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IMPROVED ALGORITHM FOR SUPERVISORY CONTROL AND DATA ACQUISITION OF COMBINED VESSEL'S ENERGY SYSTEM

Annotation. *Main development trends of modern ship power systems have been analyzed. The purpose of the paper is the analysis of energy modes and the development of criteria for transitions between different modes of an integrated marine vessel's power system, providing maximum efficiency in the use of fuel and motor resources of main vessel engines. It is proposed to identify, in addition to the shore-to-ship mode, four main operating modes in the presence of a synchronous machine on a propeller shaft and a converter that ensures an operation of this machine in both motor and generator modes. By dividing the main engine load into four levels – small, medium, nominal and large – an automatic system can accordingly control (or recommend in semi-automatic mode) the switching sequence of power equipment and actuating machines and mechanisms. Using a few container ships as an example, it is shown when the ship moves at a low speed, the main engine load becomes so low that it can be provided by diesel generators of the ship's energy system ("Power-Take-Home" mode). This, on the one hand, allows to save fuel, and on the other hand increases the completeness of fuel oil consumption, since diesel generators operate at an optimal load unlike the main engine, the load of which reaches only 10 percent. Similarly, in case of medium loading of the main engine, it is recommended to switch to the power supply of ship's grid from the main engine with the shaft generator ("Power-Take-Off" mode), and if it is necessary to obtain increased power of the propulsion system, the synchronous machine is switched to the engine mode powered by diesel generators ("Power-Take-In" mode). In addition, the ability to switch of these and main modes in emergency situations quickly increases the vessel's survivability and safety. Based on the analysis, an algorithm for switching between modes is proposed, which can be implemented in Supervisory Control Ad Data Acquisition of ship's energy systems, in particular, on a physical simulator at the National University "Odessa Maritime Academy".*

Keywords: *ship power system; ship power system operation modes; shaft generator; inverter; optimal fuel oil consumption indicator*

Introduction

International Marine Organization (IMO) has conducted comprehensive researches that allow us to distinguish the factors of fuel consumption reduction on vessels, and related to them harmful emissions of so-called Green House Gases (GHG) that contain carbon dioxide CO_2, nitrogen NO_X and sulphur SO_X oxides [1]. Siemens, ABB, Mitsubishi Heavy Industries and others who are leaders in the manufacturing of equipment for vessels pay a lot of attention to the increase of ship power systems efficiency and provision of the optimal mode of combustion engines operation that enables both fuel oil consumption and substantial GHG emissions reduction.

A few methods of fuel consumption efficiency increase are offered due to the introduction of electric motion [2-3]:

– optimal control of generation, distribution and consumption of energy;

– operation methods upgrading on existing vessels.

All modern marine power systems meeting A1 automation class use Waste Heat Recovery System (WHRS). For example, Mitsubishi Heavy Industries offers Mitsubishi Energy Recovery System (MERS) at the market which recovers and consumes energy again from the main engine exhaust gases [4]. MERS optimizes thermal efficiency, automatically regulating power in accordance with the required electric power. Solutions in this category consist of a fuel-efficient world-class engine, a WHRS, hybrid turbo-compressors, and optimized propellers [5].

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These technologies can be used for the plants thermal efficiency increase by 20 %.

In addition, Selective Catalytic Reduction (SCR) and Exhaust Gases Recirculation (EGR) technologies reduce NO_X and SO_X emissions which are the two widespread sources of air pollution considerably. SCR and EGR reduce NO_X emissions by more than 80 %, and EGR with the help of a scrubber reduces SO_X emissions by more than 98 %. The combination of these solutions provides a substantial ship power system efficiency increase and, as a result, fuel consumption and GHG emissions reduction, that meets IMO Tier III regulations [4].

Literature review

On vessels being in operation, the energy consumption efficiency increase can be attained due to implementation of wide range of actions of technical and operative character, majority of which, in one way or another, relates to the marine Power (Propulsion) Plant (PP) which consists of both main Internal Combustion Engines (ICE) and diesel-(turbo-) generators [6-7]. With the development of high-voltage equipment and semiconductor converters, the application of high-voltage networks of direct and alternating current with inverters in which it is possible to provide energy recovery modes that in combination with main diesel engines and diesel-(turbo-) generators operation modes optimization can provide the increase of fuel consumption efficiency becomes a new direction in ship power systems [8-12].

Electronically-controlled ship diesel engines, hybrid and combined or Integrated Propulsion Systems (IPS) are most suitable for this purpose [6]. The important component of such IPS is a Synchronous electric Machine (SM) which is set in the line of a propeller shaft and is called a shaft generator, that can work both in a generator mode (SG) and in an engine mode (SG / M) [13-14].

Such systems not requiring bringing of any excessive changes in the vessel construction provide the following advantages:

– increase of vessel survivability due to having of additional energy and propulsion sources;

– reduction of Brake Specific Fuel Consumption (BSFC) both of auxiliary engines and the main engine;

– reduction of oil consumption and maintenance expenses;

– reduction of the installed power or auxiliary engine capacity;

– reduction of emissions;

– use of WHRS for the main engine efficiency increase;

– a more flexible solution for connecting to the shore supply sources;

– redundancy in case of main or auxiliary engine failure;

– independent optimization of propulsors efficiency and electric power generation;

– possibility of generators operation combined modes.

Optimization of combustion engines operation modes results in a reduction of Specific Fuel Consumption (SFC) and considerable increase of engines parts service life because of vibration reduction [13].

Re-engineering process is carried out by upgrading of an existing main engine (ME) for a hybrid power-plant that is a dynamic combination of ME and a Diesel-Electric Plant (DEP) (Fig.1).

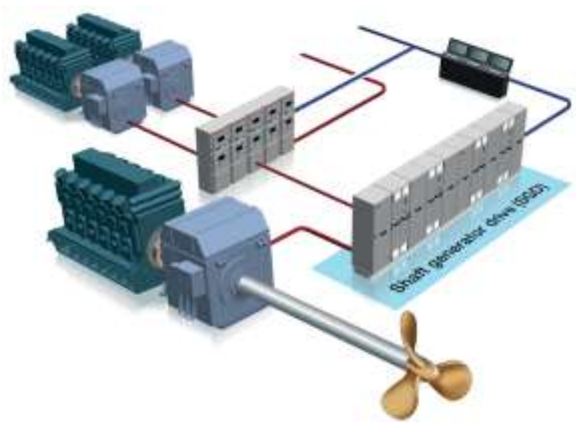

Fig. 1. Configuration of a typical Ship's Energy System with Shaft Generator Drive [2]

This system with centralized data acquisition, control and dispatching (Supervisory Control And Data Acquisition – SCADA) of all energy sources and consumers has five motion modes allowing to adapt to requirements of different operation conditions: STS is a Shore To Ship supply mode, MAIN is a main mechanical mode, PTO is a mode with transmission of power from the main engine to MPS of a vessel, PTI is a mode with which mechanical power on a propulsion shaft from the ME adds up to SM, PTH is a mode with which the ME is stopped and a propeller works from SM (Fig. 2a-e) [14-15].

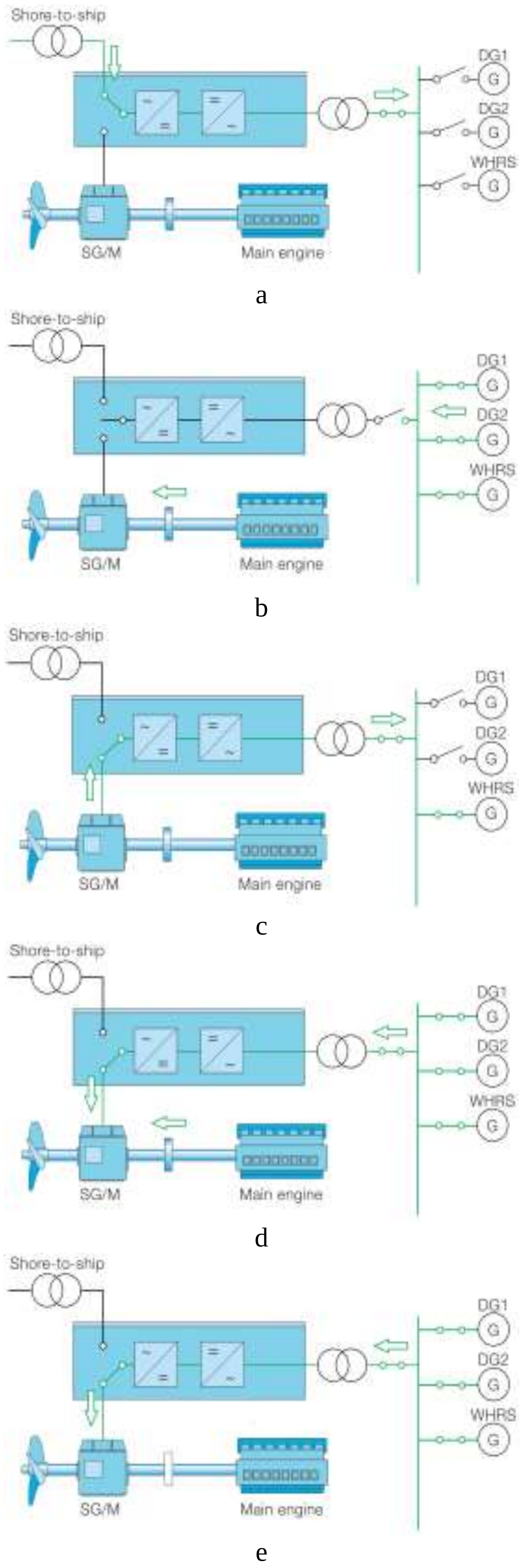

Fig. 2. Modes of propulsion systems with shaft generator:
a) STS; b) Main mechanical mode; c) PTO; d) PTI; e) PTH

Providing of survivability increase and safety on vessels [16-18] where one of the basic factors is reliability and power system surplus is a no less important problem [9; 15].

Numerous researches are conducted in this direction aimed at the analysis of emergency conditions in the generalized models and for the concrete situations at sea, control and topology analysis of ship networks for rapid taking measures in emergency situations of accidents and their consequences prevention [19; 20].

The purpose of the article

The purpose of this work is the development of marine power plant control algorithms which are realized by means of the Supervisory Control And Data Acquisition system on the basis of the analysis of loads and the grounding of the criterion of transitions between the main engine key power modes and diesel-generators of the combined propulsion plant.

Main part. Analysis of energy indicators in PTI, PTH and PTO modes

Marine power system operation modes, main engine and diesel-generators in different load ranges fuel consumption will be analyzed.

As an example, a lot of containerships (Gerda Maersk, Mathilda Maersk, Mette Maersk, Maersk Herrera and other) marine power plant will be considered [21]. Main engine nominal power is $P_{MEn} = 68.640\,MW$. At the maneuvering mode of these vessels, the marine power plant required power is $P_{ME} = 5057.37\,MW$. Each of three diesel-generators Siemens 1DK4531-8BF05-Z nominal power is $P_{DGn} = 2.520\,MW$.

From these data, it follows that in this mode main engine power is comparable with diesel-generators power of the marine power system. If the propulsion plant P_{ME} and connected electric consumers $P_{ShipGrid}$ total power does not exceed total power of diesel-generators, then it is possible to carry out switching to the PTH mode which is one of the modes the possibility of which is a fundamentally new feature of the integrated power systems [22].

The fact that such transition is expedient while considering fuel saving and, as a result, vessel ecological cleanliness increase will be shown.

Dependencies of main engine and diesel generators Brake Specific Fuel Consumption (BSFC) at the relative load $5...15\,\% \le L \le 100\,\%$ can be approximated by polynomial functions of the second order which for the machines being considered on the basis of experimental data from

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official specifications presented as charts and formulas of polynomial trends in [23, p. 24] and in more convenient form in [24]:

$$BSFC_{ME} = 0.01L_{ME}^2 - 1.513L_{ME} + 226.3\left[\frac{kg}{MWh}\right], \quad (1)$$

$$BSFC_{DG} = 0.006L^2 - 0.959L + 230.2\left[\frac{kg}{MWh}\right], \quad (2)$$

where: L is relative power in percent: $L_{1DG} = 100P/2.520$ during one diesel-generator operation; $L_{2DG} = 100P/5.040$ during two diesel-generators parallel operation; $L_{ME} = 100P/68.640$ for the main engine.

In the area of ultralow loads $L \le 5\,\%$ of $BSFC(L)$ dependence is approximated by other functions, but this range is not actual for the marine power systems.

The fuel consumption is determined by the formula:

$$SFC(P) = BSFC(L)\cdot P. \quad (3)$$

The important feature of (1) and (2) functions is the existence of an optimal point in the area of 80…85 % of nominal engine power, that meets ICE design principles. There is the most complete fuel combustion at such power, that results in more effective transformation of fuel combustion energy into mechanical energy and the least level of harmful emissions.

Let us build (1) and (2) fuel specific consumption charts, planting aside on abscise axis absolute power P for all ICEs (Fig. 3).

It is seen that in the area of small loads $BSFC_{ME}(P)$ of the main engine is considerably more than $BSFC_{1DG}(P)$ and $BSFC_{2DG}(P)$ of diesel-generators.

Therefore in the low loads range, in particular at the maneuvering operation mode, it is expedient to switch the power plant into the PTH mode, meanwhile at power up to $2.5\,MW$ it is possible to use one diesel-generator, and at power up to $5.0\,MW$ it is possible to use two diesel-generators (the third generator is in stand-for safety reasons).

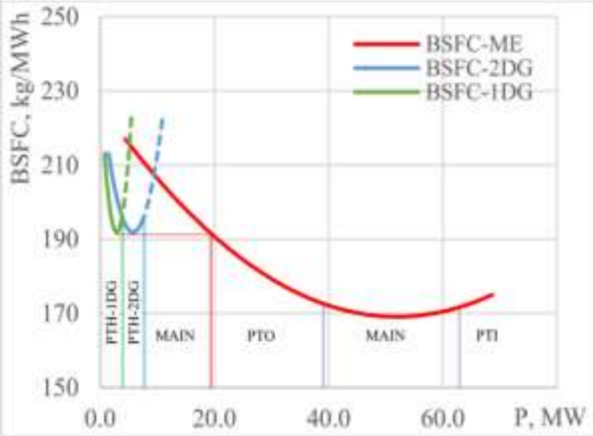

Fig. 3. Break specific fuel consumption and the principle of separating of modes

Let us calculate the fuel consumption during the main engine or two diesel-generators operation, ignoring on this stage of researches additional losses from diesel-generators to the propulsion shaft.

The main engine consumption will make:

$$L_{ME} = 100\frac{5.057}{68.640} = 7.367\,\%,$$
$$SFC_{ME} = 5.057\,BSFC_{ME}(L_{ME}) = \quad (4)$$
$$= 5.057\left(0.01L_{ME}^2 - 1.513L_{ME} + 226.3\right) = 1090\,\frac{kg}{h}.$$

Two diesel-generators consumption will make similarly:

$$L_{2DG} = 100\frac{5.057}{5.040} = 100.3\,\%,$$
$$SFC_{2DG} = 5.057\,BSFC_{2DG}(L_{2DG}) =$$
$$= 5.057\left(0.006L_{2DG}^2 - 0.959L_{2DG} + 230.2\right) = \quad (5)$$
$$= 983.0\,\frac{kg}{h}.$$

The same result we will get, if the consumption of each of diesel-generators is calculated separately (based on the supposition about the symmetric distribution of the load):

$$L_{1DG} = 100\frac{2.529}{2.520} = 100.3\,\%,$$
$$SFC_{1DG} = 2.529\,BSFC_{1DG}(L_{1DG}) =$$
$$= 2.529\left(0.006L_{1DG}^2 - 0.959L_{1DG} + 230.2\right) = \quad (6)$$
$$= 491.5\,\frac{kg}{h},$$
$$SFC_{2DG} = 2SFC_{1DG} = 983.0\,\frac{kg}{h}.$$

Thus, the economy of fuel will make:

$$SFC_{ME} - SFC_{2DG} = 107.0\,\frac{kg}{h},$$

that is $100\frac{107}{1090} = 9.8\,\%$, that exceeds the possible energy losses in the DG–FC–SG / M channel substantially.

Let us analyze another load area from $5.0\,MW$ to $20\,MW$. In this case ME and DG–SG / M (PTI mode) joint operation is inadvisable, since ME load is small, and its reduction by means of DG–SG / M will only worsen power indexes.

Let, for example, $P_{ME} = 15\,MW$.

The main engine consumption will make:

$$\begin{aligned} &L_{ME} = 100\frac{15.0}{68.640} = 21.85\,\%,\\ &SFC_{ME} = 15.0BSFC_{ME}\left(L_{ME}\right) = \\ &= 15.0\left(0.01L_{ME}^2 - 1.513L_{ME} + 226.3\right) = 2970\,\frac{kg}{h}. \end{aligned} \quad (7)$$

Let diesel-generators operate with 80 % optimal load. Then we get:

$$\begin{aligned} &L_{2DG} = 80\,\%,\\ &P_{2DG} = 0.8\cdot 5.040 = 4.032\,MW,\\ &SFC_{2DG} = 4.032BSFC_{2DG}\left(L_{2DG}\right) = \\ &= 4.032\left(0.006L_{2DG}^2 - 0.959L_{2DG} + 230.2\right) = \\ &= 773.6\,\frac{kg}{h}; \end{aligned} \quad (8)$$

$$\begin{aligned} &L_{ME} = 100\frac{15.0 - 4.032}{68.640} = 100\frac{10.968}{68.640} = 16.0\,\%,\\ &SFC_{ME} = 10.968BSFC_{ME}\left(L_{ME}\right) = \\ &= 10.968\left(0.01L_{ME}^2 - 1.513L_{ME} + 226.3\right) = \\ &= 2244.9\,\frac{kg}{h}. \end{aligned} \quad (9)$$

Adding up (8) and (9) results of calculations, in the total we find:

$$SFC = SFC_{2DG} + SFC_{ME} = 3018.6\,\frac{kg}{h}. \quad (10)$$

The fuel consumption obviously increases. Therefore, the system necessary operation mode is MAIN (ME and DGs independent operation).

Further, in the range of main engine middle loads which is more $20\,MW$, its specific fuel consumption is less than that of the MPS diesel-generators. Therefore, switching to PTO mode becomes expedient, when all marine electric network needs are provided by the SG shaft generator and WHRS. On the one hand, it will approach the main engine to the optimal operation point, and on the other hand it will save diesel-generators service life.

Obviously, that in the range of loads from 65% to 85...90 % P_{ME} main engine operates in the mode close to the optimal one, therefore switching to the MAIN mode is also expedient.

And, finally, when the required ME power becomes higher 90...95 % P_{ME}, it is necessary to switch into the PTI mode. Then diesel-generators and WHRS will increase the general power passed to the propeller by the value $2P_{DG} + P_{WHRS} - P_{Ship\,Grid}$, that will allow to bring main engine load down, again approaching to an optimal value from the both fuel consumption and combustion completeness point of view.

On the basis of the presented considerations a combined marine power system control algorithm can be offered allowing in automatic or semi-automatic operation mode to provide both optimization of fuel consumption and the rational use of ICE service life and completeness of fuel combustion what is important for the environment pollution level reduction. The corresponding procedure algorithm is shown in Fig. 4. There are four basic branches in it which divide the modes in accordance with Fig. 3.

The MPS physical simulator functions at the Department of Ship's Electromechanics and Electrical Engineering of National University "Odesa Marine Academy" consisting of two diesel-generators, an emergency diesel-generator, a shore supply module, a shaft generator module based on an asynchronous generator with the converter of frequency, a load control module, and switchgear of marine application [25]. Besides specialized comptrollers for separate subsystems, Schneider Electric M340 industrial comptroller is included in the simulator.

SCADA is realized on the base of Citect v.7.40 platform, the basic screen of which is shown in a Fig. 5 [26-27]. SCADA and the comptroller provide operation of the system in automatic, semi-automatic and manual modes. Taking into account that a simulator is built on true-to-life diesel-generators and SCADA is able to work in real-time mode, in control programs the implementation of load power analysis system is planned for forecasting and carrying out of switches between vessel power system modes and informing of the operator. For operation modes indication, pointing of direction and energy streams power, the indication of switchgear state, "pointer devices", histograms, giving complete information about the MPS state both for cadets and developers are foreseen in SCADA.

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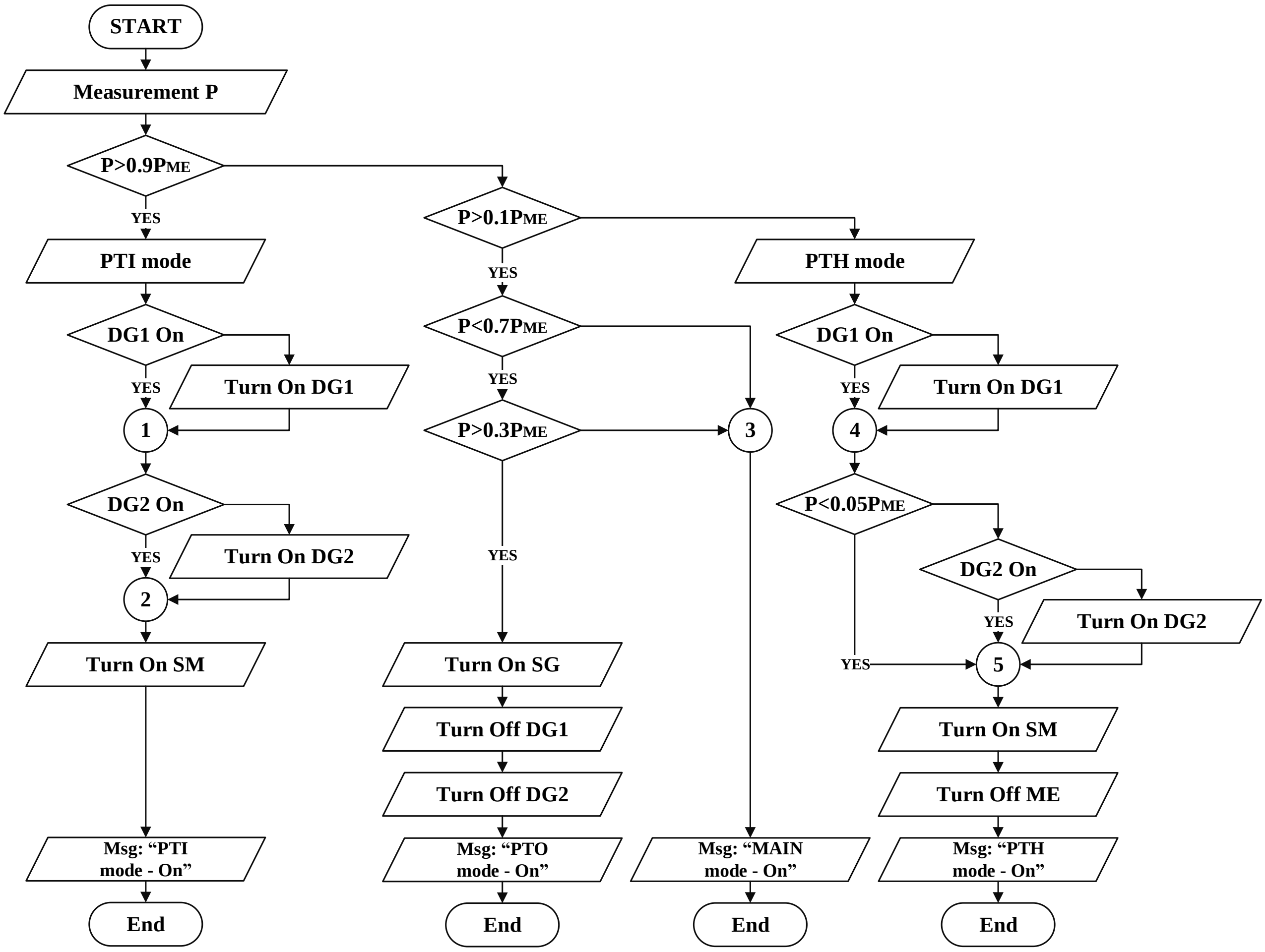

Fig. 4. The algorithm of the subroutine “Switch of PTI – PTO – MAIN – PTH Modes”

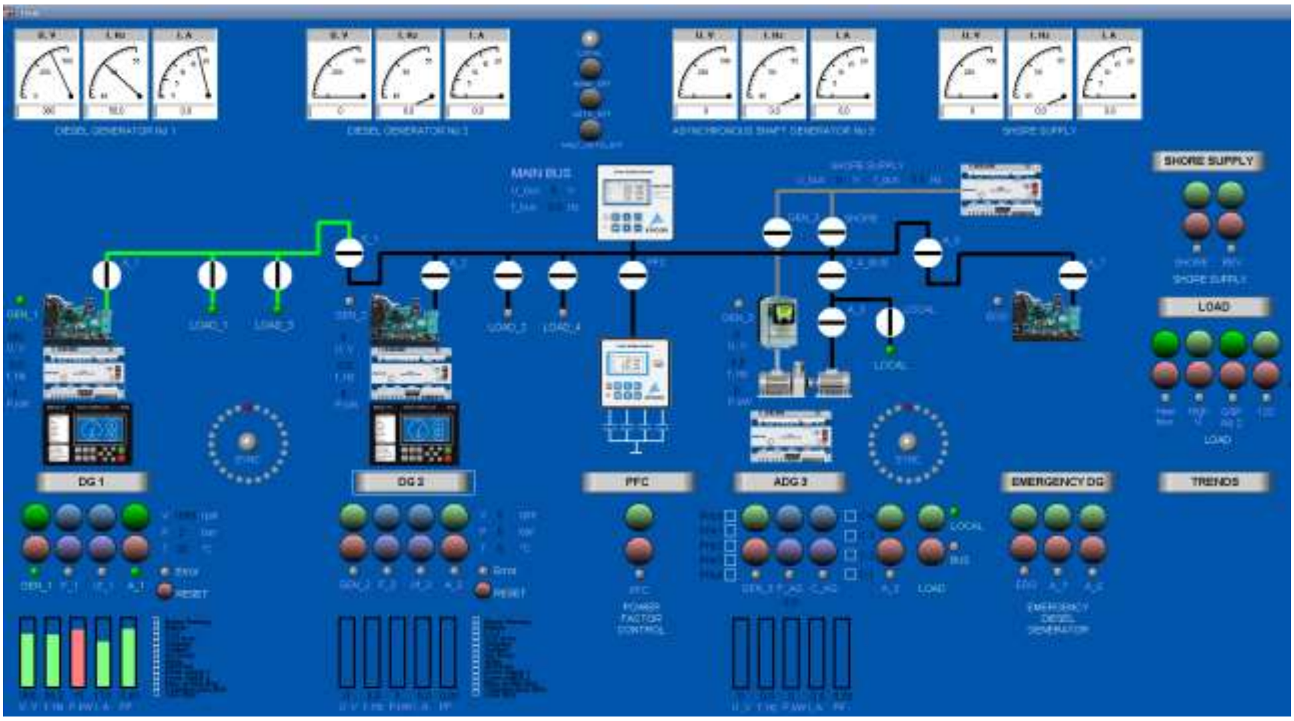

Fig. 5. The main screen of SCADA “Ship Electrical Power System”

Conclusion. The analysis of basic development trends of modern marine power systems is carried out in this work and the principle of operation modes division of the combined marine power system is offered in accordance with the main engine load. Besides a shore to ship supply mode, four basic operation modes are distinguished at the presence of a synchronous machine in the system which is on the propulsion shaft and a converter providing operation of this machine both in the propulsion and generator mode. Then according to the main engine load level which can be small, medium, nominal and large, the automatic control system can define the switchgear and actuating machines and mechanisms switching sequence accordingly. It is also necessary to mark additionally that possibilities of powertrains switching in the combined power plant in emergency modes promote a vessel's survivability and safety.

As the example a 16,000 TEU containership was chosen to show that while moving with a small speed the vessel's main engine load becomes so small, that it can be provided with marine power system diesel-generators. Then switching to the PTH mode, on the one hand, allows to save fuel (near to 107 kg/h), and on the other hand it increases fuel combustion completeness, because diesel-generators operate at the optimal load unlike the main engine, operation of which in this case is close to idling and extremely unfavorable for the machine.

Similarly on the basis of analysis of fuel consumption dependence on the main engine and diesel-generators load and combustion engines properties, the operation algorithm of the automatic control system of the marine power system is offered. This algorithm can be realized in ship SCADA, and also, in particular, on a physical simulator at National University "Odesa Marine Academy".

Further researches can be aimed at the clarification of transition borders between PTO-MAIN modes both taking into account fuel consumption and fuel combustion completeness and the risks conditioned by frequent diesel-generators starting's and stops.

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УДОСКОНАЛЕНИЙ АЛГОРИТМ ДЛЯ СИСТЕМИ ДИСПЕТЧЕРИЗАЦІЇ ТА ЗБОРУ ДАНИХ КОМБІНОВАНОЇ СУДНОВОЇ ЕНЕРГЕТИЧНОЇ УСТАНОВКИ

Анотація: *Проведено аналіз основних тенденцій розвитку сучасних суднових електроенергетичних систем. Метою роботи є аналіз енергетичних режимів і розробка критеріїв переходів між різними режимами комбінованої силової установки, що забезпечують максимальну ефективність використання палива і моторесурсу основних машин судна. Запропоновано виділити, крім режиму берегового живлення, чотири основні режими роботи при наявності в системі синхронної машини на гребному валу і перетворювача, що забезпечує роботу цієї машини в режимах двигуна та генератора. Розділивши навантаження головного двигуна на чотири рівні – мале, середнє, номінальне і велике – система автоматичного керування може відповідно управляти (або в напівавтоматичному режимі рекомендувати) послідовність перемикання комутаційної апаратури і виконавчих машин і механізмів. На прикладі суднових енергетичних установок деяких контейнеровозів показано, що при пересуванні судна з малою швидкістю навантаження головного двигуна стає настільки низького рівня, який може бути забезпечений дизель-генераторами електро-енергетичної системи (PTH mode). Це, з одного боку, дозволяє економити паливо, а з іншого боку підвищує повноту згоряння палива, так як дизель-генератори працюють при оптимальному навантаженні на відміну від головного двигуна, навантаження якого досягає лише десяти вілсотків. Аналогічно при неповному завантаженні головного двигуна рекомендується перехід на живлення всіх споживачів від головного двигуна з валогенератором (PTO mode), а при необхідності отримання підвищеної потужності пропульсивної системи - синхронна машина переводиться в режим двигуна з живленням від дизель-генераторів (PTI mode). Крім того, можливість швидкого перемикання між режимами PTH-PTO-PTI-MAIN в аварійних ситуаціях підвищує рівень живучості та безпеки судна. На підставі проведеного аналізу запропоновано алгоритм перемикання між режимами, який може бути реалізований в системі керування, диспетчеризації та збору даних суднових енергетичних систем, зокрема на фізичному тренажері в Національному університеті «Одеська морська академія».*

Ключові слова: *система рушання судна; режими роботи суднової енергетичної системи; валогенератор; інвертор; оптимальний показник згоряння палива*

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УСОВЕРШЕНСТВОВАННЫЙ АЛГОРИТМ ДЛЯ СИСТЕМЫ ДИСПЕТЧЕРИЗАЦИИ И СБОРА ДАННЫХ КОМБИНИРОВАННОЙ СУДОВОЙ ЭНЕРГЕТИЧЕСКОЙ УСТАНОВКИ

Аннотация: *Проведен анализ основных тенденций развития современных судовых электроэнергетических систем. Целью работы является анализ энергетических режимов и разработка критериев переходов между различными режимами комбинированной силовой установки, обеспечивающими максимальную эффективность использования топлива и моторесурса основных машин судна. Предложено выделить, кроме режима берегового питания, четыре основных режима работы при наличии в системе синхронной машины на гребном валу и преобразователя, обеспечивающего работу этой машины как в двигательном, так и в генераторном режиме. Разделив нагрузку главного двигателя на четыре уровня – малая, средняя, номинальная и большая – система автоматического управления может соответственно формировать (или в полуавтоматическом режиме рекомендовать) последовательность переключения коммутационной аппаратуры и исполнительных машин и механизмов. На примере силовых установок некоторых контейнеровозов показано, что при передвижении судна с малой скоростью нагрузка главного двигателя становится настолько низкого уровня, который может быть обеспечен дизель-генераторами судовой энергетической системы (PTH mode). Это, с одной стороны, позволяет экономить топливо, а с другой стороны повышает полноту сгорания топлива, так как дизель-генераторы работают при оптимальной нагрузке в отличие от главного двигателя, нагрузка которого достигает лишь десяти процентов. Аналогично при неполной загрузке главного двигателя рекомендуется переход на питание всех потребителей от главного двигателя с валогенератором (PTO mode), а при необходимости получения повышенной мощности пропульсивной системы – синхронная машина переводится в режим двигателя с питанием от дизель-генераторов (PTI mode). Кроме того, возможность быстрого переключения между режимами PTH–PTO–PTI–MAIN в аварийных ситуациях повышает уровень живучести и безопасности судна. На основании проведенного анализа предложен алгоритм переключения между режимами, который может быть реализован в системе управления, диспетчеризации и сбора данных судовых энергетических систем, в частности на физическом тренажере в Национальном университете «Одесская морская академия».*

Ключевые слова: *энергетическая система судна; режимы работы судовой энергетической системы; валогенератор; инвертор; оптимальный показатель расхода топлива*

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