



WHITE PAPER

ENGINE COLD STARTING

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Introduction

The application of ultracapacitors to internal combustion engine cranking is being offered by several after market vendors and is being investigated by several OEM's. The primary advantage of ultracapacitor (UC) assisted engine cranking will be a brisk and sound start. Compression ignition (CI) engines, most commonly referred to as "diesel" fueled engines, are more difficult to start at cold temperatures because the engine friction levels are higher due to significantly increased viscosity of the lubricating oil, tolerance creepage due to low temperature, and higher breakaway friction after longer stand times because the lubricating oil tends to drain from journal bearings, piston oil rings, and valve actuation gear. At 29 °C (20 °F) the engine viscous friction can easily be twice the friction level at 0 °C and at 40 °C as much as three times higher. The combination of effects is that at cold temperature the cranking torque to "breakaway" the engine crankshaft is dramatically higher than at 0 °C.

The lead acid batteries used for engine cranking tend to have higher internal resistance at cold temperatures. From 0 °C to 40 °C the lead acid battery internal resistance, mainly from electrolyte effects, can be as much as ten times higher. This increase in internal resistance results in the battery having far less capability to discharge the high currents necessary to adequately crank a cold engine. As the lead acid battery ages the internal resistance increases further and its ampere hour (Ah) capacity decreases. These two factors contribute to reduced cold cranking current and reduced ability to sustain this current during extended engine cranking. This is also why it is so important to maintain clean and robust mechanical connections to the battery terminals. The Society of Automotive Engineers (SAE) standard J537 covering storage batteries specifies cold cranking tests at 29°C (20°F) and at 18°C (0 °F). High temperature testing is done at +27 °C (80 °F). These same temperatures are assumed for the UC.

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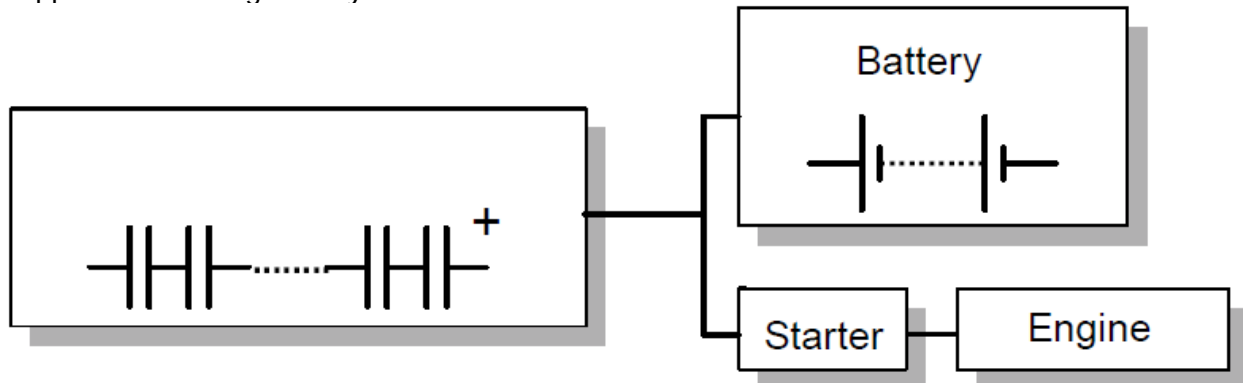
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The following figure illustrates how Maxwell Technologies BOOSTCAP®s can be connected to support the starting battery.



The following installation recommendations should be followed:

- Locate the ultracapacitor module (BOOSTCAP® in the illustration) as close to the starter motor as possible. Typically mount the module to the vehicle chassis frame rail near the starter.
- Use heavy gauge copper cable of the same size as used from the battery tray to starter motor via a high current contactor.
- Insure that all terminations have good mechanical connections and that cables are secured to the chassis members to provide strain relief during vibration encountered during driving.
- Depending on ultracapacitor type it may be necessary to observe proper orientation of the pack as well as proper polarity connections.
- Insure that the measured terminal voltage of the ultracapacitor is within 2V of the battery terminal voltage to minimize equalization currents and arcing. Always connect to the ultracapacitor last so that any connection sparks are well away from the battery vents.

Engine Cranking

The behavior of engine cold starting can be illustrated by referring to the chart below on the left that illustrates the differences between a modern inline 4 cylinder and V6 engines having displacements in the 2 to 4 liter range. When engine lubricating oil temperatures drop below 0 °C the required cranking torque begins to rise rapidly with decreasing temperature. Truck

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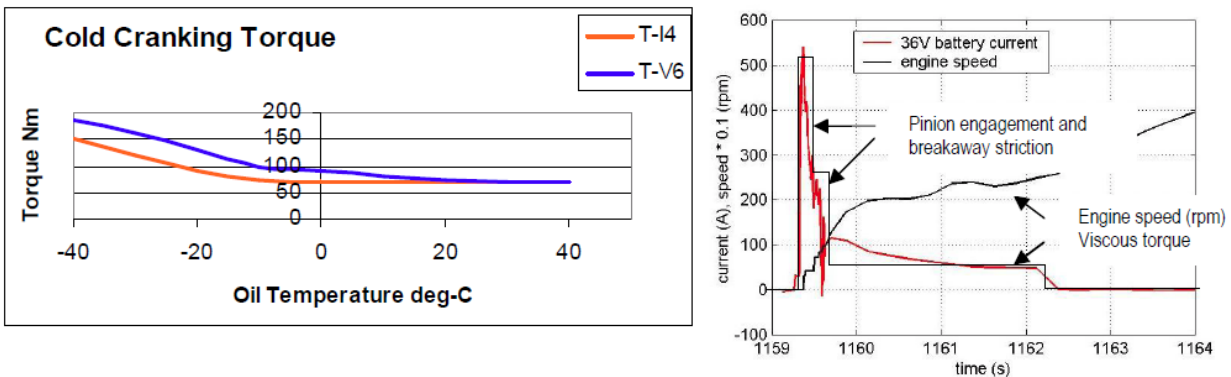
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manufacturers address this cold starting behavior of engines through specific cranking motor selection along with pinion gear and engine ring gear ratio. The need however is for engine cranking speeds that are sufficiently high to insure fuel ignition (80 to 200rpm). With ultracapacitors the cranking speeds are higher due to higher voltage being applied initially to the starter motor. With an ultracapacitor cold starting aid the starter motor current will start high and slowly taper to lower values as the capacitor becomes discharged and the voltage it can maintain on the starter motor terminals starts dropping linearly.



The right hand chart above shows three distinct regions during engine cranking and starting. In region 1 where starter motor current exhibits a high inrush magnitude (1 per unit = 500A in the chart) the pinion gear is being driven into the ring gear. Engine speed is at zero. Following this is region 2 at about 40% of the peak inrush current during which time the engine crankshaft "breaks-away" and makes its first rotation. In this region the cranking motor must deliver high torque in order to exceed the engine striction. During region 2 engine speed begins to ramp up. The final region 3 is a sustaining region wherein the engine viscous friction limits cranking speed until the fueling system engages and first firing causes the next stage of engine speed ramp up. Region 3 is characterized by starter motor currents of about 20% the peak inrush current and tapering to lower values as the lubrication system (oil pump) begins to Circulate oil and further reduce viscous friction. Engine cranking times in the modern engine during cold cranking will be below 1.5s for 99% or higher percentage of the cranking events. Ultracapacitor cold starting aides are being designed for 1.5s sustained discharges at specified power levels described in the next section. Unlike battery standards, the ultracapacitor standards do not specify starter motor voltage at the end of 1.5s, only that the specified power will continue to be available.

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Definitions

The following definitions are excerpted from the EIA/KFI draft standard and should be treated as definitions to clarify the terminology distinctions between ultracapacitors and battery language. It is very important that these distinctions be clearly understood because ultracapacitors are so much more energetic than batteries that misunderstanding can lead to misuse and misapplication of the intent of this standard.

Cold Cranking Power (CCP)

Maximum average power the capacitor system at 18° C can deliver during the first 1.5 seconds it is applied to a load, or until it reaches one-half its rated voltage if this occurs in less than 1.5 s.

Cold Peak Power (CPP)

Maximum instantaneous power that the capacitor can deliver at 18° C (0° F)

Cranking Power (CP)

Maximum average power the capacitor system at 0° C can deliver during the first 1.5 seconds it is applied to a load, or until it reaches one-half its rated voltage if this occurs in less than 1.5 s.

Electrochemical Capacitor (EC)

The EC is a two terminal component and its associated hardware that can store and deliver electrical energy with voltage decreasing in almost a linear fashion with charge removal. ECs used for engine cranking generally offer very high power performance and usually exceptional cycle life. Various designs and many sizes exist with different levels of performance. Nevertheless, all can be tested using the cranking standards described in this document.

ECs should be considered polar, that is their terminals must be properly connected. They usually have the ability to be discharged to zero volts and be maintained in this discharged state indefinitely with one exception. The exception is a type of EC that has a minimum voltage above zero that is specified by the manufacturer.

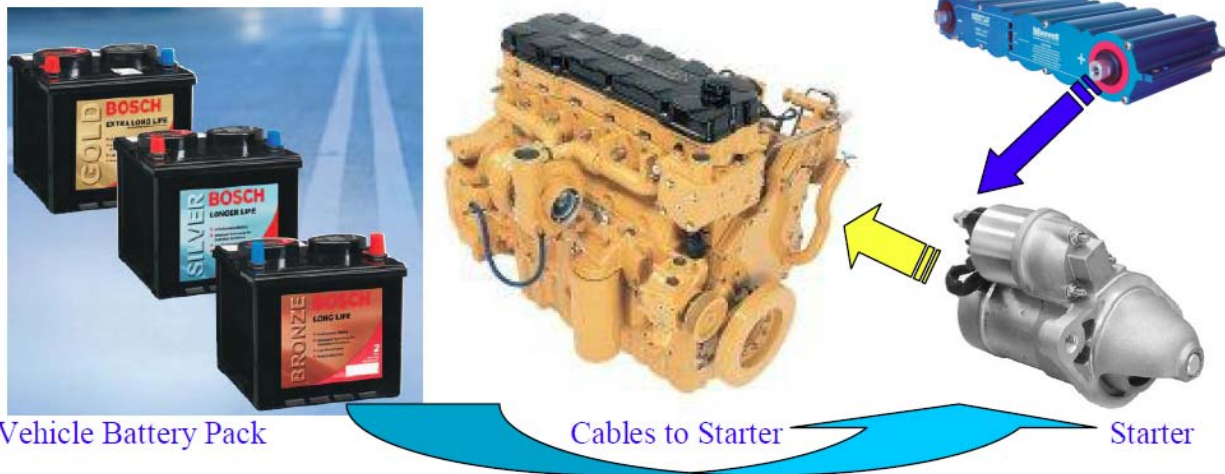
Let's augment these definitions with some further clarification. First of all, ultracapacitors are power dense components so their ratings as listed above are presented in terms of power, not energy. Batteries on the other hand are energy dense components with ratings that reflect their storage capacity in terms of Ah and cranking ampere's. Secondly, the new term Electrochemical Capacitor (EC) should be explained. EC is more general than ultracapacitor and includes the class of super-capacitors that are basically half battery and half capacitor, call them a pseudo-

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battery. Remember, EC is the general class of capacitive storage devices that includes capacitors having some battery like capability (super-capacitors) and those that are purely electrostatic storage devices (ultracapacitors UC). The UC is a symmetrical carbon electrode component that has identical anode and cathode electrodes. This is unlike the battery which has lead and lead dioxide electrodes. Batteries and super-capacitors (EC's) are polarized devices and proper polarity connections must be observed. UC's to a large degree are non polarized components, but have polarity markings added during manufacturing that must be observed. In all cases, EC's and UC's alike, and especially batteries, one terminal is marked with a "plus" and the other "minus". Proper connections must be maintained and voltages should never exceed the module rated voltage. For example, a 16V UC module for application to a 12V battery system requires higher voltage rating because the vehicle system voltage under battery charging conditions can reach 15V during cold temperature charging.

Typical Installation

Let's examine the installation of the ultracapacitor into a typical CI engine equipped vehicle.

**Ultracapacitor Pack
Close to Starter Motor**

The most important aspect of the illustration above is cable length and termination quality. To appreciate this fact consider the resistance of copper cable in Ohms/foot:

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Cable Size	4/0	2/0	1/0	2 AWG	4AWG
Resistance, mΩ/ft	0.051	0.081	0.129	0.162	0.258
Resistance of 12 feet of cable	0.611	0.972	1.54	1.944	3.1
Voltage drop across 12' at 1000A current	0.611V	0.972V	1.54V	1.944V	3.1V

Therefore, each 12' section of 4/0 (four-ought) cable represents over a half volt potential loss when carrying 1000A to the starter motor. This is very significant because a battery pack connected to the starter motor requires two of the cables for a combined potential loss of 2.2V.

If smaller gauge cable is used the loss is even higher and consequently the ability of the starter to spin up the engine is heavily compromised.

In some vehicle applications there may already be an aftermarket cold cranking aide installed. Typically these aftermarket units will be the electrochemical capacitor (EC) variety. These Pseudo-battery components do have orientation constraints because of the liquid (acid) electrolyte and the type of terminations (posts). In such a case where the BOOSTCAP® module is being used to replace an EC the prior orientation requirement does not apply. The BOOSTCAP® is a symmetric carbon capacitor and it does not have such a mounting restriction. However, it is important that the BOOSTCAP® be mounted as close to the starter motor as practical.

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Let's contrast these ultracapacitor engine cranking requirements and definitions with existing battery standards and terminology [2]:

- **Cold Cranking Amps (CCA)**
 30 s cranking current with voltage > 7.2 V at 18C (A)
- **Cranking Amps (CA),**
 30 s cranking current with voltage > 7.2 V at 0 C (A)
- **Reserve Capacity (RC)**
 25 A discharge time to 10.5 V at 27° C (minutes)
- **Capacity**
 C/20 discharge to 10.5 V at 27° C (Ah)

Ultracapacitor cold starting aides are specified to deliver prescribed amounts of power for 1.5s duration. During this time the ultracapacitor terminal voltage will decrease and with this the starter motor cranking speed. Installations will therefore be sized so that initial cranking speeds are higher which in turn guarantees higher probability of engine firing and secondly contributes to faster lubricating oil pressurization and flow. The effects are cumulative resulting in brisk and smart starts.

Illustrative cold cranking currents for various displacement engines based on existing battery standards.

Truck Class	Engine Displacement (liter)	Cold Cranking Current (A)
6 (F550, 5500, etc)	6 to 7	800-900
	8 to 10	1000-1200
7	12	1600
8 (Over the Road semi)	15-16	2400

Installation Examples

Maxwell Technologies is not making recommendations on specific installations of ultracapacitor engine cold cranking aides, rather guidelines for proper usage and application of ultracapacitor products.

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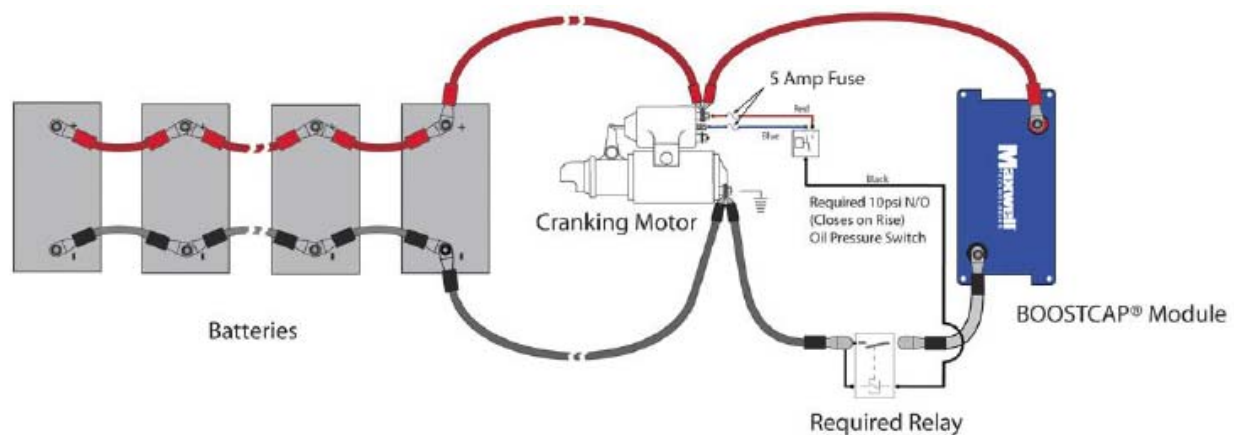
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In this section we review two particular installation systems consisting of standard Group 31 lead-acid battery modules in the typical 4 module cluster found on class-8 vehicles along with an ultracapacitor module located close to the engine starter motor. This installation is referred to as a passive parallel combination because the ultracapacitor acts in combination with the battery. The fact that cable lengths differ considerably in the passive parallel connection means that the ultracapacitor pack “sees” a much lower series resistance to current flow and therefore delivers the bulk of current to the starter. As the UC charge depletes and its voltage drops the battery begins to deliver a larger portion of the cranking load. This connection is useful because at cold temperatures the battery pack may not deliver much current at all.

**Passive Parallel Connection**

The following guidelines are recommended:

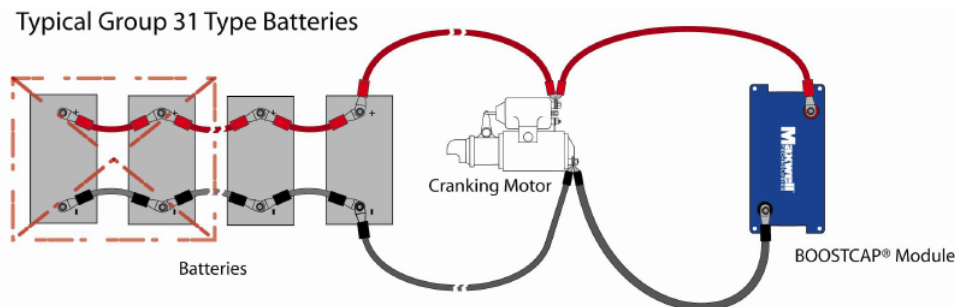
- Insure that the BOOSTCAP® module voltage is well within 2V of the battery pack terminal voltage when measured at the starter terminal. The ultracapacitor module should be pre-charged before connection. This will prevent excessive current flow when the cables are attached. If the BOOSTCAP® module is pre-charged to a potential greater than 2V above the battery voltage it may be necessary to discharge the BOOSTCAP® until the voltage is close to the battery potential. Any discharging of the BOOSTCAP® should be through an approved power resistor. If none are available then a pair of automotive headlamps connected in series will suffice and will provide approximately a 3A discharge current until the potentials are leveled.

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- Remove any protective terminal covers from the BOOSTCAP® and attach the cables. Cable size should be appropriate for each installation and typically the BOOSTCAP® cable will be the same AWG as the battery cable.
- Install the BOOSTCAP® relay.
- Attach the positive (+) cables first. Then connect the negative (-) cables finishing with the BOOSTCAP® cable attachment at the starter motor chassis bolt. Start at the BOOSTCAP® negative terminal to the relay and then relay to chassis.
- It is recommended to hold the TOTAL cable lengths for BOOSTCAP® connection to less than 4'. This will insure that the BOOSTCAP® provides the majority of cranking current when cold.
- Proper crimping or soldering (or both) of the cable lugs is required.

Concluding Remarks

With the addition of the BOOSTCAP® module the opportunity arises to reduce the number of parallel connected starting batteries. The figure below illustrates the point that one or two of the batteries in a typical application may be removed when the BOOSTCAP® module is installed. This may be advantageous in future cases when packaging space is needed for emissions equipment needed to meet 2008 and beyond stricter DP and NOx emissions.



You may be able to remove half of the batteries when using a BOOSTCAP® ultracapacitor module. Replacing existing lead acid batteries with deep cycle batteries will enhance your system

Figure 2
Connecting the BOOSTCAP® Module to a standard battery

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- When removing battery modules bear the following in mind.
- The battery modules are charged and have the capacity to deliver over 1000A of short circuit current. Keep tools and other hardware away from the battery terminals (posts).
- Disconnect the positive side cables first, then the negative cable jumper.
- When the single or pair of modules to be removed are disconnected from the remainder of the battery tray packs, then disconnect the remaining jumper cables.
- Remove the un-used battery modules(s).

Isolated Passive Parallel Connection

Maxwell recommends the isolated passive parallel connection for the BOOSTCAP® engine cranking application. This connection insures that the engine will always receive its cranking power first from the BOOSTCAP®. In cold weather when the conventional lead acid battery voltage is low the isolated connection insures that the BOOSTCAP® potential remains high.

The isolated connection provides:

- Fully isolated BOOSTCAP® from the battery pack AND from the vehicle board-net (electrical distribution system).
- Being isolated from the vehicle electrical system is important because the BOOSTCAP® will not have its charge depleted by on board (hot all times) electronics such as clocks, anti-theft modules, keyless entry modules, and the like.
- Additional control cables and connections are required with the isolated configuration, but the benefits outweigh the additional complexity.
- Installation is similar to the Passive Parallel Connection described above.

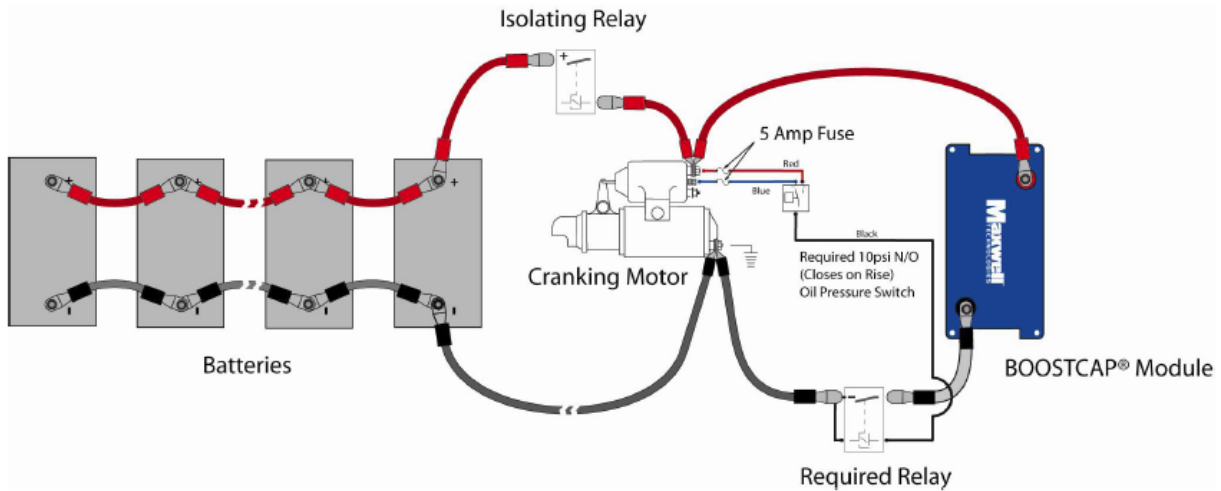
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The isolated configuration is preferred because it completely isolates the BOOSTCAP® (and the starter motor) from the remainder of the vehicle electrical system. In addition to the benefits noted above this configuration provides the following secondary benefits:

- Engine cranking will not cause transients on the vehicle electrical distribution system. This means for example that any connected electronics will not be disrupted by engine starting.
- Lights will not dim during cranking because the BOOSTCAP® provided high currents are fully isolated from the electrical system.
- Battery cycling is minimized by having the BOOSTCAP® handle most engine cranking events.
- Additional control logic will manage the isolating relay to engage the battery pack before the BOOSTCAP® voltage drifts more than 2V from the battery potential.

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References

[1] EIA/KFI draft standard PN5135, Capacitor Standard for Internal Combustion Engine Cranking, March 14, 2006. The electronic component sector (ECA) of the electronic industries alliance (EIA) in cooperation with KiloFarad International (see www.kilofarad.org). This draft prepared by Dr. John R. Miller of JM Enterprises (JME) of Shaker Heights, OH, and Mr. Ed Mikowski of ECA.

[2] Standards for Engine Starting Capacitors phone discussion, May 5, 2006. Dr. John R. Miller of JM Enterprises (JME) of Shaker Heights, OH.

[3] Maxwell Technologies, www.maxwell.com

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