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Off-loading the complexity of motor control – how intelligent peripherals simplify Field-Oriented-Control (FOC) implementations

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Introduction

Getting a brushless DC motor to rotate is fairly straightforward. Getting it to run optimally is more of a challenge. Traditionally, microcontroller-based solutions are the go-to option with the control firmware optimised to the motor and control electronics and any remaining processor capacity used for other light tasks.

Because of the complexity of motor control algorithms, microcontrollers with a digital signal processing (DSP) element, such as an extended instruction set or co-processor, are typically used. However, the processing demands and determinism required for motor control makes it difficult to schedule other processing tasks in the remaining clock cycles. Optimising code at assembly level is often an additional challenge.

Here we look at how microcontrollers with a built-in motor control algorithm peripheral essentially outsource these complex calculations in a deterministic manner to an Advanced Vector Engine (A-VE) module . We also examine some of the software tools available for both software/firmware development and tuning of the parameters of the motor control peripheral.

DC Motor Choices

With the advent of lower-cost electronics for motor control, electrically commutated motors have seen a huge growth in usage in the past few decades. While brushed type motors remain low cost, simple and easy to power, they do suffer from various shortcomings – they are relatively inefficient, have high inertia and the brushes wear out and cause EMI from their arcing contact with the rotor. Friction from the brushes also limits high speed operation. On the other hand, maintenance-free brushless DC (BLDC) motors are up to 15% more efficient, have a better power/size ratio, can operate over a wide speed range, have lower inertia and are electrically and mechanically quieter. The down-side is that a BLDC motor requires the DC supply to be converted into a three phase signal to drive to the stator windings and, in some cases, a sensor to feedback position to the controller electronics is required. The BLDC motor is a misnomer really as it is really a type of alternating current drive, although not necessarily at line frequency as in AC drive systems.

Because of the different characteristics of brushed and brushless DC motors, they suit different applications. Brushed types can be found in products where there is a low duty cycle of operation and cost is key such as in toys, simple appliances and ancillary motors in automotive, for example electric side mirrors. BLDC motors find application where their light weight, controllability and torque are more important such as in robotics, 'smart' household appliances, HVAC and in the drivetrain of vehicles, from electric bikes to supercars. The recent dramatic expansion of the drone market has been effectively enabled by the combination technologies of BLDC motors and batteries passing a 'tipping point' to make the product viable and literally 'take off'.

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Driving BLCD Motors

Generating the three phases of voltage to drive a BLDC motor can be relatively simple. Speed is controlled by the voltage and frequency of the AC applied and torque by the resulting current through the windings. (Figure 1). The frequency of the phase voltage is controlled by pulse width modulation with a base frequency chosen for practical reasons. Selecting too low a frequency can cause audible noise from magnetostriction and loose windings along with high switching ripple current. On the other hand, if set too high it can cause excessive losses in the transistors used to switch the individual phase voltages sequentially to the windings. In practice signals of a few tens of kHz are normal.

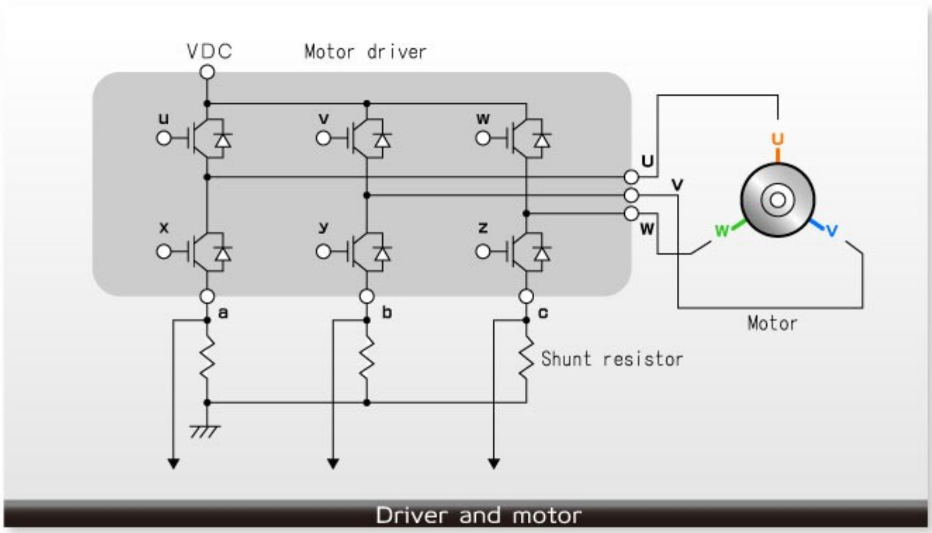

Figure 1 – Bridge drive for a brushless DC motor

Applying the AC drive voltages to the three motor windings must be done in sequence for rotation to occur. This is described as electrical commutation, compared to mechanical commutation of DC motors, and there are various schemes to achieve this [1]. The simplest is ‘trapezoidal’ where typically three hall effect sensors feed back rotor position information. In this scheme, Figure 2, a rotor sensor triggers the control electronics to drive two of the windings at the same current, leaving the third open circuit. This results in a rotational force generated at every angle of the rotor position. Because of the mechanical arrangements of windings, the back EMF generated is in a trapezoidal shape, hence the name. While any given winding is energised, the voltage applied is switched at high frequency with variable duty cycle giving variable average voltage and speed control.
A main disadvantage of this method is so-called ‘torque ripple’ where, due to the sequencing of the square-wave drive with its dead-time, the output torque is not constant but has periodic dips. In the example in Figure 2, there are 12 per mechanical revolution. At low speeds this can produce unacceptable noise and vibration.

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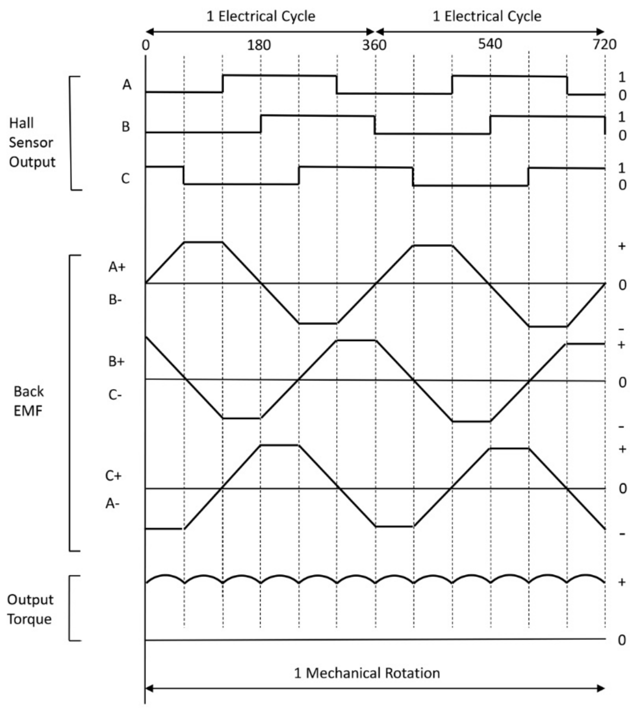

Figure 2. Trapezoidal commutation scheme showing 'torque ripple'

A better method of control is 'sinusoidal commutation' where the winding currents are forced to be sine-shaped by pulse width modulation of the driving switches (Figure 3). Control is more complex, perhaps using a microcontroller or FPGA with sine wave look-up tables for the best accuracy. This eliminates the torque ripple problem but requires much more accurate rotor position sensing, typically with an optical encoder or resolver. The benefits diminish though at high speeds where the control loop bandwidth and accuracy begin to fall off, degrading available torque.

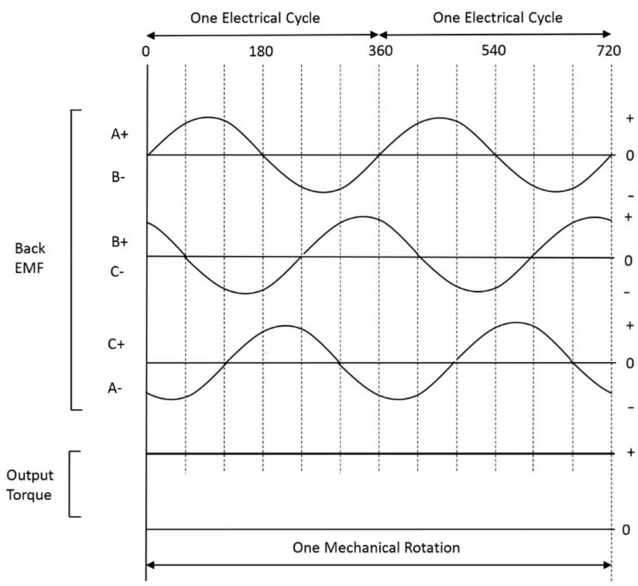

Figure 3. Sinusoidal commutation scheme

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Vector or Field Oriented Control

A technique which is becoming mainstream is Vector or Field-Oriented Control (FOC) [2]. First proposed in the 1960s, FOC promises smooth operation over the whole speed range, full torque at zero speed and superior dynamic performance with fast acceleration and deceleration. Rotor position can be determined by sensors, although there are schemes that are 'sensorless' and approximate the position. Consequential benefits are better accuracy, smaller motor size, and lower cost and power consumption. The control complexity is, however, such that, until recently, the processing power required and drive cost has been prohibitive.

FOC is a sinusoidal variable frequency commutation method which can achieve close to the ideal of keeping the rotor and stator magnetic fields at 90 degrees under all conditions, enabling maximum torque and regulation of speed/torque with changing load conditions. To achieve this, two parameters need to be derived and controlled optimally, field flux linkage and torque. These parameters need to be separated into orthogonal components (90 degrees apart in the static co-ordinates of the motor stator) and can be derived from the winding currents and rotor position. Firstly, the three-phase winding currents IU, IV, IW are passed through an A/D converter and changed to equivalent two-phase currents Iα, Iβ using the 'Clarke' conversion method, also known as '3-phase to 2-phase conversion' (Figure 4).

$$Iu + Iv + Iw = 0$$
$$I\alpha = Iu$$
$$I\beta = (Iu + 2Iv) / \sqrt{3}$$

Figure 4. Clarke conversion

Relative to the stator, Iα and Iβ are stationary. We now need the rotating coordinates Iq, Id, (quadrature, direct), representing field flux linkage and torque, which are derived from the 'Park' conversion (Figure 5) where θ is the rotation angle. This process is also called 'rotating coordinate conversion'.

$$Id = I\alpha \cdot \cos\theta + I\beta \cdot \sin\theta$$
$$Iq = -I\alpha \cdot \sin\theta + I\beta \cdot \cos\theta$$

Figure 5. Park conversion

Having calculated Iq and Id, these can be compared with target values Iqref and Idref and a compensating error signal generated, typically by a PI (proportional-integral) controller. This outputs a signal proportional to the difference between actual and reference and also proportional to the integral of the difference. This gives good dynamic response with little under- and over-shoot. The compensating signal now must be converted back to three-phase drive currents for the motor windings. This is undertaken using a reverse Park followed by a reverse Clarke conversion. A switched-bridge power stage follows, typically implemented with MOSFETs or IGBTs. The devices are pulse-width modulated to achieve sinusoidal drive currents and have associated protection features to ensure reliable operation, and filtering to meet EMI specifications. Figure 6 gives a block diagram for a FOC scheme.

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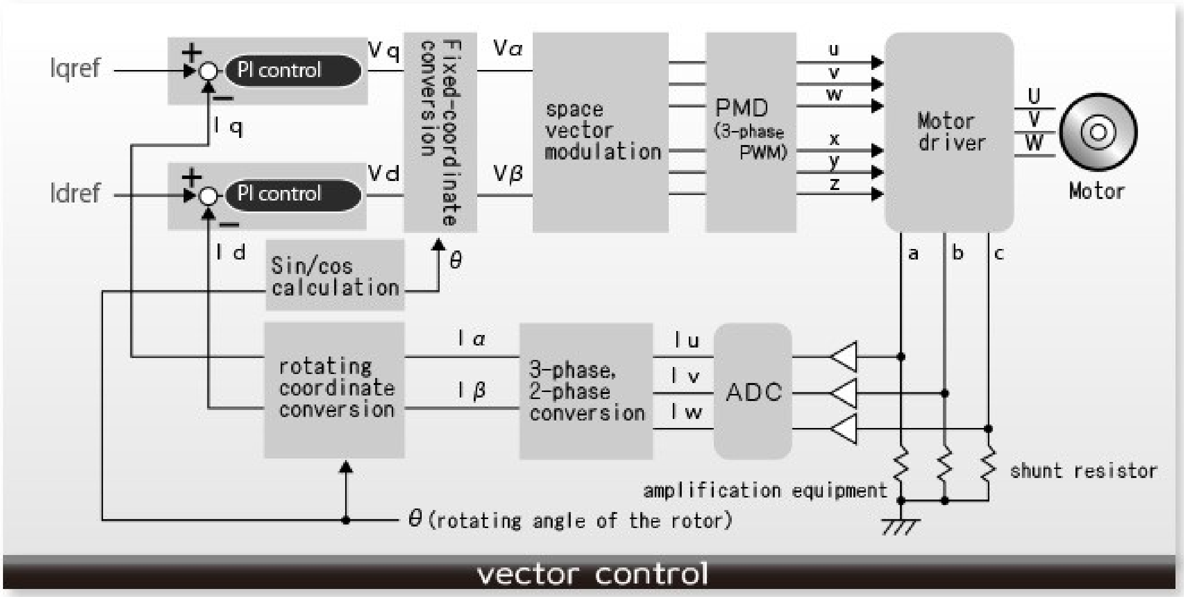

Figure 6. FOC or 'Vector' Control of a BLDC motor

Even a minimal FOC controller for a BLDC motor can be seen to be quite complex. A processing solution needs to include appropriately dimensioned ADCs, a processor that can handle vector mathematics for the Park and Clarke forward and reverse transformations, a software implementation of PI control, and suitably granular pulse width modulator. Implementing this however, can be problematic; microcontrollers typically don't have the appropriate instruction set whereas a Digital Signal Processor (DSP) does, but lacks efficient instructions for input/output control. An FPGA is an option but may not have sufficient programmability to handle the other functions that might be needed such as network connectivity and operational (human-machine) interfaces. Early systems were assembled from a general-purpose controller with external discrete hardware to perform the functions of A/D conversion and pulse width modulation with connecting logic. This allowed incremental addition of features such as analogue filtering of current signals and PWM dead time control, but came at the cost of additional device count and board space. Programming of the controller for the Park and Clarke transformations and PI control is also a complex task. As system performance demands increase and space shrinks, a dedicated controller or accelerator for FOC control becomes more attractive, ideally tailored to the exact requirements of vector mathematics with the appropriate ADC performance. All this working at a speed that would allow faithful rendering of sine-wave drive currents for 150,000 rpm motor speeds and higher.

Dedicated FOC controllers are available

A part that does just this is the Toshiba Advanced Vector Engine (A-VE) [3], part of their M4K group of devices of the TXZ4 series. Based on the competent Arm Cortex-M4 MCU platform running at 80MHz and higher, it is capable of controlling two motors leaving processing capability to spare. (Figure 7).

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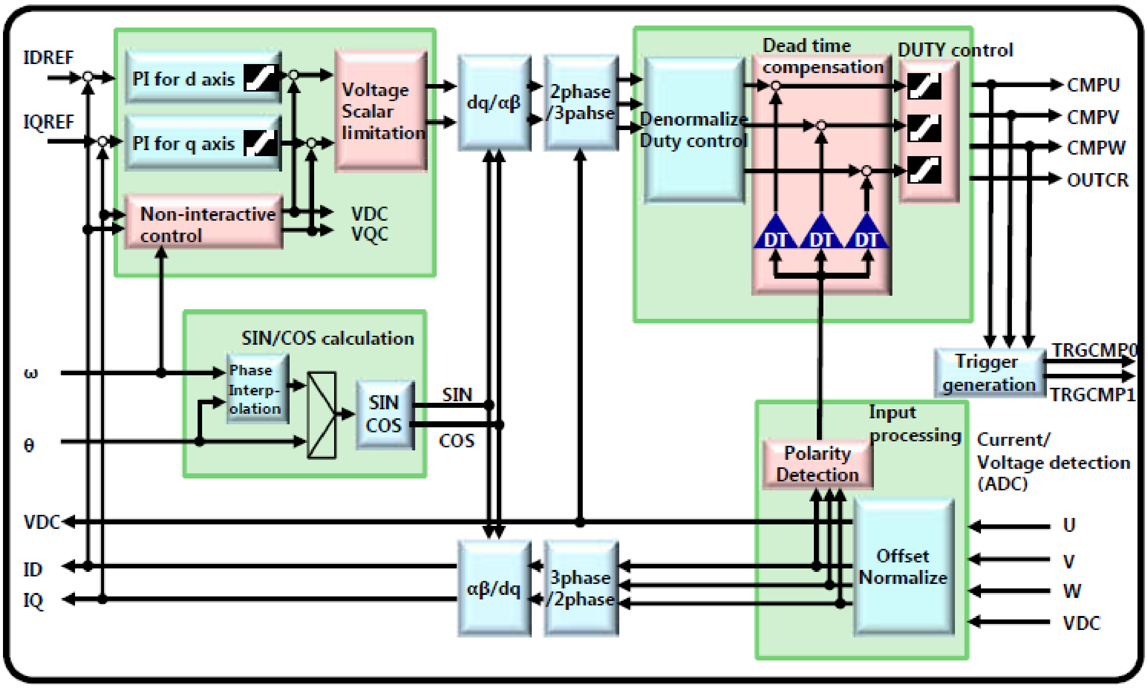

Figure 7. The Toshiba Advanced Vector Engine

In the diagram, the two sets of 3-phase/2-phase blocks implement the Clarke and reverse Clarke transforms, while the αβ/dq, dq/αβ blocks implement the Park and reverse Park transforms. Other notable features are the ‘non-interactive control’ block which compensates for interference between the d-axis and q-axis and the ‘dead-time compensation’ block which helps to prevent distortion of the drive sine waveform at zero-crossings. This version of the A-VE works in combination with a PWM stage and an ADC to pass analogue motor current signals as digital input to the A-VE.

The A-VE is actually an evolution of earlier iterations of the Vector Engine that were denoted VE and VE+. Compared with the earlier versions, the A-VE has a wider PI gain range, the inverse Clarke transform is included, and it has improved the ability to operate with a single current shunt in three-phase conversion. Further functional improvements include non-interactive control, dead-time compensation, minimum pulse width control, voltage limitation of the current control and reverse polarity operation of the current sensor. Special calculation functions available include square root (SQRT) and arctangent (ATAN). Compared with the VE and VE+ versions, more fixed configurations or ‘schedules’ can be selected (15 versus 4) for user convenience.

A particular feature of the A-VE is its ability to capture a clean representation of motor current when in single shunt mode by shifting PWM phase waveforms in time while preserving mark-space ratio. This makes control more accurate and reduces the need for software filtering of the measurement. The ADC measurement of motor current can also be triggered by the PWM stage with a pre-determined delay to avoid coincidence with switching edges which might corrupt the signal. The synthesis of a sine wave from the PWM output by its nature introduces discrete steps. However, the A-VE can apply interpolation in ‘repeat schedule’ mode which smooths the waveform to a near perfect sine wave. (Figure 8).

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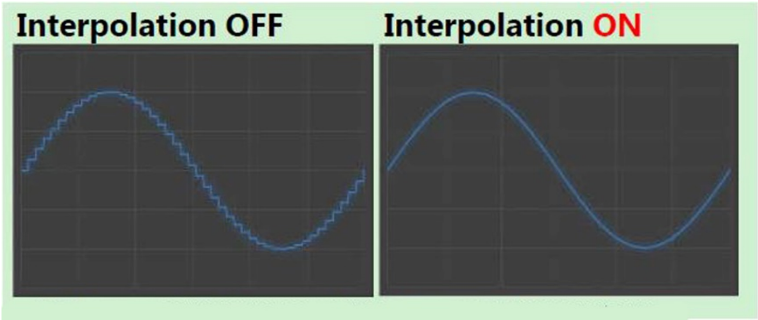

Figure 8. Improvement in sine wave output quality with A-VE interpolation function

The A-VE is a highly deterministic device using relatively little CPU processing power, freeing up the CPU for the end-application and other functions such as sensing, interfacing and other power functions such as Power Factor Correction (PFC). Reference data from Toshiba shows a typical 70% reduction in CPU load compared to pure software implementations of an FOC algorithm in the CPU. Changes to the compiled assembler code, such as enabling compiler optimisations or turning debug support on and off, has much less impact on the motor control performance when using the A-VE, helping considerably with real-time debugging and tuning. Advantages are particularly seen when two motors are controlled - if this were done by the main CPU, clock speeds would need to be increased with consequent increase in power consumption and possible EMI issues.

Compliance with IEC 60730 (White Goods Safety Standard)

A particular benefit arising from the decreased CPU load is simpler compliance with IEC 60730 (White Goods Safety Standard), which requires real-time processor and memory tests to ensure safe operation of embedded control hardware and software. Control electronics falls into three categories, A, B and C, increasing in criticality for safety. For comprehensive compliance, control equipment needs to monitor and exercise software flow, interrupt handling and execution, clock accuracy, external communications through I/O ports and memory performance, typically by cyclic redundancy checks (CRC) and more. With the A-VE handling the majority of the motor control, the the CPU is freed up to schedule these tasks as well as perform the application.

FOC systems require tuning

Development of an FOC control system also requires tuning of the PI stage gain to match the needs of the particular motor selected. This typically results in different values for light, medium and heavy loads. Too low a gain will produce a slow response to demanded changes and too large will give oscillatory over- and under-shoot, while the ideal gain provides a rapid but critically damped response (Figure 9). Motor winding resistance and inductance also need to be known, ideally with their variation over the operating temperature specified. Toshiba assist in this tuning phase with their graphical PC utility 'MotorMind'. Utilising a simple serial interface communication with the target hardware, it is possible to adjust all A-VE peripheral parameters with the changes being effected in real time. It is even possible to access and visualise information buried deep inside of the vector engine without the need to implement additional data aquistion interfacing.

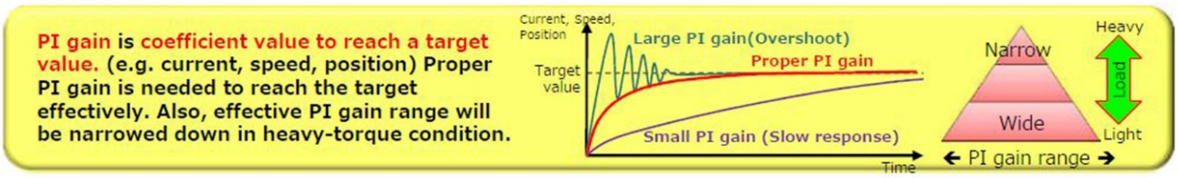

Figure 9. PI gain optimised for best response

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Software development is simplified thanks to the worldwide support and development tools available for Arm processors. These include the low-cost Toshiba MDK-ARM development environment for Cortex-M devices available with a one-year license. Real-time operating systems that can be used include UCT uT-Kerenel DevKit, uC3/Compact, ThreadX-uITRON, uC/OS-II and Toshiba's UDEOS4/Cortex-M3, as well as no-cost options such as the widely used FreeRTOS.

The Arm processor itself supports comprehensive debug functions such as core-stop, reset and stepwise execution, hardware breakpoints, data watchpoints, and optional branch/data trace functions. Debug communication (JTAG/single wire debug - SWD) and trace signal specifications follow Arm's standard specification. The A-VE itself is also simple to program, requiring essentially only three API calls: start, stop and a 'configure parameters' function.

Example products available from Toshiba include an Advanced Vector Engine capable microcontroller running at 120MHz with a single 5V supply, with options for 512KB flash ROM and 32KB RAM. It has two motor control channels and two 12-bit A/D converters. A typical application for the device would be smart home appliances or industrial motor control. A similar part is also available with CAN bus communications. For light applications such as server fan control, vector engines are available in the tiny 5 mm x 5mm VQFN32 package that can drive the gates of a MOSFET bridge directly for minimum component count and optimally dimensioned solution. Comprehensive learning and application support is available from Toshiba [3].

How fast can FOC go?

Very high-speed rotation of motors delivers a set of unique challenges, as the accuracy of the rotor position reduces due to having less sample points available per rotation. For a reasonable sine-wave approximation, at least 12 sample points per period are required. For the Toshiba solution with a one pole-pair motor, the maximum PWM frequency while performing a commutation point calculation once per PWM cycle is 50kHz (20µs). 20µs x 12 (points) offers a period length (T) of 240µs, giving a frequency or electrical speed of 4167Hz. This equates to a little over 250,000 rpm, which certainly covers all common applications with room to spare. This is all achieved within the standard limits of the A-VE without having to implement any special features or optimisations. If the application demands it, this top-end rotation speed could be pushed even further.

Summary

With a wide array of possible choices available, it can be difficult to find the FOC motor control solution that best meets the specific needs of an application. It is clear that when FOC motor control is implemented entirely in software, development and debugging of the system becomes exceptionally challenging. However, the sophisticated MCU-based hardware offerings that are now being introduced utilizing dedicated hardware modules such as the Toshiba Advanced Vector Engine' solve many of the fundamental issues relating to FOC. They are optimally designed to implement FOC in programmable microcontrollers freeing processing capacity for other system level tasks. Isolation from main processor workload and interrupts can also be achieved to allow each element to work with optimal efficiency.

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