



Article

Power-Optimized Mitigation of Power Quality Issues and Effective Power Transfer in Electrified Hybrid Marine Vehicle Using Interlinking Converter During Islanded Mode

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Abstract

The rapid electrification of marine transportation has increased the number of hybrid marine microgrids with the addition of renewables and energy storage. The continuously varying propulsion loads, fluctuating sea states, and renewable intermittency introduce significant challenges in bidirectional power transfer and power quality enhancement in marine vessels. This work presents a power-oriented operational strategy for a hybrid Roll-on/Roll-off (Ro-Ro) ferry-based marine microgrid (FMG) integrating diesel generators (DGs), Solar Photovoltaic (PV) arrays, and battery energy storage systems as the primary power sources. The proposed FMG adopts a hybrid AC/DC bus configuration linked through a bidirectional voltage source interlinking converter (ILC). The ILC facilitates multiple functionalities, including effective load compensation, mitigation of Total Harmonic Distortion (THD), continuous power support through bidirectional energy exchange, maintenance of balanced sinusoidal currents, and unity power factor (UPF) operation, thereby providing an integrated solution for improved power quality and reliable microgrid performance. A supervisory control (SC) is devised to operate the FMG seamlessly under islanded modes depending on the availability of power sources. To achieve the above-mentioned objectives, a power-optimized Dual Power-based Instantaneous Power Theory (DP_IPT) is employed and it involves a Sequential Delay Signal Cancellation (SDSC)-based Phase-Locked Loop (PLL) for the effective extraction of sequence components, so as to address the unbalance and nonlinearities in an effective manner with reduced oscillations. The proposed control strategy reduces diesel generator utilization through the effective integration of Solar PV and battery support during anchoring operation. The integration of renewable energy sources substantially enhances clean energy utilization, resulting in the reduction of overall carbon emissions, accounting for a near-40% decrease in emissions compared with the conventional diesel generator (DG)-based operating mode. The proposed FMG and control framework are validated through the Hardware-in-the-Loop (HiL) approach employing an OPAL-RT (OP4512) real-time controller. The HiL investigations demonstrate the efficacious working of the proposed control in achieving less carbonized and enhanced power quality operation for next-generation electrified hybrid maritime microgrids.

Keywords: ferry microgrid; marine electrification; power quality; power transfer

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1. Introduction

1.1. Marine Electrification

From a global view, marine transportation is undergoing a significant transformation towards decarbonization and sustainability due to stringent environmental regulations and greenhouse gas (GHG) emissions. Conventional marine vessels predominantly rely on diesel-powered propulsion systems, which contribute heavily to atmospheric pollution, fuel dependency, acoustic noise, and increased operational and maintenance costs [1]. The International Maritime Organization (IMO) has also imposed strict emission reduction targets and energy-efficiency regulations, compelling the maritime sector to adopt cleaner and energy-efficient alternatives [2]. Consequently, electrified and hybrid marine vehicles integrating renewable energy resources and advanced energy storage technologies have emerged as promising solutions for next-generation sustainable marine transportation [3–5].

Hybrid marine vessels generally incorporate renewable energy sources, such as Solar Photovoltaic (PV) systems, battery energy storage systems (BESS) and fuel cells, along with diesel generators (DGs) to achieve improved energy utilization and reduced environmental impact. Among these, Solar PV systems offer a clean and abundant energy source, while BESS provides reliable energy backup, peak shaving capability, transient load support, and enhanced operational flexibility [6]. Diesel generators continue to serve as auxiliary or backup sources to ensure uninterrupted operation during dynamic marine conditions. In this work, a Roll-on/Roll-off (Ro-Ro) ferry is considered as the test platform, incorporating diesel generators (DGs), a Solar Photovoltaic (PV) system, and battery energy storage units for onboard power generation and energy management.

1.2. Challenges in Islanded Marine Electrification

The electrification of modern marine vessels has been significantly advanced through the incorporation of renewable energy sources, leading to the development of hybrid AC/DC microgrid structures capable of supplying both AC and DC onboard loads simultaneously. These loads typically include propulsion systems, pumps, compressors, auxiliary utility equipment, electronic devices, and communication systems [7]. Hybrid AC/DC configurations provide improved flexibility for integrating diverse power sources and loads with reduced power conversion stages and minimized conversion losses. In addition, such architectures facilitate efficient bidirectional power transfer between AC and DC subgrids through interlinking converters, thereby enhancing system stability and operational efficiency [8,9].

Despite these advantages, hybrid marine microgrids encounter several technical challenges: fluctuating renewable generation might introduce loss of stability during any switchover of modes of operation in the marine microgrid system. Also, the various loads in the marine microgrid system are responsible for the loss of power quality in the microgrid and produce unbalanced voltages and distorted currents at the point of common connectivity and may also introduce other power quality disturbances [10]. The dynamic propulsion loads introduce different loading effects on the power sources and the associated interlinking converter during varying sea conditions [11]. Hence, the development of optimized and less complex energy management and control frameworks capable of ensuring reliable power transfer, improved power quality, and enhanced renewable energy utilization remains a major research focus in modern electrified marine transportation systems.

1.3. State of the Art

The increase in the penetration of renewables has improved the development of microgrids so they behave as localized power systems capable of both grid-connected and islanded modes of operations. With sophisticated energy management systems, factors such as reliability, power quality, etc., are improved and they have become an integral part of modern smart grids. In parallel, ship- or marine-based microgrids have emerged as a promising solution for maritime electrification and intend to behave the same way as that of regular or land-based microgrids. They operate autonomously under highly dynamic sea state conditions characterized by varying propulsion loads, nonlinear onboard loads, and limited generation capacity. Recent developments in shore-to-ship power transfer (cold ironing) have further highlighted the importance of interconnecting land-based and ship-based microgrids. The benefits of marine microgrids have accelerated research interest among researchers and many findings are recorded on enhanced energy diversification, operational reliability, effective power management controls, new control frameworks for interlinking converter, advanced topology for interlinking converter, improvement of power quality of marine microgrid, etc. Addressing most of these challenges under one unified framework is a challenging one and is not widely reported on.

A marine microgrid integrating multiple renewable sources, such as wind turbines, Solar PV, and sea-wave energy systems [12], suffers from modeling creating frequency instability and dynamic uncertainty in the marine microgrid environment. To counteract the stability issues, storage technologies are added to the marine microgrid [13] but it may suffer from charging and discharging issues, as many sources are involved rather than one main storage unit. An integrated shipboard microgrid model consisting of photovoltaic systems, hydrogen fuel cells, diesel generators, thermal storage, and battery energy storage is reported in [14], indicating the need for coordinated energy management, making it highly challenging. With multiple renewables involved in marine microgrids, frequency and voltage stability impose serious oscillatory behavioral issues leading to unstable transient responses [15,16].

A coordinated power management framework for shipboard microgrids integrating batteries, supercapacitors, diesel generators, and renewable sources is discussed in [17], which imposes a need for fast energy balancing and optimal power sharing among multiple energy sources. An optimized shipboard power management scheme considering photovoltaic uncertainty and integrated energy resources such as fuel cells, thermal storage, and batteries suffers from multi-energy coordination, uncertain renewable generation, and the need for real-time optimization to maintain reliable and economical ship operation. In this work, optimally, only Solar PV and battery-based energy storage are coupled to avoid issues with multiple power sources and to exert simple power management control.

The interlinking converter plays a crucial role in all marine microgrids and several controllers are proposed in the literature to exert power transfer, reduce oscillations, etc. A decoupler-based feedback controller for the interlinking converter proposed in [18] reduces d-q axis coupling effects in hybrid AC/DC microgrids. To improve the dynamic response and to enhance the voltage regulation, a modified Tilt-Integral Active Disturbance Rejection Controller (TI-ADRC) is proposed in [19] with minimal interaction between active and reactive powers. A Time-Varying Derivative Fractional Order PID (TVD-FOPID) controller for shipboard microgrids is proposed to improve frequency stability and overall power quality under renewable energy integration [20]. A hybrid compensation strategy for improving reactive power management and overall efficiency in marine supply vessel microgrids is discussed in [21] but it mainly addresses power quality problems caused by inductive propulsion loads. The hierarchical control framework proposed in [22] focuses on coordinated power sharing, voltage restoration, and frequency stabili-

zation in hybrid AC/DC shipboard microgrids through droop and sliding-mode-based secondary control. However, the work primarily emphasizes system-level energy management and stability enhancement, while detailed compensation of nonlinear loads, harmonic mitigation, and power-quality-oriented interlinking converter control remain limited. Also, to counteract the oscillations that exist in the dynamic responses of the marine microgrids, several Phase-Locked Loop (PLL) structures are proposed in the literature. The conventional Synchronous Reference Frame (SRF) PLL is widely used but performs well during any balanced state. The other PLLs, such as the Moving Average Filter (MAF) PLL, work well by holding the previous instant and the average of all windows taken for consideration. To overcome issues with unbalanced systems and adjustable filtering, generalized integrators are proposed [23] but work by considering quadrature components. During any imbalances, the effect of harmonics also needs to be captured by the PLLs so that the control scheme works well and mitigates the power quality issues that arise due to harmonics. The cascaded delayed signal cancellation (CDSC) PLL accumulates the order of harmonics and cancels out the most significant one, thereby reducing the THD well in unbalanced or nonlinear systems [24]. In this work, Sequential DSC PLL is employed for extraction of sequence components and for better reduction in harmonics.

The operation of marine-based microgrids is more prone to power quality issues owing to highly dynamic sea state conditions and has driven the work reported towards the addressal of the same with a unified framework which is not widely reported in the literature. In this work, an electrified hybrid ferry microgrid (FMG) embedded on a Ro-Ro ferry that sails on the Gulf of Cambay is presumed. The FMG architecture integrates diesel generators (DGs), Solar Photovoltaic (PV) systems, and battery storage through a hybrid AC/DC microgrid structure interconnected by a bidirectional interlinking converter (ILC). The ferry Bhavnagar is considered under varying sea states including calm, moderate, and turbulent conditions so as to investigate the dynamic power-sharing capability and power quality performance of the system. The proposed FMG encompasses nonlinear propulsion loads, thermal loads, communication loads, and constant service loads that significantly influence the dynamic behavior and power quality of the onboard microgrid. To address these challenges, a power-optimized Dual Power-based Instantaneous Power Theory (DP-IPT) is exerted on the ILC for coordinated power transfer between AC and DC microgrids while simultaneously mitigating power quality issues and maintaining uninterrupted power supply for loads. The DP-IPT-based control enables reduction in harmonics, maintains balanced sinusoidal currents at the point of common connectivity, unity power factor operation, and uninterrupted bidirectional power transfer under fluctuating load and renewable operating conditions. Also, it involves the computation of two different powers simultaneously and hence reduces the computational effort as compared to other conventional strategies. In addition, a supervisory control (SC) based power balance scheme is developed to coordinate the operation of DGs, Solar PV, and battery systems according to load demand and source availability. The SC ensures seamless operation under all voyage conditions by maximizing renewable energy utilization and minimizing dependence on diesel generation, thereby reducing the carbon footprint of the FMG. The overall framework is validated under dynamic operating scenarios to analyze the stability, power balance, and control responsiveness of the proposed marine microgrid architecture. The research gap that exists in the state of the art literature, along with the merits of the proposed work, is illustrated in Figure 1. The review was conducted by collating articles of similar work on both terrestrial and marine microgrids. They were analyzed for various heads as mentioned in Figure 1 (gray colored shape) and how the proposed system would address the same has been worked out and listed in the same figure (green colored shape).

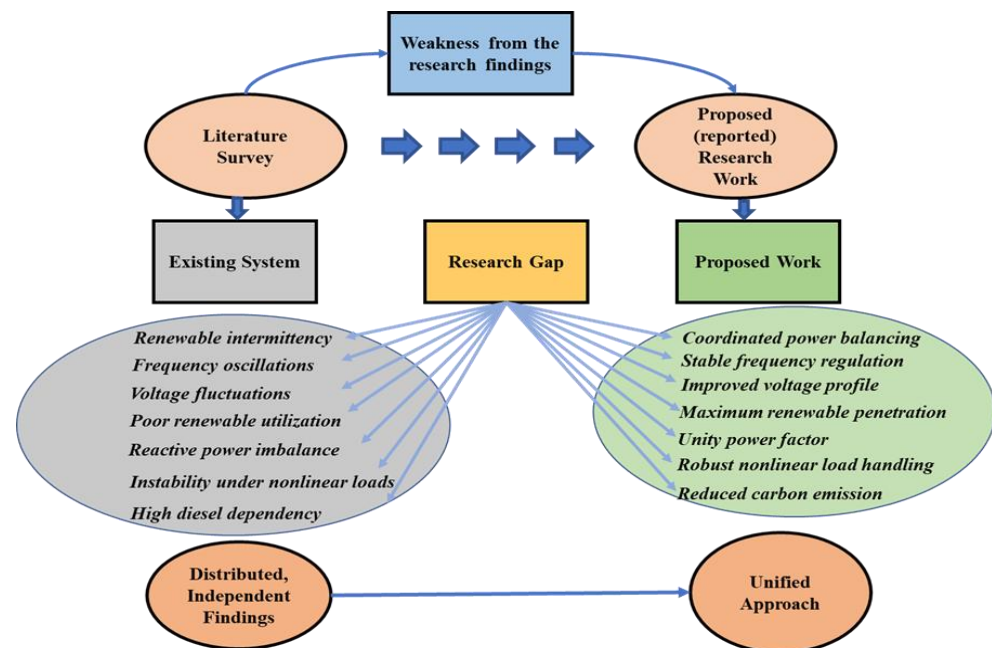


Figure 1. Comparative analysis of existing and proposed work.

The significant contributions of the work presented in this paper are summarized as follows:

- Design and development of a hybrid AC/DC electrified ferry microgrid (FMG) architecture integrating DGs, Solar PV, and battery systems for sustainable marine transportation in the Gulf of Cambay.
- Implementation of a single, bidirectional, three-phase, PWM-based voltage source interlinking converter (ILC) operated using power-optimized Dual Power-based Instantaneous Power Theory (DP-IPT) for coordinated power transfer between AC and DC microgrids.
- Achievement of multiple power quality enhancement objectives including load compensation at the Point of Common Connection (PoC), reduction in current Total Harmonic Distortion (THD), restoration of balanced sinusoidal waveforms, uninterrupted power transfer, and unity power factor (UPF) operation through a single ILC operated using a unified framework—DP_IPT.
- Development of a supervisory control (SC) for optimal coordination of renewable sources, battery systems, and DGs under varying sea states and voyage operating conditions.
- The entire FMG is implemented and validated through a Hardware-in-Loop (HiL) approach. Investigations on the performance under calm, moderate, and turbulent sea conditions are exerted considering dynamic, unbalanced and nonlinear loads. Enhancement of renewable energy utilization and reduction in DG dependency is also validated along with the computation of a reduced carbon footprint during maritime transportation.

The remainder of the paper is organized as follows: Section 2 discusses the overall framework and architecture of the proposed electrified hybrid ferry microgrid (FMG) for islanded marine applications. Section 3 describes the proposed power-optimized Dual Power-based Instantaneous Power Theory (DP-IPT) control scheme developed for the interlinking converter (ILC) along with the supervisory control strategy. Section 4 presents the real-time Hardware-in-the-Loop (HiL) investigations carried out using the OPAL-RT platform to validate the effectiveness of the proposed control framework under practical operating scenarios. Conclusions are presented in Section 5.

2. Electrified Hybrid Marine Vehicle Framework

The electrified hybrid marine vehicle presumed for study encompasses power sources—diesel generators (DGs), Solar PV, battery, and loads—propellor (dynamic, non-linear), service, communication and thermal loads. The overall hybrid marine vehicle is termed a marine ferry microgrid (FMG) and the system framework is given in Figure 2.

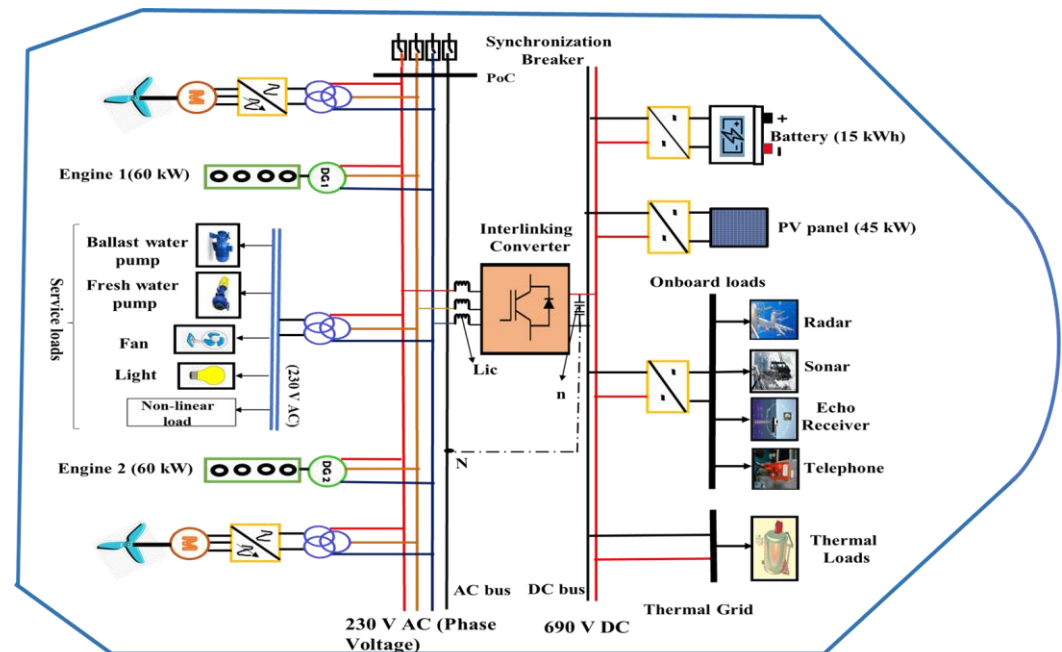


Figure 2. Overall system framework of electrified hybrid marine ferry microgrid (FMG).

The presumed ferry microgrid (FMG) is based on a Roll-on/Roll-off (Ro-Ro) ferry designed for the transportation of passengers and cargo between Hazira in Surat and Bhavnagar across the Gulf of Cambay, as illustrated in Figure 3. The vessel covers an approximate distance of 90 km with a total voyage duration of nearly 4 h. Furthermore, the proposed study evaluates the FMG operation under varying sea-state conditions in order to examine the system power balance and operational performance under dynamic maritime environments.



Figure 3. Route map for the marine vehicle.

The electrified hybrid FMG architecture consists of AC and DC microgrids, behold-ing 230 V, 50 Hz and 690 V respectively and they integrate the power sources and loads through an interlinking converter (ILC) operated with power-optimized, Dual Power-based Instantaneous Power Theory (DP-IPT) for coordinated power transfer and power quality enhancement. The diesel generator acts as the primary energy source and supports the FMG especially during high-load operating conditions, while the Solar PV and battery

units support renewable energy utilization and aid in the reduction of carbon footprint. The loads that are connected at the Point of Common Connection (PoC) on the FMG are mainly the nonlinear loads—propulsion loads, other motor loads such as ballast and fresh water pumps, constant loads—fans, lights, etc., thermal and communication loads. A detailed system specification is given under Appendix A. and the entire system is modeled in detail [25–30].

During different sea states, the loads in FMG intend to introduce harmonic distortion, voltage unbalance, and current distortions, which significantly degrade the power quality of the islanded FMG. Since the system operates without support from a stiff utility grid, maintaining stable voltage and frequency becomes a challenging task. To enable effective power exchange and to enhance the power quality in the FMG, the ILC, which is a three-phase, single-module, bidirectional, pulse-width-modulated (PWM) voltage source converter (VSC) is operated between the AC and DC microgrids using the DP_IPT. The prime contributions of the DP_IPT-operated ILC are (i) load compensation at PoC, (ii) reduction in Total Harmonic Distortion (THD), (iii) uninterrupted power supply through the bidirectional power transfer capability of ILC, (iv) balanced sinusoids at the PoC and (v) unity power factor (UPF) operation.

Depending on load demand and availability of power sources, a supervisory control (SC) is exerted along with DP_IPT to coordinate the power balance in the system by optimally operating the resources and to avoid any system shutdown. Furthermore, priority is given to maximizing the utilization of renewable energy sources in order to minimize the overall carbon footprint, and the corresponding validation results are presented in Appendix B.

3. Dual Power-Based Control Scheme for ILC

3.1. Sea States and Wave Characteristics

The power sources of FMG collectively supply the loads during cruise mode of operation. The vessel voyage duration is approximately 3 h and 20 min with the vessel making a round trip for about 4 h. Depending on the sea state, the loading on FMG (high/low loading) is presumed. The sea states are segregated as calm, moderate and turbulent with reference to the Beaufort scale [28] and the presumed marine location. The overall sea states range from state 0 to 5, with calm state (state: 0 and 1), moderate state (state: 2 and 3) and turbulent state (state: 4 and 5) having minimal to extreme wave gusts. The characteristics of the sea states for the presumed marine location are depicted in Table 1.

Table 1. Sea state details.

Sea State (Beaufort No.)	Wave Height (m)	Wind Speed (m/s)	Characteristics
0	0	0.77	Calm
1	0 to 0.1	2.57	
2	0.1 to 0.5	4.37	
3	0.5 to 1	6.94	
4	1.25 to 2.5	9.77	Moderate
5	2.5 to 3	12.60	
6	3.25 to 5	19.29	Turbulent

The variation in the vessel's submergence depth is modeled by incorporating wave-induced motion through superimposition of the same. Assuming the availability of onboard motion sensors and real-time weather forecasting data in FMG, different sea states are defined as outlined in Table 1. To realistically capture ocean conditions, irregu-

lar waves are generated by combining a regular wave with multiple harmonic components ($h = 200$), resulting in a more representative sea surface profile. The mathematical representation of regular and irregular waves is provided in Equations (1) and (2), respectively, and the corresponding wave profiles are illustrated in Figure 4.

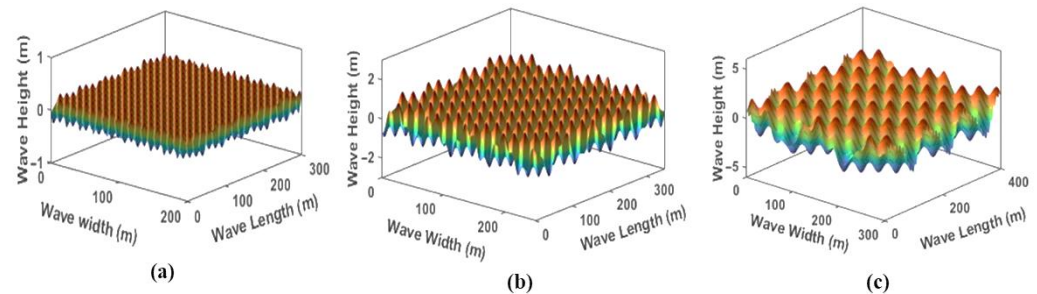


Figure 4. Structure of the wave during different sea states: (a) calm, (b) moderate, (c) turbulent.

During a calm sea state, the nature of the sea remains in either state 0 or 1 and appears to be smooth with negligible wind activity and no visible wave formation. As wind speed gradually increases to sea states 2 and 3, minor surface disturbances emerge in the form of small ripples. With further increase to sea states 4 and 5, wave heights develop significantly. This classification is used for navigation or any maritime operations so as to evaluate the sea conditions and ensure navigational safety.

The motion of the FMG is analyzed with respect to its center of gravity, considering six degrees of freedom: translational motions (surge, sway, and heave) and rotational motions (roll, pitch, and yaw). The direction of wave incidence also plays a crucial role in retrieving the wave pattern from the wave model Equations (1) and (2). The various wave patterns influenced by environmental conditions such as wind, ocean currents, and vessel interaction are depicted in Figure 4. These include regular waves (calm state) with uniform crests and troughs, progressive waves (moderate state) exhibiting continuous propagation, and irregular waves (turbulent state) characterized by complex and random interference patterns.

$$W(x, y, t) = W_m \sin(\omega t + \delta - \lambda x \cos(\chi) - \lambda y \sin(\chi)) \quad (1)$$

$$W(x, y, t) = \sum_{i=1}^h [W_m(i) \sin(\omega(i)t + \delta(i) - \lambda(i)x \cos(\chi(i)) - \lambda(i)y \sin(\chi(i)))] \quad (2)$$

3.2. Supervisory Control Based Power Balance Methodology

An overall supervisory control (SC) for the FMG during the cruise mode is framed so as to maintain a proper power balance among all the available power sources. The vessel initially operates in cruising mode for nearly 8 min before transitioning into the docking phase as it approaches the port, which lasts approximately 7 min. After successful berthing, the ship remains stationed at the port for around 5 min. The departure process begins roughly 20 min after the commencement of the operational sequence, following which the vessel undergoes another maneuvering interval of about 7 min before resuming normal cruising operation. In total, the maneuvering activities associated with port entry and exit account for nearly 17 min of operation. Based on the corresponding onboard power demand, voyage duration, and the complete round-trip travel time of approximately 4 h, the daily operational pattern of the vessel is illustrated in Figure 5. When the cruise mode is turned ON, the SC enters into monitoring operation and continuously monitors the diesel generator power (P_{dg}), photovoltaic generation (P_{pv}), battery power (P_{batt}), battery state of charge (SoC) and total load demand (P_{load}). Based on these monitored parameters, SC identifies the operational state of the vessel and accordingly deter-

mines the appropriate power-sharing configuration among the available energy sources. If the SC (user) intends to put the FMG in anchoring mode in midway, then, depending on availability, the modes are exerted. If the P_{pv} is available, then the Solar PV supplements the DG in delivering the power to loads. During deficit, the DG takes on full hold to supply the loads. If the SC (user) intends to sail, then the SC operates the FMG in sailing mode and the available load demand is identified. During calm or moderate sea state, a low loading condition is exerted with $50\% \text{ of } P_{load_rated} < P_{load} < 75\% \text{ of } P_{load_rated}$ condition and during a turbulent state, a high loading condition is exerted with $P_{load} > 75\% \text{ of } P_{load_rated}$. The power balance conditions during the various operational modes of FMG in cruise mode is shown in Table 2 and the same is depicted as a flowchart in Figure 6a,b.

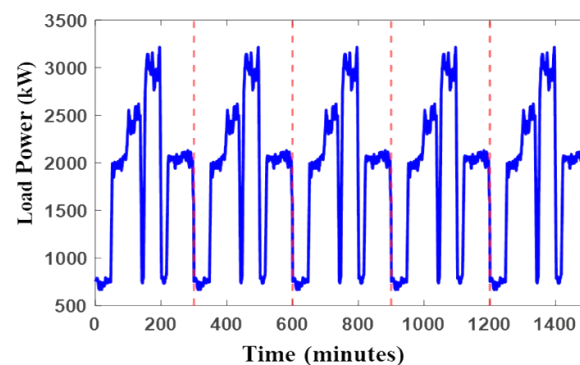


Figure 5. Operational profile per day voyage.

Table 2. Operational modes of FMG—cruise mode.

Mode	P_{dg}	P_{pv}	P_{batt}	SoC Status	P_{load}	Power Balance
Sailing	Idle mode	Surplus	Charging	$SoC_{min} < SoC < SoC_{max}$	50% of P_{load_rated}	$P_{pv} = P_{batt} + P_{load}$ $P_{dg} = 0$
	Power mode	Deficit	Charging	$SoC < SoC_{min}$	75% of P_{load_rated}	$P_{dg} + \Delta P_{pv} = P_{batt} + P_{load}$
	Power mode	Not available	Charging	$SoC < SoC_{min}$	75% of P_{load_rated}	$P_{dg} = P_{batt} + P_{load}$ $P_{pv} = 0$
	Power mode	Surplus	Discharging	$SoC > SoC_{max}$	75% of P_{load_rated}	$\Delta P_{dg} + P_{pv} + P_{batt} = P_{load}$
	Power mode	Deficit	Discharging	$SoC > SoC_{max}$	75% of P_{load_rated}	$P_{dg} + \Delta P_{pv} + P_{batt} = P_{load}$
	Power mode	Surplus	Charging	$SoC_{min} < SoC < SoC_{max}$	P_{load_rated}	$\Delta P_{dg} + P_{pv} = P_{batt} + P_{load}$
	Power mode	Deficit	Charging	$SoC < SoC_{min}$	P_{load_rated}	$\Delta P_{dg} + \Delta P_{pv} = P_{batt} + P_{load}$
	Power mode	Not available	Charging	$SoC < SoC_{min}$	P_{load_rated}	$P_{dg} = P_{batt} + P_{load}$ $P_{pv} = 0$
	Power mode	Surplus	Discharging	$SoC > SoC_{max}$	P_{load_rated}	$\Delta P_{dg} + P_{pv} + P_{batt} = P_{load}$
	Power mode	Deficit	Discharging	$SoC > SoC_{max}$	P_{load_rated}	$P_{dg} + \Delta P_{pv} + P_{batt} = P_{load}$
Anchoring	Power mode	Surplus	Charging	$SoC_{min} < SoC < SoC_{max}$	P_{load_rated}	$\Delta P_{dg} + P_{pv} = P_{batt} + P_{load}$
	Power mode	Not available	Charging	$SoC < SoC_{min}$	P_{load_rated}	$P_{dg} = P_{batt} + P_{load}$ $P_{pv} = 0$

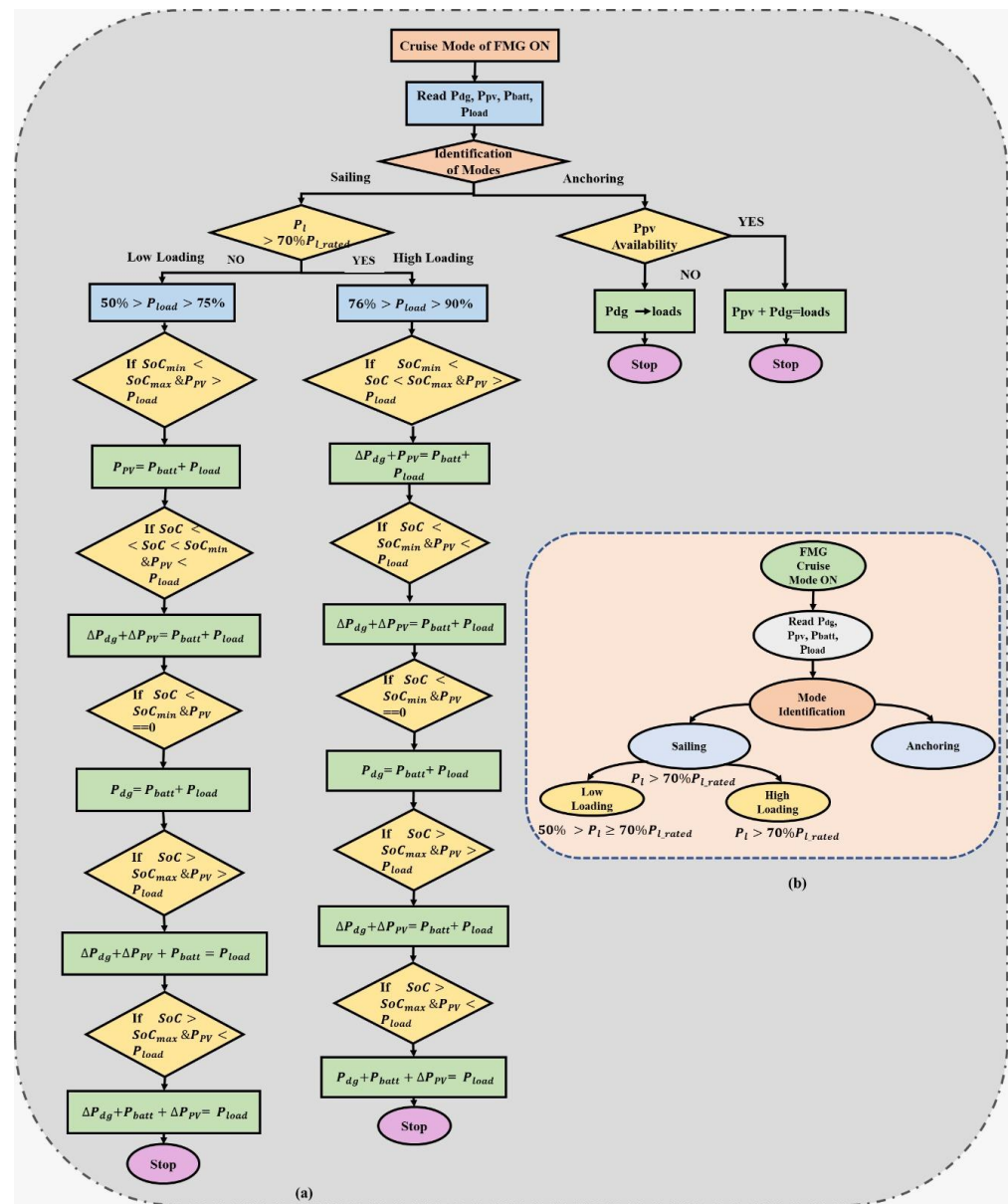


Figure 6. (a) Flowchart for SC; (b) state transition between the operational modes of the vessel.

3.3. Dual Power-Based Control Scheme

The proposed interlinking converter (IC) employing the Dual Power-based Instantaneous Power Theory (DP-IPT) control strategy is designed to enhance the operational stability and power quality performance of the islanded ferry microgrid. The controller effectively mitigates disturbances caused by nonlinear and unbalanced loads at the Point of Common Connection (PoC) and addresses the harmonic distortions by processing the three-phase voltages, currents, and instantaneous power components.

The major objectives of the proposed control strategy are summarized as follows:

- Compensation of nonlinear and unbalanced load currents at the PoC;
- Reduction in current Total Harmonic Distortion (THD) at the AC bus;
- Facilitation of bidirectional power transfer between the AC and DC buses;
- Maintenance of balanced sinusoidal source currents;
- Achievement of unity power factor (UPF) operation within the ferry microgrid.

The conventional Instantaneous Power Theory (IPT) is widely adopted for power quality compensation in three-phase systems owing to its simple mathematical structure and fast dynamic response. The method decomposes the instantaneous active and reactive

power components and compensates only the undesired oscillatory components of the load current. However, the conventional IPT exhibits limitations when applied to practical marine microgrid environments containing severe harmonic distortion, nonlinear loads, and unbalanced operating conditions. Under distorted voltage conditions, the instantaneous power decomposition becomes inaccurate, leading to improper reference current generation and reduced compensation performance. As a result, harmonic mitigation and reactive power compensation become less effective under dynamically varying operating conditions. Furthermore, the conventional IPT cannot effectively distinguish between source-side and load-side harmonic components, which may result in unnecessary compensation effort and increased converter switching stress. To overcome the limitations associated with conventional Instantaneous Power Theory (IPT), an enhanced Dual Power-based control strategy is proposed in this work. Unlike the conventional approach, the proposed method heightens the use of two/dual powers (positive sequence source and load powers) to produce positive sequence reference powers for the interlinking converter to be processed for reference current generation. As the powers that are deployed in this control scheme is completely a positive sequence extracted component, the control scheme is termed as power-optimized approach. Also, the use of filters, as in conventional schemes, to extract the average component of powers so as to achieve power quality is averted. The proposed method utilizes the three-phase AC voltage signals together with the phase AC currents at PoC and the load currents to derive optimized dual-power quantities for generating the reference currents of the interlinking converter. The three-phase parameters [voltages and currents at PoC, load current] are continuously monitored, and their fundamental positive sequence components are extracted using a Fundamental Positive Sequence Extractor (FPSE), as illustrated in Figure 7.

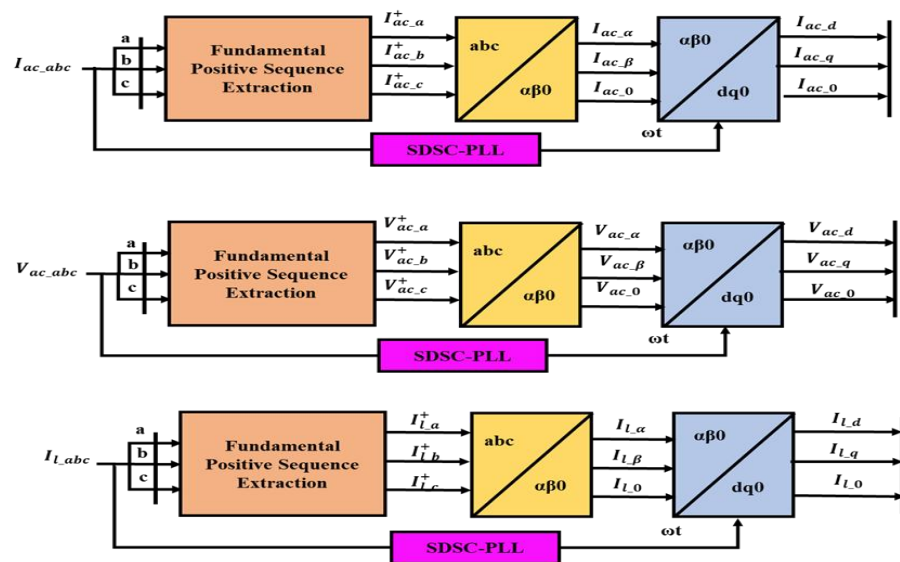


Figure 7. SDSC-PLL schematic representation.

The extracted three-phase fundamental positive sequence quantities are subsequently transformed into two-phase rotating reference frame quantities (αβ0) and further converted into orthogonal components (dq0) using the phase information of the fundamental three-phase signals. The transformation of the quantities is realized as per Equations (3a–c) and (4a–c).

$$k_0 = \frac{1}{3}(V_{ac,a} + V_{ac,b} + V_{ac,c}) \quad (3a)$$

$$\mathbf{k}_\alpha = \frac{2}{3} \cdot (\mathbf{V}_{ac_a} - \left(\frac{1}{2}\right) \cdot \mathbf{V}_{ac_b} - \left(\frac{1}{2}\right) \cdot \mathbf{V}_{ac_c}) \quad (4b)$$

$$\mathbf{k}_\beta = \frac{2}{3} \cdot \left(\left(\frac{\sqrt{3}}{2}\right) \cdot \mathbf{V}_{ac_b} - \left(\frac{\sqrt{3}}{2}\right) \cdot \mathbf{V}_{ac_c}\right) \quad (5c)$$

$$k_0 = k_0 \quad (6a)$$

$$k_d = k_\alpha \cos \theta + k_\beta \sin \theta \quad (7b)$$

$$k_q = -k_\alpha \sin \theta + k_\beta \cos \theta \quad (8c)$$

where k denotes the electrical quantities corresponding to the voltages and source/load currents of the three phases a, b, and c and $\theta = \tan^{-1}(k_\beta/k_\alpha)$. In practical ferry microgrids, the AC bus voltages are often affected by lower-order harmonics, negative-sequence components, zero-sequence distortions, and load imbalance. These disturbances significantly deteriorate the performance of conventional PLL structures, resulting in inaccurate phase estimation and degraded converter control performance. To improve synchronization accuracy under distorted and unbalanced operating conditions, an enhanced Sequential Delay Signal Cancellation Phase-Locked Loop (SDSC-PLL) is incorporated into the proposed control architecture to extract the frequency component ' ωt '.

The SDSC-PLL is employed as an advanced filtering and synchronization mechanism that introduces cascaded delayed signal cancellation stages with half-cycle symmetry characteristics, thereby eliminating selected harmonic orders without affecting the fundamental frequency component. The SDSC-PLL utilizes multiple cascaded delay operators to suppress dominant low-order harmonic components such as the 5th, 7th, 11th, and 13th harmonics, along with asymmetrical distortion components. In the proposed implementation, the delay stages are configured as ($d = 2, 4, 8, 16$ and 32 enabling effective harmonic rejection up to higher harmonic orders).

The synchronization process is executed in the synchronous (dq)-reference frame, as in Figure 8, ensuring that the positive-sequence fundamental component remains unaffected while oscillatory harmonic components are filtered out. The modeling of the SDSC-PLL involves the input signal that is delayed by a fraction of the fundamental time period according to the selected delay factor. The generalized delayed signal cancellation operation is represented in Equation (5) [29].

$$\alpha\beta \text{ DSC}_{h_n}(\mathbf{v}_{\alpha\beta}(t)) = \frac{1}{2}[\mathbf{v}_{\alpha\beta}(t) + e^{j\frac{2\pi}{h_n}} \mathbf{v}_{\alpha\beta}\left(t - \frac{T}{n}\right)] \quad (9)$$

where $\mathbf{V}_{\alpha\beta}$ denotes the orthogonal voltage components, T represents the fundamental time period, and h_n corresponds to the harmonic order targeted for cancellation. The output of the cascaded delay cancellation stages is supplied to the loop filter, which extracts the fundamental frequency component while eliminating residual oscillatory disturbances. The filtered signal is then compared with the nominal reference frequency to accurately estimate the instantaneous grid frequency and phase angle. Subsequently, the Voltage-Controlled Oscillator (VCO) reconstructs the synchronized phase information.

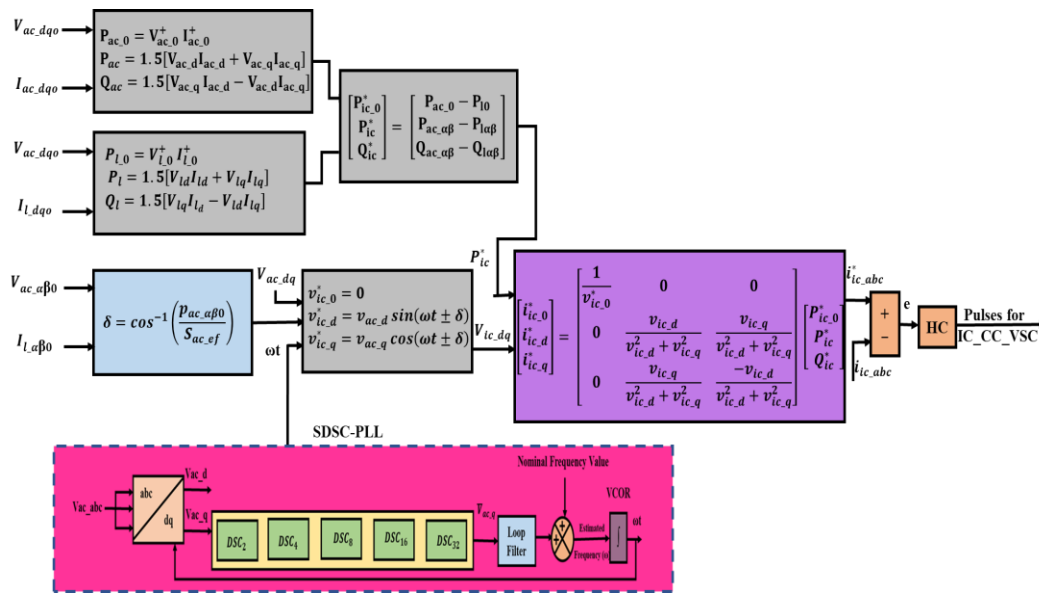


Figure 8. Dual Powerbased control methodology.

With the extracted positive sequence orthogonal voltages and currents, the dual power components are generated as in Equations (6a–c) and (7a–c).

$$P_{ac,0} = V_{ac,0}^+ I_{ac,0}^+ \quad (10a)$$

$$P_{ac} = 1.5[V_{ac,d}I_{ac,d} + V_{ac,q}I_{ac,q}] \quad (11b)$$

$$Q_{ac} = 1.5[V_{ac,q}I_{ac,d} - V_{ac,d}I_{ac,q}] \quad (12c)$$

$$P_{l,0} = V_{l,0}^+ I_{l,0}^+ \quad (13a)$$

$$P_l = 1.5[V_{ld}I_{ld} + V_{lq}I_{lq}]; \quad (14b)$$

$$Q_l = 1.5[V_{lq}I_{ld} - V_{ld}I_{lq}] \quad (15c)$$

The required interlinking converter's power, which is to be processed for achieving the objectives towards power quality, is computed with the generated dual power components as in Equation (8) [30].

$$\begin{bmatrix} P_{ic,0}^* \\ P_{ic}^* \\ Q_{ic}^* \end{bmatrix} = \begin{bmatrix} P_{ac,0} - P_{l0} \\ P_{ac,\alpha\beta} - P_{l\alpha\beta} \\ Q_{ac,\alpha\beta} - Q_{l\alpha\beta} \end{bmatrix} \quad (16)$$

where $P_{ac,0}$, $P_{ac,\alpha\beta}$, $Q_{ac,\alpha\beta}$ and P_{l0} , $P_{l\alpha\beta}$, $Q_{l\alpha\beta}$ are computed as in Equations (6) and (7). The reference currents for the interlinking converter are generated using the magnitude information obtained from the source-side orthogonal voltages, the angular frequency information derived from the Sequential Delay Signal Cancellation Phase-Locked Loop (SDSC-PLL), and the phase information obtained through the lead–lag angle (δ). These parameters collectively enable proper synchronization and facilitate the extraction of the required power from the source side. A single-phase source-side voltage signal corresponding to phase-a is supplied to the SDSC-PLL block for accurate phase-angle and frequency estimation. The per-unit input voltage signal applied to the SDSC-PLL is computed using Equation (9).

$$v_{PLL} = \frac{v_{ac,a}}{v_{ac,am}} \quad (17)$$

where $v_{ac,am}$ represents the peak source voltage of phase-a. In addition, the lead-lag angle (δ) is estimated and incorporated with the instantaneous phase information to generate the required reference currents for effective compensation and improved dynamic performance of the system. The estimation of the lead-lag angle is based on the computation of the power factor, as expressed in Equation (10). The power factor is determined as the cosine of the ratio between the total instantaneous active power and the effective apparent power at the Point of Common Connection (PoC).

$$\delta = \cos^{-1} \left(\frac{P_{ac,\alpha\beta 0}}{S_{ac,ef}} \right) \quad (18)$$

where $S_{ac,ef}$ is the apparent power given by Equation (11) with $V_{ac,ef}$ and $I_{ac,ef}$ being the corresponding effective voltages and currents as in Equations (12) and (13) respectively.

$$S_{ac,ef} = 3V_{ac,ef}I_{ac,ef} \quad (19)$$

$$V_{ac,ef} = \frac{1}{6T_{fund}} \int_{t-T_{fund}}^t \left[v_{ac,a}^2 + v_{ac,b}^2 + v_{ac,c}^2 + \frac{v_{ac,a}^2 + v_{ac,b}^2 + v_{ac,c}^2}{3} \right] dt \quad (20)$$

$$I_{ac,ef} = \frac{1}{3T_{fund}} \int_{t-T_{fund}}^t [v_{ia}^2 + v_{ib}^2 + v_{ic}^2 + v_{in}^2] dt \quad (21)$$

The leading or lagging operation of the lead-lag angle is determined based on the computed power factor condition of the system. Using the instantaneous phase information together with the estimated lead-lag angle, the desired reference source voltages for the interlinking converter are synthesized as expressed in Equation (14a–c).

$$v_{ic,0}^* = 0 \quad (22a)$$

$$v_{ic,d}^* = v_{ac,d} \sin(\omega t \pm \delta) \quad (23b)$$

$$v_{ic,q}^* = v_{ac,q} \cos(\omega t \pm \delta) \quad (24c)$$

With the desired reference source voltages and the required interlinking converter power, the reference currents are generated as in Equation (15).

$$\begin{bmatrix} i_{ic,0}^* \\ i_{ic,d}^* \\ i_{ic,q}^* \end{bmatrix} = \begin{bmatrix} \frac{1}{v_{ic,0}^*} & 0 & 0 \\ 0 & \frac{v_{ic,d}}{v_{ic,d}^2 + v_{ic,q}^2} & \frac{v_{ic,q}}{v_{ic,d}^2 + v_{ic,q}^2} \\ 0 & \frac{v_{ic,q}}{v_{ic,d}^2 + v_{ic,q}^2} & \frac{-v_{ic,d}}{v_{ic,d}^2 + v_{ic,q}^2} \end{bmatrix} \begin{bmatrix} P_{ic,0}^* \\ P_{ic}^* \\ Q_{ic}^* \end{bmatrix} \quad (25)$$

The reference currents obtained from the control algorithm are continuously compared with the measured currents of the interlinking converter. The difference between these signals is treated as the current error and is supplied to a hysteresis current controller. By maintaining a hysteresis tolerance band of ± 3 A, the controller generates the appropriate switching pulses required for the operation of the interlinking converter (ILC).

4. Real-Time Hardware-in-Loop (HiL) Investigation of FMG

The real-time Hardware-in-the-Loop (HiL) validation of FMG is carried out using the OPAL-RT (OP4512) real-time digital controller integrated with the RT-LAB environment, as illustrated in Figure 9. The photograph of the setup is shown in Figure 10. The developed hybrid marine microgrid model, including the diesel generator, photovoltaic source, battery, propulsion loads, and interlinking converter control framework, is implemented in the and deployed into the OP4512 platform through RT-LAB (Version11). The OP4512 real-time controller is equipped with a high-performance Intel Xeon multi-core processor

combined with a Xilinx Kintex-7 FPGA architecture, enabling high-speed real-time computation suitable for power electronic switching applications and fast dynamic marine microgrid studies. To set the execution parameters, use hardware-synchronized mode; to exert the HiL, use extra high performance (XHP) mode. The RT-LAB workstation acts as the supervisory interface for model compilation, parameter configuration, signal monitoring, and real-time execution of the developed microgrid model. The controller signals are exchanged between the RT-LAB workstation and the OP4512 controller via high-speed analog and digital I/O channels to ensure hardware synchronization in real-time operation. The Hardware-in-the-Loop model is executed with the OP4512 controller using a fixed-step simulation time of 500 ms to ensure deterministic real-time execution and to accurately capture converter switching dynamics, transient disturbances, and power-quality variations during islanded operation. The validated cases are captured using an MSO5104 Mixed Signal Oscilloscope to get the oscilloscopic results.

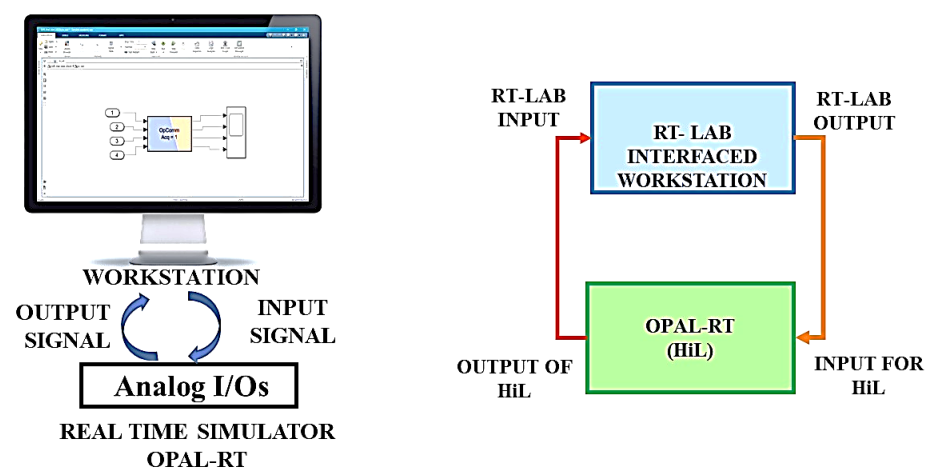


Figure 9. Realtime Hardware-in-Loop (HiL) investigation of FMG.



Figure 10. HiL testbench.

4.1. Dynamic Performance of FMG Under Sailing Mode

The electrified ferry microgrid is investigated under sailing mode for three distinct operations, each representing a specific power-sharing scenario within the hybrid AC–DC network. It is observed that the HiL responses thereby confirm the accuracy of the developed FMG and the practical feasibility of the proposed control scheme.

4.1.1. Case 1: Diesel Generator and Solar PV Supplies the Load

The dynamic performance of FMG under hybrid operating conditions wherein both the diesel generator (DG) and Solar PV system collectively supply the onboard loads, is

investigated through real-time HiL validation. A sudden load variation is introduced at time instant (t), increasing the loading level from 15% to 75%, and the corresponding responses are presented in Figure 11. The required load power is effectively shared between the diesel generator and the Solar PV source operating in coordinated mode, as in Figure 11a. Despite the abrupt load transition, the voltage at the Point of Common Connection (PoC) remains stable and regulated, demonstrating the robustness of the proposed control strategy, as shown in Figure 11b. The phase alignment between the DG voltage (phase a) and current (phase a) is depicted in Figure 11c confirming the unity power factor (UPF) operation and proper synchronization between the available power sources. Figure 11d illustrates the compensating current injected by the interlinking converter, highlighting its capability to mitigate load disturbances and maintain improved power quality at the PoC. The applied load variation profile is shown in Figure 11e. The power balance relation corresponding to this operating condition is expressed as $P_l = P_{dg} + P_{pv}$.

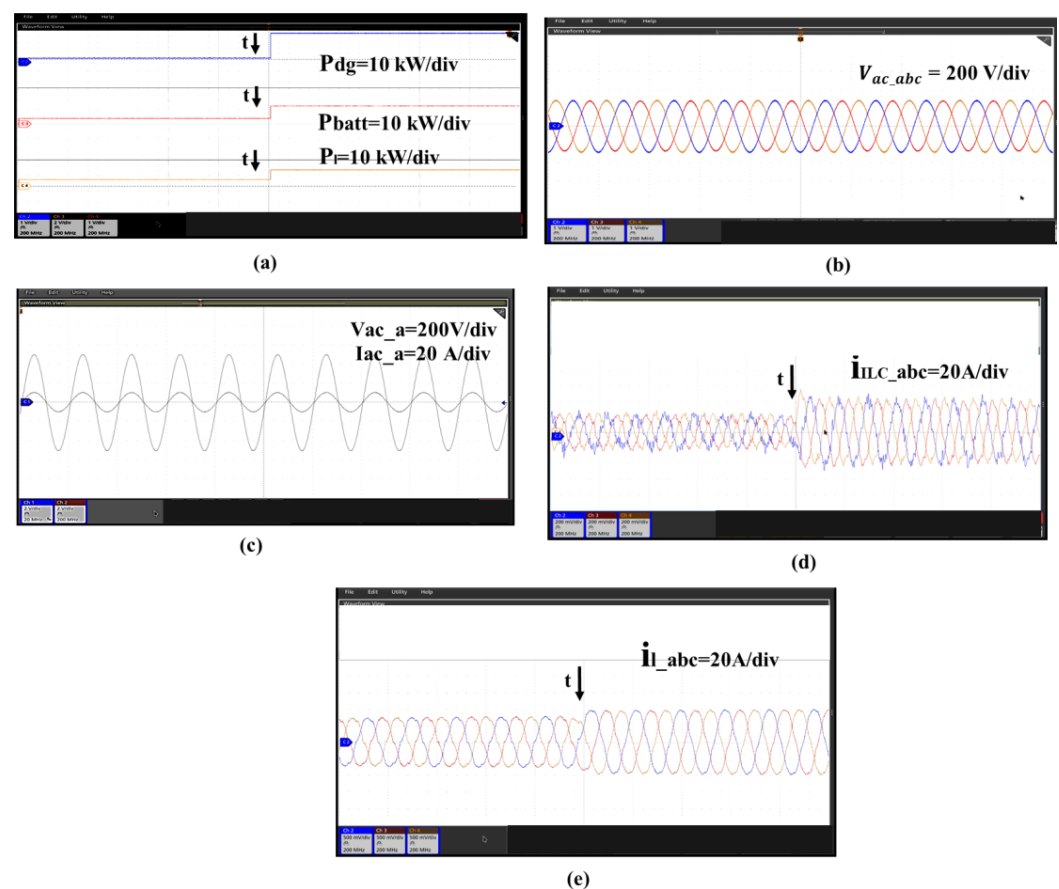


Figure 11. Dynamic performance of the FMG [Case 1] — (a) Load power sharing between the sources, (b) Voltage at PoC, (c) In phase voltage and current at PoC, (d) Compensating current injected by interlinking current, (e) Load current.

4.1.2. Case 2: Sole Supply of Diesel Generator

The case where DG alone supplies the load is validated and depicted in Figure 12. At time instant (t), the operating mode transition is initiated with the system load varying between 75% and 50%. The power-sharing characteristics during the transition are depicted in Figure 12a, satisfying the following power balance condition: $P_l = P_{dg}$. As the Solar PV contribution decreases, the diesel generator dynamically compensates for the power deficit to ensure uninterrupted load supply. The PoC voltage remains stable throughout the transition process, as shown in Figure 12b, demonstrating effective voltage regulation capability. Furthermore, the in-phase relationship between the PoC voltage

and current, as shown in Figure 12c, confirms continued UPF operation during mode transition. The compensation current supplied by the interlinking converter is presented in Figure 12d, while the corresponding load transition profile is illustrated in Figure 12e. The results validate the capability of the proposed control strategy to maintain stable operation, seamless power transfer, and enhanced power quality during dynamic operating condition changes within the islanded ferry microgrid.

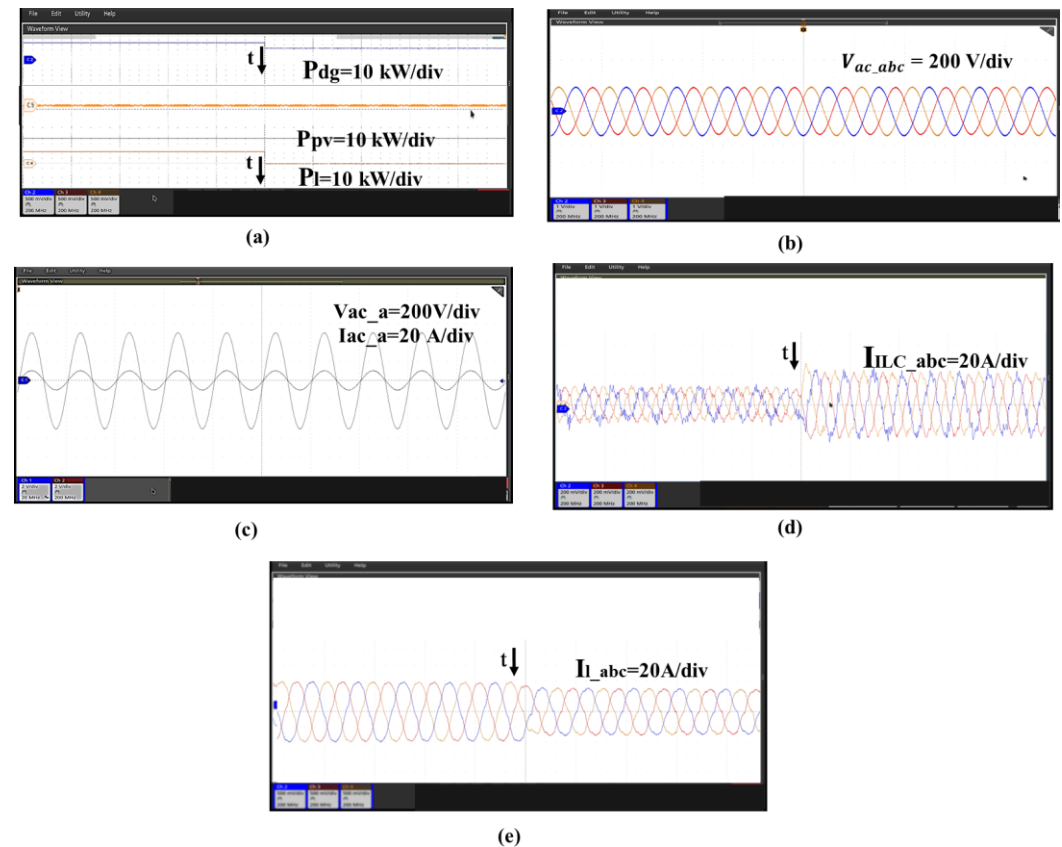


Figure 12. Dynamic performance of FMG [Case 2]—(a) Load power sharing between the sources, (b) Voltage at PoC, (c) In phase voltage and current at PoC, (d) Compensating current injected by interlinking current, (e) Load current.

4.1.3. Case 3: Diesel Generator and Battery Supply the Load

The dynamic performance of FMG under hybrid operating condition wherein both the diesel generator (DG) and battery system collectively supply the onboard loads is investigated through real-time HiL validation. A sudden load variation is introduced at time instant (t), increasing the loading level from 15% to 75%, and the corresponding responses are presented in Figure 13. The required load power is effectively shared between the diesel generator and the battery source operating in coordinated mode as in Figure 13a. Despite the abrupt load transition, the voltage at the Point of Common Connection (PoC) remains stable and regulated, demonstrating the robustness of the proposed control strategy, as shown in Figure 13b. The phase alignment between the DG voltage (phase a) and current (phase a) is depicted in Figure 13c, confirming the unity power factor (UPF) operation and proper synchronization between the available power sources. Figure 13d illustrates the compensating current injected by the interlinking converter, highlighting its capability to mitigate load disturbances and maintain improved power quality at the PoC. The applied load variation profile is shown in Figure 13e. The power balance relation corresponding to this operating condition is expressed as $P_l = P_{dg} + P_{batt}$.

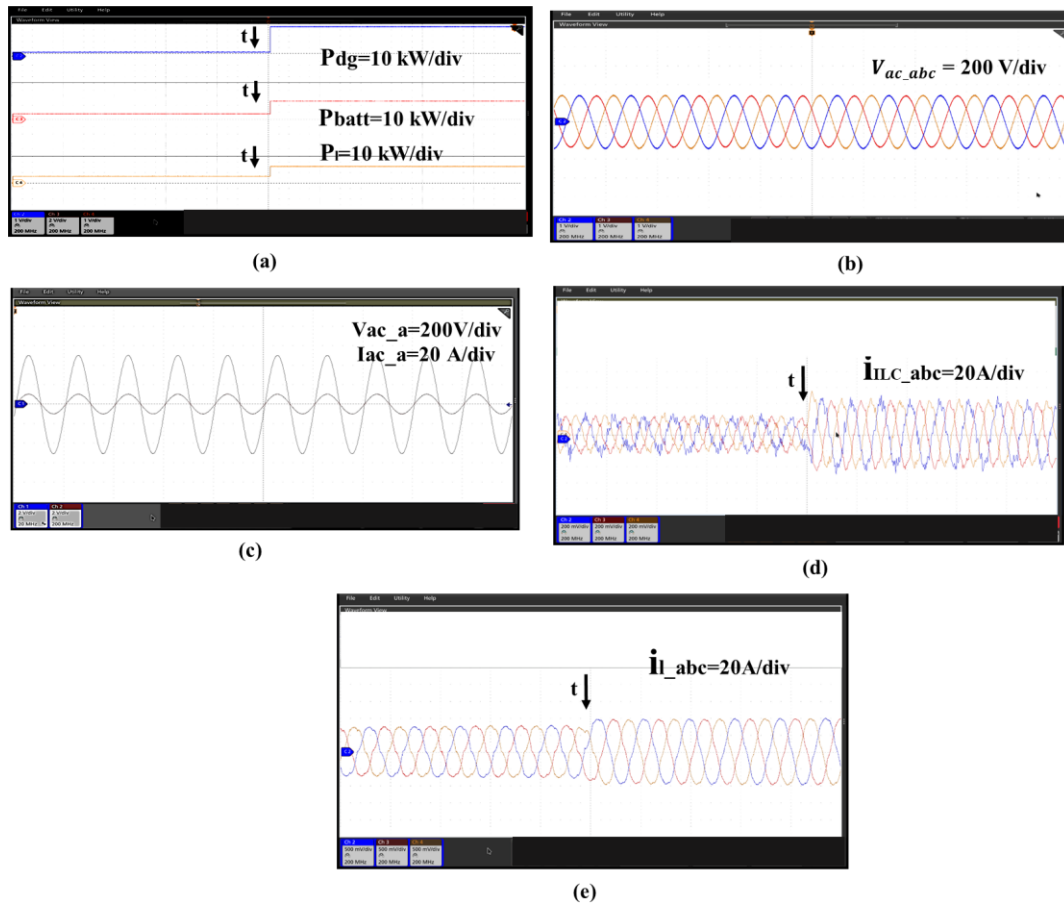


Figure 13. Dynamic performance of FMG [Case 3]—(a) Load power sharing between the sources, (b) Voltage at PoC, (c) In phase voltage and current at PoC, (d) Compensating current injected by in-terlinking current, (e) Load current.

4.1.4. Case 4: Diesel Generator, Solar PV and Battery Supplies the Load

The dynamic performance of FMG under hybrid operating condition, wherein both the diesel generator (DG), Solar PV system and battery collectively supply the onboard loads, is investigated through real-time HiL validation. A sudden load variation is introduced at time instant (t), increasing the loading level from 15% to 75%, and the corresponding responses are presented in Figure 14. The required load power is effectively shared between the diesel generator, Solar PV and the battery source operating in coordinated mode as in Figure 14a. Despite the abrupt load transition, the voltage at the Point of Common Connection (PoC) remains stable and regulated, demonstrating the robustness of the proposed control strategy, as shown in Figure 14b. The phase alignment between the DG voltage (phase a) and current (phase a) is depicted in Figure 14c, confirming the unity power factor (UPF) operation and proper synchronization between the available power sources. Figure 14d illustrates the compensating current injected by the interlinking converter, highlighting its capability to mitigate load disturbances and maintain improved power quality at the PoC. The applied load variation profile is shown in Figure 14e. The power balance relation corresponding to this operating condition is expressed as $P_l = P_{dg} + P_{pv} + P_{batt}$.

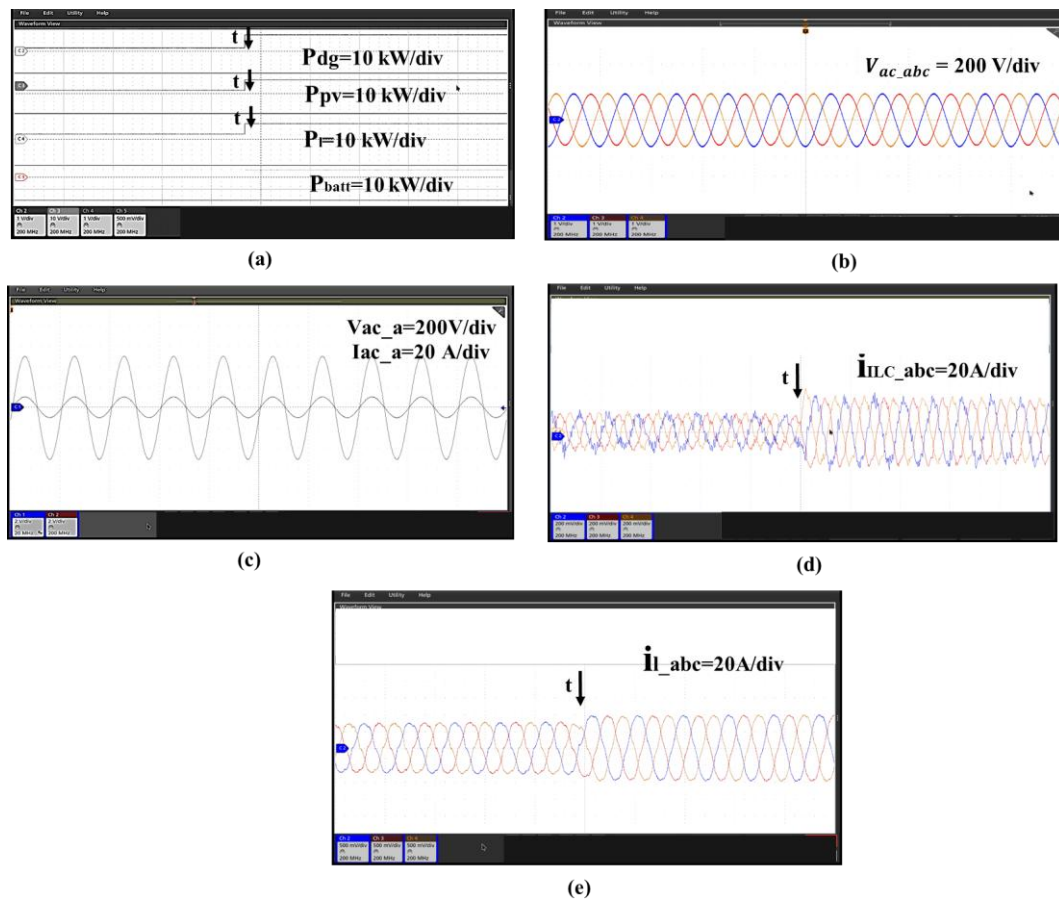


Figure 14. Dynamic performance of FMG [Case 4]—(a) Load power sharing between the sources, (b) Voltage at PoC, (c) In phase voltage and current at PoC, (d) Compensating current injected by in-linking current, (e) Load current.

4.1.5. Case 5: Diesel Generator, Solar PV Supplies the Load During Anchoring

The dynamic performance of the FMG during anchoring operation is investigated through real-time HiL validation under two major operating conditions depending on the availability of Solar PV generation. Under the PV-assisted diesel operating condition, both the diesel generator (DG) and Solar PV source collectively supply the onboard loads. The available PV power effectively supports the load demand, thereby reducing the dependency on diesel generation and minimizing carbon emissions. The corresponding power-sharing behavior between the DG and Solar PV source is illustrated in Figure 15. The corresponding power balance relation for this operating condition is expressed as $P_l = P_{dg} + P_{pv}$. During the diesel-only operating condition, which occurs at instant 't', the Solar PV source becomes unavailable and the complete load demand is supplied solely by the diesel generator, resulting in the power balance relation $P_l = P_{dg}$. These operating conditions validate the operational flexibility and adaptability of the proposed FMG under varying renewable generation conditions during anchoring mode.

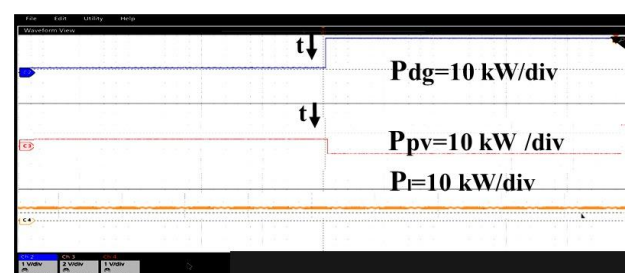


Figure 15. Dynamic performance of FMG [Case 5].

Thus, the dynamic behavior of the proposed ferry microgrid under varying loading conditions and operating mode transitions is comprehensively validated. The overall power-sharing characteristics corresponding to different operating modes are summarized in Table 3.

Table 3. Overall power balance under different operating modes.

Modes	P_{dg} (kW)	P_{pv} (kW)	P_{batt} (kW)	Power Balance	CO ₂ Mitigation
Mode 1	15	35	-	$P_{dg} + P_{pv} = \text{Load}$	219 kg CO ₂
Mode 2	50	-	-	$P_{dg} = \text{Load}$	270 kg CO ₂
Mode 3	35	-	15	$P_{dg} + P_{batt} = \text{Load}$	230 kg CO ₂
Mode 4	20	20	10	$P_{dg} + P_{pv} + P_{batt} = \text{Load}$	120 kg CO ₂
Mode 5	20	30	-	$P_{dg} + P_{pv} = \text{Load}$	108 kg CO ₂
	50	-	-	$P_{dg} = \text{Load}$	-

The obtained results demonstrate satisfactory system performance under all investigated operating conditions while emphasizing reduced dependence on conventional fossil-fuel-based generation. The coordinated integration of renewable energy sources and battery storage improves operational reliability, enhances power-sharing capability, and significantly minimizes the environmental impact of the ferry microgrid. The proposed hybrid architecture achieves considerable emission reduction and supports sustainable marine electrification under dynamic operating scenarios.

4.2. Performance Validation of Bidirectional Power Transfer Capability of the Interlinking Converter

The bidirectional power transfer capability of the ILC is validated through real-time Hardware-in-the-Loop (HiL). At instant 't', the mode of operation of the ILC is changed from rectification to inversion. Initially, the interlinking converter operates in rectification mode, enabling power transfer from the AC subsystem to the DC subsystem. At a specified time instant t, the converter operation transitions into inversion mode, wherein power is transferred from the DC bus back to the AC bus. The corresponding voltage responses of the AC and DC buses are presented in Figure 16a. It is observed that both bus voltages remain stable and well-regulated throughout the operating mode transition. The phase relationship between the Point of Common Connection (PoC) voltage (phase a) and current (phase a) clearly distinguishes the rectification and inversion modes of operation. During rectification mode, the voltage and current remain in-phase, whereas during inversion operation an out-of-phase relationship is observed, thereby confirming successful bidirectional power flow through the interlinking converter in Figure 16b.

To further validate the power-sharing capability, a consortium operating condition involving coordinated power exchange among the available sources is considered, and the corresponding power balance characteristics are depicted in Figure 16c. The obtained results indicate effective real power management and smooth transition between operational modes. Figure 16d illustrates the power quality characteristics of the system, where the power factor is maintained close to unity throughout the operation. Since the applied load remains constant, the real power demand also remains nearly constant, while the reactive power component is observed to be negligible. In addition, the lead-lag angle is maintained approximately at zero, indicating effective unity power factor operation. The interlinking converter current and load current waveforms are presented in Figure 16e and 16f, respectively. The results demonstrate stable converter operation and confirm the

proposed control strategy's ability to maintain constant load support while enabling seamless bidirectional power transfer within the islanded ferry microgrid.

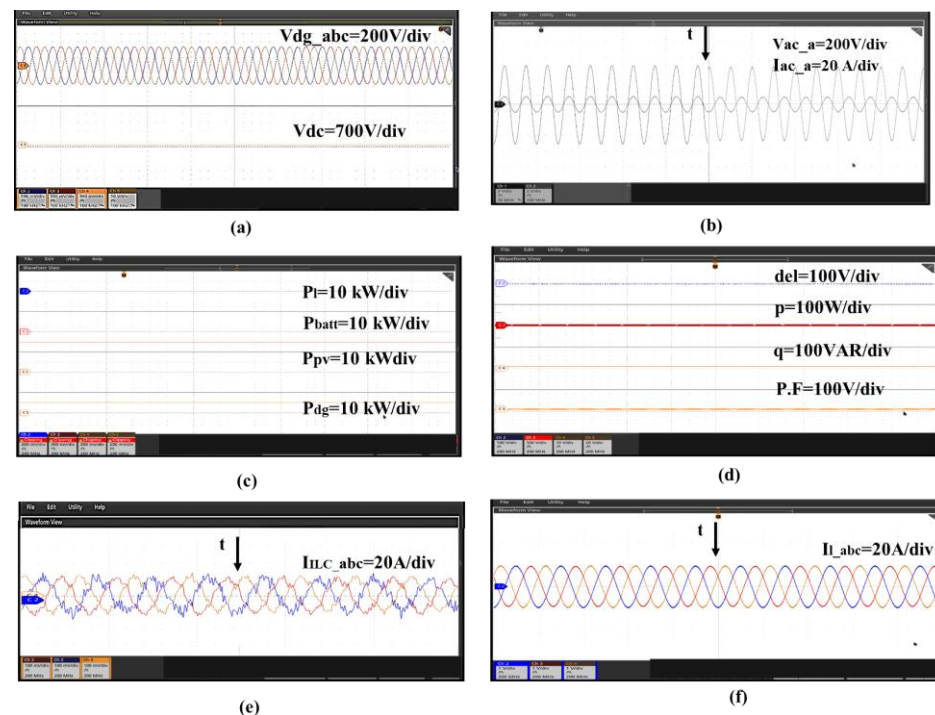


Figure 16. Bidirectional Power Transfer Capability of the Interlinking Converter—(a) Voltage and current at PoC, (b) Voltage at PoC, (c) Load power sharing between the sources, (d) power quality characteristics (e) Compensating current injected by interlinking current, (f) Load current.

4.3. Dynamic Performance of the System Under Power Quality Disturbances—Nonlinear and Unbalanced Loading Conditions

The dynamic characteristics of FMG are validated under power quality disturbances such as nonlinear loading and load unbalance conditions through a Hardware-in-the-Loop (HiL) approach. The corresponding results are presented in Figures 17 and 18, respectively. In all investigated scenarios, the proposed control strategy operates directly on the instantaneous power components of the source and load, enabling rapid dynamic response and superior power balancing capability during system disturbances and operating condition changes.

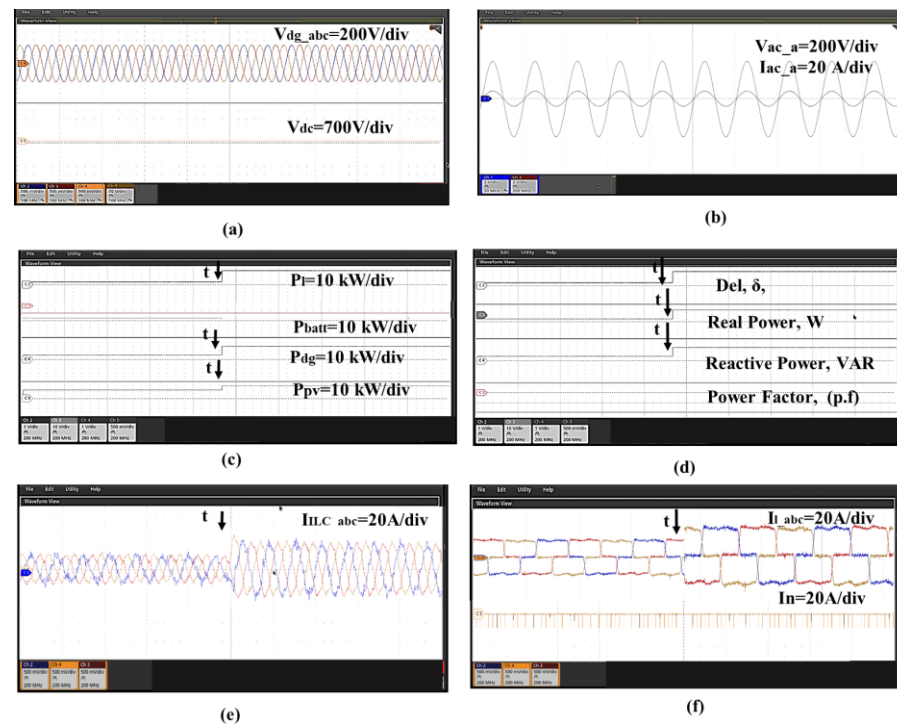


Figure 17. Performance under nonlinear loading condition—(a) Voltage and current at PoC, (b) Voltage at PoC, (c) Load power sharing between the sources, (d) power quality characteristics (e) Compensating current injected by interlinking current, (f) Load current and neutral current.

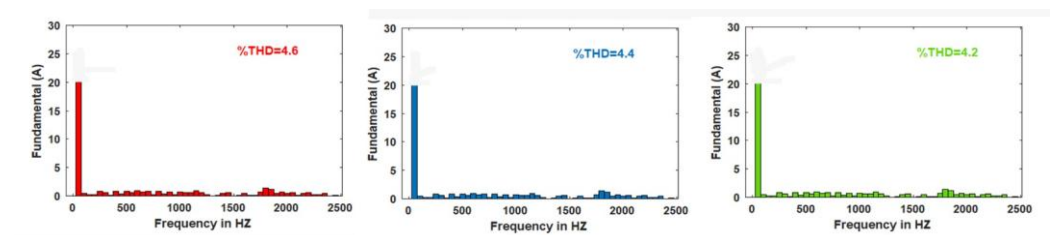


Figure 18. THD spectrum under nonlinear loading condition.

4.3.1. Case 1: Nonlinear Loading Condition

The performance of the system under nonlinear loading conditions is investigated by varying the load from 50% to 75%, and the corresponding results are shown in Figure 17. Figure 17a,b illustrate the AC bus voltages and the phase relationship between the Point of Common Connection (PoC) voltage and current (phase a). The maintained in-phase relationship confirms effective unity power factor (UPF) operation, while the regulated bus voltages demonstrate the robustness of the proposed control strategy. Despite the presence of nonlinear loads, the PoC currents remain nearly sinusoidal due to the compensation capability of the interlinking converter, thereby validating its harmonic mitigation performance. The THD spectrum of the PoC currents is depicted in Figure 18 to show that the %THD are well within the IEEE 519 std. The load transition from 50% to 75% is reflected in the power-sharing characteristics shown in Figure 17c, where coordinated consortium operation among the available power sources is achieved to satisfy the load demand. The power factor profile illustrated in Figure 17d indicates operation close to unity throughout the load variation. As the loading level changes, the real power demand correspondingly varies, while the reactive power component remains negligible. The associated variation in the lead-lag angle further confirms the adaptive nature of the proposed control methodology under dynamic load conditions. The compensating current injected by the interlinking converter is shown in Figure 17e, demonstrating its role in

suppressing harmonic distortion caused by the nonlinear loads. Figure 17f presents the nonlinear load current along with the resulting neutral current components, thereby validating the effectiveness of the proposed system in mitigating nonlinear load effects and maintaining improved power quality within the ferry microgrid.

4.3.2. Case 2: Unbalanced Load Condition

The performance of the FMG under unbalanced loading conditions is validated through both simulation and real-time Hardware-in-the-Loop (HiL) experimentation, and the corresponding waveforms are presented in Figure 19. The load currents in the three phases are intentionally maintained unequal ($I_{la} \neq I_b \neq I_c$) to emulate practical onboard unbalanced loading conditions. A load transition from 50% to 75% of the rated load is introduced at time instant t to investigate the dynamic response of the system. As illustrated in Figure 19a, both the AC and DC bus voltages remain stable and well-regulated despite the occurrence of load imbalance and sudden loading variation. The phase relationship between the Point of Common Connection (PoC) voltage and current shown in Figure 19b demonstrates in-phase operation, thereby confirming effective unity power factor (UPF) operation and proper regulation by the interlinking converter.

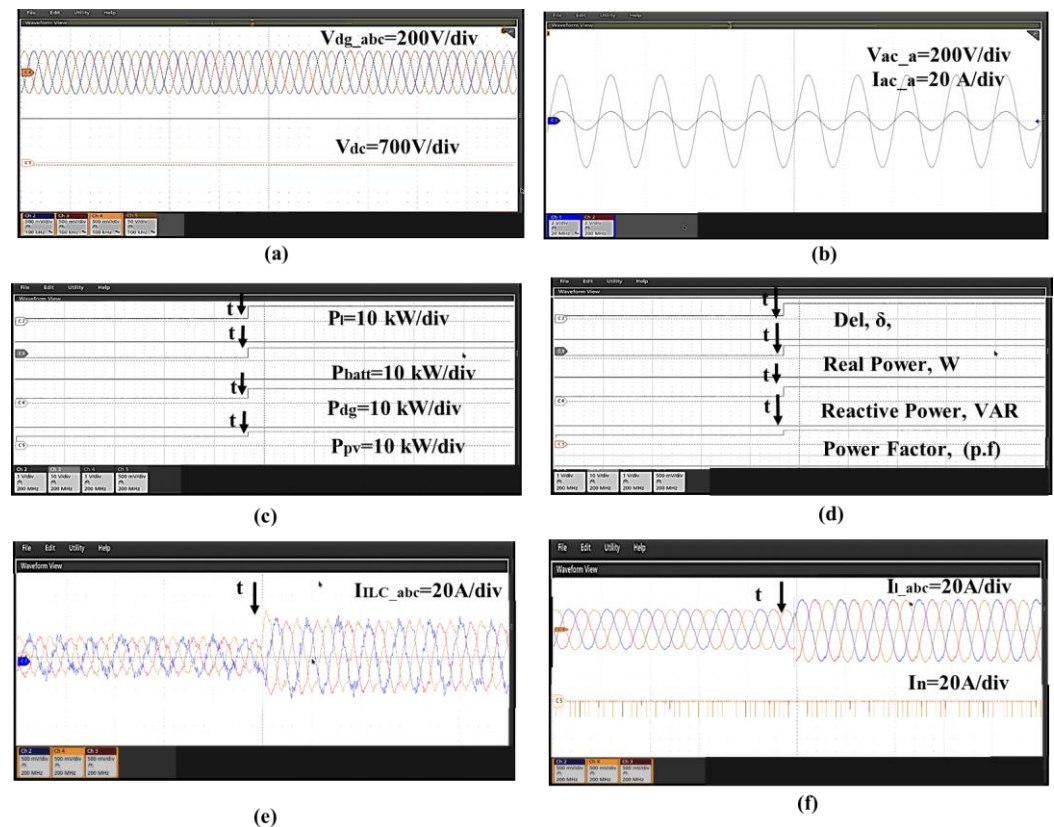


Figure 19. Performance under unbalanced load condition—(a) Voltage and current at PoC, (b) Voltage at PoC, (c) Load power sharing between the sources, (d) power quality characteristics (e) Compensating current injected by interlinking current, (f) Load current and neutral current.

The reactive power profile depicted in Figure 19c remains approximately zero throughout the operation, further validating the UPF behavior of the proposed control strategy. The corresponding power factor characteristics shown in Figure 19d indicate operation close to unity under all loading conditions. As the loading level increases, the real power demand from the source correspondingly rises, while the lead-lag angle dynamically varies to support effective modulation and power balancing within the system. This adaptive variation in the control angle demonstrates the capability of the proposed con-

troller to maintain stable operation under unbalanced loading conditions. Figure 19e,f illustrate the unbalanced phase load currents, the resulting neutral current, and the compensating currents injected by the interlinking converter. The results confirm that the proposed converter control effectively compensates load imbalance, suppresses neutral current effects, and maintains balanced source-side current characteristics, thereby enhancing the overall power quality performance of the islanded ferry microgrid. The THD spectrum of the PoC currents is depicted in Figure 20 to show that the %THD is well within the IEEE 519 std.

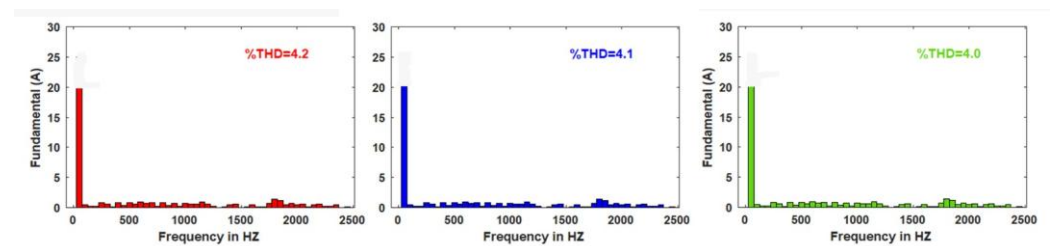


Figure 20. THD spectrum under unbalanced load condition.

A comparative analysis is made between the proposed control (DP_IPT) and conventional IPT control strategies for the same marine microgrid addressing the effects of unbalanced and non-linear loads. The performance of the control scheme under unbalanced and nonlinear loads is given in Table 4.

Table 4. Comparative performance of proposed and conventional control schemes.

Control	Case	% THD	Settling Time	Current Oscillations	Power Oscillations
DP_IPT	Unbalanced	4.1	<1 ms	±5%	±2.2%
	Nonlinear	4.6	<1 ms	±4.3%	±2.2%
IPT	Unbalanced	5.2	<5 ms	±8.4%	±5.6%
	Nonlinear	5.4	<5 ms	±7.8%	±5.4%

5. Conclusions

A power-optimized operational framework for an islanded hybrid ferry microgrid (FMG) intended for next-generation electrified marine transportation is discussed in this paper. The proposed FMG integrates diesel generators (DGs), Solar Photovoltaic (PV) systems, and battery storage within a hybrid AC/DC microgrid architecture interconnected through a bidirectional interlinking converter (ILC). A unified Dual Power-based Instantaneous Power Theory (DP_IPT) is developed for the ILC to simultaneously accomplish bidirectional power transfer and multiple power quality enhancement objectives under a single framework. The proposed DP_IPT control employs SDSC-PLL to effectively extract the fundamental sequence components and mitigate the adverse impacts of nonlinear and unbalanced loading conditions. The controller enables effective load compensation, balanced sinusoidal source currents, reduced current harmonic distortion, uninterrupted bidirectional power transfer, and unity power factor operation at the Point of Common Coupling (PoC). A supervisory control (SC) strategy is also developed for coordinated operation of DGs, Solar PV, and battery storage systems under islanded conditions. The proposed energy management framework ensured stable power sharing and enhanced renewable energy utilization during varying propulsion and service load demands. In addition, the renewable-assisted FMG reduces the total carbon emission to nearly 40% as compared with conventional DG-only operation. The overall performance of the proposed FMG and control architecture is validated through Hardware-in-the-Loop (HiL)

investigations using the OPAL-RT OP4512 real-time platform under dynamic operating conditions involving nonlinear and unbalanced loads. The obtained results confirmed the effectiveness of the proposed framework in improving marine power quality, ensuring reliable bidirectional power flow, enhancing renewable penetration, and reducing diesel dependency for sustainable electrified ferry applications.

Author Contributions: Conceptualization, K.A. and U.S.; methodology, U.S.; software, K.A.; validation, K.A. and U.S.; formal analysis, K.A.; investigation, U.S.; writing—original draft preparation, K.A.; writing—review and editing, U.S.; supervision, U.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FMG	Ferry-based Marine Microgrid
ILC	Interlinking Converter
DP_IPT	Dual Power-based Instantaneous Power Theory
SDSC	Sequential Delay Signal Cancellation
PLL	Phase-Locked Loop
SC	Supervisory Control
DG	Diesel Generator
PV	Solar Photovoltaic
HiL	Hardware-in-Loop
THD	Total Harmonic Distortion
UPF	Unity Power Factor
VCO	Voltage-Controlled Oscillator
PoC	Point of Common Connection
CC-CV	Constant Current-Constant Voltage
GHG	Greenhouse Gas
IMO	International Maritime Organization
TVD-FOPID	Time-Varying Derivative Fractional Order PID
TI-ADRC	Tilt-Integral Active Disturbance Rejection Controller
SRF	Synchronous Reference Frame
MAF	Moving Average Filter
CDSC	Cascaded Delayed Signal Cancellation
PWM	Pulse Width Modulation
HBC	High-Gain Boost Converter
STC	Standard Test Conditions
MPPT	Maximum Power Point Tracking
SP-FOCV	Semi-Pilot Cell-based Fractional Open Circuit Voltage
SoC	State of Charging
TC	Thermal Cooking
WH	Water Heating
ST	Storage Tank

HW Hot Water
 FPSE Fundamental Positive Sequence Extractor

Appendix A

Table A1. Detailed FMG Specifications.

SHIP PARAMETER
Ship length—134.6 m, Ship breadth—21 m, Ship speed—20 knots
ENGINE PARAMETER
Number of engine cycles—2, Number of cylinders—6, Rated capacity—88 kVA
EXCITER PARAMETER
Q-V droop gain— 1×10^{-3} , Rectifier smoothing time constant—0.002 s, Exciter time constant—0.002 s, Controller lag time constant—1 s
DIESEL GENERATOR PARAMETERS
Nominal frequency—50 Hz, Nominal apparent power—60 kW, RMS value of nominal phase-to-phase voltage—440 V, RMS value of nominal line current—200 A, Nominal speed—1800 rpm, Pole pairs—4
PROPELLER PARAMETER
Rated Power/kW—36, No. of blades—4, Type—Fixed pitch, Diameter/m—2.8, Pitch/m—2.4, Shaft Speed/rpm—100, Thrust Coefficient (K_T)—0.85, Torque Coefficient (K_Q)—0.075, Propeller Efficiency (%)—65, Gear Ratio (Motor to Shaft)—5:1, Water Density (kg/m^3)—1025, Advance Ratio—0.65, Propeller Inertia ($\text{kg}\cdot\text{m}^2$)—15.5
SPEED REGULATOR PARAMETERS
P-f droop gain— 3.8×10^{-5} , PI controller, K_p —5, PI controller, K_i — 5×10^{-3} , Actuator time constant—2 s
CONTROL PARAMETERS FOR THE PROPELLER DRIVER
Speed Loop PI Controller K_p , K_i —2, 0.01; Torque Controller K_p , K_i —1.5, 0.005; Gearbox Efficiency—98%, Propeller Shaft Damping—0.002
INTERLINKING CONVERTER
Filter Components— L_{ac} = 5 mH, C_{dc} = 10 mF, DC link Voltage—690 V, Interlinking converter power rating—50 kW, Switching frequency—5 KHz
BUS VOLTAGE
DC Bus Voltage—690 V, AC Bus Voltage—230 V (Phase Voltage)

Appendix B. Carbon Emission Reduction Analysis

The carbon emission produced by the ferry microgrid (FMG) is evaluated based on the energy contribution from individual power sources and their corresponding emission factors. The total carbon emission is computed using the following equations.

$$\text{Carbon emission} = \sum_{i=0}^n (E_{Fi} \times E_i)$$

where E_i = Energy produced by a source (kWh), E_{Fi} = Emission factor of the source ($\text{kg CO}_2/\text{kWh}$), n = number of sources. Presuming, anchoring mode and that the DG is the sole power source.

$$\text{DG} = 60 \text{ kWh; EF} = 0.27 \text{ kg CO}_2/\text{kWh}$$

$$\text{Total emission} = (60 \times 0.27) = 16.2 \text{ kg CO}_2$$

For a similar mode of operation, when renewables supplement the DG,

$$\text{DG} = 36 \text{ kWh; EF} = 0.27 \text{ kg CO}_2/\text{kWh}$$

$$\text{Solar} = 20 \text{ kWh; EF} = 0 \text{ kg CO}_2/\text{kWh}$$

$$\text{Total emission} = (36 \times 0.27) + (20 \times 0) = 9.72 \text{ kg } \text{CO}_2$$

The percentage reduction in carbon emission is given by

$$\% \text{ Reduction} = \frac{16.2 - 9.72}{16.2} \times 100 \% = 40\%$$

Hence, the integration of renewable energy sources significantly reduces diesel dependency and lowers the carbon footprint of the ferry microgrid.

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