2020 Guide to Power and Battery Breakthroughs: Materials, Processes, and Energy Resources for Design Engineers
About

This compilation of the most in-demand online resources in batteries, power management, and energy breakthroughs from Tech Briefs is your guide to powering the future. Discover the latest and most innovative battery and power management solutions for your design engineering challenges in automotive, robotics, and beyond.

On the Cover

The DC charging stations for the electric vehicles of tomorrow must be protected from overcurrents, overvoltages, over-temperature, and ground faults. Even as new designs for these stations evolve, the need for protection will remain constant. To stay current with new protection approaches, designers must constantly re-educate themselves about circuit protection options. Read more on page 9.
New Metal-Air Battery Design Offers a Potential Boost to Electric Vehicles

Billy Hurley, Digital Editorial Manager, Tech Briefs

Metal-air batteries are light, compact power sources with a high energy density, but they have had a major limitation. They corrode.

A new design from the Massachusetts Institute of Technology uses oil to reduce the corrosion and extend the shelf life of single-use metal-air batteries.

To prevent the deterioration of the metal, the MIT researchers placed an oil barrier between the aluminum electrode and the electrolyte — the fluid between the two battery electrodes that eats away at the aluminum when the battery is on standby.

The oil is rapidly pumped away and replaced with electrolyte as soon as the battery is used.

As a result, the energy loss is cut to just 0.02 percent a month — more than a thousand-fold improvement, according to the MIT team.

The findings were reported in the journal Science by former MIT graduate student Brandon J. Hopkins ‘18, W.M. Keck Professor of Energy Yang Shao-Horn, and professor of mechanical engineering Douglas P. Hart.

How does a metal-air battery work exactly?

A metal-air battery uses some type of metal (like aluminum) for the anode, air as the cathode, along with a liquid electrolyte.

In the case of aluminum, oxygen from the air then combines with the metal to create aluminum hydroxide, which activates the electrolysis process and creates a current.

Because aluminum attracts water, the remaining electrolyte often clings to the aluminum electrode surfaces, even after electrolyte is drained out from the cell.

“The batteries have complex structures, so there are many corners for electrolyte to get caught in,” said Hopkins.

The many corners lead to many opportunities for corrosion.

Hopkins and his team, however, placed a thin membrane barrier between the battery electrodes; both sides of the membrane are filled with a liquid electrolyte when the battery is in use.

When the battery is put on standby, oil is pumped into the side closest to the aluminum electrode, which protects the aluminum surface from the electrolyte on the other side of the membrane.

Aluminum, when immersed in water, repels oil from the surface. When the battery is reactivated and electrolyte is pumped back into the cell, the electrolyte easily displaces the oil from the aluminum surface, which restores the battery’s power.

The result is an aluminum-air prototype with a much longer shelf life than that of conventional aluminum-air batteries. When the battery was repeatedly used and then put on standby for one to two days, the MIT design lasted 24 days, while the conventional design lasted for only three.

Even when oil and a pumping system are included in scaled-up primary aluminum-air battery packs, they are still five times lighter and twice as compact as rechargeable lithium-ion battery packs for electric vehicles, the researchers reported.

Currently, aluminum-air batteries are used as backup power sources. Professor Hart spoke with Tech Briefs about why he believes the new design will someday find its way beyond niche applications and into electric vehicles.

Tech Briefs: Why are metal-air batteries valuable?

Douglas Hart, Professor of Mechanical Engineering: They are extremely high-energy-dense batteries. These are considered primary batteries, meaning they’re not rechargeable. In this case the aluminum gets consumed.

And aluminum is extremely abundant, unlike a lot of other metals that are made to make batteries. Aluminum is one of the most abundant materials on Earth, and it's distributed throughout the world, so it's not something that one country owns.

Tech Briefs: Where are metal-air batteries being used currently?

Prof. Hart: One of the problems with backup generators is that they take a while to come online and they use diesel fuel, which can go bad. So, many hospitals have aluminum-air batteries as backup systems; when the power goes down, they can go very quickly back online, at least long enough for a secondary power system to come online.

Phinergy, a company in Israel, is making aluminum-air batteries for range extenders on cars. There's a plan for them to be included, so if you run out of electrical power from a battery in an electrical vehicle, the aluminum-air battery should kick in and get you through the extra...
miles to get you to a charging station. They’re basically a battery system that can be replaced, just because they have so much higher energy than a lithium-ion battery.

**Tech Briefs:** What are the limitations of a metal-air batteries?

**Prof. Hart:** Once you turn them on, you can’t turn them off. The only way to stop the reaction is to drain the electrolyte out of the system. And when you do that, each time there’s a little bit of electrolyte that stays on the battery’s metal surface and corrodes it. After a while, you can put the electrolyte back in, and it won’t start up again; the battery becomes corroded, and on the surface this byproduct plugs it up. Some people have found that you can flush it with water, but the water gets contaminated with electrolytes.

**Tech Briefs:** Why is mitigating the corrosion effect so important?

**Prof. Hart:** You’d like to be able to use these batteries in something like an automobile; you want to park it in your driveway, leave it there for a week, come back, and expect it to start again. These batteries are slowly eating themselves way, so you lose a lot of your energy. The energy density becomes pointless then because it’s consuming itself.

People have looked at all types of ways to mitigate this corrosion process. They’ve looked at better chemistries for the surface of aluminum and alloys. We discovered a very simple approach: Instead of flushing it with water, we simply displace the electrolyte with oil.

**Tech Briefs:** What was the reaction to this idea?

**Prof. Hart:** The first reaction everybody had was: “Are you kidding me? The oil is going to plug up everything and destroy it.” It turns out that in the presence of the electrolyte, the aluminum prefers to work with the electrolyte rather than oil. The oil actually does not foul things. It simply displaces the electrolyte, shuts the reaction down (because it’s non-conductive), and as soon as you put the electrolyte back in, it starts right back up. But even better, we can flush it with the same oil over and over again and never contaminate the system.

**Tech Briefs:** Is this an easy design feature to incorporate?

**Prof. Hart:** The membrane is actually a very easy thing to put in place. It actually can be built on the cathode itself before being installed. It’s a very simple modification to existing battery tech. It’s a thin membrane to protect the cathode, because the cathode is a high surface contact material. The membrane provides a long-term longevity to the cathode material. It also allows the use of oils that are not as stable as other oils.

**Tech Briefs:** In what kinds of applications do you see this new design being used?

**Prof. Hart:** Range extenders for cars is certainly a good one. One reason that people are afraid to buy electric cars is because they’re scared to death of running out of power. And [for vehicle applications], this would be used mostly as a backup system to get over that fear of not having enough to get to the next charging system.

**Tech Briefs:** Will they still be used as backup power sources?

**Prof. Hart:** Right now, many people have small generators in their houses, but these produce carbon monoxide, so they’re very dangerous to use. Aluminum-air batteries are a far safer device to have sitting in your basement than a backup generator. If the power goes off, you can turn it on. If the power comes back on, you can turn it off. And an aluminum-air battery is certainly great for hospital use, and backup power systems for data servers.

**Tech Briefs:** Are metal-air batteries a viable option now compared to, say, the lithium-ion battery?

**Prof. Hart:** Right now, if you wanted to make our transportation system and convert it all to electric vehicles, people have pointed to lithium-ion batteries; certainly, Tesla is using lithium-ion batteries. But lithium-ion batteries require lithium, which is owned by a subset of the countries in the world. That makes it a politically difficult situation.

The worst part is that there’s simply not enough cobalt to make enough batteries for all the cars in the world. They have to find an alternative to cobalt. Some experts say they’ll be able to replace cobalt with nickel. We have to find an alternative battery system to make things like storage systems viable, because we simply don’t have enough cobalt and nickel.

Aluminum is a great energy source for any type of transportation system. I could see it being used in aircraft and other places where standard batteries might be used. Again, you can’t recharge these. They are more of a fuel than a pure energy storage device.

**Tech Briefs:** What’s next for your team regarding this research?

**Prof. Hart:** I’m hoping that it gets picked up by one of the commercial battery manufacturers. I think it has great potential, and I’d love to see it being put to use. We’ve shown about all we need to in terms of research in the lab, and I think it now needs to be implemented in a real system and proven out for commercial application.

**Tech Briefs:** What have the results shown? How well does the battery perform?

**Prof. Hart:** Phenomenally. Brandon has been able to show that you can turn it on and off for the full lifespan of the battery, and there’s almost no degradation at all, unlike previous systems. Essentially this work has given it the ability to shut off like a normal battery, so it doesn’t sit there and corrode away while it sits in your driveway, if you will.

That means, for something like a hospital, when the power goes out, you can truly turn this thing on, and if you don’t use all the energy that’s in the battery, you can shut the battery off and use it again next time. Normally, you might have a power failure that happens for a few minutes, then the power comes back on. You’ve used up this very expensive battery because, while it sits there, it corrodes away. Now, you can turn it on and off at will.

Billy Hurley, Digital Editorial Manager, Tech Briefs

Carbon fibers offer structural strength to a variety of products, including aircraft components, sporting goods, and wind turbines. By introducing a porous structure into the carbon fibers, however, a lab team from Virginia Tech has added a new function to the popular material: energy storage.

Guoliang “Greg” Liu, an assistant professor of chemistry in the College of Science, has led the development of sponge-like carbon fibers with uniform porous structures.

How could the sponge-like material someday change how vehicles are built? For starters, exterior car shells that store energy within their pores, says Liu.

Prof. Liu spoke with Tech Briefs about how he envisions the porous carbon fiber supporting new kinds of automotive design.

Tech Briefs: What is it about the porous structure that enables energy-storage capabilities?

Prof. Greg Liu: It’s the surface area. Typically, if we have a single straight filament carbon fiber, the amount of surface area is limited. Once we introduce porous structures inside the carbon fiber, we significantly increase the surface area for ion adsorption and molecule interaction. In this way, ions can be adsorbed in the pores and stored as energy.

Tech Briefs: What inspired this work and this design?

Prof. Greg Liu: This ties to my personal interest. I am always interested in improving the quality of our life. Almost every one of us drives a vehicle. I always think about this question: “How can we make our vehicles better than what we have now?”

Tesla uses batteries to store energy underneath the car seats. What if we store energy everywhere — for example, in the car shell, hood, and door panels, so that we can have much less parasitic weight? In this way, we use the shell of the car not only to support the vehicle, but also to propel it.

Our expertise allows us to try this idea. Our group specializes in using polymer materials. When we look at this problem, we realize that we can design new polymer materials from the molecular level to find potential solutions to this problem.

Tech Briefs: Can you take me through an example of how you envision a vehicle being able to store its energy “everywhere?”

One possible way to use this material is that we can replace our doorframes with carbon fibers. Today’s doorframes are mainly for mechanical strength, and functional for energy storage. This will revolutionize the manufacturing of vehicles.

Tech Briefs: Are there other applications besides automotive where these can be used?

Prof. Greg Liu: I think the material that we have here is a platform material. Our target application are automotive vehicles, but we can go beyond that. We can use them in aircraft and drones. We can also use the carbon fibers in sensors, and filtration/separation membranes.

Tech Briefs: Was this a challenging material to make? How was this made?

Prof. Greg Liu: To come to this idea was not straightforward. It took some judicious design regarding the polymer precursor. Once we decide the polymer precursor, however, it becomes straightforward.

Our precursor materials can be inserted into today’s carbon fiber industry. Today in the industry carbon fibers are typically made from polyacrylonitrile. What we need to do is to replace polyacrylonitrile with a polyacrylonitrile-based copolymer. The new precursor goes through the same procedure of oxidation, stabilization, and pyrolysis to make carbon fibers. I believe that there is no huge technology barrier if we want to implement this material in the industry.

Tech Briefs: What will you be working on next?

Prof. Greg Liu: Porous carbon fibers give us an opportunity to use them not only as a structural material but also a functional material. There’s still a lot of room for further improvement. This is our first demonstration of the concept. To fully use the material in the industry, we want to scale it up so that we can make lots of polymer precursors and carbon fibers in an industrial scale.

Tech Briefs: What is most exciting to you about this material and what is possible?

Prof. Greg Liu: The most exciting part of this material is the structures. The uniform porous structures offer us opportunities to investigate and utilize the mass transport properties for molecules and ions. The conductive nature of carbon fibers enables us to use them as electrode materials. The combined electron/ion conductivities, as well as the good mass transport properties allow us to design them for applications beyond energy conversion and storage.
A Better Battery Offers ‘All-Renewable’ Promise for the Power Grid

Billy Hurley, Digital Editorial Manager, Tech Briefs

A new-and improved battery from Ohio State University may lead to all-renewable energy storage on the nation’s power grid, as well as longer-lasting batteries in cell phones and laptops.

The potassium-oxygen battery, according to researchers, could someday be used to store surplus energy gathered from the Sun and wind.

“If you want to go to an all-renewable option for the power grid, you need economical energy storage devices that can store excess power and give that power back out when you don’t have the source ready or working,” said Vishnu-Baba Sundaresan, co-author of the study published in the journal *Batteries and Supercaps*.

“Technology like this is key, because it is cheap, it doesn’t use any exotic materials, and it can be made anywhere and promote the local economy.”

The researchers estimated that their better potassium-oxygen battery will cost about $44 per kilowatt hour. By comparison, the lithium-ion batteries that power many electric cars cost around $100 per kilowatt hour at the materials level.

Potassium-oxygen batteries have been an enticing energy-storage alternative since their invention. In 2013, a team of researchers from Ohio State, led by chemistry professor Yiying Wu, showed that the batteries could be more efficient than lithium-oxygen batteries while simultaneously storing about twice the energy as existing lithium-ion batteries.

Potassium-oxygen batteries, however, have not been widely used for energy storage because they degrade. The oxygen damages the anode, limiting the battery to about five to ten charging cycles.

Paul Gilmore, a doctoral candidate in Sundaresan’s lab, discovered a way to build a set of protections and keep oxygen from seeping into the electrode.

The new design allows air to enter the battery through a fibrous carbon layer. The air then meets a second, slightly less porous layer, and finally ends at a third one, which is barely porous at all.

The third layer, made of a conducting polymer, allows potassium ions to travel throughout the cathode, while restricting molecular oxygen from reaching the anode. With the porous design, the battery can be charged at least 125 times.

The team has not yet demonstrated that the batteries can be made on the scale necessary for power-grid storage, but Prof. Sundaresan believes that the power potential is there.
"If you have a smallish battery that is cheap, then you can talk about scaling it up," said Sundaresan. "If you have a smallish battery that is $1,000 a pop, then scaling it up is just not possible. This opens the door for scaling it up."

Prof. Sundaresan shared with Tech Briefs the promise of potassium-oxygen batteries.

**Tech Briefs:** Why have potassium-oxygen batteries not caught on?

**Dr. Vishnu-Baba Sundaresan:** Since their invention in 2013, potassium-oxygen batteries have shown promise because of their high energy density and simple battery chemistry. They have not caught on because of two reasons:

(i) Oxygen in its molecular form dissolves into the electrolyte at the cathode and gets to the anode. This forms potassium superoxide, or KO₂, on the anode and prevents the release of K⁺ ions from the anode.

(ii) The electrolyte (DME) is somewhat reactive with KO₂ and leads to a lot of side products.

While (ii) is unavoidable without using a different electrolyte, our design focuses on problem (i).

**Tech Briefs:** How did your design improve upon current potassium oxygen batteries?

**Dr. Sundaresan:** Our design has a cathode with porosity that varies across its thickness. Imagine the cathode to have large pores on one side that gradually vary, forming really tiny pores that are small enough to allow K⁺ ions through, while blocking O₂ transport. This happens via two mechanisms: the pore size obviously is one of the factors, but not the most significant.

The electrochemical properties of the conducting polymer forming the small pores in the cathode also enhance the formation of O₂⁻ (negatively charged ions). This reduction happens as the electron comes into the cathode during discharge.

This converts most of O₂ into O₂⁻ and prevents the mixing of O₂ into the electrolyte. Thus, we regulate the entry of O₂ into the battery at the source and hence have shown that the battery lasts longer.

**Tech Briefs:** What makes your battery an "economical energy storage device?"

**Dr. Sundaresan:** The materials used in our KO₂ battery require just the necessary components and a conducting polymer that is relatively inexpensive. The innovation in our battery is in its design, and we have developed a scalable and technically relevant combination of materials required to impart necessary functional properties.

The cathode redesign uses materials that are relatively inexpensive to purchase and make in a battery. Hence, it is cheap.

**Tech Briefs:** How do you envision this battery impacting the power grid?

**Dr. Sundaresan:** Due to its low cost, and sufficiently long cycle life, such batteries will first find its application in stationary applications. Hence, I anticipate that grid management could benefit from this battery.

**Tech Briefs:** What are the most exciting applications that you envision?

**Dr. Sundaresan:** I personally believe this will be important for various applications that require high energy density. There is not much of a difference between theoretical energy density and what is achievable with KO₂ battery. If you look at a study done by Prof. Juan Alonso at Stanford in 2016, this battery may meet the energy density requirements for electric propulsion in airplanes. There is a lot to be done between now and first flight with these batteries. But working towards this goal will significantly cut down emissions.
Aluminum as a Fuel

An aluminum fuel could replace lithium-ion batteries in several applications.

MIT Lincoln Laboratory, Lexington, Massachusetts

Batteries and combustion engines each have distinctive benefits and limitations. Batteries have simple construction and operate silently; however, their energy density (i.e., the energy per unit volume) is poor, and lithium-ion batteries are potential fire hazards. The energy densities of combustion engines are higher than those of batteries, but combustion engines are relatively loud and emit toxic gases.

A power system was developed that may provide the advantages of simple construction, silent operation, and high energy density. The energy system employs an aluminum-based fuel that is potentially safer, more reliable, and easier to refuel than alternatives. Additionally, an aluminum-fueled power system is simpler to start up and shut down than are gasoline engines, and the system operates in extreme environments such as beneath the sea.

The basic chemistry of aluminum as a fuel relies on a reaction with water to generate hydrogen and heat according to the following:

\[2\text{Al} + 6\text{H}_2\text{O} \rightarrow 2\text{Al(OH)}_3 + 3\text{H}_2 + Q \text{ (Heat)}\]

This reaction releases approximately 84 MJ/L of energy (almost evenly split between heat energy and potential energy in the form of hydrogen), which is more than twice the volumetric energy density of diesel fuel, and more than 3.5 times that of lithium.

Reacting aluminum with water, however, is challenging because a very stable oxide layer that forms on the surface of raw aluminum typically inhibits a reaction when the aluminum is exposed to air or water. This thin, but impervious layer is the reason that aluminum soda cans do not react with the beverage within. Because penetrating or inhibiting this oxide layer is key to unlocking the energy stored in aluminum, researchers have investigated a number of methods to remove or disrupt the oxide layer on aluminum, including applying strong acids, heating the aluminum, and alloying the aluminum with other metals.

The concept for inhibiting the oxide layer in this work is surface-treating aluminum with a thin eutectic (i.e., a mixture of two or more compounds) layer of gallium, indium, and tin. This treatment results in a fuel that consists of approximately 98% aluminum and 2% gallium, indium, and tin. This fuel reacts with water over a wide range of temperatures. But more importantly, this safe, energy-dense fuel can be stored without degrading over time.

The hydrogen released by the aluminum fuel can be used in a relatively simple system to generate electrical power with a commercial fuel cell. In this concept, water is metered into a reaction chamber containing fuel, and hydrogen from the aluminum-water reaction is fed into a fuel cell. If the system operates in air, then oxygen gas, also required by the fuel cell, can be extracted from the surrounding air. If the system operates below the ocean’s surface, then it needs a separate oxygen source such as compressed or liquid oxygen. Alternatives to oxygen gas include chemical compounds such as sodium chlorate (which disassociates into sodium chloride and oxygen with heat) or hydrogen peroxide (which disassociates into water and oxygen through a catalytic reaction with silver).

Several prototype systems have been designed, built, and tested, demonstrating the scalability of an aluminum-water power system in diverse applications. These prototypes produced power ranging from 30W to 3kW. The smallest prototype outputs 30W of power and is designed to fit in a backpack for a dismounted field soldier or hiker.

The Emergency Power Pack consists of a disposable reactor chamber containing the aluminum fuel, a processor with a fuel cell, and a water reservoir (see figure). The prototype pack weighs 734 grams and was designed to output 30W for up to 10 hours.

A larger 200W benchtop system was developed for powering a mid-sized unmanned undersea vehicle (UUV). This UUV power system was built before the aluminum fuel was optimized, and employed a different approach to overcome the aluminum oxide layer. Rather than using a eutectic coating on the aluminum, the 200W system incorporates a liquid gallium reservoir into which raw aluminum is introduced. The aluminum dissolves into the gallium bath, and when water is introduced, the aluminum reacts with the water. Hydrogen is produced from this reaction, but because the fuel cell also requires oxygen and must operate below the ocean surface, a separate oxygen system that uses sodium chlorate was developed.

This system, which ingests seawater from the environment to drive the reaction, was designed to power a mid-sized UUV for 30 days at three knots, a tenfold increase in total energy over lithium-ion batteries.

For more information, contact Nicholas Pulsone, Advanced Undersea Systems & Technology Group, at pulsone@LL.mit.edu.
The first mass-produced electric vehicles (EVs) hit the road late in 2010 with the introduction of the Nissan Leaf, which remains the world’s top-selling, highway-capable, all-electric car. In the United States, sales of EVs are gaining momentum, with 2017 sales up by 25% over 2016. EVs, however, are still outnumbered by roughly 300 to 1 by vehicles powered by internal combustion engines. EVs are unlikely to become fully mainstream until there is a nationwide network of charging stations that can charge a vehicle quickly enough to get travelers back on the road in a matter of minutes rather than hours.

The charging infrastructure necessary to keep these vehicles on the road has also begun to grow steadily. Market forecasters at Navigant Research are predicting that global sales of DC fast chargers will grow from 19,000 units in 2017 to more than 70,000 in 2026. DC charging systems allow for far faster charging than AC charging systems, which are inherently limited in power based on the capabilities of the charger installed inside of the vehicle (i.e., the onboard charger).

Electric vehicle charging stations — known in North America as Electric Vehicle Supply Equipment (EVSE) or simply as charging stations, charging posts, or charging piles elsewhere — must be engineered to withstand years of harsh environmental conditions such as heat, cold, rain, snow, and even effects due to nearby lightning strikes. In addition, they must ensure the safety of EV drivers who are holding a connector capable of carrying 1,000 DC volts or more. That means the charging station must be protected from overcurrents, overvoltages, overtemperature, and ground faults. What’s more, the charging infrastructure industry is trying to figure out this emerging application, so there are multiple design approaches and no single set of standards to guide them.

This article offers an overview of the mechanisms available for protecting users, vehicles, the public, and DC fast chargers.

Figure 1. Industrial power fuses like this UL Class L All Purpose AC/DC LDC Series Fuse can provide overcurrent protection for a DC charger’s AC input side.
An Introduction to DC Fast Charging Systems

To provide context to the discussion of DC fast charging systems, it may be helpful to describe the various AC charging approaches that preceded them. The first approach, typically intended for use in residential settings, provides 120 VAC (US)/230 VAC (EU) single-phase charging, with from 1.4 kW to 1.9 kW of output power. Depending on the capacity of the vehicle’s battery and its discharge level, a full recharge could take anywhere from 12 to 18 hours. The second approach, often used in public parking environments, provides 240 VAC (US)/400 VAC (EU) of single- or three-phase charging, with output power from 4 kW to 19.2 kW. Charging times range from two to six hours. A third approach, which is supported by several European vehicle manufacturers, provides three-phase AC fast charging at power levels of up to 43 kW. All three of these approaches use the vehicle’s onboard charger (AC to DC converter) to charge the vehicle’s battery pack.

In contrast to these approaches, DC fast charging systems are designed to bypass the vehicle’s onboard charging system and connect directly to its battery system. DC fast chargers can provide up to 400 kW of DC output power (typically from 400 VDC to 1000 VDC), converting three-phase AC power sourced from the electrical grid into DC power using highly efficient power semiconductor devices. This high output power can charge fully depleted batteries on most vehicles to 80% of their full charge in 30 minutes or less. Charger system developers around the world are striving to reduce that charging time still further, so that charging takes roughly the same time as filling a traditional vehicle’s gas tank.

An isolation transformer inside the EVSE separates the AC power on its input side from the DC output side. Once the EVSE’s connector is attached to the vehicle, the EVSE performs an automatic safety check of the circuit insulation and checks for any possible short circuits between the charger and vehicle contactors. Once energy begins flowing into the battery, if a malfunction occurs in the vehicle, communication lines in the connector signal the EVSE to open the contact to stop the DC output and indicate an error on the display.

Within the EVSE, power undergoes several conversion stages, each requiring some form of circuit protection:

- **AC input:** This requires overcurrent and overvoltage protection, residual-current or ground-fault detection, along with one or more stages of filtering for electromagnetic interference (EMI) purposes.
- **AC-to-DC rectification:** This stage converts the positive and negative cycles of the AC input power to just positive voltage.
- **Power Factor Correction (PFC):** Sometimes included in the rectifier stage, this stage compensates for energy-storing components (capacitors, inductors, etc.) used in the power converter to minimize the amount of reactive power (or non-useful power) as much as possible.
- **DC-to-DC conversion:** This stage uses high-efficiency semiconductors to adjust the DC voltage efficiently to the optimum value(s) for charging.
- **DC output:** This stage demands overcurrent, overvoltage, ground-fault protection and filtering.
- **DC fast charger overcurrent protection.**

An overcurrent is any current that exceeds the ampere rating of conductors, equipment, or devices under their conditions of use. The term “overcurrent” includes both overloads and short-circuits. In the United States, overcurrent protection requirements for EV charging stations are based on requirements from the NEC® and UL. In most other parts of the world, they are dictated by the IEC 61851 series of standards or derivatives of those standards.

All electrical systems, including DC chargers, will eventually experience some level of overcurrent. Unless removed in time, even moderate overcurrents can quickly overwhelm system components, damaging insulation, conductors, and equipment; large overcurrents can even melt conductors and vaporize insulation. Very high overcurrents produce magnetic forces capable of bending and twisting bus bars, and uncontrolled overcurrents can damage chargers, leading to fires, poisonous fumes, and explosions that can injure or kill anyone nearby.

### AC Input Side Overcurrent Protection

Industrial fuses (Figure 1) are the recommended overcurrent protection device for the charger’s AC input side. A variety of considerations must be weighed in order to select the right fuses for this application.

- **Current Rating** — The AC current (expressed in amps) that the fuse can carry continuously under specified conditions. A number of derating factors are applied to the current rating of a fuse, based on ambient temperature, expected lifetime, and other factors. Generally, these derating factors are useful in analytically determining the amount of current the fuse can carry without nuisance opening.

- **Voltage Rating** — The maximum AC voltage at which the fuse is designed to operate. Fuse voltage ratings must equal or exceed the circuit voltage where the fuses will be installed.

- **Interrupting Rating** — The highest available symmetrical RMS alternating current...
that the fuse is required to interrupt safely at its rated voltage under standardized test conditions. A fuse must interrupt all overcurrents up to its interrupting rating without damage. Standard power fuses are available with interrupting ratings ranging from 10,000 to 300,000 amps.

Type of Protection and Fuse Characteristics — Time-current characteristics determine how fast a fuse responds to overcurrents. All fuses have inverse time characteristics; that is, the fuse opening time decreases as the magnitude of overcurrent increases. When properly sized, fuses provide both overload and short-circuit protection to system components.

Current Limitation — A current-limiting fuse is designed to open and clear a fault in less than 180 electrical degrees or, in other words, within the first half electrical cycle (0.00833 seconds).

Physical Size — The size of the fuse intended for a given application is another important selection consideration. Although reducing space requirements wherever possible is almost always preferable, other considerations must be taken into account: Does the smallest fuse have the most desirable characteristics for the EVSE? Does the EVSE provide adequate space for maintenance? Do the small fuses being considered coordinate well with the EVSE’s other overcurrent protection devices?

Indication — Fuses with indicating features offer an easy way to identify which fuse in the system has opened, and which reduces downtime, increases safety, and helps reduce housekeeping or troubleshooting headaches and delays.

Output Side Overcurrent Protection

Given the high level of DC power being fed to the vehicle’s battery, the margin for error for charging properly is very narrow. The most-often overlooked aspect of this overcurrent protection application is protecting the costly power semiconductor devices like MOSFETs, thyristors, and IGBTs used in power converters (inverters, rectifiers, etc.). These devices are typically fabricated from silicon or silicon carbide and have low thermal withstand capacity. They can be greatly affected by the electrical, mechanical, thermal, and environmental stresses they undergo during operation, which can cause them to fail prematurely. When these power semiconductors fail, they can cause catastrophic conditions such as case rupture, fire, and explosion.

High-speed fuses (also known as rectifier fuses, ultra-fast acting fuses, ultra-quick fuses, and semiconductor fuses) offer the level of protection these sensitive power semiconductor devices require to withstand these harsh conditions. They are classified based on dimensions, mounting, and origin. The most common styles are North American traditional round body, square body, and cylindrical or ferrule (Figure 2). High-speed fuses offer the short-circuit characteristics required to protect semiconductor devices, including low energy let-through (I2t), low peak currents (IPEAK), low arc voltage, and high heat dissipation. They contain one or more current sensitive elements made of silver, silver-plated copper, copper, etc., each of which has a reduced cross-section at one or more points that provides a measured resistance in each element. The resistance of each element and the number of elements used in each fuse typically determine the fuse’s current rating.

Protection of Power Conversion Devices

Figure 3 represents a typical DC fast charger system made up of several building blocks, including, but not limited to the input protection, input filtering, rectifier, power factor correction, the DC bus or DC link, the DC/DC converter and output protection.

Although protection requirements vary at each location, the main purpose of the fuses in this circuit are to allow the nominal load current and any permissible overload current to go on continuously without interruption. At the same time, the fuses are selected to interrupt any overcurrent fault caused during overload or short-circuit, with minimal let-through energy in order to protect the power semiconductor devices connected in the circuit.

The location of a high-speed fuse in a rectifier circuit depends on the size of the of the system when considering power rating. Figure 4 illustrates the typical location of high-speed fuses in a rectifier circuit.

For smaller power rated devices, high-speed fuses are typically found only on the AC line side in a one-fuse-per-phase arrangement. For larger power systems, high-speed fuses are typically located both on the AC line side and individually in series with each power semiconductor device on each arm of the rectifier circuit.

High-speed fuses are used in inverter circuits to prevent line-
to-line short circuit fault conditions that can be generated in multiple ways, with the misfiring of transistors being one of the leading causes. Depending on the power rating of the inverter circuit, the location and number of high-speed fuses used in the circuit varies. For low-power applications, the high-speed fuses are typically designed only on the DC bus (one each on positive and negative). For higher-power inverter circuits, fuses can be used both on the DC bus side and individually nearer (in series) to each transistor.

**DC Fast Charging Overvoltage Protection**

Before providing power to the EV battery, most DC fast charging stations communicate with the vehicle to detect how much charge is left in the battery to determine how much power to provide. Control units communicate between the EV and the charger as well as to the driver via a display on the charger.

Because chargers are typically located outdoors, they are subject to voltage transients from which they must be protected to ensure they are operating properly. Electrical surges are the result of sudden releases of energy that was previously stored, or induced by other means such as heavy inductive loads or lightning strikes. This energy is carried to the EVSE on the power supply lines. Repeatable transients are frequently caused by the switching of reactive circuit components. Random transients, on the other hand, are caused by lightning and ESD, which generally occur unpredictably and may require elaborate monitoring to be measured accurately, especially if induced at the circuit board level.

The most suitable type of transient suppressor depends on the intended application; some applications require the use of both primary and secondary protection devices. The function of the transient suppressor is to limit the maximum instantaneous voltage that can develop across the protected loads. The choice depends on various factors but ultimately comes down to a tradeoff between the cost of the suppressor and the level of protection needed.

When it is used to protect sensitive circuits, the length of time a transient suppressor requires to begin functioning is extremely important. If the suppressor is slow-acting and a fast-rising transient spike appears on the system, the voltage across the protected load can rise to a damaging level before suppression kicks in. In a DC charging system, a metal oxide varistor (MOV) or high-power Transient Voltage Suppressor (TVS) diode is usually the best type of suppression device. Other types of protectors — such as gas discharge tubes, protection thyristors, and multi-layered varistors (MLV) or combinations of suppression devices — can also be used.

Varistors (Figure 5) are voltage-dependent, nonlinear devices with electrical characteristics similar to back-to-back Zener diodes. They are made primarily of zinc oxide with small additions of other metal oxides such as bismuth, cobalt, manganese, and others. The MOV is sintered during manufacturing into a ceramic semiconductor with a crystalline microstructure that allows it to dissipate very high levels of transient energy across the entire bulk of the device. Therefore, MOVs are typically used for the suppression of lightning-induced transients and other high energy transients.

TVS diodes are used to protect semiconductor components from high-voltage transients. Their p-n junctions have a larger cross-sectional area than those of a normal diode, allowing them to conduct large currents to ground without sustaining damage.

**Ground-Fault Protection**

DC fast chargers require protection against ground faults on both the input and output sides. A ground fault is an inadvertent contact between an energized conductor and ground or the equipment frame. The return path of the fault current is through the grounding system and any equipment or person that becomes part of that system. Ground faults are frequently the result of insulation breakdown, and they are the type of electrical fault that most often is the source of electrical shock. Wet and dusty environments, such as those found around an outdoor vehicle charging station, require extra diligence in design and maintenance to minimize the risk of ground faults.

The isolation transformer inside the charger separates the input AC power from the output DC power; therefore, the output side is not grounded. Instead, a ground-fault monitor is installed on the output side to detect any earth leakage and shut off power immediately. The ground-fault monitor is used by installing a ground-reference module between the two buses to establish a neutral point. The ground-fault relay (Figure 6) uses this neutral point as a reference to detect low-level ground faults.

Although there are many types of ground-fault protection devices for use on grounded or ungrounded systems and different applications, they can usually be simplified down to just a few different methods of operation. Current transformers (CTs) are typically used in conjunction with an AC-current-based ground-fault protection device. The CT (Figure 7) detects leakage current flowing outside the intended conductors; if it is outside of the tolerances set on the protection device, the device will trip to prevent damage to the system.

The IEC 60364-7-722 standard calls for every connection point on the input side of the charging station to be fitted with a residual-current device (RCD) with rated residual current ≤ 30 mA. The output side needs protection in the event of a DC fault current ≥ 6 mA. This protection can be provided by using a Type B RCD installed separately on each side of the installation.

**Conclusion**

In order to weather harsh environmental conditions over the long term while ensuring the safety of EV drivers and the general public, the DC charging stations of tomorrow must be protected from overcurrents, overvoltages, overtemperature, and ground faults. Even as new designs for these stations evolve, the need for protection will remain constant. To stay current with new protection approaches, designers must constantly re-educate themselves about circuit protection options.

This article was written by Tim Patel, Global EV Charging Business Development Manager at Littelfuse, Inc. (Chicago, IL).

**References**

3. Ground faults” are known as “earth faults” in some countries.
How to Generate Electricity — From Rust

Billy Hurley, Digital Editorial Manager, Tech Briefs

Scientists from Caltech and Northwestern University have found a way to generate electricity by combining saltwater with one of life's more undesirable compounds: rust.

The phenomenon discovered by Tom Miller, Caltech professor of chemistry, and Franz Geiger, Dow Professor of Chemistry at Northwestern, converts the kinetic energy of flowing droplets into current.

How their process works: The ions present in saltwater attract electrons in the iron beneath the layer of rust. As the saltwater flows, the ions attract, dragging along the electrons and generating an electrical current.

Such an “electro-kinetic” effect has been discovered before in graphene. You can drag saltwater across the atom-thin material to produce electricity.

Scaling the single-layer graphene up to usable sizes, however, is a challenge. Miller and Geiger believe their iron oxide films are easier to produce.

“It’s basically just rust on iron, so it’s pretty easy to make in large areas,” Miller said. “This is a more robust implementation of the thing seen in graphene.”

To ensure that rust formed on the iron in a consistently thin layer, the researchers turned the solid iron into a gas and then condensed the vapor onto a surface. This kind of “physical vapor deposition” allowed Miller and Geiger to create an iron layer measuring 10 nanometers thick, about 10 thousand times thinner than a human hair.

After running saltwater of varying concentrations over their rust-coated iron, the duo generated several tens of millivolts and several microamps per cm².

“For perspective, plates having an area of 10 square meters each would generate a few kilowatt-hours — enough for a standard US home,” Miller said. “Of course, less demanding applications, including low-power devices in remote locations, are more promising in the near term.”

Miller and Geiger spoke with Tech Briefs about the promising power of saltwater and rust.

**Tech Briefs:** Metal compounds and saltwater generate electricity. How is your electro-kinetic effect different from this idea, and what led you to this discovery?

**Tom Miller:** The usual way in which metal compounds and saltwater generate electricity is via corrosion, which involves energy from chemical reactions. That is different than the mechanism we have found, in which the mechanical energy of saltwater moves over the iron film to generate electricity.

**Franz Geiger:** At a meeting in Telluride last year, I saw work on graphene, which produces electrical energy when drops of ionic liquids slide over it. Having inventoried oxide-terminated iron nanolayers a few years earlier, I thought that flowing ionic solutions over the metal films should work as well. The real surprise was how well the metal nanolayers responded, which our study indicates has to do with the chemical properties of the oxide overlayer that are lacking in the previously known approaches.

**Tech Briefs:** With the ability to generate electricity by flowing saltwater over rust, what kinds of applications do you envision?

**Miller:** There are many exciting applications that can be envisioned, associated with almost any situation in which you have dripping, flowing, or periodically oscillating saline solutions. This includes harvesting electricity from ocean waves, raindrops, and even the pulsing blood in our veins.

**Tech Briefs:** What is most exciting to you about this study, and the possibilities of electro-kinetic power?

**Geiger:** The ease of scaling up the metal nanolayer to arbitrarily large areas and the ease with which plastics can be coated gets us to three-dimensional structures so that large volumes of liquids can be used. Foldable designs that fit, for instance, into a backpack are an option as well.

Given how transparent they are, it’s exciting to think about coupling the metal nanolayers to a solar cell, or to think about coating the outside of building windows with metal nanolayers so as to obtain energy during rain events. In vivo applications are also an option so as to generate power with each heartbeat in a vein, for instance, to drive an implanted insulin pump.

**Miller:** I completely agree. The combination of scalability and robustness is exciting, and we’re looking forward to seeing what the future holds!
Our industrial processes generate plenty of low-grade heat — energy that is often lost and never put to valuable use.

What if you could use those extra emissions to power electronics? Dr. Tony Shien-Ping Feng of the University of Hong Kong (HKU), sees the Direct Thermal Charging Cell someday finding a place on HVAC systems, electrochromic windows, and even the human body.

The bendable “DTCC” converts heat to electricity better than traditional thermal processes, according to the technology’s inventor.

“The newly designed DTCC is a game-changing electrochemical technology which can open new horizons for applications to convert low-grade heat to electricity efficiently. It is a simple system with the basic unit sized only 1.5 sq. cm and thickness 1 to 1.5 mm. The cell is bendable, stackable, and low cost.

**Tech Briefs:** There’s a photo of you with the charging cell attached to your arm. Can you describe what’s happening there, and what application is being demonstrated?

**Dr. Feng:** The DTCC is charged by body heat. The voltage of DTCC increases after being attached to the arm skin. With the increasing popularity of wearable technology, this system may one day harness body heat to power wearable electronic devices or medical devices for monitoring body health conditions like blood sugar levels and blood pressure.

**Tech Briefs:** What’s next for you and your research team regarding this work?

**Dr. Feng:** Further research will focus on body-heat harvesting by DTCC. The conversion of body heat to electricity is a formidable challenge, due to the low temperature differential between skin temperature and ambient temperature. The human body consumes ~2,000 kcal per day (= 100 W) to maintain a skin temperature of approximately 32°C, which equates to a theoretical maximum power of ~5 W present in released body heat. As the power required for sensing electronics continues to decrease, the conversion of body heat energy into electricity for powering wearable/attachable sensors is becoming possible.

Unlike other temperature-gradient technologies that operate at low temperature differentials, DTCCs are unique in their potential for enabling body-heat harvesting due to their low cost, flexibility, stackability, light weight, and ability to operate isothermally in a continuous thermal charge/electrical discharge process. Further research is needed to realize the full potential of DTCCs for body heat-powered technology, with particular efforts required to enable operation at skin temperature with sufficient power density and long cycle times for powering sensing electronics.

**Dr. Feng:***Ubiquitous low-grade heat energy (<100 °C) is usually wasted without use, which could be valuable for converting it into electricity. Conversion is however still a great challenge because converting low-grade heat to electricity is inefficient due to the low temperature differential and the distributed nature of the heat sources. The performance and cost of currently available heat-to-electricity converters operating in a low-grade heat regime do not merit widespread adoption.

**Tech Briefs:** Why is the DTCC such a breakthrough technology?

**Dr. Feng:** This is the first demonstration of heat-to-electricity conversion undergoing isothermal heating and chemical regeneration, which revolutionizes the design of thermoelectrochemical cells; it is fundamentally different from the state-of-the-art systems with power generation coupled to temperature differential.

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‘Unbreakable Battery’: Flexible, Cuttable Lithium-Ion Battery Won’t Catch Fire

Current lithium-ion batteries are susceptible to fire and explosive incidents because they are built with flammable and combustible materials. Johns Hopkins University researchers have designed a flexible, fireproof lithium-ion battery built to operate under extreme conditions, including cutting, submersion in water, and simulated ballistic impact. The key to the new battery design is the discovery of a new class of “water-in-salt” and “water-in-bisalt” electrolytes that, when incorporated in a polymer matrix, rid the battery of flammable and reactive solvents.

Ultralight, Corrosion-Resistant Cathode Material for Lithium-Oxygen Batteries

Rechargeable lithium-oxygen (Li-O_2) batteries have received growing attention because of their high theoretical energy density, their ability to outperform state-of-the-art lithium-ion batteries, and their potential as an alternative to gasoline. However, the successful development of lithium-oxygen battery technology depends on resolving the issue of cathode corrosion by the discharge product (Li_2O_2) or by the intermediates (LiO_2) that are generated during cell cycling. Research published by the American Chemical Society describes a Li-O_2 battery with a nano-engineered ultralight and robust all-metal cathode that consists of porous Ni with an AuNi alloy surface attached to Ni foam.

Nickel Oxide Material Made with ‘Jenga Chemistry’ Shows Superconductivity

Scientists at the Department of Energy’s SLAC National Accelerator Laboratory and Stanford University have made the first nickel oxide material that shows clear signs of superconductivity, which is the ability to transmit electrical current with no loss. Also known as a nicke-late, it’s the first in a potential new family of unconventional superconductors that’s very similar to copper oxides, or cuprates. This discovery could help crack the mystery of how high-temperature superconductors work. To create the new type of superconducting material, the scientists first made a thin film of a common material known as perovskite and “doped” it with strontium.

Wearable Liquid Metal Device Converts Mechanical Energy into Electrical

A Purdue University team created a wearable technology that converts mechanical energy into electrical energy. The “liquid-metal-inclusion-based triboelectric nanogenerator” is called LMI-TENG for short. The LMI-TENG can harvest and sense biomechanical signals from the body and use those to help power and direct devices. The LMI-TENG consists of a layer of liquid metal embedded in functional silicone, between two Ecoflex layers. The Purdue technology could have applications for many self-powered innovations for emerging tech like wearable sensors, human-machine interfaces, robotics, and the Internet of Things.