Technology and Science for the Ships of the Future
V. Crupi and V. Bucci (Eds.)

© 2025 IOS Press.
This article is published online with Open Access by IOS Press and distributed under the terms of the Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC 4.0).
doi:10.3233/PMST250059

Preliminary Analysis on the Integration of Directed Energy Systems in the Next Generation Surface Naval Vessels

Michele GIANNELLA [a,1], Paolo BORGHESE [a,2], Andrea VICENZUTTI [b,3],
Andrea Alessia TAVAGNUTTI [b,4] and Giorgio SULLIGOI [b,5]
[a] *Directorate of Naval Armaments (NAVARM), 2nd dept. Naval Plants –*
4th div. Propulsion and Energy – 3rd sect. Electrical Systems & Automation,
via di Centocelle, 301 (Palazzo "Guidoni") – 00175 Rome (Italy)
[b] *University of Trieste, Engineering and Architecture dept. –*
Digital Energy Transformation & Electrification Facility (D-ETEF),
Via A. Valerio, 6/4 (Edificio C2) - 34127 Trieste (Italy)

Abstract. The use of Directed Energy Systems (DES) provides several operational advantages in respect to conventional onboard systems, thus their integration into surface naval vessels is considered an enabler for new fleet capabilities. This paper presents a strategy for the correct integration of a DES into a surface naval vessel's electrical power system, aimed at ensuring the latter's stability and resilience despite its pulsed power load behavior. The results are presented using as case study the integration of a laser based DES onboard a next-generation frigate, by means of a direct current sub-grid that includes a multi-functional Battery Energy Storage System (BESS). The latter is aimed at supporting all the onboard pulsed and fluctuating loads, thus being not specifically dedicated to the laser supply. By means of a mathematical model developed within "Electric TEst Facility" (ETEF - smart power grid technology demonstrator), simulations have been performed to verify if the multi-functional BESS, designed to meet other scopes and requirements, is capable of supporting the laser (in place of the conventional solution, which is installing a dedicated ESS for each critical load). The results highlight the opportunity of using the "model-based design" approach for designing naval power systems, to obtain a resilient *unicum* that efficiently meets the increasingly demanding needs of "high value loads", as well as optimizing the use of power electronics devices by means of a suitable centralized and optimized BESS. The results of this activity will not only have implications in terms of Naval outfitting (i.e. weight and volume optimization), but will also have significant impacts on the operational requirements that can be fulfilled.

Keywords. Directed Energy Systems, Battery Energy Storage Systems, Electric Test Facility, DC, Pulsed Power Loads, Electrical Power System.

---

[1] Michele Giannella, Lt Cdr (Eng), michele.giannella@marina.difesa.it.

[2] Paolo Borghese, Lt Cdr (Eng), paolo.borghese@marina.difesa.it.

[3] Andrea Vicenzutti, PhD, avicenzutti@units.it

[4] Andrea Alessia Tavagnutti, PhD, andreaalessia.tavagnutti@dia.units.it

[5] Giorgio Sulligoi, Prof, gsulligoi@units.it

1. Introduction

The rise of asymmetric engagement tactics in modern defense scenarios is promoted by the increasing availability of devices that allow attaining significant consequences while being characterized by simple, rapid, and low-cost production processes. This highlighted the need to implement countermeasures based on an equally rapid and low-cost approach to their neutralization. This is the reason of a growing trend towards the developing of new systems based, in particular, on the use of concentrated energy (e.g., high energy lasers). The onboard integration of this new type of payloads, together with the new discovery sensors, poses major challenges for their effective supportability, in terms of energy availability, stability, reactivity (as dynamic response), and resilience requirements that the onboard power system must comply with, considering the impulsive and, in some cases, energy-intensive nature of these loads.

The aim of this paper is therefore to identify a possible strategy for the effective integration of directed energy systems, which from the electrical point of view represent a Pulsed Power Load (PPL), in the next generation surface naval vessels.

2. Literature Review

Integrating PPLs in onboard power systems (as per any islanded power system) requires specific attention, which justifies the prolific literature on this topic. Therefore, this section summarizes the state of the art for the integration of PPLs in Shipboard Power Systems (SPS), as the basis of the work that follows.

The simplest case (a single Diesel Generator - DG - feeding a single PPL) allows framing the problem, defining existing limits and analyzing potential solutions. In this situation, analyzed in [1], the system's correct operation directly depends on the DG's inertia, which allows managing transient loads without exceeding the power system's limits. This solution only works for PPLs that have a small magnitude in relation to the DG's power itself, and/or for DGs with significant inertia (either intrinsic, or by means of additional mechanical flywheels applied to the engine shaft). In such a case, the amount of kinetic energy stored in the rotating masses is sufficient to compensate for the transient load. Another problem related to this configuration is the high distortion of the output voltage from the generator (evaluable with the THD figure), when the power of the PPL is relevant in relation to the DG itself, due to the power electronics interface of the load. In general, in the presence of high power PPLs the need to isolate the load from the DG becomes apparent, to enable the latter correct operation. In [1] some possible strategies to improve the matching between DG and PPLs are depicted, but they involve using additional interface equipment, with associated cost/weight/volume increase.

Extending the analysis to a Naval SPS equipped with DGs only, it is possible to observe that supplying PPLs is challenging due to DGs slow response and low ramping capabilities [2] [3]. When connected, a PPL will cause stability problems, in addition to significant voltage and frequency drops in the SPS. As remarked in reference [4], as well as set in several Military Standard (like [5], [6] and [7]), strict limitations are imposed on the electrical variables to guarantee the correct operation of all the onboard loads and equipment. In addition, in [3], by replicating in a Software-In-the-Loop (SIL) environment the operation of a PPL in an AC SPS, it is highlighted the need to investigate also the mechanical stresses on the DGs and the importance of evaluating the limits for PPL (in relation with the other loads of the SPS) is remarked.

Reference [8] analyses the effects of a PPL on the stability of an AC SPS. The paper examines a significant case study, consisting of an AC/DC hybrid architecture in which the PPL is installed on the 1kV DC network section[6]. The simulations tested the effects of single pulse (1 sec) and pulse trains (10 per 0.1 sec). In the case of a single pulse, keeping a sufficiently low ratio between the PPL and the generator powers is important to avoid intervention of sub-frequency protection; the resulting frequency reduction increases in the case of the pulse train, resulting in failure to meet the required stability limits in the simulated system. It is evident that, in an electrical system without an Energy Storage Systems (ESS) capable of supporting the fast power variations required by the load, DGs must supply the related energy (specifically, via the kinetic energy stored in the rotor), which is the same case of reference [1] discussed above. The results of [8] show that in the absence of an ESS (any type) it is nearly impossible to manage PPLs having a relevant power in an islanded power system (whether AC or DC). [9] shows the change in speed of a DG when subjected to impulsive loads and, in particular, it illustrates the improvement achieved by installing a flywheel between the engine and the generator. This solution is effective, but it increases weights/volumes/costs, and the added DG's inertia leads to longer start/stop times of the machine (with consequent operational limits). The literature review highlights instead that PPLs are often integrated in combination with a Battery ESS (BESS) with adequate performance capabilities (energy, power and C-rate). This configuration can be achieved in two ways: by connecting the BESS directly to the main AC grid (usually "electrically close" to the load connection point), or by adding a DC network section (so-called "DC island") where both the PPLs and BESSs are connected [10] [11]. In the first option, it is necessary to implement a complex control system that allows effective coordination between PPL and BESS. Perfect control signal synchronization is essential[7] to ensure that the BESS injects the necessary power into the network when the PPL requires it and, nevertheless, variations in frequency and voltage remain in the system, as demonstrated in [12]. The second option instead allows obtaining more advantages, because it completely decouples PPL and DGs by interposing power electronics converters. By doing that, the deviation on voltage and frequency of the DG is minimized thanks to the immediate intervention of the BESS, which is located on the same DC bus as the load, while the AC/DC interface converter strictly controls the power flow between the two sides.

An alternative approach involves the use of a main DC power system, where the AC sections are reduced as much as possible, integrating both the BESSs (appropriately dimensioned) and PPLs [13] with the aim to increase the overall efficiency and resilience of the electricity grid. The Electric TEst Facility (ETEF) demonstrator has validated the feasibility of such an option, using a DC distribution network on an experimentally relevant scale to supply a multi-MW load step [14].

3. Case Study

The common electrical configuration used onboard Italian naval vessels consist of two Main Switchboard (MSB) at AC low voltage connected by a cross-line. For the following assumption, we will consider a main distribution at 690V – 60Hz with four DGs of 2.1

---

[6] Electrical system: two Main Turbo-Generators (MTG) of 36 MW and two Auxiliary Turbo-Generators (ATG) of 4 MW at 60 Hz; two Electric Propulsion Motors (EPM) of 36,5 MW and 4 MW vessel service load.

[7] It is not sufficient to use the voltage and frequency control of the BESSs interface converters.

MW and two Electric Propulsion Motors (EPM) of 2.1 MW, all connected to the MSBs, in a COmbined Diesel-eLectric And Gas (CODLAG) propulsion architecture. The maximum ship electrical load (hotel load, auxiliaries, etc.), is assumed to be 2.0 MW.

3.1. Technical-Operational Considerations

The primary objective of the study is to define the evolutionary trajectory of the reference electrical architecture in order to integrate, at least, four PPLs (assumed as 550 kW each with a step ramp up/down, and a duty cycle of 6 sec ON and 6 sec OFF) while ensuring reliability, efficiency and adequate future growth capability.

The following integration options have been discarded for the reasons listed.

- AC power system without BESSs: the available onboard power is sufficiently higher than that required by PPLs, to allow for compensating the slow power variation response of the single DG by means of the inertia provided by the simultaneous operation of all the onboard DGs. However, the dynamics of the electric network (and the possible mechanical stresses induced on the engines) have not been analyzed, because this option is not effective from an operational point of view. In fact, the need to use all DGs (or a large part of them) to feed PPLs would cause operational limitations on the propulsion side (reduction of the max speed with EPMs, or need to change the online propulsion machine) and negatively impact on DG's redundancy (i.e., impossibility of operating the PPLs if a single DG is not operative, which is not acceptable in a naval vessel).
- AC power system with BESSs (left in Figure 1): this solution solves the problem from an energy point of view, but shows weaknesses related to the complexity of the control system (with consequent possible compromise of the overall reliability) and increase in weight/footprint of the required power electronics, as discussed in the literature section. Finally, this option offers a reduced growth capability.
- AC power system with "DC island" (right in Figure 1): the DC sub-section guarantees the stability of the main AC network and the BESS provides ramp rate support to the DGs. At the same time, during intermittent absorption - pulsed train - the BESS fills in the power ripples that would otherwise produce pendulation of the engines. The limit of this architecture is the need to create an island for each PPL, and a consequence is the reduced opportunity for optimization, along with a limited growth capability (this option will be preferred for refitting activities).

3.2. Electrical Power System (EPS) Architecture Hypothesis

By integrating the considerations discussed above with the results obtained by ETEF research project [14], it has been hypothesized a new onboard EPS architecture with a DC subnet where to integrate both the PPLs and the BESSs (left in Figure 2), based on the Zonal Electrical Distribution System approach [14]. This configuration uses a resilient subnet on which are connected the ESS (in a centralized configuration in order to optimize its sizing by sharing its power/energy with all the loads and performing different functions), the users that require uninterruptible power supply, and the PPLs. This option also provides adequate growth capability to the system, attainable by simply adding more electrical zones to the system (right in Figure 2).

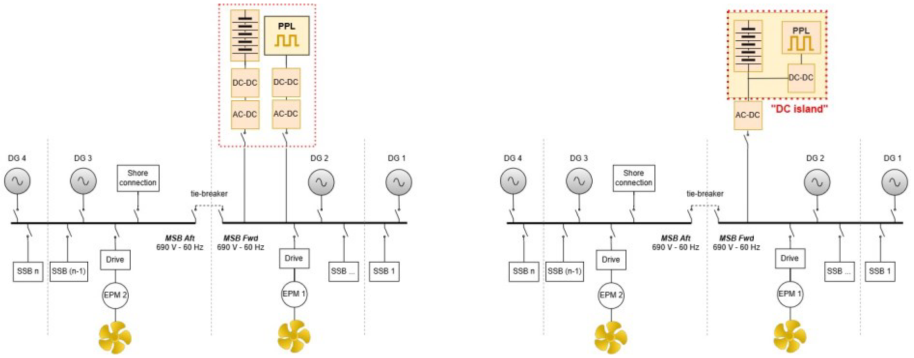

Figure 1. Schemes of PPLs integration in an AC power system with independent BESS (left) and in "DC island" (right).

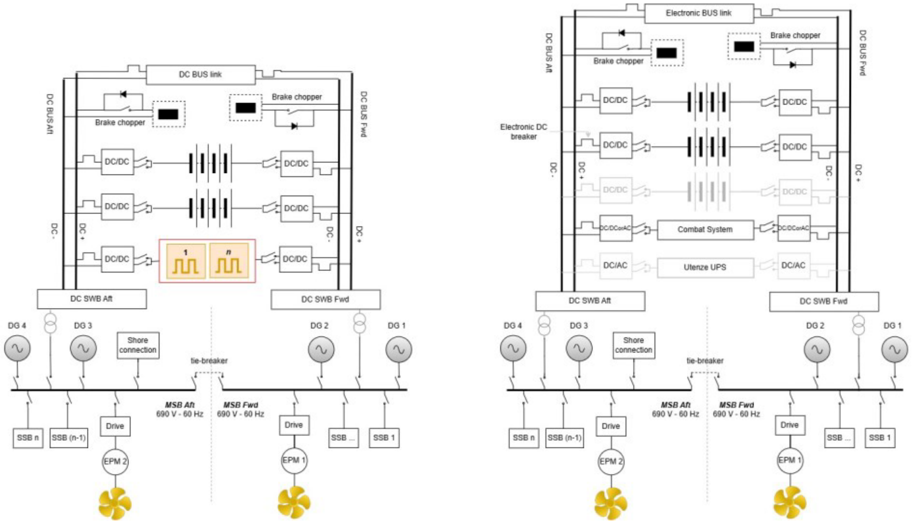

Figure 2. Scheme of the notional electrical power system architecture hypothesis (left), and its possible evolution (right).

4. Analysis and Assessment

Simulations were carried out using the mathematical model developed for ETEF[8], which was validated by means of a full-scale experimental setup [14]. Table 1 summarizes the positive results obtained for each scenarios, and Figure 3 shows some of the related dynamic simulations results. In particular, the following aspects were investigated:

- possibility of continuous electrical supply of PPLs (i.e., capability to support an unlimited number of subsequent pulses);

---

[8] Analogies between ETEF [14] and the reference EPS architecture: the DGs in ETEF are equivalent, in terms of power, compared to those of the reference architecture (the model contains two DGs, compared to four of the reference, but during simulations it will not be considered the electric propulsion load) and the DC-grid in ETEF represent the DC subnet where to attest the PPLs and to integrate the BESSs in the new electrical architecture hypothesis (the "AC-grid" and the "resistor bank" in ETEF will represent the other electrical users - total ship electrical load - outside the DC subnet).

- response of the DC subnet and BESS[9] to various PPLs combinations, to identify the "worst case scenario" (i.e., a scenario that causes the batteries to drain more quickly and at steady state leads to network instability) and the "greater resilience scenario" (i.e., a scenario that allows stability for as long as possible); the significant simulations outputs are the voltage trend on DC buses and the State Of Charge (SOC)/working C-rate of the batteries during operation.

Table 1. Summary of the scenarios and results obtained in the simulations.

Scenario	**Number of pulses**	**DC bus voltage trend**	**SOC & C-rate**
#4 synchronized PPLs *(equiv. to a single 2.2 MW steps)*	unlimited	±10% ([15] compliant)	suitable for continuous power supply
#4 PPLs synchronized with 6 sec phase-shifted pairs *(equivalent to a constant 1.1 MW load)*			
#4 synchronized PPLs + 1.2÷2.2 MW constant load			
#4 PPLs synchronized with 6 sec phase-shifted pairs + 1.2÷2.2 MW constant load			
#4 PPLs randomly combined			
#4 PPLs randomly combined + 1.2÷2.2 MW constant load			

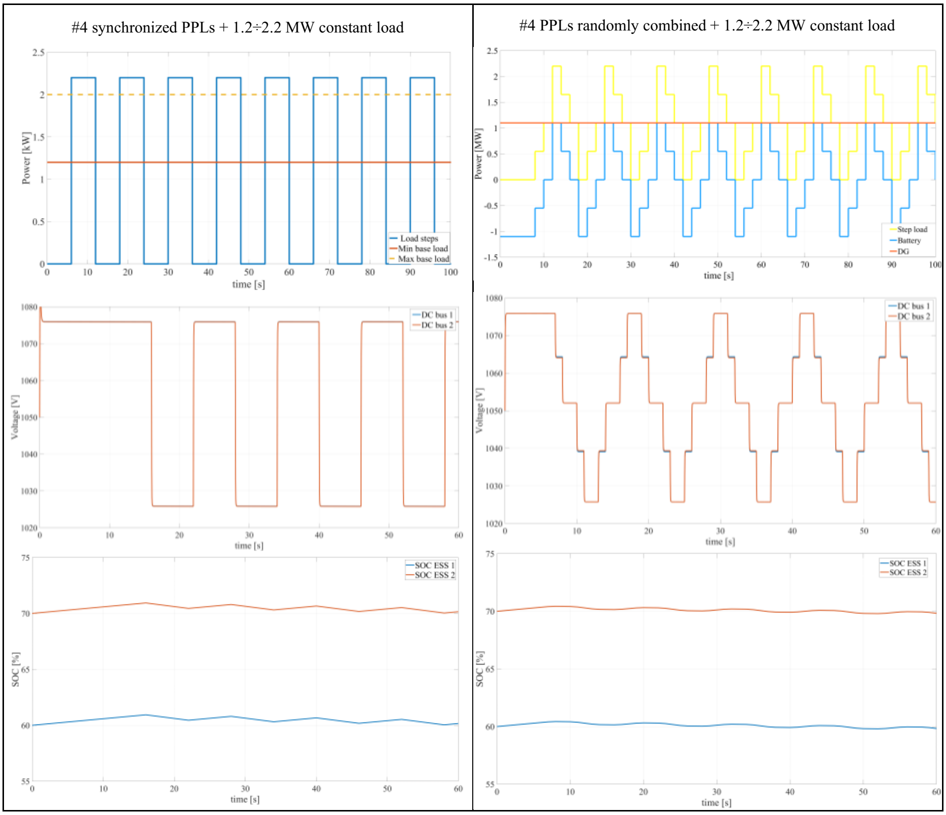

Figure 3. Results obtained during dynamic simulations, for two of the six scenarios considered.

---

[9] #2 BESS in ETEF: 256 Ah, 226 kWh, continuous C-rate of 3 and impulsive C-rate (max 10 s) of 6.

The results show that the Figure 2 architecture allows to supply the PPLs for an indefinite time, by making the DGs operate at the mean value of the impulsive load while the batteries would alternate cycles of charge and discharge with a C-rate within their continuous limit[10]. At the same time, compliance with the standard [15] regarding the “quality” of the voltage on DC buses, as well as compliance with the dynamic limits for the voltage, was observed. Finally, it is evident that the substantial constancy in the power injected by the DGs interface converters into the DC network[11] would guarantee the absence of voltage/frequency variations in the onboard AC network.

For the sake of completeness, it should be pointed out that simulations carried out can be followed in the future by a further investigation regarding the system’s behavior in the case of additional conditions (variations in electrical configuration), or in the case of “fault recovery and reconfiguration” in accordance with [15] and [16].

The integrated BESS (suitably dimensioned/configured) is not intended for the exclusive use of PPLs so, according to the energy policy adopted, it has been investigated if the BESSs allows to achieve also “secondary objectives” (compared to the primary function of ramp rate support of the DGs) during the period of inactivity of the DES. Instead of looking at an optimization of the size of the DGs, it has been analyzed the improvement of their working condition, in terms of achieving a load following behavior (instantaneous compensation of the change of load) ensuring the steady operation of the engines (and consequently the power system). In particular the analysis of the available data has highlighted that the electric propelled ships often implement a “power control mode”, in place of the normal “rpms control mode”, of the EPMs, in order to avoid oscillation on the DGs performances during rough sea condition. This mode guarantees constant power absorption from the power system, but can have, as side effect, a reduction of shaft’s rotation, and so to the whole ship speed, as a function of the magnitude of the weather conditions (determining an operational constraint). The value of these oscillations is comparable to the maximum absorption of the PPL considered in this paper, which means that it is possible of use the existing BESS to compensate/follow the load required by EPMs, leaving active the “rpms control mode” for the propulsion to achieve the desired ship speed.

5. Conclusions

In this paper the different solutions for supporting Directed Energy Systems (that are Pulsed Power Loads - PPLs for the Electrical Power System - EPS) in a naval vessel. The proposal of an EPS architecture, based on a DC zonal electrical distribution, as well as the integration of BESSs (Battery Energy Storage Systems) allowed to ensure correct PPLs supply, while complying with the power quality and operational requirements.

The results highlight the value of the model-based design approach, as a tool to define electrical architectures according to new paradigms, to obtain a resilient *unicum* that efficiently meets the increasingly demanding needs of payloads. In this context, an approach that aims at the overall integration between the onboard electric network and its connected systems, from an early design stage, would allow to optimize the use of all

---

[10] By implementing a power management system that measures the SOC of the batteries and modifies the output of the DGs to keep it constant. This is demonstrated by the SOC trend shown in the simulations, where the fixed setting of the DGs to a suitable value allows batteries to be kept at a controlled SOC.

[11] Achieved by setting the converters in power control, with fixed set point.

the power system components and equipment, and would enable the effective use of ESSs where necessary. As showed, the latter, also thanks to the continuous development of power electronics, represent a potential game changer to which pay attention in order to facilitate informed decision-making (also considering the opportunity to use hybrid ESSs that combine different technologies) and conduct optimizations in relation to the different functions they will perform in the context of the Energy Policy defined.

References

[1] G. M. Conrad, S. Mulukutla. Matching Power Generators to Pulsed Loads. Proceedings of the 2010 IEEE Radar Conference; 2010 May 10-14. doi: 10.1109/RADAR.2010.5494632.

[2] S. Faddel, A. A. Saad, M. E. Hariri, O. A. Mohammed. Coordination of Hybrid Energy Storage for Ship Power Systems with Pulsed Loads. IEEE Transactions on Industry Applications; 2020 March-April; 56(2):1136–1145. doi: 10.1109/TIA.2019.2958293.

[3] F. D'Agostino; D. Kaza; F. Silvestro; A. Chiarelli; F. Olcese. A Survey on Pulse Power Load Applications and Tools for Simulation. Proceedings of the 2023 IEEE Electric Ship Technologies Symposium (ESTS); 2023 August 01-04. doi: 10.1109/ESTS56571.2023.10220530.

[4] W. -S. Im, C. Wang, L. Tan, W. Liu, L. Liu. Cooperative Controls for Pulsed Power Load Accommodation in a Shipboard Power System. IEEE Transactions on Power Systems; 2016 November; 31(6):5181-5189. doi: 10.1109/TPWRS.2016.2538323.

[5] Naval Sea Systems Command (NAVSEA). MIL-STD-1399 Department of Defense Interface Standard SECTION 300, PART 1 - Low Voltage Electric Power, Alternating Current; 2018 September 25.

[6] Naval Sea Systems Command (NAVSEA). MIL-STD-1399 Department of Defense Interface Standard SECTION 300, PART 2 - Medium Voltage Electric Power, Alternating Current; 2018 September 25.

[7] North Atlantic Treaty Organization (NATO). NATO-STANAG 1008 Characteristics of Shipboard 440V/230V/115V 60Hz, 440V/115V 400Hz and 24/28Vdc Electrical Power Systems in Warships of the NATO Navies; 10th ed.; 2021 October 12.

[8] V. Salehi, B. Mirafzal, O. Mohammed. Pulse-Load Effects on Ship Power System Stability. Proceedings of the IECON 2010 – 36th Annual Conference on IEEE Industrial Electronics Society; 2010 November 07-10. doi: 10.1109/IECON.2010.5675297.

[9] L. -G. Yuan, F. -M. Zeng, G. -X. Xing. Improvement and Simulation Study on Turbocharged Diesel Generator Set under Pulsed Load. Proceedings of the 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering; 2010 August 24-26. doi: 10.1109/CMCE.2010.5610093.

[10] L. Farrier, C. Savage, R. Bucknall. Simulating Pulsed Power Load Compensation using Lithium-ion Battery Systems. Proceedings of the 2019 IEEE Electric Ship Technologies Symposium (ESTS); 2019 August 14-16. doi: 10.1109/ESTS.2019.8847802.

[11] G. Oriti, A. L. Julian, D. P. DeToma. Shipboard Power Conversion System to Meet MIL-STD-1399 Limits for Pulsed Power Loads. Proceedings of the 2021 IEEE Energy Conversion Congress and Exposition (ECCE); 2021 October 10-14. doi: 10.1109/ECCE47101.2021.9595586.

[12] F. Scuiller. Simulation of an Energy Storage System to Compensate Pulsed Loads on Shipboard Electric Power System. Proceedings of the 2011 IEEE Electric Ship Technologies Symposium; 2011 April 10-13. doi: 10.1109/ESTS.2011.5770904.

[13] H. H. Eldeeb, O. A. Mohammed. Control and Voltage Stability of a Medium Voltage DC Micro-Grid Involving Pulsed Load. Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and the 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe); 2018 June 12-15. doi: 10.1109/EEEIC.2018.8494603.

[14] D. Bosich, M. Chiandone, G. Sulligoi, A. A. Tavagnutti and A. Vicenzutti. High-Performance Megawatt-Scale MVDC Zonal Electrical Distribution System Based on Power Electronics Open System Interfaces. IEEE Transactions on Transportation Electrification; 2023 September; 9(3):4541-4551. doi: 10.1109/TTE.2023.3244360.

[15] IEEE Standards Association. IEEE Std 1709-2018 - IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships; 7 December 2018. doi: 10.1109/IEEESTD.2018.8569023.

[16] IEEE Standards Association. IEEE Std 1826-2020 - IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW; 25 November 2020. doi: 10.1109/IEEESTD.2020.9271958.