Battery & ultra-capacitor based energy storage vessel integration, capabilities, considerations and challenges

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Synopsis

Energy storage has been successfully used in numerous sectors, such as the automotive industry, and it is only recently that the benefits of advanced energy storage technologies are being considered or realised for marine vessels. That said, it should also be noted that some types of marine vessels are taking the lead in exploiting these technologies to bring real benefits to the vessels' operational profiles and capabilities. The main exploiters of these 'new' energy storage opportunities are ferries, mainly due to their operating profile which currently aligns with battery utilisation, charge and discharge characteristics. This has resulted in maturing of the marine sector energy storage technologies and topologies, increasing confidence and increased exploitation advantages. These advantages are also applicable to different vessel platforms such as drilling and naval platforms, bringing operational benefits, new modes of operation and integration challenges.

This paper will provide an overview of energy storage systems and describe current capabilities in terms of kW and kWh, and provide readers with considerations when integrating energy storage into marine vessels. Considerations will include types of applications, from high power, short duration to sustained power, long duration, and will describe the analysis required to optimise the energy storage asset and ensure adequate power system performance in terms of operational and common mode considerations when using pulse-width modulation (PWM) converters connected to battery or ultra-capacitor based energy storage systems. Common mode effects should not be overlooked as, if not duly considered, can lead to significant electro-magnetic compatibility (EMC) issues.

1. Introduction

Battery energy storage systems (BESS) have been available for a long time and the principles are not new. Take, for example, the traditional, rechargeable lead acid battery, first available circa 1860, with modern lead acid battery capacities and volumes of approximately 40Wh/kg & 100Wh/l[1] respectively. Contrast that to a modern lithium ion battery with a typical capacity up to 200Wh/kg & volume of 400Wh/l and you can see the evolution, given the current trend, which is perceived to continue to improve battery capacity. This increase in battery capacity without onerous weight and volumetric increase brings potential benefits in deployment and utilisation. In comparison, however, modern super-capacitors have capacities of approximately 3Wh/kg and 4Wh/l but have superior short-term discharge, temperature resilience and lifetime characteristics when compared to batteries, being able to withstand >1,000,000 cycles, irrespective of depth of discharge.

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Applying energy storage technology in the marine sector enables the following functionality, which includes, (but is not limited to) blackout support, black start, spinning reserve, pulsed power applications, silent operation and load levelling. The functionality enabled depends on the type of vessel and application, and influences the selection of the optimum energy storage solution. This is a non-trivial task and requires detailed understanding of the appropriate functionality, mission, potential energy storage types, conversion process (if any) and the impacts this conversion process may have on the wider power system. These topics will now be discussed.

2. Energy storage integration

2.1 Modes of operation

Typically, marine vessels incorporate multiple diesel generators, and / or gas turbines that provide power to the vessel services and main propulsion, depending upon vessel type and power requirements. Main propulsion can be provided via a coupling and gearbox to the main diesel engine (MDE), or alternatively by integrated full electric propulsion (IFEP) with direct drive power dense motors, or a combination of both, with modern systems having power take-off and power take-in (PTO/PTI) options to harvest or boost power from and to the prime movers. Figure 1 shows a typical offshore platform support vessel (PSV) with energy storage system added. The power system incorporates diesel generators providing power to the vessel services and electric propulsion with thruster motors. The service load and/or propulsion could be supplemented by the addition of the energy storage system.

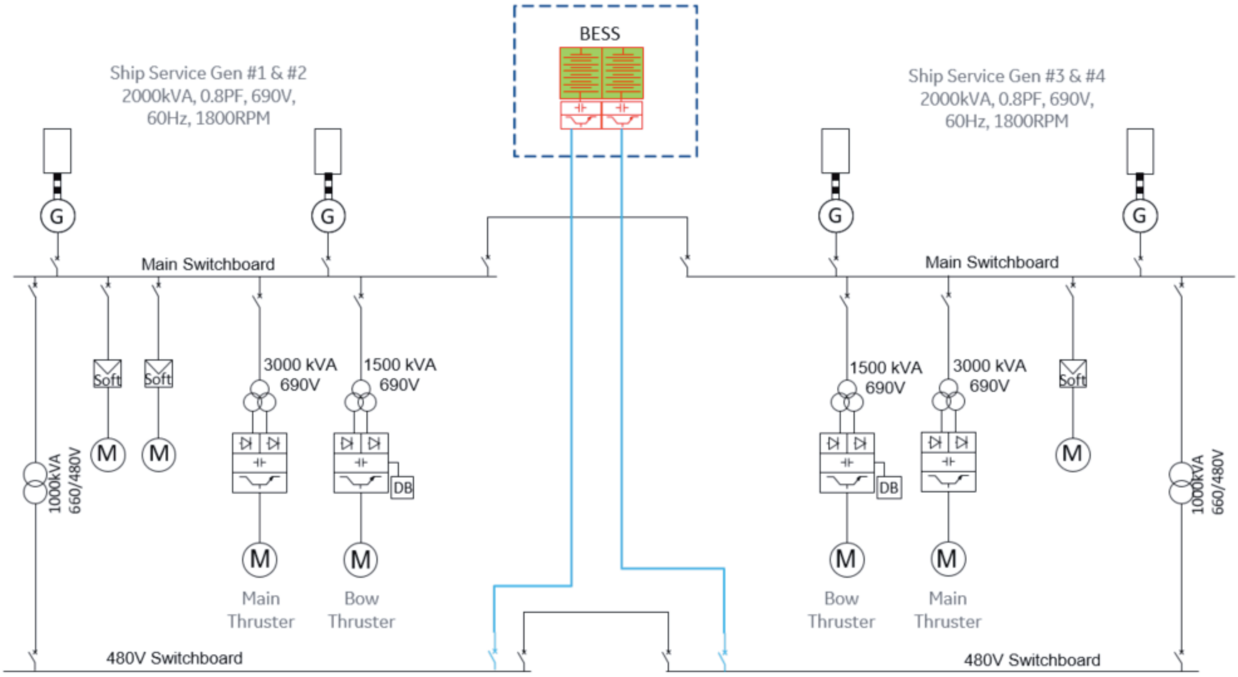


Figure 1 — Energy Store application to typical Power System, assigned to both switchboard sections

The BESS can either be integrated into the vessel, as the batteries provide flexible installation opportunities, or can be integrated into a self-contained module in the form of an ISO container. The energy storage system can be made available directly to the low voltage (LV) bus, or use the vessel transformers to facilitate the connection of the energy storage to higher voltage systems. This can bring operational advantages since the BESS performance may be improved by connecting to a lower voltage AC bus with the opportunity to 'back-feed' the higher voltage systems. This is mainly due to the battery energy store capability in respect of the converters and battery DC bus limitations, since AC/DC converters can exhibit a significant voltage drop across the pulse width modulation (PWM) input filters, which filter the converter high frequency PWM and provide a clean connection for bi-directional power transfer between the two AC busses.

For low risk operations, such as transit in calm sea states, the power system will operate in single island mode where one or more generators will be operating at optimum efficiency. For high risk operations, such as manoeuvring, replenishment at sea (RAS), combat situations, dynamic positioning, and station keeping, the power system would be operated in a split bus configuration, affording protection from entire vessel blackout should a failure or fault occur on one of the islands, with the user taking necessary actions to recover or curtail current operations. Coupled to this, advanced protection mechanisms are employed to ensure fault discrimination is afforded during single or split bus configurations, but maximum availability is provided by splitting the power system. Split or single modes of operation can incur significant operational overheads. Depending on the operational scenario, a minimum of two generators is required to be on-line, or, in the case of 'spinning reserve' usage, all available generation is required.

2.2 Spinning reserve

Figure 2 shows the principle of spinning reserve. When the generator loading margin is set to 100%, two generators will immediately operate so that should one fail the other will be loaded at 100%. However, during normal operation, each generator will only have a maximum loading up to 50% thereby not operating at maximum efficiency. Additionally, should the loading of two generators approach 50%, then the vessel power management system (PMS) will bring a third generator online, with each generator then able to operate up to 67% rated load, and so on. As more generators become available, the spinning reserve requirement from each generator drops, as shown by the grey shaded areas.

In October 2015, the class society DNV-GL included battery systems notation within its portfolio (Pt6 Ch2)[2] meaning that battery based systems can provide power to main or redundant systems providing that the status of the battery is considered and monitored. This effectively means that a battery based system can be considered as a power source, effectively a static generator with short term capability during discharge.

This 'spinning reserve mode', when using BESS should be considered holistically, and operation depends upon the vessel power requirements and duration of reserve. Typically, the battery based spinning reserve duration should be equal to the spinning reserve rating of the generator(s) it will support for approximately three to five minutes. This will allow the start-up of another reserve generator whilst the battery based system is supporting the spinning reserve mode.

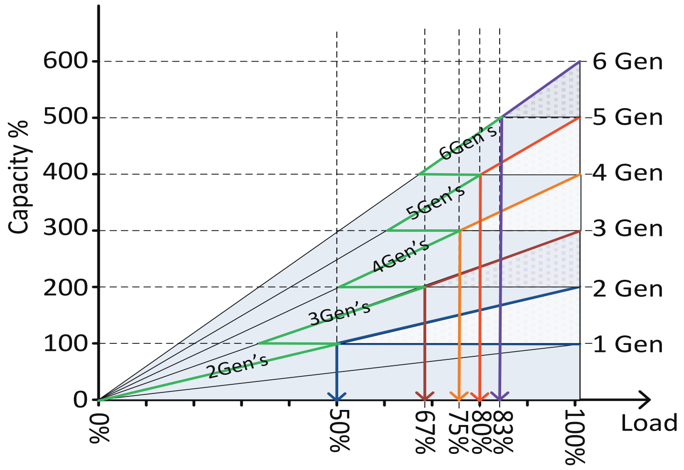


Figure 2 - Spinning Reserve Principle

2.3 UPS / blackout support and black start

Once BESS are incorporated into a vessel they also have the potential to provide an uninterruptable power supply (UPS) mode of operation (also known as blackout support), since the transition from charging to discharging is very dynamic. Full energy storage system power is available to the network with minimal delays to the end user and connected equipment can continue to operate uninterrupted. Another operational benefit is the ability to provide black start, using the energy available in the batteries to bring on the auxiliary and main power systems. Note that UPS / blackout support can ultimately be considered as an extension of the spinning reserve scenario to the single generator operating case.

2.4 Load levelling

Batteries and ultra-capacitors, when connected to a power converter with appropriate bandwidth controllers, can absorb or provide energy for deficits in power system demands, due to their inherently fast response. Figure 3 shows an example of a dynamically varying load profile (purple) with the battery energy source providing the peaks (orange), and the levelled load shown in green. This brings advantages in vessel operation, in terms of reliability and economics, since without energy storage a generator must be online, with sufficient rating to provide the peak power. However, the average load is significantly lower than rated power, thereby reducing the efficiency and reliability of the generators and increasing both the in-service operating and maintenance costs.

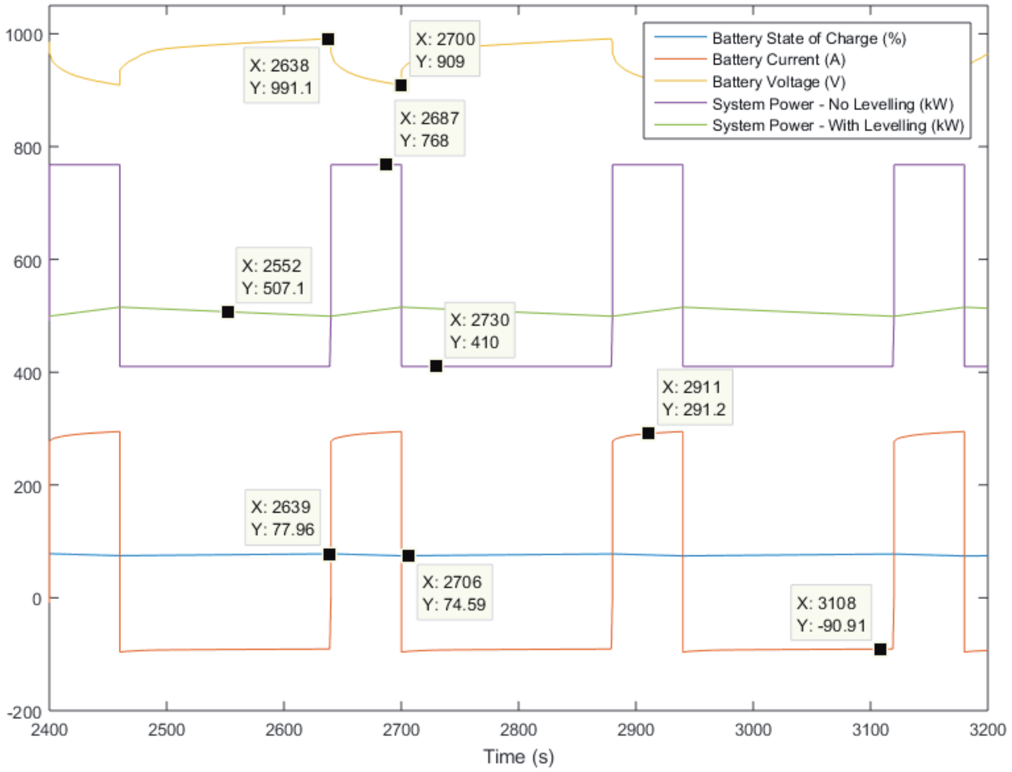


Figure 3 – Peak Shaving / Load Levelling Application

Should the vessel's power system permit dynamic regenerative and/or absorbing (motoring) loads, such as those from a drilling vessel draw-works, or energy capture and dynamic systems (for example future electromagnetic catapult launch and recovery or weapons systems), energy can be harvested dynamically at a varying rate and used as and when required. Where a net surplus of energy is available, the vessel service load may be sufficient to absorb this surplus power before finally reverting to dissipative solutions such as dynamic braking resistors.

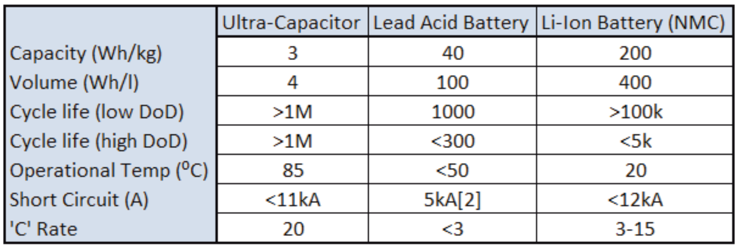
Another notable point regarding energy storage systems for pulsed power applications is that dynamic feed-forward terms can be used to further enhance system operation and keep power system perturbations to a minimum. This can be achieved, for example, in pulsed power systems if a signal is fed forward from the launch system (for example), providing advanced notice to the energy storage system to supply power rather than wait for a delayed control signal, further improving system dynamics. This principle would also apply for advance load starting, for instance a PMS initiating the start of a large load can provide advance notification to initiate power transfer from the BESS which would potentially prevent the start-up of a generator. This is sometimes referred to as pre-emptive load start.

Depending on the energy system deployment, it may operate completely autonomously, monitoring the network and providing reactionary control, depending upon the network frequency and voltage. Generally, the energy store controller functionality can be categorised as follows, depending on deployment:

- Reactive control – Responds to perturbations in the power system network.
- Pre-emptive control – Responds to advance notifications of heavy load starting.
- Dynamic control – Responds to advance feed forward terms from dynamic systems.

3. Lifetime Considerations

An important consideration when deploying batteries and ultra-capacitors is their lifecycle. The lifetime of batteries is predominantly affected by temperature and depth of discharge. For deep discharge duties, lithium ion batteries will typically support up to ~8000 cycles, whereas for very low depth of discharge more than 100,000 cycles could be achieved. Ultra-capacitors can achieve in excess of 1,000,000 cycles, irrespective of depth of



	Ultra-Capacitor	Lead Acid Battery	Li-Ion Battery (NMC)
Capacity (Wh/kg)	3	40	200
Volume (Wh/l)	4	100	400
Cycle life (low DoD)	>1M	1000	>100k
Cycle life (high DoD)	>1M	<300	<5k
Operational Temp (^{0}C)	85	<50	20
Short Circuit (A)	<11kA	5kA[2]	<12kA
'C' Rate	20	<3	3-15

Table 1 - Ultra-Capacitor, Lead Acid and Li-Ion (NMC) General Comparison

4. Energy Storage Technology and Capabilities

Generally, energy storage systems may be categorised as follows:

- High power, short duration, intermittent operation - (pulsed power / EM launchers / heavy load start)
- High power, short duration, repetitive operation – (energy weapons / drilling draw-works)
- Low power, short duration, intermittent operation – (blackout support / spinning reserve / load levelling)
- Low power, longer duration, intermittent operation – (load levelling / UPS)
- Low power long duration sustained operation – (transit / silent modes of operation / UPS)

Figure 4 shows these power and duration characteristics graphically. Pulsed power applications appear in seconds of duration, whereas intermittent operations, such as load levelling, are shown in the seconds to minute area, and sustained operations enduring from minutes to hours. Each of these areas are dynamic, given the evolution of energy storage solutions, most notably with the advent of lithium titanate batteries that have a lower energy density than (NMC), but have higher cyclic withstand capabilities, lessening the distinction between the characteristics of ultra-capacitors and batteries.

Currently, it is the author's opinion that high power applications with short duration (<~3s) are well suited to ultra-capacitors, whereas sustained operation is well aligned to lithium ion, and where a combination of both peak and sustained power, then a combination of both technologies will be applicable.

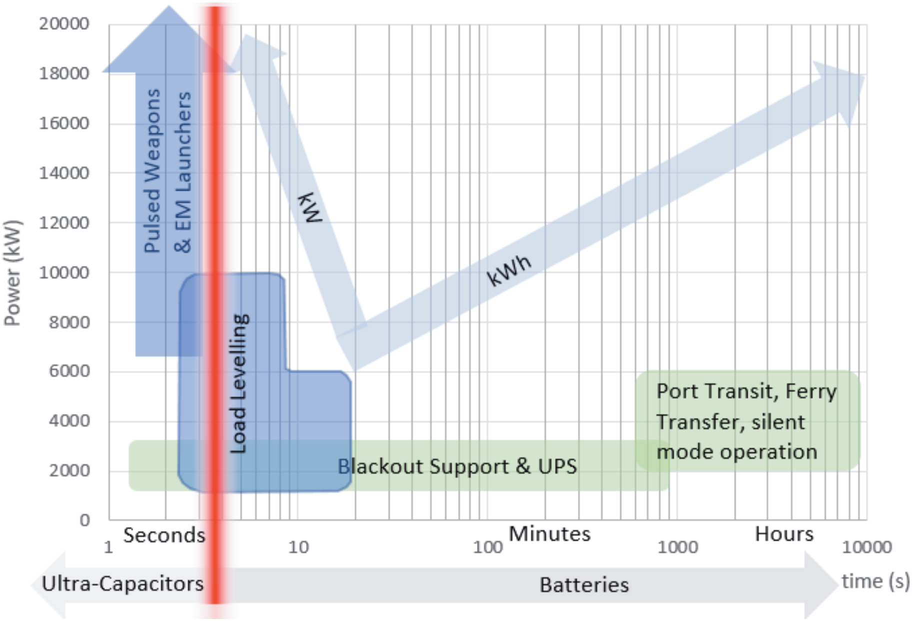


Figure 4 – Application Power vs Time Chart

To provide an indication of ultra-capacitor capability, Figure 5 below shows a capacitor discharge characteristic based on a 1MW load and 6.2 Farad (F) capacitance. Capacitance values of this order are easily achievable from numerous capacitor manufacturers, with the capacitors being deployable in numerous series modules to make up the system working voltage and parallel strings to support overall energy requirements. A notable point being the effect of the ESR, especially when deploying multiple modules in series and in high power pulsed applications where high currents dictate a large voltage drop which should not be ignored as part of the system design. It should also be noted from the formula: $E(J) = \frac{1}{2}C(V_2^2 - V_1^2)$ that the maximum energy utilisation will be higher with a larger differential voltage between maximum and minimum, i.e. doubling the working voltage quadruples the energy utilisation, given the same capacitance.

Examining Figure 5, with consideration to the ESR, a significant voltage drop occurs when considering 1100V operation - in fact, at 1MW the voltage drops used in this configuration is in the order of 100V initially which impacts the duration available assuming a minimum working voltage of 525V from approximately 2.9 seconds to 2.6 seconds. This same figure also reiterates that for a reasonably large deployment of ultra-capacitors, the energy density provides short duration capability, to the left of the red line in Figure 4. This effect becomes more pronounced at lower voltages as current increases, and due consideration should be made when considering the on-load system voltages, for example the DC bus voltage drops, which can have an adverse effect on PWM converters capability.

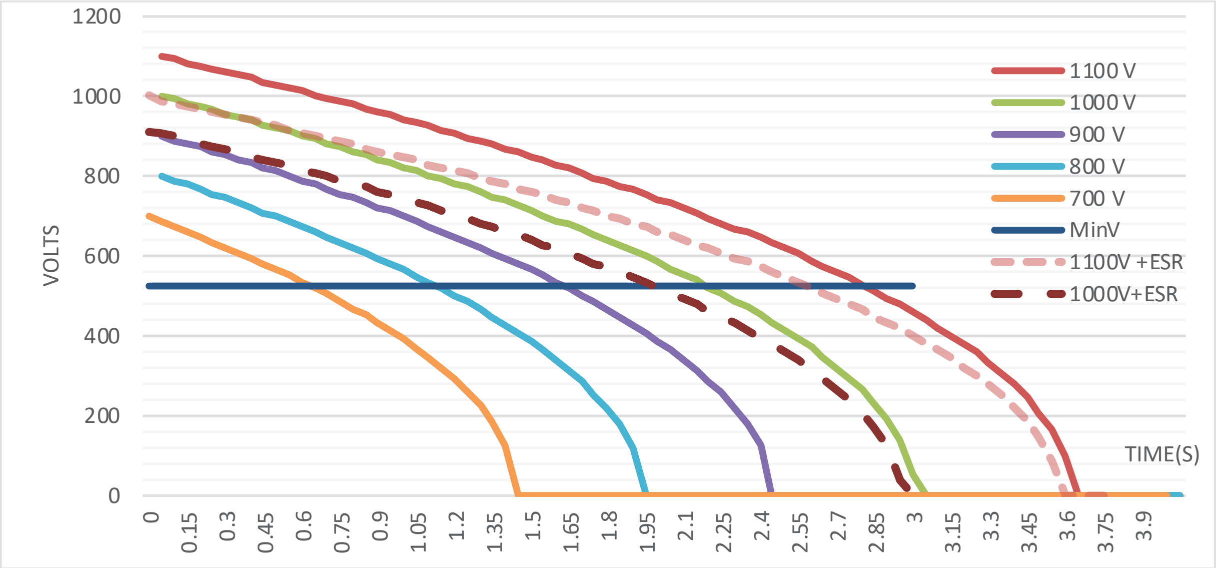


Figure 5 - 1MW 6.2F Capacitor Discharge VDC vs T(S)

Another notable factor when using ultra-capacitors is a phenomenon called 'bounce back' whereby if the capacitors have been used and completely discharged and the capacitor terminals remain open circuit for a period of time, then the terminal voltage will tend to increase. Therefore, ultra-capacitors are (or should be) always shipped with shorting links, and this must be considered as part of a safety review systems hazard analysis since this bounce back voltage can be significant in large ultra-capacitor systems if left unchecked, resulting in risk of electrocution should someone need to perform work or maintenance.

Selection of the most appropriate energy storage technology must also consider ambient temperature since this is a major factor in battery capability and lifetime. Operating batteries at elevated temperatures for sustained durations significantly degrades lithium ion battery life. It is for this reason that lithium ion batteries usually require HVAC and / or supplementary water cooling systems to maintain the operational temperature, typically less than 25°C. By contrast, some ultra-capacitor manufacturers are offering solutions capable of operation in excess of 70°C.

5. Converter Topologies

Numerous low voltage converter topologies exist which consist of power conversion stages, usually made up of insulated gate bipolar transistors (IGBT) due to their high current capability coupled to low switching and conduction losses, which operate typically at 2-3kHz for higher power applications. These IGBT's are integrated with passive components - capacitors, resistors and inductors - to make up the remaining circuitry. Figure 6 shows an AC/DC converter directly connected to a battery system. This solution tends to align well since the battery voltage generally has a small differential between minimum and maximum state of charge (SoC). In this configuration, the converter functions in a similar way to widely-deployed active front end (AFE) converters.

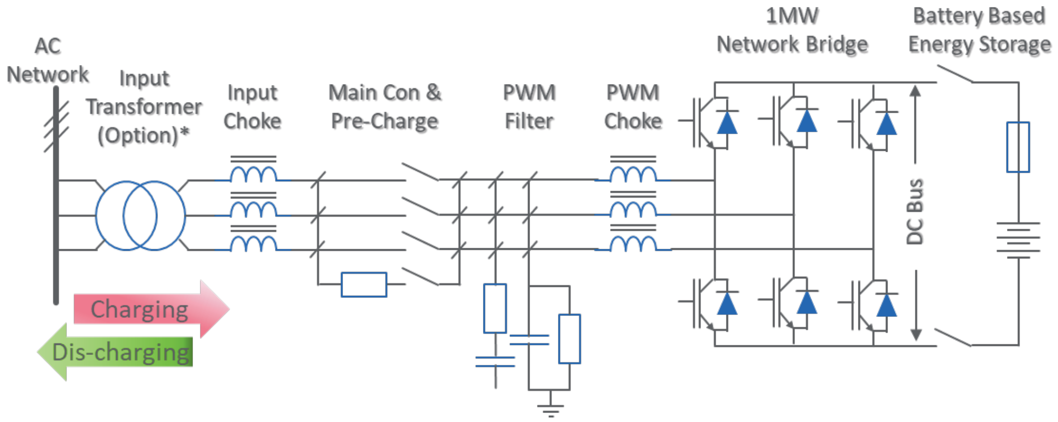


Figure 6 - AC/DC Converter with Direct Connected Batteries

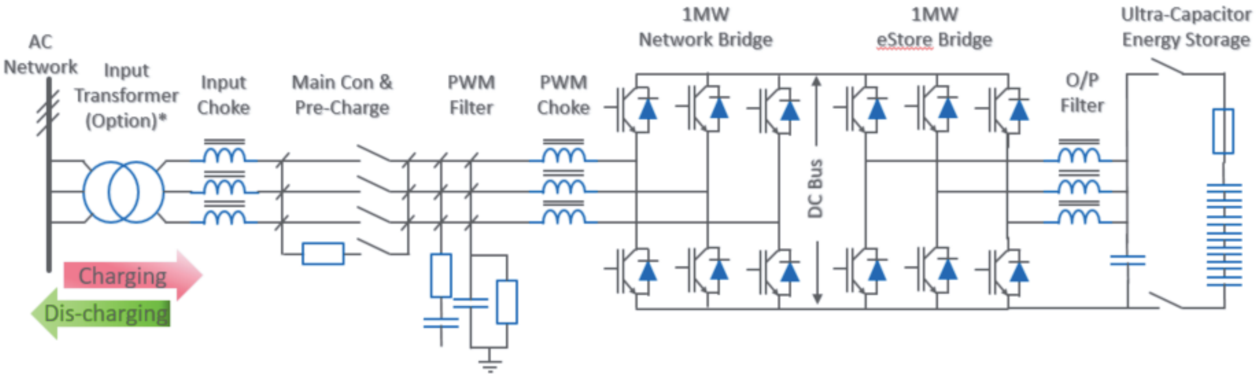


Figure 7 - AC/DC/DC Converter with Connected Ultra-capacitors

Figure 7 shows the same configuration as Figure 6, but with a second stage DC/DC converter connected which can operate in buck/boost configuration allowing bi-directional power transfer. It should be noted that the output DC terminal voltage must always remain lower than the converter DC bus, and that this configuration allows a much wider 'output' voltage working range and can be used for ultra-capacitor based systems or where a DC/DC converter is needed to decouple DC busses so that energy into and out of the connected energy storage system can be independently controlled. Careful attention must be given to design of the DC filter to ensure its behaviour does not adversely affect the ability of the energy store to accept or reject rapid load changes.

6. System Parasitic Components

Every electrical component integrated into a system exhibits parasitic effects. Take, for example, a simple cable which has series inductance and skin effects, which tend to increase cable impedance as frequency rises. For this reason, multiple, stranded cable should be used for high frequency earthing, and Litz wire is used for high frequency applications. This same cable also exhibits parasitic series resistance and resistance (albeit very high at DC) to earth and capacitance to earth. The capacitance to earth lowers the impedance to earth for very high frequencies.

The same can be said for almost every electrical component, and careful design is crucial to ensure the effects of these parasitic effects are understood and the system designed mindful of their impacts. These impacts are further highlighted by the use of high frequency converters which use PWM switching techniques. The fast edges of these PWM switching events cause very high frequency, oscillatory effects which cause over-voltages, EMC issues in the form of common and differential mode, which then propagate into conducted and radiated emissions. It should also be noted that shielded cables usually adopted to mitigate radiated EMC (cable shielding) can increase parasitic effects. The analysis of common mode effects is an independent and diverse topic, well documented and outside the scope of this paper. This paper will however present the common mode effects of adding energy storage into the lab based test system.

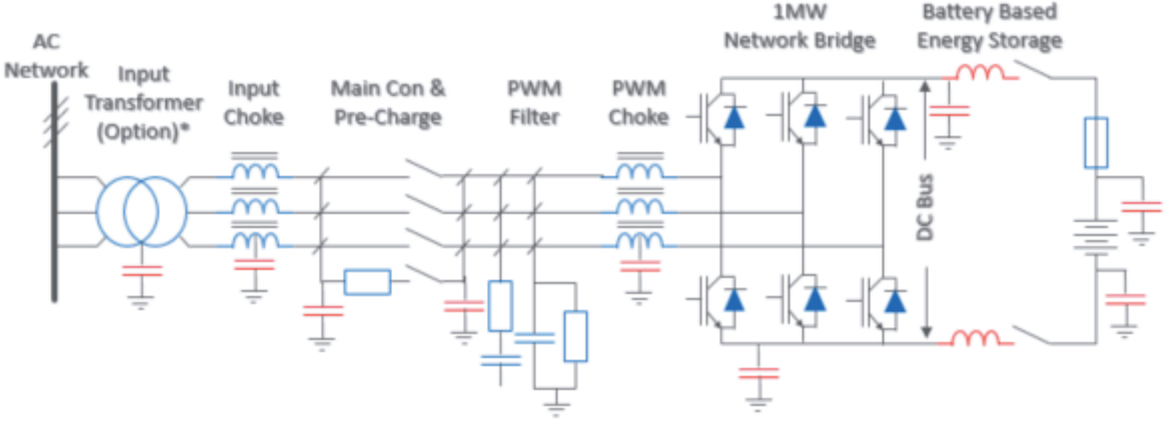


Figure 8 - AC/DC Converter with Direct Connected Batteries with Example Parasitic Components (in red)

Figure 8 is the same as Figure 6, but with some parasitic components shown (in red). For the purpose of this paper, only the parasitic effects of a battery will be presented as this is a relatively new topic, the parasitic effects of the converter being well understood.

A lab based system was constructed, similar to the configuration shown in Figure 8 in order to undertake testing and validation, with some of the results presented in Figure 10 and Figure 11.

Figure 9 shows a frequency spectrum measurement of the capacitance to earth of a single battery module. In general, the capacitance to earth can be assumed to be approximately 4nF within the range of frequencies considered. At higher frequencies, between 1MHz and 10MHz, series and parallel resonance effects can be seen due to the parasitic capacitance and inductance either of the battery module and or measurement connections and these high frequency components can be ignored for the scope of this paper. This capacitance is additive, based on the number of battery modules deployed.

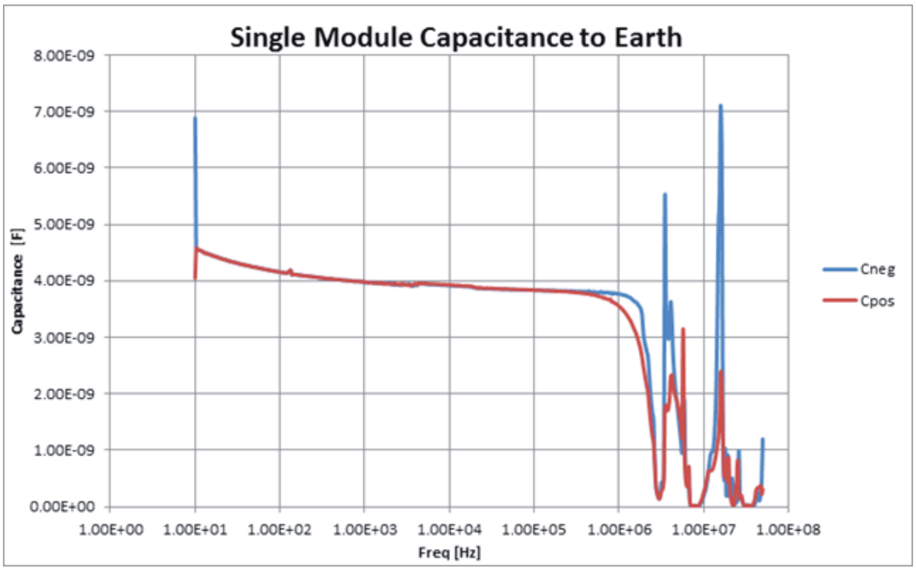


Figure 9 - Example Single Battery Module Capacitance to Earth Measurement

The effect of this parasitic capacitance has been simulated when connected to an AC/DC converter with the results presented in Figure 10.

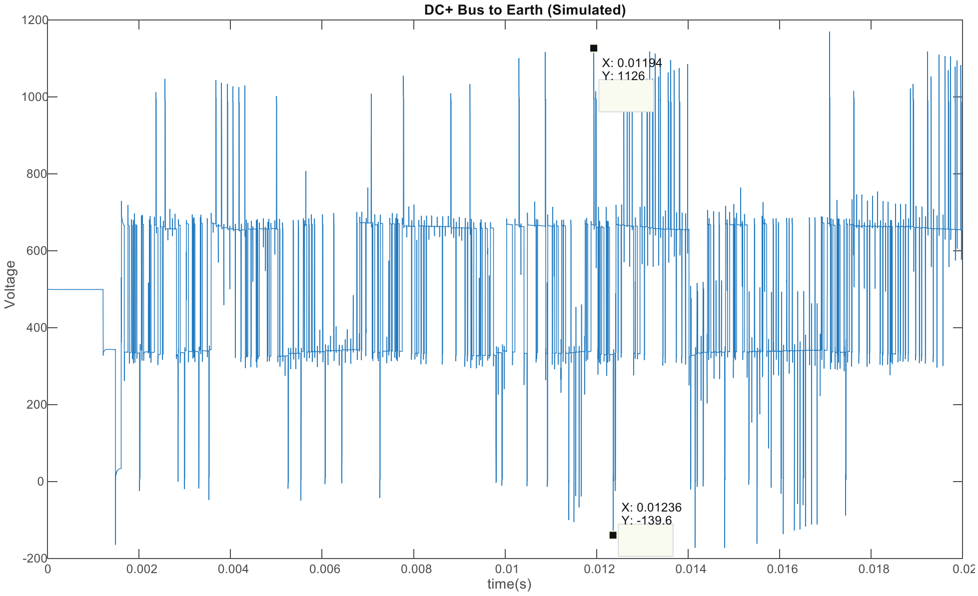


Figure 10 – DC Bus to Ground Common Mode Measurement (Simulated) Vpk-pk=1266V

Contrast the simulated measurement presented in Figure 10 against Figure 11. The simulated values correlate closely to the measured values in terms of peak-peak voltages, i.e. 1266Vpk-pk simulated and 1280Vpk-pk measured in a representative system. Using the same measured data as presented in Figure 11, but zooming in on the time-base, the effects of the high frequency parasitic components can be clearly seen, largely borne out of the resonances set up between the common mode inductive and capacitive parasitic elements.

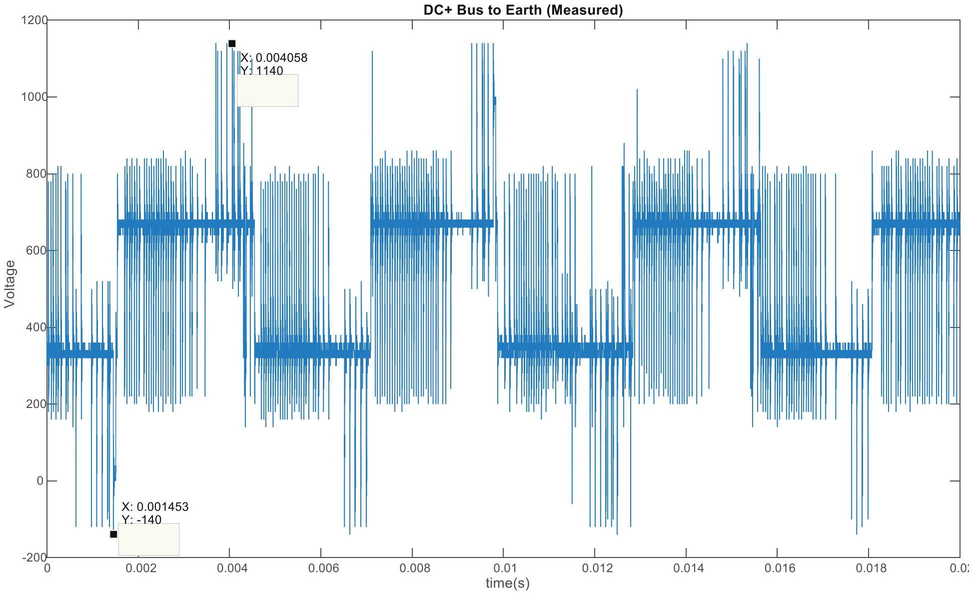


Figure 11 – DC Bus to Ground Common Mode Measurement (Measured) Vpk-pk=1280V

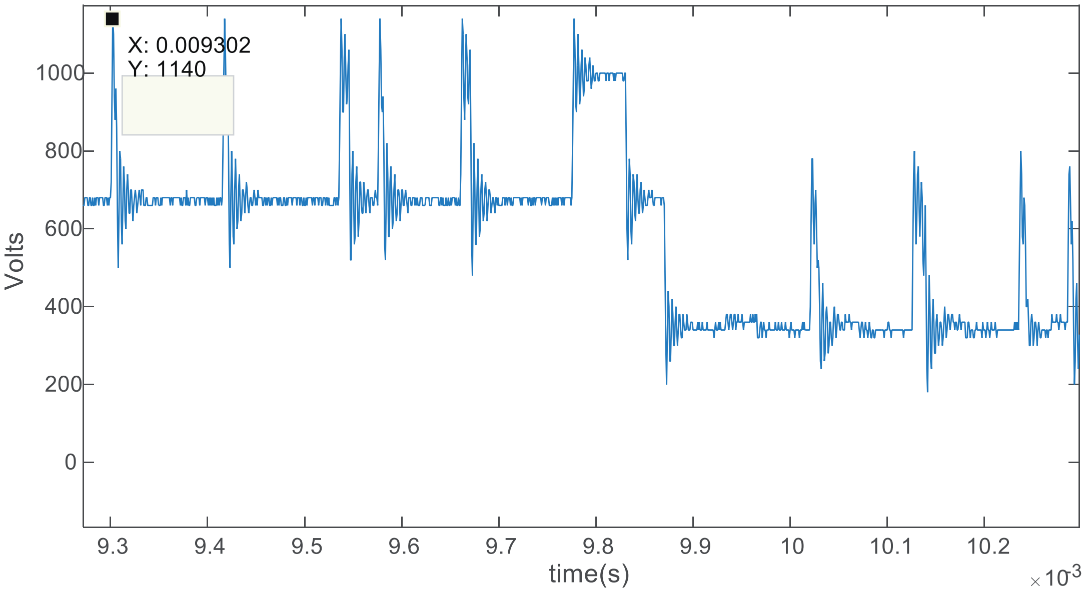


Figure 12 – DC Bus to Ground Common Mode Measurement (Measured) Vpk-pk=1280V (Zoomed)

It is for this reason that PWM converters usually employ a common mode filter in some form which can either be connected to the three phase input terminals, or to the DC bus. This common mode PWM filter is usually designed such that it has a low impedance to earth considering the anticipated high frequency contribution generated due to the parasitic components. In some cases, this introduces onerous challenges, for example in NATO Standard for electrical power quality STANAG 1008, a limited capacitance to earth value is stated, which can adversely impact effective filtering. There are numerous techniques which can be deployed to reduce common mode effect such as:

- Install DC common mode choke
- Install AC common mode reactor
- Employ high resistance between system and earth
- Increase the AC network side common mode capacitance

Each solution will need to be designed mindful of the overall system requirements and system configuration since different solutions will address differing system challenges.

7. Physical Integration Challenges

When installing batteries onto vessels, attention should be paid to the potential electrical and mechanical failure mechanisms since the failure mode of lithium ion batteries is well known. In summary, lithium ion battery technologies cell failures propagate themselves until all the energy is expended, resulting in extremely hot gas venting. Consideration must be made to this failure mode when deploying BESS, and battery vendors have different approaches when dealing with this to be considered at the design stage. Severe failures of this nature are rare since the failure and monitoring mechanisms are well understood and have been developed and deployed.

Consideration to battery fault contributions must also be considered when deploying batteries in large systems since the fault contribution from each battery string can be significant, in the order of 10kA, and designers must adequately design the protection and co-ordination system.

8. Future Considerations

Currently lithium ion batteries have been widely deployed in vessels, mainly for ferry applications, and numerous ultra-capacitor based solutions have been deployed in commercial vessels. However, the adoption of Lithium Ion batteries and ultra-capacitors onto naval platforms has been slower, possibly due to the prior limited experience, which is now developing, thus allowing future exploitation. Coupled to this are claims [3] that new lithium ion battery technologies will exhibit close to a two-fold improvement in terms of energy density, resulting in capacities up to 400Wh/kg.

When considering the improved operational knowledge and experience, coupled to the current and potentially available battery and system capacities, numerous exploitation opportunities present requiring further analysis into the capabilities and realisation challenges in terms of both electrical and mechanical aspects which has been shown to be non-trivial, but achievable.

9. Conclusions

This paper has described the potential benefits, operational modes and opportunities available when deploying energy storage systems on vessels. The exploitation benefits of these energy storage systems can be singular to multiple, ranging from minimal deployed kWh to large scale systems for high power or sustained operation, the challenges and operational opportunities of both being described.

A reference system has been designed, simulated and tested, and showed close performance correlation to the reference design validated in a lab-based environment, showing a clear understanding of the existing converter system performance coupled to an energy storage system as a functioning integrated system.

Efficiency gains [4] and new modes of operation can be deployed, meeting the mission profile of future vessels and associated power systems, ranging from pulsed power systems to quiet modes of operation bringing operational and strategic advantages.

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