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Load test on electric motor and diesel engine to energy saving of alternative marine propulsion systems

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Abstracts

The global environmental concern and the limited resources of fossil fuels enables the use of alternative and renewable energy sources. International Maritime Organization aims to reduce energy efficiency and emissions from marine vessels evaluating in with regards to the maritime sector. In this context, in addition to the conventional propulsion system, the application of hybrid propulsion system (HPS) and diesel-electric propulsion system (DEPS) comes to the fore. In this study, electric motors, one of the HPS and DEPS equipment, are examined in detail. The purpose of electric motors is to provide or assist the propulsion system and also charge battery systems. In this way, the amount of harmful greenhouse gases generated at low loads and high fuel consumption per unit power are minimized. Moreover, the maintenance intervals are prolonged which reduces costs and increases efficient operating time since the main engine or auxiliary engines of the ship generally runs at optimum loads. In this study, HPS gains are described by perform an application load tests on electric motors and diesel engine in detail. Consequently, this article stated that HPS and DEPS systems will be used more widely in the maritime industry in the future especially on tugboats operated at low loads for most of their operating time. This paper will be a prominent source for researchers and maritime sector stakeholder whose studies are with respect to HPS and DEPS particularly on electric motors.

Key words: propulsion system, energy efficiency, electric motor, marine vessels

1. Introduction

Electric motors are classified into two types as direct current motor and alternative current motor according to the type of power source used. Direct current motors are defined as motors that convert electrical energy into mechanical energy (Chapman, 2005; Nam, 2018). In a direct current motor, the rotor is rotated by the force produced on the current-carrying conductors placed in the magnetic field created by the stator. DC motors have two fixed magnetic fields, the stator magnetic field and the rotor magnetic field. The stator magnetic field is produced by the magnets and the field winding (Kim, 2017; Nam, 2018). In direct current motors, the current must be fed to the rotor by means of brushes and commutators (Hughes and Drury, 2019). The rotor magnetic field is produced by the current in the conductors of the rotor and creates a constant magnetic field despite the rotation of the rotor. In this type of motor, speed and is directly proportional to voltage and current respectively. DC motor is widely used in adjustable speed drives or variable torque controls due to wide speed control range and easy torque control. The main equipment of direct current motors is stator, rotor, brushes, commutators, coils, magnets and bearings. The brushes serve as the commutation mechanism and are made of copper material. There are two main coils in DC motors, armature winding and field winding, and currents occur on the coils when they are connected to the power source also a force is formed on the conductors, which turns the rotor with the currents obtained. Moreover, current direction is changed by collectors and brushes. DC motors require much more maintenance and have limited use high speed and voltage operations due to the wear on commutators and brushes which generally produced from carbon. DC motors have lower power density, reliability and efficiency values compared to AC motors (Marino et al., 2010; Kim, 2017; Nam. 2018).

The alternative current motor uses the force between two rotating magnetic fields unlike the direct current motor, and produces torque on the basis of electromagnetic induction. Alternating current motors are divided into two as synchronous and asynchronous electric motors. While the stator magnetic field is similar in these two types of motors, there is a differentiation in the magnetic field created by the rotor (Chapman, 2005; Kim, 2017; Nam, 2018).

In synchronous motors, the constant magnetic field on the rotor is produced by magnets or the field winding supported by a direct current power source independent of an alternative power source. In these AC motors, the rotor magnetic field remains constant relative to the rotor and rotor speed must be at the same speed as the rotating magnetic field in the stator to obtain torque. The AC motors are called synchronous motors due to this synchronous speed. Furthermore, a low value of $cos\theta$ takes the efficiency to higher levels (Kim, 2017).

The torque producing currents in the rotor of induction motors are transferred from the stator by electromagnetic induction. Therefore, a speed slip occurs between the stator field and the rotor so that this motors are expressed as an induction or asynchronous motor (Kim, 2017; Nam, 2018; Hughes and Drury, 2019). Synchronous speed is defined as n_{sync} and the difference between the rotor speed n_m is defined as the slip speed n_{slip}. Moreover, the percent slip is described as s and The slip speed value of the electric motor is related to the rotor frequency and the number of poles.

$$n_{sync} = \frac{120 * f_e}{P} \quad (1)$$

$$n_{slip} = n_{sync} - n_m \quad (2)$$

$$s = \frac{n_{sync} - n_m}{n_{sync}} \quad (3)$$

$$f_r = s * f_e \quad (4)$$

$$f_r = \frac{P}{120} * n_{slip} \quad (5)$$

No need for brushes and commutator also less mechanical contacts reduce both efficiency and maintenance costs in asynchronous motors. Various power losses occur during power transfer and the losses are calculated by using the V_T, I_L, $cos\theta$, τ_{load} and $\omega_m$values (Chapman, 2005; Nam, 2018; Hughes and Drury, 2019).

$$\text{Power losses} = \text{P}_{\text{in}}(\sqrt{3} * V_T * I_L * cos\theta) - \text{P}_{\text{out}}(\tau_{load} * \omega_m) \quad (6)$$

These power losses are composed of copper losses and friction, ventilation and deflexion losses, also the amount of these losses will increase in direct proportion to the rotation speed of the motor. Considering industrial applications, approximately 90% of all AC motors are asynchronous motors; 95% of induction motors are squirrel cage induction motors. High efficiency, low noise pollution, resistance to overheating, low copper losses, ease of installation, reliability, self-starting and lower maintenance cost of squirrel cage induction motors create the advantages of them and allows to be applied in many industries. Nevertheless, high current draw and low torque at starting, lack of speed control and low torque value at start are the disadvantages (Parekh, 2003; Chapman, 2005; Demirbaş et al., 2008; Nam, 2018, Electricalarticle, 2020). A detailed study was carried out on electrical propulsion systems of marine vessels and are described in the Table 1. especially by selecting studies performed in recent years.

Table 1: Literature review on marine vessels using electric propulsion systems

No	Author	Ship Type	Propulsion System	Description
1	Mauro et al., 2020	Slow-tourism passenger ship	Hybrid-electric propulsion	North Adriatic Area M/N Ambriabella DC Electric motor DC-AC Inverter Battery Pack (2400 Ah)
2	Bucci et al., 2020	Luxury sailing yacht	Hybrid-electric propulsion Diesel electric propulsion Diesel electric propulsion with ESS	AC Electric motor (50kW and 250kW) Energy Storage System (Li-ion battery) Operations Mode [Navigation at full speed, Maneuvering, Stationing at anchor etc.]
3	Paul, 2020	Commercial and Naval Vessels	Diesel Electric Turbo-Electric Drive Hybrid Diesel–Turbo-Electric Duel Fuel With LNG	History of Electric Propulsion S. AC Electric motor AC and DC power supply
4	Hoang and Pham, 2020	Ocean supply vessels Anchor Handling Tug Supply (AHTS) Seismic / Research ship	Hybrid propulsion Diesel-electric propulsion system	AC Electric motor Operations Mode [Docked, Pull support, DO low/high etc.]

5	Jelic et al., 2021	Merchant ships	Series hybrid propulsion Parallel hybrid propulsion Series–parallel hybrid propulsion	Liquid hydrogen Liquid ammonia Compressed hydrogen LNG (Liquefied Natural Gas) AC Electric motor
6	Altosole et al., 2020	Ro-Ro ferry	Enhanced hybrid ship propulsion	Waste Heat Recovery System (WHR) Hybrid Turbocharger (HTC) Dual Fuel Engines
7	Lebkowski and Koznowski, 2020	SWATH Ships	Electric and hybrid systems	Hybrid Energy Storage System (Battery [$LiFePO_4$] +Hydrogen Fuel Cell+ Diesel G.) BAT-D: Battery+ Diesel G. BAT: Battery FC-BAT-D: Hydrogen Fuel Cell+ Battery+ Diesel G
8	Sui et al., 2020	Ocean-Going Cargo Ship	Hybrid Propulsion Different Fuels	LNG Operations Mode [Close-to-port Maneuvering] Voyage Optimization
9	He et al., 2021	Bulk Carrier	Parallel Hybrid Electric Power System	Speed Optimisation Energy Management
10	Ruggiero, 2020	Passenger ferries	Hybrid Propulsion [Electric Generators and Batteries]	Efficiency Systems High Maneuverability Lithium polymer Battery 2*250 kW AC motor

Mauro et al. (2020) use the ship as a project that was built in 1962 and operated as a passenger ship until 2009 and then dismissed. Environmentally friendly, more economical operations, less noise and air pollution are carried out with the Hybrid-electric propulsion system created by applying the retrofitting on the passenger ship operated with the traditional propulsion system. Moreover, thanks to retrofitting, new design costs are minimized. Bucci et al. (2020) described conventional propulsion system, diesel electric propulsion system with and without energy storage system that is lithium-ion battery (326kWh) and parallel hybrid propulsion system on sailing yacht. In terms of fuel consumption, noise and pollutant emission the most gain is achieved with the parallel hybrid propulsion system. On the other hand, this system has more disadvantages than the others in the sense of the additional weight. Electric propulsion systems provide fuel efficiency, decreasing air pollution as well as meet international limitations. Paul (2020) examines the history of electric ship propulsion systems and stated that this propulsion system will be operated quite extensively in the all ship types to be built in the future. Hoang and Pham (2020) shows the gains of the electrical propulsion systems by evaluating the power consumptions and operation times of the ocean supply vessels in different operation modes. These systems comply with the EEDI (Energy Efficiency Design Index) criteria, in addition to reducing fuel consumption and emissions. Considering the international limitations and environmental perception, Jelic et al. (2021) thought that fossil-based fuels will replace their place to fuels such as biofuels, LNG, hydrogen and ammonium. Furthermore, the ease of installation and the ability to integrate into existing systems bring the hybrid propulsion system to the fore. Study performed by Altosole et al. (2020) on Ro-Ro ferry, 2 dual-fuel engine, shaft generator and new generators with lower power output were installed instead of the existing 4 main engines and generators. Moreover, WHR and HTC systems are used separately or together to increase energy efficiency up to %53 depends on engine speed.

Considering the power estimation made through the resistance analysis, a significant gain is achieved in energy consumption and operational costs with the study on Small Waterplane Area Twin Hull (SWATH) vessels by performing hybrid systems that consist Hydrogen Fuel Cell, Battery, Diesel Generator. Thanks to these systems, Lebkowski and Koznowski (2020) describe that operations can be carried out comfortably in areas where emissions and noise are not desired. Based on the use of LNG fuel, shaft generator and auxiliary generator in different operating modes of Ocean-Going Cargo Ships, Sui et al. (2020) aimed to obtain gains from fuel consumption and emissions and also meet EEDI requirements. Hybrid systems are suitable for complex operations where significant engine loads vary and these systems have high efficiency and manoeuvrability compare to conventional one. Moreover, He et al. (2021) by genetic algorithm that is used to fix both energy efficiency optimisation and speed optimisation. Thus, gains were achieved in terms of emissions and costs. In the hybrid propulsion system, which will be applied for passenger ferries by Ruggiero (2020), lithium polymer batteries are used together with asynchronous motors due to their high efficiency and low noise level. At the same time, the volumes of the systems to be installed must be taken into account with safety aspect.

2. Load Test on Electric Motor and Diesel Engine

In this section, the values obtained by performing the load test of electric motors that is carried out on electric motors test set and diesel engine are expressed. In the case of electric motors load test, observed the power, amperage and voltage values are recorded. During the testing stage, the loading is performed gradually so that data set is created. In the experiment on the squirrel-cage induction motor, transmission efficiencies of over 90% are provided that supports the literature on AC motor. The obtained efficiency values are described in Table 2 in terms of voltage, amperage and transmission coefficient.

Table 2: Squirrel-cage induction motor load test.

V_in	I_in	P_in [W]	V_f	I_f	P_f [W]	Efficiency
386	4.4	2206	108	18.6	2008.8	91.05%
386	5	2507	114	20.3	2314.2	92.31%
385	5.5	2750	120	21.5	2580	93.80%
385	6.3	3150	126	23.4	2948.4	93.58%
384	7.3	3641	134	25.6	3430.4	94.21%
384	7.4	3691	136	25.7	3495.2	94.69%

The electric motors are 3-phase and the output power is approximately 3.5 kW. The highest efficiency output is acquired at the last load test that is approximately 94.69 %. The results obtained meet the high efficiency values specified for the induction motor. The load test of the diesel engine which is planned to work in combination with the electric motor, is similarly carried out gradually. In this way, fuel consumption values at certain loads on the diesel engine are displayed. The fuel consumption curve drawn from the diesel engine load test described in Figure 1. Moreover, one of load profile of tugboat operation are highlighted to described low load process.

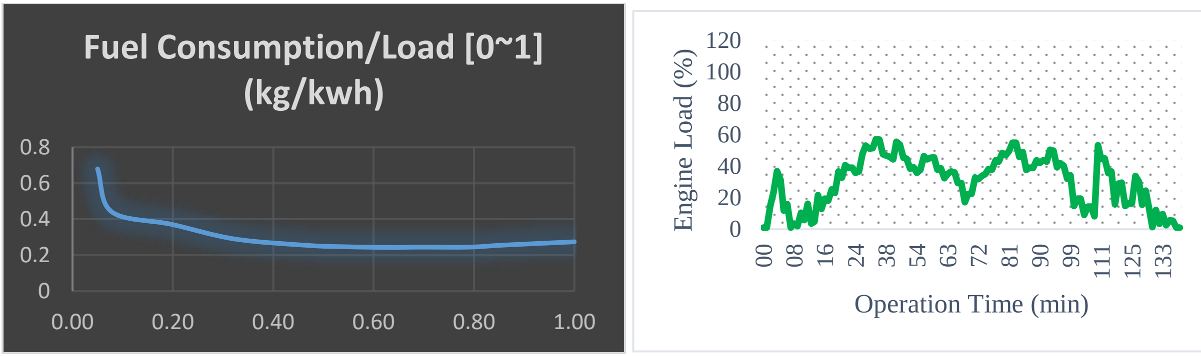

Figure 1: Diesel engine load test and one of load profile of tugboat operation

The specific fuel consumption values per unit power are quite high at low loads when Figure 1 is examined. 2-3 times more fuel consumption values are acquired until reach to 20% load compare to optimum fuel consumption. Moreover, the most optimum values are obtained at engine loads between 70% and 90%. Main engine load values obtained from the tugboat during operation describes that if the electric motor is provided at low loads for propulsion, a significant amount of fuel consumption decrease also fuel-based emissions diminish. In this way, more environmentally friendly and more efficient operations are carried out.

4. Conclusions

Various studies are performed in order to reduce fuel consumption costs and reduce fuel-based emissions especially in the maritime sector. Alternative fuels, renewable energy and alternative propulsion systems are the significant ones. In this study, the load test of the diesel engine with the electric motor that can be integrated into the propulsion system is performed. The literature review and experiments describe that the electrical propulsion systems to be installed in marine enable efficient operations to meet International limitations, reduce emissions and fuel consumption. Furthermore, zero emission applications can be realized with optimized energy storage systems especially on batteries in maritime sector. Eventually this type of propulsion systems will become widespread thanks to electric motors with high efficiency and long maintenance intervals.

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