Applied Energy 231 (2018) 747–756

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Alternating current and direct current-based electrical systems for marine vessels with electric propulsion drives

Merlin Chai[a,*], Dastagiri Reddy Bonthapalle[a], Lingeshwaren Sobrayen[a], Sanjib K. Panda[a], Die Wu[b], XiaoQing Chen[b]

[a] National University of Singapore, Electrical Machines and Drives Laboratory, E3-04-04, 2 Engineering Drive 3, 117581, Singapore
[b] ST Marine Ltd, 7 Benoi Road, 629882, Singapore

HIGHLIGHTS

- Alternating current(AC)- and direct current (DC)-based marine vessels are presented.
- Improvements in electrical performance achieved by DC-based systems is derived.
- A genetic algorithm-based technique to improve fuel efficiency is proposed.
- Quantitative benefits of moving to DC-based systems for marine vessels are studied.

ARTICLE INFO

Keywords:
Marine vessel
Diesel-electric
Hybrid
AC
DC
Fuel efficiency

ABSTRACT

The initial widespread electrification of marine vessels primarily used alternating current (AC)-based systems as they were prevalent in the electrical distribution infrastructure for land-based systems. At present, there are marine vessels that operate based on a hybrid diesel-electric system, in which the on-board diesel engines generate AC power to a common AC bus, which in turn supplies power to the electrical propulsion drives and other service loads. Recently, there has been an active interest in a transition to direct current(DC)-based electrical distribution system with diesel-electric hybrid propulsion systems for marine vessels due to potential improvements in electrical performance and fuel consumption. This paper evaluates the improvement in the move to DC-based distribution system for marine vessels in terms of electrical performance and fuel efficiency. An overview of a typical AC electrical system currently in use is provided, and modifications of the system to a DC-based system is presented. The power factor, total harmonic distortion, and voltage regulation are discussed. Both symmetrical and asymmetrical generator scheduling are examined and the potential fuel savings for an example diving support vessel is presented. A discussion on the recommendations to shift towards DC-based systems is then provided based on the findings of this paper.

1. Introduction

1.1. Diesel-electric marine vessels

The use of electricity for energy transfer has been well-documented and was enabled through the production of commercial electro-mechanical generators [1]. Although the use of both alternating current (AC) and direct current (DC) were available, it was soon realized that AC systems were more feasible due to the invention of the power transformer that can easily step up AC voltages to allow for high-voltage, low-current transmission systems, which were more efficient at that time.

The first known electrical system implemented on-board a marine vessel was a DC system designed for a commercial vessel, the SS Columbia. However, this system was primarily for electrical lighting, with the propulsion system still mechanical-based. The first electrical propulsion drive was first implemented for naval vessels, i.e. the Vandal and the USS Jupiter, in the early 1900s [2]. As land-based electricity networks trended towards the use of AC systems in distribution of electricity, so did the marine industry due to easy access to electrical equipment and knowledgeable manpower. The initial DC system was discontinued thereafter for newer ships, and AC systems with

* Corresponding author.
E-mail addresses: merlin.chai@nus.edu.sg (M. Chai), elebdr@nus.edu.sg (D.R. Bonthapalle), waren.sobrayen@nus.edu.sg (L. Sobrayen), sanjib.kumar.panda@nus.edu.sg (S.K. Panda), wudie@stengg.com (D. Wu), chenxiaoqing@stengg.com (X. Chen).

https://doi.org/10.1016/j.apenergy.2018.09.064
Received 1 November 2017; Received in revised form 23 April 2018; Accepted 6 September 2018

distribution voltages of 440 V, 690 V, 3.3 kV, 6.6 kV, and 11 kV are commonly used.

Due to environment concerns [3], there has been ongoing research on the greenhouse gas emissions produced by marine vessels [4]. Most efforts, however, has been largely focused on energy efficiency improvement attained through design changes in the marine diesel engine [5,6] or the fuel used [7,8]. There is also the possibility of improving fuel efficiency through power management of the propulsion system [9]. The inclusion of renewable energy sources, such as solar, on-board marine vessels has also been proposed [10].

1.2. State-of-the-art

The use of electric or diesel-electric propulsion systems in marine vessels are now commonplace[11]. Some marine vessels, e.g. platform supply vessels, diving support vessels, and containerships, use diesel-electric propulsion systems [12]. These vessels have both mechanical propulsion drives used during long-range, constant-speed operations and electrical propulsion drives that are used for low-speed maneuvering operations.

Newer cruise ships tend to use electric propulsion system, in which electrical generators are used to produce electricity that can then be utilized by electric propulsion drives without the need for mechanical coupling between the generators and propulsion drives. It should be noted that although the propulsion systems are electric-based, the generation of electricity still requires diesel generators. There is ongoing research on the integration of energy storage devices such as batteries and flywheels in marine vessels[13] to complement the diesel generators. However, even with inclusion of renewable energy resources, the use of diesel generators is still required to produce electricity[14]. This is due to the high power demand on-board marine vessels.

The use of electric propulsion drives to replace mechanically-linked diesel propulsion drives has been gaining traction due to their advantages[15], which include:

- Improved efficiency of the generators
- Improved efficiency of propulsion drives at low load and low speed
- Faster dynamic response
- Reduced weight and volume of electrical equipment
- Flexibility in equipment placement

With electric propulsion drive, an electrical distribution system is required to transfer energy generated by the diesel generator to the propulsion drive. At present, marine vessels, similar to land-based distribution system, primarily run on an AC distribution system. In land-based microgrid systems, such as buildings[16], there is also an interest in a shift to DC-based distribution system[17]. This is primarily driven by the increasing proliferation of renewable energy resources[18], which conventionally require a DC bus for integration purposes.

However, the adoption of DC distribution systems is not widespread. This is partly due to a historical lack of DC protection devices. Recent developments by ABB[19] and GE[20] have produced commercially available DC circuit breakers, with maximum ratings of 12 MW. However, as it has been found that smaller ships tend to have higher greenhouse emissions[21], these DC circuit breakers are applicable for smaller ships with lower power requirements. For example, offshore supply vessels and diving support vessels typically have power requirements in the 10 MW range.

The integration of renewable energy resources has also been explored for marine vessels, such as the use of solar photovoltaic panels [22] and wind-based generation sources[23]. These also require the use of a DC bus for ease of integration as DC systems do not have synchronization issues. In addition, there are potential improvements in efficiency, fuel savings, and reduction in weight and volume of electrical equipment[24,25] that can be attained via a shift to a DC distribution system. Recent research on DC distribution systems on-board marine vessels has used land-based DC smart grid technology as a comparison tool[24], and have focused on the design of the power architecture and energy storage integration[25]. However, there is a lack of research in the operational aspects of the DC system.

This study aims to address a knowledge gap in the operational efficiency gains that can be attained through the replacement of AC systems with similarly-rated DC systems. Specifically, this study examines the operational details of a diving support vessel that currently operates with an AC distribution system, and proposes an equivalent DC distribution system that can be installed in future iterations of the same marine vessel. This is performed through the use of an experimental testbed that compares both AC and DC systems with the same generator and propulsion load, which has not been found in literature elaborately. The required equipment changes and the improvement in electrical performance resulting from the changes are examined quantitatively through the use of an experimental testbed that is a scaled-down model of the actual electrical system. A novel generator scheduling method using genetic algorithm is also proposed, and the fuel savings in multiple operation modes are detailed. Through this study, the benefits of using DC systems in marine vessels during the operation of the marine vessel can be quantified.

2. Electrical system of marine vessel under study

2.1. Current AC architecture

The AC system currently installed on-board the marine vessel under study, which is a diving support vessel, is shown in Fig. 1. For this vessel, the total electrical generation capacity is 12 MVA, which supplies four electrical propulsion drives as well as the hotel/service loads on-board the vessel. There are two 690 V AC buses, which can be connected by closing the bus tie in between the two buses. This allows for transfer of power between the port and starboard generators to the electrical propulsion drives and service loads on either side of the vessel.

The electrical propulsion drives obtain power from the 690 V AC bus. The three-phase AC supply is then fed through a three-winding transformer with a star-star-delta configuration, following by a 12-pulse diode bridge rectifier. The electrical propulsion motor is then driven by a variable speed drive, which allows for variable speed and variable torque operation.

The service loads are also supplied from the 690 V AC bus, which has a step down transformer reducing the AC voltage from 690 V to a more usable 230 V single-phase or 440 V three-phase supply. These loads may include lighting, navigational equipment, auxiliary machinery, and cooling pumps.

2.2. Future DC architecture

The proposed DC system that can directly replace the current AC system is shown in Fig. 2. The main different between the DC and AC systems is the move from a 690 V AC bus to a 1 kV DC bus. As the generators used remain the same, active front-end (AFE) converters are required to convert the produced AC voltages to DC. As the bus voltage is now DC, the electrical propulsion drives no longer require three-winding transformers and 12-pulse rectifier to convert AC to DC; the variable speed drive for the electrical propulsion motor can now source power directly from the 1 kV DC bus.

For the service loads, inverters to convert DC to AC are required. These directly replace the step-down transformers that were in the AC system. Single-phase and/or three-phase loads remain able to source power from the DC bus. With the DC bus, the connection of energy storage elements such as batteries are now viable. However, DC to DC converters are required to control the power flow between the energy storage element and the DC bus.