Design Trade-Offs for Battery Chargers

Charger considerations represent a top priority for original equipment manufacturers (OEMs) looking to design electric vehicles, machines, and equipment. Regardless of other product investments and quality benchmarks, chargers (and batteries) remain necessary for providing operators with continual performance and safety.

However, every charger consideration has trade-offs to balance according to application needs, costs, and other factors.

By understanding these trade-off decisions and their effects, OEMs considering electrifying or improving their product lines can deliver optimal performance without pricing themselves out of their market.

Basic Charger Specifications

OEMs must first determine the charger's basic specifications regarding (general) location and power, as these two considerations significantly affect other design and engineering decisions. And in most cases, OEMs must meet minimum performance requirements for the product's intended application (e.g., usage environment, usage duration, recharging times). As a result, location and power offer the least decision-making flexibility.

Charger Location—On-Board, Off-Board, or Hybrid

Initial considerations for charger location primarily concern whether it will be stored on-board, off-board, or provide hybrid capabilities. Each option presents trade-offs and additional requirements:

- **Off-board** – Many products still utilize off-board charging systems, which minimize size and weight constraints. Off-board chargers best fit applications where the vehicle or machine returns to the same central depot or charging station following usage. Depending on that charging environment, considerations like reliability and sealing may be less impactful on off-board chargers' design and engineering.

- **On-board** – Current charger trends favor on-board (or hybrid) charging to meet operators' demands for 'opportunity charging' support (i.e., charging anywhere with an available power source and as workflows allow). However, on-board chargers add more constraints, such as:
    - Size and weight
    - Expected work and charging environment (e.g., sealed chargers' IP rating)
    - Power connection (e.g., standard 120V outlets)

- **Hybrid** – Some products may be best supported with both on- and off-board charging capabilities. For example, a scooter used for medical reasons may provide operators an off-board charger for at-home use and an on-board charger to ensure they do not get stuck when out and about. The additional components may require trade-offs between performance and cost, but they provide operators with greater flexibility, such as:
  - Opportunity charging
  - Faster charging when using the off-board system
  - Removable charger that facilitates battery swapping in high-usage applications

[CALLOUT BOX: [REDACTED] designs, develops, and tests many types of chargers suited for different locations, with current development and research tending to emphasize sealed, on-board models providing 300 W to 1.5 kW. [REDACTED] has also recently launched a 3.3 kW charger [REDACTED] that supports parallel operation of up to six chargers to achieve 10-20 kW.]

Charger Power Requirements

The power requirements for a product's battery and systems reflect performance demands. Similarly, a charger's power requirements reflect the battery's specifications and usage expectations.

For example, if a floorcare machine requires an 8 kWh battery that must complete charging in eight hours (e.g., overnight), then it requires a 1 kW charger at a minimum.

However, chargers that deliver greater amounts of power to the battery require higher-power outlets; a standard North American wall outlet capable of providing roughly 1.2 kW through the charger may be insufficient. This affects connector design (e.g., single-phase, three-phase) and can restrict opportunity charging and charging station compatibility.

The country (or continent) where operators use the product also affects charger power requirements and connector design (Figure 1). OEMs must meet differing standards for various outlet capacities, such as 110 or 120 V outlets in North America and 220 V outlets in Europe.

[FIGURE 1 REDACTED]

Charger Power—Model Ranges, Premium Upgrades, and Aftermarket Products

Multiple product models and higher-end upgrades often provide higher-margin opportunities for OEMs. However, these options—such as extending range with additional batteries in parallel or faster charging—also complicate charger considerations.

OEMs considering these capabilities should first collaborate with their partners to determine a modular charger supporting a standard size across all relevant applications. Adding more chargers in parallel configuration will support faster charging if space permits. Standardization helps simplify multiple challenges, including:

- Product inventory is easier to manage when varying charger quantities instead of models:
  - Associated SKUs could represent how many chargers are used.
  - Supplier and component inventory become simpler.
- Additional chargers could be sold as aftermarket parts.
- The available space may not support different charger sizes or configurations required for more powerful models. But it's often easier to fit several smaller chargers into the same space than a larger model or to distribute multiple chargers throughout the vehicle or machine.

Charger Reliability and Protection

Charger reliability and protection primarily depend on the vehicle or machine’s operational environment, with considerations becoming more complex again for on-board chargers. This is because off-board charging stations can be isolated, whereas on-board chargers remain directly subjected to liquids, dirt, impacts and other factors that can impact performance.

Charger Protection Against Impacts and Stress

Shock, vibration, and impacts (e.g., drops) remain common for many electric vehicles and machines. Chargers must be structurally sound and secure to reduce the effects of virtually all environments during operation or charging, or components may break or become loose.

For example, an on-board charger for Class I lift trucks would need to withstand the shock and vibration of traversing warehouses’ concrete floors (particularly for solid tire constructions and seams between slabs) or potential low-speed collisions. Similarly, off-road vehicles and equipment (e.g., nonroad mobile machinery, golf carts, ATVs) will need charger components to withstand bumpy, uneven terrain.

In industrial applications, off-board charging stations may be placed near conditions that can negatively affect performance (e.g., chemicals, liquids) and require more robust protections.

Off-board chargers also require greater durability against being dropped. Units may fall off shelves or mounts, or charger cables may get caught, pulling the charger from its location. Lightweight designs help improve charger robustness and protection from drops and safety for any nearby personnel.

Charger Sealing

Many vehicles and machines will be subject to environments that increase the likelihood of foreign material ingress. Liquids and dirt or dust entering the charger and related systems (e.g., fan cooling) can lead to premature failure or costly maintenance and repairs.

OEMs must ensure they adequately seal chargers (along with other electrical components) based on their product's expected applications. For example, floor care machines with on-board chargers require these components to be sealed off from water, chemicals, dirty fluids, and more for reliability and operator safety. This involves subjecting the sealing method to rigorous testing to determine its ingress protection (IP) rating.

IP ratings follow a format of IPXX, with the first X referring to ingress of solids and the second referring to liquids. IP66 (i.e., "dust-tight" and sealed against heavy sprays for at least three minutes) should be the minimum standard for any charger at risk of solid or liquid ingress, especially if maintenance may include pressure washing.

Depending on the application, OEMs may require sealing up to IP69 to protect components from water submergence or close-range, high-pressure, high-temperature sprays.

Sealing chargers and other components can become particularly challenging if applications regularly place the vehicle or machine near salt, fertilizer, and solvents and other chemicals. And although it is not necessarily a mechanical concern, plastic material durability also remains important (e.g., fan shrouds, UV protection, label durability).

Charger Cooling

Aside from external factors, chargers (and batteries) must be maintained at appropriate thermal levels for optimal performance. Unlike other reliability considerations, internal factors affect thermal regulation the most; effectiveness and efficiency heavily depend on charger and product design, engineering, and integration with other systems.

[CALLOUT BOX] Overheating can cause premature component failure, and battery lifespans halve for every average temperature increase of 7-10 C over their rating.

Standard charger cooling methods for applications requiring up to 6 kW include:

- **Passive cooling (<1 kW)** – Achieved via conduction and the use of heatsinks, passive cooling provides inexpensive, quiet, and efficient thermal regulation without introducing additional failure points (e.g., no moving parts) or parasitic power loss. This method

typically involves a metal baseplate to transfer heat. Passive cooling considerations include:
  - Mounting location and orientation
  - Size
  - Airflow constraints
  - Proximity to other components that generate heat
  - Choice of metal

- **Powered fan** – Directing airflow via fans will help maintain appropriate charger temperatures and generally requires less space than passive methods. However, adding fans introduces additional costs, noise, breakable moving parts, and potential electromagnetic interference. As a result, fans will not be suited for many dirty or impact-prone environments (without additional protection), such as those with:
  - Substances that can restrict airflow or rotation
  - Expected impacts (e.g., small rocks colliding against the fan during operation or transportation)

- **Liquid cooling (6 kW<)** – Adding a liquid cooling system helps achieve optimal thermal regulation and minimum size requirements, but it adds significant cost and complexity. Therefore, outfitting chargers with liquid cooling is most suitable for larger applications supporting integration with an existing cooling loop (e.g., cooled motor and inverter).

Of these cooling methods, passive methods likely provide the best performance for simple applications because they're easier to seal (e.g., structurally, at connectors, during maintenance) and minimize the number of failure points. But as with other considerations, the vehicle or machine's application will determine which cooling system best addresses performance requirements.

Charger Lifespan

Accurately determining charger lifespans involves extensive testing (e.g., mechanical, thermal) and conditions that accelerate aging to ensure peak performance in the harshest applications. Testing procedures should follow accepted industry standards, such as the International Electrotechnical Commission (IEC) methods and GMW3172 (i.e., automotive-grade).

A helpful rule to follow when determining chargers' average lifespans is to double the warranty provided for them—especially for professional-grade vehicles, machines, and equipment operators may use to replace or expand their fleets.

Charger Size vs. Cost

There is good news for many OEMs regarding the trade-off between charger size and cost: Up to a point, improving charger efficiency, heatsink materials, and modern switch-mode electronics over legacy chargers (e.g., ferro-resonant models, heavy and bulky steel and copper transformers) should achieve cost decreases and better power density (Figure 2). Improving heatsink materials, in particular, will net size and weight reductions.

[FIGURE 2 REDACTED]

But as power density and efficiency continue to increase along this ‘bathtub curve,’ costs begin rising. This is due to more expensive electronics and diminishing returns in heatsink performance.

In low-cost, high-volume applications, OEMs should generally strive for the midpoint—where either improved power density or efficiency begin increasing costs. For applications where price premiums are accepted, OEMs will have more flexibility to improve power density and efficiency before costs become prohibitive.

Switch-Mode Electronics and Their Effect on Cost

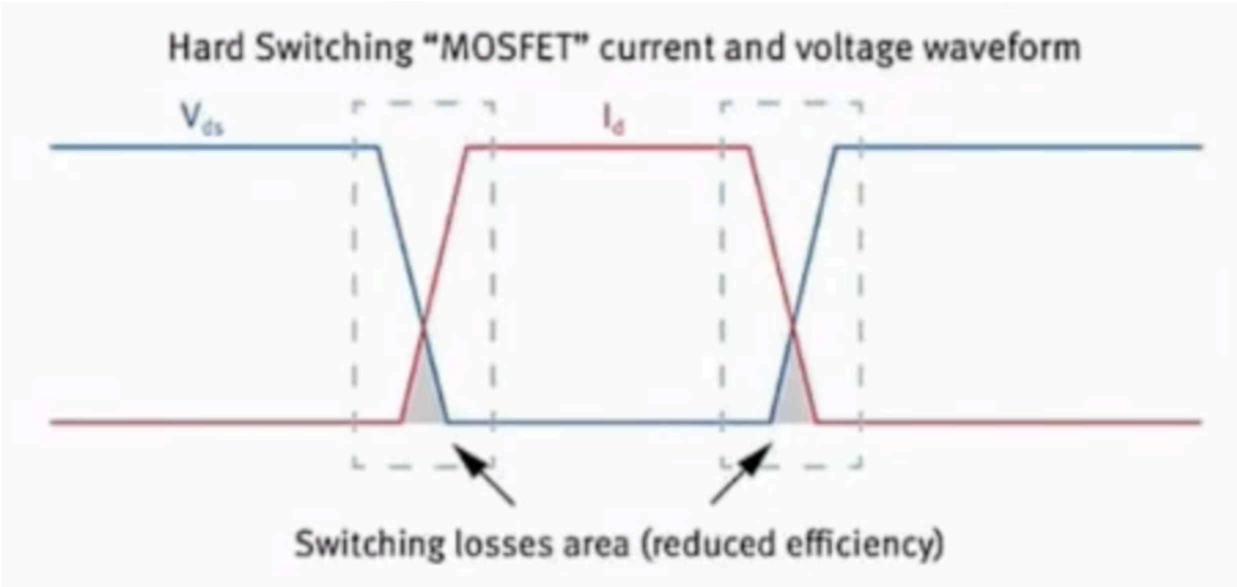
Innovations in power-switching electronics over the past two decades and the transition away from line-frequency chargers have revolutionized charger capabilities. Compared to line-frequency power supplies providing around 60 Hz, switch-mode chargers provide 60 kHz—improving performance by three orders of magnitude and reducing size reduction by roughly two orders of magnitude.

Continual innovations will further improve gains without complicating trade-off decisions, thanks to advancements like replacing silicon components with those made from gallium nitride (GaN) or silicon carbide (SiC). It’s even possible that performance improvements could jump from 100 kHz to 1 MHz. But—as with the bathtub curve—they will eventually hit a point of diminishing returns across transformer temperatures, size reductions, and cost.

The Benefits of “Soft Switching” Frequencies

Higher frequencies can be attained with “soft switching” compared to the “hard switching” transistors more common today.

With hard switching metal–oxide–semiconductor field-effect transistors (MOSFET), the transition between off and on (i.e., voltage to current) results in efficiency losses (i.e., increased heat) and increased risk of electromagnetic interference (Figure 3). These losses become exacerbated at higher frequencies.



By transitioning to soft-switching resonant converters, voltage and current return to zero before the switch occurs, significantly reducing potential losses (Figure 4). However, input AC/DC converters remain hard-switched, and further performance gains may be limited.

[CALLOUT BOX: [REDACTED] launched one of the leading soft switching battery chargers capable of charging both lead-acid (wet, AGM, or gel) and lithium batteries: the [REDACTED]. This charger's output DC/DC converter features a resonant tank with two inductors and a capacitor ("LLC").]
[FIGURE REDACTED]

Removing Diodes for Better Performance

Current rectification from AC to DC power passes through diodes, which results in fixed forward voltage drops with losses proportional to the current passing through.

Replacing the diodes with switches that operate in sync with the current (i.e., active or synchronous rectification) and provide low on-resistance can reduce these losses by up to 90%. However, this change also adds:

- **Cost** – MOSFET costs more than diodes
- **Complexity** – For example, the charger may now require isolated gate drive circuits
- **Potential failure points** – Diodes are more robust than MOSFET at withstanding events like power surges

- **Loss of bidirectional capability** – In high-voltage applications, MOSFET only provides marginal gains while diodes enable bidirectional power transfer (e.g., electric vehicles providing power back to the grid).

As a result, diode replacement is likely best suited for low-voltage, high-current applications (e.g., AC output in North America and Japan).

Leveraging 3D Space for Improved Power Density.

Assembling electrical components to take advantage of 3D space instead of flat shapes (e.g., planar printed circuit boards (PCBs) at right angles) enables a more compact design and better power density. However, as charger component assembly becomes more compact, OEMS contend with increasing manufacturing and reliability concerns:

- Required manual assembly adds costs and failure points (e.g., applying isolation tape)
- Components become more vulnerable to shock, vibration, and other stresses
- Thermal regulation becomes more complicated
- Greater chance of "crosstalk" and electromagnetic interference

System Integration Opportunities with Chargers—Making 1+1>2

Integrating chargers with other systems allows OEMs to reduce the total cost, size, and weight of the product or add new features. Typically, OEMs look for integration opportunities such as:

- **Charger and battery** – Batteries and chargers should integrate control and data flow, which requires collaboration with suppliers. However, further integration contends with batteries and chargers' conflicting thermal regulation goals—batteries should run cool, and chargers should run hot.

- **Charger and motor controller** – These two systems are best integrated by sharing a heatsink and fan because charging and operation generally do not occur simultaneously. Theoretically, they could share some power electronics and components (e.g., motor windings for boost inverters), but integration beyond shared thermal regulation can compromise:
    - Both systems' performance and efficiency
    - Safety, such as unintended torque (i.e., vehicle or machine begins moving while charging)

- **Charger and DC/DC converter** – The most promising integration is found in applications featuring a high-voltage traction battery and an auxiliary battery—where chargers and DC/DC converters can share a container, temperature control, and some power electronics. This requires reconfiguration, with the traction battery connected to the input and the auxiliary battery connected to the output.

- **Charger and EVSE charge stations** – Adding the circuitry needed for electric vehicle supply equipment (EVSE) to on-board chargers provides a practical integration that facilitates charging from standard wall or industrial outlets and EV charging stations.

- **Charger and CAN bus** – Chargers with CAN bus support can integrate with various other systems to transmit and display telematics data with a unified interface (e.g., charge status, faults). This practical integration also enables changing charge profiles more easily (e.g., manual equalizer, following battery replacement with a different make, model, or chemistry).

- **Custom integrations** – Depending on the application, other integrations may be possible, such as:
    - Charge profile switching from charging to powering a vacuum
    - An additional connector pin for supporting other functions (e.g., status LED, sparkless disconnect, drive interlock, BMS charge control).

[CALLOUT BOX: [REDACTED] currently holds patents for implementing charger and DC/DC integration in its [REDACTED] 3.3 kW charger. The [REDACTED] also supports EVSE integration.]

Navigate Charger Trade-Offs with Reliable Partners

Navigating the extent and complexity of charger considerations and their trade-offs requires OEMs to closely collaborate with their charger, battery, and other suppliers.

Determining the optimal specifications, reliability, size, cost, and integrations for systems and components is essential to providing the long-lasting, peak performance that customers expect. And OEMs' partners must be capable of designing, developing, and extensively testing chargers and their components for purpose-built applications and withstanding the harshest-expected operating environments.

About [REDACTED} Technologies

[BOILERPLATE: "ABOUT [REDACTED]"]