\International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1012

OVERVIEW OF ENERGY MANAGEMENT STRATEGIES FOR HYBRID LEISURE BOATS

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ABSTRACT

After their wide success in the field of road vehicles, hybrid propulsion technologies are gaining more and more interest for their application also in the marine sector. This interest is mainly justified by the need of reducing pollutant emissions, as required by new strictly standards and legislations for marine transport systems. This paper aims to identify the main hybrid propulsion architectures, also obtained through retrofit operations, to be considered for leisure boats, compared in terms of efficiency and on-board space/weight requirements. On the basis of the above architectures specific energy management strategies are evaluated, reporting their main advantages and disadvantages.

The evaluations reported in this paper represents a useful decision support tool, to help ship producers in the design and energy management of an efficient and sustainable maritime mobility.

Keywords: Keywords: hybrid ship; marine propulsion architecture; marine energy generation systems

1. INTRODUCTION

The reduction of exhaust emissions related to transport sector is considered as one of the major challenges to be faced in the next decades. In recent years, engineers and technicians have focused their efforts in reducing the environmental impact of road transport sector. In this regard, development of new technologies for internal combustion engines and introduction of electric and hybrid propulsion systems have given a strong contribution in increasing efficiency and reducing exhaust emissions of road vehicles [1].

As a matter of fact, great part of maritime transport systems has not been interested by similar technology improvements. This aspect can be justified by taking into account that, in the past years, legislations related to exhaust emissions, in comparison with road transport systems, were generally less restrictive for the marine transport systems. Traditional marine propulsion systems are generally based on old technologies of diesel engines, which are sized to supply maximum power demanding operations. Unfortunately, in comparison with their daily mission, ships generally operate at maximum power just for few hours. Therefore, their diesel engines work, for great part of the time, in low efficiency/high emissions operating points [4].

In recent years, the rising number of ships both in private and in corporate sector has encouraged the introduction of new legislations, aimed to pursue a relevant reduction in the exhaust emissions related to the marine sector. An example of the restriction given by these new legislations is represented by the SECA (Sulphur Emission Control Areas) standards, which have been released by the International Maritime Organization (IMO) and are active since 2015. In particular, SECA standards refer to the admitted percentage of fuel Sulphur content, which must be lower than 0.1% in many coastal regions [2][3]. Mandatory improvements for the overall ship efficiency are also required by the MARPOL Annex VI. In fact, the design of new ships must be compliant with the minimum energy efficiency requirements defined by the Energy Efficiency Design Index (EEDI). Existing ships are also required to update their systems in order to improve their efficiency on the basis of the Energy Efficiency Management Plan (SEEMP) [2].

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

A feasible solution to satisfy the above efficiency and environmental requirements is represented by the use of electric propulsion systems in the marine sector. These systems have been already successfully applied in road vehicles and are expected to introduce the same benefits also for the marine industry. In fact, as well known, electric drives are characterized by relevant advantages in terms of conversion efficiency, ship maneuverability, reliability and safety [5]. As a matter of fact, in the marine industry, the pure electric propulsion is only considered for some specific case studies, where the mission of the ship is well known and its energy requirements can be managed through frequent charging operations. For this reason, hybrid propulsion systems, based on the combined use of electric drives and thermal engines, are considered a more attractive solution to satisfy strict environmental and efficiency requirements, with acceptable investment and maintenance costs. In addition, the need to upgrade old vessels, in order to meet efficiency requirements of new legislations, has encouraged the growing interest towards hybridization kits, specifically designed to perform retrofit operations [6]-[8].

In this context, starting from an analysis of propulsion architectures for hybrid marine applications, with particular focus on leisure boats, this work describes the main energy management strategies useful to optimize the on board power exchange between batteries, electric drive and internal combustion engine.

2. HYBRID PROPULSION ARCHITECTURES

Hybrid propulsion architectures for marine applications are classified on the basis of mechanical and electrical interactions between the battery pack, electric drive, thermal engine and propeller.

The first configuration is also known as full-electric (or pure-electric) architecture. In this case, the electric drive works as prime mover and is connected to the propeller shaft through a specific gear box. The electric drive is driven by the energy coming from the on-board battery pack, which can be recharged through the direct connection of the ship with the main grid. In some cases, a small amount of power for recharging the battery pack can be supplied by means of on-board renewable energy sources (e.g. solar, wind, etc..). The main scheme of a full-electric marine propulsion system is reported in Fig 1 [9].

Differently form full-electric configurations, marine hybrid propulsion systems include an internal combustion engine (ICE), a generator, an electrochemical energy storage system and an electric drive. As a matter of fact, the performance of a hybrid propulsion system is mostly associated with the type of configuration. In the following, a description of series, parallel and series-parallel hybrid configurations is reported, with the main advantages and disadvantages depending on the specific application.

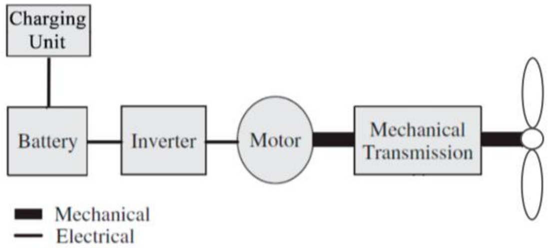

Fig 1 Main scheme of a full-electric marine propulsion system

In a *hybrid-series* architecture the mechanical power for the propeller shaft is provided by the sole electric drive, which receives electric power either from the battery pack or from the electric generator, driven by an internal combustion engine. In this way the boat can continue its normal operations even when the battery pack is completely discharged. The scheme of hybrid-series propulsion system for naval applications is reported in Fig 2 [10].

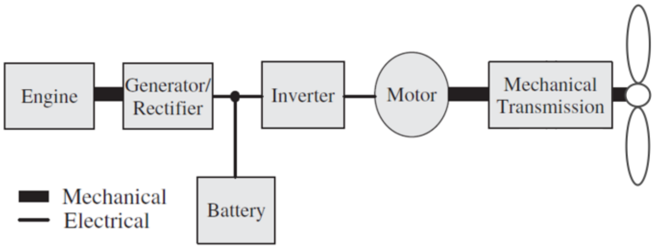

Fig 2 Main scheme of a hybrid-series marine propulsion system

The main advantage of this configuration is the absence of any mechanical connection between the internal combustion engine and the propeller shaft. For this reason, the operating point of the internal combustion engine can be chosen independently from the rotation speed of the propeller shaft. Therefore, the internal combustion engine can be controlled in order to work in an optimal operating area, characterized by high efficiency and low exhaust emissions. On the other hand, this configuration is characterized by a partial loss of efficiency related to the mechanical-electric-mechanical energy conversion steps, which characterize the power flow from the internal combustion engine to the propeller shaft.

The application of the hybrid-series architecture is generally referred to large ships (eg cruise ships, transatlantic liners, etc.) and therefore is not generally considered for leisure boats. Possible applications for smaller boats are generally related to either retrofit operations or installations where an autonomy increase is required, starting from the initial full-electric configuration of the boat. An example of such applications, created several years ago for the Venice lagoon, is represented by the LIUTO (Low Impact Urban Transport water Omnibus) waterbus [9].

In a *hybrid-parallel* architecture both internal combustion engine and electric drive are controlled to supply mechanical power to propeller shaft. In this case, the electric drive can be used either to support the ICE in moving the propeller shaft, by means of the energy coming from the battery pack, or to charge on board battery pack, working as a generator. The scheme of hybrid-parallel propulsion system for naval applications is reported in Fig 3.

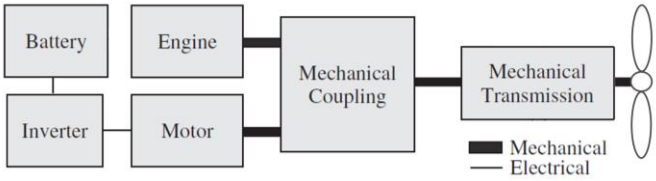

Fig 3 Main scheme of a hybrid-parallel marine propulsion system

Marine applications of hybrid propulsion architecture are generally based on the use of electro-hydraulic transmission systems that require an additional power take-offs flange, in order to allow the management of energy flows and the decoupling between the shaft of the two motors. More compact systems are based on the integration of an electric motor, interposed between the ICE and the propeller, keyed on the same rotation shaft of the ICE. This integration takes place through the realization of a specific coupling flange between the ICE bell, clutch and electric motor.

Hybrid parallel-series architecture combines both the above mentioned architectures by using the electric drive both as a motor, supplying mechanical power to the propeller shaft, and as a generator, recharging the battery pack through the power coming from the ICE. Although this last architecture is widely used for road vehicles, it is characterized by a high level of complexity both in control and in its installation. As a consequence, this architecture generally involves high cost and are not suitable for retrofit operations.

3. ENERGY MANAGEMENT STRATEGIES

The definition of energy management strategies in hybrid propulsion systems consists in deciding the amount of energy, supplied at any time, from the differnet energy sources on board, respecting specific constraints, in order to achieve predefined objectives. Energy saving objectives include minimizing fuel consumption, maintaining/depleting battery state of charge, reducing pollutant emissions and maximizing component lifetime. The mathematical formulation of management strategies in terms of inputs, outputs, objectives and constraints represents the problem to be set for the EMS. The resolution methodology, the number of objectives and the number of inputs (measured / estimated) influence the applicability of these methods in real time and the optimal degree of the solution. In this context, energy flow management strategies are classified into two main macro-categories: Rule-Based Strategies (RB) and Optimization Based Strategies (OB). In the first case, the control laws are defined either by deterministic on-off rules or by rules based on fuzzy logic. On the other hand, the OB strategies are based on control approaches aimed at finding a global optimal solution, generally obtained through either costly backward evaluations or real-time optimizations [11].

Simple Thermostatic deterministic RB control strategies are generally based on on / off controls that activate or deactivate the individual components of the power-train, making them work only in predefined operating limits. Although these strategies do not represent the optimal solution either during transient phases or for unexpected operative conditions, they are characterized by relevant advantages in terms of implementation and computational effort. A possible evolution is represented by the RB Power Follower strategies. In this case, decisions on individual components can be made on the basis of predefined control regions, which identify specific operative conditions of the hybrid propulsion system [12]. An evolution of this last energy management strategy is represented by the adaptive RB Power Follower, where the control regions are continuously updated through adaptive rules. In Fuzzy RB management strategies, the controller is based on the traditional implementation of fuzzy logic, in which the inputs are *fuzzified* according to specific membership functions. These membership functions are based on rules defined starting from the knowledge of the system to be controlled. After the *fuzzification* process, the outputs are *defuzzified* in control signals. Further RB strategies are based on the repartition of the power profile required by the operative cycle on the basis of its frequency components. In this way, high frequency parts of the cycle can be realized with the electric motor with the ICE covering the low frequency components.

Optimization-based strategies are aimed to minimize objective functions in specific operating conditions. These methodologies are mainly divided into: Global Optimization (GO) and Real-Time Optimization (RTO). The GO strategies are designed to obtain excellent global solutions, for the propulsion system to be controlled, with reference to a specific work cycle. These strategies can be applied only starting from the a priori knowledge of the operating conditions of the system on the reference work cycle. The diffusion of GO strategies is limited by the high computational complexity, which does not allow their real-time implementation. However, these strategies are generally implemented in a simulation environment and used as a benchmark for performance evaluation of other management strategies. The RTO strategies are based on real-time optimization procedures for the control parameters. These procedures are based on mathematical formulations that allow obtaining a good compromise between the degree of optimization and the computational requirements. The most common examples of these strategies are based on Model Predictive Control (MPC) and Adaptive Dynamic Programming (ADP) techniques.

CONCLUSION

In this paper, hybrid propulsion systems are proposed for marine application with particular reference to the case study of a leisure boat.

Different hybrid propulsion architectures have been analyzed, highlighting their main advantages and disadvantages in terms of space/weight constraints, costs, efficiency and performance.

Finally, on-board energy management strategies have been analyzed and classified in Rule Based and Optimization-Based strategies.

The analysis proposed in this paper represents a first useful step to support design, management and performance evaluation of hybrid propulsion architectures for leisure boats.

ACKNOWLEDGEMENT

The activities reported in this paper have been funded by the Italian Minister of the Economic Development within the iMare project.

REFERENCE

[1] OP Agarwal, S Zimmerman, K Ajay. Emerging Paradigms in Urban Mobility: Planning, Financing and Management. Elsevier, 2018.

[2] Annex VI of MARPOL 73/78, Regulations for the prevention of air pollution from ships and NOx technical code, IMO London, 1998.

[3] N Butt. The impact of cruise ship generated waste on home ports and ports of call: A study of Southampton. Marine Policy vol. 31.5, pp: 591-598, 2007.

[4] D Woodyard. Pounder's marine diesel engines and gas turbines. Butterworth-Heinemann, 2009.

[5] TJ McCoy. Trends in ship electric propulsion." Power Engineering Society Summer Meeting, 2002 IEEE. Vol. 1. IEEE, 2002.

[6] G Seenumani. Real-time Power Management of Hybrid Power Systems in All Electric Ship Applications. 2010.

[7] G Papalambrou et al. Model Predictive Control for Hybrid Diesel-Electric Marine Propulsion. IFAC-PapersOnLine 50.1: 11064-11069, 2017.

[8] B Zahedi, LE Norum. Modeling and simulation of all-electric ships with low-voltage DC hybrid power systems. IEEE Transactions on Power Electronics 28.10: 4525-4537, 2013.

[9] F Balsamo et al. Performance evaluation of an all-electric waterbus supplied by hybrid energy storage systems. In IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2018.

[10] O Veneri et al. "Overview of electric propulsion and generation architectures for naval applications." 2012 Electrical Systems for Aircraft, Railway and Ship Propulsion. IEEE, 2012.

[11] P Zhang, et al. A comprehensive analysis of energy management strategies for hybrid electric vehicles based on bibliometrics. Renew. Sustain. Energy Rev 2015. 48: 88–104.

[12] Y Cheng, et al. Global modeling and control strategy simulation for a hybrid electric vehicle using electrical variable transmission. In Proceedings of the 2008 IEEE Vehicle Power and Propulsion Conference 2008.

[13] Y Kim, et al. Stefanopoulou, A.G.; Ersal, T. Hardware-in-the-loop validation of a power management strategy for hybrid powertrains. Control Eng. Pract. 2014. 29: 277–286.