Smart Power Distribution in Zonal Architecture

AND90348/D

Introduction and Scope

Power distribution is increasingly becoming a central consideration while designing electrical systems for automotive applications. With prevalent electrification of automotive loads, actuators and switches, an optimized power distribution network is desired to drive high levels of vehicular efficiency as well as manage thermal budget of the system. A shift from domain to zonal architecture, as discussed in this application note, is a step in the direction of such optimization. This application note will present different aspects, requirements and solutions for power switching devices− namely self−protected or SmartFETs as they relate to zonal architecture deployed in automotive systems. The terms SmartFETs, Smart−switches and eFuses are interchangeably used through this document to highlight the similarities in their intended application use. At the preface, this document, in general, will highlight the key benefits provided by zonal architecture followed by an evolution in the requirements for power switching devices as entailed by new application use cases. A detailed explanation of individual features, design philosophy and drive methodologies is outside the scope of this document and will be covered in respective application notes to assist the user with the design of **onsemi** devices in zonal systems. Additionally, as switching devices are becoming smarter and being controlled with software commands, incorporating high levels of functional safety in the SDV (Software Defined Vehicle) application becomes critical and will be briefly described in the following sections. Further, the application note will briefly describe the adaptation of 48 V systems in electric vehicles but most of the discussion and examples in this document will pivot around 12 V automotive systems. It should also be noted that, while integral to zonal architecture, any discussion on changes in inter−module communication protocols, advancements in vehicular networking strategy including ethernet as well as details on power−over−data lines will not be covered in the scope of this document. Finally, for any details on generic SmartFET features, design blocks and device construction, it is recommended to refer to the applications note *High−Side SmartFETs with Analog Current Sense* (https://www.onsemi.cn/pub/Collateral/AND9733−D.PDF).

Why Zonal Architecture?

The ongoing focus on vehicular weight reduction, in an attempt to improve efficiency, requires an overhaul of the current architecture in which different control modules and electronic components connect and communicate with each other. The currently prevalent “domain” architecture (refer Figure 1) is pivoted on a centralized power distribution unit together with different electronic modules handling specific functionalities. For example, body control modules for controlling lighting− and body functions, engine− and transmission controllers for managing under−the−hood engine operation, instrument cluster modules to control cockpit− and dash display etc. Each of these functional modules utilizes smart switches, relays etc. to power end loads such as actuators, lamps, sensors etc. As the feature−set being offered and expected in contemporary automotive solutions is gradually compounding, the inputs and outputs connected to each functional module are ever−increasing, thereby requiring intensified cabling. Further, these connections often span different sections of the vehicle (as shown in Figure 1), causing the harness weight and length to grow rapidly. What ensues is a bulky, highly complicated and inter−twined mesh connecting and powering these electronic components and modules.

The zonal architecture alleviates these issues by offering a straightforward and scalable topology for connecting electronic modules. These individual modules, or zone controllers (refer Figure 2) are consolidated in functionality, i.e., each zone controller manages the functionality in a given vehicular zone regardless of the nature of the function. Further, the power distribution network is de−centralized by off−loading the central power distribution unit such that each zone controller distributes power through on−board eFuses to ECUs, loads, sensors and actuators specific to the zone. The connected ECU’s, in turn, drive further loads as shown in Figure 2. Each zone also constitutes a gateway or high−speed communication connection to the centralized gateway controlling for managing software updates, providing status of shared sensors/actuators as well as communicating with external users/networks. Such an approach significantly reduces the overheads associated with routing cables throughout the vehicle for different functions and also eliminates the need for longer and heavy cabling required with centralized power distribution. Since power distribution is handled specific to a zone, the length and routing of high current carrying wires can be carefully optimized. Harness weight and connections are one of the top contributors to the overall vehicular weight. Reducing harness weight and complexity, therefore, provides an opportunity to create more efficient, sustainable and lighter vehicles capable of supporting higher mileage and drive range.

In addition, as zones are being added or removed based on vehicle trims (a sedan, for example can have more zones than a hatch−back), the respective zone controller can be added or removed thereby creating a scalable platform solution that can be used to realize common assembly lines for different trims− something that OEMs have been targeting aggressively to reduce operational costs. An SDV takes this concept further and allows enabling/disabling features with the help of software commands to respective zone controllers with the help of advanced communication networks, thereby realizing the scalability entirely in software with common hardware platforms. Such an approach has enabled a subscription−based model to dynamically add or remove user access to features including both comfort and convenience (such as heated seats, ambient lighting control etc.) as well as drivetrain and performance (cruise control, auto−park etc.).

The shift from domain to zonal architecture is concurrent with increasing electrification and focus on autonomous driving in vehicles with many EV's adopting zonal architecture to realize their design. This also provides an opportunity to the OEMs developing ICE (Internal Combustion Engine) cars to develop forward compatible architectures as they gradually venture into EV and hybrid markets.

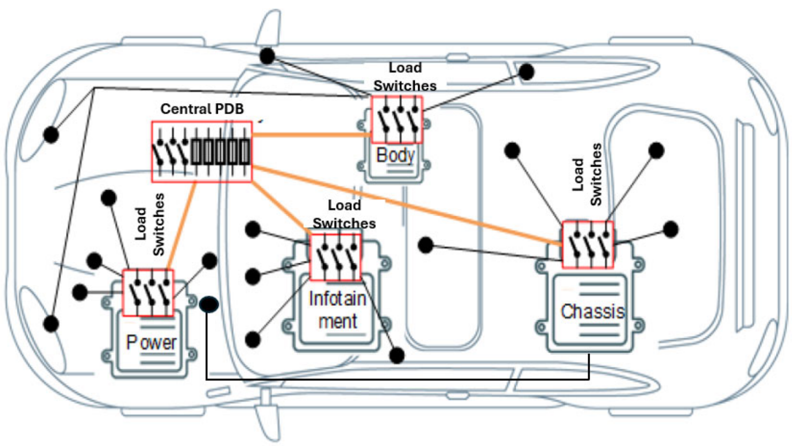

Figure 1. Power Distribution in Domain Control Architecture

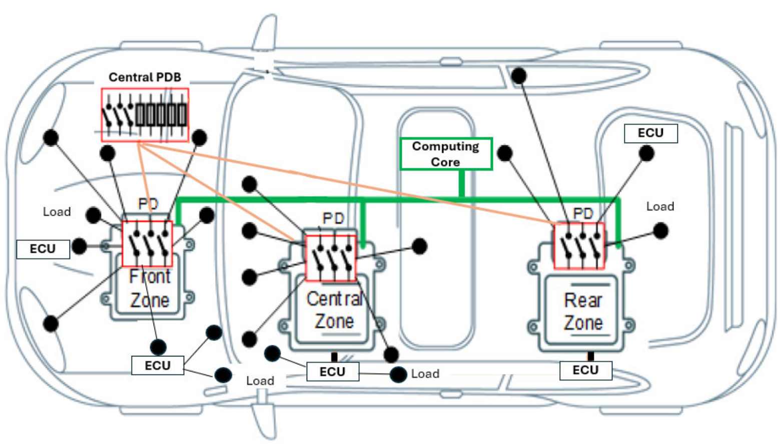

Figure 2. Power Distribution in Zonal Control Architecture

To summarize, an SDV's zonal architecture has many advantages over previous generations of wiring architectures. Where once new features could only be introduced by adding dedicated computing and associated power wiring, which increased the cost and weight of the wiring harness and added complexity to production flows, instead, a zonal architecture vehicle is organized into 'zones' each with its own dedicated electronic control unit that can be commanded to activate/disengage a specific functionality with software instructions. Such an interconnection quickens the process of adding new features to a vehicle while also keeping the additional cost and weight added to the wiring harness at a minimum.

Smart Power Distribution − Challenges and Solutions

While advantageous, zonal architecture presents a fair set of challenges as well. To begin with, not all end loads/applications, especially those that are extremely safety critical or require high levels of power to operate, can be “bundled/grouped” into zones. This implies that the operation of loads such as braking, power steering etc. will still require dedicated controllers and connections to respective zonal modules/central gateway to access information from sensors in different sections of the vehicle. Such a power distribution architecture is depicted in Figure 3 below. The transition to zonal architecture will therefore be partial to the foreseeable future and a central power distribution box (PDB) will continue to power such dedicated modules.

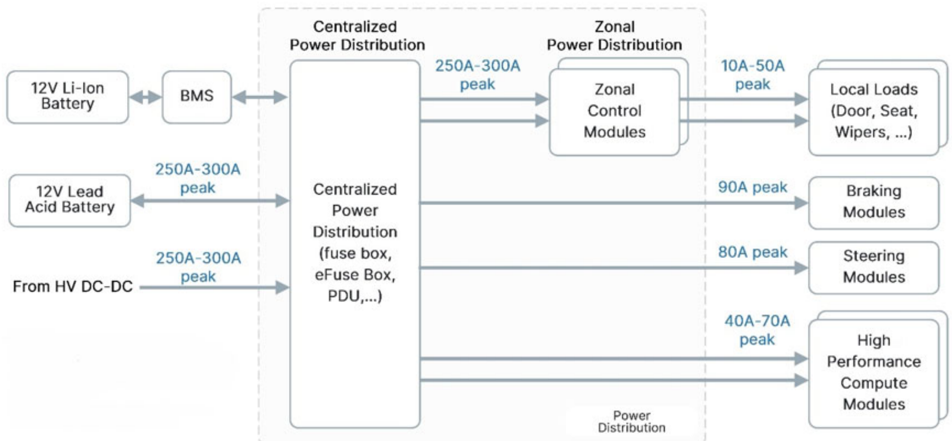

Figure 3. Power Distribution Architecture

At a system level, the increasing number of sensors, I/Os and loads as controlled by zonal modules, when all configurable in software, will imply more security threats. Therefore, onboard software will only continue to grow more critical to manage effectively for vehicle manufacturers. This may contribute to any inertia that industry may assert towards transition to the Software Defined Vehicle (SDV) approach when developing zonal architectures in electric vehicles. Secondly, adapting a common hardware solution would possibly entail features that may not ever be engaged/activated by the user leading to “wasted” harness used to connect the related hardware. This puts all the more impetus on a “lightened and optimized” wiring harness network to limit such overheads that may present a challenge in the form of mechanical stability, especially at ECU connector− something that needs to be considered while downsizing wires.

Now, from a power switching standpoint, the “lightened” harness network causes the wiring to become less robust to high−current transients and hard shorts to the chassis ground. Therefore, the lighter cabling demands more accurate protection which conventional fuses may not be able to support. Further, the desire to distribute power through dedicated zonal controllers requires fuses to be often placed in inaccessible sections (to an external user) of the car. This innate inaccessibility and therefore, lack of replaceability, requires fuses to operate through the lifetime of the vehicle and be able to shut themselves off automatically in case of overload conditions and reset upon intervention without being destroyed. A distributed power network enabling harness weight reduction, therefore, requires that mechanical fuses be replaced with intelligent silicon−based switches that can be housed inside the zone ECUs and provide power to loads and sub−modules in each zone.

A high−current smart−switch offers decision−making and fault−reporting capability which a mechanical fuse cannot provide. Such smart switches are ‘self−protected’, implying they are able to deploy integrated current, voltage, power and temperature limiting mechanisms in case of overload and high−power conditions and need not be replaced when exposed to an application failure mode. They can also diagnose application faults and report extensive information to the microcontroller as will be discussed. The figure below highlights different advantages of Smart−switches/ SmartFETs over mechanical fuses.

While most of these benefits are self−explanatory, it is imperative to mention that ensuring high reliability in electronic switches is both a benefit and a concern. A SmartFET, when compromised, is likely to fail in a short circuit as opposed to a mechanical fuse that typically opens the circuit connection when damaged. It is, therefore, critical to consider lifetime performance, long−term reliability and also integrate preventative maintenance measures to identify any performance degradation over the operational life of the switch.

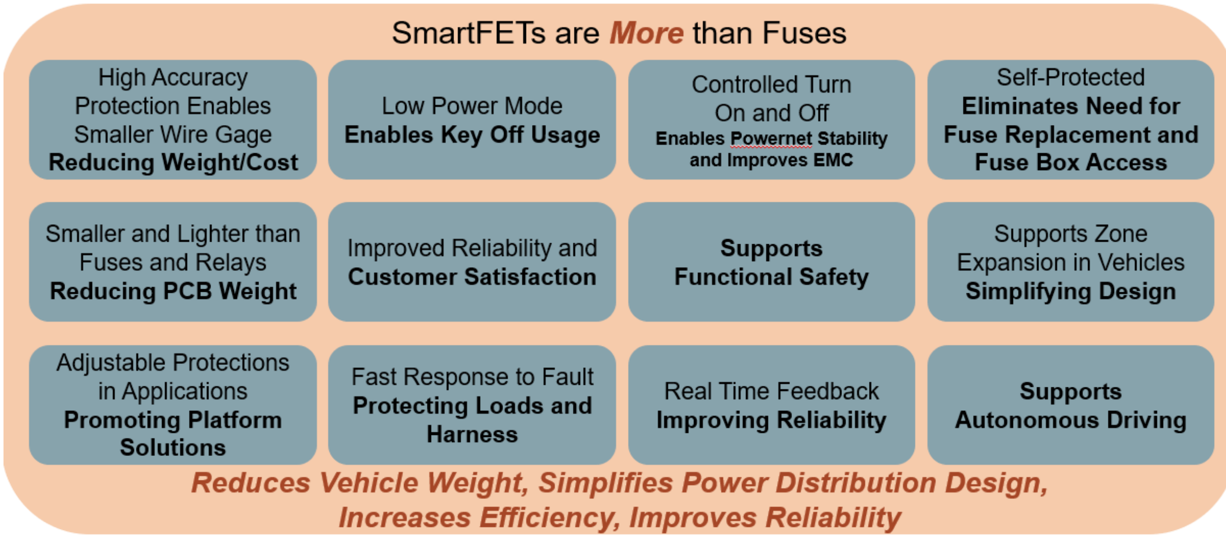

Figure 4. Advantages of eFuses over Conventional Fuses

In the backdrop of the advantages presented above, the following section will present the requirements and features desired from power switches in zonal architecture.

Redefining Power Switching

As described above, the new set of application use−cases presented by zonal architecture requires additional capabilities from SmartFETs in addition to currently supported standard feature offering for them to be deployed as eFuses. This standard feature offerings, including but not limited to integrated charge pump drive, overvoltage protection with internal clamps, ESD protection, over−current shutdown, absolute and differential thermal shutdown, high accuracy current sensing, and fault diagnosis are all described in detail in the applications note *High−Side SmartFETs with Analog Current Sense* (https://www.onsemi.cn/pub/Collateral/AND9733−D.PDF).

a.) Harness/System Level Overload Protection

Such protection is targeted to be offered through integrated I^2t protection in eFuses. The current vs time relationship of a conventional fuse can be more precisely controlled in Si based switches thereby allowing the vehicle manufacturers to select optimal wire dimensions for the application. Further, the configurability in I^2t protection levels in a device can provide the customers with a common hardware platform for serving multiple end applications. The details of this feature will be outlined in a dedicated applications note.

b.) Dedicated Capacitive Charging Mode

A quantum change, as observed by zonal SmartFETs, is the consideration of ECU's and sub−modules as potential loads. Since many of such modules are connected to bulk/reserve power supply capacitors, the eFuses powering these modules are required to offer a dedicated capacitive load charging mode. The details of this mode will once again be presented in a dedicated applications note together with bench measurement examples.

c.) Low Power Operation Mode

In an SDV, many features and functionalities will require periodic software updates− typically executed in key off state when the car is parked. In addition, with increased electrification, many loads and modules will be required to always stay on. In such case, the operating current consumption of the eFuse needs to be reduced significantly to minimize battery drain. The smart switches in zonal applications, therefore, are required to offer a special low power operating mode to serve such loads. A dedicated applications note will cover the details on this mode and its implications.

d.) Integration Communication with Robustness

As mentioned before in this document, a high speed and reliable communication system is central to designing effective zonal architecture. While not directly responsible for carrying data and sensor information, the power switch or the eFuse provides the microcontroller with valuable feedback in terms of load current, input and output voltages, operating temperatures etc. as well as diagnostic information such as device or system level fault status. Devices such as NCV84003G provide load current and diagnostic information on current sense analog output, and low power mode status on a dedicated IDLE_FLG output (refer to datasheet for details). Furthermore, board level communication protocols such as SPI, I2C etc. are also increasingly being integrated into eFuses thereby allowing a wider range of high precision diagnostic, readback and operational information to be transmitted to the microcontroller. As the number of eFuses in the application proliferate, the digitization and processing of this information before transmission on the communication bus reduces the microcontrollers overheads in such processing. Since SPI interface allows a full duplex control while not requiring any specialized hardware on the device side for arbitration, SPI is increasingly becoming the preferred communication protocol for most smart switches in zonal applications. Complementing power switching robustness and protection capabilities with feedback over communication lines offers a closed loop solution to the customer.

e.) Controllability, Configurability & Safety

The ability to control and configure the power path through the output stage as desired is a big advantage of smart switches when compared to mechanical fuses that are directly connected to power and require a redundant switch off path to the load. The power FET conduction path can be controlled via logic inputs in most smart switches. The logic input enables a standard CMOS level microcontroller output to drive the switch−on/off of the output stage by controlling internal charge pump and oscillator. In SDV applications, where a particular feature needs to be provided on−demand (for instance, heated seats, drive−assist etc.), the activation of the switching IC that provides power to the relevant load/module/actuator, can help implement such a design with least redundancy.

While advantageous in power switching, it is also extremely critical from a functional safety standpoint that the smart switch does not activate the power stage inadvertently and should stay off when commanded off by the application microcontroller. Further, for safety critical applications such as airbag controllers, or power steering modules, it is important that the smart switch turns on the power stage when commanded on. Additionally, there are other considerations such as detection of a device−level, or a system−level fault, in which case the output control is overridden by the internal protection mechanisms that can shut off the power FET. Many applications, while replacing mechanical fuses, require the switching IC to offer an extremely fast switch−off path via a dedicated external pin that ensures power to safety critical loads is disconnected immediately (as opposed to a controlled output slew down through logic input) when microcontroller detects a system failure. onsemi zonal devices are developed to meet ASIL B standards enabling simplified and safer designs.

In devices that offer SPI communication, output stage can be controlled via specific bits in the control register. In cases where SPI communication is lost, a fail−safe mode or a limp home mode is usually offered to allow controlling the output stage. In some applications, for example, microcontrollers may choose to keep the output stage switched on in case of loss of SPI bus. Multiple eFuse output stages can be controlled in daisy chain or parallel mode to limit the control hardware on the microcontroller. In addition to controlling output stage, smart switches are also expected to offer control over their modes of operation. The direct drive devices from the “G” family offer control over low power Idle and capacitive charge modes as well besides the normal operating, standby and sleep modes. The SPI devices can extend this control to other modes such as limp home and fail safe (refer to the respective product datasheet for details on output and mode control).

Another benefit derived from smart switches is in the form of configurability. The activation/de−activation of certain loads connected in the zonal architecture may require some critical parameters such as overcurrent detection (usually governed by load inrush requirements), I^2t performance (usually governed by harness ratings), slew rates (usually governed by capacitive charge requirements) etc. to be adjusted in field. Further, in the interest of reducing logistical and design complexity, there is a growing impetus on using instances of the same device for multiple applications and loads, requiring the smart switch to be configurable in its aforementioned characteristics for usage in different applications. The direct drive smart switches such as NCV84003G offer adjustability in overcurrent thresholds and I^2t profiles while devices such as NIV3071 offer adjustability in current limit and turn on slew rates. Again, SPI controlled devices can potentially extend this configurability to other features including, but not limited to, retry strategy in case of fault, internal PWM generation characteristics, mode transition thresholds, current sense ratios, etc.

f.) Enhanced Focus on Functional Safety

Deploying smart switches as eFuses in a zonal system requires integration of advanced feature sets (including, but not limited to, the ones discussed above) with a high degree of self−reliance, i.e. being capable of operating with limited intervention from the microcontroller. The eFuse device should be capable of ensuring harness and load safety together with self−governed mode transitions, inbuilt self−protection and self−tests, high speed fault response and fault reporting etc. Such integration requires an overhaul of the development process for these smart switches with an enhanced focus on safety. Safety, in this context, applies to safety at both device and application levels, which requires an extensive collaboration between Si suppliers and customers who design the application. The conventional design methodology of designing an IC followed by performing a DFMEA (Design Failure Mode Effect Analysis) to quantify design effectiveness has been substituted by an FMEDA (Failure Modes, Effects, and Diagnostic Analysis) process where the design is initiated while considering the safety implications. To begin with, high level safety goals are defined for the device to operate in an application per agreement/discussions with the customer. The safety goals are then translated to develop (for each design block) safe states and potential hazards/violations, followed by identification of safety mechanisms that prevent those hazards and any faults that may override the mechanisms. The contribution of each design block towards fault metrics is calculated as per internationally accepted standard, namely ISO26262 and then the overall design is assigned a safety, or an ASIL

(Automotive Safety Integrity Level) rating. If the rating needs improvement, then each block must be re−assessed, for example, to incorporate higher levels of design fail−safe measures or redundancies. Functional safety characteristics at the device level contribute to the overall application−level safety. Safety reports/FMEDA analysis, are therefore provided to the customer to help build an application that meets the desired safety criteria and rating. Some applications, such as braking, airbag control, for instance, will require more stringent implementation than others such as ambient lighting, comfort and convenience etc. It is recommended to ask the respective onsemi representative for more information our safety approach and available documentation.

Besides a functionally safe design implementation, it is also desired that the eFuse device offers measures to diagnose or even prevent a fault in the application before it happens. Such measures help improve the safety rating of the device. **onsemi** smart switches are being developed considering the safety implications and requirements at each process milestone in accordance with ISO26262, targeting a device functional safety level of ASIL B. Further, to address fault prevention, devices such as NCV84003G allow the user to request readback of the configured settings of safety critical parameters such as I^2t and overcurrent protection together with real−time I^2t status information for harness protection. SPI controlled devices will offer the user a readback of all configured settings and advanced diagnostic information together with built−in self−tests and pre−defined fail−safe states. In addition, warnings in case of operation close to extremes of recommended junction temperature and power supply range will also be provided to assist the user in preventing an undesired system response.

Scalability in Supply Levels

With a gradual transition to hybrid and electric vehicles, the available power nets are also witnessing a major shift from the currently prevalent and accepted 12 V nominal level to higher voltage levels: with 48 V power net as the most promising candidate in the transition. Such a transition is motivated by the ability of a higher voltage net to allow reduction in the current levels in the application by a commensurate proportion (for a fixed load power rating) and thereby, further relaxing the weight and dimensional requirements on the harness that conducts current. This change, however, would require the development of an ecosystem comprising of loads, power switches and other components in the power path that are capable of supporting 48 V.

Since the high−volume, or full−scale development of such an ecosystem is still under−way, many OEM’s are designing their zonal power distribution architecture in a manner that is scalable between power nets. In a 48 V system, for example, where “edge nodes” as depicted in Figure 5, comprise a mix of 48 V and 12 V capable loads, a DC−DC regulated 12 V line can be used to power 12 V loads. As 48 V loads proliferate, the 48 V powernet can gradually supersede its 12 V counterpart.

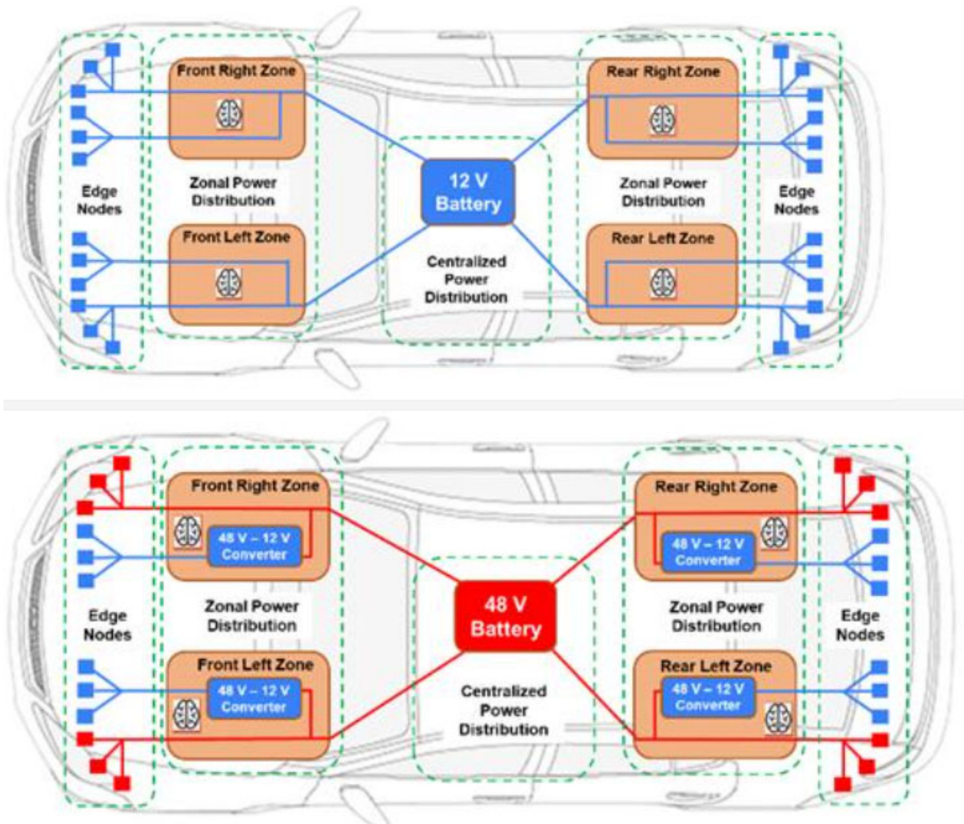

Figure 5. Zonal Power Distribution Concept in 12 V and 48 V Power Nets

From a power switching perspective, 48 V eFuses are required to offer feature sets and capabilities that not only match the 12 V versions, but are also forward−looking in meeting the new demands of a higher voltage net− such as new supply and load transient absorption capability, short circuit robustness, lifetime mission profiles etc. For more information about **onsemi**’s 48 V solutions, see NIV3071 application note at [https://www.onsemi.com/download/application−notes/pdf/and90247−d.pdf](https://www.onsemi.com/download/application-notes/pdf/and90247-d.pdf) .

REVISION HISTORY

Revision	Description of Changes	Date
0	Initial document version release.	5/28/2025