

BLDC Motor with Quadrature Encoder and Speed Closed Loop, Driven by eTPU on MCF523x

Covers MCF523x and all eTPU-equipped Devices

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This application note describes the design of a 3-phase brushless DC (BLDC) motor drive based on Freescale's ColdFire MCF523x microprocessor. The application design takes advantage of the enhanced time processing unit (eTPU) module, which is used as a motor control co-processor. The eTPU handles the motor control processing (excluding commutation processing), eliminating the microprocessor overhead for other duties.

BLDC motors are very popular in a wide array of applications. Compared to a DC motor, the BLDC motor uses an electric commutator, replacing the mechanical commutator and making it more reliable than the DC motor. In BLDC motors, rotor magnets generate the rotor's magnetic flux, allowing BLDC motors to achieve higher efficiency. Therefore, BLDC motors may be used in high-end white goods (refrigerators, washing machines, dishwashers, etc.), high-end pumps, fans, and other appliances that require high reliability and efficiency.

The concept of the application is to create a speed-closed loop BLDC driver using a quadrature encoder. It serves as an example of a BLDC motor control system design

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using a Freescale microprocessor with the eTPU. It also illustrates the usage of dedicated motor control eTPU functions that are included in the DC motor control eTPU function set.

This application note also includes basic motor theory, system design concept, hardware implementation, and microprocessor and eTPU software design, including the FreeMASTER visualization tool.

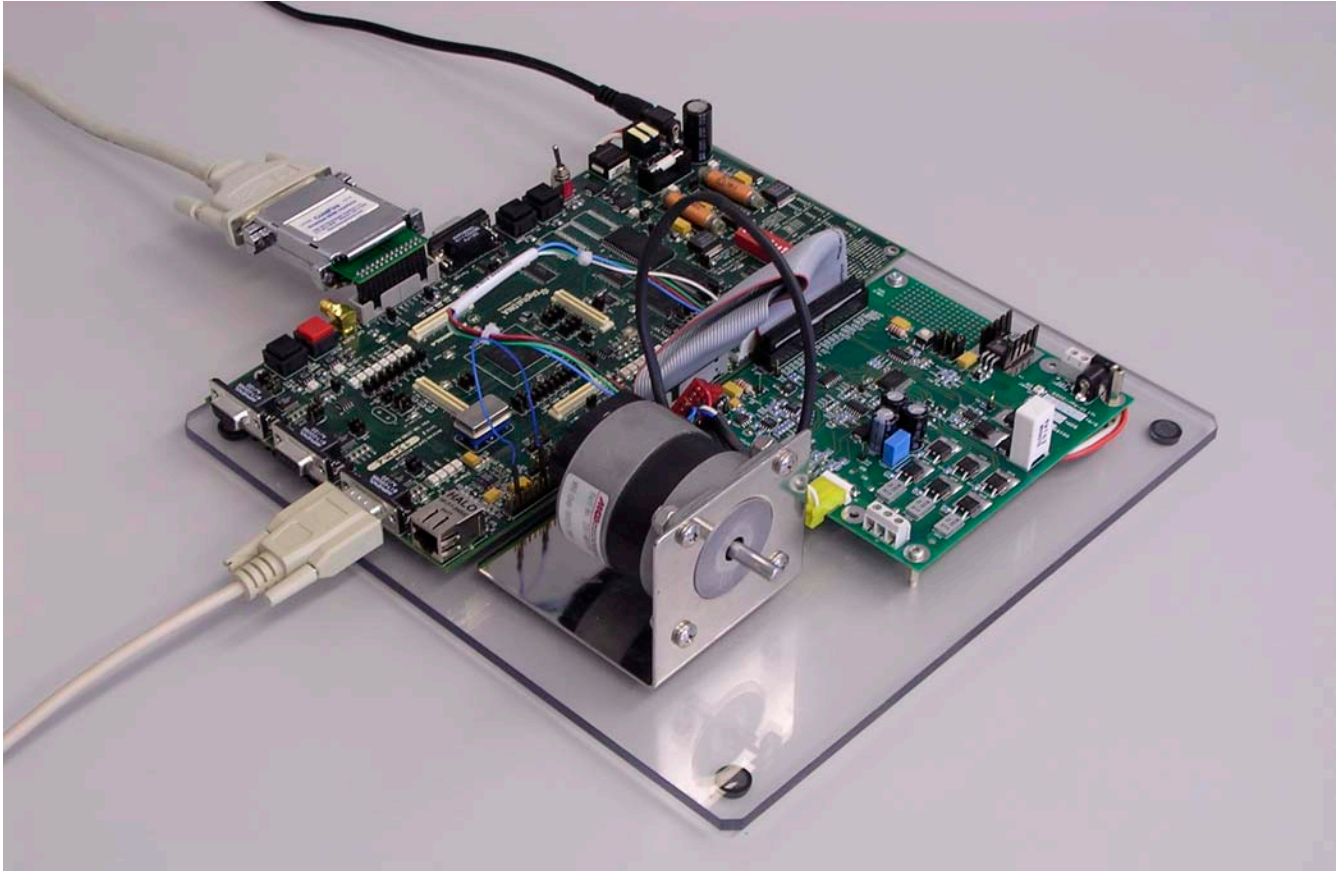


Figure 1. Using M523xEVB, 33395 Evaluation Motor Board, and MCG BLDC Motor

1 ColdFire MCF523x and eTPU Advantages and Features

1.1 ColdFire MCF523x Microprocessor

The MCF523x is a family of highly-integrated, 32-bit microprocessors based on the V2 ColdFire core. It features a 16- or 32-channel eTPU, 64 Kbytes of internal SRAM, a 2-bank SDRAM controller, four 32-bit timers with DMA request capability, a 4-channel DMA controller, up to two CAN modules, three UARTs, and a queued SPI. The MCF523x family has been designed for general purpose industrial control applications. It is also a high-performance upgrade for users of the MC68332.

This 32-bit device is based on the version 2 ColdFire reduced instruction set computer (RISC) core, operating at a core frequency of up to 150 MHz and a bus frequency of up to 75 MHz. On-chip modules include the following:

- V2 ColdFire core with an enhanced multiply-accumulate unit (EMAC) providing 144 Dhrystone 2.1MIPS @ 150 MHz
- eTPU with 16 or 32 channels, 6 Kbytes of code memory, and 1.5 Kbytes of data memory with eTPU debug support
- 64 Kbytes of internal SRAM
- External bus speed of half the CPU operating frequency (75 MHz bus @ 150 MHz core)
- 10/100 Mbps bus-mastering Ethernet controller
- 8 Kbytes of configurable instruction/data cache
- Three universal asynchronous receiver/transmitters (UARTs) with DMA support
- Controller area network 2.0B (FlexCAN module)
 - Optional second FlexCAN module multiplexed with the third UART
- Inter-integrated circuit (I2C) bus controller
- Queued serial peripheral interface (QSPI) module
- Hardware cryptography accelerator (optional)
 - Random number generator
 - DES/3DES/AES block cipher engine
 - MD5/SHA-1/HMAC accelerator
- 4-channel, 32-bit direct memory access (DMA) controller
- 4-channel, 32-bit input capture/output compare timers with optional DMA support
- 4-channel, 16-bit periodic interrupt timers (PITs)
- Programmable software watchdog timer
- Interrupt controller capable of handling up to 126 interrupt sources
- Clock module with phase locked loop (PLL)
- External bus interface module including a 2-bank synchronous DRAM controller
- 32-bit, non-multiplexed bus with up to 8 chip select signals that support page-mode FLASH memories

For more information, refer to Reference 1.

1.2 eTPU Module

The eTPU is an intelligent, semi-autonomous co-processor designed for timing control, I/O handling, serial communications, motor control, and engine control applications. It operates in parallel with the host CPU. The eTPU processes instructions and real-time input events, performs output waveform generation, and accesses shared data without the host CPU's intervention. Consequently, the host CPU setup and service times for each timer event are minimized or eliminated.

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The eTPU has up to 32 timer channels, in addition to having 6 Kbytes of code memory and 1.5 Kbytes of data memory that store software modules downloaded at boot time, and can be mixed and matched as needed for any application.

The eTPU provides more specialized timer processing than the host CPU can achieve. This is partially due to the eTPU implementation, which includes specific instructions for handling and processing time events. In addition, channel conditions are available for use by the eTPU processor, thus eliminating many branches. The eTPU creates no host CPU overhead for servicing timing events.

For more information, refer to Reference 7.

2 Target Motor Theory

A brushless DC (BLDC) motor is a rotating electric machine where the stator is a classic three-phase stator, like that of an induction motor, and the rotor has surface-mounted permanent magnets (see Figure 2).

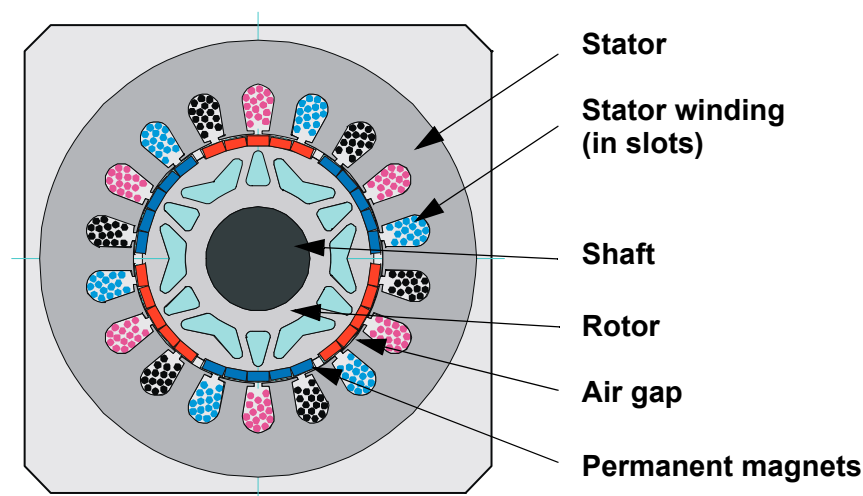


Figure 2. BLDC Motor - Cross Section

In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. In the DC commutator motor, the current polarity is altered by the commutator and brushes. Unlike the brushless DC motor, the polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position, or the position can be detected without sensors.

2.1 Digital Control of a BLDC Motor

The BLDC motor is driven by rectangular voltage strokes coupled with the given rotor position (see Figure 3). The generated stator flux interacts with the rotor flux, which is generated by a rotor magnet and defines the torque and thus the speed of the motor. The voltage strokes must be properly applied to two phases of the three-phase winding system so that the angle between the stator flux and the rotor flux is kept as close to 90° as possible, to get the maximum generated torque. Therefore, the motor requires electronic control for proper operation.

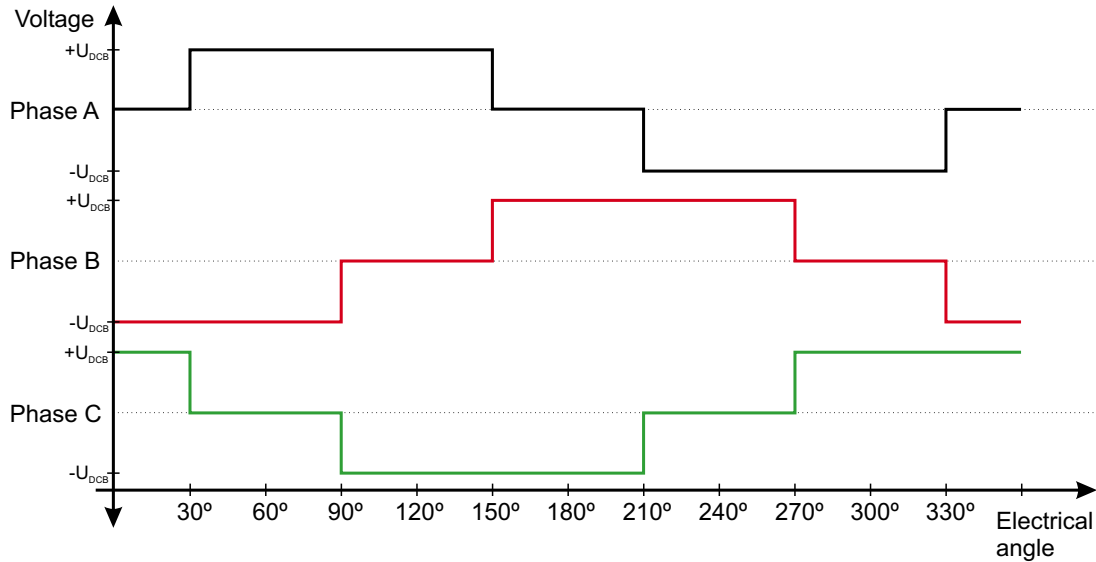


Figure 3. Voltage Strokes Applied to the 3-Phase BLDC Motor

For the common 3-phase BLDC motor, a standard 3-phase power stage is used (see [Figure 4](#)). The power stage utilizes six power transistors that operate in either an independent or complementary mode.

In both modes, the 3-phase power stage energizes two motor phases concurrently. The third phase is unpowered (see [Figure 3](#)). Thus, we get six possible voltage vectors that are applied to the BLDC motor using a pulse width modulation (PWM) technique (see [Figure 5](#)). There are two basic types of power transistor switching schemes: independent and complementary. Both switching modes are able to work in bipolar or unipolar mode. The presented application utilizes the complementary bipolar PWM mode.

For more information about PWM techniques, refer to Reference [15](#).

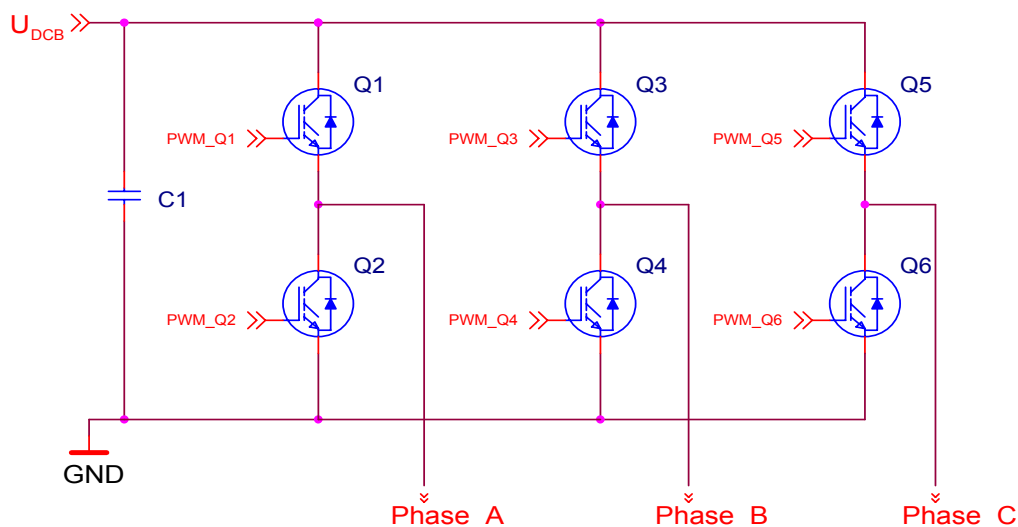


Figure 4. 3-Phase BLDC Power Stage

2.1.1 Commutation

Commutation provides the creation of a rotational field. As mentioned earlier, for proper operation of a BLDC motor, it is necessary to keep the angle between the stator and rotor flux as close to 90° as possible. We get a total of six possible stator flux vectors with a six-step control. The stator flux vector must be changed at specific rotor positions, which are usually sensed by the Hall sensors. The Hall sensors generate three signals that also consist of six states. Each of the Hall sensors' states correspond to a certain stator flux vector. All of the Hall sensors states, with corresponding stator flux vectors, are illustrated in Figure 5.

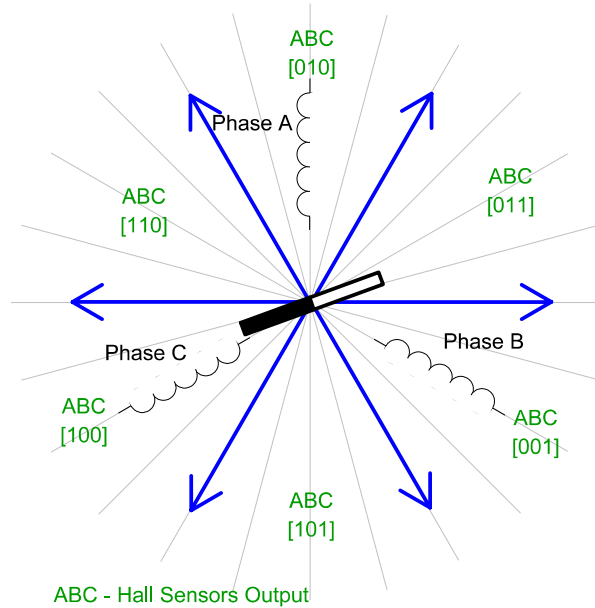


Figure 5. Stator Flux Vectors at Six-Step Control

The next two figures depict the commutation process. The actual rotor position in Figure 6 corresponds to the Hall sensors state ABC[110] (see Figure 5). Phase A is connected to the positive DC bus voltage by the transistor Q1, phase C is connected to the ground by transistor Q6, and phase B is unpowered.

As soon as the rotor reaches a certain position (see Figure 7), the Hall sensors state changes its value from ABC[110] to ABC[100]. A new voltage pattern is selected and applied to the BLDC motor.

As shown below, when using the six-step control technique, it is difficult to keep the angle between the rotor flux and the stator flux precisely at 90° in a six-step control technique. The actual angle varies from 60° to 120° .

The commutation process is repeated per each 60 electrical degrees and is critical to maintain its angular (time) accuracy. Any deviation causes torque ripples, resulting in speed variation.

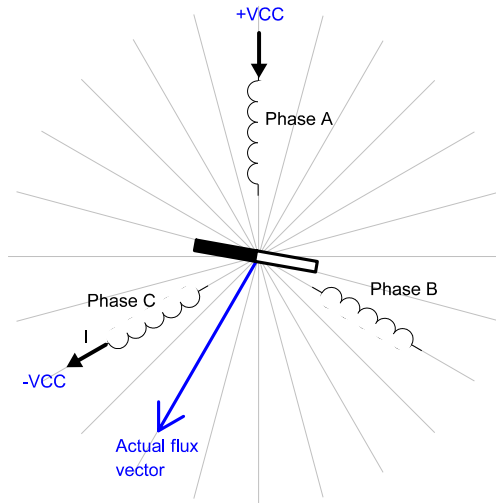


Figure 6. Situation Right Before Commutation (Counter-Clockwise Motion)

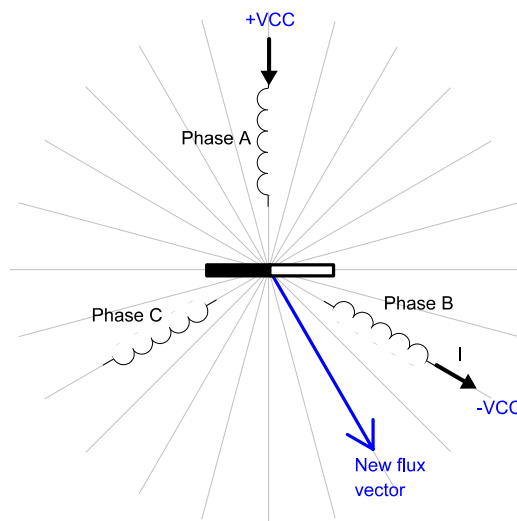


Figure 7. Situation Right After Commutation

2.1.1.1 Quadrature Encoder Versus Hall Sensors

The BLDC motor application uses the quadrature encoder for rotor position sensing. The quadrature encoder output consists of three signals. Two phases, A and B, represent the rotor position, and an index pulse defines the zero position. All quadrature encoder signals are depicted in [Figure 8](#). Compared with Hall sensors, there are some differences, which affect the control algorithm. The main difference is that the quadrature encoder does not give commutation moment and absolute position, as do the Hall sensors.

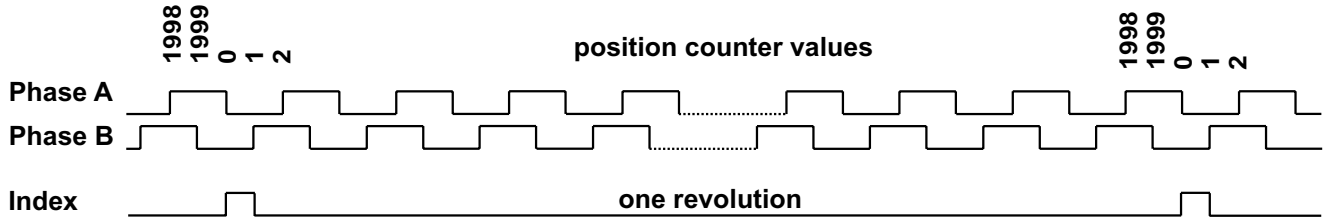


Figure 8. Quadrature Encoder Output Signals

The differences between the quadrature encoder and Hall sensors are summarized in [Table 1](#).

Table 1. Differences Between Quadrature Encoder and Hall Sensors

Quadrature Encoder	Hall Sensors
3 outputs	3 outputs
Does not give absolute position	Gives absolute position
Gives precise position	Gives 6 events per electrical revolution

The two control algorithms are described later on with the quadrature encoder. The first solution is commonly used and periodically scans the quadrature encoder. The second solution uses specific advantages of the QD eTPU function and translates the quadrature encoder outputs directly into Hall sensors signals. These internal signals are used as an input for the commutation algorithm. This algorithm is implemented in the presented application.

2.1.1.2 Commutation with Periodical Scanning of Quadrature Encoder

The commutation of the BLDC motor is performed in the six defined moments. Since the quadrature encoder gives the precise position, the one electrical revolution is divided into six sectors (see [Figure 9](#)). To recognize the commutation moment, it is necessary to scan quadrature encoder position very quickly. The frequency of scanning depends on the maximal rotor speed, the number of pole pairs and on the required precision of commutation moment detection. The same scan frequency as used in the PWM is satisfactory for the common applications.

In this case, the rotor position can be scanned in the moment of a PWM reload interrupt. The algorithm translates the actual position into the one of the six sectors. If a change of sector is detected, the commutation is performed. This algorithm is not implemented in the presented application!

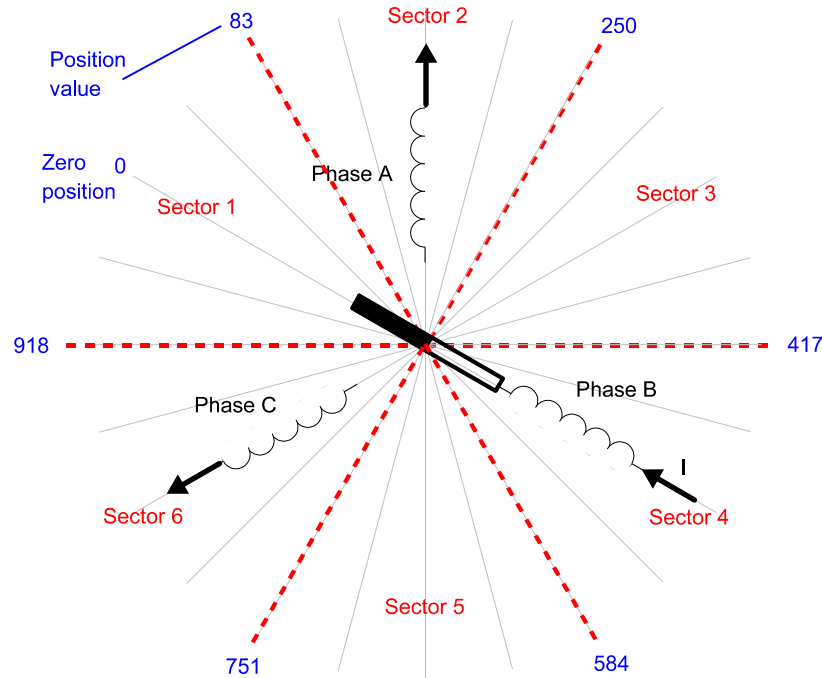


Figure 9. Separation of One Electrical Revolution into Six Commutation Sectors

NOTE:

The [Figure 9](#) considers 500 pulses per mechanical revolution, both rising and falling edges counting, two pole pairs ($500 \times 4 / 2 = 1000$ pulses per electrical revolution)

2.1.1.3 Direct Conversion of Quadrature Encoder Signals to a Commutation Sector

A different method is the direct conversion of encoder output to commutation sectors. The conversion is provided by the eTPU. The advantage of this method is that an interrupt rate depends on the actual motor speed, while in the previous method, there is a constantly high interrupt rate in order to scan the actual motor position. The direct conversion operates in following way:

The electrical revolution is divided into six sectors, as in [Figure 9](#). The rotor position is scanned by the shaft encoder, which has its outputs connected to the dedicated eTPU input pins. The quadrature decoder (QD) eTPU function uses these pins to decode the quadrature encoder signal and to process position counting. After rotor alignment to known position, two compare parameters of the QD eTPU function are set to values that correspond to sector borders and the position counter is set to zero, see [Figure 10](#). When the motor starts to move, the position counter starts to count the pulses of the quadrature encoder. No interrupt is generated until the position counter reaches one of the compare values.

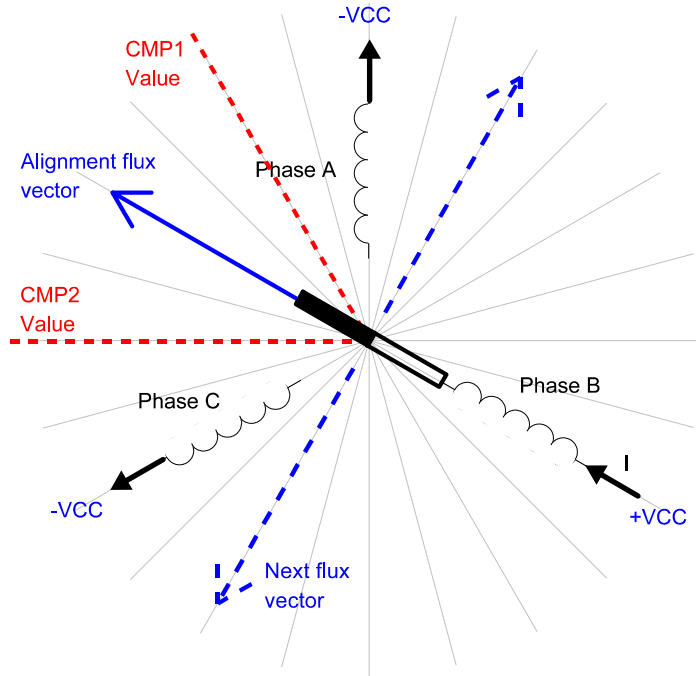


Figure 10. Alignment Rotor Position

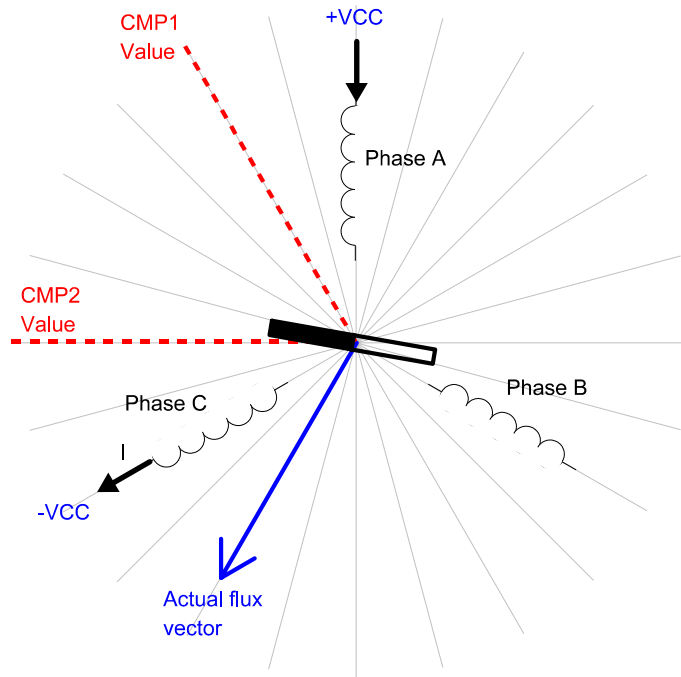


Figure 11. Situation Prior to First Compare Following Alignment

As soon as the position counter reaches one of the compare values, the position interrupt is called in order to start the commutation. The position interrupt sets the new values into the compare parameters of the QD eTPU function based on the spin direction. The new values corresponds to the next commutation sector in

clockwise or counter-clockwise direction according to actual spin direction. Then the control word, which saves the actual commutation sector, is updated and the new voltage pattern is applied to the motor. Figure 12 depicts the new situation after commutation.

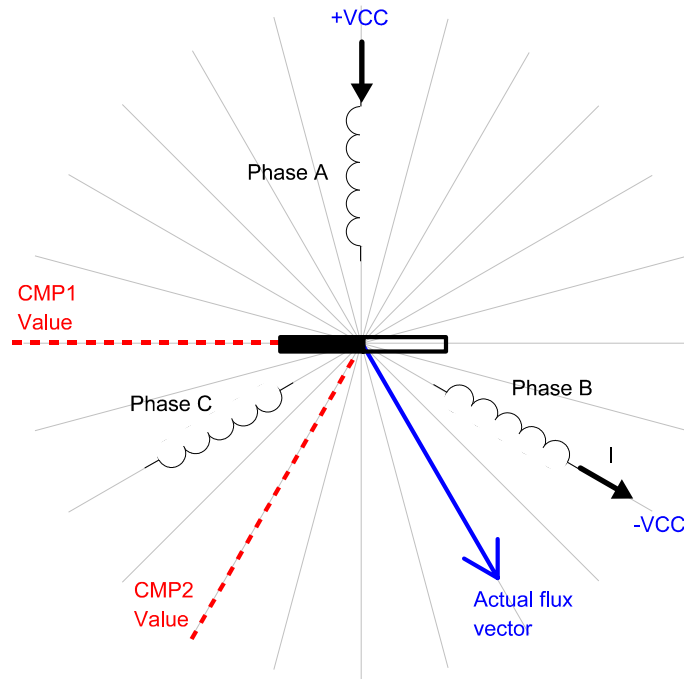


Figure 12. Situation Following Commutation

We can see that the position interrupt is called six times per electrical revolution. Note that the position interrupt is called in the same moment as when we use Hall sensors.

2.1.2 Position Alignment

Since the quadrature encoder doesn't give the absolute position, we need to know the exact rotor position before the motor is started. One possible and very easily implemented method is the rotor alignment to a predefined position. The motor is powered by a defined static voltage pattern and the rotor aligns to the predefined position. This alignment is done only once, during the initial motor start up. The Figure 10 shows the position of the aligned rotor. After alignment, the compare parameters of the position counter are set to +/- 30 electric degrees from the alignment position, in order to preset the commutation sector. The next voltage vector is set to be orthogonal to the alignment position. The resultant direction of the voltage vector is given by the polarity of applied voltage.

2.1.3 Speed Control

Commutation ensures the proper rotor rotation of the BLDC motor, while the motor speed only depends on the amplitude of the applied voltage. The amplitude of the applied voltage is adjusted using the PWM technique. The required speed is controlled by a speed controller, which is implemented as a conventional proportional-integral (PI) controller. The difference between the actual and required speeds is input to the

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PI controller which then, based on this difference, controls the duty cycle of the PWM pulses which correspond to the voltage amplitude required to maintain the desired speed.

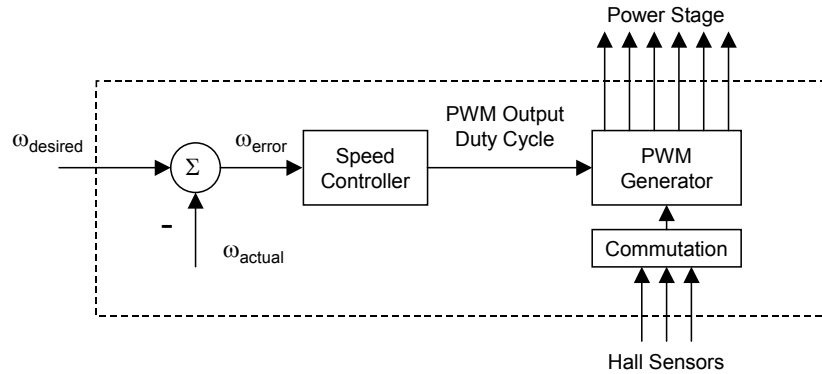


Figure 13. Speed Controller

The speed controller calculates the PI algorithm given in the equation below:

$$u(t) = K_c \left[e(t) + \frac{1}{T_I} \int_0^t e(\tau) d\tau \right]$$

After transforming the equation into a discrete time domain using an integral approximation with the Backward Euler method, we get the following equations for the numerical PI controller calculation:

$$u(k) = u_p(k) + u_I(k)$$

$$u_p(k) = K_c \cdot e(k)$$

$$u_I(k) = u_I(k-1) + K_c \frac{T}{T_I} \cdot e(k)$$

where:

$e(k)$	=	Input error in step k
$w(k)$	=	Desired value in step k
$m(k)$	=	Measured value in step k
$u(k)$	=	Controller output in step k
$u_p(k)$	=	Proportional output portion in step k
$u_I(k)$	=	Integral output portion in step k
$u_I(k-1)$	=	Integral output portion in step k-1
T_I	=	Integral time constant
T	=	Sampling time
K_c	=	Controller gain

3 System Concept

3.1 System Outline

The system is designed to drive a 3-phase BLDC motor. The application meets the following performance specifications:

- Voltage control of a BLDC motor using quadrature encoder HEDS-5640 A06
- Targeted at ColdFire MCF523x evaluation board (M523xEVB), 33395 evaluation motor board (power stage), and MCG BLDC motor (IB23810)
- Control technique incorporates:
 - Voltage BLDC motor control with speed-closed loop
 - Both directions of rotation
 - 4-quadrant operation
 - Rotor alignment to the start position
 - Minimum speed of 10 RPM
 - Maximum speed of 1000 RPM (limited by power supply)
- Manual interface (start/stop switch, up/down push button control, LED indication)
- FreeMASTER control interface (speed set-up, speed loop close/open choice)
- FreeMASTER monitor
 - FreeMASTER graphical control page (required speed, actual motor speed, start/stop status, fault status)
 - FreeMASTER speed control scope (observes required, ramp, and actual speeds, applied voltage)
 - Detail description of all eTPU functions used in the application (monitoring of channel registers and all function parameters in real time)
- DC bus over-current fault protection

3.2 Application Description

A standard system concept is chosen for the motor control function (see [Figure 14](#)). The system incorporates the following hardware:

- Evaluation board M523xEVB
- 33395 evaluation motor board
- MCG BLDC motor (IB23810)
- Quadrature encoder (HEDS-5640 A06)
- Power supply 9V DC, 2.7Amps

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The eTPU module runs the main control algorithm. The 3-phase PWM output signals for a 3-phase inverter are generated according to feedback signals from quadrature encoder and the input variable values, provided by the microprocessor CPU. Commutation of PWM phases is controlled by the CPU.

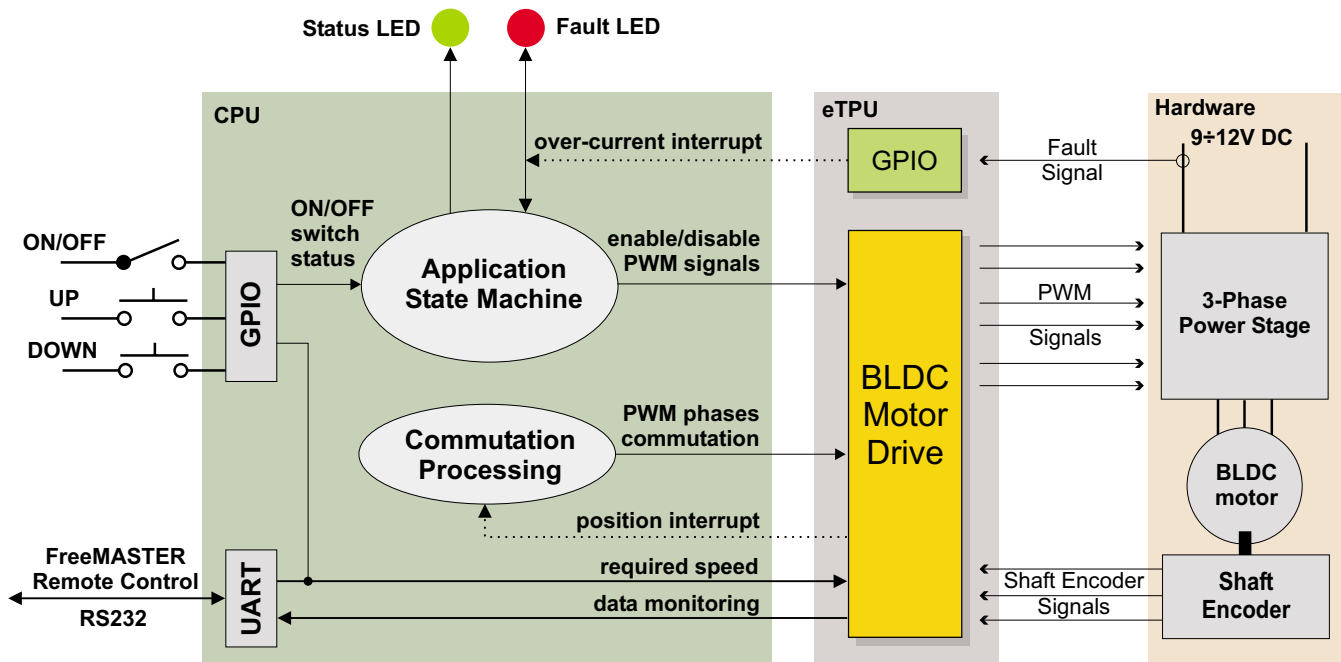


Figure 14. System Concept

The system processing is distributed between the CPU and the eTPU, which both run in parallel.

The CPU performs the following tasks:

- Periodically scans the user interface (ON/OFF switch, up and down buttons, FreeMASTER). Based on the user input, it handles the application state machine and calculates the required speeds, which is passed to the eTPU.
- Ensures processing of position interrupts coming from eTPU QD channels and consecutive commutation of PWM phases. The interrupts are generated each time the QD position counter reaches a value which corresponds to the border between two commutation sectors.
- Periodically reads application data from eTPU DATA RAM in order to monitor application variables.
- In the event of an overcurrent fault, the PWM outputs are immediately temporarily disabled by the eTPU hardware. Then, after an interrupt latency, the CPU disables the PWM outputs permanently and displays the fault state.

The eTPU performs the following tasks:

- Six eTPU channels (PWMC) are used to generate PWM output signals.
- Three eTPU channels (QD) are used to process quadrature encoder signals.
- One eTPU channel (GPIO) is used to generate an interrupt to the CPU when the over-current fault signal activates.

- eTPU controls a speed closed loop. The actual motor speed is calculated based on the QD position counter and QD last edge time and compared with the required speed, provided by the CPU and passed through a ramp. The speed PI control algorithm processes the error between the required and actual speed. The PI controller output is passed to the PWM generator as a newly corrected value of the applied motor voltage.

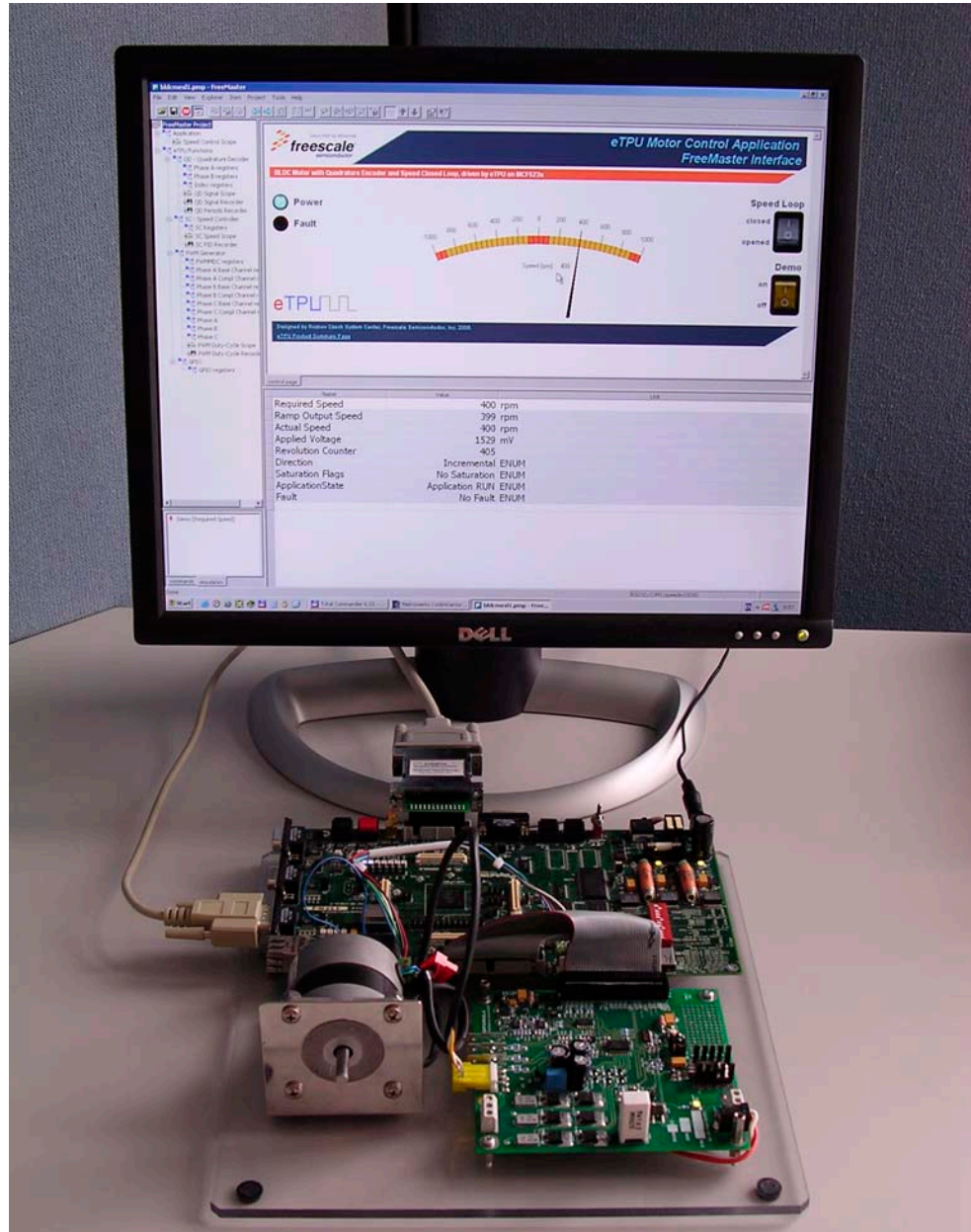


Figure 15. The Application and FreeMASTER Screen

3.2.1 User Interface

The application is interfaced by the following:

- ON/OFF switch on M523xEVB.
- Up/down buttons on M523xEVB, or FreeMASTER running on a PC connected to the M523xEVB via an RS232 serial cable.

The ON/OFF switch affects the application state and enables and disables the PWM phases. When the switch is in the off-position, no voltage is applied to the motor windings. When the ON/OFF switch is in the on-position, the motor speed can be controlled either by the up and down buttons on the M523xEVB, or by the FreeMASTER on the PC. The FreeMASTER also displays a control page, real-time values of application variables, and their time behavior using scopes.

FreeMASTER software was designed to provide an application-debugging, diagnostic, and demonstration tool for the development of algorithms and applications. It runs on a PC connected to the M523xEVB via an RS232 serial cable. A small program resident in the microprocessor communicates with the FreeMASTER software to return status information to the PC and process control information from the PC. FreeMASTER software, executing on a PC, uses part of Microsoft Internet Explorer as the user interface.

Note, that FreeMASTER version 1.2.31.1 or higher is required. The FreeMASTER application can be downloaded from <http://www.freescale.com>. For more information about FreeMASTER, refer to Reference 6.

3.3 Hardware Implementation and Application Setup

As previously stated, the application runs on the MCF523x family of ColdFire microprocessors using the following:

- M523xEVB
- 33395 evaluation motor board
- 3-phase MCG BLDC motor (IB23810)
- Power supply, 9-12V DC, minimum 2.7Amps

Figure 16 shows the connection of these parts. All system parts are supplied by Freescale and documented according to references.

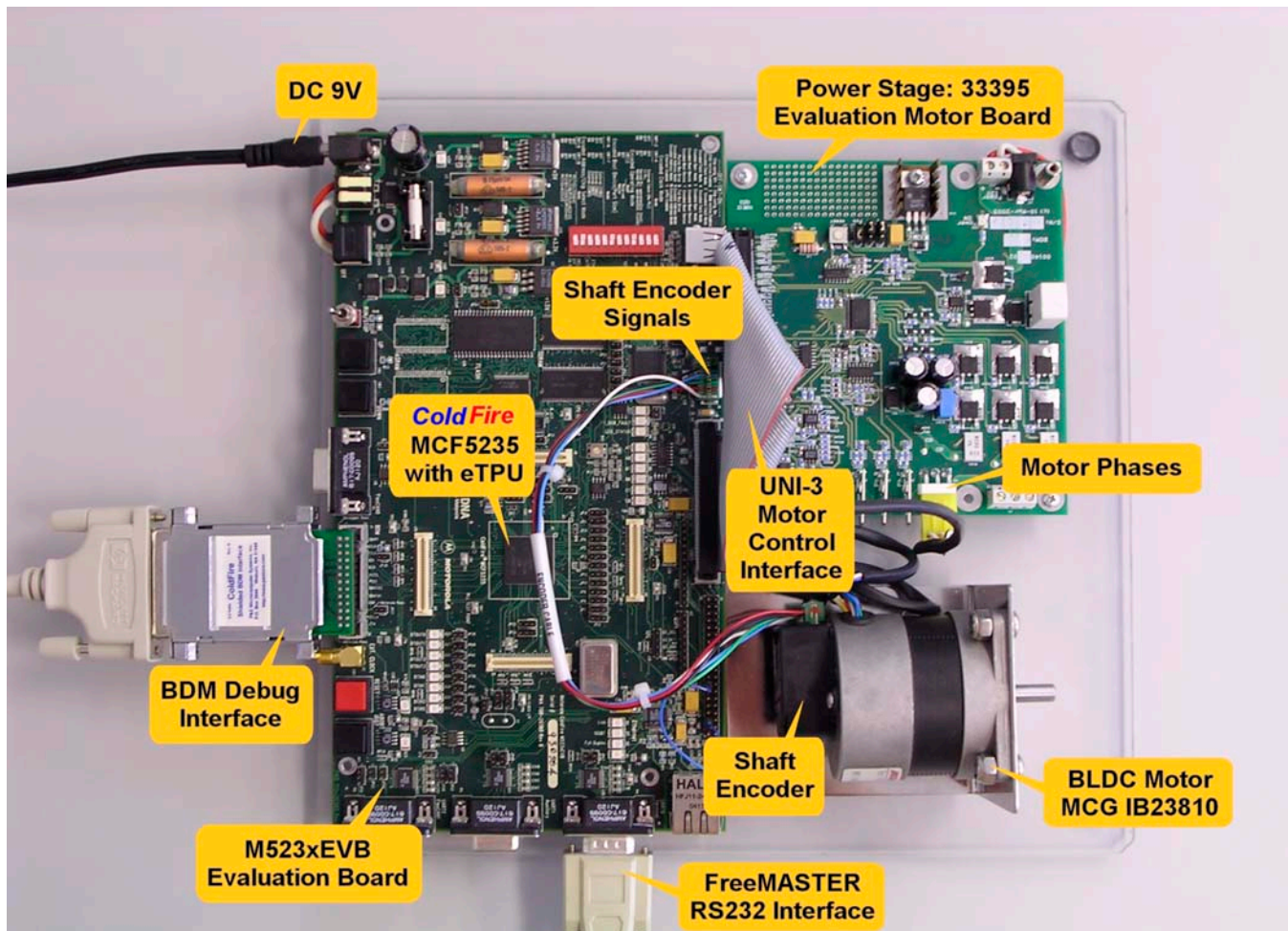


Figure 16. Connection of Application Parts

3.3.1 ColdFire MCF523x Evaluation Board (M523xEVB)

The EVB is intended to provide a mechanism for customers to easily evaluate the MCF523x family of ColdFire microprocessors. The heart of the evaluation board is the MCF5235; all other M523x family members have a subset of the MCF5235 features and can therefore be fully emulated using the MCF5235 device.

The M523xEVB is fitted with a single 512K x 16 page-mode FLASH memory (U19), giving a total memory space of 2 Mbytes. Alternatively, a footprint is available for upgrading flash to a 512K x 32 page-mode FLASH memory (U35), doubling the memory size to 4 Mbytes.

For more information, refer to Reference 2.

Table 2 lists all M523xEVB jumper settings used in the application.

Table 2. M523xEVB Jumper Settings

Jumper	Setting	Jumper	Setting	Jumper	Setting	Jumper	Setting
JP1	1 2	JP20	1 2-3	JP40	1-2	JP60	1-2
JP2	1-2	JP21	1 2-3	JP41	1-2	JP61	1-2
JP3	1 2	JP22	1 2-3	JP42	1-2	JP62	1 2
JP4	1-2	JP23	1 2-3	JP43	1-2	JP63	1 2
JP5	1 2-3	JP24	1 2-3	JP44	1-2	JP64	1 2-3
JP6	1-2 3	JP25	1-2 3	JP45	1-2	DIP1	ON
JP7	1 2-3	JP26	1-2 3	JP46	1-2	DIP2	ON
JP8	1-2 3	JP27	1-2	JP47	1-2	DIP3	ON
JP9	1 2-3	JP28	1-2	JP48	1-2	DIP4	ON
		JP29	1-2	JP49	1-2	DIP5	ON
JP10	1 2-3	JP30	1-2	JP50	1-2 3	DIP6	ON
JP11	1 2-3	JP31	1 2-3	JP51	1-2 3	DIP7	OFF
JP12	1 2-3	JP32	1-2 3	JP52	1-2 3	DIP8	ON
JP13	1 2-3	JP33	1-2	JP53	1 2	DIP9	ON
JP14	1 2-3	JP34	1-2	JP54	1 2	DIP10	ON
JP15	1 2-3	JP35	1-2 3	JP55	1 2	DIP11	OFF
JP16	1 2-3	JP36	1-2 3	JP56	1-2 3	DIP12	ON
JP17	1 2-3	JP37	1-2	JP57	1-2		
JP18	1 2-3	JP38	1-2	JP58	1-2		
JP19	1 2-3	JP39	1-2	JP59	1-2		

3.3.2 Flashing the M523xEVB

The CFFlasher utility can be used for programming code into the FLASH memory on the MCF523xEVB. Check for correct setting of switches and jumpers: SW7-6 on, SW7-7 off, JP64 2-3, (JP31 2-3). The flashing procedure is as follows:

1. Run Metrowerks CodeWarrior for ColdFire and open the project. Choose the simple_elflash target and compile the application. A file simple_elflash.elf.S19, which will be loaded into FLASH memory, is created in the project directory bin.
2. Run the CFFlasher application, click on the “Target Config” button. In the Target Configuration window select the type of board as M523xEVB and the BDM Communication as PE_LPT (see [Figure 17](#)). Click OK to close the window.
3. Go to the Program section by clicking the “Program” button. Select the simple_elflash.elf.S19 file and check the “Verify after Program” option (see [Figure 18](#)). Finally, press the “Program” button at the bottom of the window to start loading the code into the FLASH memory.
4. If the code has been programmed correctly, remove the BDM interface and push the RESET button on the M523xEVB. The application should now run from the FLASH.

The CFFlasher application can be downloaded from <http://www.freescale.com/coldfire>.

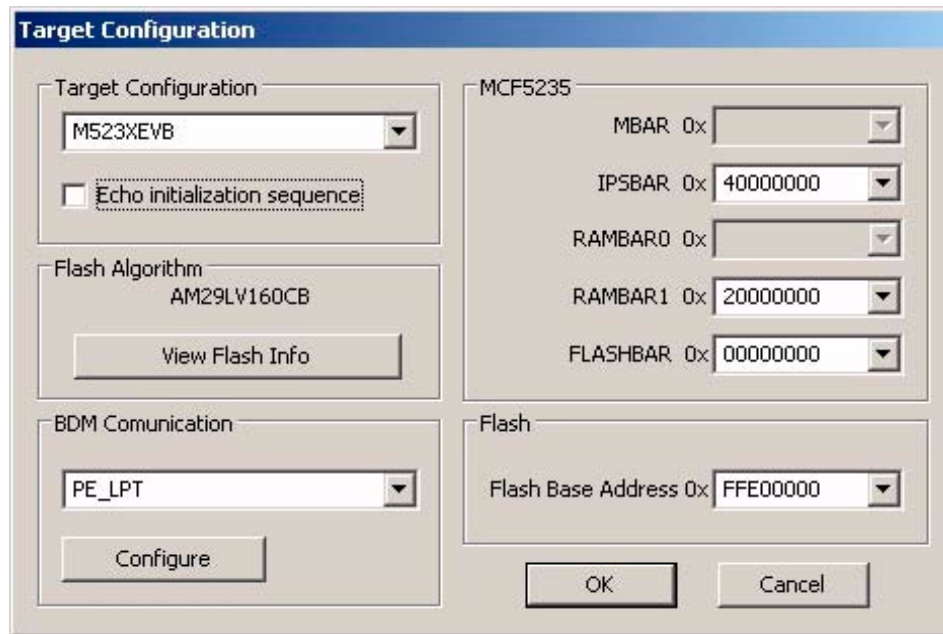


Figure 17. CFFlasher Target Configuration Window

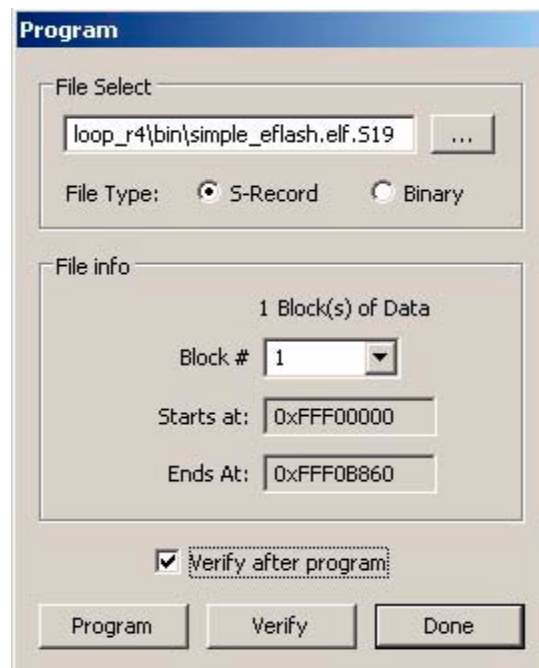


Figure 18. CFFlasher Program Window

3.3.3 Setting Overcurrent Level

The over-current fault signal is connected to the eTPU output disable pin (LETPUODIS) that handles eTPU hardware faults, along with the proper eTPU configuration. This connection is part of M523xEVB¹. In order to enable handling of the fault by software, the fault signal, available on the LETPUODIS pin,

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must be connected to eTPU channel 4, which runs the GPIO function and generates an interrupt request to the CPU in the case of a fault. This connection must be done manually. Connect pin 6 (LETPUODIS) with pin 16 (ETPUCH4) on the eTPU header (see [Figure 19](#)).

The over-current level is set by trimmer R41 on M523xEVB (see [Figure 20](#)). Reference 3 describes what voltage the trimmer defines for the over-current comparator. Follow the steps below to set up the over-current level properly without measuring the voltage:

1. Connect all system parts according to [Figure 16](#), connect pin 16 with pin 40 on the eTPU header. Now the over-current interrupt is disabled. The over-current fault is handled by hardware only.
2. Download and start the application.
3. Turn the ON/OFF switch ON. Using the Up and Down buttons, set the required speed to the maximum.
4. Adjust the R41 trimmer. You can find a level from which the red LED starts to light and the motor speed starts to be limited. Set the trimmer level somewhat higher, so that the motor can run at the maximum speed.
5. Turn the ON/OFF switch OFF.
6. Connect pin 16 with pin 6 on the eTPU header. Now the over-current interrupt is enabled. The over-current fault is handled by both hardware and software.
7. Turn the ON/OFF switch ON. Using the up and down buttons, set the required speed to the maximum.

If the application goes to the fault state during the acceleration, adjust the R41 trimmer level somewhat higher, so that the motor can get to the maximum speed.

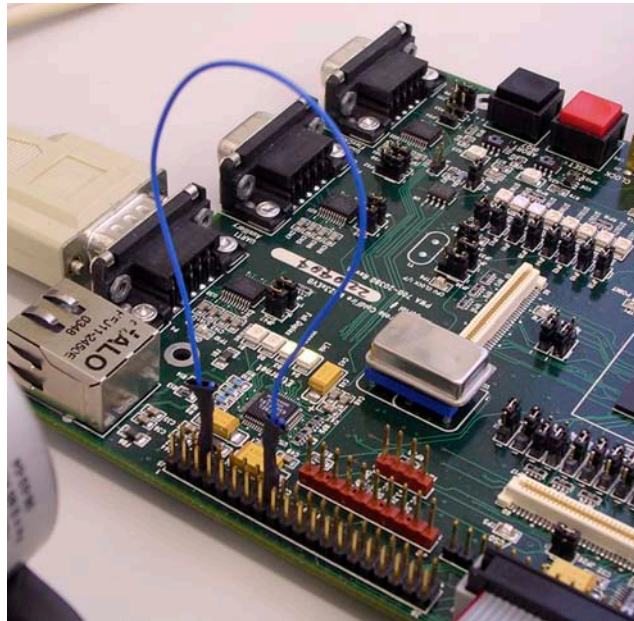


Figure 19. Connection Between LETPUODIS and ETPUCH4 on the eTPU Header

1. When the eTPU is configured for 32-channels, LTPUODIS is applicable to channels 0-15. When the ethernet is enabled (SW11 on), the function of LTPUODIS then changes to channels 0-7 and UTPUODIS thus controls channels 8-15. Therefore the UTPUODIS must be tied to LTPUODIS to enable the application to work when ethernet is enabled.

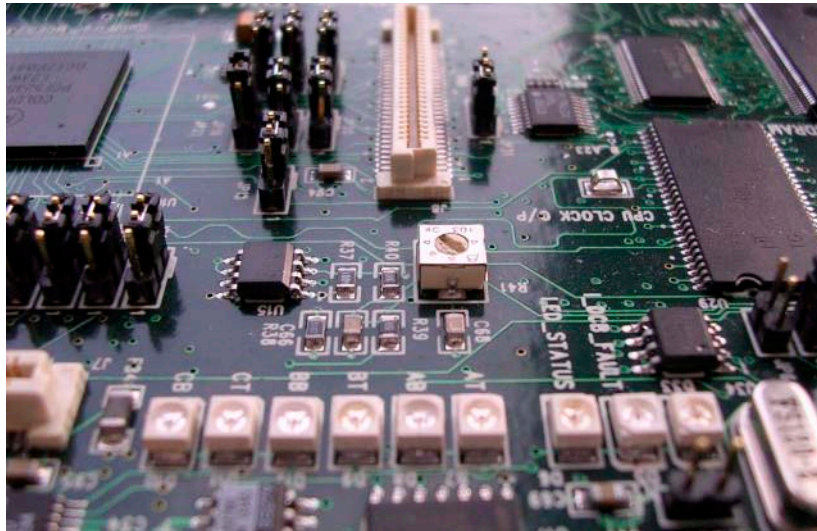


Figure 20. Overcurrent Level Trimmer on M523xEVB (R41)

3.3.4 33395 Evaluation Motor Board

The 33395 evaluation motor board is a 12-volt, 8-amp power stage, which is supplied with a 40-pin ribbon cable. In combination with the M523xEVB, it provides an out-of-the-box software development platform for small brushless DC motors. The power stage enables sensing a variety of feedback signals suitable for different motor control techniques. It measures all the three phase currents, reconstructs the DC-bus current from them, the DC-bus voltage, and the back-EMF voltages with zero cross sensing. All the analog signals are adapted to be directly sampled by the A/D converter. This single-board power stage contains an analog bridge gate driver integrated circuitry, sensing and control circuitry, power N-MOSFET transistors, DC-bus break chopper, as well as various interface connectors for the supply and the motor.

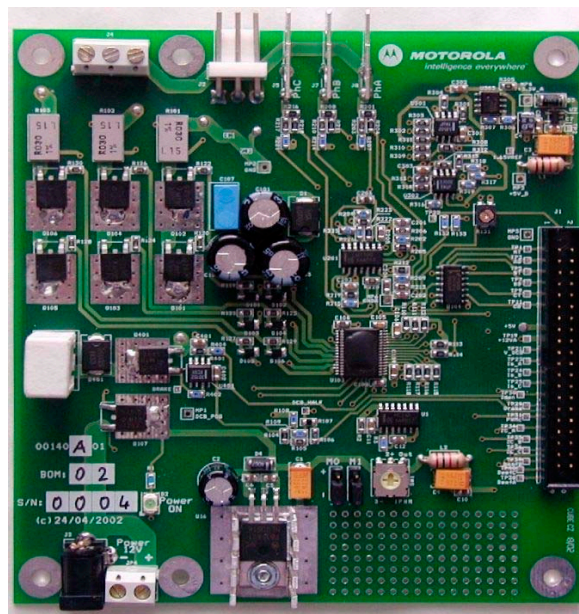


Figure 21. 33395 Evaluation Motor Board

For more information, refer to Reference 3.

3.3.5 BLDC Motor with Quadrature Encoder

The enclosed motor is a low-voltage MCG BLDC motor (IB23810). The motor characteristics in Table 3 apply to operation at 25°C.

Table 3. MCG BLDC Motor (IB23810) Motor Characteristics

Characteristic	Tolerance	Units	Value
Max. operating speed	MAX.	R.P.M.	5000
Continuous torque	MAX.	OZ-IN	20
Peak torque	MAX.	OZ-IN	60
Continuous current	MAX.	AMPS	2.0
Peak current	MAX.	AMPS	5.9
Torque sensitivity	±10%	OZ-IN/AMPS	11.4
Back EMF constant	±10%	V/K R.P.M.	8.4
D.C. resistance	±10%	OHMS	3.35
Inductance	±15%	mH	6.32
Rotor inertia	NOM.	OZ-IN-SEC ²	0.0011
Weight	NOM.	LBS	1.18

Figure 31 depicts the motor timing. For more motor specifications, refer to Reference 4.

Quadrature encoder HEDS-5640 A06 is attached to the motor in order to scan and encode shaft movement. The basic encoder features are as follows:

- Three channel quadrature output with index pulse
- Resolution 500 counts per revolution
- External mounting ears
- Quick and easy assembly
- No signal adjustment required
- Small size
- -40°C to 100°C operating temperature
- TTL compatible
- Single 5V supply

For more quadrature encoder specifications, refer to Reference 5.

3.3.6 Power Supply

The power supply supplied with the M523xEVB, 9.0V/2.7A, is also used to power the 33395 evaluation motor board. The application is scaled for this 9V power supply. In case a 12V power supply is used instead, the application should be rescaled for the wider voltage and speed range.

4 Software Design

This section describes the software design of the BLDC motor drive application. The system processing is distributed between the CPU and the eTPU, which run in parallel. The CPU and eTPU tasks are described in terms of the following:

- CPU
 - Software flowchart
 - Application state diagram
 - eTPU application API
- eTPU
 - eTPU block diagram
 - eTPU timing

The CPU software uses several ready-to-use Freescale software drivers. The communication between the microprocessor and the FreeMASTER on PC is handled by software included in `fmaster.c/.h` files. The eTPU module uses the general eTPU utilities, eTPU function interface routines (eTPU function API), and eTPU application interface routines (eTPU application API). The general utilities, included in the `etpu_util.c/.h` files, are used for initialization of global eTPU module and engine settings. The eTPU function API routines are used for initialization of the eTPU channels and interfacing each eTPU function during run-time. An eTPU application API encapsulates several eTPU function APIs. The use of an eTPU application API eliminates the need to initialize each eTPU function separately and to handle all eTPU function initialization settings, and so ensures the correct cooperation of eTPU functions.

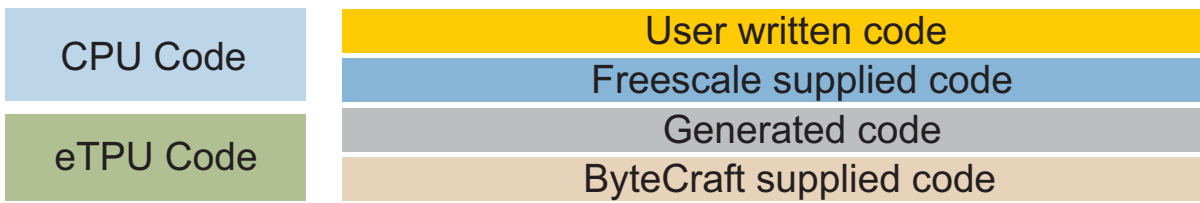
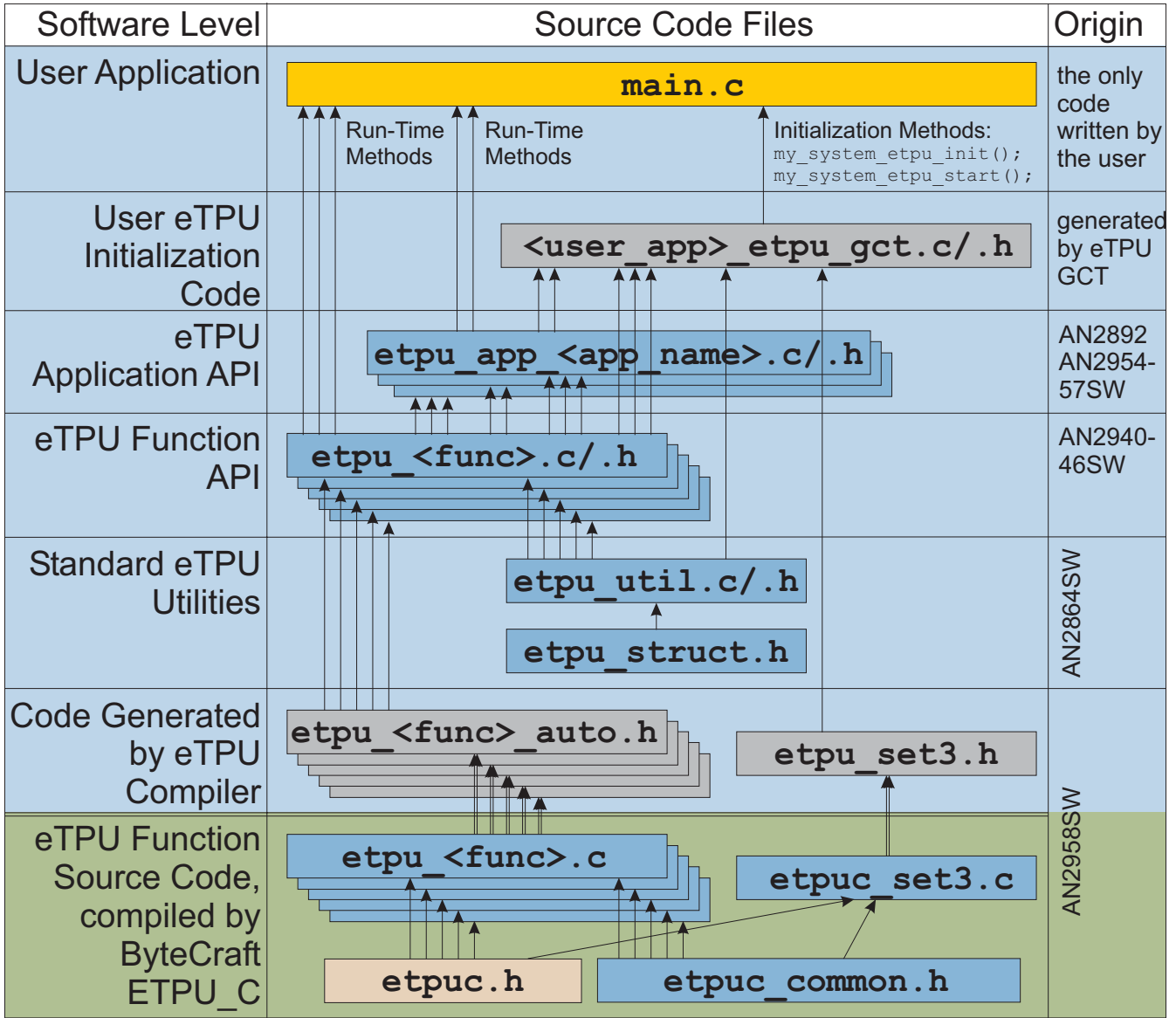


Figure 22. eTPU Project Structure

4.1 CPU Software Flowchart

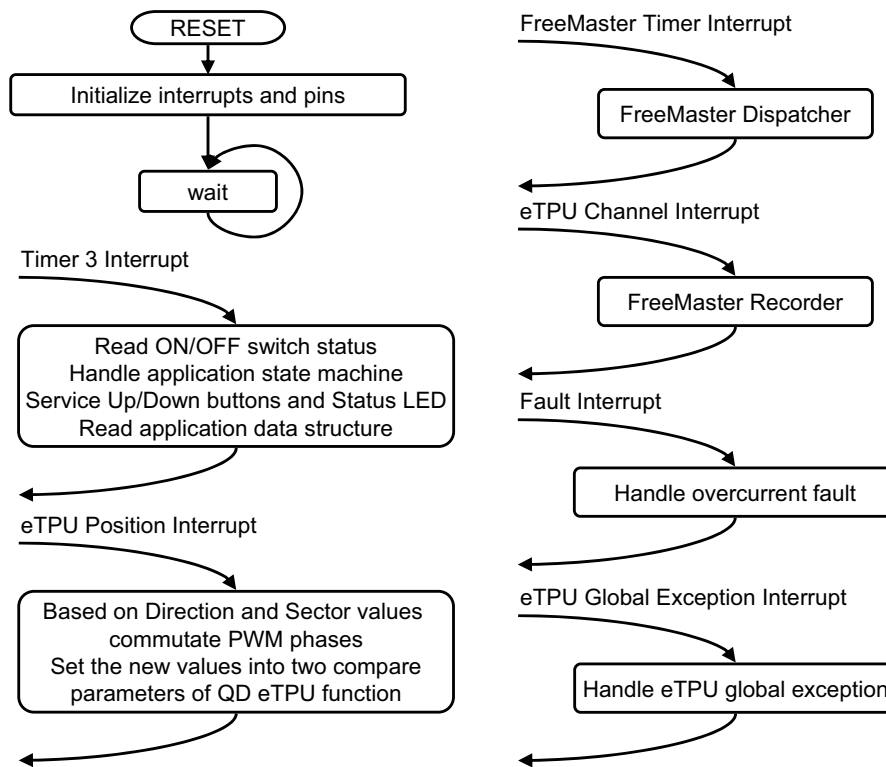


Figure 23. CPU Software Flowchart

After reset, the CPU software initializes interrupts and pins. The following CPU processing is incorporated in two periodical timer interrupts, one periodical eTPU channel interrupt, one eTPU position interrupt and two fault interrupts.

4.1.1 Initialization of Interrupts and Pins

The initialization of timer 3, eTPU channel 1, 2, 4 and 7 interrupts, and the eTPU global exception interrupt, together with initialization of the GPIO and LETPUODIS pins, is done by the `InitInterruptsAndPins` function.

4.1.2 Timer 3 Interrupt Service Routine

The timer 3 interrupt is handled by the `timer3_isr` function. The following actions are performed periodical, in `timer3_isr`:

- Read the ON/OFF switch status
- Handle the application state machine
The application state diagram is described in detail below.
- Service the up and down buttons and the status LED by the `ApplicationButtonsAndStatusLed` function

- Read the data structure through the eTPU application API routine `fs_etpu_app_bldcmesl1_get_data` (see 4.3).

4.1.3 Position Interrupt Service Routine

The eTPU position interrupt, which is raised by the QD eTPU function running on eTPU channels 1 and 2, is handled by the `etpu_ch1_ch2_isr` function. The `fs_etpu_app_bldcmesl1_commutate` application API function is called to ensure commutations of PWM phases (based on actual direction and position of the motion system). The information about the actual direction and the state of position counter is provided by the eTPU QD function. Further this application API function sets the QD eTPU function parameters `pc_interrupt1` and `pc_interrupt2` as a new compare values for QD to ensure generation of the next position interrupt.

4.1.4 FreeMASTER Interrupt Service Routine

The FreeMASTER interrupt service routine is called `fmasterDispatcher`. This function is implemented in `fmaster.c`.

4.1.5 eTPU Channel Interrupt Service Routine

This interrupt, which is raised every PWM period by the PWMMDC eTPU function running on eTPU channel 7, is handled by the `etpu_ch7_isr` function. This function calls `fmasterRecorder`, implemented in `fmaster.c`, enabling the configuration of application variable time courses with a PWM-period time resolution.

4.1.6 Fault Interrupt Service Routine

The over-current fault interrupt, which is raised by the GPIO eTPU function running on eTPU channel 4, is handled by the `etpu_ch4_isr` function. The following actions are performed in order to switch the motor off:

- Reset the required speed
- Disable the generation of PWM signals
- Switch the Fault LED on
- Enter `APP_STATE_MOTOR_FAULT`
- Set `FAULT_OVERCURRENT`

4.1.7 eTPU Global Exception Interrupt Service Routine

The global exception interrupt is handled by the `etpu_globalexception_isr` function. The following situations can cause this interrupt assertion:

- Microcode global exception is asserted
- Illegal instruction flag is asserted
- SCM MISC flag is asserted

The following actions are performed in order to switch the motor off:

- Reset the required speed
- Disable the generation of PWM signals
- Enter APP_STATE_GLOBAL_FAULT
- Based on the eTPU global exception source, set FAULT_MICROCODE_GE, FAULT_ILLEGAL_INSTR, or FAULT_MISC.

4.2 Application State Diagram

The application state diagram consists of seven states (see Figure 24). After reset, the application goes firstly to APP_STATE_INIT. Where the ON/OFF switch is in the OFF position, the APP_STATE_STOP follows, otherwise the APP_STATE_MOTOR_FAULT is entered and the ON/OFF switch must be turned OFF to get from APP_STATE_MOTOR_FAULT to APP_STATE_STOP. Then the cycle between APP_STATE_STOP, APP_STATE_ENABLE, APP_STATE_RUN, and APP_STATE_DISABLE can be repeated, depending on the ON/OFF switch position. APP_STATE_ENABLE and APP_STATE_DISABLE states are introduced in order to ensure the safe transitions between the APP_STATE_STOP and APP_STATE_RUN states. Where the over-current fault interrupt is raised (see red line on Figure 24), the APP_STATE_MOTOR_FAULT is entered. This fault is cleared by moving the ON/OFF switch to the OFF position and thus entering the APP_STATE_STOP. Where the eTPU global exception interrupt is raised (see gray line on Figure 24), the APP_STATE_GLOBAL_FAULT is entered. The global fault is cleared by moving the ON/OFF switch to the OFF position and thus entering the APP_STATE_INIT.

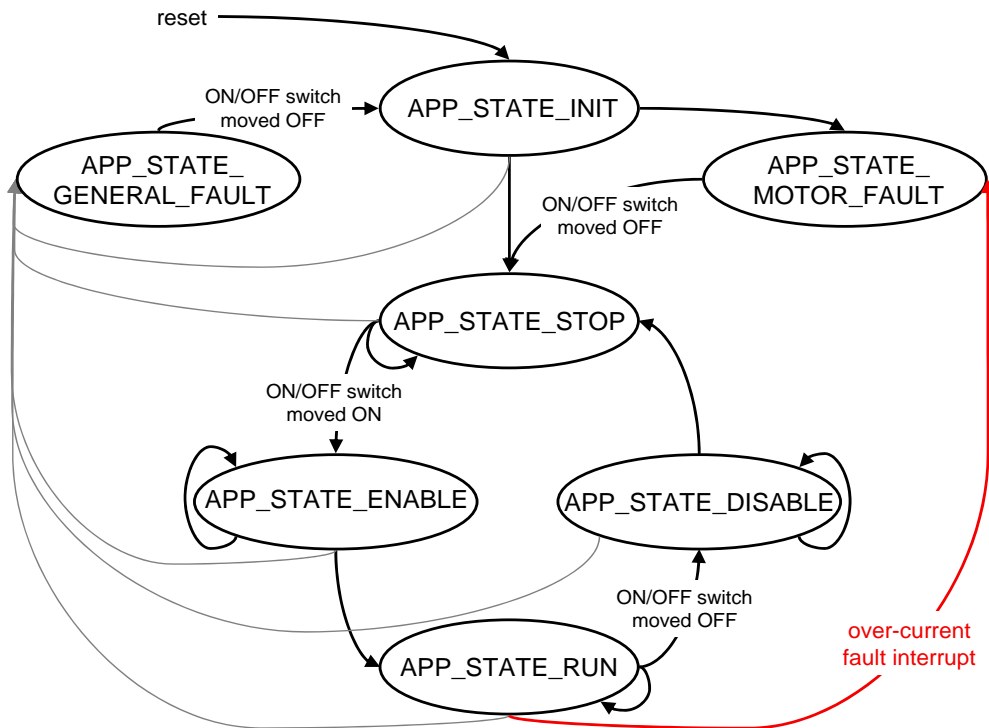


Figure 24. Application State Diagram

The following paragraphs describe the processing in each of the application states.

4.2.1 APP_STATE_INIT

This state is passed through only. It is entered either after a reset, or after the APP_STATE_GLOBAL_FAULT. The following actions are performed in order to initialize (re-initialize) the application:

- Call `my_system_etpu_init` routine for eTPU module initialization
- Get eTPU functions DATA RAM addresses for FreeMASTER
- Get the addresses of channel configuration registers for FreeMASTER
- Initialize the UART for FreeMASTER
- Initialize FreeMASTER
- Call `my_system_etpu_start` routine for eTPU Start. At this point, the CPU and the eTPU run in parallel.
- Depending on the ON/OFF switch position, enter APP_STATE_STOP or APP_STATE_MOTOR_FAULT

4.2.1.1 Initialization and Start of eTPU Module

The eTPU module is initialized using the `my_system_etpu_init` function. Later, after initialization of all other peripherals, the eTPU is started by `my_system_etpu_start`. These functions use the general eTPU utilities and eTPU function API routines. Both the `my_system_etpu_init` and `my_system_etpu_start` functions, included in `bldcmesl1_etpu_gct.c` file, are generated by the eTPU graphical configuration tool. The eTPU graphical configuration tool can be downloaded from http://www.freescale.com/webapp/sps/site/prod_summary.jsp?code=eTPU. For more information, refer to Reference 14.

The `my_system_etpu_init` function first configures the eTPU module and motor settings. Some of these settings include the following:

- Channel filter mode = three-sample mode
- Channel filter clock = `etpuclk div 64`
The input signals (from quadrature encoder) are filtered by channel filters. The filter settings guarantee filtering all noise pulses up to a width of 1.707 μ s and pass pulses from a width of 2.56 μ s (at 150 MHz system clock).
- TCR1 source = `etpuclk div 2`
- TCR1 prescaler = 1
The TCR1 internal eTPU clock is set to its maximum rate of 37.5 MHz (at 150 MHz system clock), corresponding to the 27ns resolution of generated PWM signals.
- TCR2 source = `etpuclk div 8`
- TCR2 prescaler = 1

After configuring the module and engine settings, the `my_system_etpu_init` function initializes the eTPU channels.

- Channel 1 - quadrature decoder (QD) - phase A channel
- Channel 2 - quadrature decoder (QD) - phase B channel
- Channel 3 - quadrature decoder (QD) - index channel
- Channel 5 - speed controller (SC)
- Channel 7 - PWM master for DC motors (PWMMDC)
- Channel 8 - PWM commuted (PWMC) - phase A - base channel
- Channel 10 - PWM commuted (PWMC) - phase B - base channel
- Channel 12 - PWM commuted (PWMC) - phase C - base channel

These eTPU channels are initialized by the `fs_etpu_app_bldcmes11_init` eTPU application API function (see 4.3). The application settings are as follows:

- PWM phases-type is commuted complementary pairs
- PWM frequency 20kHz
- PWM dead-time 1 μ s
- Motor speed range 1 200 RPM
- Motor speed minimum 10 RPM
- DC-bus voltage 9V
- Number of motor pole pairs 2
- Speed controller update frequency 500Hz
- PI controller parameters:
P-gain is 0.5 ($0x004000 * 2^{-15}$), and
I-gain is 0.125 ($0x001000 * 2^{-15}$).
The controller parameters were experimentally tuned.
- Ramp parameters:
0.25s to ramp up from zero to the maximum speed,
0.25s to ramp down from the maximum speed to zero.
- Number of quadrature encoder position counter increments per one revolution 2000
- Channel 4 - general purpose I/O (GPIO)
This eTPU channel is initialized by the `fs_etpu_gpio_init` API function. The setting is
 - Channel priority: high

The `my_system_etpu_start` function first applies the settings for the channel interrupt enable and channel output disable options, then enables the eTPU timers, thus starting the eTPU.

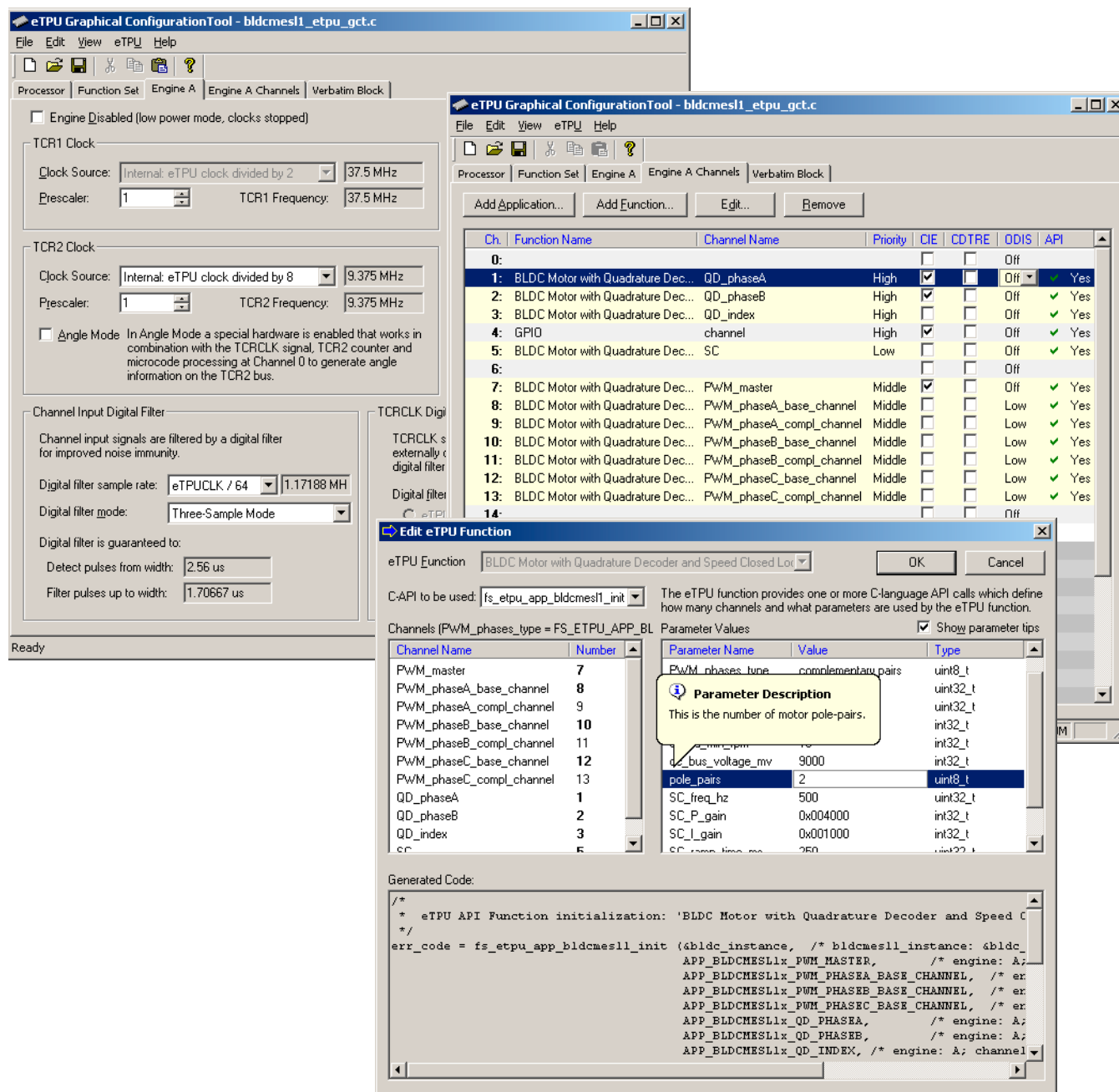


Figure 25. eTPU Configuration Using the eTPU Graphical Configuration Tool

4.2.1.2 Initialization of FreeMASTER Communication

Prior to the FreeMASTER initialization, it is necessary to set pointers to the eTPU functions DATA RAM bases and configuration register bases. Based on these pointers, which are read by FreeMASTER during the initialization, the locations of all eTPU function parameters and configuration registers are defined. This is essential for correct FreeMASTER operation.

FreeMASTER consists of software running on a PC and on the microprocessor, connected via an RS-232 serial port. A small program resident in the microprocessor communicates with the FreeMASTER on the PC in order to return status information to the PC, and processes control information from the PC. The microprocessor part of the FreeMASTER is initialized by two functions: `iniFmasterUart` and `fmasterInit`. Both functions are included in `fmaster.c`, which automatically initializes the UART driver and installs all necessary services.

4.2.2 APP_STATE_STOP

In this state, the PWM signals are disabled and the motor is off. The motor shaft can be rotated by hand, which enables the user to explore the functionality of the quadrature decoder (QD) eTPU function, to watch variables produced by the QD, and to see QD signals in FreeMASTER.

When the ON/OFF switch is turned on, the application goes through `APP_STATE_ENABLE` to `APP_STATE_RUN`.

4.2.3 APP_STATE_ENABLE

This state is passed through only. The following actions are performed in order to switch the motor drive on:

- Reset the required speed.
- Enable the generation of PWM signals by calling the `fs_etpu_app_bldcmes11_enable` application API routine. This routine also performs the motor alignment.

If the PWM phases were successfully enabled, the GPIO eTPU function is configured as input, interrupt on rising edge, and `APP_STATE_RUN` is entered. Where the PWM phases were not successfully enabled, the application state does not change.

4.2.4 APP_STATE_RUN

In this state, the PWM signals are enabled and the motor is on. The required motor speed can be set using the up and down buttons on the M523xEVB or by using FreeMASTER. The latest value is periodically written to the eTPU.

When the ON/OFF switch is turned off, the application goes through `APP_STATE_DISABLE` to `APP_STATE_STOP`.

4.2.5 APP_STATE_DISABLE

This state is passed through only. The following actions are performed in order to switch the motor drive off:

- Reset the required speed.
- Disable the generation of PWM signals.

If PWM phases were successfully disabled, `APP_STATE_STOP` is entered. Where PWM phases were not successfully disabled, the application state remains the same.

4.2.6 APP_STATE_MOTOR_FAULT

This state is entered after the over-current fault interrupt service routine. The application waits until the ON/OFF switch is turned off. This clears the fault and the application enters the APP_STATE_STOP.

4.2.7 APP_STATE_GLOBAL_FAULT

This state is entered after the eTPU global exception interrupt service routine. The application waits until the ON/OFF switch is turned off. This clears the fault and the application enters the APP_STATE_INIT.

4.3 eTPU Application API

The eTPU application API encapsulates several eTPU function APIs. The eTPU application API includes CPU methods which enable initialization, control, and monitoring of an eTPU application. The use of eTPU application API functions eliminates the need to initialize and set each eTPU function separately, and ensures correct cooperation of the eTPU functions. The eTPU application API is device independent and handles only the eTPU tasks.

In order to shorten the eTPU application names, abbreviated application names are introduced. The abbreviations include:

- Motor type (DCM = DC motor, BLDCM = brushless DC motor, PMSM = permanent magnet synchronous motor, ACIM = AC induction motor, SRM = switched reluctance motor, SM = stepper motor)
- Sensor type (H = Hall sensors, E = shaft encoder, R = resolver, S = sincos, X = sensorless)
- Control type (OL = open loop, PL = position loop, SL = speed loop, CL = current loop, SVC = speed vector control, TVC = torque vector control)

Based on these definitions, the BLDCMESL1 is an abbreviation for ‘BLDC motor with quadrature encoder and speed closed loop’ eTPU motor-control application. As there are several BLDC motor applications with quadrature encoder and speed closed loop, the number 1 denotes the first such application in order.

The BLDCMESL1 eTPU application API is described in the following paragraphs. There are 6 basic functions added to the BLDCMESL1 application API. The routines can be found in the `etpu_app_bldcmesl1.c/.h` files. All BLDCMESL1 application API routines will be described in order and are listed below:

- Initialization function:

```
int32_t fs_etpu_app_bldcmesl1_init(
    bldcmesl1_instance_t * bldcmesl1_instance,
    uint8_t PWM_master_channel,
    uint8_t PWM_phaseA_channel,
    uint8_t PWM_phaseB_channel,
    uint8_t PWM_phaseC_channel,
    uint8_t QD_phaseA_channel,
    uint8_t QD_phaseB_channel,
```



```

uint8_t    QD_index_channel,
uint8_t    SC_channel,
uint8_t    PWM_phases_type,
uint32_t   PWM_freq_hz,
uint32_t   PWM_dead_time_ns,
int32_t    speed_range_rpm,
int32_t    speed_min_rpm,
int32_t    dc_bus_voltage_mv,
uint8_t    pole_pairs,
uint32_t   SC_freq_hz,
int32_t    SC_P_gain,
int32_t    SC_I_gain,
uint32_t   SC_ramp_time_ms,
uint24_t   QD_pc_per_rev)

```

- Change operation functions:

```

int32_t fs_etpu_app_bldcmesl1_enable(
    bldcmesl1_instance_t * bldcmesl1_instance,
    uint8_t    configuration,
    int32_t    qd_pc_interrupt1,
    int32_t    qd_pc_interrupt2)

```

```

int32_t fs_etpu_app_bldcmesl1_disable(
    bldcmesl1_instance_t * bldcmesl1_instance)

```

```

void fs_etpu_app_bldcmesl1_set_speed_required(
    bldcmesl1_instance_t * bldcmesl1_instance,
    int32_t    speed_required_rpm)

```

```

int32_t fs_etpu_app_bldcmesl1_commutate(
    bldcmesl1_instance_t * bldcmesl1_instance)

```

- Value return functions:

```

void fs_etpu_app_bldcmesl1_get_data(
    bldcmesl1_instance_t * bldcmesl1_instance,
    bldcmesl1_data_t * bldcmesl1_data)

```

4.3.1 int32_t fs_etpu_app_bldcmesl1_init(...)

This routine is used to initialize the eTPU channels for the IBLDC motor with quadrature encoder and speed closed loop application. This function has the following parameters:

- **bldcmesl1_instance (bldcmesl1_instance_t*)** - This is a pointer to bldcmesl1_instance_t structure, which is filled by fs_etpu_app_bldcmesl1_init. This structure must be declared in the user application. Where there are more instances of the application running simultaneously, there must be a separate bldcmesl1_instance_t structure for each one.
- **PWM_master_channel (uint8_t)** - This is the PWM master channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B.
- **PWM_phaseA_channel (uint8_t)** - This is the PWM phase A channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B. In the case of complementary signal generation (PWM_phases_type==FS_ETPU_APP_BLDCMESL1_COMPL_PAIRS), the complementary channel is one channel higher.
- **PWM_phaseB_channel (uint8_t)** - This is the PWM phase B channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B. In the case of complementary signal generation (PWM_phases_type==FS_ETPU_APP_BLDCMESL1_COMPL_PAIRS), the complementary channel is one channel higher.
- **PWM_phaseC_channel (uint8_t)** - This is the PWM phase C channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B. In the case of complementary signal generation (PWM_phases_type==FS_ETPU_APP_BLDCMESL1_COMPL_PAIRS), the complementary channel is one channel higher.
- **QD_phaseA_channel (uint8_t)** - This is the quadrature decoder phase A channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B.
- **QD_phaseB_channel (uint8_t)** - This is the quadrature decoder phase B channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B.
- **QD_index_channel (uint8_t)** - This is the quadrature decoder index channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B.
- **SC_channel (uint8_t)** - This is the speed controller channel number. 0-31 for ETPU_A, and 64-95 for ETPU_B.
- **PWM_phases_type (uint8_t)** - This parameter determines the type of all PWM phases. This parameter should be assigned a value of: FS_ETPU_APP_BLDCMESL1_SINGLE_CHANNELS, or FS_ETPU_APP_BLDCMESL1_COMPL_PAIRS.
- **PWM_freq_hz (uint32_t)** - This is the PWM frequency in Hz.
- **PWM_dead_time_ns (uint32_t)** - This is the PWM dead-time in ns.
- **speed_range_rpm (int32_t)** - This is the maximum motor speed in rpm.
- **speed_min_rpm (int32_t)** - This is the minimum (measurable) motor speed in rpm.
- **dc_bus_voltage_mv (int32_t)** - This is the DC-bus voltage in mV.
- **pole_pairs (uint8_t)** - This is the number of motor pole-pairs.
- **SC_freq_hz (uint32_t)** - This is the speed controller update frequency in Hz. The assigned value must be equal to the PWM_freq_hz divided by 1, 2, 3, 4, 5, ...

- **SC_P_gain (fract24_t)** - This is the speed controller P-gain in 24-bit signed fractional format (9.15).
0x008000 corresponds to 1.0
0x000001 corresponds to 0.0000305 ($30.5 \cdot 10^{-6}$)
0x7FFFFFFF corresponds to 255.9999695
- **SC_I_gain (fract24_t)** - This is the speed controller I-gain in 24-bit signed fractional format (9.15).
0x008000 corresponds to 1.0
0x000001 corresponds to 0.0000305 ($30.5 \cdot 10^{-6}$)
0x7FFFFFFF corresponds to 255.9999695
- **SC_ramp_time_ms (uint32_t)** - This parameter defines the required speed ramp time in ms. A step change of the required speed from 0 to speed_range_rpm is slowed down by the ramp to take the defined time.
- **QD_qd_pc_per_rev (uint24_t)** - This is the number of QD position counter increments per one revolution.

4.3.2 int32_t fs_etpu_app_bldcmesl1_enable(...)

This routine is used to enable the generation of PWM signals, to align motor to the start position, to initialize and enable position interrupts from the quadrature encoder and to start the speed controller. This function has the following parameters:

- **bldcmesl1_instance (bldcmesl1_instance_t*)** - This is a pointer to bldcmesl1_instance_t structure, which is filled by fs_etpu_app_bldcmesl1_init.
- **configuration (uint8_t)** - This is the required configuration of the SC. This parameter should be assigned a value of:
FS_ETPU_APP_BLDCMESL1_SPEED_LOOP_OPENED, or
FS_ETPU_APP_BLDCMESL1_SPEED_LOOP_CLOSED.
- **qd_pc_interrupt1 (int32_t)** - This is the first out of two QD pc_interrupt parameters to be set. QD eTPU function generates the position interrupt to the CPU when the QD position counter reaches this value. This is used for commutation purposes.
- **qd_pc_interrupt2 (int32_t)** - This is the second out of two QD pc_interrupt parameters to be set. QD eTPU function generates the position interrupt to the CPU when the QD position counter reaches this value. This is used for commutation purposes.

4.3.3 int32_t fs_etpu_app_bldcmesl1_disable (bldcmesl1_instance_t * bldcmesl1_instance)

This routine is used to disable the generation of PWM signals and stop the speed controller. This function has the following parameter:

- **bldcmesl1_instance (bldcmesl1_instance_t*)** - This is a pointer to bldcmesl1_instance_t structure, which is filled by fs_etpu_app_bldcmesl1_init.

4.3.4 void fs_etpu_app_bldcmesl1_set_speed_required(...)

This routine is used to set the required motor speed. This function has the following parameters:

- **bldcmesl1_instance (bldcmesl1_instance_t*)** - This is a pointer to bldcmesl1_instance_t structure, which is filled by fs_etpu_app_bldcmesl1_init.
- **speed_required_rpm (int32_t)** - This is the required motor speed in rpm.

4.3.5 void fs_etpu_app_bldcmesl1_commutate(...)

This routine is used to commutate PWM phases. This function has the following parameters:

- **bldcmesl1_instance (bldcmesl1_instance_t*)** - This is a pointer to bldcmesl1_instance_t structure, which is filled by fs_etpu_app_bldcmesl1_init.

4.3.6 void fs_etpu_app_bldcmesl1_get_data(...)

This routine is used to get the application state data. This function has the following parameters:

- **bldcmesl1_instance (bldcmesl1_instance_t*)** - This is a pointer to bldcmesl1_instance_t structure, which is filled by fs_etpu_app_bldcmesl1_init.
- **bldcmesl1_data (bldcmesl1_data_t*)** - This is a pointer to bldcmesl1_data_t structure of application state data, which is updated.

4.4 eTPU Block Diagram

The eTPU functions used to drive the BLDC motor with speed closed loop are located in the motor-control set of eTPU functions (set3 - DC motors). The eTPU functions within the set serve as building blocks for various motor-control applications. The following paragraphs describe the functionality of each block.

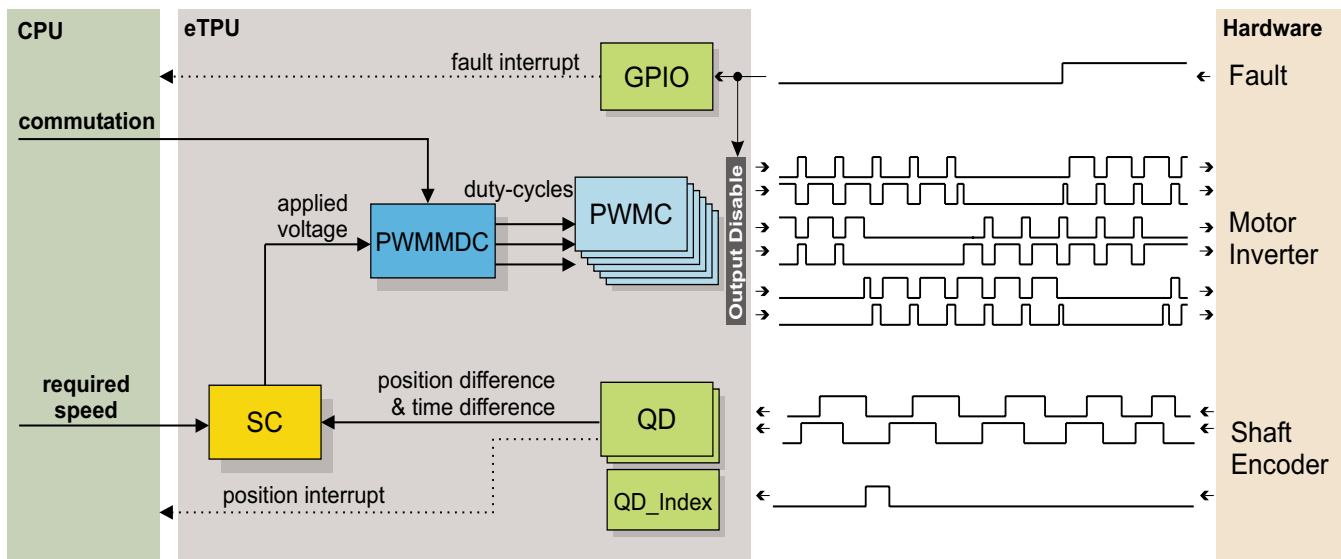


Figure 26. Block Diagram of eTPU Processing

4.4.1 PWM Generator (PWMMDC+PWMC)

The generation of PWM signals for motor-control applications with eTPU is provided by three eTPU functions:

- PWM - master for DC motors (PWMMDC)
- PWM - full range (PWMF)
- PWM - commuted (PWMC)

The PWM master for DC motors (PWMMDC) function calculates a PWM duty cycle and updates the three PWM phases. The phases may be driven either by the PWM full range (PWMF) function, which enables a full (0% to 100%) duty-cycle range, or by the PWM commuted (PWMC) function, which enables switching the phase ON and OFF. The PWMC function is used in the described application.

The PWMC function generates the PWM signals. The PWMMDC function controls three PWMC functions, three PWM phases, and does not generate any drive signal. The PWMMDC can be executed even on an eTPU channel not connected to an output pin (channels 16 to 32).

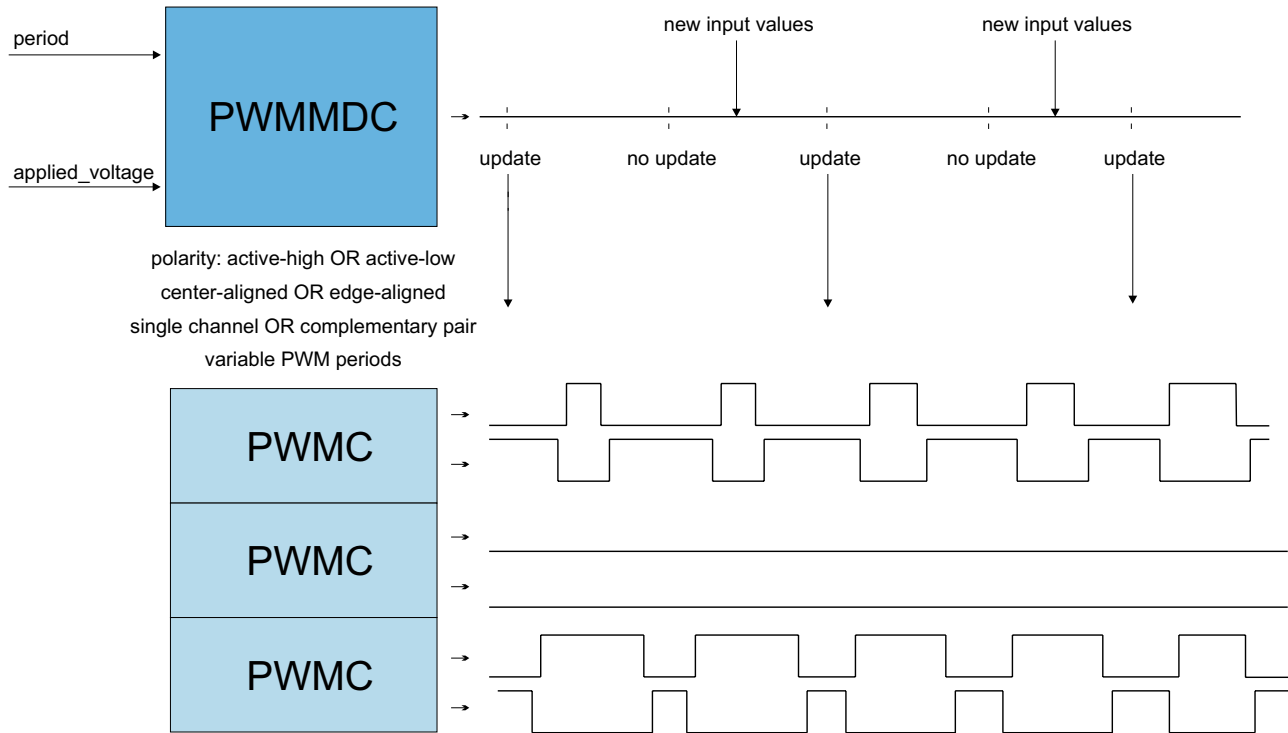


Figure 27. Functionality of PWMMDC+PWMC

For more details about the PWMMDC, PWMF, and PWMC eTPU functions, refer to Reference 10.

4.4.2 Quadrature Decoder (QD)

The quadrature decoder eTPU function set is intended to process signals generated by a shaft encoder in a motion control systems. It uses two channels to decode a pair of out-of-phase encoder signals and to produce a 24-bit bi-directional position counter, together with direction information, for the CPU. An additional input channels can also be processed. The index channel receives a pulse on each revolution.

Software Design

Based on the actual direction, a revolution counter is incremented or decremented on the index pulse. A further additional input channel can indicate a home position, but it is not used in this application.

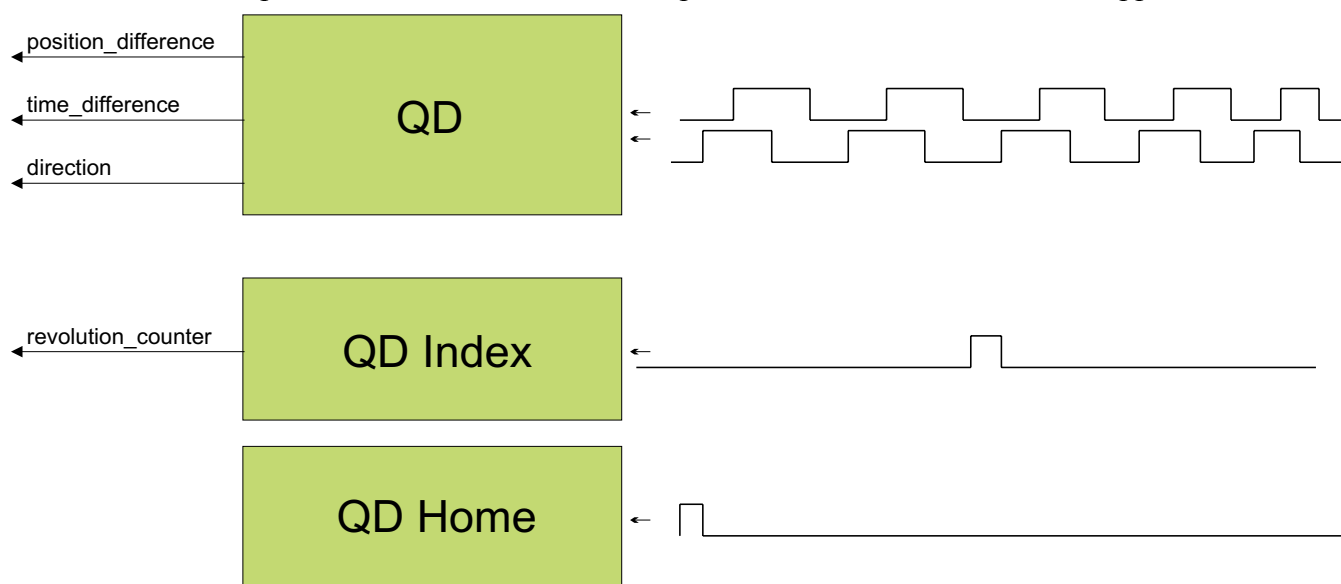


Figure 28. Functionality of QD

For more details about the QD eTPU function, refer to Reference 7.

4.4.3 Speed Controller (SC)

The speed controller eTPU function is not intended to process input or output signals. Its purpose is to control another eTPU function's input parameter. The SC function can be executed even on an eTPU channel not connected to an output pin. The SC function includes a general PID controller algorithm. The controller calculates its output based on two inputs: a measured value and a required value. The measured value (the actual motor speed) is calculated based on inputs provided by the QD function. The required value is an output of the speed ramp, whose input is a SC function parameter, and can be provided by the CPU or another eTPU function. In the motor-control eTPU function set, this function mostly provides the speed outer-loop.

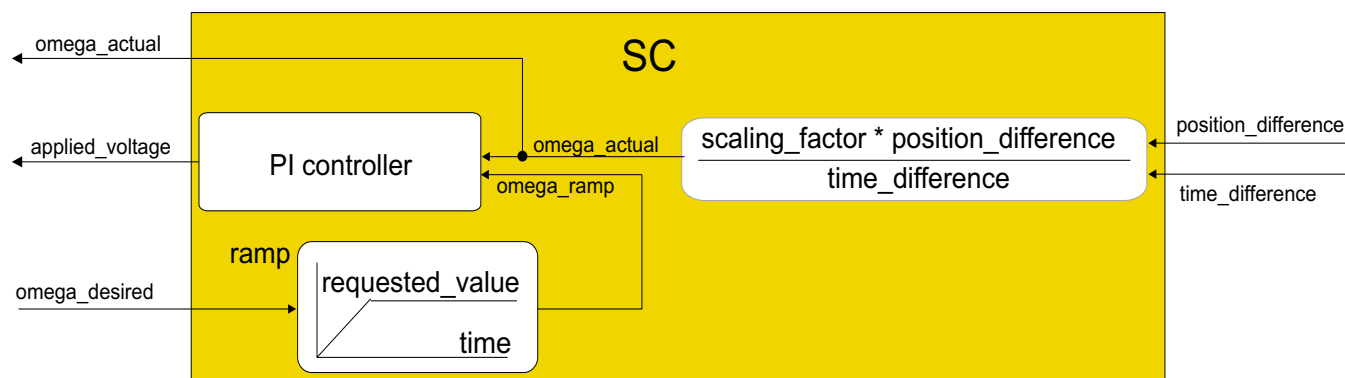


Figure 29. Functionality of SC

For more details about the SC eTPU function, refer to Reference 9.

4.4.4 General Purpose I/O (GPIO)

This function originates from the general eTPU function set (set1) and is included in the DC motor control eTPU function set as well. It allows the user to configure an eTPU channel as a general purpose input or output. There are 7 function modes supported:

- Input mode - update periodically
- Input mode - update on transition - either edge
- Input mode - update on transition - falling edge
- Input mode - update on transition - rising edge
- Input mode - update on request/disable transition and match updates
- Output mode - output low
- Output mode - output high

GPIO function is configured to generate an interrupt to the CPU in case of an overcurrent fault. The fault signal, which is usually connected to the eTPU output disable input, can be also connected to the eTPU channel assigned a GPIO function. When the fault signal turns active, selected output channels are immediately disabled by the eTPU hardware. At the same time, the GPIO function generates an interrupt, in order to notify the CPU about the fault occurrence.

For more details about the GPIO eTPU function, refer to Reference [11](#).

4.5 eTPU Timing

eTPU processing is event-driven. Once an event service begins, its execution cannot be interrupted by another event service. The other event services have to wait, which causes a service request latency. The maximum service request latency, or worst case latency (WCL), differs for each eTPU channel. The WCL is affected by the channel priority and activity on other channels. The WCL of each channel must be kept below a required limit. For example, the WCL of the PWMC channels must be lower than the PWM period.

A theoretical calculation of WCLs, for a given eTPU configuration, is not a trivial task. The motor control eTPU functions introduce a debugging feature that enables the user to check channel latencies using an oscilloscope, and eliminates the necessity of theoretical WCL calculations.

As mentioned earlier, some eTPU functions are not intended to process any input or output signals for driving the motor. These functions turn the output pin high and low, so that the high-time identifies the period of time in which the function execution is active. An oscilloscope can be used to determine how much the channel activity pulse varies in time, which indicates the channel service latency range. For example, when the oscilloscope time base is synchronized with the PWM periods, the behavior of a tested channel activity pulse can be described by one of the following cases:

- The pulse is asynchronous with the PWM periods. This means that the tested channel activity is not synchronized with the PWM periods.
- The pulse is synchronous with the PWM periods and stable. This means that the tested channel activity is synchronous with the PWM periods and is not delayed by any service latency.

- The pulse is synchronous with the PWM periods, but its position varies in time. This means that the tested channel activity is synchronous with the PWM periods and the service latency varies in this time range.

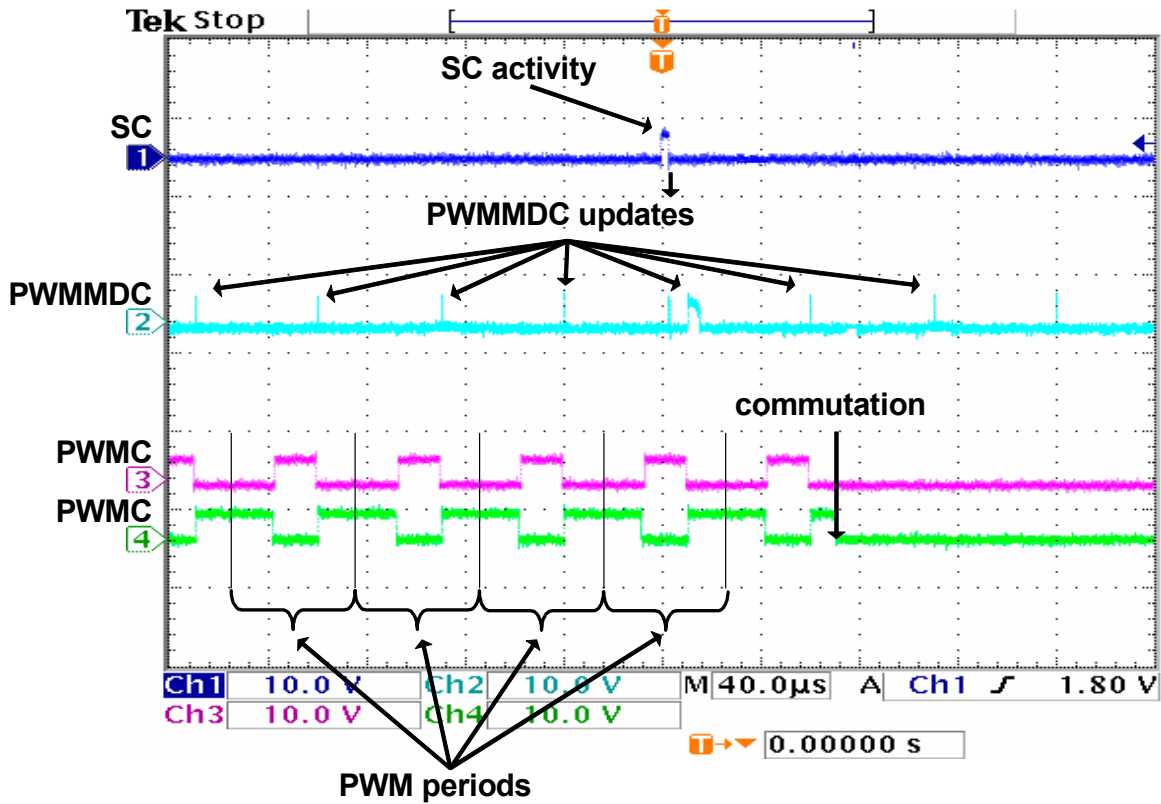


Figure 30. Oscilloscope Screen-shot and Explanation of eTPU Timing

Figure 30 explains the application eTPU timing. The oscilloscope screen-shot depicts a typical situation described below. A live view on the oscilloscope screen enables the user to see the variation of SC and PWMMDC activity pulses, which determines the channel service latency ranges.

In Figure 30, signals 3 (pink) and 4 (green) are PWM signals of one phase. It is a complementary pair of center-aligned PWM signals. The base channel (3) is of active-high polarity, while the complementary channel (4) is active-low. The PWM phase commutation is recognizable on the screen. The PWM period is 50μs, which corresponds to a PWM frequency of 20kHz.

Signal 1 (blue) is generated by the speed controller (SC) eTPU function. Its pulses determine the activity of the SC. The pulse width determines the time necessary to calculate the motor speed from the QD position counter and QD last edge time, calculate the required speed ramp, and apply the PI controller algorithm. This output is the new value of applied motor voltage. This calculation is performed periodically at a 500Hz rate, which is every 40th PWM period.

Signal 2 (cyan) is generated by the PWM master for DC motors (PWMMDC) eTPU function. Its pulses determine the activity of the PWMMDC. Immediately after each SC pulse, a very narrow PWMMDC pulse occurs. These pulses determine the service time of an SC request to update the new value of applied

motor voltage. Apart from these pulses, for every PWM period, a pulse will appear which signals a PWM update. The PWM update activity pulse is wide when a new value of applied motor voltage has been processed; it is narrow when no new value has been processed and the PWM duty-cycles are not updated.

The `fs_etpu_pwmmdc_init_3ph` function parameter `update_time` enables the user to adjust the position of the PWMMDC activity pulse relative to the PWM period frame. The activity pulse has a scheduled `update_time` prior to the end of the period frame, so that the update is finished by the end of the period frame, even in the worst case latency. Reference 10 describes how to set the `update_time` value. The difference between the values of the `fs_etpu_pwmmdc_init_3ph` function parameter `start_offset`, and the `fs_etpu_sc_init` function parameter `start_offset`, determines the position of the SC activity pulse relative to the PWM period frame. The SC activity precedes the PWMMDC activity, so that the worst case SC latency does not affect the PWMMDC latency.

5 Implementation Notes

5.1 Scaling of Quantities

The BLDC motor control algorithm running on eTPU uses a 24-bit fractional representation for all real quantities except time. The 24-bit signed fractional format is represented using 1.23 format (1 sign bit, 23 fractional bits). The most negative number that can be represented is -1.0, whose internal representation is 0x800000. The most positive number is 0x7FFFFFFF or $1.0 - 2^{-23}$.

The following equation shows the relationship between real and fractional representations:

$$\text{Fractional Value} = \frac{\text{Real Value}}{\text{Real Quantity Range}}$$

where:

Fractional value is a fractional representation of the real value [fract24]

Real value is the real value of the quantity [V, A, RPM, etc.]

Real quantity range is the maximal range of the quantity, defined in the application [V, RPM, etc.]

5.1.1 PI Controller Parameters

The PI controller parameters are set in a 32-bit extended fractional format 9.23. This format enables the user to set values in the range of -256.0 to $256.0 - 2^{-23}$. Internally, the parameter value is transformed into one of two 24-bit formats, either 9.15, or 1.23, based on the value.

5.2 Speed Calculation

The speed controller (SC) eTPU function calculates the angular motor speed using `pc_sc` and `last_edge` parameters of the QD eTPU function. The following equation applies:

$$\text{omega_actual} = \frac{\text{position_difference}}{\text{time_difference}} \cdot \text{scaling_factor}$$

where:

`omega_actual` [fract24] is the actual angular speed as a fraction of the maximum speed range
`position_difference` [int24] is the difference between the updated value of QD position counter and the previous value, which was captured by SC in the previous SC period. In fact the `position_difference` is readable from `pc_sc` parameter of the QD function. After SC reads the new updated value it resets this `pc_sc` parameters which ensures that the `position_difference` is available in the `pc_sc` parameter next time SC reads it.

`time_difference` [int24] is the difference between the updated value of QD `last_edge` and the previous value, which was captured by SC in the previous SC period

`scaling_factor` is pre-calculated using the following equation:

$$\text{scaling_factor} = \frac{30 \cdot 256 \cdot \text{etpu_tcr_freq}}{\text{omega_max} \cdot \text{pc_per_rev}}$$

where:

`etpu_tcr_freq` [Hz] is a frequency of the internal eTPU timer (TCR1 or TCR2) used

`omega_max` [RPM] is a maximal speed range

`pc_per_rev` is a number of QD position counter increments per one revolution

The internal eTPU timer (TCR1 or TCR2) frequency must be set so that the calculation of `omega_actual` both fits into the 24-bits arithmetic and its resolution is sufficient.

5.3 Definition of Commutation Tables

The PWM phases are commuted by CPU on each position interrupt generated by one of two QD channels. This is actually done by applying two commutation commands. The first command turns a phase off, and the second turns another phase on. Such pairs of commutation commands must be defined for each sector border crossing, on each phase, and for both motor directions. The commutation command is a 32-bit word that consists of the following 8-bit parts.

- Channel number of the PWM phase base channel
- New base channel commutation state. It can be:
 - ON_ACTIVE_HIGH
 - ON_ACTIVE_LOW
 - OFF_LOW
 - OFF_HIGH
- New complementary channel commutation state. It can be:
 - ON_ACTIVE_HIGH
 - ON_ACTIVE_LOW
 - OFF_LOW
 - OFF_HIGH

- New phase options:
 - DUTY_POS
 - DUTY_NEG.

For a full description of all commutation command options, refer to Reference 12.

Figure 31 depicts the MCG BLDC motor (IB23810) motor timing diagram. The following example describes how to define several of the commutation commands based on this timing diagram:

For incremental direction, read the motor timing diagram from right to left. QD position interrupt, which indicates crossing border between sectors 3 and 1, comes at 120 electrical degrees (red dotted line). The PWM phase B is turned off, with the pin in low state, and phase C on, with active-high polarity on the base channel and active-low polarity on the complementary channel, on this position interrupt. Further more, the PWM phase B option is set to not change the calculated duty-cycle value (negative duty cycle), and the phase C option is set to positive duty-cycle value, which generates a positive voltage. So, the commutation commands associated with the sector 1 in an incremental motor direction are defined, using predefined macros, as follows:

```
( (FS_ETPU_PWMDC_DUTY_NEG      <<24)+
  (FS_ETPU_PWMDC_OFF_LOW       <<16)+
  (FS_ETPU_PWMDC_OFF_LOW       << 8)+
  APP_BLDCMESL10_PWM_PHASEB_BASE_CHANNEL)

( (FS_ETPU_PWMDC_DUTY_POS      <<24)+
  (FS_ETPU_PWMDC_ON_ACTIVE_LOW  <<16)+
  (FS_ETPU_PWMDC_ON_ACTIVE_HIGH << 8)+
  APP_BLDCMESL10_PWM_PHASEC_BASE_CHANNEL)
```

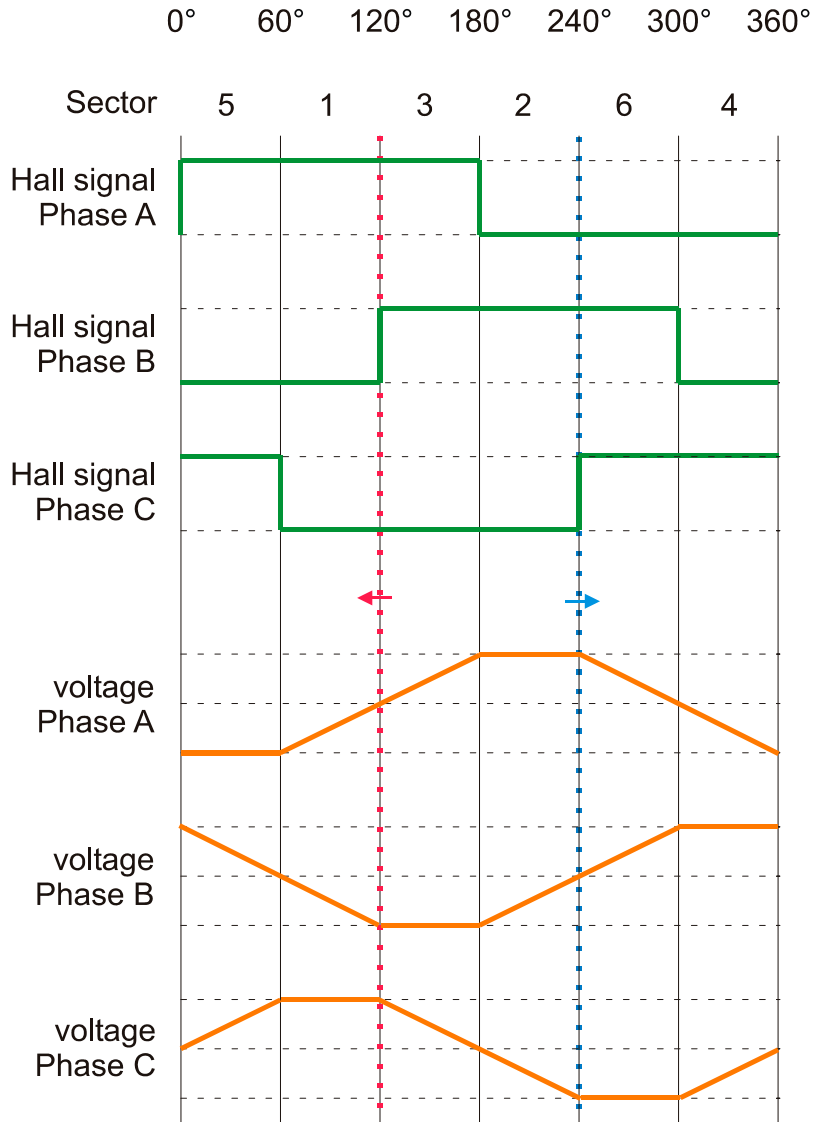


Figure 31. MCG BLDC motor (IB23810) Timing Diagram

For decremental direction, read the motor timing diagram from left to right. QD position interrupt, which indicates crossing border between sectors 2 and 6, comes at 240 electrical degrees (blue dotted line). The PWM phase A is turned off and phase C on during this position interrupt. The PWM phase C option is set to negate the duty-cycle in order to generate negative phase voltage. So, the commutation commands associated with the sector 6 in a decremental motor direction are defined, using predefined macros, as follows:

```
( ( FS_ETPU_PWMDC_DUTY_NEG          <<24 )+
  ( FS_ETPU_PWMDC_OFF_LOW           <<16 )+
  ( FS_ETPU_PWMDC_OFF_LOW           << 8 )+
  APP_BLDCMESL10_PWM_PHASEA_BASE_CHANNEL )
```

```
( (FS_ETPU_PWMMDC_DUTY_POS      <<24) +
  (FS_ETPU_PWMMDC_ON_ACTIVE_LOW  <<16) +
  (FS_ETPU_PWMMDC_ON_ACTIVE_HIGH << 8) +
  APP_BLDCMESL10_PWM_PHASEC_BASE_CHANNEL )
```

This way all commutation commands can be defined.

6 Microprocessor Usage

Table 4 shows how much memory is needed to run the application.

Table 4. Memory Usage in Bytes

Memory	Available	Used
FLASH (external)	2M	30 640
RAM	6K	5 782
eTPU code RAM	6K	6140
eTPU data RAM	1.5K	320

The eTPU module usage in terms of time load can be easily determined based on the following facts:

- According to Reference 10, the maximum eTPU load produced by PWM generation is 946 eTPU cycles per one PWM period. The PWM frequency is set to 20kHz, thus the PWM period is 3750 eTPU cycles (eTPU module clock is 75 MHz, half of the 150 MHz CPU clock).
- According to Reference 9, the speed controller calculation takes 324 eTPU cycles. The calculation is performed every 40th PWM period.
- According to Reference 8, the contribution of QD function to the overall eTPU time load can be calculated. It depends on the number of shaft encoder pulses (500) and the motor speed (maximum 1000rpm). The maximum eTPU busy time per one encoder pulse is 732 eTPU cycles.
- The GPIO function processing does not affect the eTPU time load.

The values of eTPU load by each of the functions are influenced by compiler efficiency. The above numbers are given for guidance only and are subject to change. For up to date information, refer to the information provided in the latest release available from Freescale.

The peak of the eTPU time load occurs when both the speed controller calculation and a QD signal transition are processed within one PWM period. This peak value must be kept below 100%, which ensures that all processing fits into the PWM period, no service latency is longer than the PWM period, and thus the generated PWM signals are not affected.

Table 5 shows the eTPU module time load in several typical situations. For more information, refer to Reference 13.

Table 5. eTPU Time Load

Situation	Average Time Load [%]	Peak Time Load Within PWM Period [%]
Motor Speed 10 RPM (20.8 QD pulses per second)	25.5	42.0
Motor Speed 1000 RPM (2083 QD pulses per second)	33.6	42.0

7 Summary and Conclusions

This application note provides the user with a description of the demo application BLDC motor with quadrature encoder and speed closed loop. The application also demonstrates usage of the eTPU module on the ColdFire MCF523x, which results in a CPU independent motor drive. Lastly, the demo application is targeted at the MCF523x family of devices, but it could be easily reused with any device that has an eTPU.

8 References

Table 6. References

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2. <i>M523xEVB User's Manual</i> , M5235EVBUM
3. <i>33395 Evaluation Motor Board Designer Reference Manual</i> DRM33395/D
4. MCG's Motors web: http://www.mcg-net.com
5. Quadrature Encoder HEDS-5640 A06 distributor's web: http://www.agilent.com/semiconductors
6. FreeMASTER web page, http://www.freescale.com , search keyword "FreeMASTER"
7. <i>Enhanced Time Processing Unit Reference Manual</i> , ETPURM
8. "Using the Quadrature Decoder (QD) eTPU Function," AN2842
9. "Using the Speed Controller (SC) eTPU Function," AN2843
10. "Using the DC Motor Control PWM eTPU Functions," AN2480

Table 6. References

11. "Using the General Purpose I/O eTPU functions (GPIO)," AN2850
12. "Using the Hall Decoder (HD) eTPU Function," AN2841
13. "Using the DC Motor Control eTPU Function Set (set3)," AN2958
14. eTPU Graphical Configuration Tool, http://www.freescale.com , search keyword "ETPUGCT"
15. "DSP56F80x MC PWM Module in Motor Control Applications," AN1927
16. "3-Phase BLDC Motor Control with Quadrature Encoder using DSP56F80x," AN1915/D

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