21st Century Automobile: When One Voltage Is Not Enough

By: Florent Liffran, CEO at BrightLoop Converters

The time is ripe for a once-in-a-lifetime change in automotive voltages. In fact, the revolution has already begun. It only remains to be seen which voltages the industry will converge on.

I. Introduction

Automobiles in production average 4000 meters of electrical wires. From today's perspective, a car without a supply of electricity is unimaginable. For most of us, it is equally unimaginable for a voltage level other than the ubiquitous, nominal 12V.

We have, however now reached a crossroads. Electric loads relentlessly increase in number as well as in power. Large and long-term investment in manufacturing and qualification serve as a counter-force to change. But we are at a breaking point. Next up is a generational event: the redesign of automobile voltage systems.

II. History

From fully combustion vehicles in the beginning of automotive history to today’s fully electric vehicles, batteries and loads have played a great role in the definition of which voltages are to be used in a car.

III. Loads

As on-board voltage sources became universal in automobiles, electric loads multiplied incessantly, and continue to do so. Today for example, load ampacity is double that of the days when engines were carbureted.

Besides the battery recharge current itself, common loads such as power windows, electric air pumps or brake by wire weigh on modern vehicle alternators.

Add to this widespread adoption of "auto start/stop" systems.

As electric loads relentlessly increase ampacity requirements, the electric systems are experiencing a double whammy: electrification of air-conditioning compressors and power steering pumps are achieved by electrifying air-conditioning compressors and power steering pumps. In both cases, mechanical losses are excessive at light loads and electrification creates significant vehicle mileage gains.

Voltage levels also increase significantly for traction drives because of the high- power levels. Even for "mild hybrid" vehicles, the bus voltage tends to be at least 48V.

Voltage levels are changing. But what should they be changed to?

History provides a precedent: the "42V/14V Bordnetz" or PowerNet that was rolled out in the 1990s. (In this case, "42V" referred to a nominal 36V lead acid battery.) Despite the coordinated push by Daimler-Benz and other manufacturers, this voltage was not adopted widely. Such is the difficulty in implementing change to vehicle power distribution.

Merits of various voltages are discussed below. Let's see where the industry appears to be consolidating. Note however, we are now in the Age of Customization (epitomized by a "Lot Size of One") and rather than a single answer, voltages may continue to flower.

Which Voltage?

Mechanical relays run better at 12V because of reduced arching. Solutions exist for higher voltages, but at a cost. Incandescent headlights are more robust at 12V than higher voltages because of the thicker filament. The spread of LED lights though removes this constraint.

In any case, Automotive suppliers still have large investments in 12V systems, so 12V is the lower limit.

Now we place an upper limit. Cost and weight objectives force higher voltages. The first jump, already on the road, is to a nominal 48V system. These systems can be rated "Class A" (60V max) which presents a low shock hazard. Therefore, components and insulation are cheaper, and qualification is cost effective.

Mild hybrid vehicles often use 48V batteries. Even full electric vehicles are available at 48V for niche markets.

Once designers enter "Class B" voltages, they usually go straight to the 300V ~ 400V range. For example, Tesla vehicles are designed to around 350V to 375V full charge.

Why not go to even higher voltages? Class B extends to 1500V working voltage. But once exceeding 400V working DC, power electronics and other components such as bulk capacitors and insulation systems are in shorter supply and increase in cost exponentially.

High performance vehicles tend to increase to 800V working, e.g., Fisker's Emotion, eCOPO Camaro, Porsche Taycan, Audi E-Tron GT, and Aston Martin Rapide E.

The next step is towards a 1200V battery. This voltage level still falls within Class B, but headwinds that increased exponentially with an 800V battery become practically insurmountable with 1200V battery - at least for a production vehicle.

In sum, here is a taxonomy of operating voltages which suppliers and manufacturers are converging on.

- logic (5V USB and lower)
- 12V (legacy)
- 36V (forklifts, tow tractors, golf-carts)
- 48V (AC and heavy electrical loads; mild hybrid)
- 100V (some motorcycles and off-road transport)
- 400V (EVs)
- 800V (hyper-cars)

What voltage will the industry settle on? Certainly not a single voltage if traction is considered.

In fact, for comparison, consider that an automotive circuit board may have 12V, 5V, 3.3V, 1.8V, and 1V buses. And that is just one board!

But as a practical concern, Pareto's law applies to vehicle voltages. Surely 12V nodes exceed 80% of production vehicle systems. The remainder is mostly legacy 24V in addition to 48V and 400V.

IV. Voltage Sources

With so many voltages, where do they all come from? Look to the batteries.

Legacy 12V "lead acid" batteries (specifically, lead sulfate plates and sulfuric acid electrolytes) with high cranking currents are a great tool for the job, yet inexpensive.

For the next level up, consider 48V for sake of discussion. This Class A voltage level may be supported by lead acid chemistry, but more likely, lithium-ion polymer.

Ultimately, the electrical energy comes from an alternator. In hybrid vehicles the motor/generator can charge the 48V battery. But even so a 12V/48V converter is usually designed in.

In general, whenever a vehicle contains more than on DC power bus, it interfaces them with a DC/DC static converter.

For the sake of brevity, we will consider only a 400V bus at Class B voltages. This is the most common level for traction drives. The 400V battery in a pure electric vehicle requires a charger. This takes energy from a utility (usually) to charge the battery. The charger may be "on board" the vehicle or stationery. The charger requires a rectifier on the front end to interface with the utility and condition the current to utility standards. The remainder includes a DC/DC stage not dissimilar to the other static converters discussed.

V. State of the Art DC/DC

As noted above, the difficulty in changing DC voltage levels doomed Edison's DC power distribution system. Historically, the difficulty in transforming DC voltage levels also presented a technical challenge for EV battery charging.

That has all changed now that power electronics have matured. Buck and Boost convertors are already rugged, reliable, and widely available by automotive manufacturers. Many other topologies exist, optimized for various niche applications.

Silicon chips are the de facto standard: MOSFETs, IGBTs, and bipolar devices.

Controls are advancing with ASICs and embedded architectures. System-on-a-chip (SoC) solutions greatly simplify a designer's job.

However, EMC and EMI problems have multiplied. Mitigation has become a cottage industry.

VI. Future Converters

As detailed above, DC/DC converters are already an indispensable technology not only in electric vehicles, but for all vehicles. Converters from 12V to logic levels like are ubiquitous. Fortunately for the designer, DC/DC converters are already commodity items at these levels.

On the other hand, DC/DC converters at high power levels are still in an era of innovation. They tend to be designed by electrical hardware experts, then shoe-horned into severely demanding mechanical and thermal environments.

One trend is the adoption of new transistors made of "wide bandgap" crystals such as GaN and SiC. These switching devices reduce losses at a given output power. Since they switch faster, magnetic components shrink and converters become smaller and lighter.

Suppliers experienced in the most demanding applications such as motorsports and supercars are poised to serve production market needs best. In the former, cost is less of an object and performance is highly optimized.

Using GaN and SiC transistors, BrightLoop Converters has developed a range of isolated, fully bi-directional DC-DC converters capable of creating two (or more) voltages within the same unit. Dragging high voltage from the traction battery, the converter makes an isolated conversion to the LV network. In practice, the converter's electronic boards are composed of several channels which can be connected between each other to create the desired combination (12V + 24V or 24V + 48V + 12V…).

Figure 1- example of the internal architecture of one of our converters (MPD 2-2) - the internal channels connected between each other allow to create the desired output combination. In this case, the converter could have from 1 to 4 outputs ranging from 10 to 52V$_{DC}$

Another option is to use a local, non-isolated converter, able to convert 14V->48V or 48V->14V.

• If a single 48V load is required, the LV network can be distributed in 12V, and locally converted to 48V just in front of the load, saving the need for a second wiring.

• If there is a lot of power involved in the LV network, it is possible to wire it in 48V to reduce the current, and locally convert down to 14V.

These options are made relevant if the corresponding converter is small enough. The latest GaN technology allows converters to be designed as lightweight as 300 grams for 2kW.

Integrating multiple converter functions in a single box delivers significant cost savings. Alternatively, a single box can be re-configured on the fly for arbitrary, programmable voltages. Series and parallel connections may be implemented with full flexibility. Power flow can be fully bi-directional.

VII. Conclusion

After an earlier aborted attempt to engineer an industry migration to "42V," change is finally coming to automotive voltages. We have already entered an ascent phase where various topologies and voltages are tried.

Will we eventually reach a maturity phase, consolidating again on a single voltage bus? Or maybe two? Or rather, will innovative suppliers allow designers their voltage of choice, supported with flexible electronics?

Power electronics will serve an indispensable role in any case.