Electrical design for efficiency: technical and operational measures for optimizing the use of electrical power on ships

Diseño eléctrico para la eficiencia: medidas técnicas y operacionales para la optimización del uso de la potencia eléctrica en buques

DOI: https://doi.org/10.25043/19098642.240

Oscar Alejandro Sanabria Vargas [1]
Hernán David Vergara Pestana [2]
Reynaldo Rafael Mendoza Iglesias [3]
Gabriela Guadalupe Salas Berrocal [4]

Abstract

There is currently a growing concern in the shipping industry about energy consumption and environmental impacts. According to the International Maritime Organization's (IMO) energy efficiency guidelines, today's ships must have an energy efficiency management plan to reduce the CO2 emission and other pollutants. In this article, a bibliographic review of methodologies for the optimization of energy consumption on ships is carried out, starting from the identification of sources of energy losses, to the implementation of technical and operational measures that contribute to their improvement, making a qualitative evaluation of the identified methodologies. Sources of energy losses associated with equipment and auxiliary systems are analyzed, as well as opportunities for improvement in the use of electrical energy through the implementation of intelligent energy management systems, high efficiency motors, and lighting. The technical and operational energy efficiency measures described above demonstrate the importance of their implementation from the early stages of the ship's electrical design, as well as monitoring energy consumption during its life cycle, to improve energy efficiency on board.

Key words: Energy efficiency, electrical design in ships, energy consumption, maritime transport.

Resumen

En la actualidad existe una creciente preocupación en el sector del transporte marítimo por el consumo de energía y el impacto ambiental. Según las directrices de eficiencia energética de la Organización Marítima Internacional (OMI), los buques actuales deben disponer de un plan de gestión de eficiencia energética que permita disminuir la emisión de CO2 y otras sustancias contaminantes. En este artículo se realiza una revisión bibliográfica de metodologías para la optimización del consumo energético en buques, partiendo de la identificación de fuentes de pérdidas energéticas y la implementación de medidas técnicas y operativas que contribuyan a su mejora, realizando una evaluación cualitativa de las metodologías identificadas. Se analizan las fuentes de pérdidas de energía asociadas a los equipos y sistemas auxiliares, así como las oportunidades de mejora en el uso de la energía eléctrica mediante la implementación de sistemas inteligentes de gestión de la energía, motores de alta eficiencia e iluminación led. Las medidas técnicas y operativas de eficiencia energética descritas demuestran la importancia de su implementación desde las primeras fases del diseño eléctrico del buque, así como el monitoreo del consumo energético durante su ciclo de vida, con el fin de mejorar la eficiencia energética a bordo.

Palabras claves: Eficiencia energética, diseño eléctrico en buques, optimización consumo energético, tranporte marítimo.

Date Received: December 16th, 2022 - *Fecha de recepción: 16 de diciembre de 2022*
Date Accepted: February 23rd, 2023 - *Fecha de aceptación: 23 de febrero 2023*

[1] Design & Engineering Group, COTECMAR, Cartagena, Colombia. Email: osanabria@cotecmar.com
[2] Design & Engineering Group, COTECMAR, Cartagena, Colombia. Email: hdvergara@cotecmar.com
[3] Design & Engineering Group, COTECMAR, Cartagena, Colombia. Email: rmendoza@cotecmar.com
[4] Design & Engineering Group, COTECMAR, Cartagena, Colombia. Email: gsalas@cotecmar.com

Introduction

In recent years, the International Maritime Organization (IMO) has implemented several policies to improve energy efficiency in ships and reduce environmental impact during their operation [2]. This paper proposes a methodology based on a literature review. Initially, ship energy efficiency improvement policies issued by IMO are identified. Some causes of electrical system efficiency losses in ships and measures to improve electrical systems are described.

The causes of electrical efficiency losses described are associated with the operation of the Genset engine outside the established parameters, as well as to efficiency losses in the Genset alternator and power transformers due to losses in the windings and in the core. Efficiency improvement measures found in literature include combustion engines with catalytic reduction systems and exhaust gas recirculation, load-dependent transformer efficiency, use of batteries as an additional energy source, implementation of a power management system to avoid overloads in generation, transition of lighting to LED technology, and operation of generators at high capacity

Energy efficiency in ships

Implementing policies, strategies, and technical solutions to reduce greenhouse gas emissions is one of the most significant challenges confronting shipowners and operators in the 21st century [1].
To reduce the negative environmental effects of ships, the International Maritime Organization (IMO) has developed a few tools to monitor emissions. In this context, the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI) are two standardized indicators for energy efficiency assessment. The first one concerns ship design and commissioning, whereas the second one concerns parameter control while a ship is in service [2].

As with other IMO regulations, the flag state of a ship is ultimately responsible for ensuring compliance with EEDI. A verification body issues an International Energy Efficiency Certificate (IEEC) to demonstrate compliance (Maritime Administration or Classification Society). The verification process is divided into two stages. A preliminary verification is performed based on ship design, followed by a final verification test during a sea trial. The shipowner, shipbuilder, and verifier are all involved in the process at every stage of the ship's development [3].

The ship's EEOI is calculated using statistics collected during the voyage and from the ship's operation. These statistics include parameters such as the equipment's fuel consumption, state of the navigation environment, length of the ship's stay in port, and distance traveled [2].

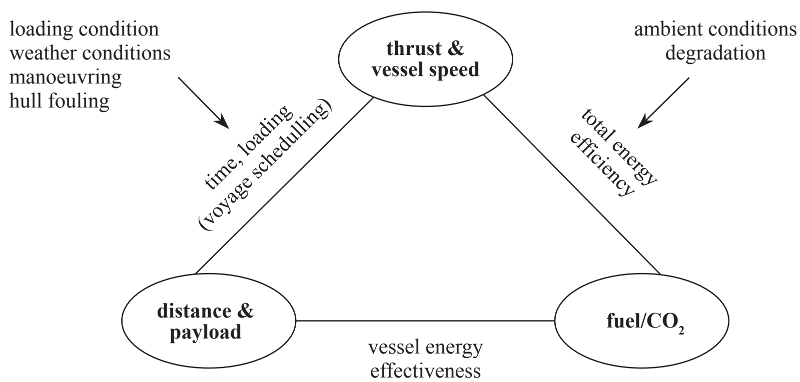
Given the significant changes that ship technologies must undergo, the planned goals are medium-term (by 2030) and long-term (by 2050), with 2008 as the base year. The desired end result is to reduce greenhouse gas emissions from shipping by up to 40% by 2030; 70% in emission intensities; and 50% in total emissions by 2050 [1].

Chemical energy saved in fuels is released as heat through combustion in conventional maritime power systems. The main engines, which are typically diesel engines, convert this heat into work and deliver it to the propellers either directly or via reduction gearboxes. The work is then converted into propulsion thrust by propellers to overcome vessel resistance and accelerate it. Auxiliary diesel engines, on the other hand, convert heat to work, for electrical power, and to power the ship's electrical grid. These power conversions and transmissions improve components, subsystem, and overall system energy efficiency [4]. Fig. 1 shows the relation between vessel energy effectiveness, total energy efficiency and influencing factors.

Sources of losses in the electrical system

A logical first step in discussing how to improve the energy efficiency of a ship's electrical system is to understand the view of power system losses. All elements of an electrical system (transformers,

Fig. 1. Illustration of the relationship between vessel energy effectiveness, total energy efficiency and influencing factors [4].



motors, etc.) provide resistance to current flow and therefore, dissipate some energy to perform their intended function [5].

The losses in power distribution systems can be as follows:

Diesel engine

Diesel engines suffer continuous internal wear during their useful life and under normal operating conditions, resulting in a reduction in efficiency. The loss of pieces is proportional to the hours of operation and can be exacerbated by impurities in the fuel or the presence of particles during combustion. It is possible to recover some engine efficiency by following a motor maintenance plan that adheres to the manufacturer's specifications [6].

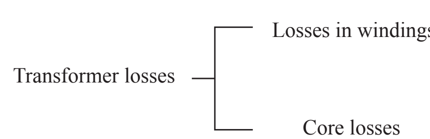
The operation of a Genset outside the nominal conditions established by the diesel engine rating can produce several negative effects. The first one being that the engine may not reach the temperature and pressure necessary to operate properly, causing a black oily fluid to be produced and seep through the exhaust system seals; part of the reason why combustion releases a higher amount of nitrogen oxides into the environment [7]. The second manifests itself when engines are operating at low loads for long periods, causing accumulation of debris in the pistons or cylinders, resulting in loss of power, accelerated wear, and in the worst case, wear of the cylinder liner [7]. Consequently, the motors must be kept operating by the restrictions of their classification so as not to reduce their efficiency and service life.

Transformers

Electrical transformers are static electrical machines that deliver electrical power by changing the voltage level from input to output (primary-secondary). There are currently three types of transformers, depending on their application: power transformers, voltage transformers and current transformers. The last two are normally used to measure or to sample high voltages and currents in circuits that require low values to operate, while power transformers are used to supply loads at the desired voltage.

All three types of transformers are used on ships, however, for the purpose of this paper, only power transformers will be discussed because of their influence on the efficiency of the electrical system. Although transformers are static electrical machines, they present the same losses as rotating electrical machines, except for those related to friction due to the lack of movement of the equipment. Fig. 2 shows the losses according to Chapman [8].

Fig. 2. Transformer losses.



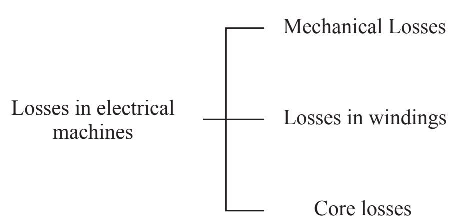
- Core losses: hysteresis, core heating due to eddy currents, vibrations, harmonic current, and voltage components.
- Losses in the windings: power loss due to the resistance of the windings, these losses are transformed into heat.

Alternator

In electrical groups, the alternator is typically a synchronous generator that supplies the required electrical power to the system. The synchronous generator is classified as a rotative electric machine, a category that also includes synchronous motors, inductors, permanent magnet motors, and so on.

Power losses (or efficiency losses) in rotating electrical machines can be broken down into the types of losses in Fig. 3.

Fig. 3. Losses in Electrical Machines.



Source: own elaboration on the base of [8].

Mechanical friction losses are associated with losses due to contact between the bearings and the structures that house them.

Losses in the windings are the result of the energy dissipated by the electrical resistance of the motor windings, including excitation in synchronous generators with this technology.

The losses in the iron core are due to the dispersion of the magnetic field joining the stator and rotor windings as they pass through the fluid, as well as losses in the coupling of the magnetic field in the motor air gap. In addition, losses caused by the eddy currents induced in the iron by the magnetic fields induced by the windings are included.

Measures to improve energy efficiency in the electricity system

High efficiency motors

Combustion engines: Ships designed for global operation must have main engines that meet the strictest Tier III emission standards. The combustion temperature has the greatest impact on harmful substance emissions because an increase in temperature results in more efficient combustion of the air-fuel mixture in the combustion chamber. This is associated with lower particulate matter emissions (primarily soot and hydrocarbons) but an unacceptable increase in nitrogen oxide NOx discharge. The need to solve this conundrum prompted the development of selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) systems [9].

Transformer efficiency as a function of load

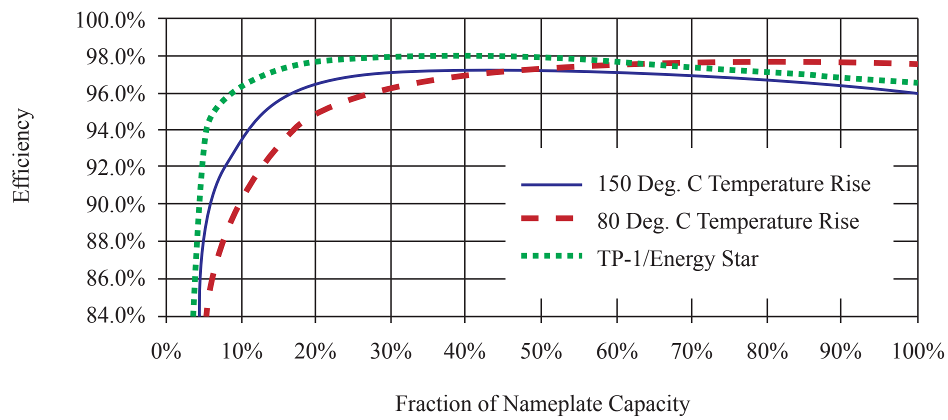
Ships require the transformers be of the dry air-cooled type. Transformer efficiency as a function of load has the behavior presented in Fig. 4 for three types of transformers: for a temperature rise of 150°C, 80°C and TP-1 type transformer with higher efficiency.

It can be noted that the maximum efficiency for all transformers occurs at load percentages between 35% and 60%, depending on the temperature rise. The efficiencies at full load are lower than the maximum transformer efficiencies, which is obtained at partial loads.

Battery compensation

The use of batteries enables an additional source of energy that helps to control the power network, allowing on occasions, one or more engines can be shut down to avoid running at low loads and therefore operating with low efficiency. Consequently, fuel consumption, emissions, and noise-vibration-hardness (NVH) level of the generator engines can be reduced. Other battery functions include peak shaving, regeneration of braking energy and standby power. In the event

Fig. 4. Transformer Efficiency Vs. Load [10].



of high power demand, battery power can help generators sustain high power demands.

Electrical power management system

Electrical generation equipped with an electrical power management system allows controlling the start-up of the service and emergency generators and the electrical power demand to avoid generator overload and blackout [11]. This system protects the generators and prevents their sequential loss using consumer discrimination, and has the following functionalities:

- Automatically reduces the vessel's power demand to keep it within the available generation capacity.
- Sectioning the electrical system, opening the main switchgear busbar disconnector in case of generator failure, to isolate the fault.
- Requesting automatic start and entry into the system of the standby generators.
- The vessel's power demand reduction is performed with the non-vital consumers, according to their classification, by opening the load center disconnectors or disconnecting large consumers at the main switchgear.
- The management system controls the automatic start-up and entry of the emergency generator in case of failure of the primary generation.
- Likewise, the system ensures that the locked-rotor current of the generators is not exceeded by starting electric motors.

Efficient lighting

Over the course of the last few years there has been a massive transition in lighting technology from conventional lighting to LED technology which is more energy and cost efficient. Research [12] suggests that significant energy savings can be achieved by applying LEDs instead of high-pressure sodium or metal halide lamps.

Some of the advantages to be highlighted are:

- Long life: the average lifetime of a LED luminaire is approximately 35,000 to 50,000 hours, therefore, they also generate an economic benefit from low replacement costs and energy consumption.
- Environmentally friendly: LED technology luminaires do not contain toxic chemicals (mercury vapor).
- The initial investment is higher than for incandescent bulbs. However, due to the long lifetime and high energy efficiency of LED bulbs, the investment is quickly amortized.

Energy efficiency potentials of the generator operations

Load sharing practices on ships affect the performance of generators. This can indirectly cause different amounts of fuel consumption, fuel cost, and emissions for the same amount of onboard electrical power generation.

In [13], the energy efficiency of a number of diesel, chemical, ro-ro and barge vessels was evaluated. The annual fuel consumption and cost, and the potential emissions that may occur from possible load sharing applications of the generator sets on the vessel were estimated. Vessel characteristics, generator specification, power demand and time of operation modes were used as input data to assess the potential effects of load sharing practices on generators. The results showed that running the generators at high capacity instead of low capacity could meet the onboard electrical power demand with less fuel. When generators run at 90% of their capacity instead of 40%, the minimum savings in terms of fuel consumption, fuel cost, CO2 and NOx emissions is about 7% [13]. This ratio should be at least 5% in the case of SOx. At the same time, the savings potential for all parameters was about 17%. Generator load sharing practices can be an important operational measure that does not require any investment among the types of energy saving applications for ships [13].

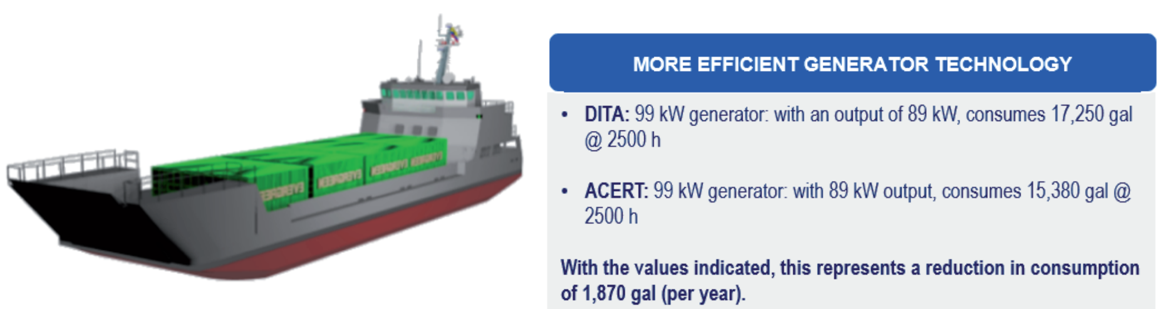
Some technical and operational measures implemented from the electrical design to optimize the use of electrical energy on ships in COTECMAR.

GEDIN-COTECMAR's design and engineering management have implemented systems/ equipment/solutions with new technologies that contribute to energy efficiency in the design phases, and therefore, to lower fuel consumption. Some of the implementations are:

More efficient generator technology

In the BDA (Buque de Desembarco Anfibio) project, generators with more efficient technology were considered to save fuel during the operation periods. Fig. 5 shows the comparison between the DITA Genset technology and the ACERT Genset installed in the BDA.

Fig. 5. ACERT (Advanced Combustion Emission Reduction Technology) Genset in BDA.



Source: own elaboration on the base of [8].

Fig. 6. Implementation of LED lighting in PAF-L.

Source: own elaboration on the base of [8].

Fig. 7. BALCL design with implementation of solar panels.

Source: own elaboration on the base of [8].

Table 1. Applications that have increased efficiency in HVAC systems.

Parameter	Equipment/System	Implementation/Results
Auxiliary systems efficiency	Air conditioning	Evaluation and diagnosis for the energy optimization of the chilled water circulation system: the arrangement of pipes and fittings allows a reduction of the resistance by approx. 40% and an increase of the current pump efficiency by up to 68% (Ref: PAFP-PAFL).
	Hydraulic Systems	Application of Pipe Flow expert, in the design and analysis of hydraulic systems, to determine the diameters, pressures, speeds and routing of pipes to achieve the most efficient operation points of the pump, as well as to determine the pressure loss in the system due to the friction with the flow in the pipes, which contributes to have more efficient auxiliary system arrangements.

Table 2. Implementation of technical and operational measures for energy efficiency on ships.

System	Integration possibility	
	Design Phase	Operational Phase
High efficiency electric motors	x	x
HVAC Optimization	x	
Battery compensation	x	x
Automation and power management systems (PMS).	x	
LED Lighting	x	
Generator operating doctrine		x
Renewable microgrids	x	

LED lighting

In the PAF-L (Patrullera de Apoyo Fluvial Liviana) project, from the design stage, LED lighting was considered to obtain better lighting levels with less power consumption.
Fig. 6 shows the comparison between conventional lighting technology and LED lighting installed in PAF-L.

Renewable microgrids

During the design development of the BALC-L (Buque de Apoyo Logistico y Cabotaje Liviano) vessel, deck 02 was extended to provide an available area for the location of the photovoltaic modules, as shown in Fig. 7. The installed peak power is 1.68kW and per year they can produce 1,903 MWh of energy, which will be used to power the lighting loads on deck 01, contributing to the reduction of fuel consumption which per year would represent 137 gallons and a reduction of 2Ton in the carbon footprint per year.

Efficiency of auxiliary systems

Table 1 shows the considerations taken into account for the optimization of the air conditioning and hydraulic systems, which represent one of the most significant impacts on electricity consumption.

Technology integration

The Table 2 shows the possibilities of integrating technical and operational measures for energy efficiency from the design phase and during the operation of the vessel.

Conclusions

The Colombian shipbuilding industry has undeniably strengthened its capabilities in the design phases to implement technical and operational measures to optimize the use of electrical energy in ships, in alignment with the energy efficiency guidelines of the International Maritime Organization (IMO). From the literature findings, electrical and mechanical losses in motors, transformers, and alternators visibly vary depending on the load and normal operation behavior of these elements. However, the points of view presented on this subject were only from a technical and operational perspective and did not cover considerations on the change of efficiency behavior as a function of time, which is crucial. Therefore, this aspect should be addressed in a subsequent study.

From the design phases, measures have been implemented to improve the use of electrical energy in ships, such as the installation of intelligent energy management systems, use of high-efficiency engines, use of LED lighting, and the optimization of air conditioning and hydraulic systems. However, the challenge is providing comprehensive solutions to support the life cycle in terms of the energy efficiency of ships that require maintenance, repair, or warranty care. Nowadays, it is not enough to design and build a good energy performance of the vessel, but also, to make improvements during the operation phase to contribute to energy efficiency and thus, lower fuel consumption.

References

[1] G. IVANOVA, "Analysis of the Specifics in Calculating the Index of Existing Marine Energy Efficiency EEXI in Force since 2023," 2021 13th Electr. Eng. Fac. Conf. BulEF 2021, 2021, doi: 10.1109/BULEF53491.2021.9690805.

[2] G. IVANOVA, "Specifics in Determining the Operational Energy Efficiency Index EEOI According to the Requirements of the International Maritime Organization IMO for the Period 2020-2025," 2020 12th Electr. Eng. Fac. Conf. BulEF 2020, Sep. 2020, doi: 10.1109/BULEF51036.2020.9326011.

[3] ICCT, "The Energy Efficiency Design Index (EEDI) for New Ships," ICCT ICCT Policy Updat. 15, no. July 2011, 2011.

[4] N. I. VASILIKIS, R. D. GEERTSMA, AND K. VISSER, "Operational data-driven energy performance assessment of ships: the case study of a naval vessel with hybrid propulsion," https://doiorg.ezproxy.unal.edu.co/10.1080/20464177.2022.2058690, 2022, doi:10.1080/20464177.2022.2058690.

[5] M. BADR AND S. ALI AHMED, "REDUCTION OF ENERGY LOSSES IN ELECTRICAL DISTRIBUTION SYSTEMS Hamed EMARA KASSEM EX-Chairman of Rural Electrification Authority-Egypt."

[6] C. MORALES, "CT-ARC-3321-311-02 Cambio en la eficiencia de elementos eléctricos

durante la vida útil y evaluación de escenarios adicionales para dimensionamiento de generadores," COTECMAR, 2017.

[7] M. ISSA, H. IBRAHIM, H. HOSNI, A. ILINCA, AND M. REZKALLAH, "Effects of Low Charge and Environmental Conditions on Diesel Generators Operation," Eng 2020, Vol. 1, Pages 137-152, vol. 1, no. 2, pp. 137–152, Oct. 2020, doi: 10.3390/ENG1020009.

[8] S. CHAPMAN, Máquinas eléctricas. 2012.

[9] P. K. KORLAK, "Multidisciplinarni znanstveni časopis POMORSTVO Multidisciplinary SCIENTIFIC JOURNAL OF MARITIME RESEARCH Comparative analysis and estimation of amounts of exhaust gas waste heat from the Tier III-compliant dual-fuel low-speed marine main engines A RT I C L E I N F O," Sci. J. Marit. Res., vol. 35, pp. 128–140, 2021, doi: 10.31217/p.35.1.14.

[10] "DOE Mandates Higher Efficiency for Distribution Transformers." https://www.copper.org/environment/sustainable-energy/transformers/education/archive/dist_trans.html (accessed Nov. 29, 2022).

[11] C. MORALES, "CT-ARC-3321-300-01 Concepto Técnico Dimensionamiento de sistemas de potencia, distribución e iluminación eléctrica," 2017.

[12] M. DAVIDOVIC AND M. KOSTIC, "Comparison of energy efficiency and costs related to conventional and LED road lighting installations," 2022, doi: 10.1016/j.energy.2022.124299.

[13] K. YIĞIT, "Evaluation of energy efficiency potentials from generator operations on vessels," Energy, vol. 257, 2022, doi: 10.1016/j.energy.2022.124687.