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Ultracapacitors in Port Applications

PEMA PAPER
2023

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Contents

1. Introduction

This paper is intended to provide information about ultracapacitor technology and the implementation of energy storage systems (ESS) for rubber tyred gantry (RTG) cranes or other port equipment based on this technology. It highlights the issues and options that ports and terminals should consider during the selection process and lays out the benefits as well as the limitations of such technology.

1.1 Disclaimer

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2. Executive Summary

Ports around the world are exploring ways to reduce emissions and optimize their use of energy resources. In addition, local communities in the vicinity of port facilities are increasing pressure for the introduction of new environmental regulations to reduce emissions.

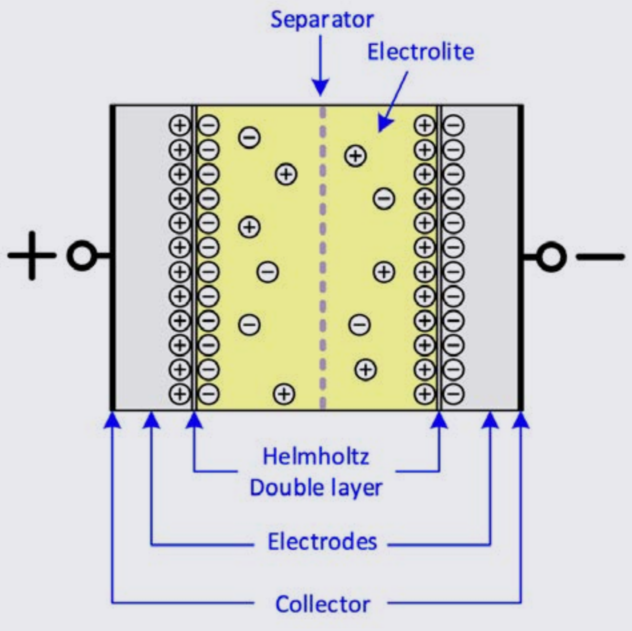
This paper describes one technology – energy storage using ultracapacitors – designed to achieve these goals on the diesel-powered RTGs that are widely used at many container terminals.

3. Ultracapacitor Technology

Ultracapacitor is a blanket term for electric double-layer capacitors, electrochemical capacitors, and electrochemical supercapacitors. Ultracapacitors store electrical energy, or charge, in an electric double layer of opposite polarity (Helmholtz double layer) at the interface of the electrode surface and the electrolyte. This molecular dielectric mimics a capacitor by storing charges electrostatically.

An electric double-layer capacitor, shown in ***Figure 1***, is constructed with an anode and a cathode which are mechanically divided by a separator, and are ionically connected to each other by an electrolyte. These electrodes are typically made of porous material such as activated carbon with a high specific surface area. The ability to manage high peak current is directly proportional to the size of the electrode's pores. However, the specific energy is inversely proportional to the size of the pores. This characteristic results in application-specific engineering trade-offs.

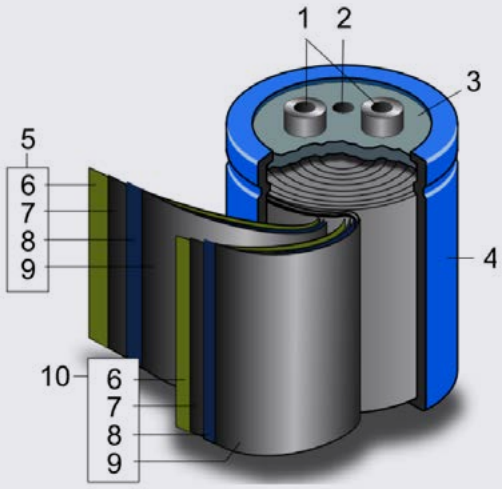
Fig. 1: Electric Double Layer Capacitors



The energy is stored electrostatically and can be used millions of times **with no chemical reactions**. This is a significant difference when compared with battery technology, which depends on a chemical reaction that eventually degrades the battery and shortens its lifetime. Furthermore, the rate of the chemical reaction process limits the rate at which energy can be delivered from or stored in batteries.

The ultracapacitor differs from a normal capacitor due to its very high capacitance rating and its power density. Ultracapacitor electrodes use a different material – carbon – that is very porous, resulting in a high surface area and a very thin dielectric, enabling a very large capacitance and storage capacity. ***Figure 2*** shows a typical cylindrical Ultracapacitor construction.

Fig. 2: Typical Ultra-Capacitor cell structure [1]



1. Terminals
2. Safety Vent
3. Sealing Disc
4. Aluminum Can
5. Positive Pole
6. Separator
7. Carbon Electrode
8. Collector
9. Carbon Electrode
10. Negative Pole

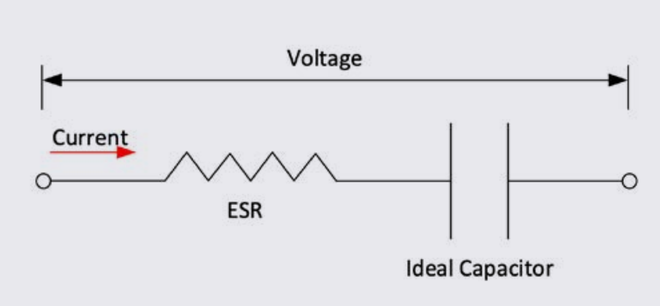
The efficiency and thermal performance of an ultracapacitor can be analyzed on the basis of its equivalent circuit. The equivalent electrical circuit of the ultracapacitor is shown in ***Figure 3***, where the Equivalent Series Resistance (ESR), represents the Ohmic losses caused by the non-ideal properties of the materials used to build the ultracapacitor.

The ESR is the sum of the resistances of the terminals, the aluminum foil current collectors, the microscopic boundary gap between the electrode carbon layer, and the carbon structure of the electrodes [2].

The contact resistance represents approximately 50% of the total ESR. The total ESR value includes the 'pore resistance,' an effect that increases at lower frequencies.

Practical values are obtained by measuring contact resistance at 100 Hz, and the total ESR at 0.1 Hz [2]. When evaluating heat losses of the ESS (Energy Storage System) for RTG applications, the total ESR must be considered.

Fig. 3: Ultracapacitor cell, equivalent circuit



The losses in the ultracapacitor cell are represented by the following expression:

Equation 1

$$P_{loss} = I^2.\mathrm{ESR}$$

Where:

I: Current flowing through the ultracapacitor in [A]

ESR: Ultracapacitor Equivalent Series Resistance in [Ω]

Due to the electrolyte characteristics, typically the ESR is nearly constant in the upper-temperature range [3]. At higher temperatures, the viscosity of the electrolyte is reduced, which improves the mobility of the ions. In the case of a controlled current, this phenomenon helps constrain losses at higher temperatures and avoids a thermal runaway situation.

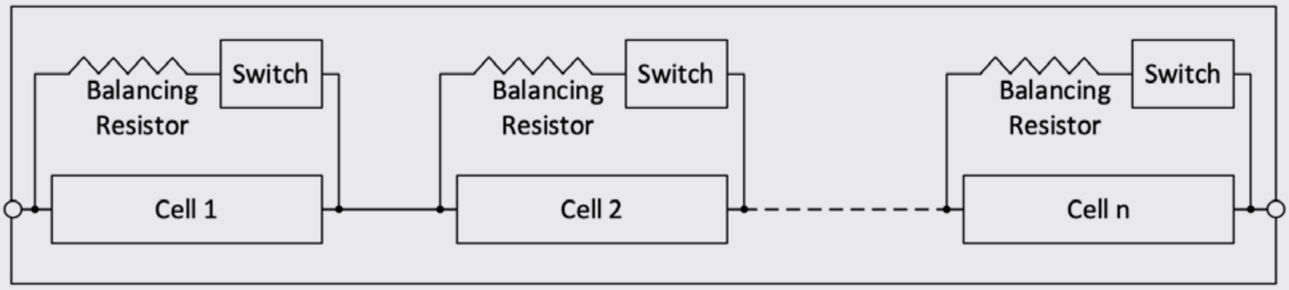
A typical capacitance of an ultracapacitor cell is 3000 F, having a rated voltage of 2.7 V with a typical DC ESR value of 250 μΩ.

To achieve higher operating voltages, ultracapacitors are provided in modules with multiple cells in series. The ESR of a module is the sum of the ESR of each individual cell connected in series. The net capacitance of the module is given by the cell capacitance divided by the number of cells in series.

Multiple-cell ultracapacitor modules include balancing resistors to help with equalizing the voltage between the series-connected cells while minimizing the risk of over-voltages in any single cell. Such a multiple-cell configuration normally includes temperature and voltage monitoring features that provide data that can be transferred to a controller via a LAN interface.

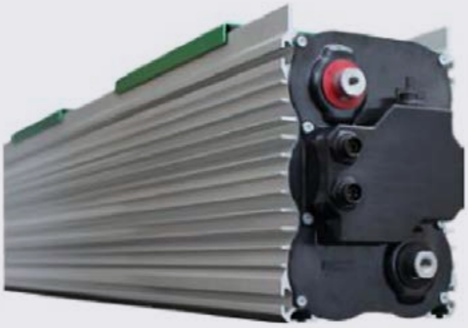
There are various circuit configurations used to balance the voltage across series-connected capacitors. One method is to connect the balancing resistor across each cell with an electronic switch. In this configuration, when the voltage across the cell exceeds a pre-set threshold, the balancing resistor is connected. When the voltage drops below a lower pre-set threshold, the balancing resistor is disconnected. This results in a reduction in losses.

Fig 4: Ultracapacitor Module



A second balancing circuit method includes permanently connected balancing resistors. Since the resistors are always connected, balancing is provided even at low voltages. This method represents a simpler, passive circuit.

Fig. 5: Ultracapacitor Module (from IOXUS)



To achieve certain energy storage capacity and voltage levels, the ESS may require an array of ultracapacitor modules including multiple strings of modules connected in both series (to obtain the desired voltage rating) and in parallel (to achieve the desired energy storage rating).

The net capacitance of the ESS is given with the following expression:

Equation 2

$$C_{net} = C_{module} \cdot \frac{N}{n}$$

Where:

C_{module}: capacitance of the module in [F]

N: number of strings connected in parallel

n: number of modules connected in series in each string

4. Energy Density versus Power Density

Energy density is the amount of energy that can be stored per unit weight, while ***power density*** is the instantaneous power that can flow to and from the device (to charge and discharge the device) per unit weight.

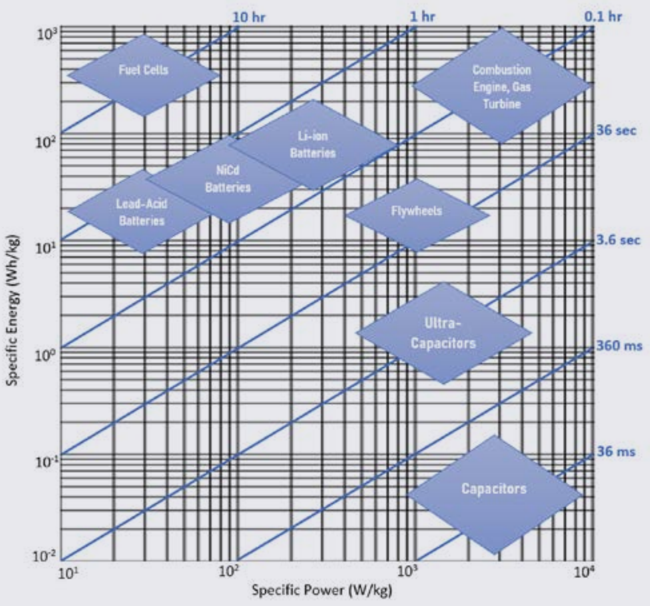
Ultracapacitor energy density is approximately 5% of the energy density that can be achieved with lithium-ion batteries. Therefore lithium-ion batteries can store 20 times more energy than ultracapacitors having the same weight. Battery life span depends on the Depth of Discharge (DOD) as well as the frequency of the charging/discharging cycle [4]. To increase the battery energy life span, either the DOD must be limited or the battery kWh capacity must be increased [4]. This tradeoff in DOD or kWh capacity means that the full advantage of the higher energy density of a battery may be reduced by a factor somewhere between two and three.

The higher power density of Ultracapacitors, when compared to lithium-ion batteries, can be explained by the C-rate, defined as the ratio of the maximum battery current in [Amps] divided by the battery capacity in [Ah]. For lithium-ion batteries, the maximum C-rate is typically limited to 6, being a function of the chemical reaction rate within the battery. This C-rate parameter defines the maximum power the battery will be able to deliver or absorb, and therefore its power density. Ultracapacitors do not depend on chemical reactions and their power density is limited only by their internal ESR. Therefore, ultracapacitors can provide in excess of 10 times more power density than lithium-ion batteries [5].

Figure 6 (adapted from [6]) is a Ragone plot that provides an indication of energy versus power density for different technologies. The plot highlights how ultracapacitors have the lowest energy density but the highest power density.

This characteristic makes ultracapacitors the optimum devices for applications where a load cycle is frequently repeated and requires high peak power demand compared with the average power demand value. This is typical of a hoisting application as experienced in RTGs.

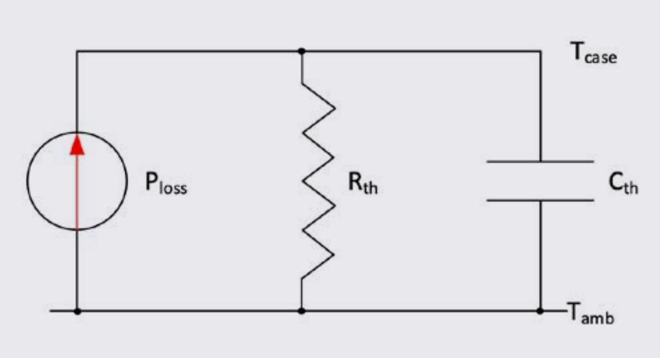
Fig. 6: Energy and Power density (adapted from [6])



5. Thermal Management

A typical ultracapacitor module thermal equivalent circuit is shown in *Figure 7*. In the case where a constant current flows through the ultracapacitor, the temperature rise is calculated based on *Equation 3*.

Fig. 7: Typical Thermal Circuit



Equation 3

$$\Delta T = I^2 \cdot \mathrm{ESR} \cdot R_{th}$$

Where:

R_{th} *is the device thermal resistance in °C/W*

C_{th} *is the device thermal capacitance in W.s/ °C*

T_{amb} *is the ambient temperature in °C*

T_{case} *is the ultracapacitor module case temperature in °C*

In the case of an RTG application, the RMS current value which results during a typical operating cycle may be used as the constant current. This is permissible as the thermal capacitance of the equivalent thermal circuit is high and will therefore filter the associated temperature transients.

The thermal resistance depends on the construction of the ultracapacitor. In general, ultracapacitor modules include multiple cells in an aluminum case that has fins. These fins increase the contact area with the surrounding air, which minimizes the thermal resistance.

Ultracapacitors have a wide operating temperature range from -40 °C to +65 °C. Utilization at an average operating temperature around 25 °C will maximize module life [7].

Because they function consistently across a wide range of operating temperatures, ultracapacitors generally do not require HVAC units to maintain the operating temperature within a narrow range. In practice, they can typically be cooled by the ambient air. Because the energy required to run HVAC units is provided by either the diesel generator or the ESS system, therefore eliminating HVAC can contribute to additional energy savings. This is particularly the case where the HVAC must be kept ON permanently to maintain the battery temperature at 25 °C. Furthermore eliminating the HVAC units also eliminates the associated maintenance costs.

6. Life Span

The life span of the ultracapacitor module is normally defined by the manufacturer under certain ambient temperature conditions and operating voltages. The life span is typically in excess of 1 million cycles at 25 °C with voltage level variations from rated to half of the rated voltage. Reference [8] is a typical datasheet from an ultracapacitor manufacturer.

The main factors influencing life span are the average operating temperature and the average operating voltage. Higher temperatures and higher voltages adversely affect the life span of ultracapacitors.

Optimal sizing of the ultracapacitor bank for the operating cycle results in an optimized RMS current such that the case temperature is maintained within a range that will ensure the required system life. Similarly, the size of the system is designed to ensure a reasonable average operating voltage.

Ultracapacitor manufacturers normally help estimate the lifetime based on the data provided for given operating conditions. Ultracapacitor-based ESS for RTG systems, for example, can be designed to support a minimum of 20 years of operation.

Since ultracapacitor design is based on over 1 million cycles, the aging of ultracapacitors is gradual. This degradation is reflected in increased module ESR and decreased capacitance. For system design purposes, end of life is reached when the ESR has reached twice its nominal value or when the capacitance has reduced to 80% of its rated value. It should be noted that even in this condition, the ultracapacitor will continue to function, but with reduced performance. Systems that use ultracapacitors should be designed to operate with this reduced output condition by limiting overall system performance where necessary (ex. reducing hoist speed).

Ultracapacitors can be fully discharged, which has a positive impact on shelf life.

7. Safety and Maintenance

During maintenance, ultracapacitors can be fully discharged where the ESS incorporates a switch to connect a resistor across the capacitor bank. Where applied in Hoisting applications, the DC-DC converter can dissipate the stored capacitor energy through the dynamic braking resistor.

By totally discharging the ultracapacitors, maintenance personnel can safely work in the system.

Excessive over-voltage or over-temperature conditions can cause ultracapacitor cell failure. In these circumstances, gas may be produced, and pressure built up within the module. However, ultracapacitors designed to meet SAE J2464 Hazard Severity Level (≤5) incorporate a venting mechanism to allow that gas to safely escape. Potential hazards such as explosion, arcing, or fire, therefore, do not exist. The gas is simply released, while some liquid electrolyte may drip out after such an event.

Figure 8 shows an ultracapacitor module subject to an overvoltage test resulting in the activation of the venting mechanism. The visible black substance is leaked electrolyte.

Fig. 8: Ultracapacitor Under Overvoltage Test

By comparison, Lithium-ion batteries cannot be totally discharged for transportation, storage, or maintenance. They pose a high risk of explosion and fire since they contain a flammable liquid electrolyte. A thermal runaway condition can cause an explosion should the electrolyte start to boil and the associated steam cannot escape the battery container. A fire caused by a Lithium-ion battery is quite difficult to extinguish as it is self-sustaining [9].

8. Storage and Transportation

Because ultracapacitors can be fully discharged, they can be safely transported and, if discharged, do not present any risk of accidentally releasing energy that could cause damage or personal injuries.

On the other hand, there are many restrictions on the transportation of Lithium based batteries considering they must be transported with a certain level of charge. Lithium batteries are regulated as a hazardous material under the U.S. Department of Transportation's Hazardous Materials Regulations (49 C.F.R., Parts 171-180).

A fully discharged ultracapacitor has a storage temperature range from -40 °C to +70 °C without losing capacity. This is a significant advantage over Lithium-ion batteries, which continuously lose capacity during storage even when temperature and state of charge (SOC) are carefully controlled during storage [10].

In summary, because ultracapacitors can be fully discharged, they can be handled safely during transportation, installation, and maintenance.

9. Disposal

Appropriate federal, state, and local regulations must be followed for the proper disposal of ultracapacitors.

Manufacturers provide a safety data sheet (SDS) that, in consultation with relevant authorities, includes the necessary information for disposal.

SDSs from some ultracapacitor manufacturers indicate that, according to federal regulations, disposal can occur only in permitted facilities.

10. Summary of Ultracapacitor versus Battery Technologies

The following tables compare the performance parameters of ultracapacitors versus Lithium-ion batteries (adapted from [11]).

Parameter	Double Layer Capacitors	Lithium-ion Batteries
Temperature Range, degrees Celsius (°C)	-40 to +70 °C	-20 to +60 °C
Maximum charge, volts (V)	1.2 to 3.3 V	2.5 to 4.2 V
Recharge cycles, thousands (K)	100k to 1000k	0.5k to 10k
Specific energy, watts-hours per kilogram (Wh/kg)	1.5 to 3.9 Wh/kg	100 to 265 Wh/kg
Specific power, watts per gram (W/g)	2 to 10 W/g	0.3 to 1.5 W/g
Self-discharge time at room temperature	Medium (weeks)	Long (months)
Efficiency	95%	90%
Load Cycles	1.000.000	5,000
Working life at room temperature, years (y)	5 to 10 y	3 to 5 y
ESR (per Cell)	0.25mOhms	18mOhms
Charge/Discharge Rate (W/Wh = C)	1250 -1500C	1 - 6C
Charge time	1 to 10 seconds	10 to 60 minutes

11. Standards

The applicable standard in the US for ultracapacitors is the UL810A, the UL Standard for Safety Electrochemical Capacitors. It includes the requirements for ultracapacitors used as energy storage capacitors.

In addition, the DC-DC converters and associated equipment are covered by UL 61800-5-1, the UL Standard for Safety for Adjustable Speed Electrical Power Drive Systems. This standard supersedes the UL508C.

In Europe the following standards apply to ultracapacitors:

- RoHS: Directive 2002/95/EC, 2011/65/EU 2)
- RoHS 2: Directive 2011/65/EU 3)
- RoHS 3: Amendment to Annex II Directive 2015/863/EU

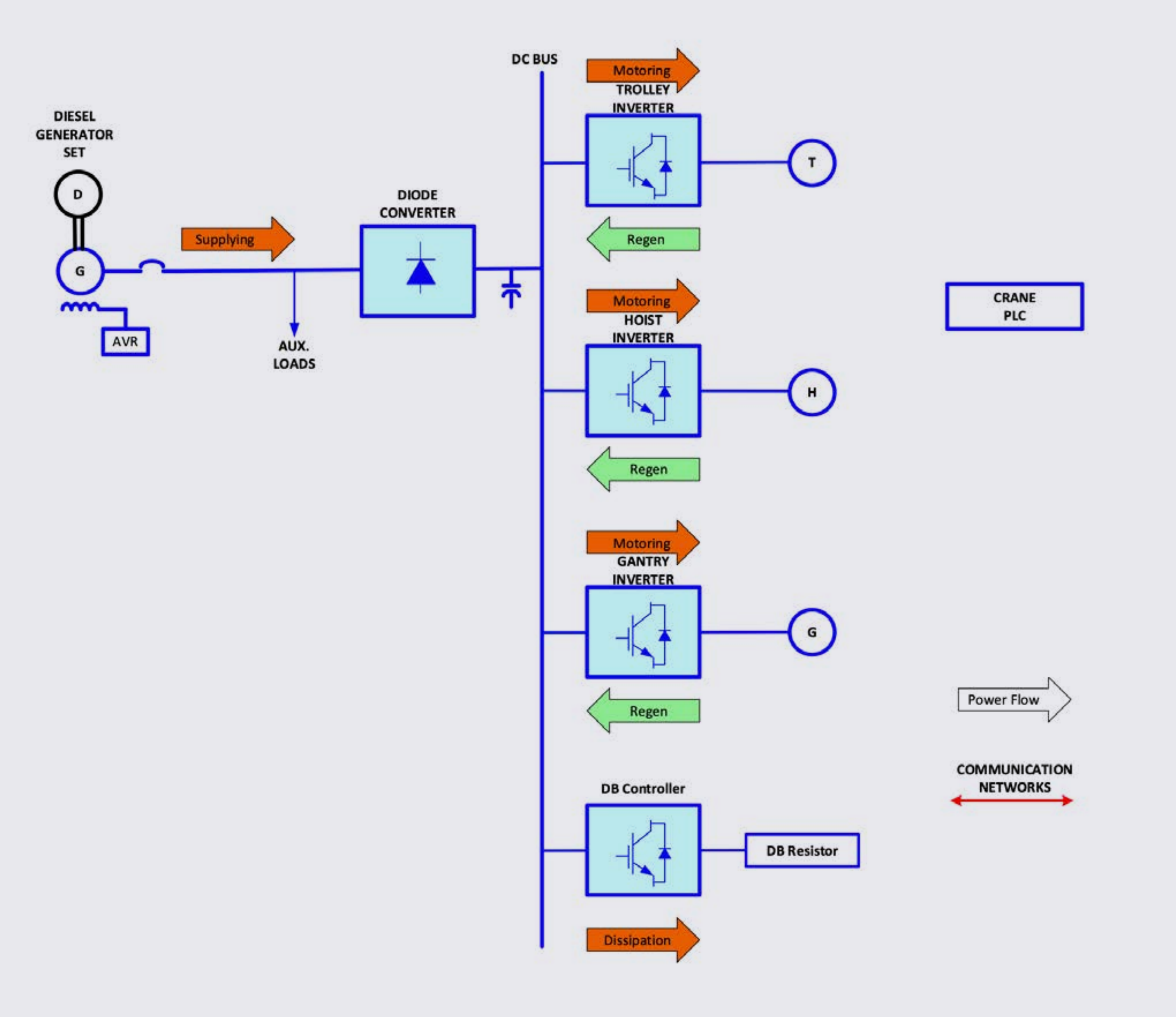
12. Application of Ultracapacitors as an Energy Storage System for RTG Cranes

In the standard RTG system, as shown in *Figure 9*, the diesel generator and the AC to DC converter must be sized to support the peak power demand of the crane.

A typical RTG system uses a 400 - 450 kW diesel generator set to achieve the handling of 40LT to 50 LT loads at 26m/min to 31 m/min hoisting speeds. In addition, the dynamic braking resistors (DBR) must be capable of dissipating the energy regenerated by the hoist while lowering a fully loaded container.

While the crane is idling, waiting for the next container, the generator is running almost unloaded, with the power demand of auxiliary loads being approximately 10 to 20 kW. This represents a very inefficient operating point on the performance curve for such a large diesel engine.

Fig. 9: Standard Diesel-Powered Crane System



Using an ESS will allow the system to store the energy while lowering the load and to reuse that energy while hoisting or for trolley and/or gantry movement. This has the effect of eliminating the need to dissipate the regenerated energy in the DBR. The greatest benefit of the ESS, however, is that the size of the diesel generator set can be significantly reduced, as most of the required energy while lifting is supplied by the ESS. Whereas previously, the diesel generator was sized for the peak load required during the hoisting motion (i.e. 450 kW), the diesel generator may now be sized for the average power demand during the entire operation cycle, typically 120 kW. This makes for a more efficient system and, generally, reduced emissions. Reference [12] provides a comparison of emissions requirements (gains) based on engine size (kW) and their designated tier standards.

Existing cranes can be retrofitted and converted to a hybrid configuration by installing a smaller diesel generator set and an ESS. This hybrid configuration requires a common DC bus to supply power to all motion inverters. If a common DC bus is not available because the existing inverters are all individual AC/AC inverters with built-in rectifiers, generally such inverters have DC input terminals available and can be connected to run on a common DC bus. In this case, since the diesel generator power is reduced, the AC/DC rectifier of the Hoist inverter can be used to provide power to the DC bus.

Figure 10 shows an ultracapacitor-based ESS.

Weight and Dimensions of the ESS unit shown in this example are: 2700 kg, 2520 mm W x 1050 mm D x 1935 mm H.

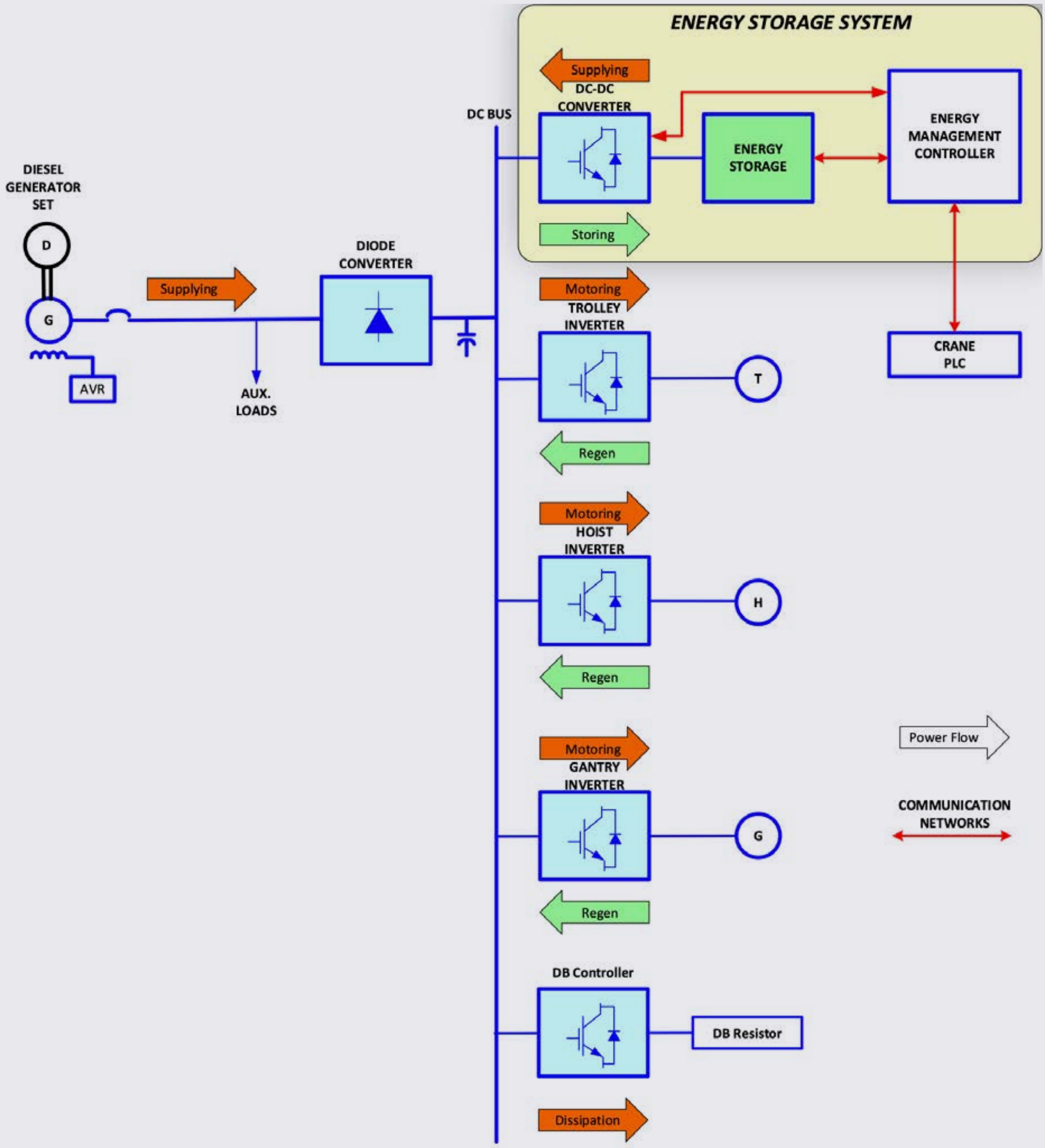
Fig.10: ESS based on Ultracapacitors

12.1 System Architecture

Figure 11 illustrates the hybrid system architecture. In this example, all the inverters feeding the crane motors connect to a common DC bus.

The diesel generator set feeds the common DC bus through a diode converter, and the ESS connects to the common DC bus through a DC-DC converter.

Fig. 11: Hybrid System with Ultracapacitors as Energy Storage



The Energy Management Controller (EMC) has the following functions:

- Controlling the power flow from:
  - the diesel generator set (achieved by modifying the DC bus voltage with the DC-DC converter) and
  - the ESS to satisfy the total power either required for or regenerated by the crane motions.
- Communicating with the ultracapacitor modules to monitor the temperature and voltage across each module and provide alarm signals.
- Communication with the PLC to transfer variables required for sequencing, protection, and display on the crane monitoring system.
- Calculate the maximum hoist lifting and lowering speeds, based on the gross load being handled and the status of the ESS. In the event that the ESS and the diesel generator cannot provide enough power, or the ESS and the DBR cannot absorb and dissipate enough power, the RTG will continue to operate at reduced performance. This situation should only occur at the ultracapacitor end of life or under certain rare operating sequences.
- Calculate the ESS equivalent capacitance and ESR in order to monitor the status of the ESS and signal the end of life.

The DC-DC converter of the ESS, typically a boost converter, is controlled by the EMC and regulates the common DC bus voltage.

The primary criterion for sizing the diesel generator is to supply the average power required by the worst-case operation cycle. A secondary criterion for sizing the diesel generator is to provide sufficient power for moving the gantry in the worst-case wind and slope conditions, considering the ESS contribution will be available only during acceleration.

When the diesel-generator power has been selected based on the above, the ESS must be sized to ensure that the energy available from the ESS plus the diesel generator is sufficient for hoisting the rated load at the rated speed. The ESS end-of-life capacitance value is used for this calculation (80% of nominal). ***Equation 4*** is used to estimate the minimum ultracapacitor bank capacitance.

Equation 4

$$\frac{Ld \cdot Dist}{\eta} = \frac{1}{2} C \cdot \left(V_{max}^2 - V_{min}^2\right) + \left(P_{gen} - Aux\right) \cdot t_{lift}$$

Where:

Ld: is the gross load weight in [N]

Dist: is the maximum hoist traveling distance in [m]

η: *system efficiency*

C: ultracapacitor capacitance at end of life in [F]

V_{max}: *maximum ultracapacitor possible voltage (it is below the DC bus voltage) in [V]*

V_{min}: *minimum target ultracapacitor voltage that, based on DC-DC converter rated current, will satisfy, together with the generator, the peak power demand, in [V]*

P_{gen}: *Generator rated power in [W]*

Aux: Auxiliary loads power in [W]

t_{lift}: *time for lifting the load in [sec]*

Multiple ultracapacitor modules are connected in series as a string to achieve an acceptable voltage rating with margin. Multiple ultracapacitor strings are connected in parallel to achieve the required capacitance.

12.2 Operation Mode

The ESS will absorb energy when the hoist is lowering and provide energy when the hoist is lifting the load or empty spreader. The EMC calculates, based on the hoist position, a target energy to be stored in the ESS.

Equation 5 shows the ultracapacitor's available energy.

Equation 5

$$\Delta E_{UC} = \frac{1}{2}C.\left(V_t^2 - V_{min}^2\right)$$

Where:

C: is the capacitance

Vt: is the targeted voltage

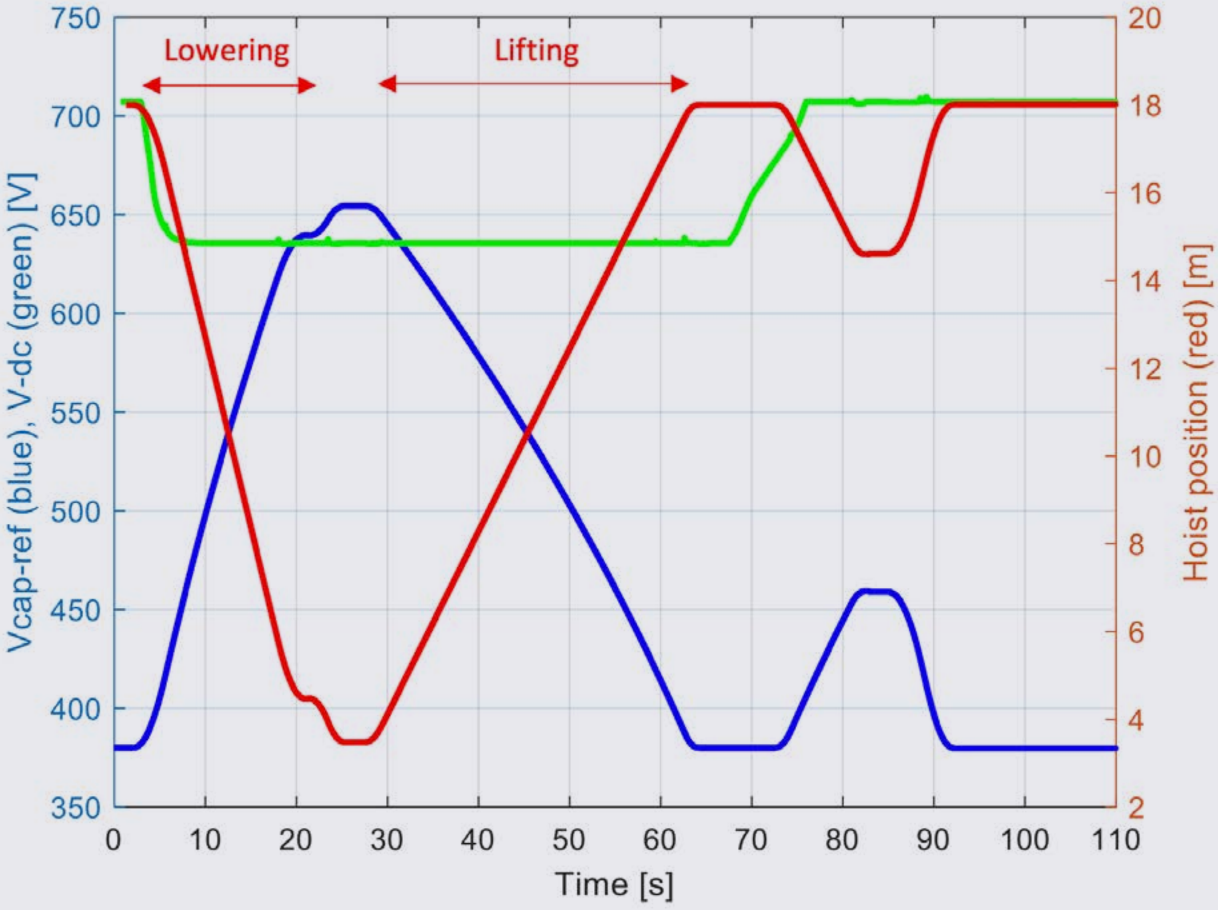
Vmin: is the minimum voltage

The EMC continuously measures the capacitance.

The maximum available targeted energy corresponds to the lowest hoist position to ensure that the ESS will be able to provide the energy required to raise the load to full height. At the highest position, the targeted available energy would be zero, although in practice even at the highest position the capacitor has energy stored since the voltage is not zero. At the highest position, the ESS is ready to absorb the energy regenerated while the hoist system is lowering. In this way, the DBR does not need to dissipate (waste) the regenerated energy.

Figure 12 shows the ultracapacitor voltage reference versus the hoist position. The figure also shows how the DC bus voltage fluctuates. This is typical for diode converters.

Fig.12: DC Bus and Ultracapacitor voltage reference. Hoist position (from ground level)



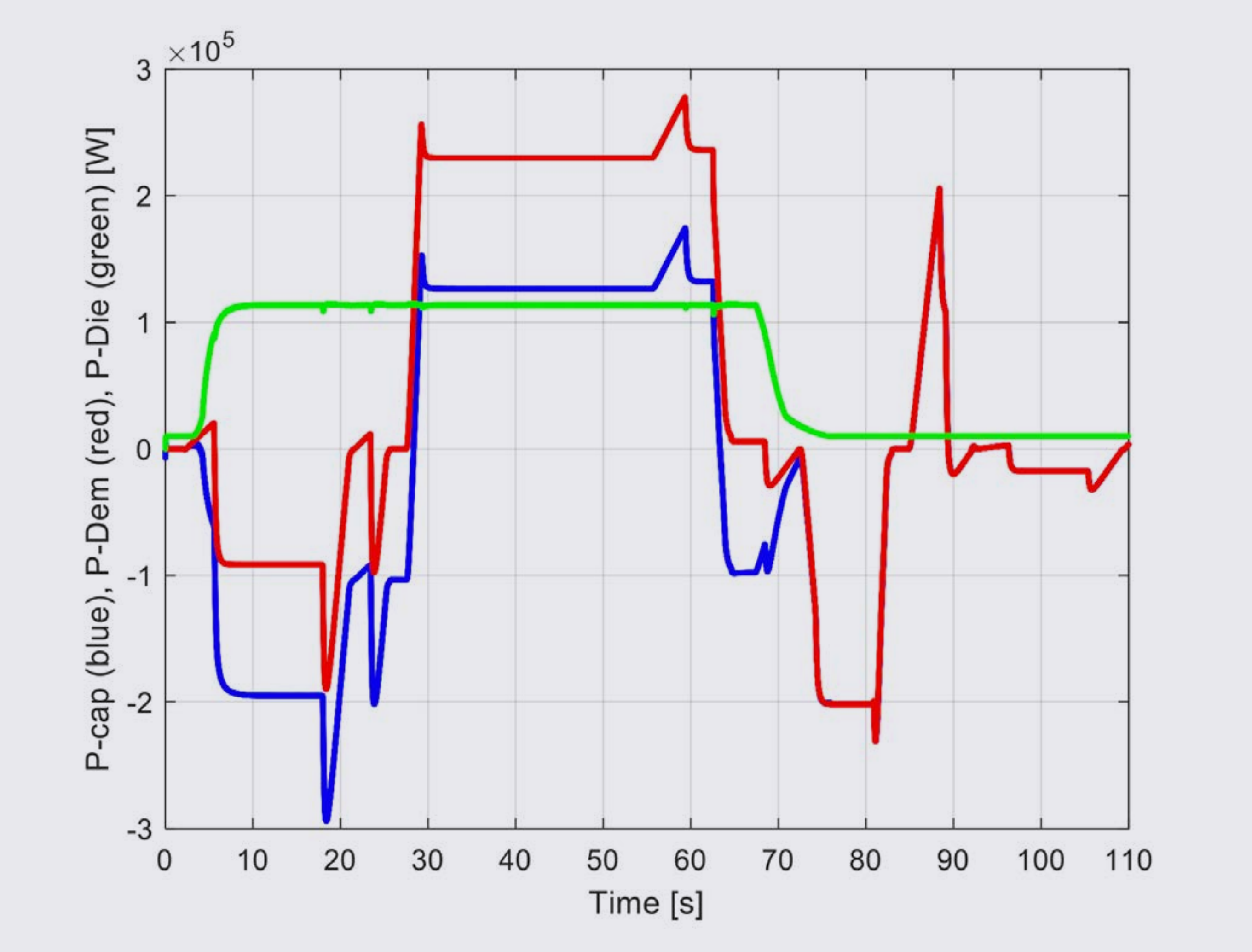
The minimum voltage determines the power that DC-DC converter will be able to deliver at the highest hoist positions.

Figure 13 shows the results for a typical operating cycle (as shown above) on a time vs power flow trend graph. Initially, the spreader is lowering empty at full speed. At the time of approx. 27sec, a 40 T container is locked, and the hoist starts lifting the container. At the time of approx. 73 sec, the fully loaded container is lowered to the corresponding stack

The green trace corresponds to the power contribution from the diesel generator set (always positive), and the blue trace is the contribution from the ESS (negative while storing energy and positive while delivering energy to the common DC bus). Finally, the red trace is the total power demand from the hoist, trolley, and gantry (in this example trolley and gantry are not moving).

It can be observed that the diesel generator delivers the average power demanded during the cycle and delivers that power at its rated output, resulting in a more efficient performance. In contrast, the ESS system dynamically absorbs or delivers power to satisfy the dynamic requirements of the cycle. While the peak power demand gets close to 300 kW, the diesel generator set contributes only 120 kW, its rated power while the ESS provides the remaining power. This level of performance is achieved by the EMC system algorithms.

Fig. 13: Power flow



12.3 Fuel Savings

The use of the ESS allows for a substantial reduction in the size of the diesel generator from the typical 450 kW to approximately 120 kW. The base losses of a smaller diesel generator are much less than those of the larger generator set. These reduced losses are the main contributor to fuel savings while additional saving is achieved by storing and reusing the regenerated energy.

Consider a typical 40 T RTG with an average load of 20 T operating at fifteen cycles per hour (which includes 24 minutes of idle time). In this case, approximately 60% fuel savings can be achieved by using the smaller diesel generator set in conjunction with the ultracapacitor-based ESS when compared to the larger diesel generator without an energy-saving system [13]. *Figure 14* illustrates the reduction in Diesel power demand over several cycles.

Further fuel saving is possible by using a variable or a two-speed diesel generator, which facilitates running the engine at a lower speed when the crane is idling. The lower-speed operation reduces friction losses and fuel consumption. In this case, a dedicated inverter with a sinewave filter at its output is required to supply the RTG auxiliary loads with a constant voltage and frequency.

12.4 Cost of Ownership Comparison - Ultracapacitors vs. Battery

Cost of ownership can be split into three categories: installation, operation, and maintenance.

12.4.1 Installation Cost

The installation and equipment costs of an ultracapacitor-based ESS is comparable to a battery-based system.

12.4.2 Operation Cost

An advantage of a battery-based ESS, in respect of operational cost, is that because batteries have a higher energy density, a battery-based system can power the RTG when it is idle without operating the diesel generator.

The advantages of the ultracapacitor-based ESS are: Generally, an HVAC system is not required, either during the operation of the RTG or during idle time and when properly sized, the lifetime of ultracapacitors is 20 years, while batteries may need to be replaced after 5 to 8 years of operation.

Fig. 14: Diesel Power demand with and without energy storage

12.4.3 Maintenance Cost

The performance degradation of ultracapacitors is gradual and should there be a failure of a single unit, then, that unit can be safely replaced instead of replacing the entire string.

Because ultracapacitors can be fully discharged, the cost associated with transportation, storage and handling is lower than with Lithium-based battery systems. The risk of explosion and fire posed by batteries may impact insurance costs.

12.5 Part Replacement

Individual ultracapacitor modules can be safely replaced provided that the complete bank is properly discharged with all the units at zero voltage.

It should be noted that before an ultracapacitor module is replaced, it is important to verify the capacitance of the remaining units. Large differences in capacitance values will affect the voltage balancing in the string of capacitors where the new units are installed. If the new module has a higher capacitance than the remaining modules in the string, the older capacitor modules will experience higher voltages when the string is charged.

Fig. 15: Ultra- Capacitor Energy Storage System

12.6 Technical Data

Illustrated below is a typical 100kW Liquid cooled Ultra Capacitor storage system including technical specifications.

Technical Data	
Storage medium	Double layer capacitors
Energy content	1,5 MJ
Storage capacity	15 F
Power discharge	100 kW / 15 seconds
Input voltage range	530 V ... 850 V DC
Control voltage	+24 V
Operating temperature range	-30° C ... +45 °C
Protection class	IP 65
Cooling	Liquid
Dimensions (HxWxD)	1,150 x 800 x 1,100 mm
Weight	400 kg

13. Conclusion

Ultracapacitors and batteries are storage technologies each having strengths for different applications. Ultracapacitors are ideal where power demand is dynamic, where there are a high number of charge/discharge cycles, and where a long lifetime of the energy storage system is required.

RTGs equipped with an ESS based on ultracapacitor technology present the following advantages:

a. Smaller diesel-generator set rated for average cycle power reducing maintenance costs and fuel use (approximately 60 %).

b. Substantial reduction in emissions and noise.

c. No need for HVAC for the ultracapacitors.

d. Long system life as ultracapacitors store energy in an electrostatic field where there are no chemical reactions.

e. Improved safety resulting from the ability to totally discharge the ESS for maintenance, installation, storage, and transportation. This zero-energy state eliminates the risk of a sudden energy discharge or injury to personnel.

f. Wide range of storage temperatures without requirement for minimum SOC.

g. Lower cost for transportation and storage since there is no possibility of accidental energy release.

h. Long operating life; 20 years for a typical operating cycle.

i. No risk of fire or explosion.

j. Ultracapacitors are disposable or recyclable depending on local regulations.

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About the Authors and PEMA

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PEMA PAPER
2023

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