Hercules™ MCUs for use in electrical vehicle battery management system

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Introduction

Electric vehicles (EV) have been around for more than a decade as a niche product. Lately, China has been pushing ahead to be the world leader of EV as one of several ways to address its air pollution problem.
In 2015, the total number of EVs (excluding EV buses) sold in the world was estimated to be 565,000, with around 214,000 EVs sold in China, 185,000 in Europe and 115,000 in the USA. This is an increase of 80% over 2014. The thick, brown, polluted air is a major health concern the Chinese would like to eliminate (Figure 1). And thanks to generous government subsidies, the EV market will see a substantial growth in the coming years (Figure 2).

Figure 1: Beijing with heavy smog

Compared to cars powered by internal combustion engines, EVs are simpler and easier to manufacture. The biggest challenges are the driving range on one charge and the battery charging time. The majority of EVs use a Lithium-ion (Li-ion) battery because of its good power density and charge/discharge efficiency. A Li-ion battery is prone to thermal runway and fire when it is operated at high ambient temperature, overload or with inappropriate charging profile. There are well-documented cases of EV fire such as Zotye M300EV taxi, BYD e6 taxi and Tesla Model S accidents (source: **https://en.wikipedia.org/wiki/Plug-in_electric_vehicle_fire_incidents**).

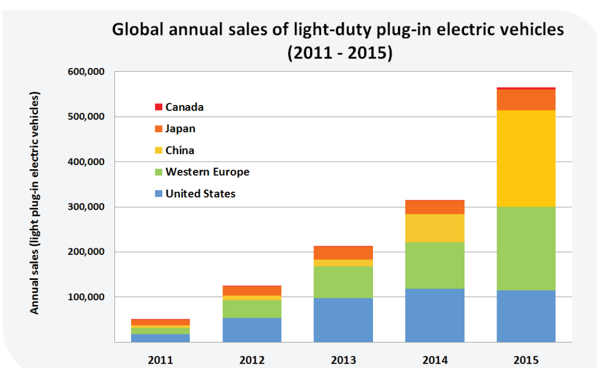


Figure 2: Source: **http://energy.gov/eere/vehicles/fact-918-march-28-2016-global-plug-light-vehicle-sales-increased-about-80-2015**

EV battery management system (BMS)

An EV Li-ion battery pack consists of multiple battery modules. Each module consists of multiple Li-ion battery cells in a stack. A BMS electronic control unit (ECU) is built in to the battery pack for state of charge (SOC) monitoring, charge/discharge control and thermal management. The BMS also includes communication and control interfaces with the other EV systems such as the inverter control and the charger modules.

For a Li-ion battery pack, it is critical to monitor and maintain charge evenly across cells. Overcharging of any cell will shorten the lifetime of the cell and in some cases cause over-temperature which could affect adjacent cells, possibly leading to thermal runaway and fire.

There are two methods of cell charge control:

- **Passive cell balancing:** The charge of each cell is monitored. Excess charge of any cell is dissipated through a resistor network.
- **Active cell balancing:** The charge of each cell is monitored. Excess charge is redistributed through a switching matrix to other cells.

Passive cell balancing has lower efficiency and converts unwanted energy into heat across a resistor, while active cell balancing has higher efficiency, but costs more due to additional passive and magnetic components.

Figure 3a shows a high-level block diagram of active cell balancing with a communication and control interface to the rest of the EV systems. The left-hand side of the “Isolation” is the active cell balancing circuit of a 12-cell battery module. Many of these battery modules stack up to form a battery pack (see Figure 3b on the following page). The right-hand side of the “Isolation” shows the BMS main control and communication circuits to the rest of the EV systems.

The Battery Stack Monitoring and Protection AFE device is used to monitor the cell voltage and temperature. The FET matrix in conjunction with the DC/DC controller is used to balance charges across cells. The MCU is used to interpret the measurements from the Battery Stack Monitoring and Protection AFE device to determine SOC and which cells are to be balanced. The MCU also performs the thermal management function and closely monitors the health of each cell.

Battery management system functional safety requirements

A BMS in an EV performs the following functions:

- State of Charge (SOC) and State of Health (SOH) determination
- Charge/discharge control
- Cell balancing
- Battery protection—ensure the battery operates within the specified operating conditions, isolation fault detection
- Thermal management
- Interface with the rest of the EV systems

A BMS malfunction could cause serious system failure leading to physical injury to people and/or damage to property. To mitigate risk such as this, an international functional safety

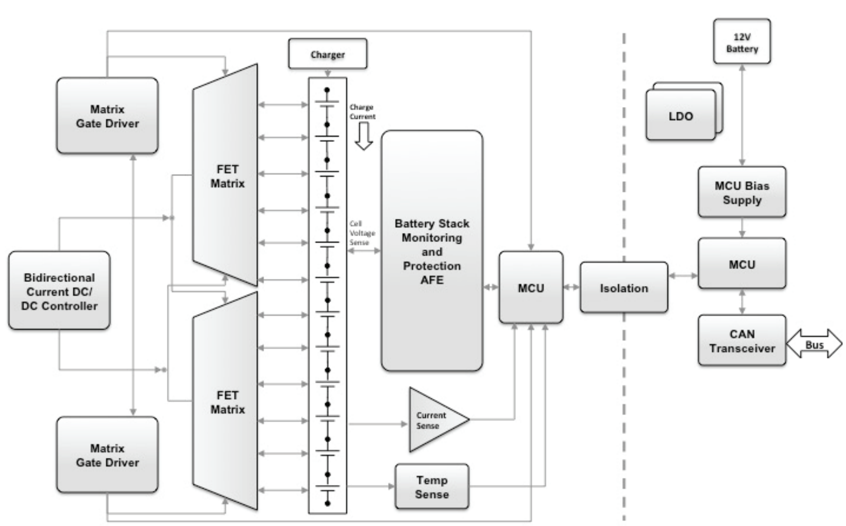


Figure 3a: BMS system overview with battery cell control and main control

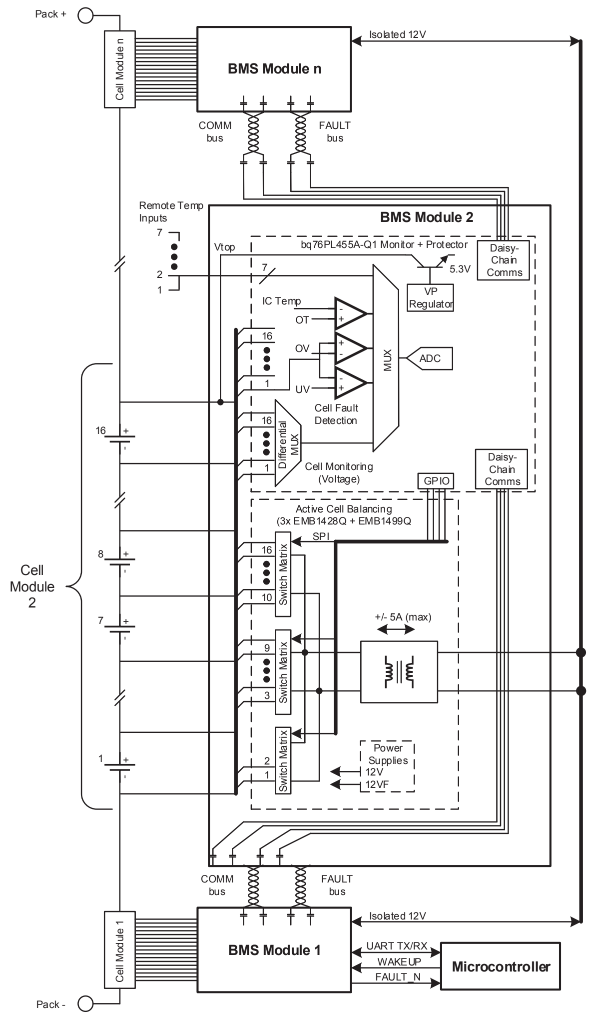


Figure 3b: Multiple battery cell modules stack up to form a battery pack

standard, ISO 26262 “Road vehicles – Functional safety”, has been created as the automotive functional safety standard. It is applicable to electronic programmable systems used in passenger cars with a maximum gross weight of 3500 Kg.

ISO 26262 requires that a hazard analysis and risk assessment should be done at the system level. Each possible system malfunction should be analyzed and its risk determined. If the risk is deemed too high, safety goals should be defined and risk reduction techniques should be applied to

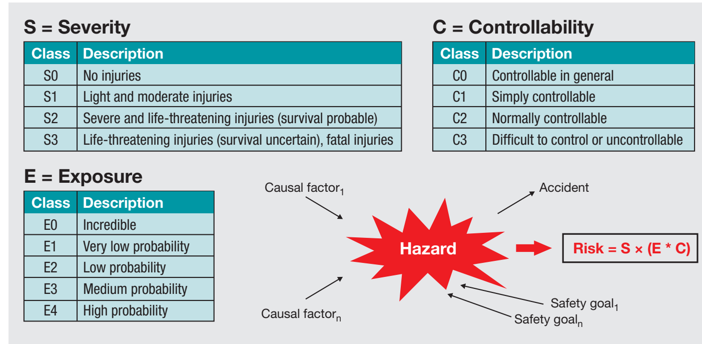


Figure 4: ISO 26262 hazard analysis and risk assessment

the system in order to reduce the risk to a level as required by the functional safety standard.

Per ISO 26262, risk is evaluated based on three criteria (see Figure 4):

- Severity (S)
- Exposure (E)
- Controllability (C)

ISO 26262 categorizes risk by Automotive Safety Integrity Level (ASIL). Figure 5 shows how ASIL is determined by S/E/C.

ASIL determination table

Risk = Severity × (Exposure * Controllability)

		Controllability		
Severity	Exposure	C1 Simply	C2 Normal	C3 Difficult
S1 Light and moderate injuries	E1 Very low	QM	QM	QM
	E2 Low	QM	QM	QM
	E3 Medium	QM	QM	ASIL A
	E4 High	QM	ASIL A	ASIL B
S2 Severe and life-threatening injuries (survival probable)	E1 Very low	QM	QM	QM
	E2 Low	QM	QM	ASIL A
	E3 Medium	QM	ASIL A	ASIL B
	E4 High	ASIL A	ASIL B	ASIL C
S3 Life-threatening injuries (survival uncertain), fatal injuries	E1 Very low	QM	QM	ASIL A
	E2 Low	QM	ASIL A	ASIL B
	E3 Medium	ASIL A	ASIL B	ASIL C
	E4 High	ASIL B	ASIL C	ASIL D

Figure 5: ISO 26262 ASIL determination table

One of the BMS functions is battery pack thermal management. The charging/discharging profile should be intelligent, with charging current adapted based on the ambient and cell temperature. At high ambient temperature, such as a hot summer day, if the EV charger is set to the fast charging mode, the high charging current may lead to higher cell temperature. This could possibly lead to thermal runaway causing smoke and fire. Below is an example to illustrate how hazard analysis and risk assessment are performed based on the hazard of charging overcurrent.

Malfunction:	Charging overcurrent -> Over temperature -> Fire
Severity:	S2 (Severe or life-threatening injuries)
Exposure:	E4 (High probability)
Controllability:	C3 (Difficult to control)
ASIL-Level:	ASIL-C

With this example, the safety goal is to prevent the overcharge of battery cells. This safety goal can be implemented by monitoring the cell voltages. When overcharge is detected, the charging current is removed. Once the implementation is defined, the failure rate of the BMS system will be evaluated to determine if the required hardware metrics are achieved per ISO 26262 requirements.

ASIL	SPFM	PMHF (FIT)	LFM
ASIL B	>90%	<100	>60%
ASIL C	>97%	<100	>80%
ASIL D	>99%	<10	>90%

SPFM: single point fault metric
PMHF: probabilistic metric for random hardware failures
LFM: latent fault metric

Figure 6: ISO 26262 hardware metrics

How Texas Instruments (TI) products can help customers develop products for use in EV BMS systems

Apart from the functional implementation, challenges faced by EV BMS system developers regarding safety aspects are:

1. Implementing a system for ASIL-C/D compliance
2. Implementing diagnostic tests with sufficient coverage for risk reduction
3. Automotive AEC-Q100 qualified analog companion components (Note: AEC-Q100 is component qualification requirements defined by Automotive Electronics Council, which is different from the functional safety standard ISO 26262)
4. System certification

1. System for ASIL-C/D compliance

As shown in Figure 6, ASIL-C requires a single point fail metric (SPFM) >=97% and a probabilistic metric for random hardware failure (PMHF) < 100 FIT at the system level.

TI's Hercules™ TMS570 MCUs are certified by TÜV SÜD as meeting ISO 26262 requirements up to ASIL-D. TÜV SÜD is an internationally recognized and independent assessor of compliance with quality and safety standards.

The Hercules MCU family is a scalable family. Its functional and safety architecture are the same from MCU to MCU. There are pin-to-pin compatible MCUs from 128 KB Flash to 4 MB and 80 MHz to

300 MHz. For more information, please consult: **www.ti.com/lsds/ti/microcontrollers_16-bit_32-bit/c2000_performance/safety/tms570/overview.page**.

2. Hardware-based CPU and memory protection

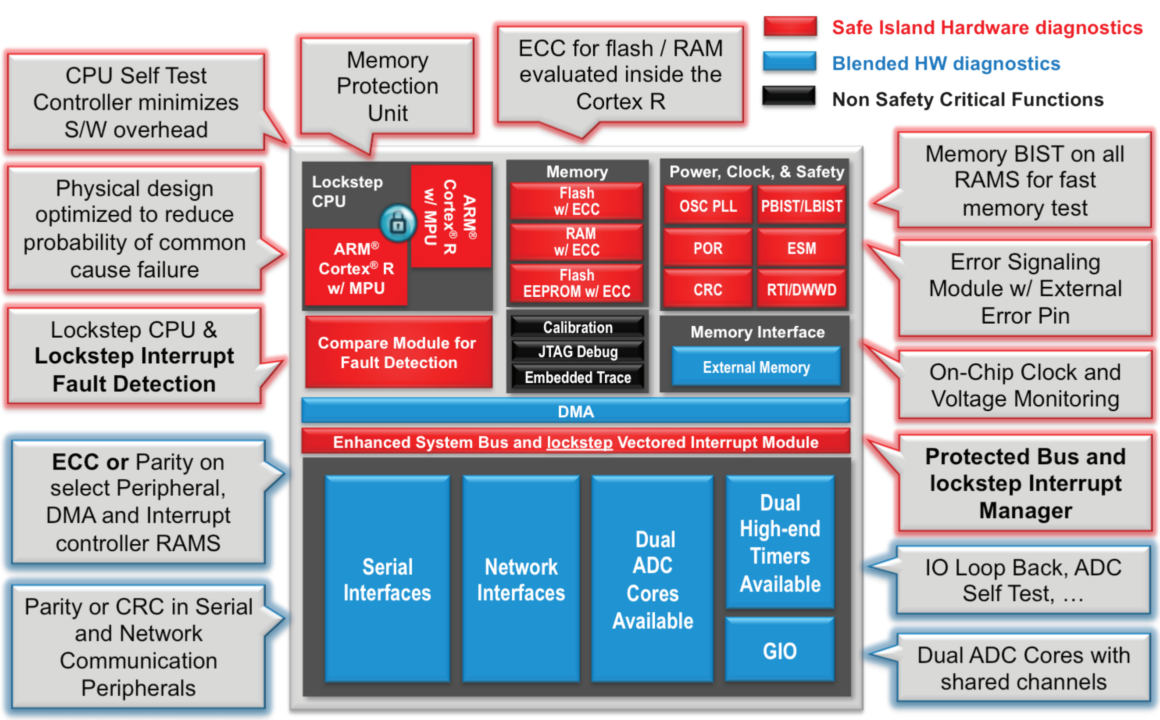
TI Hercules TMS570 MCUs offer dual-core CPU lockstep/compare and memory Error Correction Code (ECC) real-time diagnostics, as well as hardware-based CPU Logic Built-In Self Test (LBIST) and SRAM Programmable Built-In Self Test (PBIST) (see Figure 7).

These hardware-based safety features help diagnose errors in mission-critical blocks and offer high diagnostic coverage with minimum software overhead.

- The dual ARM® Cortex®-R lockstep architecture provides cycle-to-cycle high diagnostic coverage of the CPU.
- The Error Correction Code (ECC) circuit, implemented inside the lockstep Cortex-Rx CPUs, provides bus interconnect and SRAM/Flash single-bit error correction and double-bit error detection (SECDED) with little to no performance impact.
- The CPU LBIST and SRAM PBIST offer high coverage fault detection.

The TI Hercules MCU lockstep CPU with compare, memory ECC, LBIST and PBIST on-chip hardware-based diagnostic circuits facilitate the system implementation with high test coverage while minimizing software overhead.

Furthermore, TI also offers the Hercules SafeTI™ Diagnostic Library providing simple-to-use API functions to implement CPU and memory self-tests during the system start-up and during the system run-time. It also provides API support for initialization, exception handling, error handling and fault injection (see Figure 8).



Bold items are introduced with the new Cortex®-R5 devices

Figure 7: Hercules MCU safety features

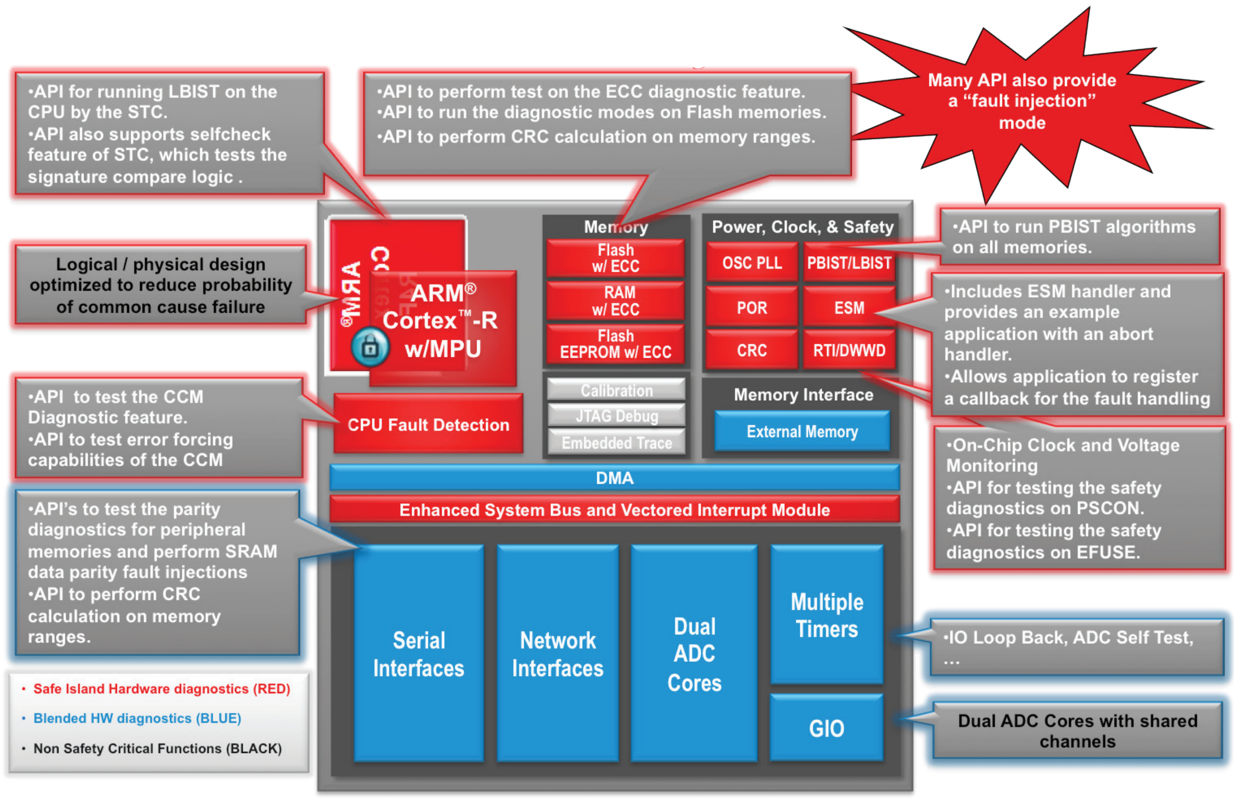


Figure 8: Hercules MCU safety features and SafeTI™ Diagnostic Library

The Hercules SafeTI Diagnostic Library can be downloaded from **www.ti.com/tool/SAFETI_DIAG_LIB**.

3. Analog companion components

TI's large portfolio of analog components provides a wide selection of power supply circuits, interfaces and signal conditioning circuits connecting the Hercules MCU to the real world.

The bq76PL455A-Q1 (16-Cell EV/HEV integrated battery monitor and protector) is an automotive AEC-Q100 qualified device for Li-ion cell monitoring and protection. It provides an analog front end and ADC to report individual battery voltages and has over-voltage and under-voltage comparators for a second level of protection against battery abuse. The device can also support passive balancing with external n-FETs or active balancing with EMB1428Q (switch matrix gate driver for active cell balancing)/ EMB1499Q (bidirectional current DC-DC controller) chipset. The bq76PL455A-Q1 has built-in self-test features that customers will find useful to help them meet their safety goals.

For more information on bq76PL455A-Q1, please consult **www.ti.com/product/bq76pl455a-q1**.

For more information on EMB1428Q, please consult: **www.ti.com/product/emb1428q**.

For more information on EMB1499Q, please consult: **www.ti.com/product/emb1499q**.

There is a TI Design system example showing active cell balancing BMS using a TMS570 MCU with bq76PL455A + EMB1428/EMB1499: **www.ti.com/tool/TIDM-TMS570BMS**.

4. System certification

MCUs may be certified up to a particular ASIL level. A "certified" MCU means that it has been reviewed and meets the requirements of a functional safety standard up to the specified ASIL. Supporting documentation and tools such as the safety manual and failure mode effect and diagnostic analysis (FMEDA) tool are required by the standards to help system developers understand the MCU safety mechanisms and to calculate the MCU failure rate.

TI's Hercules TMS570 MCUs are certified as meeting ISO 26262 requirements up to ASIL-D as previously mentioned. The MCU development process, the management of systematic failures and the management of random failures have been examined by TÜV SÜD. Safety documentation for these MCUs includes a safety manual available for general download (no NDA required) and a safety analysis report with the FMEDA tool available (under NDA). These documents and tools have also been reviewed by TÜV SÜD during the MCU certification.

Supporting the TMS570 MCUs are foundational software components such as peripheral drivers generated by TI's Hardware Abstraction Layer Code Generation (HALCoGen) tool and SafeTI Diagnostic Library. The software development process for these software components has been certified by TÜV NORD as meeting up to ISO 26262 ASIL-D levels of safety integrity. TÜV NORD is an internationally recognized and independent assessor of compliance with quality and safety standards. SafeTI Compliance Support Packages (CSP) are developed according to TI's certified software development process and are available for HALCoGen and the SafeTI Diagnostic Library. These CSPs provide a helpful starting point for customers who need to provide similar evidence for their functional safety-related software during system certification. For more information on SafeTI Compliance Support Packages, please consult **www.ti.com/lit/wp/spny007/spny007.pdf**.

The use of these certified MCUs and their supporting documentation and tools can help customers with their safety system development and reduce their certification efforts.

Summary

The TI Hercules MCU family helps customers with their BMS system development and makes industry functional safety standard certification efforts easier:

1. Up to ASIL-D certified MCUs help customers design an overall system for ISO 26262 compliance;
2. Hardware-based high coverage CPU and memory self test with minimum software overhead supported by SafeTI Diagnostic Library;
3. Automotive AEC-Q100 qualified bq76PL455A/EMB1428/EMB1499 BMS chip set;
4. ISO 26262 ASIL-D certified MCUs with the safety manual and FMEDA tools as well as the foundational software components (HALCoGen peripheral drivers and SafeTI Diagnostic Library) developed with TI's ISO 26262-certified software development process help customers with their safety system development and reduce their certification efforts.

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