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Modeling and Real-Time Scheduling of DC Platform Supply Vessel for Fuel Efficient Operation

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Abstract—DC marine architecture integrated with variable speed diesel generators (DG) has garnered attention of the researchers primarily because of its ability to deliver fuel efficient operation. This paper aims in modeling and to autonomously perform real-time load scheduling of DC Platform Supply Vessel (PSV) with an objective to minimize specific fuel oil consumption (SFOC) for better fuel efficiency. Focus has been on the modeling of various components and control routines which are envisaged to be integral part of DC PSVs. Integration with photovoltaic (PV) based energy storage system (ESS) has been considered as an option to cater for the short time load transients. In this context, paper proposes a real-time transient simulation scheme which comprises of optimized generation scheduling of generators and ESS using DC optimal power flow algorithm. This framework considers real dynamics of DC PSV during various marine operations with possible contingency scenarios such as outage of generation systems, abrupt load changes and unavailability of ESS. The proposed modeling & control routines with real-time transient simulation scheme have been validated utilizing the real-time marine simulation platform. The results indicate that the co-ordinated treatment of renewable based ESS with DGs operating with optimised speed yields better fuel savings. This has been observed in improved SFOC operating trajectory for critical marine missions. Further, SFOC minimization at multiple sub-optimal points with its treatment in the real-time marine system is also highlighted.

Index Terms—DC Shipboard Power System, DC Power Flow, Platform Supply Vessel, Real-Time Simulation.

NOMENCLATURE

P_{mech}	mechanical power at diesel engine shaft
P_{load}	load demand
u_F	fuel injection input signal
k_{pm}	fuel injection system gain
τ_{pm}	fuel injection time constant
t_d	dead-time of diesel engine
J	diesel engine rotor inertia moment
ω_G	diesel engine and generator angular speed

k_{loss}	diesel engine rotational loss
T_G	torque produced by the generator
p	number of poles of generator
i_{qs}	q-axis current of WRSG at rotor reference frame
i_{ds}	d-axis current of WRSG at rotor reference frame
λ_{qs}	q-axis flux of WRSG at rotor reference frame
λ_{ds}	d-axis flux of WRSG at rotor reference frame
T_T	Thrust developed by the thrusters
τ_T	Torque developed by the thrusters
d_P	Propeller diameter
ω_P	Speed of the propeller
P_T	Power developed by the thrusters
C_T	Thrust co-efficient
C_τ	Torque co-efficient
SOC	state of charge

I. INTRODUCTION

Platform Supply Vessel (PSV) plays a major role in the marine industry because of its ability to perform cruising and dynamic positioning operation [1]. Development of marine integrated power systems (IPS) have enabled the marine loads esp. the propulsion systems to be powered from the common generation units [2], [3]. This resulted in the reduction of the number of installed prime-movers and offered designers flexibility to place the generation system at any suitable location. The future operation of the marine vessels depends on the International Maritime Organisation's (IMO) air pollution requirements [4], [5]. To comply with the requirements, it is pertinent to develop fuel efficient marine vessels hence limiting the exhaust gas emissions. In the conventional AC marine vessels, shaft electric machines have been proposed to minimise the fuel consumption [6]. DC marine systems are also proposed as they can operate with increased fuel efficiency as compared to the corresponding AC marine vessels [7], [8]. The lack of critical phase and frequency synchronizing parameters allows the interfaced diesel engines to run at variable speeds depending on total load demand thus optimizing the specific fuel oil consumption (SFOC) and increasing the fuel efficiency [9]. Other advantages constitute the ease of integration with the energy storage systems (ESS) [10]–[12], space and

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weight reductions [13] and lower losses as compared to the corresponding AC systems.

As analogous to the land based multi-terminal DC (MTDC) systems, DC marine vessels are envisaged to have two layer control system [14], [15]. The primary control system comprises of the DC bus voltage control [16] and active/reactive power control [17] with suitable protection & fault management algorithms [18]. The secondary control system comprises of the load forecasting, power flow algorithms which will be executed for a given state and requirements of the marine missions [8], [19]. The secondary control system also helps in optimized power flow by curbing out unintended power consumption hence minimizing the risk of blackout condition. It also aids in proper co-ordination of the load and generation system which reduces the oversizing requirement of the generation systems.

The generation scheduling for commercial land based power systems is usually done beforehand [8] which has been extensively studied for land based microgrids [19] and electric vehicles [20]. Unlike land based systems, the load profile of marine vessels are continuously changing owing to variable propulsion load demands. Thus, the generation output of marine vessels might be optimised for various operating scenarios. The optimized operation of the generation systems in the marine vessel is relatively new topic with limited number of research attempts made in this area. Authors in [21] proposed the operation of diesel engine at minimum SFOC with the help of integrated ESS where the authors have considered only the steady state analysis to arrive a single point of minimized SFOC. Further, much work on SFOC has been reported in the domain of AC marine vessels, such as shaft generator system (SHG) integrated with the diesel generators for possible minimization in fuel consumption [6], [22], agent based real-time load management to control the loads [23], stochastic approaches [15], [24]. One of the key research gaps in the past research studies has been the lack of modeling and implementation of realistic marine loads and marine missions. Although, the researchers have proposed various marine operating scenarios and SFOC minimization by considering MILP (mixed integer linear programming) approach for unit commitment [25]; such approaches are NP-hard (non-deterministic polynomial) and may not be preferred choice for real-time scheduling system which is the prime focus of this paper. Hence this paper presents modeling & control of the various components of marine vessels incorporated in a real-time transient simulation scheme with DC optimal power flow (OPF) algorithms utilising reduced bus-bar model for the scheduling of generation system. This work considers SFOC minimization at multiple sub-optimal points [26] as well to incorporate the real-time dynamics of the DC shipboard systems. Further, the performance of DC OPF based secondary control algorithm and SFOC optimisation with an option of ESS has been demonstrated for various marine missions.

This paper considers platform supply vessel (PSV) as an

example of marine vessel which performs cruising operation for the logistics and dynamic positioning (DP) operation to support the offshore supply vessels (OSVs). Apart from the diesel generators this paper also considers photovoltaic (PV) based energy storage system (ESS) [10], [27] as a part of generation systems of DC PSV. The focus is given on the integrated and automated generation operation by incorporating DC OPF based algorithms in the proposed optimization framework to minimize SFOC of diesel generators with the help of scheduling of ESS. The traditional analysis by offline simulations of the bigger and complex emerging DC marine systems is expected to consume longer time to generate results. This approach becomes quite cumbersome to analyse for the multiple test studies scenarios [28]. Thus in this paper the transient simulation framework for the entire DC shipboard system has been developed by utilising the advantages of the real-time simulation platform. The study of the dynamics of the full shipboard power system along with the interaction of PV/ESS with the generation systems during contingencies have been carried out with the proposed approach. The real-time optimal power scheduling for generators and energy storage systems have been carried out for various marine missions under different contingencies such as sudden load changes and network faults to prove the efficacy of the proposed approaches. The trajectory of the SFOC of the diesel engines during the various contingencies has been studied which could effectively be realised by the real-time simulation platform. Moreover, this method could be useful to validate the hardware design, converter control and protection algorithms of the future DC marine vessels. Hence, the *smarter generation system* of the future DC PSV is proposed which should be able to operate autonomously encompassing both primary and secondary control system.

Rest of the paper is organized as follows. Section II covers the modeling of DC PSV which comprises of the generation system and various marine loads. Section III comprises of the operating structure of the DC PSV considered in this work. The transient simulation scheme with DC OPF algorithm handling AC/DC systems to minimize SFOC has been implemented in Section IV. The optimised generation scheduling applied with various marine operational scenarios are discussed in Section V. The real-time load scheduling is achieved using OPAL-RT OP5600 based simulator and the paper is concluded in Section VI.

II. MODELING OF DC PLATFORM SUPPLY VESSEL

The bus-breaker model of the representative DC PSV is shown in Figure 1. The model is in coherent with the commercially available PSVs [29], [30] with two-bus architecture to increase the reliability and survivability of the vessel. The representative vessel comprises of four diesel engines coupled with the synchronous generators ($\mathcal{P}^{DG}$) and one PV based ESS ($\mathcal{P}^{ESS}$). The total generation capacity can be illustrated as per Eq. 1. The generators are interfaced with two level

voltage source converter (2L-VSC) acting as an active front end rectifier and PV based ESS is integrated via DC/DC converter for DC bus voltage and active/reactive power control.

$$\mathbb{P}_{Gen} = \{\mathcal{P}^{DG} n, \mathcal{P}^{ESS} \mid n = 1 : 4\}. \quad (1)$$

The nominal bus voltage of DC PSV is set at 1500 Vdc which according to IEEE Std 1709-2010 falls under medium voltage DC (MVDC) shipboard architecture [31]. As compared to the land based power systems, marine vessels have loads pertaining to different marine missions. Variable frequency propulsion system ($L_{propulsion}$) comprises of main propulsion (MP) systems to cater for the cruising loads ($\mathbb{L}^{CL}$); tunnel thrusters (TT) & retractable thrusters (RT) to cater for the DP load ($\mathbb{L}^{DP}$) [1]. The total connected propulsion load is illustrated as $L_{propulsion} = \{\mathbb{L}^{CL}, \mathbb{L}^{DP}\}$. The fixed frequency hotel loads are required for air conditioning/lighting systems, cranes/winches, small hotel motors etc. The hotel loads are classified into high power ($\mathbb{L}^{HL_{high}}$) and low power ($\mathbb{L}^{HL_{low}}$) loads. The miscellaneous loads ($\mathbb{L}^{misc}$) for radar and pulsed load operation are also considered as it may form the integral part of modern PSVs. The hotel loads can be illustrated as $L_{hotel} = \{\mathbb{L}^{HL_{high}}, \mathbb{L}^{HL_{low}}, \mathbb{L}^{misc}\}$ and the total load L_{total} can be expressed as Eq. 2.

$$L_{total} = \{\mathbb{L}^{CL}, \mathbb{L}^{DP}, \mathbb{L}^{HL_{high}}, \mathbb{L}^{HL_{low}}, \mathbb{L}^{misc}\}. \quad (2)$$

The power rating of the components and converter systems are shown in Figure 1. De-rating factor of 125% has been used for selection of the converters, cables and bus-bars to cater for the short time overload demands. The modeling and control of various components are discussed in the subsequent subsections.

Figure 1. Bus Breaker model of representative DC PSV.

A. Generation System Modeling

1) *Diesel Engine*: Diesel engines (DE) are used as prime-movers for the synchronous generators in DC PSV [3]. The prime-mover model comprises of fuel injection system, dead time (t_d) representing elapsed time until a cylinder produces torque and inertia of the rotating parts. The dead-time approximation of the prime-mover is realised by exponential delay and the transfer function is given by Eq. 3 [32], [33]. The differential equation governing the active power flow through the diesel engine is illustrated by Eq. 4.

$$h_{pm}(s) = \frac{P_{mech}(s)}{u_F(s)} = \frac{k_{pm}}{\tau_{pm}s + 1} e^{-t_d s}. \quad (3)$$

$$J \frac{d\omega_G}{dt} + k_{loss} \omega_G = \frac{P_{mech} - P_{load}}{\omega_G}. \quad (4)$$

Thus the diesel engine controls the synchronous generator by adjusting the mechanical power output. By linearization of the power flow equation (Eq. 4) around the operating point $\omega_G = \omega_{Go}$, the transfer function reduces to Eq. 5.

$$h_r(s) = \frac{\omega_G(s)}{\sum P} = \frac{1/\omega_{Go}}{Js + 2k_{loss}} \quad (5)$$

where $\sum P = P_{mech} - P_{load}$. The complete block diagram for DE speed control is shown in Figure 2. In the DC PSV, DE should be able to operate at optimised SFOC by running at optimised speed. Figure 3(a) represents the brake specific fuel consumption (BSFC) of the representative diesel engine operating at different power for different operating speed [34]. The cost function of the optimised diesel engine speed ($C(\omega)$) in terms of diesel generator power output ($\mathcal{P}^{DG}$) is calculated to understand the operating points of the DE. This is achieved with the help of curve-fitting techniques and the cost function, $C(\omega)$ is derived as shown in Eq. 6.

$$C(\omega) = A_0 + A_1 \mathcal{P}^{DG} + A_2 (\mathcal{P}^{DG})^2 + A_3 (\mathcal{P}^{DG})^3 + A_4 (\mathcal{P}^{DG})^4 + A_5 (\mathcal{P}^{DG})^5, \quad (6)$$

Figure 2. Control loop diagram for the speed regulation of the diesel engine.

Figure 3. (a) BSFC chart for representative 2000 kW diesel engine [34] and (b) the corresponding curve-fit of diesel engine speed for optimised SFOC for various loading conditions .

where $A_0 = 720.93$, $A_1 = 1.2591$, $A_2 = -0.00292$, $A_3 = 3.8104 \times 10^{-6}$, $A_4 = -2.1716 \times 10^{-9}$, $A_5 = 4.5206 \times 10^{-13}$. The actual DE speed for various power requirements and the curve-fit version is shown in Figure 3(b). The same cost function has been considered in the optimization framework presented in the Section IV.

2) *Diesel Generator- Rectifier Control*: Diesel generator (DG) includes full $d-q$ model of the wound rotor synchronous generator (WRSG) with both the field and damper windings [35]. The output torque of the shipboard diesel generator is maintained by independently controlling torque producing current, i_{qs} and machine flux, λ_{ds} which is achieved by maintaining $i_{ds} = 0$ [16], [36]. With reference to [16], in this paper, d-axis flux control is done by implementing flux estimation based method in which the flux of the machine is estimated and suitably controlled for varying operating conditions [16], [36]. The DC bus voltage and line current control is realized by implementing PI regulator having bandwidth of 100 Hz and 1000 Hz respectively, such a range is suitable for simulating in the real-time operations as well. The switching frequency of the VSC is chosen to be 5 kHz and the VSC is modelled in both average and detailed switching models for comparative studies in the real-time simulation environment. The plant transfer function for DC bus voltage control is calculated by equalizing the input and output power flow while neglecting the line losses which is shown in Eq. 7. The plant transfer function for current control is calculated from the leakage inductance (L_s) and stator resistance (R_s) of the interfaced WRSG. The plant transfer functions for voltage control loop (G_V) and current control loop (G_I) are illustrated in Eq. 8. The combined control loop representation of the diesel generator system interfaced with 2L-VSC is shown in Figure 4.

$$\mathcal{P}^{DG} = T_G \cdot \omega_G \implies 3p \frac{i_{qs} \lambda_{ds}}{4} \cdot \omega_r = C \frac{dv_{dc}}{dt} \cdot v_{dc} + v_{dc} \cdot I_L \quad (7)$$

$$G_V = \frac{3}{4} \frac{p \lambda_d \omega_r}{s C V_{dc} + I_L}, \quad G_I = \frac{1}{s L_s + R_s} \quad (8)$$

B. Marine Loads

DC PSV comprises of propulsion systems, thruster systems, hotel loads and miscellaneous loads such as pulsed load to undertake different marine missions. Prioritization of the operation of these loads is dependent on the marine missions undertaken by the vessel [37] and a sample priority table considered in this research work is shown in Table I. Modeling of these loads are required to understand the power consumption pattern which would eventually be necessary for scheduling

TABLE I
LOAD PRIORITIES FOR DIFFERENT MARINE MISSIONS

Marine Mission	Main Propulsion System	Tunnel Thrusters	Hotel Loads	Pulsed Loads
Cruising	HP	MP	MP	LP
Dynamic Positioning	HP	HP	MP	LP
Naval Warfare	HP	LP	LP	HP
At Port	HP	MP	MP	MP

HP: High Priority, MP: Medium Priority, LP: Low Priority

of generation sources. The modeling and control of different loads are discussed in the subsequent sections.

1) *Propulsion Systems*: In the PSVs, the propulsion systems ($L_{propulsion}$) are the main consumers of energy which undertake cruising and DP operation. The power requirement during the cruising operation ($\mathbb{L}^{CL}$) is dependent on the operating speed of the PSV (ω_P) as shown in Eq. 9.

$$\mathbb{L}^{CL} \propto \omega_P^3 \quad (9)$$

The power requirement during DP operation ($\mathbb{L}^{DP}$) carried out by PSVs are primarily dependent on the environmental forces and desired co-ordinate locations [38]. The sea current, wind velocity, surge and sway of the vessels have to be balanced by the thrust produced by the thruster systems in order to maintain the desired co-ordinates. The generalised schematic of the DP system is shown in Figure 5 [39]. The thrust production of the propeller is dependent on the speed (ω_P), propeller geometry (α) and hydro-dynamic quantities (β). The thrust (T) and torque (τ) developed by the thrusters for speed (ω_P), diameter of the propeller (d_P) is given by Eq. 10(a), 10(b) [38], [39].

$$T_T = g_T(n, \alpha, \beta) = C_T \rho d_P^4 \omega_P^2, \quad (10a)$$

$$\tau_T = g_\tau(n, \alpha, \beta) = C_\tau \rho d_P^5 \omega_P^2, \quad (10b)$$

where, C_T and C_τ are determined by open-water tests for submerged vessels and is dependent on propeller advance velocity. In this paper $C_\tau = 0.56$, density of water, $\rho = 997 \text{ kg/m}^3$ and $d_P = 3.5 \text{ m}$ are considered. The power consumed by the thrusters of DP system is shown in Eq. 11.

$$\mathbb{L}^{DP} = 2\pi n \tau = C_\tau \rho d_P^5 \omega_P^3. \quad (11)$$

For the worst weather conditions, the power demanded by the DP system to maintain desired co-ordinates would be significantly higher than that of the power demand during the calm weather condition. Direct torque control (DTC) is chosen over field oriented control (FOC) for propulsion motors and DP thrusters for its fast and superior performance and limited dependence on the machine parameters [40].

2) *Hotel Loads*: The percentage of the hotel loads (L_{hotel}) to the total load depends on the type of marine vessels. In PSVs installed hotel load is much lower than the propulsion loads but is important part of DC PSV. As shown in Figure 1, two types of house loads are considered in this paper. The high power hotel loads ($\mathbb{L}^{HL_{high}}$) supplying power to cranes/winches and air-conditioning/humidifiers have cumulative rating of 3200 kVA, 440 Vac and operates as 60 Hz frequency. The low power hotel loads ($\mathbb{L}^{HL_{low}}$) have cumulative rating of 400 kVA, 230 Vac and operates at 60 Hz frequency and are responsible for small hotel motors and lighting loads. Two level voltage source inverter (2L-VSI) with constant output of 690 Vac, 60Hz is utilised for the house loads.

3) *Miscellaneous Loads*: Miscellaneous loads ($\mathbb{L}^{misc}$) comprise of the pulsed and radar loads. Pulsed loads have presence in the modern naval vessels which are used in the electromagnetic guns, free electron lasers, radars & high energy lasers and draw huge amount of current lasting for short period of time.

Figure 4. Complete control loop of the diesel generator interfaced with 2L-VSC.

Figure 5. Schematic of Dynamic Positioning (DP) of PSV [38], [39].

This intermittent nature of the loads has effect on the stability of the generation sources [41]. The pulsed load duration may vary from few microseconds to milliseconds. In this paper, the pulsed load duration is selected to be 20 ms. The pulsed power load can be illustrated by Eq. 12.

$$\mathbb{L}^{pulse} = \frac{1}{T} \int_{t_1}^{t_2} P_o. dt \quad (12)$$

C. Energy Storage System (ESS)

Future autonomous vessels are expected to be operated with different forms of renewables. Here, in this work it is assumed that battery based ESS (BESS) units are supplied from the PV based renewable source which are interfaced with the DC PSV to cater for the short time load requirement and power fluctuations of the shipboard system. Such energy storage system also acts as reserve generation supply during the contingencies or sudden change of load. Unlike land based power systems where energy is stored in the ESS when its cost is low and release the same when the grid electricity cost is high [19], here, there is no such variations in the cost. Electricity stored in the BESS is based on the marginal cost of the power supplied from the diesel generators. Cost function

considered for the BESS is a constant price with the maximum power transfer based on the state of SOC as depicted in Eq. 13.

$$C_{ess} = f_p / kwh \quad (13)$$

The operational capacity of the ESS is restricted to 10% of the total installed generation capacity as illustrated in Eq. 14.

$$\mathcal{P}^{ESS} = 0.1 * \mathbb{P}_{Gen} \quad (14)$$

The PV-BESS is set to operate in optimal mode by limiting the battery usage between 20% and 100% of total storage capacity, further the scheduling constraints are imposed accordingly. The selection, sizing and schematic of the PV-BESS is described below.

1) *PV Energy Sources in Marine Vessels:* As per the green ship initiative, combination of photovoltaic-diesel generator (PV-DG) based generation systems are expected to be part of future marine vessels [10]. The rating and capacity of the PV panel is dependent on the available space in the target marine vessel [27]. For marine vessels undertaking longer voyages e.g. LNG carriers having easier accessibility to roof top terrace; proliferation of PV based generation system with 20% capacity of the total generation system has been suggested [10], [27], [42]. This paper considers the PSV with size and power rating comparable with the commercial available PSVs such as Rolls-Royce UT776 [29] & Viking Queen [30]. These two PSVs are equal in size and rating according to the description provided in the whitepaper [29], [30]. The deck area of the PSV is of commercial interest and cannot be utilised for PV installation [27]. Thus the PSV has limited available space for PV array installation. It has been assumed that of the 600 m^2 of the total available area of 1800 m^2 [29], [30] is available for installing PV arrays. Considering the parameters of the commercially available Sunpower 305 Solar Panel [43] with the available installation area of 600 m^2 , the rating of total installed PV capacity is described in Table II. The economic analysis of the PV panel is dependent on several market parameter and specifications but is expected to be consistent with the method provided in [42]. The comprehensive cost analysis of PV panels in DC PSV is currently beyond the scope of this paper.

2) *Sizing of PV-BESS System:* According to the IEEE Std 1562-2007 [44] and IEEE Std 1013-2007 [45], the sizing of the BESS connected to the PV is determined while assuming that there is no power available from the PV system. The BESS

TABLE II
TOTAL PV INSTALLED CAPACITY USING SUNPOWER 305 SOLAR PANEL

Parameters	Values
Irradiance	1000 W/m ²
Power	305 W
Maximum Power Voltage (V_{pm})	54.7 V
Maximum Power Current (I_{pm})	5.58 A
Module Area	1.63 m ²
Total Available Area	600 m ²
Total Available PV Installation	112 kW $\approx$ 110 kW
Number of Modules	360
Modules in Series (N_s)	6
Modules in Parallel (N_p)	60
Rated Terminal Voltage (V_{tm})	330 V

TABLE III
PARAMETERS OF THE INTERFACED BESS

	Parameters	Values
Battery Module	Model Name	SAFT Seanergy Modules
	Nominal Voltage	46.2 V
	Nominal Capacity	60 Ah
Battery Pack	Nominal Voltage	650 V
	Nominal Capacity	1200 Ah
	Modules in Series (N_s)	14
	Modules in Parallel (N_p)	20

is installed in the DC SPS with the intention of fulfilling the intermittent loads and support the generation system during various contingencies [8]. The PV power is primarily used to charge the BESS and maintain its SOC at maximum possible level. The selection of the BESS has been done to minimize the weight and size constraints of the DC marine vessels [8]. Further, the 10% power level of BESS is chosen to make it consistent with the trends of BESS selection in commercially available marine vessels [46]. The parameters of the BESS is chosen according to the commercially available *SAFT Seanergy* modules which are suitable for hybrid propulsion applications [47]. The parameters of the battery module and the battery pack considering 10% of power demand is shown in Table III.

3) *Schematic of PV interfaced BESS*: The schematic of the PV and BESS interfaced with the DC bus is shown as per Figure 6(a) [48]. To extract the maximum power, the PV panel is interfaced with the unidirectional DC/DC-1 converter which works on perturb and observe (P&O) based maximum power point tracking (MPPT) algorithm [49] for the proposed real-time transient simulation scheme. The modeling of the PV generator and the MPPT algorithm is consistent with strategy discussed in [49]. The DC/DC-2 converter is a bi-directional converter used to interface PV-BESS system to the DC bus. The modeling and control of DC/DC-2 is consistent with the approach provided in [7]. During the normal operation when the SOC of the battery is above threshold limit (SOC_{max}), the DC/DC-2 operates at boost conversion mode supplying

Figure 6. (a) Schematic of PV based Battery Energy Storage System (PV-BESS) and (b) representation of the battery charging schemes.

the power to the DC ship as fulfilling scheduled generation requirements and complying with Eq. (15a)-(15h). The variables in Eq.(15a)-(15h) is consistent with annotations shown in Figure 6(a).

$$P_{PV} > 0, \quad (15a)$$

$$P_{Batt} > 0, \quad (15b)$$

$$P_{ESS} > 0, \quad (15c)$$

$$i_{PV_DC} > 0, \quad (15d)$$

$$i_{batt} > 0, \quad (15e)$$

$$i_{dc_i} = i_{batt} + i_{PV_DC} > 0, \quad (15f)$$

$$i_{ESS} > 0, \quad (15g)$$

$$P_{ESS} = P_{batt} + P_{PV}. \quad (15h)$$

When the SOC of the BESS is below lower threshold (SOC_{min}), it could either be charged exclusively by the PV system or by the combination of PV system and DC/DC-2 converter. Since the power output of the PV array has limitation owing to dependence on available irradiation, charging with PV panel would result in slow charging as depicted in Figure 6(b). Constant current (CC) based fast charging of the BESS can be carried out by maintaining output current of DC/DC-2 at desired charging rate suggested by the manufacturers. During the charging operation supported by both PV panels and DC/DC-2 the Eq. (16a)-(16h) are satisfied.

$$P_{PV} > 0, \quad (16a)$$

$$P_{Batt} < 0, \quad (16b)$$

$$P_{ESS} < 0, \quad (16c)$$

$$i_{PV_DC} > 0, \quad (16d)$$

$$i_{batt} < 0, \quad (16e)$$

$$i_{dc_i} = i_{batt} - i_{PV_DC} < 0, \quad (16f)$$

$$i_{ESS} < 0, \quad (16g)$$

$$P_{batt} = P_{ESS} + P_{PV}. \quad (16h)$$

III. OPERATION OF DC PLATFORM SUPPLY VESSEL

Installed generation capacity of the PSV is generally lower than the total loads connected to the system. This is because a defined set of loads are activated for particular marine mission as indicated in Table I. For cruising operation, PSV operates mostly in fixed speed condition and for DP mode, the operating speed may change depending on the environmental conditions. Hence, the brake power of PSV for DP operation is not constant as shown in Figure 7 where the vessel mostly operates between 20%-80% of the total installed brake power [34]. Thus, incorporating DC OPF algorithm and operating the vessel at minimum SFOC can be implemented to increase the fuel efficiency. For DC OPF reduced bus-branch model segregating the AC and DC subsystems with AC/DC-DC/AC boundary node is shown in Figure 8. Generators Gen-1 and Gen-3 are clubbed together and are connected to bus B1. Similarly the Gen-2 and Gen-4 are clubbed together and connected to bus B2. The total generation capacity (P_{Gen})

Figure 7. Brake power of PSV for DP operation.

Figure 8. Reduced Bus-Branch Model of representative DC PSV. of the diesel generators and the ESS with the bus they are interfaced to is illustrated in Eq. 17.

$$\mathbb{P}_{Gen} = \{\mathcal{P}_{B1}^{Gen13}, \mathcal{P}_{B2}^{Gen24}, \mathcal{P}_{B14}^{ESS}\} \quad (17)$$

The loads $\mathbb{L}_{CL}$, $\mathbb{L}_{DP}$, $\mathbb{L}_{HL_{high}}$, $\mathbb{L}_{HL_{low}}$, $\mathbb{L}_{misc}$ interfaced with respective bus are depicted in Eq. 18(a)-Eq. 18(e).

$$\mathbb{L}_{CL} = \{\mathcal{L}_{B3}^{MP1}, \mathcal{L}_{B7}^{MP2}\}, \quad (18a)$$

$$\mathbb{L}_{DP} = \{\mathcal{L}_{B12}^{TT1}, \mathcal{L}_{B16}^{TT2}, \mathcal{L}_{B5}^{RT}\}, \quad (18b)$$

$$\mathbb{L}_{HL_{high}} = \{\mathcal{L}_n^{HL1} \mid n = B8 \text{ to } B11\}, \quad (18c)$$

$$\mathbb{L}_{HL_{low}} = \{\mathcal{L}_m^{HL2} \mid m = B17 \text{ to } B20\}, \quad (18d)$$

$$\mathbb{L}_{misc} = \{\mathcal{L}_{B13}^{PL}, \mathcal{L}_{B15}^{FL}\} \quad (18e)$$

IV. PROPOSED REAL-TIME DC PSV POWER MANAGEMENT SYSTEM

A. Problem Statement

As explained in the previous sections, operation of DC PSV demands real-time scheduling mechanisms to tackle different loads and generation sources in various operating conditions. The real-time transient simulation scheme with DC OPF is more suitable for such conditions which determines the power injections of the DGs and ESS to minimize the SFOC in real-time, subjected to physical and operational constraints (relevant data in Table IV and Table V). Equality constraints

TABLE IV
LINE PARAMETERS OF DC PSV

To Bus	From Bus	Line	R (mΩ)	X (mΩ)	P (kVA)	V (pu)
4	1	L1	0.48	-na-	2x2048	1.0
6	2	L2	0.48	-na-	2x2048	1.0
12	3	L3	0.092	-na-	2x1750	1.0
4	3	L4	0.092	-na-	2x1750	1.0
5	4	L5	1.5	-na-	3000	1.0
6	5	L6	1.2	-na-	3000	1.0
7	6	L7	0.64	0.75	1600	1.0
16	7	L8	0.64	0.75	1600	1.0
9	4	L9	3.2	-na-	1100	1.0
11	6	L10	3.2	-na-	1100	1.0
9	8	L11	2.56	-na-	450	1.0
10	9	L12	2.56	-na-	450	1.0
11	10	L13	2.56	2.31	2x200	1.0
13	12	L14	2.56	2.31	2x200	1.0
14	13	L15	3.2	-na-	1100	1.0
15	14	L16	0.03	-na-	2x2048	1.0
16	15	L17	0.03	-na-	2x2048	1.0
17	13	L18	0.03	-na-	2x2048	1.0
18	17	L19	0.03	-na-	2x2048	1.0
19	18	L20	0.03	-na-	2x2048	1.0
20	19	L21	0.03	-na-	2x2048	1.0

TABLE V
BUS DATA OF DC PSV

Bus	$P_{max} \uparrow$ (kW)	$P_{min} \downarrow$ (kW)	Q(kVAr)	V(pu)
B1	+4096	0	-na-	1.05
B2	+4096	0	-na-	1.05
B3	-3000	0	-na-	1
B4	-640	0	-480	1
B5	-1100	0	-na-	1
B6	-640	0	-480	1
B7	-3000	0	-na-	1
B8	-240	0	-180	1
B9	-400	0	-300	1
B10	-400	0	-300	1
B11	-240	0	-180	1
B12	-1100	0	-na-	0.95
B13	-450	0	-na-	0.95
B14	+820	0	-na-	1
B15	-450	0	-na-	0.95
B16	-1100	0	-na-	0.95
B17	-80	0	-60	1
B18	-80	0	-60	1
B19	-80	0	-60	1
B20	-80	0	-60	1

include power balance at each node and inequality constraints include the network operating limits, DG limits, ESS limits and limits on the other control variables. These control variables include active power output of the generators, power electronic controls, amount of load disconnected, and the status of storage devices. Hence, subsequent to the modeling of DC PSV, real-time DC OPF with the objective of minimizing SFOC considering all control and state variables with real-time optimization framework is the objective behind this work.

B. Problem Formulation

The real-time transient simulation system for generation scheduling of the DC PSV is governed in such a way to effectively utilize the available resources onboard to minimize the SFOC of the DGs. In this process, the optimization considers the set constraints as follows:

Minimize SFOC

$$F(\{\mathcal{P}_{B1}^{Gen13}, \mathcal{P}_{B2}^{Gen24}, \mathcal{P}_{B14}^{ESS}\}) = f(x, u) \quad (19)$$

subject to

$$w(x, u) = 0 \quad (20)$$

$$q(x, u) \leq 0 \quad (21)$$

where the cost function referring to the active power of the energy resources is minimized while respecting the equality constraints $w(x, u)$ and inequality constraints $q(x, u)$. These constraints can be viewed as linear and nonlinear constraints:

$$w(x, u) = \begin{bmatrix} w_{nl}(x, u) \\ J_e(x, u) + o_e \end{bmatrix} \quad (22)$$

$$q(x, u) = \begin{bmatrix} q_{nl}(x, u) \\ J_i(x, u) + o_i \end{bmatrix} \quad (23)$$

where, J_e and J_i are constants and need to be calculated only once. State variables of converter and DC network are set up to this framework. Energy storage and DC side converter power feed-in are mapped to the corresponding AC buses to satisfy the Kirchhoff Law.

The vector x consists of dependent variables such as: fixed parameters such as reference angles, non-controlled generator or ESS outputs, non-controlled loads, and line parameters. The vector u consists control variables including: real power generation, PSV load shedding parameters/priorities, ESS charging and discharging limits, ramp rates of the diesel generator, DC line flows, and converter control settings. The equality and inequality constraints are namely, power flow equations, limits on all control variables, generation/load balance, branch flow limits and SOC limits. Considering Figure 8 which represents reduced bus-bar model of DC PSV (having DGs, ESS, and different types of loads); for an anticipated group of loads, total system generation should be scheduled in such a way to minimize the SFOC of diesel generator. In such cases, the network equality constraints are represented by the standard load flow equations [14]. PSV load balance equation is as follows in the real-time operation:

$$\sum_{i=1}^B (\mathcal{P}_{Bi}^{Gen} + \mathcal{P}_{Bi}^{ESS}) - \sum_{i=1}^D (\mathcal{P}_{Di}^L + \mathcal{P}_{Di}^{ESS}) - \mathcal{P}_{Losses} = 0. \quad (24)$$

Inequality constraints limits are set accordingly, for example, generator limits are set as :

$$\mathcal{P}_{Bi_{min}}^{Gen} \leq \mathcal{P}_{Bi}^{Gen} \leq \mathcal{P}_{Bi_{max}}^{Gen}, \quad (25)$$

$$\mathcal{Q}_{Bi_{min}}^{Gen} \leq \mathcal{Q}_{Bi}^{Gen} \leq \mathcal{Q}_{Bi_{max}}^{Gen}. \quad (26)$$

Load shedding or load balancing limits has been set as:

$$0 \leq \mathcal{L}_{Bi}^{shed} \leq \mathcal{L}_{Bi}^{D_{total}}. \quad (27)$$

Energy storage limits set as:

$$\mathcal{P}_{Bi_{min}}^{ESS} \leq \mathcal{P}_{Bi}^{ESS} \leq \mathcal{P}_{Bi_{max}}^{ESS}. \quad (28)$$

Converter voltage limits on the AC side are non-linear in nature and can be set as:

$$\mathcal{V}_{conv_{min}}^2 \leq \mathcal{V}_{conv}^2 \leq \mathcal{V}_{conv_{max}}^2. \quad (29)$$

Converter filter side constraints are as follows, where V_R and V_I are real and imaginary parts of the voltage:

$$\mathcal{V}_{filter_{min}}^2 \leq V_{R_{filter}}^2 + V_{I_{filter}}^2 \leq \mathcal{V}_{filter_{max}}^2, \quad (30)$$

and the limits on the converter current and DC voltages are linear in nature and are as follows

$$\mathcal{V}_{min}^{DC} \leq \mathcal{V}^{DC} \leq \mathcal{V}_{max}^{DC}, \quad (31)$$

$$I_{min}^{conv} \leq I^{conv} \leq I_{max}^{conv}. \quad (32)$$

The $q(x, u)$ in Eq. 23 is formed by the Eq. 25-32 as stated above. It is to be noted that the voltage and branch flow limits are the only non-linear limits on the AC side. Options of setting branch limits, and other operational limits in the DC PSV are implemented as well, but skipped for better readability of the paper.

Power generation schedules obtained from the optimization framework have been fed to the SFOC calculation block to calculate the speed ($C(\omega)$) based on the equation derived in Section II, where speed is derived as a function of generator schedules

$$C(\omega) = f(\mathcal{P}^{DG}). \quad (33)$$

SFOC at each optimized speed point corresponding to the power schedules has been calculated using the *SFOC lookup table* available in the SFOC calculation block as shown in Figure 9(a).

C. Real-Time Transient Simulation of DC PSV

The architecture of the real-time transient simulation setup comprising of generator scheduling scheme based on DC OPF is shown in Figure 9(a). Depending on the operating mode, the scheduling block takes the input from the operating personnel. The available generation is also fed to calculate the reserve generation capacity and setting the upper limits of the generation system. Load estimation is the critical step where the rate of the load changes has been assessed and passed as an input to the proposed algorithm. Tabulation methods for electrical loads during marine missions which are proposed in the reference [50] are adopted in this work. Line parameters (Table IV) and bus-bar parameters (Table V) are fed to ensure that the loading in each line/bus stays within prescribed limits. The scheduled generation is calculated and fed to the SFOC optimization block to calculate the power demand and corresponding speed set point of each of the in-line DGs. The scheduling block and the SFOC algorithm is the part of the controller while the rest of the system of DC PSV system is divided into master/slave computational subsystems and loaded into computing cores of OPAL-RT OP5600 based real-time simulator. The segregation of cores of the real-time simulation model has been realized with the help of gyrators and the partitioning contours of the divided subsystems are shown in Figure 9(a). The description of the real-time simulation system is described below.

1) *Overview of Real-Time Simulation System:* The real-time simulation is conducted on the OPAL-RT based OP5600 real-time simulator which operates on RedHat Linux based operating system and is interfaced with the host PC by TCP/IP cable. The setup of the real-time simulation system is shown in Figure 9(c). OPAL-RT uses RT-LAB based real-time platform which facilitates the conversion of MATLAB/Simulink models into real-time executable models [55]. It has dedicated toolboxes such as RT-Events, RTE-drive, ARTEMiS[®] to support the real-time simulation system [55], [56]. The execution of the model is achieved by ARTEMiS[®] solver which is a high-order

Figure 9. (a) Architecture of the Real-Time Load Scheduling of DC PSV (b) schematic in MATLAB/SIMULINK environment and (b) representative OPAL-RT setup for real-time simulation.

time-step integration algorithm and is not prone to numerical oscillations [55], [56]. The minimum time step available for real-time simulation in the DC transient real-time simulation model is $10 \mu s$. To comply with such requirements, all the interfaced converters are operated with switching frequency of 5000 Hz. Further, all the results obtained with the switching models are compared with the averaged models to analyse the performance of VSCs under such time step limitations as well. The partitioning of system using gyrators helps in avoiding numerical inaccuracies by ensuring parallel computation of the partitioned subsystems.

2) *Gyrator Based Partitioning of System:* Gyrator is an ideal energy transducer used for bond graph representation of a physical system [51], [52], [53]. This method has been used for partitioning of the bigger marine DC power system into smaller subsystems for parallel computation in real-time transient simulation framework. With reference to Figure 10(a), 10(b) the bigger system is divided into Subsystem-1 and Subsystem-2 with the help of gyrator, G_Y while satisfying the Equations 34(a) and 34(b).

$$V_1 = f(I_2) \quad (34a)$$

$$V_2 = f(I_1), \quad (34b)$$

From Eq. 34(a) and 34(b), it can be implied that current I_2 in Subsystem-2 is dependent on the voltage V_1 of Subsystem-1 or vice versa. This approach can be realised by implementing dependent current and voltage sources. The partitioning

Figure 10. (a) Representation of gyrators for partitioning between Subsystem-1 and subsystem-2 and (b) Bond graph structure of a gyrator.

of subsystems for ' n ' number of elements utilising gyrator based partitioning approach is shown in Figure 11. In both Figure 10(a) and Figure 11, a very high value resistance (R_T) is placed to ensure numerical consistency of the simulation and memory block is used to avoid algebraic loop errors. The measured current and voltage between the computational subsystems is transferred using OpComm block [55], [56]. With the gyrator based approach the entire DC marine system is divided into four subsystems (three computational subsystems and one console subsystem). The computational subsystems comprise of one master (SM_Generator) and two slave subsystems (SM_Bus1Load, SM_Bus2Load). The console subsystem (SC_Console) is the user interface for data logging. The final partitioned executable file for transient real-time simulation is shown in Figure 12.

3) *Obtaining Results:* The output results from the real-time simulator have been obtained by: (1) monitoring scopes in the console subsystem (SC_Scope), (2) by viewing the results in the monitoring oscilloscope and (3) by saving the data in .mat file by OpWrite block [55], [56] for offline analysis. All the results presented in this paper are obtained by processing .mat files. The results obtained from the oscilloscope are also

Figure 11. Gyrator based system partitioning for ' n ' number of elements.

Figure 12. Representative MATLAB/Simulink model into partitioned subsystems for real-time simulation in OPAL-RT.

presented in Section V for comparison with the offline analyzed results.

D. Algorithm for Real-Time Transient Simulation

Pseudo-code for real-time generation scheduling of DC PSV for minimized SFOC is shown as Algorithm 1. It presents the basis for real-time transient simulation scheme in the context of handling various marine missions for minimized SFOC.

Algorithm 1 Pseudo-code of Scheduling for DC PSV

- 1: – Read generation data, network data, load estimation data, static load data, SOC of ESS, and other PSV parameters.
- 2: – Define operating limits based on the shipboard real-time marine missions. $\triangleright$ Eq. (23)-(30).
- 3: – Build initial Z-bus by handling isolated nodes, if any. $\triangleright$ Table II
- 4: – Create incidence matrix for the existing shipboard network. $\triangleright$ Eq. (17)-(21)
- 5: – Initialize the proposed Optimization Suite. $\triangleright$ Eq. (6), (13)
- 6: **while** ((Error tolerance for power) < Set limit) **do**
- 7: **while** (All options are not processed) **do**
- 8: – Find ΔX_{bus} with power injection matrices
- 9: – Calculate power flow, line outage conditions (if any), SOC of ESS
- 10: **while** (All scheduling options are not processed) **do**
- 11: – Initialize power calculation process of each generator considering different sub-optimal points
- 12: **end while**
- 13: – Store optimized scheduling options
- 14: – Treatment of sub-optimal points. $\triangleright$ Section V-C
- 15: – Evaluate objective function f $\triangleright$ Eq. (6), (13)
- 16: **end while**
- 17: **for** (Each optimized schedule P_i $i = 1, 2, \dots, \text{no. of generators: } P$ **do**
- 18: (a) Create speed vector from scheduled generations P_i ;
- 19: (b) Evaluate the schedules for minimized SFOC
- 20: Check the error criterion to met. Otherwise, the appropriate speed is chosen from the corresponding generator speed vector.
- 21: **end for**
- 22: **end while**
- 23: – Print the scheduling plans

V. REAL-TIME SIMULATION RESULTS

With reference to the operational aspects of the proposed DC PSV power management system, this section presents the simulation results of various cases of operating modes and associated contingencies in the real-time operation. The various contingencies associated with DC PSV are listed in Table VI which has been prepared considering both availability and unavailability of 10% ESS described in Section II-C. From Table VI, it can be observed that the generator and ESS output are marked in red color for some specific contingencies. This indicates the overload capabilities of the generation system for supplying high power output for short durations [54]. In the proposed optimization framework, such relaxation has been set for the PSV generation systems to emulate real-time characteristics.

A. PSV Operating Modes and Associated Contingencies

1) *Dynamic Positioning Operation:* For the DP operation, $\mathbb{L}_{CL}$ is set to zero while $\mathbb{L}_{HL_{high}}$, $\mathbb{L}_{HL_{low}}$ are set at 1000 kVA and 270 kVA respectively and $\mathbb{L}_{misc}$ is set to the rated value. As described previously, the value of $\mathbb{L}_{DP}$ is dependent on the weather conditions, propeller design & characteristics. Under normal weather condition $\mathbb{L}_{DP}$ is set at lower value with all the thrusters operating at lower loading conditions as shown in Eq. 35(a). On the contrary at harsh weather conditions the thrusters are set to be operating at higher loading conditions as shown in Eq 35(b).

$$\mathbb{L}_{DP_{low}} = \{\mathcal{L}_{B12}^{TT1}, \mathcal{L}_{B16}^{TT2}, \mathcal{L}_{B5}^{RT}\} = \{-300kW, -300kW, -300kW\}, \quad (35a)$$

$$\mathbb{L}_{DP_{high}} = \{\mathcal{L}_{B12}^{TT1}, \mathcal{L}_{B16}^{TT2}, \mathcal{L}_{B5}^{RT}\} = \{-800kW, -800kW, -800kW\}. \quad (35b)$$

Various contingency cases have been prepared such as loss of generation system and unavailability of ESS (inadequate SOC) at low DP load & high DP load conditions. Utilizing the transient simulation framework formulated in Section IV, the desired power and corresponding operating speed set point of the generation systems $\mathbb{P}_{Gen}$ for all the contingency cases have been listed in Table VI. During the fault at bus-2 ($\mathcal{P}_{B2}^{Gen24} = 0$) with harsh weather conditions, power demand to the ESS ($\mathcal{P}_{B5}^{ESS}$) exceeds its rated capacity which cannot be suitably fulfilled. This inadequate generation availability can be mitigated by load shedding operation by referring to Table I. However, the ESS helps in optimized generation scheduling when the Bus-2 is isolated during low load DP operation and also during sudden gain/loss of DP loads which is indicated in blue color in Table VI. The results pertaining to sudden gain in DP load as per Case 1A of Table VI is shown in Figure 13. The path of transition of the operating point of the optimized SFOC from initial set-point to the final set-point has been traced in Figure 13(d). The trajectory of the SFOC for fixed speed operation is also plotted for comparison with the proposed operation methodology. From Figure 13(d) it can be inferred that there is substantial reduction of SFOC with the proposed method. The reduction in SFOC is 19% when the DGs are allowed to operate in optimised speed rather than fixed speed during low load DP mode. The operating regime of the DG exceeds the prescribed contour of operation because of the abrupt increase in the load. However, in the real-system the load transition is expected to be smoother rather than sudden abrupt changes. Nevertheless, the initial and final SFOC is optimised and lies within stable region. The output from the monitoring oscilloscope is presented in Figure 13(e) for comparison with the offline results.

2) *Cruising Mode Operation:* For the cruising operation, $\mathbb{L}_{DP}$ is set to zero while $\mathbb{L}_{HL_{high}}$, $\mathbb{L}_{HL_{low}}$ and $\mathbb{L}_{misc}$ are set to similar value that of DP operation. The $\mathbb{L}_{CL}$ primarily depends on the operating speed of the vessel. For low cruising speed the loading of the main propulsion systems are given in Eq. 36(a) while for higher speeds, the loading of the main propulsion systems are given by Eq. 36(b).

$$\mathbb{L}_{CL_{low}} = \{\mathcal{L}_{B3}^{MP1}, \mathcal{L}_{B7}^{MP2}\} = \{-1000kW, -1000kW\}, \quad (36a)$$

$$\mathbb{L}_{CL_{high}} = \{\mathcal{L}_{B3}^{MP1}, \mathcal{L}_{B7}^{MP2}\} = \{-2500kW, -2500kW\}. \quad (36b)$$

TABLE VI
CONTINGENCY LIST

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CASE	CONTINGENCY CONDITION	CONNECTED LOADS					Gen-1		Gen-2		Gen-2		Gen-4		ESS
		TT1	TT2	RT	MP1	MP2	P_{G1}	ω_{G1}	P_{G2}	ω_{G2}	P_{G3}	ω_{G3}	P_{G4}	ω_{G4}	
1A	Sudden gain of DP load	-300	-300	-300	0	0	+949	1130	+949	1130	+949	1130	+949	1130	+4
1B	Sudden gain of DP load with inadequate SOC	-800	-800	-800	0	0	+1324.88	1280	+1324.88	1280	+1324.88	1280	+1324.88	1280	+0.49
2A	Sudden loss of DP load	-300	-300	-300	0	0	+950	1130	+950	1130	+950	1130	+950	1130	-
2B	Sudden loss of DP load with inadequate SOC	-800	-800	-800	0	0	+1325	1280	+1325	1280	+1325	1280	+1325	1280	-
3A	Bus-2 isolated at low DP load	-800	-800	-800	0	0	+1324.88	1280	+1324.88	1130	+1324.88	1130	+1324.88	1130	+4
3B	Bus-2 isolated at low DP load with inadequate SOC	-200	-200	-200	0	0	+899.37	1108	+899.37	1108	+899.37	1108	+899.37	1108	+2.5
4	Inadequate SOC at low DP load	-800	-800	-800	0	0	+1325.88	1280	+1325.88	1130	+1325.88	1130	+1325.88	1130	-
5A	Bus-2 isolated at high DP load	-200	-200	-200	0	0	+900	1109	+900	1109	+900	1109	+900	1109	-
5B	Bus-2 isolated at high DP load with inadequate SOC	-300	-300	-300	0	0	+949	1130	+949	1130	+949	1130	+949	1130	+4
6	Inadequate SOC at high DP load	-300	-300	-300	0	0	+1701	1425	+1701	1425	0	0	0	0	+398
7A	Sudden Gain in Cruising Load	-300	-300	-300	0	0	+950	1130	+950	1130	+950	1130	+950	1130	-
7B	Sudden Gain in Cruising Load with inadequate SOC	-300	-300	-300	0	0	+2100	n/a	+2100	n/a	0	0	0	0	-
8A	Sudden Loss in Cruising Load	-800	-800	-800	0	0	+949	1130	+949	1130	+949	1130	+949	1130	+4
8B	Sudden Loss in Cruising Load with inadequate SOC	-300	-300	-300	0	0	+950	1130	+950	1130	+950	1130	+950	1130	-
9	Bus-2 isolated at low Cruising Load	-800	-800	-800	0	0	+1324.88	1280	+1324.88	1280	+1324.88	1280	+1324.88	1280	+0.49
10A	Bus-2 isolated at high Cruising Load	-800	-800	-800	0	0	+1934.60	1650	+1934.60	1650	0	0	0	0	+1430.8
10B	Bus-2 isolated at high Cruising Load (partial load shedding)	-800	-800	-800	0	0	+1325	1280	+1325	1280	+1325	1280	+1325	1280	0
10C	Bus-2 isolated at high Cruising Load(maximum load shedding)	-800	-800	-800	0	0	+2650	n/a	+2650	n/a	0	0	0	0	0
7A	Sudden Gain in Cruising Load	-800	-800	-800	0	0	+949	1130	+949	1130	+949	1130	+949	1130	+0.49
7B	Sudden Gain in Cruising Load with inadequate SOC	-800	-800	-800	0	0	+948.8	1130	+948.8	1300	+948.8	1300	+948.8	1300	-
8A	Sudden Loss in Cruising Load	0	0	0	-1000	-1000	+1224.86	1243	+1224.86	1243	+1224.86	1243	+1224.86	1243	+0.55
8B	Sudden Loss in Cruising Load with inadequate SOC	0	0	0	-1000	-1000	+1875.17	1570	+1875.17	1570	+1875.17	1570	+1875.17	1570	+399.32
9	Bus-2 isolated at low Cruising Load	0	0	0	-1000	-1000	+1225	1243	+1225	1243	+1225	1243	+1225	1243	-
10A	Bus-2 isolated at high Cruising Load	0	0	0	-2500	-2500	+1975	1716	+1975	1716	+1975	1716	+1975	1716	-
10B	Bus-2 isolated at high Cruising Load (partial load shedding)	0	0	0	-2500	-2500	+1875.17	1570	+1875.17	1570	+1875.17	1570	+1875.17	1570	0.55
10C	Bus-2 isolated at high Cruising Load(maximum load shedding)	0	0	0	-2500	-2500	+1879.62	1575	+1879.62	1575	0	0	0	0	+1140.76
10B	Bus-2 isolated at high Cruising Load (partial load shedding)	0	0	0	-2500	-2500	+1875.17	1570	+1875.17	1570	+1875.17	1570	+1875.17	1570	+399.32
10C	Bus-2 isolated at high Cruising Load(maximum load shedding)	0	0	0	-2500	-2500	+2750.25	n/a	+2750.25	n/a	0	0	0	0	+2399.5
10C	Bus-2 isolated at high Cruising Load(maximum load shedding)	0	0	0	-2500	-2500	+2384.5	n/a	+2384.5	n/a	0	0	0	0	+3130.96
10C	Bus-2 isolated at high Cruising Load(maximum load shedding)	0	0	0	-2500	-2500	+1652.5	1400	+1652.5	1400	0	0	0	0	+2014.85

TT: tunnel thruster; RT: retractable thruster; MP: main propulsion; Gen: Generator

Output of the generator, ESS and load consumption in kilo watts (kW). Generator shaft speed in rpm.

Figure 13. (a) Speed set point vs DG speed, (b) power variation of DG-1, (c) change in total load demand and (d) transition of SFOC to optimized point in real-time and (e) output in monitoring oscilloscope during sudden gain in DP load as per Case 1A of Table VI.

Similar to the DP operation, various contingency conditions have been prepared for the cruising loads which is described in Table VI. In the contingencies associated with fault at Bus-2, the $\mathcal{P}_{B14}^{ESS}$ exceeds its rated capacity thus implementation of load shedding algorithm becomes impertinent. However, when the Bus-2 is isolated and by setting maximum load shedding by employing $\mathbb{L}_{HL_{high}} == 0$ and $\mathbb{L}_{misc} == 0$ the $\mathcal{P}_{B14}^{ESS}$ still exceeds the rated limits as highlighted in Case 10C of Table

VI. Thus during this contingency, higher cruising load cannot be supported by optimised operation of $\mathbb{P}_{Gen}$ thus the speed of the PSV needs to be slowed down to prevent inadvertent black-out condition. However, scheduling of ESS is helpful for the sudden gain/loss of the cruising loads indicated with blue color in Table VI. The real-time simulation results during sudden loss of cruising load are shown in Figure 14. The transition of SFOC operating point from initial to final set point value is

Figure 14. (a) Speed set point vs DG speed, (b) power variation of DG-1, (c) change in total load demand and (d) transition of SFOC to optimised point in real-time and (e) output in monitoring oscilloscope during sudden loss in cruising load as per Case 8A of Table VI.

shown in Figure 14(d). The same operation is repeated when the vessel operates with fixed speed generation system and the SFOC is compared in Figure 14(d). It can be established that the SFOC is minimized with the proposed method. Although the power is abruptly decreased, the operating point lies within the contours of the operating limits of the DG. As discussed earlier, the change in load would not be abrupt in real scenario hence the DG would operate with optimized SFOC in the stable region. The output from the monitoring oscilloscope is presented in Figure 14(e) for comparison with the offline results.

B. Dynamics of the PV based BESS System

- 1) **Charging of BESS:** As discussed in Section II-C, the charging of the BESS could be carried out either by slow charging or fast charging schemes. Figure 15(a) shows the variation of irradiance and the output power of the DC/DC-1 while operating at MPPT mode of operation. The PV current (i_{pv}) for charging the BESS is shown in Figure 15(b). For fast charging the DC/DC-2 maintains battery charging current determined by the set point ($i_{batt-SP}$) as shown in Figure 15(c). With the DC/DC-1 current i_{pv} the variation of i_{dc-i} and i_{batt} with change of irradiation and battery charging current set point is shown in Figure 15(c). Figure 15(d) shows the variation of SOC of the BESS when it is subjected to slow charging and fast charging respectively. The slow charging of the BESS can be employed while the PSV is in dockyard. Alternatively, the fast charging schemes might be employed by forecasting the nature of job to be done by the PSV and if the job requires intermitted power requirements.

- 2) **Discharging of BESS:** The discharging of the BESS is explained with reference to Case 8A of Table VI. During sudden change of the DP operation, the power demand off the BESS decreases from 399.32 kW to 0.55 kW. The power delivered by the PV-BESS system is shown in Figure 15(e).

C. Treatment of Sub-Optimal Points

Treatment of sub-optimal points has been explained with respect to the contingency scenario 8A of Table VI where the initial derived generation schedule of 1875.17 kW and ESS of 399.32 kW are the points-1 in Figure 16(a) and Table VII at which the SFOC is calculated. Such a SFOC is dependent on the operating speed of the diesel generator and the ESS output. However, it has been observed that the scheduling constraints are also satisfied at the sub-optimal locations with certain generator schedules and corresponding SFOC values associated with it. These set of points are termed as *local optimum* points. To illustrate this $\mathcal{P}_G^n$ is considered as generator schedule and f as the objective function used in Algorithm 1. The Eq. 37(a) and 37(b) represents the conditions for *minima* [26],

$$\mathcal{P}_G^n \in \mathbb{R} \implies f'(P_G^n) = 0, \quad (37a)$$

$$f'(\mathcal{P}_G^n) > 0. \quad (37b)$$

Conditions for local minima (sub-optimal point) is given in Eq. 38

$$f^* = f(\mathcal{P}_G^{n*}), \quad (38)$$

for local minimizer $\mathcal{P}_G^{n*}$. This is the smallest function value in some feasible neighbourhood defined by Eq. 39,

$$\mathcal{P}_G^{n*} \in \Omega. \quad (39)$$

Figure 15. (a) Change in power availability from PV panels with change in irradiation, (b) variation of current output of PV panel while operating it in MPPT mode, (c) charging current characteristic from DC/DC-2 (d) change in SOC of BESS when it is charged from PV panel and both with PV panel and DC/DC-2 and (e) DC/DC-2 output for contingency 8A in Table VI.

There exists a $\delta > 0$ such that

$$f^* \leq f(\mathcal{P}_G^{n*}) \forall P_G^n, \quad (40a)$$

$$\text{in } \{\mathcal{P}_G^{n*} \in \Omega : |\mathcal{P}_G^n - \mathcal{P}_G^{n*}| \leq \delta\}. \quad (40b)$$

Thus, there can be many local minima i.e. multiple sub-optimal points which are not global minima. Special properties such as convexity of feasible region ' Ω ' and objective function ' f ' imply that any local solution is a global solution. It has been observed that during real-time simulations such sub-optimal (local optimum points) which satisfy the given constraints have the potential to speed up the calculations of the scheduling process while diligently treating the associated ESS to arrive at better SFOC values than the corresponding SFOC at global optima. This has been demonstrated using Table VII corresponding to Figure 16(a), where the ESS is varied at all sub-optimal locations to study the impact on the SFOC. Absence of ESS during the initial state at P_{G1} would improve the SFOC operating scenario (*Point-2*), however the limits of generator capacity (2048 kW) are enforced to consider the ESS as an option (*Point-1*). Here, ESS is delivering at 399.32 kW and the corresponding SFOC is 207 (*Point-1*). Now, with

sudden loss of the cruising load we could notice that before arriving to the global optimum point $P_{G2(g)}$ (*Point-5*), it has been passing through a local optima $P_{G2(l)}$ (*Point-3*) where the corresponding SFOC is 205 against the global optimum SFOC of 197 ($P_{G2(g)}$, *Point-5*). During such a phase, it is evident that ESS is no longer required to contribute to the load, and accordingly scheduling algorithm suggested the output of ESS at +0.55kW. However, considering enforced operation of ESS at this instant shall make the corresponding SFOCs of P_{G2} and $P_{G2(l)}$ at 195 (*Point-6*) and 200 (*Point-4*) respectively. Hence, instead of abrupt suspension of ESS supply, slowly adjusting the ESS in such a way to yield the best scenario of SFOC is a possibility and where the sub-optimal points can be diligently treated.

Table. VII shows the variation of SFOC corresponding to these sub-optimal points considering ESS in operation even after the sudden loss of load and at optimized speed of generators. However, it may not be prudent to consider such points in all the contingency cases owing to operational constraints such as availability and SOC of the interfaced ESS. So, it is evident that the sub-optimal point can yield better SFOC at optimized speed and further it also has an upper hand in reducing the time propagation of schedules for feeding to the shipboard controllers.

So, in the proposed work it was noticed that sub-optimal points can accommodate ESS for better performance of DGs. To speed up the calculation in scheduling process and to treat the consideration of ESS; sub-optimal schedules can yield a feasible solution.

TABLE VII
VARIATION OF SFOC AT SUB-OPTIMAL POINTS DURING SUDDEN LOSS OF CRUISING LOAD

Points	ESS Output (kW)	Generation Output (kW)	Optimised Speed (p.u.)	SFOC (g/kWh)
1	400	1875	0.872	207
2	0	1975	0.953	204
3	0	1330	0.72	205
4	400	1230	0.70	200
5	0.55	1225	0.69	197
6	400	1125	0.66	195

Dependence of ESS output on sub-optimal locations is further demonstrated with the help of Figure 16(b), 16(c), 16(d). In Figure 16(b), power extraction from ESS is varied from 0 kW to 300 kW to visualise the changing operating points of the SFOC of DG while fulfilling constant load demand of 1875 kW. The location of the global optima with minimized SFOC and local optima is highlighted in Figure 16(b). In Figure 16(c), 16(d) it is further compared with the DG operating at constant speed. With reference to the Figure 16 the following observations can be cited below:

- 1) Figure 16(b) depicts the surface plot of the SFOC variation with ESS and DG speed in the aforesaid treatment of suboptimal points. The sub-optimal scheduled points are also marked in the figure.
- 2) Figure 16(c), 16(d) shows the comparative analysis of the location of sub-optimal points for fixed speed and optimised speed operation of the DGs. It can be observed that the minimum SFOC for the corresponding sub-

Figure 16. (a) Trajectory of the SFOC during sudden loss of cruising load with locations of various sub-optimal points, (b) surface plot of SFOC variation for varying ESS and DG speed, (c) comparison of the changing operating points and (d) location of suboptimal points for DGs operating at optimised speed and fixed speed.

optimal points for fixed speed DGs are achieved while operating at rated conditions denoted by *Point FS_A* in Figure 16(d).

- 3) For the DGs operating at optimised speed, there are multiple sub-optimal points depending on ESS output and operating speed of DG. These sub-optimal points the variable speed DGs the sub-optimal locations are dependent on the injected power from ESS and DG operating speed as shown in Figure 16(d). The location of the sub-optimal points are shown as *Point OS_A*, *Point OS_B*, *Point OS_C* and *Point OS_D*, in Figure 16(d).

D. Comparison with the Operation at Different Speeds

For all the operating cases in Table VI, SFOC is compared when the generator is running at 1800 rpm, 1600 rpm against the calculated optimized speed. The variation of the operating points are plotted in Figure 17. It can be seen that SFOC is significantly reduced when run at optimized speed thus highlighting the advantages of the proposed real-time transient simulation scheme and corresponding optimization framework.

Figure 17. (a) Variation of operating point of SFOC for generator running at 1800 rpm, 1600 rpm and variable speed (optimised speed) and (b) comparison of SFOC for generator running at 1800 rpm and optimised speed.

E. Influence of ESS on SFOC

From the earlier sections, it is evident that ESS has strategic influence on various marine missions not only on dealing with short time-load transients for smooth operations but also on improving the transient responses of DGs and corresponding SFOC. The set point to ESS and DG output have been decided based on the cost functions, cable loadings and the realistic criteria discussed in Section IV. From Figure 17(b) it is evident that at higher loads the SFOC is almost constant for optimised variable speed and constant speed operation with or without ESS and the same has been shown in Table VIII. However, having ESS during generators meeting higher loads can reduce

the initial speed deviations and torsional stress and further it enables the option of catering any unexpected load demand.

VI. CONCLUSIONS

This paper investigated the modeling and control approaches of DC PSV with real-time transient simulation framework to minimize the fuel consumption in terms of SFOC while considering treatment of sub-optimal points along with an option of utilizing onboard PV based energy storage facility. This sort of real-time operation is expected to be key ingredient of the future autonomous marine vehicles.

- DC OPF based algorithms have been applied for real-time scheduling of generation resources with an objective to minimize the fuel consumption. This operation is within the framework of the proposed real-time transient simulation setup and has been successfully demonstrated in this work. Results obtained are promising and strengthens the ability of the future DC marine vessels to comply with the upcoming stringent laws on pollution control. It has been shown that the output of ESS can influence the generator set points particularly during sudden load changes for DP and cruising missions.
- Traditionally, the power sharing happens according to generator ratings through droop control rather than optimal generation scheduling as per load demand for a particular marine mission. Hence, an optimal scheduling system based on DC OPF for tackling any specific nature of marine missions has been demonstrated in this work and the results indicated such an approach will enable the PSV to operate in fuel efficient regime with improved transient responses.
- Responses of the DGs to various contingencies are studied and it has been found that unavailability of the generation system due to fault at bus bar demands higher requirement of ESS to satisfy the load demands. In such cases it is pertinent to have load shedding routines which are dependent on the marine missions to prevent power blackout of the vessel. This highlights the necessity for considering such routines in future autonomous DC PSVs. Some cases have been highlighted using the proposed real-time transient simulation framework.
- Higher fuel savings are noticed while the generators are operated at optimised speed for low power demand. In comparison to fixed speed operation, reduction in SFOC of 19% has been reported when the PSV was operating at low power DP operation.

TABLE VIII
INFLUENCE OF ESS ON SFOC DURING SUDDEN LOSS OF CRUISING LOAD

WITHOUT ESS									WITH ESS								
P_{G1}	ω_{G1}	P_{G2}	ω_{G2}	P_{G3}	ω_{G3}	P_{G4}	ω_{G4}	SFOC (CS/OS)	P_{G1}	ω_{G1}	P_{G2}	ω_{G2}	P_{G3}	ω_{G3}	P_{G4}	ω_{G4}	SFOC (CS/OS)
+1974.97	1716	+1974.97	1716	+1974.97	1716	+1974.97	1716	203/204	+1875.17	1570	+1875.17	1570	+1875.17	1570	+1875.17	1570	203/204
+1224.99	1243	+1224.99	1243	+1224.99	1243	+1224.99	1243	222/200	+1224.86	1243	+1224.86	1243	+1224.86	1243	+1224.86	1243	222/200

CS: Constant Speed (1800 rpm); OS: Optimised Speed

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