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Analysis of Synchronous Generator Operation in Ship Electrical Systems: A Literature Review

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Abstract

Shipboard electrical systems operate as isolated microgrids, with synchronous generators serving as key components for maintaining power continuity, voltage and frequency stability, and preventing blackouts. However, the evolution toward AC/DC hybrid architectures, energy storage integration, intelligent Power Management Systems (PMS), and data-driven protection has altered the technical requirements for generator operation. This article presents a critical literature review—conducted according to the PRISMA workflow—on synchronous generator operation in modern shipboard electrical systems. A structured search was performed across IEEE Xplore, ScienceDirect, MDPI, SpringerLink, and Google Scholar. The review compares strategies for voltage regulation, governor- and droop-based frequency control, synchronization and parallel operation, protection coordination, dynamic stability, and PMS functions. Mathematical formulations—such as the swing equation, power-angle relationship, active and reactive power control, droop characteristics, and excitation response—are also discussed to underpin the analysis. Synthesis of the findings indicates that the reliability of shipboard generators cannot be assessed solely through steady-state parameters; rather, it requires analysis of the interactions between excitation systems, governors, synchronization conditions, protection schemes, PMS optimization, transient stability, and maintenance practices. Research gaps identified include the experimental validation of AI-based excitation control, cyber-resilient PMS, generator protection in AC/DC hybrid grids, and digital twin-based diagnostics. This article proposes a comparative technical framework for analyzing synchronous generators within integrated shipboard electrical architectures.

Keywords: *Synchronous Generator, Shipboard Electrical System, Power Management System*

Abstrak

Sistem kelistrikan kapal beroperasi sebagai mikrogrid terisolasi, dengan generator sinkron sebagai komponen utama untuk menjaga kontinuitas daya, kestabilan tegangan dan frekuensi, serta mencegah blackout. Namun, perkembangan menuju arsitektur hibrida AC/DC, integrasi penyimpanan energi, Power Management System yang cerdas, serta proteksi berbasis data telah mengubah tuntutan teknis terhadap pengoperasian generator. Artikel ini menyajikan kajian literatur kritis berbasis alur PRISMA mengenai pengoperasian generator sinkron pada sistem kelistrikan kapal modern. Penelusuran dilakukan secara terstruktur melalui IEEE Xplore, ScienceDirect, MDPI, SpringerLink, dan Google Scholar. Kajian ini membandingkan strategi pengaturan tegangan, pengendalian frekuensi berbasis governor dan droop, sinkronisasi dan operasi paralel, koordinasi proteksi, stabilitas dinamis, serta fungsi PMS. Formulasi matematis seperti persamaan ayunan, hubungan daya-sudut, pengaturan daya aktif-reaktif, karakteristik

droop, dan respons eksitasi juga dibahas untuk memperkuat dasar analisis. Hasil sintesis menunjukkan bahwa keandalan generator kapal tidak dapat dinilai hanya dari parameter keadaan tunak, melainkan harus dianalisis melalui interaksi sistem eksitasi, governor, kondisi sinkronisasi, proteksi, optimasi PMS, stabilitas transien, dan praktik pemeliharaan. Kesenjangan penelitian meliputi validasi eksperimental kontrol eksitasi berbasis AI, PMS tahan serangan siber, proteksi generator pada jaringan hibrida AC/DC, dan diagnostik berbasis digital twin. Artikel ini mengusulkan kerangka teknis komparatif untuk analisis generator sinkron dalam arsitektur kelistrikan kapal terintegrasi.

Kata kunci: Generator Sinkron, Sistem Kelistrikan Kapal, Sistem Manajemen Daya

Introduction

Shipboard electrical systems are fundamentally different from land-based interconnected power systems because they operate as isolated or islanded microgrids. During voyage operation, electrical energy for propulsion auxiliaries, navigation, communication, safety loads, hotel loads, pumps, compressors, and automation systems must be supplied by onboard generation units. The absence of a strong external grid means that disturbances in the generator, governor, excitation system, busbar, distribution network, or Power Management System (PMS) can immediately affect the continuity of ship operation and, in severe cases, can lead to blackout.

Synchronous generators remain widely used in marine electrical systems because they can provide controllable AC power, voltage support, and short-term overload capability. Their operation, however, is no longer limited to simple voltage and frequency maintenance. Modern vessels increasingly combine diesel generators with battery energy storage, permanent magnet synchronous generators, DC distribution systems, fuel cells, and intelligent energy management algorithms. As a result, synchronous generator operation must be interpreted as an interaction among the machine, the excitation system, the governor, the Main Switchboard, protection relays, energy storage devices, and supervisory PMS functions [1]-[7].

Previous studies have examined excitation control, loss of excitation, generator-battery coordination, hybrid ship power management, and blackout probability monitoring [1]-[6]. Other studies have expanded the discussion toward hierarchical ship energy management, hybrid generating plants, hardware-in-the-loop validation, and load distribution in LNG electric propulsion plants [7-8]. In parallel, recent review articles have mapped shipboard microgrids, DC architectures, energy storage, and optimization-based energy management [9-14]. These contributions are valuable, but they often discuss energy management, shipboard microgrids, or hybrid propulsion at system level without critically connecting those developments to the operating requirements of synchronous generators.

The research gap addressed in this review is therefore not the absence of publications on ship electrical systems, but the fragmentation of the discussion. Voltage regulation studies focus mainly on excitation and AVR response; PMS studies emphasize scheduling and fuel efficiency; protection studies focus on relay functions; and DC microgrid studies analyze converter-dominated architectures. Limited attention is given to how these domains interact when a synchronous generator must remain stable under fluctuating loads, parallel operation, transient disturbances, and hybrid AC/DC

integration. This fragmentation makes it difficult for engineers, researchers, and educators to identify which technical parameters most strongly determine generator reliability in modern shipboard electrical systems.

The contribution of this article is threefold. First, it develops a reproducible review methodology that defines the databases, search terms, screening criteria, and quality-assessment logic used to select the literature. Second, it provides a critical comparison of generator control, synchronization, protection, PMS, and hybrid AC/DC trends rather than presenting a descriptive summary of individual studies. Third, it introduces mathematical formulations and technical synthesis tables to connect steady-state operation, dynamic stability, and future research directions. Accordingly, this review aims to answer the following research questions: RQ1) Which control and protection functions determine the reliability of ship synchronous generators? RQ2) How do modern PMS and hybrid AC/DC architectures change generator operating requirements? RQ3) What research gaps remain in voltage regulation, frequency control, synchronization, protection, and blackout prevention?

Method

This study adopts a PRISMA-informed literature review approach. The purpose is not to conduct a statistical meta-analysis but to ensure that the literature selection process is transparent, reproducible, and technically justifiable. PRISMA 2020 emphasizes clear reporting of identification, screening, eligibility, and inclusion phases in systematic reviews [11]. This principle was adapted to the engineering context of shipboard electrical systems.

The literature search was conducted using IEEE Xplore, ScienceDirect, MDPI, SpringerLink, and Google Scholar. Search strings combined maritime and electrical-engineering keywords, including: "shipboard power system", "ship synchronous generator", "automatic voltage regulator ship generator", "ship generator synchronization", "load sharing ship generator", "Power Management System ship", "shipboard microgrid", "DC shipboard microgrid", "blackout prevention ship power", "generator protection", and "hybrid electric ship energy management". Boolean combinations used AND/OR operators, for example: (shipboard OR marine OR vessel) AND (synchronous generator OR diesel generator) AND (AVR OR governor OR synchronization OR load sharing OR PMS).

The inclusion criteria were: (1) peer-reviewed journal articles, conference papers, technical standards, or authoritative textbooks/guides relevant to ship electrical systems; (2) publications addressing synchronous generators, excitation, governor control, PMS, load sharing, microgrids, hybrid AC/DC systems, protection, or blackout prevention; (3) publications from 2021 to 2025 for recent scientific developments, with older foundational sources retained only for mathematical models and protection standards; and (4) sources with sufficient technical detail to support comparison. Exclusion criteria included non-ship applications without transferable relevance, papers focusing solely on mechanical propulsion without electrical analysis, duplicated studies, inaccessible full texts, and publications with insufficient technical information.

The quality appraisal considered four aspects: methodological clarity, relevance to shipboard electrical systems, validation approach, and contribution to control/protection/stability analysis. Simulation-only studies were not excluded, but their limitations were explicitly considered. Standards and foundational textbooks were used to support definitions, installation requirements, protection functions, and mathematical modeling.

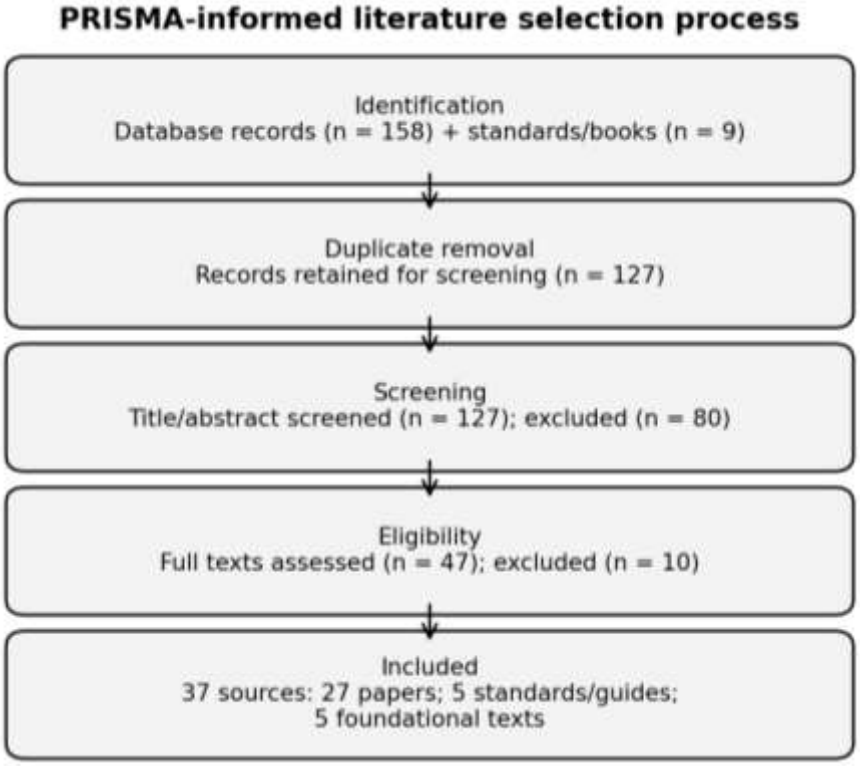


Figure 1. PRISMA-informed Literature Selection Flowchart

Table 1. Review Protocol and Quality Assessment Criteria

Item	Description	Purpose
Databases	IEEE Xplore, ScienceDirect, MDPI, SpringerLink, and Google Scholar	To cover electrical engineering, maritime engineering, microgrid, and open-access journal sources
Search scope	2021-2025 for recent studies; older references retained for models, standards, and protection fundamentals	To balance recency and theoretical completeness
Main keywords	shipboard power system, synchronous generator, AVR, governor, synchronization, PMS, load sharing, blackout prevention, DC shipboard microgrid	To capture generator-level and system-level studies
Inclusion criteria	Technical relevance, clear method or model, shipboard or transferable microgrid context,	To ensure scientific and technical applicability

Item	Description	Purpose
	availability of bibliographic details	
Exclusion criteria	Non-electrical focus, non-ship context without relevance, duplicated theme, inaccessible full text, insufficient technical content	To reduce descriptive or weakly related sources
Quality indicators	Model clarity, validation method, treatment of control/protection/stability, and explicitly reported limitations	To enable critical comparison instead of simple summarization

a. Theoretical Foundation of Synchronous Generator Operation

A synchronous generator is an electromechanical energy-conversion device whose rotor magnetic field rotates synchronously with the stator magnetic field. In a shipboard power plant, the generator is usually driven by a diesel engine or another prime mover. The electrical frequency is proportional to rotor speed and the number of poles, while terminal voltage depends strongly on excitation. Therefore, generator performance is governed by coupled mechanical, magnetic, and electrical dynamics rather than by a single operating variable.

The rotor-angle dynamic response is commonly represented by the swing equation. In simplified form, it may be written as: $M\, d^2\delta/dt^2 + D\, d\delta/dt = Pm - Pe$, where δ is the rotor angle, M is the inertia constant, D is damping, Pm is mechanical input power, and Pe is electrical output power [12]. This equation is important for shipboard systems because a sudden load increase, short circuit, or generator trip changes the balance between mechanical and electrical power. If the disturbance is large and the system lacks sufficient damping or reserve, the generator may lose synchronism or trigger protective tripping.

For a simplified round-rotor generator connected to an equivalent bus, the active power transfer can be approximated by $P = (EV/X) \sin \delta$, while reactive power is influenced by excitation and terminal voltage. These relationships explain why excitation control affects voltage and reactive power, while governor control affects frequency and active power. In parallel generator operation, the governor determines active load sharing, whereas AVR settings and reactive droop determine reactive load sharing. Consequently, unstable voltage or frequency is not merely an indicator of poor control; it is also a sign of energy imbalance between mechanical input, excitation, electrical load, and busbar conditions.

Frequency control is commonly represented by droop characteristics. A simplified droop relationship can be expressed as $\Delta f = -R\, \Delta P$, where R is the droop coefficient and ΔP is the change in active power. Droop permits multiple generators to share active load without requiring identical speed commands. However, excessive droop, governor delay, fuel-system lag, or poor damping can lead to transient frequency deviations. In isolated shipboard power systems, these deviations may be more severe than in terrestrial grids

because spinning reserve is limited and loads may change rapidly. Excitation models are commonly represented through regulator gain, time constants, limiters, and power-system stabilizer functions. IEEE excitation-system models provide a standard basis for representing AVR dynamics in stability studies [13]. For ship applications, however, excitation response must be interpreted together with the generator operating mode, load character, insulation condition, and Main Switchboard protection settings. A high-gain AVR may improve voltage recovery but can also contribute to oscillatory behavior if damping and limiter coordination are inadequate.

Result and Discussion

a. Voltage Regulation and Excitation-Control Strategies

The literature indicates that voltage regulation in ship synchronous generators has moved beyond conventional AVR tuning. Classical PID regulators are still widely used because they are simple, familiar, and easy to implement. Nevertheless, PID performance is sensitive to operating-point variation, load nonlinearity, and parameter drift. Under sudden load changes, poorly tuned PID-based AVR may produce overshoot, slow recovery, or oscillatory voltage response.

Active disturbance rejection control has been applied to ship generator excitation to improve disturbance rejection under load variation [1]. This approach is attractive because it estimates and compensates for disturbances without requiring a perfect plant model. However, its implementation requires careful tuning of observer bandwidth and controller gains. If these parameters are not properly selected, the controller may amplify noise or become difficult to validate in safety-critical shipboard environments.

Hardware-in-the-loop testing provides an important bridge between simulation and actual shipboard implementation. Studies on AVR testing using HIL technology show that different generator operating states can be evaluated without exposing the real generator to unsafe conditions [14]. This is particularly relevant for ship operators because full-load or fault-like testing on an actual generator is often impractical. The limitation is that HIL accuracy depends on the quality of the real-time generator model, sensor emulation, and controller interface.

Adaptive, robust, fuzzy, model predictive, and AI-based excitation controls are increasingly discussed in broader power-system literature, but their shipboard application remains limited. Fuzzy control can handle rule-based uncertainty but may lack formal stability guarantees. MPC can manage constraints and multi-variable interactions but requires computational resources and a reliable prediction model. AI-based excitation systems may identify nonlinear patterns, but their explainability, certification, and fault tolerance remain unresolved. Thus, the main research gap is not the absence of advanced control concepts, but the lack of experimentally validated, class-approved, and cyber-secure excitation strategies for shipboard use.

Table 2. Comparative Analysis of Excitation and Voltage Regulation Strategies

Control Strategy	Strengths	Limitations	Applicability in Shipboard Systems
Classical PID AVR	Simple, low-cost, mature, easy to implement	Sensitive to tuning, nonlinear loads, and operating-point variation	Highly applicable for conventional ships but requires periodic tuning
ADRC	Strong disturbance rejection and reduced dependence on exact model	Observer tuning and noise sensitivity may be challenging	Promising for variable ship loads if validated through HIL and sea trials
Fuzzy control	Handles qualitative operating rules and nonlinear response	Rule design may be subjective; stability proof can be weak	Useful for hybrid systems but needs verification under faults
MPC	Can handle constraints, multi-objective control, and prediction	Computational burden and model dependence	Promising for integrated PMS-AVR coordination
AI-based control	Can learn nonlinear patterns and support adaptive operation	Explainability, cybersecurity, certification, and data quality issues	Future-oriented; currently requires extensive validation before deployment
HIL-based AVR testing	Allows safe testing under simulated load variations	Accuracy depends on model fidelity and interface design	Highly valuable for commissioning and preventive maintenance

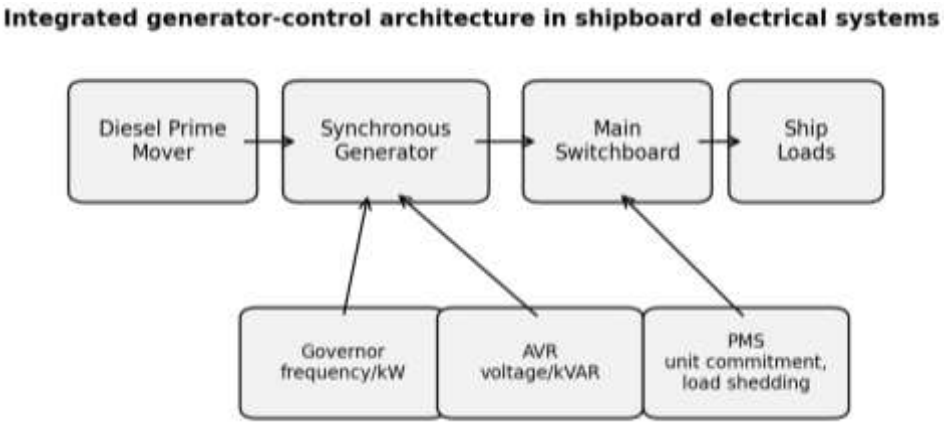


Figure 2. Integrated Generator-Control Architecture in Shipboard Electrical Systems

b. Frequency Regulation, Governor Dynamics, and Load Sharing

Frequency stability is governed by the dynamic interaction between mechanical input and electrical load. When electrical demand suddenly increases, the generator decelerates, causing frequency to fall. The governor then increases fuel input to restore speed. However, the governor and diesel engine include delays, dead bands, ramp-rate limitations, and combustion dynamics. These dynamics explain why shipboard frequency deviations can be large during motor starting, bow-thruster operation, compressor loading, or loss of a generator unit. Droop control is essential for parallel operation because it enables multiple generators to share active power without fighting each other.

If droop settings are not coordinated, one generator may absorb a disproportionate kW load while another remains lightly loaded. Unequal active load sharing can reduce fuel efficiency, increase thermal stress, and accelerate maintenance requirements. Studies on generator-battery coordination and hybrid ship power management show that energy storage can reduce generator loading peaks and improve efficiency [3-4], [15-16]. However, these benefits depend on battery state of charge, converter limits, and the PMS dispatch strategy.

Load sharing also has an economic and environmental dimension. LNG electric propulsion studies show that load distribution among generating units affects fuel consumption and emission performance [8]. Optimization-based PMS studies similarly indicate that generator unit commitment and dispatch can improve efficiency if minimum-loading constraints and spinning reserve are respected [17-18]. A critical limitation in the literature is that many studies optimize dispatch but do not fully discuss governor dynamics, transient frequency nadirs, or protection consequences when generator output changes rapidly.

Therefore, future frequency-control studies should integrate mechanical diesel-engine models, governor equations, generator swing dynamics, battery ramp-rate limits, and PMS decision logic. Without this integration, the result may be an efficient steady-state dispatch that remains vulnerable to transient frequency instability during emergency conditions.

c. Synchronization, Parallel Operation, and Dynamic Stability

Generator synchronization is usually explained through four conditions: voltage magnitude, frequency, phase sequence, and phase angle compatibility. Although these conditions are necessary, they are not sufficient for a rigorous assessment of secure parallel operation. The closing instant of the circuit breaker determines the magnitude of transient current and synchronizing torque. A large breaker closing angle error can produce mechanical stress, electromagnetic torque oscillation, busbar disturbance, and protective relay operation. The synchronizing power coefficient, which describes the change in electrical power with rotor angle, is fundamental to dynamic synchronization stability. When the coefficient is positive and sufficient damping is available, the generator tends to return toward synchronism after small disturbances. Under weak damping, high load, or improper governor-AVR interaction, oscillations may persist. This is particularly important in isolated shipboard electrical systems because the electrical network is small, source inertia is limited, and load changes can be abrupt.

The literature on shipboard DC hybrid systems also shows that hybrid AC/DC architectures introduce new synchronization and stability challenges [9], [19]. In DC systems, rectifier interfaces may decouple generator electrical frequency from the DC bus, but they introduce converter-control interactions, constant-power-load instability, and protection selectivity challenges. Consequently, the future role of synchronous generators may shift from directly supplying AC loads to feeding converters, stabilizing hybrid buses, or operating in coordinated dispatch with batteries and fuel cells.

Transient and dynamic stability should therefore be integrated into generator-operation reviews. Large load steps, short-circuit faults, voltage collapse, generator

tripping, black start, and post-fault recovery all influence blackout risk. A steady-state analysis of voltage and frequency is insufficient because a system that appears stable at one operating point may fail during a transient disturbance.

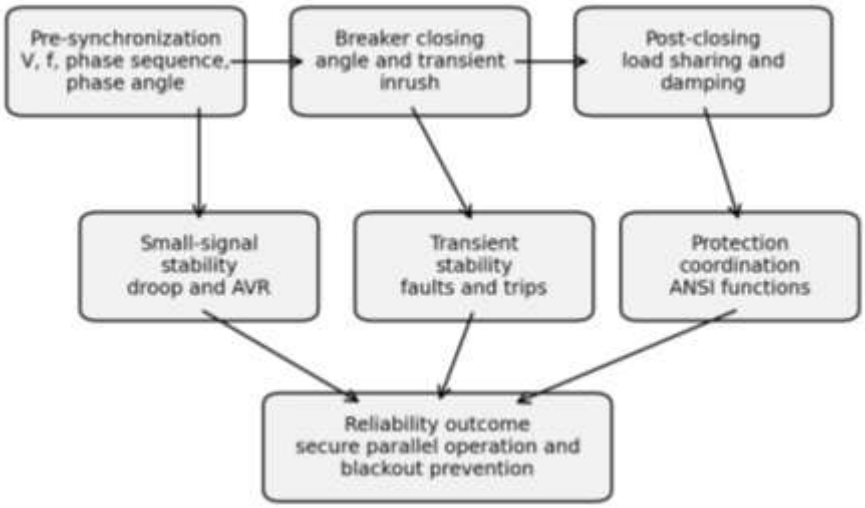


Figure 3. Synchronization, Dynamic Stability, and Protection Coordination Map

d. Protection Coordination and Generator Protection Functions

Protection systems are critical because a shipboard electrical system must isolate faults without causing unnecessary total power loss. Generator protection should address both internal generator faults and abnormal operating conditions. IEEE generator protection guidance describes generally accepted forms of protection for synchronous generators and excitation systems [20], while IEEE device-function numbers provide standardized identification for relays and protection functions [12].

Essential protection functions include differential protection (87G), reverse power protection, loss-of-excitation protection, overexcitation protection, negative-sequence protection, stator ground fault protection (64G), rotor ground fault protection (64F), thermal protection, overcurrent protection, under/over voltage protection, under/over frequency protection (81U/81O), and out-of-step protection. Their coordination with PMS is important because a relay trip may require fast load shedding, standby generator starting, or black-start preparation.

The critical research gap is that protection studies and PMS studies are often separated. PMS algorithms may optimize fuel consumption or dispatch, but protection constraints determine whether a dispatch remains secure during faults. Similarly, protection settings may isolate the fault but inadvertently reduce available generation below load demand. Cybersecurity adds another layer of concern because false data injection, communication delay, or denial-of-service attacks against PMS signals may lead to incorrect load shedding or generator dispatch. Recent marine cybersecurity reviews emphasize that cyber threats can affect marine power-system measurement and control channels [21].

Table 3. Generator Protection Functions Relevant to Shipboard Reliability

ANSI Code	Protection Function	Technical Risk Addressed	Relation to PMS/blackout Prevention
87G	Generator differential protection	Internal stator winding faults	Requires rapid isolation and standby generation response
32	Reverse power	Prime mover failure or motoring condition	Prevents diesel engine damage and abnormal generator operation
40	Loss of excitation	Reactive power absorption, voltage instability	May trigger voltage collapse if not coordinated with load shedding
24	Overexcitation	Excessive V/Hz and magnetic saturation	Protects generator core and transformer equipment
46	Negative sequence	Unbalanced loads and overheating	Important in ship networks with asymmetric or faulted loads
64G/64F	Stator/rotor ground fault	Insulation failure	Supports fault localization and maintenance planning
27/59	Under/over voltage	Voltage collapse or overvoltage	Coordinates with AVR, PMS, and non-essential load shedding
81U/81O	Under/over frequency	Governor failure or generation-load imbalance	Direct input for PMS emergency actions
78	Out-of-step	Loss of synchronism	Critical during severe transients and improper synchronization

e. Power Management System, Blackout Prevention, and Hybrid AC/DC Transition

The PMS is no longer merely an automation tool for starting and stopping generators. In modern vessels, it functions as a supervisory decision-making layer that coordinates generator commitment, automatic synchronization, load sharing, spinning reserve, load shedding, battery charging and discharging, and emergency recovery. Hardware-in-the-loop PMS validation for LNG carriers demonstrates that real-time testing can verify PMS behavior before actual onboard implementation [22]. This is valuable because field testing of blackout-related scenarios can be unsafe and expensive.

Optimization-based PMS can reduce fuel consumption and emissions by selecting the most efficient generator operating points [5], [16]. Hybrid generator-battery systems can also reduce excessive low-load operation and improve response to transient demand [15], [17], [21]. However, optimization introduces new challenges. An algorithm that minimizes fuel consumption may reduce spinning reserve if reliability constraints are not explicitly modeled. Security-constrained PMS addresses this weakness by embedding contingency constraints and blackout prevention into the dispatch problem [17].

Energy-storage integration changes the role of synchronous generators. Batteries and supercapacitors can support fast power response, while generators provide sustained energy. Fuel cells and hydrogen-based systems introduce low-emission alternatives but require careful power balancing and transient support. Fuzzy logic and deep reinforcement learning strategies have been proposed for hybrid propulsion and fuel-cell systems [23-24]. Nevertheless, data-driven and AI-based strategies remain difficult to certify because their decisions may be difficult to explain under abnormal or unseen operating conditions.

The transition toward hybrid AC/DC shipboard systems is therefore both an opportunity and a risk. DC shipboard microgrids can improve converter controllability and facilitate energy storage integration [9], [25], but they also introduce constant-power-load instability, converter fault-current limitations, and new protection requirements. The implication for synchronous generators is significant: generator operation must be coordinated with rectifiers, batteries, DC-bus controllers, and PMS algorithms rather than only with AC busbar conditions.

Table 4. Comparative Synthesis of Selected Literature Themes

Theme	Dominant Methods in Literature	Validation Approach	Main Limitation or Unresolved Question
AVR and excitation	PID, ADRC, HIL-based AVR testing, excitation-loss analysis	Simulation, HIL, disturbance scenarios	Limited sea-trial validation of advanced controllers
Frequency and load sharing	Governor droop, generator-battery coordination, optimal dispatch	Simulation and optimization models	Governor transients often simplified in EMS studies
Synchronization	Classical matching, synchronizer logic, busbar connection criteria	Mainly analytical or operational procedure-based	Limited treatment of breaker closing angle and synchronizing torque
PMS and blackout prevention	Unit commitment, load shedding, HIL PMS validation, security-constrained dispatch	Optimization, HIL, notional ship cases	Cybersecurity and fault-tolerant PMS remain underexplored

Theme	Dominant Methods in Literature	Validation Approach	Main Limitation or Unresolved Question
Hybrid AC/DC systems	DC grids, ESS, fuel cells, converters, model-based design	Simulation and review studies	Protection and generator-converter interaction need deeper study
Protection systems	ANSI functions, generator protection guides, microgrid protection reviews	Standards and relay studies	Coordination between PMS optimization and relay settings remains weak
Future intelligent systems	AI, digital twins, predictive maintenance, data-driven EMS	Mostly conceptual or simulation-based	Explainability, certification, and data availability are unresolved

f. Bibliometric and Thematic Mapping Perspective

A formal bibliometric analysis using VOSviewer or Bibliometrix was not performed because the review is focused on technical synthesis rather than citation-network measurement. However, a descriptive thematic mapping was added to identify publication tendencies within the selected sources. The selected literature shows four dominant clusters: (1) synchronous generator control and AVR behavior; (2) PMS, optimization, and blackout prevention; (3) hybrid AC/DC shipboard microgrids and energy storage; and (4) protection, cybersecurity, and maintenance. Publications from 2021-2022 are dominated by coordinated generator-battery control, blackout monitoring, and DC microgrid reviews. Publications from 2023-2025 increasingly emphasize hybrid energy management, HIL validation, fuel-cell and battery systems, cybersecurity, and intelligent PMS.

This mapping suggests that the research frontier is moving from component-level generator control toward integrated cyber-physical energy management. Nevertheless, the synchronous generator remains a key dynamic element because it determines inertia, fault response, voltage support, and frequency behavior whenever rotating generation is present. Therefore, future review work should not treat generator control, PMS, protection, and hybrid architecture as separate themes.

g. Future Research Directions

Several research priorities emerge from the critical synthesis. First, advanced excitation control should be validated under ship-representative conditions using HIL, controller-in-the-loop, and sea-trial data. Comparative testing should include PID, robust control, ADRC, fuzzy control, MPC, and AI-based strategies under identical disturbance scenarios. Second, frequency-control research should incorporate diesel-engine dynamics, governor delay, battery ramp-rate constraints, and primary/secondary frequency control within isolated marine microgrids. Third, synchronization research should move beyond static matching requirements and analyze breaker closing angle optimization, synchronizing torque, transient inrush current, and failure mechanisms. Fourth, generator protection should be integrated with PMS optimization so that dispatch decisions remain secure under relay operation, generator loss, short circuit, and load-

shedding events. Fifth, hybrid AC/DC architectures require new protection and stability frameworks because converter-dominated systems have different fault behavior from conventional AC systems.

Sixth, intelligent PMS should be developed with cybersecurity, explainability, and fault tolerance as primary requirements rather than optional features. Digital twins can support predictive maintenance, virtual commissioning, operator training, and condition-based diagnostics, but they require high-quality sensor data, validated physical models, and secure communication. Seventh, zero-emission vessels using hydrogen, fuel cells, batteries, supercapacitors, and renewable sources should be studied from the perspective of generator interaction, reserve management, black-start capability, and emergency operation.

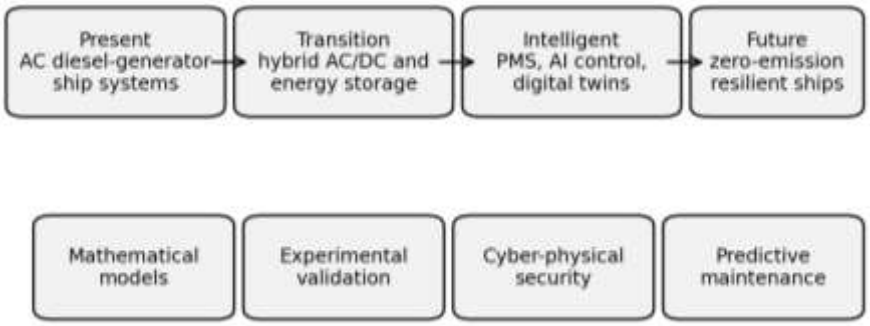


Figure 4. Future research Roadmap for Synchronous Generator Operation In Modern Shipboard Electrical Systems

Conclusion

This review demonstrates that synchronous generator operation in shipboard electrical systems must be analyzed as an integrated control, protection, and energy-management problem. Voltage regulation depends on excitation and AVR behavior, while frequency control depends on governor dynamics, mechanical response, droop settings, and generation-load balance. In parallel operation, synchronization must consider not only voltage, frequency, phase sequence, and phase angle, but also synchronizing torque, breaker closing angle, transient current, and post-closing load sharing.

The review also shows that modern PMS functions influence generator reliability through unit commitment, automatic synchronization, load sharing, spinning reserve management, load shedding, and blackout prevention. As vessels move toward hybrid AC/DC architectures, batteries, fuel cells, supercapacitors, and converter-based networks modify the operating requirements of synchronous generators. Therefore, generator reliability cannot be evaluated solely from steady-state voltage and frequency values. It must be assessed through dynamic models, protection coordination, PMS logic, transient stability, cybersecurity, and standards-based maintenance. The main scientific gap identified in this article is the lack of integrated and experimentally validated frameworks linking synchronous generator dynamics, advanced AVR and governor control, PMS optimization, protection coordination, and hybrid AC/DC shipboard architectures. Future research should develop HIL-validated and field-tested models that combine mathematical formalization, AI-assisted diagnostics, digital twins, predictive

maintenance, and resilient energy management. Such research is essential for improving the safety, efficiency, and blackout resilience of modern marine electrical systems.

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