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SURVEY

Power System Control in DC Shipboard Power Systems: A Review of Methods and Architectures

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ABSTRACT The electrification of shipboard power systems (SPSs), combined with the introduction of heterogeneous power sources and energy storage technologies, is driving a need for more advanced and structured control strategies. This review examines control methods and architectures for DC ships, with a specific interest in power systems integrating energy storage systems and zero-emission power generation. Control methods are categorized based on both their functionality and architecture, evaluating their resilience, adaptability, and scalability. Different hierarchical layers are reviewed, distinguishing local control, coordinated control, and energy management methods. Key challenge in the coordinated control arise due to large load fluctuations, constant-power loads, low inertia, and diverse dynamic capabilities of power sources and storage systems. These characteristics complicate voltage stability, dynamic power sharing, and state-of-charge management. Decentralized, centralized, and distributed control architectures are reviewed with respect to scalability, communication requirements, and fault tolerance. At the high-level layer, energy management strategies are discussed in terms of operational efficiency and resiliency, with predictive and distributed methods forming key trends in shipboard power system control. The review highlights the need for resilient, adaptive, and scalable control solutions tailored to future DC SPSs, particularly those integrating fuel cells and energy storage technologies.

INDEX TERMS Shipboard power systems, DC distribution, energy management, power system control, control architecture.

I. INTRODUCTION

The design of modern shipboard power systems (SPSs) features an increasing system complexity due to its number of power generation, energy storage, and demanding loads, while requirements on availability, reliability, and other factors put additional strain on the power system. On the other side, modern equipment, especially due to power converters, high computational power, and fast communication technology, enable more advanced control possibilities of the SPS. This article is dedicated to giving an overview of the underlying challenges and functionalities for the operation of a vessel's power distribution system. In addition to a review of the control hierarchy and methods, additional emphasis is placed on the control architecture, focusing on approaches that support the resilient operation of electrified DC SPSs with heterogeneous power system resources. In this context, specific attention is given to future-oriented technologies, such as energy storage systems (ESSs) and zero-emission power generation. Conventionally, AC distribution is used for the electric system on ships. DC distribution, however, is receiving increasing interest as a solution to tie heterogeneous components together into a shipboard DC microgrid [1]. This promises efficiency gains and cost reductions, and improves system reliability [2]. Interfacing components via power electronics converters

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increases the controllability of power flows. This further supports the separation of component-level from system-level control, by making synchronization requirements and speed restrictions, as present in AC systems, obsolete [3]. With an increased amount of DC sources (fuel cells (FCs), batteries, etc.), as well a variable speed generators, the reduction of conversion stages is kept minimal. The increased flexibility is in line with a trend towards modularization and distribution of generation and storage units [4]. In the context of decarbonization, an increasing importance is attributed to hydrogen FCs [5] and renewable energy sources [6], for which DC distribution and ESS is specifically suitable, as shown in [7].

A proper coordination of the power system components is not only required to ensure power availability and an efficient utilization of resources, but also for the system's reliable and fault-tolerant operation. For the control of the SPS, many parallels can be drawn to the terrestrial power system, especially regarding the system design and control architectures. In the same regard, mission- or trip-based energy management strategies are pioneered in automotive systems. However, the specific demands arising from the operation in a maritime environment lead to dedicated control strategies. As a first step, the prevalent control architectures and archetypal communication layouts in ships are reviewed. Moreover, the SPS control is dissected into distinct layers whose tasks and functionalities are identified, leading to a differentiation between local control, coordinated control and energy management. This article presents an overview of methods applied on different layers and with differing communication layouts. A specific interest in control approaches suitable for modular and zero emission SPS designs is brought forward. This article reviews the power system control for DC ships from several angles, focusing on optimization-based, adaptive, and resilient methods. Thus, this review collects methods that are in line with key developments we see in the development of SPSs. In particular, the article brings forward the following contributions:

- Comprehensive review of the control hierarchy and functionalities for the power system control of full-electric SPSs with DC distribution.
- Structured analysis of coordinated control and energy management strategies based on their method, scope and communication architecture.
- Review of coordinated control and energy management methods for hydrogen-based and hybrid DC SPSs.
- Identification of power system control methods for SPSs that allow an efficient, resilient, and scalable integration of heterogeneous power system resources.

This article is organized as follows. Section II reviews the hierarchy for SPS control, defining control layers and assigning relevant power system control functionalities. Section III introduces approaches to the control architecture, distribution of functionalities among centralized and local control units, and communication requirements. Section IV gives a brief overview of local control functionalities for various power system resources connected to the DC distribution system. Section V defines key goals for the coordinated control and reviews approaches with different aims, architectures and giving insights into important methods. Section VI reviews energy management methods, again emphasizing different control architectures and focusing on optimization-based and resilient methods. Section VII concludes this article with a review of its insights and identification of future trends.

II. CONTROL HIERARCHY

Whereas small-scale power systems can be approached with a comparably simple control strategy, the control architecture in complex power systems is commonly organized in a hierarchical structure. Hierarchical control is state-of-the-art in terrestrial power grids [8], and commonly also adopted in shipboard power grids [1]. Typically, the bandwidth of control loops is increasing towards the lower layers, with real-time control algorithms typically implemented in the component level control.

The literature provides various definitions and nomenclatures for the tasks and scope of control layers. A general description of a standardized three-level control hierarchy in power systems is brought forward by [8], usually adopted in microgrid control [9], [10], [11], and also in several maritime studies [12], [13]. However, other researchers prefer to separate between low-level and high-level control [14], [15] or between local and coordinated control [16]. The coordinated control is further divided into power and energy management in [17]. In this work, we adopt the nomenclature from [17] and [18], differentiating between power system control and a high-level control layer, in which the energy management functions are located. The power system control is further divided into local and coordinated control. Apart from the functionalities, these layers are further separated in their time-scale. Local control typically implements the fastest control loops, whereas coordinated control functions are slightly slower. High-level control, specifically the energy management, acts significantly slower. This hierarchy is sketched in Fig. 1. The tasks, scope and functionalities of these three layers are described as follows.

A. LOCAL CONTROL

On the component level, control-loops for the output current and voltage of power generation, storage systems and controllable loads are implemented. In modern DC SPSs, the current and voltage control is usually realized via a power electronics interface, connecting the component to the distribution bus [1], [19]. Additionally, this layer includes controllers for the components' inner state variables, balance of plant, as well as component level protection functions. The local control is usually encapsulated and does not require communication. However, information exchange with a higher-level is required for receiving reference values and providing local states and measurements.

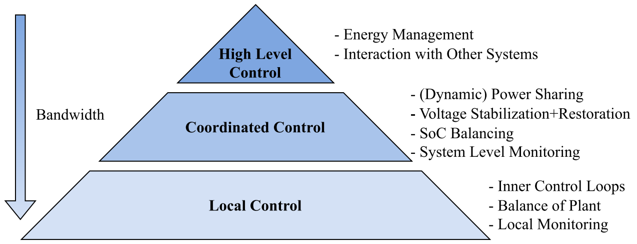

FIGURE 1. Hierarchical control layers and power system control functionalities.

B. COORDINATED CONTROL

The key challenge in the coordinated control is the provision of an instantaneous power balance in the system and to ensure stable operation within system-level operational constraints [1]. This generally includes protection and protection functions. An overview on fault detection, protection and reconfiguration methods in SPSs is described in [20]. This work focuses on the coordinated control for the DC distribution system on ships. A key task is the DC voltage control, encompassing its stabilization and restoration to its nominal value. This layer further includes the power sharing, i,e. the manner how load changes are allocated among power generation components. Here, we differentiate between static power sharing and dynamic power sharing given that heterogeneous system components have different transient capabilities and thus are required to be operated differently at the moment of a load change and in steady-state conditions. Finally, in the presence of ESSs, it is desirable to balance the state-of-charge (SoC) of parallel storage systems. This balancing is typically included in the coordinated control methods as well. The coordinated control acts in the ms-range, with the voltage stabilization and instantaneous power sharing being the fastest functionalities. The dynamic power sharing acts in the s-range, depending on the dynamic capabilities of main power generation devices taking over from fast-acting supply units. Similarly, the SoC-balancing acts in the s- to min, depending on storage capacities and desired balancing speed.

C. HIGH-LEVEL CONTROL

On the high-level control layer, functions for the monitoring, optimization and decision-making in the operation of the system and its interaction with other systems are implemented. In our review, we focus on the energy management as the central functionality in the high-level control layer. The key responsibility of this function is the dispatch of power system resources in order to satisfy the mission requirements, usually with economic or strategic objectives [1]. The energy management strategy (EMS) computes power set-points, operational states, and possibly SoC references to be handled by lower control layers. The energy management functionality covers time scales of min to h, in certain applications covering entire missions. Beyond the energy management, we investigate methods where the optimal dispatch is combined with other functionalities, primarily voyage scheduling [21] and maneuvering control [22], [23], which directly influence the power demand. In most cases, due to the limited size of SPSs, a central controller is preferred for the EMS. Thus, all information can be taken into account for optimal control actions. However, depending on the size and, furthermore, redundancy requirements of a vessel, a distributed approach for the energy management can be feasible as well [24].

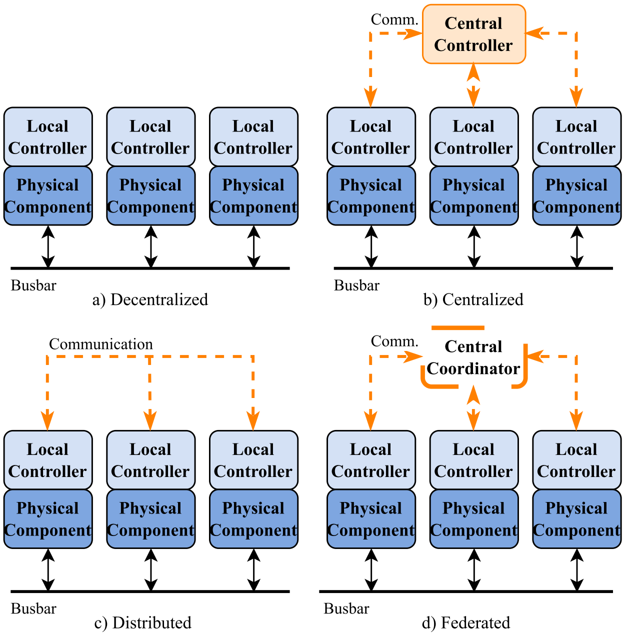

FIGURE 2. Archetypal control architectures, adapted from [19], federated architecture added.

III. CONTROL ARCHITECTURES

The cyber-physical system includes local and centralized controllers. Control architectures differ in how functions are allocated to the controllers and how the communication network between the controllers is established. Different architectures are shown in Fig. 2. The archetypal schemes follow a centralized, a decentralized or a distributed approach. A review of power system control strategies and their categorization into these three schemes is presented in [19] where the focus is on stabilization techniques on the coordinated control layer for DC microgrids. An additional case is realized in a federated architecture, which implements distributed methods, although utilizing a central coordinator for aggregation and monitoring rather than consensus. These architectures are generically applicable for the coordination of multiple components. The challenge in SPSs lies in how their utilization addresses application-specific requirements. Advantages and drawbacks from these architectures, and their possible utilization in maritime applications are put together in Table 1.

A. DECENTRALIZED CONTROL

A decentralized architecture is characterized by a lack of dedicated communication infrastructure. Instead, the system elements operate based on local measurements of system wide quantities, such as bus voltage or frequency [19]. The absence of a dedicated communication network for a coordinated control of the power system makes this approach inexpensive, simple to set up, robust and easily scalable. Especially for primary control in systems with long distances, such as terrestrial power grids, a decentralized control approach is preferred [25]. This architecture is inherently fast and robust to communication faults, making it useful for low-level functionalities, such as voltage stabilization and instantaneous current sharing. Due to the lack of information sharing, adaptive funcionalities and system-wide coordination is limited. Accordingly, this architecture is not suitable for high-level control functions.

B. CENTRALIZED CONTROL

An architecture employing a centralized layout is able to benefit from a central optimization of the energy management or power system control, due to a global information awareness in one central controller [26]. However, such a system requires an extensive communication infrastructure enabling high-bandwidth data exchange between the central controller and all local controllers. Especially in systems that are large in size or amount of controlled components, this can become unfeasible [25]. Furthermore, the central controller and communication network pose a single points-of-failure, leading to a low fault-tolerance of the control system. However, a centralized architecture is beneficial for tight coordination in small-scale systems or subsystems, and for the implementation of highly complex optimization algorithms.

C. DISTRIBUTED CONTROL

In applications where coordination is required but a centralized unit is either not feasible or not desired, distributed control offers a promising alternative [27]. In this architecture, the main computations are implemented locally while a communication network is used for exchanging information. A key for the application lies in the minimization of communication overhead and information exchange. Reference [9] notes that distributed control for coordinated functionalities attracts interest due to its reliability, stability, and facilitation of easy network expansion (plug-and-play characteristic [28]). Reliability challenges and opportunities arising from adopting DC distribution in SPS are analyzed in [2]. Reference [29] discusses the implementation of distributed EMSs as a candidate solution to enhance the survivability and robustness of the power system to meet the increasing requirements in naval vessels. Architectures can be further divided into federated and fully distributed implementations [30]. The former features a central coordinator that aggregates and broadcasts information from distributed units. A fully distributed setup only has communication among local controllers, typically with a sparse network. This setup requires consensus algorithms for determining shared control variables. Both setups have similar advantages and disadvantages. The presence of a centralized unit, as typically given in SPS for system monitoring, operator inputs and interfaces to other systems, facilitates a federated architecture, unless specific resilience requirements necessitate a full distribution.

D. COMMUNICATION NETWORK

One can typically differentiate between high- and low-bandwidth communication networks for the coordinated control in a power system. Information exchange for real-time control of distributed components requires a high bandwidth communication, e.g. in a network with a centralized controller computing power references for all local controllers. The required communication would be expensive, especially with increasing system size and the communication network posing a single point of failure [31]. Alternatively, a low-bandwidth (LBW) communication network can be used for the exchange of information, while real-time control functions are implemented locally, shaping a federated setup. For instance, [32] uses low-bandwidth communication to realize adaptive functionalities in a central controller, so a communication failure would only result in a loss of adaptability. Distributed control architectures typically use low-bandwidth communication for implementing consensus-based algorithms [33], [34], [35], completely bypassing a central coordinator. Moreover, decentralized control can be considered to be communication-less, using only the DC bus voltage as information carrier [36].

IV. LOCAL CONTROL

The various power system resources in a DC power system are typically interfaced by a power converter, depending on the source type. Most relevant zero-emission technologies, e.g. FCs, batteries, capacitors, provide a DC output and are therefore connected with a DC-DC converter. This is typically a uni- (for power supplies) or bi-directional (energy storage) boost converter. In order to regulate the output of the source, the power electronics interface is current or voltage controlled, depending on the chosen strategy. Furthermore, component- or converter-specific local constraints, e.g. on the current, voltage or ramp rates are respected by the local control. A recent review on advanced control strategies for DC-DC converters in DC systems is presented by [37].

The common approach for tracking the current reference in power electronics converters is via cascaded proportional-integral (PI) control and pulse-width modulation (PWM) to set the voltage, which is easy to implement and tune. However, for systems with specific requirements for high control accuracy or robustness, more advanced methods might be required [38]. Especially non-linearities in the components lead to instabilities and performance degradation with conventional methods. Reference [39] reviews various non-linear control strategies for DC-DC converters to stabilize the DC-grid voltage under the influence of constant power loads (CPLs). Reference [40] proposes a modified

TABLE 1. Key advantages, disadvantages and applications of control architectures.

	Decentralized	Centralized	Distributed
Advantages	-Fast response -Robust to comm. faults	-Globally optimal -Full coordination possible	-High adaptability -Scalable and maintainable -Privacy-preserving, vendor-agnostic
Drawbacks	-Limited coordination possible -No system-wide interaction Adaptation only local	-Full system knowledge required -Single point-of-failure -Communication-heavy -Poor scalability	-Limited to specific problem types -Response speed limited by communication and convergence
Applications	-Voltage stabilization -Power sharing -Emergency/fault-ride-through	-Supervisory control -Tight coordination for integrated SPS/subsystems -Complex optimization problems	-Large-scale/multi-zone SPS -Coordination of heterogeneous units -Plug-and-play integration -SPS with high resilience needs

PI-based dual loop controller that acts on the energy in the bus rather than the voltage to eliminate the non-linearities of CPLs.

A popular method for the control of DC-DC converters is sliding-mode control due to its robustness when implemented in non-linear systems. Reference [32] employs such a controller to track the reference output voltage and current in a DC-DC converter interfacing an ESS.

Reference [38] uses distributed MPC controllers for the current control of DC-DC converters which serve as interfaces for photovoltaic (PV) and FC systems to the DC-link. This solution is presented as an alternative to classic PI control and uses a simplified model predictive control (MPC) with a prediction model for the inductor current. A prediction horizon of one switching period is implemented where the control inputs are chosen so that the deviation from the reference current is minimized. Reference [41] additionally presents local MPC controllers for batteries and diesel generators (DGs). A challenge for MPC arises from the high computational requirements in real-time control, especially with increasing complexity and prediction horizon of the optimization problem.

The researchers in [42] investigate the accuracy of control algorithms for the DC-DC converters in a DC power system. In a case study, the boost converter supplying a CPL is investigated and a sliding-mode controller-based fuzzy-logic approach is proposed for the current control. A conventional PI controller and an MPC approach are used as benchmark solutions and it was shown that the approach yields significantly improved power and voltage tracking and stabilization under changing operation conditions.

The reference values for current and voltage control of the distributed components is dependent on the source-dependent functions. While main power supplies and ESSs are typically involved in the coordinated control for power sharing, auxiliary power supplies, especially renewable energy sources (RESs), are often operated with maximum power point tracking [6], [43]. However, curtailment of RESs can be a supportive function in the system stabilization [14].

Loads are subject to inputs from the user or a high-level control layer. The current of power electronics interfaced loads is tightly controlled, making them appear as CPLs to the DC system [39], [44]. Load limiting control can be utilized as a tool in power system control by degrading the height or gradient of the power demand [22], [45], [46].

A challenge with many advanced DC-DC converter control strategies is their scalability. Complex stabilization methods that are designed for a single power supply are not applicable to multiple parallel supplies, and much less for a modular power system with heterogeneous resources.

V. COORDINATED CONTROL

As already outlined in section II, the primary objective of the power system control is to maintain operational constraints, e.g. voltage stability and power availability, and to achieve an accurate steady-state and dynamic power sharing [47]. With the introduction of ESSs, the management and balancing of their SoC has become an additional challenge. The parallels between SPSs and islanded microgrids are regularly pointed out in the literature, however, the challenge of power system control in SPSs meets additional, specific challenges [48]. E.g., high load fluctuations and environmental influences as well as short lines with low impedances are notable differences. Moreover, ships have to deal with specific reliability and power quality requirements. In the following, the challenges for the coordinated control to achieve power sharing and voltage stability in SPSs are summarized:

- *Fluctuating loads and intermittent generation:* An essential difference between shipboard and terrestrial power systems is the high amount of fluctuating loads in the MW-range [48] for propulsion and service equipment. It is important to maintain sufficient quality of power supply while ensuring power availability. While terrestrial grid applications focus on steady-state power sharing, an efficient dynamic power sharing is a necessity in SPSs. Reference [49] points out that intermittent generation from renewables effectively functions as a negative load, since these are typically current-controlled to supply maximum power. Although rarely used in SPSs, these sources can further de-stabilize the power system.
- *Constant and pulsed power loads:* One major challenge for the stability in DC power systems is the presence of

CPLs [23]. These are tightly regulated loads which draw a constant power, resulting in an increasing current when the DC-link voltage falls [39]. This problem is reviewed in detail by [44] who furthermore presents strategies for the mitigation of effects from CPLs. Another type of load, which is extensively discussed in the literature, are pulsed power loads. Especially in the naval field, advanced weaponry systems and sensors have a high, intermittent power draw with a detrimental effect on power system stability [28]. Mitigation methods for these adverse effects of pulsed loads are accordingly studied in several works [50], [51].

- *Energy storage integration:* The integration of ESSs means a fundamental shift from conventional SPS designs, enhancing the operational capabilities of the overall power system. ESSs differ in their characteristics. In [52], functions for ESSs in maritime applications are defined and corresponding requirements for their energy and power density, as well as the need for coordinated control strategies, are derived.
- *Lack of inertia:* Systems with a high share of converter-interfaced generation and low inertia are particularly susceptible to voltage instabilities. Hence, suitable strategies for stabilizing the grid are needed [53], [54].
- *Quality of power supply:* [55] mentions frequency and voltage deviations and harmonic distortions as main challenges for the coordinated control in ships. Power quality is increasingly becoming important as a design target for ships [28]. An extensive review on power quality and energy efficiency issues in maritime microgrids is conducted in [56].
- *Fault handling:* Depending on specific reliability requirements, the power system is required to ride through fault scenarios. For this reason, the coordinated control needs to mitigate the effects from faults and re-establish stable operation [43], [45].
- *Heterogeneous capabilities:* A decisive factor in the coordinated control is the consideration of differing characteristics of power sources and storage systems [1]. Power sources, such as conventional DGs and FCs, have low dynamic capabilities and are preferably operated in their efficient operation range. ESSs show varying power and energy characteristics, hence both their available power, power gradients and SoC range play an important role in their optimal utilization [57].
- *Component degradation:* The lifetime of many components is influenced significantly by their operating profile. Especially FCs [58], [59] and batteries [57] are susceptible to degradation and costly to replace. Hence, lifetime prolongation, by keeping their power output and the batteries' SoC steady and within an efficient range, is key for the reduction of operating costs [1].

Additional challenges and opportunities arise from the inclusion of ESSs, whose design is driven by their targeted functionality, e.g. load levelling, ramp support, power backup, spinning reserve, etc., [52]. To achieve these, ESSs are typically designed as high-power or high-energy components [57], whose operation should be reflected in their utilization in the power system control. Further, the simultaneous integration of both ESS types as a hybrid energy storage system (HESS) is possible to provide a broader range of functionalities [60]. High-power energy storage systems are essential for meeting high load fluctuations, ramp support and providing reserve power. High-energy systems provide buffer to enable strategic charging, optimal loading of generators, backup power, and ESS-only operation. Challenges for the power system control that arise from the ESS integration is the SoC management of individual units, as well as the SoC balancing among parallel units. As described in section III, control approaches can be categorized into centralized, decentralized and distributed methods. In the following, common approaches for coordinated control in DC SPSs with power electronics interfaced generation, storage and load components are reviewed. The main question here is what methods are appropriate to overcome the prevalent challenges for power system stability and efficient power sharing in DC SPSs and what conclusions we can draw for coordinated control in zero emission ships (ZESs). The focus of this overview lies on methods for (dynamic) power sharing, voltage restoration, and SoC balancing. Overviews of their applications in SPSs are listed in Tables 2, 3, 4, and 5.

A. DECENTRALIZED COORDINATED CONTROL

A common decentralized method for power sharing in microgrids is droop control. Various modified droop methods are commonly used for load sharing and system stabilization as part of primary control [25], and typically implemented as a P/V or I/V droop in DC power systems [1], [53]. This method uses the DC bus voltage as information carrier. However, challenging issues are unknown line impedances, inefficient dynamic power sharing and a residual bus voltage deviation. This method is easy to set up with the droop gain of generators normally proportional to their power rating [19]. As noted by [13], conventional droop control for power sharing and voltage stabilization is not recommended in diesel-dominant systems due to the efficiency drops and slow transients of the internal combustion engine. This can be extended to ZESs with FC systems which should preferably be operated steadily and within their optimal operation range.

Reference [61] presents a decentralized droop for power sharing between parallel DGs in an SPS, embedded within a hierarchical control scheme. However, as noted in [13], limitations of conventional droop arise due to efficiency drops at off-design conditions and low transients of the DGs. In addition, droop control leads to inefficiencies in dynamic conditions and the power sharing problem becomes more complex as soon as power generation and storage with differing dynamic characteristics are added. To handle this, different component types are equipped with specific local

TABLE 2. Power sharing approaches in DC ships.

Power System	Communication	Method	Ref.
DG	Decentralized	Droop	[61]
DG-Bat	Decentralized	Droop	[62]
GT-Bat-UC	Decentralized	Inverse droop	[13]
GT-Bat	Federated	Adaptive droop	[63]
DG-Bat-CI	Federated	Adaptive droop	[48]
DG-Bat	Federated	Adaptive droop	[64]
Bat	Federated	Adaptive droop	[32]
Bat	Federated	Adaptive, local PI	[40]
GT-FC-Bat	Centralized	PI	[65]
DG-Bat	Centralized	Master-Replica	[66]

TABLE 3. Voltage restoration approaches in DC ships.

Power System	Communication	Method	Ref.
DG-Bat	Decentralized	Local PI loop	[70]
GT-Bat-UC	Decentralized	Local PI loop	[13]
DG	Centralized	Central PI loop	[61]
GT-FC-Bat	Centralized	Central PI loop	[65]
FC-Bat	Federated	Adaptive local PI	[40]
DG	Distributed	Voltage shifting	[34]
Bat-PV	Distributed	Voltage shifting	[35]

controls, depending on their characteristics. References [13] and [62] assign low or even zero gain to DGs and FCs, leaving the batteries to cover large power mismatches. These schemes then rely on the EMS to provide an efficient references for the main power supplies. Various methods for power sharing in DC SPSs are listed in Table 2, which shows that this functionality is dominated by decentralized methods utilizing various types of droop control with a trend towards adaptive implementations.

These droop control schemes with virtual resistances are primarily designed for steady-state power sharing, which is inefficient under fluctuating loads. To mitigate this, [67], [68] propose a virtual impedance to achieve a frequency separation, based on the dynamic characteristics of power system components. Accordingly, fast-response components, e.g. high-power batteries or ultra-capacitors (UCs) can react immediately to voltage deviations, while energy-dense technologies, e.g. DGs or FCs, can be tuned to change their output efficiently, matching their capabilities. Reference [69] uses virtual capacitances for UC control in a DC microgrid for stabilization under surge loads, showcasing the plug-and-play capability of this approach.

The remaining voltage deviation created by droop control is not necessarily critical, but can lead to undesired side-effects. A decentralized method for voltage restoration is via local PI controllers [13], [70]. Table 3 lists applications for the voltage regulation in DC ships. However, fully decentralized control for the voltage restoration with multiple parallel units is challenging due to stability issues and circulating currents. The overall trend indicates a utilization of a centralized unit for aggregating information and update references for the distributed controllers to realize the voltage restoration in a coordinated fashion.

TABLE 4. SoC balancing approaches in DC ships.

Power System	Communication	Method	Ref.
DG-Bat	Decentralized	Adaptive Droop	[70]
FC-Bat	Decentralized	Adaptive Droop	[74]
GT-Bat	Federated	Adaptive Droop	[63]
DG-Bat-CI	Federated	Adaptive Droop	[48]
DG-Bat-UC-flywheel	Federated	Current Correction	[67]
Bat	Centralized	Voltage shifting	[32]
Bat-PV	Distributed	Voltage shifting	[35]
Bat-PV	Distributed	Adaptive Droop	[75]

In addition to power sharing and voltage regulation, the balancing of SoCs among parallel ESSs is required. One option is to employ adaptive droop coefficients based on each storage's SoC [71], [72]. This approach is quite popular in the maritime sector for power sharing and voltage stabilization as observed in [48], [63], and [70]. The virtual impedance of the droop controllers is adjusted based on the SoC so that batteries with a high charge contribute more to the power sharing. In [73], this approach is extended to a DC seaport microgrid for communication-less power sharing among multiple ships. As an alternative to adapting droop coefficients, SoC management can be done by voltage switching [35] or current correction [67]. However, for improved accuracy, these approaches usually include aggregated information, e.g. average SoC, from a federating agent. The virtual impedance-based approach complemented by a centralized voltage restoration loop is applied to FC-battery hybrid SPSs in [74]. For fully catering to a modular power system with heterogeneous components with individual characteristics and states, the existing methods require further extension to enhance their adaptability and resilience without compromising performance. Different strategies for SoC management are summarized in Table 4. Similar to the voltage restoration, the majority of the approaches utilize an aggregation of SoC information to realize the balancing, although fully decentralized implementation is shown to be possible with proper tuning of the adaptive droop.

B. CENTRALIZED COORDINATED CONTROL

The availability of information in a central controller with high-bandwidth communication enables a more efficient coordination of all power system components. Reference [61] implements a central PI controller for voltage restoration by adjusting the output voltage of the synchronous generators, while power sharing is still realized through droop control. Similarly, in [65] a central PI controller determines the required total DC-link current for stabilizing the voltage. This current is split over the power sources based on a given ratio from an EMS. An application of power sharing with a central controller, implemented in a master-replica configuration with the ESS controller as master, is shown in [66]. The power sharing is taken over by the energy storage devices while the main supplies can operate in their efficient operating point.

TABLE 5. Dynamic power sharing approaches in DC ships.

Power System	Com.	Method	Ref.
DG-UC	Decentralized	Complex Droop	[69]
Bat-UC	Decentralized	Complex Droop	[68]
DG-Bat-UC-FW	Decentralized	Complex Droop	[67]
FC-Bat	Decentralized	Complex Droop	[74]
DG-Bat-UC	Centralized	Load-filtering	[76]
Bat-UC	Centralized	Load-filtering	[31]
DG-Bat-UC-PV	Centralized	Load-filtering	[49]
GT-Bat-UC	Centralized	Load-filtering	[13]
FC-Bat-UC	Centralized	Adaptive load filter	[78]
DG-Bat-UC	Centralized	Load filter with constraint handling	[79]
FC-Bat-UC-PV	Centralized	Wavelet transform	[49]
DG-Bat-UC	Centralized	PI loop	[31]

Constraints on the SoC of the ESS are disregarded here, and this approach requires a sufficiently sized storage to function efficiently.

A frequency-based separation of the load power in order to assign differing frequency bands to generating devices with differing response times is presented in [76]. A series of low-pass filters is employed to compute power references with differing band-widths to DGs, batteries and UCs, according to their capabilities. In a HESS, the component-level controller typically coordinates both integrated ESS in a centralized fashion for the subsystem. The methods employed for this task can generally be extended for the coordination between main power supply and ESS. Reference [31] uses a filter-based approach for separating high frequency load fluctuations to be mitigated using the UC while a battery is covering low frequency load changes. Here, the load power is directly transferred to power references. Similarly, [49] employs a HESS with load frequency-separation in order to mitigate effects of fluctuating PV generation. In the same fashion the frequency separation of load fluctuations is achieved using a wavelet transform in [77] where a semi-active HESS topology is used. In [13] the filter-based approach is combined with an underlying droop control for parallel connected HESSs. In [78], the filter-based references are additionally modified to meet power and SoC constraints of battery and UC. An alternative approach aiming for voltage stability is proposed in [31] where deviations from the DC-link reference voltage are used to generate PI-controlled current references for the battery and UC. Table 5 lists the described methods for dynamic power sharing in DC SPSs. An overarching trend in dynamic power sharing approaches is the implementation of filtering either directly in a centralized or through complex droop gains in a decentralized architecture.

C. PREDICTIVE COORDINATED CONTROL

Several researchers investigate the utilization of predictive control for optimal coordination of power system resources by explicitly formulating control objectives and constraints and leveraging predictions. MPC is able to realize multiple functions simultaneously, e.g. dynamic power sharing and voltage regulation. In [23] the stabilization of the DC-link voltage with MPC under the effects of CPLs and sudden changes in loading conditions of a diesel-electric power system is demonstrated. Load forecasts are obtained from a higher-level motion controller. An extension to a battery hybrid system is shown in [41], implementing a multi-level MPC. Here, a system-level MPC computes current set-points for all components, which are tracked by component-level predictive controllers. Reference [80] expands the problem formulation to holistically include system efficiency, component wear, thrust production and DC voltage deviations. Reference [81] conducts a joint optimization of switching actions in parallel active front-end (AFE) rectifiers and DC-DC converters to minimize the deviation from power and voltage setpoints.

TABLE 6. Predictive coordinated control in SPSs.

Power System	Scope	Ref.
DG-FC-Bat-PV	Local current control	[38]
DG-Bat	DC voltage stabilization and local current control	[41]
Bat-UC	Voltage stability and loss minimization	[60], [82]
DG	DC voltage stabilization with CPL	[23]
GT	Non-linear MPC for stability under pulsed loads	[50]
DG-Bat	Non-linear MPC for power smoothing using load power spectral density	[85]
DG-Bat	Adaptive MPC for stability and loss minimization	[80]
DG-Bat-UC	MPC with short-term load prediction for loss minimization	[86]
GT-Bat-UC	Voltage stability under pulsed loads	[51]
DG-Bat-UC	Adaptive MPC for prediction and mitigation of torque fluctuations	[80]
Bat-UC	Stability, Loss Minimization, SoC tracking	[83]
DG-Bat	Voltage stability	[81]
GT-Bat	mixed integer linear programming-based MPC for load shedding and mode switching	[87]

MPC also receives much attention for the control of HESSs. Proposed methods for HESS control can also be expanded to systems incorporating a broader variety of technologies. Reference [82] coordinates the power flows with a battery and UC using an MPC with the aim of minimizing the total losses of the HESS while keeping the system states within its defined boundaries. Reference [83] proposes a real-time MPC approach for addressing both fluctuating loads as well as pulsed power loads. This work is later expanded upon by an adaptive MPC considering uncertainties of the HESS parameters [84].

Reference [50] uses MPC for real-time generation control of gas turbines (GTs) and voltage stability of a naval DC power system with pulsed loads. The power system analyzed in [51] additionally incorporates a HESS to improve voltage stabilization and load leveling for the main power supplies. The results show that such an approach is effective in providing voltage stability under extreme load fluctuations while keeping system variables within defined limits. Various studies on MPC for coordinated control are summarized in Table 6. This overview shows that MPC on this layer is typically implemented centrally and aims at stabilizing the systems under specific challenges, such as CPLs or pulsed loads.

D. DISTRIBUTED COORDINATED CONTROL

Whereas the previously mentioned approaches rely on a high-bandwidth communication and computation in a centralized controller, concerns for system scalability, reliability and survivability constitute the development of distributed approaches. In [33], power sharing in a DC microgrid is implemented in the local controllers, enhanced by low-bandwidth information exchange via a common bus. Reference [88] describes how cooperative control can be employed in DC microgrids, e.g. for voltage restoration.

Reference [34] presents a hierarchical control scheme with distributed voltage regulation for a medium-voltage DC power system with parallel DGs. Power sharing is decentralized via droop control, while a consensus-based algorithm introduces corrective terms on the output voltage reference of the rectifiers to regulate voltage and increase fuel efficiency of the engines. An application for distributed control using a multi-agent system for power sharing and balancing of SoC among distributed ESSs is presented in [35]. Through communication with neighboring ESSs and a consensus algorithm, agents estimate the average SoC and DC-link voltage in the system. An underlying droop control scheme is extended using these system wide variables for SoC balancing and DC bus voltage regulation. In [89], cooperative consensus is used to realize SoC balancing, voltage restoration and power sharing among parallel ESSs. Next to consensus algorithms, cooperative diffusion for DC microgrids trades exactness for improved stability and faster convergence [90]. Table 7 lists distributed approaches for coordinated control in SPS. The application is specifically applicable in systems with multiple parallel ESS or conventional units and is mostly used as an alternative to centralized loops for SoC management, voltage stabilization and accurate current sharing.

TABLE 7. Applications of distributed coordinated control.

Power System	Scope	Ref.
-	Consensus to ensure accurate power sharing and voltage regulation in DC microgrids	[33]
GT-Bat	Distrib. PSO for power reference tracking in naval ships	[91]
DG	Consensus on voltage regulation and power sharing for parallel DGs	[34]
ESS	Consensus on SoC balancing and voltage regulation	[35]
ESS	Consensus on unified state factor for SoC balancing, voltage regulation and current sharing in DC microgrid	[92]
ESS	SoC balancing, voltage regulation and current sharing via multi-objective fusion and dynamic diffusion	[93]
ESS	SoC balancing and voltage regulation via cooperative consensus	[89]
-	Voltage regulation and current sharing via distributed diffusion	[90]
GT	Unified power tracking and voltage control for improved transient response	[94]
GT-Bat	Dynamic power allocation under ramp-rate and servicing constraints via ADMM	[95]

E. COORDINATED CONTROL IN ZERO-EMISSION SHIPS

Among applications of power system control in ships using fuel cells, e.g., [65], [79], and [96], it can be observed that FCs are preferably not participating in voltage stabilization due to their limited transient capabilities. Instead, it is necessary to combine fuel cells with more dynamic technologies, typically batteries [96] or HESS [79].

Studies considering the coordinated control with FC systems are usually focusing on the power balance in a small-scale or simplified systems consisting of a single FC and one ESS. For instance, [97], [98], propose a PI-based power system control for distributing the load power to the FC and battery. Such an approach is only applicable for a small system with a central controller. Hence, scalability to a larger system with parallel power generation is not given. Furthermore, the FC serve as quasi-steady current sources in these studies, while voltage stability and fast load fluctuations are responsibility of the batteries. Methodologies for coordinated control in diesel-electric (e.g. [61]) and diesel-hybrid systems (e.g. [13]) can potentially be adapted to FC-hybrid systems, with alterations catering for the changed characteristics of the main power supply and accounting for the replacement of rectifiers by DC-DC converters. Also, methodologies for the control of HESSs, such as [83], do not consider the main power supply and are, therefore, applicable to ZESs as well.

For future research, it will be necessary to investigate the coordinated control in ships with multiple parallel FCs as main power supplies as a prerequisite for utilizing this technology as sole power sources in more complex ZESs. It can be expected that various ESSs and possibly RESs and demand-side management need to be considered for an efficient coordinated control. Hence, with SPSs incorporating a broader spectrum of power system technologies, the approach for coordinated control should adapt to the available power system resources. A control architecture that accounts for the modular integration of technologies with differing characteristics facilitates the adoption of new technologies and scalability of the system. Furthermore, it benefits the system's reliability and adaptability for handling uncertainties, e.g. component faults, parameter alterations, and topology changes.

VI. ENERGY MANAGEMENT

An efficient energy management is a major challenge in maritime vessels with multiple energy sources, especially with a heterogeneous set of components [99]. Dedicated EMSs are typically situated on the high-level control layer. However, energy management functionalities can also be intertwined with the coordinated control, blending the boundary between the functional layers. This section presents the challenges for energy management in SPSs and which functionalities it covers. We then provide a classification of methods and finally present a review of applications for different energy management methods and architectures.

A. CHALLENGES FOR SHIP ENERGY MANAGEMENT

EMSs are applied in various systems with unique characteristics and challenges. In automotive applications and terrestrial power systems, energy management has been much discussed. In the following, we discuss challenges in these sectors and how they relate to shipboard EMSs.

1) ENERGY MANAGEMENT IN AUTOMOTIVE SECTOR

It is worthwhile to investigate which methods are applied in other fields in order to assess what the maritime sector can learn from them. The challenge of optimizing the power split for SPSs has similarities to the challenge in the automotive field [100]. Especially relevant is the research on hybrid electric vehicles, incorporating combustion engines and batteries [101], [102], as well as FC-powered vehicles [58], [103]. In fact, many of the methods we see in maritime applications today originate in the automotive field, such as equivalent consumption minimization strategy (ECMS) [104], sequential dynamic programming (SDP) [58] and applications of predictive control [105].

Nevertheless, it must be noted that there are several distinguishing characteristics between maritime and automotive applications. Hence, the challenge differs and methods need to be adapted. Key differences are listed here:

- Larger variety and number of generation and storage devices in SPSs than in vehicles [106], where one main supply and an optionally an ESS are standard [107]. The coordination of multiple parallel generators and storage systems increases the problem complexity [17].
- Different reliability requirements, standards and legislation apply [56]. Hence, there are unique operational requirements for ships [108].
- Vastly different power ratings between vehicles (kW-level) and ships (MW-level). Automotive systems primarily supply traction power [109], whereas ships often feature service equipment with high and specific load profiles [110]. Consequently, load ramp rates are significantly higher and follow different patterns [82].
- The EMS in hybrid electric vehicles relies heavily on the ability to regenerate energy under braking, which cannot be applied to a significant effect in ships [57], [107]
- The load requirements in ships are heavily influenced by environmental factors, e.g. wind and waves. In addition, large drive shaft torque fluctuations occur at wave frequency and propeller rotational frequency [82].

2) ENERGY MANAGEMENT IN MICROGRID APPLICATIONS

The topology and technology in SPSs shares some resemblances with terrestrial microgrids, especially islanded microgrids [55]. Hence, both coordinated control and EMSs from such applications serve as an additional reference for control in ships. Reference [111] provides an overview of heuristic and optimization-based approaches for the EMS in terrestrial microgrids as well as a brief review of control architectures. For residential microgrids, in which the use of distributed energy sources and smart control systems are vital, the energy management problem is analyzed by [112] and [113]. However, once again it is important to point out the decisive dissimilarities in the challenge between microgrid and maritime applications. SPSs typically need a tighter coordination of power system components and subsystems, and feature different objectives, which influence the choice of control methods and architectures. Furthermore, different standards, legislation and reliability requirements apply [56], [108]. SPSs need to supply high power gradients and continually fluctuating loads [55], while their design is subject to limited space requirements and constant movement of the ship [114], [115]. Finally, ships follow a mission-based operation profile with distinctive tasks and a limited duration [56], whereas microgrids need to provide power indefinitely and usually follow a stochastic load distribution [9].

3) ENERGY MANAGEMENT FOR SHIPS

In SPSs, a broad variety of different EMSs and methods can be found, many of which are application-specific. The following overview aims at providing an overview of general approaches and challenges in the energy management.

a: POWER SPLIT BETWEEN PARALLEL MAIN POWER SUPPLIES

A key challenge for the energy management is the allocation of power generation among parallel power supplies, conventionally, DGs or GTs, whereas in a hydrogen-based ship, FC systems are the predominant technology. A conventional approach is the tuning of droop gains to ensure proper balance of load and generation while operating generators according to their power ratings [13]. Similarly, [61] employs virtual impedance control-based on generator ratings as a method for an efficient steady-state power split among DGs. For improved efficiency and adaptability and incorporating further objectives, e.g. emissions and component wear, more elaborate strategies are needed. Those are discussed below, among the optimization-based techniques.

b: POWER SPLIT BETWEEN MAIN POWER SUPPLY AND ESS

The EMS becomes significantly more complex by the introduction of ESSs. A large amount of studies on energy management in all-electric ships focuses on the utilization of ESSs to assist the power generation for minimal operation costs or fuel consumption. A common aim when managing power flows between battery and the main power supply is to level the load profile of the main supply so that it can operate in its efficient loading. Reference [70] proposes to operate DGs at their rated power and leave voltage regulation and thereby all fluctuating loads to the batteries. In [48], the power allocation between diesel generators and batteries is using a rule-based approach, aiming at operation of DGs with a steady profile within an efficient operation range. Power fluctuations and deviations between DGs and loads are covered by the battery packs. For the ESSs, an additional set of rules is employed to manage their SoC. Reference [43] uses a rule-based approach for determining the charge and discharge of the ESSs. Such rule-based approaches are often implemented as decision trees, whose output is based on net power demand and SoC of the ESSs [38], [43]. Another possibility to leverage expert knowledge is to employ a fuzzy logic controller in the EMS. Similar to rule-based approaches, the inputs to the controller are usually the power demand and SoC, yielding an efficient instantaneous power split [116]. In [117], a fuzzy logic control strategy is applied to a small diesel-battery ship. As an alternative to expert knowledge, [77] uses an offline optimization for the fuzzy logic design.

c: ON-OFF SWITCHING OF MAIN POWER SUPPLIES

A key decision in the operation of each individual component is their on- and off switching, which poses an integer-valued decision variable. Conventionally, the state reference is determined heuristically through rules or more recently using fuzzy control. Reference [118] presents a methodology to determine an optimal number of running generators so that the loading and consequently fuel consumption of each generator is optimized. For FC systems there generally is a trade-off between component wear and system efficiency [119].

d: POWER SPLIT BETWEEN FC AND CONVENTIONAL POWER SUPPLY

A further issue arises in SPSs where different types of power supply systems are integrated. Such is the case when combining FC systems together with conventional power supplies. A power system design with DG and FC is proposed in [38]. However, the FC is serving as an auxiliary power supply in this study by providing a constant power at the system's maximum efficiency. Such a solution can be beneficial for retrofits so that the original EMS of the diesel-battery hybrid system can be kept. Reference [120] investigates the EMS for a dredging vessel incorporating FCs together with GTs and batteries. In this approach, power fluctuations are covered by the ESSs, as in a normal hybrid system. The remainder, a moving average of the load power, is split between gas turbines and solid-oxide FCs, so that the instantaneous equivalent fuel consumption is minimized, resembling an ECMS.

e: RENEWABLE ENERGY INTEGRATION

One special type of power system resource is given by RESs. Their power profile is subject to environmental conditions and therefore intermittent rather than controlled. The maximum power point tracking of RESs yields a stochastic power output, which can be seen as a negative load. In [38], which investigates PV integrated in the SPS, the EMS aggregates the power demand and RES generation to a net power load. In [115], the fluctuations of PV generation are estimated and the ESS is sized and operated to compensate for the fluctuating generation, hence explicitly anticipating the renewable energy influx. A further means to account for the uncertainties related to renewable energy generation is to employ a predictive energy management strategy as shown in [121].

f: VOYAGE AND PROPULSION CONTROL

One promising addition to the energy management problem is the inclusion of voyage or propulsion control. A joint optimization of both control levels offers the possibility to adapt the propulsive load demand in a manner which is beneficial for the energy management. For instance, the propulsion control can flatten load gradients or shift load peaks. Reference [18] optimizes the propulsion shaft speed and load demand of a ship-based on a reference trajectory and predicted environmental uncertainties. This consequently has an influence on the energy management by providing a load forecast and smoothing the load profile. In a similar fashion, [22] proposes an MPC formulation for maneuvering control through trajectory tracking. The work aims at optimizing the ship's voyage for maximum efficiency.

B. CLASSIFICATION OF METHODS

In the literature, a plethora of differing approaches for optimal and robust EMSs can be found. Reference [100] points out the similarity of the energy management problem for ships and hybrid-electric vehicles. The research literature on EMSs in the automotive sector is significantly more extensive than for maritime applications. Moreover, additional references for EMS solutions can be observed in power system, building and microgrid applications [111], [112], [113]. Many authors attempt a classification of these methodologies [100], [122]. However, varying definitions of the energy management functions and the broad variety of differing EMS designs make an exhaustive classification challenging. The aim in this review is to provide an overview of common and promising approaches for designing the EMS, with a specific interest for

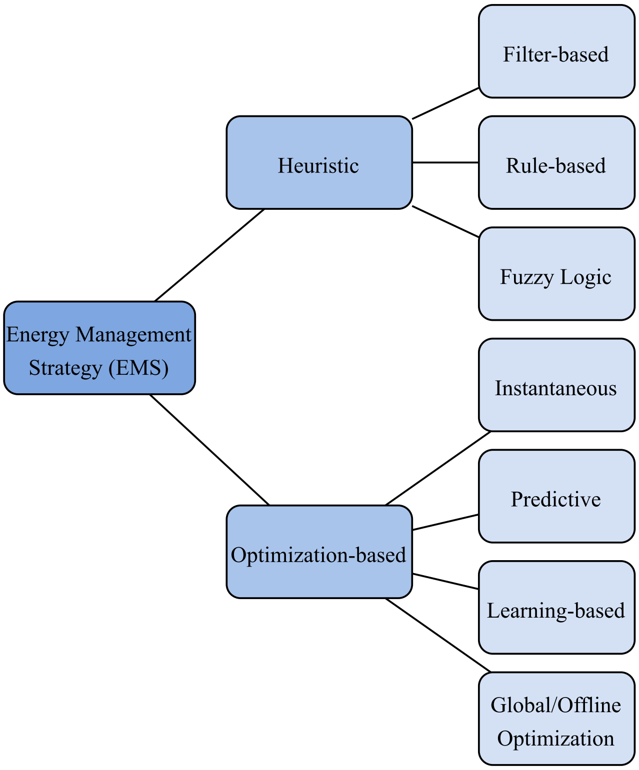

FIGURE 3. Classification of energy management strategies.

solutions in all-electric ships and utilization of FCs. A generic classification is shown in Fig. 3. The methods can generally be divided into optimization-based and rule-based or heuristic approaches [17]. Heuristic or rule-based approaches can further be split into state-based, PI-based and fuzzy logic-based approaches [102], [123]. These approaches are usually simple, easily implemented and computationally efficient. However, the design and consequently the performance of these approaches rely heavily on human experience as input. Some approaches incorporate adaptive features to overcome their shortcomings in performance [102], however, for complex and novel systems a more elaborate EMS is required.

Among optimization-based methods, a differentiation must be made between global or offline-computed and real-time applicable methods. Real-time solutions include instantaneous methods, such as an ECMS [12] or SDP [58], [122], which do not require any knowledge about the future mission profile. In contrast to these approaches are predictive methods which incorporate knowledge or predictions of future states and use results from explicit optimization for real-time control of the system [9]. This is especially interesting for energy management challenges with load predictions [124]. Moreover, learning-based and data-driven control add to the possible approaches for an optimized energy management in ships [100].

Global optimization is possible for offline computation of the optimal dispatch of energy resources. Methods include classic analytical, numerical (e.g. dynamic programming) and meta-heuristic approaches. Even though the online application of a pure global optimization is not possible, their outputs can be used for the design of an online EMS or these methods can be combined with predictive and learning-based control approaches. Using knowledge from global optimization in a real-time application is e.g. proposed for future research in [17]. Finally, offline generated control inputs can serve as a benchmark for the performance of real-time strategies.

C. APPLICATIONS

As described above, a main distinction can be made between conventional and optimization-based energy management methods. Conventional energy management strategies, mainly consisting of rule-based, deterministic and fuzzy logic formulations, are listed in Table 8. The overview shows that a key decision-making for a beneficial power split lies in the utilization of the ESS, typically utilizing information on load power and SoC. More advanced applications of energy management for ships use optimization-based methods. In the following, we present applications of instantaneous and predictive optimization, as well as investigations that study distributed control architectures. Finally, we investigate applications of various methods for zero-emission vessels.

1) OPTIMIZATION-BASED ENERGY MANAGEMENT

Optimization-based control methods can be characterized on whether they are instantaneous or predictive. Applications of instantaneous optimization predominantly focus on the challenges of optimal loading of parallel power supplies as well as the power split between main power supplies and ESSs. A minimization of the instantaneous fuel consumption in a diesel-electric ship is proposed in [118], where ESSs are used to shift the total power demand for the generators for minimizing their specific fuel consumption. The predominant optimization-based approach for instantaneous allocation in hybrid systems is ECMS [101], [125], [126]. An application of this method to a battery-hybrid SPS is proposed in [127] and [128]. The equivalence factor, describing the cost ratio between power from the main supply and the ESS, can be adapted based on the SoC in order to manage the ESS's charge [129]. Reference [130] expands the ECMS with an additional cost term for the degradation of the ESS. An overview of optimization-based EMS for ships is provided in Table 9. Most of the listed methods focus on the challenge of hybrid SPS where the challenge evolves around both the power allocation and SoC management. ECMS-type algorithms are popular in hybrid systems for deriving the optimal power split between power generation and ESS deployment. The focus mostly lies on reducing the fuel consumption of the main power supplies.

2) PREDICTIVE ENERGY MANAGEMENT

Predictive methods can be employed to leverage knowledge on future system states and disturbances. MPC allows

TABLE 8. Heuristic energy management in ship applications.

Power System	Method	Scope	Ref.
DG	Virtual impedance	Steady state power sharing	[61]
DG-Bat	PI loop	Voltage regulation by ESS	[70]
DG-Bat-CI	Rule-based	Power split for DG and ESS	[48]
DG-FC-Bat-PV	Rule-based	Power split for DG and ESS	[38]
DG-Bat-RES	Rule-based	Charge-discharge of ESS and fault-tolerant operation	[43]
DG-Bat	Fuzzy logic, PSO	Power split for DG and ESS for DG and ESS with param. optimization	[117]
FC-Bat-PV-UC	Fuzzy logic, dynamic programming	Power split for DG and ESS leveraging global opt.	[77]
GT-FC-Bat	Equivalent specific fuel consumption minimization	Split of moving average power between GT and solid-oxide FC	[120]
DG-Bat-PV	Load leveling	Mitigating PV fluctuations with ESS	[115]

TABLE 9. Optimization-based energy management in ship applications.

Power System	Method	Scope	Ref.
DG-Bat	Specific fuel consumption minimization	Optimal fuel eff. for 4 DG with ESS	[118]
DG-Bat	ECMS	Power split for DG and ESS	[127]
DG-Bat	ECMS	Power split for DG and ESS	[128]
DG-Bat	ECMS	Power split for DG and ESS	[131]
DG-Bat	ECMS, ant colony optimization	ECMS with opt. equivalence factor	[132]
GT-FC-Bat	Equiv. specific fuel consumption min.	Split of moving average power between GT and solid-oxide FC	[120]
GT	MPC	Fuel efficiency of parallel GT	[133]
DG-Bat	MPC	Optimal DG dispatch and SoC management with short-term load prediction	[134]
DG-Bat	MPC	Fuel efficiency of DGs and SoC management	[135]
DG-Bat-CI	2-level MPC	Fuel efficiency, SoC management and short-term constraint handling	[136]
GT-Bat-UC	MPC, optimal power flow	Generation scheduling leveraging load predictions	[68]
DG-Bat-PV	Stochastic MPC	Scenario-based optimization	[121]
GT-Bat	2-level MPC	Set-based MPC to guarantee operation in state and input constraints	[137]
DG-Bat-UC	2-level MPC	Decoupled steady-state and dynamic MPC problems	[138]
DG-FC-Bat	3-level MPC	Time-scale decomposition of control problem	[139], [140]
DG-Bat-UC	2-level MPC	Propulsion control + opt. power split	[18]
DG-Bat	MPC	Maneuvering and optimal power split	[22]
DG-Bat-CI	2-level MPC	Mission-scale SoC trajectory	[136]
DG-Bat-UC	MPC, ECMS	ECMS with equivalence factor based on MPC output	[141]

TABLE 10. Applications of mission-scale optimal ship operation.

Power System	Method	Scope	Ref.
DG	Dynamic programming	Opex minimization with demand-side management	[142]
DG	Dynamic programming	Global opex minimization with DC system	[143]
DG-Bat	Dynamic programming	Global opex minimization with ESS	[144]
DG	PSO	Global multi-objective opt. for parallel DG	[145]
DG	Interior-point algorithm	Large-scale nonlinear programming for min. fuel and emissions	[146]
DG-Bat	Mixed-integer non-linear programming	Sizing and operation for min. total cost of ownership	[147]
DG-Bat-CI	Genetic algorithm	Global joint voyage schedule and EMS optimization	[148]
DG-Bat-CI	Mixed-integer linear programming	Global joint voyage schedule and EMS with electricity price prediction	[149], [150]
Multi-Energy	Mixed-integer linear programming	Global joint voyage schedule and EMS for min. cost and emission	[151]
DG-Bat-UC-CI	Genetic algorithm	Scenario-based global joint route plan, voyage schedule and EMS optimization	[152]
DG-Bat-CI-PV	PSO	Large-scale global optimization	[153]
DG-Bat	Mixed integer linear programming	Optimal power dispatch and voyage scheduling incl. power reserve management	[154]

to explicitly formulate objectives and constraints while accounting for the system's dynamics. An overview of various strategies is given in Table 9. In contrast to the simpler, instantaneous optimization methods, more complex, often multi-timescale, predictive methods are proposed to represent the complexity of decision-making in the SPS operation.

A conventional power system in a naval vessel with parallel GTs is controlled using an MPC in [133]. A perfect load prediction is assumed, and the turbines are operated so that total fuel consumption is minimized over the prediction horizon, considering the non-linear efficiency characteristics of the turbines. Reference [135] additionally regards batteries next to the conventional generators in the SPS. The MPC formulation aims at operating the internal combustion engines in their most efficient operating point while keeping a steady battery SoC. As in [133], no prediction model is implemented. Instead, the load is assumed to be constant over the prediction horizon, which can be feasible in ships with an unknown operating profile.

An optimal power flow calculation, as typically conducted in terrestrial power systems, leveraging load predictions in a medium-voltage DC SPS with GTs, batteries and UCs is proposed in [68]. Although the solution yields minimized operation costs, the constructed optimization problem is computationally expensive and subject to prediction and model errors. In [138], a two-level MPC with frequency decoupling is proposed. A high-level MPC optimizes the power system in quasi steady-state operation to match the slow load dynamics, while a low-level MPC with higher band-width optimizes the dynamic dispatch of generation power to meet the load requirements. A load prediction based on propulsion torque estimation is proposed in [80]. The formulated problem involves a broad range of objectives for voltage stability, component wear, efficiency, and propeller thrust, with the aim of mitigating the effects of torque oscillations on the propulsion shaft. A three-level MPC is proposed by [139] for a naval vessel with GTs, FCs and batteries. The three layers operate with different band-widths from optimizing long-term generation scheduling, over optimal static power split between power sources of different types, to short-term disturbance rejection at the highest bandwidth.

In [18] and [22], the maneuvering control is included in the problem formulation. The authors present a two-level MPC in which the top layer determines an optimized shaft speed and torque, from which a load power prediction can be derived as input for the bottom layer MPC. The latter optimizes the power split between a DG, battery and UC to minimize the overall losses and the deviation from the required load power.

For ships with a known operation profile, knowledge over the entire mission duration can be used for predictive control. Reference [136] uses this knowledge for the control of a diesel-hybrid ship with a charge-depleting-charge-replenishing strategy for the ESS. A top-level mission-scale optimization regularly updates the optimal trajectory for the battery SoC. The authors in [141] implement an ECMS whose equivalence factor is updated based on inputs from a predictive controller.

Although an offline optimization of the power scheduling is not real-time applicable due to computational constraints and required a-priori knowledge, it is able to provide a benchmark for the optimal achievable control strategy, as showcased in [77] and [136]. Generally, mission-scale optimization is relevant for predictive control, as they can be employed within a multi-timescale MPC scheme [141]. Applications of a global optimization commonly focus on cost optimization via quasi-static dispatch of resources, while neglecting faster dynamics. An investigation of optimized power generation control in a conventional cruise ferry with DC distribution is conducted in [142], [143], and [144]. The authors formulate the dispatch of energy resources as a non-linear constraint optimization problem in steady state conditions with a known mission profile and employ dynamic programming to solve this. The work of [147] occupies itself with the optimized operation planning of a hybrid diesel-battery ship. The authors use mixed-integer non-linear programming to simultaneously solve the optimal power generation scheduling and sizing of the battery energy storage system for minimization of the total cost of ownership. Complex and large scale optimization problems are commonly approached using meta-heuristics. In [153], the authors optimize the energy management strategy for a diesel-battery ship with additional RESs and cold ironing (CI) capability using particle swarm optimization (PSO). Applications of global optimization for ship operation are listed in Table 10, showing that the key methods here are dynamic programming and meta-heuristic algorithms.

3) DISTRIBUTED ENERGY MANAGEMENT

The previously described EMS methods assume availability of all information in a central controller. However, in more complex power system architectures, a distributed energy management is promising to achieve a higher degree of resilience and reduction of computational load. Generally, distributed EMSs are proposed for zonal distribution architectures, typically in naval applications where survivability is a critical design target [108].

Specifically with the aim of creating a modular energy management solution, [155] describes a distributed EMS for electric vehicles. Generally, power systems and especially microgrid applications provide a range of methods for distributed optimization, with several relevant references listed in Table 11. The most widespread methods for distributed optimization in multi-agent systems are Lagrangian dual decomposition solved via iterative gradient-based methods [30], [156], [157], [158] and alternating direction method of multipliers (ADMM) which uses an augmented Lagrangian formulation [158], [159], [160], [161]. These methods allow for local optimization and feasibility while ensuring global feasibility through consensus. Global optimality is guaranteed for modules with convex cost functions. One prevalent method for incorporating non-convex functions and decision-making is through market- or auction-based algorithms [162], [163], albeit without guarantee for global optimality.

Applications for SPSs generally follow these methods, implementing dual decomposition [34], [164], [165] and ADMM [31], [166]. EMSs that are both distributed and predictive use the same methods, i.e. dual decomposition [167], [168] and ADMM [169], [170], [171]. Whereas most studies focus on economic dispatch or balancing of marginal costs among parallel generators, several researchers incorporate specific objectives. Especially for naval vessels, more focus is placed on resilience and mission fulfillment. Researchers utilize distributed optimization for reconfiguration [166], [172], [173] and load utilization [174]. Especially for increasing survivability and load servicing in emergency situations these aspects are relevant [175]. A range of distributed methods for ship energy management are listed in Table 12. This overview highlights that Lagrangian optimization methods (dual decomposition, ADMM) are pre-dominant in this field, whereas in microgrids we additionally observe the realization of market- and auction-based methods.

4) ENERGY MANAGEMENT FOR ZERO-EMISSION SHIPS

The energy management in ZESs, especially with integrated FCs, has received little attention in the past. In this section, case studies for the energy management in ZESs are reviewed in order to identify challenges and trends for the control of hydrogen-based power systems on ships. Whereas the focus in conventional ships mainly on fuel efficiency and power balance, an additional objective that is often regarded in the EMS for ZESs is the degradation of the FCs and batteries. Table 13 presents an overview of studies on EMSs for ZESs in the literature. The following subsection provides a categorization of archetypal energy management methods applied in FC-based SPSs.

a: RULE-BASED CONTROL

A rule-based EMS is proposed by [98]. Here, the FC system does not follow the demanded load, but instead a PI controller tracks a power reference determined based on load power and battery SoC. The scheme aims at operating the FC with an optimized and smoothed reference. In a similar fashion [96] presents a rule-based EMS for a small FC-battery passenger ferry aiming at a steady FC operation within an efficient operating band. A multi-scheme approach, combining of four distinct EMSs into with heuristic rules for mode switching is proposed by [189]. Rule-based approaches generally yield satisfactory results, but the rule definition relies on expert knowledge, and is typically applied only to small-scale systems. Rules and heuristics appear in varying shapes and complexities. Increased complexity, however, should be motivated and requires more extensive input for parameter definition.

b: LOAD LEVELING

A common goal of EMSs incorporating FCs is to level the load for the main power supply. Reference [185] proposes constraint programming for an optimal power split between main power supply and auxiliary energy storage. This work points out the trade-off between storage sizing and degree of load leveling. A FC-battery hybrid system is regarded in [97], proposing load leveling via a central PI-controller. The power reference follows the load demand via a PI feedback loop. Since the dynamic capabilities of the FCs are limited, the deviation between load and FC output is compensated by the batteries. In [79] a HESS is proposed for load leveling. The storage system absorbs power fluctuations, while the SoC of the storage components is maintained using PI controllers, hence decoupling the FCs from the immediate load demand. References [186] and [187] implement a load-leveling, a peak-shaving and a charge-depleting-charge-replenishing strategy, observing FC degradation, hydrogen consumption, power balance and space requirements. Generally, the strategies underscore the required trade-off between fuel consumption, FC aging and component sizing.

c: FUZZY-LOGIC CONTROL

Fuzzy logic offers an alternative method for applying expert knowledge into the control strategy. For a ZES with an FC-battery-UC system, a fuzzy logic strategy is designed in [116], and with additional RESs in [77]. Generally, fuzzy logic in FC-ESS systems derives a power reference for the FCs or power split between multiple units based on instantaneous load and SoC. Results generally show promising performance regarding energy consumption and FC lifetime degradation. As shown in [194]., fuzzy logic control can be combined with adaptive elements to improve the performance over time, which is especially beneficial with insufficient expert knowledge.

d: EQUIVALENT CONSUMPTION MINIMIZATION

Whereas ECMS strategies are common for hybrid SPSs with DGs, their application for hydrogen-based systems is much less developed. An elaborate approach for a FC-battery-UC ship, inspired by an ECMS, is applied in [122]. A real-time control strategy is realized by formulating an instantaneous multi-objective optimization problem considering hydrogen consumption of the FC and an equivalent consumption for battery and UC utilization. Additionally, FC and battery degradation costs are included in the problem formulation. The optimization problem is consequently solved via SDP, a powerful tool for the energy management, which had already been applied to FC-hybrid electric vehicles [58]. In [193], a system with multiple FCs and ESSs is considered for total generation cost minimization. The method accounts for the state-of-health of parallel units for their optimal dispatch.

e: PREDICTIVE CONTROL

As for the EMS in conventional ships, MPC is promising for the optimized control of zero emission power systems. Reference [190] investigates the generation scheduling of

TABLE 11. **Applications of distributed energy management in microgrids.**

Power System	Method	Scope	Ref.
Distrib. generation+loads	Auction-based	Federated buying-selling for economic dispatch	[162]
Distrib. generation+loads	Auction-based	Federated buying-selling for economic dispatch	[176]
Quadratic costs	Dual decomposition	Consensus on marginal cost	[156]
Convex generator costs	Dual decomposition	Consensus on marginal cost	[30]
Convex generator costs	Diffusion Strategy	Diffusion of marginal cost	[177]
Convex generator costs	Lambda iteration	Federated economic dispatch	[157]
GT-Bat-PV-Wind	Dual decomposition	Consensus on marginal cost	[158]
Convex gen. costs+ESS	ADMM	Economic dispatch	[158]
Convex generator costs	ADMM	Economic dispatch with limited communication	[159]
Convex generator costs	Relaxed ADMM	Increased convergence speed and robustness	[160]
Convex generator costs	Scenario-based MPC	Robust, ECMS-based economic dispatch	[178]
Convex generator costs	ADMM+distributed resource allocation	Simultaneous static and dynamic dispatch	[161]
Convex gen. costs+ESS	MPC, dual decomposition	Federated MPC for intra-hour economic dispatch	[179]
Distrib. generation+loads	Market emulation	Predictive, trading-based multi-agent system	[163]

TABLE 12. **Applications of distributed energy management for ships.**

Power System	Method	Scope	Ref.
-	Maximum flow	Automatic reconfiguration with load priorization	[175]
-	Flocking	Optimal load utilization in zonal SPS	[180]
Ship-Harbor	Dual decomposition	Consensus on marginal cost	[164]
DG	Dual decomposition	Consensus on marginal cost for DC SPS	[34]
DG-ESS	Dual decomposition	Marginal cost balancing and ESS mode	[165]
DG-ESS	Leader-follower	Min. loss and economic dispatch in zonal SPS	[181]
DG-Bat-UC	ADMM	Distributed ECMS for zonal SPS	[31]
GT-Bat	Predictive heuristics	SoC management in zonal SPS with high ramped loads	[182]
GT-Bat	Flocking, predictive	Predictive distributed crow search for economic dispatch	[95]
DG-Bat	MPC, dual decomposition	Battery degradation-aware economic dispatch	[183]
GT-Bat	MPC, dual decomposition	Fault-tolerant load and SoC management	[168]
FC-Bat	MPC, dual decomposition	Short-term operation cost minimization	[167]
DG-Bat	MPC, ADMM	Load leveling+SoC management, zonal arch. with pulsed loads	[169]
DG-Bat	MPC, ADMM	Economic dispatch in zonal SPS + reserve allocation	[170]
DG-Bat-PV	MPC, ADMM	Static economic dispatch with load forecasting	[171]
Power+Heat Networks	MPC, dual decomposition	Mission-scale cost and carbon emission optimization in coupled power and heat networks	[184]
FC-Bat	Coupled ADMM	Topology-aware multi-bus cost optimization	[166]

an FC-battery hybrid passenger ferry with CI capability, focusing on the minimization of operation costs. In [121], a PV system is additionally included in the power system, for which generation predictions are leveraged in the MPC formulation. This work is later expanded upon [192] with a stochastic MPC in order to account for environmental uncertainties represented as probabilistic scenarios. In these works, hourly time intervals are used, while any kind of dynamics is disregarded. Reference [191] describes a health-aware short-term optimal power dispatch accounting for real-time load fluctuations. However generally, current literature is sparse on predictive energy management solutions for ZESs that incorporate detailed system dynamics and handles load fluctuations.

f: GLOBAL OPTIMIZATION

Several studies investigate the global optimization of the power dispatch in ZESs, typically in a joint effort with component sizing and overall cost minimization. A simultaneous component sizing and energy management for a FC-Battery passenger ferry has been conducted by [196]. The authors take into account the total costs based on investment and operation costs for component acquisition and fuel consumption and further representing fuel cell degradation by considering replacement costs. The large-scale problem is formulated as a mixed-integer linear program (MILP), which is consequently solved in a multi-objective optimization. Another study for cost optimization is conducted in [197], presenting a feasibility study of a tourist boat. Due to the problem complexity, the authors employ a meta-heuristic sine-cosine algorithm, commonly used for complex, large-scale optimization problems. Reference [119] developed a dynamic programming algorithm that optimizes for cost-minimal operation with multiple FCs, allowing time-optimized on- and off-switching of individual systems.

g: LEARNING-BASED CONTROL

The hourly power scheduling with the aim of minimizing operation costs is approached using deep reinforcement learning in [195]. The authors regard a tourist boat powered

TABLE 13. Energy management in hydrogen-based power systems.

Power System	Method	Scope	Ref.
Bat-UC	Constraint programming	Minimal stress on battery	[185]
FC-Bat	PI	Peak-shaving for FC by ESS	[97]
FC-Bat	PI	Peak-shaving for optimal fuel efficiency and component wear	[186], [187]
FC-Bat-UC	PI	Load leveling and SoC management	[78]
FC-Bat	PI, rule-based	Rule-based FC operation and PI voltage regulation	[98]
FC-Bat	Rule-based	Optimal fuel efficiency	[96]
FC-Bat	Rule-based	Load-leveling for optimal fuel efficiency and component wear	[186], [187]
FC-Bat	Rule-based	Optimal fuel efficiency and component aging with charge-depleting-charge-replenishing strategy	[186], [187]
FC-Bat	Rule-based	Total cost of ownership minimization through optimal sizing and operation	[188]
FC-Bat-UC	ECMS, sequential dynamic programming	Optimal fuel efficiency and component degradation	[122]
FC-Bat-CI	Multi-scheme	Minimized opex and component degradation	[189]
FC-Bat-UC	Fuzzy-logic	Voltage regulation and SoC management for ESS	[116]
FC-Bat-UC-PV	Fuzzy-logic	Optimal fuel efficiency and SoC management for ESS	[77]
FC-Bat-CI	MPC	Optimized power scheduling for opex minimization	[190]
FC-Bat	MPC	Short-term, health-aware optimal power dispatch	[191]
FC-Bat-CI-PV	Stochastic MPC	Opex minimization	[121]
FC-Bat-CI	Stochastic MPC	Minimized opex and degradation of components	[192]
FC-Bat	Generation cost min.	Hierarchical control with economic dispatch for multiple FC and ESS systems	[193]
FC-Bat	Generation cost min.	Hierarchical control with economic dispatch for multiple FC and ESS systems	[193]
FC-Bat	Adaptive neuro fuzzy inference system	Optimal fuel efficiency and SoC management	[194]
FC-Bat-CI	Deep reinforcement learning	Optimized power scheduling for opex minimization	[195]
FC-Bat	Mixed integer linear programming	Global multi-objective optimization	[196]
FC-Bat-CI	Sine cosine algorithm	Global opex minimization	[197]
FC-Bat	Dynamic Programming	Health-aware, global opex min. for multiple FC systems	[119]

by FCs and batteries with possibility for charging the ESSs when berthed. For this purpose, the scheduling of energy resources is modeled as a Markov Decision Process (MDP). The resulting EMS based on reinforcement learning is applied for real-time power scheduling on a test-bench. Currently, little attention lies on learning-based approaches, which, given sufficient data, is a promising research avenue for the future studies.

VII. CONCLUSION

The ongoing changes in the design of modern SPSs impose new challenges on the power system control and energy management for the operation of these vessels. The research literature provides novel methods to meet the requirements of increasingly complex power system architectures and technologies. In this article, the challenges for the overall control of SPSs have been analyzed and suitable control architectures and methods for local, coordinated and high-level control have been reviewed. This literature research was carried out with a specific interest in DC power systems and the modular integration of zero emission technologies.

This investigation provides a categorization of methods for distinct control layers and defines essential control functionalities relevant for the coordinated control and energy management for ships. The control architecture is investigated as an additional dimension in the categorization of SPS studies. The targeting of DC power systems, hybrid energy systems and zero-emission power generation systems as emerging solutions opens up the structured analysis of methods for future ship power systems. We bring forward distributed and federated architectures as a key factor in handling the shift towards more sustainable power system designs, discussing the move from centralized, integrated solutions to modular, scalable, adaptive and more resilient SPSs.

The main conclusions are summarized as follows:

- SPSs are incorporating a growing variety of technologies. This necessitates control strategies that account for the varying characteristics of these power system resources. Generation and storage components differ in dynamic capabilities, efficiency, power and energy density and should be operated accordingly.
- A trend in power system design is pointing towards modular integration of power system components, which should be reflected in the control strategies as well. It is key to develop methods that facilitate a simple integration of new technologies. DC distribution is deemed to be an enabler for this plug-and-play capability in both design and control of the SPS.

- There are similarities in the coordinated control and energy management of SPSs with automotive applications and terrestrial microgrids. However, application-specific objectives and requirements necessitate specific choices for the control method and architecture. Centralized optimization allows tight coordination for highly complex problems, while distributed optimization enhances resilience and scalability. A compromise using a federated architecture is promising for SPS.
- An often overlooked aspect in power system control is the consideration of faulty and degraded subsystems. The coordinated control and energy management should be designed to support fault-tolerant operation while meeting load servicing requirements and efficient utilization of resources.
- Given individual characteristics of power system components, the identification of local parameters and states, and consequent adaptation the local, coordinated, and energy management functionalities are required. Generally, adaptive control, demand-side management and mode-based operation can play an important role in enhancing the resilience of the ship.
- Distributed and federated control architectures are a promising solution for tying together complex power systems with heterogeneous resources in a modular fashion. The adaptability of this approach is able to increase the system resilience and adaptation under faults and uncertainties.
- Studies on control for ZESs with FCs focus on small passenger ships and ferries. There is a clear lack in research for the control of FC-based ships with a larger number of parallel generation and storage systems. Applications with high energy needs and significant service loads and reliability requirements need to be addressed.
- With new ship designs incorporating FCs and batteries, component degradation is becoming an increasingly important objective for the control of SPSs, next to the minimization of fuel consumption and operating costs.
- The literature on energy management for FC-hybrid vessels is focused on deterministic and rule-based approaches. Optimization-based EMSs, especially predictive and learning-based methods, show high potential for improving the performance.
- Current literature studies lack experimental validation of control strategies. Most studies rely on numerical investigations. Especially for the real-time control of SPSs, experimental work will create valuable insights and showcase the methods' applicability in the field.

Future research must focus on these aspects to develop methods that meet the requirements of modern SPSs and to take on the challenges the maritime sector is currently facing. Faced with the challenge of integrating and coordinating vastly different novel technologies, the power system control is subject to a series of requirements. Whereas power availability and efficiency play an important role, resilience, safety and adaptability are gaining in relevance. DC distribution, power electronics converters and modern computing and communication equipment provide opportunities to handle these challenges. Reviewing control architectures and the distribution of control functionalities is a promising ingredient in developing suitable control methods.

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