Power Flow Approach for Modeling Shipboard Power System in Presence of Energy Storage and Energy Management Systems

Flavio Balsamo, Pasquale De Falco, *Member, IEEE*, Fabio Mottola, *Senior Member, IEEE*, and Mario Pagano, *Senior Member, IEEE*

***Abstract*—Recent improvements in shipboard systems focus on the use of new technological systems and the adoption of innovative operating strategies for both increasing energy efficiency and reduce gas emissions. In such a context, this article studies a ship power system, where an energy storage system and a tailored energy management system are applied. It focuses on a detailed model of the on-board power system and points out a scenario of analysis larger than those usually adopted in the literature. The model is carried out with reference to DC, AC and hybrid AC/DC power grid architectures, by means of a power flow approach. The strategy of the energy management system optimally controls the on-board power system integrated with a battery storage device. The strategy aims to minimizes fuel consumption of the prime movers, while satisfying time-varying load demand under different operating scenarios. The procedure, tested on actual operative conditions of a supply vessel, shows feasibility and effectiveness of the power flow approach, giving evidence to the reduction of fuel consumption, while the correct operation of the power system is guaranteed.**

***Index Terms*—Ship power system, energy storage system, energy management system, hybrid grid, power flow, energy efficiency.**

I. Introduction

TODAY, the worldwide public interest in reducing greenhouse gases emissions is a key-driver in designing and operating transport systems. Since 1983, the International Maritime Organization has released regulations for reducing pollutant emissions in the maritime sector [1]. Consequently, the sector is involved in promoting on-board power systems more efficient and greener by exploring innovative technology, grid architectures and management strategies [2]. Among the various studies and proposals reported in the literature, it emerges as an element of interest the opportunity of enhancing shipboard electrification (e.g., [3], [4]). Starting by 1880 (i.e., date of the first shipboard electrical system), the on-board electrical system is evolved according to the novelties proposed by the technology market as soon as their use was rational with both international maritime regulations and cost [5]. Actual on-board electrical systems are multilevel power grids, which typically use power electronics for integrating multiple electromechanical devices operating with different voltage values and waveforms (i.e., AC, DC or hybrid AC/DC), for satisfying time-varying power requirements of the electrical services for propulsion, motor control, auxiliary and emergency.

Ship power system includes thermal prime movers, generators, distribution systems, electric propulsion drives and thruster units. Prime movers are usually diesel engines operating in medium or high rotational speed range, with fixed or variable speed operation. Their efficiency is limited, i.e., about 50% for two-stroke slow speed engines and slightly lower for four-stroke medium and high-speed engines [6]. Large part of the thermal energy generated by the combustion is wasted and discharged to the ambient, together with a considerable amount of noxious emissions to the atmosphere, which are a greater problem especially in ship-port interface [7]. The electrical section consists of the generators (i.e., wound rotor or permanent magnet synchronous machines) and the distribution system (i.e., typically, one main higher and other lower voltage systems). Electric propulsion motors are induction motors, fed by power converters. In Fig. 1(a) representative scheme of ship power system is reported. Limited generation capacity, small rotating inertia, presence of high share of nonlinear and dynamic loads are typical drawbacks of such a system.

The extensive electrification can boost energy efficiency measures, operating the equipment in order to save energy, to reduce fuel consumption/emission, while solving typical drawbacks [8]. The flexibility introduced by renewable energy sources [9], fuel cells [10] and gas turbine gensets [11] is particularly indicated in such tasks. DC systems, variable frequency drives, unit commitment and power system dispatch practices can be framed within extensively electrified systems, to further boost the efficiency [12], [13]. In particular, the use of power converters and DC systems, even combined with AC distribution grid, brings advantages in terms of technical, economic, and environmental benefits [14]. Since load profiles are typically

Manuscript received January 9, 2020; revised March 30, 2020; accepted May 21, 2020. Date of publication May 27, 2020; date of current version November 24, 2020. Paper no. TEC-00022-2020. *(Corresponding author: Fabio Mottola.)*

Flavio Balsamo is with the Department of Industrial Engineering, University of Naples Federico II, Naples 80125, Italy (e-mail: flavio.balsamo@unina.it).

Pasquale De Falco is with the Department of Engineering, University of Naples Parthenope 80143, Naples, Italy (e-mail: pasquale.defalco@uniparthenope.it).

Fabio Mottola and Mario Pagano are with the Department of Electrical Engineering and Information Technology, University of Naples Federico II 80125, Naples, Italy (e-mail: fabio.mottola@unina.it; mario.pagano@unina.it).

Color versions of one or more of the figures in this article are available online at https://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TEC.2020.2997307

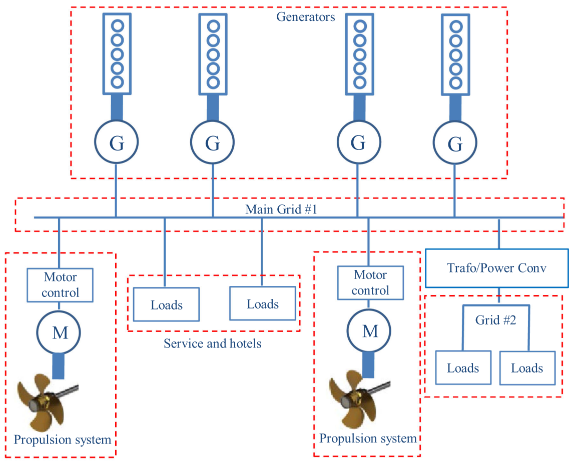

Fig. 1. Typical scheme of on-board power system.

time-varying, various proposals explored the opportunities of recovering and storing electrical energy by means of Energy Storage Systems (ESSs) [15], [16]. ESSs contribute to cover the variations of fluctuating power, while reducing global energy consumption of prime movers and ensuring reliability and power quality [17].

The energy management system (EMS) of the shipboard network equipped with ESS should be developed on the basis of the final objectives that are pursued, and considering the technical constraints related to the considered on-board power system. This paper provides a contribution in this framework, proposing a new power-flow-based approach to the EMS of an onboard power system. The next Section reviews the related researches developed in the literature, and it explains the novelties of this manuscript.

II. Literature Review and Research Contribution

ESSs in shipboard power systems are studied to minimize the fuel consumption, by calculating engine loading and energy demand [17], with the aim of optimizing the size of the storage itself [18] and of reducing polluting emissions. Hybrid systems (e.g., battery/diesel generation [19] and systems with flywheel energy storage [20]) have been proposed to add versatility in addressing technical, economic and environmental purposes. EMS algorithms for these hybrid propulsion systems with ESSs are typically developed using dynamic models and considering uncertainty [21].

The literature on EMSs of shipboard power systems covers a widespread range of technologies, methods and applications. Particularly, researches deal with the integration of innovative energy resources for efficient and sustainable systems and the application of optimal management strategies accounting for economic, environmental and technical aspects.

In [22], the on-board power generators, storage units, and loads are interconnected through power converters to a DC bus, and a method is proposed to estimate the dynamic behavior of the DC bus, dealing with the lack of detailed information related to the use of commercial-off-the-shelf. Ref. [23] addresses the optimal power management and greenhouse gas emissions limitation for a full-electric propulsion ship, by proposing a method for the optimization of generation power, storage system power, and navigation speed. The EMS proposed in [24] focuses on different technical and environmental objectives and constraints, by proposing a scheduling method that properly adjusts the propulsion load at the demand side to approach the optimal points of operation of the electric generators. The optimal scheduling methodology presented in [25] manages the ship operation aiming at reducing the fuel consumption and the emission of the diesel generators. Energy and power balances are addressed in [26] to estimate the system marginal costs through simple mathematical formulations. The EMS in [27] efficiently balances the amount of generated, saved and demanded power. The performance of droop control-based power sharing at different operating conditions is analyzed in [28]. The EMS approach for cruise-ferry on-board power system management developed in [29] simultaneously minimizes the power production and limits the air pollution, by adjusting the total load on the basis of optimal operating points of controllable power sources and navigation speed control. The method in [30] coordinates the voyage scheduling and the energy dispatch of a hybrid AC/ DC ship microgrid, accounting for operation uncertainties and grid constraints. The EMS described in in [31] aims at minimizing the fuel consumption and polluting emissions, by adaptively adjusting the instantaneous power balance among the storage devices and diesel engines.

To perform design and control tasks (e.g., security, reliability, data detection analyses), it is mandatory to electrically model the entire new power system by means of an approach that should be robust and able to analyze contingencies and to determine corrective actions against failures. The Power Flow (PF) is the approach typically used in power system application to characterize the operation state of generators and loads connected to a common power grid. PF requires the knowledge of the grid topology and impedance parameters to calculate nodal voltage magnitudes and phase angles, allowing to characterize the system operating conditions in terms of bus voltages, line electrical currents, active and reactive powers, power losses [32]. EMS tools can include PF to monitor, control, and optimize the performance of the power system, possibly by using remote terminal units or the more recent phasor data concentrators [33].

Motivated by above, this paper proposes an EMS that focuses on the active and reactive power flows in the whole ship power system, by minimizing the fuel consumption while satisfying technical constraints on generator capability curves (in terms of both active and reactive powers), bus voltages admissible ranges, lines ampacities, operation of storage devices, and limits imposed by power quality issues.

In details, the proposed EMS strategy uses a multi-temporal optimal approach, which allows coordinating the BESS's charging/discharging in terms of both active and reactive powers of synchronous generators and BESS state variables. The approach copes with the technical constraints, and it accounts for economic, environmental and efficiency aspects. The proposed strategy is suitable to meet the multiple functionalities specified in the multilevel hierarchical control defined in [12]. Indeed, it is able to (i) manage the outputs of each power converter; (ii) ensure that the variables of the system fall within the required ranges; (iii) manage the power exchanges among the components of the system; and (iv) achieve optimal conditions.

Compared to the reviewed literature, two are the major contributions brought by this paper. The first contribution is the proposal of a PF model for the new generation of maritime power system, integrating a hybrid grid with both AC and DC sections. The second contribution is the proposal of an EMS strategy for a supply vessel that permits to: (i) reduce pollutions in the sea-port and near the off-shore platforms by properly discharging the on-board Battery ESS (BESS); (ii) improve the efficiency of on-board generators during the voyages, properly managing the charging of the BESS.

In addition to the different details of the on-board equipment and operation strategies, there are significant differences with the other reviewed approaches. Compared to [22] and [27], the proposal implies the scheduling of both active and reactive power flows over longer travelling time periods. Compared to [23]–[26], [29], and [31], the proposal implies the reactive power management, thus allowing the control of generators operation points, bus voltages, and line currents. Moreover, the proposed method allows for the optimal scheduling for the whole mission profile, by implying constraints linking different operation stages. Compared to [28], the proposal considers the impact of the load/generation active and reactive power on the line currents and bus voltages over longer travelling time; it also accounts for the optimal usage of the storage devices. Compared to [30], the proposal allows for including the control on the network and generators electrical parameters, as well as for including storage devices.

As a final, general consideration, the proposed EMS allows managing hybrid AC/DC networks by considering the constraints of both AC and DC section, at the same time. The possibility to use the proposed EMS for both AC and hybrid AC/DC systems makes it able to integrate designing tools, in order to compare different system architectures [34].

III. Supply Vessel Power Requirements and Energy Management Strategy

Supply vessels present cyclical working load, which differ according to the services required by the off-shore installation. To supply off-shore oil and gas platforms, vessels repeatedly voyage between the port and the platform and have to exhibit stringent dynamic positions feature [35]–[37]. A typical working cycle consists of four different phases:

- port operation;
- laden voyage;
- dynamic positioning;
- partial load voyage.

Each phase is characterized by its representative power values for load and auxiliaries. During the operation in port, the loads are low and are typically supplied by only a part of the on-board generators. During the dynamic position, the power requirements of thrusters and prime movers are limited, but highly variable. In partial load and laden voyages, the power requirement is high. The resultant power profile can be represented by a constant value plus a variable value, which depends on operating and weather conditions. The operating conditions lead to large fuel consumption, even because, in order to prevent forced contingencies, the vessel has high power reserve and the generators, operating at low load, consume high amounts of fuel [18].

In order to minimize consumption of fuel and, hence, reduce cost and pollutant emission, an EMS related to the installation of a BESS, can be studied. BESS, frequently applied to aid generation systems in facing with varying load demand, in maritime application, can be also used for: (i) integrating sources of intrinsic slow dynamics; (ii) realizing hybrid structure, connecting the AC section with a DC microgrid, according to the paradigm of multi-level distribution system and zonal survivability (e.g., [12], [38]). EMS strategy can operate to: (i) keep the variables representative of the power system within admissible ranges for all the operating phases; (ii) reduce emission, (iii) increase efficiency, (iv) improve the quality of energy supplied to propulsion and loads.

IV. EMS Strategy: The Optimization Model

The EMS strategy is based on an optimal power flow, which calculates active and reactive powers of the generators and the BESS. During laden and partial load voyages, the BESS is charged, while optimizing the operation states of both generators and prime movers. During the dynamic positioning, when the thrusters' operation implies highly variable load profile, and in port, when the load is low, the BESS is discharged, aiding generators and engines to operate more efficiently. The aim of the strategy is to reduce the fuel consumption during the whole working cycle, while the constraints upon engines, generators, BESS and grid are satisfied.

For each operation phase, the strategy is formulated in terms of multi-temporal, non-linear, constrained, single-objective, minimization problem as:

$$\begin{array}{ll} \min_{\boldsymbol{x}} & f(\boldsymbol{x}) \\ \text{subject to} & \boldsymbol{h}(\boldsymbol{x}) = 0 \\ & \boldsymbol{g}(\boldsymbol{x}) \leq 0 \end{array} \tag{1}$$

where $\boldsymbol{x}$ is the optimization variable vector, $f(\boldsymbol{x})$ is the objective function, $\boldsymbol{h}(\boldsymbol{x})$ and $\boldsymbol{g}(\boldsymbol{x})$ are the vectors of the equality and inequality constraints, respectively.

The optimization variable vector includes active and reactive powers of synchronous generators and BESS, voltage magnitude and phases at the buses of the power grid. Objective function and constraints related to grid, synchronous generators, static converter and BESS are detailed in the following subsections. The optimization strategy is presented with reference to all the four working phases. It is solved imposing on the state variables the conditions of continuity between successive working phases.

A. Objective Function: Fuel Consumption

The objective function to minimize is the fuel consumption (FC) of the diesel engines, which can be expressed in the discrete time domain as follow [36]:

$$FC = \sum_{t=t_{i_k}}^{t_{f_k}} \sum_{j=0}^{n_{eng}} \left(sfoc_{t,j} \cdot P_{eng_{t,j}} \Delta t \right) \quad (2)$$

where:

- n_{eng} is the number of the on-board diesel engine;
- FC is measured in grams (g);
- t_{i_k} and t_{f_k} are the initial and final time intervals of the considered operation stage k, with $k = \{po,\ lv,\ dp,\ plv\}$, being po the port operation, lv the laden voyage, dp the dynamic positioning and plv the partial load voyage;
- Δt is the duration of each time interval (h);
- $sfoc_{t,j}$ is the specific fuel consumption of the engine j at time interval t (g/kWh);
- $P_{eng_{t,j}}$ is the hourly power delivered by the diesel engine j at time interval t (kW).

The $sfoc$ depends on the engine and generator typology. According to [39], it can be expressed as a cubic function of the ratio between actual, $P_{eng_{t,j}}$, and the rated power, P_{dn}, of the diesel engine, by fitting the values provided in all the engine loading:

$$sfoc_{t,j} = \alpha_1 \left(\frac{P_{eng_{t,j}}}{P_{dn}} \right)^3 + \alpha_2 \left(\frac{P_{eng_{t,j}}}{P_{dn}} \right)^2 + \alpha_3 \left(\frac{P_{eng_{t,j}}}{P_{dn}} \right) + \alpha_4 \; t = t_{i_k}, \ldots, t_{f_k} \; j = 1, \ldots n_{eng} \quad (3)$$

where the parameters $\alpha_1, \alpha_2, \alpha_3,\ \alpha_4$ are the characteristic coefficients of the diesel engine, and $P_{eng_{t,j}}$ is given by:

$$P_{eng_{t,j}} = \frac{P_{g_{t,j}}}{\eta_{g_{t,j}}} \quad t = t_{i_k}, \ldots, t_{f_k} \quad j = 1, \ldots n_{eng} \quad (4)$$

with $P_{g_{t,j}}$ the power supplied by the synchronous generator j at time interval t, and $\eta_{g_{t,j}}$ its efficiency which depends on the generated power [36]:

$$\eta_{g_{t,j}} = k_1 \cdot \left(\frac{P_{g_{t,j}}}{P_{g_n}} \right)^3 + k_2 \cdot \left(\frac{P_{g_{t,j}}}{P_{g_n}} \right)^2 + k_3 \cdot \left(\frac{P_{g_{t,j}}}{P_{g_n}} \right) + k_4 \; t = t_{i_k}, \ldots, t_{f_k} \; j = 1, \ldots n_{eng} \quad (5)$$

where the parameters $k_1, k_2, k_3,\ k_4$ are the characteristic coefficients of the synchronous generator.

Eqs. (3)–(5) relate the objective function to the active powers of the synchronous generators, which are assumed as optimization variables.

B. Grid Operating Constraints

The PF equations, in terms of equality constraints, relate the power of the synchronous generators to the loads:

$$\begin{aligned} P_{i,t} &= f_P(V_{i,t}, g_{i,k}, b_{i,k}, \delta_{i,t}) \\ Q_{i,t} &= f_Q(V_{i,t}, g_{i,k}, b_{i,k}, \delta_{i,t}) \\ t &= t_{i_k}, \ldots, t_{f_k} \qquad \forall i \in \Omega_n \end{aligned} \quad (6)$$

where $P_{i,t}$ $(Q_{i,t})$ is the active (reactive) power injected in the i-th bus at the time t, obtained as function $f_P(f_Q)$ of: $V_{i,t}$ (i.e., voltage magnitude of the i-th bus at the time t), $\delta_{i,t}$ (i.e., the voltage argument of the i-th bus at the time t), $g_{i,k}$ $(b_{i,k})$ (i.e., the conductance (susceptance) of the line between buses i and k). Ω_n is the set of busses of the grid. Active and reactive powers of the load buses are assumed known and constant during each time interval. Note that all the electrical quantities can be expressed in per unit (pu) values. One bus of the Ω_n is assumed as "slack", where the following equality constraints are imposed:

$$\begin{aligned} V_{i,t} &= V_{i,t}^{sp} \\ \delta_{i,t} &= 0 \end{aligned} \qquad t = t_{i_k}, \ldots, t_{f_k} \quad (7)$$

where $V_{i,t}^{sp}$ $(\delta_{i,t})$ is the imposed value of the voltage magnitude (argument) at the bus i, during the time interval t.

Inequality constraints are imposed on:

i) the magnitude of the bus voltages:

$$V^{min} \leq V_{i,t} \leq V^{max} \quad t = t_{i_k}, \ldots, t_{f_k} \quad (8)$$

ii) the line currents:

$$I_{l,t} \leq I_l^{max} \; t = t_{i_k}, \ldots, t_{f_k} i \in \Omega_l \quad (9)$$

where $I_{l,t}$ is the current in the line l during the time interval t, I_l^{max} is the line ampacity and Ω_l is the set of all the grid's lines. Note that line currents are calculated by the values of the bus voltage, which are optimization variables.

In presence of multi-level grid, transformers are used. For each of them, the following constraint can be imposed in order to satisfy requirements of the rated apparent power:

$$\sqrt{P_{k,t}^2 + Q_{k,t}^2} \leq S_k \qquad t = t_{i_k}, \ldots, t_{f_k} \; k \in \Omega_{tr} \quad (10)$$

where, with reference to the transformer k and time interval t, $P_{k,t}$ $(Q_{k,t})$ is the active (reactive) power flowing through the transformer, S_k is its rated power and Ω_{tr} is the set of the transformer in the system.

C. Synchronous Generator Operating Constraints

Generator active and reactive powers have to not exceed the operating limits of the capability curve. The following inequality constraints can be imposed:

$$P_{i,t} \leq P_{g_{max}} \qquad t = t_{i_k}, \ldots, t_{f_k} \qquad i \in \Omega_{gn} \quad (11)$$

where Ω_{gn} is the set of the generators, $P_{g_{max}} = P_{g_n} - \Delta P_{g_{i,t}}$, and $\Delta P_{g_{i,t}}$ is the reduction of active power due to the reactive power $Q_{g_{i,t}}$ supplied by the generator. The value of $\Delta P_{g_{i,t}}$ is derived from the approximated capability curve of the generator (Fig. 2) [40]:

$$\Delta P_{g_{i,t}} = \begin{cases} \frac{P_{g_n} - P_{lim_2}}{Q_{lim_1} - Q_{lim_2}} \left(Q_{g_{i,t}} - Q_{lim_1} \right) & \text{if } Q_{g_{i,t}} \in \Omega_{Q1} \\ (P_{lim_2} - P_{g_n}) + \frac{P_{lim_2}}{Q_{lim_2} - Q_{max}} \left(Q_{g_{i,t}} - Q_{lim_2} \right) & \text{if } Q_{g_{i,t}} \in \Omega_{Q2} \end{cases} \quad (12)$$

where $\Omega_{Q1} = \{Q_{g_{i,t}} :\ Q_{lim_1} \leq Q_{g_{i,t}} \leq Q_{lim_2}\}$ represents the limit imposed by the armature of the generator, $\Omega_{Q2} = \{Q_{g_{i,t}} : Q_{lim_2} \leq Q_{g_{i,t}} \leq Q_{max}\}$ is the region where the field limit applies, P_{g_n} is the limit imposed by the prime mover, and Q_{min} and Q_{max} are the limits imposed on the reactive power imposed by the generator.

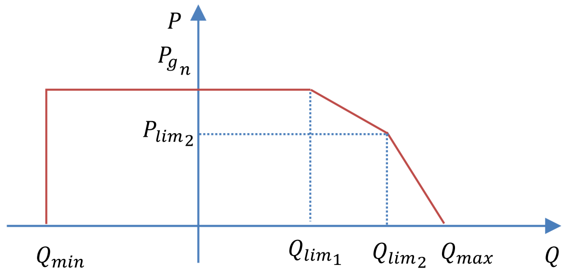

Fig. 2. Approximated curve of capability of the synchronous generator.

TABLE I
BESS EQUALITY CONSTRAINS ACCORDING TO EMS STRATEGY

port operation	laden voyage	dynamic positioning	partial load voyage
$SOC_{bt_{i,po}} = SOC_{max}$	$SOC_{bt_{i_{lv}}} = SOC_{bt_{fpo}}$ $SOC_{bt_{f_{lv}}} = SOC_{max}$	$SOC_{bt_{i_{dp}}} = SOC_{max}$	$SOC_{bt_{i_{plv}}} = SOC_{bt_{f_{dp}}}$ $SOC_{bt_{f_{plv}}} = SOC_{max}$

D. BESS Operating Constraints

Active and reactive powers cannot exceed the rated power of the BESS converter:

$$\sqrt{P_{b_t}^2 + Q_{b_t}^2} \leq S_b^{max} \quad t = t_{i_k}, \ldots, t_{f_k} \tag{13}$$

where P_{b_t} (Q_{b_t}) is the active (reactive) power of the BESS and S_b^{max} is the rated power of the BESS converter. Moreover, BESS is characterized by a rated power P_b^{max}, whose values cannot be exceeded in both charging and discharging stages:

$$-P_{b_t}^{max} \leq P_{b_t} \leq P_{b_t}^{max} \; t = t_{i_k}, \ldots, t_{f_k} \tag{14}$$

In order to limit the state of charge of the BESS at the time interval t (SOC_{b_t}) within a minimum (SOC_{min}) and maximum (SOC_{max}) value, the following constraints are included:

$$SOC_{min} \leq SOC_{b_t} \leq SOC_{max} \quad t = t_{i_k}, \ldots, t_{f_k} \tag{15}$$

with the SOC_{b_t} given by:

$$SOC_{b_t} = SOC_{b_{t-1}} - \gamma_t P_{b_t} \Delta t \tag{16}$$

where $\gamma_{i,t}$ is related to the BESS efficiency as:

$$\gamma_{i,t} = \begin{cases} \eta_{ch}^b & \text{if } \mathrm{P_{b_t}} < 0 \\ \frac{1}{\eta_{dch}^b} & \text{if } \mathrm{P_{b_t}} \geq 0 \end{cases} t = t_{i_k}, \ldots, t_{f_k} \tag{17}$$

where η_{ch}^b (η_{dch}^b) is the charging (discharging) efficiency. The efficiencies in (16) depend on both the efficiency of the interfacing converter and the round-trip efficiency of the battery.

Minimum and maximum values of the SOC in (15) define the maximum allowable depth of discharge and, hence, the expected lifetime of the BESS. Table I synthesizes the equality constraints assigned to the SOC imposed in the consecutive operating phases for the assigned EMS strategy.

In details:

- In port operation, the BESS has to be initially fully charged;

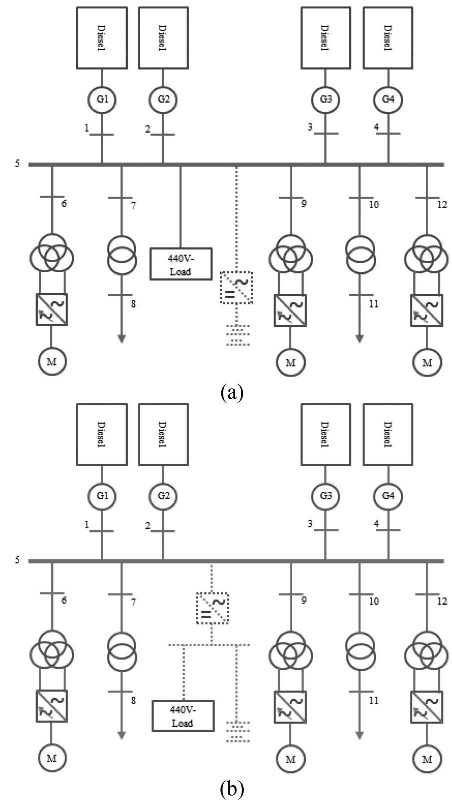

Fig. 3. Ship power system equipped with BESS (a), DC section (b).

- During the laden voyage, the BESS has to be fully recharged starting from the final SOC of the "in port" phase;
- In dynamic positioning, the BESS has to be initially fully charged;
- During partial load voyage, the BESS has to be fully recharged from the final SOC of the "dynamic position" phase.

E. Interfacing AC/DC Converter Constraints

DC sections are used in order to supply DC and sensitive loads by managing BESS. When the BESS is directly connected to DC loads, constraint (13) has not to be included in the optimization problem, as well as the efficiencies in (16) include only the battery efficiency.

The DC section is connected to the AC distribution system by means of an interfacing AC/DC converter, thus an inequality constraint is to be included:

$$\sqrt{P_{ic_t}^2 + Q_{ic_t}^2} \leq S_{ic}^{max} \quad t = t_{i_k}, \ldots, t_{f_k} \tag{18}$$

where P_{ic_t} (Q_{ic_t}) is the active (reactive) power through the interfacing converter and S_{ic}^{max} is the its rated power. P_{ic_t} is derived from the sum of the BESS active power and the powers of the loads connected to the DC section. It has to be considered the converter efficiency and that the P_{ic_t} can be bidirectional based on the battery size and load request. The reactive power Q_{ic_t} is typically an optimization variable.

TABLE II
RATED POWERS OF ON-BOARD COMPONENTS

Bus	Component	Rated power [MW]
1 - 4	Generator	0.8
5	440V - Load	2.1
6	Propulsion system R	1.05
8	220V - Load	0.065
9	Manoeuvring thrusters	0.4
11	220V - Load	0.05
12	Propulsion system L	1.05

TABLE III
ON-BOARD LINES DATA

From Bus	To Bus	Length [km]	X [Ω/km]	R [Ω/km]
1	5	0.04	0.104	0.095
2	5	0.04	0.104	0.095
3	5	0.04	0.104	0.095
4	5	0.04	0.104	0.095
5	6	0.015	0.104	0.095
5	7	0.005	0.096	1.40
5	9	0.08	0.107	0.192
5	10	0.005	0.096	1.40
5	12	0.015	0.104	0.095

The voltages at the AC ($V_{ic_t}^{AC}$) and DC ($V_{ic_t}^{DC}$) sides of the converter has also to be related:

$$V_{ic_t}^{DC} = \frac{2\sqrt{2}}{m_{a_t}\sqrt{3}} V_{ic_t}^{AC} \quad t = t_{i_k}, \ldots, t_{f_k} \tag{19}$$

with m_{a_t} the amplitude modulation ratio of the interfacing AC/DC converter [41].

V. NUMERICAL APPLICATION

The electrical scheme of a typical supply vessel power system is shown in Fig. 3. This is a 60 Hz-AC power grid. The BESS and the DC section are included in the system as reported in Fig. 3(a) and Fig. 3(b), respectively.

Details on components and lines are highlighted in Table II and III. The 440/220V transformers between buses 7 and 8 and between buses 10 and 11 have rated power of 65 kVA and 50 kVA, respectively, and a short-circuit voltage of 4.2%. Fig. 4 shows the profiles of real aggregated loads in the four operation phases: (i) port operation (21 hours); (ii) laden voyage (11 hours); (iii) dynamic positioning (46 hours); (iv) partial load voyage (11 hours) [36]. The different time duration in the profiles shown in Fig. 4 depends on each mission time. The time interval resolution of each mission time is always one hour. This implies that issues related to the dynamic operation and to real time control are not considered in this application, since this would imply different time resolutions, to account for their simulation, and different approaches, from both theoretical and technical point of view.

During the port operation the EMS strategy manages only one of the four generators, whereas, during the dynamical positioning, two generators operate. According to [36], for the four generation units, the following coefficients of specific fuel consumption and efficiency are used: $\alpha_1 = -22.26$, $\alpha_2 = 110.18$, $\alpha_3 = -128.56$, $\alpha_4 = 232.59$ and $k_1 = 0.1208, k_2 = -0.2888$, $k_3 = 0.2203,\ k_4 = 0.915$.

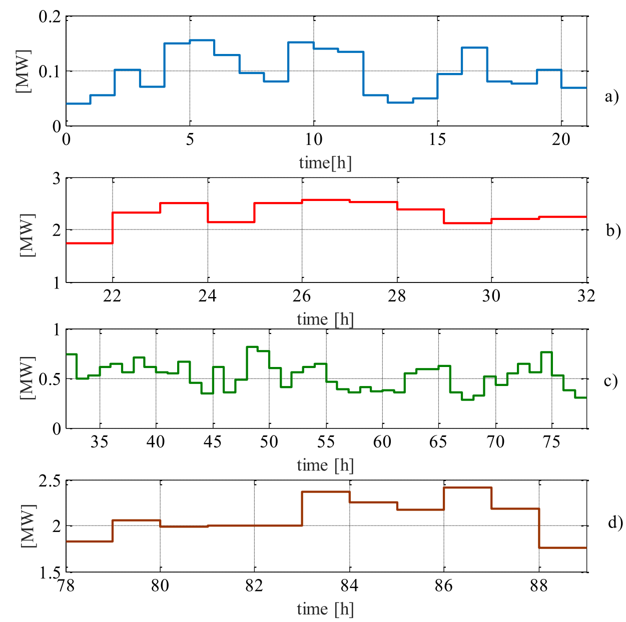

Fig. 4. Aggregated load active power profile in (a) port operation; (b) laden voyage; (c) dynamic positioning; (d) partial load voyage.

TABLE IV
FUEL CONSUMPTION IN CASE A

Operation stage	Fuel consumption [t]
port operation	0.43
laden voyage	4.70
dynamic positioning	4.81
partial load voyage	4.36
TOTAL	14.30

Three case studies were examined. *Case A* is the reference scenario, where the vessel operating phases are examined without EMS strategy and pure AC grid. *Case B* examines the integration of the BESS (connected at the bus #5, Fig. 3(a)) and *Case C* focuses on a hybrid AC/DC grid (Fig. 3(b)). In *Case B* and *Case C* the BESS is equipped by a lithium NMC/LMO battery whose energy capacity is 5 MWh.

A maximum depth of discharge of the 80% is assumed [42]. In *Case B*, the BESS is connected to the AC grid by means of a 5 MVA AC/DC converter, whereas in *Case C*, a 7 MVA interfacing AC/DC converter was used, according to the rated power of BESS and loads. The efficiency of both converters is 98% in rectifier and inverter operation mode. Specifically, in the *Case C*, assuming the presence of sensitive loads connected to the DC section, a minimum value of 0.985 pu is imposed to the voltage on the DC side of the AC/DC converter.

A. Case A: Reference Scenario

Table IV highlights the results of fuel consumption for the entire working cycle, when the on-board generators supply the loads of Fig. 4 and no EMS is applied.

B. Case B: EMS and BESS

Table V highlights the results of fuel consumption for the entire operating cycle when the EMS strategy in applied on the

TABLE V
FUEL CONSUMPTION IN CASE B

Operative phase	**Fuel consumption [t]**
port operation	0
laden voyage	5.12
dynamic positioning	3.86
partial load voyage	5.15
TOTAL	14.13
Aggregate percentage reduction [%]	1.19

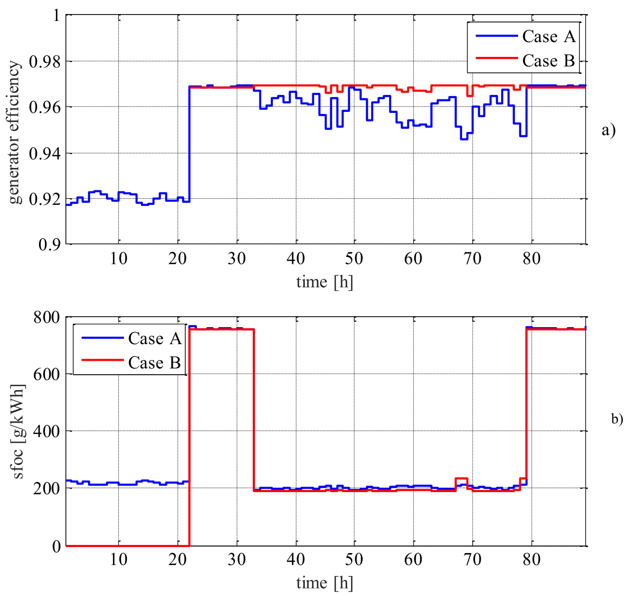

Fig. 5. Generator efficiency (a) and specific fuel consumption (b) profiles for *Case A* and *Case B*.

power system of Fig. 3(a). Also, the percentage variations with respect to the reference *Case A* are reported. The most relevant results are the nil values on the raw "in port", where the most restrictive limits are typically imposed by regulations on urban sustainability. A relevant reduction of the fuel consumption (about 20% lower than that resulting in the Case *A*) is obtained also during the dynamic positioning, because the BESS permits to switch-off one generator and makes to optimally manage the performance of the single operating generator.

The increases in fuel consumption during the laden voyage and the partial load voyage are due to the BESS charging. The aggregate fuel consumption is reduced of 1.19%. The optimization approach guarantees the maximization of the generator efficiency profile (Fig. 5(a)) and the minimization of the specific fuel consumption (Fig. 5(b)). The EMS strategy forces the synchronous generator to work at higher efficiency values (in Fig. 5(a), the blue line is almost always over the red line; during the port operations, all the generators are switched off and the blue line is missed). In Fig. 5(b), the comparison of the red and blues lines points out that the optimal management guarantees the best performances of the diesel engine.

Fig. 6 focuses on the aggregated active power profiles provided by the power generators in Case B. Comparing Figs. 4 and Fig. 6 it is relevant to observe that the EMS strategy acts to smooth the power profiles, forcing the generators to operate

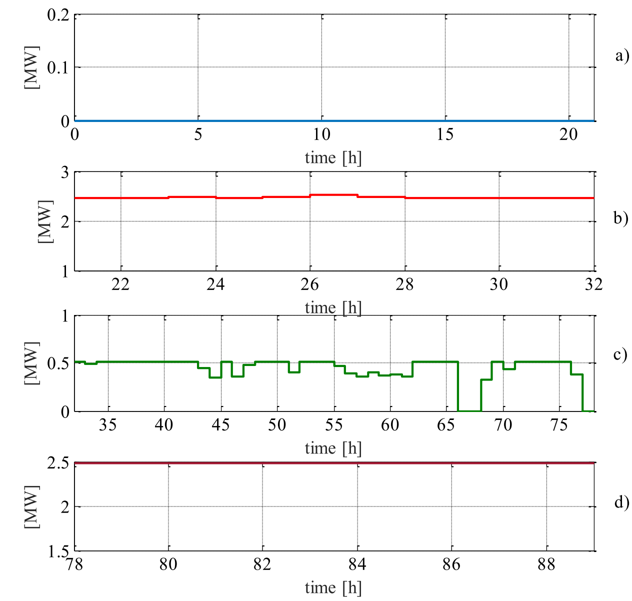

Fig. 6. Aggregated active power profile of the generators (Case B) in (a) port operation; (b) laden voyage; (c) dynamic positioning; (d) partial load voyage.

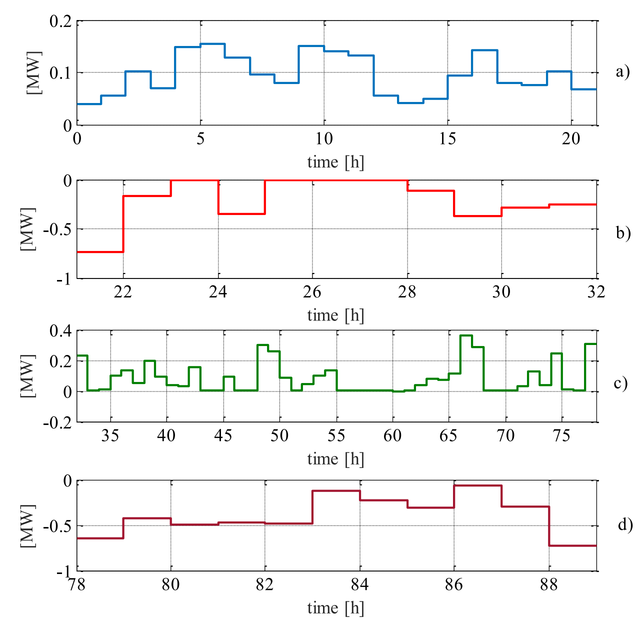

Fig. 7. BESS active power profile (case B) in (a) port operation; (b) laden voyage; (c) dynamic positioning; (d) partial load voyage.

closer to their maximum efficiencies for all the observation time. Observing Fig. 6(c) it can be noted that the BESS is also able to cover all of the power requirements for two hours (from 66-*th* hour to 68-*th* hour), allowing the nulling of exhaust emissions.

Figs. 7 and 8 report the BESS's power and SOC profiles, respectively. The profiles verify the correctness of the BESS size and it can be used to verify that the profile of the depth of discharge is coherent with the limits assigned to contain BESS life degradation [42].

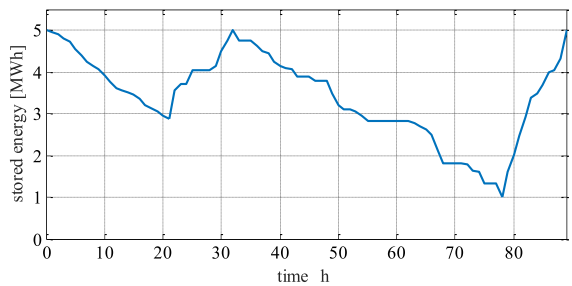

Fig. 8. BESS SOC vs hours on the entire working cycle (*Case B*).

TABLE VI
FUEL CONSUMPTION IN CASE C

Operative phase	Fuel consumption [t]
port operation	0
laden voyage	5.10
dynamic positioning	3.84
partial load voyage	5.13
TOTAL	14.07
Aggregate percentage reduction [%]	1.6

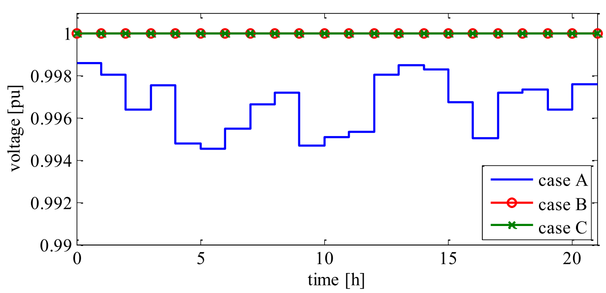

Fig. 9. Voltage profile at bus #5 in Case *A*, *B* and *C* in port operation.

C. Case C: EMS and DC Section

In this case, it is imposed that the voltage value at the DC side of the AC/DC converter cannot be lower than the value of 0.985 pu. In this case the fuel consumption (Table VI) in the various operative phases is still lower than the case A. Also, it can be noted that the percentage reduction of fuel consumption is slightly increased if compared to the value of case *B*. This is probably due to the use of an AC/DC interfacing converter having a larger rating than the rating of the battery converter in case *B*. In fact, this allows improving the reactive power support to the network, thus obtaining a reduction of losses in all the phases.

Figs. 9-12 report the voltage profiles at the bus #5 for the three case studies. The voltage profiles of *Case C* are almost always higher than those in the other cases. Moreover, they are smooth, because the EMS strategy forces the AC/DC converter to increase the AC bus voltage by injecting reactive power. During the dynamic positioning, the voltage profiles obtained in both *case C* and *case B* are generally lower, because only one generator is working (two generators work in *case A*).

The operating of a single generator makes it able to supply the loads with a greater value of efficiency, with different operating point within the capability curve limits. The current to feed the loads, flowing along only the 1-5 line, increases, producing

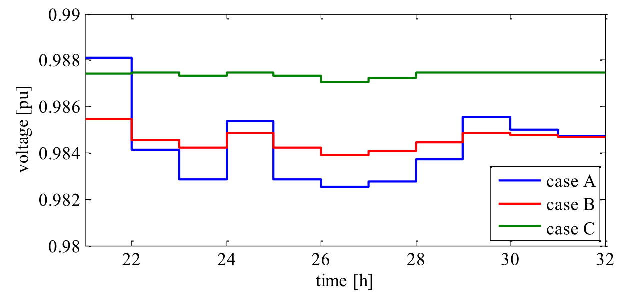

Fig. 10. Voltage profile at bus #5 in Case *A*, *B* and *C* in laden voyage.

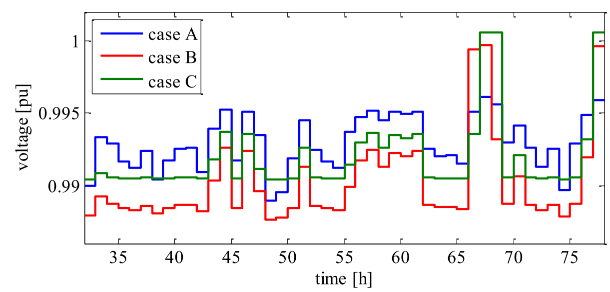

Fig. 11. Voltage profile at bus #5 in Case *A*, *B* and *C* in dynamic positioning.

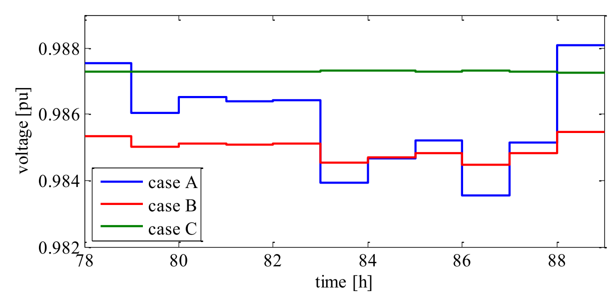

Fig. 12. Voltage profile at bus #5 in Case *A*, *B* and *C* in partial load voyage.

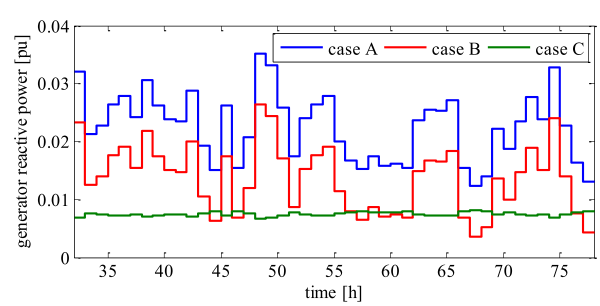

Fig. 13. Reactive power injected by a single generator Case *A*, *B* and *C* in dynamic positioning.

the increase of voltage drop, which is partially compensated by the reactive power injection. In Fig. 13 the reactive power profiles of *case A* and *case C* for a single operating generator are reported with reference to the dynamic positioning operation. The deviations between the two curve profiles during dynamic positioning are evident. In particular, it can be observed that the presence of BESS allows reducing the reactive contribution from the generators. Larger reduction is obtained in the case of DC section, thus implying a more constant profile.

VI. Conclusion

The paper focused on an EMS strategy for maritime application. The strategy is applied by equipping the power system of a supply vessel with a battery energy storage system (BESS) and managing optimally the source for energy efficiency and reducing pollutant emissions. To cover the aim, a power flow (PF) methodology was introduced. The modelling of the system was formulated in terms of fuel consumption minimization and satisfaction of constraints on grid, generators, loads and storage system. Three alternative case studies were examined. The results were discussed by comparing the reference scenario (where no EMS strategy was applied) with two alternative solutions. The numerical results focused on both the feasibility of the proposed modelling and the advantages carried out by the EMS strategy. Finally, the proposal evidenced high flexible and capability to suit for different reference scenario of ship on-board power system. The proposed management strategy can be useful in planning studies, to compare the operation of different solutions from both technical and economic point of view. This implies new and extensive analyses which the authors are intended to conduct in future research.

Acknowledgment

The authors acknowledge Prof. Guido Carpinelli for his significant contribution to this research activity and for the precious suggestions in the carrying out this paper. Also, thanks to Dr. Luisa Alfieri for her collaboration in carrying out the numerical applications.

References

[1] IMO, Review of Maritime Transport 2015. Geneva, Switzerland: United Nations, Oct. 2015. [Online]. Available. http://unctad.org/en/ pages/ PublicationWebflyer.aspx?publicationid = 1374

[2] T. D. Anvari-Moghaddam, L. Meng, B. Sun, and J. M. Guerrero, "Optimal planning and operation management of a ship electrical power system with energy storage system," in *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, Florence, Italy, Oct. 23-26, 2016, pp. 2095–2099.

[3] T. J. McCoy, "Electric ships past, present, and future [technology leaders]," *IEEE Electrif. Mag.*, vol. 3, no. 2, pp. 4–11, Jun. 2015,

[4] G. Seenumani, J. Sun, and H. Peng, "Real-time power management of integrated power systems in all electric ships leveraging multi-time scale property," *IEEE Trans. Control Syst. Technol.*, vol. 20, no. 1, pp. 232–240, Jan. 2012.

[5] E. Skjong, E. Rødskar, M. Molinas, T. A. Johansen, and J. Cunningham, "The marine vessel's electrical power system: From its birth to present day," *Proc. IEEE*, vol. 103, no. 12, pp. 2410–2424, Dec. 2015.

[6] G. Benvenuto, U. Campora, and A. Trucco, "Comparison of ship plant layouts for power and propulsion systems with energy recovery," *J. Mar. Eng. Technol.*, vol. 13, pp. 3–15, 2015.

[7] B. Anderson *et al.*, "Study of emission control and energy efficiency measures for ships in the port area," International Maritime Organization (IMO), London, U.K., Feb. 2015.

[8] A. J. Sorensen *et al.*, "Toward safer, smarter, and greener ships: Using hybrid marine power plants," *IEEE Electrific. Mag.*, vol. 5, no. 3, pp. 68–73, Sep. 2017.

[9] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuña, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, Jan. 2011.

[10] J. Kumar, L. Kumpulainen, and K. Kauhaniemi, "Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions," *Int. J. Elect. Power Energy Syst.*, vol. 104, pp. 840–852, 2019.

[11] A. Hasanzadeh, C. S. Edrington, N. Stroupe, and T. Bevis, "Real-time emulation of a high-speed microturbine permanent-magnet synchronous generator using multiplatform hardware-in-the-loop realization," *IEEE Trans. Ind. Electron.*, vol. 61, no. 6, pp. 3109–3118, Jun. 2014.

[12] Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J. C. Vasquez, and J. M. Guerrero, "Next-generation shipboard DC power system: Introduction smart grid and dc microgrid technologies into maritime electrical networks," *IEEE Electrific. Mag.*, vol. 4, no. 2, pp. 45–57, Jun. 2016.

[13] F. D. Kanellos, G. J. Tsekouras, and N. D. Hatziargyriou, "Optimal demand-side management and power generation scheduling in an all-electric ship," *IEEE Trans. Sustain. Energy*, vol. 5, no. 4, pp. 1166–1175, Oct. 2014.

[14] K. Kim, K. Park, G. Roh, K. Chun, "DC-grid system for ships: A study of benefits and technical considerations," *J. Int. Maritime Safety, Environmental Affairs Shipping*, vol. 2, no. 1, pp. 1–12, 2018.

[15] S. Y. Kim, S. Choe, S. Ko, S. K. Sul, "Naval Integrated power system with a battery energy storage system: Fuel efficiency, reliability, and quality of power," *IEEE Electrific. Mag.*, 2015, 3, pp. 22–33, 2015.

[16] E. Fasano, D. Lauria, F. Mottola, and R. Rizzo, "Analytical approach for the optimal design of combined energy storage devices in ship power system," in *Proc. 6th Int. Conf. Clean Elect. Power, Santa Margherita Ligure*, Jun. 27-29, 2017, pp. 761–767.

[17] E. K. Dedes, D. A. Hudson, and S. R. Turnock, "Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping," *Energy Policy*, vol. 40, pp. 204–18, 2012.

[18] A. Boveri, F. Silvestro, M. Molinas, and E. Skjong, "Optimal sizing of energy storage systems for shipboard applications," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 801–811, Jun. 2019.

[19] E. Ovrum and T. F. Bergh, "Modelling lithium-ion battery hybrid ship crane operation," *Appl. Energy*, vol. 152, pp. 1–11, 2015.

[20] M. M. Ramli, A. Hiendro, and S. Twaha, "Economic analysis of PV/diesel hybrid system with flywheel energy storage," *Renew. Energy*, vol. 78, pp. 398–405, 2015.

[21] A. Maheri, "Multi-objective design optimization of standalone hybrid wind-PV diesel systems under uncertainties," *Renew. Energy*, vol. 66, pp. 650–61, 2014.

[22] A. Francés-Roger *et al.*, "Dynamic assessment of COTS converters-based DC integrated power systems in electric ships," *IEEE Trans. Ind. Informat.*, vol. 14, no. 12, pp. 5518–5529, Dec. 2018.

[23] F. D. Kanellos *et al.*, "A cost-effective and emission-aware power management system for ships with integrated full electric propulsion," *Electric Power Syst. Res.*, vol. 150, pp. 63–75, 2017.

[24] F. D. Kanellos, A. Anvari-Moghaddam, and J. M. Guerrero, "Smart Shipboard Power System Operation and Management," *Inventions*, vol. 1, 2016, Art. no. 22.

[25] M. Othman *et al.*, "Scheduling of power generation in hybrid shipboard microgrids with energy storage systems," in *Proc.IEEE Int. Conf. Environ. Elect. Eng. IEEE Ind. Commercial Power Syst. Europe*, 2018, pp. 1–6.

[26] G. J. Tsekouras, F. D. Kanellos, and J. Prousalidis, "Simplified method for the assessment of ship electric power systems operation cost reduction from energy storage and renewable energy sources integration," *IET Elect. Syst. Transp.*, vol. 5, no. 2, pp. 61–69, Jun. 2015.

[27] M. R. Banaei and R. Alizadeh, "Simulation-based modeling and power management of all-electric ships based on renewable energy generation using model predictive control strategy," *IEEE Intell. Transp. Syst. Mag.*, vol. 8, no. 2, pp. 90–103, Summer 2016.

[28] A.-Falahi *et al.*, "AC ship microgrids: Control and power management optimization," *Energies*, vol. 11, 2018, Art. no. 1458.

[29] H. Bouaicha, S. Nejim, and H. Dallagi, "Optimal economic and pollution-constrained management of a hybrid DC shipboard power system," in *Proc. Int. Conf. Adv. Syst. Elect. Technol.*, 2018, pp. 435–440.

[30] Z. Li, Y. Xu, S. Fang, X. Zheng, and X. Feng, "Robust coordination of a hybrid AC/DC multi-energy ship microgrid with flexible voyage and thermal loads," *IEEE Trans. Smart Grid*, To be published. doi: 10.1109/TSG.2020.2964831

[31] J. Zhu, L. Chen, X. Wang, and L. Yu, "Bi-level optimal sizing and energy management of hybrid electric propulsion systems," *Appl. Energy*, vol. 260, 2020, Art. no. 114134.

[32] L. Alfieri, L. Battistelli, and M. Pagano, "Impact on railway infrastructure of wayside energy storage systems for regenerative braking management: A case study on a real italian railway infrastructure," *IET Elect. Syst. Transp.*, vol. 9, no. 3, pp. 140–149, 2019.

[33] Y.-F. Huang, S. Werner, J. Huang, K. Kashyap, and V. Gupta, "State estimation in electrical power grids," *IEEE Signal Process. Mag.*, vol. 29, no. 5, pp. 33–43, Sep. 2012.

[34] K. Ni, Y. Hu, and X. Li, "An overview of design, control, power management, system stability and reliability in electric ships," *Power Electron. Drives*, vol. 2, no. 2, pp. 5–29, 2017.

[35] H. E. Lindstad, G. S. Eskeland, and A. Rialland, "Batteries in offshore support vessels – pollution, climate impact and economics," *Transp. Res. Part D: Transport Environ.*, vol. 50, pp. 409–417, 2017.

[36] C. A. M. Vásquez, "Evaluation of medium speed diesel generator sets and energy storage technologies as alternatives for reducing fuel consumption and exhaust emissions in electric propulsion systems for PSVs," *Ciencia y Tecnología De Buques*, vol. 9, pp. 49–62, 2016.

[37] B. Zahedi, L. E. Norum, and K. B. Ludvigsen, "Optimized efficiency of all-electric ships by dc hybrid power systems," *J. Power Sources*, vol. 255, pp. 341–354, 2014.

[38] P. Kankanala *et al.*, "Optimal control of voltage and power in a multi-zonal MVDC shipboard power system," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 642–650, May 2012.

[39] R. Prenc, A. Cuculic, and I. Baumgartner, "Advantages of using a DC ´power system on board ship," *Pomorski zbornik*, vol. 52, pp. 83–97, 2016.

[40] R. Caldon, F. Rossetto, and A. Scala, "Reactive power control in distribution networks with dispersed generators: A cost based method," *Electric Power Syst. Res.*, vol. 64, no. 3, pp. 209–217, 2003.

[41] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications and Design*. New York: John Wiley & Sons, 1989.

[42] IRENA. Electricity storage and renewables: Costs and markets to 2030. International Renewable Energy Agency, Abu Dhabi, 2017.

Flavio Balsamo was born in Piano di Sorrento, Naples, Italy in 1962. He received the M. Sc. degree in naval and mechanical engineering from the University of Naples, Italy in 1987, then he started working at Fincantieri shipyards. He received the Ph.D. degree in Naval Engineering from the University of Naples in 1995. Since 2000 he is Assistant Professor at University of Napoli "Federico II". From 2012 to 2016 he was lecturer of Propulsion Plants at Italian Naval Academy. His research activity focuses on several topics including hybrid and full electric propulsion, full scale tests on board, exhaust gas emissions and marine fuels, marine propulsion plant simulation, roll motion identification. He also developed several original testing devices and procedures for the towing tank of the University of Naples.

Pasquale De Falco (Member, IEEE) received the Ph.D. Degree in Information Technology and Electrical Engineering from the University of Naples Federico II, Italy, for which he was awarded with the 2018 Best Thesis Award in Power Engineering by the IEEE Italy Section PES Chapter. He is currently a Research Fellow with the Department of Engineering at University of Napoli Parthenope, Italy. His research activities mainly focus on energy forecasting, energy optimization techniques and probabilistic methods applied to power systems.

Fabio Mottola (Senior Member, IEEE) received the M.Sc. (with honours) and Ph.D. degrees in Electrical Engineering from the University of Naples Federico II, Italy, in 2004 and 2008, respectively. He is currently an Assistant Professor with the Department of Electrical Engineering and Information Technology of the University of Naples Federico II. His research interests include the planning and operation of electrical power systems in the presence of distributed energy resources and lightning effects on power systems.

Mario Pagano (Senior Member, IEEE) was born in Naples, Italy, in 1970. He received the MSc (with honours) and the PhD in Electrical Engineering from University of Naples 'Federico II', Italy, in 1995 and 1999, respectively. In 2002, he was appointed Researcher in electric power systems at University of Naples. Currently, he is Associate Professor. Member of AEIT and CIFI, he is author or co-author of over 100 scientific papers published in journals and proceedings of international and national conferences; his research interests include power systems, renewable sources, storage systems, railway and mobility systems.