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HYDROGEN POWERED VESSELS AT SEA:FUEL CELL & BATTERY UPSCALING

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ABSTRACT

There is today a strong effort in developing fuel cell / battery systems for ship propulsion to achieve zero-emission maritime transport, in accordance with UN sustainability goals and the Fit For 55 plan to achieve the climate goals agreed by the EU Council and the European Parliament. Critical for successful implementation of fuel cell / battery systems are system design and control during operation. Fuel cells and batteries have ideal operating ranges. Use outside of this range will cause degradation, impacting system lifecycle. Fuel cell / battery systems are used for transport today but applying such systems for maritime transport requires significant upscaling. Cars typically have a power of 100 to 300 kW, while ocean going ships require tens of MW of power to handle the loads required. To achieve such system capacity, systems are assembled with multiple fuel cells and batteries in stacks. A better understanding of the effect of such upscaling, and system dynamics with respect to load, is therefore required for successful implementation of fuel cell / battery systems for maritime transport. This paper discusses fuel cell types, methods and models applicable for this purpose.

Keywords: PEM fuel cell, Battery, Upscaling, Marine vessel hybrid system.

HYBRID FUEL-CELL/BATTERY DRIVEN SHIP

A hydrogen fuel cell is an electrochemical cell using hydrogen and oxygen as fuels to convert chemical energy to electrical energy. Commercial solutions for hydrogen-based transport using fuel cell systems, generally combined with batteries acting as an energy buffer, has existed for a couple of decades. The use in cars manufactured in series started in the late 2000s, and the first passenger-ship running on a hybrid FC/batteries system was put into service in 2008 [1]. With the national and global green transition, there is today a strong incentive for increasing the use of such technology in maritime transport. This technology transfer requires upscaling of both fuel cell and battery technology to cover the increase in power requirements [2], which for large ships can be several MW when in transit. The operational properties of individual battery and fuel-cell components are normally known. However, for an upscaled system such as a large ship with an integrated fuel cell as the main power generator, the system requires the consideration of fuel cell stacks and battery packs, but the properties of scaled systems with multiple elements are not necessarily proportional [3]. The energy / power requirements will vary with time, these load variations depend on such factors as ship schedules, speed/current, waterline (cargo), wind, and waves, making it challenging to predict system power and energy requirements. Poor predictability means that systems must have the capacity to deal with a large variability in load. This introduces a challenge with respect to systems engineering and systems control. Additionally, reliable and predictable upscaling of fuel cell technology remains a challenge, with respect to the system performance of a fuel cell which are characterized by durability, reliability and robustness [4]. So, uncertainty in systems performance, or degradation of system components, must also be considered in engineering. Relevant characteristics of ships and ship components are illustrated in Fig. 1.

The type of fuel cell and battery technology also impacts system performance. Oxide fuel cells provide high energy efficiency and fuel versatility but are unsuitable for rapidly varying loads [5]. Polymer Electrolyte Membrane (PEM) fuel cells, more suited to maritime application, are also limited with respect to fast current transients [6]. To accommodate for load transients on a PEM fuel cell and quick upstarts/shutdowns, a battery pack is integrated to minimize such transient behavior. Such a power splitting between a fuel cell and a battery requires a fuel cell-battery management strategy and system (FCBMS). Recent advances in autonomy, connectivity and machine learning have given rise to methods for predictive power management systems but has not yet been applied to large-scale ships in transit at sea. Also, recent health-conscious power management strategies have been considered for fuel cell-battery hybrid systems for on ground vehicles [7], however these advances do not properly account for the thermal dynamics which are strongly connected to fuel-cell/battery aging.

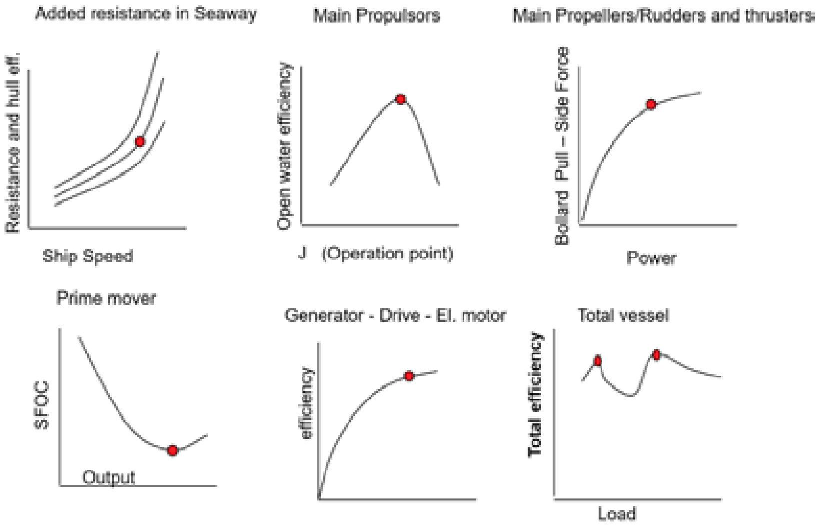

Fig. 1. Typical ship characteristics

For fuel cells, power output is constrained by compressor saturation limits. Exceeding these limits cause oxygen starvation, increase in temperature, fuel cell degradation, and reduced stack lifetime. Sufficient hydrogen and oxygen, provided by the compressor, must always be available at the cathode for the required power output to avoid oxygen / hydrogen starvation and subsequent stack degradation. It is well-known that load variations induce temperature changes in a fuel cell, and that temperature has an impact on both degradation (thermal degradation) of the membrane and on its performance. However, the temperature dynamics involve on a faster timescale than that of degradation. This imposes challenges on how to capture instantaneous effects of degradation on the fuel-cell/battery by implementing the thermal dynamical behavior. Most research in literature has not been focused on such instantaneous effects [8]. Ideally instantaneous effects of degradation should be described in terms of power requirements over time [9]. The performance of a PEM fuel cell can be classified into four processes, the membrane, catalyst layers, GDL/MPL and the channels. Each of these can further be described by the internal dynamics of the fuel cell including transport phenomena. In fact, in order to achieve realistic and detailed accounts of system degradation then atomic and system scale coupled models must be constructed [10]. For a PEM fuel cell ideal operating temperature is close to $80^{\circ}C$, for which thermal degradation can be completely neglected. Therefore from this perspective, it is crucial to develop a temperature control strategy to avoid thermal cycling and induced stress on the fuel cell and other related components [10], [11]. For a battery its health indicators often use the charge capacity as a characteristic parameter which is a fixed value, while for a fuel cell the charge capacity is not fixed since it depends on the fuel supply. This induces issues on how to properly define the SOH of a fuel cell, in the literature health indicators that have been considered include voltage and impedance-based indicators. However, most research done has been for steady-state systems, thus for a dynamical system where load variations occur and change rapidly i.e., for actual operating conditions, estimating the SOH of a PEM fuel cell has not been considered [8].

The charge capacity for batteries fades over time. How the battery is used affects this degradation. Batteries have a minimum state of charge where further discharge will cause permanent damage [12], so this should be avoided. Further, depending on the cell chemistry, both high and low state of charge may deteriorate performance and shorten battery life. Subsequently, the state of charge of a battery should vary as little as possible around its ideal state of charge. Deviation from this state of charge increases battery degradation. On a ship simultaneously the SOH and SOC of both the fuel cell and battery must be estimated along with possibly other relevant states of their domain, this is referred to as multi-state joint estimation. This type of estimation is challenging, since there is often a coupling between states and even for a single battery, most multi-state joint estimation that has been described in the literature are for two-state joint estimation. There is also a challenge with respect to upscaling, in the sense of how state estimation algorithms developed for a single fuel-cell/battery can be generalized to a fuel cell stack respectively battery pack [13]. This issue strongly depends on the modeling complexity of the fuel cell stack/battery pack needed for the system-level estimation requirements, i.e., lumped vs distributed configurations.

Models exist for predicting battery lifetime, and capacity, as a function of state of charge history [3]. There is a comparison issue that needs to be addressed between modeling types, particularly towards upscaling, a proper analysis in literature comparing lumped models versus distributed models is lacking. For a PEM fuel cell, lumped parameter models are the most common ones explored in the literature, from static to dynamic, and in some cases they are represented as an electrical equivalent circuit [14]–[16]. However, to implement degradation into a dynamical model, which strongly depend on the internal dynamics including mass, water and heat transport, then one needs to consider more spatial dimensions, i.e., distributed parameter models. The latter model types are more complex to work with from the computational and simulation aspect, in the sense that their state spaces are infinite dimensional and involve PDEs which are highly non-linear. They also come with a high number of parameters to estimate, and discretizing methods must be applied which pose numerical challenges [15]. In contrary to lumped models they are not naturally suited for control because of their computational complexity, and model order reduction techniques need to be applied. In literature distributed parameter models have also been considered, for example model order reduction techniques have been applied to a single PEMFC distributed parameter model, for which a model suitable for control and simulation was found [17].

It may be concluded that batteries have operational sweet spots or zones, while fuel cells have upper operational limits: Operating outside of these zones will cause component degeneration, impacting both system capacity and life cycle. To ensure staying within battery and fuel cell limits, process management requires intelligent systems control with predictive capability (or equivalent manual systems management). There must always be sufficient power to drive the vessel with respect to required loads, while the fuel-cell and battery systems should ideally operate within their ideal operating limits. Through model prediction, future energy demand, through the current sailing leg, needs to be estimated. Ideally the fuel cell / battery system should be regulated so that the combined power supply of both will provide the power needed at any time while still working within ideal component operating limits. For full power, electricity from both battery and fuel-cells can be directed to the ships electric drive system, but battery charge will run out in such a mode, so such operation is unsustainable. Further, if required, it should be possible to run the system at full capacity, overriding any possible limitation with respect to ideal operational limits. However, such operation will cause significant increase in component degradation, having a high impact on the lifetime of fuel cells and batteries. Subsequently, operational management of the fuel cell / battery system needs to cover not only the current sailing leg, but the entire life cycle of the system, where choices in systems engineering impact operational constraints. Constraints in optimization with respect to lifetime are subsequently maintenance / upgrading cost, ship/system lifetime expectancy, and fuel cell / battery energy density and available system space – impacting total possible capacity.

Further knowledge of system behavior is subsequently required for optimization, including such properties as fuel cell and battery degradation as a function of power load and time [9], battery discharge rate as a function of load [18], and also load capacity for system components as a function of degradation [19]. There may also be a question with respect to properties of scaled systems. Gains in energy efficiency, and time spent, may be gained by integrating dynamic models with the ships control systems for optimizing dynamic operational sequences such as ship accelerations – both building and reducing speed, and for ship maneuvering in general. A good analogy in drilling process control is optimization of drill pipe movement and starting of pumps for drilling fluid circulation [20], where automation must account for available power, operational constraints, and specific sequence requirements.

Finally, if optimal operation is to be achieved using continuous predictive models, enforcing limits, accounting for breach of limits, and always ensuring optimal combined use of fuel cell / battery system, then a certain degree of automation is needed. Automation / semi-automation using model prediction, enforcing constraints, and continuous model updating, has been applied in other domains, such as for control of petroleum drilling operations [18]. Technology transfer from such development is therefore highly relevant.

CONCLUSIONS

Designing hydrogen driven hybrid fuel cell battery power systems for ships requires systems upscaling from today's hydrogen powered systems to meet power demands. A better understanding of the effects of upscaling on individual battery and fuel cell components is required for systems design and control.
Degradation of battery and fuel cells as a function of load and other operating conditions impacts system lifecycle. Such effects must be understood and accounted for in systems control. Automated control can help optimize and prolong system lifetime.
Predicting operational loads as a function of weather, waves, ship routes and schedules enables improved systems control. Efforts should be made to improve such prediction, thereby improving operating reliability and system lifetimes.

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REFERENCES

1. A. Alaswad, A. Baroutaji, H. Achour, J. Carton, A. Al Makky, and A. G. Olabi, “Developments in fuel cell technologies in the transport sector,” *Int. J. Hydrog. Energy*, vol. 41, no. 37, pp. 16499–16508, Oct. 2016, doi: 10.1016/j.ijhydene.2016.03.164.
2. L. Birk, *Fundamentals of Ship Hydrodynamics: Fluid Mechanics, Ship Resistance and Propulsion*, 1st ed. Wiley, 2019. doi: 10.1002/9781119191575.
3. A. Perez, V. Quintero, H. Rozas, F. Jaramillo, R. Moreno, and M. Orchard, “Modelling the degradation process of lithium-ion batteries when operating at erratic state-of-charge swing ranges,” in *2017 4th International Conference on Control, Decision and Information Technologies (CoDIT)*, Barcelona, Apr. 2017, pp. 0860–0865. doi: 10.1109/CoDIT.2017.8102703.
4. J. Wang, “Barriers of scaling-up fuel cells: Cost, durability and reliability,” *Energy*, vol. 80, pp. 509–521, Feb. 2015, doi: 10.1016/j.energy.2014.12.007.
5. L. Kistner, A. Bensmann, and R. Hanke-Rauschenbach, “Optimal Design of Power Gradient Limited Solid Oxide Fuel Cell Systems with Hybrid Storage Support for Ship Applications,” *Energy Convers. Manag.*, vol. 243, p. 114396, Sep. 2021, doi: 10.1016/j.enconman.2021.114396.
6. A. Vahidi, A. Stefanopoulou, and H. Peng, “Current Management in a Hybrid Fuel Cell Power System: A Model-Predictive Control Approach,” *IEEE Trans. Control Syst. Technol.*, vol. 14, no. 6, pp. 1047–1057, Nov. 2006, doi: 10.1109/TCST.2006.880199.
7. Y. Wang, S. J. Moura, S. G. Advani, and A. K. Prasad, “Power management system for a fuel cell/battery hybrid vehicle incorporating fuel cell and battery degradation,” *Int. J. Hydrog. Energy*, vol. 44, no. 16, pp. 8479–8492, Mar. 2019, doi: 10.1016/j.ijhydene.2019.02.003.
8. X. Hu and T. Zhang, “Review on State of Health Definition in Relation to Proton Exchange Membrane Fuel Cells in Fuel Cell Electric Vehicles,” Apr. 2021, pp. 2021-01–0735. doi: 10.4271/2021-01-0735.
9 J. Wu *et al.*, “A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies,” *J. Power Sources*, vol. 184, no. 1, pp. 104–119, Sep. 2008, doi: 10.1016/j.jpowsour.2008.06.006.
10.T. Jahnke *et al.*, “Performance and degradation of Proton Exchange Membrane Fuel Cells: State of the art in modeling from atomistic to system scale,” *J. Power Sources*, vol. 304, pp. 207–233, Feb. 2016, doi: 10.1016/j.jpowsour.2015.11.041.
11. F. Barbir, *PEM fuel cells: theory and practice*. Amsterdam; Boston: Elsevier/Academic Press, 2013. Accessed: Feb. 23, 2022. [Online]. Available: http://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=1032957
12. C. Bordin and O. Mo, “Including power management strategies and load profiles in the mathematical optimization of energy storage sizing for fuel consumption reduction in maritime vessels,” *J. Energy Storage*, vol. 23, pp. 425–441, Jun. 2019, doi: 10.1016/j.est.2019.03.021.
13 .X. Hu, F. Feng, K. Liu, L. Zhang, J. Xie, and B. Liu, “State estimation for advanced battery management: Key challenges and future trends,” *Renew. Sustain. Energy Rev.*, vol. 114, p. 109334, Oct. 2019, doi: 10.1016/j.rser.2019.109334.
14. BEI. N. GOU and B. WOONKI. DIONG, *FUEL CELLS: dynamic modeling and control with power electronics applications, second edition.* S.l.: CRC PRESS, 2020.
15. M. Guarnieri, P. Alotto, and F. Moro, “Distributed and Lumped Parameter Models for Fuel Cells,” in *Thermodynamics and Energy Engineering*, P. Vizureanu, Ed. IntechOpen, 2020. doi: 10.5772/intechopen.89048.
16. S. M. C. Ang, E. S. Fraga, N. P. Brandon, N. J. Samsatli, and D. J. L. Brett, “Fuel cell systems optimisation – Methods and strategies,” *Int. J. Hydrog. Energy*, vol. 36, no. 22, pp. 14678–14703, Nov. 2011, doi: 10.1016/j.ijhydene.2011.08.053.
17. M. L. Sarmiento-Carnevali, C. Batlle, M. Serra, and I. Massana, “Distributed parameter PEMFC model order reduction,” 2014, p. 4.
18. J. Zhang, S. Ci, H. Sharif, and M. Alahmad, “Modeling Discharge Behavior of Multicell Battery,” *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1133–1141, Dec. 2010, doi: 10.1109/TEC.2010.2048904.
19. Y. Wu, Z. Liu, J. Liu, H. Xiao, R. Liu, and L. Zhang, “Optimal battery capacity of grid-connected PV-battery systems considering battery degradation,” *Renew. Energy*, vol. 181, pp. 10–23, Jan. 2022, doi: 10.1016/j.renene.2021.09.036.
20. F. Iversen, E. Cayeux, E. W. Dvergsnes, R. Ervik, M. Welmer, and M. K. Balov, “Offshore Field Test of a New System for Model Integrated Closed-Loop Drilling Control,” *SPE Drill. Complet.*, vol. 24, no. 04, pp. 518–530, Dec. 2009, doi: 10.2118/112744-PA.