Supercapacitors integrated into electrified drivetrains

Supercapacitor modules are increasingly featured in heavy transportation and commercial xEV drivetrains.

The automotive world is becoming more electrified through multiple different systems, including infotainment, advanced driver assistance systems (ADAS), active suspension and full drivetrains. This is driving a paradigm shift on how we think about the next generation of drivetrains, from small people movers to automobiles to large industrial transport and commercial vehicles. This shift is being driven by the desire for better fuel/energy efficiency, fewer greenhouse emissions, reducing the use of fossil fuels and advancing environmental sustainability. These benefits are pushing regulators to approve mandates on eliminating drivetrains with only traditional combustion engines as seen in California[1], New York City[2] and the Netherlands[3].

Other benefits include lower total cost of fleet ownership and improved performance in torque and responsiveness. This does not come without its set of design challenges resulting in consideration of different methodologies. The first is deciding on the powertrain topology to drive the vehicle, which we will discuss in this paper.

Powering Business Worldwide

Electrified drivetrain example

Electrified drivetrains are often segmented into Hybrid (HEV), Plug-in Hybrid (PHEV) and full Battery (BEV) electric vehicles. The replacement of the "x" prefix in xEV represents the classification.

Hybrids generally have an internal combustion engine (ICE), with fuel sources such as gasoline, diesel or compressed natural gas. This is paired with an electrical energy storage system (ESS), commonly a battery. Hybrids have their ICE as the primary energy source with the ESS as secondary energy source. Hybrids can be further segmented with mild hybrids not capable of full ESS propulsion while full hybrids capable of operating on just the ICE, ESS or both.

Plug-in Hybrids also have an ICE or fuel cell and an ESS. The ESS is designed to be the primary energy source, charged via external sources and driven initially in charge depleting mode. The ICE or fuel cell is the secondary energy source and provides range extension, typically charging the ESS. Once the ESS is fully discharged, the drivetrain operates in charge sustaining mode like a traditional HEV.

Battery electric vehicles have the ESS as the sole energy source and is plugged in to external systems to charge.

Selecting a topology

In selecting a topology for large commercial and industrial vehicles, different performance characteristics and certain tradeoffs are weighed and considered. A few of these would be fuel economy, energy efficiency, drive range, reliability, safety, cost and, ultimately, how the vehicle would be driven. Frequent start and stops would drive different decisions compared to long haul trips. Maintenance practices and operations could be factored in as these can be part of an overall cost of a fleet of vehicles for end customers. Having drastically different O&M practices can drive end user decisions one way or another when purchasing a new vehicle as part of their overall fleet.

In evaluating different energy storage technologies and systems, batteries, regardless of chemistry, have long been thought as the default choice to place on board in electrified drivetrains. Supercapacitors offer an alternative to batteries and can influence the aforementioned performance characteristics. This is due to the very low ESR, light weight, inherent reliability and safety, high efficiency and capability of millions of charge/discharge cycles. Low ESR and light weight offers very high power density. The millions of charge/discharge cycles translate into long lifetimes, up to 15 years. These features and benefits are reasons that supercapacitors are increasingly integrated into more xEV drivetrains.

Power and energy

To evaluate supercapacitors against batteries for the purposes of energy storage in xEV systems, it is key to understand some differences between the two types of technology. The first would be understanding power and energy. Both the power and energy delivery capabilities are very important characteristics to understand. Batteries are often investigated for how much energy they can store so in limited footprints in transportation, their energy density. This is often measured in kWh/L or kWh/kg. Higher energy density tends to provide longer drive range in PHEV and BEVs. Supercapacitors on the other hand are often investigated for how much instantaneous power they are capable of delivering, also called their power density or specific power. This is often measured in kW/L or kW/kg. A 3.0 V, 3000 F supercapacitor, a cell commonly used as a building block in large supercapacitor modules, offers a specific power of near 19,000 W/kg. Lithium iron phosphate, a Li-ion chemistry commonly found in xEVs offers roughly 200 W/kg.

An example of this can be visualized in Figure 1. The energy capacity is represented by the size of the tank while the power capacity is the size of the faucet. In this analogy, supercapacitors are exemplified by the smaller reservoir with large faucet, while lithium-ion batteries (LiBs) are larger reservoir with smaller faucet. Supercapacitors and batteries are compared by how much "water" they can store and how fast they can absorb or deliver it.

Batteries, no matter the chemistry, are more restrictive in the rate in which they can deliver and capture energy. High rates of charge, discharge and/or frequent cycling rapidly shortens the life. Supercapacitors are much less restrictive in how they are charged and discharged. Given these characteristics, there is a harmonious relationship in xEVs, taking advantage of energy dense batteries and the power dense supercapacitors to create a Hybrid Energy Storage System (HESS). The HESS discharges the supercapacitors during the times of high power requirements caused by vehicle acceleration and drawing energy in the batteries at a slower rate, offering improved battery life and potentially longer drive ranges. Similarly, during deceleration, greater amounts of energy are captured via the supercapacitors to reduce stress on the batteries while still saving energy. In HEVs, the higher power density can offer advantages in greater energy capture in regenerative braking, thereby providing enhanced fuel efficiency for the ICE.

Energy storage devices have a finite lifetime, regardless of technology. For batteries, this is measured against initial capacity (in Amp-hours) and ESR. For supercapacitors, this is capacitance and ESR, both measured against initial specifications. The number of discharge/charge cycles, duty cycle, temperature all affect lifetime for energy storage technologies. Supercapacitors, all things being equal, offer longer lifetimes when compared to batteries in both calendar life and number of cycles. By integrating longer lifetime devices, the iterations of replacing components in the ESS reduces the lifecycle costs of the vehicle, providing a lower total cost of ownership as the ESS is often one of the most expensive components of xEVs. The physical construction and electrochemical storing of charge provides superior reliability rather than relying on chemical reactions. This ensures more predictable performance over the lifetime of the vehicle and reduces the risk of unexpected ESS failures and abbreviated lifetimes.

The previously mentioned construction of supercapacitors also offers high stability using organic materials. The construction combined with the operation mechanics reduces the high risk of thermal runaway associated with batteries and provides a safety advantage. Eaton's supercapacitor modules are rated from –40 ˚C to +65 ˚C, resulting in the capability to be applied in a wide variety of climates, especially at the extreme hot and cold temperatures. This temperature range can also boost performance of the drivetrain as batteries traditionally cannot react as quickly in cold climates due to the slowing of the chemical reactions taking place inside the battery cells. The temperature flexibility of supercapacitors also provides the designer with more options in terms of placement in the vehicle.

While energy contained within the xEV ESS may be the first characteristics specified after evaluating the anticipated drive cycle, the lifetime, power density, reliability and environmental characteristics could drive different decisions. The benefits of supercapacitors in these areas are the reasons why they are increasingly integrated across the different xEV drivetrains. The rest of this document will cover how supercapacitors are integrated into different xEV drivetrain topologies. The potential benefits discussed will certainly vary depending on energy source specifications (ICE, battery and/or supercapacitors), the ambient environment and drive cycles.

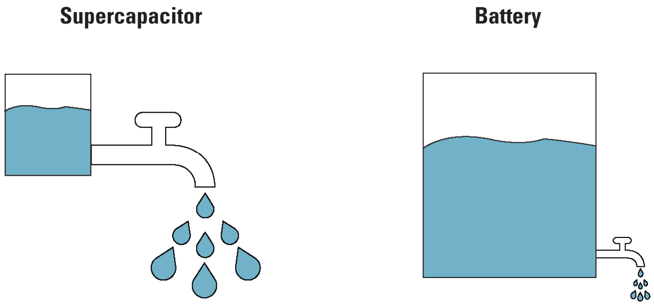

Figure 1. Supercapacitor and battery power and energy visualization example

Example of HEV and PHEV topologies

Parallel hybrid

A parallel hybrid topology is illustrated in Figure 2. This topology has an ICE placed directly in parallel with an ESS plus motor with the mechanical power of each delivered to the differential. In relating this to the classifications discussed earlier, this topology can be considered a mild hybrid or full hybrid depending on the size of the ESS. There are OEMs who have implemented low voltage systems, such as 48 V up to 125 V, for mild hybrid and higher voltages, up to 400 V, for full HEVs with predicted future systems at an even higher voltage. In this topology, the ESS captures regenerative energy and delivers power back to the drivetrain during idle and/or acceleration. With the ESS providing peak power, fuel consumption can be reduced during acceleration when the ICE is most inefficient. The greater the size of the ESS, the greater the improvement in fuel economy. This benefit must be balanced against the initial ESS cost. However, the ICE also can be downsized as the peak power required to be delivered by the drivetrain can be split between the two sources.

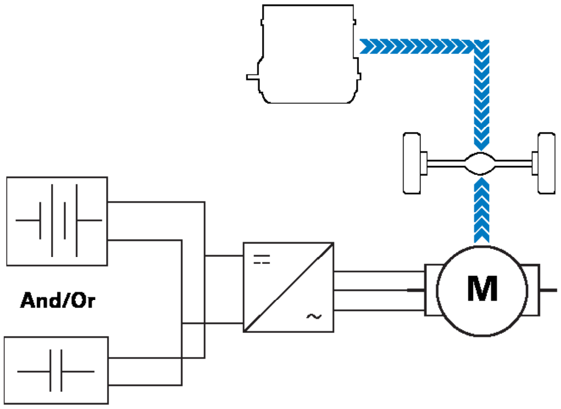

Figure 2. Parallel hybrid topology

The measure of ICE downsizing will vary upon desired overall acceleration, vehicle weight, various force losses of the vehicle (tire friction, aerodynamic drag, etc) and contribution from the ESS. In an example, Volvo has reduced the size of their ICE by 33 percent when integrating a parallel hybrid scheme in their buses. The combination of the power split between the two energy sources plus the ICE size reduction can reduce fuel consumption up to 30 percent, depending on the ESS size, drive cycle and ICE reduction. The more frequent the start/stop and the larger the ESS will contribute to higher fuel economy. By integrating supercaps in the drivetrain as the sole ESS or creating a HESS, higher peak power can be captured and delivered to the drivetrain due to the higher power density nature of supercapacitors. In comparing the different xEV topologies, the parallel scheme can be the least incrementally expensive path to electrifying drivetrains due to the lowest increase in number of components.

Series hybrid

In series hybrid topology, represented in Figure 3, an ICE, generator and AC-DC converter are tied into the electrical VDC bus that is shared with the ESS. In pursuing this topology, the ESS are generally designed to have enough energy capacity and high enough voltage to support operation in charge depleting mode for portions of a drive cycle and can be designed to be the primary energy source. This is especially the case if it has the capability to be charged externally (PHEV) where the beginning of the drive cycle will be in full electric mode. Batteries in this topology are desired to be energy optimized, or higher energy density, to improve the all-electric range (AER). One of the tradeoffs in using energy optimized chemistries is that power density is sacrificed in support of the higher energy density. Like the parallel hybrid topology, the ESS captures regenerative braking energy and delivers it back to the drivetrain during periods of load demand for higher efficiency. Adding in supercapacitors to the ESS to create a HESS can provide additional peak power cycling. To create a peak power supply (PPS), this supercapacitor integration can offer AER extension and higher energy efficiency through higher power density and lower resistance.

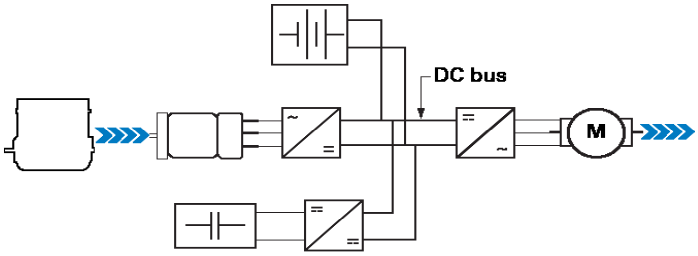

Figure 3. Series hybrid topology

The lower resistance of supercapacitors can reduce the heating impact placed on the batteries. Studies have shown this type of integration can extend the AER by up to 11 percent and improve energy efficiency in frequent start/stop drive cycles by seven percent. This can also lead to a 27 percent decrease in the average current from the battery, which can drastically extend its lifetime[4]. After this AER expires, the vehicle enters charge sustaining mode where the drivetrain is supplemented by use of the ICE. Just as in the case of the parallel hybrid, the ICE can be downsized as the required motor power is delivered from the DC bus that can be supplied from the ICE/generator, ESS/PPS or both. Alexander Dennis has reduced the size of the ICE on their series hybrid bus platform by 33 percent. As noted in the Figure 3, this topology does contribute to an additional number of drivetrain components when compared to a parallel hybrid. However, a series hybrid can contribute to higher fuel economy given larger energy and power capacity from the ESS, especially in the case of a PHEV with an AER. This topology can also allow for the possibility for the ICE to charge the ESS, which can help alleviate issues with electric range anxiety that can accompany a full BEV.

Power split hybrid

A power split hybrid, example shown in Figure 4, can be considered a PHEV or full HEV and similar in performance to a series hybrid topology in that there is a generator tied to the ICE for electrical energy, but the ICE can deliver mechanical power directly to the differential with the addition of the continually variable transmission. This topology is more common in passenger vehicles and currently has not been widely adopted for larger commercial vehicles. Therefore, we will not cover it in extensive detail.

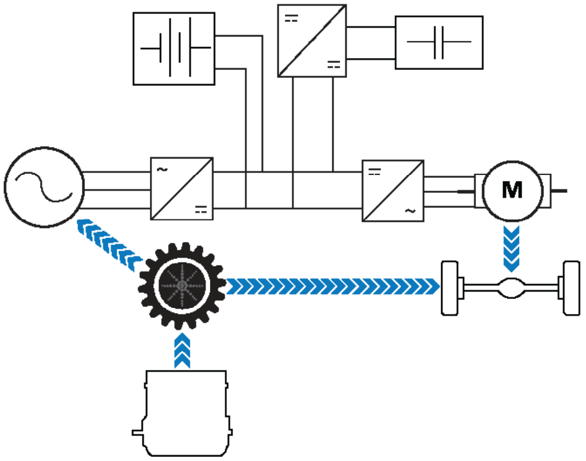

Figure 4. Power split hybrid topology

Examples of BEV topologies

Passive BEV using a HESS

The first of two full electric, but hybridized drivetrains discussed in this paper is shown in Figure 5. This topology is known as a Passive BEV using a HESS. The passive nomenclature is chosen as this topology requires that the charge voltages of the battery and supercapacitor should be equal. The two storage devices will charge and discharge at different rates during the drive cycle due to their inherent resistance and responsiveness differences. However, they will eventually voltage balance themselves with equalizing currents due to those same features. This balancing does not infer that they equalize in terms of energy. In this topology, the battery is desired to store more energy than the supercapacitors and leverage the lower resistance of the supercapacitors to respond and deliver greater amounts of instantaneous power during acceleration. The balance of power would be delivered by the batteries, but at a much lower current, until the vehicle is up to speed and overall power demand is reduced.

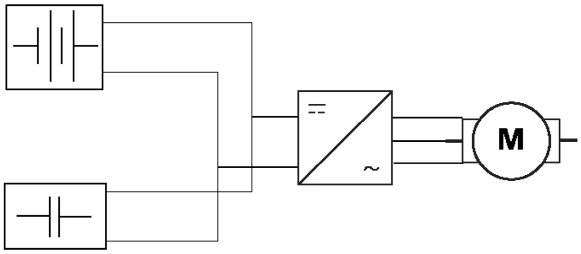

Figure 5. Passive BEV using a HESS topology

By reducing the peak current of the battery, the supercapacitor can help offer lifetime extension of the entire HESS. Inversely, during periods of deceleration and regenerative braking, the lower resistance and higher charge efficiency of the supercapacitors captures more power than batteries alone. The combination of these two factors has been demonstrated to provide a seven to eight percent improvement in driving range for frequent start/stop drive cycles and an eight percent improvement in overall energy efficiency[5]. The passive HESS systen results in a 6.2 ˚C decrease in battery temperature which extends the life of the battery by 1.5x due to peak current reduction plus heat reduction impacts.

Active BEV

The second drivetrain covered here is an Active BEV, shown in Figure 6. In this configuration, the passive HESS topology is modified by placing power electronics (i.e. a bidirectional DC-DC converter) between the inverter and the supercapacitors. This is an active system in that the control logic programed into the DC-DC converter should be designed to control which energy storage delivers and captures drivetrain energy. In this topology, it is desired to lower the supercapacitor voltage compared to the passive system by limiting the number of modules in the string; the battery voltage is not impacted. This lower supercapacitor voltage helps ensure the drivetrain maximizes the effect of the low ESR of the supercapacitor. Adding supercapacitors in series can maintain the same power specifications and incremental benefits can be studied and seized. For example, in Figure 6 below, there is only one supercapacitor and DC-DC converter string. This by itself will provide range extension, energy efficiency and battery lifetime extension benefits. By adding another string in parallel, incremental range, efficiency and lifetime benefits can be added. This process can be repeated until there are diminishing marginal returns due to the added equipment costs outweigh the range, energy and lifetime benefits.

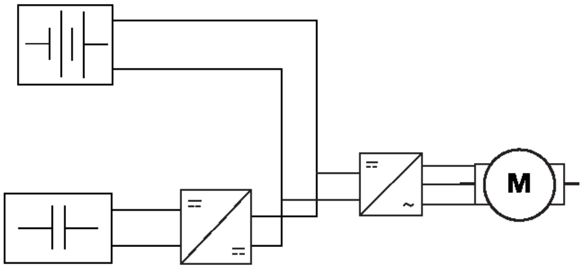

Figure 6. Active BEV topology

This type of topology has demonstrated a range extension of seven percent compared to a battery only system and improved energy efficiency by 16.2 percent in frequent start/stop drive cycles. With the addition of the DC-DC converter, the output current can be reduced due to the boosted voltage. During supercapacitor discharge in a constant power application, the voltage follows a decreasing slope while current increases. In a passive system, this increase in current flows directly to the inverter with its own power dissipation. When an increase in current occurs, the power dissipation increases by its square, P=R*I2 (where P is power, R is resistance and I is current). Therefore, maintaining a constant voltage in this application can provide higher energy efficiency. The DC-DC converter can help provide this voltage stability from the supercapacitors.

This topology can also contribute an 8.8 ˚C drop in temperature when compared to a battery only system. Due to the ability of the logic to control the frequency of equalizing currents between the batteries and supercapacitors, battery cycling can further be reduced. Utimately, adding supercapacitor modules can contribute up to a 3x extension in battery lifetime, potentially matching the lifetime of supercapacitors, while also dramatically improving the total cost of ownership when purchasing large fleets. The overall impact of this depends on the time constants within the logic.

Batteries rely upon chemical reactions to deliver the stored energy. xEV energy storage devices, no matter the technology, degrade over time in energy capacity and resistance. Research indicates that at colder temperatures (<=10 ˚C), batteries alone may not be able to power the entire designed drive range. Integrating an HESS with supercapacitors is essential to maintain vehicle performance[6]. These improvements ultimately make xEVs more cost effective to operate.

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