IOXUS, INC.
118 Winney Hill Road
Oneonta, NY 13820

Ultracapacitors and Diesel Engine / Locomotive Cranking –The Facts

Ioxus Applications Engineering

Abstract

When dealing with the biggest diesel engine starting needs – mining trucks, heavy equipment, and locomotives, this is an application where ultracapacitors can reduce the load on the power source, which is most often a lead acid battery. The best solution turns out to be a combination of ultracapacitors and a lead acid battery, working together for the benefit of both devices. This white paper illustrates the specific system benefits which are achieved by incorporating the strengths of both battery and ultracapacitor technologies into diesel engine starting systems. Battery and capacitor combinations have been used in Russia for railway transport for more than 16 years, which has gradually forced changes in their "batteries only" types of systems.

Peculiarities of Locomotive Starting (Large Diesel Engine Starting)

Large diesel engine starting applications are a unique power application, and not because of the power level alone. A number of different factors come into play. The starting of large diesel engines differs greatly from starting engines of small combustion volume such as car and trucks. This difference lies in the heavier weight of the moving parts. These are the crankshaft, pistons, and also the higher resistance to piston motion in the cylinder. Diesel engine efficiency is determined by this resistance – the higher the rate of compression, which is the cylinder pressure, the higher the engine's efficiency.

When starting a traditional low-powered engine, the starter battery is discharged into the load of the electric starter, which runs the main engine shaft up to the proper starting speed. After a few working strokes of the crankshaft, the engine starts with proper fuel, appropriate fuel mixture, compression, and ignition.

While starting a locomotive diesel engine, the starter battery has to power up the hydraulic pumps, which in-turn creates the pressure to suspend the engine shaft before starting. In cold weather, there is a period known as "pre-heat time", which is necessary to allow for smooth start-up without any damage to the components of the engine. As a rule, pre-starting preparation time is about 30 – 60 seconds. During this period of time the battery pack will have become nearly exhausted and most of its capacity will have been spent by the time the engine starts.

In addition to the power needs of pre-starting preparation and starting function, on board locomotive batteries must also provide power for the operation of automatic equipment, air compressors, and brake systems – even when the main locomotive engine is not operating.

During certain operating conditions, such as ecological restrictions at passenger terminals, the locomotive often has to stop and shut down its engine. During this time, the on board alternator only has the capacity to maintain the normal level of the on board battery state of charge to approximately 70%. Very often, the battery capacity is reduced to approximately 30% of its nominal value. When the battery is in such a compromised condition, the internal resistance of the on board battery is increased, the starting current is decreased, and the cranking time of the engine shaft rotation before stable starting is increased as well. These conditions greatly reduce the reliability of the locomotive starting operation, and in some cases there is a break down when attempting to start the engine. Frequent and deep discharges may lead to on board battery failure, especially with lead-acid batteries. Locomotive companies, when often faced with this dilemma, either choose not to shut down the engine during stops and thereby waste fuel during engine idle time, or they choose to increase the installed capacity of the battery and the on board alternator increasing equipment and operating costs.

Toll Free: +1 877-751-4222 Fax: 607-433-9014 http://www.ioxus.com e-mail: sales@ioxus.com

Ultracapacitor Operating Modes

There are two operating modes for ultracapacitors when installed in industrial equipment by application type:

The first is to keep the capacitors in the operating circuit in an uncharged state. In this case, the capacitor is charged just before it is used, and then after being discharged into the load, it is disconnected from the charging circuit until the next time it is needed. The advantage of this kind of operation lies in the increased service life of the ultracapacitor, because in the time intervals between "uses", its voltage is close to zero, which reduces "cell ageing". Given more than 500,000 discharge/charge cycles from ultracapacitors, the advantage of this type of operating mode would seem to be of diminishing value.

The second mode of operation – a floating regime, provides the highest system readiness. The ultracapacitors are ready for immediate discharge. The service life of the ultracapacitor array would be lower than the first operating mode, and special care is needed to be able to equalize the voltages of stacked ultracapacitor high-voltage circuits. Locomotives have used the first operating mode with power coming from the on board battery system.

Locomotive Battery Starting Current/Voltage Profiles

There are three different types of electrochemical systems that are used in starter batteries for diesel locomotives. They are lead-acid, nickel-cadmium, and nickel-iron batteries. For lead-acid and nickel-cadmium batteries the rule "5 C" is used. This means that battery capacity is chosen at a rate of 1/5 of maximum value of peak current. Thus, if the peak current during starting is 2000 – 2200 A, then nominal battery capacity would be 400 – 500 Ah. For cell design of these first and third battery types, relatively thick electrodes of greater than 3 mm, and free electrolyte volume are used. Unfortunately, their ESR is high, so their starting mode voltage drops up to 50% of the nominal value.

For nickel-cadmium batteries "10 – 15 C" rule is used. Their design uses thin electrodes, which provides lower ESR for the battery cells as compared to lead-acid and nickel-iron batteries.

The ambient temperature range of starter batteries operation is wide; from - 45°C up to + 55°C. That is why all locomotive batteries are of a non-sealed, vented design or otherwise it would be impossible to ensure stable temperature conditions when charging batteries consisting of sealed cells - with the exception of "thermal runaway". Operating expenses are increased due to the regular maintenance needed by the vented cells. Current overload at the initial moment of starting leads to electrolyte loss during operation; current overload for lead-acid batteries accelerates the swelling of the active material of the positive electrodes. For nickel-iron and nickel-cadmium batteries with cells of "pocket-type" electrode design, current overload increases the washing out of electrode material powder through lamella holes ("pocket"). These processes often result in internal shunting of the electrodes in the cell block and premature battery failure.

Historically two standards of locomotive board voltages were used. The older standard was 64 Volts and the newer standard is 96 Volts. For 96 Volts, the lead-acid battery contains 48 cells and the nickel-cadmium battery contains 72 cells. Multi-cell, series circuits with components, disposed in different temperature patterns (edge – center), also prevents principle sealing of on-board batteries.

Service life of on-board starter batteries is from one to five years. Critical zones of operation are regions with cold and hot climates, and within the above range of service life. Long-term operation is maintained by regular battery servicing on the shed stands, including replacement of the failed cells with new ones.

Regarding the economics side of electrochemical systems, capital costs for the purchase of new board batteries increases in the following order:

Lead-Acid < Nickel–Iron < Nickel-Cadmium

As a rule, for the same locomotive type, the nickel-cadmium battery price is 3 times higher than the lead-acid battery price. On the other hand, operating expenses go down in the following order:

Lead-Acid ≈ Nickel-Iron >Nickel-Cadmium

<u>A Step by Step History of Locomotive Diesel Starting</u>

1. The power of the locomotive diesel in this "history" is 3000 h.p., and the type of battery used is a nickel-iron 550Ah battery. The system voltage is 64V, and the battery charge level is 100%, with an ambient temperature at +26°C.

2. Even under favorable starting conditions, the voltage drop in a fully charged battery was -40% at the initial moment that the starting current was approximately 1930 Amps. The Diesel was stable and started in 8.3 seconds.

3. If we look at the total power taken out of the battery during diesel cranking, it turns out to be approximately 70kW, and is about 40-50kW during the first 2 seconds. Total energy is about 150kJ during the next 3 seconds and 140kJ during the next 2 seconds.

4. For comparison let's analyze the change of battery power during diesel cranking at 35% state of charge of the on-board battery: Over 3 seconds, the maximum discharge power at the peak does not exceed 25kW, and the energy delivered during this 3 second interval is 67kJ. In this instance, in the course of cranking, voltage was reduced from 55V to 20V by the 16th second, and diesel engine starting did not happen. <u>The battery charge level of 35% is an extreme case, but this often takes place, especially in winter.</u>

5. Statistical analysis of starting reliability reveals that starting guarantee drops abruptly when the state of charge of the on-board battery is decreased. The range of stable starting is 70 – 100% of charge level, while the real operating range is 50 – 80%. For reliable starting of diesel locomotives in the range of 3000 h.p., it is necessary to have a battery, capable of generating 100 to 120kW of peak power, taking into consideration operating at low temperature. In such cases as this, the on-board battery's state of charge needs to be controlled very closely.

<u>Ultracapacitors for Diesel Engine Starting - A Russian Point of View</u>

In the process of adapting today's ultracapacitors into a locomotive diesel engine's starting systems, there are a number of important aspects to remember:

1. Ultracapacitors possess higher, by 1-2 orders of magnitude, specific power than starter batteries. That is why they may be effectively used with on-board locomotive batteries – for realizing the most powerful processes - cranking of engine shaft at the initial moment of starting.

   There are various types of technical approaches used with ultracapacitors in starting systems. In most cases, the capacitor array is parallel connected to the on-board battery through the control circuit. This control circuit involves pre-charging before use using a charge thyristor, which is then turned off, and the ultracapacitor is ready for use.

Discharge of the ultracapacitor and the on-board battery into the main electrical machine load, i.e. the diesel starter motor, takes place simultaneously for the battery and capacitor, usually through a diode when the contacts of the starting circuit are closed.

2. After starting, the ultracapacitors are removed from the load. The energy storage of the ultracapacitors may vary over a wide range depending on engine power and operating conditions. Let's analyze a practical test with the starting of a 3000 h.p. diesel. A description of its starting from a 550 Ah battery was mentioned earlier.

3. Based on the delivered energy at the initial seconds of starting, the capacitor energy storage is within the range of 90 to 180kJ. This was analyzed as the worst case condition when the on-board battery state of charge was only 35% and the minimum capacitor energy stored was approximately 90kJ. (ESR: 10 milliohms).

4. According to the data, the discharged battery was unable to generate the initial starting current for this diesel type (Approximately 2000 A), but only delivered 610A. The ultracapacitor however, was easily able to deliver current into the 1400A range. Because of this, weak battery current with normal shaft rotation at the beginning of starting now becomes possible.

5. The advantages of ultracapacitors, even with minimum energy storage, for this diesel type over batteries are clearly shown at the first second of starting. From data of released energy versus starting time, it is clear that the ultracapacitor has advantages initially during the first 1.8 second time, and that this is at the moment of maximum energy demand. Only in going to long stationary rotation, does the on board battery deliver more energy than the capacitor. Keep in mind that this test had normal starting at the 10th second, and the on-board battery state of charge was only 35%.

Let's consider another case of ultracapacitors for locomotive engine starting. The pertinent items are:

- Decreased diesel power of only 1200 h.p. instead of 3000 h.p.
- Increased energy storage of the ultracapacitor set at 144kJ instead of 90kJ
- Critical state of the on board battery (100 V, 450 Ah); charge level is only 30%
- Unfavorable starting conditions with an ambient temperature of +2°C

Engine cranking without starting from the battery separately and from the battery + capacitor up to automatic switching off of the starting relay was carried out. The current/voltage profile showed significant voltage drop –54% of nominal and a rather low pulse current – 876A, while actually 1300 – 1500A is needed.

A power profile of battery discharge at the initial period of cranking shows that the peak value was approximately 43kW, and the delivered energy value actually reached 43kJ for 1.2 seconds, and 49kJ for 1.4 seconds. The total cranking time was 2 seconds.

A parallel connected capacitor set of 144kJ, 15 milliohms, 96V was charged from the battery during a 30 second window, and at the same time, cranking was carried out. The current/voltage profile showed less voltage drop – 34% and normal pulse current on the starter – 1413A, which is the sum of the battery current – 378A and the capacitor current –1035A.

Therefore, the starter battery at the initial moment of starting was discharged by the current less than "1 C".
The power profile of the initial cranking time shows almost a three-fold excess of the ultracapacitor power over the on-board battery within the time period of approximately 100 milliseconds.

Total peak power of the ultracapacitor and the battery reached 94kW, compared with 43kW in case of the battery alone. (This is an increase of 219%)

As far as delivered energy, the ultracapacitors outperforms the battery within the interval of 1.4 seconds, delivering more energy to the starter. In this case, the battery delivers only 21kJ, which is more than 200% less than by cranking only from the battery. Total energy output from the system capacitor-battery was 47kJ for 1.2 seconds – a little bit more than just the energy output from the battery only.

However, the total cranking time with the combined system was increased more than twice to 4.5 seconds, instead of just 2 seconds with the battery by itself.

With further testing from the battery alone with its state of charge at 30%, locomotive starting did not happen.
Starting from the system ultracapacitors + battery was stable in 0.5 second, and starting from only ultracapacitors was stable in 0.5 second.

Tests showed that for the ratio of 1200 h.p. /144kJ, using the battery is not necessary for warranted starting of the locomotive diesel.

Further investigation led to the development and mass production of the unified starting system with the following technical data:

Parameter Values:

• System Type SPD 2200/64 (96)	• Total energy store 135kJ
• Power of engines being started 1000 to 3200 h p.	• Capacity 26/58F
• Nominal operating voltage 96/64 V	• ESR < 0.010 Ohm
• Maximum operating voltage 110V	• Insulation resistance > 5 MOhm
• Nominal discharge current 3500A	• Service life (cycling) > 100,000
• Maximum discharge current 10000A	• Mass < 120kg
	• Dimensions 426 x 420 x 545mm

The system consisted of 3 capacitors connected parallel-series depending upon the on board system voltage charging and control circuitry.

Ultracapacitor + Battery Locomotive Diesel Starting Advantages
Improved Reliability and Efficiency

When comparing the results of testing and long-term operation of starting systems with batteries only, or with combined systems of battery + ultracapacitors, we get the following conclusions:

1. The ultracapacitor array in conjunction with the on-board battery takes up all power functions during maximum starting energy demand (initial seconds of engine starting) and its power by several times exceeds the starter battery power.

2. The ultracapacitor energy output to the starter is higher than that of the battery at the initial starting period.

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3. The state of charge of the on-board battery does not affect the starting characteristics, and since the on-board battery is not subjected to large current loading during starting, its operating conditions become more moderate.

4. The starting energy was used efficiently – only 43kJ from the battery during 1.2 seconds rotated the engine shaft only for 2 seconds, but engine start did not happen.

5. The 47kJ supplied during the initial 1.2 seconds from the system battery + capacitor rotated the engine shaft for 4.5 seconds. During these operating conditions, the engine started for 0.5 seconds.

6. The advantages of the combined system battery + capacitor over the common locomotive starting system on the basis of the battery only should be noted since warranted starting of the locomotive diesel at any charge state of the on-board battery, and operation in cold climate, is assured.

7. Starting is possible without an on-board battery or with an on-board battery of several times reduced capacity.

8. Remember that the cycle life of ultracapacitors is hundreds of thousands of charge/ discharge cycles. Depth of discharge of the on-board battery during operation in a team, with the ultracapacitors is several times less, so the battery's service life is increased. The ultracapacitor <u>and</u> the battery system are operating at least 200% longer. With that advantage, the on-board battery maintenance and repair expenses are reduced by approximately 50%.

9. The ultracapacitor array is a compact unit and the fact that ultracapacitors are sealed and maintenance-free makes it possible to arrange the ultracapacitor array in almost inaccessible places of the locomotive compartments. The above advantages of the combined system prove its high reliability during operation and practical independence of many exposure factors.

10. Aspects of economic efficiency of capacitor applications for locomotive starting systems are based on the proper choice of the capacitor energy storage type and taking into consideration the specific character of locomotive operation. For example, shunting locomotives need higher energy storage than mainline locomotives because of the many more stops in the "start-stop" mode for shunting locomotives. This is also a concern for commuter trains which often stop more.

Efficiency aspects of combined system applications may be subdivided into long-term and short-term. Long-term economy is determined based on increasing the system service life and the reduction of maintenance expenses .It is well-known that maintained batteries during service life need expenses equal to or sometimes exceeding the initial battery cost. It is easy to calculate cost when the service life is increased by twice and maintenance expenses are reduced by a factor of 300%.

Short-term economy is calculated on the basis of being able to apply an on-board battery with 2-3 times reduced capacity and accordingly reduced cost and reduction of fuel consumption when the capacitor array is used as well with an on-board battery with large capacity. This provides the option of often being able to stop the engine and to guarantee its further starting – as well as an increase in the engine operating life because of the increase in fuel economy during the time of the battery-capacitor operating together. When looking at fuel and operating costs, the capacitor array compensates for the first 2-4 months of capital expenses.

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Although there seems to be no decrease in reliability or economy by the use of the battery-capacitor combination, there can be an increase of heat in the surrounding compartments unless efficient dc/dc converters are used for capacitor charging.

Conclusion

Ultracapacitors can be easily implemented into diesel trucks and locomotive starting systems for operation into any charge algorithm, and specific parameters of the ultracapacitors do not have any influence on the charging scheme.

Ultracapacitors can be effectively applied in the worst kind of starting system applications, heavy mining equipment and locomotive systems, guaranteeing engine starting with no dependence on state of charge of on-board battery and weather conditions – thereby significantly increasing the reliability of the vehicle's operation.
Lastly, the application of ultracapacitors are very economically beneficial because they prolong the service life the diesel starting system, and reduce on-board battery maintenance expenses and fuel consumption, and increase engine shelf life.

Reference:
Starting of Locomotive Diesel Engines Using Electrochemical Capacitors, AlexeyI.Beliakov, ELIT Co., Kursk-26, Russian Federation, Presented at "Advanced Capacitor World Summit 2003", Washington DC, August 11–13, 2003

Toll Free: +1 877-751-4222 Fax: 607-433-9014 http://www.ioxus.com e-mail: sales@ioxus.com

THETA-J ASSOCIATES
MICROWAVE RESOURCE ENGINEERS
Ph: 847-549-8820 ♦ Fax: 847-549-8824
www.theta-j.com