requirements for FOC such as 2x 11-channel 12-bit ADCs for fast current sensing and shutdown capability. An ADC-timing network including op-amp and comparator functions is also integrated, which enables precise measurement over the full positive and negative current range of the motor without requiring an external op-amp to perform level shifting.

> Conclusion

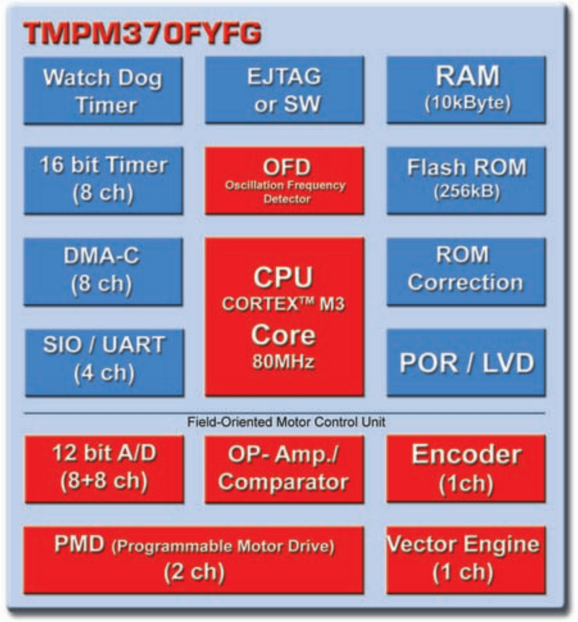
FOC/VC overcomes the low-speed imprecision of trapezoidal motor control, as well as the high-speed inefficiency experienced with conventional sinusoidal control. in addition to reducing energy consumption, FOC delivers advantages such as lower audible noise, reduced wear, constant torque over the complete speed range including zero-speed operation, and good velocity control under varying load conditions.

Hardware-based execution of the computationally intensive FOC calculations, as well as built-in analogue IP optimised for motor control, avoids the complications and performance limitations experienced when implementing FOC in software.

> TMPM370 family

Cortex
Intelligent Processors by ARM®

- CPU core (ARM Cortex-M3)
  - Max. operating freq.: 80MHz (PLL x8)
  - Operating voltage: 5V single power supply
    Low power consumption (80mA@FLASH 80MHz)
  - High-speed arithmetic unit: 1-cycle multiplier, hardware divider
  - SWD function (On-chip debugging using two wires)
- Built-in functions
  - Programmable Motor Drive (PMD): 2 CH
  - Vector engine (VE): 1 CH
  - Oscillation Frequency detector: 1 CH
    CPU Clock monitoring by HW
  - Comparator for emergency stop: 2
  - 12-bit ADC: Conversion < 2us [2units (8CH+8CH)]
  - Encoder input: 1 CH
  - 16-bit timer counter: 8 CH
  - Serial interface: UART/SIO 4CH
  - DMAC : 8CH
  - ROM correction: 8 words x 8 blocks
  - POR/LVD



Product No.	PMD / VE	ROM (kbytes)	RAM (kbytes)	Package
TMPM370FYFG	2 / 1	256	10	LQFP100
TMPM371FWFG*	1 / 1	128	6	LQFP48
TMPM372FYFG*	1 / 1	256	8	LQFP64

*) Under development/planning

In addition to above selection, you can find out more about TOSHIBAs motor control solutions at:
http://www.toshiba-components.com/motorcontrol

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Optimum Vector Control for Brushless Motors

Hardware and Software Design for Highest Performance and Lowest Whole-Life Cost

Field Oriented Control, or Vector Control, is preferred in systems using brushless motors; a number of microcontroller vendors offer FOC software as an aid to motor-control development. A new generation of MCUs that incorporate hardware-based FOC processing now simplifies design challenges as well as achieving higher performance at lower operating frequencies.

> Brushless Motor Control

Brushless DC motors offer several advantages over traditional brushed AC and DC motors, including lower materials costs, greater reliability, and longer lifetime. However, since brushless motors do not self commutate, torque control, which is fundamental to successful operation of any servo system, presents a more complex challenge. Several strategies have evolved for controlling torque in brushless motors, which perform commutation on the motor's behalf as well as calculating the optimal current for each stator to produce the maximum torque.

Torque control for a brushless motor seeks to maximise torque by adjusting the current in the stator windings to produce a net magnetic field that is orthogonal – or in quadrature - to the rotor field. Any component of the stator field acting parallel to the rotor's field will produce a force that has no turning effect. This direct component wastes energy and places additional stress on the rotor bearings. While maximising the quadrature component, torque control aims to minimise or, ideally, eliminate the direct component to ensure optimal efficiency and reliability.

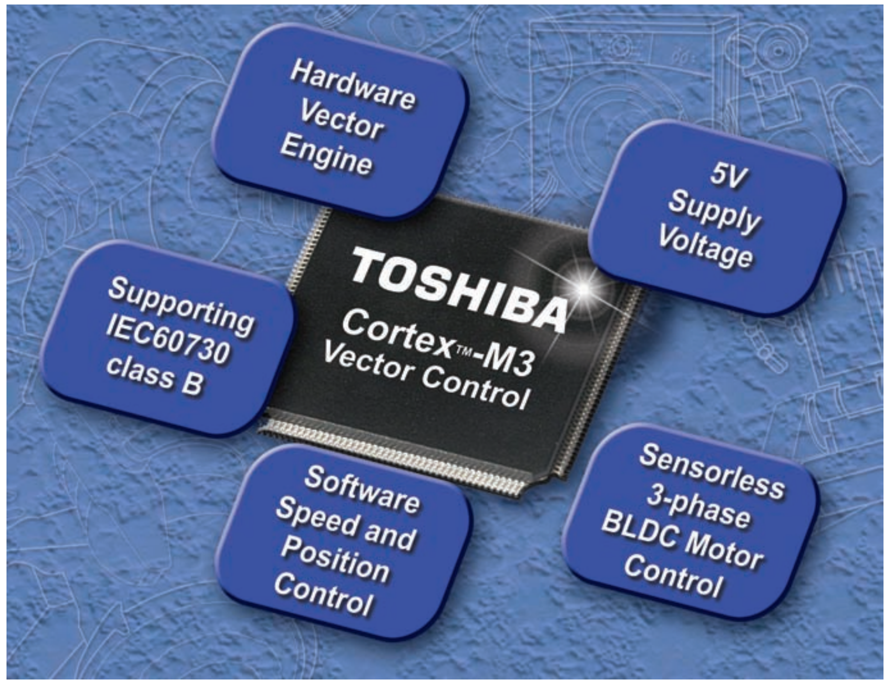


Figure2: ARM® Cortex^{TM}-M3 microcontroller with integrated hardware based vector engine and analog circuit.

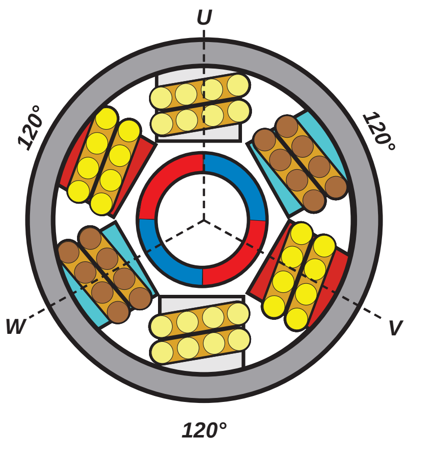


Figure1: Typical prinzip of a 3-phase BLDC motor; each phase is positioned on a 120° interval arround the axis.

For controlling three-phase brushless motors, having three stator phases positioned at 120-degree intervals around the axis of the rotor, several commutation techniques are applicable to adjust the current in each phase to produce a net stator field in quadrature with the rotor field. Common to each method of commutation, the motor current is sensed and compared with the desired torque, and a proportional-integral (PI) function then acts on the resulting error signal to generate a correction. This correction signal is subsequently pulse-width modulated and used to control the output bridge of the motor driver.

In trapezoidal motor control, also known as 6-phase motor control, the stator currents have equal magnitude in the two phase pairs either side of the rotor, while the third stator is disconnected from the power source. Rotor-position data from three Hall sensors located in between each pair of stator phases determines which phase is to be disconnected. As the rotor turns the current in each phase is switched between the maximum positive value, zero, and the maximum negative value. The resulting trapezoidal current approximates to a sinusoidal waveform. Although the *average* stator field in any period is in quadrature with respect to the rotor field, the instantaneous net stator field can lead or lag by up to 30 degrees. At low rotor speeds this results in imprecise control, as well as high levels of audible noise.

> Sinewave Control

Sinusoidal control produces smoother torque by applying sinusoidal current waveforms to the stator windings. The currents are mutually phase shifted by 120 degrees, so that the vector sum of the stator field is orthogonal to the rotor field. Compared to trapezoidal control, more accurate rotor-position information is required to generate the sinusoidal current waveforms. This may be achieved using an angular encoder or, alternatively, using sensorless position detection based on analysis of instantaneous motor current. However, accurate torque control is dependent on rapid computation of the required current value as soon as the rotor position is sensed. At high rotor speeds the limited bandwidth of the PI function results in an increasing lag between the calculated stator current and the actual rotor position, leading to inefficient operation.

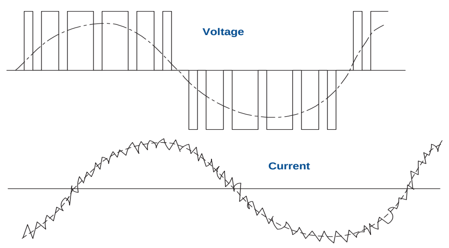
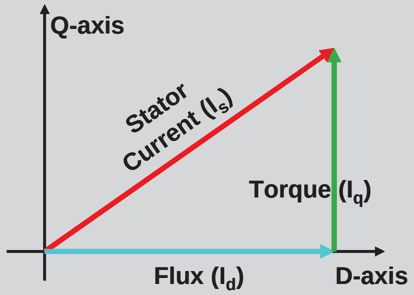


Figure3: PWM motor supply voltage and sinusoidal winding current.

Field Oriented Control (FOC):

Mathematical technique utilized for achieving a separate control (decouple) of the field producing and the torque producing portions of the currents in a three-phase machine.
In this scheme Stator current I_S is decomposed into:

- > Magnetizing current I_d, producing a magnetic field
- > Quadrature current I_q, which controls torque.



> Field Oriented Control

Field Oriented Control (FOC), also known as Vector Control, overcomes the poor low-speed accuracy of trapezoidal control as well as the high-speed inefficiency of sinusoidal control. By manipulating the motor currents and voltages with reference to the rotor's direct and quadrature axes, FOC maintains a constant stator field in quadrature with the rotor field irrespective of any bandwidth limitations of the PI controllers.

In FOC, the sensed stator currents are translated into rotor direct (D) and quadrature (Q) components by a transform function. To achieve maximum torque, the D and Q currents are then compared respectively with zero and the torque requested by the application. The resulting error signals are input to the two PI blocks, which generate signals in the D-Q reference plane. These must then be transformed into the stator domain to generate the PWM signal for each stator phase. Figure 4 illustrates the functional blocks of a generic FOC function.

Because the inputs to the PI functions are constant, FOC maintains high efficiency at all rotor speeds regardless of any limitations on PI-controller bandwidth. However, to perform FOC in real time requires fast execution of the functions that first transform the sensed stator current signals into the rotor domain and subsequently transform the static PI values into the voltage-control signals for the output bridge. Software-based FOC places maximum demands on CPU performance and operating frequency, to complete the loop within an acceptable time period in relation to rotor speed. Other factors such as integration challenges and any licensing issues must also be borne in mind when developing a motor controller using software-based FOC.

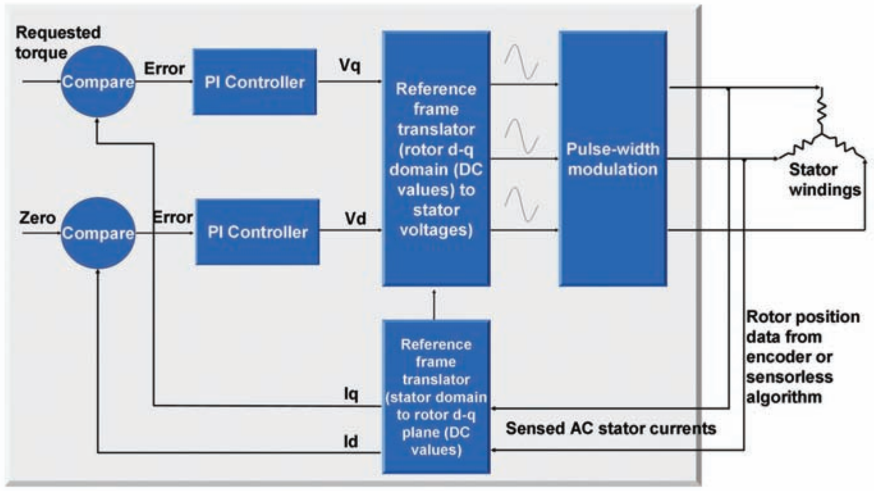


Figure4: Functional block of a generic FOC with sensorless back EMF detection.

> Hardware-Based FOC

Performing time-critical FOC computations in hardware can increase the speed of the control loop, as well as reducing operating frequency and freeing valuable processor cycles to be used for application-level functions. Figure 5 illustrates a re-partitioned FOC function taking advantage of the hardware-based vector-control engine embedded in the Toshiba TMPM370 and TMPM372 MCU for brushless-motor control. In this scheme, all FOC processing tasks that are fixed and independent of the application are performed in hardware. To perform these functions the MCU's embedded vector engine implements functions including decoding, a scheduler for event and priority control, and calculation resources including a multiply-accumulate (MAC) block for computationally intensive operations. Two vector-control units implement the PI controllers and associated functions.

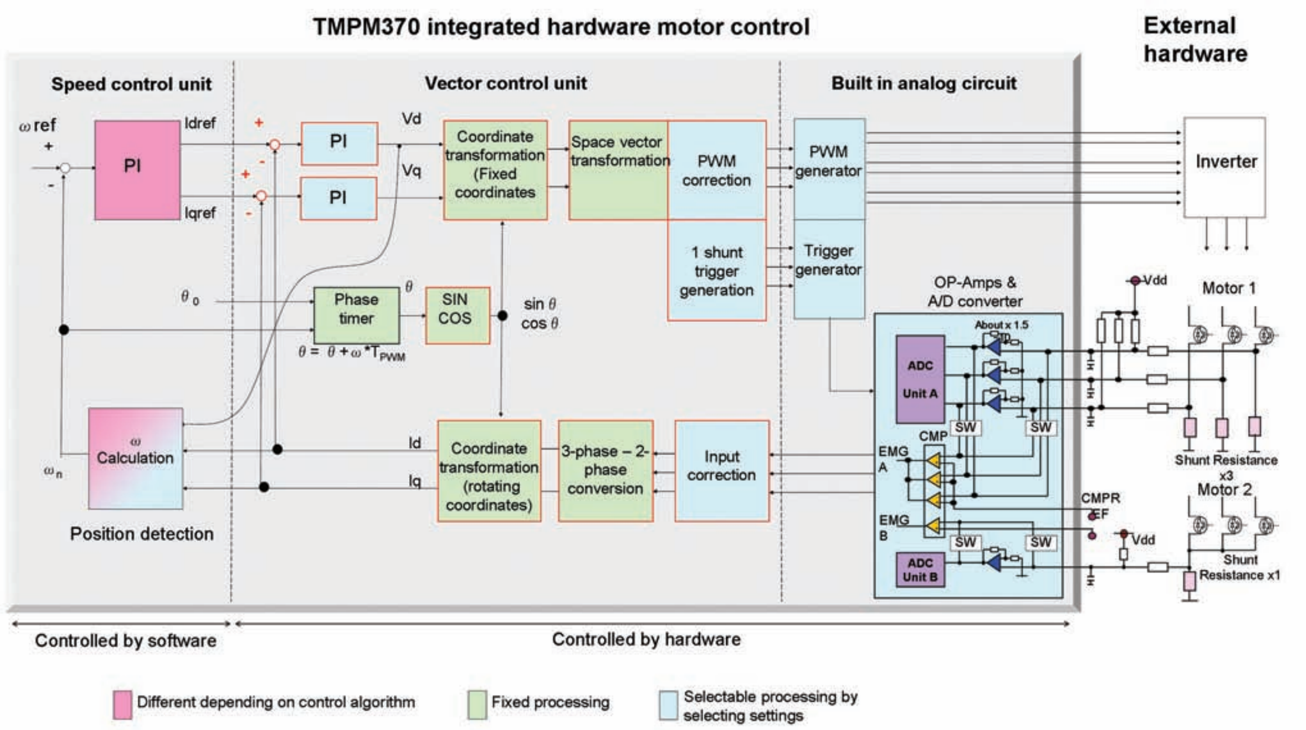
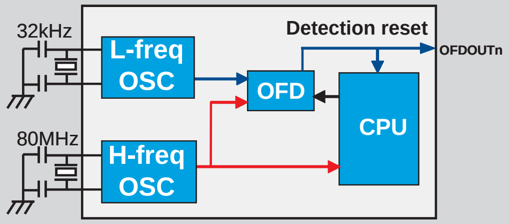


Figure5: TMPM370 with integrated hardware based PMD3+, Vector Engine and analog circuit.

Oscillation Frequency Detector (OFD):

TMPM370 group is equipped with an Oscillation Frequency Detector (OFD) which supports IEC60730 class B regulation for Conformity Testing to Standards for Safety of Electrical Equipment. The oscillation frequency detector function is a hardware to monitor CPU clock. This function automatically detects abnormal clock operation without a complex software and secures save operation.



By offloading the complex and time-critical processing to the vector engine, the TMPM370 restricts the software component of FOC to application-dependent tasks such as ω calculation and speed control. These are performed in the device's 32-bit ARM Cortex™-M3 core. With these processing resources, the TMPM370 is able to complete the control loop within each PWM period, resulting in better control stability for PWM frequencies up to 100kHz. Even when operating at 40MHz (max. 80MHz), this MCU is not only capable of controlling two brushless motors simultaneously, but also has been shown to outperform software-based vector control using a conventional MCU operated at 80MHz, thereby reducing challenges associated with thermal management, system power budget and EMI. By complying with the one-MCU-for-one-motor convention, designers can use the TMPM372 operating at 40MHz to take advantage of cost and size savings without affecting performance.

Both M372 and M370 are suitable for high-end motor control applications including next generation of appliances, pumps, industrial machinery, compressors, and HVAC (heating ventilation air-conditioning) systems. Permanent magnet brushless AC/DC, stepper and 3-phase AC induction motors are all suitable for both devices. Additionally, the TMPM370 and M372 both feature an oscillation frequency detector (OFD), which enables them to meet the IEC60730 class B safety standard.

As well as the vector engine, integrated analogue IP fulfils specific