Pb Battery and Super Capacitor Power Supply Combinations for High Performance Electric Vehicles

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Introduction: Electric vehicles (EV) performance is largely related to the power capability of the traction or main battery and will be referred to as the power supply (PS). Lead acid batteries are readily available, but newer battery technologies have increased current EV performance while electronic power circuits are becoming more efficient. Capacitors used in power electronics can store larger amounts of energy from those available only a decade ago. A hybrid of power supplies could be used to increase the acceleration of electric vehicles because power electronics could enhance, with increased efficiency, the power needed in performance applications [1].

The Lead Acid (Pb) Battery: Pb batteries are available in two different design and application categories: The design types are flooded (also known as spillable, wet-cell, or vented) and the other is non-flooded (sealed, non-spillable, non-venting, or AGM) batteries. Maintenance free battery titles in cars are normally associated with flooded batteries as non-flooded is maintenance free. Flooded Pb batteries are the lowest cost and are somewhat tolerant to overcharges and deep discharges. One problem with flooded Pb batteries is the deposit of sulfuric acid on the roadway if damage occurs and EV motorcycles are not allowed to use flooded batteries on a race track. Non-flooded batteries are required for EV racing. Current designs of this battery use an absorbed glass mat (AGM), while gel cell designs are being phased out of production.

The major application categories for both flooded and non-flooded are starter (also called cranking) or deep cycle batteries. Most low cost, commercial off-the-shelf (COTS) flooded batteries are starter batteries and sometimes referred to as SLI's (starting, lights, and ignition batteries). Starter batteries are designed with a higher number of thinner parallel plates so the internal resistance is lower. More instantaneous current, or power, is available but with poor long term amp hour drainage known as energy. A deep cycle battery has thicker but fewer plates which increases the available energy at lower discharge rates along with higher internal resistance. Electrical DC circuits offer maximum power transfer when the source (PS) resistance is equal to the load resistance. Figure 1 illustrates how internal battery resistance effects power transfer.

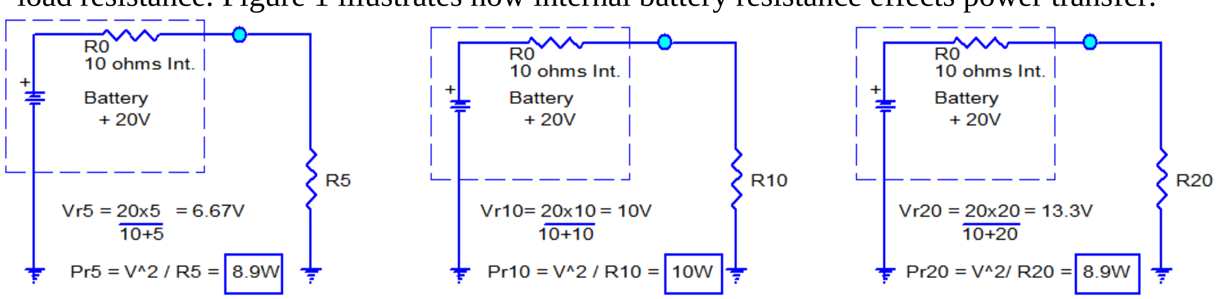
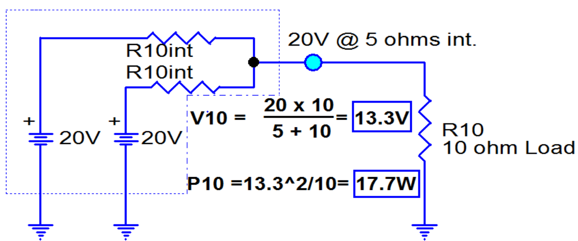


Fig 1: 5 Ω, 10 Ω and 20 Ω loads with a 20 V, 10 Ω internal source power supply.

A 20V battery with 10Ω of internal resistance is connected to various loads of 5Ω, 10Ω, and 20Ω. Using ohms law, the 10Ω load in the center schematic offers the highest power dissipation of 10W. The Pb battery will offer all the power capable from that battery which is *approximately* ½ the rated terminal voltage as it approaches maximum power transfer which in this case is 10V under load. Some Pb battery designs can tolerate this amount of voltage drop longer than others. This operating condition will reduce the battery's life cycle, as noted from several test runs over an EV racing season. Increasing amp hour rating (AHr) requires more cost and added weight but some reserve capacity to prolong the life cycle of batteries is desirable. Adding another battery in parallel (**Fig 2**) lowers the PS internal resistance in half (5Ω). Applying ohms law to the new battery with the same circuit does increase the power to the load by maintaining a higher minimum voltage from the battery of 13.3V ($V_{Load} = ((V_{Bat} \times R_L) / (R_{Bat} + R_L))$). Power is equal to E^2/R; therefore power is higher than 10W, but is short of doubling at 17.8W. Maximum power would have occurred with a 5 ohm load. With the added Pb weight and less than doubled power increase with a constant load, the real world performance increase seems less than would have been expected by paralleling batteries.

Fig 2: Adding second battery in parallel to increase current rating of PS.



During EV test with 144V of Pb dropping to 72V at start, the ¼ mile recovery voltage was 115V. A 50% voltage recovering to 80% impedes the top end speed when motor HP is dropping; an increase of 10 MPH from eighth to quarter mile was measured [graph 3].

Ways to offset the extreme voltage drop with Pb batteries during acceleration:

- Start with a higher PS voltage while using a voltage limiting circuit to the motor.
- Add additional batteries and switch-in series parallel arrangements.
- Prevent the motor from drawing large currents at the start with current limiting.
- Provide a hybrid power supply source.

Adding an extra PS could be used to offset the maximum current capability of the Pb battery. An analysis of other lighter, lower impedance batteries designs in parallel combination with Pb shows promise. This would reduce the total cost of an EV conversion if newer technology batteries, like Li-Ion, were placed as a hybrid PS. Another possibility is to use lightweight, higher current capacity electrolytic capacitors.

The Super Capacitor: Capacitors in some ways are like batteries and with an equivalent series resistance (ESR). Standard electrolytic capacitors are not suitable for high current (> 100A) applications as they have higher ESR values. Very low ESR capacitors are known as: ultra-capacitors, electric double layer capacitors (EDLC), or supercapacitors. Their typical ESR ranges from 3mΩ to 0.3mΩ. Supercapacitors currently have a maximum operating voltage of approximately 2.5v +/-0.3v.

Calculated operating currents range from 200 to 2,000 amps, which is two to ten times higher when compared to Pb batteries of the same size. Supercapacitors can also tolerate a higher number of discharges, in the order of 500,000 or more [2]. The cons though are higher cost (3 to 6 times the cost of LiPo cells) and low energy density as compared to batteries. The amount of room to carry the supercapacitors required could be a problem for small vehicles.

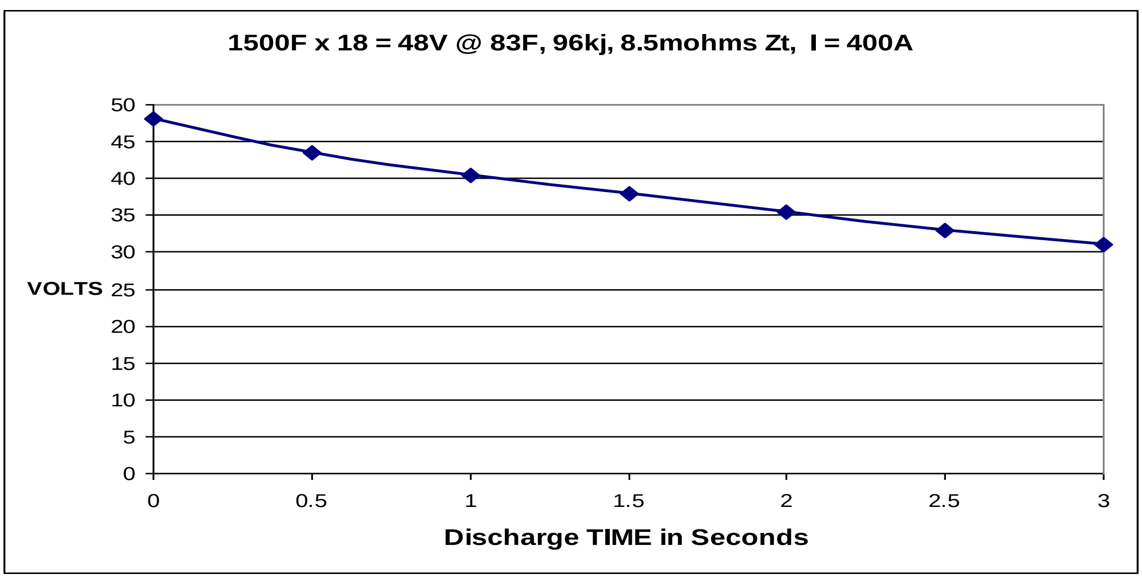
Capacitors have two major ratings: voltage and capacitance (storage size measured in Farads (F)). A 10F capacitor in the 1960's could have been as large as a living room. Using nano technology and carbon, scientists have increased the surface area 1000's of times to increase capacitance. Currently a 10F capacitor is the size of a short stack of dimes. Due to this increase in surface area, the plate distance has become very thin (a capacitor is two plates separated by a dielectric), which lowers their voltage rating. Several manufactures are producing supercapacitors well over 500F [3] [4] [5]. Tested were a variety of 650F, 1500F and 2600F supercapacitors. The formulas in figure 3 were used to calculate the performance of the capacitor bank. Calculations show about 10 times less energy than a Pb battery but 20 to 80 times more power. Capacitor storage power is generally used before the first time constant which is found from t=RC. The first EV test required a 48V PS with a 400A average load current for 3 seconds. A 1500F capacitor was selected which is specified to have 0.63mΩ ESR and 13.2 kW/kg [3]. A bank of 18 series connected supercapacitors with a total C of 83F was needed to provide a 36% voltage drop (48V to 30V) to the 3 second mark as noted in Graph 1.

Fig 3: Formulas

Graph 1: Discharge Rate

$$Ct\,series = \frac{1}{\frac{1}{C1}+\frac{1}{C2}+\frac{1}{C3}} \qquad dv = i*\frac{dt}{C}+i*R$$

$$Weff = \frac{1}{2}C*(V_{max}^2 - V_{min}^2) \qquad Peff = \frac{1}{8}*\frac{V^2}{R}$$



Power Supplies with Supercapacitors were analyzed in the following PS systems:

- Placing capacitors permanently in parallel with the main batteries.
- Start with Capacitors then disconnect from motor a short time later.
- Capacitors in-place of batteries as the only PS.

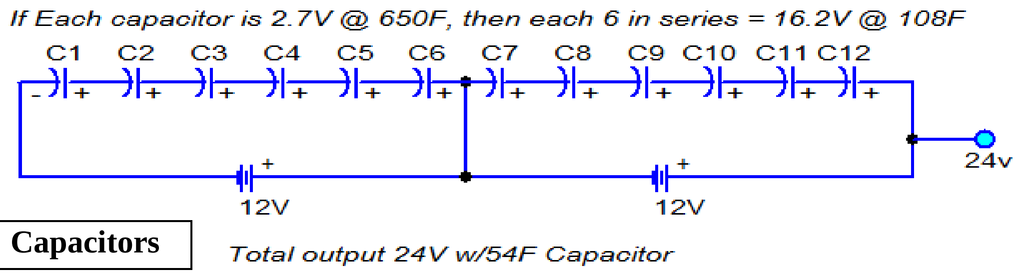


Fig 4: Capacitors

Using supercapacitors in parallel w/Pb solved many charging issues as they were charged along with the 12V batteries (**Fig 4**). Six capacitors placed in series totals a maximum voltage of 16.2v which is high enough protection from battery over charging. The problems occurred later in the ¼ mile, when the batteries will also try to recharge the depleted capacitors. Another issue in higher voltage systems is total series capacitance is decreasing (Fig 3) due to the number of capacitors needed to match the main battery voltage. Removing the capacitor bank from the main battery at some calculated time later did increase performance. Adding a SPST relay produced improved results and a basic system schematic with a capacitor balancing circuit is shown in figure 5.

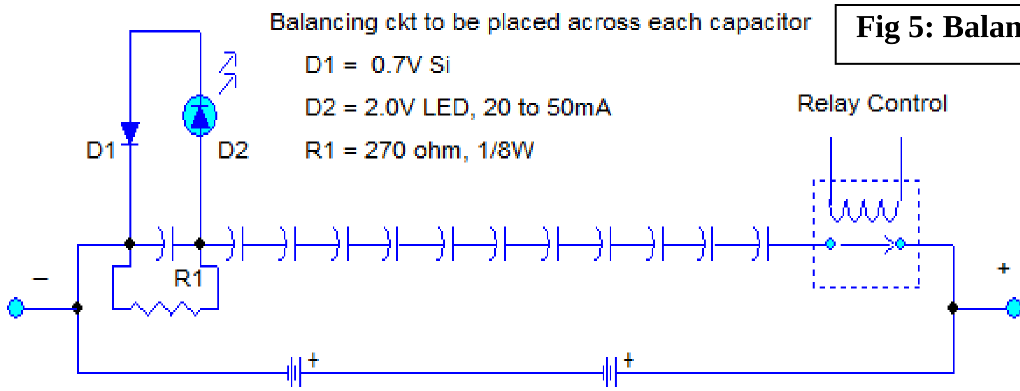


Fig 5: Balancing

Capacitor Balancing: With the operating voltages near V_{MAX} a bleeder current is needed to equalize the capacitor voltage drops. Passive circuits work but are 5% less efficient than active balancing circuits [6]. For racing applications the stored energy is used in a manner of seconds so passive circuits meet our goals. With 270Ω resistors placed across each capacitor, a maximum bleeder current of 10mA will flow. Adding the LED (D2) and a 1N4001 diode (D1) will require 10mA to 25mA of bleeder current at full charge and a brightness indication of the charge level will appear as compared to the rest of the LED string (**Fig 5**). A zener diode may also be used but a string of Si rectifier diodes provided greater voltage regulation (4 series Si diodes = 2.8V). The capacitor bank is switched “off” during storage or else battery drain will take place.

Shown is figure 6 is another EV power circuit. The motor starts only with capacitors. After 2 to 3 seconds, the capacitor circuit would switch out and batteries switched in using a SPDT high current relay (S1). The capacitor bank was charged to 32V and increased to 240F, this easily provided 1000A of starting current. Once the EV motor was near max speed on the draining supercapacitors, the main battery was switched for the remaining power. A small 15AHr Pb battery pack was used. With this arrangement, the capacitors could be at a much larger voltage differential compared to the main PS battery voltage. Care is to be taken not to allow the two voltages to be connected in parallel.

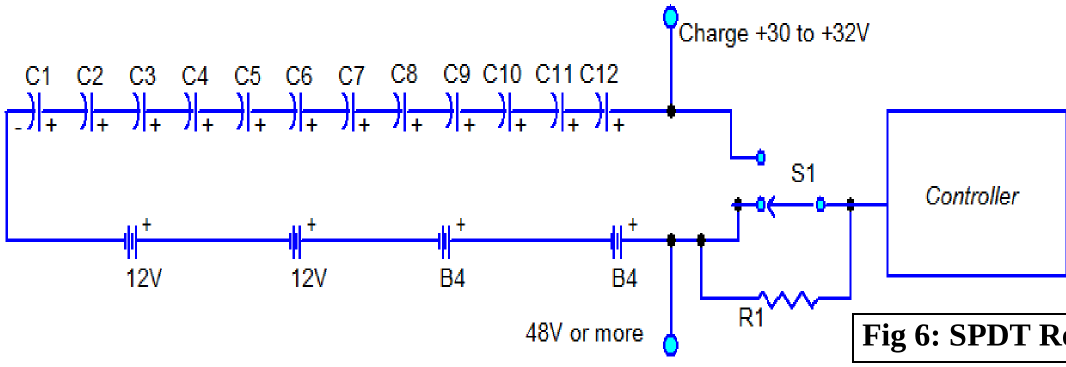


Fig 6: SPDT Relay

A problem arose with the PS switching method in figure 6. Two different motor controllers experienced a dead power zone of up to 3 seconds when switched. This was due to the motor controller experiencing a PS interrupt during the SPDT relay switching time. The solution was to provide a higher constant current for the controller voltage input on the battery side of the SPDT relay. For voltages of 120V or less, a 20W 1000Ω resistor is used for R1. This provided 100 to 250mA of bleeder current for the controller circuitry to remain active in relay transition. R1 does provide a current path for the capacitors to receive charging from the higher battery voltage when switched in. However at this current level, not enough time is allowed for the capacitors to experience an over charge state during racing applications. The self discharge rate of supercapacitors along with their balancing circuits almost cancels out this trickle charging current through R1. In any case, the capacitor bank is only switched into the controller circuit just before the race. After it is depleted of useful energy it is switched out and remains out of the circuit until recharge for the next EV testing.

Another circuit which eliminated current flowing back into the capacitors after discharge is the installation of a high current blocking diode (**Fig 7**). This arrangement tested satisfactory in low current circuits but was not tested in the motorcycle. Diode (D1) would have 2 times the PIV and current rating as needed for safety. The capacitor and battery could be charged at the same potential. This circuit does away with the high power relay.

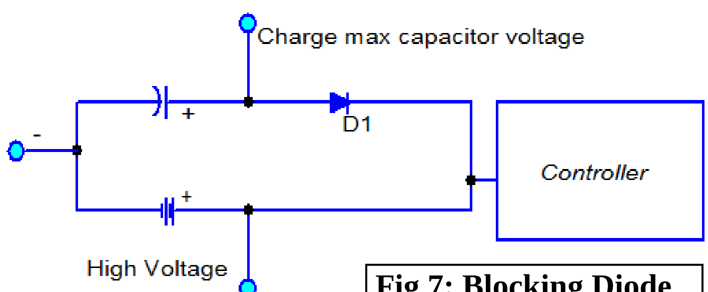
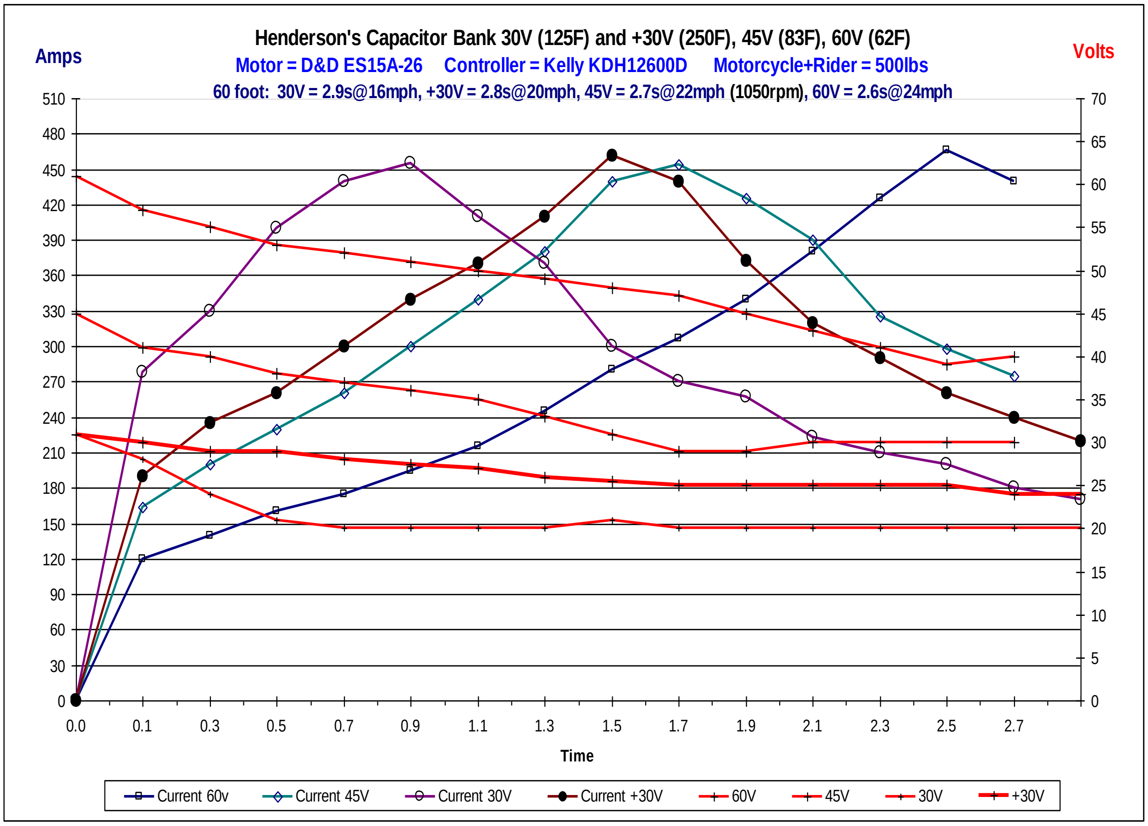


Fig 7: Blocking Diode

The last PS experiment used only supercapacitors (no batteries), much like the BYU team did with their EV1 project [7]. Preliminary analysis: near endless lifecycle, reduced total PS weight, and no need of a battery management system (BMS). Several capacitor arrangements were tested. A high constant voltage-current supply was used for charging. One capacitor configuration used 60V @ 50F and switched after 3 seconds to a 54F @ 120V bank. It took 25 minutes to charge and was sufficient for one ¼ mile test run. The capacitor banks provided favorable 0-60 foot acceleration times.



Graph 2: Capacitor only Power Supply Test, 0-60ft under 3sec power times

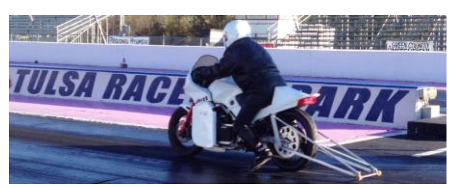
Zero to 60 foot acceleration using Supercapacitors: Graph 8 illustrates several PS measurements using supercapacitors. Voltage and capacitor combinations were: <u>30v @ 125F</u>, <u>+30V @ 250F,</u> <u>48v @ 83F</u>, and <u>60v @ 62F</u>, also shown are the corresponding battery current curves for 0 – 60 foot starts which were all less than 3 seconds each. Maximum battery current peaked at 470A. Lower voltages developed battery current sooner than the higher voltages although the quickest times occurred at higher voltages. Interesting to note is the current limiting/delay of two commercial controllers tested from standing start as the voltage is increased. These controllers would not allow a 0 – 60 foot time faster than 2.4 seconds with the PS tested. When a third higher performance controller was evaluated, a rapid current draw was noted with all voltages and a reduction of 0.3 seconds in 60 foot time was measured. The best ¼ mile time was two series strings of BCAP1500 (totaled 50F) at 75V and SPDT switched to BCAP0010 (totaled 54F) at 115V. All configurations are listed in figure 8.

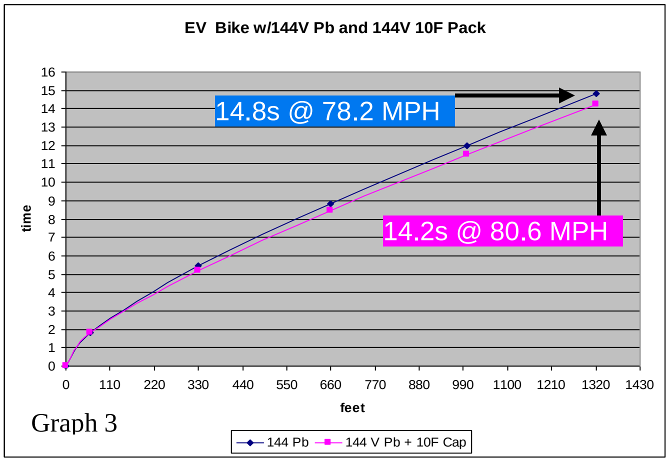
Other battery combinations tested: NiMH batteries could benefit from a capacitor support circuit but not if operated in parallel. NiMH batteries load voltages are to remain above ½ cell voltage. Li-Ion benefits from paralleled supercapacitors are even less as the lowest voltage operating point is well above ½ cell voltage to prevent battery damage. Current LiPo batteries are smaller with about one half the power and 100 times the energy density as compared to supercapacitors as seen in chart 1[8]. From PS data taken in performance applications, it was not beneficial to use supercapacitors in the new LiPo system. A unique chemistry occurs with NiCd batteries. NiCad's battery voltage can be reduced to zero and recharged again without battery damage. A paralleled supercapacitor could complement this battery characteristic although NiCad's are being phased out of production due to environmental hazard concerns. NiCd batteries have one of the highest current discharges rates.

Conclusions: Supercapacitors offered 5% higher performance in conjunction with Pb batteries for the TCC electric motorcycle when used for drag racing (Graph 3). The capacitor/Pb hybrid battery set one National Electric Drag Racing Association (NEDRA) record in the street conversion class [9]. Depth of battery discharge or state of charge (SOC) was conserved using capacitors in a hybrid PS system and extended battery life during a racing season. Capacitor bank space, high cost, and low energy density are the major disadvantages of using supercapacitors as the primary power source. There was not enough capacitance to maintain the needed voltage in the area available on a motorcycle chassis. Supercapacitors combined with car EV's using regenerative breaking would be a great asset to battery life with any of the above battery chemistries.

Fig 8:
Left and Center: 48 x 2600F caps = 120V max @ 54F placed inside the 1986 Honda VF500 frame. Pictured right is the last bank tested which were 60 x 650F caps = 163V max @ 10F. This Supercap (mounted above the back wheel) was used in hybrid with a bank of 144V Pb batteries.

***TCC EV Capacitor Testing History*: Fall of <u>2008</u> - 32V @ 25F in parallel with 24V Pb.**
<u>2010</u> - 32V @ 54F switched in/out with 70V LiFePO.
<u>2013</u> - *Capacitor only* 75V @ 50F followed with switching in a 120V @ 54F bank (1/4 mi 16sec).
<u>2014</u> – Switched to a *capacitor hybrid PS*:
144V Pb and a 163V @ 10F bank switch in/out (best 1/4 mi 13.7s). Bike weighed 550lbs w/Pb.
<u>2015</u> – LiPo's+Pb





Graph 3

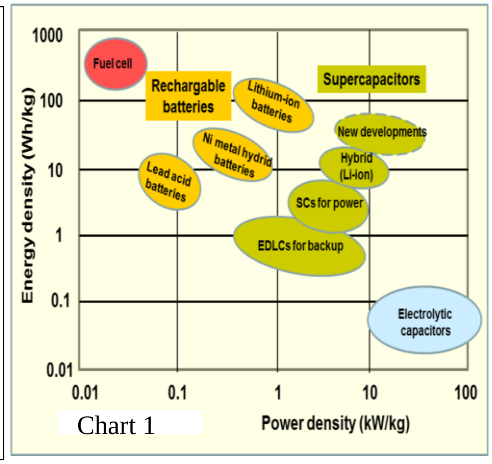


Chart 1

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