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Integrated Digital Solutions in the Management of Ship Electrical Systems

Abstract

The article analyzes the impact of integrated digital control systems applied in the modern shipping industry on the operation of ship power plants. The advantages of the transition from traditional analog control systems to digital platforms are examined, in particular, the working principles of the power management system and integrated automation system are examined. The article also highlights the contributions of digital solutions to energy efficiency, fuel economy and ship safety. The main contributions of digital solutions to energy efficiency, fuel economy and ship safety are the optimal operation of generators as a result of automatic load balancing, the prevention of excess and unnecessary energy consumption, the early detection of faults that cause power loss and the collection of accurate statistical data on energy consumption. In this case, energy efficiency increases and equipment wear and tear decreases.

Keywords: *ship, electrical systems, power management system, digitalization, integrated, energy efficiency*

Introduction

Maritime transport remains the dominant force in the world economy and the backbone of the global supply chain, accounting for approximately 90% of global trade. However, in the 21st century, the maritime industry is undergoing a radical technological transformation under the influence of the "Industry 4.0" revolution (Sultanov, Jalilov, 2018). Modern ships are no longer simply vehicles for transporting goods, but rather complex engineering structures (floating power plants) with power measured in megawatts. In particular, the increase in electrically powered ships and the introduction of high-voltage systems have significantly complicated the structure of ship power (Patel, 2012).

Historically, in traditional shipping, power plants, navigation systems and cargo operations operated in an isolated, local mode. This fragmented approach limited information exchange, slowed down operational decision-making and increased the risk of accidents caused by the human factor. However, in the face of the challenges of the modern era, increasing energy demand, the global fuel crisis and the need to optimize operating costs, this approach requires a change (Fernandez, 2018).

Integrated digital solutions are a set of technologies that enable the control, monitoring and analysis of all electrical and electrotechnical systems on board a ship through a single digital platform. These solutions increase the safety and efficiency of ship operations by combining automation, information exchange and decision-making processes in a single center (Sultanov, Hasanov, Ismayilov, Mammadov, 2023).

Integrated digital solutions perform the following functions:

Automatic control of electricity generation and distribution, load balancing and energy efficiency improvement, early fault detection and warning systems, continuous monitoring of the condition of electrical equipment, collection of analytical data for technical service.

At the same time, environmental factors have begun to play a decisive role.

Stringent regulations such as the Energy Efficiency Design Index (EEDI) and the Carbon Intensity Index (CII) introduced by the International Maritime Organization (IMO) force ship owners to reduce carbon emissions and maximize energy efficiency. On the other hand, the optimization of ship crew numbers and the transition to the concept of the "autonomous ship" of the future have made the introduction of intelligent systems that minimize human intervention in management inevitable.

All these factors have made the implementation of "integrated digital solutions" a necessity. Thanks to advanced sensor technologies and real-time data analysis, ship electrical systems now operate as a single digital system (IMO International Maritime Organization, 2020). As the technical complexity of ships in modern maritime transport increases, the role of electrical systems for their safe, efficient and reliable operation is becoming increasingly important. Since traditional local control methods do not meet modern requirements, the concept of controlling ship electrical systems from a single digital center has become widespread in recent years. This approach is distinguished by its automation, digitalization and real-time monitoring capabilities. Ship electrical systems include energy production (generators), energy distribution (distribution boards), consumers (navigation equipment, engines, lighting, security systems) and backup energy sources. Each of these systems works in close interaction with each other, and any malfunction can seriously affect the overall operation of the ship. A single digital control center (SDCC) is an integrated platform that provides control, monitoring and analysis of all electrical and electrotechnical systems on board from a single center through software. This center is usually built on the basis of SCADA, PLC, IoT sensors and industrial network protocols (for example, Modbus, CAN, Ethernet).

Control from a single digital center performs the following main functions:

Real-time monitoring: Continuous monitoring of parameters such as voltage, current, frequency, load level. Automatic control: Load balancing, automatic connection and disconnection of generators. Early detection of faults: Prediction of potential accidents based on analysis of sensor data. Data archiving: Creation of a database for technical maintenance and analysis. Remote control and diagnostics: Possibility of controlling systems from the shore or bridge (Hassan, Amer, Williams, 2018).

The application of this approach creates a number of important advantages:

This approach contributes to increasing safety, improving energy efficiency, reducing operating costs, enhancing operational decision-making, and ensuring compliance with international standards.

However, the implementation of single digital control systems is also accompanied by certain difficulties. These include high initial investment costs, cybersecurity risks, the need to increase the qualification level of personnel, and integration problems with legacy systems. In the future, the management of ship electrical systems will be further improved with the application of artificial intelligence and machine learning technologies. Predictive maintenance, fully autonomous energy management, and the "smart ship" concept are considered the main development directions in this field (Jimenez, Kim, Minima, 2022). The main purpose of the article is to analyze the technical structure of controlling ship electrical systems from a single digital center, and to scientifically investigate the impact of this transition on energy efficiency, operational safety, and economic efficiency.

Research

Modern ship electrical system control is based on multi-level digital architectures. These systems typically consist of 3 main levels:

1. Area (This includes sensors, measuring transformers and actuators);
2. Management (Here information processing takes place. The main role is played by programmable logic controllers (PLC);
3. Monitoring and management (This is the level at which the operator monitors the process through the human–machine interface (HMI) and SCADA systems).

The basis of digital integration is considered to be the power management system. The power management system is a set of digital algorithms that control the generators of the ship's power plant without human intervention (Sultanov, Jalilov, 2018).

The main functions of the power management system are as follows:

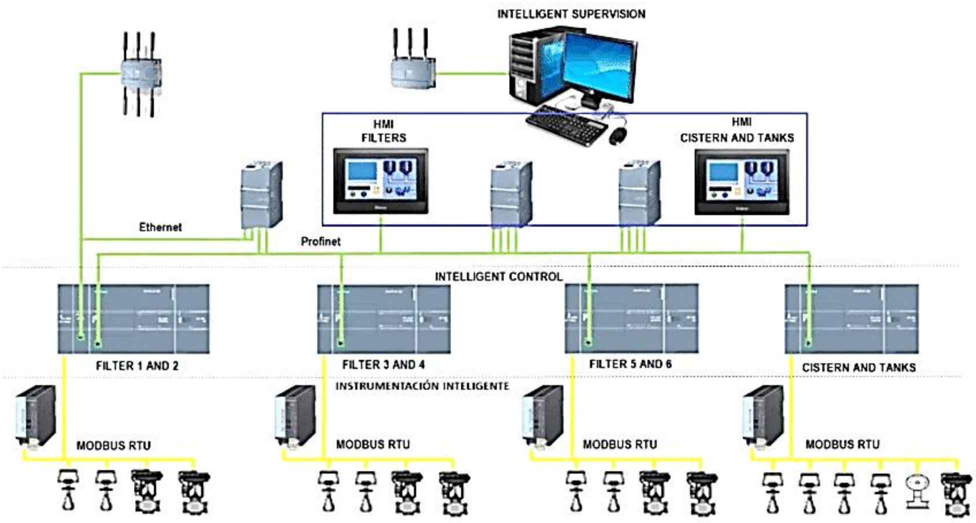

Figure 1. *Block diagram of ship electrical power system automation*

Load distribution: Equal distribution of active and reactive load between generators operating in parallel using digital controllers. This process is based on the static characteristic (droitness) of motor speed controllers (Wildi, 2014).

Modern digital controllers realize this dependence with the following linear equation:

$$f = f_0 - k_p \cdot P$$

Here:

f – current network frequency (Hz);

f_0 – generator no-load operating frequency;

k_p – droop coefficient of the speed controller;

P – is the active power provided by the generator (kW).

To distribute reactive power and maintain voltage stability, the static characteristic of the automatic voltage regulator is used:

$$U = U_0 - k_q \cdot Q$$

Where: U_0 – nominal voltage (V), k_g – voltage droop coefficient, Q – reactive power (kVar).

The digital control system automatically adjusts these coefficients (kp and kg), ensuring stable operation of generators of different power in a single network.

Automatic synchronization: The moment of connection of the generator to the network (matching the frequency, voltage and phase angle) is carried out by microprocessors with millisecond accuracy (Hasanova, Yusifbayli, 2023).

The image of the human-machine interface of the power control system in the ship's main switchboards is given in Figure 2.

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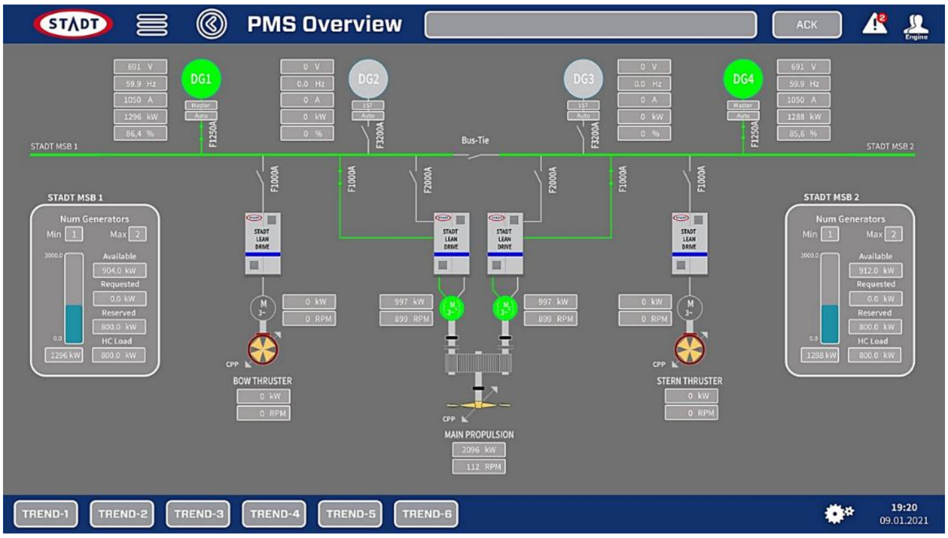

Figure 2. *Image of human-machine interface in a modern control system*

Opening of low-responsibility users: This function prevents the ship's power system from completely shutting down. If the operating generators cannot carry the load, the system automatically disconnects the tertiary generators from the network. Figure 3 shows the fuel consumption optimization graph of the ship's electrical power management system (Ismayilova, Mirzaeva, Ismiyeva, 2024).

Digital control not only means convenience, but also savings. While in traditional systems an additional generator was always kept running for backup, modern "Smart" systems predict load demand.

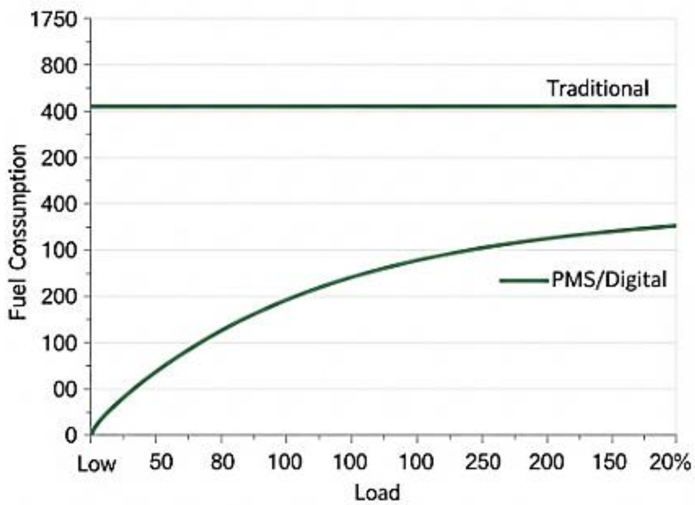

Figure 3. *Fuel consumption optimization chart of the ship's electrical power management system*

The graph below shows a comparison of fuel consumption with traditional and digital control. Integrated systems store all parameters (temperature, pressure, etc.). Thanks to "big data" analysis, engineers receive warnings before equipment fails. This minimizes the downtime of the ship.

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Conclusion

The conducted analyses show that the application of integrated digital solutions in ship electrical systems is a fundamental approach transformation in the maritime industry. Digital power management systems (PMS) minimize specific fuel consumption and operating expenses (OPEX) by ensuring optimal operation of generators in accordance with the load schedule. Automated synchronization, active/reactive load sharing and intelligent load shedding functions increase the resilience of the network by eliminating risks arising from the human factor. These technologies directly contribute to the implementation of international environmental regulations (IMO EEDI/CII) limiting carbon emissions. In the future, the transition to fully autonomous marine energy installations with the integration of artificial intelligence is inevitable.

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