Diesel Engine/Locomotive Cranking & Supercapacitors

Introduction

When dealing with the largest diesel engine starting application needs such as mining trucks, heavy equipment and locomotives, supercapacitors can reduce the load on the power source, which is often a lead acid battery. The best solution is a combination of supercapacitors and a lead acid battery, working together for the benefit of both devices. Benefits can be achieved by incorporating the strengths of both battery and supercapacitor technologies into diesel engine starting systems. Battery and capacitor combinations have been used in Russia for railway transport for over 16 years, which has gradually forced changes in their “battery only” types of systems.

Peculiarities of Locomotive Starting

Large Diesel Engine Starting

Large diesel engine starting applications are a unique power application, and not just because of the power level, but a number of different factors. 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 such as the crankshaft and pistons, as well as the higher resistance to piston motion in the cylinder. Diesel engine efficiency is determined by this resistance. The higher the rate of compression (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. Pre-starting preparation time is approximately 30–60 seconds. During this 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%. 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, starting current is decreased, and cranking time of the engine shaft rotation before stable starting is also increased. These conditions greatly reduce the reliability of the locomotive starting operation and, in some cases, there is a breakdown 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 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 resulting in increased equipment and operating costs.
Supercapacitor Operating Modes

There are two operating modes for supercapacitors when installed in industrial equipment by application type. The first mode of operation is to keep the capacitors in the operating circuit in an uncharged state. Thus, 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 supercapacitor. In the time intervals between uses, its voltage is close to zero which reduces cell aging. Given the more than 500,000 discharge/charge cycles from supercapacitors, 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 supercapacitors are ready for immediate discharge. The service life of the supercapacitor array is lower than the first operating mode, and special care is needed to equalize the voltages of stacked supercapacitor 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: lead-acid, nickel-cadmium, and nickel-iron batteries. For lead-acid and nickel-cadmium batteries, the “5 C” rule is used, which 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 to 2200 A, then nominal battery capacity would be 400 to 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, because the ESR is high, the starting mode voltage drops up to half of the nominal value.

For nickel-cadmium batteries “10 to 15 C” rule is used. This battery 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 ranges from -45°C up to +55°C. That is why all locomotive batteries are of a nonsealed, vented design. 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, or the “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 old standard is 64 V and the new standard is 96 V. For 96 V, 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 to center), prevent 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 economic side of electrochemical systems, capital costs for the purchase of new board batteries increases in the following order:

\[
\text{Lead-Acid} < \text{Nickel-Iron} < \text{Nickel-Cadmium}
\]

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

\[
\text{Lead-Acid} \approx \text{Nickel-Iron} > \text{Nickel-Cadmium}
\]
A History of Locomotive Diesel Starting

The power of the locomotive diesel in this history is 3,000 hp, and the type of battery used is a nickel-iron 550 Ah battery. The system voltage is 64 volts, and the battery charge level is 100% with an ambient temperature at +26°C.

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 1,930 amps. The diesel was stable and started in 8.3 seconds.

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

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

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 to 100% of charge level, while the real operating range is 50 to 80%. For reliable starting of diesel locomotives in the range of 3000 hp, it is necessary to have a battery capable of generating 100 to 120 kW of peak power, taking into consideration operating at low temperature. In such cases, the on-board battery state of charge needs to be controlled very closely.

Supercapacitors for Diesel Engine Starting

A Russian Point of View

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

1. Supercapacitors possess higher specific power than starter batteries by 1 to 2 orders of magnitude. Thus, can be used with on-board locomotive batteries for realizing the most powerful processes—cranking of engine shaft at the initial moment of starting.

2. There are various types of technical approaches used with supercapacitors 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 supercapacitor is ready for use. Discharge of the supercapacitor 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.

3. After starting, the supercapacitors are removed from the load. The energy storage of the supercapacitors vary widely depending on engine power and operating conditions. Let’s analyze a practical test with the starting of a 3,000 hp diesel. A description of its starting from a 550 Ah battery was mentioned earlier.

4. Based on the delivered energy at the initial seconds of starting, the capacitor energy storage is within the range of 90 to 180 kJ. 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 with approximately 90 kJ and ESR of 10 milliohms.

5. According to the data, the discharged battery was unable to generate the initial starting current for this diesel type (approximately 2,000 A), but only delivered 610 A. However, the supercapacitor was easily able to deliver current into the 1,400 A range. As a result, weak battery current with normal shaft rotation at the beginning of starting now becomes possible.

6. The advantages of supercapacitors, 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 supercapacitor has advantages initially during the first 1.8 second time, and at the moment of maximum energy demand. Only in 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 supercapacitors for locomotive engine starting. The pertinent items are:

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

Engine cranking without starting from the battery separately and from the battery and capacitor up to automatic switching off of the starting relay was carried out. The current/voltage profile showed a significant voltage drop of 54% of nominal value and a low pulse current of 876 A, when 1,300 to 1,500 A is needed.

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

A parallel connected capacitor set of 144 kJ, 15 milliohms, 96 V was charged from the battery during a 30 second window, at the same time cranking was carried out. The current/voltage profile showed a lower voltage drop of 34% and normal pulse current on the starter of 1,413 A, which is the sum of the battery current, 378 A and the 1,035 A capacitor current. Therefore, the starter battery at the initial moment of starting was discharged by the current in less than “1 C.”

The power profile of the initial cranking time shows almost a three-fold excess of the supercapacitor power over the on-board battery within the time period of approximately 100 milliseconds. Total peak power of the supercapacitor and the battery reached 94 kW, compared with 43 kW in case of the battery alone. This is an increase of 219%.

As far as delivered energy, the supercapacitors outperform the battery within the interval of 1.4 seconds, delivering more energy to the starter. In this case, the battery delivers only 21 kJ, which is more than 200% less than by cranking only from the battery. Total energy output from the system capacitor-battery was 47 kJ for 1.2 seconds—slightly more than just the energy output from the battery alone. However, the total cranking time with the combined system was increased more than twice to 4.5 seconds, instead of two 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 supercapacitors and battery system was stable in 0.5 seconds, and starting from only supercapacitors was stable in 0.5 seconds.

Tests showed that for the ratio of 1,200 hp /144 kJ, 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)  
- Power of engines being started 1000 to 3200 hp  
- Nominal operating voltage 96/64 V  
- Maximum operating voltage 110V  
- Nominal discharge current 3500A  
- Maximum discharge current 10000A  
- Total energy store 135 kJ  
- Capacity 26/58F  
- ESR < 0.010 Ohm  
- Insulation resistance > 5 MOhm  
- Service life (cycling) > 100,000  
- Mass < 120kg  
- Dimensions 426 x 420 x 545mm

The system consisted of three capacitors connected parallel-series depending upon the on-board system voltage charging and control circuitry.
**Supercapacitor and 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 and supercapacitors, following conclusions can be made:

1. The supercapacitor 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 exceeds the starter battery power by several times.
2. The supercapacitor energy output to the starter is higher than that of the battery at the initial starting period.
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 43 kJ from the battery during 1.2 seconds rotated the engine shaft only for 2 seconds, but engine start did not happen.
5. The 47 kJ supplied during the initial 1.2 seconds from the system battery and 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 battery and capacitor system 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 lifecycle of supercapacitors consists of hundreds of thousands of charge/discharge cycles. Depth of discharge of the on-board battery during operation in a team with the supercapacitors is several times less, so the battery service life is increased. The supercapacitor and the battery system are operating at least 200% longer. With that advantage, the on-board battery maintenance and repair expenses are reduced by approximately half.
9. The supercapacitor array is a compact unit and supercapacitors are sealed and maintenance-free, thus making it possible to arrange the supercapacitor array in nearly inaccessible locations 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, while taking into consideration the specific character of locomotive operation. For example, shunting locomotives need higher energy storage than mainline locomotives because of the increased stops in the shunting locomotive start-stop mode. This is also a concern for commuter trains which have more stops.

Efficiency aspects of combined system applications may be subdivided into long-term and short-term. Long-term economy is determined by increasing the system service life and the reduction of maintenance expenses. 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 two to three times reduced capacity and accordingly reduced cost and reduction of fuel consumption when the capacitor array is used with a large capacity on-board battery. This provides the option of being able to stop the engine 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 two to four months of capital expenses.

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

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

Supercapacitors can be effectively applied in the worst kind of starting system applications including heavy mining equipment and locomotive systems, guaranteeing engine starting with no dependence on state of charge of on-board battery and weather conditions. Thus, significantly increasing the reliability of vehicle operation.

Lastly, the application of supercapacitors is economically beneficial as they prolong the service life of the diesel starting system, reduce on-board battery maintenance expenses and fuel consumption, and increase engine shelf-life.

About KEMET

KEMET Corporation is a leading global supplier of electronic components. We offer our customers the broadest selection of capacitor technologies in the industry, along with an expanding range of electromechanical devices, electromagnetic compatibility solutions and supercapacitors. Our vision is to be the preferred supplier of electronic component solutions demanding the highest standards of quality, delivery and service.

Reference: