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Analysis of High-Voltage Options (400V vs 800V) in Electric Vehicle Architecture

Subhankar Das
Engineer
Platform Architecture
Renault Nissan Technology & Business Centre India

Abstract: The growing adoption of electric vehicles (EVs) has transformed vehicle design, driven by innovations in battery technology, electric motor engineering, and thermal management systems. This study investigates the impact of voltage levels on the design, packaging volume, and thermal behaviour of the key high-voltage components, including battery pack, electric motor, inverter, on-board charger, charging inlet, and high-voltage harnesses.

Using a battery with an energy capacity of 55.44 kWh, two configurations (400V and 800V) are evaluated for packaging volume and resistive power losses. The packaging space required for the two configurations will be studied with detailed studies on the battery pack and high-voltage harness.

The volume reduction of the electric motor and harness helps the integration of high voltage components, supporting the opportunity to increase the cabin space for the passengers. The higher efficiency of these components contributes to the extended driving range of the vehicle. These benefits make the vehicle more acceptable to the customers. It supports the adoption of 800V or higher voltage levels in the next generation of electric vehicles.

Keywords: Electric Vehicle, 400V Architecture, 800V Architecture, Packaging, Power Electronics, High Voltage Cables

I. Introduction

Electrical Architectures have evolved with the developments in battery chemistry and architecture, electric motor design, power electronics, and charging infrastructure. The broad adoption of new electrical components such as battery, inverter, motor, OBC, charging inlet, and HV cables has forced automakers to make an efficient packaging of the new components in the available packaging space.

Early electric vehicles (EVs) used low-voltage systems (typically 48V–120V). These low-voltage systems had limited range, power output and low efficiency. These constraints make their practical use only for short-distance and low-speed applications. The evolution to 350V-400V has led to improved thermal performance, efficiency, and faster charging speed. These advantages have motivated even more manufacturers to implement high voltage levels on their cars. Of late, these developments have further progressed, with manufacturers including 800V architectures on their vehicles. This transition provides superior performance, increased efficiency, and faster charging speed.

While existing works have analysed the performance and thermal behaviour of 800V architectures, very few studies explore packaging volume as a function of voltage system architecture in EVs. Through a framework using equivalent battery energy capacity, this study quantifies the impact of voltage levels on component sizing, thermal performance, and conductor optimisation, providing insights for platform-level design decisions. Also, the impact of silicon and wide-bandgap devices on the packaging volume is analysed.

According to the *Global EV Outlook 2023* by the International Energy Agency, the EV market is experiencing exponential growth [1]. Many of the countries are actively transitioning into pure electric vehicle nations as per the plan to completely phase out the ICE vehicles in the next 10-15 years.

Aghabali et al. [3] reviewed 800V powertrains in depth. They noted the advantages of weight reduction in cable and losses in the inverter but also noted integration challenges in size and cost of wide-bandgap materials. Subsequent research compared the performance characteristics of 400V and 800V systems. Conlon et al. [2] proposed a switchable 400V/800V system for Ultium battery electric trucks, highlighting the increasing adoption of 800V levels for better performance, efficiency and charging flexibilities. However, this approach added design complexity and insulation challenges.

Designing the battery is vital for scalability in voltage. Yao et al. [4] and Mekonnen et al. [6] summarised the properties of carbon-based and upcoming anode and cathode materials. They highlighted energy density and thermal stability. IDTechEx [5] also placed the rising importance of silicon anodes in future battery packs into perspective. This has potential implications for cell design and packaging at higher voltages.

From a power electronics viewpoint, Xu et al. [8] reported empirical evidence that inverters and compressors constructed with SiC MOSFETs surpass conventional Si IGBTs at 800V with better thermal behaviour and packaging density. The trade-offs, however, include cost, electromagnetic shielding, and thermal design restrictions.

Despite these findings, few quantitative comparisons were made between the packaging implications of main EV components (battery, inverter, motor, OBC, charging inlet, and HV cables) for both 400V and 800V systems. This paper fills that gap by providing a component-wise volumetric and thermal loss analysis, with practical configuration models using a 55.44 kWh battery architecture.

The efficiency of packaging significantly impacts EV design. It decides component content, mass distribution of the vehicle, and crash load paths. 800V systems and high-voltage systems support smaller conductor sizes and lower component volumes. This is particularly so when implemented with wide-bandgap semiconductors. The semiconductors support better thermal management and better power efficiency.

Efficient packaging supports modular vehicle platforms, allowing OEMs to standardise component layouts across models, cutting costs and reducing development time [2][7]. Lower current requirements in high-voltage systems also reduce cooling needs, freeing up space and improving energy efficiency. Ultimately, optimised packaging enhances passenger comfort and storage without sacrificing performance.

II. Methodology

This study assesses the effect of high-voltage (HV) system architectures—400V and 800V—on the packaging space, thermal performance, and overall efficiency of critical electric vehicle (EV) components. A contemporary EV has both High Voltage (HV) and Low Voltage (LV) systems, which perform different functions.

2.1. Low Voltage (LV) Components

- LV systems (usually 12V or 48V) are required for the supply of non-propulsion electrical subsystems, including:
  - Infotainment and display systems
  - Lighting
  - HVAC controls
  - Power windows and seats
  - Electronic control units (ECUs) and gateway controllers
- Interaction with HV Systems:
  - DC-DC converters are employed to step down the HV battery voltage (400V/800V) for powering LV systems.
  - 800V architectures require DC-DC converters to handle higher input voltages, which demand increased insulation, component derating, and an improved design.
  - The improved efficiency of 800V HV systems can reduce the thermal and electrical load on LV components (e.g., reduced HVAC demand due to better thermal management).
  - LV cable sizing generally remains unchanged, but overall packaging efficiency improves through the use of smaller, more efficient HV-to-LV converters.

Even though LV components are not individually changed by HV voltage levels, their supporting systems (conversion and cooling) gain advantage from the improved efficiency of 800V systems, which contributes to improved space utilisation, system integration, and thermal performance.

2.2. High Voltage (HV) Components

The key HV components that are affected by the selection of system voltage are:

- Battery Pack
- Electric Motor
- Inverter
- On-Board Charger (OBC)
- Charging Inlet
- High-Voltage Harnesses and Cables

Each of these components reacts in its own way to variations in system voltage. The subsequent sections discuss such effects in terms of:

- Packaging volume
- Thermal losses
- Electrical efficiency
- Integration feasibility

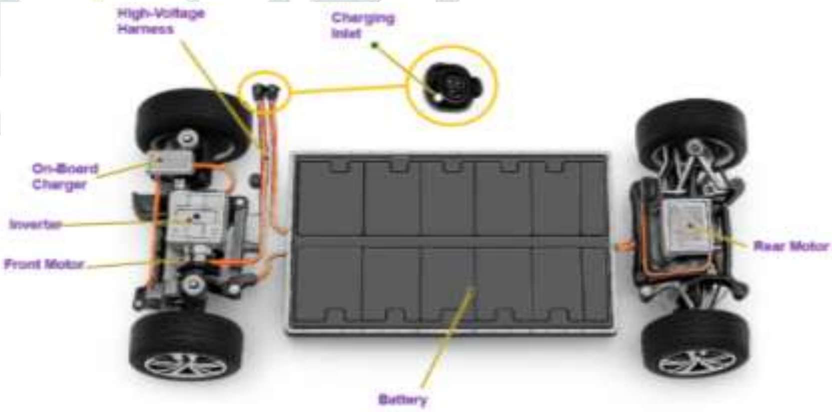


Figure 1: High Voltage components [11]

2.2.1. Battery Pack

As the Energy Storage System in an Electric vehicle, the Battery Pack plays a key role in the performance, efficiency, and packaging feasibility. A typical Battery

- ➢ Occupies 10-20% of the total volume of an electrical vehicle.
- ➢ Accounts for 30-40% of the total cost of the electric vehicle.
- ➢ Constitutes about 30% of the total weight of the vehicle.

Thus, it is important to understand the impact of voltage systems on the Battery.

In a standard battery pack, the cells are connected in series to increase voltage, and the cells are connected in parallel to increase Current. We know that the energy capacity of a battery pack is defined as:

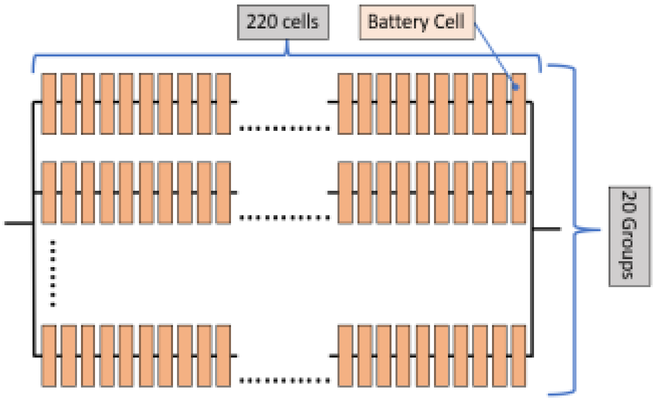
Energy capacity (Wh)= Voltage(V) * Current Capacity (Ah)

Using NMC Cell 3.5Ah 3.6V, two configurations are considered:

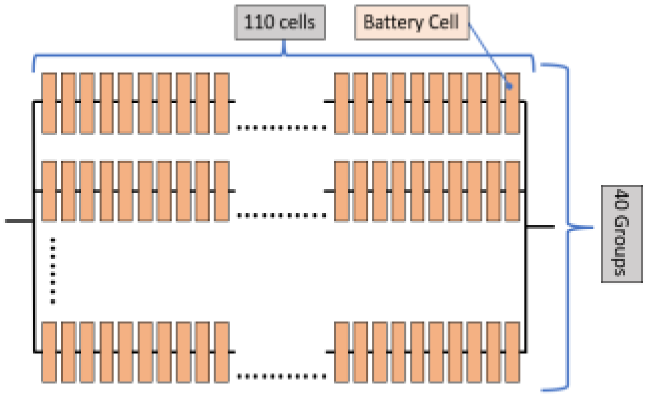
Table 1: 400V and 800V Configurations Comparison

Parameters	**~400V Configuration**	**~800V Configuration**
Architecture	**110s40p**	**220s20p**
Voltage	110 cells in series = 3.6*110 = **396V**	220 cells in series = 3.6*220 = **792V**
Current Capacity	40 groups in parallel=3.5*40 = **140Ah**	20 groups in parallel=3.5*20 = **70Ah**
Energy	396V × 140Ah = **55.44 kWh**	792V × 70Ah = **55.44 kWh**
Total Cells	110 × 40 = **4,400 cells**	220 × 20 = **4,400 cells**

Although with varying voltages, for the same energy capacity of the pack, the number of cells remains the same. Cell counts and packaging space are not affected by the voltage level selection. [3]



a) 400V Configuration



b) 800V Configuration

Figure 2: Battery Pack Configurations

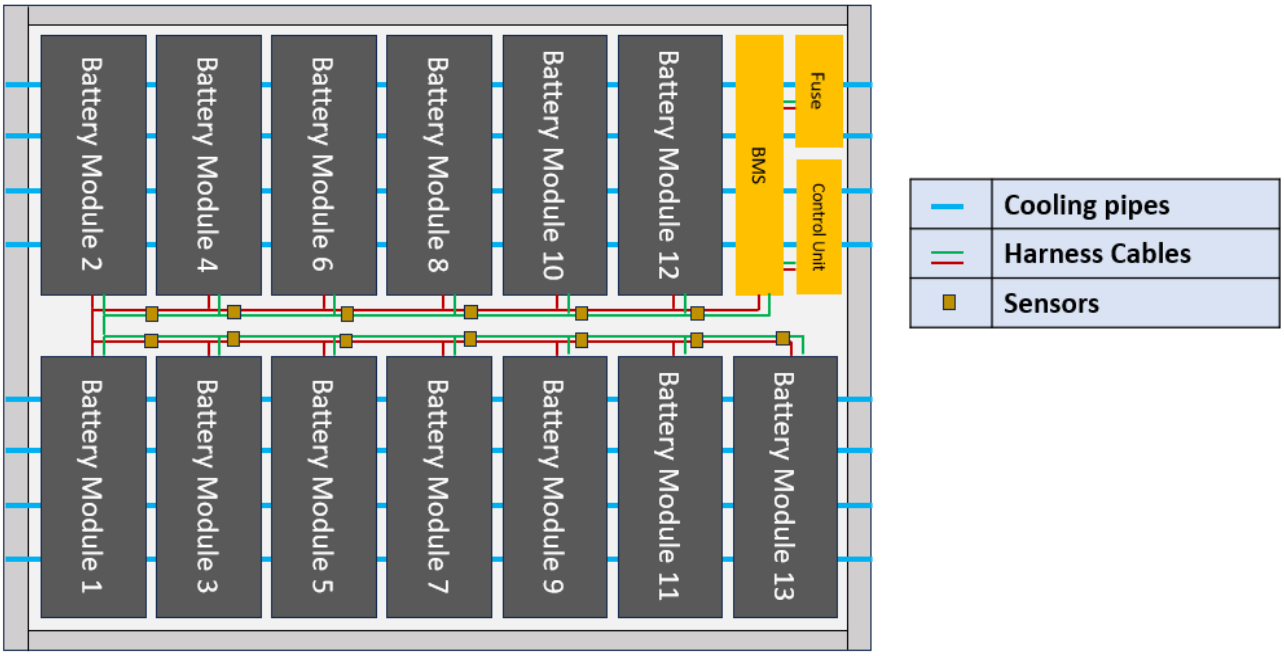


Figure 3: Battery Internal Components

Assuming internal resistance per cell = a Ω
Internal Resistance Calculation:

Table 2: 400V Vs 800V Internal Resistive Losses of the cells

Parameters	**~400V Configuration**	**~800V Configuration**
Resistance	2.75**a* Ω	11**a* Ω
Current	140A	70A
Resistive losses	53900*a W	53900*a W

In both cases, power loss due to internal cell resistance is the same.

But there are auxiliary items in a battery pack, like:

- Fuse breakers
- BMS units
- Main cables
- Cooling sensors

Some of the auxiliary items take less current, nearly half in the 800V system than in the 400V system. Because of less current, the resistive power losses in these items are also less. So 800V systems experience less thermal stress than 400V systems, improving the performance, efficiency, safety, and lifespan of the system.[2]

2.2.2. Electric Motor

The electric motor converts electrical energy into mechanical energy to drive the wheels. It is the primary component responsible for providing traction to the vehicle. While the basic construction of the motor is similar for both 400V and 800V systems, there are differences in power density, thermal design, and volume.

Figure 4: Motor Section

For the same power output, an 800V motor will draw half the current compared to a 400V motor.

Since power loss due to resistance is $P = I^2R$, reducing the current by half allows the resistance R to increase 4 times while maintaining the same power loss.

When the current is reduced by half for the same resistive power losses:

- The electrical resistance increases by 4×
- Copper windings required cross-sectional area reduces by 4×

(We understand that: R=ρ*(l/A) where ρ is the material's resistivity, l is the conductor's length, and A is the cross-sectional area.)

- Due to this, the quantity of copper needed for the windings also reduces by 4×

It is done by stepping up to an 800V system with improved thermal management and Silicon Carbide (SiC) or Gallium Nitride (GaN) technology, which decreases the motor volume by about 30-40%, enhancing packaging and efficiency.[7]

2.2.3. Inverter

The inverter also converts battery DC current to AC to power the motor and provides regenerative braking by reverse-converting AC to DC.

At 800V, higher voltage induces greater electrical stress, necessitating:

- Higher voltage rated semiconductor switches
- Larger internal clearances and better insulation

With traditional silicon technology, 800V inverters are normally 30–70% bigger than 400V inverters. But with Silicon Carbide (SiC) or Gallium Nitride (GaN) semiconductors used in 800V systems, the inverters are smaller and more efficient, being only 0–10% bigger in volume than 400V silicon-based systems [8].

Figure 5: Inverter [9]

2.2.4. On-board Charger

The On-Board Charger (OBC) is responsible for converting AC current from a wall outlet or charging stations into DC current that can be stored in the vehicle's high-voltage battery. It is a crucial component that allows the vehicle to charge its battery from an external AC power source.

The Rectifier and DC-DC Converter are the most affected by the conversion from 400V to 800V. The conversion requires:

- Semiconductor switches with higher ratings.
- Greater internal clearances and better insulation.

Since Silicon for 800V is not a preferred solution, normally SiC or GaN is used, which are smaller in size and have high efficiency in an 800V system.

So, comparing Si technology in a 400V system and SiC/GaN in an 800V system, the OBC chargers will be 0-20% larger in Volume. [8]

Figure 6: On-Board Charger [10]

2.2.5. Charging Inlet

It is one of the most important components in an electric vehicle as a gateway for connecting the external power supply with the Traction Battery.

The main components in the construction of the Charging Inlet are.

1. Housing & Mounting
2. Electrical Cables / Pins
3. Sealing and Gaskets
4. Locking Mechanism
5. Temperature Sensors (Optional)
6. Communication Electronics

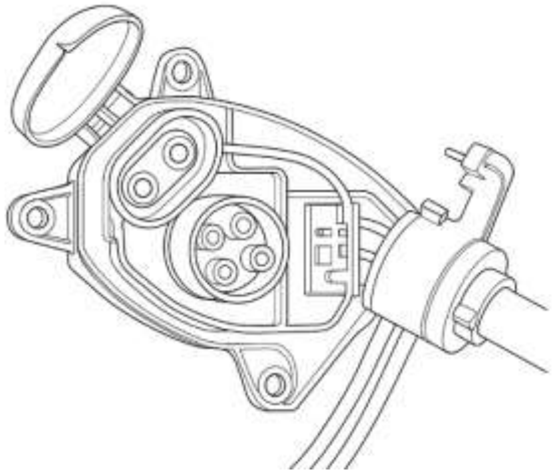


Figure 7: Charging Inlet

Electrical Cables / Pins are the only contacts that are connected to the high-voltage systems. Typically, Cables/Pins take up ~3% to 5% of the overall volume of the EV charging inlet.

Because in an 800V system, less than 70A current passes through the power pins, harness, and other internal components. The resistive losses are lower than those of a 400V system. With the decrease in the resistive power loss, which is dissipated in the form of heat, the charging inlet's efficiency increases.

When the current is halved for the same resistive power losses:

- Electrical resistance increases by 4×
- The required cross-sectional area of copper windings decreases by 4×
- As a result, the volume of pins also decreases by 4×

So, we can say that as we move from 400V to 800V, the volume of the charging Inlet can be reduced by 3-5% considering the same power loss.

2.2.6. High-voltage cables

Harness cables are a vital component of an electric vehicle. With the increasing number of features available in an electric vehicle, the electrical components are increasing, and so are the harnesses that connect them.

Typically, in an electric vehicle

- Low voltage harness length up to 1-1.5km
- High voltage harness length up to 20-30m.c

We know the relation of power in a conductor with voltage, Current and Resistance.
$P = I^2R; P = VI$

There is a constraint on the minimum cross-section that a wire conductor can have, depending on the material of the wire. The wire should be thick enough to withstand the heat generated due to the power losses.

But with higher voltage, the concern for insulation also becomes crucial. The insulation of the harness depends on factors like insulation material, thermal performance, mechanical protection, and electromagnetic protection.[2]

Assuming that in a 400V system the harness contains an insulator of 1.5mm, while in an 800V system we have a thicker one of 2.5mm

Comparing total harness volume for a 3-meter high-voltage cable with a 50 mm² cross-section, we have:

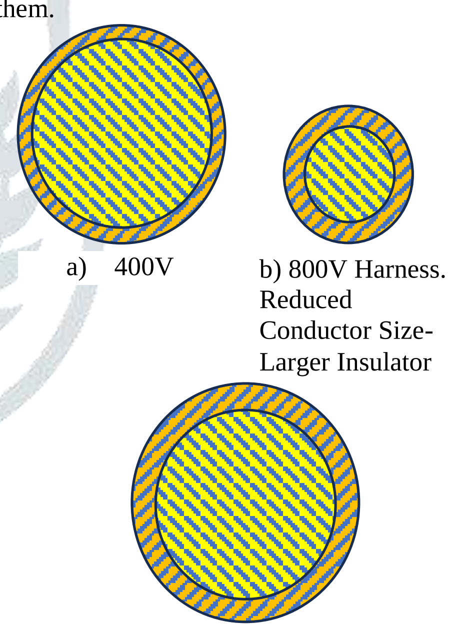


Figure 8: Harness Cross-section

Case 1: 400V System

- Conductor volume: 150 cm³
- Insulator volume: 133 cm³
- Total harness volume: 283 cm³

Case 2: 800V System (Same Power Loss, Smaller Conductor)

- Conductor volume: 37.5 cm³
- Insulator volume: 152.7 cm³
- Total harness volume: 190.2 cm³

Result: ~33% volume reduction from a 400V system.

Case 3: 800V System (Same Conductor Size, Reduced Power Loss)

If we keep the same conductor size (50 mm²) and length:

- Current is halved → power loss is 4 times lower.
- Conductor volume: 150 cm³
- Insulator volume: 247 cm³ (larger insulation)
- Total harness volume: 397 cm³

Result: ~40% volume increase, but 75% less power loss.

III. Results

The impacts on Vehicle Architecture due to the conversion of 400V systems to 800V systems are listed below:

Table 3: Vehicle Architecture Impact of 800V over 400V

Systems/Components	Impact
Battery	No difference in packaging volume in 400V & 800V.
	Less Thermal Stress in the 800V battery due to less power loss in the Fuse, BMS and Cables.
Electric Motor	30-40% reduction in motor volume in 800V compared to 400V due to copper windings volume reduction, and also using SiC/GaN technology
Inverter	The 800V Inverter will be 0-10% larger in Volume using SiC/GaN technology compared to the 400V
On-board Charger	OBC chargers will be 0-20% larger in Volume using SiC/GaN technology compared to 400V
Charging Port	Charging Port Volume can be reduced by 3-5% considering the same power loss compared to 400V
High-voltage cables	33% volume reduction compared to a 400V system, considering the Same Power Loss.
	40% volume increase, but 75% lower power loss compared to 400V, considering the same Conductor Size

IV. Conclusion

The move to 800V electrical systems from 400V is a pivotal development in electric vehicle (EV) design that has a direct impact on powertrain efficiency, thermal performance, and component packaging.

One of the deep benefits of migrating to 800V is that it has the capability to provide the same amount of power using half the current that 400V systems have. This current reduction has a substantial impact on all the high-voltage components in the vehicle, with reduced resistive losses leading to heat generation and higher efficiency.

In terms of packaging, the electric motor has a volume reduction of 30-40% and the electric harness benefits from size reductions up to 33% due to the shift to 800V. While not all the components see benefit with size reductions. Components like on-board chargers and inverters have increased by 10-20% in volume even after using wide-bandgap materials like SiC & GaN.

The results support the manufacturers implementing 800V voltage levels in their vehicles. In future, even higher voltage levels greater than 800V will be adopted for better efficiency and space optimisation, but there will be a challenge to implement proper high voltage insulation mechanisms before adopting higher voltage levels.

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