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Power beneath the surface: electrical propulsion, energy storage, and power management technologies for submarines

Absin Marsan Wahiddin[1], Watra Arsadiando[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

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ABSTRACT

Submarines are complex electrical platforms in which propulsion, energy storage, power conversion, sensing, and auxiliary services must operate reliably within a confined and demanding environment. Conventional diesel–electric arrangements rely on battery banks for submerged operation, while air-independent propulsion (AIP) technologies extend underwater endurance by supplying electrical energy without atmospheric intake. These architectures create distinctive engineering challenges involving energy density, motor efficiency, power management, thermal control, electrical protection, electromagnetic compatibility, and acoustic-vibration constraints. This review examines submarine-related electrical engineering through literature published no later than 2016, with emphasis on propulsion drives, batteries, fuel-cell systems, power electronics, and shipboard electrical architectures. Research on underwater vehicles and electrically propelled vessels is also considered where it provides transferable evidence for submarine applications. The review identifies the central trade-off between endurance, power capability, system volume, and operational reliability, and explains why no single energy source or motor technology is universally optimal. It further argues that integrated design and validation are essential because improvements in one subsystem can impose additional demands on cooling, control, protection, or energy storage. Finally, the paper outlines research priorities for robust, efficient, and maintainable submarine electrical systems.

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1. INTRODUCTION

A submarine is a highly integrated engineering platform in which electrical systems support propulsion, navigation, monitoring, communication, and essential auxiliary services. Unlike surface vessels, submarines operate for extended periods without direct access to atmospheric oxygen or external electrical supplies. This operating environment makes energy availability, conversion efficiency, and electrical reliability central design considerations. Consequently, electrical engineering is not merely a supporting discipline in submarine development, but a fundamental part of the vessel's overall performance and operational endurance [1], [2].

Conventional submarines commonly use diesel–electric arrangements in which diesel generators supply electrical energy and charge onboard batteries when atmospheric operation is possible. During submerged operation, the battery system supplies the propulsion motor and other electrical loads. Although this arrangement is technically established, its submerged endurance is constrained by battery capacity and the energy consumed by propulsion and auxiliary systems. Air-independent propulsion (AIP) technologies, including fuel-cell systems, have therefore attracted considerable attention as alternatives or supplements to conventional battery-based energy storage [3], [4].

The main engineering problem is how to provide sufficient electrical power and energy within strict constraints on mass, volume, thermal management, and reliability. Increasing installed energy capacity may extend endurance, but it can also increase equipment volume and impose additional demands on cooling,

electrical protection, and system integration. Similarly, selecting a high-performance propulsion motor is not sufficient if its drive electronics, power supply, or thermal environment cannot support reliable operation. This review examines these interdependent challenges through electrical engineering research published up to 2016.

2. REVIEW SCOPE AND ELECTRICAL ARCHITECTURE

This review focuses on five interconnected technical areas: electrical power generation, energy storage, propulsion motors and drives, power conversion, and system-level control. Research specifically addressing submarines is prioritized, while relevant studies of underwater vehicles and marine electrical systems are included to provide additional engineering evidence. The literature includes peer-reviewed journal papers and conference publications with identifiable DOI records. The review emphasizes the engineering principles and design challenges rather than operational or tactical characteristics of specific submarine platforms.

A conventional diesel–electric electrical architecture consists of generating equipment, battery banks, distribution equipment, power converters, propulsion drives, and auxiliary loads. The battery bank acts as the principal electrical energy source during submerged operation, while the propulsion motor converts electrical energy into mechanical power. Power-management equipment must coordinate energy delivery to propulsion and essential onboard services without exceeding the capabilities of the storage system. Research on marine electrical power systems shows that the increasing integration of power electronics and electrical loads makes system-level coordination increasingly important [5], [6].

An integrated electrical architecture offers opportunities to improve energy utilization and simplify the coordination of different power sources. However, integration also creates interactions among generators, storage devices, converters, and loads that can affect voltage stability and power quality. Mindykowski discussed power-quality challenges in ship electrical systems and highlighted the importance of appropriate assessment and improvement methods [7]. These findings are relevant to submarine engineering because electrical disturbances can affect the performance of multiple interconnected subsystems.

3. ENERGY STORAGE AND AIR-INDEPENDENT PROPULSION

Battery technology is one of the most important factors determining the endurance of conventional electrically propelled submarines. Lead–acid batteries have historically been used because of their established technology, relatively mature manufacturing processes, and ability to provide substantial current. Nevertheless, their energy density, charging characteristics, maintenance requirements, and service life impose limitations on the overall electrical architecture. Battery selection must therefore consider not only nominal capacity but also discharge behaviour, charging requirements, thermal conditions, and long-term reliability.

Fuel-cell systems provide another approach to supplying electrical energy during submerged operation. Unlike conventional combustion-based generation, fuel cells convert chemical energy directly into electricity through electrochemical reactions. Psoma and Sattler described the development of submarine fuel-cell systems from early feasibility studies to serial production, illustrating the progression of fuel-cell technology toward practical underwater applications. Their work demonstrates the importance of system integration, controlled development, and reliability validation when adapting electrochemical power sources to demanding marine environments.

Polymer electrolyte membrane fuel cells are particularly relevant because they operate at relatively low temperatures and can provide electrical power with limited mechanical vibration. Han et al. developed a PEM fuel-cell stack for an underwater vehicle using hydrogen and pure oxygen, emphasizing high reactant utilization, efficient operation, and durability [8]. Their reported long-duration testing illustrates the importance of stack performance under continuous operation rather than relying exclusively on short laboratory demonstrations. Although an underwater vehicle is not identical to a crewed submarine, the study provides useful evidence for the engineering requirements of enclosed underwater power systems.

Fuel-cell integration introduces additional electrical and thermal engineering requirements. The fuel-cell stack generally requires power-conditioning equipment to provide a suitable electrical output for the connected loads and propulsion system. The balance-of-plant equipment, including pumps, cooling devices, and control components, also consumes electrical power and affects the overall system efficiency. Van Biert et al. reviewed fuel-cell systems for maritime applications and identified power density, system volume, safety, and economic considerations as important factors in selecting suitable technologies [9].

Hybrid fuel-cell and battery arrangements can combine the sustained energy supply of fuel cells with the rapid power response of batteries. In such configurations, the battery can support transient loads while the fuel-cell system provides a comparatively steady contribution to the electrical demand. Shih et al.

developed a hybrid fuel-cell power system for small ships and underwater vehicles, demonstrating the potential of combining electrochemical generation with battery storage [10]. Choi et al. subsequently demonstrated a PEM fuel-cell and lithium-ion battery hybrid propulsion system for a tourist vessel, providing evidence of the practical integration of fuel cells, batteries, DC–DC converters, and electric propulsion equipment [11].

4. ELECTRIC PROPULSION MOTORS AND POWER ELECTRONICS

The propulsion motor is a critical electrical component because it determines how efficiently electrical energy is converted into mechanical propulsion power. Motor selection must consider torque capability, operating speed, efficiency, physical dimensions, cooling requirements, and mechanical integration. Traditional DC motors offer relatively straightforward speed control, whereas modern AC motor technologies provide opportunities for improved efficiency and reduced maintenance. The broader development of marine electric propulsion has therefore been closely associated with improvements in electrical machines and power electronic control [5], [6].

Permanent-magnet synchronous motors are particularly attractive for compact propulsion applications because they can provide high torque density and efficient operation. Hong et al. investigated the design of a permanent-magnet synchronous motor for an integrated motor propulsor intended for an unmanned underwater vehicle. Their study considered electrical performance together with noise and vibration characteristics, showing that motor design must account for both electromagnetic and mechanical behaviour [12]. This is relevant to submarine-related engineering because vibration and acoustic characteristics can influence the suitability of a propulsion arrangement even when its electrical performance is satisfactory.

Power electronic converters provide the interface between electrical sources, storage devices, and propulsion motors. Inverters regulate the electrical supply to AC motors, while DC–DC converters can adapt voltage levels and coordinate power transfer between different DC components. The selection of switching devices, converter topology, and control strategy affects efficiency, power quality, thermal losses, and electromagnetic interference. Han et al. reviewed fuel-cell technologies for ship applications and identified power conversion and system integration as important considerations for the development of marine fuel-cell power systems.

The development of all-electric ship architectures provides additional insight into the future direction of submarine electrical engineering. Thongam et al. reviewed all-electric ship technologies and discussed the integration of electrical propulsion, power electronics, and intelligent control systems. Although surface ships and submarines have different operating constraints, both require reliable electrical distribution and coordinated control of propulsion and auxiliary loads. Skjong et al. further examined the historical development and future challenges of marine electrical power systems, highlighting the increasing importance of power electronics, energy storage, and integrated electrical architectures [5].

5. POWER MANAGEMENT, RELIABILITY, AND PROTECTION

Power management is essential because a submarine's electrical demand varies with propulsion requirements and the operation of onboard equipment. The control system must coordinate available energy sources, storage capacity, and load demand while maintaining acceptable electrical operating conditions. Hybrid fuel-cell and battery systems require particular attention because the two sources have different dynamic characteristics and operating constraints. Bassam et al. investigated an improved energy-management strategy for a hybrid fuel-cell and battery passenger vessel, showing how control decisions can influence fuel-cell efficiency, hydrogen consumption, and component stress [13].

Reliability is equally important because a failure in the electrical distribution system can affect propulsion and other essential functions. Redundant electrical paths, appropriate protection devices, and carefully designed distribution topologies can help maintain service when a component or circuit becomes unavailable. Dubey and Santoso proposed a two-level topology design framework for reliable shipboard power systems, emphasizing continuity of service and survivability under fault conditions [14]. Although the study addresses shipboard electrical systems more generally, its design principles provide useful guidance for considering reliability in complex submarine electrical architectures.

Power quality and electromagnetic compatibility also require attention in integrated electrical systems. Switching converters and motor drives can introduce harmonics, voltage disturbances, and electromagnetic emissions that interact with other electrical equipment. These effects may influence control circuits, monitoring systems, and sensitive electronic devices if the system is not designed and tested appropriately. Mindykowski's review of ship power-quality challenges supports the need for systematic measurement, assessment, and mitigation of electrical disturbances [7].

6. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

The reviewed literature indicates that submarine electrical engineering is shaped by the need to balance energy density, power capability, efficiency, and reliability. Batteries offer a comparatively direct source of electrical energy but constrain endurance through their stored capacity. Fuel cells can extend energy availability, although their integration requires additional reactant storage, power-conditioning equipment, thermal management, and safety provisions. Hybrid architectures provide a promising way to combine the strengths of different energy sources, but they also increase control and integration complexity.

Future research should give greater attention to integrated modelling and experimental validation of the complete electrical system. Studies that examine batteries, fuel cells, motors, converters, and control systems separately may overlook interactions that become important during actual operation. More representative testing should include variations in electrical demand, transient propulsion loads, component degradation, and fault conditions. Research should also investigate compact and efficient power converters, reliable energy-management methods, and improved monitoring techniques for long-term system operation.

A further priority is the development of propulsion motors and power electronic drives that combine high efficiency with suitable thermal and vibration characteristics. Advances in permanent-magnet machines, inverter control, and converter design may provide opportunities for more compact electrical propulsion systems. However, these developments must be evaluated within the constraints of underwater operation, where equipment access, heat rejection, and maintenance opportunities are limited. The most effective future designs will therefore require coordinated work across electrical machines, power electronics, energy storage, control engineering, and system reliability.

7. CONCLUSION

Electrical engineering is fundamental to submarine performance because propulsion, energy storage, power conversion, and onboard services depend on reliable electrical energy. Conventional diesel–electric systems provide an established architecture, while fuel-cell-based AIP systems offer additional possibilities for extending submerged energy availability. Research on underwater vehicle motors and hybrid fuel-cell systems demonstrates the potential of advanced electrical machines, power converters, and coordinated energy management. Nevertheless, the integration of these technologies introduces challenges involving system volume, thermal management, electrical protection, power quality, and long-term reliability. The literature published up to 2016 supports an integrated design approach in which energy sources, propulsion drives, converters, and control systems are evaluated as a complete electrical system. Continued progress will depend on validated system-level designs that balance efficiency, endurance, safety, and maintainability.

REFERENCES

[1] Y. Ajioka and K. Ohno, "Electric propulsion systems for ships," *Hitachi Review*, vol. 62, no. 3, pp. 231–232, 2013.
[2] J. J. De-Troya, C. Álvarez, C. Fernández-Garrido, and L. Carral, "Analysing the possibilities of using fuel cells in ships," *International Journal of Hydrogen Energy*, vol. 41, no. 4, pp. 2853–2866, 2016, doi: 10.1016/j.ijhydene.2015.11.145.
[3] J. Han, J. F. Charpentier, and T. Tang, "State of the art of fuel cells for ship applications," in *IEEE International Symposium on Industrial Electronics*, 2012, pp. 1456–1461. doi: 10.1109/ISIE.2012.6237306.
[4] A. Psoma and G. Sattler, "Fuel cell systems for submarines: From the first idea to serial production," *Journal of Power Sources*, vol. 106, no. 1–2, pp. 381–383, 2002, doi: 10.1016/S0378-7753(01)01044-8.
[5] E. Skjong, E. Rødskar, M. Molinas, T. A. Johansen, and J. Cunningham, "The marine vessel's electrical power system: from its birth to present day," in *Proceedings of the IEEE*, 2015, pp. 2410–2424. doi: 10.1109/JPROC.2015.2496722.
[6] J. S. Thongam, M. Tarbouchi, A. F. Okou, D. Bouchard, and R. Beguenane, "All-electric ships - a review of the present state of the art," in *2013 8th International Conference and Exhibition on Ecological Vehicles and Renewable Energies, EVER 2013*, IEEE, Mar. 2013, pp. 1–8. doi: 10.1109/EVER.2013.6521626.
[7] J. Mindykowski, "Case study—based overview of some contemporary challenges to power quality in ship systems," *Inventions*, vol. 1, no. 2, p. 12, 2016, doi: 10.3390/inventions1020012.
[8] I. S. Han, B. K. Kho, and S. Cho, "Development of a polymer electrolyte membrane fuel cell stack for an underwater vehicle," *Journal of Power Sources*, vol. 304, pp. 244–254, 2016, doi: 10.1016/j.jpowsour.2015.11.049.
[9] L. van Biert, M. Godjevac, K. Visser, and P. V. Aravind, "A review of fuel cell systems for maritime applications," *Journal of Power Sources*, vol. 327, pp. 345–364, 2016, doi: 10.1016/j.jpowsour.2016.07.007.
[10] N. C. Shih, B. J. Weng, J. Y. Lee, and Y. C. Hsiao, "Development of a 20 kW generic hybrid fuel cell power system for small ships and underwater vehicles," *International Journal of Hydrogen Energy*, vol. 39, no. 25, 2014, doi: 10.1016/j.ijhydene.2014.01.113.
[11] C. H. Choi *et al.*, "Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat," *International Journal of Hydrogen Energy*, vol. 41, no. 5, pp. 3591–3599, 2016, doi: 10.1016/j.ijhydene.2015.12.186.
[12] D. K. Hong, D. S. Joo, J. Y. Lee, and B. C. Woo, "Effects of the pole-slot combination on the PMSM of an integrated motor propulsor for an unmanned underwater vehicle considering its electric performance, noise and vibration," *International Journal of Applied Electromagnetics and Mechanics*, vol. 52, no. 3–4, pp. 1689–1695, 2016, doi: 10.3233/JAE-162162.
[13] A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, "An improved energy management strategy for a hybrid fuel cell/battery passenger vessel," *International Journal of Hydrogen Energy*, vol. 41, no. 47, 2016, doi: 10.1016/j.ijhydene.2016.08.049.
[14] A. Dubey and S. Santoso, "A two-level topology design framework for reliable shipboard power systems," *Inventions*, vol. 1, no. 3, p. 14, 2016, doi: 10.3390/inventions1030014.