Electrical Scalar” and the “Position Estimated” should be minimal (see Figure 32) for the Back-EMF position and speed observer to work properly. The position difference depends on the motor load. The higher the load, the bigger the difference between the positions due to the load angle.

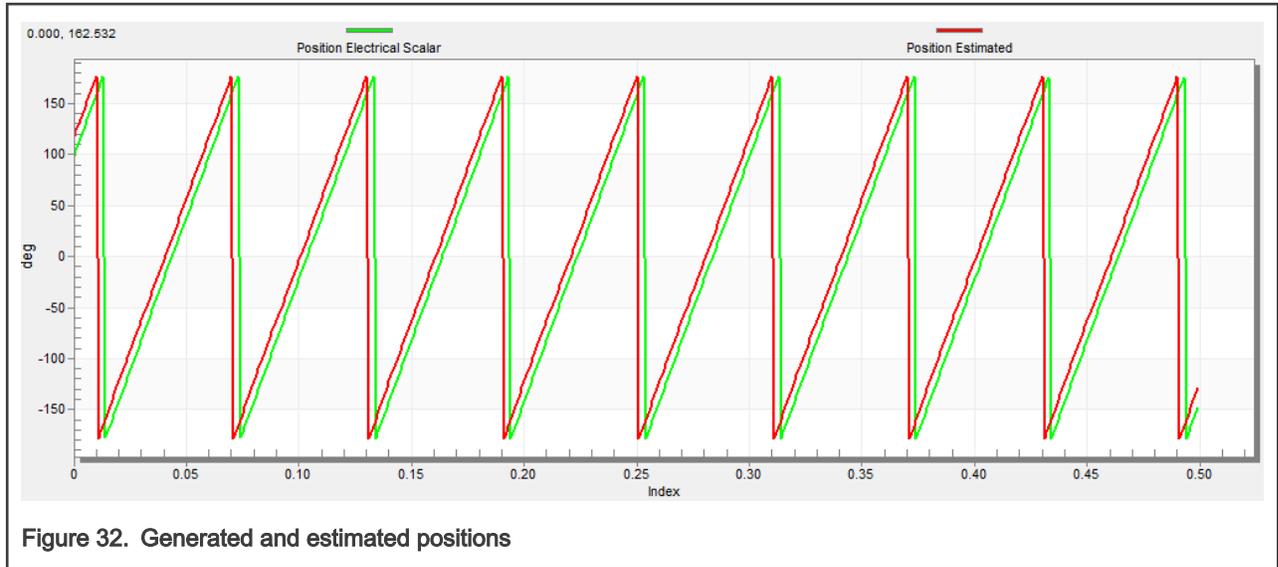


Figure 32. Generated and estimated positions

7. If an opposite speed direction is required, set a negative speed value into the “Freq_req” field.
8. The proper observer functionality and the measurement of analog quantities is expected at this step.
9. Enable the voltage FOC mode by clicking the “DISABLED” button in the “Voltage FOC” section while the main application switch is turned off.
10. Switch the main application switch on and set a non-zero value in the “Uq_req” field. The FOC algorithm uses the estimated position to run the motor.

11.4 Alignment tuning

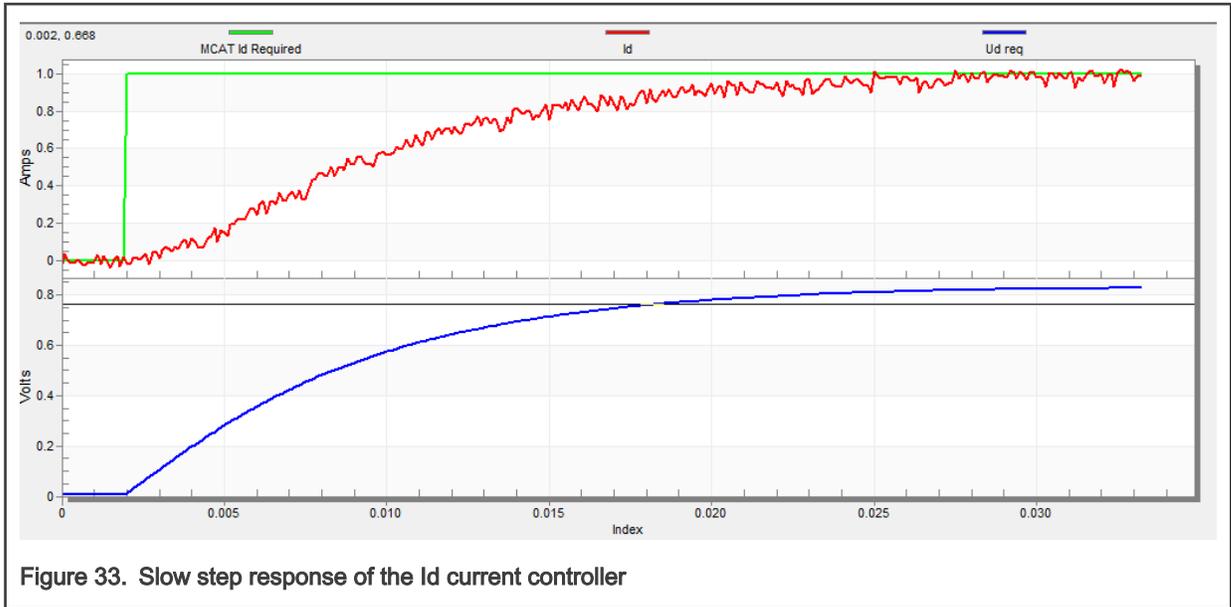
For the alignment parameters, navigate to the “Parameters” MCAT tab. The alignment procedure sets the rotor to an accurate initial position and enables you to apply full start-up torque to the motor. A correct initial position is needed mainly for high start-up loads (compressors, washers, and so on). The aim of the alignment is to have the rotor in a stable position, without any oscillations before the startup.

1. The alignment voltage is the value applied to the d-axis during the alignment. Increase this value for a higher shaft load.
2. The alignment duration expresses the time when the alignment routine is called. Tune this parameter to eliminate rotor oscillations or movement at the end of the alignment process.

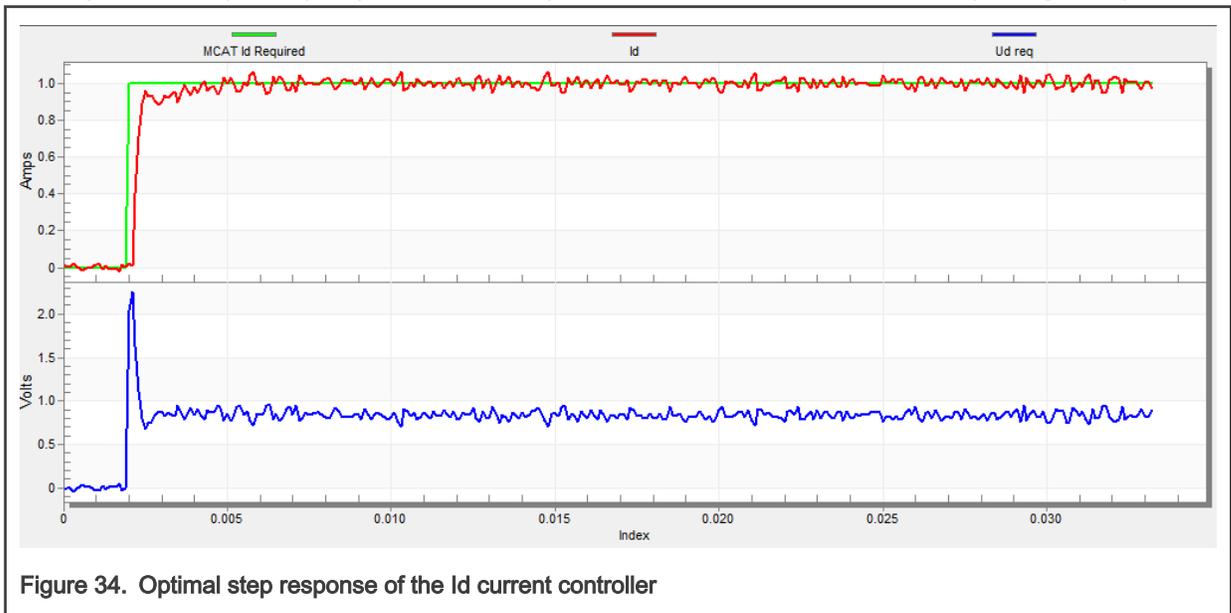
11.5 Current loop tuning

The parameters for the current D, Q, and PI controllers are fully calculated in the “Basic” mode using the motor parameters and no action is required in this mode. If the calculated loop parameters do not correspond to the required response, the bandwidth and attenuation parameters can be tuned.

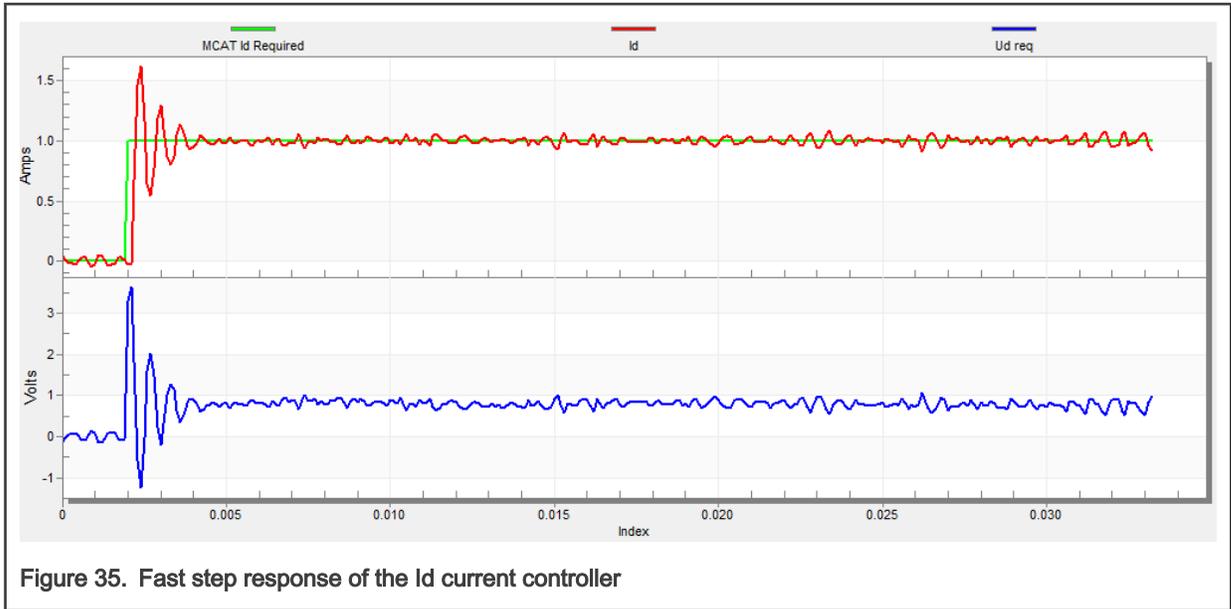
1. Lock the motor shaft.
2. Set the required loop bandwidth and attenuation and click the “Update Target” button in the “Current Loop” tab. The tuning loop bandwidth parameter defines how fast the loop response is whilst the tuning loop attenuation parameter defines the actual quantity overshoot magnitude.
3. Select the “Current Controller Id” recorder.
4. Select the “Control Structure” tab, switch to “Current FOC”, set the “Iq_req” field to a very low value (for example 0.01), and set the required step in “Id_req”. The control loop response is shown in the recorder.
5. Tune the loop bandwidth and attenuation until you achieve the required response. The example waveforms show the correct and incorrect settings of the current loop parameters:
 - The loop bandwidth is low (110 Hz) and the settling time of the Id current is long (Figure 33).



- The loop bandwidth (400 Hz) is optimal and the response time of the Id current is sufficient (see [Figure 34](#)).

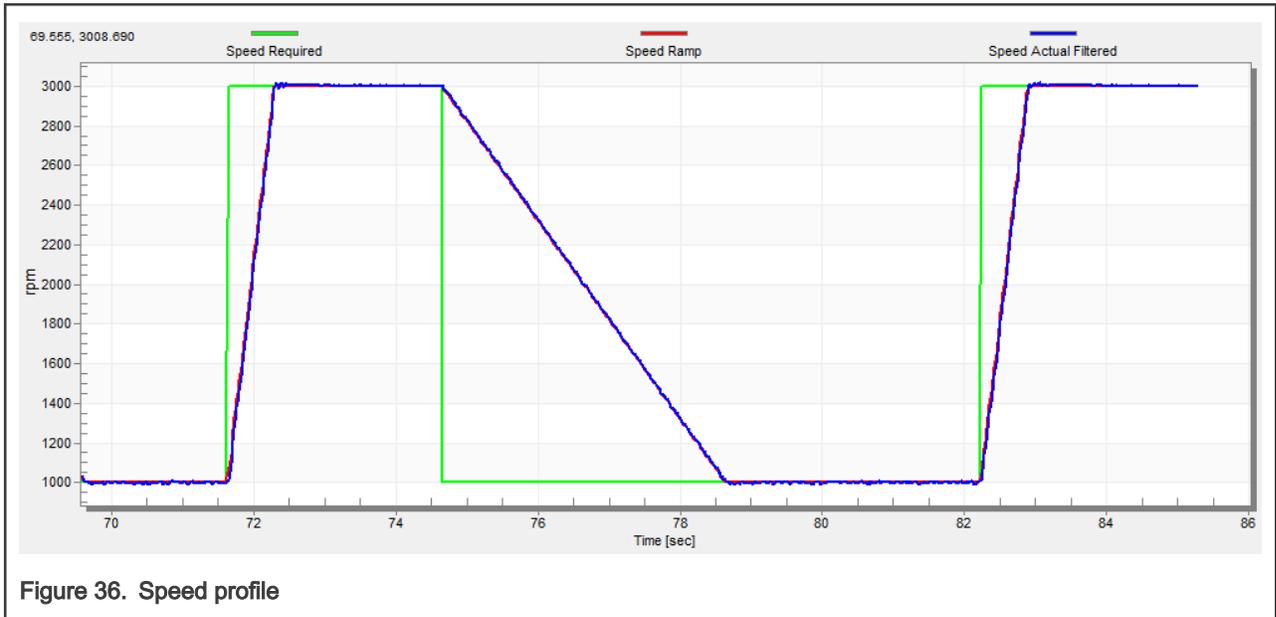


- The loop bandwidth is high (700 Hz) and the response time of the Id current is very fast, but with oscillation and overshoot (see [Figure 35](#)).



11.6 Speed ramp tuning

1. The speed command is applied to the speed controller through a speed ramp. The ramp function contains two increments (up and down) which express the motor acceleration and deceleration per second. If the increments are very high, they can cause an overcurrent fault during acceleration and an overvoltage fault during deceleration. In the “Speed” scope, you can see whether the “Speed Actual Filtered” waveform shape equals the “Speed Ramp” profile.
2. The increments are common for the scalar and speed control. The increment fields are in the “Speed & Pos” tab and accessible in both tuning modes. Clicking the “Update Target” button applies the changes to the MCU. An example speed profile is shown in Figure 36. The ramp increment down is set to 500 rpm/sec and the increment up is set to 3000 rpm/sec.
3. The start-up ramp increment is in the “Sensorless” tab and its value is usually higher than that of the speed loop ramp.



11.7 Open loop startup

1. The start-up process can be tuned by a set of parameters located in the “Sensorless” tab. Two of them (ramp increment and current) are accessible in both tuning modes. The start-up tuning can be processed in all control modes besides the scalar control. Setting the optimal values results in a proper motor startup. An example start-up state of low-dynamic drives (fans, pumps) is shown in [Figure 37](#).
2. Select the “Startup” recorder from the FreeMASTER project tree.
3. Set the start-up ramp increment typically to a higher value than the speed-loop ramp increment.
4. Set the start-up current according to the required start-up torque. For drives such as fans or pumps, the start-up torque is not very high and can be set to 15 % of the nominal current.
5. Set the required merging speed—when the open-loop and estimated position merging starts, the threshold is mostly set in the range of 5 % ~ 10 % of the nominal speed.
6. Set the merging coefficient—in the position merging process duration, 100 % corresponds to a half of an electrical revolution. The higher the value, the faster the merge. Values close to 1 % are set for the drives where a high start-up torque and smooth transitions between the open loop and the closed loop are required.
7. Click the “Update Target” button to apply the changes to the MCU.
8. Switch to the “Control Structure” tab, and enable the “Speed FOC”.
9. Set the required speed higher than the merging speed.
10. Check the start-up response in the recorder.
11. Tune the start-up parameters until you achieve an optimal response.
12. If the rotor does not start running, increase the start-up current.
13. If the merging process fails (the rotor is stuck or stopped), decrease the start-up ramp increment, increase the merging speed, and set the merging coefficient to 5 %.

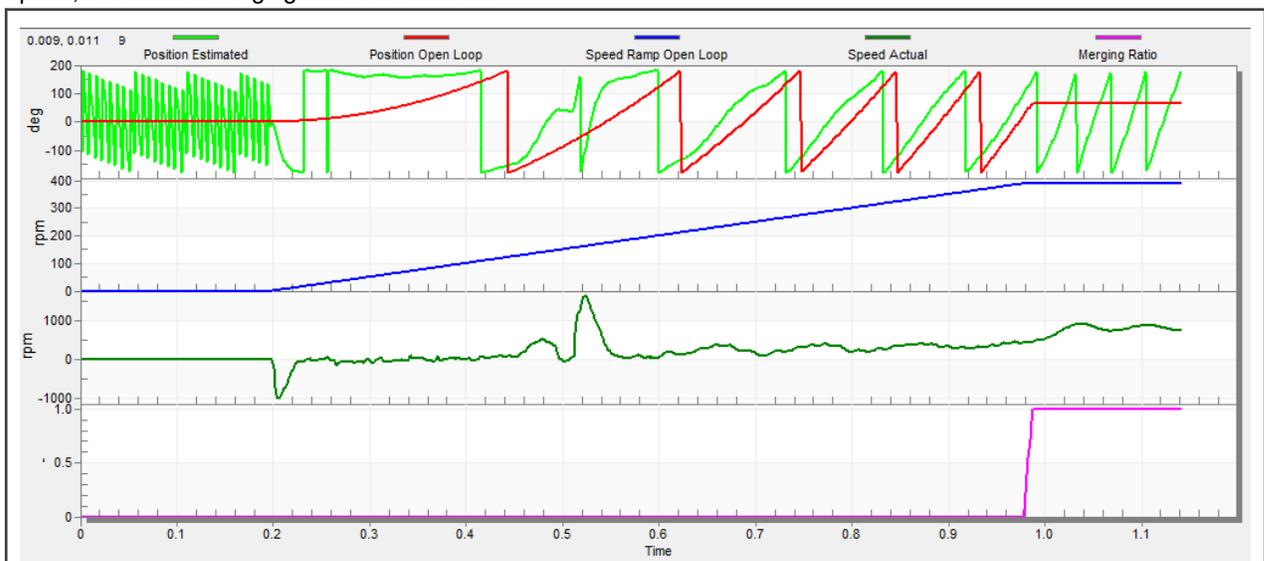


Figure 37. Motor startup

11.8 BEMF observer tuning

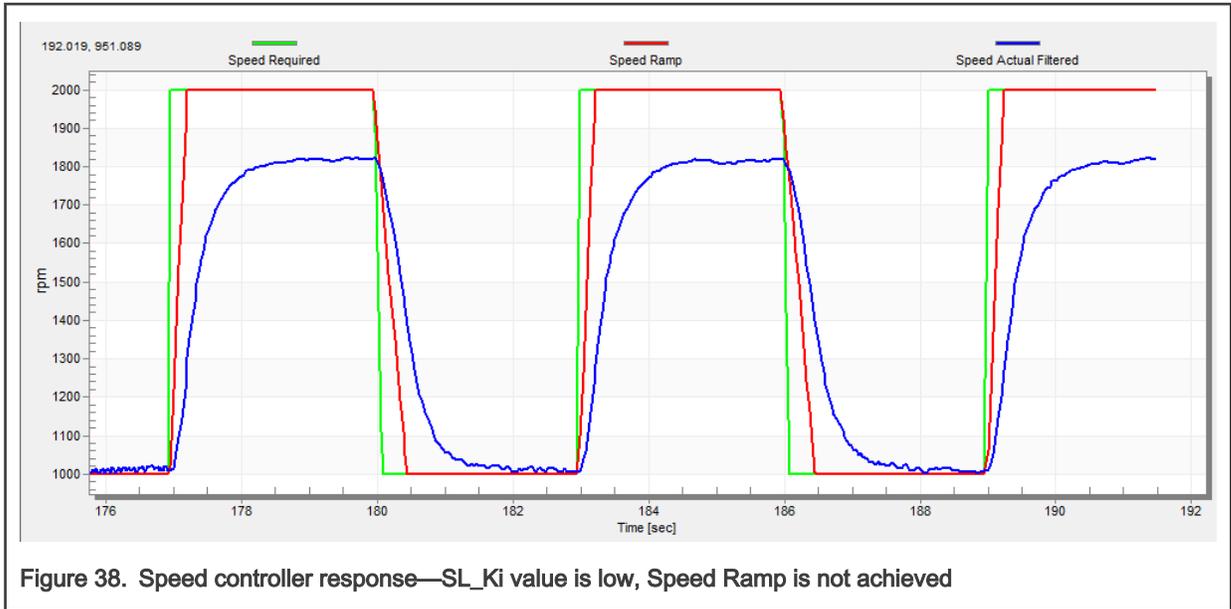
1. In the “Basic” mode, the parameters of the BEMF observer and the tracking observer are fully calculated using the motor parameters and no action is required. If the calculated loop parameters do not correspond to the optimal response, the bandwidth and attenuation parameters can be tuned.
2. Select the “Observer” recorder from the FreeMASTER project tree.

3. Set the required bandwidth and attenuation of the BEMF observer—the bandwidth is typically set to a value close to the current loop bandwidth.
4. Set the required bandwidth and attenuation of the tracking observer—the bandwidth is typically set in the range of 10 – 20 Hz for most low-dynamic drives (fans, pumps).
5. Click the “Update Target” button to apply the changes to the MCU.
6. Check the observer response in the recorder.

11.9 Speed PI controller tuning

The motor speed control loop is a first-order function with a mechanical time constant that depends on the motor inertia and friction. If the mechanical constant is available, the PI controller constants can be tuned using the loop bandwidth and attenuation. Otherwise, the manual tuning of the P and I portions of the speed controllers is available to obtain the required speed response (see the example response in [Figure 38](#)). There are dozens of approaches to tune the PI controller constants. The following steps provide an approach to set and tune the speed PI controller for a PM synchronous motor:

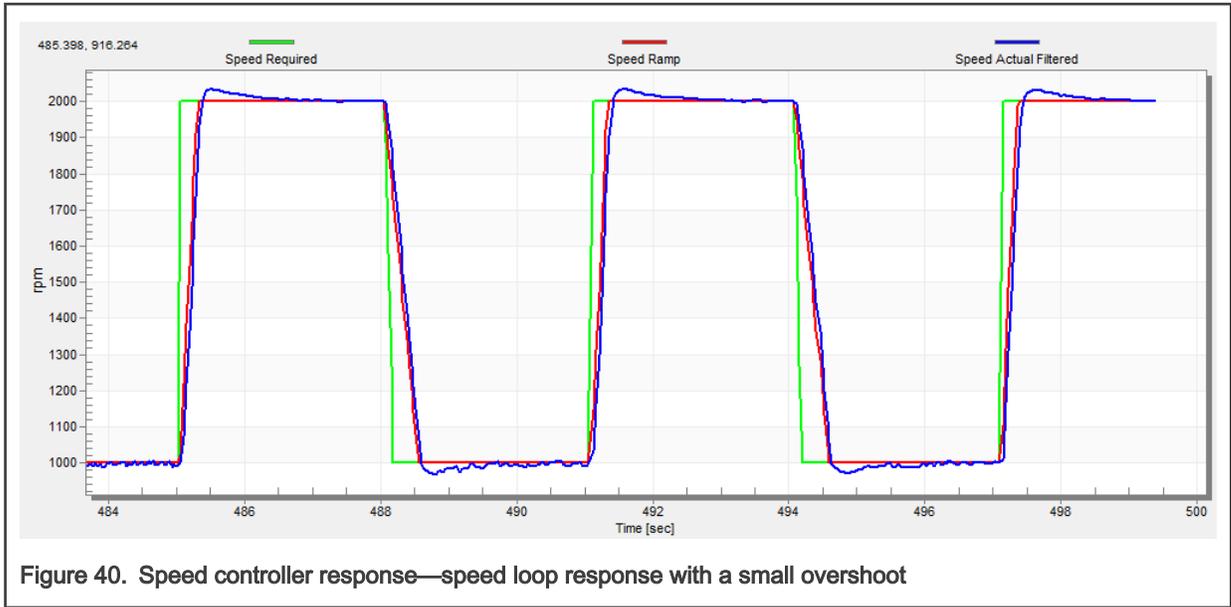
1. Select the “Speed Controller” option from the FreeMASTER project tree.
2. Select the “Speed & Pos” tab.
3. Check the “Manual Constant Tuning” option—that is, the “Bandwidth” and “Attenuation” fields are disabled and the “SL_Kp” and “SL_Ki” fields are enabled.
4. Tune the proportional gain:
 - Set the “SL_Ki” integral gain to 0.
 - Set the speed ramp to 1000 rpm/sec (or higher).
 - Switch to the “Control Structure” tab and run the motor at a convenient speed (about 30 % of the nominal speed).
 - Set a step in the required speed to 40 % of N_{nom} .
 - Switch back to the “Speed loop” tab.
 - Adjust the proportional gain “SL_Kp” until the system responds to the required value properly and without any oscillations or excessive overshoot:
 - If the “SL_Kp” field is set low, the system response is slow.
 - If the “SL_Kp” field is set high, the system response is tighter.
 - When the “SL_Ki” field is 0, the system most probably does not achieve the required speed.
 - Click the “Update Target” button to apply the changes to the MCU.
5. Tune the integral gain:
 - Increase the “SL_Ki” field slowly to minimize the difference between the required and actual speeds to 0.
 - Adjust the “SL_Ki” field such that you do not see any oscillation or large overshoot of the actual speed value while the required speed step is applied.
 - Click the “Update Target” button to apply the changes to the MCU.
6. Tune the loop bandwidth and attenuation until the required response is received. The example waveforms with the correct and incorrect settings of the speed loop parameters are shown in the following figures:
 - The “SL_Ki” value is low and the “Speed Actual Filtered” does not achieve the “Speed Ramp” (see [Figure 38](#)).



- The “ SL_K_p ” value is low, the “Speed Actual Filtered” greatly overshoots, and the long settling time is unwanted (see Figure 39).



- The speed loop response has a small overshoot and the “Speed Actual Filtered” settling time is sufficient. Such response can be considered optimal (see Figure 40).



Chapter 12

Conclusion

This application note describes the implementation of a sensorless field-oriented control of the 3-phase PMSM using 32-bit Kinetis V series devices and the High-Voltage Platform and Freedom development platforms. The hardware-dependent part of the control software is described in [Hardware setup](#). The motor control application timing is described in [MCU features and peripheral settings](#) and the peripheral initialization in [Motor-control peripheral initialization](#). The motor user interface and remote control using FreeMASTER are as follows. The motor parameters identification theory and the identification algorithms are described in [Identifying parameters of user motor using MCAT](#).

Chapter 13

Acronyms and abbreviations

Table 12. Acronyms and abbreviations

Acronym	Meaning
ADC	Analog-to-Digital Converter
ACIM	Asynchronous Induction Motor
ADC_ETC	ADC External Trigger Control
AN	Application Note
BLDC	Brushless DC motor
CCM	Clock Controller Module
CPU	Central Processing Unit
DC	Direct Current
DRM	Design Reference Manual
ENC	Encoder
FOC	Field-Oriented Control
GPIO	General-Purpose Input/Output
LPIT	Low-power Periodic Interrupt Timer
LPUART	Low-power Universal Asynchronous Receiver/Transmitter
MCAT	Motor Control Application Tuning tool
MCDRV	Motor Control Peripheral Drivers
MCU	Microcontroller
PDB	Programmable Delay Block
PI	Proportional Integral controller
PLL	Phase-Locked Loop
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse-Width Modulation
QD	Quadrature Decoder
TMR	Quad Timer
USB	Universal Serial Bus
XBAR	Inter-Peripheral Crossbar Switch

Chapter 14

References

These references are available on www.nxp.com:

1. *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)).
2. *Motor Control Application Tuning (MCAT) Tool for 3-Phase PMSM* (document [AN4642](#)).
3. *Sensorless PMSM Field-Oriented Control on Kinetis KV* (document [AN5237](#)).
4. *PMSM Sensorless Application Package User's Guide* (document [PMSMSAPUG](#))

Chapter 15

Useful links

1. MCUXpresso SDK for Motor Control www.nxp.com/motorcontrol
2. [FRDM-MC-PMSM Freedom Development Platform](#)
3. [TWR-MC-LV3PH Tower Development Platform](#)
4. [HVP-MC3PH High-Voltage Platform](#)
5. [MCUXpresso IDE - Importing MCUXpresso SDK](#)
6. [MCUXpresso Config Tool](#)
7. MCUXpresso SDK Builder (SDK examples in several IDEs) <https://mcuxpresso.nxp.com/en/welcome>

Chapter 16

Revision history

[Table 13](#) summarizes the changes done to this document since the initial release.

Table 13. Revision history

Revision number	Date	Substantive changes
0	01/2022	Initial release

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