Integration of energy storage system on naval platforms

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Hawwooi Chuan holds a PhD in Electrical and Electronics Engineering from the University of Edinburgh. He is currently working as a System Engineer at GE Power Conversion. He is responsible for designing and improving the reliability of the power system of Navy Vessels. Previously, Hawwooi worked as a Research Associate at the University of Bath.

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Mr. Martin Southall has worked at Ultra Electronics, Emerson Industrial Automation, TRW and is currently employed at GE Power Conversion as Naval Systems Engineering Manager. He has extensive power systems, drives, application and programme management knowledge and experience. He qualified with a BEng (Hons) from Staffordshire University in 1995, and achieved a Masters with distinction from Nottingham University in 2014. He is a Chartered Engineer and was admitted as a Fellow to the IET in 2011. Martin is an active member of GE's and the Energy Research Partnership's (ERP) energy storage steering committees, and has led the delivery of numerous vessel power systems.

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Synopsis

Integrating energy storage systems (ESS) into marine vessels could add benefits to the overall power system, such as providing support to mitigate blackout events, increasing heavy pulsed load capability or improving the propulsion system dynamics, improving the efficiency of diesel generators, etc. In this paper, the capabilities and limitations of Lithium Ion battery, Nickel Zinc battery, and Supercapacitors are discussed. Overall, Lithium ion battery has a higher energy density and it is a more mature technology, but it may suffer from thermal runway issue. Nickel Zinc battery has a better fault tolerant capability and a higher safety level, however, it has a lower maturity and cycle life. Supercapacitor has a much higher cycle life and power density, but it suffers from low energy density which limits the functionality. Furthermore, the power converter topologies are discussed.

The transient stability of the power system, with and without ESS is presented; a pulsed load application is used as an example herein. When a pulsed load is added to the power system, the voltage and frequency of the system will fluctuate during the transient state, which may lead to the power system exceeding the limit defined by the class society. The performance of the power system is investigated in the Matlab/ Simulink environment, where the simulation model is built based on an existing vessel. The simulation results show that the voltage and frequency modulation can be suppressed under the STANAG-1008 limit when ESS is integrated to the power system, which is more effective than increasing the Diesel Generator size or increasing the rotor inertia. Finally, the required capacity of each ESS to meet the pulsed load requirement is assessed, where the weight and dimension of the ESS are estimated.

Keywords: Vessel Energy Storage System, Pulsed load, Li-ion battery, NiZn battery, Supercapacitor

1. Introduction

With the technology advancement of energy storage system (ESS), there is a significant improvement in their energy density, power density and cycle life. The technology maturity has also been increased, since ESS, such as lithium ion battery and supercapacitor, have been widely used across different industries. Therefore, it has become a major trend to integrate larger scale ESS on the vessel, since it can provide benefits such as improve the power system dynamics and stability. For instance, to meet the power, or spinning reserve requirements set by class societies, typically generators will not operate at their maximum efficiency which may reduce the overall vessel efficiency [1]. ESS can be used as the power or spinning reserve to enable the generators to run at the optimum load, with the ESS being available online to pick up 'spinning' reserve duties.

At present, surface navy vessels generally only utilize ESS as uninterruptible power supplies for critical equipment such as essential auxiliary services, navigation or communication systems, where the required energy and power

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for this type of support is typically low. However, the current vessel power system may not have been originally designed to maintain the power quality due to the evolution of weapons transitioning to directed energy weapons, or stochastic electronic warfare systems. Typically, the electrical inertia is not enough to withstand the high pulsed load demand with high power ramp rates from these advanced mission systems [2]. This may cause excessive heating and mechanical stress to the generator and adversely affect connected loads. Integrating ESS can smooth the power perturbations from the pulsed, or dynamic loads which reduces the generator stress and improves the power distribution network power quality.

2. Functionality of integrating ESS to the power system

Integrating ESS in maritime sector applications could enable different functionality, which are described in Table 1. The power and energy requirement for these described support types are presented in Figure 1.

Table 1: Summary of the type of support that can be provided by ESS

Type of support	Duration	Comments
Blackout support/Spinning reserve	2-3 min	Generators are running and supporting the load, ESS is used to prevent blackout in case of a generator trip, by providing the power reserve. This enables the system to operate with more spinning (power) reserve without starting additional gensets.
Short-term demand reduction	5-10 min	ESS supports short term load demands and prevents engines from temporarily accepting higher load operating points. This keeps the load at the engines under certain limit. If the load demand lasts longer than ESS envisaged to support, then ESS can transfer the load back to diesel engine until ESS recharges.
Dynamic Engine support / Load booster mode	0.1-1 min	In case of sudden step or quick ramp increase of the load at the generators, ESS will provide temporarily power until engines are able to fully accept the load, which will improve the grid stability while enabling quick load availability. This mode can be useful for enabling quick force to thrusters during critical vessel operations. Then, diesel or gas engines will take over the load.
Load Leveling (Intermittent)	<2 min	For intermittent load leveling operation, the power fluctuations on the grid will be smoothed out by charging the ESS during light load and discharging the ESS during high load. The load pattern is not repetitive or not planned.
Load Leveling (Repetitive)	<0.5 min	High energy weapon or repetitive dynamic loads fall into this category, which is usually a predictable and controllable high-power pulsed load. ESS will be discharged to support the pulsed load, and it will be recharge during the dwell, or off period of the repetitive load. This would smooth the output power demand from the generators and improve the transient stability.
Support high pulsed load	<5 min	For this type of support, the ESS will be responsible to provide all the required energy for the pulsed load, so the generators will operate as usual. If ESS is used to support high energy weapons, the ESS should only be standby with high State of Charge (SoC).

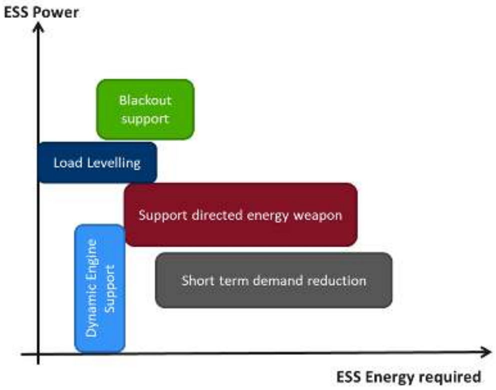

Figure 1: Power and energy requirement for different type of supports

3. Energy Storage options

Several energy storage technologies will be discussed, which are Lithium-Ion (Li-ion) battery, Nickel- Zinc (NiZn) battery and Supercapacitor.

3.1. Lithium ion battery

In Li-ion batteries, the lithium ions move from the anode to cathode during discharge, while the ions move from cathode to anode when it is charging. The materials used for the anode and cathode have an influence on the battery capacity and performance. The electrodes materials have their own voltage potential, which is shown in Figure 2. The battery cell potential is the difference between positive and negative materials. The three potential Li-ion battery technologies for naval application are described in Table 2.

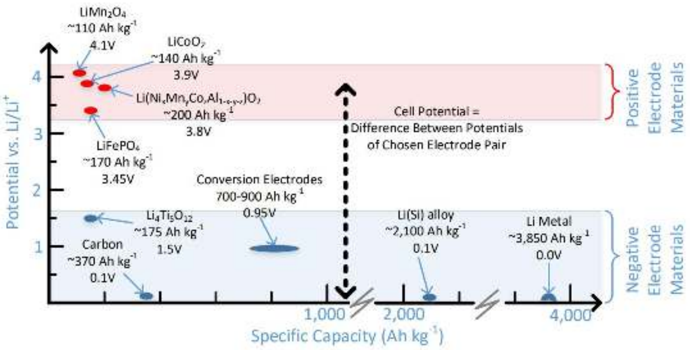

Figure 2: Types of Li-ion [3]

Table 2: Summary of different type of Li-ion battery

Battery type	Comments
Nickel-Manganese-Cobalt (NMC) *Widely used, with high TRL*	Since NMC batteries have good overall performance, including high energy and power density and high cycle life, it is the most common type of li-ion battery in high power and energy applications, such as electric vehicle. The main disadvantage of the NMC battery is the thermal runaway issue. Protection system can be designed to mitigate this risk. If a cell does experience thermal runaway then it will release a significant amount of gas. The battery modules have to be sealed units with built-in emergency exhaust channels that vent through the rear of the battery modules. These vent ports are sealed to an exhaust duct integrated with the ESS cabinet system, which channels the gases out of the battery space and out of the vessel, as presented in Figure 3.
Lithium Titanate (LTO) *Currently available in the market but the TRL is lower*	Use of LTO as the negative electrode for Li-ion battery could be a potential option for pulse load application in a few years, as the Technology Readiness Level (TRL) of this battery technology is currently low. The battery can be charged/discharged at rates higher than 10C. At 10C, the battery can be fully charged/discharged in 6 minutes (60 minutes divided by C rate). In addition, LTO has higher efficiencies and longer cycle life than NMC battery [4]. It is also suitable for use in naval applications due to its high safety level. Since LTO batteries are entirely free of carbon (typically carbon is used as negative electrode for Li-ion battery), thermal runaway or overheating can be avoided. However, the biggest disadvantage of LTO is the low energy density, since LTO has a lower battery voltage 2.4V (vs NMC 3.7V). Additionally, currently the cost of LTO batteries is much higher than NMC batteries.
Lithium Sulfur (Li-S) *Still at development stage, not commercially available*	Li-S battery technology could be an attractive option in the future due to its high energy density (approximately four times higher than NMC battery) and ability to withstand abuse tests such as penetration tests. In addition, 100% SoC of Li-S battery can be accessed, while typical usable SoC of Li-ion battery is 80% (to prevent degradation or premature failure). Although the high energy density of Li-S is very attractive, it might not be suitable for the pulsed load application. This is because the power density of Li-S is ~2 times lower than Li-ion battery [5]. In addition, at present, the lack of cycle life and low TRL are the main drawbacks in this technology [6]. Li-S battery may also suffer from high self-discharge rate and low coulombic efficiency [7].

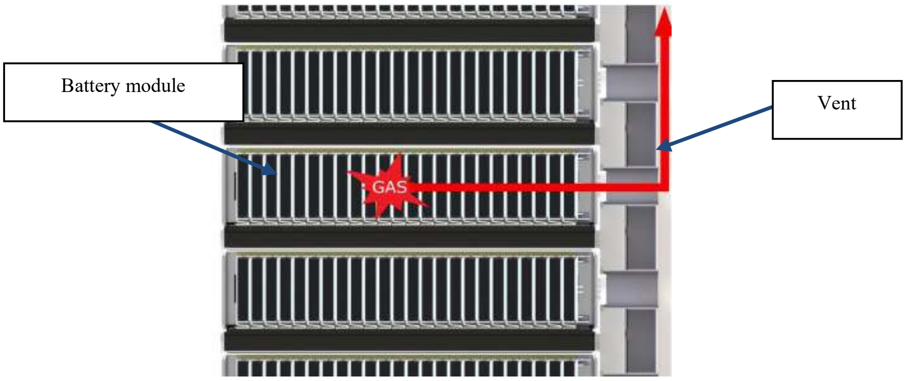

Figure 3: Exhaust system for battery thermal runaway protection

3.2. NiZn battery

Nickel Zinc battery technology was originally developed and patented in 1901 by Thomas Edison. The NiZn technology is based on a Ni(OH)2 cathode and a ZnO/Zn based anode which are electrically separated by a separator material [8]. In the past, the performance was limited by cyclic capability and stability of the rechargeable system. With the advancement of materials, NiZn battery has become a re-emerging technology in recent years, where the lifetime, power density and energy density had been improved.

3.2.1. Strength and weakness

The newly developed NiZn battery has not been widely seen in the market. So, the information presented herein is based on the information provided by the manufacturer(s) [8] [9].

The biggest benefit of NiZn battery is its high fault tolerant capability, which can be seen in the abuse tests reported in the next sub-section. In addition, the 'C rate' (discharge rate relative to the battery capacity) can be higher than Li-ion battery because it is not sensitive to temperature variation; it can be discharged at 60°C. Other than offering high C rate and safer option, NiZn battery is more environmentally friendly than Li-ion battery, and it has a relatively lower cost than Li-ion battery.

However, currently, NiZn battery suffers from short cycle life, where the cycle life is comparable to lead acid batteries but is much lower than Li-ion batteries. Also, the energy density is around 30% lower than Li-ion. Finally, as this NiZn battery technology is relatively new, the TRL remains low.

In summary, NiZn battery could be a potential option for high power and short duration applications on naval vessels, because it has high C rate but low energy density.

3.2.2. Abuse tests

No significant hazard is reported by the manufacturer in the abuse test [9], apart from some hydrogen gas released. The followings abuse tests are performed to investigate potential hazards:

Overcharge : The cell did not show any visual signs of structural instability and after the test no external damage was visible. The recorded temperature data, which peaked at +45°C, gave no indication of an uncontrollable reaction (i.e. thermal runaway). There is only hydrogen emission during overcharging.

Over-discharge : There is no sign of an uncontrolled reaction proceeding within the cell. The structure of the cell was not harmed or deformation.

Extended short circuit test: During an extended short circuit discharge which fully discharged the whole cell from 100% SoC to 0% SoC, the cell terminals can reach >250°C which allows release of some alkaline steam electrolyte. However, this test is only done at cell level.

3.3. Supercapacitor

Supercapacitors can store higher energy than the conventional electrolytic capacitors. A supercapacitor has a high power density because the charge and discharge are dependent only on the physical movement of ions, which can store and release energy much faster than batteries. The types of supercapacitor are shown in Table 3.

Table 3: Types of supercapacitor

Type of supercapacitor	Comments
Electrochemical double layer capacitor	The most common type of supercapacitor is the electrostatic double layer capacitor, which accommodates approximately 85% of the supercapacitor market. Carbon electrodes with much higher double layer capacitance to achieve separation. The supercapacitor is built with two electrodes, separator and electrolyte, where the two electrodes are separated by a separator.
Pseudo-capacitor	Fast and reversible redox reactions take place on the surface of the electrode materials, which could enhance the capacitance. The capacitance could be 10-100 times higher than double layer capacitor, but the pseudo-capacitor usually has lower power density than double layer capacitor [10].
Hybrid Capacitor	This capacitor has two different electrodes (one is made of carbon material and the other is made of pseudo-capacitor material)

3.3.1. Cycle life

Electrochemical double layer capacitors have long life expectancy because of negligible chemical charge reactions and phase change are involved during charging and discharging. Typically, the cycle life could reach a few millions cycle. Figure 4 shows the aging of supercapacitor (measured and estimated) taken from literature [11]. Although operating at high temperature could increase the performance, it will drastically increase the degradation rate.

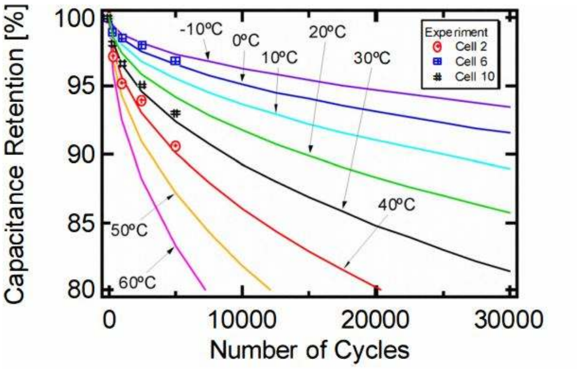

Figure 4: Capacitance retention for different operating temperature [11]

3.4. Comparison

Table 4 shows the comparison for different ESS. It has been shown that supercapacitors have a higher cycle than the battery type energy storage. However, there is a common misconception that supercapacitors have higher power densities, which is not the case for continuous power operation since heat exchange and dissipation is the main factor that determines the limited continuous power rating. The highest safety level against abuse and high C rate were shown in the NiZn battery, but it suffers from low cycle life and low TRL. A Li-ion battery has a good overall performance and high maturity level, but thermal runaway issue is the major concern.

Table 4: Comparison table for different ESS

	NMC Li-ion battery	NiZn battery	Supercapacitor
Cycle life	2500 cycle for 80% DoD at 1/3C 6500 cycle for 50% DoD at 1/3C	200 cycle for 100% DoD >800 cycle at 40% DoD	>1 million cycles
Operating temperature	0 to 40°C The performance is sensitive to temperature variation. The optimum operating temperature would be ~20°C.	-20 to 60°C Can be discharged at high temperature of 60°C, but it needs to be recharged at a lower temperature.	-40 to 70°C Can be charge/discharged at high temperature, but the cycle life will be reduced at high temperature. For example, the cycle life when operates at 40°C is >5 times higher than 65°C.
Efficiency	High efficiency, due to low internal resistance and high charge acceptance rate. (round trip efficiency of 80% - 90%)	Lower efficiency, since the internal resistance is 2-3 times higher than NMC Li-ion battery. (round trip efficiency of 70 - 80%)	Higher efficiency, due to low internal resistance. (round trip efficiency of ~ 90%)
Safety	Short circuit fault, overvoltage, penetrated, over-discharge, overcharge, etc., may cause thermal runaway, which may lead to fire, toxic gas emission and explosion. However, the protection scheme has been well established with class approval.	High fault tolerant capability. No hazard is reported by the manufacturer in their abuse test and puncturing test. In their puncturing test, there is some hydrogen gas emission.	Made from non-flammable material, except for Acetonitrile electrolyte which may be ignited by external source at extremely high temperature. In addition, overvoltage may cause hydrogen gas emission.
Maturity	High TRL, which has been widely used across different industries.	Low TRL. Although the individual cell TRL has been established, it has not been widely used in the industries.	High TRL, which has been widely used across different industries.
Specific energy	~130Wh/kg	~66Wh/kg	~4Wh/kg
Energy density	~195Wh/L	~135Wh/L	~2Wh/L
C rate / discharge current	~6C (short duration discharge) ~3C (single discharge cycle) ~2C (continuous charge and discharge)	~4C (single discharge cycle) ~3C (continuous charge and discharge)	2700A (1s) 200A (Continuous)

4. Power converter topologies

Power converters could enable ESS to be connected to the vessel power distribution network. Two different topologies are discussed herein:

- AC/DC converter
- AC/DC – DC/DC converter

4.1. *AC/DC converter*

Figure 5 shows the AC/DC converter topology, which also include filter and the transformer. For high power applications, voltage source converters are commonly used. Voltage source converters can only work as a boost converter, where the output AC voltage needs to be lower than the DC bus voltage. A general guideline of selecting the minimum ESS voltage is that the minimum DC bus voltage needs to be higher than the line-to-line voltage of the grid. For example, the minimum VDC for the three phase 440VAC system is 682VDC, where 0.95 and 0.96 are the maximum voltage tolerance and PWM modulation factors respectively:

$$V_{dc} = V_{L-L} \times \sqrt{2} = \frac{440\ \times \sqrt{2}}{0.95 \times 0.96} = 682V$$

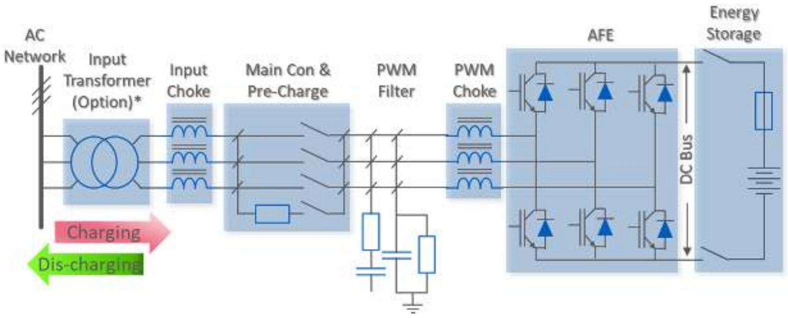

Figure 5: AC/DC converter topology

Although adding a transformer will increase the size of the system, there are several advantages of adding the transformer, which are:

- Help to optimise the secondary voltage for the AFE (active front end) converter, which could increase the available active power that can be supplied by the ESS.
- Restrict the earth fault and common mode voltage.
- The input transformer specifications could include the inductance of the input choke, therefore mitigating the input chokes requirement. A suitably specified transformer should be proposed.

When integrating the ESS, it is important to also consider the parasitic capacitance contribution from the ESS, as the parasitic capacitance of the battery may cause the voltage total harmonic distortion (THD) to exceed the STANAG (NATO standard) limit. This parasitic capacitance effect was discussed in [12].

4.2. *AC/DC/DC converter*

An additional DC/DC conversion stage can be added between the ESS and AC/DC converter, as shown in Figure 6. This would an improved design of a grid tied converter. In addition, having an additional DC/DC converter stage could help to eliminate the low-order harmonics current flowing in the battery which could potentially increase battery lifetime. Also, the DC/DC converter topologies could act as a protection mechanism for the energy storage.

Generally, the output voltage is defined by the energy storage. To fully utilize the stored energy in ESS, grid-tied converters need to accommodate the entire voltage range, because of the voltage variation caused by the SoC of ESS. However, for constant power load, a wider voltage range would mean that the current would be higher at low voltage, which might cause overcurrent for the supercapacitor in continuous mode operation. Also, the additional active component would reduce the efficiency.

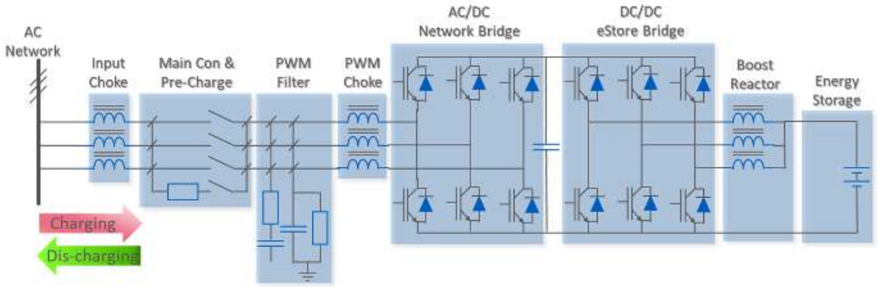

Figure 6: AC/DC – DC/DC converter topology

4.2.1. Hybrid energy storage system

Multiple converters can be parallel connected for multiple energy storage system, as shown in Figure 7. With this converter configuration, the energy storage can be split into multiple cubicles to improve flexibility, which can be the same type of ESS or different type of ESS.

The integration of battery ESS with supercapacitor becomes more popular, as the hybrid ESS can get the best out of both ESS, which could have high power and energy density. With optimal energy control, this can also improve the battery lifetime. However, integrating hybrid ESS in the existing power system relies on effective energy management strategies and proper hardware configuration to achieve the desired benefits.

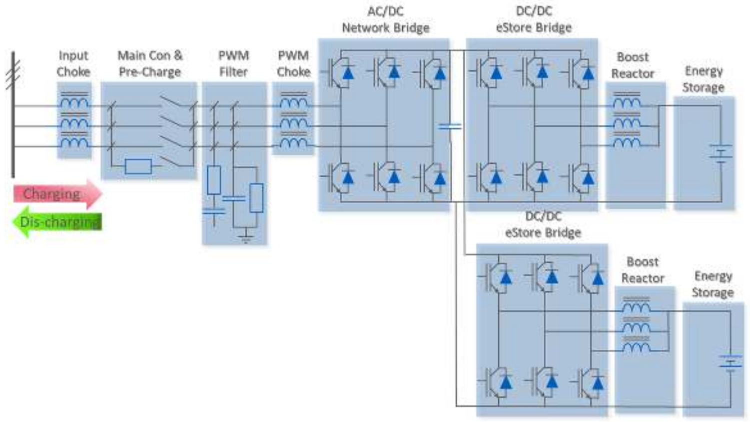

Figure 7: Hybrid energy storage system

4.3. Summary

The summary of the two converter options with respect to the ESS options is shown in Table 5

Table 5: Converter option for different type of ESS at 440V AC system

	Comments
Li-ion battery	Since the difference between fully charged and fully discharged voltage typically less than 20%, both converter options can be used, if the right DC bus voltage of ESS is selected. However, the current maximum string voltage of Li-ion battery is limited to ~1.5kV, which means the maximum AC voltage should not exceed 967V, when AC/DC converter is used.
NiZn battery	NiZn battery can be directly connected to the DC bus and maintain at float voltage without deteriorating the battery lifetime. However, due to low TRL, the maximum string voltage of NiZn battery maybe lower. When the AC/DC converter is used, transformer can be added to step the voltage down to the suitable bus voltage for NiZn battery.
Supercapacitor	Although an AC/DC/DC converter could help to extend the range of operating voltage to increase the supercapacitor capacity utilization, a constant power load may cause the current to exceed the supercapacitor rating at low voltage for continuous operation. Therefore, RMS current has to be taken into account, when determining the required capacitance.

5. Case Study (Pulsed load)

It was previously discussed that ESS could help in improving the power system in different ways. Here, a pulsed load application is taken as an example to investigate the impact of integrating ESS in the power system. During the transient state, there is a change of generator rotor angle when the pulse load is applied. The diesel engine response is relatively slow - up to a few seconds to respond to the load change. To compensate the power difference due to increase of load, the generator rotation speed or system frequency will temporarily decrease, which converts the rotational energy into electrical energy.

In STANAG 1008, periodic or quasi-periodic variations of voltage and frequency caused by the repeated loading are referred as “modulation”. The voltage and frequency modulation can be calculated using:

$$\text{Voltage modulation (\%)} = \frac{(E_{max} - E_{min}) \times 100}{2 \times E_{nominal}}$$

$$\text{Frequency modulation (\%)} = \frac{(F_{max} - F_{min}) \times 100}{2 \times F_{nominal}}$$

The voltage and frequency modulation limit set by STANAG 1008 are 2% and 0.5% respectively. In addition, according to STANAG 1008, active power of the pulsed load should not exceed 25% of the rated supply apparent power, while the reactive power should not exceed 6.5% of the rated apparent power.

5.1. Simulation setup

A simplified platform is used, which consists of a 2MW diesel generator (DG) at the high-voltage (HV) bus and a 1.5 MW service load at the low-voltage (LV) bus. The pulsed load and the ESS are then connected at the LV bus. The parameters of the generator and the service load are extracted from an existing reference vessel. The overview of the platform is shown in Figure 8. The simulation is performed in Matlab/Simulink r2020a. A time step of 2μs is used.

For the simulation, the following assumptions had been made:

1) The pulsed load has a diode front end, and 6% line reactors were used.
2) The pulse load is assumed to rise instantaneously. In the simulation, it may take 2 to 3 time steps to reach the target.
3) For the 1.5MW service load, 80% of the load is assumed to be linear, and 20% of the load is assumed to be non-linear which has a diode front end.
4) The power output from the ESS is controlled by the AC/DC converter, where the reference current is set based on the current measured from the pulsed load feeders.

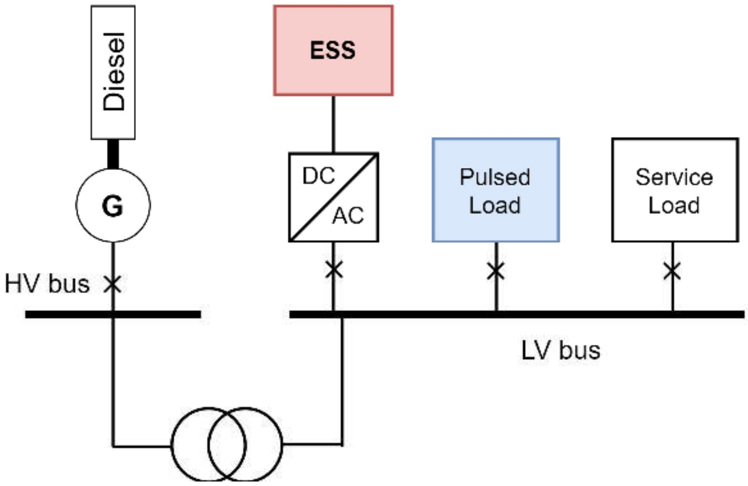

Figure 8: Single line diagram of the test platform

5.2. Simulation Results

Figure 9 shows the voltage and frequency modulation at different pulsed loads. For a single 2MW DG system, the maximum pulsed load that can be withstood by the power system before exceeding the STANAG limit is 150kW, where the frequency modulation will exceed the limit at 150kW. After adding the ESS to the network, the voltage and frequency modulation can be reduced (see Figure 10).

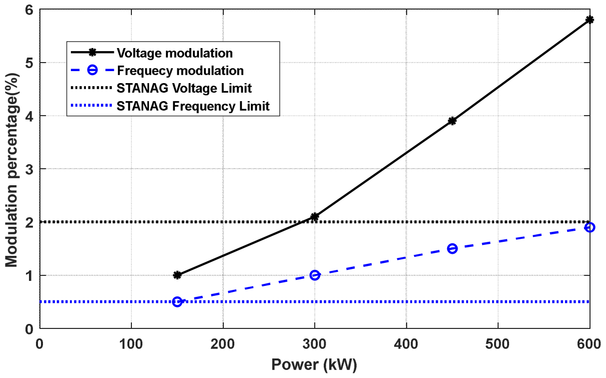

Figure 9: Voltage and frequency modulation at different pulsed load (Without ESS)

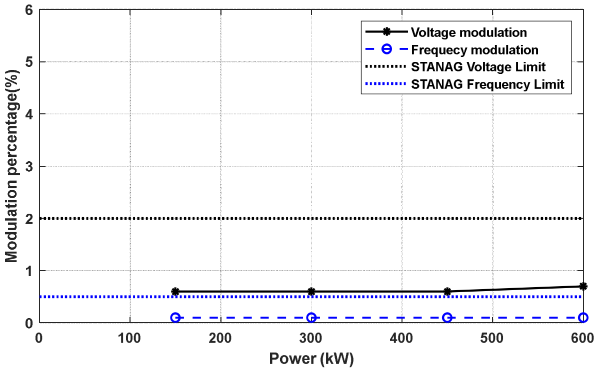

Figure 10: Voltage and frequency modulation at different pulsed load (With ESS)

5.3. Sensitivity Analysis

The increase of rotor inertia and increase of DG rating are investigated by applying a 500kW pulsed load . Figure 11 shows that the 70% increment of DG rating can only reduce the frequency modulation by a third. Similarly, increase of rotor inertia by three times could only reduce the frequency modulation by a third. Therefore, solving the frequency modulation problem by increasing the DG size or rotor inertia is ineffective.

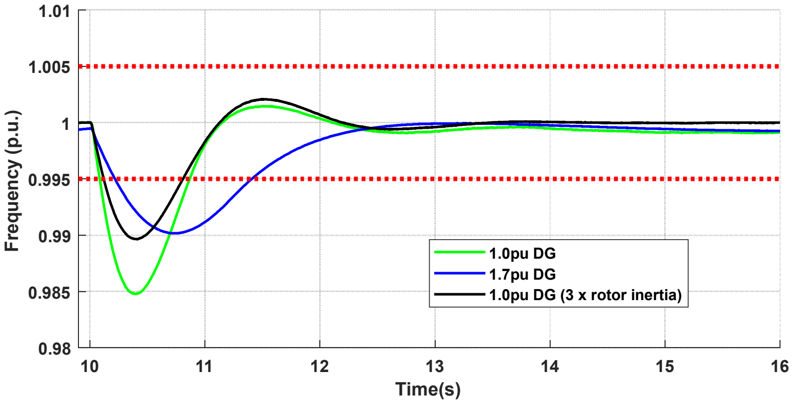

Figure 11: Frequency response when applying a 500kW pulsed load (without ES)

As the ESS output power is used to compensate the pulsed load demand, to test the sensitivity of the delay in feedback, different time delays are included to the feedback signal for the ESS power converter. With the same 500kW pulsed load, the relationship between the delay and percentage of modulation is shown in Figure 12.

Results show that delays of over 60ms may cause the modulation percentage to exceed the limit. Since the estimated delay time is less than 5ms, it is safe to conclude that adding ESS could effectively mitigate the voltage and frequency variation.

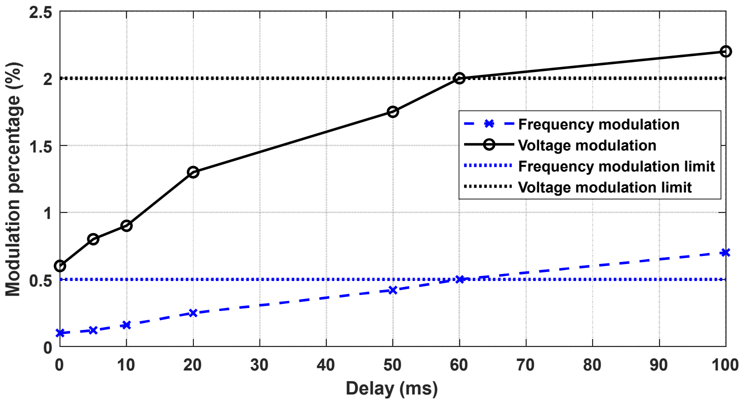

Figure 12: Frequency and voltage modulation for different compensation time delay

5.4. *Required energy storage capacity for different number of pulsed load*

Three different ESS are compared, NiZn battery, Li-ion (NMC) battery and supercapacitor. With the assumption that the required energy is fully supplied by the ESS, the required capacity for each ESS to power different numbers of pulsed load is presented in Figure 13; each pulsed load is rated as 500kW with 5s on-time and 5s off-time, so the RMS power of the pulsed load is 353kW. The maximum C rate for a NiZn battery and a NMC Li-ion battery are assumed to be 4C and 3C respectively, which is estimated based on manufacturer datasheets. An approximately 20% margin is included in the capacity calculation. Then, the estimated dimension and weight of the ESS are calculated in Figure 14, which include the casing and auxiliary equipment.

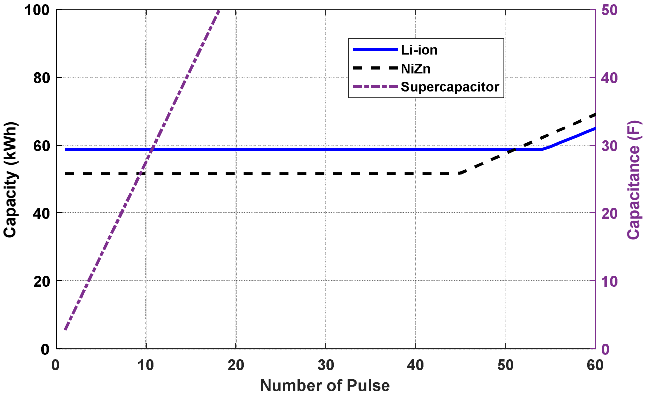

Figure 13: Required capacity for each ESS for different number of pulsed loads

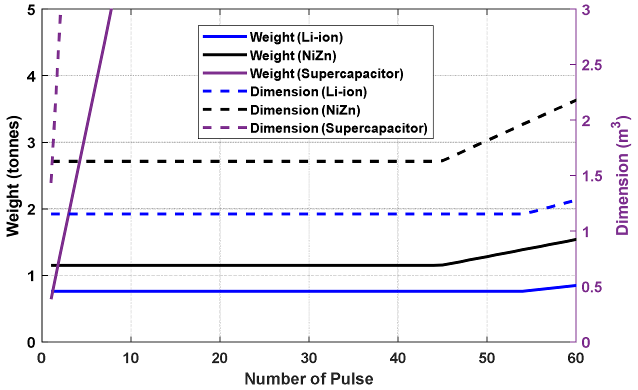

Figure 14: Estimated dimension and weight of the ESS for different number of pulsed loads

At low number of pulses, battery type energy storage is sized to meet the power requirement of the pulsed load. When the number of pulses increases, it will be sized based on the energy requirement. For <50 pulses, due to the higher C rate of NiZn battery, less kWh capacity is needed for a NiZn battery if compared to a Li-ion battery (see Figure 13). However, when the number of pulses increases, more kWh capacity is needed for a NiZn battery because of its lower energy density and efficiency, where the internal resistance of a NiZn battery is up to ~2.5 times higher than Li-ion battery. Comparing the weight and dimension, the Li-ion battery is slightly better than the NiZn battery at a low number of pulses, but the difference increases when they are sized to meet the energy requirement.

For a supercapacitor, it is sized based on the energy requirement, so the required capacitance increases linearly as the load increases. Figure 14 shows that the size of the supercapacitor could be a problem for this application. Therefore, a supercapacitor is more suitable to be used in load-levelling applications, which could smooth out the power variation due to the pulsed, highly repetitive loads.

6. Conclusions

In summary, a Li-ion battery has good overall performance and a high TRL, but the thermal runaway issue is the main concern. However, most manufacturers have developed a protection system to mitigate the thermal runaway risk. Meanwhile, for supercapacitors, the high cycle life and TRL are the strengths, but it is limited to be used in load levelling applications due to its low energy density. For NiZn battery, it is a safe option and could have a high discharge rate, but the low TRL and cycle life are the main concerns. Furthermore, two converter topologies were discussed, which are also included in the design consideration.

A pulsed load application is chosen as a case study to assess the impact of pulsed load. When pulsed load is added, the voltage and frequency modulation may exceed the STANAG limits. Sensitivity analysis was performed to investigate the increase of generator size and rotor inertia. Both methods are not effective in solving the problem, as an 70% increment of generator size or 200% increment of rotor inertia could only reduce the modulation percentage by up to 33%. Therefore, ESS is recommended to reduce the modulation percentages, in which the voltage and frequency modulation are reduced from approximately 3.8% and 1.5% to 0.6% and 0.1%. Furthermore, the output power from the ESS can be delayed by up to 60ms before exceeding the STANAG limit. Finally, the required capacity and the size of each ESS for different number of pulsed loads are presented.

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References

[1] Geertsma, R., Negenborn, R., Visser, K. and Hopman, J.: “Design and control of hybrid power and propulsion systems for smart ships: A review of developments”, Applied Energy, 194, pp.30-54, May 2017.

[2] Kim S., Choe S., Ko S. and Sul S.: "A Naval Integrated Power System with a Battery Energy Storage System: Fuel efficiency, reliability, and quality of power", IEEE Electrification Magazine, vol. 3, no. 2, pp. 22-33, Jun. 2015.

[3] Miao, Y., Hynan, P., von Jouanne, A. and Yokochi, A.: “Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements”, Energies, 12(6), pp.1074, Mar. 2019.

[4] Moorthi, M.: “Lithium Titanate Based Batteries High Rate and High Cycle Life Applications Applications”, Nei Corporation.

[5] Benveniste, G., Rallo, H., Casals, L. C., Merino, A. and Amante, B.: “Comparison of the state of Lithium-Sulphur and lithium-ion batteries applied to electromobility”, Journal of Environmental Management, 226, pp. 1–12, Nov. 2018

[6] IEEE Spectrum: Technology, Engineering, and Science News. 2020. Full Page Reload. [online] Available at: <https://spectrum.ieee.org/energywise/energy/batteries-storage/lithium-sulfur-battery-news-ev-electric-vehicle-range> [Accessed 3 April 2020].

[7] Peled, E., Goor, M., Schektman, I., Mukra, T., Shoval, Y. and Golodnitsky, D.: “The Effect of Binders on the Performance and Degradation of the Lithium/Sulfur Battery Assembled in the Discharged State”, Journal of The Electrochemical Society, 164(1), Jan. 2017.

[8] Blakey, Graham.: “Power and responsibility – Integrating a new technology battery into an existing power network” Marine Electrical and Control Systems Safety Conference 2019 (MECSS 2019), London, 2 – 3 July 2019.

[9] Wang, G., Wang, H., Zhong, B., Zhang, L. and Zhang, J.: “Supercapacitors' Applications” in Electrochemical Energy, 2015.

[10] R. W. Evans, S. L. Vechy, A. C. Loyns, C. Oettel, A. S. Pensado and B. S. Leshtanski, "Development of Nickel Zinc technology for reserve power industrial applications — Part 1," 2015 IEEE International Telecommunications Energy Conference (INTELEC), Osaka, 2015, pp. 1-6,

[11] Uno, M. and Tanaka, K.: “Accelerated ageing testing and cycle life prediction of supercapacitors for alternative battery applications”, 2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC), Amsterdam, Oct 9-13 2011.

[12] Southall, M. and Ganti, K.: “Battery and ultra-capacitor based energy storage vessel integration, capabilities, considerations and challenges.” Proceedings of the International Naval Engineering Conference and Exhibition (INEC), Glasgow, UK, Oct 2-3 2018.