Result report for project:

Optimization of Marine Energy Storage Systems for Desired Lifetime, Energy Saving and Safety

Project No.: 254766
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1 Project background and objective

The project has addressed the task of optimizing the power and energy rating as well as optimizing the usage of energy storages in hybrid electrical power and propulsion systems in ships with diesel both generator sets and energy storage (hybrid system). Hybrid systems had at project start already been shown to give significant reduced fuel consumption as well as reduced emissions for several kinds of vessels and operations. However, back in year 2015, the industry project partner Rolls Royce Singapore, found that the knowledge and experience on how to select the best combination and size of energy storage within the required constraints was not in the public domain. They therefore initiated this joint research effort with research and industry partners from Singapore and Norway aiming to make new knowledge on design and optimization of marine energy systems available to a wider industry.

The optimized choice of energy and power rating is a complex task that depend on several factors as illustrated in Figure 1. This is further complicated by the close interdependency between storage rating, desired lifetime, and usage as illustrated in Figure 2. They can typically not be optimized independent of each other.

The defined primary objective of the project was to develop methodology for optimized sizing of energy storage in hybrid ship power and propulsion systems.

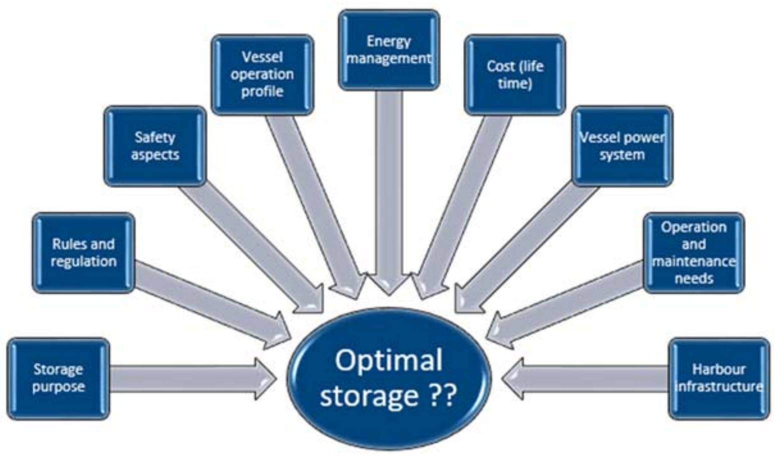

Figure 1 Factors having impact on optimal storage energy and power rating

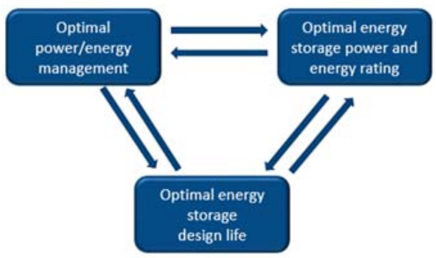

Figure 2 Close dependency between storage power and energy rating, design lifetime and operation strategy

2 Organization and project partners

The project is one of the projects that received funding from the Joint Call for Proposal in Maritime Research between Singapore and Norway back in 2015. The call asked for collaborative projects involving research groups (universities, university colleges and research institutions) from Singapore and Norway. The partners of this project have been:

- Nanyang Technological University (NTU), Singapore
- Rolls Royce Singapore Pte. Ltd.
- SINTEF Energi, Norway
- Kongsberg Maritime, Norway (from 2019 after their acquisition of the initial project partner Rolls Royce Marine, Power Electric systems, Norway)

The project activities were started in June 2016. Activities in Singapore were finalized in end of November 2019, while the activities in Norway is finalized end of May 2020.

Financially, the activities in Singapore and Norway have been independent of each other. The activities in Singapore have been funded by the Singapore Maritime Institute, while the activities in Norway have been funded by the Research Council of Norway and Rolls Royce Marine. In addition, there have been a significant in-kind contribution from Rolls Royce Singapore in the form of management of the Singapore activities, engineering, and research, as well as in-kind from NTU (professor involvement and EPSIL@N laboratory facility). The collaboration between the partners have been regulated by a consortium agreement.

3 R&D tasks and main result

The project has given results in line with the project objective. Early in the project it was realized that the optimal sizing of energy storage is closely linked to the power management strategies and that these need to be optimized together. This is reflected by more work done and more results related to power management compared to the plans laid down in the project proposal. Similarly, the Singapore activities focused somewhat more than original plan on how to integrate battery systems in high voltage maritime power systems. The effort in Singapore has given new results related to use of Modular Multilevel Converters with integrated batteries, fault handling and control.

The main research tasks and results of the activities carried out in Norway are:

- Methodology for determination of expected fuel saving from using batteries for spinning reserve and for strategic loading of engines on hybrid vessels using predicted relative time spend at different load levels [4]. The predictions needed for this method is believed to be easier to obtain than the load series in time domain that will be the typical alternative. It also gives better insight in the what matters for the fuel saving potential for a given vessel.
- Methodology for design of minimum fuel consumption energy management strategy for hybrid marine vessels with multiple diesel engine generators and energy storage [4]. This also includes simple procedures for favourable trade-off between fuel saving and storage lifetime.
- Exploration of methods to consider the battery degradation in the optimization
- Implementation of robust tool for estimation of battery system degradation utilizing the scarce degradation data that realistically will be available for ship system designers. Suitable for integration in the industry partners power system design tool as well as maintenance monitoring systems for ships in operation.
- Method to include power management strategies and load profiles in the cost function for mathematical optimization of energy storage sizing for fuel consumption reduction in maritime vessels [3]. The key contribution is the proposed methodology to formulate technical and safety constraints, represent different vessel modes of operation and battery storage degradation in a way suitable for inclusion within mathematical optimisation models.

- Utilization of model predictive control (MPC) for marine power plants with gas engines and battery [2]. The goal of the work was to utilize the MPC to operate the system in such way that battery size is minimized and battery lifetime is maximized while ensuring that the gas engines are prevented from taking fast load changes (collaborative work with SFI Smart Maritime, NRC project number 237917)
- Methodology for the design and tuning of real-time power and energy management systems for plug-in marine vessels [1]. Main contributions are: (1) Method to design and tune the energy management strategy that will optimally share the load between onboard, fixed speed, diesel generator units and on-board energy storage, in such way that fuel consumption is minimized for a given expected load probability distribution (2) Method adaption for cases where the crew, for operational or safety reasons, decides to run with non-optimal number of diesel engines. (3) Outline of possible inclusion of adaptive tuning to cope with uncertain or unknown load probability distribution.

Highlights of results from the activities carried out in Singapore are:

- Optimization formulation for the use of Particle Swarm Optimization (PSO) to solve the optimal sizing problem (constrained nonlinear optimization problem) [7]. Method has been implemented in a tool for possible integration in Industry partner design tool.
- Research related to use of Modular Multilevel Converters. The use of MMC and distributed energy storages can help to address the voltage matching issue of low voltage (LV) energy storage modules and onboard 12kV DC link where low voltage energy storage modules can be connected to the submodules of MMCs. This work included MMC fault detection and isolation method based on Model Predictive Control (MPC), control strategies for frequency support from batteries and MMC reliability analysis (several papers published)[5][6][8][9][11][13]
- Testing of Nickel Manganese Cobalt (NMC) and Lithium-Titanate Oxide (LTO) battery in the laboratories in Singapore to gain more knowledge about the characteristics of these, especially focused on degradation during high charge/discharge cycling. Results were used by industry partner in their work on their next generation battery system.
- Exploration of the capability of power electronic converters in providing power system virtual inertia in ship power systems [12]

4 Implementation

The cooperation within the project worked out well with no internal conflicts or disagreements. The only administrative challenge has been the different regimes for reporting to SMI in Singapore and the RCN in Norway. A more coordinated regime for progress and financial reporting would have been appreciated. The different reporting periods set by SMI and RCN became a challenge since RCN also required reporting of the financial numbers for the part of the project funded by SMI.

The geographical distance between the partners are large. Regular telcon status meetings and telcon technical presentations where therefore organized and led by the industry partner Rolls Royce in Singapore to coordinate and update the involved parties.

On the Singapore since two research fellows and one research associate have been working full time on the project at NTU, while at SINTEF the project has funded in average 750 hours per year, shared between two to four researchers each year. The competence and research interests of the research groups involved in Singapore and Norway were somewhat complementary which have been both an advantage and disadvantage. The disadvantage has been little work on common tasks while the advantage has been increased need and value of competence and system knowledge transfer between the partners. Two of the NTU researchers working on the project spend three weeks at SINTEF for knowledge exchange.

At NTU, 3 master students and 6 final year undergraduate students have been working on project related topics. The university in Norway was not partner in this project, but one master student at NTNU was co-supervised by SINTEF in his investigations of battery degradation.

There have also been activities to establish contacts and get updates from the industry. This includes participation as well as a presentation both at Maritime Battery Forum member meetings as well as their yearly Watts Up conference that gathers the Norwegian industry working with batteries for maritime use. SINTEF hosted one of the member meetings during the project period. Other relevant conferences to get update from industry was participation in the seminar "Nullutslippsløsninger i maritim transport", arranged by Zero and participation at Electric Hybrid Marine World Expo Conference in Amsterdam.

5 Utilization of results

Most of the key project results have already been published. The scientific publication that is a result of this project is listed at the end of this document. There is however ongoing work on one more paper, extending the ideas presented in [1] to be able to optimize also the operation of plug-in vessels that charges both from shore and from onboard engines.

The project has produced results that have the potential of reducing the cost related to the use of battery systems in ships since results can be used for more optimal sizing of battery storage, as well as more optimal usage of the battery storage in operation such that the value of the installed storage is maximized. This will in the long term contribute to reduced fuel usage and reduced emissions from the type of vessels considered in this work.

The project has given significant increased competence at SINTEF Energy on the use of batteries in general and on use of batteries onboard maritime vessels in specific. Methodology is in place for use in other projects, not only for batteries for maritime vessels, but also for similar isolated power grids such as offshore installations, electrification of transport and use of batteries in the grid.

Competence, experience and methods from the project have already been valuable in other projects. This includes an IPN project on offshore wind integration with the stand-alone electric grid at oil and gas offshore installations (including batteries), an IPN project on new energy storage systems for ships, Pilot-E project on offshore hydrogen technologies for CO2-free energy production (includes battery systems) as well as one bilateral project with an industry partner that experienced too fast degradation of their battery systems for the storage system robots they are producing.

The research group at SINTEF has now been invited as partner in two EU proposals addressing battery systems. The first one, BAT4GRID, did not get funding, the second one, SEABAT, addressing solutions for large batteries for waterborne transport was recently submitted and are now under evaluation.

It is also anticipated that results, experience, and competence from the project will be useful if the SFI application Zero emission transport accelerator (ZETA) gets funding (https://www.sintef.no/projectweb/zetainitiative/)

Draft ideas for an IPN application to partly follow-up some of the projects results and partly to investigate new topics related to the use of batteries are being discussed with the project industry partner.

The project has given many contacts within other SINTEF departments as well as with industry contacts. One of the new industry contacts was now in May 2019 informed that they will get a small funding from the "forsker til låns"-programme to hire one SINTEF researcher to assist their development of battery drive systems for small boats. The established contacts have also led to participation in the project "Kunnskapspakke Godstrafikk" for Trøndelag Fylkeskommune, and now also as participant in an offer for consultancy services on zero emission fast passenger boats.

As a result of the contacts established, the project manager was invited and involved in the establishing of the Battery Ecosystem Accelerator of Norway (BEACON) (https://www.sintef.no/projectweb/beacon/). Beacon is to be a gathering place to exchange R&I advances, funding opportunities, and inter-disciplinary networking. A significant number of stakeholders have joined the initiative. This arena will hopefully give more opportunities to establish projects that can further exploit competence and results from the project.

Project scientific publications

[1] 2019 O. Mo and G. Guidi, "Optimized use of Energy Charged from Shore in Plug-in Hybrid Marine Vessels", 2019 J. Phys.: Conf. Ser. 1357 012023, https://doi.org/10.1088/1742-6596/1357/1/012023

[2] 2019 T. I. Bø, E. Vaktskjold, E. Pedersen and O. Mo, "Model Predictive Control of Marine Power Plants With Gas Engines and Battery," in *IEEE Access*, vol. 7, pp. 15706-15721, 2019. doi: 10.1109/ACCESS.2019.2895163

[3] 2019 C. Bordin, O. Mo, "Including power management strategies and load profiles in the mathematical optimization of energy storage sizing for fuel consumption reduction in maritime vessels", Journal of Energy Storage, Volume 23, 2019, Pages 425-441, ISSN 2352-152X, https://doi.org/10.1016/j.est.2019.03.021.

[4] 2018 O. Mo and G. Guidi, "Design of Minimum Fuel Consumption Energy Management Strategy for Hybrid Marine Vessels with Multiple Diesel Engine Generators and Energy Storage," *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*, Long Beach, CA, 2018, pp. 537-544. doi: 10.1109/ITEC.2018.8450263

[5] D. Zhou, S. Yang, and Y. Tang, "Model-predictive current control of modular multilevel converters with phase-shifted pulsewidth modulation," IEEE Trans. Ind. Electron., vol. 66, no. 6, pp. 4368–4378, 2019.

[6] D. Zhou, H. Qiu, S. Yang, and Y. Tang. "Similarity-Based Fast Open-Circuit Fault Diagnosis Method for Modular Multilevel Converters." 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019-ECCE Asia), pp. 1830-1835, 2019.

[7] R. Tjandra, S. Wen, D. Zhou, and Y. Tang, "Optimal sizing of BESS for hybrid electric ship using multi-objective particle swarm optimization," ICPE 2019 - ECCE Asia - 10th Int. Conf. Power Electron. - ECCE Asia, pp. 1460–1466, 2019.

[8] D. Zhou, S. Yang, and Y. Tang, "A fast open-circuit fault diagnosis scheme for modular multilevel converters with model predictive control," 2018 Int. Power Electron. Conf. IPEC-Niigata - ECCE Asia 2018, pp. 428–433, 2018.

[9] D. Zhou, S. Yang, and Y. Tang, "A voltage-based open-circuit fault detection and isolation approach for modular multilevel converters with model-predictive control," IEEE Trans. Power Electron., vol. 33, no. 11, pp. 9866–9874, 2018.

[10] D. Zhou and Y. Tang, "An online open-circuit fault diagnosis and fault tolerant scheme for three-phase AC-DC converters with model predictive control," 2018 Int. Power Electron. Conf. IPEC-Niigata - ECCE Asia 2018, pp. 434–438, 2018.

[11] D. Zhou, P. Tu, H. Qiu, and Y. Tang, "Cascaded open-circuit fault ride-through of modular multilevel converters with model predictive control," 2018 IEEE Energy Convers. Congr. Expo. ECCE 2018, pp. 113–118, 2018.

[12] H. Qiu, J. Fang, and Y. Tang, "Explore the capability of power electronic converters in providing power system virtual inertia," 2018 IEEE Energy Convers. Congr. Expo. ECCE 2018, pp. 215–221, 2018.

[13] D. Zhou, S. Yang, and Y. Tang, "Integrating phase-shifted pulse-width modulation to model predictive current control of modular multilevel converters," 2018 IEEE Energy Convers. Congr. Expo. ECCE 2018, pp. 4845–4850, 2018.

[14] D. Zhou, X. Li, and Y. Tang, "Multiple-vector model-predictive power control of three-phase four-switch rectifiers with capacitor voltage balancing," IEEE Trans. Power Electron., vol. 33, no. 7, pp. 5824–5835, 2018.