Case study:

Powercapacitor batteries

for a full electric 220 ton mining truck

Introduction

On the road towards decarbonization in the mining industry, going electric is one of the main options to to reach zero-emission mining. Currently a mining truck consumes 135 liter diesel per hour. We replace it with a battery that can deliver 2 MW in power and can be used with a variety of fast charging options.

A major concern for the mining industry is operational cost. A mining truck has to drive 24/7 with barely 15 minutes per day for refueling. When it is not driving for maintenance or refueling it costs money. In addition, mining operations happen in extreme cold as well as in and desert-like warm temperatures. Inside a mine, fire safety is paramount.

This means that the design of a mining vehicle battery is a challenging task. It must deliver high power, it must charge fast, it must be very robust and safe in all conditions. This makes that regular Li-ion batteries are unfit, they are prone to unpredictable fires for example.

This paper will discuss a solution with hybrid carbon-based powercapacitors. The powercapacitors deliver the power to the electric motor, and act as the energy buffer between charging points, be it by regenerative braking or by charging on the road.

The mining environment

The driving profile of a mining vehicle looks like the following. First, it picks up the ore at a loading site. This is often relocated (every couple of months). A second segment consists of the pit haul roads. These are semi-permanent, i.e. the infrastructure is operational for a couple of months to a year and more. The last segment consists of long-term infrastructure where the ore crushing takes place. This part of the infrastructure can remain in place for up to 30 years.

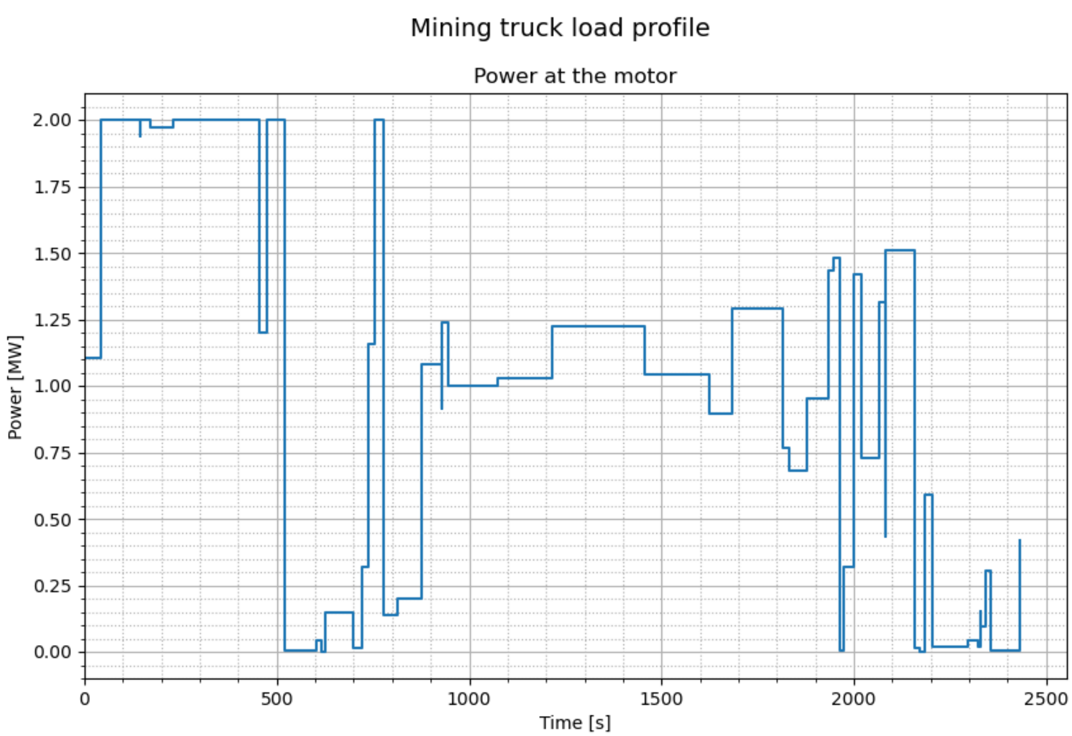
Not always, but often the first segment of the mine is a road with a serious slope. When the truck is fully loaded this part requires a lot of energy and full power. In addition, it is difficult to put a charging infrastructure in this place because the road is winding and narrow and moves up as the ore is being extracted. The best locations for charging equipment are evidently on the more permanent parts of the road.

The mining vehicles themselves are huge and heavy. They measure as much as a 2-story house and weight 150 ton, being able to transport a few 100 tons of ore. The space for equipment in the truck is limited to 20 to 25 m^3 with a weight limit of about 15 to 20 ton. With room to spare, this can house a powercapacity battery of around 600 to 900 kWh. While using a heavy diesel engine, the traction on the wheels is done using electric motors (like in train locomotives). Typical motor powers are 2 MW.

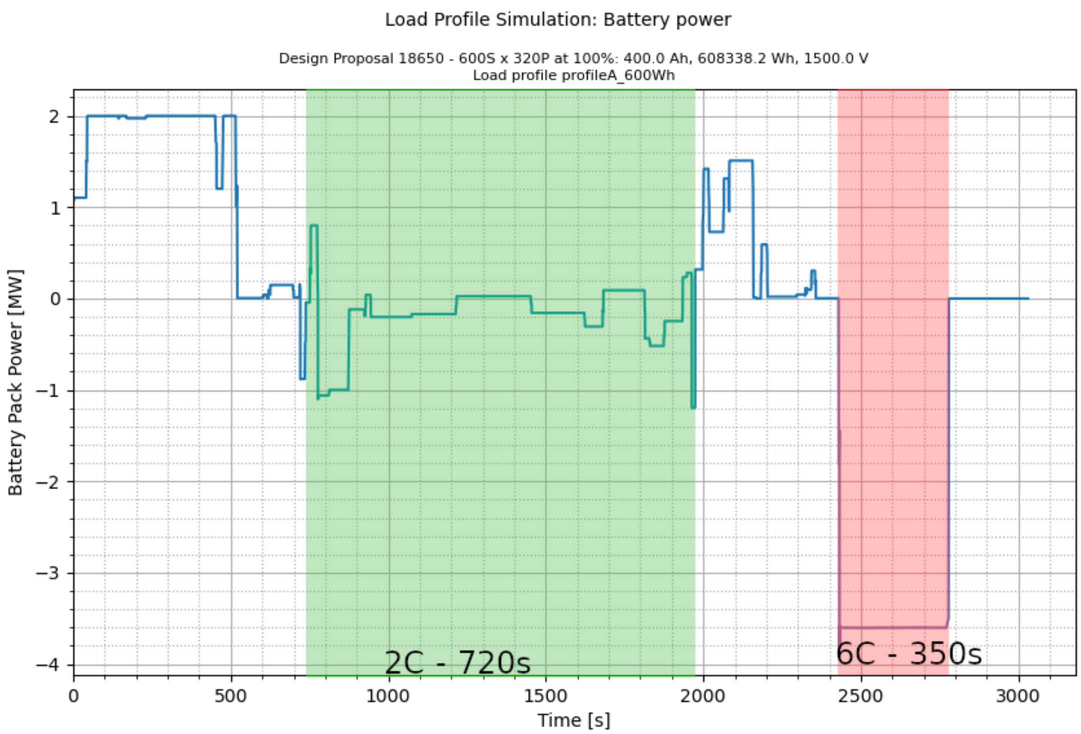
A typical driving profile

As described, the mining environment is a demanding one. The combination of steep slopes and heavy loads also generate a rather dynamic load on the motors and hence on the energy needs to drive the motors. Therefore, it is also difficult to predict the energy consumption. The fuel for a full day's trip (about 3000 l) can be carried on board, but this is not possible with a battery as the energy density is much lower.

Below is a typical driving profile. It shows a mining truck leaving the mine on a steep road, hence requiring the full 2 MW in power. This is followed by a relatively flat road. At the end the ore is dumped, to reach the turning point. When the motor is idle on a down-ward slope, then regenerative braking can partly recharge the battery as well.



In the graph below, the driving profile has been translated onto a power profile with the colored zones indication the charging zones (green: mobile charging, red: stationary charging). The assumption is that a 600 kWh battery is installed. Given the high power, hence high currents, requirements, a 1500V is selected as the nominal voltage. The first zone (green) is using overhead charging at a modest 2C rating (at 1.2 MW) and at the turn-around (red) a charger is used at 6C (3.6 MW). In the next section this driving profile is simulated to see how the battery evolves over such a trip.



From diesel-electric to full electric

Current mining trucks already use electric motors in a diesel-electric set-up. They also use overhead charging with a pantograph to ascend straight slopes. This allows them to drive uphill twice as fast as when only using the diesel-generator. See [1] and [2] for an example.

How can the diesel engine be eliminated altogether? As the truck already drives electrically, the solution is simple: take out the diesel engine and put in a sizable battery. What's the problem? The battery needs to output up to 2 MW in power and do that for 24 hr/day. How do we minimize the down-time due to charging? First, we allow charging while driving using the existing overhead wires. The battery can even

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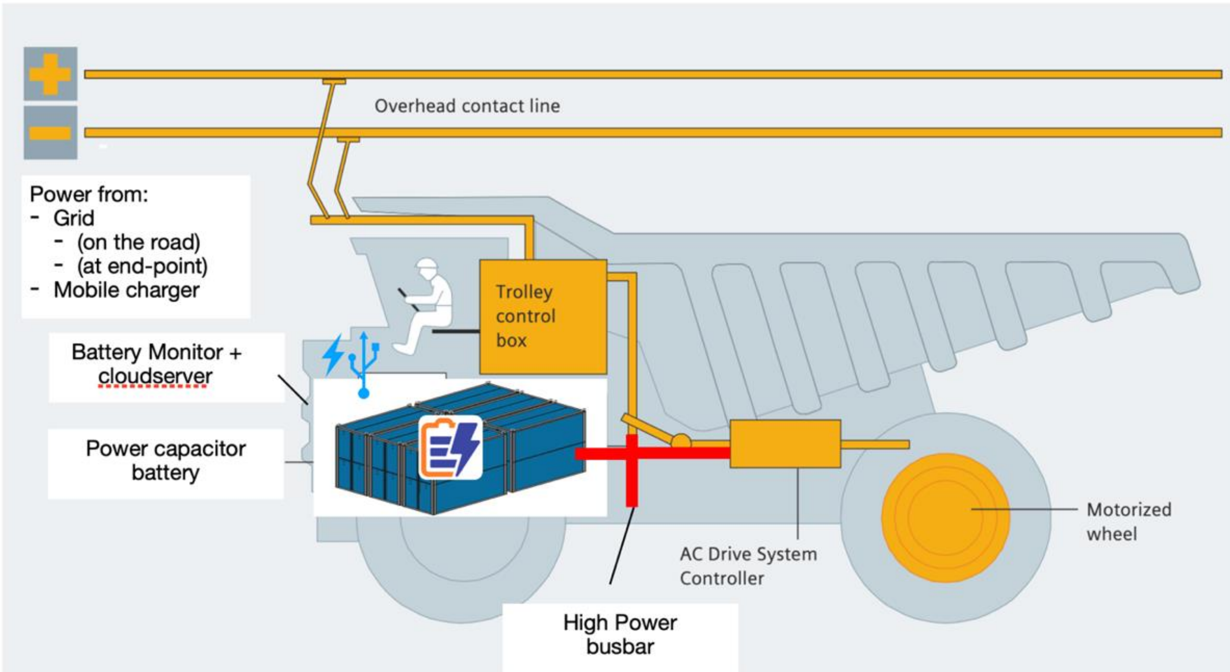
1. https://www.youtube.com/watch?v=oNTm-jd_4lE

2. https://new.abb.com/news/detail/79698/abbs-high-power-battery-technology-helps-transition-to-all-electric-mining-operations

boost the power when needed. Secondly, we use fast charging at the end of a trip. This is why hybrid powercapacitors come into play. They can deliver high power and charge very fast in a safe way.



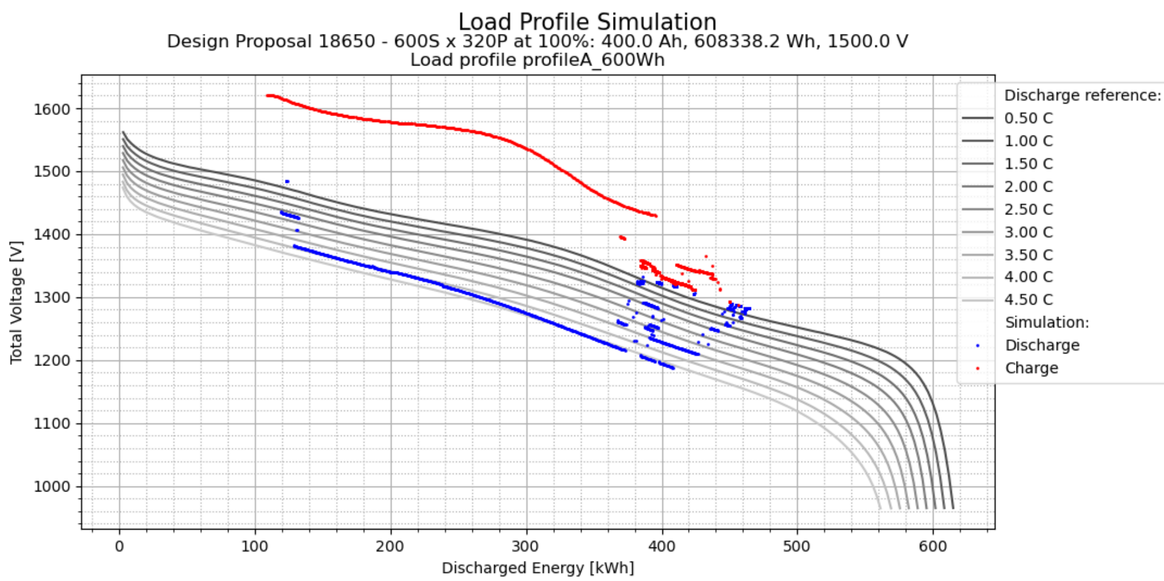
Hybrid powercapacitors

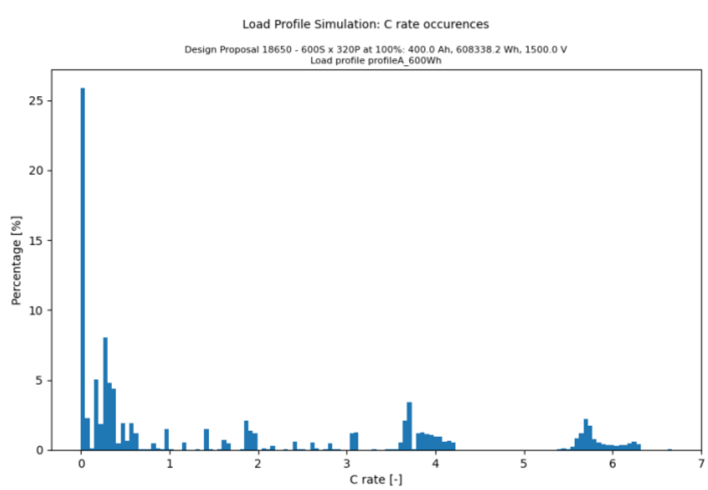
Electricity can mainly be stored in batteries and capacitors. While batteries rely on a chemical reversible reaction (so-called redox reaction), (super)capacitors store the electric charges physically. This allows them to be charged and discharged very fast but they cannot store that much energy. Hybrid powercapacitors are a blend between these two types of devices. They store the charges like a supercapacitor, the anode uses the intercalation process like a Li-ion to store charges and the cathode stores charges like an EDLC. The result is a device that has good power capabilities with adequate energy storing capability. They inherit the safety, long lifetime and thermal properties of supercapacitors. As no dendrites can develop, the failure mode is "open-circuit" and hence no cell will short-circuit and deflagrate.

Hybrid powercapacitors can operate from -40°C to 80°C. In this temperature range the battery remains operational but below 0°C the instantaneous capacity is reduced. The capacity at low temperatures is not really lost and comes back due to self-heating if the battery is under load. The battery has at the start of its life 20000 cycles (till 75% capacity remaining). Even when capacity is lost over the years, it can still deliver the required power, although degradation then accelerates. Another advantage of hybrid power capacitors batteries is that there is no need for a BMS. This is addressed by a "parallel-first then serial" interconnection topology. This reduces the complexity and the probability of failure. And in contrast to Li-ion batteries there will be no formation of dendrites, this means that there will be no short circuit after the battery ages and no spontaneous combustion. The failure mode of a cell is open circuit, resulting in a resilient battery. Some capacity will be lost, but the battery remains operational. This makes for a good start in a fail-safe design.

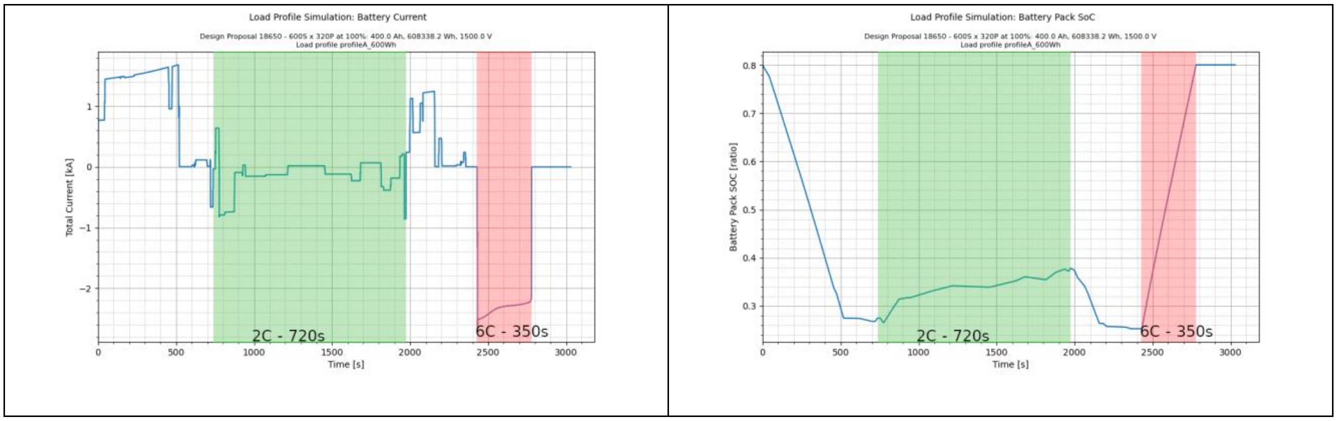
Simulating the driving profile

The complete driving cycle above would require 715 kWh over 45 minutes. It is impossible to have a battery to drive a truck for an entire day. With possibly up to 28 cycles a day this would require a battery of 20MWh. Such a battery would be larger and heavier than the payload of the truck. Having a vehicle at rest for charging after one haul trip is an expensive solution as there needs to be twice as many vehicles (one in action, one charging) and it would require a serious power plant on the mining site. There are many possible solutions but we will only discuss a solution with charging infrastructure on the permanent part of the road. The battery has to be charged during the trip to minimize the truck round-trip time. On this driving profile, we can charge for about 720 seconds while driving. The rest has to be charged while queuing at the dig site. While a hybrid powercapacitor battery can discharge at 20C and charge at 12C, we take into account safety margins and aging effects. Hence, we charge at 2C on the road and at 6C while queueing to start a new trip. This also gives reasonable currents and constraints on the charging infrastructure. The first graph is a Voltage-Energy plot on the battery map. The next graphs show the expected current and evolution of the SoC (State of Charge) of the battery.



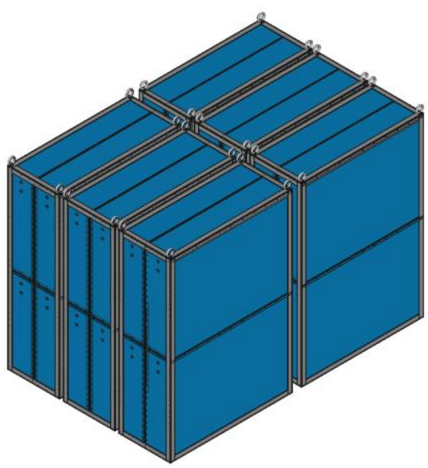


The C-rate is on average 2C with peaks up to 6.9C while charging and 4.4C while discharging. In general, the battery load is relatively low. This will increase as the battery ages but remains well within the maximum values.



The graphs above show the evolution of the current and the evolution of the SoC level of the battery for the selected set-up. If for example it would be feasible to charge with higher currents on the overhead charging segment, then the end-of-trip charging time can be further reduced.

A modular battery



The battery is constructed from 24 modules, divided over 4 lifting frames, resulting in compactness and modularity. Each frame contains four 25kWh modules. They will fit in a 2.6m x 1.8m x 1.9m space. The proposed solution requires 9 m³ with a total mass of 13 ton.

The design gives flexibility in the use of the battery. It is possible to change only one frame or module. In addition, it makes it easy to scale the solution to larger truck sizes by using more modules.

The battery should work in the range from 20 to 80% SoC. In this range the battery can optimally charge fast and have spare capacity when the trip deviates. The estimated calendar lifetime is at least 2.8 years (till 75% capacity) after 20000 cycles. This can actually be more as the driving and charging profile keeps the battery away from very high and very low SoC levels. However as we can expect higher environmental temperatures, that reduce the lifetime, we ignore this beneficial effect. Note that the battery still has sufficient capacity after 20000 cycles to complete a second life with 20000 cycles, for example to be used as a buffer battery at the charging point. This calculation assumes that the battery consumes 19 (battery) cycles per day. One could increase the size of the battery, but this would add to the weight and cost. A smaller battery would also be able to deliver the power, but then the C-rate would increase. Also by staying below 6C, no complicated cooling solution is needed, only an external forced airflow around the battery modules.

Conclusion

Hybrid powercapacitors are currently one of the best solutions for full electric and hybrid vehicles in demanding applications, such as mining environments. They are safe, have a long lifetime and reduce the operational cost. In this example, the charging times were reduced to about 5 minutes downtime over a trip of 45 minutes. Powercapacitor batteries are simple, requiring no BMS and no active cooling, resulting in close to zero maintenance yet providing robustness and the capability to be used in very cold as well as warm environments.

For more information:

www.kurt.energy