AN1904
Application note

ST7MC three-phase AC induction motor control software library

Introduction

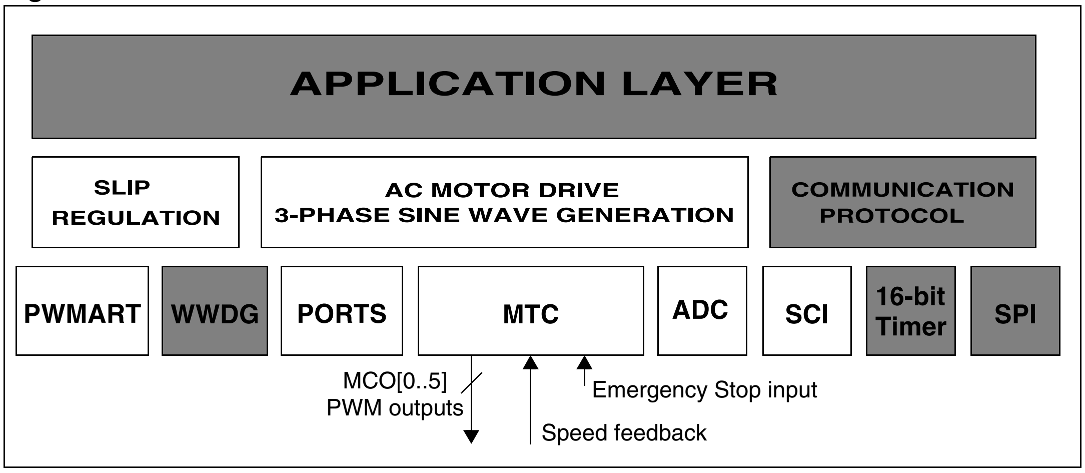
This Application Note describes a 3-phase induction motor control software library developed for the ST7MC. This 8-bit microcontroller contains a peripheral dedicated to 3-phase brushless motor control, making it suitable for AC induction motors and permanent magnet DC/AC motors (PMDC/PMAC also called BLDC).

The library described here is made of several C modules that contain a set of convenient functions for the scalar control of AC induction motors and is compatible with COSMIC (www.cosmic-software.com) and METROWERKS (www.metrowerks.com) compilers. The control of a Permanent magnet motor in Six-step mode is detailed in application note AN1905. The control of a PMAC motor in Sine wave mode with sensors is detailed in application note AN1947.

This software allows users to quickly evaluate both the MCU and the available tools, and to have a motor running in a very short time when used together with the ST7MC starter kit (ST7MC-KIT/BLDC) and the demonstration AC motor (ST7MC-MOT/IND). It also eliminates the need for time consuming development of sine wave generation and speed regulation algorithms by providing ready-to-use functions that let the user concentrate on his application layer.

The prerequisite for using this library is the basic knowledge of C programming, AC motor drives and power inverter hardware. In-depth know-how of ST7MC functions is only required for customizing existing modules and when adding new ones (grey modules in *Figure 1*) for a complete application development.

Figure 1. Overall software architecture



Contents

1 Features

ST7MC Library Version 1.0.1 Overview (CPU running at 8 MHz):

- Stator Frequency Range: From 0.2 Hz up to 680.0 Hz (see Section on page 44) with resolution depending on PWM frequency (typically ~0.1Hz)
- Voltage Resolution: 8-bit modulation index
- 9 to 10-bit PWM generation for sine wave (typical resolution in inaudible PWM range)
- PWM Frequency: can be set by default to 1.95, 3.9, 7.8, 12.5 and 15.66 kHz, with centred pattern PWM generation
- Brake capabilities (DC current injection)
- Speed reversal
- Tacho generator Speed acquisition
- Speed regulation and control routines for speed profile management
- CPU Load (sine wave generation only) around 20%, adjustable (see Section). Total CPU load (including closed loop control) is typically around 30% for a standard application (see Section 6.3)
- Free C source code and spreadsheet for look-up tables

The 12.5 kHz switching frequency is proposed by default, providing a PWM resolution close to 10-bit with a 16-MHz CPU clock. In addition, this frequency is a good compromise between the reduction of switching losses and acoustic noise (rejected in the inaudible range due to centred mode PWM patterns).

Note: *These figures are for information only; this software library may be subject to changes depending on the use of the final application and peripheral resources. It must be noted that it was built using robustness-oriented structures, therefore preventing the speed or code size from being fully optimized.*

Table 1 below summarizes the memory required by the software library, as it is delivered. These metrics include non motor control related code, implemented for demo purposes (such as ADC management, software timebases, etc.). These must therefore be considered only as indicative figures, which will be lower in the final application.

Table 1. Memory size metrics

	ROM (bytes)		**RAM (bytes)**	
	Cosmic 5.2b	**Metrowerks 1.1**	**Cosmic 5.2b**	**Metrowerks 1.1**
Closed Loop	4943	5729	136	161
Open loop	3840	4361	108	130

2 Working environment set-up

This section presents the available material that is needed to start working with the ST7MC and the library discussed in this document.

2.1 Development tools

2.1.1 Integrated Development Environments (IDE)

This library has been compiled using Cosmic & Metrowerks C compilers, launched with STVD7 release 2.5.4 (ST Visual Debugger) and STVD7 release 3.x.x.

A complete software package consists of:

- An IDE interface: ST's proprietary STVD7 (free download available on internet: www.stmcu.com), or third party IDE (e.g. Softec Microsystems' STVD7 for InDART-STX).
- A third party C-compiler: either Cosmic or Metrowerks (if needed, time limited evaluation versions can be get upon request).

The choice of the C Toolchain is left to the appreciation of the user. Both COSMIC and METROWERKS are fully supported, and the dedicated workspace (compatible with 'STVD7' & 'STVD7 for Indart') can be directly opened in the root of the library installation folder (AC_Metrowerks.wsp, AC_Cosmic.wsp, acmotor.stw).

2.1.2 Emulators

Two types of real-time development tools are available for debugging applications using ST7MC:

- In-circuit debugger from Softec (sales type: STXF-INDART/USB).

  The inDART-STX from Softec Microsystems is both an emulator and a programming tool. This is achieved using the In-circuit debug module embedded on the MCU. The real-time features of the Indart include access to the working registers and 2 breakpoint settings. However trace is not available.
- ST7MDT50-EMU3 emulator

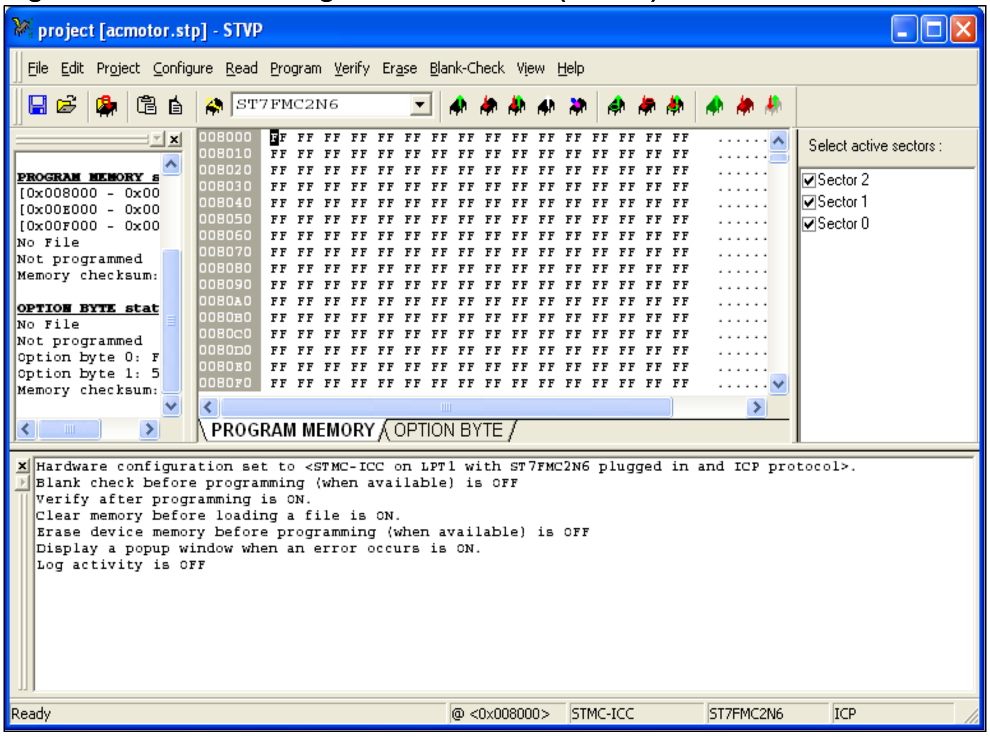
  Full-featured emulator: real-time with trace capability, performance analysis, advanced breakpoints, light logical analyser capabilities, etc. It can also be a programming tool when used with the delivered ICC ADDON module (select STMC-ICC as hardware target in STVP7). This ICC-ADDON module allows In-Circuit-Debugging with STVD7.

2.1.3 Programmers

In order to program an MCU with the generated S19 file, you should also install the ST Visual Programmer software (please visit our internet web-site) and use a dedicated programming interface (stick programmer for example for In-Circuit-Programming). The Visual Programming tool provides an easy way to erase, program and verify the MCU content.

Please note that the inDART-STX from Softec Microsystems is also a programming tool (installation of DataBlaze Programmer software is required).

Figure 2. STVisual Programmer software (STVP7)


project [acmotor.stp] - STVP
File Edit Project Configure Read Program Verify Erase Blank-Check View Help
ST7FMC2N6
Select active sectors :
Sector 2
Sector 1
Sector 0
PROGRAM MEMORY
OPTION BYTE

```
PROGRAM MEMORY s
[0x008000 - 0x00
[0x00E000 - 0x00
[0x00F000 - 0x00
No File
Not programmed
Memory checksum:

OPTION BYTE stat
No File
Not programmed
Option byte 0: F
Option byte 1: 5
Memory checksum:
```

```
008000 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008010 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008020 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008030 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008040 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008050 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008060 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008070 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008080 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
008090 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
0080A0 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
0080B0 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
0080C0 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
0080D0 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
0080E0 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
0080F0 FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ......
```

```
Hardware configuration set to <STMC-ICC on LPT1 with ST7FMC2N6 plugged in and ICP protocol>.
Blank check before programming (when available) is OFF
Verify after programming is ON.
Clear memory before loading a file is ON.
Erase device memory before programming (when available) is OFF
Display a popup window when an error occurs is ON.
Log activity is OFF
```

```
Ready    @ <0x008000>    STMC-ICC    ST7FMC2N6    ICP
```

2.1.4 Starter kit

The present software library was fully validated using the main hardware board (a complete inverter and control board) included in ST7MC-KIT/BLDC starter kit, and the demonstration AC motor from SELNI (Sales type ST7MC-MOT/IND). See *Section A.2 on page 100* for electrical specifications of this motor. The ST7MC-KIT/BLDC starter kit also includes a low-cost inDART hardware emulator, making this tool an ideal set for starting a project and evaluating/using the library. Finally, the graphical user interface included in the starter kit (ST7MC Control Panel) is primarily intended to run motors from a PC for testing and demo purposes, and is also able to generate library configuration files, with defines corresponding to your own motor. This makes the first implementation of this library significantly easier. See *Section 4* of this document for details.

Therefore, for rapid implementation and evaluation of the software discussed in this application note, it is recommended to acquire the ST7MC-KIT/BLDC starter kit and one of the two compatible C-toolchain (or at least time limited evaluation versions).

2.2 Library source code

2.2.1 Download

The complete source files are available for free on ST website (www.stmcu.com), in the *Technical Literature and Support Files* section, as a zip file. This library is also copied by default on the hard-disk when installing the ST7MC Control Panel from Softec micro systems, or available on www.softecmicro.com, in the Downloads section, software part (AK-ST7FMC System Software).

Caution: It is highly recommended to check for the latest releases of the library before starting a new development, and then verify the release notes from time to time to be aware of new features that might be of interest for the project. Registration mechanisms are also available on the web sites of ST and Softec Microsystems to get automatically update information.

2.2.2 File structure

Once the files are unzipped, the following library structure appears, depending on the toolchain.

- Library release 1.0.0

  This release only supports STVD7 2.5.x workspace; this IDE does not provide C builder capabilities. All build information is provided in makefiles and linker command files, in dedicated folders: config\Cosmic and config\Metrowerks (see *Figure 3*). Object files are also provided in dedicated folders.

Figure 3. Library structure for release 1.0.0

```
ACmotor \ config \ cosmic
                 \ metrowerks
        \ object \ cosmic
                 \ metrowerks
        \ source
```

- Library release 1.0.1

  This library contains the workspace for both the STVD7 2.5.x and STVD7 3.x IDEs. Two separate sets of folders are provided to differentiate object and configuration files, with a common set of source files (see *Figure 4*).

  This is to ensure the compatibility with STVD7 for inDART-STX, based on STVD7 2.5.3.

Figure 4. Library structure for release 1.0.1

```
ACmotor_1.0.1 \ config \ cosmic       \
                       \ metrowerks    |  For STVD7_2.5.x
              \ object \ cosmic        |
                       \ metrowerks   /
              \ Debug     \  For STVD7_3.x
              \ Release   /
              \ Source
              \ Utilities
```

2.3 Utilities

2.3.1 lib.h file

The purpose of this header file is to provide useful macros and type re-definitions which will be used throughout the entire library:

- Re-definition of data types using the following convention: a first letter indicating if a variable is signed (s) or unsigned (u), plus a number indicating the number of available bits (for instance: u8, s16, etc.),
- Defines for assembly mnemonics used in C source code: Nop(), Trap(),...
- Common macros used for bit-level access (SetBit, ClrBit,...), to get the dimension of an array (DIM[x]), etc.

2.3.2 Sine wave look-up table spreadsheet

A sine3.xls Excel file is provided with the library, in the \utilities folder. It contains the data and calculations necessary to re-generate the sine wave reference look-up table. This look-up table includes 3rd harmonics and is therefore not suitable as it is for bi-phase motor control. *PWM frequency set-up on page 39*.

2.3.3 HyperTerminal file

An AC Library.ht file is also provided in the \utilities folder to set-up the HyperTerminal software when the RS232 communication is enabled. *Serial communication interface on page 76*.

2.4 Technical literature

More information can be found on the ST website (www.st.com).

3 Getting started with the library using the ST7MC-KIT/BLDC

There a two ways to get started with this software library.

- The first method is to edit (with your motor specific features) and compile the modules described in *Section 4* of this application note. Then program ST7MC and run your motor using the ST7MC-KIT/BLDC Starter-kit hardware or your own design.
- The second method is to use the ST7MC-KIT/BLDC Starter-kit and follow this process:
  - run and fine tune motor parameters with the ST7MC Control Panel,
  - generate *.h files and select/save manually key parameters,
  - edit some of the .h files with run-time parameters collected with the GUI (see *Section 4.2.3* and *Section 4.3.3* for details),
  - compile, link and program the ST7MC,
  - run the motor.

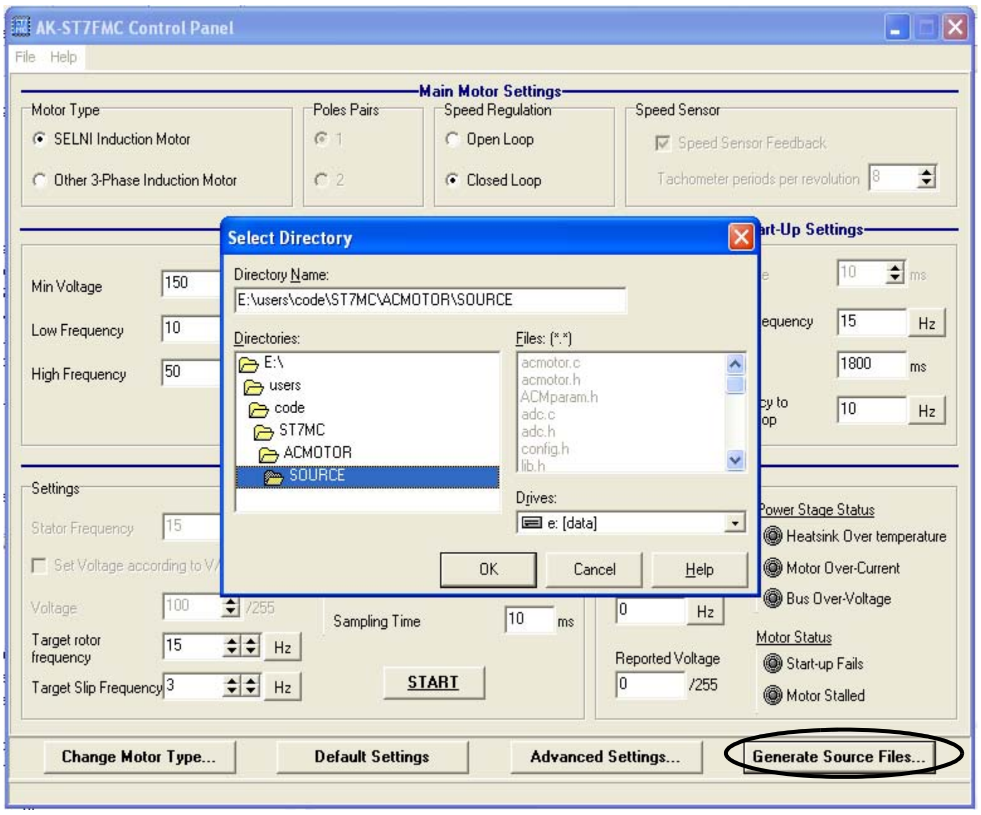
This second method is highly recommended and is described below.

3.1 Running the motor with the ST7MC control panel

As a starting point, the open loop mode can be used for the first trials. Low voltage values can be used for safety and then increased smoothly step by step. *Incremental system build on page 86* for details.

Once the motor settings have been finely adjusted (whatever the driving mode, open or closed loop), the parameters have to be imported into the stand-alone library. Simply click on ‘Generate *.h Files’ and select the source directory of the stand-alone library: see *Figure 5*

Figure 5. . ST7MC Control Panel: library header files generation



AK-ST7FMC Control Panel

Main Motor Settings

Motor Type: [✓ SELNI Induction Motor] Other 3-Phase Induction Motor

Poles Pairs: [✓ 1] 2

Speed Regulation: Open Loop [✓ Closed Loop]

Speed Sensor: [✓ Speed Sensor Feedback] Tachometer periods per revolution 8

Min Voltage 150
Low Frequency 10
High Frequency 50

Start-Up Settings: 10 ms; Frequency 15 Hz; 1800 ms; 10 Hz

Select Directory

Directory Name: E:\users\code\ST7MC\ACMOTOR\SOURCE

Directories: E:\ users code ST7MC ACMOTOR SOURCE

Files: (*.*) acmotor.c acmotor.h ACMparam.h adc.c adc.h config.h lib.h

Drives: e: [data]

Settings: Stator Frequency 15; Set Voltage according to V/f; Voltage 100 /255; Target rotor frequency 15 Hz; Target Slip Frequency 3 Hz

Sampling Time 10 ms

0 Hz; Reported Voltage 0 /255

Power Stage Status: Heatsink Over temperature; Motor Over-Current; Bus Over-Voltage

Motor Status: Start-up Fails; Motor Stalled

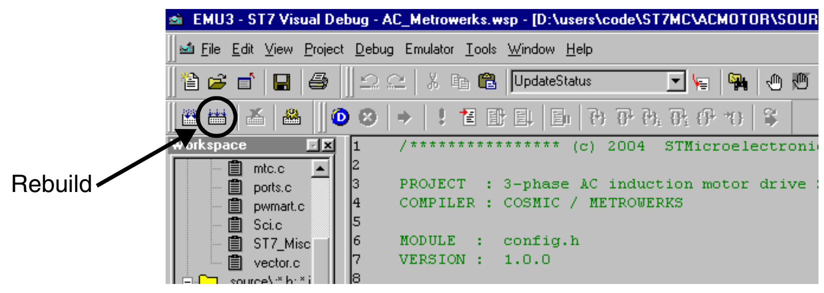
This interface generates 3 header files containing the motor and application parameters plus a file with conditional compilation keys for library re-build (see *Section 3.2*):

- MTCparam.h contains parameters of routines directly related to the motor controller peripheral, mainly PWM, sine wave generation and speed feedback processing (see *Section 4.2.3 on page 38*),
- ACMparam.h contains parameters related to the motor and the load, such as V/f curve and speed regulation (see *Section 4.3.3 on page 58*),
- Mainparam.h contains some application/demo specific features (see *Section 5.4 on page 84*).

Once the above files have been generated, the whole library must be re-built. The library and its demo program will then include the new settings automatically.

To launch the compilation, click on the 'rebuild all' icon of STVD7: see *Figure 6*

Figure 6. Rebuilding the whole application with STVD7



EMU3 - ST7 Visual Debug - AC_Metrowerks.wsp - [D:\users\code\ST7MC\ACMOTOR\SOUR

```
/**************** (c) 2004  STMicroelectroni

PROJECT  : 3-phase AC induction motor drive
COMPILER : COSMIC / METROWERKS

MODULE   :  config.h
VERSION  :  1.0.0
```

3.2 Library configuration file

The purpose of this file is to declare the compiler conditional compilation keys which will be used throughout the entire library compilation process, to:

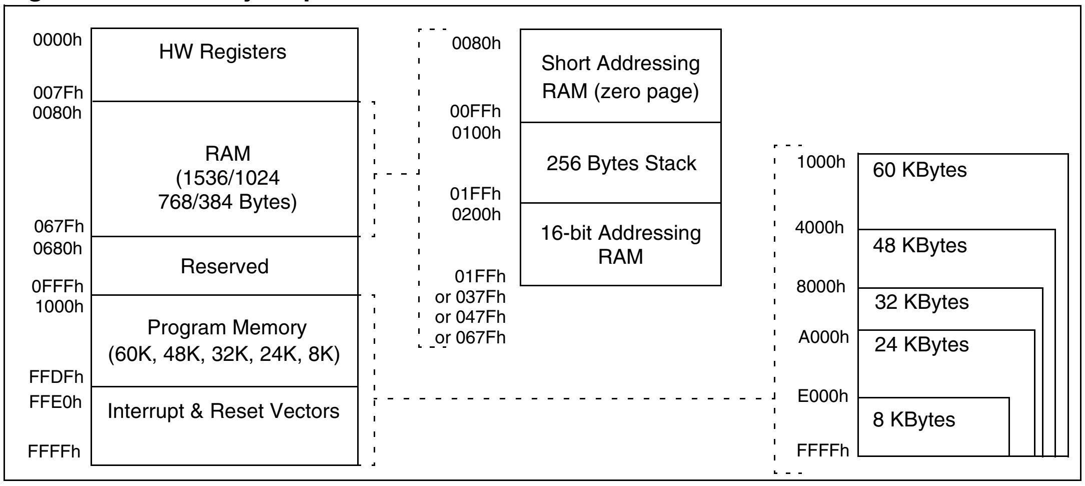
- define the AC motor driving mode: open / closed loop (see *Section 5* and *Section 5.3*),
- define the PWM resolution (needed to define the PWM frequency range, see *Section*),
- enable or disable the RS232 communication (see *Using the serial communication interface on page 83*),
- enable or disable the PI parameters tuning (see *Regulation tuning procedure on page 62*).

Below are the compilation key definitions in config.h:

```
// Define here the desired control type
   // 0 -> Open loop
   // 1 -> Closed loop
#define CONTROL1
//----------------------------------------------------------------------------
// Define here the chosen PWM resolution (linked to PWM switching frequency)
   // 0 -> 9-bit: 1.95kHz, 3.9kHz, 7.8kHz, 15.66kHz: cf. "MTCparam.h"
   // 1 -> 10-bit: 12.5 kHz
#define PWM_RESOLUTION 1
//----------------------------------------------------------------------------
// Define here the way the closed loop parameters (Kp, Ki) are set
// if this label is commented, Kp and Ki are set according to a look-up table
// defined in ACMparam.h.
//#define PI_PARAM_TUNING
//----------------------------------------------------------------------------
// Define here if you want to use the SCI interface to monitor some internal
// variables during run time
// IMPORTANT NOTE: As communication is done by polling, this will decrease
// the sampling rate of the PI Speed controller
#define ENABLE_RS232
```

3.3 Customizing the files for your ST7MC derivative

Figure 7. Memory map



The ST7MC memory is shown on *Figure 7*. The memory arrangement may vary depending on the type of the MCU. Please refer to the ST7MC datasheet for more information.

The library is dedicated by default to the ST7FMC2N6B6 MCU (SDIP56, 32KB *Flash*, 1K RAM). In order to target another ST7MC MCU, you may need to modify the C-toolchain configuration files. Here's a basic example of what has to be done prior to any other modifications.

The above example is based on the ST7FMC2S4 MCU (TQFP 44, 16K Flash, 768 Bytes RAM).

3.3.1 Memory mapping with COSMIC toolchain

Go to \config\Cosmic, edit 32K.lkf and check the following lines, in 'SEGMENT DEFINITION':

```
# SEGMENT DEFINITION (.text, .const,.data,.bss,.bsct,.ubsct are c compiler
predefined sections)

+seg .text    -b0x8000 -m0x8000 -nCODE -sROM          # executable code

+seg .const   -aCODE -it -sROM                        # constants and strings

+seg .bsct    -b0x0080 -m0x007F -nZPAGE -sRAM #initialized variables in SHORT range

+seg .ubsct   -aZPAGE -nUZPAGE -sRAM # uninitialized variables in SHORT range

+seg .share   -aUZPAGE -is -sRAM # shared segment (defined when using compact or
memory models only)

+seg .data    -b0x0200 -m0x27F -nIDATA -sRAM # NO initialized variables

+seg .bss     -aIDATA -nUDATA -sRAM                  # uninitialized variables
```

This section contains the memory placement for the object files, listed just after this declaration.

In order to enter the memory mapping of the *ST7FMC2S4*, the size of ROM and RAM memory have to be changed (32K -> 16K Flash, 1K RAM -> 768 Bytes RAM). For ROM:

```
+seg .text    -b0xc000 -m0x3fe0 -nCODE -sROM          # executable code
```

(where 0xc000 is the new starting address of the program memory and 0x3fe0 the size in bytes). For RAM:

```
+seg .bss     -b0x0200 -m0x0180 -nUDATA -sRAM         # uninitialized variables
```

(where 0x0180 is the new size of the 16 bit addressing RAM memory).

3.3.2 Memory mapping with METROWERKS toolchain

Go to \config\Metrowerks, edit acmotor.prm and check the following lines:

```
SECTIONS

ZRAM = READ_WRITE 0x0080 TO 0x00FF;

        RAM   = READ_WRITE 0x0200 TO 0x047F;

        ROM   = READ_ONLY  0x8000 TO 0xFFDF;
```

This part of the prm file contains the memory locations of pages declared at the end of the file.

To modify the memory size for the ST7FMC2S4, ROM and RAM memory settings have to be changed (32K -> 16K Flash, 1K RAM -> 768 Bytes RAM):

```
ROM = READ_ONLY  0xC000 TO 0xDFFF;
```

(where 0xc000 is the new starting address of the program memory),

```
RAM          = READ_WRITE 0x0200 TO 0x027F;  // 16 bit addressing RAM
```

(where 0x027F is the end address of the 16 bit addressing RAM memory).

Caution: The application layer has been written for the STMFC2NB6. Using a different ST7MC sales type can imply the need to do some modifications to the library, according to the available features (some of the I/O ports are not present on low-pin count packages). Please refer to the datasheet for details.

3.3.3 Hardware registers description

The library is based on the ST7FMC2N6.h file, which contains the hardware registers declarations and memory mapping for the ST7FMC2N6. It also contains most of the bit masks for the peripherals, at the exception of some Motor Controller bits and bitfields described in mtc_bits.h.

The ST7FMC2N6.h is provided by default with the STVD7 release 3.x.x toolchain, usually in:

```
C:\Program Files\STMicroelectronics\st7toolset\include
```

All other ST7MC derivative descriptions can be found in this folder, from the ST7FMC1K2 to the ST7FMC2M9. The name of the corresponding header file will have to be changed in the config.h file.

3.4 How to define and add a C module

This chapter describes how to define and declare a new module in a project based on the library. The example is based on the addition of 2 files: ‘my_file.c’ and the corresponding header file ‘my_file.h’.

The first step is the creation of these files. Existing files can be copied, pasted and renamed, or created by clicking on the ‘new files’ icon and then saving them with the right extension (*.c or *.h).

Three files (two source and one object) have to be declared in the toolchain configuration files.

3.4.1 Using STVD7 release 2.5.x

COSMIC compiler

COSMIC compiler is launched using a makefile (acmotor.mak) and the linker gets information from the linker command file 32K.lkf file. These two files need to be modified.

In 32.lkf, the new object file has to be added in the common object file list, or apart from this object list with correct settings (for instance for interrupt vectors or constants that need to be at fixed location, see documentation of C compiler for details).

```
# OBJECT FILES


..\..\object\cosmic\main.o

...

..\..\object\cosmic\my_file.o

...


# OBJECT FILES END
```

In acmotor.mak, ‘my_file.c’ has to be added in the C source file list:

```
C_SRC = \

  main.c \

  acmotor.c \

  ... \

  my_file.c \

  ... \

  vector.c
```

and the list of dependencies has to be updated accordingly:

```
# RULES FOR MAKING THE OBJECT FILES:

main.o: main.c lib.h ports.h adc.h pwmart.h Sci.h mtc.h acmotor.h
config.h Mainparam.h ST7FMC2N6.h

    $(CC) ..\..\source\main.c
```

```
...
my_file.o: my_file.c my_file.h lib.h ST7FMC2N6.h ...
    $(CC) ..\..\source\my_file.c
```

METROWERKS compiler

For METROWERKS users, modifications have to be done in acmotor.prm and acmotor.mak files. In the makefile, the new object file my_file.o has to be added in the ‘Object file list’ section and the corresponding dependencies have to be set in the ‘Application files’ section:

```
# ----------------------------- OBJECT FILES LIST -----------------------------
OBJ_LIST  = main.o mtc.o ... my_file.o
...
# --------------------------- APPLICATION FILES ------------------------------
main.o : $(ENV) main.c lib.h ports.h adc.h pwmart.h sci.h mtc.h acmotor.h \
config.h MainParam.h ST7FMC2N6.h
    $(CC) main.c

my_file.o : $(ENV) my_file.c my_file.h lib.h ST7FMC2N6.h ...
    $(CC) my_file.c
```

In acmotor.prm the new object file has to be added in the ‘Project module list’ section:

```
/*** PROJECT MODULE LIST ***/

NAMES
   main.o
   mtc.o
   ...
   my_file.o
   ...
   start07.o
   ansi.lib
END
```

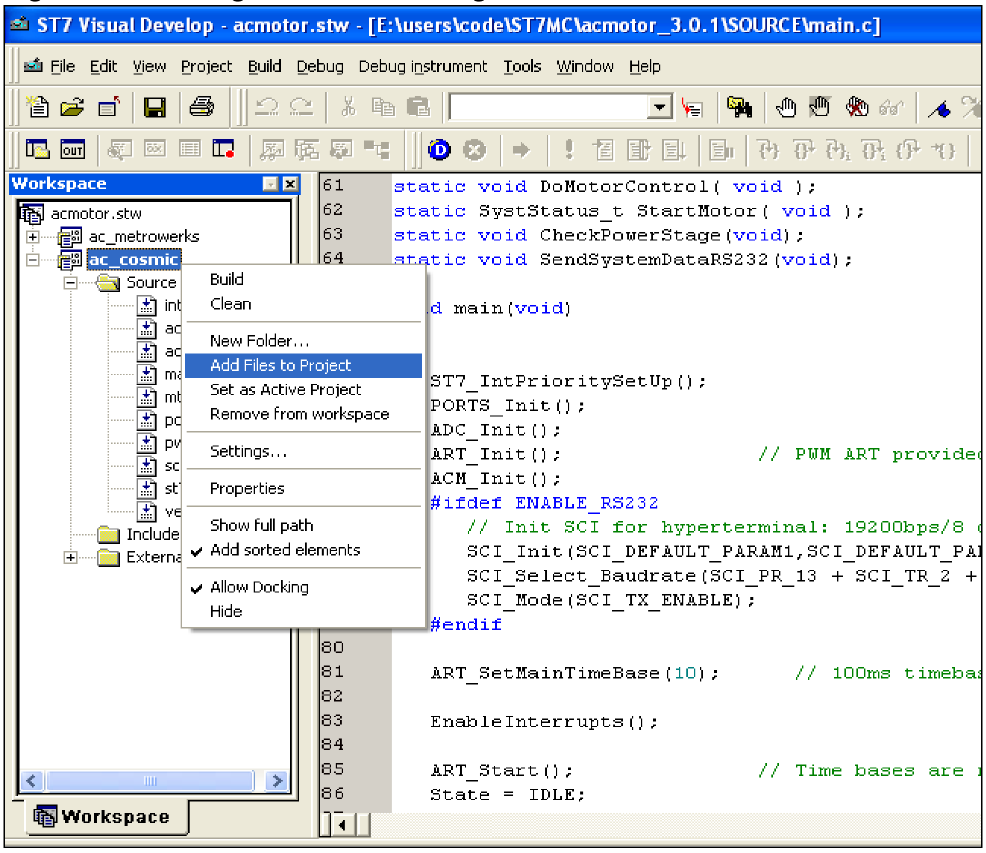
3.4.2 Using STVD7 release 3.x.x

The procedure is far easier with STVD7 3.x.x, as the makefile and linking command files are automatically generated.

In the workspace window, just right click on the selected project (either cosmic or metrowerks) and select “Add Files to Project”. You’ll be asked to select source file.

When rebuilding the library, the configuration files will be updated accordingly.

Figure 8. Adding a source file using STVD7 3.x.x



```
static void DoMotorControl( void );
static SystStatus_t StartMotor( void );
static void CheckPowerStage(void);
static void SendSystemDataRS232(void);

d main(void)


ST7_IntPrioritySetUp();
PORTS_Init();
ADC_Init();
ART_Init();              // PWM ART provide
ACM_Init();
#ifdef ENABLE_RS232
   // Init SCI for hyperterminal: 19200bps/8 
   SCI_Init(SCI_DEFAULT_PARAM1,SCI_DEFAULT_PA
   SCI_Select_Baudrate(SCI_PR_13 + SCI_TR_2 +
   SCI_Mode(SCI_TX_ENABLE);
#endif

ART_SetMainTimeBase(10);      // 100ms timeba

EnableInterrupts();

ART_Start();             // Time bases are 
State = IDLE;
```

4 Library functions per software module

4.1 Function description conventions

The functions are described in the format given below:

Synopsis	This section lists the required include files and prototype declarations.
Description	The functions are described with a brief explanation on how they are executed.
Input	In few lines, the format and units are given.
Returns	Gives the value or error code returned by the function.
Caution	Indicates the limits of the function or specific requirements that must be taken into account during library integration.
Warning	Indicates important points that must be taken into account to prevent hardware failures.
Functions called	Allows to prevent conflicts due to the simultaneous use of resources.
Duration	The approximate duration of the routine. This is performed using the maximum CPU clock frequency (8 MHz) without interrupts if not notified. Slight variations may be expected when changing compiler, options, memory models,...
Code example	Indicates the proper way to use the function if there are certain prerequisites (interrupt enabled, etc.).

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

4.2 Sine wave generation and speed feedback (MTC)

4.2.1 Overview

The “mtc.c” module is intended to handle all motor control functionalities directly linked to the motor control peripheral hardware (initialization or run-time accessed registers, interrupt service routine).

It can be seen as an interface between the AC motor control specific module and the low level control routines having direct influence on the hardware (PWM outputs, speed sensor, Emergency Shutdown pin).

It contains, among other functions:

- basic setup / control functions for the Motor Controller Peripheral (MTC),
- Sine wave generation (through PWM interrupt processing),
- DC current braking,
- Direction reversal,
- speed acquisition related interrupts and functions.

The prototype functions are located in the “mtc.h” header file.

4.2.2 List of available functions and interrupt service routines

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

MTC_ResetPeripheral

MTC_InitPeripheral

MTC_InitSineGen

Synopsis

```
#include "mtc.h"
void MTC_ResetPeripheral(void);
void MTC_InitPeripheral(void);
void MTC_InitSineGen(void);
```

Description

The purpose of these three functions is to set-up the Motor Controller peripheral and to initialize the software variables needed for sine wave generation.

MTC_ResetPeripheral

Resets the whole circuitry of the Motor Controller peripheral of the ST7MC, as it is found after a microcontroller RESET, with the sole exception of the MDTG and MPOL write-once registers (see datasheet for details).

MTC_InitPeripheral

Performs the initialization of the Motor Controller peripheral hardware registers, for the sine wave general parameters (such as PWM frequency, output polarity, deadtime, interrupts,...) and speed feedback processing (tacho input selection, edge sensitivity,...). It also starts the 12-bit PWM timer and the tacho dedicated timer (MTIM:MTIML). All required motor control related interrupts are unmasked upon completion of this routine.

MTC_InitSineGen

Initialization of software variables needed for sine wave generation and used in the PWM update interrupt routine. Ensures that once the PWM update interrupts will have been enabled, the sine wave generated will have a null voltage and that stator frequency change will be taken into account.

Duration

2.75µs for MTC_ResetPeripheral, 26µs for MTC_InitPeripheral and 392µs for MTC_InitSineGen.

Note: These three functions do not need to be called by the user application, as they are managed by the ACM_Init function.

MTC_EnableMCOutputs

MTC_DisableMCOutputs

Synopsis	#include "mtc.h"
	void MTC_EnableMCOutputs(void);
	void MTC_DisableMCOutputs (void);

Description	The purpose of these two functions is to configure the MCOx outputs of the ST7MC. MTC_EnableMCOutputs Enables the MCOx pins to output the PWM signals of the Motor Controller Peripheral. This function must be called to re-start PWM generation after an emergency shutdown (low state on MCES pin). MTC_DisableMCOutputs This function immediately disconnects the MCOx PWM outputs pins from the Motor Controller peripheral. It resets the MOE bit in the MCRA register, thus causing the MCOx pins to be in their reset configuration, as defined in the options bytes (high impedance or low impedance high/low state).
Duration	2.15 µs
See also	ST7MC Datasheet: MTC chapter.

MTC_CheckEmergencyStop

MTC_ClearEmergencyStop

Synopsis	#include "mtc.h"
	BOOL MTC_CheckEmergencyStop(void);
	void MTC_ClearEmergencyStop(void);

Description	The purpose of these two functions is to provide to the higher level control modules information regarding an Emergency Stop of the PWM operation. This information is returned by a function call once the related interrupt routine has been serviced. For users requiring immediate action taken as soon as the NMCES event occurs, the interrupt routine needs to be used directly (see *MCES_SE_IT on page 36*). *MTC_CheckEmergencyStop* Indicates if PWM outputs are enabled or not, and therefore if MOE bit (Main Output Enable) has been cleared by hardware, upon Emergency Stop event. *MTC_ClearEmergencyStop* Resets the boolean where the emergency Stop interrupt routine execution was recorded, regardless of the MOE bit state.
Returns	MTC_CheckEmergencyStop returns a boolean parameter, TRUE if an emergency Stop interrupt has been serviced, causing the PWM outputs to be disabled.
Duration	2.5 µs
See also	ST7MC Datasheet: Motor Controller section, Emergency feature section. *MCES_SE_IT on page 36*.

MTC_StartBraking

Synopsis	#include "mtc.h"
	void MTC_StartBraking(u16 DutyCycle);

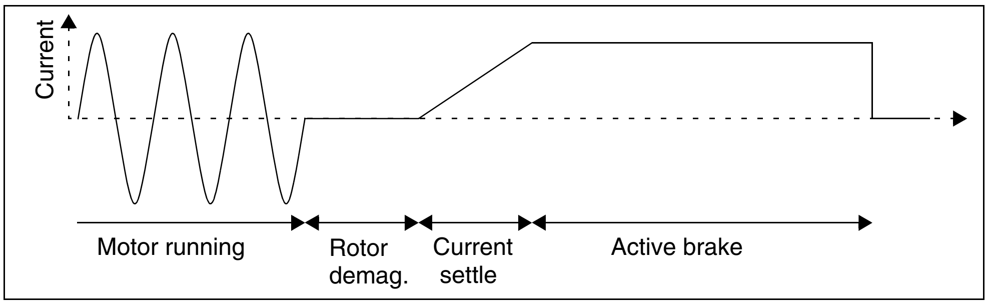
Description	The purpose of this function is to start the braking sequence by initializing the brake related flags, stopping the PWM interrupts generation, disabling the PWM outputs and starting the timebase needed for stator demagnetization. It also set the sine wave voltage to zero in case the braking sequence is interrupted and sine wave generation is re-started. Braking is obtained by sinking DC current in one motor winding. The braking torque is also defined in this function, in direct relation with the duty cycle applied to one of the motor winding, the other two phases being grounded (low side switches continuously ON).
Input	Duty cycle value is entered as a u16 variable without unit: to get the applied duty cycle, the value has to be compared to the CMP0 register value, defining the PWM frequency. For instance, for a PWM frequency of 12.5kHz, CMP0 = 639 (refer to the *Section* for details). If the DutyCycle variable is set to 32, this will lead to an applied duty cycle of 32/(639+1) = 10% (with center-aligned patterns). As the AC motor is driven in voltage mode, there’s no way to define a relationship between this duty cycle, the braking torque and the current feed in the motor. This duty cycle will therefore have to be defined empirically.
Functions called	MTC_UpdateSine, MTC_DisableMCOutputs, ART_SetSequenceDuration.
Duration	70 µs
See also	MTC_Brake, MTC_StopBraking, flowchart on *A.1.6 on page 95*, *Section 5.4 on page 84* and *Section on page 45* for timings set-up.

MTC_Brake

Synopsis	#include "mtc.h"
	void MTC_Brake(void);

Description	The purpose of this function is to handle the three phases of the braking sequence, as represented below in *Figure 9* 1. A waiting time for the Stator current to decrease down to zero (demagnetization), all PWM being OFF. 2. A smooth DC current increase up to expected value to avoid inrush current in the stator. 3. The sustaining of this current permanently up to the MTC_StopBraking function call.

Figure 9. . Current waveform during brake sequence



This function must be called as often as possible (typically from the main loop) to respect the required timings. Once the steady state current is attained, the brake continues permanently, until the MTC_StopBraking function is called.

Caution 1	Independently from software timebase jitter (+/-1ms), the programmed duration may vary depending on the interval between two MTC_Brake function call (the lower the interval, the better the resolution).
Caution 2	If the user stops calling this function, the current will be maintained to its last value (either null during rotor demagnetization or below the final expected value).
Duration	14 µs average
Functions called	ART_IsSequenceCompleted, ART_SetSequenceDuration, MTC_EnableMCOutputs, MTC_DisableMCOutputs
See also	MTC_StartBraking, MTC_StopBraking, *Section 5.4 on page 84* and *Brake on page 45* for timings set-up, flowchart on *A.1.7 on page 96*.

MTC_StopBraking

Synopsis	#include "mtc.h"
	void MTC_StopBraking(void);

Description	This function stops the active braking, whatever the current sequence (stator demagnetization, current settle, steady state). It disables the PWM outputs and re-starts the PWM Update interrupts generation.
Duration	41.5 µs
Functions called	MTC_DisableMCOutputs

Caution: The PWM outputs are disabled when exiting this function. In order to resume motor operations, it is mandatory to call a start function (ACM_InitSoftStart, ACM_InitSoftStart_OL) or MTC_EnableMCOutputs.

See also	MTC_StartBraking, MTC_Brake, flowchart on *A.1.8 on page 96*

MTC_Toggle_Direction

MTC_Set_ClockWise_Direction

MTC_Set_CounterClockWise_Direction

MTC_GetRotationDirection

Synopsis	#include "mtc.h" void MTC_Toggle_Direction(void) void MTC_Set_ClockWise_Direction(void) void MTC_Set_CounterClockWise_Direction(void) Direction_t MTC_GetRotationDirection(void)
Description	These functions are used to set, modify or get indication of the rotating direction. Rotation direction change is achieved by modifying the sign of the variable holding the phase shift between the three phases (either 120° or -120°). The clockwise direction is defined randomly. The real direction will only depend on the physical connection of the motor.
Duration	2.25 µs for MTC_Set_ClockWise_Direction and MTC_Set_CounterClockWise_Direction, 3.5µs for the other two functions.
Returns	The Direction_t type is a public enumerated typedef defined in the mtc.h file: {CLOCKWISE, COUNTERCLOCKWISE}.

Caution: No tests are performed on motor status (running or stopped) inside these functions. You must therefore be sure that motor is stopped before calling any of the three routines able to modify the rotation direction. On the contrary, if direction is changed while motor is running, it can immediately become generator, thus injecting reactive energy in the high voltage DC bus capacitor, causing the voltage to go above capacitor’s maximum voltage rating.

MTC_GetVoltage

MTC_GetStatorFreq

MTC_GetSlip

Synopsis	#include "mtc.h"
	u8 MTC_GetVoltage(void);
	u16 MTC_GetStatorFreq(void);
	u16 MTC_GetSlip(void);
Description	*MTC_GetVoltage*
	This function returns the current modulation index, corresponding to the voltage applied on the motor winding.
	MTC_GetStatorFreq
	This function returns the current Stator frequency; if a stator frequency update (done in PWM Update interrupt) is on-going after a call to the MTC_UpdateSine function and it has not been completed, the previous value is returned.
	MTC_GetSlip
	This function returns the difference between the stator and rotor frequencies. This value will always be positive (unsigned variable) assuming that this software library is not designed to handle negative slip operations (i.e. motor used as a generator). However, if the slip is negative, the returned value will be zero.
Returns	Stator and slip frequencies are given in [0.1Hz] unit using 16-bit format: a returned value of 357 corresponds to 35.7Hz.
	The voltage is an 8-bit value; 0 to 100% modulation index is described within the 0 to 255 range; 255 corresponds to full voltage.
Duration	MTC_GetVoltage: 1.85 µs
	MTC_GetStatorFreq: 3.5 µs
	MTC_GetSlip: 620 µs (including ~20% of CPU time spent in interrupt for sine wave generation)
See also	MTC_GetRotorFreq, MTC_UpdateSine.

Note: *MTC_GetSlip duration mainly comes from the Rotor speed calculation, done in MTC_GetRotorFreq; if MTC_GetRotorFreq and MTC_GetSlip have to be used in the same function of your own, it may be interesting to compute the slip directly from the Stator and rotor speed information to spare CPU processing time.*

MTC_InitTachoMeasure

MTC_StartTachoFiltering

Synopsis	#include "mtc.h"
	void MTC_InitTachoMeasure(void);
	void MTC_StartTachoFiltering(void);
Description	*MTC_InitTachoMeasure*
	The purpose of this function is to initialize the flags and variables associated with speed acquisition: the software FIFO stack where the last 4 speed acquisitions are stored, the tacho timer clock prescaler and the flag disabling rolling average. Upon completion of this routine, MTC_GetRotorFreq function call will return a speed calculated from the very last tacho capture only.
	MTC_StartTachoFiltering
	Once called, this function enables the MTC_GetRotorFreq to return a speed corresponding to the average of the last four captured values. On the tacho event following this function call, the whole software FIFO stack is filled with the latest captured value to start the rolling average with values up to date.
Duration	MTC_InitTachoMeasure: 26 µs
	MTC_StartTachoFiltering: 2.75 µs

Code example

...

...

```
IMC_InitTachoMeasure();/*Must be called before motor start*/
...
/* Start routine */
if (MTC_ValidSpeedInfo(MinRotorFreq))
{
   MTC_StartTachoFiltering (); /* Must be called once we
}     are sure that we have reliable speed information */
```

See also MTC_GetRotorFreq, MTC_ValidSpeedInfo.

MTC_ValidSpeedInfo

Synopsis	#include "mtc.h"
	BOOL MTC_ValidSpeedInfo (u16 MinRotorFreq);

Description	The purpose of this function is to determine if the motor has actually started and if the rotor speed exceeds a given threshold above which the tachometer can be considered has providing reliable information. Two conditions are evaluated: - If the actual speed is higher than the defined threshold, - If the acceleration is positive: the very last speed captured is higher than the average of the four previous values. This is necessary to discard the parasitic information appearing at the beginning of motor rotation. This spurious tacho events are usually due to the tachogenerator technology, made of winding and magnet; at very low speed, the tacho output signal is in the range of hundreds of mV, with relatively low signal vs noise ratio.
Input	The input parameter is the minimum rotor speed at which the motor is considered as really being started, in tenth of Hz. For instance, MinRotorFreq=105 corresponds to 10.5Hz. The minimum Rotor speed has to be set inside the intrinsically stable tile of the motor's torque versus frequency characteristic (typically 10-20Hz), keeping in mind that it must not be too high: the higher this value, the bigger will be the stator voltage/current inrush current at start-up. Furthermore it is recommended to set a value as close as possible to the target speed to be reached when exiting the start-up routine to ease the transition to the closed loop speed regulation. If the target frequency is too high, then a ramp function has to be implemented.
Returns	Boolean parameter, TRUE if both the above conditions are verified, FALSE otherwise. The function will also return FALSE if called with the MinRotorPeriod parameter set to 0 (incorrect value).
Duration	88 µs maximum

Caution: There is no way to differentiate rotation directions using a tachogenerator. Take note that this routine may return TRUE in certain conditions, even if the motor is not started in the right direction. In this case, you should manage a minimum amount of time before re-starting (for instance with high inertia load). Obviously, this function may be ineffective if the start-up duration is far shorter than time needed to have at least few consecutive speed values.

Functions called MTC_GetRotorFreq, GetAvrgTachoPeriod, GetLastTachoPeriod.

MTC_GetRotorFreq

Synopsis	#include "mtc.h"
	u16 MTC_GetRotorFreq (void);

Description	The purpose of this function is to provide the rotor rotational frequency. The frequency is calculated using the period between two edges of the sensor signal (typically a tachometer), the [MTIM:MTIML] counter and the MPRSR prescaler. If the MTC_StartTachoFiltering function has been called previously to this function, the rotor frequency is computed as the average of the last four values and the speed value is up-to date whatever the motor speed and the tacho information rate (rolling average). On the contrary, the very last tacho period is used to do the computation; this is of interest during the start-up phase of the motor, when the tachogenerator signal is very weak.
Returns	Rotor frequency with [0.1Hz] unit; for instance a returned value of 357 corresponds to rotor mechanical frequency of 35.7Hz If the calculated speed is less than a minimum speed the returned value will be 0. This minimum speed is checked using the MPRSR prescaler value, which is automatically updated (refer to the ST7FMC datasheet for details): if its value is >= `MAX_RATIO` constant, the returned speed is zero. `MAX_RATIO` is defined in MTCparam.h; it is set by default to 7: if no tacho edges are detected within a period of 500 ms to 1 second, the motor is considered to be stopped. This time out period depends on the previous value of the MPRSR prescaler: see the equations below.

Figure 10. Time Out duration before having Freq=0, depending on MPRSR value

$$\text{Timeout} = \frac{0xFFFF \times 2^7}{16MHz} = 524ms \qquad \text{MPRSR=7}$$

$$\text{Timeout} = \frac{0xFFFF \times 2^5}{16MHz} + \frac{0xFFFF \times 2^6}{16MHz} + \frac{0xFFFF \times 2^7}{16MHz} = 917ms \qquad \text{MPRSR=5}$$

Note on accuracy	With the 16-bit timer range and its automatically updated prescaler, the accuracy is better than 0.1Hz up to tacho input frequency of 1265Hz. This limit is lowered when having Fmtc below 16MHz.
Duration	560 µs (inc. ~20% CPU time spent in U interrupt for sine generation)
Functions called	GetAvrgTachoPeriod, GetLastTachoPeriod.
See also	*MTC_StartTachoFiltering on page 28*, *MTC_C_D_IT on page 34*, Customization hints in *Rotor frequency computation on page 38*, flowchart on *A.1.3 on page 92*

MTC_UpdateSine

Synopsis	#include "mtc.h"
	BOOL MTC_UpdateSine (u8 NewVoltage, u16 NewFrequency);

Description	The aim of this function is to update the 3-phase sine wave parameters: the amplitude (voltage) and the frequency. This routine will limit the frequency within a range defined in the constants section of the MTCparam.h file (between LOWEST_FREQ and HIGHEST_FREQ limits). The new parameters are taken into account in the PWM Update interrupt following this function completion, thus with a maximum delay of two PWM periods, due to the PWM preload registers mechanism.
Inputs	NewStatorFrequency is given with [0.1Hz] unit. This unit does not correspond to the real frequency resolution, which varies with the PWM switching frequency (refer to *Stator frequency resolution on page 43* for details). With the default PWM frequency of 12.5kHz, the resolution is around 0.1Hz. NewVoltage is the value of the modulation index, in 8-bit format. The 0 to 100% modulation index corresponds to the 0 to 255 range. 255 corresponds to full voltage.
Returns	Boolean type variable. FALSE if the previous call to MTC_UpdateSine has not yet been taken into account in U interrupt.
Duration	630 µs (inc. ~20% CPU time spent in U interrupt sine generation).
Warning	No tests are performed in this function on the input parameters, except for the frequency range. You must therefore verify the following conditions before calling the function: – voltage and frequencies must be compliant with the characteristics of the motor: over-voltage can cause motor flux saturation, excessive frequency is incompatible with motor mechanics (ball bearings or rotor may explode for instance). – voltage and frequencies values should not vary too suddenly when the motor is running, to avoid over current conditions. This is usually handled by the AC motor control software layer, by means of smoothing functions and/or regulation loops. – Stator frequency must not be set below the rotor frequency value: this would cause the motor to become a generator, thus injecting reactive energy in the high voltage DC bus capacitor, causing the voltage to go above the capacitor’s maximum voltage rating. If this situation is foreseen in the final application, a dissipative brake has to be implemented on the three-phase power inverter. By correctly managing a PWM signal applied to a brake dedicated transistor, regenerative power can be dissipated in a power resistor.

Note: MCOx outputs state (enabled/disabled) is not tested in this routine.

GetLastTachoPeriod

GetAvrgTachoPeriod

Synopsis	None (mtc.c module private functions).
Description	These functions provide the raw results of the tacho speed measurement, as a period between two capture events. Their result is converted by the MTC_GetRotorFreq function to get the speed of the motor in Hz.
Returns	The function returns a 32 bit variable corresponding to the time interval (averaged or not) between two tacho capture events. The unit is Tmtc, set by default to 62.5ns (1/16MHz). GetLastTachoPeriod returns the very last captured period, GetAvrgTachoPeriod returns the average of the four last captured values.
Duration	GetLastTachoPeriod: 32.6 µs GetAvrgTachoPeriod: 115 µs

Caution: The GetAvrgTachoPeriod function disables the tacho capture interrupts for 5.5µs (Fcpu=8MHz) to avoid the software FIFO stack being written in the capture interrupt while it is being read from the main program.

Note: By default, these functions are defined as private to the module, assuming they are only used by MTC_GetRotorFreq function.

See also	Flowcharts, on *A.1.4 on page 93* and *A.1.5 on page 94*.

MTC_U_CL_SO_IT

Synopsis	Not relevant (interrupt service routine).
Description	In this interrupt are the PWM duty cycles updated for the sine wave generation. This is done by loading the appropriate values in the MCPUx, MCPVx and MCPWx registers. This algorithm is extensively described in a dedicated application note. The Update (U) interrupt is triggered when the repetition counter is at zero value, corresponding to the loading of the values stored in the compare preload registers into the active registers. Using preload registers (with automatic hardware loading) decreases real time constraints, but as a consequence, introduces a delay: the values loaded in the current U interrupt will be used when the next one occurs.
Duration	34.1 µs, including average interrupt latency of 13 cycles and IRET execution.
Caution	A software preload mechanism is implemented in the U interrupt to avoid potential problems if the interrupt is triggered during the 16-bit frequency variable update (SineFreq) in the MTC_UpdateSine function. Consequently, any change of stator frequency done by calling MTC_UpdateSine will be inactive as long as U interrupts are masked, and MTC_UpdateSine will return a boolean equal to FALSE.

Note: No SO (Sampling Out) event is generated when running an induction motor. CL (Current Limit) interrupt can be used but is not handled in the software library as of today.

See also	Section *Nested interrupt controller on page 78*, flowchart on *A.1.1 on page 90*.

MTC_C_D_IT

Synopsis	Not relevant (interrupt service routine).
Description	This interrupt is triggered after every active edge on the MCIx input pin. The time interval since the last event is captured in the [MZREG:MZPRV] registers and the [MTIM:MTIML] counter registers are cleared (by hardware). The purpose of this interrupt is to store this period, which will be used later to compute speed feedback by converting it into the frequency domain with the correct unit (0.1Hz). The last four acquired values are stored in a software FIFO stack which is useful to average the raw results and thus reduce errors due to noise, tachogenerator dissymmetry, etc. In this routine the FIFO stack is also initialized in a synchronous manner, if the MTC_StartTachoFiltering function has been called.
Duration	22 µs, including average interrupt latency of 13 cycles and IRET execution (CPU running at 8 MHz)

Note: No D event is generated when running an induction motor

See also	*MTC_GetRotorFreq on page 30*, flowchart on *A.1.2 on page 91*, section *Nested interrupt controller on page 78*.

MTC_R_Z_IT

Synopsis	Not relevant (interrupt service routine).
Description	This interrupt occurs as soon as the prescaler of the MTIM timer is modified (this automatically updated prescaler allows to optimize the speed measurement resolution). Two flags are set in the MTCStatus byte to indicate that the prescaling ratio was increased or decreased (R+ or R- events). This information is mandatory when computing the period between two speed information in the MTC_C_D_IT interrupt service routine.
Duration	14 µs, including average interrupt latency of 13 cycles and IRET execution.

Note: No Z event is generated when running an induction motor.

See also	*MTC_C_D_IT on page 34*, section *Nested interrupt controller on page 78*, ST7MC datasheet, section 9.6.7.5 “Speed Measurement Mode”.

MCES_SE_IT

Synopsis	Not relevant (interrupt service routine).
Description	This routine is executed with top priority as soon as a low level is applied on the MCES input pin. It allows the passing of information that the MCOx PWM outputs have been disabled (this is done automatically by hardware) and stores the information in the MCES_Status variable. It also gives the possibility to add some application specific code to be processed immediately after a MCES event.
Duration	13.5 µs, including average interrupt latency of 13 cycles and IRET execution.

Note: This routine is also intended to handle Speed Error interrupts. No specific processing of this event is done in the current version of the library. Nevertheless, the corresponding SEI flag of the MCRC register is reset.

See also	*MTC_CheckEmergencyStop on page 22*, section *Nested interrupt controller on page 78*.

SET_MTC_PAGE

ToCMPxH

ToCMPxL

MTC_EnableClock

MTC_DisableClock

Synopsis	#include "mtc_bits.h"
	SET_MTC_PAGE(x); (x = 0 or 1)
	ToCMPxL(MCPxL, 16-bit compare value);
	ToCMPxH(MCPxH, 16-bit compare value);
	MTC_EnableClock();
	MTC_DisableClock();

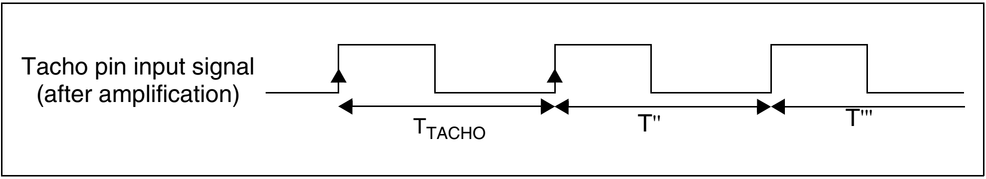
Description	These macros are intended to ease the handling of motor control peripheral bits and specific registers. SET_MTC_PAGE selects the active peripheral register page. It must be set to page 0 once the peripheral initialization is done. ToCMPxL and ToCMPxH allow the two 8-bit PWM compare registers to be loaded without taking care of their left-alignment (bits 0..2 are not significant). MTC_EnableClock and MTC_DisableClock act directly on the motor control peripheral clock: it is not recommended to disable the clock while the motor is running, as this will freeze the PWM output state and may result in excessive current in the motor.

4.2.3 Detailed explanations and customization of MTCparam.h

Rotor frequency computation

In order to process speed feedback with minimal CPU overhead, the MTC peripheral contains a dedicated timer. The method used to determine the rotor frequency is shown in *Figure 11* (*Tacho* refers to the tachogenerator, a common low-cost speed sensor).

Figure 11. Tacho Signal for rotor frequency calculation



The basic principle is to have a clear on capture counter triggered by tacho signal edges. For this, a small conditioning stage may be needed to get a clean square wave signal from the sine wave generated by the tachogenerator, particularly at low speed. It is possible to have both edges sensitivity but this is not recommended to avoid problems that may arise due to a dissymmetry of the tacho magnets/coils. For the same reasons, it is also recommended to average the information over several periods, when possible (usually every time, at the exception of the starting phase where tacho information is not yet reliable enough): this is done by calling the MTC_StartTachoFiltering function.

Note: ***Note:*** *when using one or several Hall sensor(s) for speed feedback, signal conditioning is not necessary and the signal can be directly input on the MCIx pins.*

In order to minimize the CPU consumption, the only information stored during the capture interrupt routine are the register contents (*MTC_C_D_IT on page 34*). The conversion of the raw register's content into a convenient variable is then only done when needed, for instance every time the speed regulation task is executed (See flowchart on *A.1.3 on page 92*).

Several parameters must be taken into account to compute the rotor frequency with a convenient unit (see *Figure 12* for formula):

- The number of pulses per rotor revolution (TachoPulsePerRev): this depends on the sensor (either position sensor: hall, etc. or velocity sensor: tacho generator with *n* number of poles, etc.),
- Input clock of the timer (F_{mtc}): the higher, the better the resolution, usually set to 16MHz,
- Number of motor poles pairs (PolesPairs).

To obtain the required accuracy (0.1 Hz) throughout the entire speed range, the dynamic range of a 16-bit capture registers (MZREG and MZPRV) is not enough. The tacho counter input clock is automatically prescaled according to the rotor frequency that is to be measured (see ST7MC datasheet for details on this mechanism); this is reported as a factor $2^{ST[3:0]}$, where ST[3:0] are the prescaler bits from the MPRSR register.

Figure 12. Equations giving rotor frequency with 0.1Hz unit

$$F_{rotor[0.1Hz]} = \frac{PolesPairs \times F_{mtc} \times 10}{TachoPulsePerRev} \times \frac{1}{Capture \times 2^{ST[3.0]}}$$

$$Capture = 256 \times MZREG + MZPRV$$

■ Customizing Rotor Frequency Acquisition

This parameter can be automatically modified by the ST7MC Control Panel. Depending on the system parameters (sensor characteristics, etc.), you can edit the following defines:

```
#define POLE_PAIR_NUM ((u8)1) /* Number of motor's pole pairs */
```

```
#define TACHO_PULSE_PER_REV ((u8)8) /* Number of pulses per revolution */
```

`TACHO_PULSE_PER_REV` is the number of logical pulses issued (directly or after amplification) by the speed sensor after each mechanical revolution of the rotor.

`POLE_PAIR_NUM` is necessary to compute a rotor frequency that ease slip frequency evaluation. *Using P Pole Motors on page 71*. For instance 4 pole motors (two pairs) will be coded as `POLE_PAIR_NUM=2`.

■ Zero speed detection

This parameter is not modified by the ST7MC Control Panel but can be edited. *MTC_GetRotorFreq on page 30* for details.

```
#define MAX_RATIO ((u8)7)    /* Max MTIM prescaler ratio defining the lowest

         expected speed feedback */
```

■ Acquisition FIFO size

The depth of the software FIFO stack where tacho information is stored can be modified in a define (this parameter is not modified by the ST7MC Control Panel):

```
#define SPEED_FIFO_SIZE ((u8)4)
```

Increasing this size will result in additional computing time to get the rotor frequency value. *MTC_StartTachoFiltering on page 28* for details of use. Furthermore attention must be paid to the size of the FIFO, located in memory page 0 for speed optimization: each level of the stack uses 3 bytes.

PWM frequency set-up

This parameter can be automatically modified by the ST7MC Control Panel. Five values are proposed: 15.66kHz, 12.5kHz, 7.8kHz, 3.9 kHz and 1.95kHz.

These five values are actually resulting from two base frequencies: 12.5kHz and 15.66kHz. The other values are derived by modifying the PWM timer prescaler (7.8kHz is 15.66kHz/2, 3.9kHz is 15.66KHz/4, etc.).

For each of these two base frequencies, several parameters have to be modified:

- PWM_PRSC is the value loaded in the PWM counter prescaler
- PWM_MCP0 is the value loaded in the Compare 0 register, which directly sets the PWM frequency; it is set to 639 for 12.5kHz (and thus linked to the PWM_10BIT key defined in config.h), while it is set to 511 for all the other frequencies (compiled with the PWM_9BIT key).
- OFFSET: this value is coding for the neutral point of the sine wave, where the PWM duty cycle is 50%; this value corresponds to the most significant byte only and has to be modified according to the MCP0 value.
- const u8 SINE3RDHARM[256]: this is the sine wave reference look-up table stored in Flash memory. As the maximum value of this table is also linked to the MCP0 value, it must be changed with the PWM switching frequency. This table can be easily re-computed with the Excel file provided with the library (sine3.xls).

According to the above listed values, the preprocessor recomputes at compile time the conversion factors used to get the expected stator frequency with 0.1Hz unit (`PWM_FREQ` and `STATOR_FREQ_RESOL`, see *Adjusting the CPU load related to sine wave generation on page 42* for details).

Note: 1 The provided look-up tables contain 3rd harmonics by default, which allows around 15% more voltage to be obtained on a motor, out of a given DC bus, compared to pure sine, see Third harmonics modulation on page 40 for explanations.

2 The sine wave generation method will be described in details in a dedicated Application note. Refer to it for implementation details.

To summarize, PWM frequency can be manually modified by editing a conditional compilation key in config.h:

```
// Define here the chosen PWM resolution (linked to PWM switching
frequency)

// 0 -> 9-bit: 1.95kHz, 3.9kHz, 7.8kHz, 15.66kHz: cf. "MTCparam.h"

// 1 -> 10-bit: 12.5 kHz

#define PWM_RESOLUTION 1
```

and the PWM counter prescaler in MTCparam.h:

```
// Prescaler ratio defines PWM frequency in a rough way:

// 0 -> 15.66kHz, 12.5 kHz (depending on CMP0 value)

// 1 -> 7.8kHz

// 3 -> 3.9kHz

// 7 -> 1.95kHz

#define PWM_PRSC ((u8)0)
```

Third harmonics modulation

To fulfil the basic AC induction motor voltage needs, the reference PWM modulating signal can be a pure sine wave (*Figure 13* left), but this kind of modulation has the drawback that it makes poor usage of the DC bus voltage.

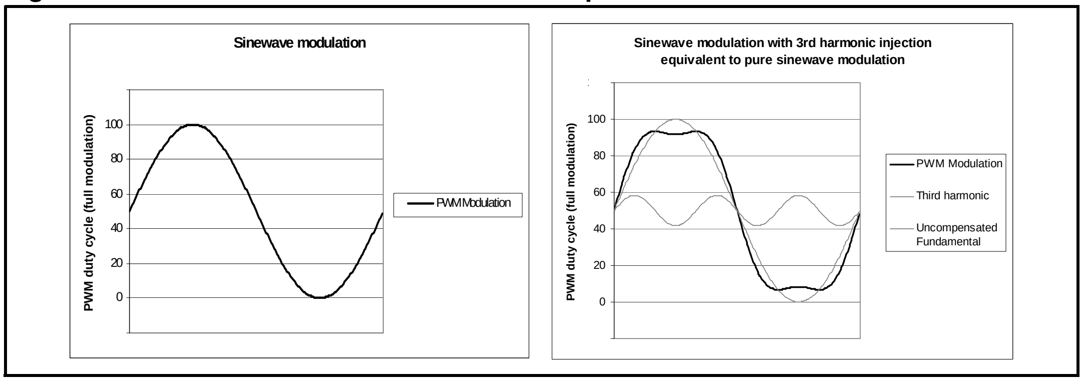
Let’s consider Vbus as the bus voltage after mains rectification. One can easily find that the maximum available voltage on a motor using a standard three-phase power inverter is around 86% of Vbus.

$$V_{phase-neutral} = \frac{V_{bus}}{2} \quad \text{with} \quad V_{neutral} = \frac{V_{bus}}{2}$$

$$V_{phase-phase} = \sqrt{3} \cdot V_{pk} = \frac{\sqrt{3}}{2} \cdot V_{bus}$$

Adding a third harmonic modulation to the reference sine wave fundamental decreases the overall amplitude of the resulting PWM modulation (PWM duty cycle never reaches either 0% or 100%, *Figure 13* right). This is due to the fact that the minimum of the 3rd harmonic corresponds to the maximum of the fundamental and vice versa.

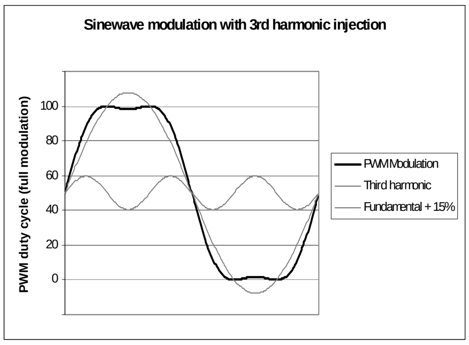
Figure 13. Pure sine wave modulation and equivalent with third harmonic added



As a consequence, this allows the fundamental + 3rd harmonic resulting signal amplitude to be increased up to the point were the modulating signal reaches the DC bus limits (i.e. 100% PWM modulation): see *Figure 14*

It can be shown that by applying an appropriate coefficient to the third harmonic component, the fundamental amplitude can be increased by 15%.

Figure 14. Third harmonic injection with increased fundamental amplitude



Finally, when considering the phase to phase voltage on the motor, third harmonic components are mutually cancelled out (a 120-degree phase-shift on the fundamental corresponds to a 360-degree shift for the third harmonic) and we have on the motor winding:

- Sinusoidal voltage (and therefore currents) on the motor, meaning no extra iron losses due to current harmonics,
- Phase to phase voltage 15% higher than with pure sine wave PWM modulation.

Figure 15 below shows on top the filtered PWM modulation on one of the three half-bridges and the corresponding currents in the three motor phases.

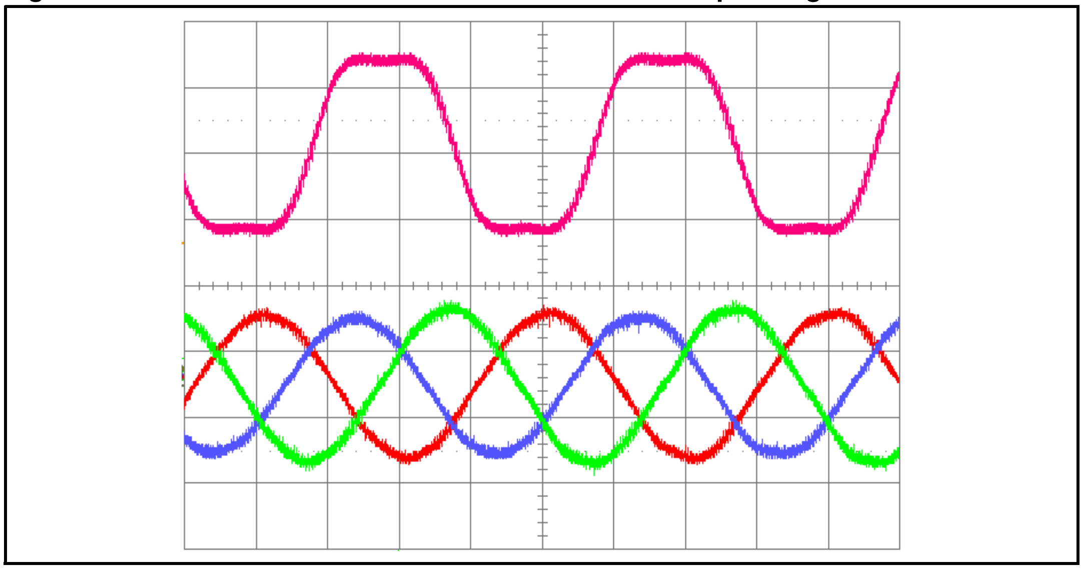


Figure 15. Third harmonic PWM modulation and corresponding currents

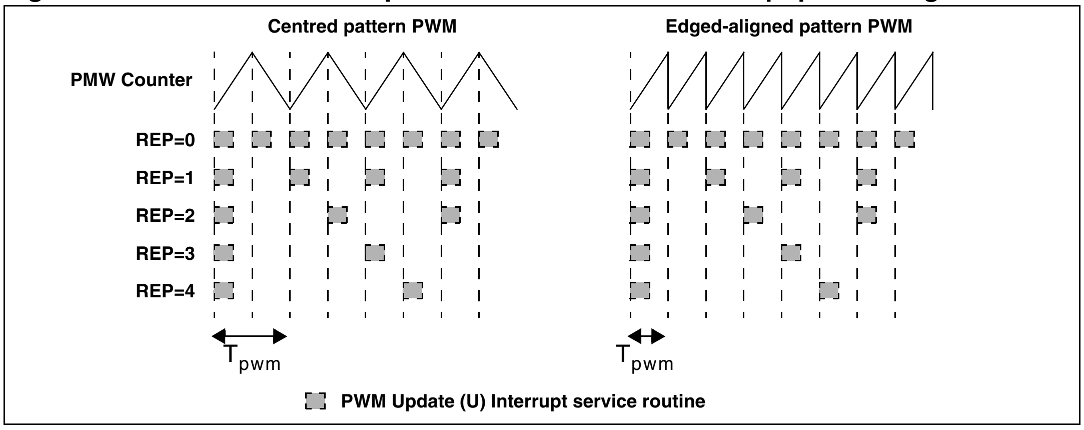
To summarize, third harmonic injection allows:

- a decrease in the diameter of the copper winding in the motor for a given power rating,
- an increase in the current in the motor for a given frequency, therefore providing more output power,
- an increase in the maximum reachable speed for a given motor, as long as mechanics (ball-bearings mainly) are suited for higher speed operations.

Adjusting the CPU load related to sine wave generation

The Motor controller peripheral has the built-in capability to avoid systematic generation of PWM compare registers update interrupts (so called U events). This is handled by a repetition counter (see ST7MC datasheet for details) which allows to finely adjust the CPU load related to the sine wave generation, for a given PWM frequency. The *Figure 16* shows the time spent in ISR versus the Repetition counter (REP) settings (where $T_{pwm}=1/F_{pwm}$).

Figure 16. Influence of the repetition counter on the interrupt processing load


Centred pattern PWM
Edged-aligned pattern PWM
PMW Counter
REP=0
REP=1
REP=2
REP=3
REP=4
Tpwm
Tpwm
PWM Update (U) Interrupt service routine

Knowing the duration of the U interrupt service routine (MTC_U_CL_SO_IT): 34,1µs and the PWM frequency, it is easy to compute the CPU load, following the equation on *Figure 16*

Figure 17. CPU load vs switching frequency and repetition rate

$$CPU_{load} = \frac{F_{pwm}}{RefreshRate} \times 34.1\times10^{-6} \times 100 = \frac{F_{pwm}}{(REP+1)/2} \times 34.1\times10^{-4} \text{(Centred patterns)}$$

$$CPU_{load} = \frac{F_{pwm}}{RefreshRate} \times 34.1\times10^{-6} \times 100 = \frac{F_{pwm}}{REP+1} \times 34.1\times10^{-4} \text{(Edge-aligned patterns)}$$

For instance, 12.5kHz PWM, REP=3, centred patterns will give:

CPU load = (12500/2)x34.1x10-6x100 = 21.3%.

- Repetition rate set-up with library release 1.0.0

This is done directly in the mtc.c file, in the MTC_InitPeripheral function:

```
MREP = 1; // Preload registers are loaded every PWM cycle
```

To maintain the correct conversion factor for the stator frequency, one must also modify a define in the MTCparam.h file (set by default for REP=1 with centred patterns):

```
#define PWM_FREQ ((u16) (MTC_CLOCK / (u32)(PATTERN_TYPE * PWM_MCP0 *
(PWM_PRSC+1)))) //Resolution: 1Hz */
```

For REP=2 with centred patterns, one must divide by 1.5:

```
#define PWM_FREQ((u16) (MTC_CLOCK * 2 / (u32)(PATTERN_TYPE *
PWM_MCP0 * (PWM_PRSC+1)*3)))
```

For REP=2 with centred patterns, one must divide by 2:

```
#define PWM_FREQ((u16) (MTC_CLOCK / (u32)(PATTERN_TYPE * PWM_MCP0 *
(PWM_PRSC+1)*2)))
```

And so on...

- Repetition rate set-up with library release 1.x.x

A parameter has been added in the MTCParam.h file: REP_RATE, which has to be set to the desired refresh rate (the value loaded in the repetition counter). For instance, for REP=3:

```
#define REP_RATE ((u8)3)
```

The PWM_FREQ factor is now automatically adjusted according to this value:

```
#define PWM_FREQ ((u16) (MTC_CLOCK * 2 / (u32)(PATTERN_TYPE *
PWM_MCP0 * (PWM_PRSC+1)*(REP_RATE+1))))
```

Stator frequency resolution

With the current sine wave generation method, the Stator frequency resolution is constant and depends on the PWM frequency and on the repetition rate, as shown in the formula in *Figure 18*).

Figure 18. Frequency resolution

$$Resolution = \frac{F_{pwm}}{RefreshRate}/65536 = \left(\frac{F_{pwm}}{(REP+1)/2}/65536\right) \quad \text{(Centred patterns)}$$

$$Resolution = \frac{F_{pwm}}{RefreshRate}/65536 = \left(\frac{F_{pwm}}{REP+1}/65536\right) \quad \text{(Edge-aligned patterns)}$$

For instance, with 12.5kHz PWM, REP=3, centred patterns, the resolution is:

Res = 12500/1/65535 = 0.1Hz.

Stator frequency range

This parameter can be automatically modified by the ST7MC Control Panel, and sets the stator frequency range for the motor, with 0.1Hz unit. *MTC_UpdateSine on page 31*.

```
#define HIGHEST_FREQ ((u16)3400)// Sine wave Max Frequency (max
theoretical: 65535)
```

```
#define LOWEST_FREQ ((u16)30)// Sine wave Min. Frequency
```

Caution: Sampling theorem constraints must be kept in mind when defining the maximum stator frequency. A minimum ratio of 15 to 30 between the stator frequency and the reference look up table sampling is mandatory to avoid sub-harmonics in the motor current (refer to the formula on *Figure 19*). For instance, with Fpwm = 12.5kHz, centred pattern PWM, REP = 3, Fmax = 12500 / 2 / 15 = 416Hz.

Figure 19. Maximum Stator frequency

$$F_{Max} \le \frac{F_{pwm}/((REP+1)/2)}{15} \quad \text{(centred pattern)}$$

$$F_{Max} \le \frac{F_{pwm}/(REP+1)}{15} \quad \text{(Edge-aligned pattern)}$$

Motor Control Peripheral Clock

This parameter is not modified by the ST7MC Control Panel but can be edited. It indicates the motor control peripheral input clock (in Hz) and is necessary to properly compute both:

- the rotor frequency from the tachogenerator information,
- the stator frequency.

```
#define MTC_CLOCK ((u32)16000000) /* Resolution: 1Hz */
```

Deadtime

This parameter can be automatically modified by the ST7MC Control Panel, for values above 625ns in order to be compatible with the provided hardware. If needed, for lower values for instance, the value can be edited, keeping in mind that only the 6 least significant bits are coding for the deadtime value. The MDTG bits coding for six-steps / sine wave generation and deadtime enable/disable are managed directly in the MTC_InitPeripheral routine).

```
#define DEADTIME ((u8)4)
```

Polarity

This parameter is not modified by the ST7MC Control Panel (polarity is a critical parameter linked to the gate drivers logic). It can be edited if needed.

The polarity is the value loaded in the MPOL register, where bit 6 and bit 7 are not significant for AC motors. Two pre-defined polarity set-ups are provided, for drivers having the same logic for high and low-side switches:

```
#define L6386_POLARITY ((u8)0x3F)// Positive logic level for L6386D
drivers
```

```
#define NEGATIVE_POLARITY((u8)0x00)// Negative logic level drivers
```

to be used for the set-up:

```
#define DRIVERS_POLARITY L6386_POLARITY
```

Phase shift

The phase shift is set-up to get 120° for three-phase AC motors, knowing that 360° are represented by a 8-bit variable (256). We thus have Phase shift = 256 x (120/360) = 85.

```
#define PHASE_SHIFT ((s8)85)// (85/256) * 360 = 120 degrees
```

Brake

Brake parameters are divided in two categories: some of them are application dependent and can be modified by the ST7MC control panel in the mainparam.h file: the braking current and duration (see *Section 5.4.2 on page 84*), the rest are system critical parameters directly coded in the mtc.c file.

These last are:

```
#define STATOR_DEMAG_TIME((u16)300)// Time in ms before applying DC
current braking
```

```
#define CURRENT_SETUP_TIME ((u8)5) // Time in ms between two
consecutive values of duty cycle during braking current increase
```

Figure 20 represents the current in a SELNI motor winding, with library default parameters, to show a normal current shape during braking. It must be noted that:

- demagnetization time appears to be greater than the programmed value: this is due to the fact that current is negligible at the beginning of the current settle time (low duty cycles),
- using a current probe, motor standstill can be monitored by a little current spike on top of the DC current. Beware when setting up the braking torque that this can trigger the overcurrent protection if the DC braking current is too close from the current limitation threshold.

The above two mentioned parameters must be set prior to the others, by empirical tests, starting from high values (typically 500ms for demagnetization time and 5ms as the interval between current increase steps). They can then be reduced step by step, while monitoring the current wave form to avoid situations where the power stage can be damaged (see *Figure 21*):

- if the demagnetization time is too short, a regenerative current will appear and the energy will be transferred to the DC bus capacitor, causing the bus voltage to increase,
- if the current settle is too steep, there will be a current overshoot.

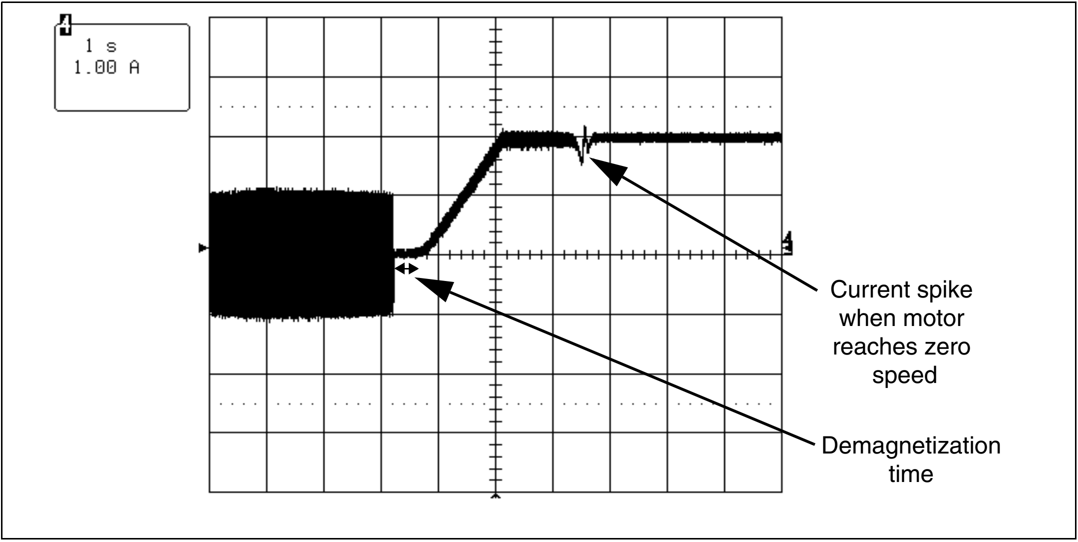


Figure 20. Motor current in one phase when braking

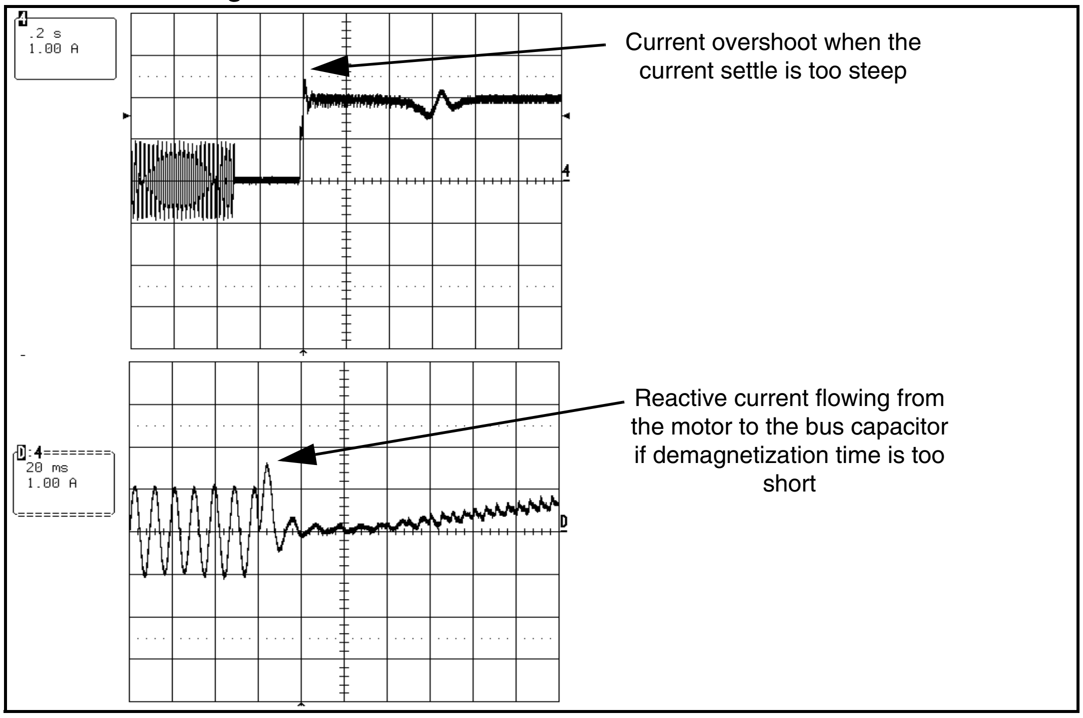


Figure 21. Over-current and regenerative energy hazard in case of wrong brake settings

4.3 Induction motor scalar control (ACMOTOR)

4.3.1 Overview

The purpose of this module is to provide the AC motor control specific routines, which will be called from the application software layer:

- Voltage versus frequency characteristic of the motor,
- Start-up management,
- Speed regulation if the speed sensor is available.

It handles the lower layer functions implemented in mtc.c and has no direct access on the motor control peripheral hardware registers and interrupts.

Two kinds of control are possible:

- In Open loop, classical V/f control can be easily implemented, where voltage is simply adjusted depending on the stator frequency. This solution is sufficient when no precise speed control is necessary, nor efficiency optimization. Typical application field is where loads are slowly varying and are known: pumps, fans,...
- In closed loop, an improved scalar control method is proposed, which allows good performance and avoids the drawbacks of the classical scalar control implementations: this method is based on a slip regulation which dynamically adjusts the motor voltage to maintain the best efficiency.

Among the set of functions described in the following pages, the following can be distinguished:

- *ACM_SustainSpeed* is here just as an example, its structure must be modified to implement a state machine in the main program and avoid spending the complete speed ramp duration inside the related routine (to be able to return periodically in the main routine to refresh the watchdog for instance).
- ACM_Init, ACM_VoltageMaxAllowed, ACM_InitSoftStart, ACM_InitSoftStart_OL, ACM_SoftStart, ACM_SoftStartOL, ACM_InitSlipFreqReg, ACM_SlipRegulation, ACM_GetPIParam, ACM_GetOptimumSlip, are on the contrary ready-to-use functions: their duration is set to minimum for them to be used in a state machine (such as the one implemented in main.c for demo purposes).

The prototype functions are located in the “acmotor.h” header file.

4.3.2 List of available functions

As listed in the acmotor.h header file.

ACM_Init

Synopsis	#include “acmotor.h”
	void ACM_Init (void);

Description	This function performs the initialization of the ACM module. It initializes the hardware related software layer (mtc.c module) and the sine wave generation with the variable Voltage = 0 to be sure that duty cycle on each phase is 50% (corresponding to a null motor voltage) when starting the PWM operation.
Duration	460 µs.
Functions called	MTC_InitPeripheral, MTC_InitSineGen, MTC_Set_ClockWise_Direction, ART_SetSpeedRegPeriod.

ACM_VoltageMaxAllowed

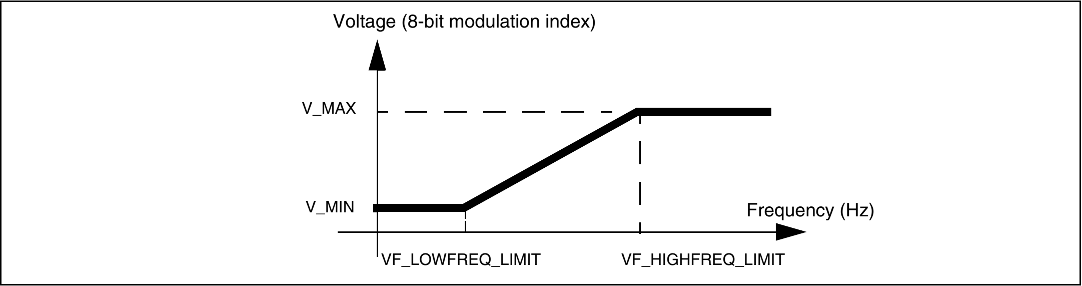
Synopsis	#include “acmotor.h”
	u8 ACM_VoltageMaxAllowed(u16 StatorFrequency);

Description

This function returns an indicative voltage value corresponding to a given stator frequency. This is usually know as the V/f curve. The characteristic points of this curve are represented in the figure below and can be set in the ACMparam.h file. Refer to *Section on page 58* for cautions and the procedure to set-up this curve.

This function does not update the stator voltage; this has to be done with the MTC_UpdateSine function.

Figure 22. Standard Voltage/Frequency Characteristics and Set-points



The use of ACM_VoltageMaxAllowed depends on the motor control type.

In open loop, it can be used to maintain a constant voltage versus a frequency ratio throughout a given speed range (know as rated flux operating range). The curve must be set to have the nominal torque available on the rotor shaft. It can be set also to follow a specific load torque characteristic, such as a fan.

In closed loop, it must be set for the maximum motor current (given by the motor manufacturer), before motor flux saturation.The returned value is then considered as the maximum voltage which cannot be exceeded. The voltage applied to the stator can be decreased if needed when running a load below the maximum motor torque, to limit ohmic losses in the winding (operation below the rated flux operation).

Inputs	StatorFrequency is given with [0.1Hz] unit.
Returns	Modulation index voltage (unsigned 8-bit variable).
	If the Frequency parameter is outside the linear interpolation domain, the returned value will be V_MIN or V_MAX (no error code returned).
Duration	33.5 µs maximum

ACM_InitSoftStart

ACM_InitSoftStart_OL

Synopsis	#include "acmotor.h"
	void ACM_InitSoftStart(u16 StatorFreq);
	void ACM_InitSoftStart_OL(u16 StatorFreq);

Description	These functions initialize the soft start procedure: it forces the voltage to be null, enable the PMW outputs and set-up the timebases required to smoothly increase voltage and have a start-up time out. They must be called from the upper software layer just before starting the motor.

Caution: Before calling this function, you must have started the PWM ART timer to have access to the miscellaneous timebases (see *Section 4.6 on page 74*).

Duration	850 µs for ACM_InitSoftStart 540 µs for ACM_InitSoftStart_OL
Functions called	MTC_UpdateSine, MTC_EnableMCOutputs, ART_Set_TimeInMs In addition, for ACM_InitSoftStart only: ACM_VoltageMaxAllowed, MTC_InitTachoMeasure, ART_SetSequenceDuration
See also	ACM_InitSoftStart flowchart on *A.1.9 on page 97*, *MTC_ValidSpeedInfo on page 29*, customization hints in *Section on page 68*.

ACM_SoftStart

Synopsis	#include “acmotor.h”
	StartStatus_t ACM_SoftStart(u16 MinRotorFreq);

Description	This function provides a soft start which limits the inrush current in the motor. It also monitors the speed feedback to stop the voltage increase when a given minimum rotor speed is reached. The function ramps up the stator voltage linearly while the stator frequency remains constant. The ramp ends when one of the following conditions occurs: – the `START_TIMEOUT` duration is elapsed, – the motor starts and the rotor speed reached MinRotorFreq. At the end of this ramp, if the rotor speed is too low, the tacho is monitored for an additional duration (user defined `EXTRA_TIMEOUT` constant); this may be needed when driving high inertia loads. At the end of this time period, if the rotor speed is still not high enough, the motor is stopped and PWM outputs are disabled. Tip: Comparing the maximum voltage and the current voltage at the end of ACM_SoftStart can give an indication of the motor load.
Inputs	MinRotorFreq is the minimum expected rotor frequency below which the motor will not considered as started (see MTC_ValidSpeedInfo description for details). Unit is [0.1Hz].
Returns	Variable StartStatus_t typedef-ed in acmotor.h: START_OK indicates that the motor successfully starts during the pre-defined period. START_FAIL indicates that the motor either did not start or its speed was too low during the defined period. This is also returned if the input parameter is not correct (minimum expected rotor frequency higher than the current stator frequency). START_ONGOING indicates that soft start procedure is not yet completed.

Caution: The function must be called as often as possible during the start-up phase to have a linear voltage profile and accurate Time out period.

Note: ACM_InitSoftStart must have been called before using this routine.

Duration	95 µs
Functions called	MTC_GetStatorFreq, MTC_GetVoltage, MTC_UpdateSine, ACM_VoltageMaxAllowed, MTC_ValidSpeedInfo, MTC_StartTachoFiltering, ART_IsSequenceCompleted, MTC_DisableMCOutputs, ART_Is_TimeInMsElapsed.
See also	*MTC_ValidSpeedInfo on page 29*, Customization hints in *AC motor start-up method on page 68*, flowchart on *A.1.10 on page 98*.

ACM_SoftStartOL

Synopsis	#include "acmotor.h"
	BOOL ACM_SoftStartOL(u8 TargetVoltage);

Description	This function provides a Soft Start which limits the starting torque and the inrush current in the motor, when driving the motor in open loop. The voltage on the stator winding is smoothly increased until it reaches the required value, providing this function is called as often as possible until it is completed. The duration of the Soft Start depends on the voltage at the end of the start-up and on the timebase set in ACM_InitSoftStart_OL. For instance, if VOLT_SLEWRATE has been set to 15ms and Target voltage is 50, then the total duration will be: $\mathrm{VOLTSLEWRATE} \times \mathrm{TargetVoltage} = 15 \times 50 = 750\mathrm{ms}$ Finally, once the soft start is completed, the minimal interval between two sine wave parameters changes (voltage, frequency) is set; this is usually needed to avoid steep current variation during motor run time (refer to *Section 5.1 on page 81* for details).
Input	Target modulation index (voltage) in unsigned 8-bit format, to be reached at the end of the soft start.
Returns	Boolean, FALSE until soft start completion

Note: It is mandatory to call the ACM_InitSoftStart_OL function before calling this routine.

Caution: The function must be called as often as possible (at least with an interval lower or equal to VOLT_SLEWRATE time) during the start-up phase. This will guarantee a linear voltage profile; on the contrary the time between voltage increment will be defined by the interval between two function calls.

Duration	21 µs
Functions called	MTC_GetVoltage, MTC_UpdateSine, ART_Set_TimeInMs.
See also	Customization hints in *AC motor start-up method on page 68*.

ACM_SustainSpeed

Synopsis	#include "acmotor.h"
	void ACM_SustainSpeed(u16 Time);

Description	This function maintains the actual speed on the motor for a given duration. This is achieved using a closed loop slip control that maintains the optimum voltage level in steady state conditions.
Input	Time is given in ms.
Duration	As defined by input parameter.
Functions used	MTC_GetStatorFreq, ART_Set_TimeInMs, ART_Is_TimeInMsElapsed, ART_IsRegPeriodElapsed, ACM_GetOptimumSlip, ACM_SlipRegulation, MTC_UpdateSine.

Caution: The two functions ACM_InitSlipFreqReg and ACM_Init must have been called before ACM_SustainSpeed to set-up the regulation properly.

ACM_InitSlipFreqReg

Synopsis	#include “acmotor.h”
	void ACM_InitSlipFreqReg(u8 OptimumSlip);

Description	This function must be called before calling the regulation routine (typically after completing the ACM_SoftStart function). It guarantees a smooth transition from open loop to closed loop operations. It performs the initialization of the integral term of the PI regulator (VoltageIntegralTerm) formula below and reset the PI regulator clamping flags.

$$\text{Voltage} = \text{Integral} + \text{Proportional} \rightarrow (\text{Integral} = \text{CurrentVoltage} - \text{Proportional})$$

Input	Optimum Slip value for the current stator frequency, with [0.1Hz] unit.

Caution: Since OptimumSlip is expected with u8 format, its value must be within the 0 to 25.5 Hz range.

Duration	1.45 ms (inc. ~20% CPU time spent in U interrupt sine generation).
Functions called	MTC_GetVoltage, MTC_GetSlip, ACM_GetPIParam.

ACM_SlipRegulation

Synopsis	#include “acmotor.h”
	u8 ACM_SlipRegulation(u8 OptimumSlip);

Description	This function performs a closed loop slip control to maintain the optimum voltage on stator winding. It can be shown that the AC motor efficiency is related to the slip frequency, having a maximum between zero and maximum torque slip values. This function uses a PI (Proportional and Integral) regulation algorithm to determine the most appropriate voltage value to get the expected slip frequency. Maintaining this slip optimizes the motor efficiency.
Input	OptimumSlip with [0.1Hz] unit, in u8 format. Its value must thus be within the 0 to 25.5 Hz range. Data returned by ACM_GetOptimumSlip function can be directly used as input.
Returns	Modulation index voltage (u8 variable).

Caution: 1. This function is executed regardless of regulator sampling time; this period must be managed by the calling function.

Caution: 2. The sine wave parameters are not modified in this routine; the MTC_UpdateSine function has to be called afterwards using the voltage value returned.

Duration	2.7 ms [1)] (including ~20% of time spent in interrupt for sine wave generation).
Functions called	MTC_GetSlip, ACM_GetPIParam, ACM_VoltageMaxAllowed.
See also	*Figure 31* on *Figure 31. on page 68*, ACM_GetPIParam function description.
Code example	*PI regulator implementation and tuning on page 62*.

Note: 1 This function uses 32-bit arithmetic to be compatible with the widest range of application and speed domains. In certain conditions, it is possible to use 16-bit, which will result in a shorter execution time (see Section 6.3.2 on page 89).

ACM_GetPIParam

Synopsis	#include “acmotor.h”
	void ACM_GetPIParam(u16 StatorFrequency);

Description	This function updates the value of the proportional and integral coefficient (so called Kp and Ki) needed by the PI regulator. In some applications, these coefficients have to be adjusted depending on the motor stator frequency, to reflect system dynamic response changes. The higher the speed range of the application, the higher the chance to have to modify these coefficients. For instance, at high speed, some loads may become so inertial that the proportional term may be greatly reduced or cancelled. The Kp and Ki values are extracted from a characteristic curve with two set-points, between which linear interpolation is performed (see *Figure 30* on *Figure 30. on page 66* for details); the corresponding global variables (Kp and Ki) are updated accordingly.
Input	Stator frequency with [0.1Hz] unit, in u8 format.

Note: *NoteThe Kp and Ki variables are declared as module global variables when using the ACM_GetPIParam function, to avoid returning a pointer to a structure.*

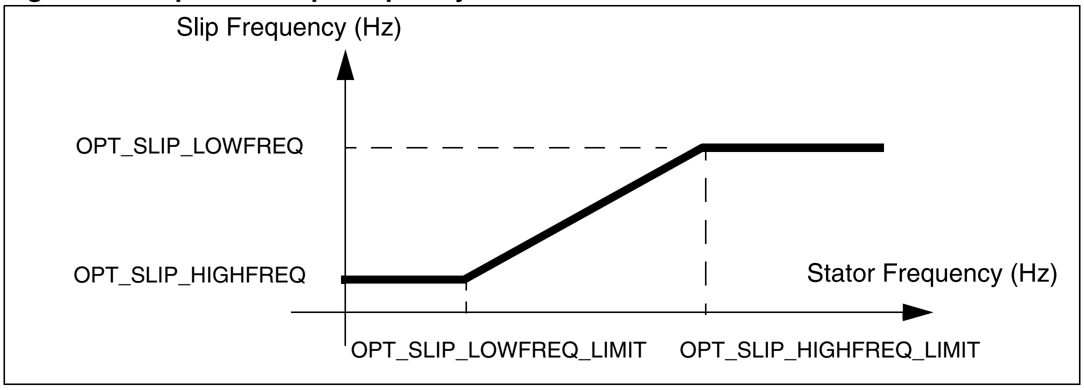
	This also allows you to initialize these variables once only, in the ACM_Init function for instance, if the application does not need these parameters to be modified during run time.
Duration	15 µs
See also	*Section* for detailed explanations on how the Kp and Ki parameters have to be set-up.

ACM_GetOptimumSlip

Synopsis	#include “acmotor.h”
	u8 ACM_GetOptimumSlip(u16 StatorFrequency);

Description	The purpose of this function is to return the most appropriate slip frequency, based on the stator frequency, if this value changes within the motor operating range. Set-points for this curve may be obtained either from the motor manufacturer or from empirical trials.

Figure 23. Optimum Slip Frequency



Inputs	StatorFrequency with [0.1Hz] unit.
Returns	OptimumSlip with [0.1Hz] unit, in u8 format, from 0 to 25.6Hz maximum.
Duration	31.5 µs (CPU running at 8 MHz).
See also	*Section on page 60*.

4.3.3 Detailed explanations and customization of ACMparam.h

Voltage vs frequency curve / ACM_VoltageMaxAllowed function

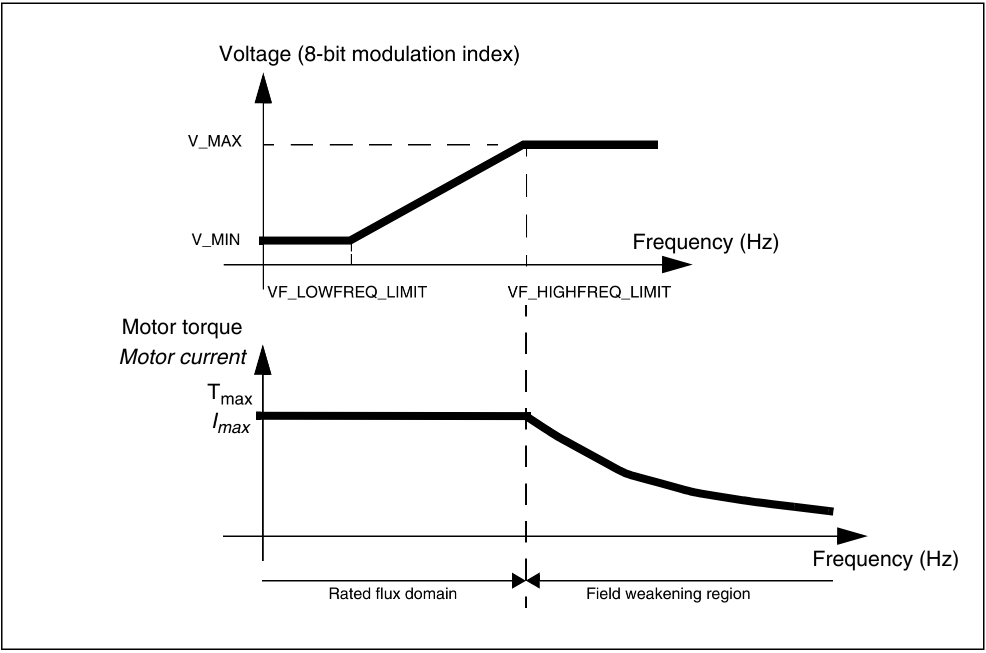
- **Theoretical background**

The stator winding of an AC motor can be approximately represented as an inductance, whose impedance increases with the stator frequency. First order, the current in the motor is proportional to the voltage applied and the torque in direct relation with the current (indeed the magnetic flux). The torque can thus be maintained to its rated value by keeping a constant voltage versus frequency ratio.

This is what is called scalar control, a method commonly used for basic AC motor drives.

Above a certain frequency limit, this ratio will decrease as the voltage is limited by the inverter topology, practically when modulation is at 100% (i.e. voltage = 255). A minimum voltage must also be maintained at low speed in order to energize and compensate the ohmic losses in the stator winding, and maintain a minimum magnetic flux. This finally leads to the characteristic shape shown in *Figure 24*

Figure 24. Standard V/f Characteristics and corresponding torque



- **Implementation**

Voltage is calculated by the following equations:

$$\boxed{\text{Voltage} = \frac{(\text{StatorFrequency} \times \text{VF\_COEFF}) - \text{VF\_OFFSET}}{256} + \text{V\_MIN}}$$

$$\text{VF\_COEFF} = \frac{(256 \times (\text{V\_MAX} - \text{V\_MIN}))}{(\text{VF\_HIGHFREQ\_LIMIT} - \text{VF\_LOWFREQ\_LIMIT})}$$

$$\text{VF\_OFFSET} = \text{VF\_COEFF} \times \text{VF\_LOWFREQ\_LIMIT}$$

Set-points can be entered directly in the ACMparam.h header file or using the ST7MC Control Panel. Both VF_COEFF and VF_OFFSET are re-computed by the preprocessor at compile time (multiplication by 256 is used here to maintain a sufficient accuracy and to decrease quantization effects).

Important: All variables used in this function are 16-bit. When modifying set-points, you must verify the following:

$$\mathrm{VF\_OFFSET} \le \mathrm{0xFFFF}$$

$$((\mathrm{VF\_HIGHFREQ\_LIMIT} \times \mathrm{VF\_COEFF}) - \mathrm{VF\_OFFSET}) \le \mathrm{0xFFFF}$$

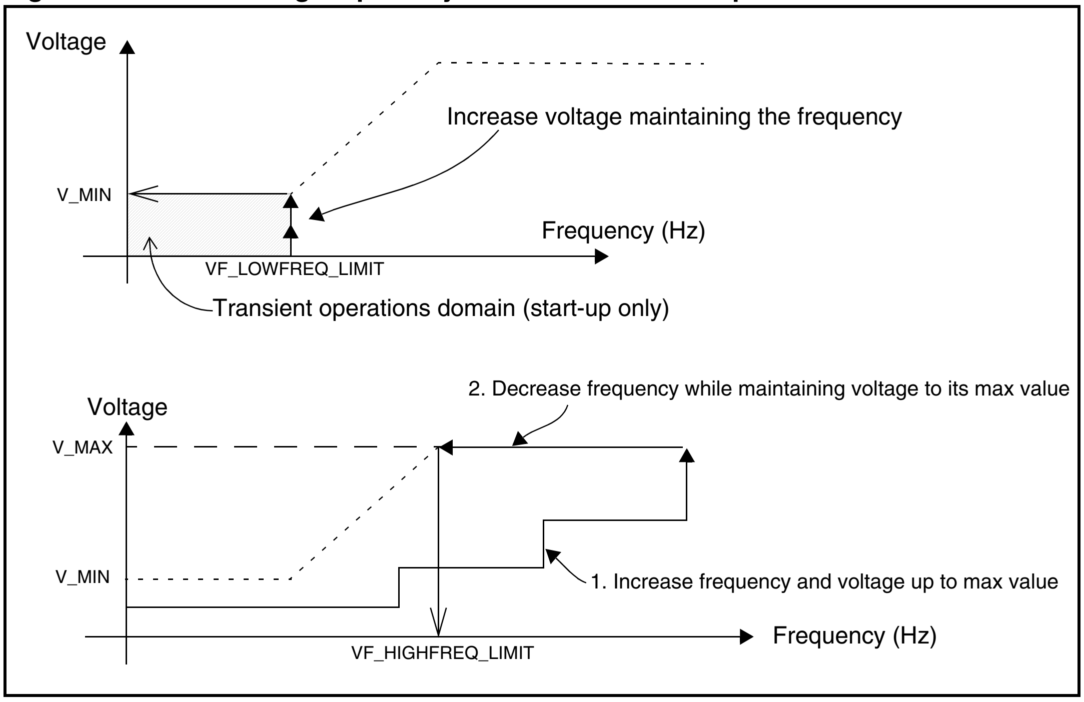
On the contrary, **certain variables and constants may have to be declared as u32 instead of u16**. (Buffer declared inside ACM_VoltageMaxAllowed, VF_OFFSET, etc.).

- **Tuning the V/f characteristic**

The following method can be followed to determine the three V/f curve set-points empirically (a current probe is mandatory). This must be done in open loop, to be able to freely apply any voltage or frequency on the motor and a speed sensor may be helpful.

- `VF_LOWFREQ_LIMIT`: this is the first parameter to be set, usually corresponding to the application's lowest operating frequency, or a value slightly above.
- `V_MIN`: to determine this point, slowly increase the voltage on the motor, while maintaining the frequency to `VF_LOWFREQ_LIMIT`. This will result in an increasing current in the stator winding. Stop when the current level in the motor reaches the max value indicated by the motor manufacturer. Without indication, stop when the current shape become distorted from a pure sine wave to a triangular waveform, indicating flux saturation. This is the first set-point (`VF_LOWFREQ_LIMIT`, `V_MIN`).
- `VF_HIGHFREQ_LIMIT`: in no-load conditions, accelerate the motor by sequential increasing the frequency and the voltage; the voltage must be increased when the torque is not sufficient: if a speed sensor is available, this is indicated by a rapidly growing slip. Once a sufficiently high speed has been reached (if not the application's highest speed), the voltage must be set to its highest value (`V_MAX` =255) without saturation effects. From this point, the stator frequency must be slowly decreased, keeping in mind that the stator frequency must never be below the rotor frequency value: this would cause the motor to become a generator, thus injecting reactive energy in the high voltage DC bus capacitor, causing the voltage to go above capacitor's maximum voltage rating. This is easy to ensure with a speed feedback; if not available, just slowly decrease the frequency while checking the bus voltage value to monitor regenerative current effects. While decreasing the frequency, the current will increase in the stator winding. Stop when the current level in the motor reaches the max value indicated by the motor manufacturer. Without indication, stop when the current shape becomes distorted from a pure sine wave to a triangular waveform, indicating flux saturation. This is the second set-point (`VF_HIGHFREQ_LIMIT`, `V_MAX`=255).

Figure 25. Determining empirically the two V/f curve set-points


Voltage
Increase voltage maintaining the frequency
V_MIN
Frequency (Hz)
VF_LOWFREQ_LIMIT
Transient operations domain (start-up only)
2. Decrease frequency while maintaining voltage to its max value
Voltage
V_MAX
V_MIN
1. Increase frequency and voltage up to max value
Frequency (Hz)
VF_HIGHFREQ_LIMIT

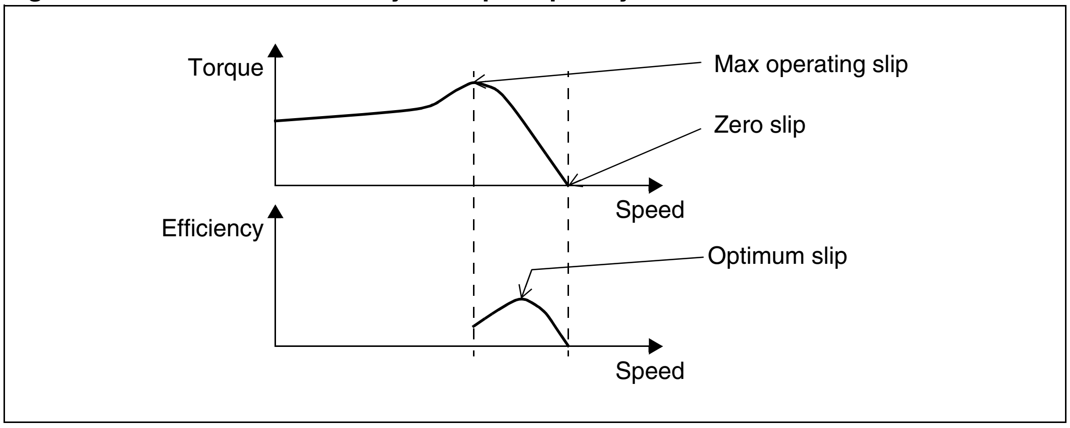
Induction motor Optimum Slip Characteristics

- **Theoretical background**

It can be shown that an AC motor efficiency varies with the slip frequency (see *Figure 26*):

- If the slip is close to zero, the efficiency tends to be null (no additional mechanical power available)
- If the slip is too high, the current in the rotor increases up to values where the ohmic losses in the rotor become significant, which in turns affects the motor efficiency.

Figure 26. AC motor efficiency vs Slip frequency



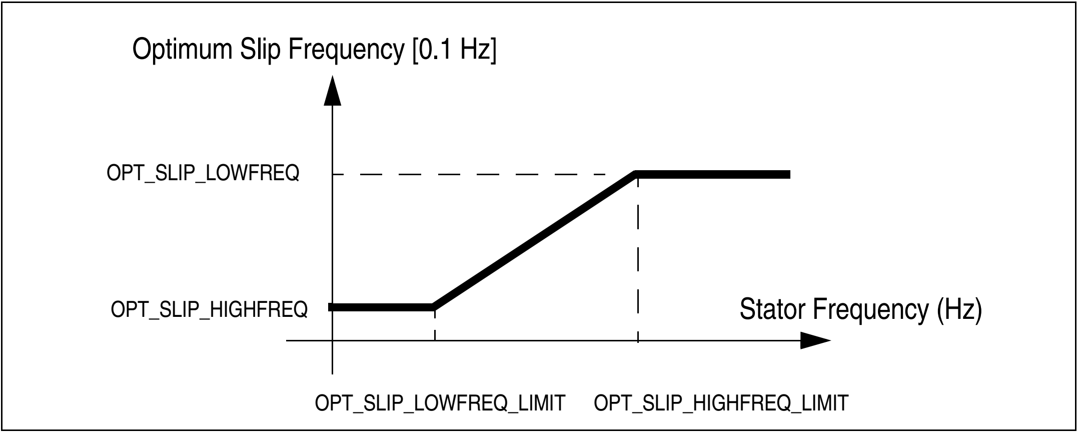
- **Implementation**

The purpose of this function is to return the most appropriate slip frequency, based on stator frequency, providing this value changes the motor operating range inside. Set-points for this curve (see *Figure 27*) may be obtained either from the motor manufacturer or from empirical trials. In this case, it is possible to determine the values using the ST7MC Control Panel in closed loop mode, a three-phase power meter and a motor brake. By varying the regulated slip frequency and comparing the motor input power and the mechanical power, a value giving the best efficiency will be found. The same can be done using the ST7MC starter kit in stand-alone mode, modifying the slip frequency to be regulated with a trimmer.

These optimum values will then have to be reported in the code to be used by the slip regulation algorithm.

The proposed function (ACM_GetOptimumSlip) performs linear interpolation between two set-points and can be used in most of the cases, provided that the measured optimum slip frequencies can be linearized. On the contrary, a look-up table may be necessary.

Figure 27. Example of linear function returning Optimal Slip Value



To enter the set-points described above, some defines in the ACMparam.h file must be edited according to the collected parameters:

```
#define OPT_SLIP_LOWFREQ_LIMIT   ((u16)2000)// 0.1Hz unit
#define OPT_SLIP_HIGHFREQ_LIMIT ((u16)2500)// 0.1Hz unit


#define OPT_SLIP_LOWFREQ         ((u8)30)// 0.1Hz unit
#define OPT_SLIP_HIGHFREQ        ((u8)80)// 0.1Hz unit
```

The equations used to obtain the optimum slip value are comparable to the one described for the ACM_VoltageMaxAllowed function (see *Section*).

Set-points can be entered in the ACMparam.h header file. Both `SLIP_COEFF` and `SLIP_OFFSET` are re-computed by the preprocessor at compile time (multiplication by 256 is used here to maintain a sufficient accuracy and to decrease quantization effects).

Important: All variables used in this function are 16-bit. When modifying set-points, you must verify the following:

$$\text{SLIP\_OFFSET} \le 0\text{xFFFF}$$

$$((\text{OPT\_SLIP\_HIGHFREQ\_LIMIT} \times \text{SLIP\_COEFF}) - \text{SLIP\_OFFSET}) \le 0\text{xFFFF}$$

However, **certain variables and constants may have to be declared as u32 instead of u16.** (Buffer declared inside ACM_GetOptimumSlip, SLIP_OFFSET, etc.).

PI regulator implementation and tuning

PID regulator theory and tuning methods are subjects which have been extensively discussed in the technical literature. Here is a basic reminder on the theory and a proposal of the empirical tuning method.

■ Theoretical background

The implemented regulator is actually a Proportional Integral one (see the note below regarding the differential term). The purpose of the regulation loop (see equation 1) is to adjust the voltage on the stator winding depending on the slip frequency.

$$V_{Stator} = f(Slip) \qquad (1)$$

$$V_{Stator} = V_{Start} + K_p \times Error_{Slip} + K_i \times \sum_t Error_{Slip} \qquad (2)$$

The equation 2 corresponds to a classical PI implementation, where:

- V_{start} is a constant corresponding to the voltage on the motor at the end of the soft start (see *Section on page 68* for details),
- K_p is the proportional coefficient,
- K_i is the integral coefficient.

The tuning and respective actions of these three parameters are discussed below.

Note: *No differential correction is implemented in the current regulator. Practice shows that this term leads to increased noise in the regulation loop (high pass function), in particular with low cost speed sensors such as tachogenerator. As a result, the system may become unstable or difficult to tune. Additional software filtering can be implemented to get proper differential slip error, but may result in additional response delay.*

- **Regulation tuning procedure**

To tune the PI regulator parameters, it is advised to proceed in the following order:

- sampling time,
- proportional coefficient,
- integral coefficient.

In order to modify in real-time the values of the coefficients, one can use the ST7MC Control Panel or operate the ST7MC starter kit hardware in stand-alone mode. For this, a conditional compilation key must be set in the config.h file (disabled by default):

```
#define PI_PARAM_TUNING
```

When this mode is activated, the ST7MC starter kit's trimmers assignmentis as follows:

- RV1 sets the target speed (by default between 10 and 266 Hz by 1Hz steps)
- RV2 sets the K_i parameter (8-bit value, [0..255] range).
- RV3 sets K_p parameter (8-bit value, [0..255] range).

For convenience, it is also advised to activate the RS232 communication interface using the following key, in config.h:

```
#define ENABLE_RS232
```

This will allow to read directly the Target speed and the K_p and K_i values on a PC Hyperterminal software (see *Section 4.7 on page 76*); it is also possible to get the rotor speed, the voltage applied on the motor or the current slip value.

- **Adjusting the regulation sampling Time**

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 will decrease its effects (accumulation will be slower and the integral action on the output will be delayed). Inversely, decreasing the loop time will increase its effects (accumulation will be faster and integral action on the output will be increased). This is why this parameter has to be adjusted prior to set-up the integral coefficient of the PI regulator.

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

- the related CPU load will grow accordingly; for instance, a 2.6ms PI routine executed every 10ms gives a 26% CPU load.
- the inputs of the system are usually for discrete information: a usual tachogenerator just provides 8 pulses per rotor revolution.This gives one speed information every 12.5ms if the rotor speed is 10Hz: no need in that case to have a sampling time lower than 12.5ms.
- at high speed, in most of the cases, system inertia is such that system response is slow: in these conditions there is no need to have a high sampling rate.

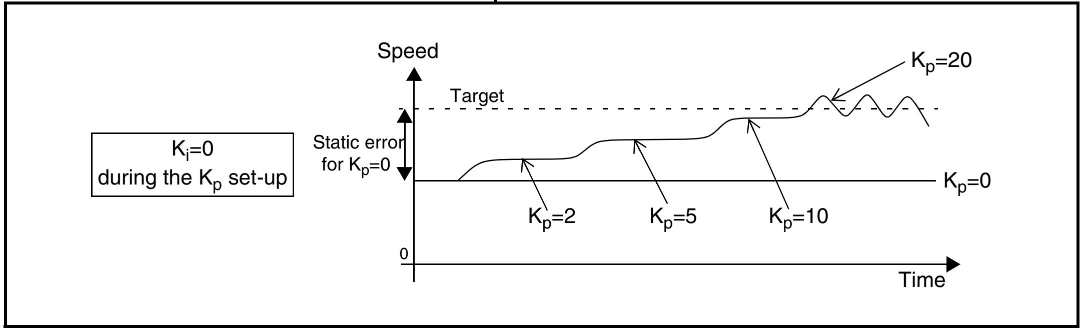
This parameter must be reported in the ACMParam.h file, in a specific define, in ms (10ms in the example below):

```
#defineSAMPLING_TIME((u8)10)
```

- **Tuning the Proportional coefficient Kp**

The K_p parameter provides the instantaneous error correction and is independent from the sampling time value. The higher the K_p, the lower the speed error and the better the dynamic response. Nevertheless, a value too high will lead to instability (see *Figure 28* for speed response vs K_p value).

Figure 28. Speed correction versus K_p value (with K_i =0)



Here is an empirical method to tune the K_p coefficient:

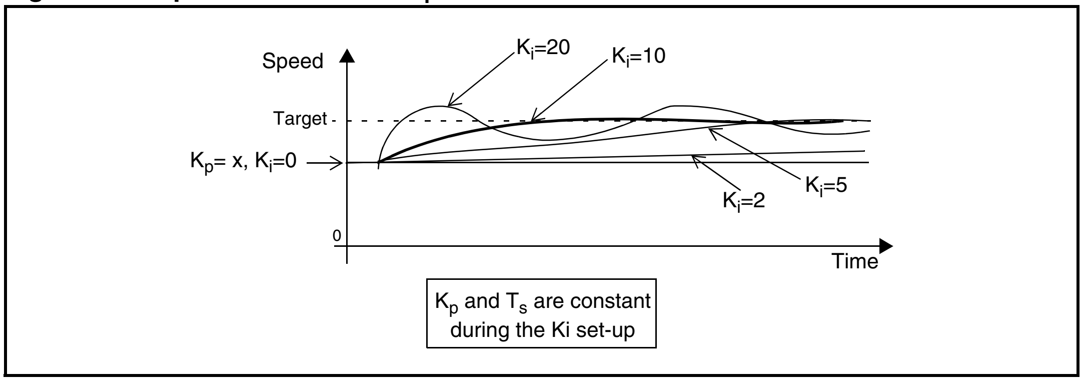
- With K_i=0 and K_p=0, start the motor; this is corresponding to open loop drive.
- At a given speed, with some load, there will be an error respect to the target speed (so called static error); by slowly increasing the K_p value, the error will decrease.
- When the system becomes unstable (oscillations), stop increasing K_p (this is $K_{p\ limit}$).
- The appropriate value of K_p to start working with will then be $K_p = K_{p\ limit} / 2$ (this is to provide a reasonable phase and gain margin).
- Confirm this result by trying several load conditions (if any) and slight speed variations to verify the system's dynamic response. The K_p can be slightly adjusted if necessary, keeping in mind that the final static error cancellation will be handled by the integral part of the PI regulator. The only important points to be validated are the lack of unstable behaviour over the whole working domain and a correct dynamic response (this last point will be further improved by the integral term action).
- Repeat the procedure for several speeds to scan the entire speed range of the application; for large speed ratios, it is most likely that several K_p values will have to be used to get the best results.
- **Tuning the Integral coefficient Ki**

This parameter K_i provides remaining static error cancellation over time.

In the current implementation, as mentioned above for sampling time set-up, the integral term effectiveness is linked to the time interval between two PI regulator execution. This is to decrease the PI execution time (it removes one run-time calculation). Consequently, when starting the parameter set-up, the sampling time T_s should be frozen; if it has to be modified after having tuned the K_i, the K_i parameter will have to be re-adjusted so that its influence remains constant.

The higher the K_i, the faster the speed error cancellation and the better the dynamic response. Nevertheless, a value too important will lead to instability (see *Figure 29* for speed response vs K_i value). During the set-up, Kp and Ts must be kept constant with the determined values below .

Figure 29. Speed error versus K_i



Here is an empirical method to tune the K_i coefficient:

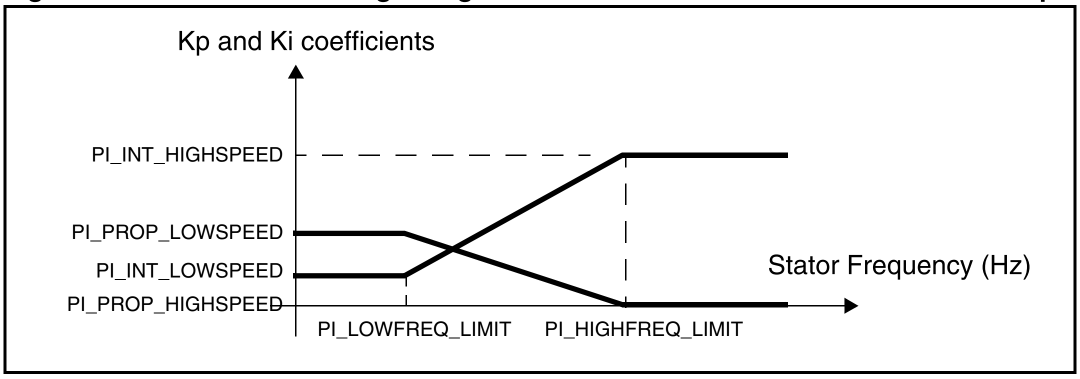
- With K_i=0 and K_p=x and T_s=y, start the motor.
- At a given speed, with some load, there will be a static error respect to the target speed; as soon as the K_i value is different from zero, the error will start to decrease.
- Contrary to proportional term adjustment, one cannot slowly increase the Ki to evaluate properly its action: it is necessary to have dynamic conditions. This can be done by suddenly applying a given Ki coefficient (as represented on *Figure 29*). This can also be done by modifying the target speed or the load to verify that the speed settle time is correct and there's no or limited speed overshoot. A sharp variation as provided by dynamic brakes will represent the most difficult conditions and is most of the time not very representative of real applications. It is usually easier to work with the final application speed profile or load variations.
- When the system becomes unstable (big speed overshoot or oscillations), stop increasing K_i (this is $K_{i\ limit}$).
- The appropriate value of K_i to start working with will then be $K_i = K_{i\ limit} / 2$ (this is to provide a reasonable phase and gain margin).
- Confirm this result by trying several load conditions (if any) and slight speed variations to verify the system's dynamic response. The K_i can be slightly adjusted if necessary to find the best trade-off between settle time and speed overshoot, keeping in mind that it is important to validate the lack of unstable behaviour over the whole working domain.
- Repeat the procedure for several speeds to scan the entire speed range of the application; for large speed ratios, it is most likely that several K_i values will have to be use to get the best results.

- **Adjusting Ki and Kp vs the stator frequency**

Depending on the application and/or the speed range, it might be necessary, as seen in the previous sections, to use different values of K_p and K_i parameters depending on stator frequency.

These values will have to be reported in the code to feed the slip regulation algorithm. A function performing linear interpolation between two set-points (ACM_GetPIParam) is provided as an example in the software library and can be used in most of the cases, as long as the coefficient values can be linearized (see *Figure 30* for details). On the contrary, a function with a larger number of set-points or a look-up table may be necessary.

Figure 30. Function returning PI regulator coefficients as a function of stator freq.



To enter the above described set-points, some defines in the ACMparam.h file must be edited according to the collected parameters:

```
#define PI_PROP_LOWSPD      ((u8)5)
#define PI_PROP_HIGHSPD((u8)0)


#define PI_INT_LOWSPD      ((u8)50)
#define PI_INT_HIGHSPD((u8)60)


#define PI_LOWFREQ_LIMIT       ((u16)500)// 0.1Hz unit
#define PI_HIGHFREQ_LIMIT      ((u16)800)// 0.1Hz unit
```

- **Tricks and traps**
  - When tuning the PI parameters one should look for the worst case conditions, which may be when the load is quickly and unpredictably varying, when the inertia is minimum, or when the mains voltage is maximum for a off-line application.
  - Slip regulation output is an 8-bit variable: this intrinsically limits the accuracy that can be expected on the motor speed. Quantization effect can be evaluated in open loop, doing a voltage increment and measuring the speed difference.
  - The slip regulation has some non-linearities, in particular at low frequency and low voltage. For instance, if the voltage variable value is equal to 20, a +/-1 difference on it will result in a +/- 5% relative change on voltage.
  - A regulation tuned on a motor bench with a brake may become unstable on the final application, in particular if the load is highly varying and not predictable
  - A regulation tuned in no-load condition (at the highest slip versus voltage gain) will most probably be unresponsive in the final application, and vice versa: a regulation tuned in the application may become unstable in no-load conditions.
- **Implementing the Slip regulation**

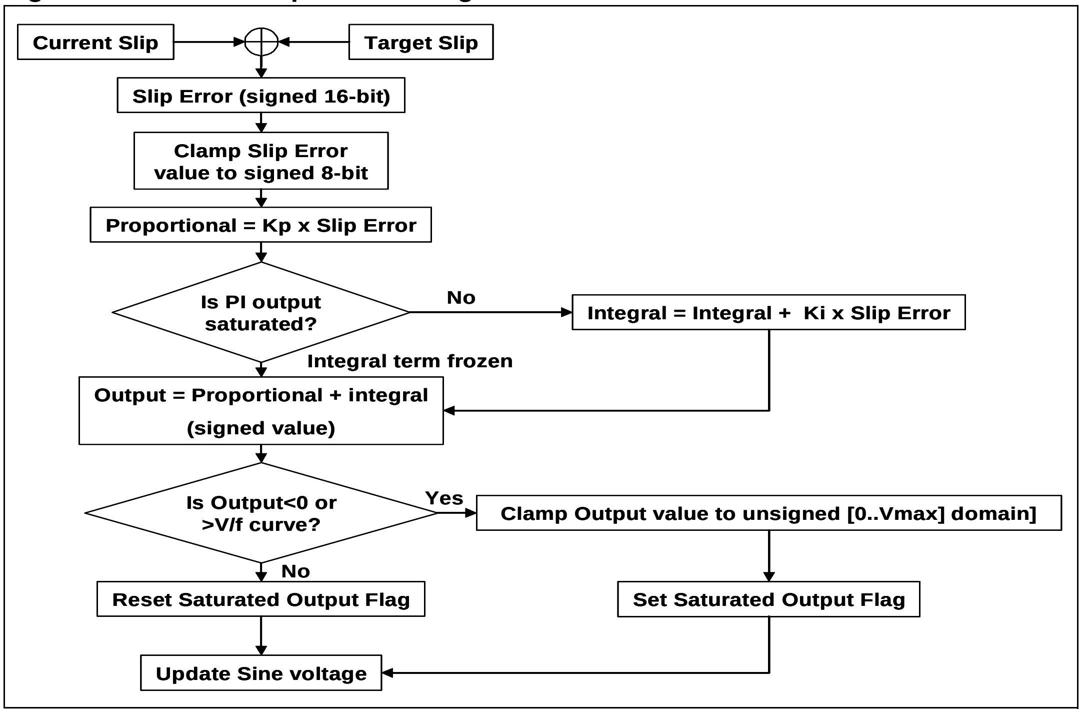
Below is an example of the use of this regulation process. It must be noted that the motor voltage only is handled by the slip regulation (see *Figure 31* below); the stator frequency is usually managed in open loop (see *Figure 39* on *Figure 39. on page 82* for details)

```
ART_Init();/* PWM ART provided general purpose time bases */
```

```
ACM_Init();/* Includes regulation sampling time set-up */
...
EnableInterrupts();
...
ACM_InitSoftStart(START_FREQ); /* Open loop*/
...
/* Simplified Start example without error handling*/
while (ACM_SoftStart(MIN_START_FREQ) != START_OK);
...
OptimumSlip = ACM_GetOptimumSlip(MTC_GetStatorFreq());
ACM_InitSlipFreqReg(OptimumSlip); /* Mandatory regulation
initialization */
   /* From here regulation can be called periodically */
...
while (NoStopOrderReceived()) /* Example of regulation stop event */
{
   if (ART_IsRegPeriodElapsed()) /* Periodic re-start */
   {
      OptimumSlip = ACM_GetOptimumSlip(StatorFreq);
      NewVoltage = ACM_SlipRegulation(OptimumSlip);
   }
}
```

Note: ACM_SoftStart is considered as an open loop control: the tacho feedback is just used at that time to limit the voltage when the rotor speed is considered as sufficient (indeed when tachogenerator feedback is reliable enough). It is recommended to exit this routine with a slip that is close to or slightly lower than the slip to be regulated for smoothing the transition to closed loop operations (using MinRotorFreq variable, to be determined empirically).

Figure 31. Closed loop stator voltage control


Current Slip
Target Slip
Slip Error (signed 16-bit)
Clamp Slip Error value to signed 8-bit
Proportional = Kp x Slip Error
Is PI output saturated?
No
Integral = Integral + Ki x Slip Error
Integral term frozen
Output = Proportional + integral (signed value)
Is Output<0 or >V/f curve?
Yes
Clamp Output value to unsigned [0..Vmax] domain]
No
Reset Saturated Output Flag
Set Saturated Output Flag
Update Sine voltage

Finally, it must be remembered that two functions have to be called before starting the regulation process:

- ACM_Init to set-up the regulation timebase,
- ACM_InitSlipFreqReg to initialize the integral term.

AC motor start-up method

The soft start function imposes a voltage profile to start the motor without an excessive inrush current, while maintaining a constant frequency on the stator. This voltage profile, which can by modified depending on the application, depends on control type (open or closed loop): see the sections below for details.

To enter the Stator frequency at start, a define in the Mainparam.h file must be edited:

```
#defineSTART_FREQ ((u16)150) // Open & Closed Loop, 0.1Hz unit
```

This value is a trade-off between the time needed to reach the nominal speed, the inrush current and the voltage slew rate: the faster the slew-rate and the stator frequency, the higher will be the inrush current.

Usually, if this value is low (typically below 25Hz), it can be directly set to the target stator frequency (equal to the target rotor frequency plus the optimum Slip).

- **Closed loop Start-up**

Closed loop voltage profile during start-up is described on *Figure 32*. Two timing parameters can be set using defines in the ACMparam.h header file:

```
#define START_TIMEOUT((u16)1800) /* Resolution: 1ms */
```

```
#define EXTRA_TIMEOUT((u16)1000)
```

`EXTRA_TIMEOUT` is needed for high inertia loads, when the correct rotor speed can be long to be reached.

Another parameter must be set via a define in the Mainparam.h file to specify the MinRotorFreq input of the ACM_SoftStart function:

```
#define MIN_START_FREQ ((u16)100) // Closed Loop only, resolution:
0.1Hz
```

This frequency is application dependent and must be set slightly below the target stator frequency when starting the closed loop operations, to avoid a potential speed overshoot. For instance, if:

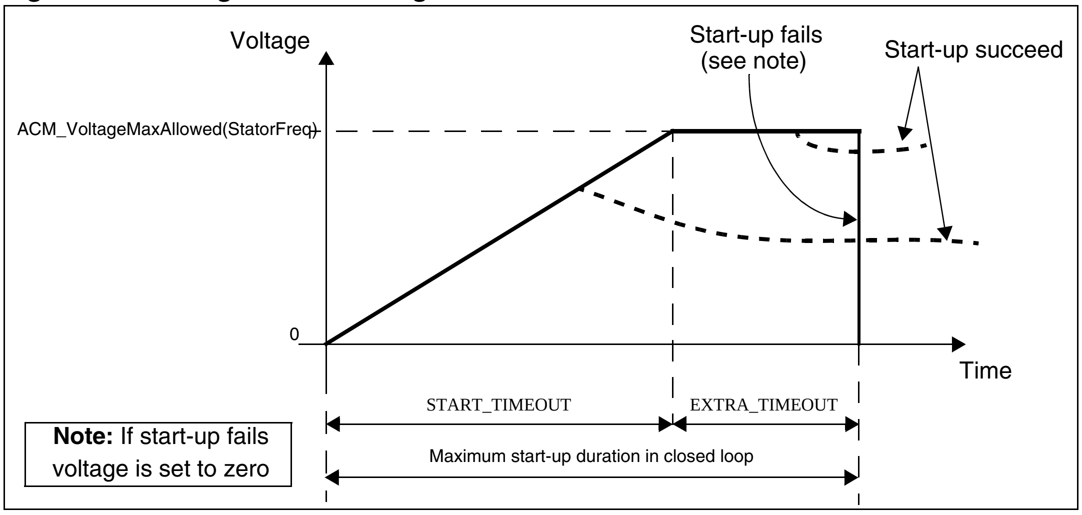
- target rotational speed is 12Hz
- Optimum slip is 3Hz

Then:

- Stator freq will be set to 15Hz
- `MIN_START_FREQ` can be set to 10Hz

Then the PI regulator will take care to smoothly bring the rotor speed from 10Hz to 12Hz.

Figure 32. Voltage Profile during closed ACM_SoftStart Routine



A flowchart for closed loop start-up is also given in *Figure A.1.10* on *A.1.10 on page 98*.

- **Open loop Start-up**

Open loop behaviour is simpler (see *Figure 33*): the slope of voltage increase is set-up using a define in ACMparam.h header file:

```
#defineVOLT_SLEWRATE ((u8)10)// Unit: 1ms
```

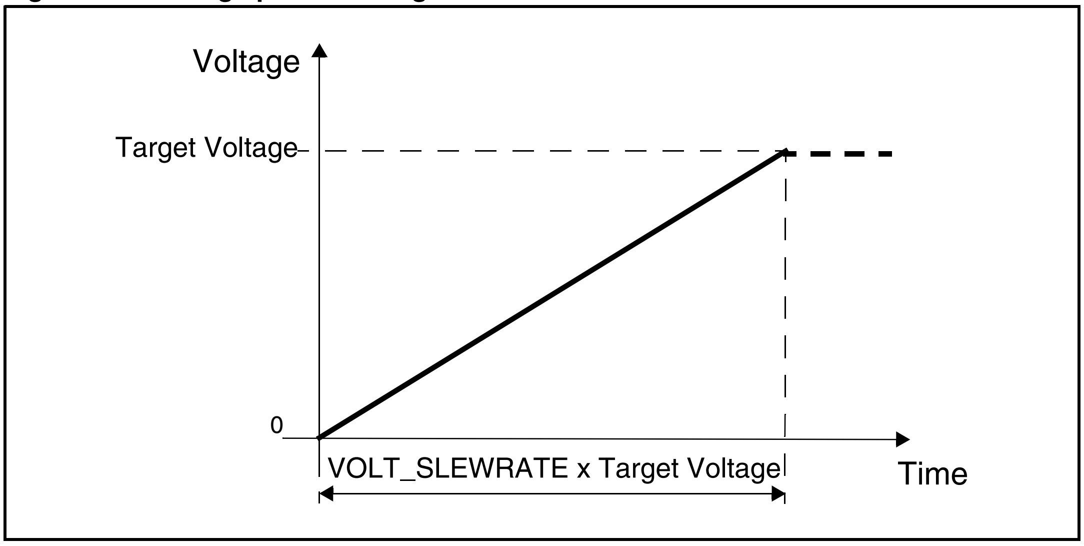
The slew-rate has to be determined as the best trade-off between the soft start duration and the inrush current in the motor.

The second parameter to be set is the target voltage, using in a define in Mainparam.h:

```
#define START_VOLTAGE ((u8)30);// Open Loop only
```

This target voltage is usually selected as the voltage giving the highest torque, to be sure that motor will start spinning. Once the Target Voltage has been reached, the voltage value is kept constant and the start routine is exited.

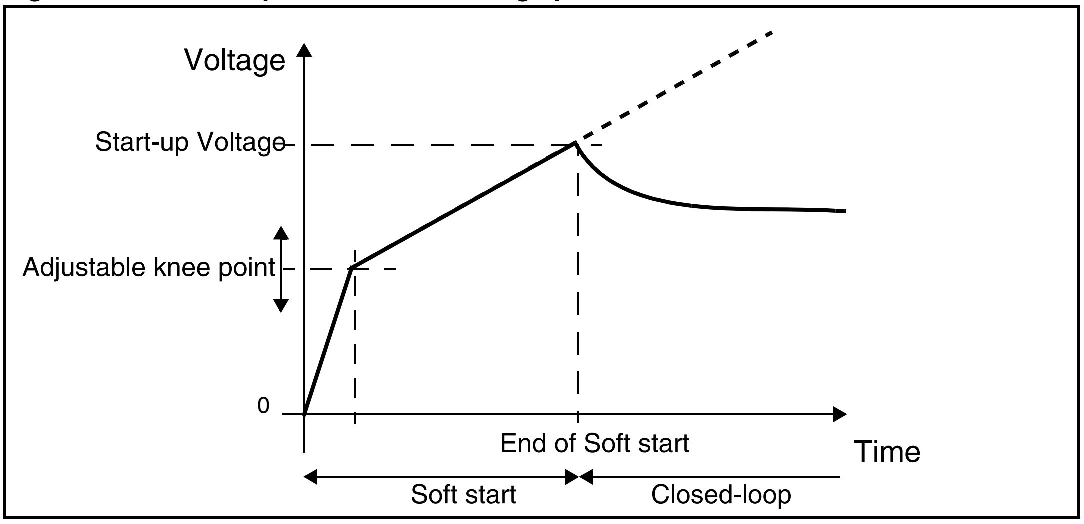
Figure 33. Voltage profile during ACM_SoftStartOL routine



- Fast start-up

If start-up duration has to be very short, a double slope soft start procedure can be implemented. This will allow the time spent in the first part of the slope to be reduced, where the stator current is only used to magnetize the winding, without mechanical torque production. The inflexion point can be dynamically adjusted depending on the load, if it can be foreseen, to achieve an adaptive fast soft start (see *Figure 34*).

Figure 34. Fast adaptive soft start voltage profile



Using P Pole Motors

The current library has been setup for an AC motor with a single pair of poles, where the stator and rotor frequencies are directly comparable and the slip can be simply calculated (subtraction).

Generally (motors with p pair of poles) the following relations apply:

$$\boxed{F_{rotor} = \frac{F_{stator}}{p}}$$

Electrical slip: $F_{slip} = \frac{F_{stator}}{p} - F_{rotor}$

Pseudo slip: $F_{slip}' = F_{stator} - p \times F_{rotor}$

In order to make the setting of the parameters easier, only the pseudo slip will be taken into consideration. This means that value returned by MTC_GetSlip will be p times the real electrical slip frequency.

You should keep this definition in mind when:

- measuring the rotor speed via the MTC_GetRotorFreq function, which also returns p times the real rotor speed,
- characterizing its motor (efficiency vs slip characteristics),
- setting-up ACM_GetOptimumSlip parameters.

Parameters are customized in the MTCparam.h file, by modifying the `POLE_PAIR_NUM` define used in the MTC_GetRotorFreq function to calculate the frequency.

4.4 Analog to digital converter

4.4.1 Module description

This module (adc.c) starts and initializes the analog to digital converter, and launches upon request a conversion on a channel. It is able to provide ready-to-use values to the upper software layer.

It was basically written to monitor signals that vary slowly, such as trimmers, since the returned results are the averaged values of 8 successive conversions.

The ADC is first initialized in the ADC_Init. The variable holding the status of the power stage is also cleared in this function.

Finally this module contains routines related to motor control tasks, needed to run the software library demos on the ST7MC Starter kit hardware.

The '***u16 ADC_Get_10bits(u8 Channel)***' and '***u8 ADC_Get_8bits(u8 Channel)***' functions return the ADC result on the selected channel. In order to smooth the result, 8 successive samples are added in an intermediate buffer and their average value is calculated by division. These functions are declared as static functions: they are only accessible inside the adc.c module.

The '***u8 ADC_GetRV1(void)***', '***u8 ADC_GetRV2(void)***' and '***u8 ADC_GetRV3(void)***' routines return the value read on the trimmers connected to the MCU (RV1, RV2, RV3) on the ST7MC starter kit hardware.

The '***BOOL ADC_CheckOverTemp(void)***' returns a boolean. This function returns 'TRUE' if the voltage on the thermal resistor connected to channel AIN0 has reached the threshold level or if the voltage has not yet reached back the threshold level minus the hysteresis value, after an overheat detection. In order to set the temperature and hysteresis threshold, the `NTC_THRESHOLD` and `NTC_HYSTERESIS` values can be adjusted in the adc.c file.

The '***BOOL ADC_CheckOverVoltage(void)***' returns a boolean. This function returns 'TRUE' if the voltage of the HVBUS connected to channel AIN1 has reached the threshold level or if the voltage has not yet reached back the threshold level minus the hysteresis value after an over-voltage detection. In order to set the voltage and hysteresis threshold, the `HVBUS_THRESHOLD` and `HVBUS_HYSTERESIS` values can be adjusted in the adc.c file.

One can also directly get the heatsink temperature or the DC bus voltage using respectively '***u8 ADC_GetHeatsinkTemp(void)***' or '***u8 ADC_GetBusVoltage(void)***' functions.

4.4.2 Synopsis

```
#include <adc.h>

...

PORTS_Init();

ADC_Init();

  /* From this point, you can call ADC functions */

...

{

    u8 SpeedCommand;

  SpeedCommand = ADC_GetRV1();

  if (ADC_CheckOverVoltage() || ADC_CheckOverTemp()) State = FAULT;

}
```

4.4.3 Timing

Each conversion is achieved in 28 clock cycles. This means that the following is required in order to complete 8 conversions with no ADC input clock prescaling: 8 x 3.5µs = 28 µs. Together with averaging code, this gives a duration of 50.5µs to get the result of ***ADC_GetRV2*** function call.

4.4.4 Caution

The following important points must be taken into consideration when using adc.c functions.

Sampling rate

The maximum frequency for input signals to be correctly sampled is in direct relation with the ADC functions call rate.

For instance, it the function ***ADC_Get_RV1*** is called every 2ms in the main loop, Shannon's theorem will allow signals to be monitored up to approximately 250 Hz (i.e. 1/(0.002 x 2).

Port Initialization

The I/O ports corresponding to the ADC channels must be previously initialized as Analog Inputs in another module before being used (here in the PORTS_Init function). By default, the library uses the following I/Os:

- AIN0 for heatsink temperature reading,
- AIN1 for Bus voltage monitoring,
- AIN7 for RV3 trimmer,
- AIN11 for RV2 trimmer,
- AIN13 for RV1 trimmer.

4.4.5 Customizing the ADC module

This module is just an example of ADC use. You can perform the following actions depending on the application:

- decrease the speed of conversion by increasing the ADC Clock prescaler, currently set to zero,
- use 10-bit conversions rather than 8-bit, keeping in mind total un-adjusted error of the ADC (see AN636 ‘Understanding and minimizing ADC conversion errors’ for more details on using ST7 ADCs).
- modify the comparison thresholds for bus over-voltage or heatsink over-temperature indications, as well as the respective hysteresis.

4.5 I/O ports

The purpose of this module (ports.c) is to centralize all information regarding the I/O ports (including alternate functions) within the same file.

It is intended to clarify the sharing of I/Os between the peripherals and the functions requiring standard input/outputs, such as LEDs and push button reading.

I/Os are initialized at the beginning of the main program, using the PORTS_Init function. Two functions are handled by this module, needed when running the software library with the ST7MC starter kit hardware.

4.5.1 Push button reading

The function ***BOOL PORTS_KeyScan(void)*** returns a boolean, TRUE if the push button has been pushed during at minimum duration. This duration can be programmed in ms, to debounce the button reading. This timing is verified using PWMART.c module resources: this must be remembered when using this module with a different timebase (for instance provided by the 16-bit timer or the Main Clock Controller).

The location of the push button (port and bit location) must be specified at the beginning of the ports.c file. The push button must be connected between the ground and a pull-up resistor to get a low level on the input pin when it is pushed (refer to ST7MC starter kit schematics for details).

4.5.2 LEDs

A set of functions can be called to switch ON, OFF or toggle the two LEDs present on the starter kit: ***PORTS_RedLedOn***, ***PORTS_RedLedOff***, ***PORTS_RedLedToggle***,... It must be remembered that these two LEDs are powered using a single I/O (see schematics for details). Consequently:

- they cannot be turned ON simultaneously
- the I/O port state can be configured either as an output or as a floating input to switch OFF the LEDs.

The location of the LEDs (port and bit location) must be specified at the beginning of the ports.c file (refer to ST7MC starter kit schematics for details).

4.6 PWM auto reload timer

The purpose of this module (pwmart.c) is to group together functions related to the PWM Auto Reload Timer (PWMART).

This peripheral is used in this library to provide a set of software timebases available for the periodic and asynchronous execution of the various tasks (Time Out checks, regulation sampling time, serial link data exchange rate, etc.) which may have different periods.

This can be considered as the heartbeat of the motor control library. It is convenient for simple sequencing of various tasks, in a cooperative way, but does not provide any RTOS features.

In particular, adding new task's timebases must be done manually by modifying the PWM ART interrupt routine and adding some specific functions, as described in the sections below.

Finally, these timebases are used in the whole library in such a way that their replacement by another timebase generator, a sequencer or a RTOS should be straightforward. The sole exception to this is the use of the variable `DebounceButton` dedicated to push button reading, directly handled in the ART_Interrupt routine.

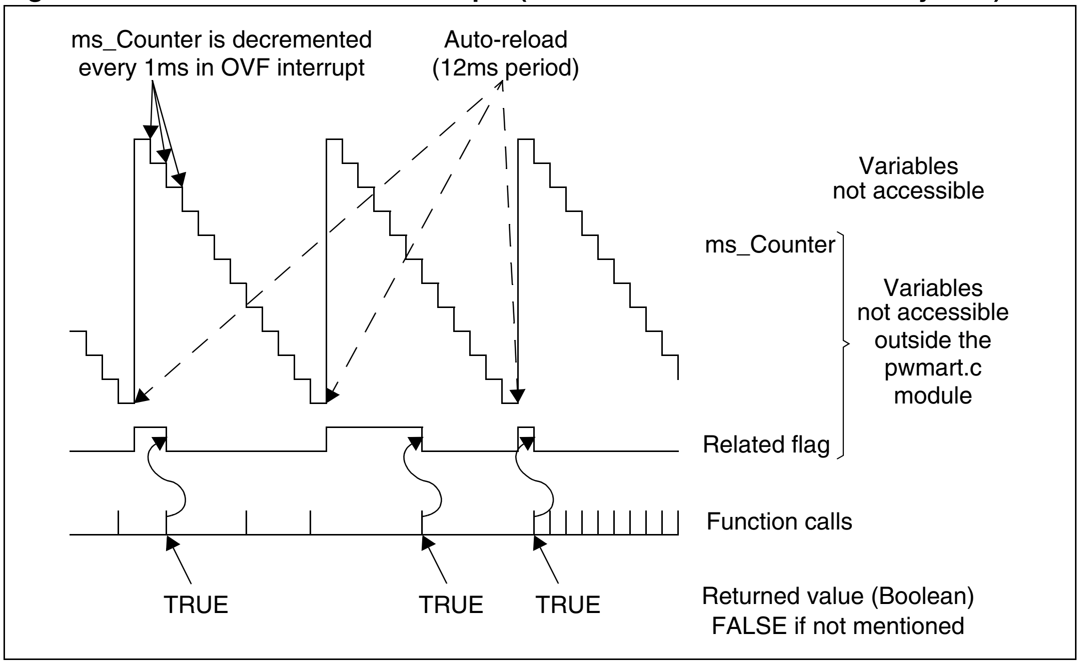
4.6.1 Software timebases working principle

These timebases are managed by the timer's overflow interrupt occurring every 1 ms. This unit can be changed modifying the `#define TB_UNIT` value in the pwmart.c, to increase or decrease the timebase accuracy (and consequently slightly increase or decrease CPU load). All related functions setting the timing intervals or periods will have to be modified to provide the same 1ms unit for input parameters, if needed.

These timebases are designed to be used in polling mode. Timing accuracy is therefore tightly linked with the polling rate of the considered function: the higher the function call rate, the better will be the timing accuracy and the lower will be the jitter.

Figure 35 shown below, presents how the ART_Is_TimeInMsElapsed function works, once its period has been set (in the above example: 12ms).

Figure 35. Software timebase Principle (ms_Counter decremented every 1ms)


ms_Counter is decremented every 1ms in OVF interrupt
Auto-reload (12ms period)
Variables not accessible
ms_Counter
Variables not accessible outside the pwmart.c module
Related flag
Function calls
TRUE
TRUE
TRUE
Returned value (Boolean) FALSE if not mentioned

From this figure, it is clear that ART_Is_TimeInMsElapsed will return TRUE if the pre-defined duration has been completed, but without any information on the time elapsed since this event occurred. A while structure minimizes jittering:

```
while (! (IMC_ms_Counter_Elapsed ())
{
   DoTheJob();/* ... while duration is not elapsed */
}
```

4.6.2 Timebase use for the AC motor control library and demo program

Six independent software timebases are provided for demo purposes.

Two complementary functions are needed per timebase:

- a first one sets the period; for instance: ART_SetTimeOutDuration(30) will program the Time Out duration to be 30ms.
- a second one indicates to the user that the programmed duration is elapsed; for instance, following the below example, ART_IsTimeOutElapsed will return a boolean TRUE every 30ms.

These functions have auto-reload capabilities: even if the duration is used a single time, the timebase will be maintained with the same period.

Table 2. **Summary of timebase use in the AC motor software library**

Name	Unit (ms)	Range	Usage in Open Loop	Usage in Closed Loop	Associated functions
TimeOut	1	16-bit	In ***main.c***: set the duration of the whole active braking and the 1s idle time before re-starting		ART_SetTimeOutDuration ART_IsTimeOutElapsed
Sequence	1	16-bit	In ***mtc.c***: sets the Stator Demag Time (in MTC_StartBraking) and the DC current increase rate (in MTC_Brake)		ART_SetSequenceDuration ART_IsSequenceCompleted
				In **acmotor.c**: sets the SoftStart maximum duration.	
SpeedReg	1	8-bit	No	In ***acmotor.c*** and in ***main.c***, sets the regulation sampling time.	ART_SetSpeedRegPeriod ART_IsRegPeriodElapsed
TimeInMs	1	16-bit	In ***acmotor.c***: sets the voltage increase rate during SoftStart.		ART_Set_TimeInMs ART_Is_TimeInMsElapsed
			In ***main.c***: sets the interval between frequency or voltage increments	In ***acmotor.c***: sets the duration of the ACM_SustainSpeed function	
MainTimeBase	10	8-bit	In ***main.c***: sets the LED blinking rate		ART_SetMainTimeBase ART_IsMainTimeElapsed
WdgRfrsh	1	8-bit	No	No	ART_SetWdgRfrshTime ART_IsWdgTimeElapsed

Note: All timebases used in mtc.c and acmotor.c must be considered as 'reserved' for the AC motor software library. However, the timebase used in main.c module can be re-used if needed.

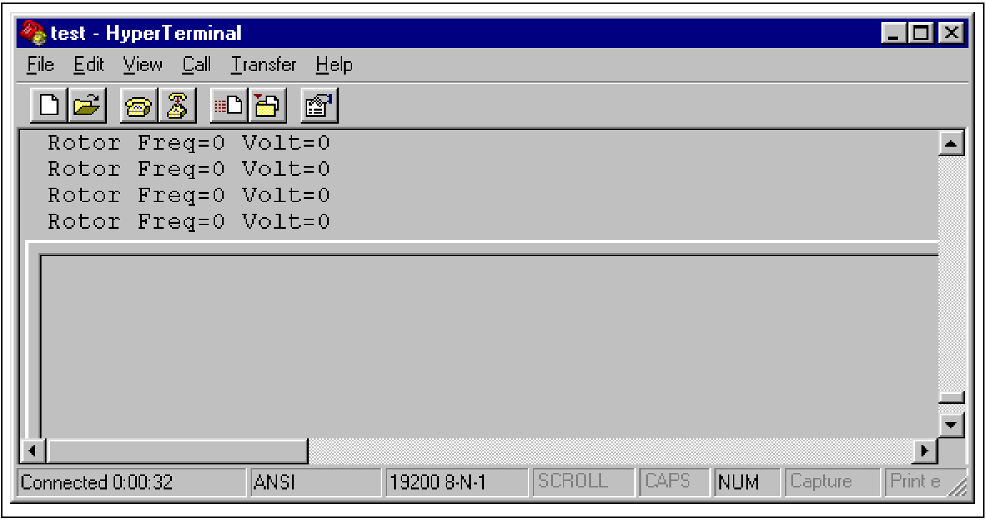
4.7 Serial communication interface

4.7.1 Description

This module is a modified version of the SCI module delivered with the ST7 library Rev 1.0. When used with the appropriate software (for instance HyperTerminal, present by default on most of PCs, see *Figure 34*), it becomes a very convenient tool that helps to monitor, trace and store any MCU's run-time data and variables without using a debugger.

This is particularly useful when dealing with high-voltage (where emulator use is not recommended) and with closed loop system (where a breakpoint only provides MCU internal variables values at a given time, without possibility to directly re-start from the current state).

Figure 36. HyperTerminal



```
Rotor Freq=0 Volt=0
Rotor Freq=0 Volt=0
Rotor Freq=0 Volt=0
Rotor Freq=0 Volt=0
```

4.7.2 Implementation

Here are the serial communication characteristics:

- 19200 baud,
- 8-bit data,
- 1 stop bit,
- No parity,
- No communication protocol,
- Transmission only.

Three-lines only are needed for such asynchronous transmission; the pin number corresponds to a standard DB9 female connector:

- Tx and Rx (pin 2 and 3 on a standard null modem cable),
- Ground (pin 5 of DB9 female connector).

Since the ST7 is sending the data with its own timebase, the transmission period is known. For instance, speed regulator reaction time in closed loop mode can be easily evaluated by importing on a spread sheet editor the data files coming from Hyperterminal, assuming an interval between data frames of 100ms for instance to have a consistent time axis representation.

Refer to *Section 5.3 on page 83* for examples of SCI use in the software library.

4.7.3 Changes vs ST7 library

- The current set of files (sci.c, sci.h) have been customized for the ST7MC hardware registers, and the ST7 library set-up files have been removed (sci_hr.c, sci_hr.h, st7lib_config.h). Consequently this module is not compatible as it is with products other than ST7MC.
- Three routines have been added to convert variables in character strings:

```
void PrintUnsignedInt(unsigned int x);
void PrintUnsignedChar(unsigned char x);

void PrintSignedChar(signed char x);
```

These functions call the SCI_PutString subroutine to send the character string after the conversion. In their current form, they are not compatible with interrupt driven transmission.

- Another routine has been added to concatenate an unsigned integer in a character string, for both polling and interrupt driven transmission:

void strcatu16(const unsigned char *PtrtoString, unsigned int x);

4.7.4 Customization

Please refer to the ST7 library documentation for help on functions, communication set-up and implementation examples.

Transmission / reception method

Two methods are available: polling or interrupt driven. The first method has been chosen for the current library: once a SCI function is called, it is only exited upon completion of the transmission. This must be remembered when a watchdog is used. It can be changed in the config.h file to have access to the right functions prototypes:

```
#define SCI_POLLING_TX                         /*Polling mode transmission*/

//#define SCI_ITDRV_WITHOUTBUF_TX  /*Interrupt driven without buffer transmission
mode*/

#define SCI_POLLING_RX                          /*polling mode reception*/

//#define SCI_ITDRV_WITHOUTBUF_RX /*Interrupt driven without buffer reception mode*/
```

Baud rate

The communication baud rate can be adjusted from 38400 to 1200 bauds or less, keeping in mind that the length of the transmission will increase accordingly.

4.7.5 Important notice for hardware implementation

There must be a galvanic isolation between the ST7MC and the PC serial port if there is none implemented between the MCU and the power inverter. This will lower the risk of user injury and damage to the computer's serial port.

This is achieved by adding optical-isolators between the MCU and the level converter (RS 232 transceiver) directly connected to the serial bus.

4.8 Nested interrupt controller

The demo program provided to start working with the software library benefits from the ST7 nested interrupts controller. Below is a table summarizing the priorities of the available interrupts.

It must be noted that any missed Update interrupt (MTC_U_CL_SO_IT) will lead to sine wave distortion, which in turn may be a source of reactive current in the inverter. This is the reason why the sine wave generation dedicated interrupt is and must be maintained at the highest priority level.

The only case where these interrupts may be delayed is upon emergency stop event, when PWM outputs are not active any more.

Table 3. ST7MC Software library interrupt priorities

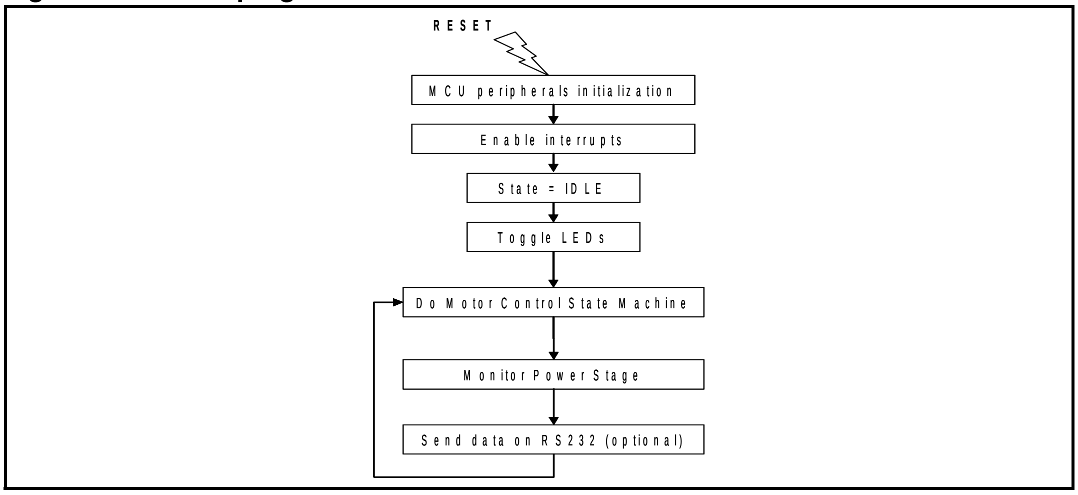
Priority	Interrupt Name	Purpose
Top Level	MCES_SE_IT	Emergency Stop Event management
	MTC_U_CL_SO_IT	Sine wave generation
Medium/High	MTC_C_D_IT	Tachogenerator signal capture
	MTC_R_Z_IT	Automatic MTIM prescaler update
	ART_Interrupt	1 ms timebase
Medium/Low	All others	Not used

5 Running the demo programs

Two demo programs are included in the main.c routine to demonstrate either the Open Loop or Closed Loop operations.

The choice is made with conditional compilation keys in config.h file (see *Section 3.2 on page 12*). These programs are just intended to provide examples on how to use the software library functions. After the MCU initialization phase, a simple state machine handles the motor control tasks in the main loop, as well as a basic monitoring of the power stage and, if needed, transmission of data on the serial interface (see *Figure 37*).

Figure 37. Demo program flow chart


RESET
MCU peripherals initialization
Enable interrupts
State = IDLE
Toggle LEDs
Do Motor Control State Machine
Monitor Power Stage
Send data on RS232 (optional)

The state machine described on *Figure 38* does not differentiate open from closed loop control, at the exception of the starting phase initialization (when state = IDLE).

The power stage is monitored using the ADC and the MCES input to verify the following parameters:

- Heatsink over-temperature (on ADC's channel AIN0),
- DC bus over-voltage (on ADC's channel AIN1),
- Over-current protection (low state on MCES input).

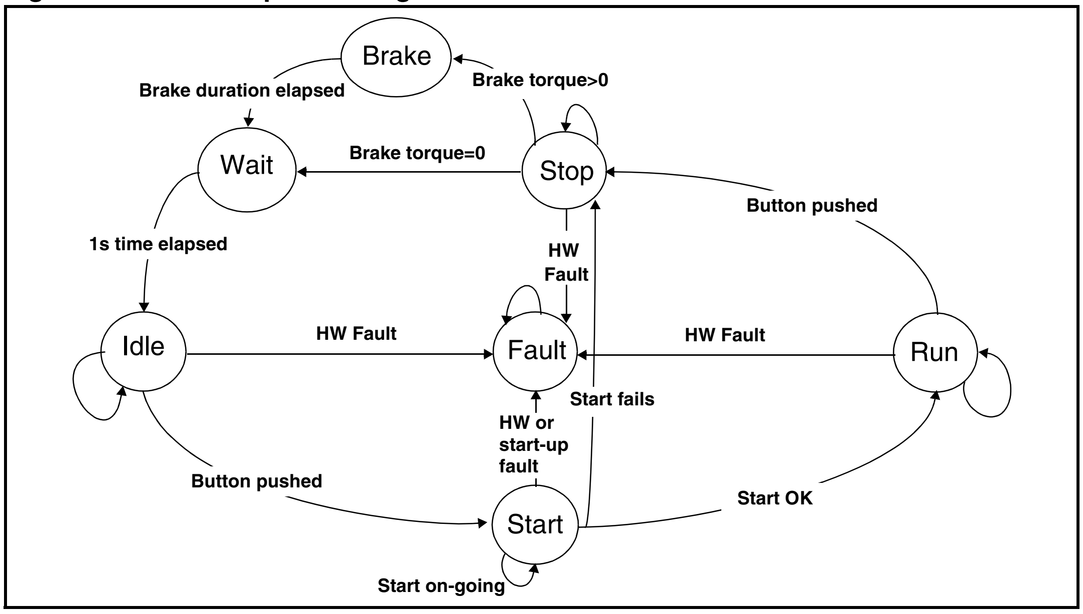
Any of these three conditions will cause the PWM to be stopped and the state machine to go in the FAULT trap state (meaning that a hardware reset is needed to re-start the motor).

The following sections detail the particularities of these controls, located in two functions:

```
void DoMotorControl(void)
```

```
SystStatus_t StartMotor(void)
```

Figure 38. Main loop state diagram



5.1 Open loop

This program converts the RV1 and RV2 trimmer readings (channels AIN13 and AIN12) into stator frequency settings (10.0 to 265.0 Hz) and voltage (0 to 255 modulation index) respectively. See flowchart on *A.1.11 on page 99* for details.

These parameters are taken into account at start-up, then modified in real time every time the main loop is executed.

It must be noted that the voltage on the motor is limited by the V/f curve defined by default; you have the choice to:

- scan the whole voltage domain below the V/f curve by modifying both RV2 and RV1, to characterize the motor for instance,
- set RV2 to its maximum value, and then run the motor following the V/f curve, just modifying the speed (stator frequency) with RV1.

Since no tests are performed on the stator frequency, RV1 trimmer should be set at a low value during the start-up to limit the inrush current in the motor. Then, it must be modified smoothly to avoid:

- entering the unstable working domain of the AC motor, which will cause it to stop,
- entering the generator domain if the slip is negative (stator frequency below rotor frequency).

However, a variation rate limitation is implemented, to limit the frequency variation to +/- 5Hz per second and the voltage variation to +/- 50 per second. This slew rate is set-up in the `ACM_SoftStartOL` function, using `ART_Set_TimeInMs(SLEW_LIMIT)`. The `SLEW_LIMIT` constant is defined to 20ms at the beginning of the acmotor.c file (which gives 1s/20ms=50).

Note: By default, a tachogenerator is available in the system (the function MTC_GetSlip is used to avoid if possible any operation with negative slip). This is convenient for demo purposes with the SELNI motor and during incremental system build (see Section 6.2). For an application *without any sensors available, all functions related to speed feedback processing (at the sole exception of the capture interrupt service routine) will be automatically be removed by the linker if not used.*

5.2 Closed loop

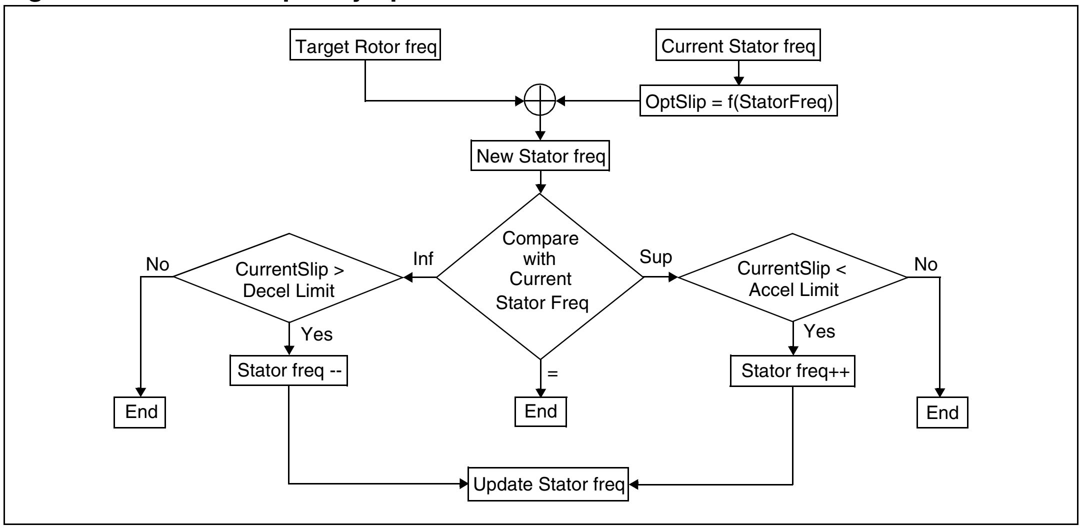
In this mode, the RV1 trimmer is read on channel AIN13 to set the target rotational frequency. Optionally, the RV2 and RV3 trimmers can be used to set the Kp and Ki parameters on the fly. *PI regulator implementation and tuning on page 62*.

The speed regulation is achieved using a closed loop slip control. Actually, only the voltage is controlled by the regulator to maintain a constant slip during the motor operation: see *Figure 31 on page 68*. This regulation loop is executed in the `DoMotorControl` function every 10ms, as defined by the `SAMPLING_TIME` parameter set in ACMparam.h (see *l on page 63*).

It must be noted that the rotor frequency is measured every time this function is called, independently from the regulation sampling time; if the returned rotor frequency is zero, the motor is considered to be stalled and the state machine will enter the FAULT state, requiring a hardware reset to be exited (see state diagram on *Figure 38. on page 81*).

In parallel with the voltage regulation, the stator frequency is modified in open loop, as represented on the flow chart on *Figure 39*

Figure 39. Stator frequency update



During closed loop operations, the slip frequency is continuously monitored to be maintained between two limits, to be entered with 0.1Hz unit.

- **Maximum Slip (acceleration limit)**

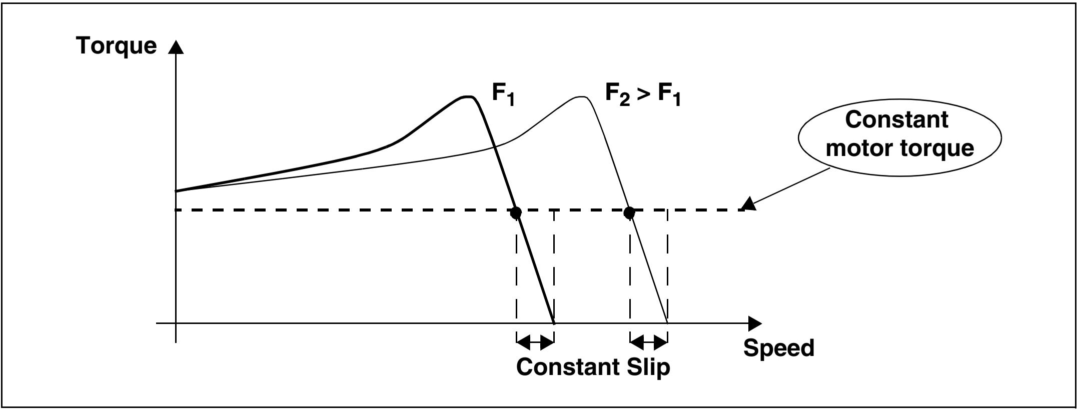
This threshold is here to avoid the motor entering its unstable working domain in case of excessive torque request: this will cause it to stall. If this limit is exceeded (`ACCEL_SLIP_LIMIT` define, set in Mainparam.h header file), the stator frequency will not being increased any further.

This may occur in the following cases:

- the desired acceleration rate exceeds the gain / bandwidth capabilities of the regulation algorithm and/or motor torque capabilities,
- the resistive torque exceeds maximum motor ratings.

It is worth noting that this feature allows a torque control mechanism during speed ramp-up, assuming that torque is a function of the slip, in the first order: see *Figure 40*

Figure 40. Controlled slip during acceleration provides torque control



- **Minimum slip (deceleration limit)**

This limit is here to avoid re-generative currents that are produced when the stator frequency goes below the rotor rotational frequency, during a deceleration for instance.

If this limit is exceeded (`DECEL_SLIP_LIMIT` define, set in Mainparam.h header file), the stator frequency will not be decreased any further.

5.3 Using the serial communication interface

The serial communication interface is not enabled by default. To use it, one must edit a define in the config.h file (`#define ENABLE_RS232`, see *Section 3.2 on page 12*). Once this is done, the following parameters are transmitted continuously on the Tx pin, depending on the mode:

- Open Loop mode

  The stator frequency is sent, with 0.1Hz unit (Freq=125 corresponds to 12.5Hz), as well as the voltage modulation index (8-bit value, Volt=255 corresponds to full voltage). This is convenient to know exactly the value set with the trimmers.
- Closed Loop mode

  The speed command is send, with 0.1Hz unit (S= 568 means a speed target of 56.8Hz rotational frequency), to get the value read on the trimmer which set the speed. If the `PI_PARAM_TUNING` key is defined in the config.h file, the K_i and K_p parameters are also transmitted.

Note: The interval between two frames in not constant: data transmission is restarted during the main loop if the previous frame is completed, giving some jitter equal to the main loop duration.

5.4 Mainparam.h file description

Mainparam.h contains some application/demo specific features, subject to change during run-time (depending on the target speed for instance).

5.4.1 Start-up parameters

In this section, parameters for both closed and open loop demos are grouped together. See *Section on page 68* for details.

```
#define START_VOLTAGE ((u8)30); //Open Loop only

#define START_FREQ ((u16)150)// Open & Closed Loop

#define MIN_START_FREQ ((u16)100) // Closed Loop only, resolution:
0.1Hz
```

5.4.2 Brake parameters

Two out of the four brake parameters are defined in this section: the duty cycle (defining the braking torque) and the duration. They may be modified in the application depending on the current stator frequency and conditions (for emergency brake or normal deceleration).

When adjusting these parameters, attention must be paid to thermal and over-current limitations if the braking phase is too long and/or with too high current.

```
#define BRAKE_DUTY_CYCLE ((u16)64)

#define BRAKE_DURATION ((u16)3000)
```

The remaining parameters are discussed in the *Brake on page 45*.

5.4.3 Closed-loop slip control

These values are necessary during speed variations (see *Section 5.2*) and may vary during run-time to adjust for instance the maximum torque during ramp-up.

```
#define ACCEL_SLIP_LIMIT ((u16)100)

#define DECEL_SLIP_LIMIT ((u16)10)
```

6 Designing your application with the library

6.1 Library maintenance

Once the tools and demo programs have been successfully run, you will have to integrate this library in your own design. Some modules will be used as they are, others will have to be completed and some will have to be created.

Before starting this process, two important points must be considered to benefit from:

- updates (various improvements, new modules or modulation methods, etc.)
- STMicroelectronics assistance and support on tools and/or application software (even though source codes and flowcharts are provided to make customization and in depth library understanding as easy and clear as possible).

You should follow the recommendations listed below in order to benefit from the latest library upgrades (by simply replacing existing modules with the new ones without any source level modifications):

- Try not to modify mtc.c and acmotor.c modules. These modules can be almost completely customized in the MTCparam.h and ACMparam.h header files (see *Table 4* for other modules). If you edit mtc.c and acmotor.c , carefully trace all modifications in order to ease STMicroelectronics' support and follow future upgrades of the library.
- Try to maintain existing function interfaces; create new functions if the existing ones are not convenient. The linker will remove unused functions at link time.
- A modular approach should be used as often as possible.
- Use functions such as ACM_SustainSpeed as an example, and implement modified versions outside source modules if they do not fit your application.

The following matrix (*Table 4*) describes the module classification for customization:

- Class A: Code inside the module can be removed and modified
- Class B: Code can be added to a module. Existing functions, define statements and constants should nevertheless be maintained for upward compatibility,
- Class C: Code must not be modified (Motor control software library core modules, header files maintained by ST, such as *ST7FMC2N6.h* file).

Table 4. Module classification (cf. above text for explanations on A, B, C classes)

Module Name	acmotor.c & .h	mtc.c & .h	adc.c & .h	sci.c & .h	ST7_Misc.c	pwmart.c & .h	ports.c & .h	main.c	MTCparam.h	ACMparam.h	Mainparam.h	config.h	lib.h	mtc_bits.h	ST7FMC2N6.h
A								x							
B			x	x	x	x	x		x	x	x	x	x	x	
C	x	x													x

6.2 Incremental system build

The methodology below should be considered only as a set of guidelines which can be followed when developing the final application (hardware and firmware), to minimize the development time and to progressively gain confidence in both:

- the newly implemented software modules
- the various part of a hardware motor drive design.

All the steps here-below described can be managed either with trimmers/push-buttons or with the help of the ST7MC Control panel.

This methodology does not supersede standard software development processes or hardware qualification procedures.

6.2.1 Preliminary notice on debugging tools

Low voltage applications (below 30V)

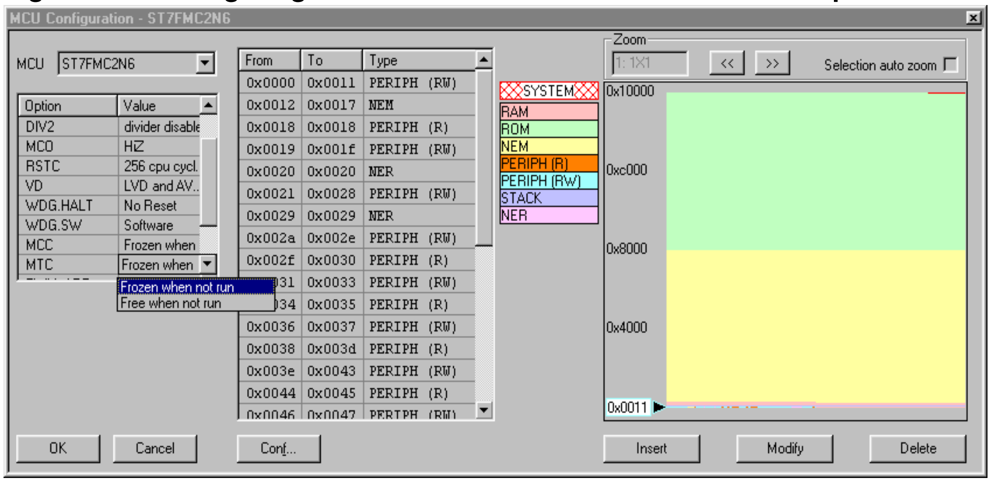
For these voltage levels, the real-time emulator can be connected in the application, taking care to connect the protective boards provided with the MDT50 emulator (refer to the emulator datasheet for details). It offers trace and advanced breakpoints capabilities, as well as the possibility to automatically disable the PWM outputs on a breakpoint to avoid any DC current injection in the motor (see *Figure 41*).

This emulator is delivered with a set of three boards to protect some of the motor control dedicated I/Os from voltages greater than 5V. It is highly recommended to have them connected during the development. A neutral board is also provided in case the protection network's impedance (1K series resistor plus 5V3 zener diode) is an issue for the application. Refer to ST7MDT50-EMU3 Probe user guide section 3.1 for details.

An In-Circuit Debugging tool can also be directly connected, as long as an ICC connector is available on the application.

Caution: When using ICD, during a breakpoint, the clock circuitry is not disabled: a permanent DC current may flow in the motor is the PWM outputs are enabled. It is thus recommended to use a power supply with fast current limitation capabilities or if possible to disable the PWM outputs (by inserting MTC_DisableMCOutputs function) before the breakpoint.

Figure 41. Configuring the Motor Controller clock state on breakpoint with MDT50



MCU Configuration - ST7FMC2N6

MCU: ST7FMC2N6

Option	Value
DIV2	divider disable
MCO	HiZ
RSTC	256 cpu cycl.
VD	LVD and AV..
WDG.HALT	No Reset
WDG.SW	Software
MCC	Frozen when
MTC	Frozen when

Frozen when not run
Free when not run

From	To	Type
0x0000	0x0011	PERIPH (RW)
0x0012	0x0017	NEM
0x0018	0x0018	PERIPH (R)
0x0019	0x001f	PERIPH (RW)
0x0020	0x0020	NER
0x0021	0x0028	PERIPH (RW)
0x0029	0x0029	NER
0x002a	0x002e	PERIPH (RW)
0x002f	0x0030	PERIPH (R)
31	0x0033	PERIPH (RW)
34	0x0035	PERIPH (R)
0x0036	0x0037	PERIPH (RW)
0x0038	0x003d	PERIPH (R)
0x003e	0x0043	PERIPH (RW)
0x0044	0x0045	PERIPH (R)
0x0046	0x0047	PERIPH (RW)

Medium-high voltage application (above 30V)

Here, use of the real-time emulator is not recommended, even if protective boards are inserted.

Warning: In case of high voltage applications connected on the mains, the application ground may be at a dangerous voltage; as would the MDT50 emulator (the protective boards do not provide galvanic isolation).

For voltages above 30V, it is highly recommended to use only programmed devices. ICD debugging can be used in conjunction with an ICC isolation board, as the one provided with the ST7MC-KIT/BLDC starter kit, but the limitations mentioned in *Section* nevertheless applies, and are even emphasized by the high voltage levels.

Good practice for real-time applications debugging is to use "diagnostic tools" such as:

- RS232 communication (refer to *Section 5.3 on page 83*), which can be easily isolated,
- Stand alone DAC (serial SPI-based model for instance) to be able to monitor signals on an oscilloscope,
- debug outputs of the ST7MC itself (MCDEM and MCZEM pins), to monitor the U and C events (refer to datasheet for details).

Refer to AN438 (Safety Precautions for Development Tool Triac + Microcontroller) for further details when working on the mains.

6.2.2 Build step1: open loop, low voltage, no motor connected

In these conditions, some functions not related to motor control can be tested and debugged (such as serial communication, some analog measurements,...).

Supplying only the MCU and the gate drivers (if any), one can verify that the PWM signals are present on the MCOx outputs, on the MOSFET/IGBT gates, with no voltage applied on the inverter. This can be tested either with the standalone demo program, using push-button and trimmers to start the motor control tasks, or using the ST7MC control Panel.

If the signals are correct, a low voltage can be applied on the inverter power stage (<30V) to verify the signal on the central point of the half-bridges and the expected shape of the motor current by low-pass filtering the PWM modulated signals. Sine wave voltage can be displayed on an oscilloscope using a RC network (10K / 22nF for instance for 12kHz PWM frequency).

It is recommended to restart from this first step every time a major modification is done on either the hardware or the software part of a design.

6.2.3 Build step2: open loop, rated voltage/power, motor connected

With the trimmers or the ST7MC control Panel, scan the whole motor (and inverter) working domain, at increasing voltage levels (or increasing current levels for low voltage applications):

- verify that the inverter is running fine and gain confidence in the power stage,
- verify that the electronics are able to deliver the rated power (this power level is independent from any speed regulation and will not be increased when implementing the closed loop control),
- verify that the motor is able to deliver the maximum expected torque in the application.

Good practice for applications connected to the mains is to verify these parameters taking into account the voltage variations (for instance $230V_{rms}$ +15/-10% imposes a $207\text{-}264V_{rms}$ operating range for the drive).

The DC braking functionality can also be tested and the braking torque set-up during this phase.

Caution: During this phase, nothing prevents the stator frequency going below the rotor frequency. It is therefore necessary to pay attention to avoid reactive current generation when modifying the stator frequency (*MTC_UpdateSine on page 31* for details).

6.2.4 Build step3: open loop, rated power, motor connected with speed feedback

If the motor has a speed sensor, one can verify that the speed feedback processing is correctly set-up (returned rotor frequency should be close to stator frequency). This must be done in the worst case conditions (from EMI point of view):

- maximum voltage or current (for instance mains supply +15%)
- at null voltage modulation index (variable voltage = 0): this will lead to synchronous 50% duty cycle PWM signals on each of the three half-bridges and therefore synchronous dV/dt transients, resulting in very high conducted EMIs when charging/discharging the three motor’s stray capacitance.

This will avoid doubts on the speed measurement reliability during the further development steps.

At that time, it is also convenient to evaluate the quality of speed feedback in very stable speed conditions (such as no-load or on a dynamo meter): any variation on the speed sensor feedback which may appear will either reflect the sensor’s mechanical dissymmetry or add errors induced by electrical noise to the tachogenerator signal. These effects will help in knowing if speed averaging is necessary, and on how much information the rolling average must be done.

The minimum reliable speed feedback can also be measured during this build step (at low speed, tacho generator signal is very low and may not be properly amplified by the conditioning stage.

Finally, on a motor bench, with a static brake and a dynamo meter, the optimum slip versus speed characteristic can be easily characterized if needed.

6.2.5 Build step4: closed loop operation

Start the motor with the PI controller disabled (K_p=K_i=0) and then close the loop by starting to tune the PI algorithm, following the procedure described in *Section on page 62*.

From this point, it is then more or less mandatory to work on the final application's load.

Having these 4 steps completed successfully will give full confidence on the motor control modules when integrating the motor control library within the complete application.

6.3 Motor control related CPU load in the application

6.3.1 Estimation

The CPU load consumption induced by the motor control comes from three tasks mainly, listed below.

- Sine wave generation

  This is the main source of work for the CPU and it is done in interrupts (MTC_U_CL_SO_IT) at a fixed rate: the related value is thus constant whatever the sine wave frequency or voltage; calculation is discussed in *Section on page 42*.
- Speed feedback processing

  This is also done in interrupt (MTC_C_D_IT), at a rate proportional to the motor speed. For instance, taking the SELNI motor (with 8-poles tachogenerator) running at 20000RPM (highest speed), this gives:
  - 20000RPM / 60 = 333.3Hz rotational frequency
  - 333.3Hz x 8 = 2666.6Hz tacho frequency and 375µs tacho period

Thus the tacho related CPU load is 22µs/375µs = 5.8% (i.e. interrupt duration/tacho period).

- PI regulator

  This term includes the ACM_SlipRegulation and the MTC_UpdateSine functions (respectively 2.7ms and 630µs) and takes into account the 20% of CPU spent for sine generation: this should be remembered when calculating the total load.

  This contribution is inversely proportional to the sampling time of the PI regulator.

  For instance, if $T_{sampling}$ = 20ms, this will lead to:

  (2.7+0.63) / 20 =13.5%.
- Total CPU load

  Here below is an example for a SELNI motor running at 10000RPM:

  Total CPU load = 13.5% (PI) + (1-13.5%) x 21.3% (sine) + 2.9% (tacho) = 35%.

Note: For open loop applications, CPU load is constant and sine wave generation is the only parameter to be taken into account.

6.3.2 Adjustment guidelines

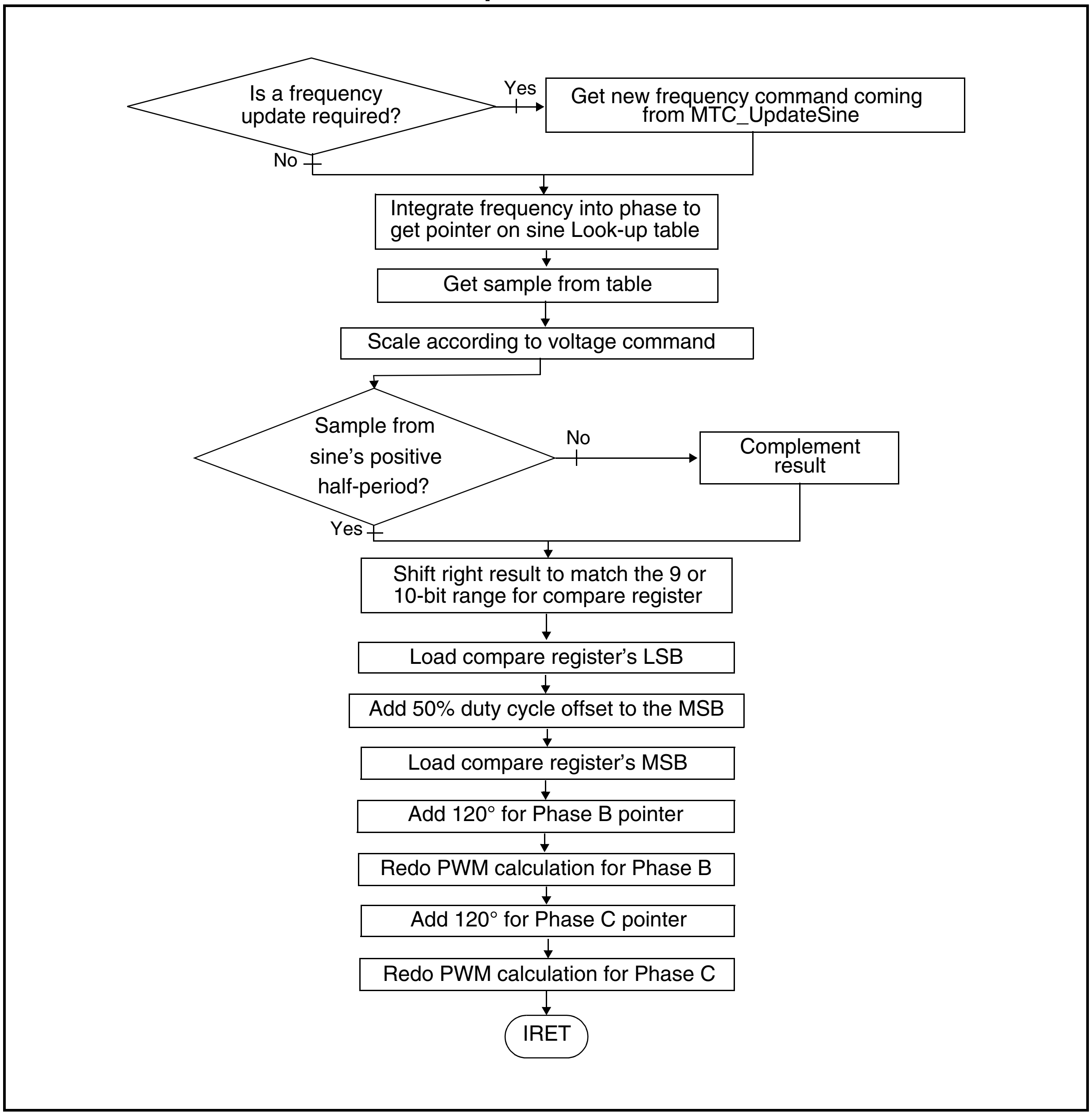
Besides adjusting the CPU load related to the sine wave generation, one can adjust several parameters to speed things up if this is necessary.

- the PI regulator can be re-written using 16-bit arithmetic rather than 32-bit.
- the T_S sampling time can be increased (at high speed particularly if inertia is high).
- the conversion from rotor period to rotor frequency takes more than 500µs. One could use the period for speed measurement and regulation, instead of rotor frequency. This would save 16-bit division (but has the disadvantage of imposing management of non-linear speed characteristics in 1/x form).

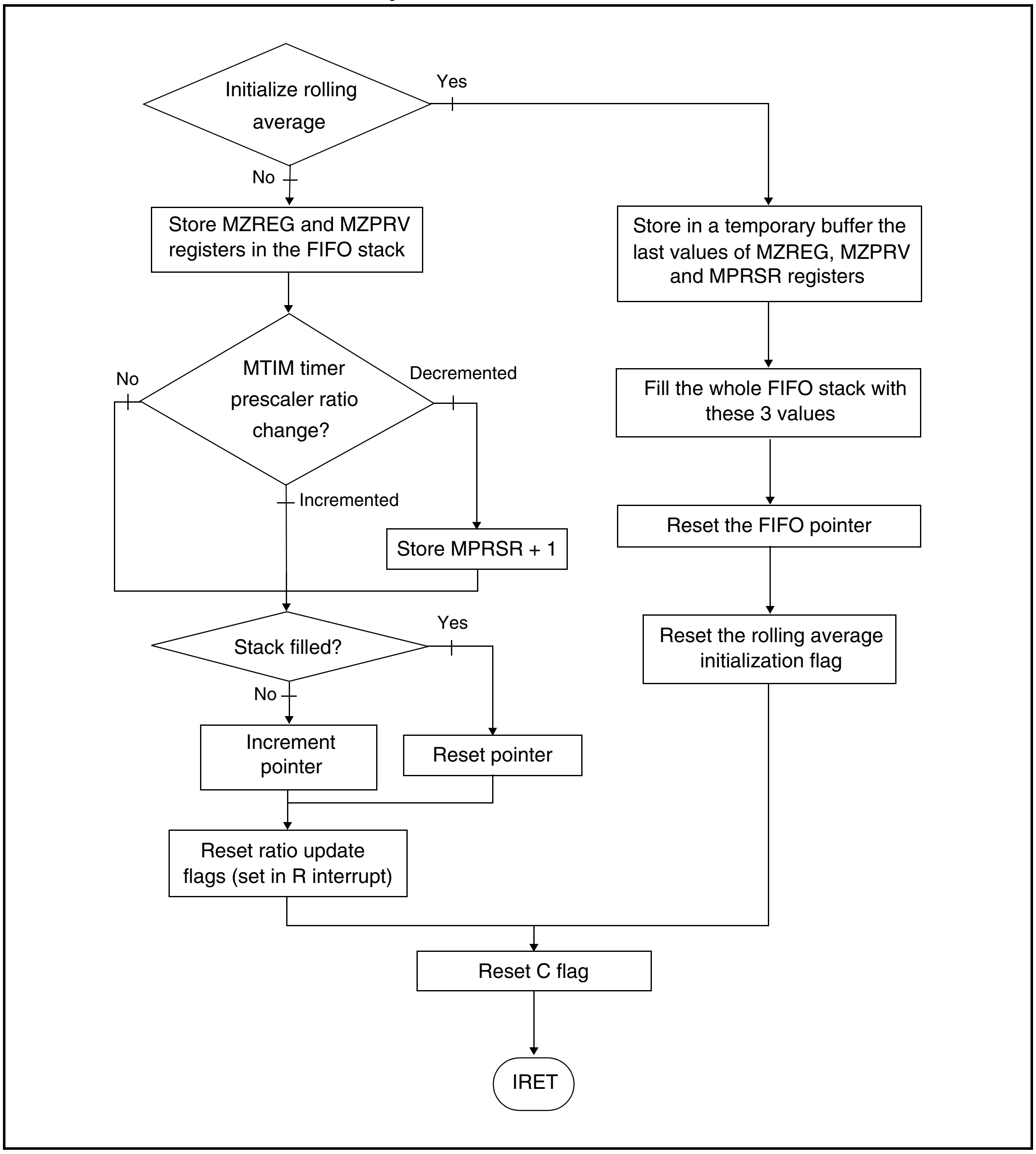
Appendix A Appendix

A.1 Flowcharts

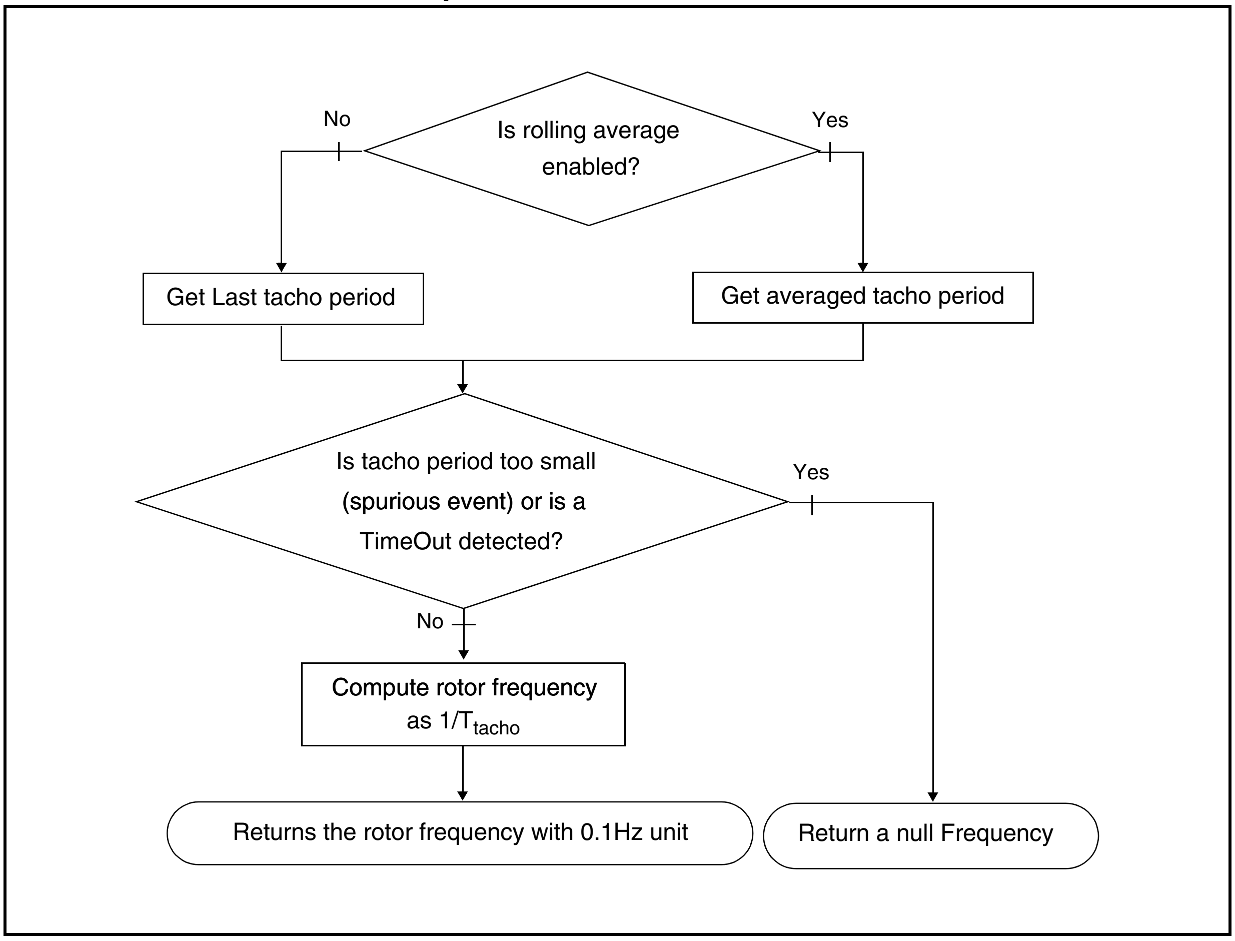
A.1.1 MTC_U_CL_SO_IT interrupt routine


Is a frequency update required?
Yes
Get new frequency command coming from MTC_UpdateSine
No
Integrate frequency into phase to get pointer on sine Look-up table
Get sample from table
Scale according to voltage command
Sample from sine's positive half-period?
No
Complement result
Yes
Shift right result to match the 9 or 10-bit range for compare register
Load compare register's LSB
Add 50% duty cycle offset to the MSB
Load compare register's MSB
Add 120° for Phase B pointer
Redo PWM calculation for Phase B
Add 120° for Phase C pointer
Redo PWM calculation for Phase C
IRET

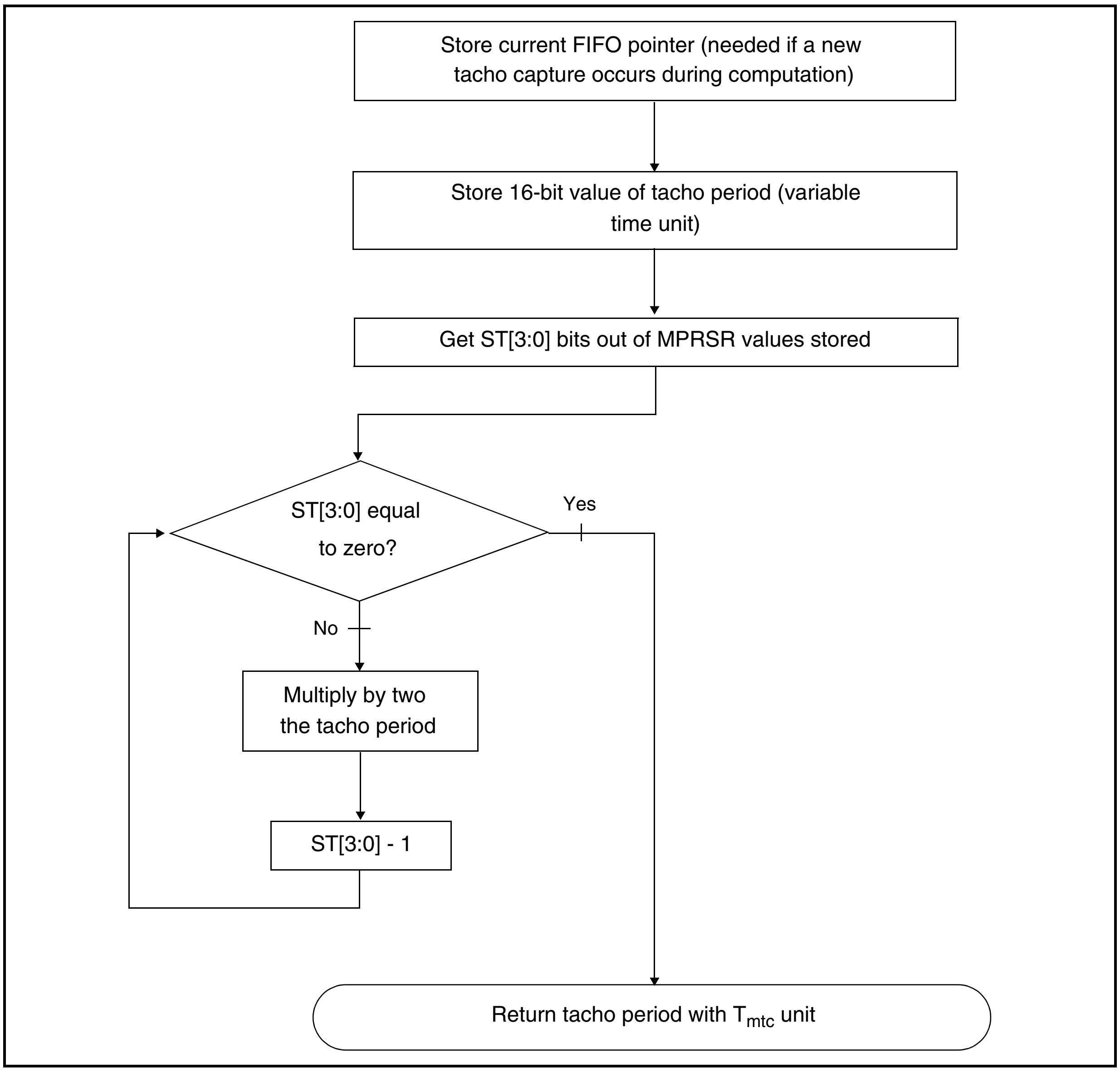
A.1.2 MTC_C_D_IT interrupt routine


Initialize rolling average
Yes
No
Store MZREG and MZPRV registers in the FIFO stack
Store in a temporary buffer the last values of MZREG, MZPRV and MPRSR registers
MTIM timer prescaler ratio change?
No
Decremented
Incremented
Store MPRSR + 1
Fill the whole FIFO stack with these 3 values
Reset the FIFO pointer
Stack filled?
Yes
No
Increment pointer
Reset pointer
Reset the rolling average initialization flag
Reset ratio update flags (set in R interrupt)
Reset C flag
IRET

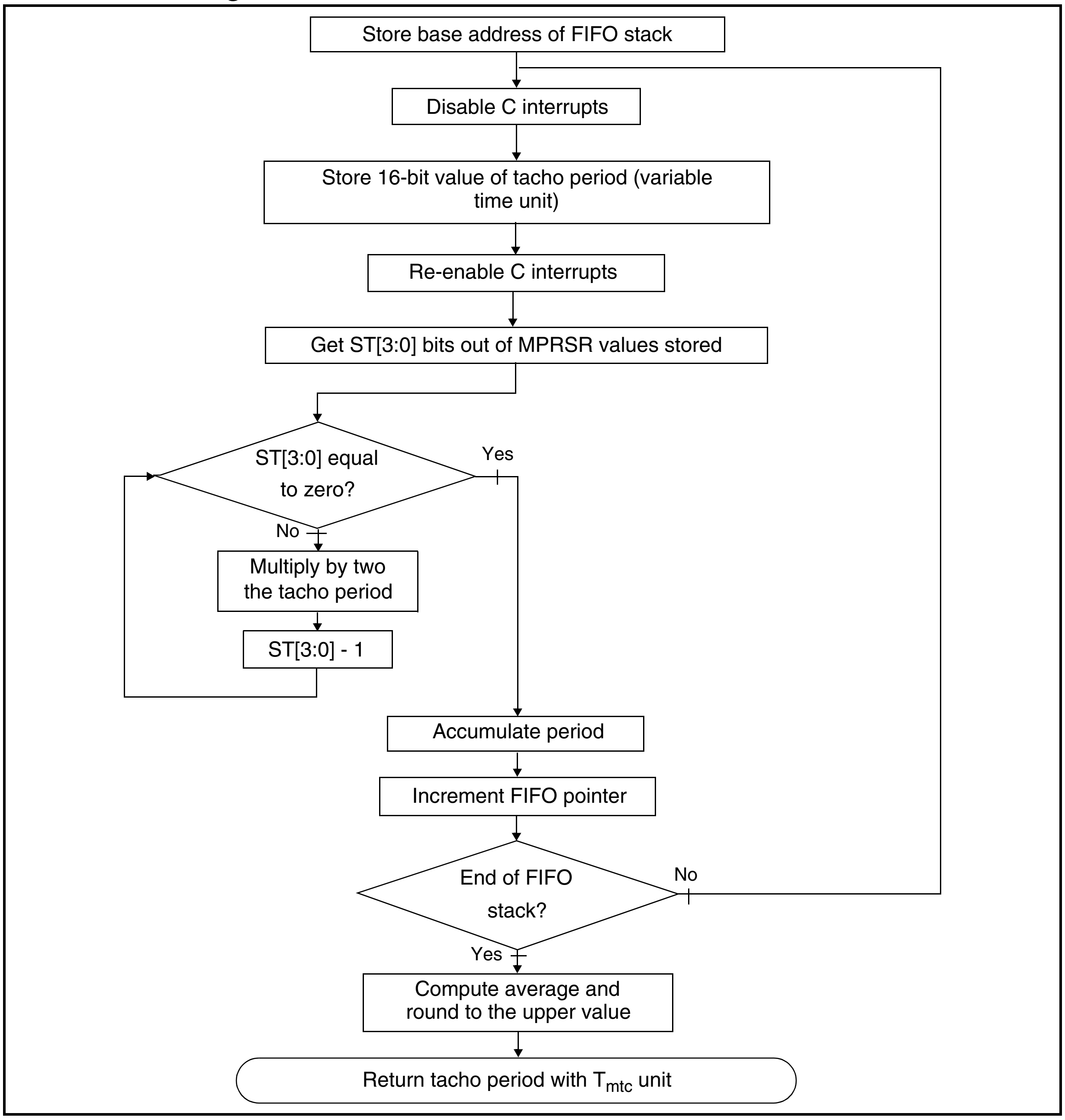
A.1.3 MTC_GetRotorFreq function


No
Is rolling average enabled?
Yes
Get Last tacho period
Get averaged tacho period
Is tacho period too small (spurious event) or is a TimeOut detected?
Yes
No
Compute rotor frequency as 1/T tacho
Returns the rotor frequency with 0.1Hz unit
Return a null Frequency

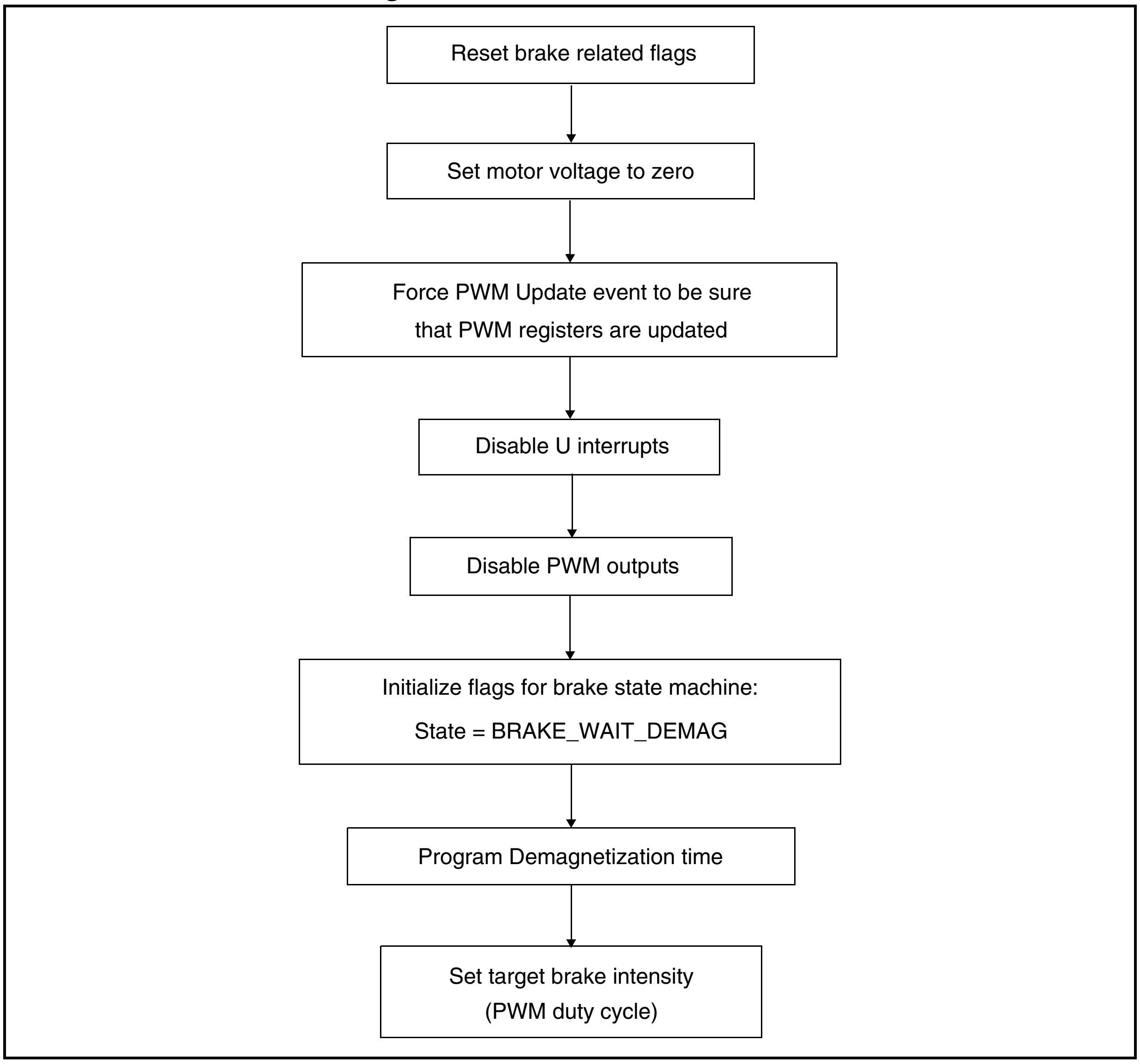
A.1.4 GetLastTachoPeriod function


Store current FIFO pointer (needed if a new tacho capture occurs during computation)
Store 16-bit value of tacho period (variable time unit)
Get ST[3:0] bits out of MPRSR values stored
ST[3:0] equal to zero?
Yes
No
Multiply by two the tacho period
ST[3:0] - 1
Return tacho period with T_{mtc} unit

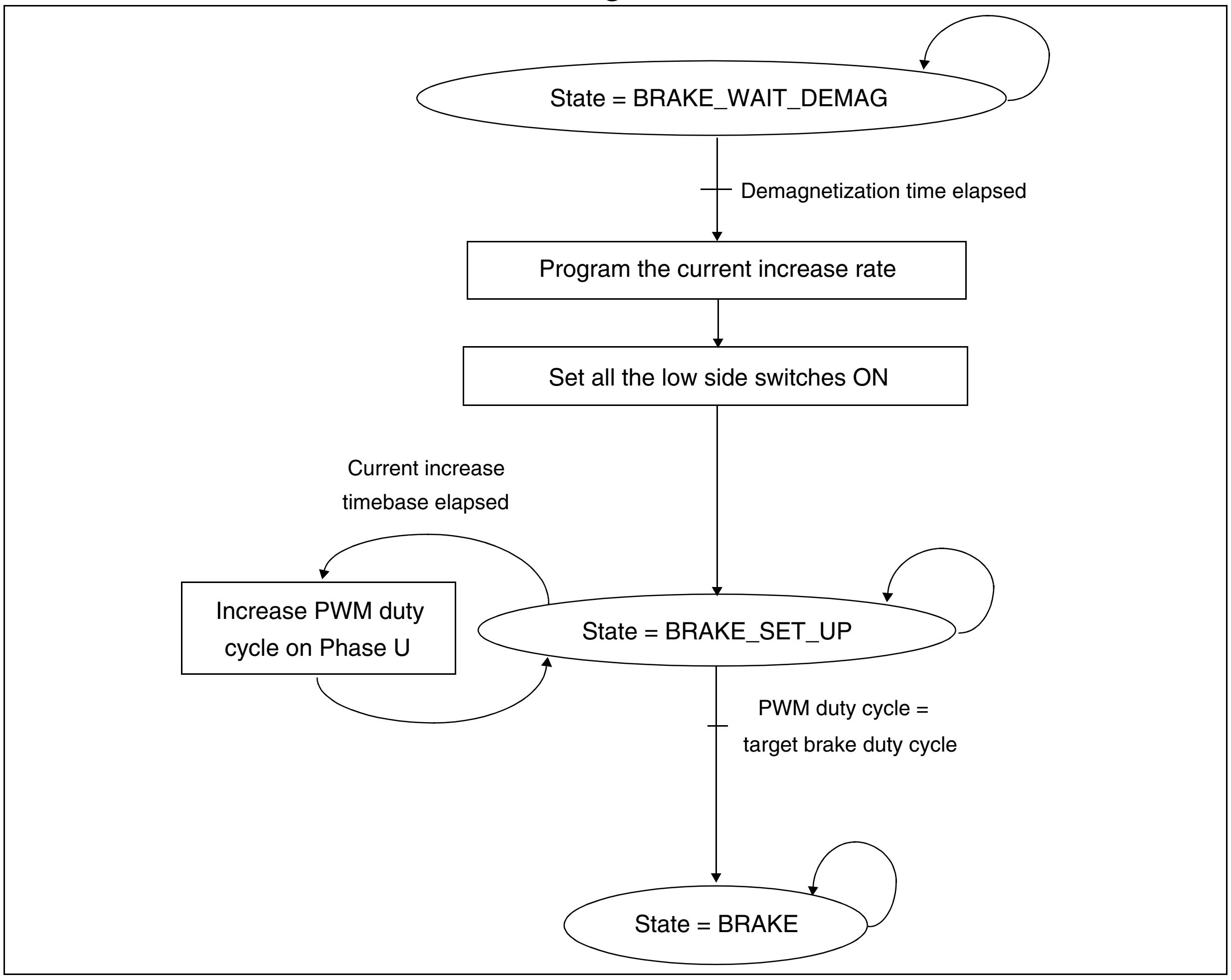
A.1.5 GetAvrgTachoPeriod function


Store base address of FIFO stack
Disable C interrupts
Store 16-bit value of tacho period (variable time unit)
Re-enable C interrupts
Get ST[3:0] bits out of MPRSR values stored
ST[3:0] equal to zero?
Yes
No
Multiply by two the tacho period
ST[3:0] - 1
Accumulate period
Increment FIFO pointer
End of FIFO stack?
No
Yes
Compute average and round to the upper value
Return tacho period with T_{mtc} unit

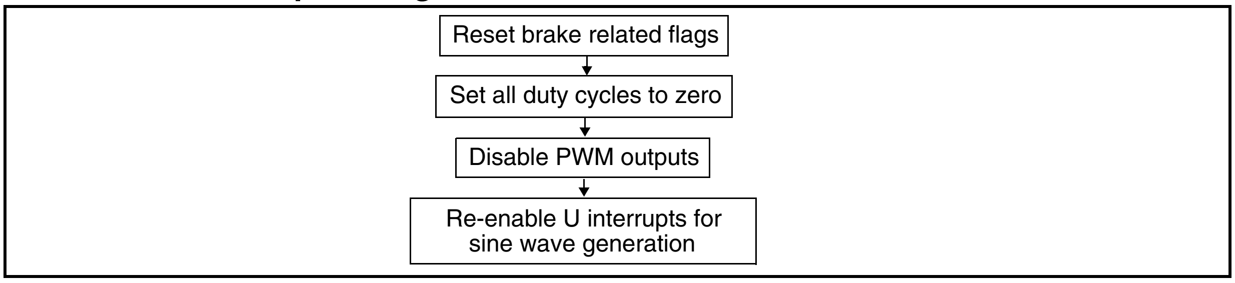
A.1.6 MTC_StartBraking function


Reset brake related flags
Set motor voltage to zero
Force PWM Update event to be sure that PWM registers are updated
Disable U interrupts
Disable PWM outputs
Initialize flags for brake state machine: State = BRAKE_WAIT_DEMAG
Program Demagnetization time
Set target brake intensity (PWM duty cycle)

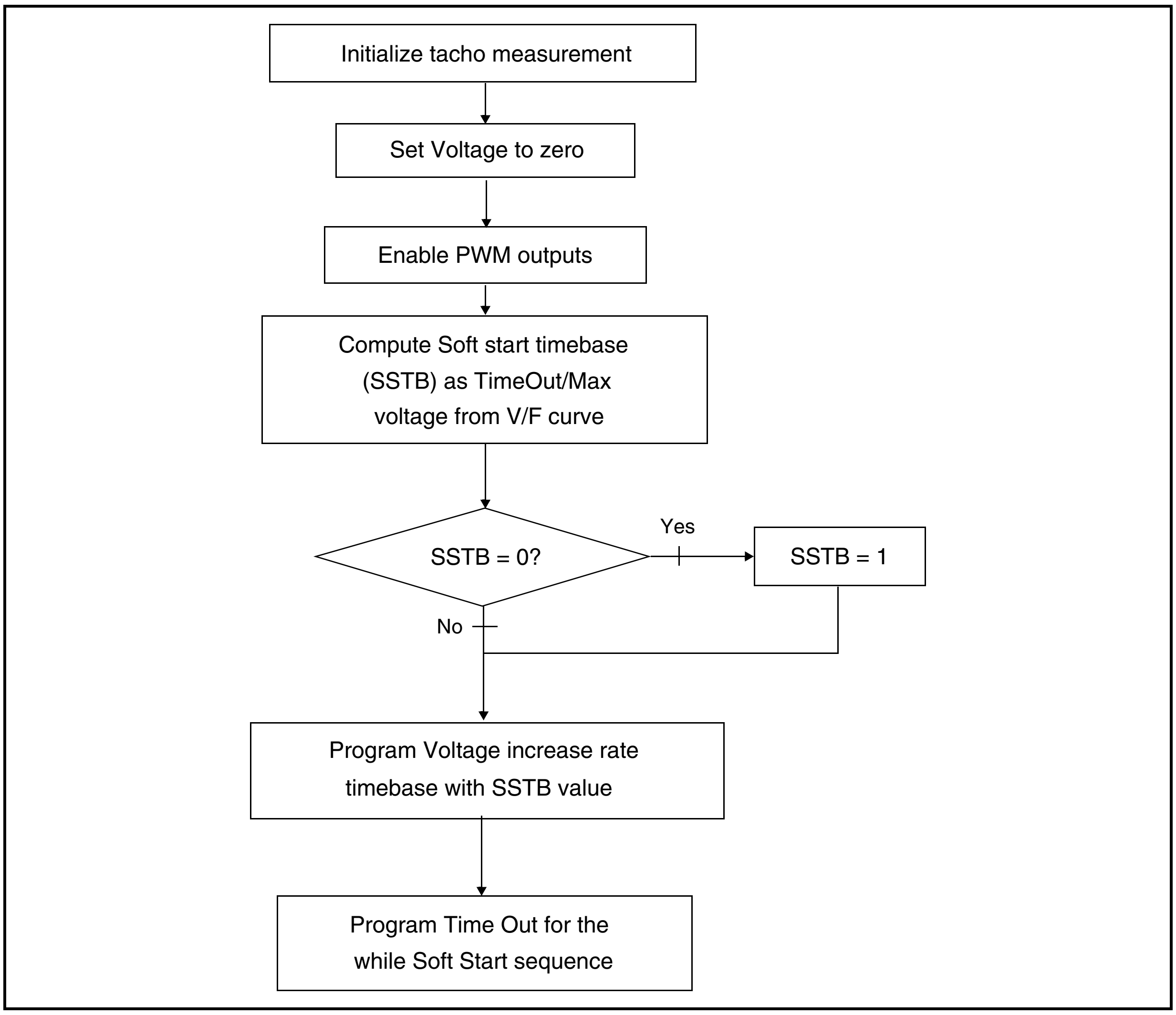
A.1.7 MTC_Brake function state diagram


State = BRAKE_WAIT_DEMAG
Demagnetization time elapsed
Program the current increase rate
Set all the low side switches ON
Current increase timebase elapsed
Increase PWM duty cycle on Phase U
State = BRAKE_SET_UP
PWM duty cycle = target brake duty cycle
State = BRAKE

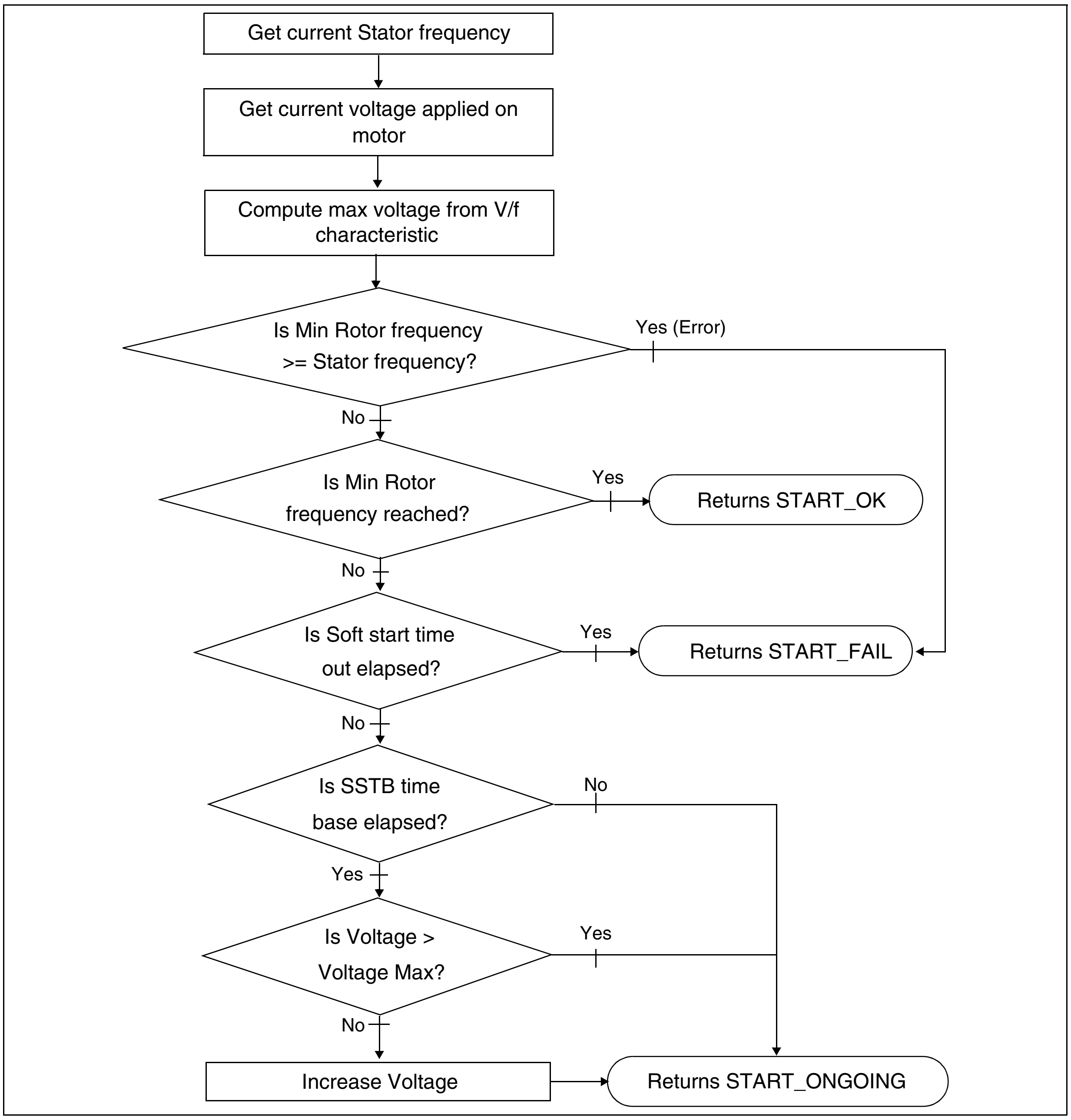
A.1.8 MTC_StopBraking function


Reset brake related flags
Set all duty cycles to zero
Disable PWM outputs
Re-enable U interrupts for sine wave generation

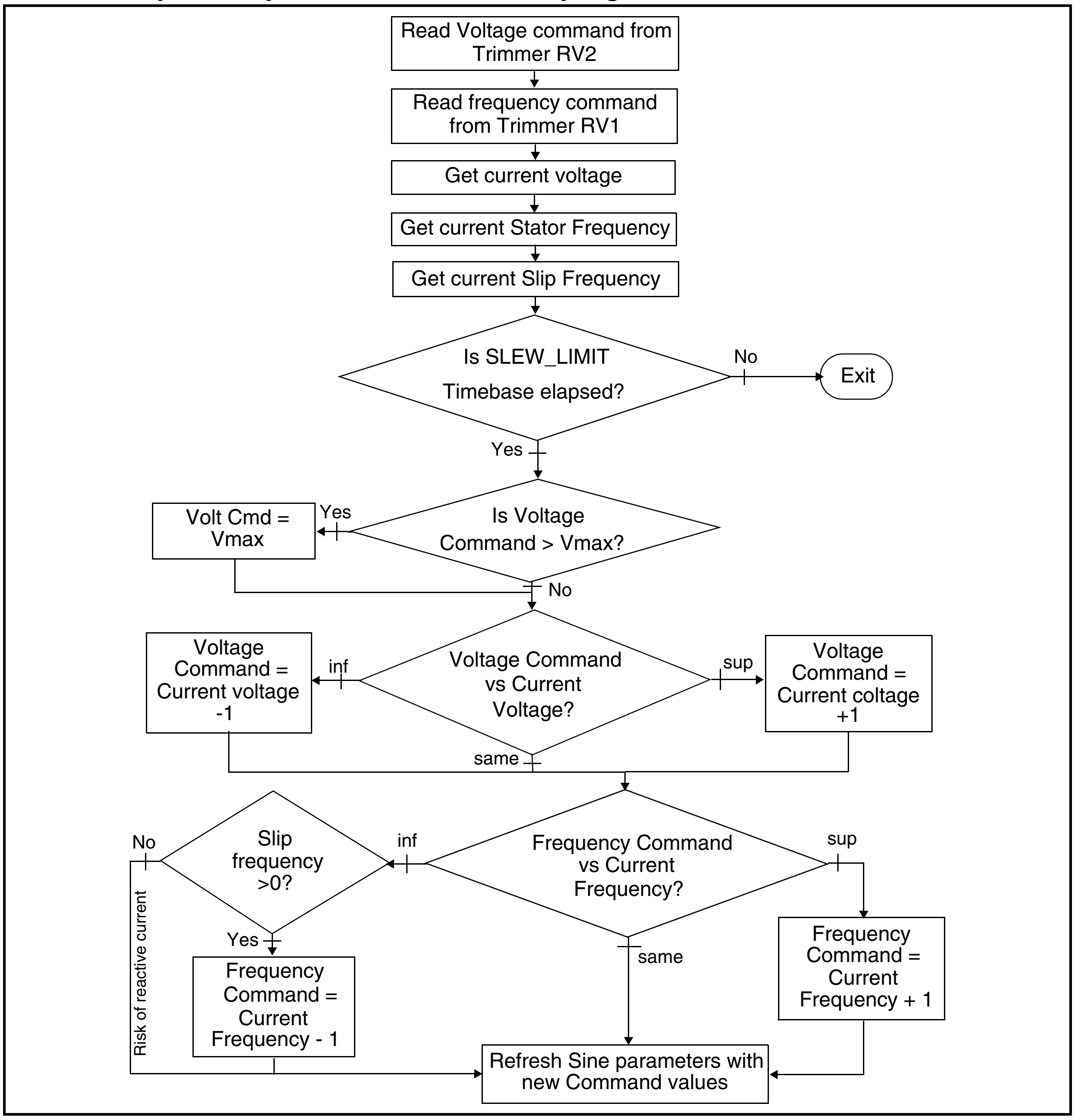
A.1.9 ACM_InitSoftStart function


Initialize tacho measurement
Set Voltage to zero
Enable PWM outputs
Compute Soft start timebase (SSTB) as TimeOut/Max voltage from V/F curve
SSTB = 0?
Yes
SSTB = 1
No
Program Voltage increase rate timebase with SSTB value
Program Time Out for the while Soft Start sequence

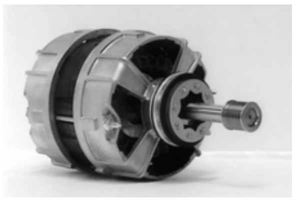
A.1.10 ACM_SoftStart function


Get current Stator frequency
Get current voltage applied on motor
Compute max voltage from V/f characteristic
Is Min Rotor frequency >= Stator frequency?
Yes (Error)
No
Is Min Rotor frequency reached?
Yes
Returns START_OK
No
Is Soft start time out elapsed?
Yes
Returns START_FAIL
No
Is SSTB time base elapsed?
No
Yes
Is Voltage > Voltage Max?
Yes
No
Increase Voltage
Returns START_ONGOING

A.1.11 Open Loop motor control demo program


Read Voltage command from Trimmer RV2
Read frequency command from Trimmer RV1
Get current voltage
Get current Stator Frequency
Get current Slip Frequency
Is SLEW_LIMIT Timebase elapsed?
No
Exit
Yes
Is Voltage Command > Vmax?
Yes
Volt Cmd = Vmax
No
Voltage Command vs Current Voltage?
inf
Voltage Command = Current voltage -1
sup
Voltage Command = Current coltage +1
same
Frequency Command vs Current Frequency?
inf
Slip frequency >0?
No
Risk of reactive current
Yes
Frequency Command = Current Frequency - 1
sup
Frequency Command = Current Frequency + 1
same
Refresh Sine parameters with new Command values

A.2 Selni motor characteristics



MANUFACTURER:

SELNI - NEVERS - FRANCE

MOTOR:

AHV 2-42-

MAIN CHARACTERISTICS:

MOTOR for WASHING MACHINES

Phase to phase voltage:	0 to 190 V or 0 to 250V
Frequency (F):	0 to 340 Hz
Insulation Class:	F
Geometry:	drawing 10102
Speed ratio (belt):	10 to 16
Speed:	0 to 20000 RPM

Special characteristics:

Stack Thickness:	42 mm
Stator ref.:	drawing 10230
Stator lamination ref.:	21760 (24 slots)
Winding:	2 poles, embedded, real poles
	R= 3,5 Ω ± 5% ph to ph. at 23°C
Without thermal protector	
Rotor ref.:	drawing 10207T01
Rotor lamination ref.:	27525 (28 slots)
Tacho Generator:	Electromagnet T 31 (2*8 poles)
Optimum slip:	From 3 Hz at low Frequencies to 8 HZ at high Frequencies
Maximum Torque:	2 to 3 Nm at low speed
Maximal slip:	For F ≤ 5 Hz ⇒ 5 Hz
	13 Hz ⇒ 5 Hz 25 Hz ⇒16 Hz
	200 Hz ⇒28 Hz 340 Hz ⇒35 Hz

7 Revision history

Table 5. Document revision history

Date	Revision	Changes
24-Jan-2006	1	Initial release.
21-Jun-2007	2	Added watermark referring to obsolete products.
10-Jul-2007	3	Removed reference to obsolete products.