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Power Generation Optimization for Next-Generation Cruise Ships with MVDC Architecture: A Dynamic Modeling and Simulation Approach

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Abstract: The cruise industry is obliged by economic and environmental initiatives to pursue fuel-efficient solutions and lower ship exhaust emissions. The medium voltage DC (MVDC) distribution with intelligent power management has become a concept for next-generation onboard power systems as its energy-saving feature is to eliminate the frequency constraint and simultaneously optimize engine loads and speed in response to load variations. The incentive for this transition lies on one hand in the fuel efficiency consideration and the reduction of power losses from serial conversion stages. On the other hand, the DC-based technology has been conceived as high-power density design, thus significantly increasing the payload. This study investigates such potential benefits focusing exclusively on large cruise vessels. A highly representative model of the integrated power platform that incorporates all dynamic interactions from the ship hull and essential machinery typically installed on board cruise ships is proposed. The power management strategy also takes account of actual sea conditions and real-time operation requirements. The simulation results demonstrate that the optimization-based MVDC system is able to maximize the opportunity of search agents in finding optimum fuel efficiency areas throughout the scenario time. An analysis of the system structure weight and space reduction of the MVDC architecture is also performed through the utilization of more compact electrical distribution devices and very high power-dense combustion turbines.

Keywords: integrated power system; medium-voltage DC distribution; ship power management; variable engine speed operation; weight and volume analysis



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1. Introduction

The entirety of cruise ship power systems is presently endowed with a medium-voltage AC (MVAC) integrated power system that has been conceived to enhance fuel efficiency and payload system design. However, the penetration of power electronic converters and significant progress in the development of fast switching power electronics are giving rise to a tendency toward onboard medium-voltage DC (MVDC) distribution that has been envisioned to increase even more efficiency and power density [1,2]. The adoption of the onboard DC grid is also considered a solution for fulfilling the requirements of efficiency and environmental sustainability imposed by the MAROL Annex VI regulation of the IMO. More specifically, technical challenges of the conventional AC that are of environmental and economic concerns include sub-optimal prime mover operation due to the need for generator synchronization and power quality issues due to reactive power flow and harmonic current distortion. Compared to the conventional AC counterpart, the DC system provides advantages as follows [3–6]:

- Phase angle synchronization is no longer necessary, which simplifies connection for power generation sets of various power ratings.

- Fuel consumption and maintenance of power generation sets can be reduced due to their optimal operation at variable speed.
- Power control in various modes of operation can be enhanced by exploiting DC power converters to directly feed variable speed propulsion motors.
- Size and weight of electrical equipment, especially converters, switchgears, and cables, can be reduced by the removal of harmonic mitigation devices, large low-frequency transformers, and rectifiers for variable speed drives.

Many practical cases of onboard DC grid systems have been implemented with low-voltage DC (LVDC) or DC voltage of below 1 kV, especially for small-scale ships and specific mission type vessels such as platform supply vessels, offshore service vessels, dredgers, and drilling rigs [5,6]. An effort to deploy the DC distribution to larger-scale platforms is found in the MVDC large ship research program [7–9]. The project investigates the possibility of improving energy efficiency on large diesel-electric cruise ships by taking into account the technical foundation for the DC-based system design and associated equipment such as power electronic conversion and innovative compact generators.

As the conventional AC system usually converts more than 80% of total electrical power into local DC devices mainly from variable speed drives (VSD), the adoption of the MVDC architecture that transmits power directly to the propulsion drives should be able to reduce power losses from many stages of series conversion. It is also possible to characterize the DC-based technology as high-power density design for next-generation onboard power systems due to the removal of large and dedicated power conversion devices. Thus, the available space for ship payload and facilities can be significantly increased, as shown in Figure 1.

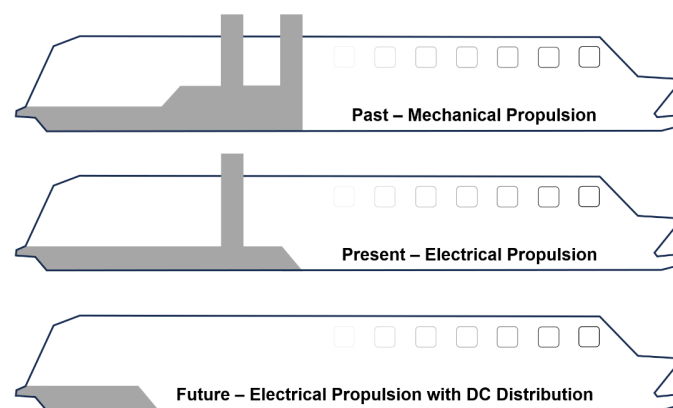


Figure 1. The evolution of cruise ship propulsion systems toward a future scenario.

There are studies that investigate the efficiency of an onboard DC grid as provided in [2,10–13]. However, most research pays attention to small-scale or LVDC with hybrid systems, while the existing research on larger-scale or MVDC architecture is not comprehensive or limited to particular interests [14–18]. Specifically, they pay particular attention to dynamic behaviors of electrical components and their associate properties such as system current and voltage, pulsed load initialization, and zonal load distribution. In this study, the integrated power system of a large cruise ship, the *Carnival Vista*, is reconfigured to the MVDC and thoroughly investigated in respect of comprehensive system modeling, intelligent power management, and system weight volume analysis.

The proposed power management for the DC grid system should manage the load distribution more effectively as the engine speed, which is normally kept constant for stabilizing electrical supply in the conventional AC grid, can also be adjusted. More precisely for the optimization objective, the engine load and speed should be simultaneously optimized to consume minimum fuel. There also exists an opportunity to develop a full-scale model of the MVDC integrated power system for large cruise ships. The interactive

mechanical and electrical dynamics of model components can be regulated on a real-time basis by ship power management and local controllers.

The model development and simulation can be carried out in the MATLAB/Simulink R2023a, which offers all fundamental components comprising power generation modules, propulsion power modules, non-propulsion system loads, and propeller coupled with hydrodynamics. Special features typically installed on cruise ships such as maneuvering thrusters and podded propulsors are also mathematically modeled. Ship dynamics that encompass the response of motions to distinct forcing functions such as wave excitations, wind, and ocean currents are taken into account in the ship resistance. Finally, the simulation scenarios are based on an existing itinerary of the case study ship, which includes real-time ship operation and environmental data obtained from the automatic identification system (AIS).

The significant contributions of this study can be highlighted as follows:

- An end-to-end simulator for a cruise ship with the MVDC integrated power system is developed on the basis of mechanical and electrical dynamic interactions between system elements and environmental disturbances.
- The ship power management is primary functioned to simultaneously optimize engine load and speed under various load applications. The power management also takes account of actual sea conditions and real-time operation requirements.
- An analysis of system weight and volume of the MVDC architecture is performed through the utilization of more compact distribution devices and very high power-dense gas turbines.

The article is organized as follows. Section 2 details the model development of the MVDC integrated power system including hydrodynamic interactions. Section 3 describes the formulation of an optimization problem including a discussion on the results. Section 4 analyzes the potential payload gains from the proposed MVDC system. Finally, conclusions including prospects and challenges are given in Section 5.

2. Dynamic Modeling of MVDC Integrated Power System

The model development of the MVDC architecture is based on the modification of the conventional MVAC integrated power platform of the *Carnival Vista* consisting of five diesel generator sets coupled with engine governors, exciters, and automatic voltage regulators (AVR) that shall be capable of supplying ship electrical loads including propulsion motors, thrusters, and service loads. Table 1 details the MVAC power system characteristic of the *Carnival Vista*.

Table 1. Existing power system configuration of the *Carnival Vista*.

System	Description
Power generation	2 × MAN 14V 48/60 CR 16,800 kW 3 × MAN 8L 48/60 CR 9600 kW 2 × synchronous generator ABB AMG 1600UT 14LSE 3 × synchronous generator ABB AMG 1600QM 14LSE Three-phase AC 11 kV, 60 Hz at 514 rpm Total power generation 62,400 kW
Propulsion	2 × ABB Azipod XO2100 with 16,500 kW electric motor 2 × fixed pitch five-blade propeller Total propulsion power 33,000 kW
Maneuvering thruster	3 × 2500 kW induction squirrel cage motor AMI 560L8L Total thruster power 7500 kW

2.1. General MVDC Requirements

The specification requirements of the MVDC distribution can be based on IEEE Std1709 [19] as there are no existing standards specifically for DC systems operated with voltage of more than 3 kV. The common MVDC rating should be selected from rated

maximum voltage, withstand voltage, lightning impulse withstand voltage to ground, continuous current, short-time withstand current, and duration of short circuit. Table 2 categorizes the MVDC class voltage according to the technology development and maximum capability of associated DC components. For the *Carnival Vista* with the alteration from AC to DC configuration, the selected MVDC class is 12 ± 6 kV due to the conversion of its previous AC voltage of 11 kV.

Table 2. Recommended MVDC voltage classes.

Development	MVDC Class (kV)	Nominal Rated Voltage (kV)	Maximum Rated Voltage (kV)
Already established classes	1.5	1.5 ± 0.75	2 ± 1
	3	3 ± 1.5	5 ± 2.5
	6	6 ± 3	10 ± 5
	12	12 ± 6	16 ± 8
	18	18 ± 9	22 ± 11
Future design classes	24	24 ± 12	28 ± 14
	30	30 ± 15	34 ± 17

The rated withstand voltage or tolerance limits of DC sources at steady state should be within $\pm 10\%$ according to IEC 60092-101 [20]. For transient conditions, the corresponding rated withstand voltage for the recommended MVDC class can be derived from IEEE Std C57.18.10 [21]. The short-duration (one minute) and lightning impulse withstand voltages to ground for the selected MVDC class of 12 ± 6 kV are 35 kV and 95 kV, respectively. For rated continuous current, short-time withstand current and duration of short circuit are limited by the design and protection system of individual power electronics and also subject to agreement between manufacturers and users [19].

The recommended MVDC structure types include radial, zonal, and ring distribution. The design selection usually depends on a trade-off between reliability and complexity. Other factors such as specific mission requirements and survivability may also be taken into consideration. The radial distribution type as shown in Figure 2 privileges simplicity and cost-effectiveness and tends to be preferred for ships that require operation with many electric motors [5]. The configuration also represents the future conceptual shift and the most practical architecture type possibly installed on large commercial vessels [22]. By taking into account the simplicity of the system reconfiguration, the radial distribution is the most attractive due to the similarity to the standard MVAC, thus simpler to redesign and operate for both naval architects and onboard engineers.

For voltage polarity network, the DC power can be transmitted throughout the ship by either unipolar or bipolar topology. The unipolar allows transmission of electricity over the DC bus at only one voltage level via positive and negative poles (two-wire). On the other hand, the bipolar network consists of positive, negative, and neutral (three-wire), which facilitates various voltage levels and thus more flexible for the system operated with various voltage demands. However, the bipolar requires a voltage balancer circuit for stabilizing the DC bus from unequal load distribution and voltage imbalance. In summary, the unipolar system is selected due to the elimination of chances for asymmetry issues between the DC poles and also its less complex structure, which is favored with the real-time simulation requirement.

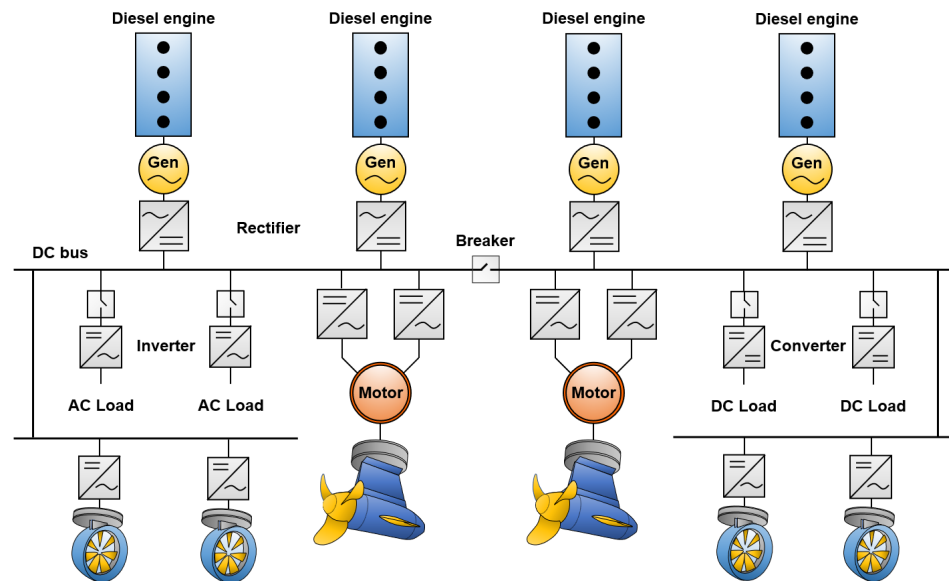


Figure 2. MVDC distribution architecture with radial structure.

2.2. Ship Resistance and Propulsion

This section delves into the principles and methodologies involved in modeling ship resistance and propulsion used for prediction of delivered power. The ITTC-78 performance prediction method is recommended to estimate the full-scale resistance as the individual components of the prediction function can be scaled and updated. The parameters of the *Carnival Vista* and significant properties required for the hydrodynamics calculation are summarized in Table A1.

2.2.1. Total Ship Resistance

The computation of the total resistance coefficient C_T according to the ITTC-78 performance prediction consists of resistance components as follows [23]:

$$C_T = (1 + k)C_F + \Delta C_F + C_A + C_R + C_{AA} \quad (1)$$

where k is the form factor; C_F is the frictional resistance coefficient; ΔC_F is the roughness allowance; C_A is the correlation allowance; C_R is the residual resistance coefficient; C_{AA} is the air resistance coefficient. The coefficients for the estimation of total resistance at the ship speed of 22.5 knots are given in Table A2.

The total resistance R_T in calm water then can be estimated using the total resistance coefficient as follows:

$$R_T = \frac{1}{2} C_T \rho_W S V^2 \quad (2)$$

where ρ_W is the sea water density; S is the wetted surface area; V is the ship speed.

2.2.2. Added Resistance and Speed Correction Due to Environmental Effects

The influences of realistic sea conditions such as wind, waves, and ocean current specifically relate to an increase in the total resistance, which results in either slowing down the ship speed for a given power absorption or an additional power requirement to the propeller in order to maintain the intended speed. The total resistance in actual sea conditions R_{TW} then can be calculated by attaching the resistance due to wind and waves as [24]:

$$R_{TW} = R_T + \Delta R_{wind} + \Delta R_{wave} \quad (3)$$

where ΔR_{wind} and ΔR_{wave} are the additional resistance exerted by wind and waves.

The resistance increase due to the relative wind can be determined as [24]:

$$\Delta R_{wind} = \frac{1}{2} C_X(\psi_{RW}) \rho_A A_V V_{RW}^2 - \frac{1}{2} C_X(0) \rho_A A_V V^2 \quad (4)$$

where C_X is the wind resistance coefficient; ρ_A is the air density; A_V is the transverse projected area of the ship above waterline; V_{RW} is the relative wind velocity; ψ_{RW} is the relative wind direction.

For moderate sea conditions, the wave exerted resistance is dominated merely by the effect of wave reflection, which is influenced by the ship geometry above waterline as [25]:

$$R_{wl} = \frac{1}{16} \rho_W g H_{1/3}^2 B \sqrt{\frac{B}{L_{BWL}}} \quad (5)$$

where R_{wl} is the resistance in long-crested irregular waves and can be represented by ΔR_{wave} ; g is the gravitational acceleration; $H_{1/3}$ is the significant wave height; B is the ship breadth; L_{BWL} is the distance of the bow on waterline to 95% of ship maximum breadth.

The correction of ship speed due to the effect of ocean current can be estimated as:

$$V_G = \sqrt{V_C^2 + V^2 + 2V_C V \cos(\psi_C - \psi)} \quad (6)$$

where V_G is the ship speed overground; V_C is the current speed; ψ_C is the current direction.

2.2.3. Delivered Power Due to Podded Propulsors

The podded propeller can be assumed to operate in a consistent manner with the conventionally mounted propeller. The particular differences that need to be taken into account include the drag from pod housing and supporting strut, and the effect of propeller slipstream.

The effective power P_E to move the ship at a given speed in the absence of propeller action in actual sea conditions can be determined as:

$$P_E = R_{TW} V_G \quad (7)$$

Finally, the correction of the delivered power $P_{D,Pod}$ due to pod drag can be determined as follows [26]:

$$R_{Pod} = R_{Body} + R_{Strut} + R_{Interfere} + R_{Lift} \quad (8)$$

$$K_{T,Total} = K_T - \frac{R_{Pod}}{\rho_W n^2 D_{Pod}^4} \quad (9)$$

$$\eta_{O,Pod} = \frac{J K_{T,Total}}{2\pi K_Q} \quad (10)$$

$$\eta_{D,Pod} = \eta_H \cdot \eta_R \cdot \eta_{O,Pod} \quad (11)$$

$$P_{D,Pod} = \frac{P_E}{\eta_{D,Pod} N_P} \quad (12)$$

where R_{Pod} is the total pod resistance; R_{Body} is the pod body resistance; R_{Strut} is the strut resistance; $R_{Interfere}$ is the strut-pod body interference resistance; R_{Lift} is the resistance due to propeller rotating flow downstream; $K_{T,Total}$ is the corrected total net thrust coefficient; K_T is the thrust coefficient; n is the propeller rotational speed; D_{Pod} is the pod diameter; $\eta_{O,Pod}$ is the corrected open water efficiency; J is the advance coefficient; K_Q is the torque coefficient; $\eta_{D,Pod}$ is the corrected quasi-propulsive efficiency; η_H is the hull efficiency; η_R is the relative rotative efficiency; N_P is the number of propellers.

2.3. Power Generation Components

2.3.1. Main Diesel Engine

The prime mover driven generators consist of five medium-speed four-stroke MAN 48/60 CR diesel engines compliant with IMO Tier II. The engine model is built by a steady-state core engine block using lookup tables comprising power, air and fuel flow, exhaust temperature, efficiency, and emission performance. The parameters for the calculation and generation of tables are based on the manufacturer datasheet as detailed in Table A3.

For the DC system, the engine operation needs to be changed from a constant speed to alternative mechanical option with variable speed. The speed variation facilitates the engine operation more efficiently, i.e., higher speed for increased loads and lower speed for decreased loads. The achievement of such speed–load organization is due to the capability of the DC bus controller that regulates the system voltage to be fixed during the variation of generator rotor speed. This decoupled controllability also allows execution of an energy optimization plan to optimally adjust both power and speed in accordance with the engine specific fuel consumption (SFC).

The SFC map for the engine model can be generated using the manufacturer data given in Table A4 and by the instruction of graphic calculation of SFC [27]. The SFC contour plot as a function of engine speed and power is shown in Figure 3. The optimal fuel-efficient region is extended from around 85% of maximum continuous rating (MCR) at the fixed engine speed of 100% to between 70 and 80% of the MCR at the engine speed range between 85 and 95%. The 3D maps of SFC and mechanical torque data generated for the engine model block are shown in Figure 4.

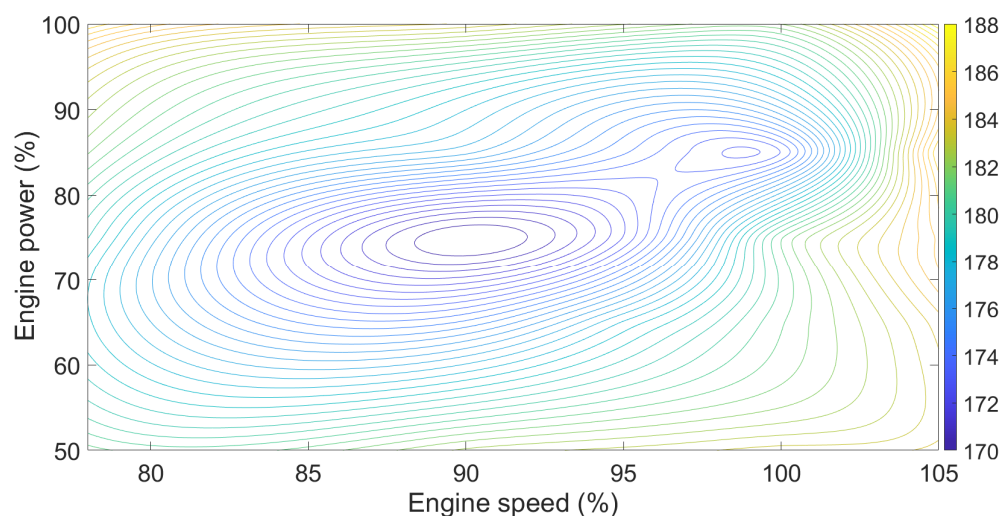


Figure 3. Contour plot of engine specific fuel consumption.

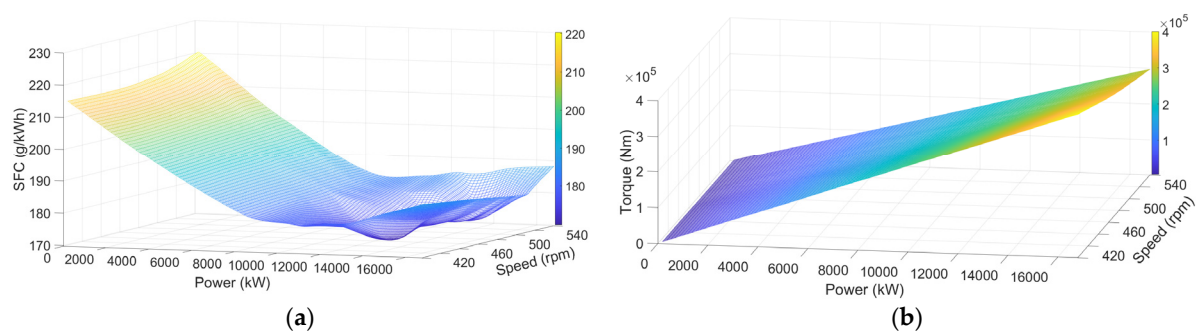


Figure 4. Cont.

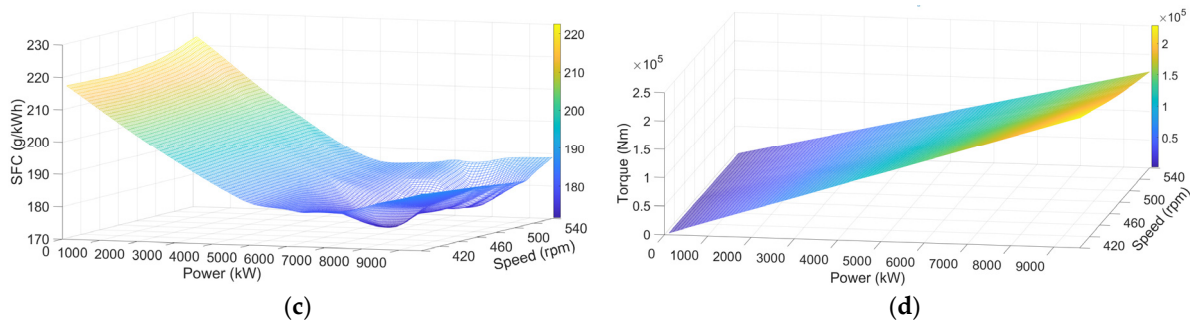


Figure 4. SFC and torque tables for the engine model: (a) V-type engine SFC; (b) V-type engine torque; (c) L-type engine SFC; (d) L-type engine torque.

2.3.2. Synchronous Machine

The alternator connected with the diesel engine is built by a brushless synchronous machine salient pole model block. The model is expressed with respect to a rotating reference frame by using the park transformation, and the electrical machine dynamics can be introduced by d-axis and q-axis windings which are representations of the stator and rotor fields. The machine operation is based on steady state, transient, and sub-transient reactance to characterize the machine behavior during the initial electromagnetic state and the occurrence of disturbances in operation. The fundamental equations associated with the machine modeling and operation can be derived from synchronous machine theory described in [28]. The parameters used for modeling are based on the machine specifications and default dataset of the model block as given in Table A5.

2.3.3. Exciter and Automatic Voltage Regulator

The excitation system and automatic voltage regulator of the synchronous machine are modeled by a field-controlled alternator rectifier designated by SM AC1C in conformance with IEEE 421.5 [29]. The AC type excitation employs an alternator and either stationary or rotating rectifiers to generate the direct current required for the synchronous machine field. The produced voltage output from the exciter is also proportional to the revolution speed of the machine. The parameters for modeling the system are given by the dataset of the SM AC1C block as specified in Table A6.

2.4. Power Distribution Components

2.4.1. Rectifier

The rectification is an integral process for the DC configuration due to the interface function for converting electricity between generators and distribution bus. The dedicated rectifier therefore takes the responsibility of stabilizing and maintaining the quality of DC voltage. Basically, the unidirectional power flow is realized for the rectifier function since the generator is the only source of power supply to the system. Various rectifier topologies available for marine applications includes diode, thyristor, and insulated gate bipolar transistor (IGBT) rectifiers. The thyristor rectifier block is selected due to the need for regulating the DC bus voltage in a narrow voltage range and fault current control capabilities. Also, the thyristor technology has been deployed for LVDC marine network and considered for extension to the MVDC supply side converter [30].

The output voltage V_{DC} and power P_{DC} of the rectifier can be determined as [31]:

$$V_{DC} = 3 \frac{\sqrt{2}}{\pi} V_{RMS} \quad (13)$$

$$P_{DC} = -v_p i_p - v_n i_n \quad (14)$$

where V_{RMS} is the root mean square voltage; v_p and v_n are the voltages at the positive and negative terminals; i_p and i_n are the currents flowing into the positive and negative terminals.

2.4.2. Inverter

The conversion of DC voltage to three-phase AC voltage for supplying AC applications requires the power inverter. The average-value inverter model block is used as an interface between the DC bus and ship AC loads including ship facilities and thruster motors. The inverter model can be used as a full-wave converter which behaves as a DC voltage-controlled AC voltage source.

The output AC voltage V_{RMS} and power on the AC side P_{AC} can be given as [31]:

$$V_{RMS} = v_{ratio} V_{DC} \quad (15)$$

$$P_{AC} = -v_a i_a - v_b i_b - v_c i_c \quad (16)$$

where v_{ratio} is the ratio of rated AC to DC voltage for the inverter; v_a , v_b , and v_c are the respective AC phase voltages; i_a , i_b , and i_c are the respective AC phase currents.

2.4.3. DC Voltage Control

The output voltage of the rectifier is regulated by the proportional-integral (PI) based DC voltage regulator block which determines firing angles using the cosine wave-crossing technique, i.e., the cosine wave obtained from an integration of input supply is compared with a droop-based DC voltage reference signal to determine the generation time of trigger pulses. Figure 5 illustrates the control structure, which includes phase-locked loop (PLL), PI controller with integral anti-windup, low-pass filter, and pulse generator blocks. The phase-locked loop is modeled as a closed-loop control which tracks the frequency and phase of a sinusoidal three-phase signal by employing an internal frequency oscillator. The oscillator function is also modified by the controller to maintain a phase difference of zero.

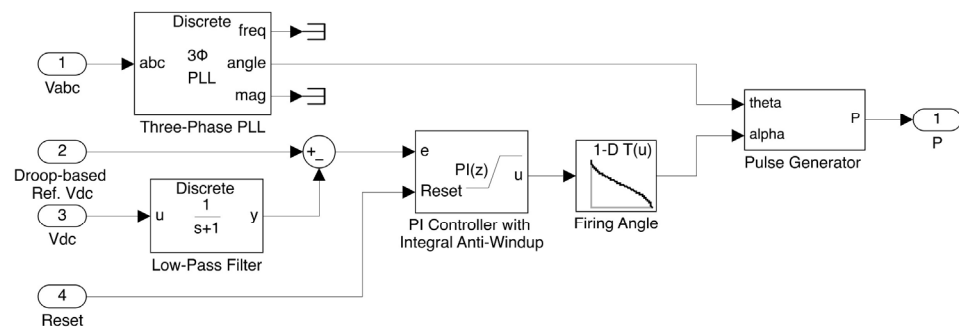


Figure 5. PI-based DC link voltage controller for the rectifier.

The low-pass filter block is referred as a simple time constant and in conformance with IEEE Std 421.5. The PI controller determines the firing angle based on the generated control signal using the backward Euler discretization method. Finally, the six-pulse generator block measures the synchronization angle of the AC signal (theta) with a phase-lock loop and the firing angle (alpha) to generate a pulse for the rectifier based on internally produced six-pulse waveforms.

2.4.4. Power Control Strategy

The conventional way to obtain active power allocation among all power generation sources can be based on P - V_{DC} droop characteristics as shown in Figure 6. The amount of active power transferred in the DC network can be determined by the DC voltage. In case of load changes, the DC bus voltage varies accordingly. The DC voltage regulation

implemented on local power electronic interface then adjusts the output power from the rectifier using the droop control strategy in response to the voltage variation [32].

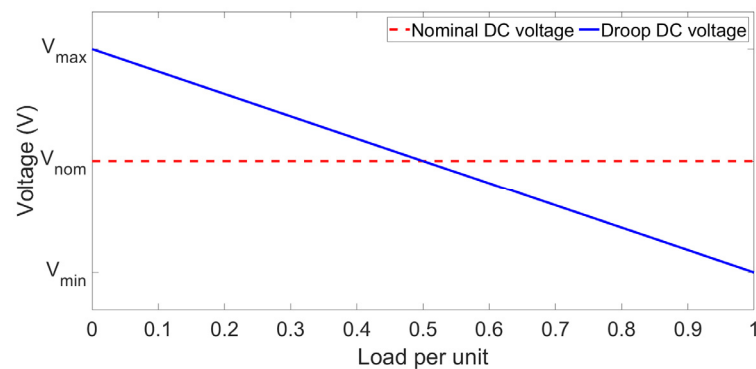


Figure 6. DC voltage droop control characteristic.

The overall power distribution process for the proposed MVDC architecture is illustrated in Figure 7. It is noted that the conventional engine governor has limited capability for responding to sudden load changes, probably affecting the DC power stability [33]. In this case, the droop ramp rate parameter for the distribution controller determined by the following equation can be used as a control input to prevent significant and sudden changes in demand [4].

$$Droop_{rate} = \sum_{k=1}^N (K_{droop}(k) - K_{droop}(k-1))^2 \quad (17)$$

where $Droop_{rate}$ is the droop ramp rate that needs to be minimized; K_{droop} is the droop gain ramp rate; k is the sample time of simulation; and N is the final time step.

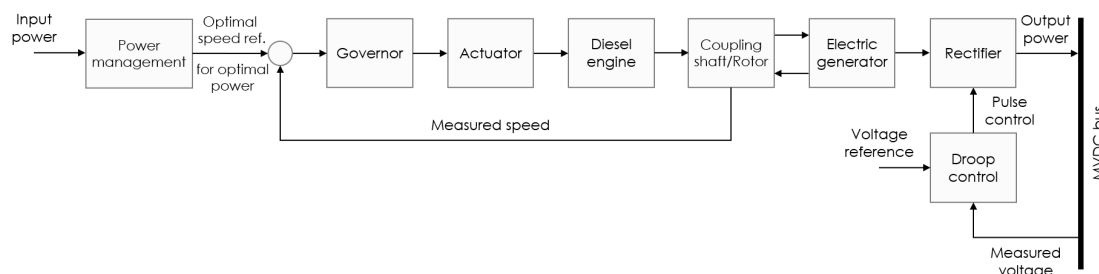


Figure 7. Power control strategy for the proposed MVDC architecture.

2.5. Power Consumption Components

2.5.1. Ship Propeller

The ship propeller is modeled by a marine propeller block which converts rotational motion into linear thrust. The thrust and rotational drag can be calculated by non-dimensional thrust and resistive torque coefficients, which are functions of the open water efficiency as described in the estimation of ship resistance and propulsion. The total resistance in calm water can be modeled as a function of Froude number Fn and total resistance coefficient C_T as shown in Figure 8. The resistance coefficient chart indicates the minimum ship resistance is in the Froude number range of 0.15–0.17 or equivalent ship speed of 16–18 knots. The propeller block is also linked with associated components such as bearing damping, ship mass, and propeller inertia as shown in Figure 9. The dynamics of the propeller are based on the data transmission between the propeller and the ship total resistance in calm water plus the additional resistance from sea state conditions.

2.5.3. Service Loads

The ship service loads are defined as all auxiliary services necessary for maintaining the ship functions to operate continuously under habitable condition. The services typically include non-propulsion functions such as navigation, communication, propulsion auxiliaries, habitability, safety, lighting, ventilation, and onboard entertainment facilities for cruise passengers. All service systems of the *Carnival Vista* can be approximated at 14,500 kW throughout the operation period as shown in Table 3 and can be simply modeled using a three-phase variable load block which calculates electrical resistance required for real power demands at a specified voltage.

Table 3. Electrical load balance of the *Carnival Vista* [34].

Function Service	Harbor (Winter)	Maneuvering	Navigation Speed 10 kn	Navigation Speed 20 kn	Navigation Max Speed	Navigation Ext. Condition
Hull and deck service	63 kW	9852 kW	212 kW	204 kW	267 kW	266 kW
Safety service	261 kW	289 kW	289 kW	289 kW	286 kW	289 kW
Propulsion service	77 kW	5370 kW	6520 kW	27,260 kW	36,438 kW	36,438 kW
Engine service	3714 kW	4627 kW	4986 kW	5028 kW	5106 kW	5670 kW
Air condition service	5360 kW	6125 kW	5083 kW	5083 kW	5102 kW	6155 kW
Galley service	1031 kW	1044 kW	1202 kW	1199 kW	1202 kW	1202 kW
Accommodation service	1059 kW	1119 kW	1158 kW	1142 kW	1159 kW	1155 kW
Lighting service	1303 kW	1505 kW	1517 kW	1517 kW	1517 kW	1517 kW
Total	12,868 kW	29,931 kW	20,967 kW	41,721 kW	51,080 kW	52,692 kW
% MCR	20.62%	47.97%	33.60%	66.86%	81.86%	84.44%

2.6. Model Verification and Validation

The full-scale model of the MVDC integrated power system is shown in Figure 11. The model architecture is based on the radial distribution structure with unipolar topology and the MVDC class of 12 ± 6 kV. The AC power generated from the main diesel engines connected with the synchronous generators is converted to DC power via the thyristor rectifiers controlled by the PI-based voltage regulators to supply the distribution bus. The DC power from the bus directly supplies the variable speed drives for propulsion system modeled as the variable resistors connected with the propeller. The DC bus also supplies all other AC loads like the thruster motors and the ship service loads by converting back the bus voltage via the inverters.

This section then provides the simulation results of the model for verification and validation purposes. The model verification refers to the evaluation of system operation in compliance with specifications and classification standard where available, while the validation is intended to ensure system operation meets the operational needs of the user. The validation of model components includes the engine operation in terms of response time for load application and reduction, the engine specific fuel consumption, the estimation of delivered power due to pod drag, the respective propulsion power for increased ship speed requirement, the propeller efficiency, and the maneuvering thruster operation. The simulation was carried out under calm water conditions for a specific duration appropriate for each component.

The operation of diesel engines in respect of load steps and revolution speed can be verified by the manufacturer data on the specific duration of load application and reduction as given in Table 4. The procedure of starting the engine model was based on standby mode; accordingly, the engine could be switched on just after the start request from the power management. For the load shedding from full to zero load, the model used the shortest possible duration for continuously ramping down the engine. Figure 12a shows the operation of a V-type engine with a full load when receiving start and stop requests. The specific fuel consumption from the simulated V-type engine was compared with the interpolation and manufacturer data given in Table A4 at the engine speed of 514 rpm as

shown in Figure 12b. The simulation indicates the obtained SFC is fully compliant with the manufacturer datasheet and highly consistent with the interpolation curve.

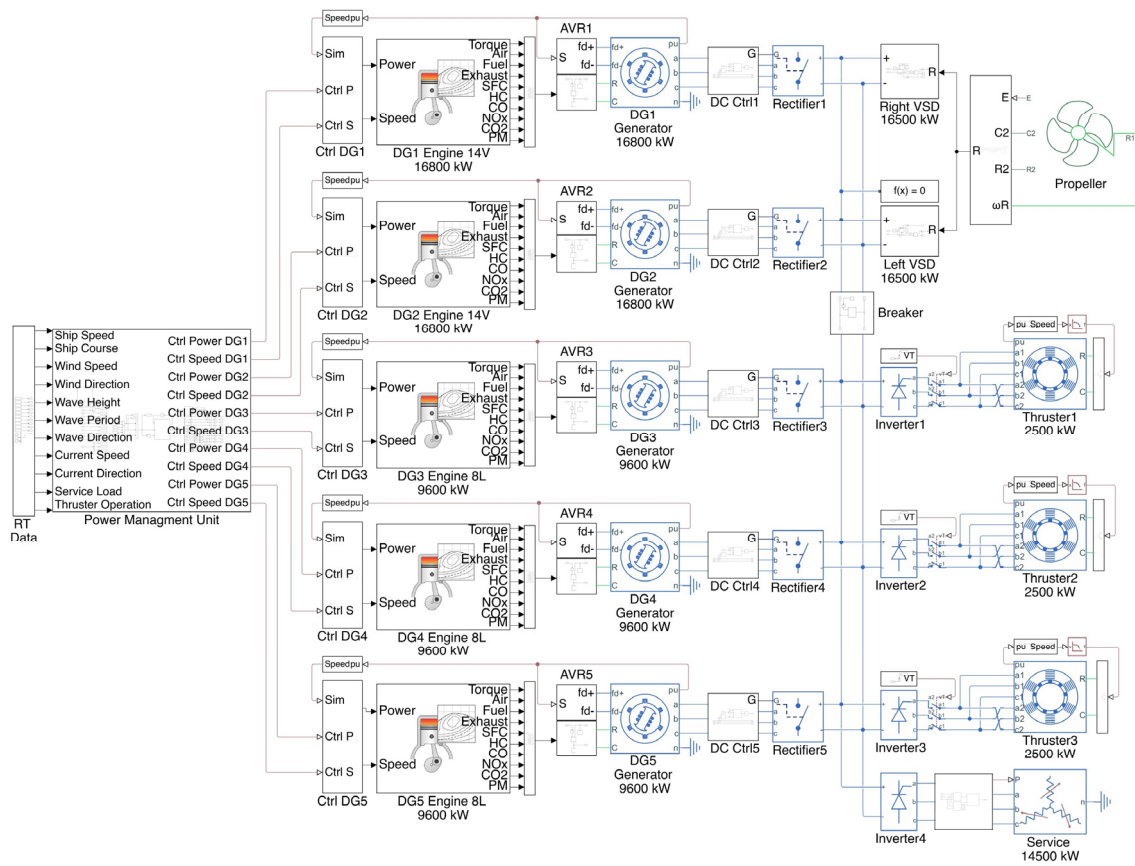


Figure 11. The reconfigured MVDC integrated power system model of the *Carnival Vista*.

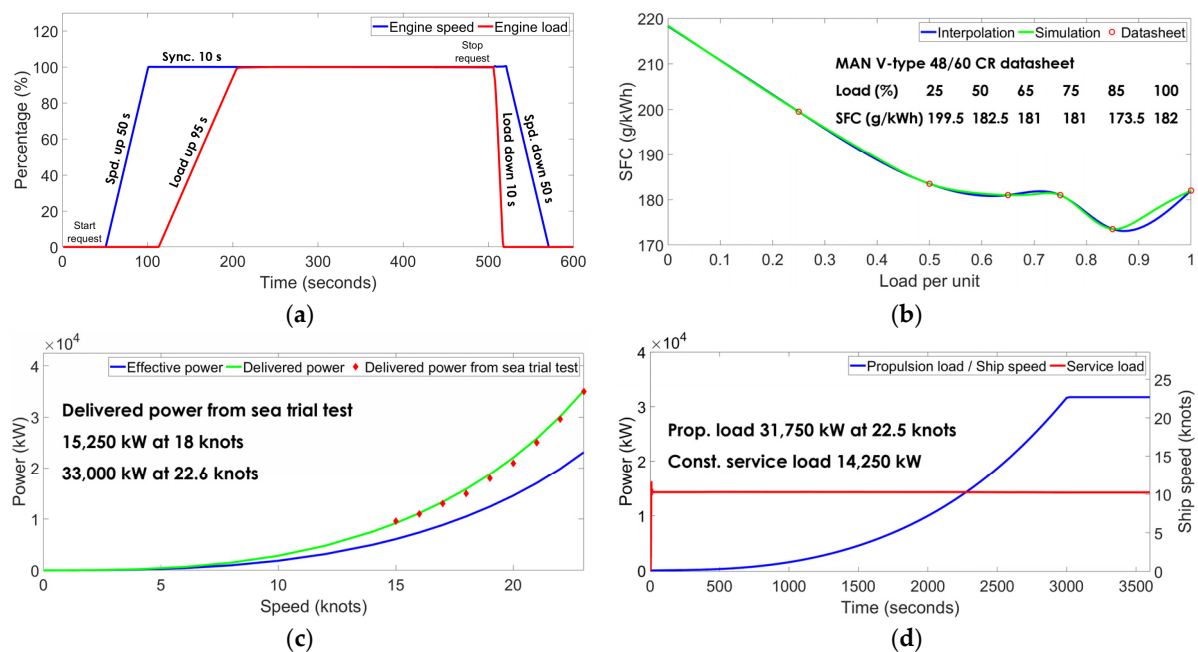


Figure 12. Cont.

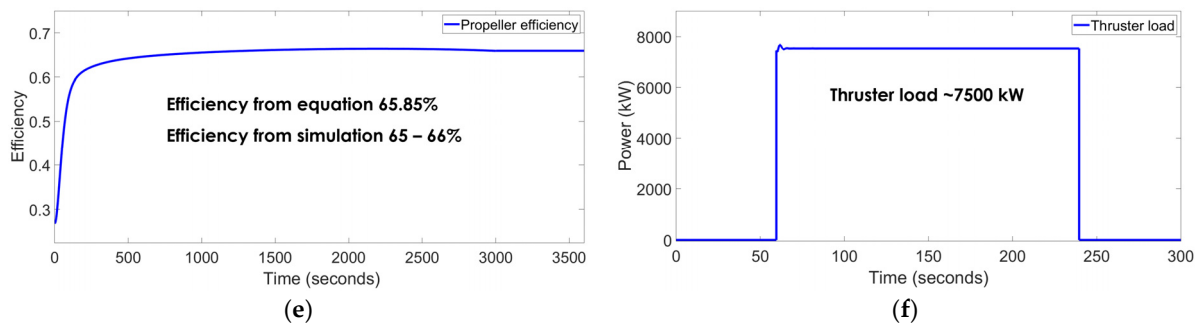


Figure 12. Verification and validation of model components. (a) Engine operation for load application. (b) Simulated SFC compared with interpolation and datasheet. (c) Comparison of delivered power from the simulation and sea trial test. (d) Service load and propulsion power with respective ship speed. (e) Ship propeller efficiency. (f) Operation of all maneuvering thrusters.

Table 4. Duration of the load application and reduction [35].

MAN 48/60 CR	Speed Ramp-Up/ Down (s)	Synchronization (s)	Load Ramp-Up/ Down (s)	Start Request to 100% Load/ Stop Request to 0% Load (s)
L-type	50/50	10	70/10	130/60
V-type			95/10	155/60

The delivered and effective power under the scenario of increasing ship speed is shown in Figure 12c. The simulated data of delivered power were also compared to the data from the sea trial test. The result indicates the accuracy of the ship resistance calculation and the correction of propulsion power due to pod drag. Figure 12d shows the required power for respective ship speed and service loads. The maximum load of 31,750 kW was required for the ship speed at 22.5 knots, and the constant load of approximately 14,250 kW was consumed by the ship service facilities. Figure 12e displays the propeller efficiency between 65.88 and 66.39% at the ship speed from 10–22.5 knots, which comes close to the estimation of the corrected open water efficiency. For a situation that requires high maneuvering and thrust power, all three thrusters could be switched on to provide additional propulsive power of 7500 kW, as shown in Figure 12f.

3. Real-Time Optimization of Ship Power Management

The power management unit is functioned to optimize the power generation under actual sea condition scenarios. The ship navigation and environmental data obtained from the AIS dynamic information are transmitted to the power management unit through the sensors, which are modeled as external data receiver blocks and then are processed with the respective power demands. The power management production is the transmitted signal to control the engine operation in such a way to effectively utilize all available power resources on board.

3.1. Simulation Scenarios

The simulation scenarios are based on the itinerary of the *Carnival Vista* traveling in the Gulf of Mexico from Cozumel, Mexico to Galveston, USA with a total distance of approximately 720 nautical miles. Three periods of the voyage with two hours each are selected for observation consisting of departure, navigation, and arrival scenarios, as shown in Figure 13. The environment-related information throughout the periods can be received in real time from the AIS and the environmental data service provider consisting of wave height, period, and direction, wind speed and direction, and current speed and direction as shown in Figure 14. The corresponding environmental data generated for the simulation are specifically based on the ship position. Examples of the real-time environmental data obtained for the departure scenario are shown in Figure 15.

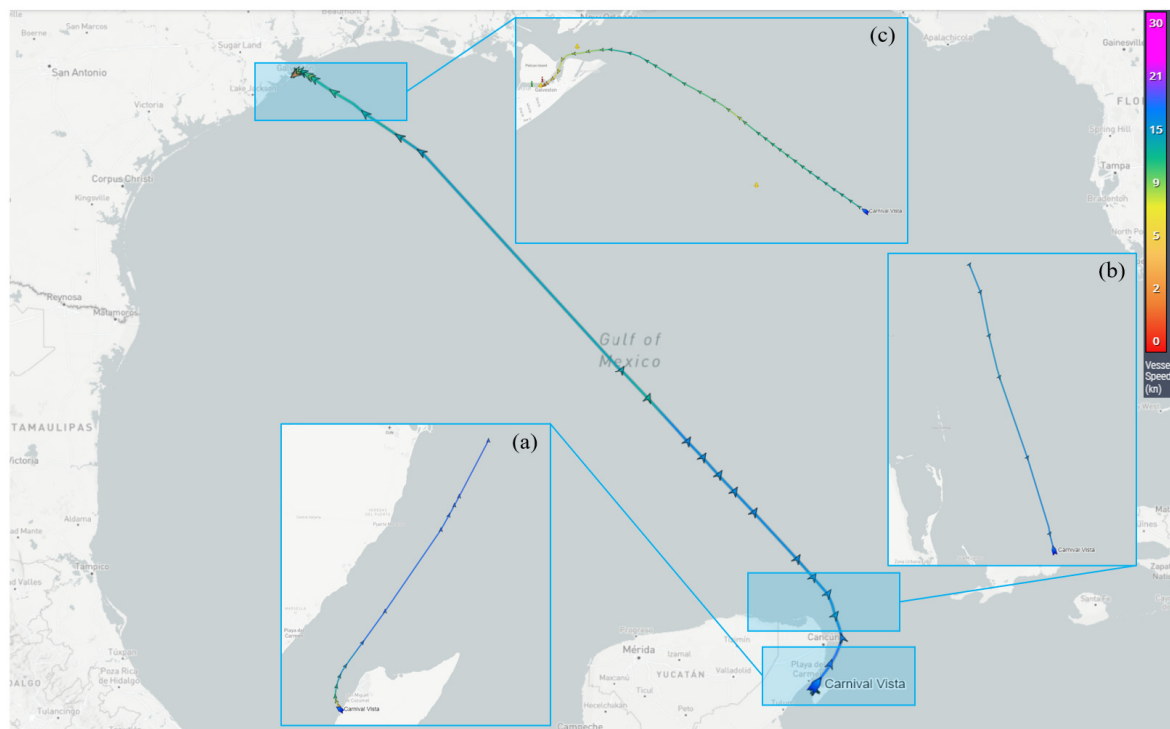


Figure 13. Simulation scenarios: (a) Departure; (b) Navigation; (c) Arrival.

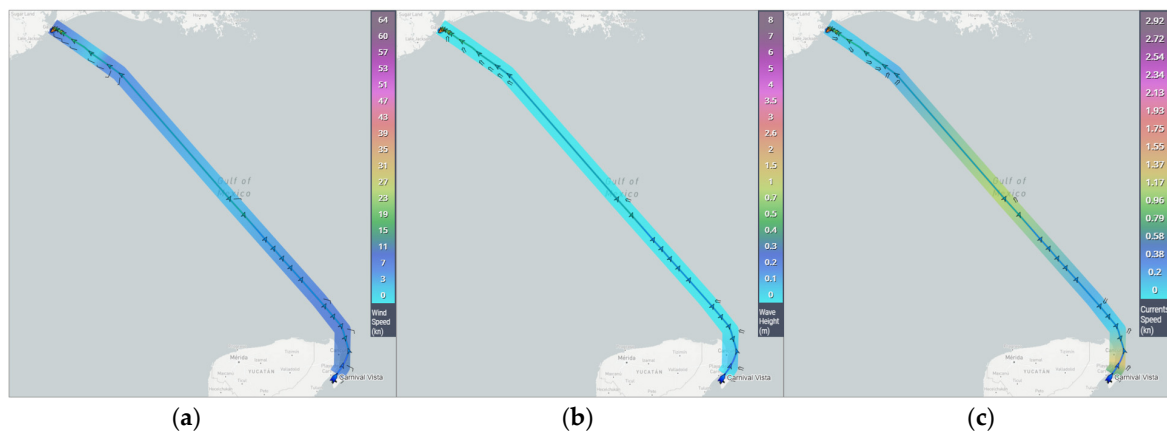


Figure 14. Environment information: (a) Wind; (b) Ocean wave; (c) Ocean current.

The departure scenario including the maneuvering period covers the simulation time of 7200 s. In this scenario, the ship speed and load demands consisting of propulsion, thruster, and service is shown in Figure 16a. The estimation of ship resistance with and without environmental effects is shown in Figure 16b. The difference in resistance is due to the effect of wave reflection, wind resistance, and water current that a ship experiences when cruising in the open sea. Typically, the additional resistance arisen by these phenomena is very limited in the proximity of harbor areas and increasing in correspondence with the intensity of the environment and the influence of the disturbance directions. The cruising data for the navigation and arrival scenarios are also shown in Figures 17 and 18. It is noted that the use of the thrusters during the maneuvering duration of 300 s is assumed for the departure and arrival scenarios.

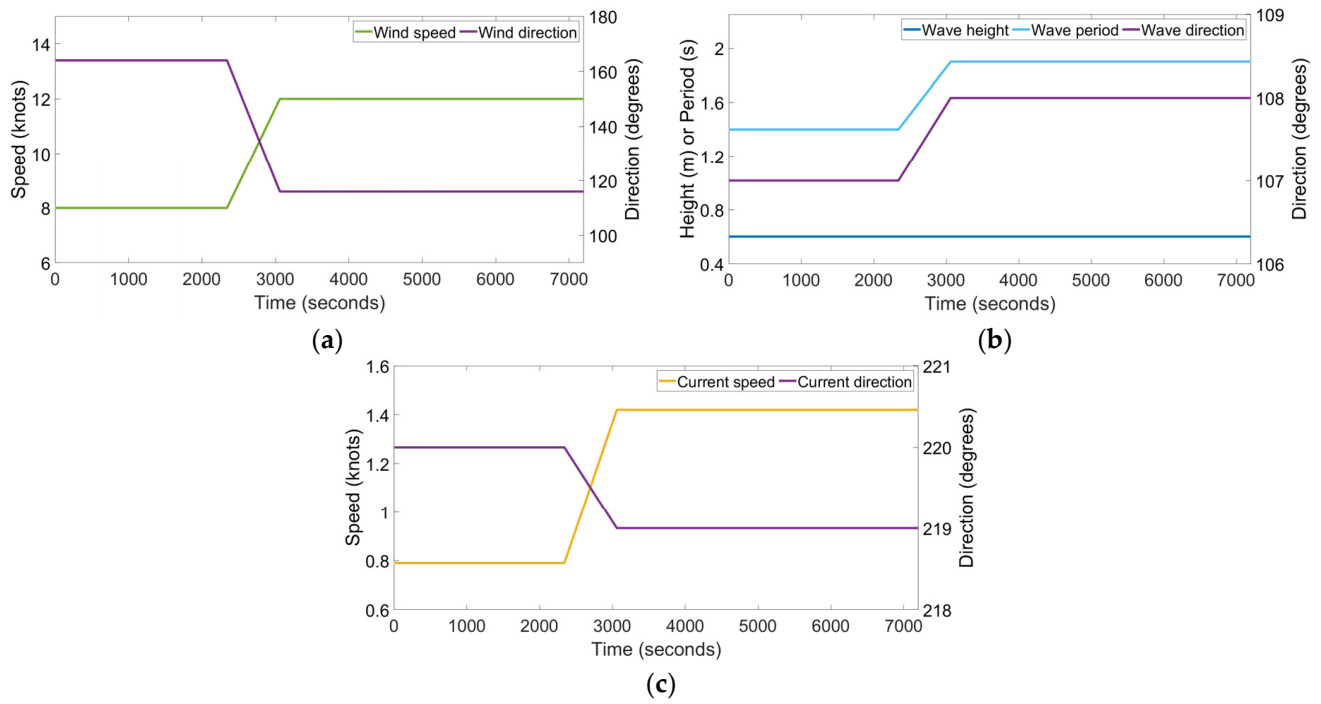


Figure 15. Real-time environmental data for the departure scenario: (a) Wind speed and direction; (b) Ocean wave height, period, and direction; (c) Ocean current speed and direction.

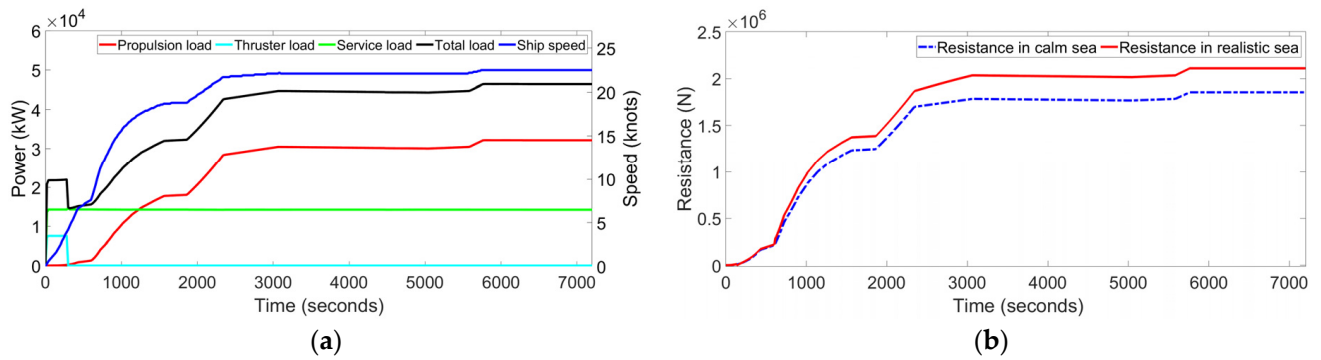


Figure 16. Departure scenario: (a) Ship speed and load demands; (b) Ship resistance.

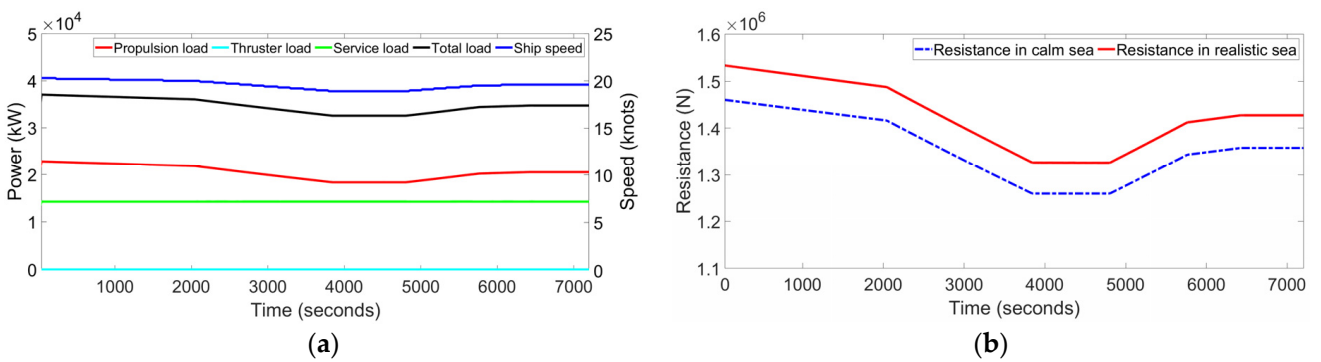


Figure 17. Navigation scenario: (a) Ship speed and load demands; (b) Ship resistance.

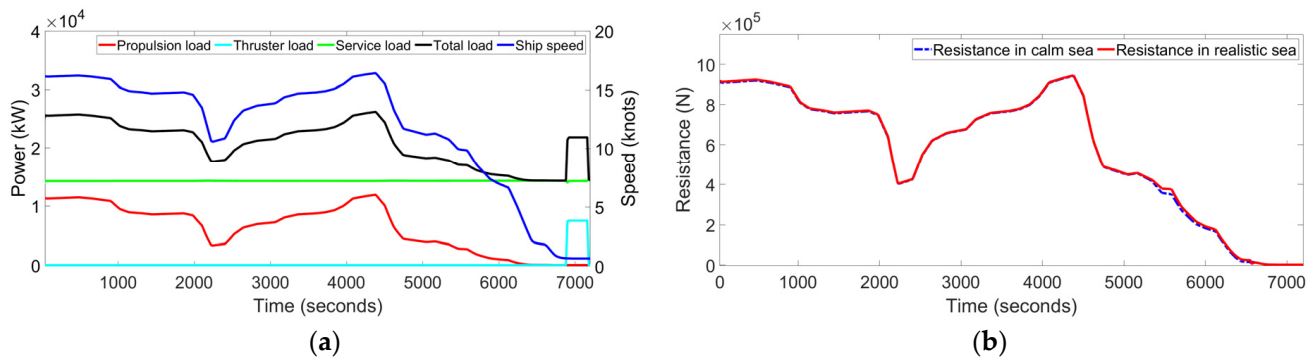


Figure 18. Arrival scenario: (a) Ship speed and load demands; (b) Ship resistance.

3.2. Optimization Problem Formulation

The objective function of the power generation with the DC distribution problem is to minimize fuel consumption through the optimization of ten variables consisting of five variables for power assigned to all prime movers and five variables for their optimal rotating speed. The formulation of the optimization problem including a set of constraints is as follows:

The number of power generation components can be specified to the maximum of N . The additional power requirement due to additional resistance from environmental disturbances is described by Δp and the power assigned to j th prime mover unit operating for a sample time interval Δt is given by $(p + \Delta p)_j$. The rotational speed of the prime mover operating at that assigned power is defined by ω_j . The SFC of the prime mover defined as $SFC((p + \Delta p)_j, \omega_j)$ then can be obtained by querying the grid coordinates that lie on the surface of the pre-generated 3D map of SFC. The summation of fuel consumed by all power generation components for a transient interval is given by:

$$F(\vec{p} + \Delta \vec{p}) = \sum_{j=1}^N \left[SFC((p + \Delta p)_j, \omega_j) \cdot (p + \Delta p)_j \cdot \Delta t \right] \quad (18)$$

The optimization problem for the minimization of the total fuel consumption over the whole period of simulation time t then can be formulated as:

$$\text{Minimize } \int_0^t (F(\vec{p} + \Delta \vec{p})) = \text{Minimize } \int_0^t \sum_{j=1}^N \left[SFC((p + \Delta p)_j, \omega_j) \cdot (p + \Delta p)_j \cdot \Delta t \right] \quad (19)$$

The objective function is subjected to the constraints as follows:

(1) Power balance constraint: The generated power from all power generation components must be equal to the total load demand:

$$P_{\Delta t} = \sum_{j=1}^N (p + \Delta p)_j \quad (20)$$

where $P_{\Delta t}$ is the total power demand for a sample time interval Δt .

(2) Engine loading constraint: The generated power is limited by minimum and maximum power generation capability of the prime mover:

$$p_j^{\min} \leq p_j \leq p_j^{\max} \quad (21)$$

where $p_j^{\min}$ and $p_j^{\max}$ are the minimum and maximum power rating of j th engine.

(3) Engine speed constraint: The engine operating speed is limited by minimum and maximum engine speed functioning for mechanical propulsion:

$$\omega_j^{\min} \leq \omega_j \leq \omega_j^{\max} \quad (22)$$

where $\omega_j^{\min}$ and $\omega_j^{\max}$ are the minimum and maximum operating speed of j th engine.

(4) Engine loading–speed relation constraint: The continuous service range of engine loading and speed is restricted by available air supply for combustion represented by limitation on the combination of torque and speed:

$$P_j(\tau_j, \omega_j)^{\min} \leq P_j(\tau_j, \omega_j) \leq P_j(\tau_j, \omega_j)^{\max} \quad (23)$$

where $P_j(\tau_j, \omega_j)$ is the loading–speed relation as a function of torque τ and speed ω for j th engine.

(5) Instant engine load step constraint: the load ramp-up/down of the engine is limited by maximum load acceptance capability:

$$|p_{j,\Delta t} - p_j| \leq R_{j,L_up/down} \quad (24)$$

where $p_{j,\Delta t}$ is the power assigned to j th engine for the next step of sample time; $R_{j,L_up/down}$ is the maximum permissible instant load step.

(6) Instant engine speed step constraint: the speed ramp-up/down of the engine is limited by maximum speed increase/decrease rate:

$$|\omega_{j,\Delta t} - \omega_j| \leq R_{j,S_up/down} \quad (25)$$

where $\omega_{j,\Delta t}$ is the speed assigned to j th engine for the next step of sample time; $R_{j,S_up/down}$ is the maximum permissible instant speed step.

(7) Uptime of generator set constraint: The continuous operation time of the start-up generator set is restricted by the minimum uptime constant:

$$\int_0^{t_{j,uptime}} \Delta t_{j,uptime} \geq T_{uptime}^{\min} \quad (26)$$

where $\Delta_{j,uptime}$ is the sample time for an uptime interval of j th engine; $t_{j,uptime}$ is the total uptime of operating j th engine; $T_{uptime}^{\min}$ is the minimum uptime requirement for the operating engine.

(8) Downtime of generator set constraint: The out of operation time of the shutdown generator set is restricted by the minimum downtime constant:

$$\int_0^{t_{j,downtime}} \Delta t_{j,downtime} \geq T_{downtime}^{\min} \quad (27)$$

where $\Delta_{j,downtime}$ is the sample time for a downtime interval of j th engine; $t_{j,downtime}$ is the total downtime of j th engine; $T_{downtime}^{\min}$ is the minimum downtime requirement for the shutdown engine.

The pattern search algorithm which is a built-in MATLAB function is implemented for the model development due to its relatively fast and proven convergence characteristics required for the real-time optimization as shown by comparing with other built-in algorithms in Figure 19. The pattern search is a derivative free method providing single global solution and local search capability. The searching behavior consists of exploratory move for acquiring knowledge about the search direction and pattern move for utilizing the information and accomplishing the actual minimization of the function as described in Algorithm 1. Further details of the algorithm can be referred to [36].

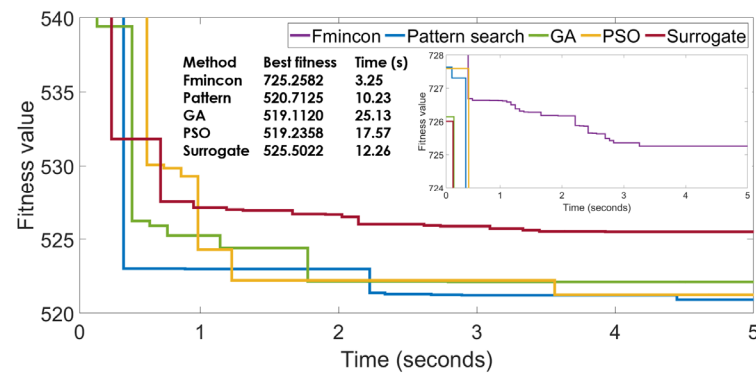


Figure 19. Convergence characteristics of optimization algorithms for a load demand of 42,000 kW.

Algorithm 1. Pseudo-code of the pattern search algorithm.

```

Initialize the input parameters, i.e., acceleration factor  $v$ , perturbation vector  $P^0$ , perturbation tolerance vector  $\tau$ 
Initialize the current perturbation vector  $P \leftarrow P^0$  and select the value for the starting point  $x^{int}$ 
Update  $x^{int}$  to  $x^{iter}$  using exploratory move around  $x^{int}$  to find an improved  $x^{iter}$ 
if  $x^{iter} > x^{int}$ 
     $P_i \leftarrow P/2$ 
    if  $P < \tau$ 
         $x^{final} = x^{int}$ 
    else update  $x^{iter}$  using exploratory move
    end
else  $x^{final} = x^{iter}$ ,  $P \leftarrow P^0$ 
end
(a) Obtain tentative  $x^{iter+1}$  by pattern move from  $x^{int}$  through  $x^{iter}$ 
(b) Obtain final  $x^{iter+1}$  by exploratory move around tentative  $x^{iter+1}$ 
if  $f(x^{iter+1}) > f(x^{iter})$ 
     $x^{int} \leftarrow x^{iter}$ 
else  $x^{int} \leftarrow x^{iter}$ ,  $x^{iter} \leftarrow x^{iter+1}$ 
end

```

3.3. Comparative Analysis on the MVAC and MVDC Systems

The power management with the pattern search algorithm was executed for the proposed MVDC and the conventional MVAC system models in the provided scenarios. The result analysis also includes the non-optimized MVAC system operating in equal load sharing for a comparative study. The highlights to be considered are the differences in the number of activated generators and the proportion of individual engine loads assigned and speed with their respective SFC.

For the departure scenario, the MVAC system operated with four generator sets when cruising at high speed and assigned load to them with respect to their optimal ranges (especially for DG1, DG2, and DG3), i.e., between 80 and 90% of the MCR at 100% engine speed specified by the frequency requirement. On the other hand, the MVDC system operated with all five generators and proportionally allocated load to them for approximately 70–75% of the MCR at varied engine speed, mostly around 90% of the rated speed, as shown in the SFC plots in Figure 20. The plots also indicate the higher possibility of the DC distribution for optimizing fuel efficiency due to the extension of optimum SFC areas along the extending engine operating speed from a specific 514 rpm between 402 and 514 rpm.

For the navigation scenario, during the slight reduction of ship speed, the power balance constraint of the MVAC system caused an active generator (DG3) to operate at low load condition, i.e., less than 50% of the MCR and occasionally switched off. This permitted the other two generators (DG1 and DG2) to operate more than 90% of the MCR for the rest

of the period of time. On the contrary, the MVDC system seemed not to suffer from any non-optimized condition as the optimum engine load areas varied from 70 to 90% of the MCR in respect of variable engine speed and thus providing more flexibility to manage engine load assigned. The plots in Figure 21 obviously show superior performance of the MVDC power management that was able to place conditions of all active generators into optimum SFC areas. More specifically, the load assigned and respective SFC conditions of DG1, DG2, and DG3 for the MVDC were located at minimum value areas of 170–176 g/kWh throughout the period, while the MVAC system was not able to do so.

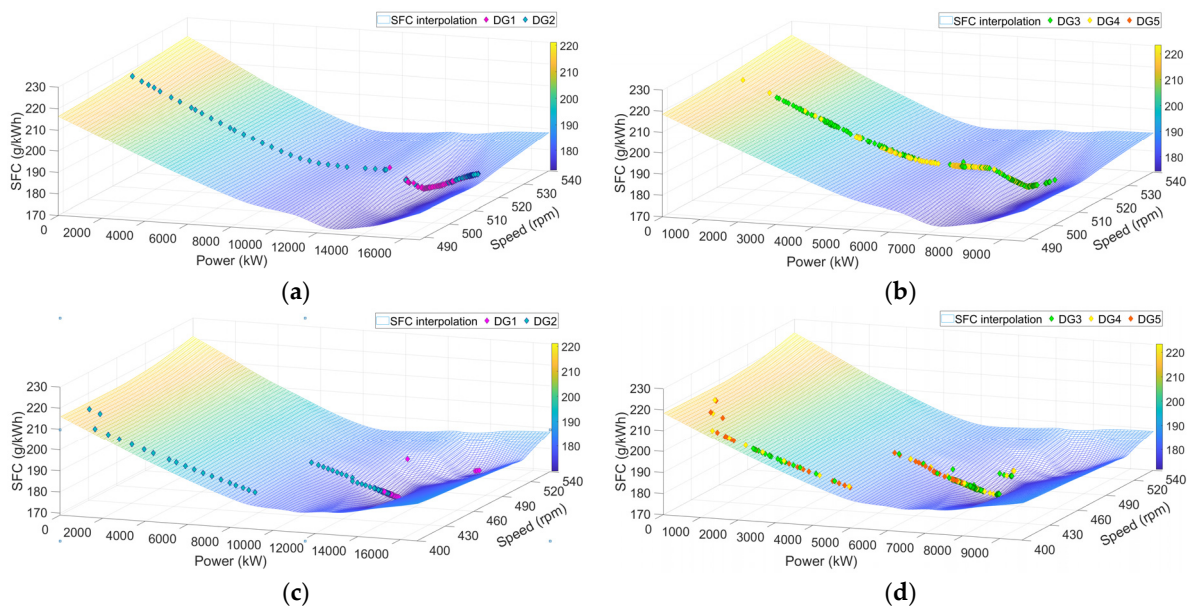


Figure 20. Optimized SFC for the departure scenario: (a) V-type engines MVAC; (b) L-type engines MVAC; (c) V-type engines MVDC; (d) L-type engines MVDC.

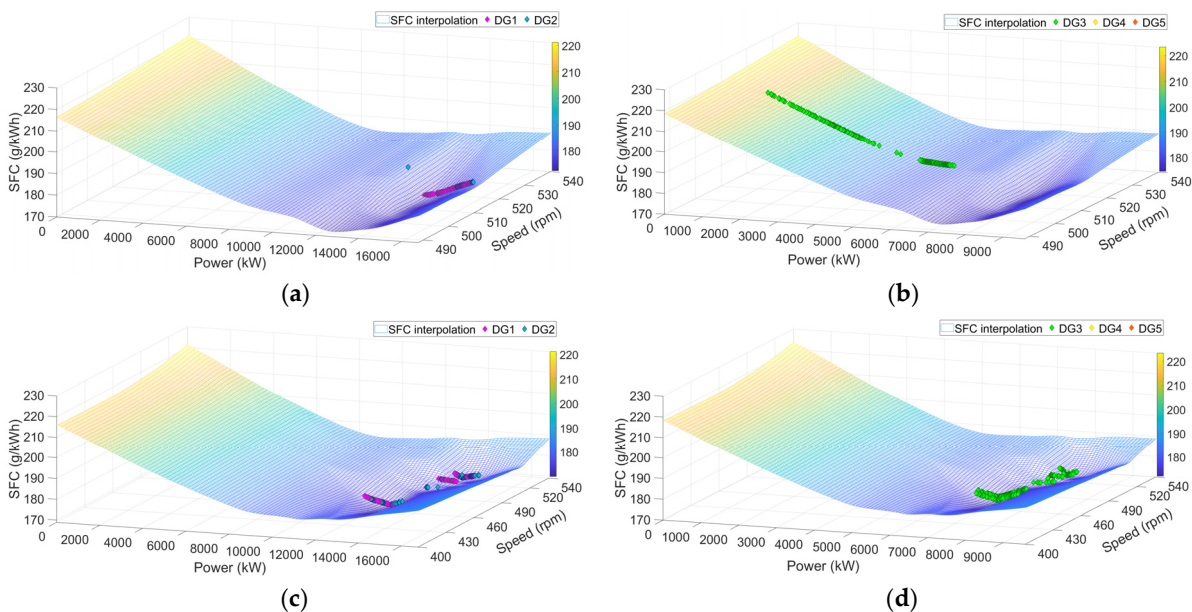


Figure 21. Optimized SFC for the navigation scenario: (a) V-type engines MVAC; (b) L-type engines MVAC; (c) V-type engines MVDC; (d) L-type engines MVDC.

For the arrival scenario as shown in Figure 22, both the MVAC and MVDC configurations provided insignificant difference in terms of engine load apportionment. However,

the MVDC system appeared to locate the load conditions of the V-type engine into more efficient areas. It is noted that the V-type or larger-size engine is more efficient than the L-type or smaller engine at all operating conditions as indicated in Table A4. This is due to the cube–square relation that causes the cylinder surface area to increase more slowly than the volume. The larger engine therefore can use the heat from combustion to expand the gas more effectively and thus giving more force, while the heat that drifts away through the cylinder surface can be reduced proportionally compared to the smaller engine.

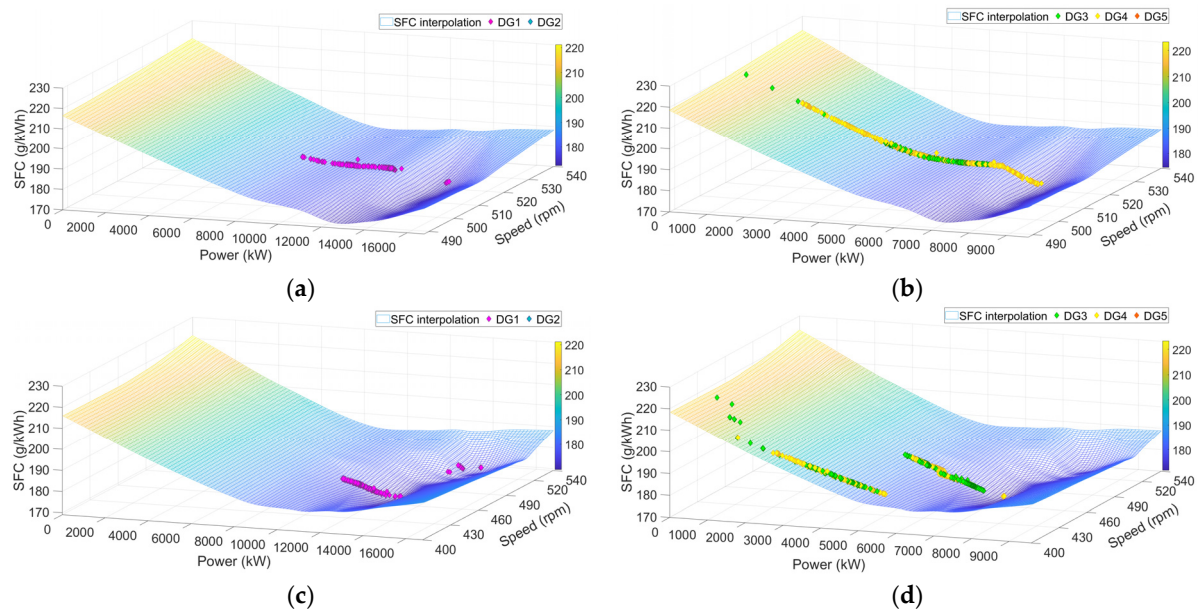


Figure 22. Optimized SFC for the arrival scenario: (a) V-type engines MVAC; (b) L-type engines MVAC; (c) V-type engines MVDC; (d) L-type engines MVDC.

The rectification process of the MVDC system model has been validated as shown in Figure 23. The rectifier converted the AC side voltage of 11 kV to DC voltage of approximately 14.7 kV for the distribution bus based on Equation (13). The oscillation of DC bus voltage was due to the voltage droop control when the ship speed was varied and behaved in a steady state when the ship speed was relatively constant. The results also verify the stability of the DC bus voltage that was regulated within the permissible level of $\pm 10\%$ in spite of load variations due to starting up and shutting down of multiple thruster motors in the departure and arrival scenarios. It is noted that the frequency fluctuation and harmonic distortion are not considered for the DC bus. The majority of the power and quality issues that appeared in the DC grid system are therefore attributed only to voltage variations resulting from cyclic or non-cyclic load transients [37].

The fuel saving of all distribution architecture and all scenario profiles are summarized in Table 5. The saving in percentage of the optimized MVDC system compared to the non-optimized MVAC were 3.75%, 4.78%, and 7.37%, respectively, for the departure, navigation, and arrival profiles. The significant amount of saving from the arrival profile was due to the minimization of active generators for the requirement of using low ship speed when approaching the port of destination. Meanwhile, all five generators were switched on by the equal load sharing scheme and operated with unfavorable conditions over the whole simulation time. The fuel saving results obtained in this non-optimized condition can be compared with the saving results of 8.9–12.4% from the large-scale container ships with variable speed engine operation in [38].

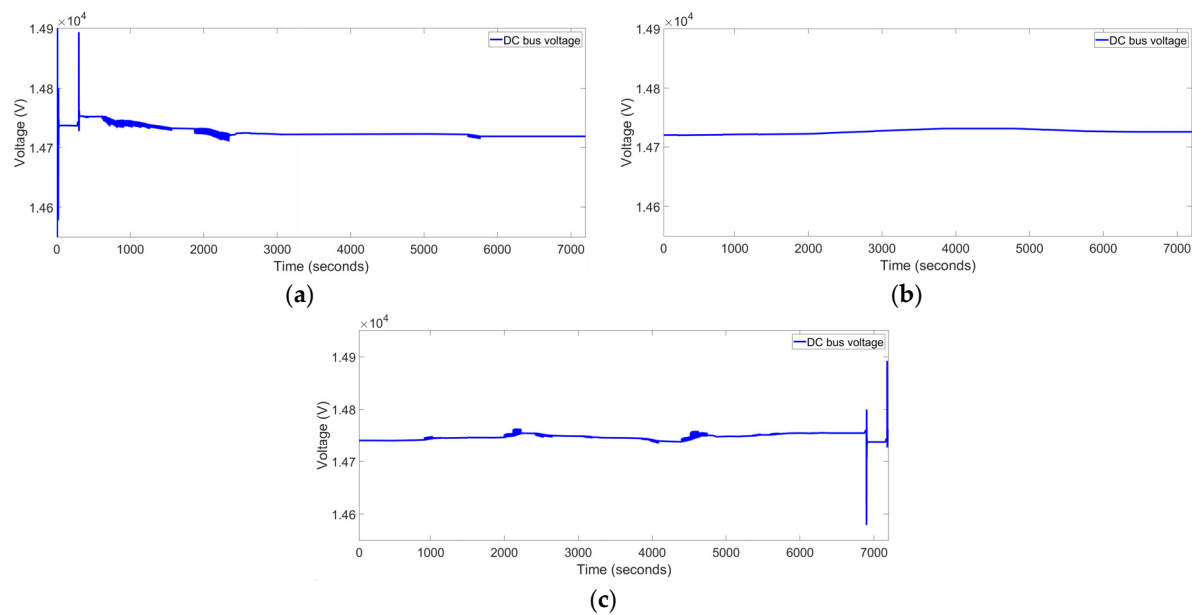


Figure 23. DC bus voltage in the scenarios: (a) Departure; (b) Navigation; (c) Arrival.

Table 5. Fuel saving results for all system architecture.

Scenario Profile	Distance (NM)	Simulation Time (s)	Non-Optimized MVAC (kg)	Optimized MVAC (kg)	Optimized MVDC (kg)	Fuel Saving Compared with Non-Opt./Opt. MVAC
Departure	28.95	7200	14,267.03	13,997.06	13,732.48	3.75%/1.89%
Navigation	38.69	7200	12,660.50	12,482.50	12,055.21	4.78%/3.42%
Arrival	22.92	7200	8075.26	7623.38	7479.88	7.37%/1.88%

By comparison with the optimized MVAC system, the fuel saving results of the MVDC with their respective GHG emission reduction were 1.89%, 3.42%, and 1.88%, respectively, for the sequential scenarios. It is noted that the fuel saving of 4.78% by comparing with the non-optimized MVAC and the saving of 3.42% by comparing with the optimized MVAC received from the navigation scenario may be set as a benchmark for the immediate benefit of the MVDC architecture as the navigation period usually accounts for almost all of the total ship cruising time and distance.

In order to encourage the further reduction of GHG emissions, the carbon credit which permits charging a fee based on the amount of carbon released has been recently effective. The credit also imposes the emission quota that can be traded on a carbon market, hence providing a mechanism toward carbon neutrality by offsetting ship emissions against GHG reduction made elsewhere [39].

The carbon credit cost can be calculated by the following equation:

$$\text{Carbon credit cost} = \text{Tax}_{\text{carbon}} \cdot \text{FC}_{\text{annual},f} \cdot C_{F,f} \quad (28)$$

where $\text{Tax}_{\text{carbon}}$ is the carbon emission tax given by USD per metric ton of CO_2 ; $\text{FC}_{\text{annual}}$ is the annual mass of consumed fuel in tons; C_F is the fuel mass to CO_2 mass conversion factor given by ton CO_2 /ton fuel; f is the fuel type.

The calculation can be based on the average saving figure of 4.78% against the conventional MVAC system, the CO_2 emission factor of 3.206 ton CO_2 /ton fuel, the MGO price of \$926/ton as of Q2/2024, the carbon emission tax of \$37.02/ton CO_2 as of Q2/2024 [40], and the annual ship operation time according to the itinerary of 53 trips/year and 80 h/trip. As a result, the environmental and economic benefits obtained from the MVDC system employment include the annual fuel saving of 1283 ton, the annual CO_2 emission reduction of 4114 ton, the annual fuel cost saving of \$1,188,257, and the annual carbon credit cost saving

of \$152,300. The saving obtained could also be further exploited through the high-power dense DC-based architecture by replacing traditional heavy distribution equipment and thus reducing the ship weight and respective fuel consumed.

4. System Weight and Volume Analysis

This section provides a comparative analysis between the MVAC and MVDC in terms of system weight and volume. The actual data of the MVAC distribution equipment can be obtained from the manufacturer of the *Carnival Vista*, while the estimated data of the MVDC equipment can be obtained from the scaling approach as introduced in [41]. The scaled data for the equipment weight can be established by modular multilevel converter (MMC) and DC switch, which are proposed as scalable technology required for compacting overall network arrangement. The scalability of the multilevel converter is achieved by the string of submodules as shown in Figure 24 that can convert electrical power while facilitating voltage scalability and weight/size optimization [41]. The MMC cabinet and DC switch data detailed, respectively, in [42,43] provide the reference for the calculation of power distribution system density in terms of rating power per metric ton (mt) as the following procedure:

- Estimate the required number of MMC cabinets and DC switches according to power generation units and system arrangement.
- Estimate the total mass of MMC cabinets according to DC bus voltage, individual submodule ratings, and their power density.
- Estimate the total mass of DC switches by using available scaled data.
- The power density of the distribution system can be calculated by the sum of total mass from the MMC cabinets and DC switches divided by the installed power capacity.

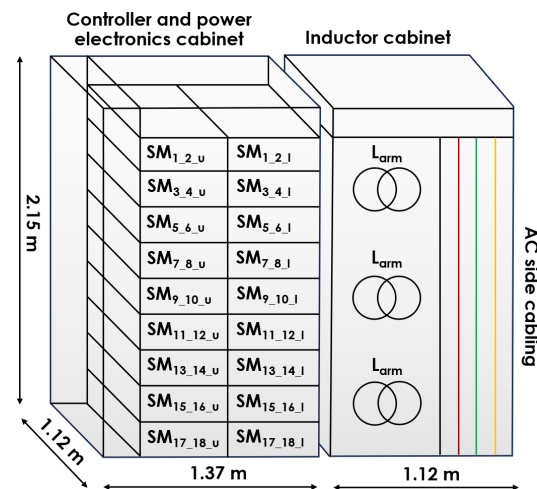


Figure 24. Reference dimensions of a modular multilevel converter. Figure adapted from [41].

The reference data from [43] introduce an MVDC-based configuration with the installed power of 89.4 MW consisting of six MMC cabinets and 40 units of DC switches to represent rectifier/inverter, associated power distribution, and switch modules. The total mass of equipment modules according to DC bus voltage is shown in Figure 25. The power density in terms of MW/mt of total distribution equipment then can be derived from the provided references as shown in Figure 26.

The DC bus voltage converted from the default voltage of the *Carnival Vista* was approximated at 15 kV. The power density ratio of 0.5318 MW/mt for the distribution system then could be derived from the power density chart and thus the total weight of DC equipment on board the *Carnival Vista* with the 62.4 MW power generation was estimated at 117.34 mt. By comparing with the total weight of 225.34 mt aggregated from the existing AC equipment weight of the *Carnival Vista* as listed in Table A8, the system weight saving of 108 mt or 47.92% could be achieved.

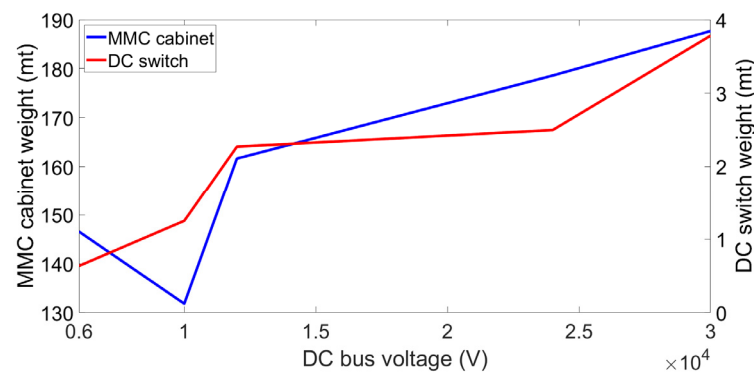


Figure 25. Total mass of reference DC equipment with respect to DC bus voltage.

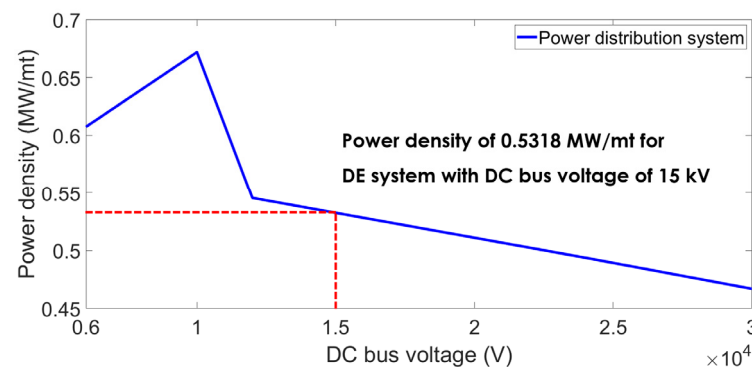


Figure 26. Power density of reference DC equipment with respect to DC bus voltage.

The MVDC network also made it possible to employ very high-speed prime movers such as gas turbine (GT) engines to further minimize power generation system weight and dimensions. The gas turbine engine demonstrates an alternative power generation for large cruise vessels as evaluated in [44], which offers environmental and economic benefits through compliance of emission regulations and significantly increasing ship payload. Additionally, the technology of synchronous machinery compatible with the high-speed combustion turbine is significantly more compact. The weight and dimension details of the potential turbine engine and the existing generation machines installed on the *Carnival Vista* are given in Table A9.

The power density of the turbine generator unit consisting of the engine body of GE LM2500 + G4 and compatible generation machinery was defined in terms of weight and volume as 0.358 MW/mt and 0.159 MW/m³ [42]. Thus, the weight and space for the 62.4 MW system of the *Carnival Vista* could be estimated at 174.30 mt and 392.45 m³ by using the power density ratio as delineated in Figure 27. By comparing with the existing diesel system that has the total weight of 1118.30 mt and the volume of 1637.53 m³, the drastic reduction of 84.41% and 76.03%, respectively, for system weight and volume could be achieved.

The overall power density in terms of mass for the gas turbine electric with the MVDC distribution is shown in Figure 28. The derived power density plot was established by the reference information of MMC cabinets, DC switches, and GE LM2500 + G4 with compatible synchronous machines. For the DC bus voltage requirement of 15 kV, the total system weight of power distribution and power generation was estimated at 291.84 mt based on the power density ratio of 0.2138 MW/mt, which was much lighter than the conventional diesel electric by 78.28%, as illustrated in Figure 29. However, it is noted that the turbine generator has lower electric efficiency and may cause an increase in fuel consumption by approximately 10–20% [44].

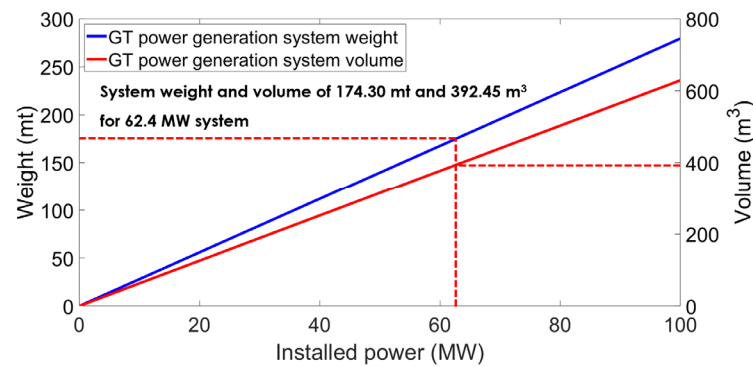


Figure 27. Weight and volume requirements as a function of GT generation power.

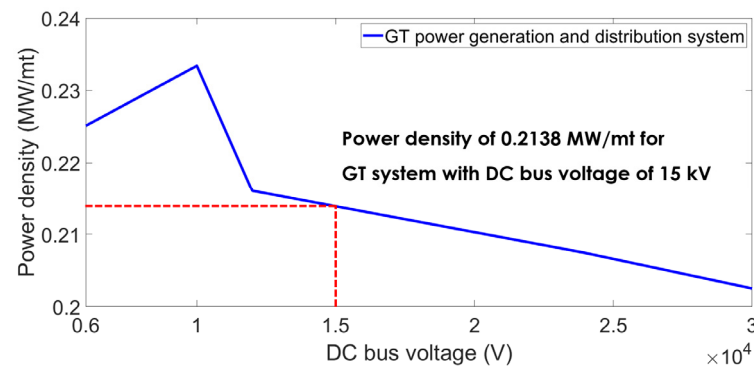


Figure 28. Power density of GT electric set with MVDC architecture.

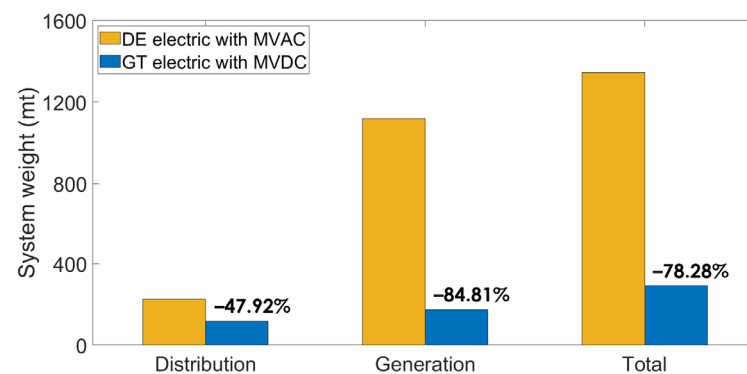


Figure 29. Comparison of system mass between generation and distribution technologies.

Another consideration is the maintenance requirement. The turbine generator generally has very low onboard maintenance, while the maintenance cost of depot level is relatively high compared to the diesel generator counterpart. The trade-off between the significant payload gains and the increased operating costs therefore needs to be considered and thoroughly evaluated in view of economic implications.

5. Summary and Prospects

5.1. Conclusions

An optimal power management strategy has been applied to the developed MVDC system model for the requirement of minimizing fuel consumption under actual sea conditions in real time. The MVDC architecture for the case study large cruise vessel was established by the modification of the conventional AC to DC grid employing radial structure and unipolar topology with an appropriate voltage class. The complete model consisted of all essential machinery for power generation, DC distribution, and particular features typically

installed on board cruise vessels such as maneuvering thrusters and azimuthing podded propulsion. The ship hydrodynamics considering the interaction of the ship body with surrounding fluid and real-time environmental disturbances from wind, waves, and ocean current were also incorporated.

A significant advantage of the MVDC operation is the elimination of frequency constraints allowing the simultaneous optimization of engine load and rotational speed. The simulation results demonstrated the maximum fuel saving from 3.42 to 7.37%, respectively, by comparing to the optimized MVAC and non-optimized MVAC systems. The use of variable speed engine operation increased opportunity of search agents in finding optimum SFC as the optimum load areas were expanded from around 85% to 70–90% of the MCR, while the engine speed could be widely varied depending on the optimal load assigned. By giving priority on the value of dimensions availability, the modularity concept of the DC distribution equipment facilitated the replacement of large and heavy AC transformers and hence reduced the total weight of distribution components by 47.92%. The substitution of traditional diesel generators with very high-speed combustion turbines was also possible and especially suited as per high power density ratios. Accordingly, the drastic reduction of system weight and volume by 84.41% and 76.03%, respectively, could be achieved. The available space obtained enables the integration of DC power source applications and the installation of abatement devices such as De-SO_x and De-NO_x, which occupy significant space and raise the ship total weight.

Finally, the environmental and economic benefits analyzed from this study enhance the growth prospect of the MVDC-based technology for the marine sector due to the burgeoning demand for more efficient shipboard architecture against the economic requirements and stricter environmental control.

5.2. Challenges and Prospects

The transition from AC to DC distribution for onboard power systems is anticipated to become more prevalent in the near future. However, this shift may not be entirely smooth due to various technological limitations. Additional investigation is particularly needed in the realms of protection measures and concerns regarding stability. The absence of natural current zero crossing in the DC system presents a notable difficulty in designing a DC breaker to extinguish the arc. Existing protection schemes therefore employ a mix of fuses, isolators, circuit breakers, and converter control to ensure the system is adequately protected. Reconfiguration following faults may also be accomplished by optimizing the bus architecture and implementing load shedding strategies based on load prioritization. Furthermore, a comprehensive examination of solid-state power converters is necessary to maintain the bus voltage stability within the specified quality standards.

Apart from technological constraints, there are also several aspects that need to be considered such as the maintenance cost of DC rotating machines and associated components which are higher than the AC machines counterpart; the need for relevant standard development for all aspects of DC grid systems including voltage standardization, power quality, and safety measures; the training requirement for relevant crew members and onboard engineers; and the compatibility of shore power supply systems between onboard DC grids and existing onshore infrastructure. These considerations are essential to enhance the readiness level of this technology for broader industrial and commercial deployment.

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Appendix A

Table A1. Parameters of the *Carnival Vista* for the calculation of hydrodynamics.

Description	Parameter	Value	Description	Parameter	Value
Gross tonnage		133,596 grt	Displacement volume	∇	67,786 m ³
Length overall	L_{OA}	323.63 m	Length perpendiculars	L_{PP}	287.1 m
Length waterline	L_{WL}	299.06 m	Molded breadth	B	37.2 m
Molded depth	D	11.2 m	Maximum draft	T	8.55 m
Maximum air draft	T_A	61.75 m	Maximum speed	V	22.6 kn
Number of propellers	N_P	2	Number of propeller blades	Z_P	5
Propeller diameter	D_P	5.15 m	Maximum propeller speed	n	138 rpm
Sea water density	ρ_W	1025 kg/m ³	Air density	ρ_A	1.225 kg/m ³
Viscosity of water	ν	0.00001188 m ² /s	Gravitational acceleration	g	9.81 m/s ²
Static pressure	p_0	101,000 N/m ²	Vapor pressure	p_v	3000 N/m ²

Table A2. Coefficients for the ITTC-78 performance prediction.

Description	Parameter	Value
Form factor	k	0.037816
Frictional resistance coefficient	C_F	0.001346
Viscous resistance coefficient	C_V	0.001398
Residual resistance coefficient	C_R	0.000624
Roughness allowance	ΔC_F	0.000167
Correlation allowance	C_A	0.000001
Air resistance coefficient	C_{AA}	0.000143

Table A3. Specifications of MAN 14V and 8L 48/60 CR engine [35].

Engine model	14V/8L 48/60 CR	Number of cylinders		14 Vee/8 In-line	
Brake power	16,800 kW/9600 kW	Power per cycle		1200 kW	
Engine revolution	514 rpm	Cylinder diameter		480 mm	
Piston stroke	600 mm	Cylinder distance		1000 mm/820 mm	
Connecting rod length	1370 mm/600 mm	Crankshaft offset		300 mm	
Clearance volume	7.59 L	Swept volume per cylinder		108.57 L	
Engine volume	1520 L/869 L	Average piston speed		10.28 m/s	
Mean effective piston pressure	26.50 bar	Rated torque		312,140 Nm/178,366 Nm	
Compression ratio	15.30	Stoichiometric air to fuel ratio		14.50	
Engine load	%	100	85	75	50
Air flow rate	kg/kWh	7.27	7.24	8.21	8.38
Exhaust gas temperature	K	599.15	571.15	571.15	584.15

Table A4. Specific fuel consumption and torque of MAN 14V and 8L 48/60 CR engines [35].

Parameter		Constant Speed								Variable Speed			
Speed	rpm	514								501	487	462	402
Load	%	100	85	75	65	50	25	100	85	75	65	50	25
14V SFC	g/kWh	182.0	173.5	181.0	181.0	182.5	199.5	182.0	173.5	175.5	178.0	182.5	197.0
14V Torque	Nm	312,117	265,300	234,088	202,876	156,059	78,029	312,117	265,300	241,328	213,554	173,398	100,038
8L SFC	g/kWh	184.0	175.5	183.0	183.0	186.0	202.0	184.0	175.5	177.5	180.0	185.0	199.5
8L Torque	Nm	178,353	151,600	133,764	115,929	89,176	44,588	178,353	151,600	137,902	122,031	99,085	57,164

Table A5. Specifications and parameters of synchronous machine [45].

Generator model	ABB AMG 1600UT 14LSE/ABB AMG 1600QM 14LSE				
Apparent power	20,494 kVA/11,671 kVA				
Active power	16,395 kVA/9337 kVA				
Reactive power	12,296 kVAR/7002 kVAR				
Voltage/Frequency	Three-phase AC 11,000 V/60 Hz at 514 rpm				
No. of poles/PF/Connection	14/0.8/Star				
Description	Parameter	Value	Description	Parameter	Value
<i>Impedances</i>			<i>Time constants</i>		
Sator resistance	R_a	0.011 Ω	d-axis transient open-circuit	T'_{d0}	5.25 s
Sator leakage reactance	X_1	0.15 Ω	d-axis subtransient open-circuit	T''_{d0}	0.03 s
d-axis synchronous reactance	X_d	1.05 Ω	q-axis subtransient open-circuit	T''_{q0}	0.05 s
q-axis synchronous reactance	X_q	0.7 Ω			
zero-sequence reactance	X_0	0.15 Ω			
d-axis transient reactance	X'_d	0.35 Ω			
d-axis subtransient reactance	X''_d	0.25 Ω			
q-axis subtransient reactance	X''_q	0.325 Ω			

Table A6. Parameters of SM AC1C excitation system [29].

Description	Parameter	Value	Description	Parameter	Value
<i>General</i>			<i>Exciter</i>		
Initial field voltage	E_{FD0}	1 pu	Exciter field proportional constant	K_E	1.0 pu
<i>Pre-control</i>			Exciter field time constant	T_E	0.8 s
Resistive component of load compensation	R_C	0 pu	Rectifier loading factor proportional to commutating reactance	K_C	0.2 pu
Reactance component of load compensation	X_C	0 pu	Demagnetizing factor, function of exciter alternator reactances	K_D	0.38
Regulator input filter time constant	T_R	0 s	Exciter output voltage for saturation factor	E_1	4.18 pu
<i>Control</i>			Exciter saturation factor at exciter output voltage	$S_E(E_1)$	0.1
Regulator output gain	K_A	400 pu	Exciter output voltage for saturation factor	E_2	3.14 pu
Regulator output time constant	T_A	0.02 s	Exciter saturation factor at exciter output voltage	$S_E(E_2)$	0.03
Regulator denominator (lag) time constant	T_B	0 s	Maximum exciter field current limit reference	$V_{FE\max}$	99 pu
Regulator numerator (lead) time constant	T_C	0 s	Minimum exciter voltage output	$V_{FE\min}$	0 pu
Rate feedback excitation system stabilizer gain	K_F	0.03 pu			
Rate feedback time constant	T_F	1 s			
Maximum regulator output	$V_{A\max}$	14.5 pu			
Minimum regulator output	$V_{A\min}$	−14.5 pu			
Maximum exciter field voltage	$E_{FE\max}$	6.03 pu			
Minimum exciter field voltage	$E_{FE\min}$	−5.43 pu			

Table A7. Specifications and parameters of asynchronous machine.

Motor Type	Squirrel Cage	Model	AMI 560L8L
Rated power	2500 kW	Rated torque	26,656 Nm
Synchronous speed	900 rpm	Mechanical speed	896 rpm
Number of poles	8	Voltage	11 kV
Frequency	60 Hz	Current	165 A
Relative starting current	5	Relative starting torque	0.54
Relative maximum torque	2.1	Power factor	0.82
Description	Parameter	Value	
Impedance			
Sator resistance	R_s	0.8025 Ω	
Sator leakage inductance	L_{ls}	0.01289 H	
Referred rotor resistance in cage 1	R'_{r1}	0.1907 Ω	
Referred rotor leakage inductance in cage 1	L'_{lr1}	0.01541 H	
Referred rotor resistance in cage 2	R'_{r2}	2.344 Ω	
Referred rotor leakage inductance in cage 2	L'_{lr2}	0.01289 H	
Magnetizing inductance	L_m	0.2475 H	

Table A8. Weight of power distribution equipment of the *Carnival Vista* [34].

Power Distribution and Associated Equipment	Quantity	Unit Weight (kg)	Total Weight (kg)
Engine room transformer	4	8750	35,000
Engine room spare transformer	2	10,960	21,920
Galley transformer	2	5700	11,400
Accommodation transformer 1500 kVA	3	5495	16,485
Accommodation transformer 1800 kVA	2	5600	11,200
Accommodation transformer 2100 kVA	1	5900	5900
Voltage regulator cubicle	2	174/182	356
Generator neutral point cubicle	5	250	1250
Propulsion transformer	4	14,250	57,000
Propulsion converter with interface	2	8012	16,024
Propulsion converter without interface	2	7662	15,324
Brake resistor cubicle	4	890	3560
Premagnetization transformer	4	500	2000
Aft main switchboard	1	13,420	13,420
Fwd main switchboard	1	13,800	13,800
Remote control panel	2	300	600
Propulsion connection management	1	100	100

Table A9. Specifications of weight and dimensions for power generation sets.

Specification	Synchronous Machine (Existing) [46]		Diesel Engine (Existing) [35]		Turbine Engine [47]
Manufacturer	ABB		MAN		GE
Model	AMG 1600UT 14LSE	AMG 1600QM 14LSE	14V 48/60 CR	8L 48/60 CR	LM2500 + G4
Rated power	16,395 kVA	9337 kVA	16,800 kW	9600 kW	25,060 kW
Speed	514 rpm	514 rpm	514 rpm	514 rpm	3600 rpm
Weight	63,400 kg	53,500 kg	213,000 kg	135,000 kg	19,900 kg
Dimension	5015 × 4570 × 4140 mm	5015 × 4570 × 4140 mm	4730 × 11,790 × 5500 mm	3280 × 10,540 × 5300 mm	2600 × 8000 × 2400 mm
Volume	94.88 m ³	94.88 m ³	306.72 m ³	183.23 m ³	49.92 m ³

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