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Electric Propulsion Optimization Model Based on Exploitation Profile and Energy Price

Preliminary communication

This paper presents an optimization model of merchant ship's electrical propulsion system. Proposed model is based on exploitation profile and average energy as optimization criteria. Energy price is calculated at the selected positions within the ship's power system by using an optimization module which consists of two main parts: power module and economic module. Each module is represented by corresponding transfer function that calculates energy price at the output of subsystem based on the energy price at its input and other relevant influential factors. This approach allows greater flexibility during energy price calculation and enables evaluation of different electrical propulsion solutions, even if all exploitation indicators are not available. The same model can be extended and applied to the ships with mechanical power transmission or with combined propulsion.

Keywords: *electrical propulsion, energy price, exploitation profile, optimization, ship*

Model optimizacije električne propulzije na bazi eksploatacijskog profila i cijene energije

Prethodno priopćenje

U radu je iznesen model optimizacije sustava električne propulzije na trgovačkom brodu. Predloženi model baziran je na eksploatacijskom profilu i srednjoj cijeni energije koja je ujedno i kriterij optimizacije. Cijena energije računa se na odabranim pozicijama unutar brodskog elektroenergetskog sustava pomoću optimizacijskog modula koji se sastoji od dva glavna dijela: energetskog i ekonomskog. Svaki modul predstavlja odgovarajuću prijenosnu funkciju, koja računa cijenu energije na izlazu podsustava na osnovi cijene energije na njegovom ulazu i ostalih relevantnih utjecajnih faktora. Takav pristup omogućuje veću fleksibilnost kod izračuna cijene energije i evaluaciju različitih rješenja električne propulzije, čak i u slučaju kada svi eksploatacijski podaci nisu dostupni. Isti model može se proširiti i upotrijebiti na brodove s direktnim mehaničkim pogonom i brodove s kombiniranom propulzijom.

Ključne riječi: *brod, cijena energije, eksploatacijski profil, električna propulzija, optimizacija*

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1 Introduction

To build an energy efficient ship equipped with electrical propulsion, it is necessary to optimize every possible detail of electrical power plant and energy supply system onboard.

Optimization is a continuous process which lasts during the whole design phase of the ship. It is very important to define all required system parameters before the project actually starts. If the system parameters are defined in a wrong way at the beginning, the total effect of optimization will be very limited.

During the optimization process, electrical system variables are represented with discrete functions, often without any firm correlation between them. A mitigating circumstance is a relatively small number of possible system configurations, due to the fact that only a few manufacturers are able to offer the complete solutions for electrically propelled ships. Optimal system configuration can be chosen within the reasonable time, by comparing the limited number of solutions with the exploitation profile defined during the pre-project phase. For that reason it is necessary to define optimization criteria and to build an appropriate evaluation model based on the most important exploitation parameters [1] [2].

The main task of every merchant ship is generation of profit for the ship owner. Total efficiency of the vessel can be determined simply by the ratio between total income and outcome [3]. That is a very simple and exact approach which is irreplaceable in business analysis, but it is not quite appropriate for optimization of electrical power system on a ship equipped with electrical propulsion.

Electrical propulsion systems are under constant development and they consist of many components that are coming from different vendors [4]. Because of that, the final product is very often brought to the market without exact economical and exploitation indicators. Even if the reference ship with electrical propulsion exists, it is very hard to distinguish the influence of applied technical solution on the total economic efficiency of the vessel.

There are not many published articles covering technical and economic optimization of ship's electric propulsion systems.

An interesting optimization model for minimizing economic costs of transport for an oil tanker, which is based on known operational and economic data, is proposed in [1]. Economic data variables from that model can be easily applied to electrically propelled ships as well. However, the mass and volume of the propulsion equipment, which has a direct influence on freight transfer effect, are not included.

The optimization model presented in [2] is intended for design of electric power plant system with regard to minimization of fuel consumption. It is an interesting tool for optimizing the size and number of generator sets, but it does not take into account economic parameters such as investment and maintenance costs.

The model introduced in this paper is specific because it enables the evaluation of different electric propulsion solutions even if exact exploitation indicators are not available. It also differs from the models [1] and [2], because it takes into account a mass and volume of electrical equipment. The main optimization criterion in the proposed model is average price of energy during the finite period of exploitation.

2 Model description

The average price of energy for a finite period of exploitation can be calculated by dividing the sum of used energy costs at the selected positions with the total of used energy:

$$c_{\mathrm{AV}} = \frac{\sum_{i=1}^{n} c_{\mathrm{i}} W_{\mathrm{i}}}{\sum_{i=1}^{n} W_{\mathrm{i}}}, \tag{1}$$

where W_i is used energy and c_i is unit price of energy at position i [5].

The simplest way of calculation would use only the price of electrical energy delivered to the various groups of electrical consumers. An ideal calculation, on the other hand, would use the total yield of every consumer or a group of consumers. Both of these models are not suitable for electrical power system optimization in case of an electrically propelled ship. The first one does not include the components of electrical propulsion system which have the major influence on the total efficiency and configuration of electrical propulsion. Therefore, by using this model the optimization result would be corrupted. The calculation method of the other model is too detailed, unsuitable for early optimization stages and practically impossible for implementation.

The model proposed in this work is the combination of those two methods. It calculates the price of propulsion energy for main propulsors and thrusters, while the other systems are conjoined through the price of energy at three main voltage levels. That gives five positions which present the limits of optimization domain. These are:

- Thrust energy of the main propulsors
- Thrust energy of bow and stern thrusters
- Energy delivered to other high voltage consumers
- Energy delivered to low voltage consumers, without lighting
- Energy delivered to lighting network.

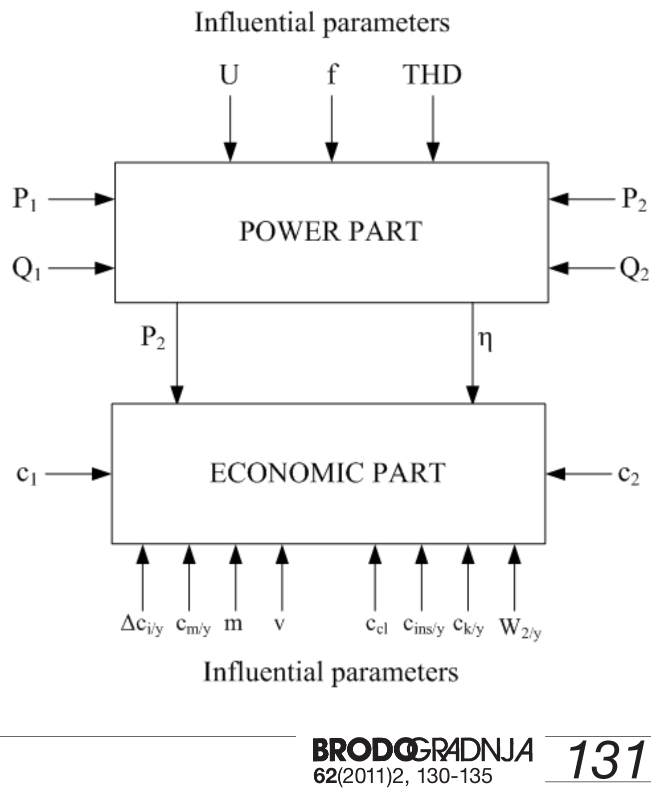
For all these five points it is necessary to make an exploitation profile, balance of power, balance of energy and calculation of energy price.

High voltage consumers which are not used for propulsion are rarely encountered on merchant ships, so they can be easily included into detailed model. In that case, the price of energy delivered to the drive mechanism can be used instead of the price at high voltage bus. The power consumed by electrical propulsion is usually much higher than the power of cargo handling devices, so the cargo handling operations will have influence only on the exploitation profile, but not on the total installed electrical power. With this approach, the electrical system can be isolated from the ship's economic system, while all the factors that are relevant for economic efficiency of the ship remain present.

By using this model, different solutions can be compared on a component or a subsystem level. That simplifies optimization process, because it is possible to perform a partial optimization by choosing a single component or a subsystem, which offer lower energy price for the same final yield. The same model can be extended to all ship's subsystems, both on the ships with electric and diesel-mechanical propulsion.

The optimization process begins with the defining of the type and purpose of the ship, in order to make the exploitation profile. Then the best solutions are chosen by performing partial optimization on a component level. When the initial configuration of the system is defined, it is necessary to make a balance of power. It allows proper dimensioning of the main system elements, to fulfil the classification society's rules and energy consumption specified in the exploitation profile. After that, a balance of energy is calculated by using the exploitation profile and energy price at previously defined positions of the system. Finally, an average price of energy is determined as optimization criteria.

Figure 1 **The basic module of optimization model**
Slika 1 **Osnovni modul optimizacijskog modela**



The algorithm should be iteratively repeated for different system configurations to get solutions with the lowest average price of energy.

Every module of the optimization model is represented by the corresponding transfer function that calculates energy price at the output of subsystem c_2, based on the energy price at its input c_1 and other relevant influential factors, as it is shown in Figure 1. Traditionally, in shipping business, all the revenues and expenditures are calculated in $, so the price of energy in this model is expressed in $/kWh accordingly. Optimization results depend on currency rate fluctuations and prices of fuel and freight. This does not affect model behaviour, because the operation of the ship is also determined by those specified categories.

Each basic module consists of two main parts: power module and economic module. The economic module is the basis of the optimization system and it is connected with the power module via efficiency factor η and output power P_2.

Both of those modules can be also used independently. In that case the power part is used for determining the balance of power and the economic part for partial optimization when the credible measuring results with calculated fuel consumption and efficiency factor are available.

Active power flow is determined by the algorithms which calculate efficiency factor $\eta = P_2/P_1$ and presents a base of the power module. The increase of reactive power $\Delta Q = Q_2 - Q_1$ and consequently the increase of power losses is calculated separately. Influential factors of the power module such as voltage U, frequency f and harmonic distortion THD are depending on the type of components in use [6].

The base of the economic module is the unit price of energy in $/kWh. Increase of energy price is primarily caused by energy losses, associated with efficiency factor η of the component in use. In other words, the output kilowatts are always more expensive than the input ones. The transfer function of the economic module can be expressed as:

$$c_2 = c_1 + c_{cl} + c_{inv} + c_{vl} + c_m + c_{ins}, \tag{2}$$

where are:

c_1 - unit price of energy at the component input
c_2 - unit price of energy at the component output
c_{cl} - unit cost due to component losses
c_{inv} - unit investment cost
c_{vl} - unit cost due to the loss of ship's volume capacity
c_m - unit maintenance cost
c_{ins} - unit cost of insurance and/or malfunction.

Efficiency factor η is determined by the total losses of component P_{tl}:

$$\eta = \frac{P_2}{P_1} = \frac{P_1 - P_{tl}}{P_1} = \frac{P_2}{P_2 + P_{tl}}. \tag{3}$$

Unit costs due to component losses c_{cl} are:

$$c_{cl} = (\frac{1}{\eta} - 1)c_1. \tag{4}$$

Specific investment cost c_{inv} is:

$$c_{inv} = \frac{\Delta c_{i/y}}{W_{2/y}}, \tag{5}$$

where $\Delta c_{i/y}$ is annual loss of the value of component in use. Total output energy during one year of exploitation $W_{2/y}$ can be obtained from the ship's exploitation profile.

Annual loss of value can be defined in many ways. The simplest one is to divide the total investment into components, together with interests for the entire repayment, with planned economic life of the ship. It is assumed that a life time of a component is greater than the planned economic life of the ship and that a component is never going to be replaced during the total exploitation time.

Specific maintenance cost c_m is defined as:

$$c_m = \frac{c_{m/y}}{W_{2/y}}, \tag{6}$$

where $c_{m/y}$ are total annual maintenance costs.

Total annual maintenance costs are closely related to total exploitation time of the ship, since the major overhauling of electric equipment is usually carried out in multi-year periods. They can be expressed as:

$$c_{m/y} = \frac{c_{tot}}{t_{\exp}}. \tag{7}$$

The calculation of total maintenance costs c_{tot} during the planned exploitation period $t_{\exp}$ can be based on manufacturer's data or own exploitation data, if those are available.

Unit cost of insurance and/or malfunction c_{ins} can be expressed as:

$$c_{ins} = \frac{c_{ins/y} + c_{k/y}}{W_{2/y}}, \tag{8}$$

where $C_{ins/y}$ is a sum of annual insurance premium in a part related to the modelled system and $C_{k/y}$ are total annual costs caused by malfunctions that are not covered with the insurance policy. These costs can be also used as a measure of system availability. Systems with longer mean time between failures (MTBF) and shorter mean time to repair (MTTR) will have lower costs due to malfunctions, as well as the insurance costs.

Specific costs due to reduction in ship's volume capacity c_t are specificity of ships systems and this particular model. These costs are evaluating loss of cargo at the expense of the ship's volume loss, which has a direct impact on ship operations by reducing the active capacity. Therefore, in this model these costs appear as a separate variable in expression (1).

The base unit for the calculation of fare depends on the type of ship. On a general cargo ship it will be a mass unit of cargo, on a tanker a volume unit of liquid cargo, on a cruise ship the number of cabins, etc. For that reason, it is better to use a ship's transfer effect as a basis for fare prices calculation. It allows more flexibility and better prediction of fares under different operating conditions. Freight transfer effect expressed in ton miles (tM) represents a product of certain amount of cargo m and a travelled distance s.

It is very suitable to express the specific costs c_{vl} through the loss of freight transfer effect ms:

$$c_{vl} = \frac{msc_{avf}}{P_2 t} = \frac{msc_{avf}}{W_2}. \tag{9}$$

In equation (9), m is the mass of subsystem that corresponds to the hypothetical mass of the cargo which could be transferred inside the ship's volume capacity which is taken by the considered subsystem, s is the travelled distance, c_{avf} is the average fare per ton mile and W_2 is the energy that has passed through the considered subsystem.

Since the ship's speed is $v = s/t$, equation (9) can be expressed as:

$$c_t = \frac{mvc_{avf}}{P_2}. \tag{10}$$

Finally, by substituting equations (4), (5), (6), (8) and (10) into (2), the transfer function of the economic module can be calculated as:

$$c_2 = \frac{c_1}{\eta} + \frac{mvc_v}{P_2} + \frac{C_{m/y} + C_{ins/y} + C_{k/y} + \Delta C_{i/y}}{W_{2/y}}. \tag{11}$$

3 Exploitation profile and power trend

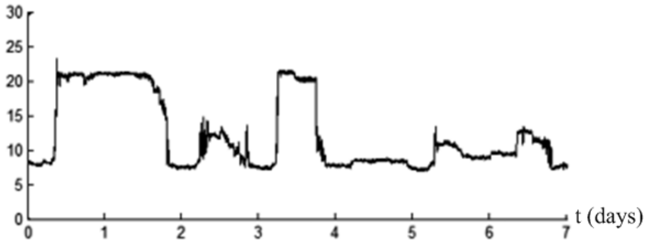
Exploitation profile is a statistical measure of how much time has been spent on each operational phase of the ship during specific time period and specific exploitation conditions. It is usually presented in a form of simple diagram and has a very important role in defining ship's power system and configuration of electric propulsion during the design phase, since the type of propulsion device and power transmission mode for the future ship are usually based on the information included in exploitation profile.

Analysis of exploitation of the reference ship is the best and very often the only way to collect the data required for the exploitation profile [1], [2]. It is not necessary for the reference ship to have the same configuration or a type of propulsion, as long as it operates under the same or very similar conditions as those that are planned for the new building. To make a precise exploitation profile it is necessary to record the following parameters during the desired time period:

- ship's speed
- draught and trim
- propulsion power
- power used by cargo handling devices
- power used by other consumers
- generator power and number of connected generators.

Although the exploitation profile can be also used for defining ship's energy requirements during a particular operational phase, it is much better to use the power trend for that purpose. Power measurements can be taken during any time period that represents one exploitation cycle of the future ship. As an example, a power trend of electrically propelled cruise liner for one typical seven-day round-trip cruise is shown in Figure 2.

Figure 2 **Recorded power trend of electrically propelled cruise liner**
Slika 2 **Oscilogram snage putničkog broda s električnom propulzijom**



In order to get the authentic results from the power trend it is necessary to have the information about the number of connected generators, which depends on the current operational phase of the ship. For example, during manoeuvring energy consumption is low, but all the generators are connected due to the safety reasons. Without that information it would be impossible to get correct figures about fuel consumption.

When optimizing the power system of an electrically propelled ship, it is also very important to have the information about specific fuel consumption in dependence on fuel quality and total generator load.

4 Balance of power

Balance of power is a basic calculation of every power system and a standard project task that is usually carried out after the exploitation profile has been made. A well defined balance of power ensures a sufficient amount of electric energy during all operational phases of the ship, with optimal load distribution between generators in use.

In the considered optimization model, the balance of power for the electrically propelled ship is somewhat different than the usual one. The main differences are in:

- analysis of the navigational categories for various ship's speeds
- more precise balance of reactive power
- calculation of the short circuit current.

Electric propulsion has a major impact on electric power system loading, so the number of generators and their power ratings have to be adapted according to the most common sailing speed in the exploitation profile. The other fact that has to be taken into consideration when choosing generators is the type of propulsion converter. Some converters have a very small power factor at low loads, which increases reactive power in the system. That requires more generators to be connected on the power network than it would be needed for active power only. To avoid running of the generator driving engines with too low load and consequently higher specific consumption it is necessary to use the generators with lower power factor or higher power ratings. It can be seen that the size of the generator can be optimized only with the precisely defined balance of reactive power.

Short circuit current has a direct influence on energy price, since it determines the dimensions and accordingly the price of switchgear equipment [7]. If the short circuit current is too high, then a higher nominal voltage of the ship's network has to be used. That is why the short circuit current has to be calculated through the balance of power, because the change of nominal voltage completely changes the configuration of ship's electric power system.

Default system parameters which are subject to change during the optimization process are set for two boundary conditions: maximal consumption at top speed which defines the total power of ship's electric network and minimal consumption that usually occurs while the ship is at berth or anchorage.

Sometimes, it is very convenient to use generators with different power ratings, or even with different types of driving engines onboard electrically propelled ships. That approach allows more flexibility in adjusting the generator loads to various exploitation scenarios and reduces the fuel consumption.

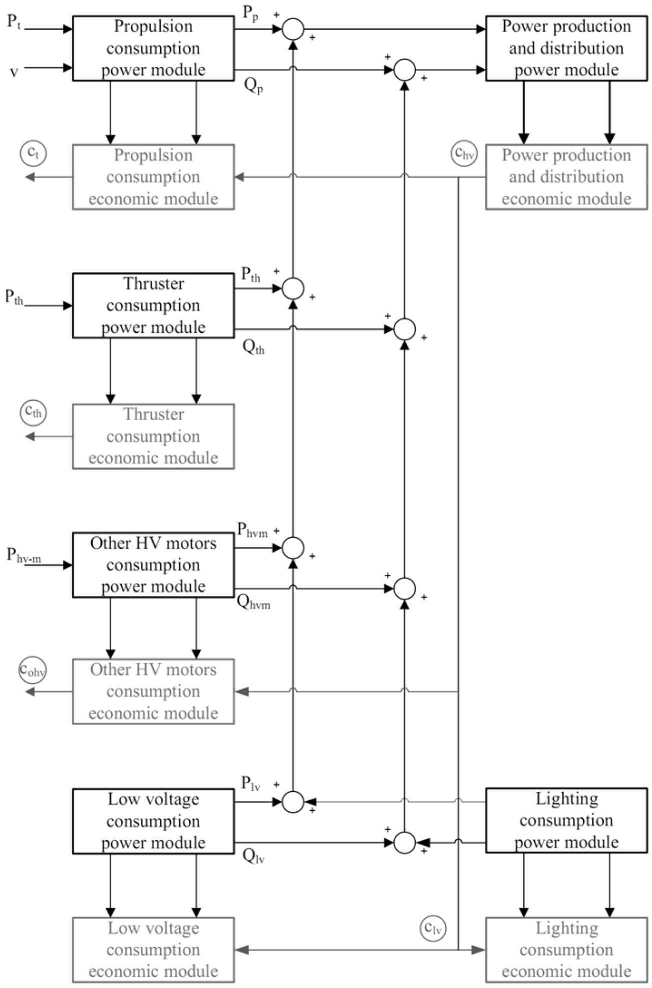


Figure 3 Simplified block diagram for the calculation of energy price on five main positions inside the electric power system of the ship equipped with electric propulsion
Slika 3 Pojednostavljeni dijagram toka za izračun cijene energije na pet ključnih pozicija unutar elektroenergetskog sustava broda s električnom propulzijom

After the total number of the main generators and their power ratings are set, the balance of power for various sailing speeds can be determined. Thereby, the balance of power is calculated only for speeds that are defined in the ship's exploitation profile and is made for each operational phase separately, by using only the power parts from the basic optimization module shown in Figure 1. A simplified block diagram for the calculation of energy price on five main positions inside the electric power system of the ship equipped with electric propulsion is shown in Figure 3.

The first step is to determine required thrust power P_{th} for desired stationary speed v which is defined in the exploitation profile (Figure 4). After that, the required number of turns n, efficiency factor η_{prop} and power delivered to propeller are determined from the speed vs. power diagram of the propeller:

$$P_D = \frac{P_{th}}{\eta_{prop}}. \tag{12}$$

Electric propulsion power P_{pem} is obtained as a sum of power delivered to propeller P_D and power losses in the shaft line P_{sl}:

$$P_{PEM-el} = P_D + P_{sl} = \frac{P_D}{\eta_{sl}}. \tag{13}$$

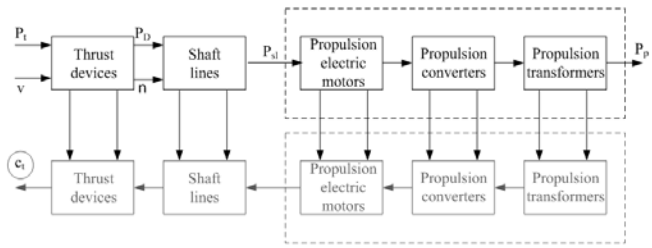


Figure 4 Detailed block diagram of propulsion power module
Slika 4 Detaljni dijagram toka energetskog modula propulzije

The power of drive engines P_{DE} corresponds to the total power of connected generators PG plus generator losses P_{Gl} (Figure 5) Total load of working engines can be calculated by dividing the power of drive engines with the rated power of running engines P_{DEr}:

$$P_{G\%} = \frac{P_G + P_{Gl}}{P_{DEr}}. \tag{14}$$

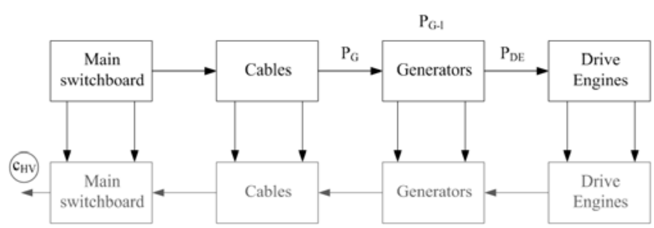


Figure 5 Detailed block diagram of power production and distribution module
Slika 5 Detaljni dijagram toka energetskog modula proizvodnje i distribucije energije

Specific fuel consumption can be easily determined from the engine load vs. fuel consumption diagram. When all of these steps are completed, the power balance for a given speed is done. Balance of power for different speeds, manoeuvring, cargo handling operations and other operational phases of the ship can be done in the same way.

The only relevant factor for defining a rated voltage of ship's main voltage electric network and switchgear equipment is short circuit current at full load when all the generators are connected to the network. Short circuit currents at low voltages (440 V, 220 V and 110 V) are not depending on the number of connected generators and remain constant regardless of the electric network configuration and voltage changes, due to the fact that the leakage reactance of transformers at those voltage levels are much higher than the reactance of the generators.

5 Balance of energy and energy price calculation

Balance of energy allows calculation of total energy that is used on a ship during certain exploitation cycle and is based on balance of power and exploitation profile. Exploitation cycle is theoretically any time period after which the exploitation profile repeats itself. This period is usually chosen to be one year or longer. It should include average share of individual operational phases of the ship, together with overhaul and dry docking phases.

The calculation of the balance of energy is obtained by multiplying power values from the balance of power P_i with the time spent in certain operational phase of the ship t_i according to the exploitation profile:

$$W_i = P_i t_i . \tag{15}$$

Total sums of output energy for each component W_i and all operational phases are used as inputs for the economic part of the optimization module, as it is shown in Figure 1.

$$W_{2/y} = \sum_i W_i . \tag{16}$$

The price of energy at a particular position in the system (Figure 3) is calculated by using the economic part of the optimization module and the economic influential factors.

The only prices that are important for optimization process are those at the key positions of the system (shown as circled in Figure 3). For each of these key positions in every individual balance of power, the total price of energy is calculated by multiplying specific price of energy with total energy consumption.

Finally, the average price of energy is calculated by using equation (1). By comparison of average energy prices for different system configurations, an optimal power system solution can be found.

6 Conclusion

Electrical propulsion has a major influence on total electric load and ship's power system configuration. The analysis of electrically propelled ships currently in operation has shown a total domination of integrated full electrical propulsion (IFEP) concept [8].

One of the main problems which obstruct development of IFEP systems is a completely passive role of shipping companies in the process of its development, which is left solely to the manufacturers of electrical equipment.

The optimization of electrical power system onboard an electrically propelled ship is a multidisciplinary project task which has to be led by the experts in marine transport technologies, with the necessary cooperation of shipbuilding and technologically oriented electro-technical experts.

The presented model of optimization allows isolation of electrical power system from other ship's systems and its appropriate evaluation using the relevant influential factors. The lowest average price of energy is a proper choice for the optimization criteria. It is calculated as an average price of energy at five key positions within the ship's system: thrust energy, energy of high voltage consumption, bow and stern thrusters energy, energy of low voltage consumption and energy consumed by the lighting system. All these energy prices are calculated based on ship's exploitation profile and include costs of investment, insurance, malfunctions, maintenance and ship's capacity loss.

Due to its modular structure, the presented model is relatively simple. The main problem is electro-technical part of the power system design, which includes proper dimensioning of electric devices, calculation of short circuit currents, and calculation of total harmonic distortion. These calculations require a large amount of precise data which are usually known only to manufacturers of the electrical equipment. For that reason it is more convenient and less expensive to choose one manufacturer and make it responsible for the whole electrical power system design. With this approach, the whole optimization model is simplified and reduced to the comparative analysis of complete designs from different manufacturers. There are only four manufacturers today that offer complete solutions for the podded electrical propulsion systems, so the total number of possible configurations is very limited and easy to compare.

The same optimization model can be used by shipping companies as an optimal solution for making the pre-design documentation of ship's electrical power system, which can be used during the negotiation phase with the shipyard. Model can be also extended and applied to the ships with mechanical power transmission and ships with combined propulsion, either to the entire power system, or only partially to the electrical power system. It is also very suitable for the evaluation of electrical power system when purchasing a second hand ship.

The presented model brings up many possibilities for further research. Thus, it can be used for the comparative analysis of existing ships with electrical and direct mechanical propulsion. Results of the analysis can provide valuable information for the selection of drive and electrical power system configuration, according to the exploitation profile, type and size of the ship. They can also give the guidelines for further technological development of electrical propulsion systems and their components, particularly electric motors and variable speed drives.

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