Smarter Power Distribution: Shaping the Future of Automotive Technology

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This white paper discusses how the emergence of zone architectures, 48V systems and other trends has enabled smarter, safer, more optimized power distribution in vehicles.

At a glance

1 **Why is power distribution changing?**
Discover how changing power sources, zone architectures, 48V low-voltage rails, and safety requirements are driving changes in automotive power distribution

2 **Power distribution architecture evolution**
Read how changing automotive architectures are sparking the need for optimized wiring and increased software control.

3 **A look inside power distribution modules**
Learn about design approaches to power distribution modules and various design considerations.

Introduction

Vehicle power distribution architectures and electronic control units (ECUs) are evolving to safely, reliably and efficiently distribute power through the addition of intelligent semiconductor solutions. As vehicles continue to advance toward autonomous driving and electric powertrains, there are new regulations to guarantee safe and reliable power distribution in the event of fault conditions.

This white paper will cover how government regulations, zone architectures, 48V and safety-conscious power design are all influencing changes in power distribution architectures, as well as what challenges and considerations these architectures face today.

Why is power distribution changing?

With new regulations making it more challenging to sell lead-acid battery cars (especially in the European Union), automotive original equipment manufacturers (OEMs) are turning away from the traditional lead-acid battery. Although lead-acid batteries are cheaper and easier to produce than lithium-ion batteries, they have a shorter lifespan and detrimental environmental consequences. These government regulations and the popularity of electric vehicles have led OEMs to use different input sources such as lithium-ion batteries, DC/DC converters and supercapacitors, as shown in Figure 1.

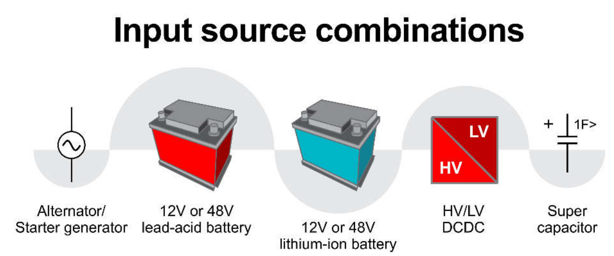

Figure 1. *Comparing various power sources for vehicles.*

The transition to lithium-based batteries, supercapacitors, or both requires additional circuitry to prevent overcharging conditions. The circuits for charging these supplies need a dedicated high to low voltage DC/DC supply charging circuit and use intelligent power switches to distribute and monitor the charging voltage and current. With the emergence of battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs), using the power distribution circuitry to recharge the battery while the car is off or on the move is especially vital to maximize driving range.

Supercapacitors are an interesting addition to automotive input sources. Although they are not great for long-term energy storage, they excel in applications that require burst-mode power because they offer more cranking cycles – the amount of times that a source can deliver large bursts of power before it's energy significantly falls – than lead-acid batteries over a short time. Therefore, supercapacitors are great for handling load transients such as capacitive inrush currents and motor startups or cranking. By using a battery with a supercapacitor, designers can decrease the stress on a car battery, extending the battery lifetime.

Zone architectures and smart eFuses

OEMs are starting to transition their vehicles from domain architectures to zone architectures, which is a concept of grouping electronic control based on location rather than function, as shown in **Figure 2**. A zone architecture offers a huge cost-savings opportunity by reducing the amount of vehicle wiring.

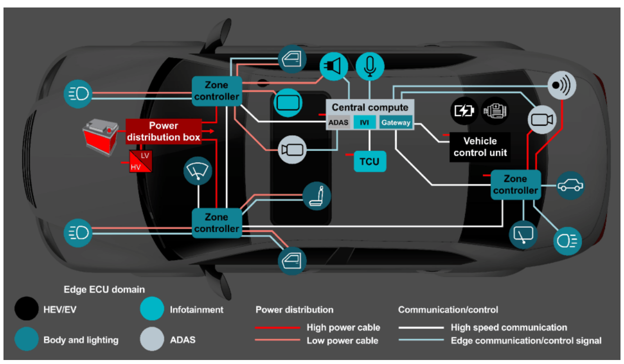

Figure 2. *A zone architecture in a modern vehicle.*

Instead of routing power from fuse boxes, zone architectures distribute electrical power through power distribution boxes (PDBs) and zone control modules (ZCMs). The PDB provides primary high-current power distribution from the vehicle's power supplies to ZCMs and other high-power ECUs. ZCMs then provide secondary power distribution to ECUs and sensors located close by. This design practice optimizes wiring and increases control of electronic power consumption.

ZCMs and PDBs also use semiconductor-based switches called smart eFuses that combine the functionality of melting fuses and mechanical relays. By adding software-resettable switches, the zone architecture effectively removes the need for accessible PDBs because the software can now manage each switch individually, including the algorithms needed to protect wire harnesses and recover from faults.

Zone architectures also help OEMs increase control of their power distribution systems by enabling them to better manage vehicle power consumption. In context, this involves the vehicle software switching off eFuses to switch off power from miscellaneous or unused functions so that safety critical-functions have enough power to operate.

The concept of switching off power to specific loads expands to minimizing total power consumption by driving powered-at-all-times (PAAT) loads using an eFuse's low-power state. Even in a vehicle's key-off or parked state, PAAT loads, such as door latches, are still powered so that safety-critical functions remain operational and large bulk capacitances remain charged. When PAAT functions operate, the eFuses exit their low-power state to fully drive loads and alert the local microcontroller (MCU). The eFuses then return back to their low-power state after idling for a certain amount of time.

48V low-voltage rails

Another source of cost savings is to move to a power source higher than 12V. 48V power distribution, although not a new concept in automotive, can further optimize vehicle wiring, weight, and cost while increasing the electrical power distributed throughout the vehicle. Specifically, the current needed to run high-power functions such as steer-by-wire at 48V is approximately 25% of the load current requirement when using 12V. Lower load current requirements thus reduces the gauge, weight and cost of vehicle wiring, further extending the driving range of BEVs.

Safer power distribution to enable autonomous vehicles

The last reason why power distribution systems are changing is because OEMs are motivated to make vehicles safer by incorporating enhanced vehicle intelligence for unrivaled driver assistance technology. Many OEMs are racing to innovate their vehicles beyond Society of Automotive Engineers Level 2 and the few Level 3 vehicles we have today to enable self-driving vehicles. The safety principles needed for Level 3 power distribution and beyond must exercise design practices such as redundant input supplies, intelligent load management when one supply fails, and freedom from interference to isolate faults in a system. These safety principles are extensively defined in the ISO26262 and VDA450 standards.

Power distribution architecture evolution

Power distribution in vehicles is evolving because automotive architectures are changing as a whole, sparking the need for optimized wiring and increased software control. As shown in Figure 3, power distribution networks feed vehicle power supplies into a PDB, which distributes power to each zone. Each zone then distributes power locally to nearby ECUs, actuators or sensors.

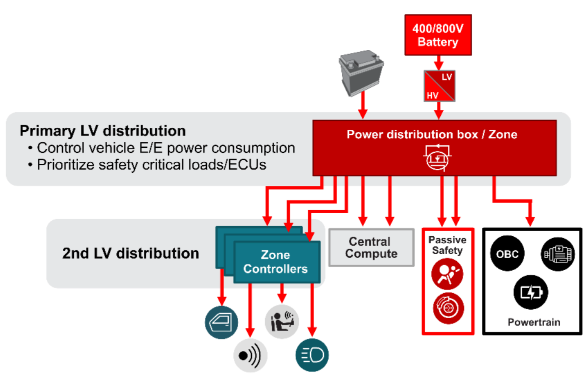

Figure 3. A modern power distribution architecture.

Figure 4 illustrates different power distribution architectures. With the introduction of smart eFuses, and 48V systems, OEMs are enhancing their systems by replacing accessible fuse boxes managed by the driver with electronic fuse boxes managed by vehicle software. The transition to 48V power distribution will take time, as not all loads and actuators are ready to make the jump to this higher voltage level. As a result 12V loads will remain in first generation 48V systems. As OEMs continue to evaluate 48V power distribution, power distribution architectures will continue to evolve, possibly replacing 12V sources altogether.

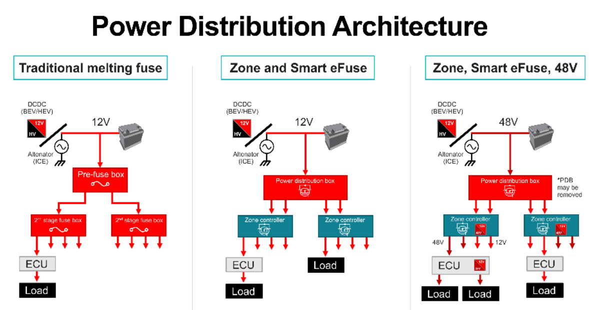

Figure 4. Comparison of future power distribution architectures.

48V systems enable further evolution by allowing you to use a backbone architecture where ZCMs distribute both primary and secondary power. It then becomes possible to remove the PDB as shown in Figure 5. The reduced load currents with 48V architectures allow more power distribution input and outputs in the ZCMs given lower thermal losses. This topology greatly simplifies the power distribution network.

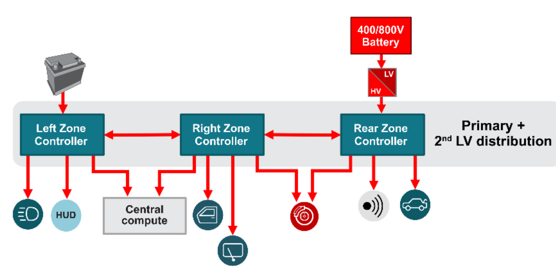

Figure 5. A backbone power distribution architecture.

A look inside power distribution modules

Typical PDBs and ZCMs employ several practices to enable smarter vehicles. If a system doesn't have a PDB, these practices are likely integrated in a ZCM. **Figure 6** shows a generic implementation of the primary level of power distribution.

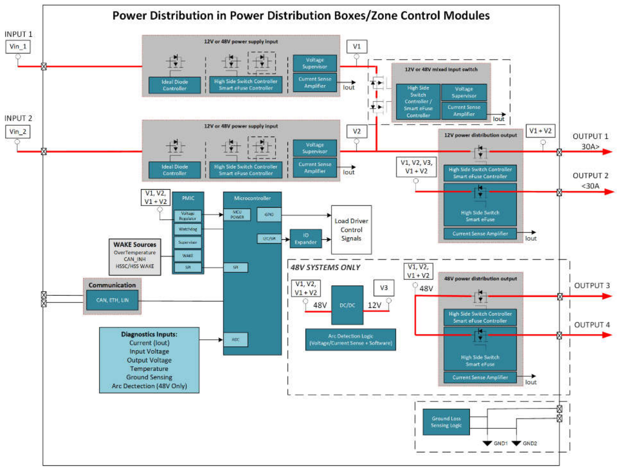

Figure 6. Generic power distribution module.

Input considerations

To reiterate, a PDB or ZCM can use any of five different power sources as shown in **Figure 1**. For selecting redundant inputs, you must consider questions such as what load transients exist in the system, whether there needs to be a low-power mode (especially for BEVs) or reverse-current protection, whether bidirectional current is allowed, and what safety mechanisms the system needs.

Load transients are vital to consider because supercapacitors or batteries can handle inrush currents, ensuring uninterrupted power. On the other hand, DC/DC controllers and smart eFuse switches require the ability to current limit and charge capacitive loads to ensure downstream components are protected from these transient inrush currents.

A low-voltage battery is the main input source to consider when designing for low-power modes. Low-voltage batteries consume miniscule amounts of current and their voltage level is stable over a longer time unlike supercapacitors. In comparison, a high-power DC/DC converter will consume a non-negligible amount of quiescent current. Nonetheless, a parallel low-quiescent-current DC/DC converter meant to support the system in its low power state can reduce power consumption from the high-voltage battery. Designing for a vehicle's key-off state also involves charging this battery in BEVs. Using a DC/DC converter as the secondary input source, turning on the mixed-input switches will charge the battery in its key-off state, allowing current to flow from Vin_2 to Vin_1 if downstream switches are disabled, as shown in **Figure 7**.

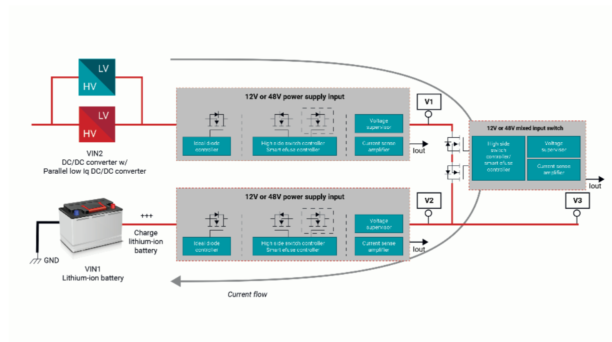

Figure 7. Charging Lithium-Ion using mixed-input switch.

Ideal diodes, as discussed in the white paper, "**Basics of Ideal Diodes**," are great for applications that require reverse current blocking and/or reverse polarity. Since ideal diodes offer reverse current protection, they are also useful in applications where multiple supplies must be combined to increase system redundancy.

On the other hand, smart eFuses or high-side switches are great for unidirectional and bidirectional current applications. Bidirectional current, in addition to charging the battery, is a requirement when supporting one ECU using multiple voltage busbars or domains for safety. Using **Figure 3** or **Figure 5** as an example, if the DC/DC converter or controller fails in this system, the vehicle software can modify the vehicle power distribution such that power from the battery is routed from the left zone to high-priority functions in rear zone. In case supporting these extra functions might overwhelm the battery itself, the vehicle software senses the supply current through current-sense amplifiers so it can determine which loads in the system to switch off to make sure these high-priority functions maintain a steady supply.

Finally, safety mechanisms can greatly alter the power distribution architecture. Using the mixed-input switch to combine both the V1 and V2 output rails will create an additional protected V1+V2 output for ECUs. A supercapacitor can also sustain power for critical components such as the MCU or external ECUs. Today, supercapacitors are used in vital car functions such as an electric door latch to open the door if power is somehow lost after a crash. These examples show how creative designers can be when selecting their power sources to implement different safety functions.

Output considerations

There is a growing need to replace melting fuses and relays with smart eFuses for intelligent power distribution. Considerations for selecting the appropriate smart eFuse include features such as programmable wire protection (I2T), capacitive charging, low-power mode, pin count for control and configuration, current and voltage sensing, and safety.

Load profile characteristics such as operating current, peak current, type of load, PAAT requirements and Automotive Safety Integrity Level rating (ASIL) will determine what features the selected switch needs. For supporting very high operating currents, consider a high-side switch controller that drives an external field-effect transistor (FET) to support any load requirement. An external FET solution is recommended to drive very high continuous current levels, 30A or greater for example, because this current level will increase the junction temperature of an integrated FET solution to an unsustainable level depending on the Rdson specification of the integrated FET.

In contrast, high side switches and smart eFuses excel in supporting lighter currents in both performance and cost. The PDB generally consists of high-side switch controllers instead of high-side switches because these devices need to support upwards of hundreds of amperes to support the power needed for all downstream zones. The load profile characteristics also indicate what the programmed wire characteristics of the smart eFuse should be so that the smart eFuse will shut off automatically upon detection of overcurrent without intervention from the local MCU. An example of an eFuse's programmable fuse characteristics is shown in **Figure 8**.

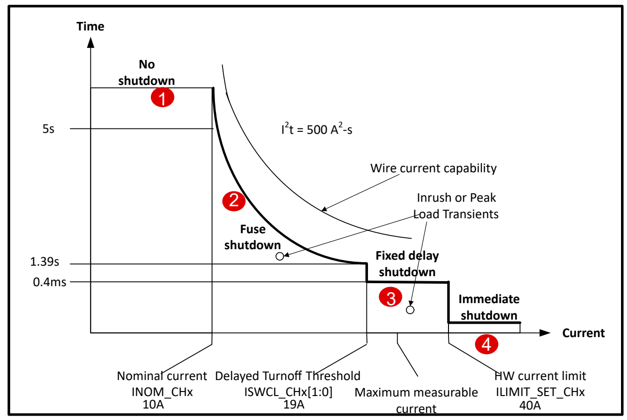

Figure 8. *Examples of different eFuse programmable fuse characteristics.*

The type of load and peak current also determine whether it's possible to use a smart eFuse capacitive charging method. Smart eFuse switches are typically equipped with capacitive inrush techniques to handle capacitive inrush and prevent damage to the metal-oxide semiconductor field-effect transistor (MOSFET). On the other hand, motorized inrush current from starting a brushed-DC motor will typically require a decrease in the smart eFuse drain-to-source on-resistance, or an external MOSFET in the absence of pulse-width modulation or current limiting.

It's important to consider the smart eFuse's safety mechanisms as well – more specifically its limp-home mode features. Limp-home mode is a programmable safe state the device enters if the failure conditions are met such as the high side switch losing SPI communication with its SPI controller which is typically an MCU. When designing limp-home states that preserve required vehicle functions, it's important to consider whether the outputs should stay on and what the recovery method is, which are both programmable features of smart eFuses before they enter this failure state.

System considerations

The design considerations for a PDB include system diagnostics, bill of materials (BOM), inputs/outputs (I/Os), and smart eFuse fault recovery.

System diagnostics can include parameters such as fault status and the voltage, current and temperature of each switch, as well as system-level parameters such as ground loss. For sensing voltage and current, you could select a current-sense amplifier or voltage-sense amplifier for accuracy requirements below 1% and use the MCU's integrated analog-to-digital converter (ADC). For 1% to 5% current sense accuracy requirements, using the integrated sense capability of a switch helps reduce system BOM. The integrated sense capability is also great for applications where current or voltage readings are needed in both active and low power modes. In contrast, at least two current-sense amplifiers will be needed to accurately sense the currents in these two states. Ultimately, knowing the system diagnostics for each switch enables the vehicle software to intelligently implement many safety features.

Determining the amount of MCU general-purpose I/Os and other peripherals for the power distribution module will greatly save costs by determining how the MCU interacts with the system. PDBs, especially ZCMs, can have more than 60 high-side switch, half-bridge and smart eFuse outputs. This translates to >300 I/O and ADC MCU pins needed to interface to multiple load-driver and smart eFuse integrated circuits. Using Serial Peripheral Interface (SPI)-based eFuses and SPI/I2C I/O expanders enables optimization of MCU package size and pin count. Figure 9 shows that for each IO-based eFuse, four pins are needed (EN, Diagnostic enable, WAKE, ISNS) and the I2T characteristics are not programmable. In contrast, one SPI-based eFuse only needs five MCU pins, adding only one chip select for each additional device.

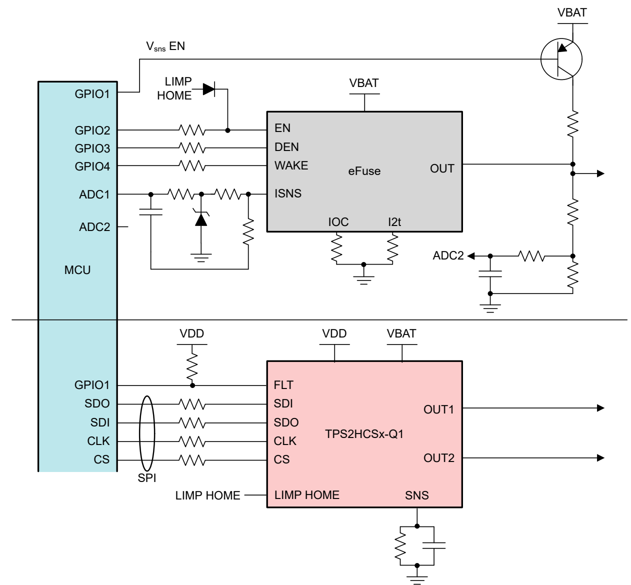

Figure 9. *Optimizing IO count through SPI-based eFuse.*

Software is also vital to determining the recovery method for each eFuse. Melting fuses will melt and disconnect the input and output to stop the flow of current upon detection of an overcurrent. Texas Instruments smart eFuses will simply switch off the output and provide the option to automatically turn the output on again after a set time. It is also possible to implement more complex load recovery algorithms within the local MCU and power distribution system by estimating wire temperature using cable thermal models and wire resistance to determine whether it is safe to turn the output back on. Automating how these switches reset ultimately reduces the need for an accessible PDB and enables the placement of switches closer to their loads, reducing cable lengths from the power source to the ECU.

48V considerations

A 48V architecture is very similar to a 12V architecture, though it does come with additional challenges.

First, voltage arcing is an issue at 48V, so the outputs and components must have enough creepage and clearance to prevent arcing between two points of different voltage levels. A combination of software, voltage and current sensing will help detect arcing and quickly shut down the necessary switches to stop the arc. Machine learning algorithms can also be developed to better distinguish arcing waveforms from natural transients in the vehicle to help avoid false detections. Figure 10 shows the most common causes of arcing for 48V architectures.

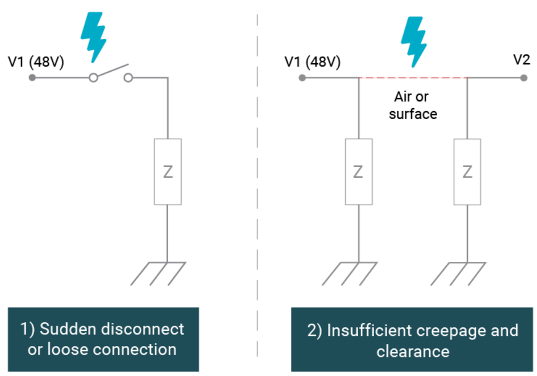

Figure 10. *Common causes of arcing on 48V architectures.*

In addition, a 48V-to-12V DC/DC converter is still necessary in many first generation 48V architectures, as not all actuators and semiconductors have transitioned to 48V operation or benefit from transitioning. There are many different topologies to consider for 48V-to-12V conversion depending on power required, board size, cost and efficiency. A standard approach is a traditional buck converter or controller, along with advanced topologies such as switched capacitor converters (SCC) and switched tank converters (STC).

References

1. To learn more about zone architectures, see **How a Zone Architecture Paves the Way to a Fully Software-Defined Vehicle**.
2. For additional benefits of zone architectures and their impact on software defined vehicles, see **Software-Defined Vehicles Shift the Future of Automotive Electronics Into Gear**.
3. To learn more about 48V architectures, their design challenges, and why they have reemerged, see **48V Automotive Systems: Why Now?**
4. To better understand the system benefits and considerations for smart eFuses, see **Fully Software Configurable High Side Switch for Power Distribution Applications in Zone Controllers.**
5. To learn how smart eFuses can help mitigate I/O requirements, see **Reducing System Bill of Materials and MCU Pin Requirements With SPI eFuse Switches.**

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