The Tesla Roadster Battery System

Tesla Motors

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Summary

This paper provides details about the design of the Tesla Roadster's lithium-ion (Li-ion) battery pack (otherwise known as the ESS, or Energy Storage System) with a particular focus on the multiple safety systems, both passive and active, that are incorporated into the pack. This battery pack has been under development and refinement for over three years and is the cornerstone of the Tesla Roadster. The high level of redundancy and multiple layers of protection in the Tesla Roadster battery pack have culminated in the safest large Li-ion battery that we or many of the experts in the field, with whom we've consulted, have seen.

Background

The battery pack of the Tesla Roadster electric vehicle is one of the largest and technically most advanced Li-ion battery packs in the world. It is capable of delivering enough power to accelerate the Tesla Roadster from 0 to 60 mph in about 4 seconds. Meanwhile, the battery stores enough energy for the vehicle to travel more than 200 miles (based on EPA city/highway cycle) without recharging, something no production electric vehicle in history can claim.

Designed to use commodity, 18650 form-factor, Li-ion cells, the Tesla Roadster battery draws on the progress made in Li-ion batteries over the past 15 years. Under the market pull of consumer electronics products, energy and power densities have increased while cost has dropped making Li-ion the choice for an electric vehicle. In the past, to achieve such tremendous range for an electric vehicle it would need to carry more than a thousand kilograms of nickel metal hydride batteries. Physically large and heavy, such a car could never achieve the acceleration and handling performance that the Tesla Roadster has achieved.

Due to their high energy density, Li-ion batteries have become the technology of choice for laptops, cell phones, and many other portable applications. Precisely because they have all this energy stored in a small space, Li-ion batteries can be dangerous if not handled properly. In fact, there have been several cases of Li-ion batteries going into thermal runaway in laptop applications leading to recalls by Dell, Apple, IBM, and other manufacturers. However, even with this high energy density, the Li-ion batteries in the Tesla Roadster only store the energy equivalent of about 8 liters of gasoline; a very small amount of energy for a typical vehicle. The pack operates at a nominal 375 volts, stores about 53 kilowatt hours of electric energy, and delivers up to 200 kilowatts of electric power. The power and energy capabilities of the pack make it essential that safety be considered a primary criterion in the pack's design and architecture.

Fundamentally, cells within the pack need to be protected from adverse situations that could be electrical, mechanical, or thermal in nature. The entire design must also be fault tolerant to reasonably expected manufacturing defects in the cells and in the pack itself. In the body of the paper that follows, we discuss aspects of the Tesla Roadster battery pack design that address these concerns. However, this is not a complete summary of all the battery pack safety features, since some aspects of our design and implementation are proprietary and/or patent pending.

Picking a Cell Design and Supplier

We started our design by purposely picking a small form factor battery cell. This cell is called the 18650 because of its measurements of 18mm diameter by 65mm length (i.e., just a bit larger than a AA battery). Due to its small size, the cell contains a limited amount of energy. If a failure event occurs with this cell, the effect will be much less than that expected from a cell many times larger. Billions of 18650 cells are made each year. Though the chance of a safety event in a laptop is small, the number of safety incidents involving Li-ion batteries is rising each year because there are so many more devices using small and powerful power sources.

The Tesla Roadster battery pack is comprised of about 6800 of these 18650 cells, and the entire pack has a mass of about 450kg.

The engineers at Tesla Motors selected cells from reputable Fortune 500 battery suppliers that have each produced billions of safe, reliable, Li-ion batteries. All the cell manufacturers that Tesla Motors has considered invest a great deal of money and engineering resources to minimize manufacturing defects within their cells. Overall, the selection criteria used by Tesla Motors included multiple factors, confirmed by extensive internal and external testing, that directly relate to the cell's overall safety in the Tesla Roadster.

Design Safety Features: Cell Level

Since the 18650 cell is the fundamental building block of the battery pack, it is important that it be fault tolerant. The cells used in the Tesla Roadster all have an internal positive temperature coefficient (PTC) current limiting device. The primary role of this PTC is to limit short circuit current on an individual cell level. It is important to note that this device is completely passive and functions without any inputs from the rest of the battery pack systems.

A second level of protection is provided by the Current Interrupt Device (CID). Each battery cell used in the Tesla Roadster has an internal CID. These devices serve to protect the cell from excessive internal pressure. In such a case the CID will break and electrically disconnect the cell. High internal pressure is generally caused by over-temperature or other failures that then result in over-temperature.

The cells also incorporate numerous mechanical, thermal, and chemical factors that contribute to their safety in the Tesla Roadster. For example, cells used in the Tesla Roadster battery pack are all packaged in steel cans. This feature offers multiple safety benefits. From a mechanical standpoint, the steel case of each cell provides structural rigidity and strength. This helps dissipate extreme mechanical loading as well as providing protection against objects penetrating or compressing a cell and thereby shorting it. From a thermal standpoint, the steel case also offers good thermal conductivity. The dissipation of heat from a cell both extends battery life and helps maintain the pack at an even temperature. From a chemical and materials standpoint, the materials used in the cell's construction can greatly impact the flammability and initiation temperature of thermal runaway. Tesla Motors has chosen a very safe cell with great attention paid to both these factors.

Design Safety Features: Battery Pack Level

Due to the size, weight, and cost of the Tesla Roadster battery pack, we have the opportunity to add many more safety features than can be contained in a laptop battery pack. Overall, some of these battery pack safety features are active and others are passive. Some are mechanical and others are electrical. For example, the battery pack is controlled internally by several embedded microprocessors that operate both when the battery pack is installed in the car, and when the pack is being transported. An example of a passive safety feature is the selection of Aluminum for our battery enclosure instead of plastic as in all laptop packs. The Aluminum provides greater structural strength in case of mechanical abuse tolerance and does not easily melt or burn. Collectively, the high levels of redundancy and layers of protection culminate in the safest large battery seen by the experts in the field with whom we've consulted.

Architecturally, the battery pack is comprised of 11 battery modules (otherwise referred to as "Sheets"), a main control and logic PCB (printed circuit board), and a 12V DC-DC power supply. Each of the 11 modules carries a monitoring PCB (with its own microprocessor) that communicates with the rest of the vehicle microcontrollers, broadcasting the voltage and temperature measurements of its module over a standard CAN bus.

The method by which the cells are electrically connected together can have a huge impact (positive or adverse) on the overall pack safety. In the Tesla Roadster battery pack, each of the thousands of cells has two fuses (one each for the cell's anode and cathode). This results in tremendous safety benefits since a cell becomes electrically separated from the rest of the pack if either of its fuses blow (generally by a short circuit). In addition to cell fuses, each of the 11 battery modules has its own main fuse that guards against a short circuit across the complete module.

The picture below (Figure 1) shows the complete battery pack on a cart. Note the tubes and manifold extending out of the battery pack at its lower long edge. These are used to circulate cooling fluid (a 50/50 mix of water and glycol) throughout the pack via sealed fluid paths. This enables us to keep the cells thermally balanced. This extends the life of the battery pack and also has numerous safety benefits.

Figure 1 – Tesla Roadster battery pack

This cooling system design is especially effective because we have chosen to combine thousands of small cells rather than several large ones to build an ESS, dramatically increasing the surface to volume ratio. For example, with seven thousand 18650 cells the surface area is roughly 27 square meters. If there were an imaginary set of 20 much larger cube-shaped cells that enclosed the same volume, the surface area would be only 3.5 square meters, more than seven times smaller. Surface area is essential to cooling batteries since the surface is where heat is removed; more is better. Also, because of their small size, each cell is able to quickly redistribute heat within and shed heat to the ambient environment making it essentially isothermal. This cooling architecture avoids “hot spots” which can lead to failures in large battery modules.

The multiple microprocessors within the ESS communicate via a CAN Bus, a robust automotive communication protocol. During normal vehicle operation and storage, the battery logic board communicates with the vehicle to initiate battery cooling, report state of charge, and signal battery faults. A fundamental element of the vehicle and battery pack safety design is the ability to electrically disconnect the high voltage of the pack from the rest of the car (by controlling two high voltage contactors) if any of a number of adverse conditions are detected.

The microprocessors, logic circuitry and sensors are continually monitoring voltages, currents and temperatures within the pack. These sensors also monitor inertia acceleration (e.g. to detect a crash) and vehicle orientation to the ground (e.g. to detect a rollover). Our battery packs also include smoke, humidity, and moisture sensors. If certain sensors exceed the specified range, then the high voltage contactors will immediately (within milliseconds) disconnect the high voltage of the battery pack from the car. In fact, the contactors are only closed (connected) when commanded and energized to do so. Without the proper commands these contactors will open.

In more severe fault conditions such as a vehicle collision, active protection systems including the logic board could fail due to damage. Therefore, the battery pack design incorporates an array of passive safety features as well. The passive design improves the robustness of the battery pack, particularly against mechanical damage and potential foreign object penetration of the battery pack.

None of the Tesla Roadster's high voltage systems are accessible to accidental contact outside their protective enclosures and jacketed cables. Only with special tools can someone gain access to any high-voltage components. Our high-voltage systems are enclosed, labeled, and color-coded with markings that service technicians and emergency responders already understand.

Finally, the battery pack enclosure is designed to contain all the battery modules, fuses, bus bars, and safety circuitry of the system. The enclosure is electrically isolated from the battery pack and prevents users from directly accessing any high voltage connections. The enclosure is also designed to withstand substantial abuse in the vehicle, including collision, while maintaining the integrity of the battery modules and circuitry inside.

Testing

Upon completion of our design, we collaborated with an outside firm known for expertise in lithium-ion batteries to perform hundreds of tests to validate the abuse tolerance and effectiveness of our design.

We have performed further tests including SAE (Society of Automotive Engineers) shock and vibration, crush, and vehicle collision testing. Additionally, the United Nations (UN) imposes strict rules regarding the transport of lithium-ion batteries. Tesla Motors will not be able to sell and deliver cars to its customers unless the production battery pack has met rigorous testing standards set by the UN or substitute testing agreed to by the United States Department of Transportation. Finally, we have passed all required tests from the Federal Motor Vehicle Safety Standards (FMVSS). This involves crashing of complete cars with functional battery packs in them.