Mitigation of Voltage Deviations in DC Shipboard Microgrids Through the Active Utilization of Battery Energy Storage Systems

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***Abstract*—DC shipboard microgrids are currently of interest since several benefits can be obtained from their adoption. One of the most important challenges in this type of systems is related to sudden load events that demand significant amounts of power within a short period of time. This kind of events leads to large deviations in voltage magnitude at the main dc busbars. To cope with this problem the usage of storage systems has been identified as a possible solution. This paper proposes a control strategy, based on the participation of a battery energy storage system, that aims to reduce the voltage deviations. In order to carry out the proposed strategy, only few signals are exchanged among the converters, while the required measurements are usually available locally at the installed devices. The proposed strategy can be adapted to the usual schemes used for on-board microgrids in order to effectively mitigates the voltage deviations under sudden load changes, with the aim to ensure secure operations and to increase the stability of the system.**

***Index Terms*—DC microgrid, dc shipboard power plant, power management system, microgrid stability.**

I. Introduction

SHIPBOARD microgrids are complex and relatively weak inertia power systems containing loads, generators and storage devices [1].

In general, the majority of shipboard microgrids have adopted ac distribution for their operation [2]. However, dc distribution has presented several advantages over ac distribution, such as [3]: no synchronization of energy resources, no reactive power neither frequency control, no harmonic currents, etc., attracting the interest of researchers. In addition, dc shipboard microgrids may introduce some advantages in low carbon-emission and fuel-efficient operation, as well as weight and space savings, important aspects in this type of applications [4].

Nevertheless, to successfully achieve a proper and secure operation of a dc shipboard microgrid, some particular aspects mainly related with the control of these systems must be addressed. One of the most important challenges is due to the presence of load events that demand load variation within a short period of time, leading to large deviations of the voltage, resulting in complex control task requirements [4], [5].

In order to mitigate these deviations, a common practice is to over-design the power plant, with the aim to maintain an adequate spinning reserve. This method introduces additional weight, space and increases costs, which have caused the search of new alternatives.

In [6] a supercapacitor is used as an energy storage device to directly support some critical loads. In this case, load variations do not have direct effect on the system behaviour, but the charging of the capacitor can still impact both the quality of power supply and system stability. In [7] a model predictive control is used to assess ramp rates (RR) violations and to coordinate the power generators and the battery storage systems under high-power conditions.

This work investigates a control strategy of the battery energy storage system of a dc shipboard microgrid. The proposed method pursuits the proper and secure operation of shipboard system, resulting in a reduction of the voltage deviation at the main dc voltage busbar. To carry out the proposed strategy, only few signals are exchanged among converters (operation signal of the battery and the active power measured by each converter), while the other required signals are local measurements, which increase the general reliability of the control strategy. The proposed control strategy can be adapted to the usual schemes used for on-board microgrids.

This paper is structured as follows. In Section II the system under study is described. Section III details the proposed control methodology, whose effectiveness is validated in Section IV, considering the previously described classical shipboard microgrid. Finally, conclusions are drawn in Section V.

II. System Model

The proposed shipboard microgrid is depicted in Fig. 1. It is composed by two main dc busbars (750 V) connected by a normally closed tie-breaker. Two Diesel Generators (DGs), interfaced by two ac/dc converters, and two storage systems, connected by two dc/dc converters, compose the power plant.

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The nominal power of the synchronous machines (coupled with the two DGs) is 450 kVA, while each battery energy storage systems (BESSs) is composed by a 120 kWh battery pack, with a 240 kW of maximum power discharge.

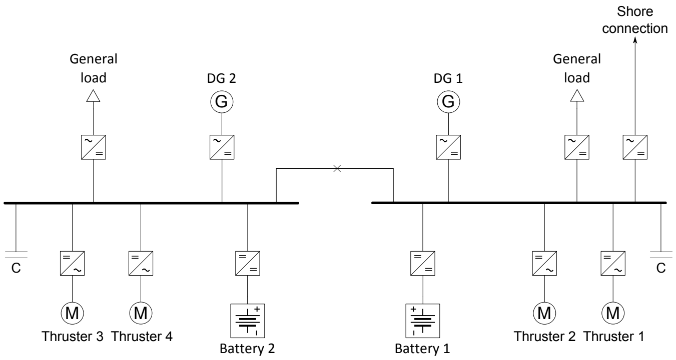

Figure 1. One-line diagram of the simulated grid.

A. Battery model

The adopted battery model is presented in [8], [9], where it is represented as a voltage source in series with a resistance, as shown in Fig. 2. Thus, the battery voltage $V_{\rm bat}$ is given by:

$$V_{\rm bat} = E_{\rm bat} - R_{\rm int} I_{\rm bat} \qquad (1)$$

where $R_{\rm int}$ is the internal resistance of the battery [Ω], $I_{\rm bat}$ is the battery current [A] and $E_{\rm bat}$ is the open circuit voltage [V], obtained by equation (2):

$$E_{bat} = E_0 - K\frac{1-{\rm SoC}}{\rm SoC}Q + Ae^{-B(1-{\rm SoC})Q} \qquad (2)$$

where E_0 is the battery constant voltage [V], K is the polarization voltage [V], Q is the battery capacity [Ah], A is the exponential zone amplitude [V] and B is the exponential zone time constant inverse [Ah^{-1}].

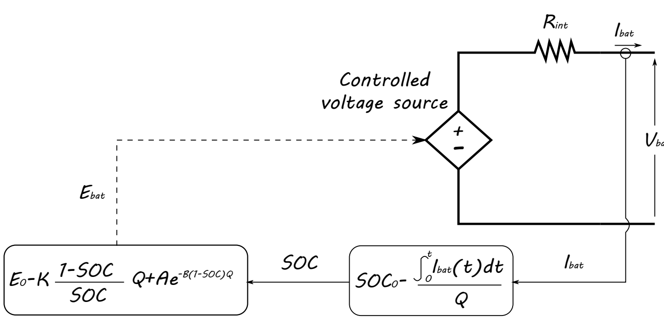

Figure 2. Model of the battery.

B. DG Converters Control

Vector control strategy has been adopted for the DG converter interface. It offers decoupled control of active and reactive power and a good response under fast dynamics, it makes possible the utilization of a control system in the form of a cascade structure, adopting PI control loops, one for the outer and another one for the inner control loop.

The outer controllers can be designed according to the application, such as dc voltage control, active power control, reactive power control, etc. and the reference values of the inner loops are provided by the outer loops, e.g., the direct reference current can be provided by the dc voltage controller, while the reference value for the quadrature current can be provided by the reactive power controller.

For example, the current controller used in this investigation is shown in Fig. 3. As it can be seen the output of the physical system, $i_{\rm d}$ is taken and compared with the reference current value (coming from an outer loop). The error of these values is the input of the PI regulator. Then, a compensation is performed, obtaining as a final result the reference voltage required by the converter, i.e., the modulation index.

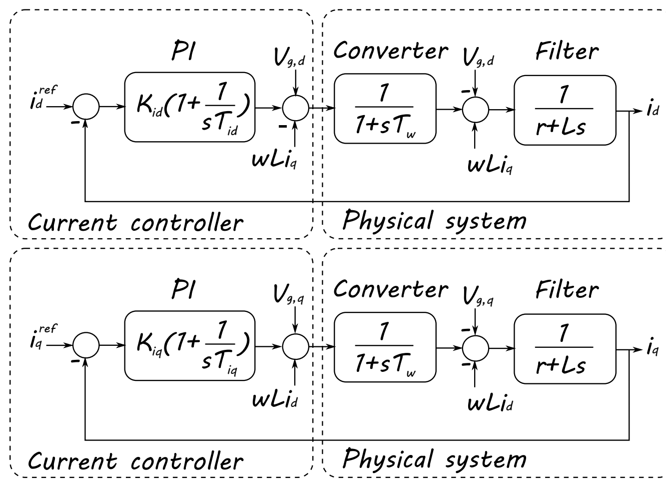

Figure 3. Block diagram of current and voltage controllers of the ac/dc converters.

The control system must guarantee a fast inner current control loop for a good performance. Moreover, the tuning of the PI regulators, for closed loop, is chosen, if possible, to cancel the dominant pole in the external circuit [10]. The closed loop bandwidth must be at least 10 times smaller than the converter switching frequency.

III. Proposed Methodology

The main goal of the proposed control strategy is to mitigate the voltage deviations at the main dc busbar system, by means of the utilization of a BESS when sudden changes of load occur. The proposed methodology is shown in Fig. 4 and Fig. 5. As it can be notice a continuous monitoring of the system is carried out. When a load event occurs (e.g. at $t = t_1$), the battery controller performs an assessment to determine if the load event has exceeded the ramp rate of the generator(s) (${\rm RR_{DG}}$, thus this parameter is needed as an input to the scheme). In the left part of the diagram, in case, the ramp rate of the load (${\rm RR_{load}}$) has not exceeded the ${\rm RR_{DG}}$, the normal control operation continues. This means that the generator can suitably handle that load event, and that it is responsible for the voltage control. As a consequence, the battery remains idle. In the opposite way, when the $\mathrm{RR}_{\mathrm{load}}$ exceeds the $\mathrm{RR}_{\mathrm{DG}}$ the BESS is activated and takes the role of voltage controller and, at the same time, it sends a signal to the generator controller to change from voltage control to power control. In this way, during a sudden load event, the BESS discharges as fast as possible and this action gives time to the generator to reach the new value of load according to its capabilities. Once the balance has been reached, the controllers go back to their initial condition and are ready to act should a new event occur. If the balance is not achieved other control actions must be taken.

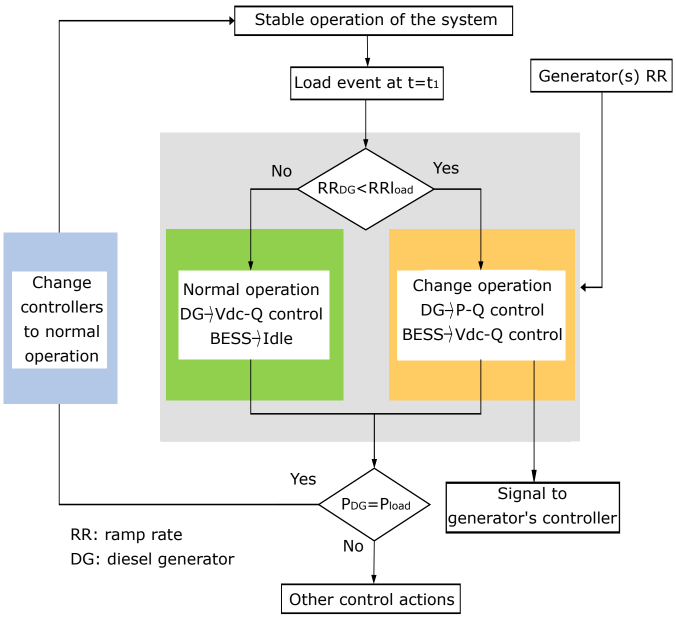

Figure 4. Flowchart of the proposed methodology for BESSs and DGs coordination.

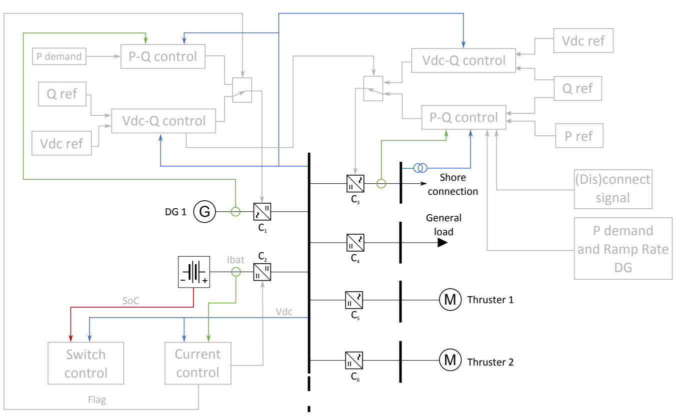

Figure 5. Functional scheme of the interactions between DGs ac/dc converter and BESS dc/dc converter.

A. Normal operating mode

In normal operation, i.e., when there are no significant variation within a short period of time, the generator takes the responsibility to regulate the voltage at the dc bus, this is done configuring the generator's converter in $V_{\mathrm{dc}} - Q$ control, this means that for normal changes of load (i.e., changes that do not exceed $\mathrm{RR}_{\mathrm{DG}}$), the generator is able to feed the load. The battery's converter exchanges zero power to the grid but it is ready to act if a sudden change occurs.

In the other hand, if a sudden change of the load occurs the operation of the battery is required. The sudden changes of load can be classified into two types: i) a long-term fast change of load, and ii) a short-term fast change of load.

When a long-term fast change of load occurs, the battery must follow the change until the generator response is able to achieve the new final value of the load. In this way, the load change is followed, first by the battery but as the generator increases its output, the battery at the same rate decreases its output. During this process, momentarily the battery will regulate the dc voltage of the main dc bus but once the generator reaches the new state of the system (i.e., the battery does not deliver power anymore), the generator goes back to its duty of dc voltage regulation.

When a short-term fast change of load occurs, the battery must follow the change and as it is very fast and for a very small period of time, the generator never enters in action. Thus, this process is all mitigated by the battery.

In normal operation, after several sudden changes of load, it is also possible to charge the battery once the system reaches steady state. It is important to notice that the charging process has to be smooth to allow the generator to properly follow the event.

B. Shore-connected operation

If a signal of connection is received, the circuit breaker at connection to the terrestrial distribution grid is closed and the transition from normal to shore-connected mode starts. During this procedure, the local generator continues its normal operation, i.e., it performs the dc voltage regulation, therefore grid's converter is in $V_{\mathrm{dc}} - Q$ control. The grid converter is enabled, operating in $P-Q$ control, starting with an exchange of active power equal to 0, meanwhile the synchronization is carried out. Then, to avoid a sudden transition, the grid's converter starts to smoothly increase the injected power (i.e., the power delivered by the utility grid) according to the corresponding downward ramp rate of the local generator. This, in turn, will result in a decrease of the power injected by the generator. When the power exchanged with the utility grid is equal to the power demanded by the loads, the grid's converter is idle and the generator is turned off. At this moment, the grid converter changes from $P - Q$ to $V_{\mathrm{dc}} - Q$ control and the connected-mode transition is completed.

It is assumed that during the transition there are no sudden changes in the load and in case some smooth changes occur, the local generator is able to control them, hence the battery's converter is disabled. Load converters continue demanding to the network the power required for the load and motor, respectively.

In a similar way to the disconnection from the main grid, when the signal of disconnection is received, the generator is turned on and generator's converter enables the dc voltage regulation, while the grid's converter changes its control from $V_{\mathrm{dc}} - Q$ control to $P - Q$ control. Then, the grid's converter reduces smoothly the injected power (i.e., the power delivered by the utility grid) according to the corresponding upward ramp rate of the local generator. When the power exchanged with the utility grid is equal to 0, the disconnection of the terrestrial distribution grid performed and the normal operation re-starts.

IV. Results

Time-domain simulations have been carried out to validate the proposed strategy. All the models and the dynamic simulations have been performed in DIgSILENT PowerFactory [11], and some of the results have been exported in MATLAB [12] for a more detailed analysis.

The study cases consider the operation of the system in normal mode under different sudden long-term load changes. In order to study the system performances, a step load event (for example a boiler connection) is produced by a variation in the general load at $t = 5$ s.

Simulations have been performed with and without the activation of the proposed control strategy, for wide range of load variation, up to 200 kW.

The system response is shown in Fig. 6. Fig. 6(a) clearly shows that the voltage at the main dc busbar drastically drops till 0.7 pu when the load connection occurs. The slow dynamical response of the diesel generator under this type of load changes (see Fig. 6(d)) results in very large deviations of the voltage, that can produce the intervention of the protection system (under-voltage trip) and the disconnection, for example, of the thrusters with serious consequences in terms of safety.

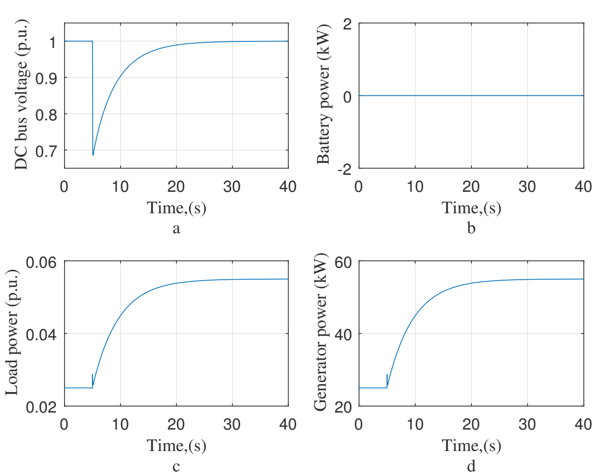

Figure 6. System response without the proposed methodology: (a) main dc busbar; (b) power supplied by the BESS; (c) load request (that cannot be met); (d) diesel generator response. The load step is 30 kW.

If the proposed control strategy is activated (considering an initial state of charge (SoC) equal to 90%) and under the same load event described in the previous paragraph, the response of the system is as shown in Fig. 7(b), which shows that the voltage at the main dc busbar oscillates in between 0.97 pu and 1.03 pu.

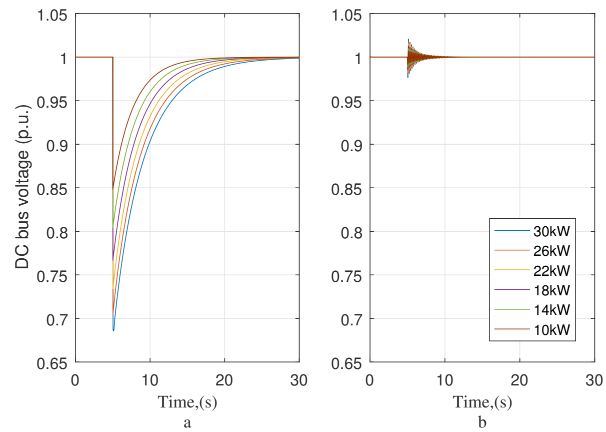

Figure 7. Comparison of dc-bus voltage behavior without (left) and with (right) the proposed methodology.

Comparing the results, it can be noticed that, if different load changes are analyzed, from 10 kW until 30 kW, it can be noticed that the voltage deviation is completely reduced when the proposed control strategy is adopted, assuring a secure operation of the system.

Table I summarizes the minimum measured values at the main dc bus without and with the proposed control strategy. As it can be noticed a reduction in the voltage drop of 29.08% in the worse case (the load event of 30 kW) is achieved and from Fig. 7, in the same case it can be observed that the recovery time of the system goes from 30 s to less than 10 s.

Table I
Minimum measured voltage at the main dc busbar.

Load step (kW)	Minimum measured voltage (p.u.)	
	w/o battery	w battery
10	0.8483	0.9920
14	0.8045	0.9888
18	0.7668	0.9857
22	0.7342	0.9826
26	0.7058	0.9795
30	0.6857	0.9765

A. Sensitivity analysis

With the combined action of the BESS and the proposed control strategy, if a wider sensibility analysis is performed (i.e., a step variation of 20 kW from 60 kW to 200 kW), the response of the system is as shown in Fig. 8.

Fig. 8(a) shows that the voltage at the main dc busbar oscillates in between 0.87 pu and 1.06 pu. In Fig. 8(b) it can be seen that the battery system once the load event occurs,

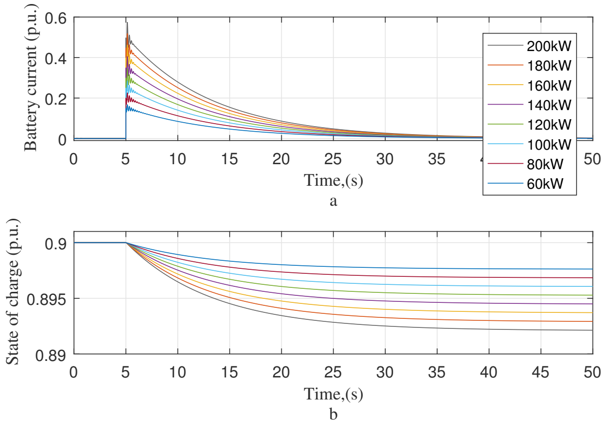

Figure 9. Battery response for long-term load step: current provided by the BESS (top chart), and SoC (bottom chart) for each load step.

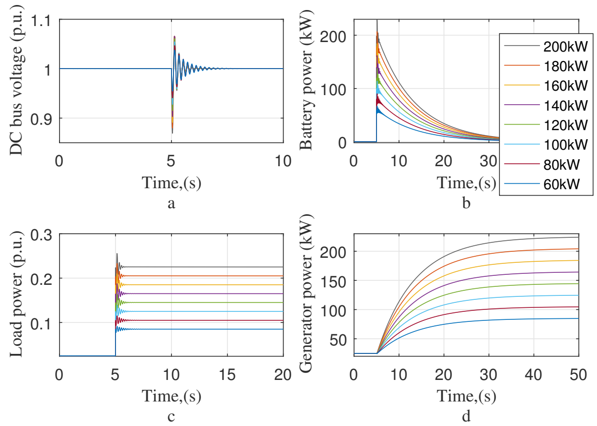

Figure 8. Wider sensitivity analysis with the proposed methodology.

enters in operation and discharges to maintain the power balance, at the same time it sends a signal to the converter of the generator, to indicate that the load has increased. This signal changes the operation mode of this converter from voltage control to power control and this, in turn, results in the increase of the output power of the generator in a regulated manner (see Fig. 8(d)) until the generator takes all the load and, consequently, the battery delivers no power. In all the cases, once this new state has been reached, the generator takes again the role of voltage regulation and the battery is ready to act if a new load event takes place. Fig. 8(c) presents how the load is supplied and it can be noted that in a very fast manner, the new steady state is reached. In addition, it can be noticed that the smaller is the load step, the less time is required to get the new steady state of the system and the lower is the voltage deviation.

Furthermore, the behavior of the state of charge of the battery under the different power steps is presented in Fig. 9. As it can be noted, the SoC stays very close to its initial value since the operation of the battery occurs in a very small time frame and the capacity of the battery is high compared to the demanded current during its operation.

V. Conclusion

This paper proposes a control strategy, based on the active participation of a BESS, that aims to reduce the voltage deviations at the main dc busbar. It compares the ramp rate of the generator(s) with the ramp rate of the load events and assess if the BESS needs to be discharged.

The proposed control strategy is based on the classic master-slave architecture but with some modifications in order to allow the active participation of the BESS. Here, the master role is shared between the generator and the BESS. The former takes the role of "master" (i.e., it regulates the main dc busbar voltage) during the normal operation of the system, while during sudden changes of load it becomes a "slave" and the BESS takes the role of "master".

The obtained results show that the proposed control strategy effectively mitigates the voltage deviations at the main dc busbar, either for sudden long-term or short-term load changes, allowing a secure operation and increasing the general stability of the system.

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References

[1] J. s. Thongam, M. Tarbouchi, A. F. Okou, D. Bouchard, and R. Beguenane, "All-electric ships-a review of the present state of the art," in *2013 Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, 2013.

[2] J. M. Guerrero, Z. Jin, W. Liu, M. B. Othman, M. Savaghebi, A. Anvari-Moghaddam, L. Meng, and J. C. Vasquez, "Shipboard microgrids: Maritime islanded power systems technologies," in *PCIM Asia 2016*, Jun. 2016.

[3] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 387–405, 2013.

[4] S. G. Jayasinghe, L. Meegahapola, N. Fernando, Z. Jin, and J. M. Guerrero, "Review of ship microgrids: System architectures, storage technologies and power quality aspects," *PCIM Asia 2016*, Jun. 2016.

[5] A. Boveri, F. D'Agostino, A. Fidigatti, E. Ragaini, and F. Silvestro, "Dynamic modeling of a supply vessel power system for dp3 protection system," *IEEE Trans. Transport. Electrific.*, vol. 2, no. 4, pp. 570–579, Dec. 2016.

[6] Y. Luo, S. Srivastava, M. Andrus, and D. Cartes, "Application of distubance metrics for reducing impacts of energy storage charging in an mvdc based ips," in *Electric Ship Technologies Symposium (ESTS), 2013 IEEE*, April 2013.

[7] T. V. Vu, D. Gonsoulin, F. Diaz, C. S. Edrington, and T. El-Mezyani, "Predictive control for energy management in ship power systems under high-power ramp rate loads," *IEEE Trans. Energy Convers.*, April 2017.

[8] O. Tremblay, L.-A. Dessaint, and A.-I. Dekkiche, "A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles," in *2007 IEEE Vehicle Power and Propulsion Conference*, 2007, pp. 284–289.

[9] M. Daud, A. Mohamed, M. Che Wanik, and M. Hannan, "Performance evaluation of grid-connected photovoltaic system with battery energy storage," *PECon 2012 - 2012 IEEE International Conference on Power and Energy*, pp. 337–342, 2012.

[10] S. Grillo, V. Musolino, L. Piegari, E. Tironi, and C. Tornelli, "Dc islands in ac smart grids," *IEEE Trans. Power Electron.*, vol. 29, no. 1, pp. 89–98, Jan. 2014.

[11] DIgSILENT PowerFactory, ed. Heinrich-Hertz-Straße, Germany.

[12] MATLAB R2010a: Natick, Massachusetts: The MathWorks Inc., 2010.