Hybrid Supercapacitors for Implantable Energy Storage

[https://symbiontlabs.io/]

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Introduction

Medical implant companies such as Boston Scientific and Medtronic use various energy storage solutions for their implantable technologies. For critical applications like pacemakers, non-rechargeable “primary” cell batteries are common. There are several quality of life applications where implantable pulse generators with rechargeable “secondary” cell batteries are used. Some examples include:

- Pain relief through spinal cord stimulation (WaveWriter ALPHA) **[1]**
- Obstructive sleep apnea therapy (Inspire) **[2]**
- Sacral nerve stimulation for incontinence (InterStim II) **[3]**

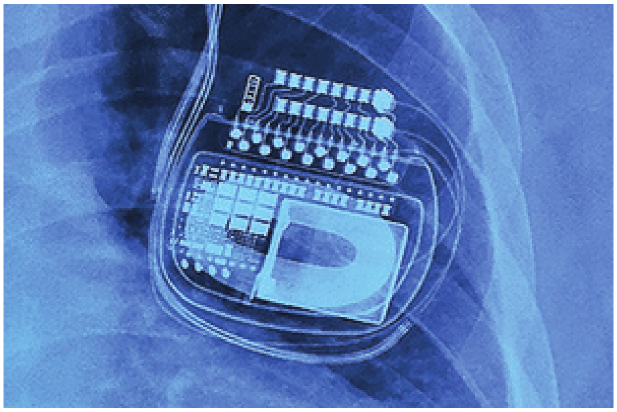


Figure 1 - Implantable Pulse Generator **[4]**

These devices receive power through wireless charging, using alternating magnetic fields to inductively couple with the device through the skin. The energy storage system consists of a capacitor bank coupled with specific lithium battery chemistries, for example lithium-titanate batteries **[5]**. The capacitor bank is included because it can react quickly to inconsistent wireless charging conditions, and smooth the supply to the battery charging circuitry. The battery is included because it can more densely store energy for a longer runtime.

The battery itself and the entire implant assembly are hermetically sealed in titanium enclosures using laser or electron-beam welding with inert gasses **[6]**. Even with careful chemistry selection and protection circuitry, the battery can still present significant risk to the user and its condition must be closely monitored. This risk greatly increases as the market is expanding for more “consumer grade” implantable technologies made by startup companies incorporating their own energy storage solutions with limited sourcing options. These companies and individual inventors do not necessarily plan to be compliant with FDA 510(k) clearance or similar regulatory frameworks, because of the extensive costs and time involved.

A promising new technology that combines some of the strengths of both capacitors and batteries is called “hybrid supercapacitors”. While potentially a good fit for implantable technologies, it has not been proven in the market because of the novelty relative to the long timelines required for regulatory approval. In this document we will explore some of the work done by Cory Lord and Symbiont Labs to characterize the behavior and utility of hybrid supercapacitors for implantable energy storage.

1 Lithium-ion Batteries

A detailed analysis of lithium-ion batteries is beyond the scope of this document **[7]**. Here we will focus on the strengths and limitations of lithium-ion batteries when used for implantable energy storage. The major strengths of lithium-ion batteries are their high specific energy (J/kg), while maintaining a relatively stable voltage across the majority of the discharge curve. Some of the limitations of lithium-ion batteries are: thermal runaway, gas evolution, cycle life.

1.1 Thermal Runaway

Thermal runaway is a process by which the internal functions of the battery begin to fail and cause excess heat generation which further damages the battery by cascading effects **[8]**. Poor heat management inside the hermetically sealed environment of the implant allows internal heating of the battery, which causes damage over time that can lead to thermal runaway. Overcharging of the battery is another common cause of damage that leads to thermal runaway. Wireless charging solutions require switching mode power supplies that modulate the voltage to properly charge the battery. Poor management of transients and ripple may cause voltage spikes that damage the battery and lead to thermal runaway. These factors are taken into consideration for all medical implants on the market, but consumer grade implantable technologies must also prioritize mitigation of these failure mechanisms.

1.2 Gas Evolution

Gas evolution is caused by a variety of electrochemical processes within the battery that either generate or liberate gasses **[9]**. In the hermetically sealed environment of the implant, gas evolution will cause an increase in pressure which can compromise the encapsulation material. Gas evolution can also damage the battery itself, potentially leading to thermal runaway. A large proportion of the gas evolution will occur during the first charge/discharge cycles after battery manufacture, which can be removed with a prestress regimen before implant assembly. Much of the remaining gas evolution potential can be mitigated by precise control of the charge and discharge characteristics, ensuring they stay within a safe operating range for the battery chemistry selected.

1.3 Cycle Life

Cycle life is an estimation of the number of charge/discharge cycles a battery can undergo before it ceases to function **[10]**. Manufacturers will often only guarantee battery function for a relatively small number of cycles (300-800). In reality batteries can often function for thousands of cycles. Factors influencing the cycle life of a lithium-ion battery are the “depth of discharge” and the “peak charge voltage”. The depth of discharge is the lower voltage threshold that the system allows the battery to sink to before the under voltage protection is triggered. The peak charge voltage is the upper voltage threshold that the system allows the battery to raise to before the over voltage protection is triggered. Maintaining the battery in a narrow operating voltage range will increase its cycle life, while decreasing the usable energy per cycle.

2 Supercapacitors

Capacitors store energy in an electric field present between positively and negatively charged electrodes **[11]**. These electrodes are separated by an insulating “dielectric” material that augments the energy storage capabilities of the field. In higher capacity “electrolytic capacitors” the dielectric is an oxide layer formed on the surface of the electrodes, while the charge on the electrodes attracts ions within an electrolyte solution to store energy.

Hybrid supercapacitors employ two additional effects that further improve their energy storage capabilities, “double-layer capacitance” and “pseudocapacitance”. Double-layer capacitance is an electrostatic effect caused by solvent molecules in the electrolyte solution forming a monolayer on the electrode surfaces, which serves as a much thinner dielectric separator. Psuedocapacitance is an electrochemical effect where ions in the electrolyte solution adsorb to the surface of the electrode and form reversible ionic bonds. These mechanisms bring hybrid supercapacitors closer to electrochemical batteries than traditional capacitors.

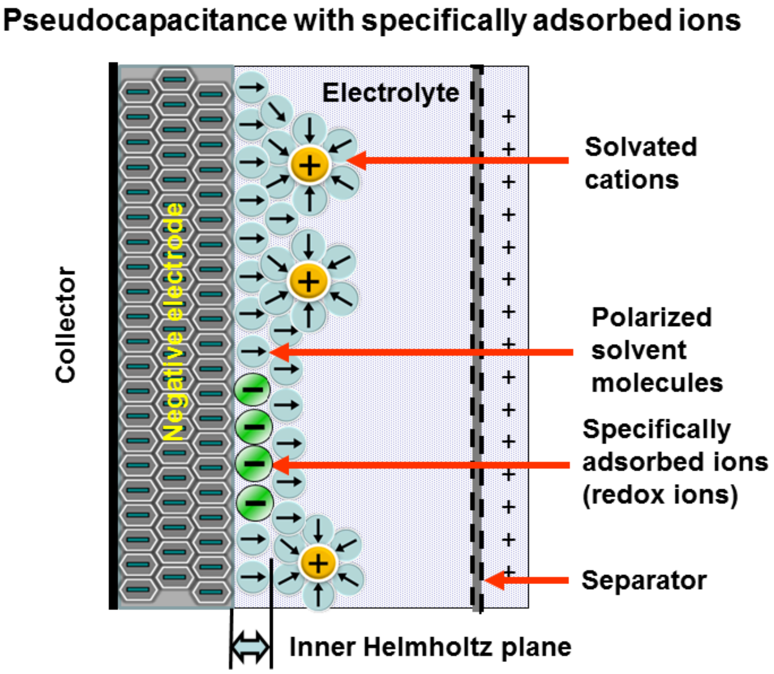


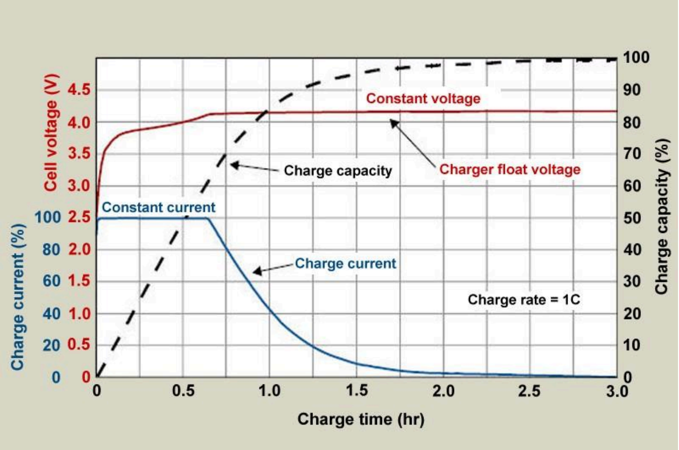
Figure 1 - EDLC and Psuedocapacitance
Elcap, CC0, via Wikimedia Commons

Despite the dramatic increase in capacity, their specific energy still does not approach lithium-ion batteries. The strengths of hybrid supercapacitors lie in their extensive cycle life, faster rate of charge/discharge, and wider operating temperature range. Where a lithium-ion battery may be rated for 500 charge/discharge cycles, a hybrid supercapacitor could easily be rated for 50,000. More details on these specifications will be explored in section “3.1 Example Specifications”.

Hybrid supercapacitors suffer from some of the same safety limitations as lithium-ion batteries, such as thermal runaway and gas evolution. Thermal runaway is less of a concern because the specific energy is much lower, and the wider operating temperature range limits damage caused by heat. Gas evolution can still be a serious concern with hybrid supercapacitors when used for implantable energy storage. The rate and composition of gas evolution is heavily dependent on the electrolyte used, but judicious overvoltage and overcurrent limits will greatly improve outcomes **[12]**. Hybrid supercapacitors also have functional limitations when used in a circuit, which are their linear voltage/current relationship and rate of self discharge.

2.1 Linear Voltage/Current Relationship

Unlike electrochemical batteries which have a relatively stable voltage over much of their operating range, hybrid supercapacitors have a linear voltage curve.



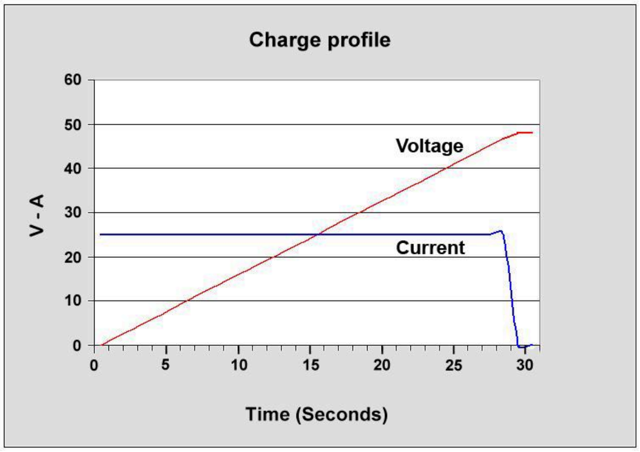


Figure 2 - Lithium-ion Charge Curve **[7]**

Figure 3 - Supercapacitor Charge Curve **[11]**

This behavior means that any implantable energy storage solution utilizing hybrid supercapacitors must be able to accommodate a wide input voltage range. This limitation can be managed with a low ripple buck/boost switching mode power supply, but as the voltage sinks the efficiency of the conversion will decrease dramatically. A significant percentage of the specific energy of the hybrid supercapacitor is also concentrated near the maximum rated voltage, as power is the product of voltage and current. As with any novel technology, the selection of application specific integrated circuits available for hybrid supercapacitor power supply management is currently somewhat limited.

2.2 Self Discharge

Self discharge occurs when processes within an energy storage solution cause a loss of accumulated charge, even when no load is attached. Self discharge processes are affected by storage conditions like temperature and humidity, and if left unchecked can create unsafe operating conditions below the low voltage protection cutoff. The stability of electrochemical energy storage allows lithium-ion batteries to have a very low rate of self discharge, often less than 5% over a 30 day period **[11]**. Supercapacitors relying exclusively on double-layer electrostatic effects have a very high rate of self discharge, with 100% discharge occurring within 10-30 days **[13]**. Hybrid supercapacitors that include psuedocapacitive electrochemical effects have a greatly reduced rate of self discharge, comparable to that of lithium-ion batteries. This rate of self discharge is heavily impacted by ambient temperature conditions, which in an implantable energy storage scenario is raised to approximately 37°C inside the body.

3 Characterization and Testing

The specific line of hybrid supercapacitors used during our testing were a series called 196 HVC ENYCAP from Vishay Dale **[13]**. Factors influencing our selection were: sourcing availability, large capacity, and higher voltage rating options.

3.1 Example Specifications (MAL219691254E3)

Case Size L x W x H (mm)	24.0 x 24.0 x 2.5
Mass (g)	4.4
Rated Capacitance -20% / +80% (F)	15
Rated Voltage (V)	5.6
Lowest Discharge Voltage (V)	3.2
Maximum Surge Voltage (V)	6.4
ESR DC (Ω)	10
Recommended Charge Current (mA)	5 to 20
Maximum Discharge Current (mA)	70
Charge/Discharge Cycles at 25°C	100,000

3.2 Rated Voltage

The rated voltage options available for the 196 HVC ENYCAP series are: 1.4V, 2.8V, 4.2V, 5.6V, 7.0V, 8.4V. The internal surface area of the electrodes plays a significant role in the capacity rating in Farads. As manufacturers fit more electrode surface area within a package, the distance between the electrodes shrinks and reduces the voltage level necessary to bridge the gap through the electrolyte and separator, causing an internal short which can destroy the hybrid supercapacitor. To overcome this issue manufacturers can place several individual capacitive elements electrically in “series” with each other to increase the rated voltage. Due to the lack of active cell balancing within the hybrid supercapacitor, high current charge/discharge scenarios may cause variations in the voltage between cells. Care should be taken to ensure the “maximum surge voltage” rating is not exceeded.

3.3 Capacitance and milliAmpere-hours

Lithium-ion battery capacity is often measured in milliAmpere-hours (mAh). For example a lithium-ion battery with a 500mAh capacity could discharge 1000mA for 0.5hrs, and the voltage would remain within the range of 4.2V - 3.0V. The capacity rating of a hybrid supercapacitor is measured in Farads (F), which can be converted into mAh for system runtime comparisons. Unlike capacitors relying exclusively on electrostatic effects, hybrid supercapacitors should not be completely discharged during normal operation to maintain their cycle life. This operating voltage range makes runtime calculations very similar to batteries, but the unit conversion requires charge and discharge threshold voltages be taken into account.

Equation 1: $$Farad = \frac{Coulomb}{Volt}$$

Equation 2: $$Ampere = \frac{Coulomb}{Second}$$

Equation 3: $$Coulomb = Ampere * Second$$

Equation 4: $$Farad = \frac{Ampere * Second}{Volt(start) - Volt(end)}$$

Equation 5: $$milliAmpere * Hour = (Ampere * 1000) * \frac{Second}{3600}$$

Using the example specifications above, with the start and end voltages from page 9 of the datasheet (5.4V - 4.4V) we can approximate the milliAmpere-hour capacity of a hybrid supercapacitor **[13]**. Using 15mA (0.015A) as a constant discharge current value, we can rearrange Equation 4 to solve for 1000 seconds. Using all of these values and Equation 5, we can determine that the hybrid supercapacitor will have approximately 4.17mAh of capacity across the voltage range in which the 15F capacitance was measured.

Due to the variable operating voltage range of hybrid supercapacitors, the conversion efficiency of a power supply across the entire range will affect the usefulness of these calculations. Ensure that the start and end voltages used in Equation 4 relate to those used to measure the Farad rating. For capacitors using exclusively electrostatic effects, “deep discharge” will not reduce their cycle life. In these cases the Farad rating often uses the rated voltage and zero as the start and end voltages.

The capacity rating of a lithium-ion battery (denoted “C”) is used to communicate the rate at which it can be charged and discharged. To protect cycle life a manufacturer may recommend a charge/discharge rate of 0.5C. For a 500mAh battery this would be 250mA, which means safely charging the battery would take 2 hours. Hybrid supercapacitors by comparison allow much higher C ratings for charge and discharge. Using the example specifications above, the hybrid supercapacitor could safely charge at 4.65C and discharge at 16.28C.

3.4 Charging Hybrid Supercapacitors

Provided in Figure 4 is an example schematic for a hybrid supercapacitor charger using the BQ25173 integrated circuit from Texas Instruments **[14]**. Components of interest are the voltage divider formed between R21 and R22 which sets the regulation voltage, and R20 which sets the fast charge current limit. The regulation voltage provides a degree of overvoltage protection. A complete power management solution for hybrid supercapacitors must also include undervoltage protection to prevent discharge below the lowest discharge voltage rating. This cutoff can be incorporated into a buck/boost switching mode power supply.

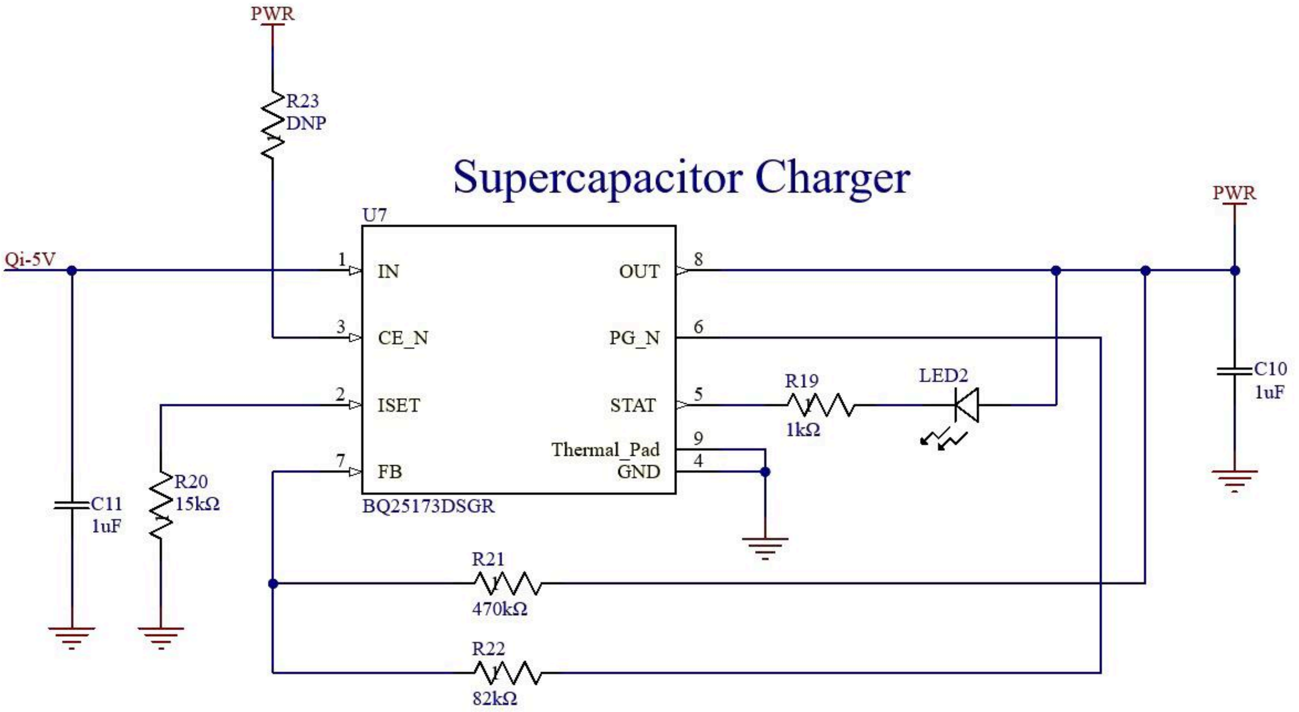


Figure 4 - BQ25173 Example Schematic

4 Conclusions

Hybrid supercapacitors fill a niche between the high specific energy of batteries and the fast response times of traditional electrostatic capacitors. Faster charge times and impressive cycle life make them an attractive option for certain applications. The increasing prevalence of wireless charging technology standards such as NFC and Qi make intermittent charging plausible for users with a smartphone or dedicated charger. Hybrid supercapacitors can enable unique possibilities in implantable energy storage like trickle charging from wireless transmitters, energy harvesting from the body, and small-scale betavoltaic generators. The availability of different hybrid supercapacitor specifications and supporting application specific integrated circuits will only increase as the technology advances. Some of the safety concerns with “consumer-grade” implantable technologies can be alleviated with the thoughtful application of hybrid supercapacitors instead of relying exclusively on lithium-ion batteries.

5 Resources

1. Boston Scientific WaveWriter ALPHA
   https://www.bostonscientific.com/us/en/healthcare-professionals/products/spinal-cord-stimulation-scs-systems/wavewriter-alpha-spinal-cord-stimulator-system/fp00000267.html
2. Inspire Sleep Apnea Treatment
   https://www.inspiresleep.com/en-us/
3. Medtronic InterStim II
   https://europe.medtronic.com/xd-en/healthcare-professionals/products/urology/sacral-neuromodulation-systems/interstim-ii.html
4. Cardiac Surgery in a Patient with Implanted Brain Pacemaker: A Case Report
   https://www.researchgate.net/figure/Chest-radiograph-showing-implanted-pulse-generator-with-extension-leads_fig1_328722382
5. Implantable devices using rechargeable zero-volt technology lithium-ion batteries
   https://patents.google.com/patent/US7184836B1/en
6. EB Industries Laser Hermetic Sealing Titanium
   https://ebindustries.com/laser-hermetic-sealing-titanium/
7. BU-204: How do Lithium Batteries Work?
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8. A review of thermal runaway prevention and mitigation strategies for lithium-ion
   https://www.sciencedirect.com/science/article/pii/S2590174522001337
9. A review of gas evolution in lithium ion batteries
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10. BU-808: How to Prolong Lithium-based Batteries
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11. BU-209: How does a Supercapacitor Work?
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12. Comparison of pressure evolution in supercapacitors using different aprotic solvents
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13. Vishay Dale 196 HVC ENYCAP™ Product Information
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