

Assessment of Electric Power Quality in Ship Systems: A Technical Guide to Converter Subsystems and Regulatory Compliance

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The maritime industry is currently undergoing a paradigm shift, transitioning from traditional mechanical propulsion systems to complex, integrated electrical power systems. This evolution, often referred to as the move toward the "All-Electric Ship" (AES), has brought about unprecedented efficiency and control. However, it has also introduced a significant challenge for marine engineers and vessel operators: the management of **Electric Power Supply Quality (PSQ)**. As ships become floating microgrids laden with high-power electronics and converter subsystems, the volatility of the power network increases, necessitating a rigorous and technical approach to Power Quality (PQ) assessment.

The Critical Importance of Power Quality in Maritime Environments

Unlike terrestrial power grids, shipboard power systems are "isolated" or "islanded" networks. They lack the stabilizing inertia of a massive national grid. In this confined environment, even a minor disturbance can propagate quickly, leading to catastrophic equipment failure, loss of propulsion, or total blackouts. The quality of the power supply is defined by the degree to which voltage, frequency, and waveform stay within specified limits. Deviations from these limits—commonly caused by **converter subsystems** like Variable Frequency Drives (VFDs) and Active Front End (AFE) rectifiers—can result in the overheating of motors, premature aging of insulation, and interference with sensitive navigation and communication equipment.

Research led by prominent figures such as **Janusz Mindykowski** and **J. Prousalidis** highlights that the assessment of power quality is no longer a luxury but a regulatory and operational necessity. As maritime technology advances, the interaction between non-linear loads and the ship's limited generating capacity creates complex harmonic environments that traditional measurement methods often fail to capture accurately.

Core Technical Concepts and the Theoretical Framework

To understand the assessment of PQ in ship systems, one must first master the core metrics that define electricity in these specialized networks. In a ship fitted with converter subsystems, the primary focus is on **Harmonic Distortion** and **Voltage Fluctuations**.

1. Harmonic Distortion (THD and Individual Harmonics)

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency (typically 60Hz or 50Hz in marine systems). Converter subsystems, which utilize high-speed switching power electronics (IGBTs, Thyristors), are non-linear loads. They draw current in pulses rather than a smooth sine wave, injecting harmonics back into the system.

- **Total Harmonic Distortion (THD):** A collective measure of the harmonic content present in the signal. For voltage (THDu), most classification societies like IACS (International Association of Classification Societies) set a limit of 5% to 8% for the entire system.
- **Total Demand Distortion (TDD):** Often more relevant for current, as it relates the harmonic distortion to the

maximum demand load rather than the instantaneous load.

2. Voltage Unbalance and Transients

Voltage unbalance occurs when the voltages of the three phases in a three-phase system are not equal. In ship systems, this is often caused by unequal distribution of single-phase loads. Transients, or "voltage spikes," are sudden, high-magnitude changes in voltage often caused by the switching of large inductive loads or converter operations.

3. The Role of Converter Subsystems

Converter subsystems are the backbone of modern ship propulsion and auxiliary systems. They include:

- AC/DC Rectifiers: Converting generator output for DC buses.
- DC/AC Inverters: Driving propulsion motors at variable speeds.
- DC/DC Converters: Managing battery storage and fuel cell integration.

While these provide efficiency, they are the primary sources of **Electromagnetic Interference (EMI)** and harmonic pollution. The interaction between the converter's switching frequency and the system's resonant frequency can lead to amplified disturbances.

Technical Analysis: Measuring and Evaluating PQ Metrics

Assessing power quality in a ship requires more than just a multimeter. It requires high-fidelity data acquisition and mathematical modeling to interpret the signal in both the time and frequency domains.

Mathematical Modeling of Harmonics

The assessment often begins with the **Fourier Transform**, which decomposes a distorted time-domain waveform into its constituent frequency components. For a periodic signal $f(t)$, the Fourier series is expressed as:

$$f(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)]$$

In ships with converter subsystems, the high switching frequency of the Pulse Width Modulation (PWM) controllers introduces **inter-harmonics**—components that are not integer multiples of the fundamental frequency. These require more advanced techniques like the **Short-Time Fourier Transform (STFT)** or **Wavelet Transform** for accurate assessment, especially during transient states like motor startup or load shedding.

IACS Requirements and Legal Aspects

The legal framework for shipboard power quality is governed by classification societies and the **IACS E24** unified requirement. Recent updates in 2021 have addressed the "novelisation" of ship technology, acknowledging that older standards did not account for the high density of power electronics in modern vessels. Compliance requires continuous monitoring and the ability to demonstrate that the THD remains within limits even during peak load and maneuvering conditions.

Comparison of Power Quality Issues: Traditional vs. Modern Ship Systems

The following table illustrates the shift in PQ challenges as vessels move from traditional mechanical systems to those heavily integrated with converter subsystems.

Feature	Traditional Ship Systems	Modern Converter-Integrated Systems
Primary Load Type	Linear (Induction Motors, Lighting)	Non-Linear (VFDs, AFE Rectifiers, UPS)
Harmonic Profile	Low (typically <3% THDu)	High (potentially >10% THDu without filters)
Frequency Stability	Governed by mechanical engine inertia	Governed by electronic controller response
Disturbance Types	Voltage drops, frequency dips	Harmonics, inter-harmonics, high-frequency EMI
Mitigation Requirement	Minimal (standard circuit protection)	Extensive (Active/Passive filters, Multi-pulse transformers)

Practical Implementation: A Technical Workflow for PQ Assessment

Marine engineers must follow a structured procedure to assess and manage power quality. This guide outlines the necessary steps for a comprehensive field assessment.

Step 1: System Mapping and Identification of Critical Nodes

Identify all non-linear loads (converters) and sensitive loads (navigation, automation). Assessment points should be established at the **Point of Common Coupling (PCC)**—the main switchboard where different sub-networks meet.

Step 2: Continuous Data Acquisition

Standard spot-checks are insufficient. Permanent Power Quality Monitors (PQMs) must be installed. These devices should have a sampling rate high enough (typically >10 kHz) to capture high-order harmonics and transients caused by converter switching.

Step 3: Harmonic Propagation Analysis

Using the gathered data, engineers must model how harmonics propagate from the converter subsystems back to the generators. This involves calculating the **short-circuit ratio** at the PCC. A lower short-circuit ratio indicates a "weaker" grid, which is more susceptible to voltage distortion from current harmonics.

Step 4: Evaluation of Mitigation Strategies

If THD levels exceed IACS limits, mitigation must be implemented. Common technical solutions include:

- 12-Pulse or 24-Pulse Rectifiers: Using phase-shifting transformers to cancel out specific harmonic orders (e.g., 5th, 7th, 11th, 13th).
- Passive Filters: Using LC circuits tuned to specific frequencies to "trap" harmonics.
- Active Power Filters (APF): Modern converters that inject equal and opposite harmonic currents to cancel out distortion in real-time.

Case Study: Harmonic Resonance in an Electric Propulsion Ship

In a documented case involving a Diesel-Electric cruise ship, the installation of high-power VFDs for propulsion caused unexpected failures in the ship's auxiliary capacitor banks. Technical analysis revealed a **Parallel**

Resonance condition.

The Problem:The capacitance of the system (used for power factor correction) interacted with the inductance of the main transformers. This created a resonant circuit at the 11th harmonic frequency. Because the propulsion converters were 6-pulse systems, they naturally generated significant 11th harmonic current.

The Technical Solution: The engineering team utilized a **Detuned Filter**strategy. By adding a series reactor to the capacitor banks, they shifted the resonant frequency of the system to a point where no significant harmonic energy was present (e.g., the 3.8th harmonic). This effectively protected the capacitors and reduced the overall THDu at the main switchboard from 9.2% to 4.1%.

Common Failure Modes and Troubleshooting Table

Symptom	Potential Technical Cause	Diagnostic Action
Nuisance tripping of breakers	High Crest Factor (current peaks)	Analyze current waveform peak-to-RMS ratio.
Overheating of transformers	Skin effect due to high-frequency harmonics	Check K-Factor rating of the transformer.
Generator voltage hunting	Interaction between AVR and converter harmonics	Adjust AVR dampening or install isolation transformer.

The Evolution of Assessment Metrics

As suggested by the work of **Mindykowski**, traditional metrics like THD may be insufficient for future ship systems. New harmonic metrics are being introduced to assess the **propagation of disturbances** more effectively. These include the **Individual Harmonic Distortion (IHD)** and the assessment of **Supraharmonics**(distortions in the 2 kHz to 150 kHz range), which are increasingly common in systems with high-speed switching silicon carbide (SiC) power electronics.

Furthermore, the integration of **Energy Storage Systems (ESS)**, such as large-scale lithium-ion battery banks, adds another layer of complexity. During discharge, the DC/AC converters of the ESS act as sources of power, but during charging, they act as non-linear loads. The bidirectional nature of these systems requires a dynamic assessment of PQ, where limits and filter settings may need to change based on the ship's operational mode (e.g., harbor mode vs. transit mode).

Synthesizing the Future of Shipboard Power Systems

The assessment of electric power quality in ship systems is a multidisciplinary challenge that bridges the gap between traditional power engineering and modern power electronics. As converter subsystems become more prevalent, the maritime industry must move toward a more proactive "PQ by Design" approach. This involves rigorous simulation during the vessel's design phase, followed by the implementation of smart monitoring systems that provide real-time feedback to the crew.

The legal and regulatory landscape is also evolving to keep pace with these technological advancements. With the IACS leading the way in harmonizing requirements, shipbuilders and owners must ensure that their vessels not only meet current standards but are also equipped to handle the high-frequency harmonic environments of the future. By prioritizing power quality, the maritime sector can ensure that the transition to the All-Electric Ship is marked by increased reliability, safety, and operational excellence, rather than technical failure and instability. The work of researchers like Mindykowski serves as a foundational pillar for this transition, emphasizing that in the world of modern ship systems, the quality of power is as vital as the power itself.

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