

Modular Control for Hydrogen-based DC Shipboard Power Systems

Kopka, T.; Coraddu, A.; Polinder, H.

Publication date

2024

Document Version

Final published version

Citation (APA)

Kopka, T., Coraddu, A., & Polinder, H. (2024). *Modular Control for Hydrogen-based DC Shipboard Power Systems*. 462-467. Paper presented at European PhD Hydrogen Conference, Ghent, Belgium.

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Modular Control for Hydrogen-based DC Shipboard Power Systems

T. Kopka*, A. Coraddu, H. Polinder

Department of Maritime and Transport Technology, Delft University of Technology, The Netherlands

Introduction

The transport and energy sectors are confronted with a series of challenges, pushing the industries to develop innovative and sustainable alternatives. The International Maritime Organization (IMO) has been prompted to define targets for the reduction of the carbon impact of ships [1], [2]. Hence, the maritime industry is under pressure to provide solutions for lowering its dependency on fossil fuels. Accordingly, more and more effort is put into research for zero emission ships (ZES) equipped with alternative power generation and storage technologies. With the SH2IPDRIVE project [3], a consortium has been brought to life that pursues the powering of the Dutch maritime sector with hydrogen. Produced from renewable energy sources (RESs), green hydrogen has the potential to serve as the main energy carrier in a ship. Hydrogen fuel cells (FCs) have emerged as the most prominent alternative as the main power supply in state-of-the-art applications [4], [5]. These are usually hybridized with energy storage systems (ESSs) due to their limited dynamic capabilities and specific operation characteristics [6]. Hence, FC-battery shipboard power systems (SPS) are a promising solution for decarbonizing the maritime transport in certain applications. A major challenge for fully exploiting the FC technology is the control of the electric power system and optimizing the coordination of the integrated energy resources, which is in the focus of this research.

A key development in the design of the SPS for FC-battery hybrid systems are the use of electric propulsion with an integrated power system (IPS) [7]. Moreover, the trend goes towards utilizing direct current (DC) distribution technology [8], [9], especially with many DC sources on board, e.g. FCs, batteries, and ultra-capacitor (UC). As identified in [10], state-of-the-art approaches for the control in hydrogen-based DC SPS focus on centralized solutions, typically for small systems with a single FC system and ESS. Examples involving a centralized controller computing the power references for the power sources are PI-control as in [11]–[13] and rule-based control as in [13]–[16]. Filter-based approaches can also commonly be observed in centralized control strategies in order to achieve a separation of load frequencies matching the differing characteristics of power supply and storage systems [17]–[19]. For the application in larger SPS that involve multiple parallel power supplies and ESS systems in a distributed fashion, centralized solutions are not feasible anymore.

Future SPS are expected to incorporate a wider variety of power supply and ESS technologies with differing characteristics [5]. All-electric ships (AES) with DC distribution technology and power electronics interfaces already offer a high degree of flexibility in the power system topology. This facilitates a simpler integration, extension and reconfiguration of the power system topology. Hence, components can be connected to the SPS in a modular fashion. This

*Corresponding author: t.kopka@tudelft.nl

research aims to develop control strategies for ZESs that also reflect this modularity in its power system control and energy management. A key part of this is to offer a plug-and-play (PnP) capability that minimizes the effort of integrating new technologies with unique characteristics into an existing power system topology. Moreover, a modular control framework can support the fault-tolerance and adaptation to changing circumstances, leading to a more resilient operation of the ship.

Methodology

This research aims to bring forward modular control strategies that can be implemented in real-time for the operation of an SPS with a DC distribution system. Specific interest lies in investigating zero-emission power supplies as an alternative to conventional fossil-fueled systems. With power electronics interfaced subsystems, the regarded SPS enable a high degree of controllability of power flows between power supplies, ESSs and loads. An exemplary FC-battery DC SPS is displayed in Fig. 1.

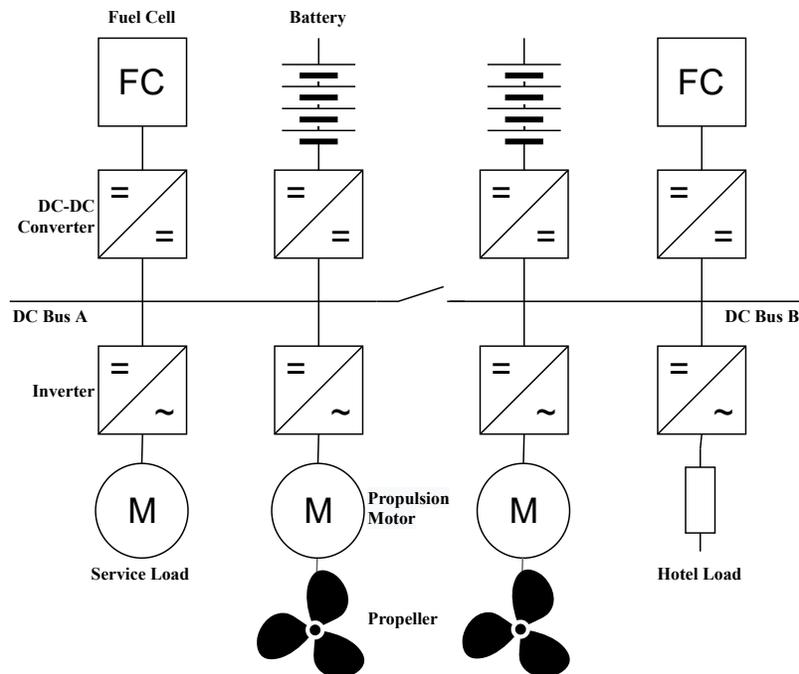


Figure 1: Exemplary DC SPS with FC-battery hybrid energy system

Whereas small, integrated power systems can be approached with a central controller computing all power references, more complex topologies also demand a higher control complexity. Figure 2 shows a generalized control hierarchy for power systems in which functionalities are distributed among local control, coordinated control, and high level control layers, typically with an increasing control bandwidth from top to bottom.

Each control functionality can be realized using a specific architecture, depending on the communication infrastructure used. Whereas current solutions on control for FC-battery SPS employ a centralized controller for the coordinated control, a decentralized or distributed architectures offers a more resilient and scalable alternative. Also, the high level control layer, including the energy management strategy (EMS), can in principle, be realized in a distributed or decentralized manner, which increases the modularity of the overall power system control. The three distinct control architectures are outlined in Fig. 3. Furthermore, the communication can be realized using either a high- or low-bandwidth network.

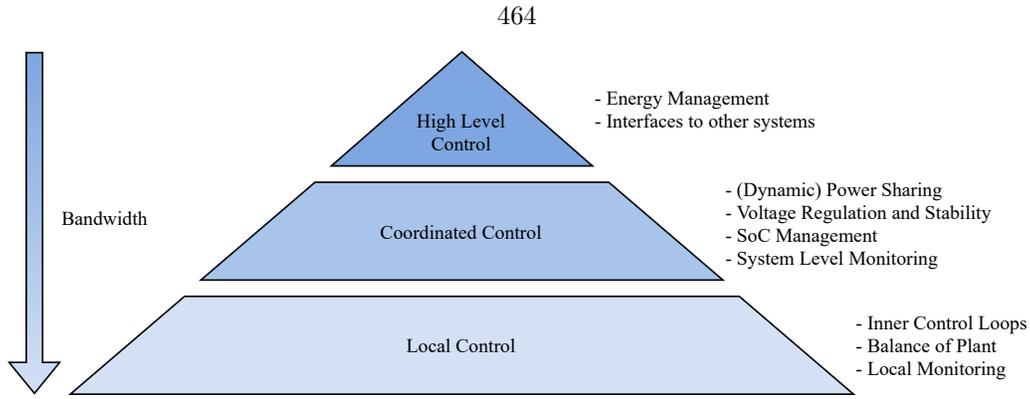


Figure 2: Control hierarchy for electric power systems on ships

In the context of a modular control framework, it is proposed to use standardized decentral controllers for the coordinated control, with parameters tuned depending on the devices' respective characteristics. A potential synergy between the control layer and physical system can be achieved by using common equipment, e.g., DCDC converters, for connections to the DC bus. This yields a unified, standardized hardware and control interface for connecting a wide variety of sources to the system. To stabilize the DC-bus voltage using FCs and batteries, droop-based approaches are investigated. In order to account for differing dynamic capabilities of subsystems, a bandwidth decoupling for different technologies is proposed, aiming at achieving an efficient dynamic power sharing. The scalability of this approach will be investigated by extending the baseline FC-battery system, e.g., with additional parallel FC and battery modules. The addition of new technologies offers further opportunities to showcase the benefits of the PnP capability, where especially UCs as fast-response ESS and photovoltaic (PV) systems as RES offer promising features. A benefit of the approach also lies in the replacement of old components with riper technology at their end-of-life.

An additional power allocation and generation scheduling for power supplies can be realized via an EMS to enhance the overall system efficiency. In a FC-battery hybrid system, this encompasses the power split between main power supply and ESS and among parallel power supplies. A central aim of the EMS is the minimization of fuel consumption and component degradation. Using a centralized controller with low-bandwidth communication can be regarded as modular if all real-time computations are executed in the local controllers, while the central controller is merely used for information sharing and as an interface to other systems. In the first step, it is proposed to utilize a central controller and low-bandwidth communication to realize EMS functionalities via adaptive functions in the local controllers.

A further challenge for the operation of SPSs arises from uncertainties and changing condi-

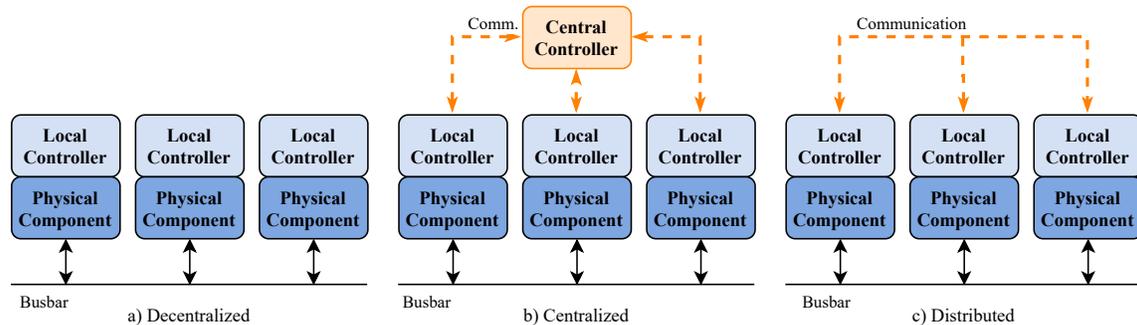


Figure 3: Generic control architectures for electric power systems

tions during a mission. Both component degradation and operational faults can alter the optimal conditions for system performance, affecting the availability of resources. The SPS shall be able to mitigate the effects of changing conditions and faults while maintaining power availability and an efficient operation of the system's resources. One focus point is the effect of altered parameters due to the degradation of components. Especially FCs and batteries show significant aging effects, which in turn influences the optimal operation of these systems. This issue will be addressed via adaptive functionalities in the (dynamic) power sharing, state of charge (SoC) management and EMS, so that system alterations are accounted for. The analysis and mitigation of effects from faults follows as a next step. The failure of a generation or storage component, the partial or total failure of an energy conversion device, and the failure of a communication link are of key interest to this research. The sudden discontinuation of power generation due to a component failure must be compensated. Hence, sufficient reserve must be maintained for stabilization, e.g., through virtual inertia provided by ESS, and the EMS shall be able to shift to a new efficient steady-state operation point. The proposed modular control approach will be extended to be able to reflect these faults in its coordinated control.

A library-based simulation environment is set up in Matlab/Simulink, including models of main and auxiliary power supplies, energy storages, power electronics converters, DC bus, and loads. This allows the modular configuration of power system topologies for the purpose of testing the developed control strategies on different systems. Real vessels and their measurements are used as reference designs, which can be virtually reconfigured and extended using the simulation environment. Finally, the proposed control strategies are aimed to be validated in a power hardware-in-the-loop (PHIL) test-bed, to prove their applicability and performance in real time.

Discussion

An initial study of the modular control approach for a FC-battery hybrid DC SPS has been conducted in [10]. This work describes a decentralized, virtual impedance-based strategy for the coordinated control covering dynamic power sharing, voltage control, and SoC management. Simulation results show that this architecture without communication links can achieve the same quality of power supply and load frequency separation as a centralized PI controller, given a proper tuning of the local controllers. Here, all components are parameterized so that they are utilized depending on their dynamic capabilities, which is especially beneficial for the operation of the FC. This approach has been extended by a modular EMS within a control hierarchy in [20]. The modularity of the approach is maintained by utilizing a low-bandwidth communication to enable information sharing among local controllers. A central controller is added to aggregate information while all key functionalities remain in the local controllers. This work showcases that a hierarchical control architecture can be realized using a modular approach. Furthermore, a central controller can contribute to facilitate awareness of global parameters and operator inputs while critical computations for the coordinated control remain decentralized.

Conclusions

The design of SPS is shifting from conventional diesel-driven topologies towards all-electric ships with an IPS, DC distribution, and zero-emission technologies. More components are integrated into future SPS, increasing their complexity and demanding for appropriate control strategies. This research proposes the development of a modular control framework facilitating the integration of a wide variety of differing power supply and storage technologies. Current contributions have shown that this modular approach can be used for both the coordinated control and energy management in a hierarchical control scheme for FC-battery systems.

In future investigations, the modular framework will be expanded to include further technologies and prove its effectiveness in dealing with a reconfiguration of the power system. A key challenge will be to deal with a multitude of power supplies and ESS with differing characteristics while maintaining an efficient operation of the power system. Furthermore, an analysis of system level faults and real-time adaptation to system alterations will be in the focus of research on this topic.

References

- [1] T.-H. Joung, S.-G. Kang, J.-K. Lee, and J. Ahn, "The IMO initial strategy for reducing Greenhouse Gas(GHG) emissions, and its follow-up actions towards 2050," *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, vol. 4, no. 1, pp. 1–7, Jan. 2020.
- [2] "Fourth Greenhouse Gas Study 2020," <https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx>.
- [3] "Sustainable Hydrogen Integrated Propulsion Drives (SH2IPDRIVE)," <https://sh2ipdrive.com/>.
- [4] J. F. Hansen and F. Wendt, "History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends," *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2229–2242, Dec. 2015.
- [5] C. Nuchturee, T. Li, and H. Xia, "Energy efficiency of integrated electric propulsion for ships – A review," *Renewable and Sustainable Energy Reviews*, vol. 134, p. 110145, Dec. 2020.
- [6] N. Shakeri, M. Zadeh, and J. Bremnes Nielsen, "Hydrogen Fuel Cells for Ship Electric Propulsion: Moving Toward Greener Ships," *IEEE Electrification Magazine*, vol. 8, no. 2, pp. 27–43, Jun. 2020.
- [7] S. Jayasinghe, L. Meegahapola, N. Fernando, Z. Jin, and J. Guerrero, "Review of Ship Microgrids: System Architectures, Storage Technologies and Power Quality Aspects," *Inventions*, vol. 2, no. 1, p. 4, Feb. 2017.
- [8] M. Butcher, R. Maltby, and P. S. Parvin, "Compact DC power and propulsion systems - the definitive solution?" in *2009 IEEE Electric Ship Technologies Symposium*. Baltimore, MD, USA: IEEE, Apr. 2009, pp. 521–528.
- [9] L. Xu, J. Guerrero, A. Lashab, B. Wei, N. Bazmohammadi, J. Vasquez, and A. Abusorrah, "A Review of DC Shipboard Microgrids—Part II: Control Architectures, Stability Analysis, and Protection Schemes," *IEEE Transactions on Power Electronics*, vol. 37, no. 4, pp. 4105–4120, Apr. 2022.
- [10] T. Kopka, F. Mylonopoulos, A. Coraddu, and H. Polinder, "Decentralized Power Sharing with Frequency Decoupling for a Fuel Cell-battery DC Shipboard Power System," in *Modelling and Optimisation of Ship Energy Systems (MOSES)*, Delft, The Netherlands, Oct. 2023, in press.

- [11] C.-L. Su, X.-T. Weng, and Ching-Jin Chen, “Power generation controls of fuel cell/energy storage hybrid ship power systems,” in *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*. Beijing, China: IEEE, Aug. 2014, pp. 1–6.
- [12] H. Chen, Z. Zhang, C. Guan, and H. Gao, “Optimization of sizing and frequency control in battery/supercapacitor hybrid energy storage system for fuel cell ship,” *Energy*, vol. 197, p. 117285, Apr. 2020.
- [13] L. Balestra and I. Schjølborg, “Energy management strategies for a zero-emission hybrid domestic ferry,” *International Journal of Hydrogen Energy*, vol. 46, no. 77, pp. 38 490–38 503, Nov. 2021.
- [14] J. Han, J.-F. Charpentier, and T. Tang, “An energy management system of a fuel cell/battery hybrid boat,” *Energies*, vol. 7, no. 5, pp. 2799–2820, 2014.
- [15] A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, “Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship,” *International Journal of Hydrogen Energy*, vol. 42, no. 1, pp. 623–635, Jan. 2017.
- [16] L. Zhu, J. Han, D. Peng, T. Wang, T. Tang, and J.-F. Charpentier, “Fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid ship,” in *2014 First International Conference on Green Energy ICGE 2014*, Mar. 2014, pp. 107–112.
- [17] Z. Jin, L. Meng, J. C. Vasquez, and J. M. Guerrero, “Frequency-division power sharing and hierarchical control design for DC shipboard microgrids with hybrid energy storage systems,” in *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Mar. 2017, pp. 3661–3668.
- [18] K. Kwon, D. Park, and M. K. Zadeh, “Load Frequency-Based Power Management for Shipboard DC Hybrid Power Systems,” in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, Jun. 2020, pp. 142–147.
- [19] P. Xie, S. Tan, N. Bazmohammadi, Josep. M. Guerrero, Juan. C. Vasquez, J. M. Alcala, and J. E. M. Carreño, “A distributed real-time power management scheme for shipboard zonal multi-microgrid system,” *Applied Energy*, vol. 317, p. 119072, Jul. 2022.
- [20] T. Kopka, C. Loeffler, A. Coraddu, and H. Polinder, “Hierarchical Control Strategy for Fuel Cell-Battery Shipboard Power System Utilizing a Modular Control Architecture,” in *IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC-AP)*, Chiangmai, Thailand, Nov. 2023, in press.