A faster current loop reduces the size of EV motors

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Introduction

When it comes to the design and manufacturing of electric vehicles, the goal of automotive OEMs is to provide an ownership experience that meets or exceeds ICE-based cars today.

One major goal for OEMs is to reduce size and weight of mechanical components within the EV vehicle in order to save on cost and due to the limited space available. One novel way to reduce the physical size of the EV traction motor while maintaining the same rated power level is by improving the overall performance of the EV traction inverter. And by improving traction inverter performance, this will also improve overall efficiency for the motor drive system. Therefore the next major step in advancing EV motor system design is to significantly increase the speed of the motor in order to achieve smaller motor size with higher efficiency.

Motor power = torque x speed

The key to reducing motor size but maintaining its power level is to reduce the amount of torque needed for the motor system and increase speed. Since the power (size) of the motor is a product of the torque times motor speed, OEMs and Tier 1s can aim to double motor speed (rpm) in order to cut the amount of torque needed by ½.

However, as motor speed increases, motor frequency increases as well which will require higher system current-loop performance (or torque response) and thus pushes the need for higher PWM switching frequencies that challenge traditional IGBTs.

The current control loop bandwidth becomes the linchpin upon which the rest of the traction inverter drive system depends. In order to improve current loop bandwidth, more OEMs and Tier 1s are either considering adding costly FPGAs to the system or demanding more CPU MIPS from MCU supplier to improve performance.

Only one solution in particular can optimize or eliminate the design trade-offs involving expensive FPGAs or increased CPU speeds. This solution, which is based on TI's C2000™ real-time microcontrollers (MCUs) and the enhanced MotorControl Software Development Kit, increases the bandwidth of a EV traction motor drive's current control loop.

Current loop close-up

The current loop controls the torque in an EV traction motor by manipulating the pulse-width modulator (PWM) outputs that drive an inverter. The motor currents are monitored and fed back to the current-loop controller and the controller updates the PWM outputs if necessary. The current-loop feedback path quantifies the analog output of the motor current sensor with a high-precision analog-to-digital converter (ADC), and then feeds the result to the current-loop controller. Several different modules of field-oriented control (FOC) algorithms process this sample before the controller makes any adjustments to the PWM's outputs.

Many conventional proportional integral (PI) current-loop controllers limit the current-loop bandwidth to approximately 10 percent of the PWM carrier frequency, which is typically in the 10kHz – 20kHz range. This would yield a current-loop bandwidth of 1 to 2 kHz. To increase the bandwidth, some drive systems increase the carrier frequency to 30kHz or higher, which can indeed increase the current loop's bandwidth but will wear on the IGBTs in the system while increasing the inverter switching losses. Increasing carrier frequency will also demand higher processing performance from the digital control system. A higher switching frequency requires increased gate-drive power, which then increases the size and complexity of the system's power supply. Plus, the higher switching losses will mean additional heat dissipation, necessitating more extensive thermal-management strategies such as larger, heavier and more expensive heat sink, fan or coolant.

Clearly, the historical solutions for increasing current-loop bandwidth come with strings attached. The cleanest, most effective architecture would simultaneously address the need for improved processing capabilities to accommodate shorter feedback cycles and retain a lower carrier frequency to avoid the undesirable power and thermal trade-offs.

Fast Current Loop (FCL) technology

TI has harnessed two decades of real-time industrial control system design experience when applying C2000 real-time MCUs to the development of a new Fast Current Loop (FCL) technology. FCL, quite simply, breaks many of the long-held design assumptions in current-loop design. For instance, designers of motor control applications have for years placed limitations on the current-loop bandwidth because they assumed that the controller could update the PWM only once every cycle of the control loop. Now, with an integrated

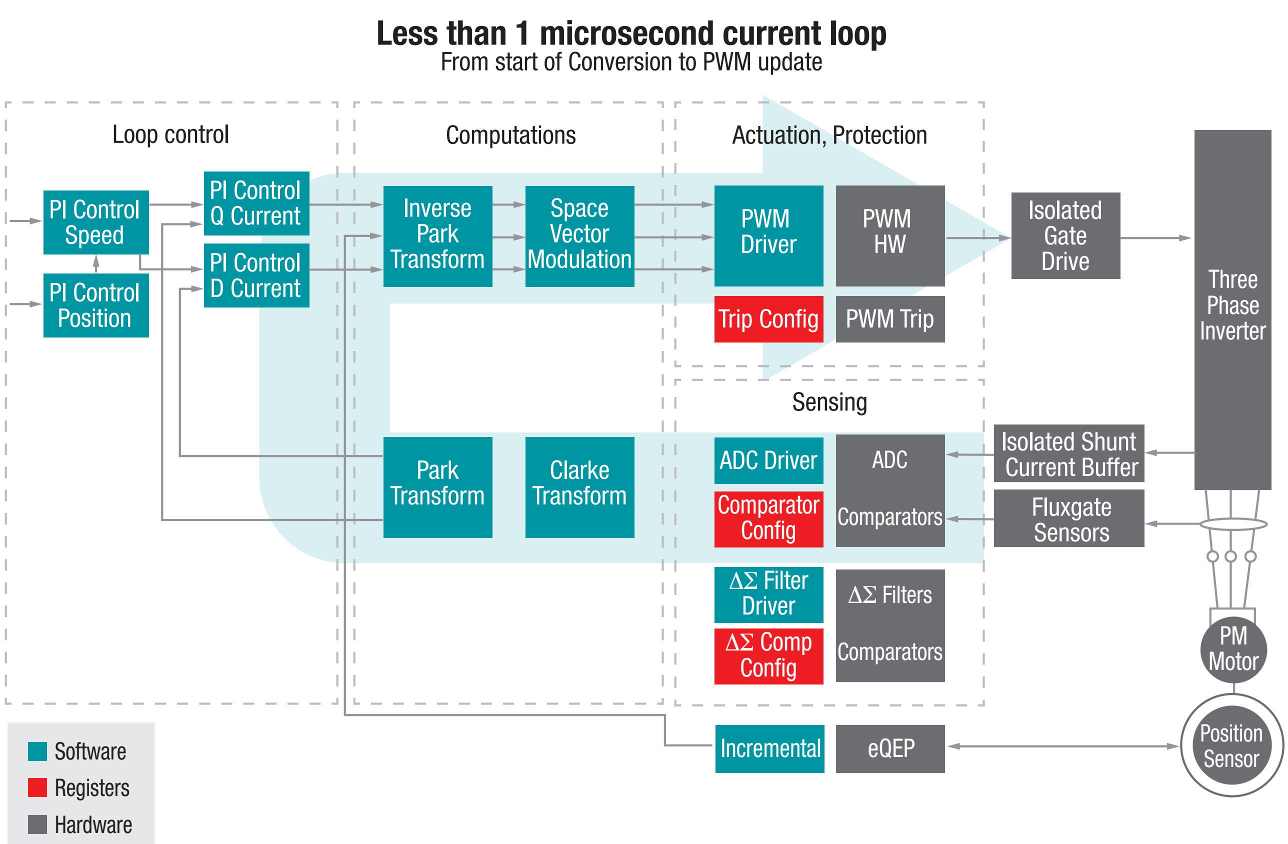

***Figure 1**. Less than 1 uS current loop with FCL (replace "QEP" with "Resolver" in the picture).*

high-performance successive approximation register (SAR) ADC, ADC post-processing hardware, trigonometric math instructions, and other cycle-scavenging resources, C2000 MCUs can sample motor currents, convert them to digital data, process the data and update the PWM generator in less than 1µs. (**Figure 1**.) The field-oriented control (FOC) processing and PWM update takes less than 500ns. Because of FCL technology and C2000 MCU ePWM's immediate mode capabilities, sub-cycle PWM updates occur as soon as possible, instead of waiting for an entire control loop cycle to transpire.

Conventionally, designers assume that increasing the current-loop bandwidth will require higher carrier frequencies. So, for example, increasing the current-loop bandwidth by a factor of 3 from 1kHz to 3kHz will require increasing the carrier frequency from 10kHz to 30kHz.

But C2000 real-time MCU's ability to perform sub-cycle PWM updates in less than a microsecond improves the current-loop bandwidth, making it possible to reduce or optimize the switching frequency for a given bandwidth requirement. Tests have shown that FCL can increase the current-loop bandwidth by a factor of 3 from 1kHz to approximately 3.3kHz while maintaining a carrier frequency of 10kHz. This avoids the trade-offs of increased power consumption, greater heat dissipation, and more complex and expensive thermal-management strategies, all of which become a non-issue with FCL. Therefore, in order to meet a certain desired bandwidth in closed-loop current control, FCL makes it possible to reduce the PWM frequency dramatically and eases IGBT control and thermal design. In other words, FCL enables the motor to run at a higher speed with the same PWM frequency.

Another challenge of high-performance current-loop design has been keeping stability of the current-loop controller at high speeds. Digital or transport delays progressively reduce the phase margin of the current control loop at higher speeds, eventually leading to a loss of control. Traditional controllers in the current loop do not model these digital delays well.

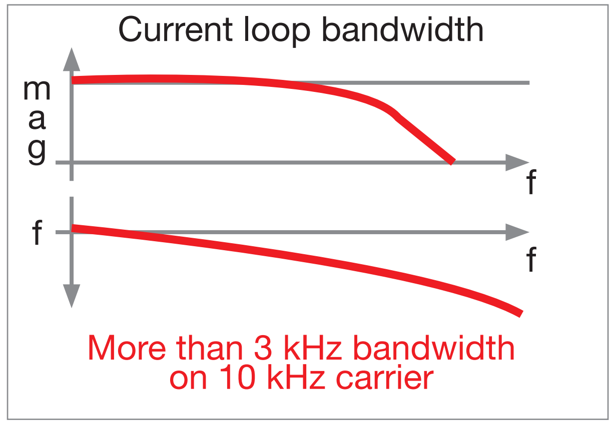

***Figure 2**. Improving current loop bandwidth while maintain carrier frequency.*

However, FCL software includes an efficient algorithm that assumes a more appropriate system model, compensating for the inherent transport delay of the system. This is embodied in the complex controller (CC) and results in perfect pole-zero cancellation at all times, ensuring stability at high speeds.

Conclusion

The TMS320F2837xD MCUs are highly integrated real-time MCUs for EV traction drive systems. On-chip features such as sigma delta filters, analog comparators, and PWM protection circuits save system level costs when compared to adding these components externally.

The technology breakthrough that contributes to FCL have emerged from more than 20 years of experience in embedded processing and motor-control algorithm development by C2000 MCU motor engineers. Certainly, the MCUs themselves have been endowed with powerful, high-performance processing units, coprocessors; and specialized instruction sets; but the C2000 MCU's architecture is just as essential because it enables a high degree of real-time parallel processing through very low latencies and high processing determinism. Ultimately, this makes a C2000 MCU in an EV motor drive application a cycle scavenger, saving processor cycles over the entire loop and transforming what may have been longer sequential steps into shorter simultaneous processes.

For example, 200MHz C28x cores are, of course, critical for breaking apart the workload to optimize parallel processing, but so is the real-time deterministic architecture that surrounds the CPUs. Because the architecture keeps the system's processing as jitter-free as possible, cycles are not wasted recovering from timing issues or running error-correction routines. There are no data-transfer latencies between the ADC and the C28x cores, or between the cores and the PWM. Transferring a sample from the ADC to the C28x cores or updating the PWM takes only a single cycle. See **Figure 3**.

Several C2000 real-time MCUs, such as the Delfino™ TMS320F2837xD, include a powerful ADC post-processing block capable of performing certain sample-preparation routines in dedicated hardware that the C28x cores would normally have executed, saving cycles on the main CPUs and freeing

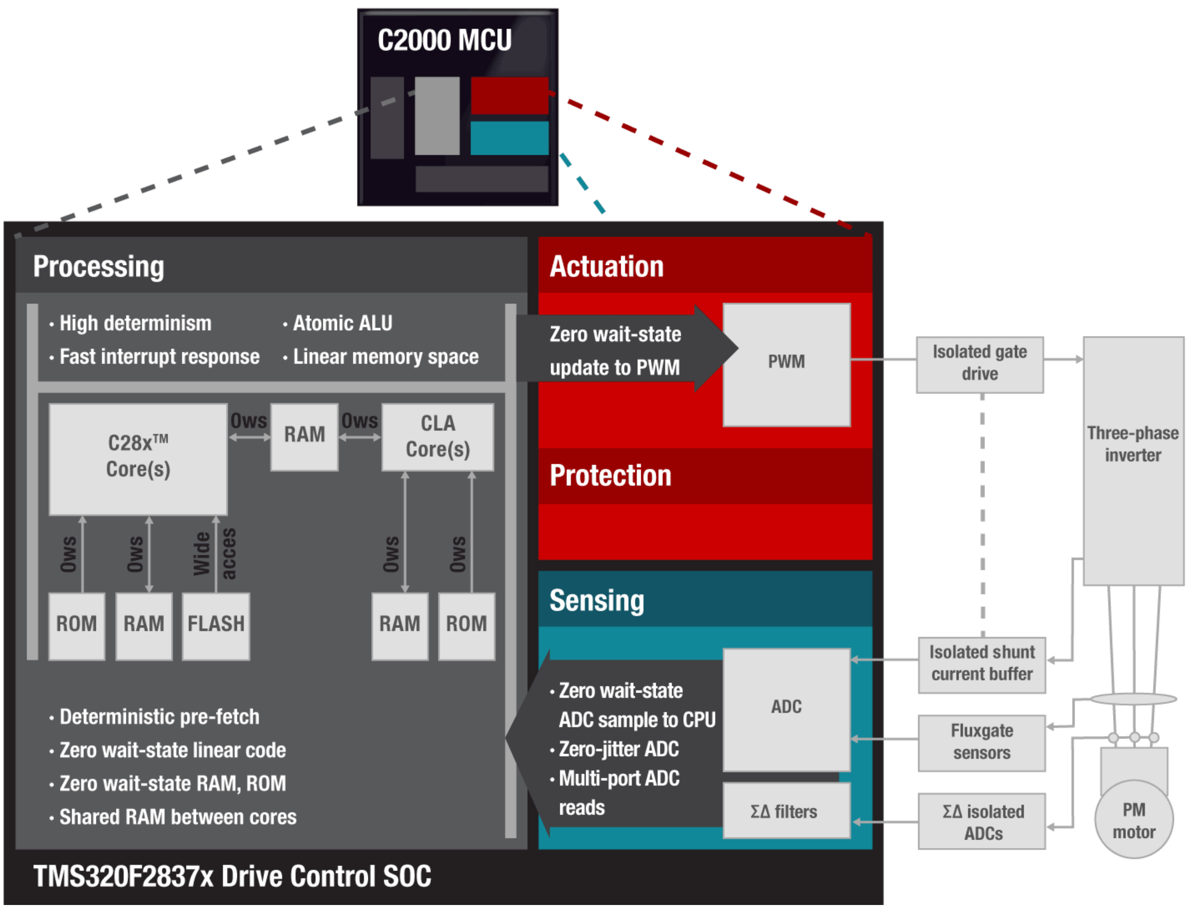

Figure 3. C2000 MCU architecture for real-time motor control

them to perform other tasks in parallel. The cores themselves have been equipped with coprocessors and specialized processing units that prove useful in motor control applications. For instance, the main processing cores can offload resolver feedback processing to the control law accelerator (CLA) coprocessor, which excels at high-level mathematical processing. Moreover, both the FOC processing and the complex controller (CC) use a specialized processing unit, the trigonometric math unit (TMU). With the aid of the TMU, you can improve Park transform cycle performance by a factor of 8 over comparable MCUs in the industry. In addition, the C28x core's 32-bit floating-point instructions accelerate the execution of several different types of mathematically intense calculations used by the FCL algorithms, such as minimum/maximum, compare and square root.

During the design development of an EV motor traction drive application, designers face a diverse set of subtle trade-offs, many times placing high performance, cost-effectiveness, power efficiency and other factors in direct opposition with one another. Simple yet effective solutions may be hard to come by, but fortunately, the experience and expertise in real-time motor drive control systems that TI has amassed over the last 20 years has led to many enhancements to the C2000 family of real-time MCUs.

The Motor Control SDK developers kit features the latest enhancement, FCL software. Taking advantage of a real-time cycle-scavenging architecture, high-performance processing resources and the fast data throughput of C2000 MCUs to significantly increase the current control loop bandwidth, FCL software achieves subcycle updates of the PWM in less than 1μs and without the assistance of external processing elements like an FPGA or ADC. And in addition, compared to traditional MCU-based systems, FCL can potentially double an EV traction motor's maximum speed without increasing the carrier frequency thus reducing the size of an EV traction motor while maintaining its power level. This is how OEMs can save space in an EV vehicle with faster current loop.

For more information

For additional information about Fast Current Loop software, visit our www.ti.com/c2000ev

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