Achieving Low-Noise, Sensorless Field-Oriented Motor Control

Implementing low-noise sensorless FOC from a standstill

Introduction

The move to electronically commutated motors has seen massive improvements in energy efficiency, which in turn contributes to the reduction of both the operational cost and the amount of greenhouse gases that industry and consumer goods emit. However, this switch is not without its challenges. Brushed DC motors were able to use their brushes and slip-ring configuration to commutate the motor at the correct moment in time as this configuration also served to indicate the angle of the rotor in relation to the permanent magnets. Regardless of the rotor orientation the coils would always be energized at the appropriate time, enabling an efficient motor start-up.

With the introduction of brushless electronic commutation motors (permanent magnet synchronous motor, PMSM), this inherent knowledge regarding the rotor angle is lost. Simply applying energy to a randomly selected combination of coils and hoping for the best can, in the worst case, result in a sudden movement of the rotor as it tries to align itself with the stator's magnetic field causing mechanical stress and potential damage to both the motor and the housing. In the laboratory, this often results in the motor jumping violently in the air. The obvious way to avoid this is by implementing a sensor that, together with the control electronics, can determine the rotor angle at any moment in time (figure 1). At spin-up, a rotor-mounted sensor such as a resolver ensures that the appropriate coil combination can be energized while, during operation, electrical commutation can be applied at precisely the correct moment in time.

There are, however, many reasons why the addition of such rotor sensors cannot be implemented. Typically, they are mounted at the rear end of the motor's shaft, consequently adding to the volume of the motor and requiring additional wiring. While Hall sensor implementations are relatively cheap, even this may still be too expensive for cost-sensitive applications. And, finally, every extra component is a failure risk, especially when mounted to the motor itself. The sensor's electronics, along with its wiring and connector, are additional items that are exposed to vibrations and can thus 'go wrong'. Consequently, the desire to operate such motors without sensors is very appealing. One challenge remains: How should the rotor angle be determined to guarantee optimal electronic commutation?

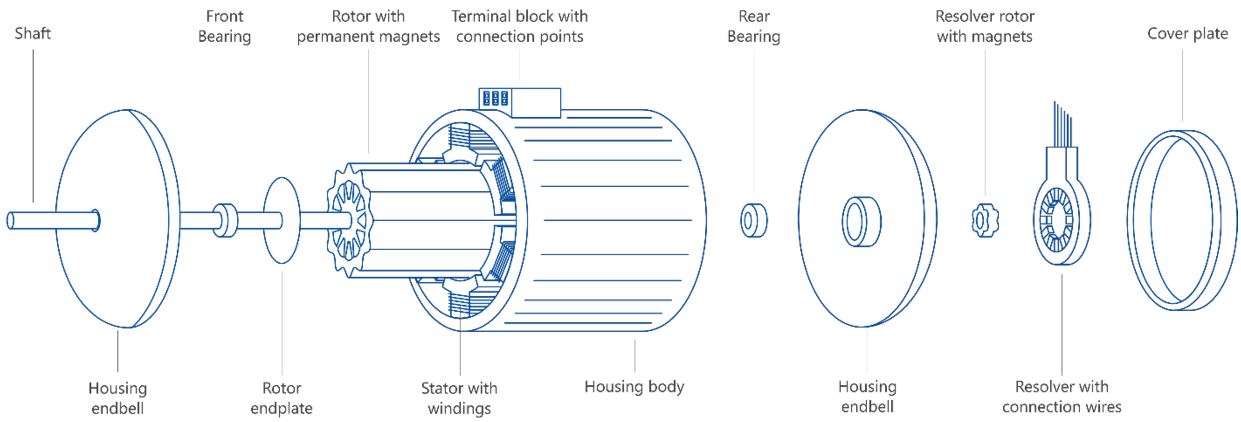

Figure 1: An exploded view of the PMSM; the resolver adds to the cost, volume, and weight, while also adding another potential failure-point in the final system.

The magic of mathematics

Thanks to Faraday's law of induction we know that an electromotive force (EMF) is generated by a magnet passing through an electric coil.

$$\varepsilon = -\frac{\delta\Phi_B}{\delta t}$$

In the case of a PMSM, the permanent magnets of the rotor are passing by the stator coils and thus generate an EMF into the stator windings. This back EMF effect can be measured by the microcontroller being used, typically via an analog-to-digital converter (ADC) and is provided to the control algorithm. From here, the rotor angle can be determined mathematically. The issue with this approach is that the rotor must be moving in order to be able to generate back EMF in the stator windings. At start-up, the rotor is stationary. Therefore, no back EMF is being generated. Even when the rotor is moving, it requires a certain rotational speed before enough back EMF is being generated for the microcontroller to acquire a reasonable signal. Thus, sensorless motor control algorithms struggle when the rotor is stationary or rotating at a slow RPM (revolutions per minute).

One option is to forcibly, but carefully, commutate the motor to get the rotor rotating in order that enough back EMF can be generated. A frequently used technique is 6-step commutation, a simple commutation method that results in high power consumption and significant torque ripple which, in turn, generates mechanical stress in terms of vibrations resulting in audible noise. There are, however, a wide array of applications for which high initial power consumption, vibration and the associated noise generated is unacceptable, ranging from pumps, motors, and compressors in white goods, to heating, ventilation and air conditioning (HVAC) systems and variable frequency drives in conveyor belt systems. Those looking to achieve higher reliability and lower levels of audible noise will be using Field-Oriented Control (FOC) approaches, so would prefer to also find a sensorless FOC solution that operates from start-up, through low rotational speed, and up to the final operational speed.

FOC – a brief overview

Torque ripple in the control of brushless motors using 6-step control methods occurs because it is not possible to ensure that the magnetic fields of the stator and rotor are maintained at a constant angle of 90° to one another. Instead, it fluctuates between 60° and 120° degrees causing alternating acceleration and deceleration of the rotor resulting in a ripple in the rotor speed. This causes vibrations that are not only perceived as audible noise but also create significant mechanical stress on the motor components, lowering the system's reliability. FOC, which is also known as vector control, resolves such issues by generating a smoothly rotating stator magnetic field that is continuously controlled to ensure a constant 90° lead angle to the rotor magnetic field (figure 2). Use of FOC results in constant torque and thus prevents speed ripple that, in turn, minimizes both mechanical stress and acoustic noise.

Knowing the position of the rotor, the required 90° lead angle stator magnetic field can be calculated to achieve a constant torque. Three signals need to be generated to excite the stator coils that will result in this precise angle of the magnetic field. The rotor will then, naturally, rotate toward this point. This movement needs to be anticipated by the control algorithm so that the excitation of the coils can be appropriately modified to maintain the 90° angle. The result is three sinusoidal control signals, each 120° phase shifted to one another, generating a smoothly rotating magnetic field that drives the rotor with a constant torque to achieve the desired RPM set-point for the motor (figure 2).

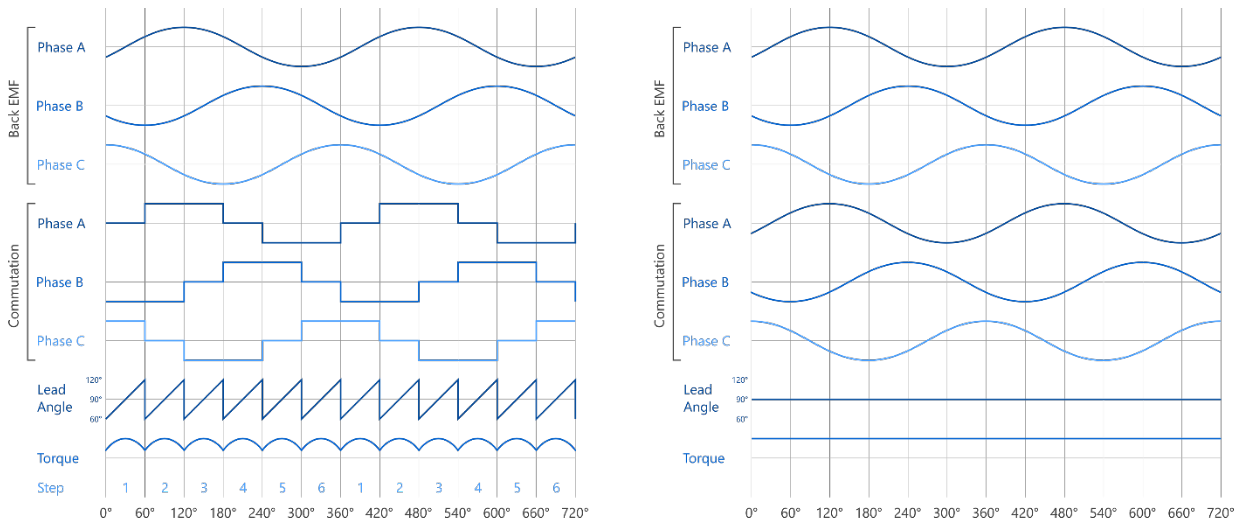

Figure 2: Torque ripple of a 6-step commutation (left) compared with FOC (right).

Unfortunately, the control of the time variant sinusoidal three-phase currents is challenging to implement in a PI(D) (proportional, integral, differential) controller. FOC algorithms prefer to use a time invariant representation by transforming these three-phase currents into a two dimensional reference frame which is related to the moving rotor and consists of direct (or flux) and quadrature (or torque) currents I_d and I_q. The mathematics used to do this is known as the Clarke and Park transformations. From here, time invariant and relative to the rotor angle, the 90° angle can be maintained by applying the 'donkey and carrot principle'. The current I_d along the direct axis is pushed towards 0 and the current I_q along the quadrature axis is pushed towards the required torque value using two PI controllers.

Once this has been calculated, the time invariant, two-dimensional result can be converted back into a time variant, three-phase signal that will generate the required stator field to maintain the constant 90° lead angle, ensuring that the rotor continues to rotate at the desired RPM. This is implemented using inverse Clarke/Park transforms. More details regarding the Clarke/Park transforms can be found in other Toshiba white papers on motor control [1].

To generate the required sine control signal, the microcontroller varies the mark/space ratio of its pulse-width modulated (PWM) output continuously from 0% to 100% at three of its output pins so that three sinus signals, 120° apart, result from the motor inverter at a frequency that reflects the desired motor RPM (figure 3). The motor inverter (marked 'Motor Driver' in figure 3) is required to deliver the necessary current to power the motor's stator coils.

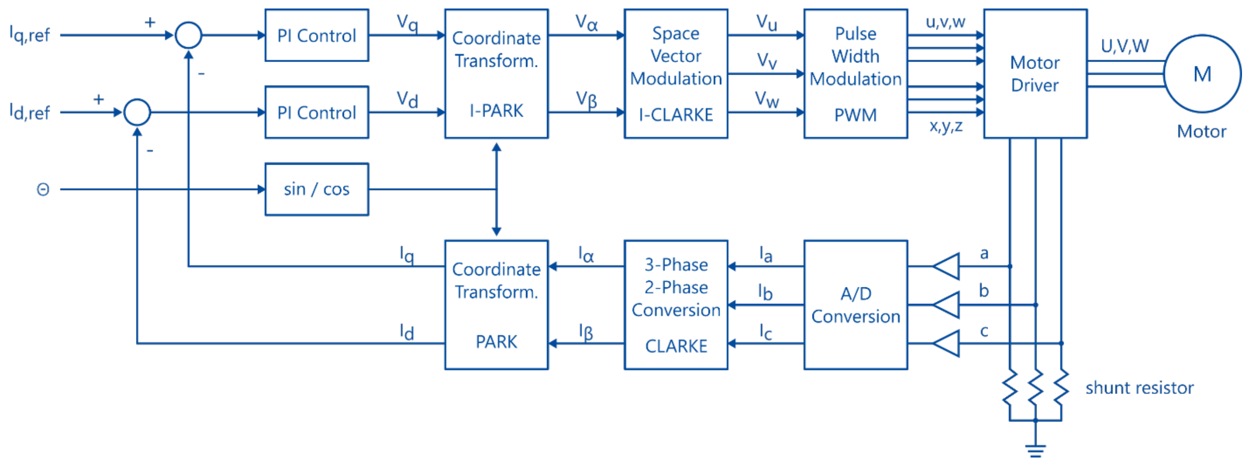

Figure 3: FOC, or vector control, block diagram with transformations from the time variant three-phase motor currents into the time invariant d, q reference frame.

Rotor position sensing options

As already pointed out, an accurate picture of the position of the rotor is an essential element in these calculations. This can be achieved using either sensors or using sensorless approaches.

The most straightforward method to determine the rotor position is to use an incremental or line encoder. This optical device detects marks on a wheel mounted on the rotor shaft and provides signals to the controller every time a mark passes the device. Encoders provide by far the highest accuracy (depending on the density of marks on the wheel, usually less than 1°) but are the most expensive option. As already highlighted, form factor and mounting position can make them challenging to accommodate, and the additional wiring and connector can be perceived as an additional failure source.

Resolvers or Hall sensors are the next best options. They can detect the magnetic field of the rotor's permanent magnets and thus determine the current rotor position. Resolvers are expensive but feature excellent accuracy even at very high RPMs. Hall sensors are a significantly cheaper solution but require a compromise on accuracy and maximum possible RPM. Similar to encoders, both resolvers and Hall sensors need to be mounted on the motor where they occupy additional space for the devices, the wiring and the connectors. And, similar to encoders, they constitute an additional potential failure source.

Sensorless techniques do not require any encoder or sensor to be mounted on the motor while providing sufficient accuracy for most FOC applications. They rely upon the physical effect of the magnetic flux of a permanent magnet inducing a current in a stator coil when passing. In the case of brushless DC motors it is the rotor's permanent magnet that induces a current into the stator windings when passing the stator coils. The current induced by the magnets can be converted into a voltage by using shunt resistors that then can be measured by an ADC. As depicted in figure 3, the basic FOC loop already includes ADCs used to measure the phase current applied to the stator coils. The same ADCs can be re-used to detect the back EMF generated by the rotor and thus to determine the current rotor position. This requires complex algorithms to separate the current used to excite the stator phases from the back EMF currents induced by the rotor. Popular techniques either use three individual shunt resistors for each motor phase (3-shunt) or a common, single shunt resistor for all motor phases (1-shunt). As can be imagined, 1-shunt solutions are the cheapest option but require the most complex algorithms for the detection of the back EMF and the calculation of the current rotor position.

From this, it is clear that the sensorless approaches are very low cost, offer a higher reliability thanks to their lower system complexity and enable small form factors, while providing adequate precision of the rotor position. However, establishing rotor angle is challenging when the motor is stationary or at low RPMs.

Low-speed sensorless PMSM control

FOC control algorithms for PMSM control typically include a range of additional blocks that are engaged and disengaged using a state machine that depends upon the current state of the rotor operation. In normal operation, the FOC algorithm can be executed as normal. However, at low RPMs (the threshold of which needs to be determined for the system) additional algorithmic functionality may be applied to compensate for the loss in back EMF. The final state is that of rotor standstill, where a further set of algorithms may be implemented to achieve rotor spin-up.

The simplest approach to spin-up is to simply and gradually generate the rotating magnetic field and hope that, at some point, the rotor follows the field. Then, at some point, the motor will generate enough back EMF for the algorithm to use for accurate rotor position calculation. The issue with this approach is that it requires high currents and may generate a lot of torque ripple leading to vibration and audible noise. There is also the risk of serious mechanical damage if the rotor makes sudden and large rotational movements. If such a process was implemented in the compressor of a consumer refrigerator, both user experience and product lifetime could suffer.

More advanced approaches monitor changes in the inductance of the stator windings that are caused by the passing magnetic field of the rotor. The inductance is at its maximum where the stator coil and the rotor's main flux axis (d-axis) are orthogonal to each other (at 90° and at 270°) while its minima are where the stator coil and the rotor's main flux axis are parallel to each other (at 0° and at 180°). When plotting the inductance over time it will be a sine waveform with a frequency twice that of the rotor speed (figure 4).

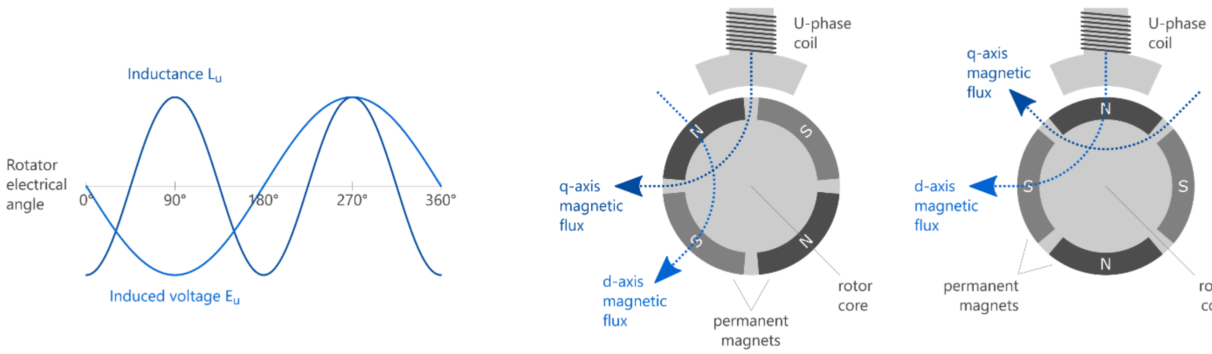

Figure 4: The inductance of the stator coils varies at twice the rotor speed due to 'magnetic saliency' and can be used to determine rotor angle.

This variation in inductance, known as 'magnetic saliency', is a prominent feature of Interior Permanent Magnet motors (IPM). It can be determined using methods such as high-frequency voltage application that superimposes a high-frequency, low-amplitude signal on top of the stator current signal. The resulting variations in motor current are then monitored, allowing the rotor position to be calculated mathematically. However, the approach is not without its challenges. The constant application of a high-frequency signal may result in problems achieving electromagnetic compatibility (EMC). It also induces torque ripple, which is less energy efficient, and is the cause of vibration and additional acoustic noise – precisely those challenges we are attempting to overcome.

Another approach making use of the magnetic saliency is a technique known as the INFORM method. It is similar to the previous method but, instead of a continuous application of the high-frequency signal, the signal is applied intermittently during the space of the PWM output. Again, the amount of change in the stator current is measured to calculate the rotor angle. If the current variation is the same, this method can detect the rotor's magnetic polarity with a higher level of accuracy than the previous method. This is due to the measurement being unaffected by switching characteristics, such as deadtime and on-voltage drop. Despite these benefits, the INFORM method still results in significant acoustic noise as well as EMI caused by the application of the intermittent signal (figure 5).

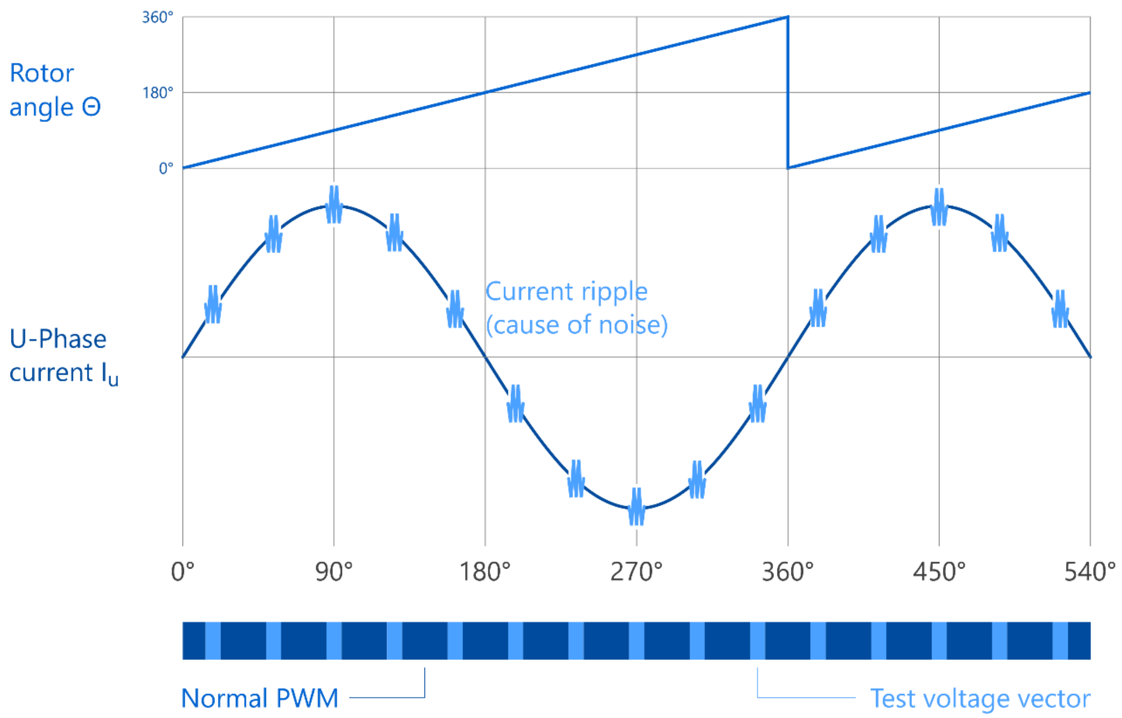

Figure 5: The INFORM method applies intermittent high-frequency pulses to the phase control signal, but this can still result in higher-than-desired acoustic noise.

Symmetric carrier PWM Method

In order to avoid the use of high-frequency injected signals, Toshiba is developing an alternative method that utilizes symmetrical PWM carriers for the three motor phases [2]. This resolves the issues of the methods discussed previously while also offering reliable rotor position estimation at both low RPMs and rotor standstill.

The approach makes use of the unique modulation features of advanced PWM modules in Toshiba's TXZ+™ microcontrollers allowing each of the three PWM outputs to individually use one of three possible modulation carrier waveforms: triangular wave, sawtooth wave, and inverse sawtooth wave. The 'Advanced Programmable Motor Driver' (A-PMD) PWM modules also generate a common trigger for the device's ADCs that are synchronously monitoring the current on two of the three motor phases (e.g., phase U and W) prior to and after the synchronization point of the three PWM outputs. Due to the interaction of the synchronously linked PWM carriers, all current measurements happen while only two of the three phases are excited.

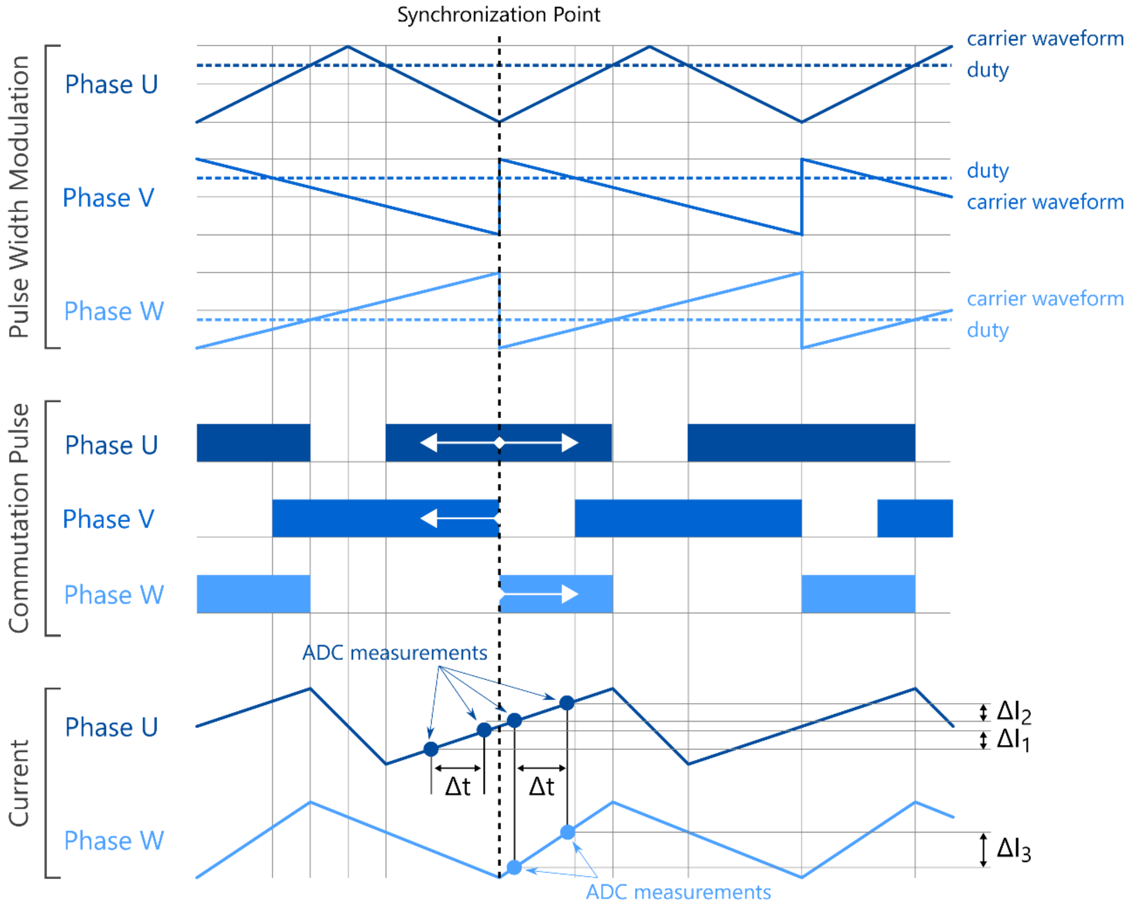

Figure 6: Using three symmetric carriers the phase currents can be acquired when one of the three PWM outputs is inactive.

As can be seen in figure 6 above, each PWM only outputs its signal when the carrier waveform lies below its duty setting. The point in time where all three reference waveforms change in direction forms the moment in time around which the ADCs can determine the change in current. One differential current measurement is performed before this synchronization point when only phases U and V are energized. The other two differential current measurements are performed after this synchronization point when only phases U and W are energized. The estimation of the rotor angle position is based on these three differential current measurements and can be achieved with minimal additional computational effort. Still it has been proven to provide sufficient accuracy while generating significantly lower levels of noise at low rotational speed (compared to the previous methods reviewed, figure 7).

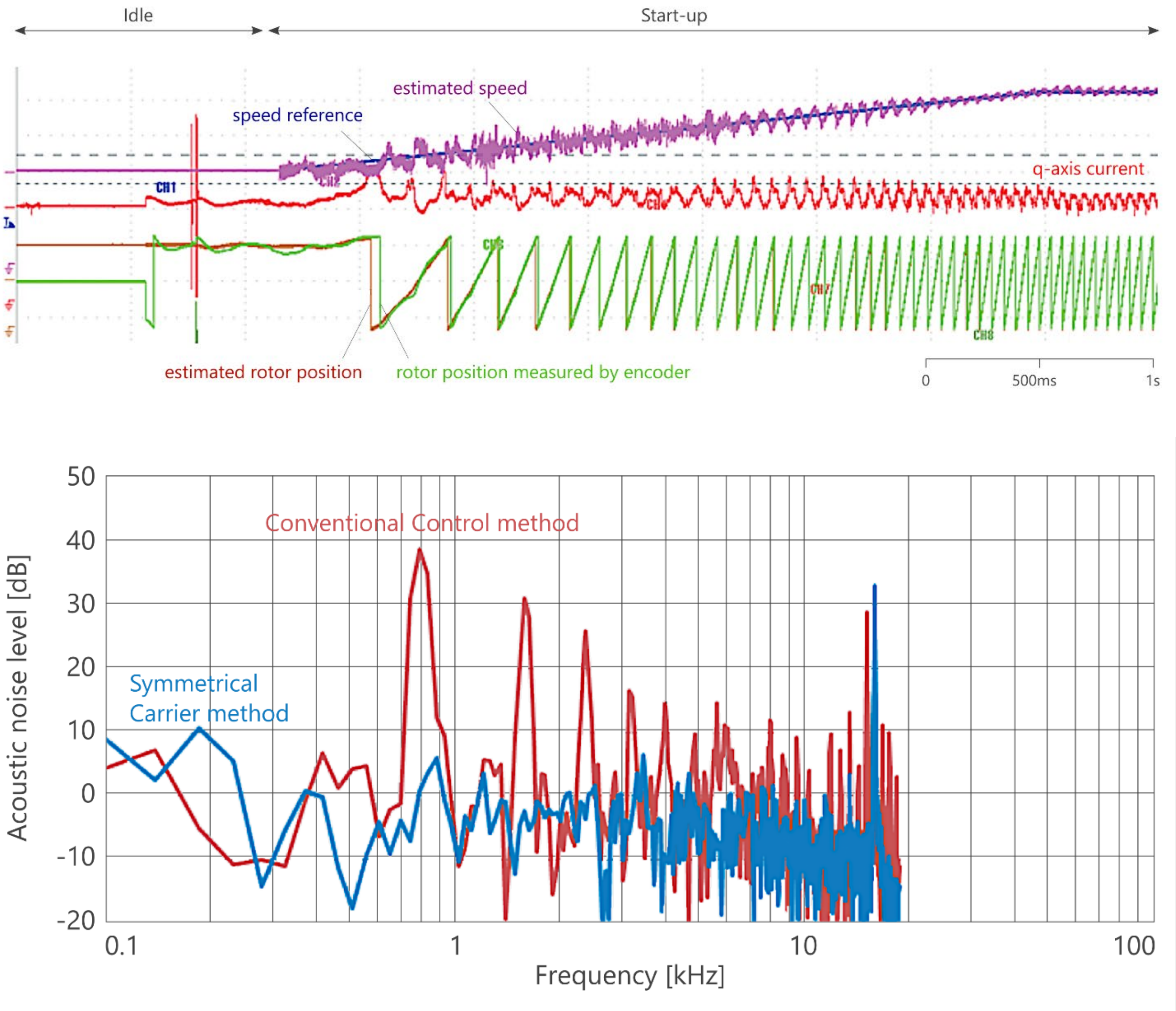

Figure 7: A comparison of estimated and measured rotor position (using an encoder) (top) with a comparison of acoustic noise over frequency between symmetrical and conventional control methods.

Hardware support

Already well-known for their motor control performance are the M3H and the M4K groups from Toshiba's TXZ+™ microcontroller family. These are powered by Arm® Cortex®-M3 and Cortex®-M4 processor cores respectively, with the latter also featuring a hardware floating-point unit (FPU). Manufactured in a state-of-the-art 40 nm low-power CMOS process, they are designed for the vector control of brushless DC and PMSM motors.

The key to supporting the symmetrical PWM carrier method discussed is their Advanced Programmable Motor Driver (A-PMD) peripheral, providing versatile control of 3-phase inverters. The A-PMD supports the pulse with modulation of the motor control signals with PWM carrier frequencies between 80 Hz and 156.25 kHz and adds dead time control as well as emergency stop and over voltage protection functions. Most importantly, however, the PWM carrier of each phase can be individually configured for (inverse) sawtooth or (inverse) triangle-waveform. To ensure that current measurements are taken at the correct moment in time, the A-PMD supports six types of carrier comparison to generate the necessary trigger signal for the ADCs (figure 8).

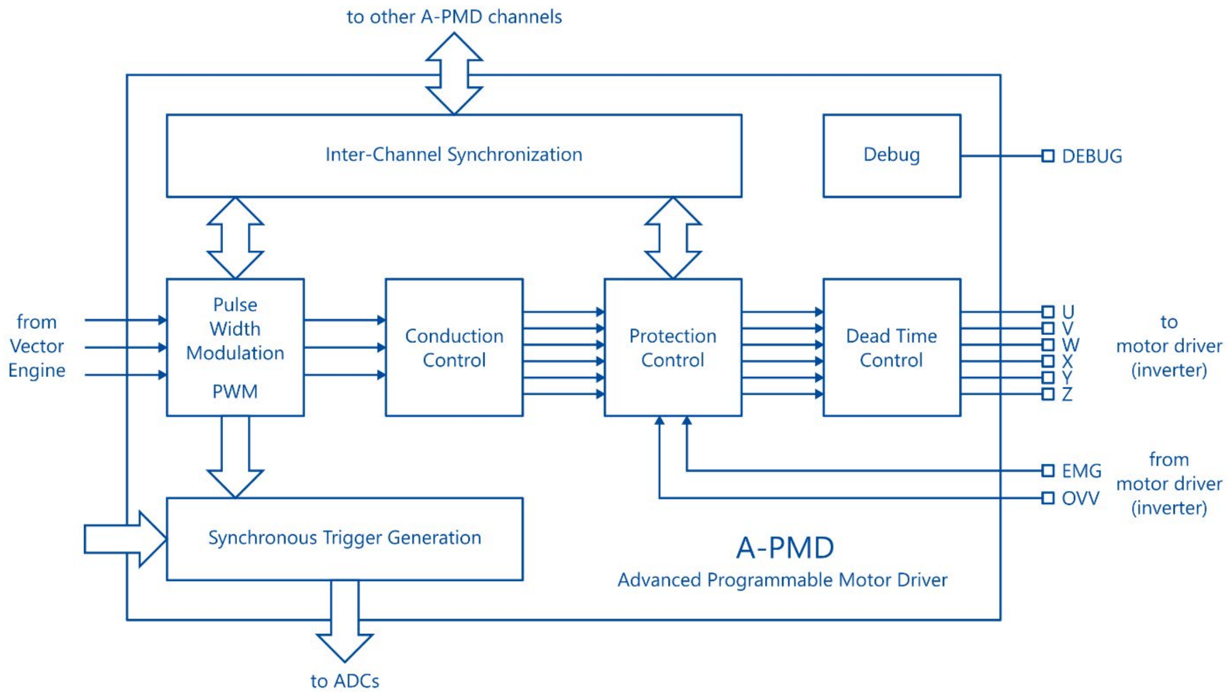

Figure 8: Block diagram of the Advanced PMD, supporting the symmetrical PWM carriers required for the rotor estimation approach described.

To further simplify the implementation of FOC algorithms, Toshiba's M4K microcontrollers feature an Advanced Vector Engine Plus (A-VE+). This powerful coprocessor implements the (inverse) Clarke/Park transformations, current PI control, Space Vector Modulation (SVM), as well as useful trigonometric functions in hardware. Once configured, it results in a significant reduction in load for the main processor core, leaving plenty of performance for other application code. It is also tightly coupled with the A-PMD and ADC peripherals and includes a powerful scheduler, allowing for an almost independent execution of the FOC functionality, if desired (figure 9).

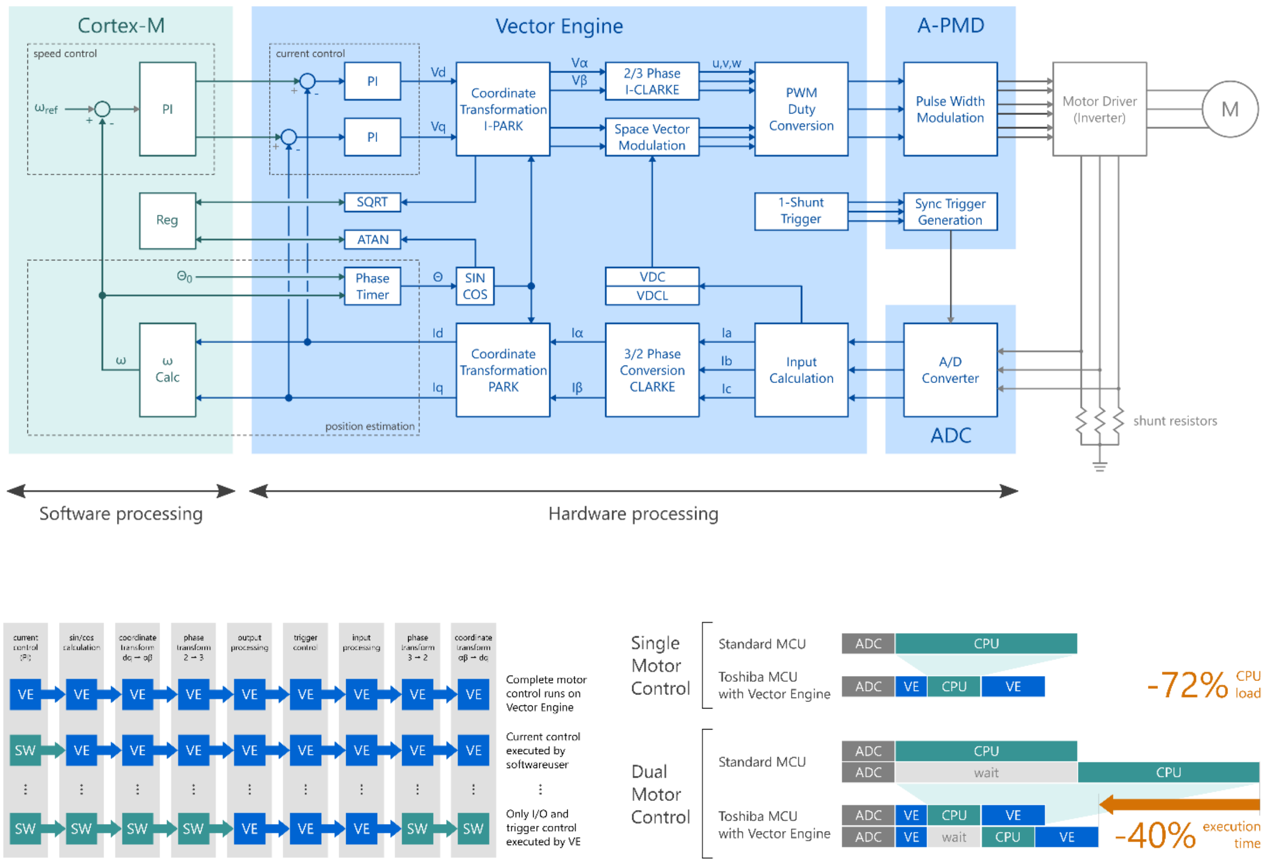

Figure 9: The A-VE+ coprocessor can significantly offload the complexity of FOC PMSM algorithms, offers flexible configuration of the implementation, and can even support multi motor implementations.

Summary

The march toward electronically commutated motor control solutions continues unabated, thanks to the wide range of advantages they offer, such as reductions in size and weight, higher power for the same volume, and significant improvements in efficiency. The use of Field Oriented Control (FOC) provides the best torque output for brushless DC or other permanent magnet synchronous motors (PMSM) while minimizing torque ripple and thus reducing both mechanical stress and audible noise. However, control of such motors without some sort of rotor sensor is challenging, especially at low RPMs and standstill. Without knowledge of the rotor angle, FOC algorithms are hard-pressed to determine the correct commutation. While there are a range of clever techniques that make use of the magnetic saliency property of permanent magnet based motors, they result in additional challenges of audible noise and electromagnetic interference (EMI). The use of symmetrical PWM carriers has been demonstrated to both minimize vibration, limit EMI, and provide an accurate estimate of the rotor angle from a standstill and throughout the low RPM range. Toshiba's M3H and M4K group microcontrollers are well placed to implement this approach thanks to their ability to use different carrier waveforms for each individual motor phase in the A-PMD PWM generation module. This, coupled with the A-VE+ FOC coprocessor, provides an exceptionally powerful solution for advanced PMSM control applications.

References

1. Link to TCM0456 White Paper: https://toshiba.semicon-storage.com/eu/semiconductor/design-development/innovationcentre/articles/tcm0456_mcumotorcontrol.html
2. "TMPM4K Motor Control Microcontroller for High-Performance PMSM Drive Systems at Lower Cost", Toshiba Review Vol.74, No.1, January 2019, https://toshiba.semicon-storage.com/content/dam/toshiba-ss/shared/docs/company/technical-review/technical-review-33_e.pdf

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