ADVANCING DOWNHOLE ENERGY STORAGE

JOSEPH LANE, NANORAMIC LABORATORIES, USA, DISCUSSES UTILISING HIGH TEMPERATURE CAPACITORS FOR RECHARGEABLE STORAGE.

Ever since the adoption of measurement while drilling (MWD) and logging while drilling (LWD) in the late 1960s, engineers have been challenged with providing a reliable source of downhole electrical energy. Early attempts utilised wirelines or wired pipe to accomplish the task. Wireline is essentially the extension cord for downhole drilling. In theory, it requires only a surface power source and an electrical connection to the downhole tool to work. The benefits of wireline include practically unlimited energy downhole as surface power is either readily available or easily sustained. However, the complications of maintaining a continuous connection and supporting isolated tools drove the industry to incorporate new forms of energy storage and generation. The invention of lithium-thionyl chloride (Li-$SOCl_2$) batteries in the late 1960s, and their adoption in the 1970s, provided one means of supplying power downhole. Li-$SOCl_2$ batteries have extremely high energy density, relatively good power handling capabilities, but suffer from safety concerns and from the inability to be recharged. Downhole generators would become the dominant source of downhole energy when operations exceeded the practical lifetime of Li-$SOCl_2$ batteries. While generators support much longer trips without recovery or replacement, they cannot provide energy without continuous mud flow, forcing engineers to incorporate batteries to support activity when mud flow has ceased.

These types of challenges and trade-offs have long been present in MWD and LWD but there are alternatives enabled by technology developed in recent years. FastCAP Ultracapacitors, a division of Nanoramic Laboratories, began in 2009 derived from research investigating carbon nanotubes for use in ultracapacitors. The somewhat unintentional side effect of this research was that it enabled ultracapacitors, typically limited to a maximum operating temperature of 65˚C, to operate beyond 150˚C. With funding in hand from the US Department of Energy (DOE) targeting geothermal applications, FastCAP developed what is today the only ultracapacitor suitable for downhole oil and gas exploration.

What is an ultracapacitor?

An ultracapacitor, or supercapacitor, is any capacitor that stores its energy through an electric double layer. The double layer phenomenon enables substantially more charge storage by volume and mass when compared to other capacitor technologies. As an example, a standard ultracapacitor will typically have an energy density that is 10 - 100 times higher than that of a tantalum or electrolytic capacitor. On the other side of the spectrum, Li-$SOCl_2$ batteries typically have an energy density that is 10 - 100 times than that of an ultracapacitor. Therefore, in terms of energy density, the ultracapacitor generally sits right in between electrolytic or tantalum capacitors and lithium batteries.

Nanoramic has re-engineered the fundamental components of the cell to survive both high temperature and high shock and vibration environments. Each cell is capable of 150˚C operation with 20 g vibration, 500 g shock survival. Capacities range from 35 F in a AA cell form factor to 350 F in a D cell form factor.

Applications

Ultracapacitors can be used in a variety of applications within downhole exploration and production. This article will highlight a mud pulse telemetry application and then focus on voltage buffering for generator based solutions.

Battery augmentation

One use case of battery augmentation is enhanced mud pulse telemetry systems. The low internal resistance of the ultracapacitors make them ideally suited for high power discharge events. In mud pulse telemetry, a burst of power is needed to open and close a mud valve. Strong telemetry pulses require that the valve actuation is well timed, quick, and not hindered by particulates that may clog or disrupt the valve. Operating in parallel to a Li-$SOCl_2$ battery, an ultracapacitor module significantly increases the peak current handling capacity of the battery while buffering the battery from large current spikes. Benefits include a longer lasting battery pack and a higher performance mud pulse telemetry. Clever power systems could also vary the voltage on the ultracapacitor module depending on the drill depth. A low voltage conserves battery energy and could be used during shallow parts of the well. As drilling continues, pulse power can be increased by increasing the ultracapacitor voltage.

Generator buffering

As introduced, generators are an excellent means of providing high power downhole energy over long durations of time. The drawback of most generators is that they cannot produce power when mud flow is off, a time that is often used for sensitive measurements

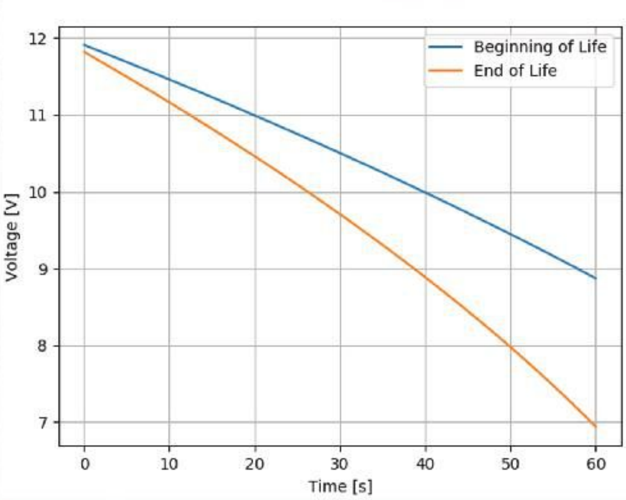

Figure 1. *Simulated discharge event.*

Table 1. System requirements.		
Parameter	**Value**	**Unit**
Maximum output voltage	12	V
Minimum output voltage	5	V
Power discharge	15	W
Discharge period	60	s
Chassis OD	1.5	in.
Maximum operating temperature	150	˚C

Table 2. EE150-350 capacitor specifications.		
Parameter	Value	Unit
Rated voltage	1	V
Rated capacitance	345	F
Initial ESR	5.8	mΩ
Leakage current	0.2	mA
Rated lifetime	1500	hrs
Maximum operating temperature	150	˚C
Height	2.75	in.
Diameter	1.25	in.

in directional drilling and well logging. Ultracapacitors offer a long lifetime, high reliability, and safe form of energy storage to buffer generator power for when mud flow is off. Throughout this example, the design and integration of an ultracapacitor module to support measurement and communication operations will be discussed.

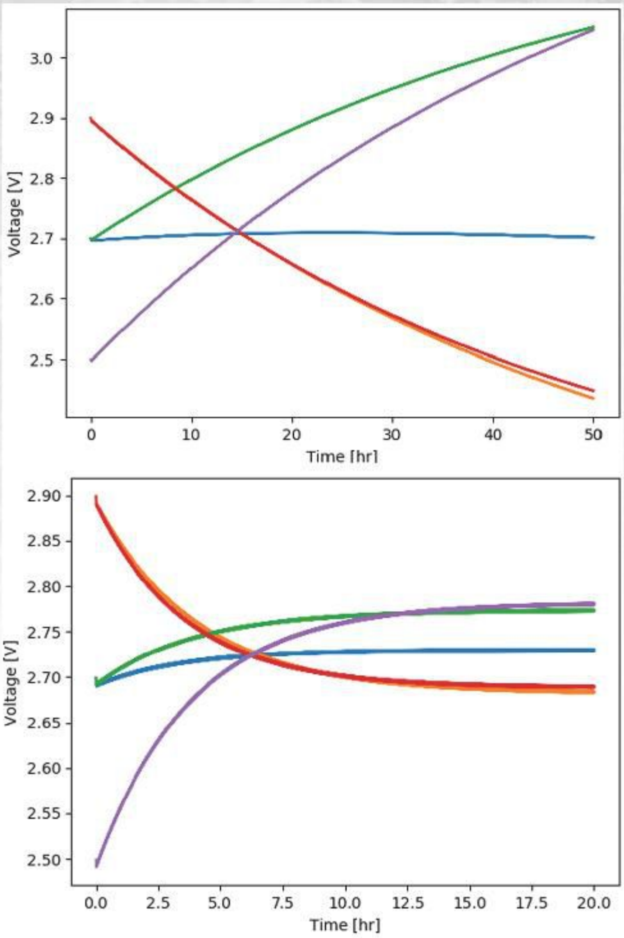

Figure 2. *Five cell module without balancing (top) and with balancing (bottom) the time constant of convergence is estimated by the R-C time constant of each capacitor – balancing resistor network.*

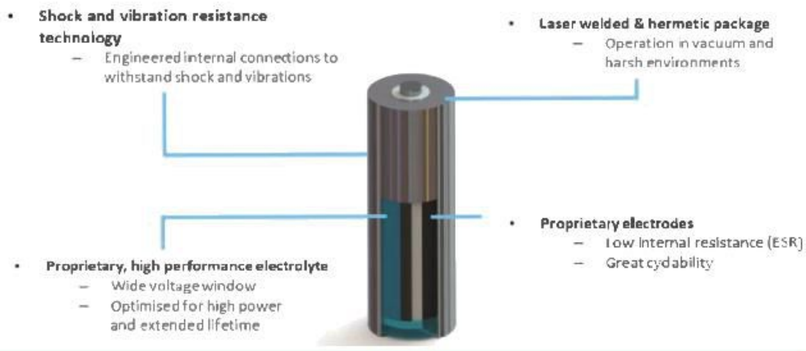

Figure 3. *Each cell part and process has been optimised for the downhole environment. Shown here are features necessary for survival in harsh environments.*

The design criteria are shown in Table 1. Here, voltage, discharge power, and discharge period are chosen to represent a generic load profile. The analysis can be used for a range of similar applications of varying voltage, power, and time.

ULTRACAPACITOR SELECTION

In this example, the maximum output voltage target is 12 V. It is possible to address this requirement by incorporating a DC/DC converter at the output of the ultracapacitor module to provide a fixed 12 V rail. In this way, the capacitor module does not need to directly support a full 12 V. However, the minimum output voltage is only 5 V. Using the formula shown below, the low minimum voltage enables a relatively high energy utilisation percentage making it feasible to use the capacitor module without an additional output DC/DC converter. If higher cell utilisation is required, a DC/DC converter can discharge the cells to an even lower voltage, converting more total energy.

$$\frac{V_0 - V_f}{V_0} = \frac{12^2 - 5^2}{12^2} = 83\%$$

The voltage rating for 150 ˚C capacitors begins at 1 V per cell. Thus, this design will require at least 12 cells connected in series. Given that the peak power of the discharge event is relatively low, how much energy is required will be considered first.

$$E = P_{discharge} * t$$

$$= 15*60$$

$$= 900\ J$$

The minimum capacitance can then be calculated using the following equation:

$$E = \frac{1}{2}C({V_0}^2 - {V_f}^2)$$

This equation demonstrates that the module must have a capacitance greater than 15.1 F. With 12 cells in series, each cell must therefore have a final capacitance of at least 71 F. It is important to adjust for degradation of the cell as it nears end of life. Most capacitors are rated for 1500 hours at their rated voltage and maximum operating temperature. At this point, capacitance is expected to have dropped by 30% while ESR will have increased by 100%. Therefore, the initial module capacitance target is adjusted up to 21.6 F. ESR of the capacitors will contribute to additional voltage loss throughout the discharge period. Therefore, for high current discharges, it is important to simulate the full discharge period considering resistance losses. Given a 12-cell module capacitance of 21.6 F, the single cell target capacitance is 260 F.

The cell that meets these requirements is the Nanoramic EE150-350 High Temperature FastCAP Ultracapacitor. The relevant specifications for the ultracapacitor are shown in Table 2.

It should be emphasised here that the module is being designed for a full 1500 hrs of operation. A typical moderate rate 8-cell Li-$SOCl_2$ module under the same power conditions would be expected to last ~45 hrs. The lifetime of the capacitor module increases exponentially as theoperating temperature or operating voltage are decreased from their rated maximum levels.

SIMULATION

A transient simulation is used to combine cell capacitance variations, ESR, leakage, and degradation. Other factors such as wiring harness resistance and protection diodes may be incorporated for more accurate results. Shown in Figure 1 is a simulated discharge at beginning of life and end of life. Even at end of life, the capacitor module exceeds performance specifications.

CHARGING CIRCUITY

For charging the ultracapacitor bank, a converter with output current regulation is recommended. The reason for output current regulation is that, when discharged, the capacitor voltage will be near 0 V but the series resistance can still be very low. Therefore, for an unregulated supply, such as a battery, or for a voltage controlled regulator, there is a danger of drawing too much current from the supply.

There are custom ultracapacitor charging IC's on the market, for example the Linear Technology LTC3255, that typically incorporate both charging and balancing for a small number of series capacitors. Alternatively, any current regulated converter IC will be suitable and can be adapted for much higher voltage and power operation. A large segment of these IC's can be found as LED drivers. One example that has been used extensively is the Linear Technology LT3791.

CELL BALANCING

Variations in the cell manufacturing processes and environmental exposure will lead to variations in capacitance, ESR, and leakage current between cells in the module. Generally, capacitance and ESR may vary by +/- 10% while leakage current may vary +/-50%. These parameter variations will inevitably cause the series connected cells to operate at slightly different voltages. Divergence will begin as a function of the initial variation between cells. However, cells that operate at a higher voltage will likely age faster than cells operating at a lower voltage potentially worsening performance variation as time continues.

Whether or not a module requires balancing is only answered with the expected performance and environment of the module. Generally, for modules that undergo many high power charge/discharge cycles, passive balancing will not suffice and active balancing is recommended. For modules that may be used for a voltage bus hold-up application or a backup energy supply, passive balancing may be suitable. In some rare instances, modules may take advantage of leakage rate characteristics to eliminate the need for additional balancing circuitry.

A typical rule of thumb for sizing balancing resistors is to maintain a balancing current through the balancing resistor that is 10x the expected leakage current. In this way, disturbances in cell voltage caused by leakage current can be compensated for by the balancing current.

Shown in Figure 2 are two plots showing simulations of a module with and without resistive balancing. Without balancing resistors, cell voltages diverge until eventually the rate of voltage decay for each cell is equal. With balancing resistors, high voltage cells are discharged and low voltage cells are charged to the nominal value. The cells will not reach exactly the same voltage as the leakage currents still vary from cell to cell.

SUMMARY

This example has simulated an ultracapacitor module for buffering generator output power. A power discharge of 15 W for 60 seconds was selected to demonstrate the capacitor's capability for providing sustained power for a full 1500 hours of operation.