Energy Infrastructure:

Power System Design and Energy Storage

ON Semiconductor®

NEWS

Hardware-in-the-Loop Simulation and Power System Design: An Interview with Dr. Sudipta Chakraborty

Sudipta Chakraborty is the Director of Energy Systems at OPAL-RT. In this Engineer Spotlight, Dr. Chakraborty speaks about challenges facing power system design, how hardware-in-the-loop simulations are important for problem-solving with grid integration, and his work on the IEEE-1547 standard for power grid test procedures.

The future of power and energy is rapidly changing—increasing pressure is being put on energy grids to reliably deliver power, with emerging trends such as electric vehicles and renewable energy generation adding more complexity to their operation and management.

The work of Dr. Sudipta Chakraborty, Director of Energy Systems at OPAL-RT, is looking to foster these changes by focusing on developing real-time simulation technology for power systems, as well as automotive, robotics, aerospace, and other applications.

Dr. Sudipta Chakraborty

Dr. Chakraborty is using his experience and expertise as a technical leader, engineer, designer, and researcher to bridge the gaps between industry, research laboratories, and academia. Over the years, has innovated the use of hardware-in-the-loop for power systems applications, chaired the IEEE 1547 standard committee (which outlines test procedures for power grids), and worked on grid integration of renewable and distributed energy sources.

Currently, Dr. Chakraborty is working at OPAL-RT with an aim to help power systems and power electronics engineers by providing real-time simulation and hardware-in-the-loop tools. His goal is to help these engineers make better designs that are more efficient and provide improved power system-level performance at reduced cost.

"Hardware-in-the-loop can answer big questions in power systems, power electronics, and grid integrations of renewable energy which are all important research fields. As I see more and more system-level needs increasing for energy applications, I think hardware-in-the-loop is one of the fields that everybody is now looking into to solve these research challenges."

All About Circuits writer, Chantelle Dubois, recently had a chance to talk to Dr. Chakraborty about his fascinating career and what his thoughts are on the future of energy systems and renewable energy.

Chantelle Dubois (AAC): Tell us a bit about yourself. What's your career been like so far that brought you to OPAL-RT?

Dr. Sudipta Chakraborty (SC): *I completed my Bachelors in Electrical Engineering in India and then I came to the US to the Colorado School of Mines to do my Ph.D. on power systems and power electronics. I was working on power electronics and power system applications for a renewable and grid integration. I graduated from the Colorado School of Mines in 2007.*

After that, I joined the National Renewable Energy Laboratory (NREL), a US Department of Energy national lab, as a post-doctoral researcher in 2007. At NREL, I started working on a similar topic, 'Grid Integration of Renewable and Distributed Energy,' mainly focusing on power electronics, which is the power conversion needed for converting a renewable energy to an energy that you can use. I started as post-doc, then I became an engineer, then a senior engineer. At one point, I was actually leading a Power Electronics and Controls section at NREL.

Then, finally, I became a principal engineer, which, at that time, was the second-highest engineering level position at that time. I was at NREL for 10 years, from 2007 to 2017, working on grid integration, how to add more renewable energy for the grid, [dealing with issues like] how can you make them operate safely with the current electric grid structure.

I was with NREL until last July. I then came across OPAL-RT and I was interested in bringing my experience and expertise [in academia to help industry], bridging that gap.

AAC: What's OPAL-RT's background?

SC: *It started 20 years back, founded by Jean Belanger, current President and CTO. And it come from an idea: How can we make a real-time simulation tool and put it in the hands of the common researcher? Not everybody will have a supercomputer in their lab for applications like photovoltaic system design.*

How can you make these things cheaper? How you can give them to the common researcher to solve the research problems which are very challenging and which are not easy to solve without the help of such tools? Without these tools, it will be all trial-and-error.

AAC: What inspired you to get into the field that you're in? It sounds like you started in power electronics and then branched out into renewable energy and real-time simulations.

SC: *Yes, exactly. Power electronics, power systems—as I said, those are broad categories. So, you have electrical engineering: a very broad category. And then there are different research topics, one of those related to power systems. And, under power systems, there are various subtopics, like power electronics, controls, operations, planning, etc.*

My initial training was to build the power electronics systems for grid integration from scratch and then I quickly realized—yes, it's good to build one of those systems and show they work. But, at the end of the day, you need to make sure they work very well when you put them into a bigger, larger power system like an electric grid. Utility companies have concerns about grid reliability, so they don't want things to be put into their grid that can create problems into their systems.

So, as a researcher, I started getting more interested in how you could validate or look into system-level interaction of power devices. Around 2009-2010 [while at NREL], I came across this new technology called 'hardware-in-the-loop' or HIL. Hardware-in-the-loop is not a new technology—in other industries, like aerospace space applications, they use hardware-in-the-loop testing since they cannot test their systems on a real airplane or in real space flight. That would be billions of dollars' worth of problems. But it was not, I would say, that common for the electrical engineering field in terms of how you validate or how you test things. So we started looking into how you could create a flight simulator for power systems.

So, here's how I put it. How can you create a flight simulator where you don't really need to run an airplane but you can have a model of the airplane and then you can test some other things with that *airplane, without actually destroying the actual hardware or the actual costly systems. That's the motivation that got me into hardware-in-the-loop simulation, [which has become] more and more popular.*

Hardware-in-the-loop can answer big questions in power systems, power electronics, and grid integrations of renewable energy, which are all large research fields. So, that is the main motivation for me. I am still a power electronics engineer by training. I know power electronics controls very well. I can develop inverters. But as I see more and more system-level needs increasing, I think hardware-in-the-loop is one of the fields that I think everybody is now looking into to solve those problems.

OPAL-RT considers modular multi-level converters (MMC), hybrid and electrical transportation, and energy conversion controls to be its top three power electronics applications.

AAC: What kind of problems does hardware-in-the-loop solve with power systems?

SC: *There are several system-level questions that can be addressed. For example, grid integration of renewable energy: What happens when you have high penetration of those inverter-based renewable energy systems in your grid?*

Another example is that there are lots of micro-grids around you nowadays, so how do you validate a micro-grid that consists of a number of sources and loads? Do you want to go to the field and do a million dollar experiment to do that? Or is there any other way that you can validate the controls and some of the operations before you go to the field?

A third example that is more common is how you can look into the cybersecurity aspect of a grid. So it is not just the electrical system anymore—it also has communications and the interaction of the communications with the actual power devices.

Hardware-in-the-loop allows you to run models of systems (such as power systems or power converters) with real components (such as controllers or sensors) together and create some of the conditions that those components will experience in real life.

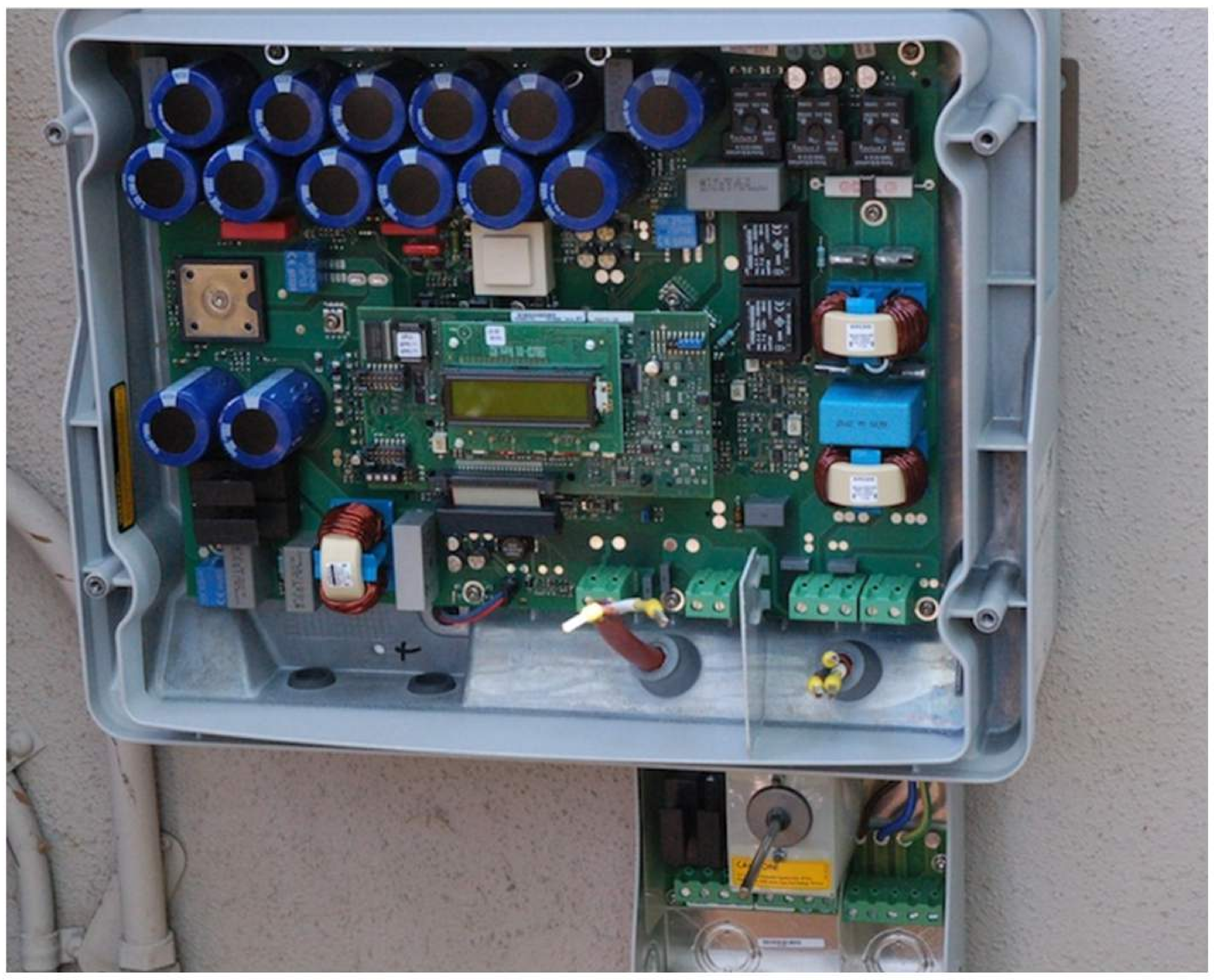
In some applications, you can even test a power systems component, such as an inverter with a simulated power systems model. For example, you can use these hardware-in-the-loop techniques to test a photovoltaic (PV) inverter that you will see in real life without actually putting it in the real distribution feeder. You can simulate the rest of the power systems in our real-time platform and then, using power amplifiers, you can test how that PV inverter will behave if you put it in real-world conditions and see how it will impact the whole power system.

AAC: Tell us a bit about your involvement with the IEEE-1547 standard committee. What has that work been like?

SC: *You can think of IEEE-1547 as more or less the standard that anybody or everybody has to use in the US when they have to connect distributed energy resources (DERs) to the electric grid. IEEE-1547 was developed to address the need to standardize the interconnection of these DERs to the electric grid.*

For example, if someone is connecting a PV inverter, how will the electric utility know that the inverter is compatible with the rest of the system? Is it safe? Is it going to last for five years? Ten years? You don't know. And how's that's going to work?

Before 2002-2003, there was no specific way you could test those devices. So, that's the reason for this particular standard which is the "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces".



An example of a solar converter. Image courtesy of Russell Neches [CC BY 2.0].

The work on IEEE-1547 started around the year 2000, published in 2003, and it became very successful in terms of coming up with a standard that could be trusted and works reliably. When you connect a photovoltaic inverter in your home, initially, there was no certification, which was actually hindering some of the growth of the photovoltaic industry.

The standards working group also developed a test procedure for this standard, which is IEEE 1547.1, published around 2005, for power electronics, power converters, and devices for DERs. Later, UL adopted those test procedures as a part of their standards which is called UL-1741.

As we now have significantly higher DERs in the grid, IEEE 1547 and 1547.1 needed major revisions. So, my work at NREL was to support the revision of IEEE-1547 based on our experience, our expertise, what's needed for the future grid. That work was recently concluded and the revised standard was published this month.

One of the roles I was also doing before I joined OPAL-RT was to help in the testing of DERs. If you have an inverter, for example, how are you going to test it so you know it will comply with the revised IEEE-1547? Before I left NREL, I was the chair for the IEEE-1547.1 revision working group. One of my colleagues is now leading it, although I am still very involved and I am very proud of that involvement.

At NREL, I was also involved in several other IEEE standards in parallel, like some of the micro-grid-related standards. These standards will help with grid stability, allow it to accept more renewable energy, and enable additional functions that are not available as of today.

These standards will help with grid stability, allow it to accept more renewable energy, and enable additional functions that are not available as of today.

On the OPAL-RT side, we are very involved in terms of how we can test these devices with new functionalities using new techniques such as hardware-in-the-loop. Suppose you're developing a new inverter with these new functions. How are we going to do the product development and test those products in an efficient way? Because you cannot just go to a certification testing and expect everything is going to work in the first trial. And the certification process is costly. So, many inverter manufacturers have some of the hardware-in-the-loop tools in-house—as well as some of the research labs used HIL—to validate those kinds of things before they go into either a field demonstration or a certification.

So, we're playing a part there. Our part is to support product development and validation and to make those products more robust before they are put into the field. So, that's my relation to standards-related activities nowadays because I'm not actively running those—but I want to still learn about the new products that are coming out and develop ideas on how we can contribute to make this whole process, whole ecosystem, work better.

AAC: Your work at OPAL-RT brings all of your expertise and experience together through better simulation systems. Why is this important for the industry?

SC: *I talked about various power systems challenges, talked about components such as inverters for renewable energy, talked about microgrids—all kinds of different applications. But, the inherent theme for all of that discussion is the fact that you need to have a better product, you need to have a better system, you need to have new controls and algorithms. All of those has to be validated before you put in a costly demonstration or testing.*

OPAL-RT provides the hardware and software tools for real-time simulation and hardware-in-the-loop. We have different types of simulator hardware and software packages that can address all these research challenges I talked about before.

Suppose you are a power electronics engineer developing a new power converter A power converter consists of various components. It includes power electronics switches. It includes some filters and protection. It includes a control. So you have your control algorithms to make all these components work as a functional system. And how you do that? In the olden days, when I was in grad school, I used to do just the simulation. And I said, "Okay, the simulation is good. Now, I'll build it in my hardware and hope I translate what I did in my simulation properly into my actual controller, in the hardware. I hope it will work."

On the OPAL-RT side, we have a couple of tools for such applications. One we call eFPGASIM, which is for which is for fast, real-time switching simulation. The other one is called eMEGASIM, which is our EMT (electromagnetic transient) simulation. These tools allow the manufacturer or researcher to develop their controls first in simulation. They can then proceed to build their controller hardware and develop firmware code in that hardware.

They can now test the actual controller board through this method called controller-hardware-in-the-loop, where the controller is connected to a simulated converter and behaving the same way as a real converter. This mitigates a lot of risk out of product development and testing.

OPAL-RT also provides the tools that actually can model the power systems, either in the electromagnetic transient domain or in phasor domain. All these tools are useful depending on the test and validation needs and depending on system size, the types of phenomena you are trying to test, and the devices you are trying to test.

The bottom line here is that the fact that our HIL tools, both hardware and software, can be used easily in an integrated way. You can now connect that convertor that you developed or even the controller board that you developed, up to a system-level simulation of the electric grid. And remember how I was talking about the questions such as how multiple inverters will work? How multiple controls will work? You can address those questions easily because now you don't have to connect them to a real power system but you can still look into their system-level behavior using our tools.

We are providing tools and systems to our customers, who are then using them for their own research challenges. But we also have to evolve because the research challenges change, which influences our own R&D to improve our platform or add more capabilities to our tools to help those researchers.

AAC: Thank you for your time, Dr. Chakraborty!

Power Storage for Renewables: The History of Batteries and the Advent of the Virtual Power Station

With renewable energies on the rise, there is a growing need for high-capacity energy storage. One possible solution is the "virtual power plants".

People all over the globe depend on batteries for power. We're also increasingly seeking renewable resources to supplement rising power demands. Unfortunately, modern batteries have been insufficient to effectively store the energy harvested from renewable sources on large scales. In order to address this challenge, the evolution of the battery may be about to take a large step forward.

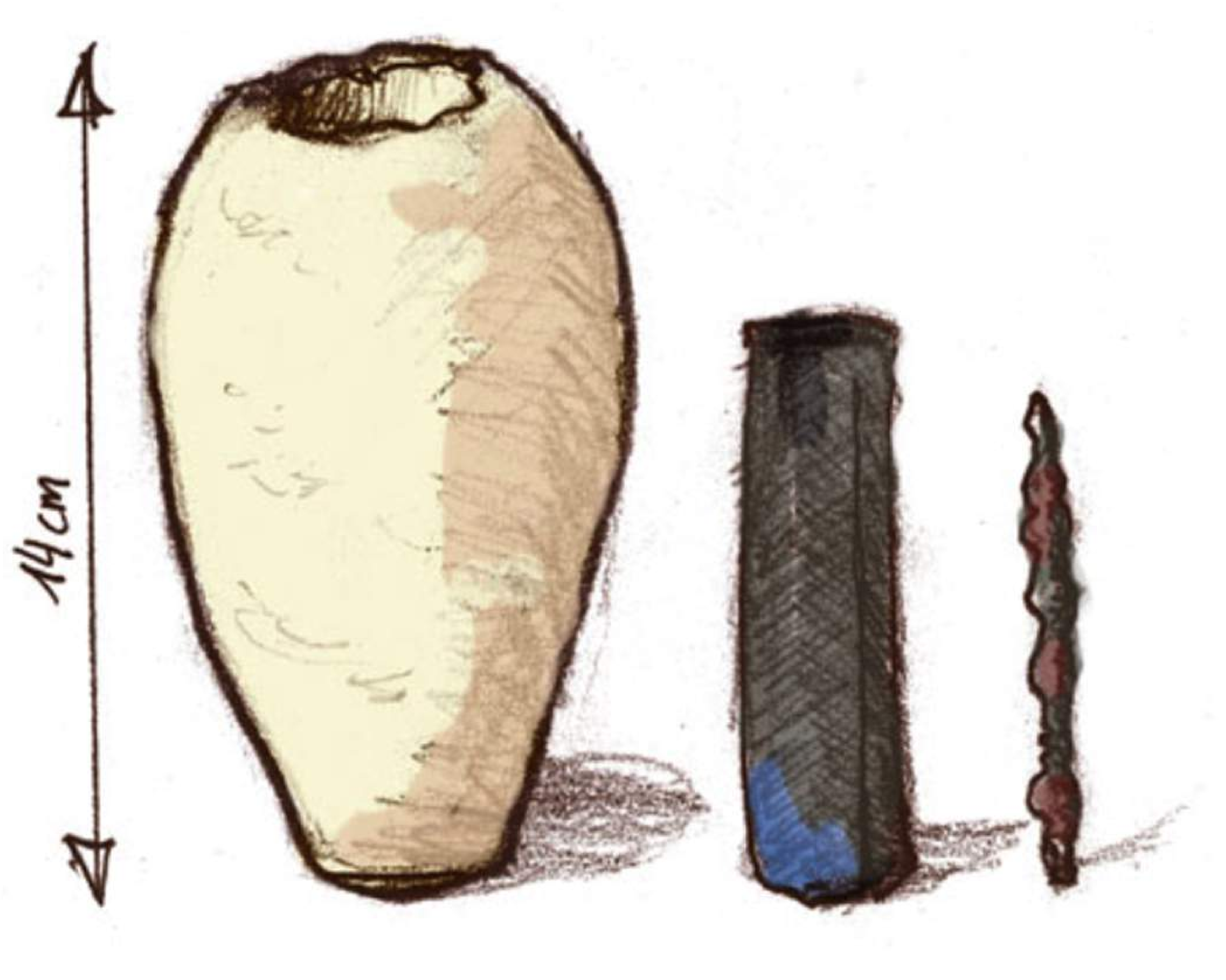
In this article, we'll review historical batteries, the power storage challenges that modern power grids face, and introduce the concept of a virtual power pxlant.

The History of the Battery

Depending on who you ask, you will get different answers to the question "What was the first battery?"

Benjamin Franklin is credited with the modern discovery of electricity as well as coining the term "battery" in 1749 when connecting multiple capacitors together in parallel.

Some archaeologists, however, believe that the first battery could have been in existence 2000 years ago. The "Baghdad Battery" is an artifact discovered in modern Khujut Rabu (Iraq) consisting of a ceramic jar, a tube of copper, and an iron rod. Some have theorized that the device (when filled with an acid) was used as a battery for electroplating gold onto metals but other scientists have said that there is no evidence of electroplated gold from this era. However, counter-arguments suggest that gold museum pieces have been assumed to be solid gold as no museum in their right mind would dissect a gold trinket from 2000 years ago.



The Baghdad Battery. Image courtesy of Irønie
By Ironie [CC BY-SA 2.5]

51 years after Benjamin Franklin's battery, Alessandro Volta invented the voltaic pile which consisted of copper and zinc discs stacked separated by a moist cloth. The cloth was soaked in brine which provided an electrolyte between the copper/zinc discs and the result is a voltage difference across the pile; the voltaic pile was the first wet electrochemical battery. This was likely the world's first true battery.

Some history-savvy reader may bring up the Leyden jar as a contender for this title. Invented in about 1746 by Pieter van Musschenbroek, the Leyden jar is a glass jar that incorporates metal coating and brass elements to store electricity until it is given a discharge path. Unlike the Leyden jar, however, the voltaic pile can provide a consistent voltage and current.

Since the voltaic pile, batteries have gone through a massive transformation using different chemistries and materials. The lead-acid battery (invented in 1859) was the world's first rechargeable battery. The nickel-cadmium battery was invented in 1899 and the 1990s saw the commercialization of nickel-metal hydride battery.

It can be argued, however, that the single most important battery technology, commercially made available in 1992, was the lithium-ion polymer battery. Not only are lithium-ion batteries one of the most energy dense battery technologies, they are also capable of releasing their energy very quickly (similar to a supercapacitor). This has led them to be found in a range of devices including laptops, smartphones, and even car batteries.

Lithium-ion batteries have changed portable devices. Image courtesy of Aney [CC BY-SA 3.0]

Batteries have come a long way and have found their way into most devices but one area remains battery-free: the power grid.

This is theoretically about to change with several companies teaming together to create the world's first virtual power station. But before we look at what virtual power stations are we need to look at the issue with some renewable power sources.

The Problem of Power Grids

All electrical grids around the world, no matter where they are or who runs them, have the same problems. Electrical generation is most easily achieved with 3-phase dynamos but then having three phases means that each phase needs to be balanced correctly. Electrical distribution is much safer at voltages such as 12V but this would result in unimaginable currents and therefore large energy losses so voltages in the region of 500kV is used.

Power plants could be made to be very efficient by always operating at the same rate—but to prevent overloading the grid, power station outputs need to be carefully regulated.

While some renewable energy sources such as hydroelectricity can easily be regulated and are consistent, other sources are not. For example, solar energy is only available during the day and reaches peak efficiency on non-overcast days and wind energy is only available when there is a breeze. But the inconsistency of these sources is compounded when electrical energy supplied to the grid cannot be stored. This means that in the event of a windy night when power consumption is at its lowest, wind farms can generate electricity which does not go to use.

What makes the problem even worse is that renewable sources are very easy to turn off/disengage whereas coal and gas are not (as they have steam boilers with industrial scale fires that take time to start and stop). This means that when the grid needs to quickly reduce power station outputs (to prevent overload), they are more likely to disconnect renewable power plants. Interestingly, nuclear power plants are the single most difficult plant to “turn on and off” which is why their power output is effectively constant (see the GB National Statistics Grid Status Below).

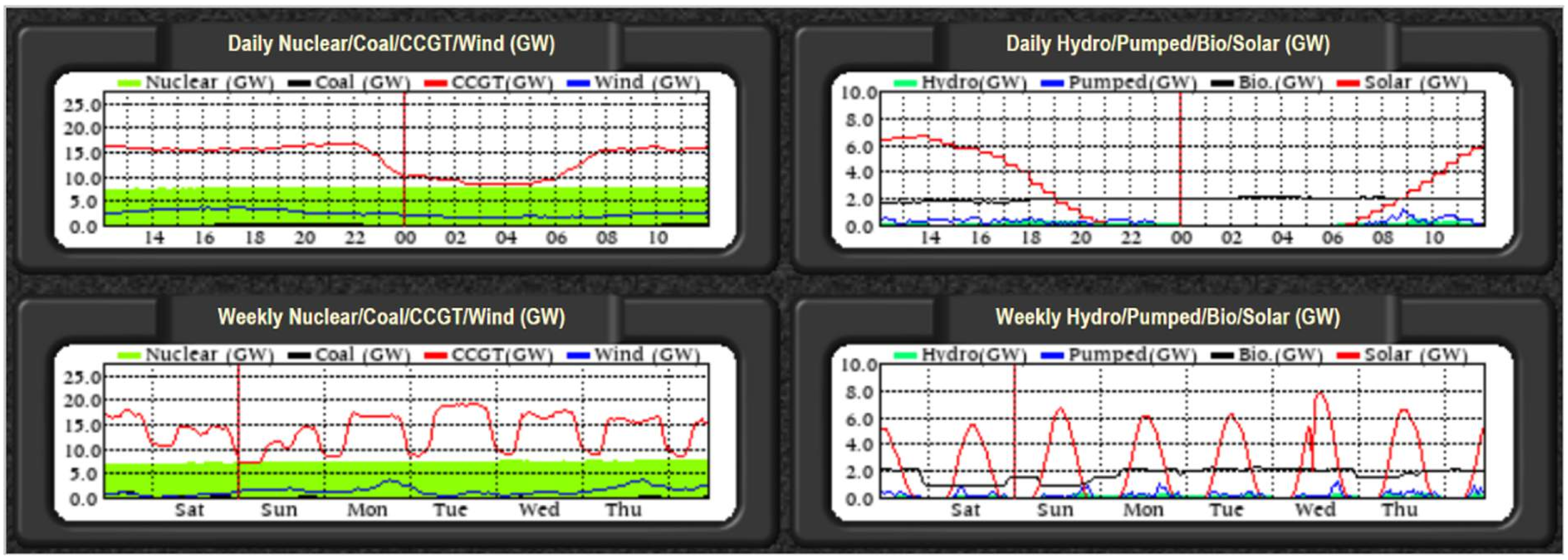


Image courtesy of Gridwatch

Storing energy on these large scales is a large challenge to tackle. What is a virtual power plant and how does it propose to solve these issues?

The Virtual Power Plant

In its simplest form, a virtual power plant is a system whereby the grid can store excess power for future use when demand increases. Unlike electrical generation, virtual power plants can instantly output power to the grid to respond to changes in the power line frequency and voltage which can help to make power stations more efficient (as they are not required to rapidly change their power outputs, which results in downtime of generators).

But virtual power plants will also be instrumental in renewable power as they will be able to store excess power generated by wind farms and solar plants when there is little demand and then supply power when the renewable sources of energy are minimal (such as calm days or at night).

Image courtesy of Next Kraftwerke

Integrating a virtual power plant is not as obvious as you may think. Simply connecting a battery to the grid would have a negative effect as the power draw from the battery would increase the overall demand and therefore require power stations to output more power. Instead, the battery banks need to be charged when demand is lower than the power being produced. This requires coordination with power generation companies and the virtual power plant.

Next Pool, a developer of virtual power plants, have developed algorithms that not only determine when battery banks should be charged but also when to discharge them back into the grid to maintain the power line frequency to within 200mHz. This communication, however, requires power companies to purchase “charging space” from the virtual power plant but this cost is lower than the cost of power cycling power stations.

One market in particular that will heavily benefit from virtual power plants is the European Power Grid. By EU law, the EU must obtain 32% of its energy from renewable sources by 2030. Since solar energy is only available during the day and wind is not constant, the power grid will 32% rely on sometimes sporadic sources. However, the use of virtual power plants will enable renewable power plants to generate more than that is needed during times of plentiful energy and then supply energy when those energy sources are absent.

Two companies, Eneco and Mitsubishi Corporation, have teamed up to build Europe’s largest battery bank for use as a virtual power plant. Located in Germany, the system will have a power capacity of 48MW and a storage capacity of 50MWh. While this power capacity is small on the scale of power plants (a typical coal plant can produce 600MW of power), it can power up to 5000 homes.

Conclusion

Virtual power plants are still in their infancy but will play a key role in electrical grids of the future. While renewable power is better for the environment and has inspired a great deal of technological development, it will need a higher level of dependability to gain true popularity. For that to happen, energy storage needs to scale smartly.

ON Semiconductor Announces New SiC-based Hybrid IGBT and Gate Drivers Series Ahead of PCIM 2019

With PCIM 2019 right around the corner, ON Semi has announced the launch of new SiC-based power components.
The AFGHL50T65SQDC is a hybrid IGBT (insulated-gate bipolar transistor) featuring a silicon-based IGBT co-packaged with a SiC (silicon-carbide) Schottky barrier diode. The NCD(V)57000 series of IGBT drivers are high-current, single channel IGBT drivers with high internal galvanic safety isolation.

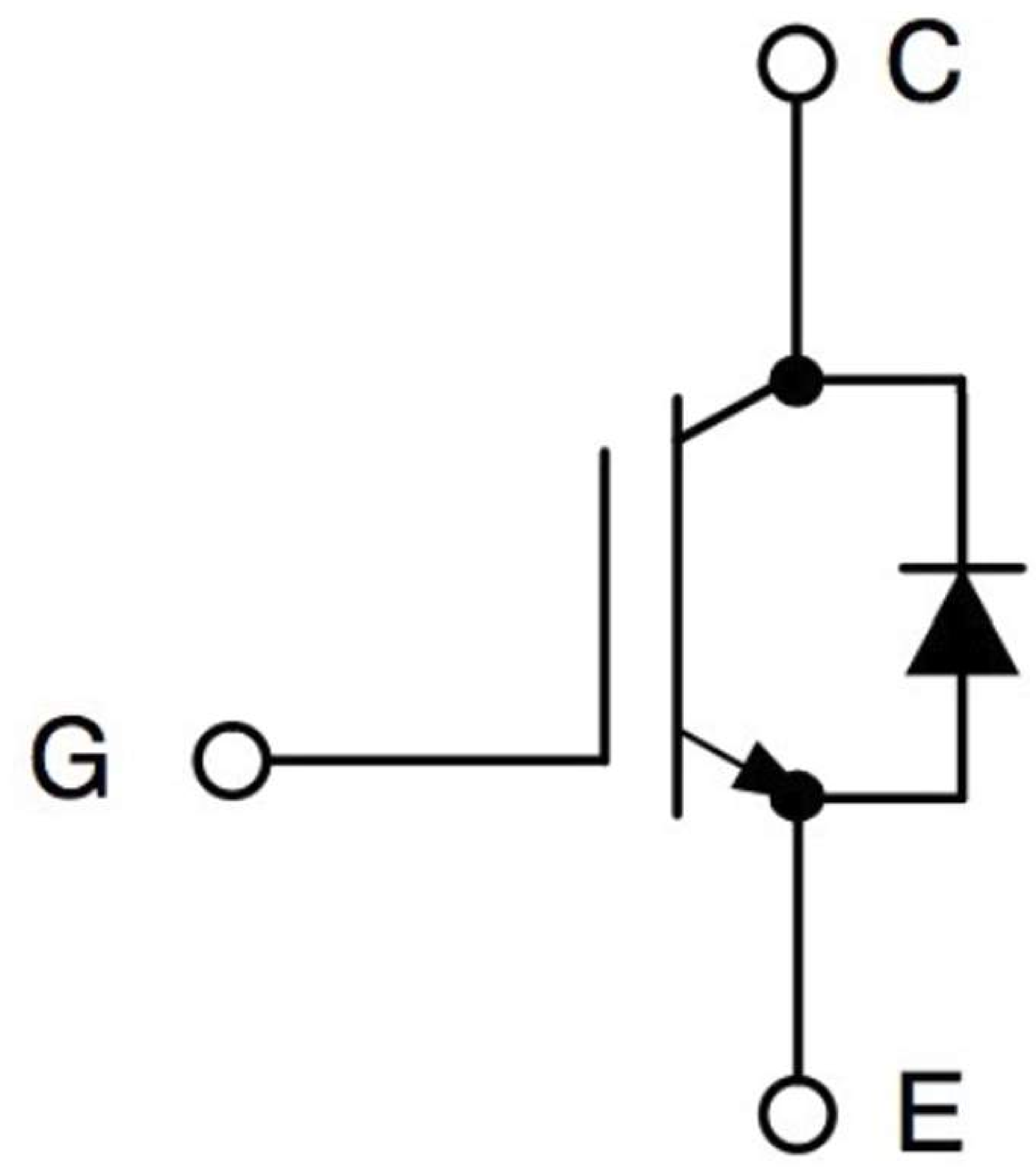
The AFGHL50T65SQDC Hybrid IGBTL: Cost vs Performance

The device co-packages a silicon-based, field stop IGBT with an SiC Schottky barrier diode. The result is a tradeoff between the lower performance of silicon-based solutions and the higher cost of entirely SiC-based solutions.

For power applications, the performance benefits include low conduction and switching losses, particularly interesting for those applications which benefit from lower reverse recovery losses. ON Semi points out that an example of this may be totem pole-based bridgeless power factor correction (PFC) devices and inverters.

The AFGHL50T65SQDC. Image from ON Semiconductor

The device is rated for 650 V operation and able to handle continuous currents up to 100 A @ 25°C (50 A @ 100°C) as well as pulsed currents up to 200 A. For systems requiring greater current capability, a positive temperature coefficient allows for easy and convenient parallel operation.



The AFGHL50T65SQDC co-packages a silicon-based, field stop IGBT with an SiC Schottky barrier diode. Image from the datasheet

The device is especially useful in automotive applications, because it may be the case that an EV might serve as a source of power, rather than the more usual case where the vehicle only receives power through the charger. In this case of a bi-directional charger, an IGBT with an external SiC diode is significantly more efficient than a MOSFET solution, as there are no associated forward or reverse recovery losses.

ON Semi suggests suitable applications are DC-DC converters, power factor correction (PFC), on- and off-board chargers, industrial inverters, and automotive power systems.

The unit is AEC-Q101 qualified and will be available in a TO-247-3LD package.

Important Features:

- Maximum junction temperature: TJ = 175°C
- Positive temperature coefficient for easy parallel operating
- High current capability
- Low saturation voltage: VCE(Sat) = 1.6 V (Typ.) with collector current at 50 A
- Fast switching
- Tighten parameter distribution
- No reverse recovery/No forward recovery

The NCD(V)57000 Series of IGBT Drivers

The NCD(V)57000 series are high-current single channel IGBT drivers. Features include complementary inputs, open drain FAULT and Ready outputs, active Miller clamp, DESAT protection and soft turnoff at DESAT. There are separate high and low driver outputs for to facilitate system design.

The NCD57001. Image from ON Semiconductor.

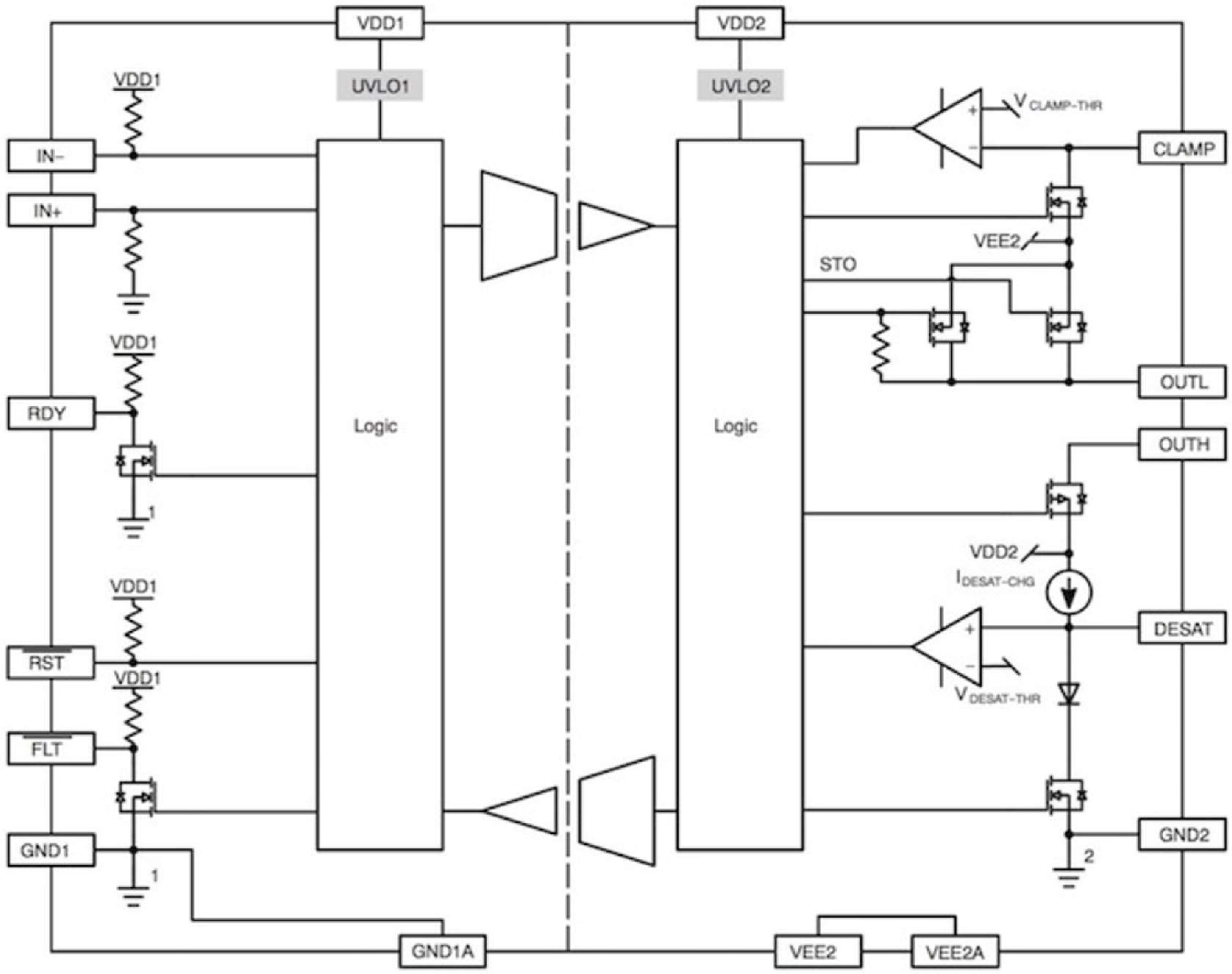
Members of the NCV57xxx series:

- NCD57000
- NCD57001
- NCV57000
- NCV57001

Members of this series are available in a wide–body SOIC–16W package.

Other Important Parameters:

- High current output (+4/−6 A) at IGBT Miller plateau voltages
- Low output impedance for enhanced IGBT driving
- Short propagation delays with accurate matching
- Soft turn off during IGBT short circuit
- IGBT gate clamping during short circuit
- IGBT gate active pull down
- Tight UVLO thresholds for bias flexibility
- Wide bias voltage range including negative VEE2
- 3.3 V to 5 V input supply voltage
- 8mm creepage between input and output



NCD(V)57xx series block diagram. Image from the datasheet. Click to enlarge.

Certifications:

- Designed for AEC−Q100 certification
- 5000 V Galvanic Isolation (to meet UL1577 requirements)
- 1200 V Working Voltage (per VDE0884−11 requirements)

Similar IGBT Products

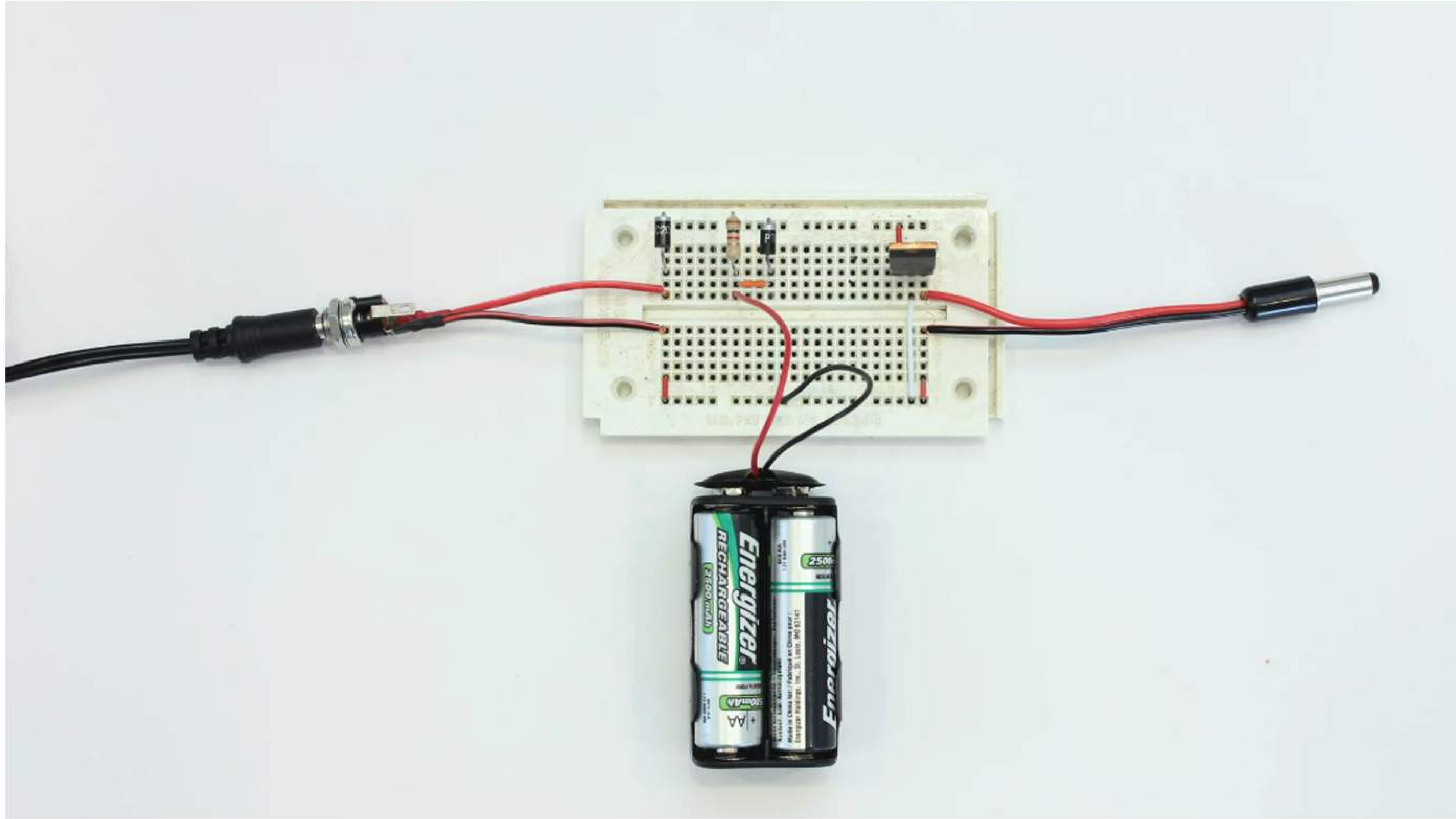
The QID1210006 from Powerex is a module containing two IGBT's with each transistor having a reverse connected super-fast recovery free-wheel silicon carbide Schottky diode. The device can handle as much as 100 A at 1200 V.

The UCC53x0 from Texas Instruments is a family of single-channel, isolated gate drivers designed to drive IGBTs as well as MOSFETs, SiC MOSFETs, and GaN FETs. Working voltages range from approximately 1 kV to 2 kV.

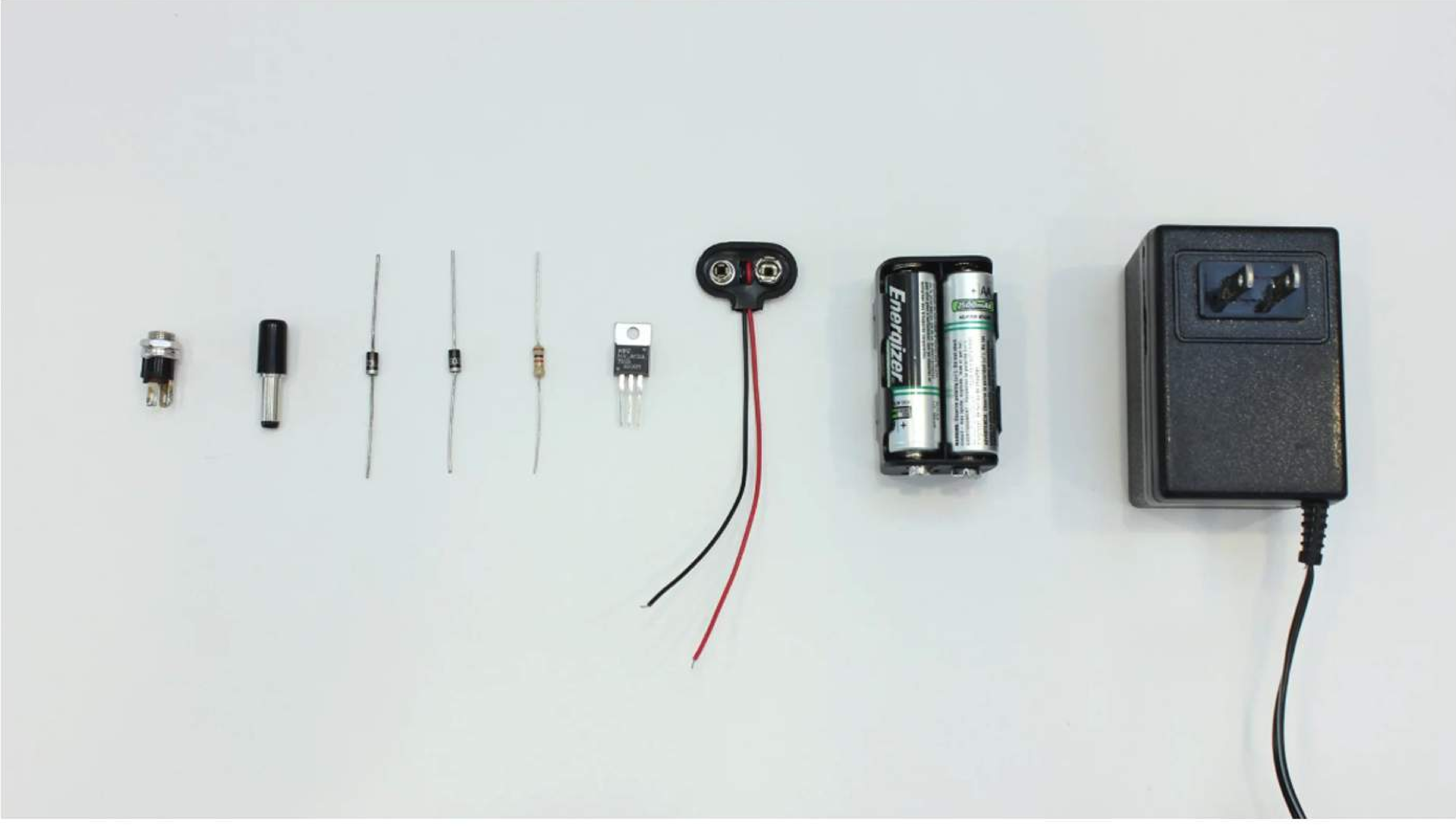
PROJECTS

Create Your Own Battery Backup Power Supplies

Learn to build a battery backup supply for small electronics so you never run out of power.

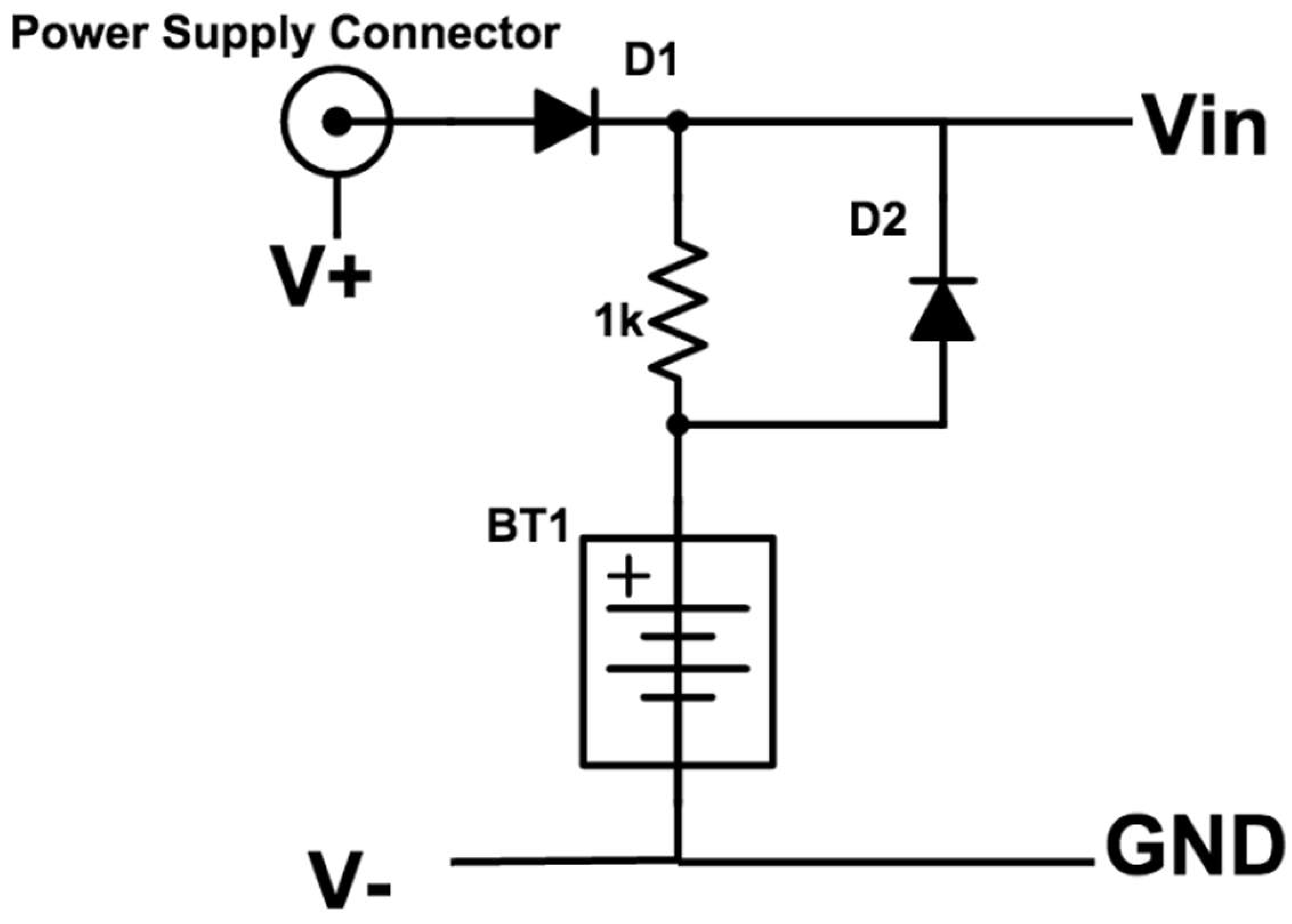


There are a lot of electronics that need to be reliably on all the time. Alarm clocks are a good example of this. If the power goes out in the middle of the night and your alarm doesn't go off, you could miss a very important appointment. The simplest solution to this problem is a battery backup system. That way, if the grid power drops below a certain threshold, the batteries will automatically take over and keep everything running until the grid power is restored.



Materials:

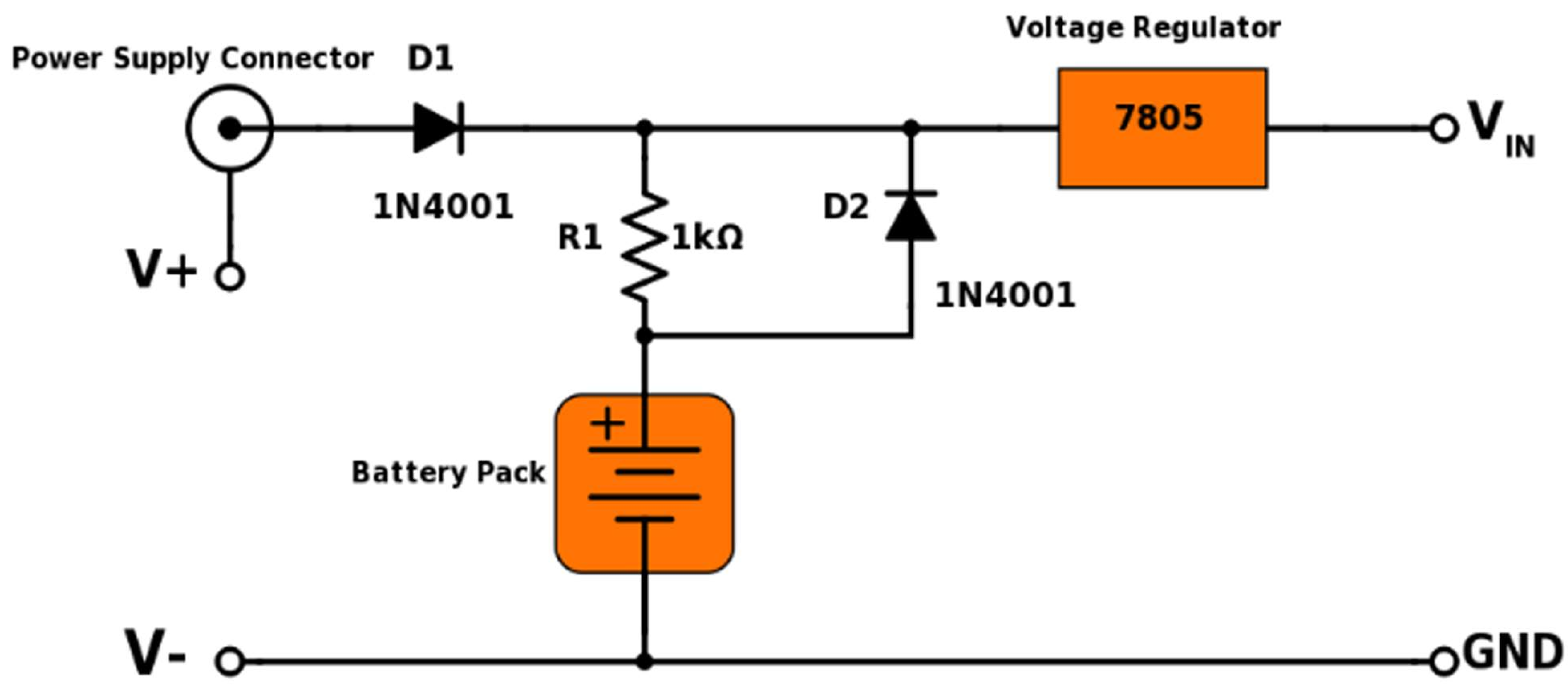
- DC Power Supply
- Rechargeable Batteries
- Battery Pack
- Voltage Regulator (optional)
- 1k ohm Resistor
- 2 x Diode (rated for a higher current than the power supply)
- Male DC Connector
- Female DC Connector



The Circuit

There are many different kinds of battery backup systems, and the type that you use is largely dependent on what you are powering. For this project, I designed a simple circuit that you can use to power low power electronics that run at 12 volts or less.

First, you need a DC power supply. These are very common and come in a variety of voltages and current ratings. The power supply connects to the circuit with a DC power connector. This is then connected to a blocking diode. The blocking diode prevents electricity from the battery backup system from feeding back into the power supply. Next, a rechargeable battery is connected using a resistor and another diode. The resistor allows the battery to be slowly charged from the power supply, and the diode provides a low resistance path between the battery and the circuit so that it can power the circuit if the voltage of the power supply ever drops too low. If the circuit that you are driving requires a regulated power supply then you can simply add a voltage regulator onto the end.



If you are powering an Arduino or similar microcontroller, you should keep in mind that the Vin pin and the DC power connector are already connected to an internal voltage regulator. So you can connect any voltage between 7V and 12V directly to the Vin pin.

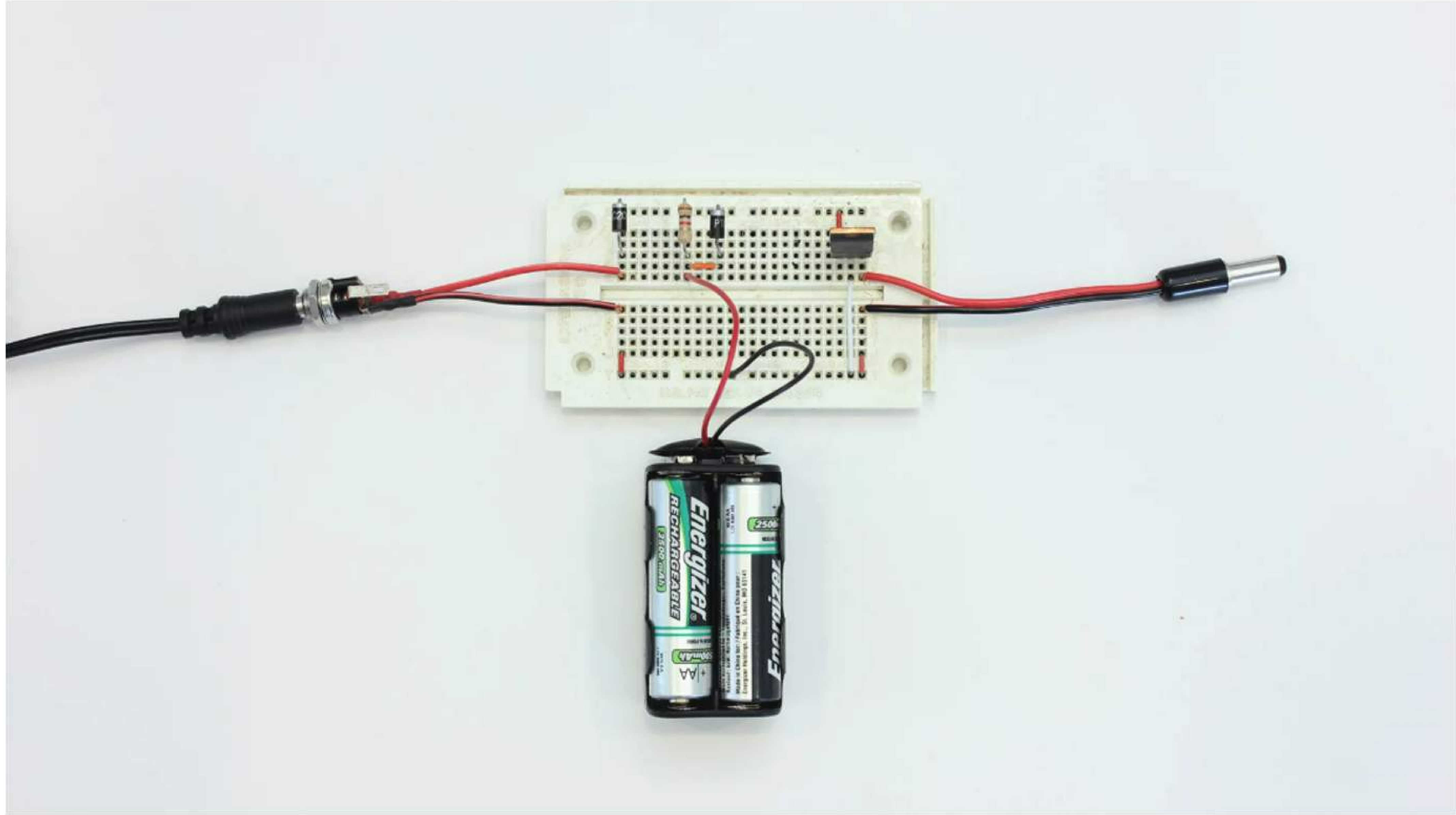
Choose the Resistor Value

The value of the resistor needs to be chosen carefully so that the battery isn't overcharged. To figure out which value resistor you should use, you first need to consider your power supply. When you are working with a non-regulated power supply, the output voltage is not fixed. When the circuit that it's powering is turned off or disconnected, the voltage at the output terminals goes up. This open circuit voltage can be as much as 50% higher than the voltage label on the housing of the power supply. To check this, take a multimeter and measure the voltage at the output terminals of the power supply while no other circuit is connected. This will be the maximum voltage of the power supply.

A NiMH battery can be safely charged at a rate of C/10 or one-tenth of its capacity per hour. Once the battery is fully charged, however, continuing to apply this amount of current could quickly damage it. If a battery is to be continuously charged over an indefinite time period (such as in a battery backup system), then the charge rate needs to be very low. Ideally, you will want the charge current to be C/300 or less.

In my case, I'm using a battery pack that is made from AA NiMH batteries that have a capacity of 2500mAh. To be safe, I want the charge current to be 8mA or less. Given this, you can calculate what the value of the resistor needs to be.

To calculate the necessary value of your resistor, start with the open circuit voltage of the power supply, then subtract the voltage of the fully charged battery pack. This gives you the voltage across the resistor. To find the resistance, divide the voltage difference by maximum current. In my case, the power supply had an open circuit voltage of 9V and the voltage of the battery pack was about 6V. This gave a voltage difference of 3V. Dividing these 3 volts by the current of 0.008 amps gives a resistance of 375 ohms. So your resistor should be at least 375 ohms. I used a 1 kohm resistor to be extra safe. Keep in mind, however, that using a larger resistor will slow down the charging significantly. This isn’t a problem if the backup power system is very rarely used.



Using Your Battery Backup Power Supply

Using the battery backup circuit that I designed, you can plug your power supply into a female DC power connector. This is connected to the battery backup circuit. Then at the output of the battery backup circuit, there is a male DC power connector that can plug into the electronic device that you want to power. This simple plug-in design means that you don’t have to modify either the power supply or the appliance.

INDUSTRY ARTICLE

Positioning ON Semiconductor in Today's Energy Infrastructure

The industrial market is in the midst of an infrastructure revolution where old mechanical systems are being replaced with electronic systems. These electronic systems provide dramatic increases in efficiency and reduce the world's carbon emissions. Governments understand the significant impact that these electronic systems provide and are implementing policies and regulations to accelerate the transitions.

Starting with how power is actually generated there is a rapid transition to alternative energies that consists of solar and wind from legacy methods such as coal power plants. This transition is happening much faster than expected resulting in governments to set aggressive targets. For example, China's National Development & Reform Commission (NDRC) has proposed a policy to increase the renewable energy target from 20% to 35% by 2030. In terms of power semiconductors this energy revolution provides a significant opportunity as the power semiconductor content for a solar inverter can be up to $650 from essentially $0 used in a coal power plant. That $650 content consists mainly of IGBT power modules used to boost the DC voltage from the solar panels to a higher voltage to then be converted with a different IGBT module to an AC voltage that is supplied to the grid.

The conversion to alternative energies has one major drawback and that is the peak generation does not occur at the same time as peak consumption. This creates an additional opportunity for power semiconductors to be used in energy storage systems (ESS) that are now being deployed to solve this drawback. The power semiconductor content in a typical ESS is about $836.

ON Semiconductor is the second largest supplier in the power discrete and modules market with a leading portfolio in MOSFETs and IGBTs. Moving to higher power levels ON Semiconductor offers Power Integrated Modules (PIMs) incorporating these leading IGBTs, FETs, diodes and SiC devices in a module.

ON Semiconductor has a strong portfolio of SiC diodes in both 650V and 1200V nodes. In addition to the recently released 1200V SiC MOSFET family that enables increased efficiency, smaller solutions, and system cost reductions.

TECHNICAL ARTICLES

FET vs. BJT vs. IGBT: What's the Right Choice for Your Power Stage Design?

This article will help you understand the different types of power semiconductors: how they work, their key parameters, and trade-offs.

There is considerable overlap in application areas for the major types of high-power semiconductors. So how does the designer determine whether to use BJTs or MOSFETs in his/her application's power stage? Or should the designer use IGBTs? And what about thyristors? Would they work in the design? Would they be better?

So there are several choices, but which is the best?

The answer is: “It depends.” I know, not a very informative or satisfying response. But it's valid, nonetheless, as the selection is truly dependent on a wide variety of factors and aspects of your project. For example, the application area (motor control, power supply, audio amplifier, etc.) will influence your choice, as well as the load power modulation technique (e.g., linear, switching, static, etc.) and operating frequency. You will need to clearly define your design criteria and approach first, then you can begin to evaluate the advantages and trade-offs of the various available power semiconductors.

Channel, Junction—What's the Function?

Channels or junctions? How many? What type? These and other aspects of the internal device geometry and construction might be one way of looking at power semiconductors, as they are indeed different for the different types of solid-state power devices. But that approach could lead us away from the real point, which is how the device is controlled to vary the load current.

Keep in mind that varying the current through the load in a controlled manner is the primary function (the raison d'être, if you please) of any power semiconductor device. You have a load through which you wish to drive current, and the state of that current flow (either fully on, fully off, or at some predetermined intermediate level) is a function of a signal delivered to the control terminal of the power semiconductor device.

There are several considerations that will steer your choice of power transistor technology. Among them are the magnitude of current your particular load requires, the desired voltage to be applied across the load to achieve that current, and the maximum rate of change of current (dI/dt) and voltage (dV/dt) required.

Succinctly put, there are three key performance parameters that help us understand which power transistor technology might best fit your power stage design: max operating voltage, max operating current, and max switching frequency.

The Semiconductor Menu for Power-Hungry Loads

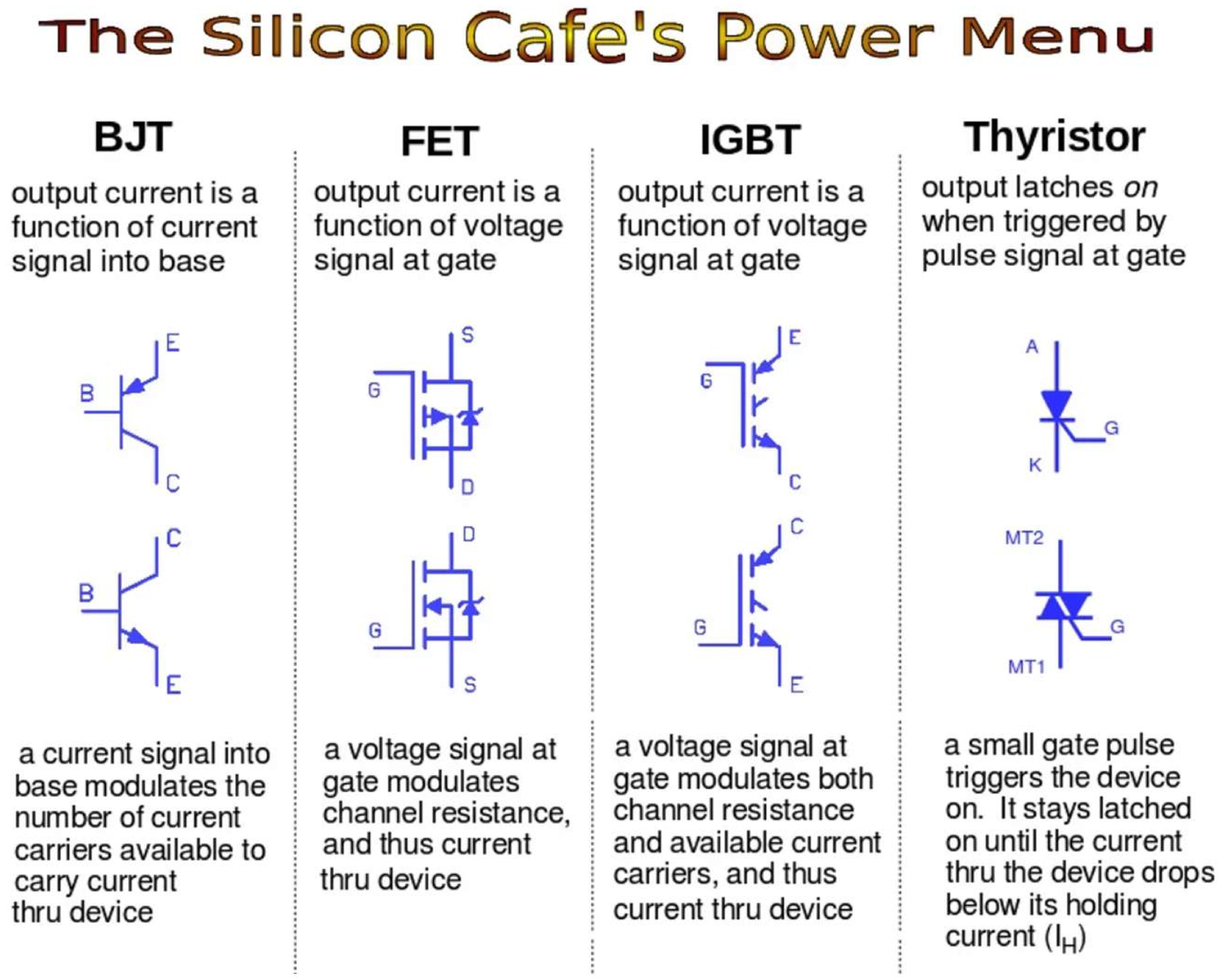
You have, of course, defined the key power parameters of your load:

- Maximum voltage and current
- Maximum frequency of operation
- Reactive parameters of your load (load inductance and load capacitance)
- DC characteristics (and even potential fault characteristics) of your load

Having your load characteristics well-defined means that you are ready to explore the menu of choices for driving your load.

The entrée list includes not only popular high-power transistors like MOSFETs, BJTs, and IGBTs, but also more exotic thyristor fare like Triacs and SCRs (for the restricted palate of AC-only or pulsating DC diets, which we will address in a future article).

And, of course, there are the requisite side dishes like ultrafast and Schottky rectifiers (no power design is complete without them, but that's a future article as well). Peruse this menu of solid-state, three-terminal, high-power devices and you'll see that each one controls the load in a different manner.



BJT

The BJT varies its output current (defined here as the current flowing through the device from emitter to collector or vice versa) according to its base drive current multiplied by its current gain (hFE). Because of this, the BJT is often described as a current-controlled device.

MOSFET

In contrast, the MOSFET is described as a voltage-controlled device, because its output current varies as a function of a small voltage applied to its gate. Functionally what is happening is that the electrostatic field of the gate is impinging on and affecting the resistance of the source-to-drain channel of the device (hence the term "field-effect transistor").

IGBT

The IGBT can also be considered a voltage-controlled device, as its output current is also a function of a small voltage applied to its gate. It differs functionally, however, in that this control signal voltage modulates a channel resistance which in turn also varies the number of current carriers (both electrons and holes) available to carry current from the emitter terminal to the collector terminal.

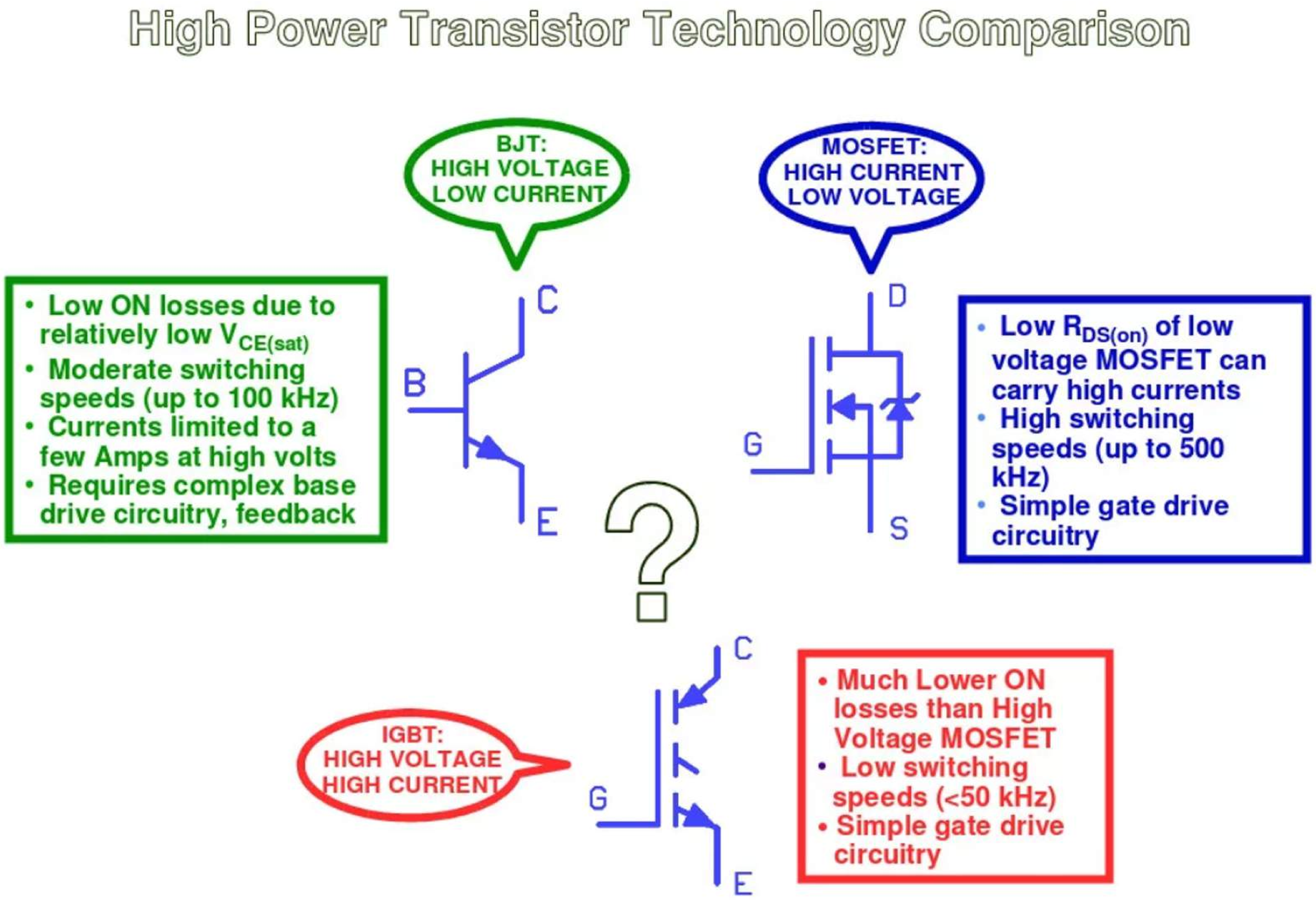
All three types of power transistors have gain and thus can be used as amplifiers as well as switches. The fourth item on our menu, the thyristor, can only be used as a latching switch: a device which, once triggered, will stay on until the current through the device is externally reduced to near zero. This limits thyristors to applications where the load is powered from either an AC or pulsating DC supply (where the applied current will drop to zero every cycle and commutate—i.e., turn off or reset—the thyristor).

Right now, we will focus on the three power transistor types and leave thyristor applications to be covered in a different article.

Technology Comparison and Trade-offs

Now that I've whetted your appetite, let's examine this triad of power transistor types in a bit more depth. We will focus this closer look by constraining our comparison to their use as high-power switching transistors. This is appropriate as most modern power circuitry applications, even audio, use pulse width modulation (PWM) to control the power into a load, whether it be a transformer, inductor, motor winding, LED, lamp, resistor, or even loudspeaker. This is because PWM is inherently more efficient than linear control/regulation of a load.

So, from this focus, we need to look at the power transistors' switching speed performance as well, not just the voltage- and current-handling capabilities.



A bipolar junction transistor designed for use as a high-power transistor will exhibit a fairly modest current gain (with hFE in the single-digit to low double-digit range). And although it is capable of operation as an RF amplifier, the complexities of providing the significant base drive current in a switching application typically limit the use to 100 kHz or lessv. Within this switching speed range, there are BJTs which can efficiently handle tens of amps while withstanding voltages from several hundred to one thousand volts or more. In terms of comparison to the other two power transistor technologies, we can consider the BJT as a high-voltage, but low-current device.

Conversely, MOSFETs designed for use as high-power transistors will usually be high-current, but low-voltage devices. Switching frequencies up to 500 kHz are feasible, and there are MOSFETs that can carry several hundred amps, but they are usually limited to voltages much less than 100V. A significant advantage of MOSFETs is that the circuitry required to drive the gate is very simple and low power.

Interestingly, IGBTs were developed specifically as power transistors, with the aim of combining both high-current and high-voltage. In this role, they have supplanted both BJTs and MOSFETs (as well as thyristors) in many high-power applications. There are quite impressive devices in this technology that can handle currents higher than 1000A while switching several thousand volts!

They do have limitations, however, switching speed being a significant one. Manufacturers of these devices work continually to improve the switching speed (specifically by reducing the fall-time) and, in the decades since IGBTs were first commercially introduced, switching speeds have nearly tripled. Nevertheless, practical switching speeds for high-power IGBT power stage designs are seldom more than 50 kHz.

Key Power Transistor Parameters

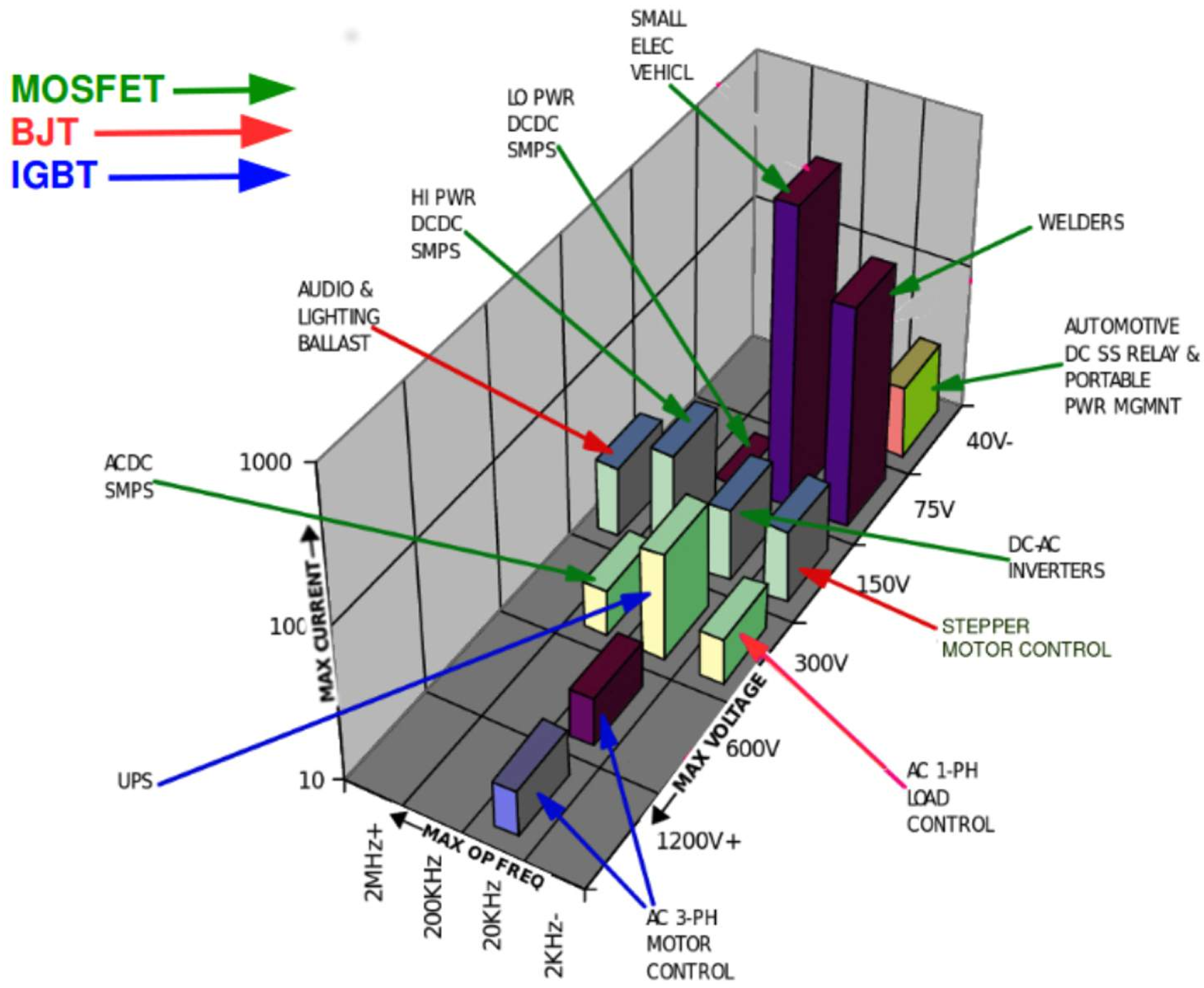
PARAMETER	BJT	IGBT	MOSFET
BREAKDOWN VOLTAGE	V_{CEO}	V_{CES}	V_{DSS}
CONTINUOUS CURRENT RATING	I_C	I_C	I_D
THRESHOLD VOLTAGE	-	$V_{GE(th)}$	$V_{GS(th)}$
FORWARD TRANSCONDUCTANCE	-	g_{FE}	g_{FS}
CURRENT GAIN	h_{FE}	-	-
ON-VOLTAGE	$V_{CE(sat)}$	$V_{CE(sat)}$	-
ON-RESISTANCE	-	-	$R_{DS(on)}$
TURN OFF TIME	$t_s + t_f$	$t_{d(off)} + t_f$	$t_{d(off)} + t_f$

Besides evaluating these key parameters, you should also consider both the reactive and fault behaviors of your load when reviewing and comparing power transistor datasheets. For example, IGBTs may latch up (like a thyristor) if subjected to a short-circuit current exceeding their rated short-circuit withstand time (t_{SC}) in microseconds. And inductive loads can create large voltage spikes that may exceed a BJT's breakdown voltage, or overtax the avalanche energy capacity of a MOSFET's body diode (E_{AC}).

Three Dimensions of Power Transistor Applications

We have discussed the three key performance parameters that help us understand which power transistor technology might best fit your power stage design. To reiterate, these are max operating voltage, max operating current, and max switching frequency.

These and other datasheet parameters provide the designer with the technical information needed to make thoughtful design decisions. But often designers would also like to know how these devices are commonly utilized in commercial/industrial market applications, as this provides insight into how other designers have evaluated the performance and cost trade-offs.



This graph illustrates the power transistor applications space in three dimensions. Each axis of the graph represents one of the three key performance parameters, and each power transistor technology is represented by a different color arrow.

For example, at the top of the graph, you will note a bar representing small electric vehicle applications (e.g., golf carts, electric forklifts). The motor controllers in these typically operate at voltages from 48V to 72V and currents up to several hundred amps, and they commonly utilize MOSFETs PWM'ing the motor at frequencies around 20 kHz (comfortably above human hearing).

As a caveat, the data driving this graph is properly considered anecdotal, as it is drawn from my own personal observation. I have provided it in hopes of sharing my insight from four decades in the industry working with a wide range of customers and applications.

Conclusion

You should now have a good idea of your options and where to start when choosing the type of power transistor to use in your next high-power design. Keep an eye out for future articles on related topics.

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