WHITE PAPER

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TEXAS INSTRUMENTS

Microcontrollers for the drive train in hybrid and electric vehicles

Introduction

The electric drive train is superior in many respects to the conventional drive train with combustion engines. The electric motor has higher efficiency, as well as better torque and performance. An electric drive train provides a much simpler mechanical design while eliminating undesirable noise and pollution emissions. Although today's electrical energy storage systems limit the vehicle range employing intelligent battery management and the hybrid concept (i.e., the combination of electric motor and combustion engine), helps to compensate for this. In addition, certain system faults can be dangerous to passengers and damage the electrical components of the vehicle, so automotive safety requirements, under the ISO 26262 standard, must be taken into account. This article describes the types of e-machines used, the electronic controller for e-motor control, and the resulting specific demands on the microcontroller. With the Hercules™ TMS570LS safety microcontroller series, Texas Instruments offers controllers that have the characteristics needed for use in the electric motor controller.

The various development stages of electric vehicles range from simple start/stop systems, to mild hybrids, in which an electric motor provides the combustion engine with torque support, to full electric vehicles. In full electric vehicles, a distinction is made between parallel and serial architectures. In parallel architectures, either combustion engines or electric motors directly power the vehicle. Serial architectures, also known as "range extenders," can drive solely on electric power. A small combustion engine is switched on when the batteries need recharging.

Switched reluctance machines and three-phase asynchronous machines are sometimes used for electric motors, but permanent magnet synchronous motors (PMSM) are most widely used because of their high efficiency, high-power density and high torque, even at low speeds. The synchronous machine runs with a synchronous rotor and stator frequency speed.
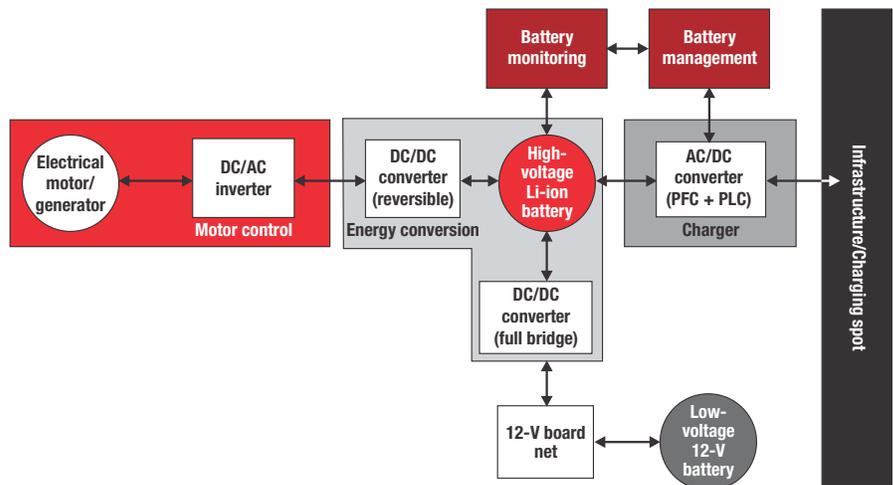

Figure 1: System architecture of an electric vehicle

Depending on the type of vehicle, it can be powered by a single electric motor, one electric motor per axle or one per wheel, as in wheel-hub motors. All of these systems have been realized in electric vehicles or prototypes today. When braking in recuperation mode, the kinetic energy is converted into electrical energy and stored in the battery (regenerative braking). During this mode the electric motors of the drive are used as generators.

Power inverter and electric control unit

The high-voltage battery in mild hybrids has a range of about 40–150V; in full hybrids the voltage range is several hundred volts. The pulse inverters used (DC/AC inverters) typically have a B6 bridge configuration with MOSFETs as electronic circuit breakers for voltage ranges up to approximately 120V. At higher voltages, insulated gate bipolar transistors (IGBTs) with the lowest possible on-state resistance and low-switching losses are used. The motor controller consists mainly of the digital microcontroller, components for regulating and monitoring the motor and power electronics and modules for processing sensor signals, communication and power supply.
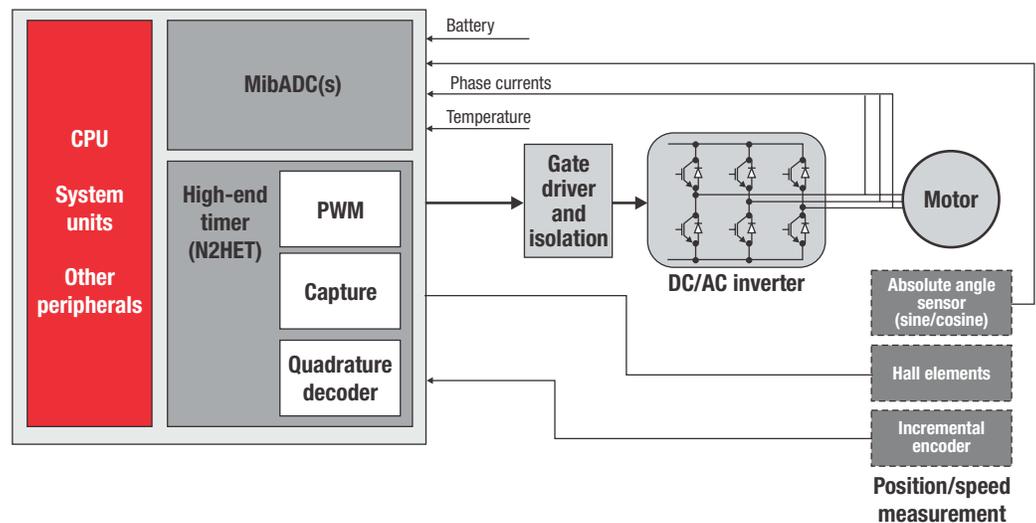
Figure 2. Microcontrollers and power electronics for controlling the electric motor

Measuring the phase currents

To regulate the torque of the motor, the microcontroller requires instantaneous information on the phase currents of the motor in every control cycle. Phase currents of several hundred amps can occur at high torques. For this reason, current transformers with galvanic isolation are used between the primary (heavy current circuit) and secondary circuit (electronic circuit). These converters are based on the Hall Effect and typically deliver an output voltage on the secondary side that is proportionate to the current to be measured. The advantage of Hall Effect current converters is that they can be placed outside the signal cable therefore they do not interfere with the signal (contact-free). Using an alternative of serial measuring shunt resistors, resistive losses and overheating would occur which is problematic for measuring high currents, but these Hall Effect current converters do not exhibit these effects and even resist very high currents in the primary cable.

Isolation

Since currents and voltages in the inverter are much higher than in the control unit of the microcontroller, isolation is required at all interfaces between these components in order to protect the control unit from failure and malfunction. Texas Instruments offers automotive-qualified digital isolators with the ISO72xx family featuring low-power consumption and clock speeds of up to 250 Mbps. These modules use capacitive

galvanic isolation, which compared to optical or magnetic isolation, exhibits very good characteristics with regard to clock speed, reliability, ESD protection and EMC behavior.

The microcontroller

With the Hercules™ TMS570LS safety microcontroller series, Texas Instruments offers microcontrollers that are used today in the automotive sector in complex and safety-critical systems. These microcontrollers aid in the development of safety-critical applications since they were specifically designed to meet and have been deemed suitable for use in safety integrity level 3 (SIL3) under the IEC 61508 standard. Hercules TMS570LS safety microcontrollers will be highlighted in greater detail below with respect to function and safety characteristics for use in drive controls for electric vehicles.

The field-oriented principle for controlling rotating field e-machines is state-of-the-art. Communication networks, online safety and diagnostic functions, standardized software architectures (i.e., AUTOSAR), and the field-oriented control routines can lead to high demands on the microcontroller's processing power and memory requirements. Faster microcontrollers generally permit a higher function density and especially for e-motor drives, better dynamics and control efficiency because shorter control loop times can be achieved.

To tackle the increased processing load, the Hercules TMS570LS safety microcontroller series offers the 32-bit ARM® Cortex™-R4F CPU which can be clocked at up to 180 MHz (>280 DMIPS) and includes a double-precision floating-point unit (FPU) for fast 32-bit and 64-bit floating-point operations (IEEE 754). The floating-point and integer operations can run in parallel to achieve higher processing power. The FPU facilitates software development since control and regulating algorithms are increasingly being developed with model-based code generators, whose results are then integrated into the entire project as floating-point subprograms.

The ARM Cortex-R4F core can process 16- or 32-bit commands, depending on the requirements of the program code because of the Thumb®-2 instruction set, resulting in an optimal compromise between processing speed and code size. The Hercules TMS570LS safety microcontroller series is currently available with large amounts of integrated Flash memory from 1 to 3 MB and data memory from 128 kB to 256 kB.

High-end timer coprocessor

The high-end timer (N2HET) module of the Hercules TMS570LS safety microcontroller series is a flexible, user programmable, timing generator and capture engine. A single program can control up to 32 pins that can be freely configured as input or output. The N2HET program is copied into its local RAM during system initialization. During operation, the core can update key values in the N2HET RAM in order to create pulse width modulations (PWM) or read out values captured by input pins. In order to further reduce the CPU's load, transactions between the N2HET RAM and the CPU memory can also be carried out by system direct memory access (DMA) or the high-end transfer unit (HTU), a DMA controller specific to N2HET. Due to its high degree of flexibility, the N2HET is capable of generating simple, as well as very specialized timer requirements, such as the PWM control of an electric motor or the reading in sensor signals. The N2HET also has the ability to implement state machines without CPU load because it can process input signals and create appropriate output responses or status information on its own.
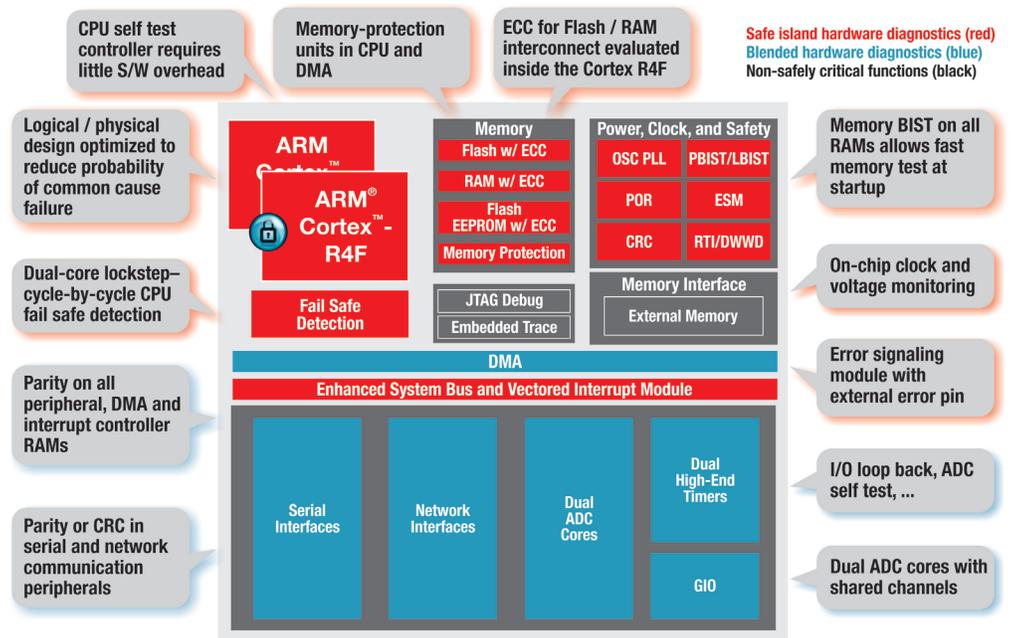
Figure 3: Safety features on TI's Hercules™ microcontroller family

In order to control a three-phase electric motor, timer modules must typically generate six pulse-width modulated (PWM) signals. Therefore, with the appropriate pulse pattern on the power switches of the inverter, a three-phase voltage system of a specific amplitude, phase angle and specified frequency is generated. It is generally possible to control two three-phase motors with a single N2HET module. Because the TMS570LS21x/31x microcontrollers provide two NHET modules, additional functionality can be realized. The second N2HET can be used for a number of different purposes, such as to control different motors with various inverter circuits or even other sensor communication protocols such as single-edge nibble transmission (SENT).

Analog-to-digital converter

TI's Hercules TMS570LS safety microcontroller has two multi-input-buffered analog-to-digital converters (MibADC) with 12-bit resolution and 24 input channels to convert analog sensor signals. In order to reduce the CPU load, each MibADC module has its own multi-buffered RAM capable of storing up to 64 conversion results per module. This RAM is memory mapped and can be read out by CPU or DMA at defined time points. The N2HET module has extensive configuration options for triggering A/D conversions. For electric motor control applications, the N2HET can start multiple A/D conversion sequences within the PWM period at freely programmable time points.

Communication

Although the trend indicates an integration of vehicle functions in a smaller number of electronic controllers, the communication interfaces play an important role. The integrated Ethernet, FlexRay™ and CAN modules of the Hercules™ TMS570LS safety microcontroller can be used for local communication or connection to

the main vehicle network. Similar to the HTU, the FlexRay module includes a transfer unit (FTU) to read out the data without CPU interaction. In addition, sensors and application-specific integration circuits (ASICs) can be connected to the controller via the SPI or LIN/SCI module. Many modules have their own RAM in which the data to be sent or received can be buffered.

Safety requirements

The rotor magnet field of a PMSM motor energizes the stator coils as long as the motor is turning. This is true even in case of an error that may short circuit the inverter, or the stator windings of the motor. In such a case, the error must be detected quickly and countermeasures must be taken in order to prevent damage due to the high currents, but most important is to prevent a dangerous, undesirable braking moment of the PMSM motor.

The architecture of the electric vehicle, which comes out very differently in wheel-hub motors and mild, parallel or serial hybrids, is a deciding factor in the vehicle's safety considerations. For a mild hybrid, for example, lower safety demands are placed on the electric drive than for pure electric driving. It is obvious that braking processes are critical to safety and thus the safety consideration must include the use of the electric motor in the generator operation as regenerative or recuperation braking.

The international standard IEC 61508, mandatory since 2004 in Europe, controls the development of safety-critical electronic systems, including their associated development processes and quality assurance practices. The standard ISO 26262 is derived from IEC 61508 and has been adapted to the specific circumstances of the automotive sector for safety-relevant electrical/electronic systems in motor vehicles. The safety features of the Hercules™ TMS570LS safety microcontroller, as a central component in a control electronics system, are explored below.

The Hercules TMS570LS safety microcontroller series was specifically designed for use in safety integrity level 3 (SIL3) systems as defined under IEC 61508 and also benefits from Texas Instruments' 20+ years of experience with safety-critical microcontroller applications in the automotive sector. The development process and safety concept of Hercules TMS570LS safety microcontrollers were certified as suitable for use in SIL3 systems by exida, an independent company that specializes in certifications in the field of functional safety.

The Hercules TMS570LS safety microcontroller series uses two identical ARM® Cortex™-R4F cores on the chip, which run the same program and receive the same input in a lockstep fashion. Operations and results of both calculations are logically compared to one another on every CPU cycle to detect and respond to possible errors. Both CPUs are implemented in silicon with geometric, as well as time diversity, in order to reduce the chance of physical common-cause failures. The second ARM Cortex-R4F core is physically mirrored and rotated in silicon and its processing is delayed by a few cycles.

The advantages of a lockstep architecture are high diagnostic coverage and reduced diagnostic software development effort. The hardware comparison of the two cores happens on each CPU cycle. Therefore, when an error is detected, a fail-safe state, such as safely shutting down the system's actuators, can be achieved within a few CPU cycles. Since the error detection on the core is executed purely by the hardware, it requires no CPU load and little software as compared to software-based detection schemes. Other types of errors

detected in the microcontroller by the hardware mechanisms are presented below. This reduces the cost and complexity of the software development and safety validation on the system side. Users can integrate third-party software packages into the overall project with little effort and the step from a dual- to a single-processor system can help reduce costs.

In order to detect and respond to errors both in the program memory and the data memory of the Hercules™ TMS570LS safety microcontroller, every ARM® Cortex™-R4F core has integrated error correction code (ECC) logic. This module makes it possible to correct individual bit errors and detect double errors. In addition, address buses and decoders are monitored internally.

Two types of built-in self-test modules monitor the cores – logic built-in self-test (LBIST) and the data memory programmable build-in self test (PBIST) – respectively. The LBIST module can check the Cortex-R4 core for defects during controller initialization or while the application is running. The PBIST module can test any or all integrated data memory (RAM) with various selectable algorithms. The built-in self-test modules simplify the software development and code space since no test routines must be implemented for the core and data memory. All peripheral modules that have their own data memory (N2HET, MibADC, FlexRay™, DCAN and MibSPI) are protected by parity logic in the hardware. These RAM areas can also be tested with PBIST.

The integrated memory protection unit (MPU) can be used to monitor access to specific memory areas and assign specific access rights to these areas. A 64-bit cyclic redundancy checker (CRC) unit is included for testing stored static data and can be operated in the background by DMA. In addition, the peripheral modules have their own error detection abilities, such as the self-test of the analog-digital converter (ADC). All modules used for error detection are connected with the error-signaling module. This module enables centralized prioritization and configurable external signaling of all detected errors.
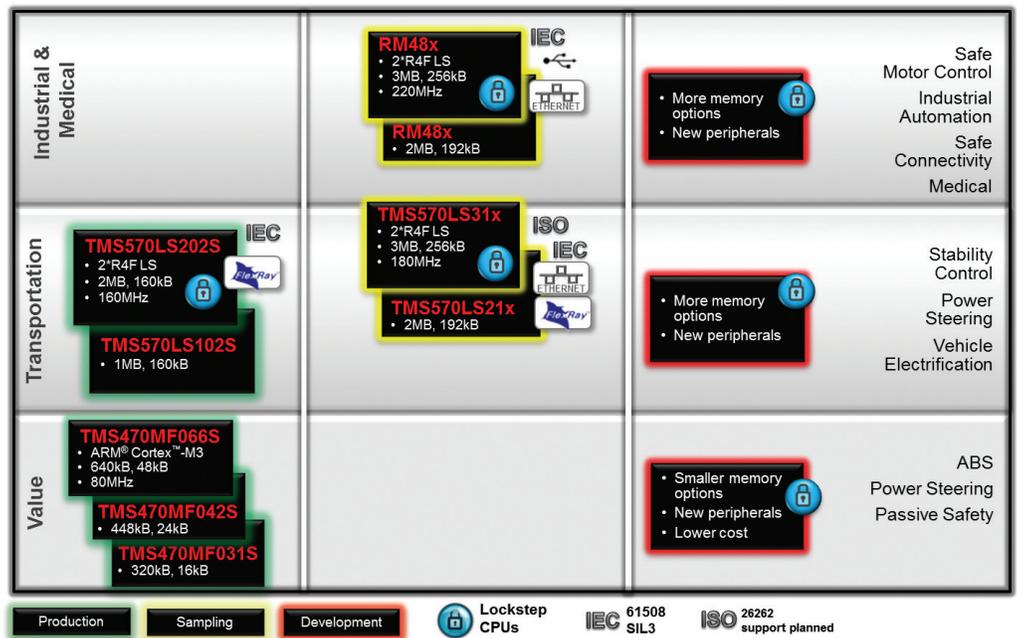
Figure 4: Hercules™ Safety Microcontroller Roadmap

Summary and outlook

The ARM cores implemented on the Hercules safety family of microcontrollers are used as processor cores by many semiconductor manufacturers. There are many advantages of ARM-based cores due to the standardization that has made it possible for a number of third-party vendors to support these cores with development tools and software components. FlexRay drivers and AUTOSAR packages are available for Hercules TMS570LS safety microcontrollers.

The Hercules TMS570LS safety microcontroller offers the performance, the peripherals and the safety functions to be used for drive control in electric vehicles.

The Hercules TMS570LS safety microcontroller roadmap supports up to 4 MB Flash memory and variant architectures that include the current lockstep approach as well as a dual independent Cortex-R configuration capable of executing two different programs simultaneously. The use of cache with these derivatives will allow even higher processing power. For more information on the Hercules family of microcontrollers, including Hercules TMS570LS safety microcontrollers and development tools, visit **www.ti.com/hercules**. For more specific information on the Hercules Safety features please see the "**Safety Manual for TMS570LS31x/21x and RM48x Hercules ARM Safety Critical MCUs**."

In addition, the "**Hybrid and Electric Vehicle Solutions Guide (Rev. A)**", offers a wide range of TI semiconductor modules for use in hybrid and electric vehicles.

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