Energy Optimization of a Series Hybrid Electric Ship Propulsion System

Energetska optimizacija serijskog hibridnog električnog brodskog porivnog sustava

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Abstract

The electric ship propulsion system due to its economic advantages and, first of all, better mechanical properties than internal combustion engines (influence on ship manoeuvrability) have gained popularity in recent years. This paper presents an investigation of a series hybrid electric propulsion system where two sources of power are used: a permanent magnet synchronous generator and energy storage battery to supply electric propulsion system, which is a permanent magnet synchronous motor. Controlling the power flow from multiple power sources in a series hybrid mechatronic system is important to increase the energy efficiency of the propulsion system. Developing a suitable power flow control method is difficult due to the nonlinear nature of the power sources in the series system. In this paper a method of energy optimization of the system has been verified which allows to improve energy efficiency by reducing reactive power in the system. In this paper, an analytical study of the mechatronic system of a serial hybrid electric ship propulsion system is carried out based on the analysis of the steady-state electromagnetic and energy relations. The proposed control with energy optimization was compared with the commonly used FOC control. The analytical studies have been confirmed by performing simulation studies in Matlab-Simulink program. The proposed optimization method allows its use not only in ship electric drives but also in other autonomous electric drives using the series topology of the hybrid system.

KEY WORDS
series hybrid systems
energy optimization
control of the active converter
electric ship propulsion system

Sažetak

Brodski električni porivni sustav zbog svojih ekonomskih prednosti, nadasve boljih mehaničkih svojstava od motora s unutarnjih sagorijevanjem (utjecaj na manevarske sposobnosti broda), posljednjih je godina sve popularniji. U ovome radu prikazuje se istraživanje serijskog hibridnog električnog porivnog sustava, uz uporabu dvaju izvora snage: sinkroniziranog generatora sa stalnim magnetom i akumulatora za pohranu energije za napajanje električnog porivnog sustava, tj. sinkroniziranog motora sa stalnim magnetom. Za povećanje energetske učinkovitosti porivnog sustava važna je kontrola dotoka snage iz više izvora u serijskom hibridnom mehatroničkom sustavu. Teško je razviti odgovarajuću metodu kontrole dotoka snage jer izvori snage u serijskom sustavu nisu linearni. U ovome radu provjerava se metoda optimizacije energije ovoga sustava, što omogućuje poboljšanje energetske učinkovitosti smanjivanjem reaktivne snage u sustavu. Za potrebe ovoga rada provedena je analitička studija mehatroničkog sustava serijskog hibridnog električnog brodskog porivnog sustava na temelju analize stacionarnih elektromagnetskih i energetskih odnosa. Predložena kontrola uz optimizaciju energije uspoređuje se s FOC kontrolom koja se obično koristi. Analitičke studije potvrđene su izvođenjem simulacijskih studija u Matlab-Simulkin programu. Predložena optimizacijska metoda može se upotrijebiti ne samo na brodskim električnim porivima nego i na drugim autonomnim električnim porivima koji se koriste serijskom topologijom hibridnog sustava.

KLJUČNE RIJEČI
serijski hibridni sustavi
optimizacija energije
kontrola aktivnog konvertera
brodski električni porivni sustav

1. INTRODUCTION / *Uvod*

With new power electronics and electrical machine design technologies, diesel-electric ship propulsion has been gaining importance in recent years due to the ease of maneuverability. This is due to the favorable mechanical characteristics of the electric motor. Additionally, the lack of mechanical linkage between the power generation source and the propulsion shaft is advantageous [1]. An example of hybrid solution of such drives can be ships with two sources of electric energy for propulsion - Diesel -Generator and energy storage system [2 - 4].

Electric ship propulsion differs from the electric drives used in road transport. This is due primarily to the specific nature

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of the object, which is the ship. The load torque and propeller speed vary with sea conditions despite the use of sophisticated regulators. In marine conditions, in inclement weather, the ship's propeller rapidly emerges (the speed controller maintains a constant speed) and relieves the electric motor to then submerge and rapidly overload the electric motor. This can be considered the hardest (worst) impact on the system, which does not occur in road transportation. Therefore, if the control system responds correctly to rapid load changes (in the case of ship propulsion), it will respond correctly in road transport propulsion systems, where load changes are not so rapid. The second important feature that distinguishes ship electric propulsion from electric propulsion used in road transportation is power. The power of a ship's electric propulsion motor (for Permanent Magnet Synchronous Motor (PMSM) for technological reasons) can range from a few to a dozen MW, while the power of an electric motor in road transport is tens to hundreds of kW.

The difference between onshore and offshore power systems should also be noted. A characteristic feature of the marine electric power system, compared to onshore systems, is the small power of generating sets in relation to the power of consumers [5]. The marine electric power grid is a "soft" grid, while the onshore grid is a "rigid" grid

The popularity of electric drives in various means of transport (land, water or air) increases not only due to ecological reasons, but also because of its advantages over diesel-mechanical drive. The main advantages of the electric drive (also diesel-electric) are: reduced fuel costs, excellent torque and speed characteristics, (including fast dynamics), as well as reduced vibrations.

Examples of such systems are, in particular, mechatronic systems in autonomous electric transport. A universal solution that ensures all working conditions and improves the energy performance of transport systems is realized through the use of active semiconductor converters (ASC) [6, 7].

In the case of the emergency of new technologies, there are many different approaches to design hybrid systems for means of transport with electric drive. The article proposes an analysis of the system in a series hybrid design [2, 3, 8 -12] (Figure 1).

Electric machines used in the analyzed system are synchronous machines with permanent magnets (generator (PMSG) - Permanent Magnet Synchronous Generator and electric motor drive PMSM. The use of such machines results from the advantages of these machines – i. e. high efficiency, especially in the case of underload generator, mainly caused by the elimination of excitation losses, high operational reliability and simple construction due to the lack of windings on the rotor and the lack of exciter, high power density and low vibration level [7, 13].

Currently used converters using semiconductor elements (e.g., IGBTs) are not limited by high power since multilevel topologies can be commonly used [14].

The article presents mathematical models of subsystems and the applied ASC control strategy in order to optimize the energy performance of a hybrid mechatronic system.

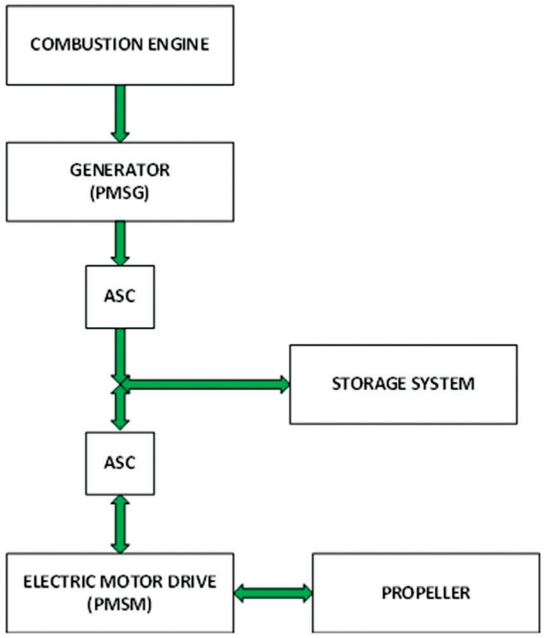

Figure 1 Typical Series Hybrid Architecture
Slika 1. Tipični serijski hibridni sustav

2. EQUIVALENT CIRCUIT OF THE SERIES HYBRID SYSTEM / *Ekvivalentni krug serijskog hibridnog sustava*

The structure of the vehicle Serial Hybrid Mechatronic System (SHMS), shown in Figure 1, includes two primary power sources. The first source includes the internal combustion engine (CE) with PSMG and ASC - i.e. active rectifier (AR) with active rectifier control system (ARCS). The second source is an electrical energy storage (batter with supercapacitor). An additional source is a PMSM with ASC, i.e. an active converter (AC) with ACCS (Active Converter Control System) when operating in generator mode. It enables the power to flow in both directions. A substitute scheme for the analysis of SHMS, is shown in Figure 2, where the following values are marked:

ω_{mg} - rotational speed of the PMSG shaft,
$\bar{E}_{GS}$ - EFM of PMSG,
$\bar{I}_{GS}$ - PMSG armature current,
$\bar{U}_{AR}$ - voltage on the AC side of the AR,
r_g, x_g - resistance and reactance of the PMSG,
P_{GS}, Q_{GS} - active and reactive power in the PMSG-AR system,
$\bar{I}_{D\_AR}$ - current in the AR – DC side,
ω_m - rotational speed of the PMSM synchronous shaft,
$\bar{E}_{EM}$ - EFM electromotive force of PMSM,
$\bar{I}_{EM}$ - PMSM armature current,
$\bar{U}_{AC}$ - alternating voltage (AC),
r_m, x_m - resistance and reactance of the PMSM,
P_{EM} - active power in the AC-PMSM system,
Q_{EM} - reactive power in the AC-PMSM system,
$\bar{I}_{D\_AC}$ - current in the AC – DC side,
P_{dc} - active power in the DC circuit.

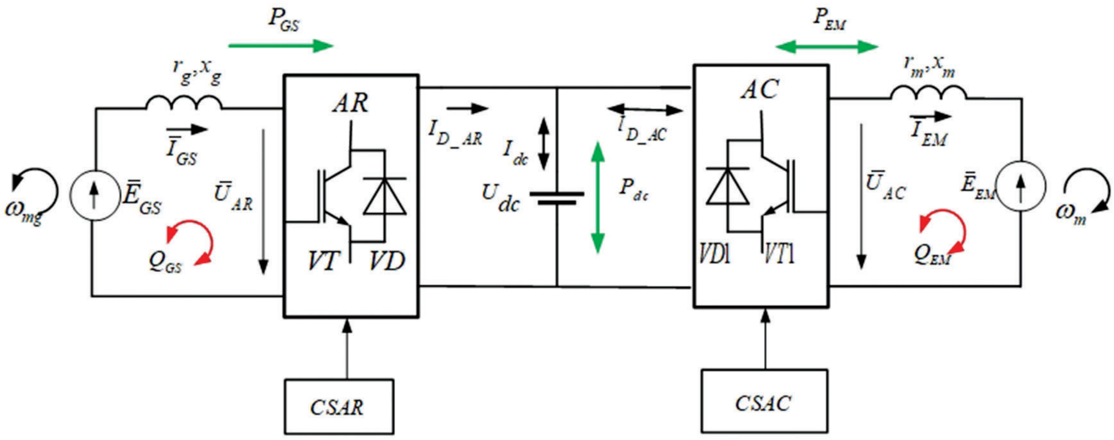

Figure 2 Equivalent Circuit of SHMS
Slika 2. Ekvivalentni krug SHMS-a

Only active power P_{dc} is transferred in the DC circuit. In AC circuits, there is an active power transfer P_{GS}, P_{EM} and reactive power circuit Q_{GS}, Q_{EM}. Active powers are rigidly coupled, and reactive powers depend on the method of controlling the AR and AC active converters. Reactive powers are decoupled and they can be controlled independently of each other.

Analytical and model studies of SHMS energy characteristics are performed based on the analysis of electromagnetic processes in quasi-stationary modes [15]. The electromagnetic processes in the system are studied using an equivalent circuit diagram (Figure 2), taking into account the theoretical ones developed [16-20].

3. MATHEMATICAL DESCRIPTION AND EXAMINATION OF THE SHMS SYSTEM / *Matematički opis i pregled SHMS sustava*

Analytical and simulation studies were verified using the Matlab-Simulnik application. The tests are performed for SHMS, where the parameters of machines are presented in Table 1.

3.1. Mathematical description of the PMSG-AR system of the SHMS electric drive / *Matematički opis PMSG-AR sustava SHMS električnog poriva*

In the considered substitute scheme (Figure 2), on the AC side of the AR, the voltage source is connected in series with the EFM PMSG through the stator windings of the PMSG $\bar{U}_{AR}$.

The mathematical description of the PMSG-AR generating set of the SHMS system is carried out in a coordinate system rotating synchronously with the generator rotor using the method [20] and the fundamental harmonic method [19]. This mathematical description takes the following form:

$$\bar{E}_{GS}(t) = \bar{U}_{AR}(t) + L_g \frac{d\bar{I}_{GS}(t)}{dt} + r_g \bar{I}_{GS}(t) + jx_g \bar{I}_{GS}(t). \quad (1)$$

where:

$\bar{E}_{GS} = p\omega_{mg}\psi_0 = \omega\psi_0$ - spatial vector of EMF voltages on the stator's windings of the PMSG,

$\omega = p\omega_{mg}$ - angular frequency of AR voltage,

p – number of pole pairs.

Investigation of this system requires the use of vector diagrams to study energy properties of the "PMSG-AR" system. When constructing the vector diagram according to equation (1), it should be taken into account that the AR is controlled by the rotor position sensor (RPS). Therefore, electromagnetic processes in the generator are rigidly related to the rotational coordinates (*d*, *q*), which (in turn) are determined by the generator's structure. In this case, the flux vector coincides with the RPS null state and is oriented in the longitudinal axis (*d*) of the coordinate system rotating at synchronous speed. Simultaneously, the EMF of rotation ($\bar{E}_{GS} = j\bar{\varphi}_0 p\omega_m$) is 90 degrees ahead of flux $\bar{\varphi}_0$ and it will be directed along the imaginary (transverse) axis - *q*. Electromagnetic processes in the AC circuit (AR), related to the voltage and current of the active rectifier, are considered in the rotational *x*, *y* coordinate system, which (in general) do not coincide with the *d*, *q* axis. In the rotational coordinate system (*d* is the real axis) and (*q* is the imaginary axis), when the real axis is set in line with the machine's excitation flux vector, equation (1) - in the *d, q* axes - takes the following form:

Table 1 Parameters of Machines
Tablica 1. Parametri strojeva

parameter	Nominal torque for continuous operation	Nominal speed	Armature winding resistance	Inductance of the armature winding	EMF	Number of pole pairs
unit	Nm	rad/s	Ω	H	Vs/rad	-
value	126	300	0.05	0.000635	0.192	4

$$0 = U_d(t) + L_g \frac{dI_d(t)}{dt} + r_g I_d(t) - x_g I_q(t),$$
$$E_{GS} = U_q(t) + L_g \frac{dI_q(t)}{dt} + r_g I_q(t) + x_g I_d(t). \quad (2)$$

In the steady-state, the vector system of equations (1) is converted to the form:

$$\bar{E}_{GS} = \bar{U}_{AR}(t) + r_g \bar{I}_{GS} + jx_g \bar{I}_{GS} \quad (3)$$

The scalar system of equations (2) in the steady-state is presented as:

$$0 = U_d + r_g I_d - x_g I_q,$$
$$E_{GS} = U_q + r_g I_q + x_g I_d. \quad (4)$$

Vector diagrams constructed using equation (3) are presented in Fig. 3a,b for two methods of controlling the active rectifier. In the first method, the active rectifier is controlled only along one (transverse) q axis. This control method is often referred to in the literature as field-oriented control (FOC) by analogy to asynchronous control systems. The vector diagram for this control method is presented in Fig. 3a In the second method that has been described in detail and analyzed, control signals are set appropriately to ensure that there is a zero reactive current in the active rectifier. This method is called the optimal method, and the vector diagram corresponding to the optimal control method is presented in Figure 3b.

3.2. Energy characteristics of the PMSG-AR system of the SHMS with FOC control / *Energetske karakteristike PMSG-AR sustava SHMS-a s FOC kontrolom*

AR current control with FOC control, when $I_d^* = 0,\ I_q^* = I_{GS}^*$ the electromagnetic and energy characteristics of the PMSG-AR r set are calculated from equations (5):

$$U_d = x_g I_{GS}^*,$$
$$U_q = E_{GS} - r_g I_{GS}^*,$$
$$P_{GS} = 1.5 U_q I_{GS}^*,$$
$$Q_{GS} = -1.5 U_d I_{GS}^*. \quad (5)$$

Equations (5) at a given speed of rotation of the generator (ω_{mg}), the known parameters of the generator (r_g, x_g) are solvable and allow to calculate the energy characteristics of the "PMSG-AR" system at a given current and speed.

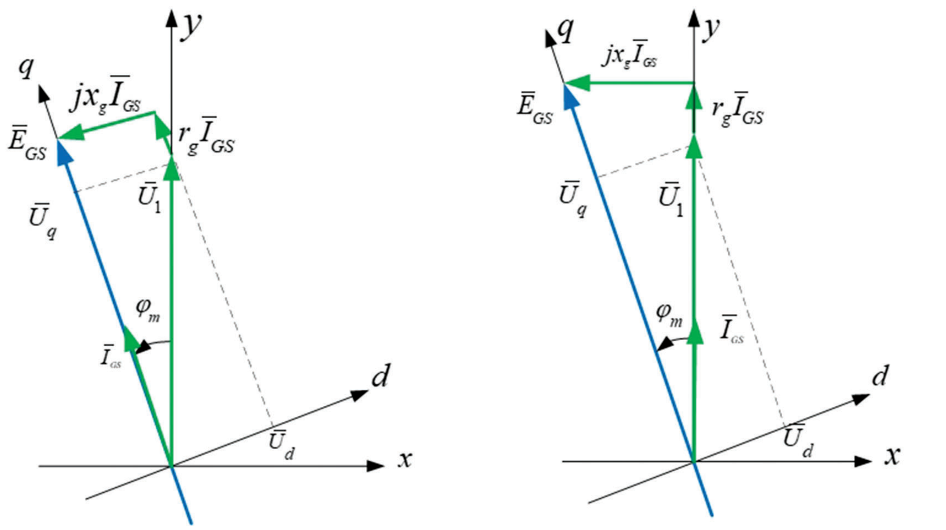

Figure 3 SHMS vector diagrams with different control methods in the PMSG-AR system, a – FOC, b – optimal control
Slika 3. SHMS vektorski dijagrami s različitim metodama kontrole u PMSG-AR sustavu, a – FOC, b- optimalna kontrola

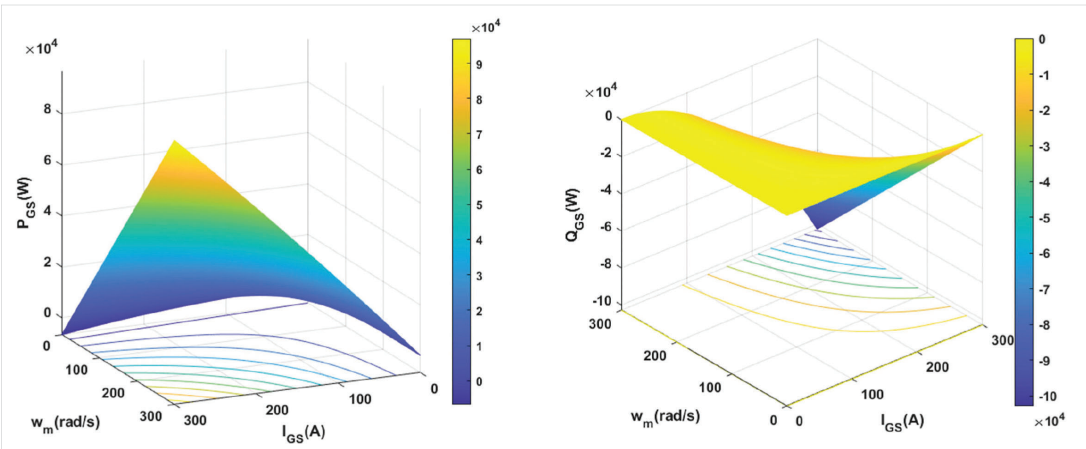

Figure 4 Energy characteristics (P_{GS}, Q_{GS}) of the PMSG-AR system of the SHMS with FOC control
Slika 4. Energetske karakteristike (P_{GS}, Q_{GS}) PMSG-AR sustava SHMS-a s FOC kontrolom

The calculated energy characteristics of the system in spatial coordinates under FOC control are shown in Fig. 4, from which it follows:

- The active power in the GMHSTS electric drive under FOC control grows in proportion to the increase in control current and rotation speed of the generator shaft,
- The reactive power in the GMHSTS electric drive under FOC control grows in proportion to the speed of rotation of the generator shaft and approximately parabolically depends on the current,
- The reactive power in the electric drive of SMHSD at FOC control has a commensurate with the active power.

3.3. Energy characteristics of the PMSG-AR system of the SHMS with optimal control / *Energetske karakteristike PMSG-AR sustava SHMS-a s optimalnom kontrolom*

If the current control is used in the AR, the PMSG-AR system, by controlling by coordinate *q* and *d*, can maintain zero reactive power while changing speed and setpoint current.

This mode of operation of the genset is called the optimum mode of operation. The vector diagram for the optimal mode of operation is shown in Fig. 3b. The power characteristics of the GMSTS generator set at the optimal current control are calculated using the geometric relations of the vector diagram.

From the second equation of the system of equations (6) it follows that to ensure the optimal mode of the PMSG-AR generator set, the control currents along axes *d* and *q* non-linearly depend on the set current.

$$\begin{aligned}
&\varphi_m = \arcsin\left(\frac{x_g I_{GS}^*}{E_{GS}}\right),\\
&I_d^* = I_{GS}^* \sin\varphi_m,\ I_q^* = I_{GS}^* \cos\varphi_m,\\
&U_{AG} = E_{GS}\cos\varphi_m - r_g I_{GS}^*,\\
&U_d = U_{AG}\sin\varphi_m,\ U_q = U_{AG}\cos\varphi_m,\\
&P_{EM} = P_{dc} = 1.5(U_d I_d^* + U_q I_q^*),\\
&Q_{EM} = 1.5(U_q I_d^* - U_d I_q^*).
\end{aligned} \tag{6}$$

The energy characteristics of the PMSG-AR electric SHMS drive with optimal control are shown in Fig.5.

The calculated and constructed energy characteristics of the system in spatial coordinates under optimum control are shown in Fig. 5, from which it follows:

- Under optimal current control of the PMSG-AR, the active electromagnetic power increases with increasing speed. As the current increases, the active power first increases and then decreases. This feature allows you to choose the optimal rotation speed of the generator itself. Such mode of operation is called Maximum Power Point Tracking. For a machine with the parameters given in Table 1, this mode is shown in Fig. 5, it corresponds to a speed of 300 rad/s and a current of about 203 A.
- The reactive electrical power in a system with optimum current control is zero at all speeds and currents.

3.4. Mathematical description of the AC-PMSM system of the SHMS electric drive / *Matematički opis AC-PMSM sustava SHMS električnog poriva*

In the rotating coordinate system, the electromagnetic processes occurring in the SHMS drive are described by the following equation:

$$\overline{U}_{AC} = \overline{E}_{EM}(t) + L_m \frac{d\overline{I}_{EM}(t)}{dt} + r_m \overline{I}_{EM}(t) + jx_m \overline{I}_{EM}(t) \tag{7}$$

In the coordinate system (*d* is the real axis and *q* is the imaginary axis), when the real axis is aligned with the PMSM excitation flux vector, the equation $\overline{\varphi}_0$ (7) transforms into a system of scalar equations:

$$\begin{aligned}
&U_d(t) = L_m \frac{dI_d(t)}{dt} + r_m I_d(t) - x_m I_q(t),\\
&U_q(t) = E_{EM} + L_m \frac{dI_q(t)}{dt} + r_m I_q(t) + x_m I_d(t).
\end{aligned} \tag{8}$$

The equations of electromagnetic processes in the steady-state result form (7, 8) and are indicated in the form:

$$\overline{U}_{AC} = \overline{E}_{EM} + r_m \overline{I}_{EM}(t) + jx_m \overline{I}_{EM} \tag{9}$$

$$\begin{aligned}
&U_d = r_m I_d - x_m I_q,\\
&U_q = E_{EM} + r_g I_q + x_g I_d.
\end{aligned} \tag{10}$$

Vector diagrams constructed using equation (9) are shown in Fig. 6 a, b for the FOC methods and optimal control of the active converter. The vector diagram for FOC is presented in Fig. 6, a. In the case of the optimal control method, the vector diagram is presented in Fig. 6, b.

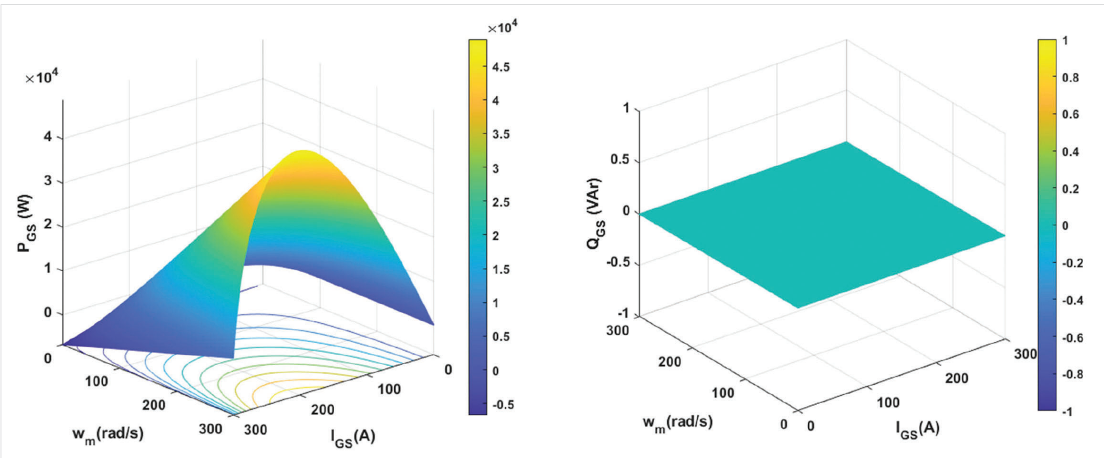

Figure 5 Energy characteristics (P_{GS}, Q_{GS}) of the PMSG-AR system of the SHMS with optimal control

Slika 5. Energetske karakteristike (P_{GS}, Q_{GS}) PMSG-AR sustava SHMS-a s optimalnom kontrolom

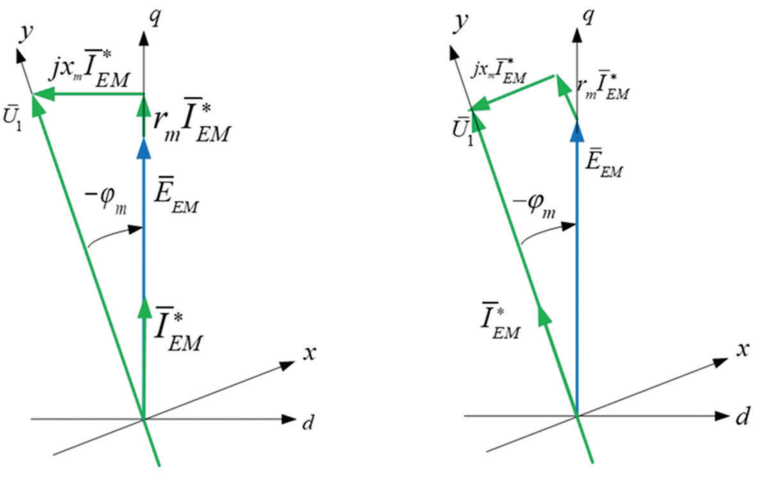

Figure 6 SHMS vector diagrams with different control methods in the AC-PMSM system, a – FOC, b – optimal control
Slika 6. SHMS vektorski dijagram s različitim kontrolnim metodama u AC-PMSM sustavu, a – FOC, b – optimalna kontrola

The vector diagram for the optimal mode of operation of the electric drive is shown in Fig. 6, b. From the geometrical relations of the vector diagram we can determine the longitudinal and transverse components of currents, at which the reactive power in the "PMSM-AC" system is maintained equal to zero. Calculation of power characteristics of electric drive at optimum control is carried out according to equations obtained from geometrical relations of the vector diagram.

3.5. Energy characteristics of the PMSM-AC system of the SHMS with FOC control / *Energetske karakteristike PMSM-AC sustava SHMS-a s FOC kontrolom*

The energy characteristics of a PMSM-AC electric drive with FOC control are calculated using equations (10) at a given motor control current of the electric drive $I_d^* = 0, I_q^* = I_{EM}^*$.

$$\begin{aligned} &U_d = -x_m I_{EM}^*, U_q = E_{EM} + r_m I_{EM}^*, \\ &P_{EM} = 1.5\left(U_d I_d^* + U_q I_q^*\right) = 1.5 U_q I_q^*, \\ &Q_{EM} = 1.5(U_q I_d^* - U_d I_q^*) = 1.5 U_d I_q^*. \end{aligned} \qquad (11)$$

The calculated and constructed energy characteristics of the system in spatial coordinates under FOC control are shown in Fig. 7, from which it follows:

- The active power in the SHMS electric drive under FOC control grows in proportion to the increase in control current and rotation speed of the generator shaft;
- The reactive power in the SHMS electric drive under FOC control grows in proportion to the speed of rotation of the generator shaft and approximately parabolically depends on the current;
- The reactive power in the electric drive of SHMS at FOC control has a commensurate with the active power.

3.6. Energy characteristics of the PMSM-AC system of the SHMS with optimal control / *Energetske karakteristike PMSM-AC sustava SHMS-a s optimalnom kontrolom*

The vector diagram for the optimal mode of operation of the electric drive is shown in Fig. 6, b. From the geometrical relations of the vector diagram we can determine the longitudinal and transverse components of currents, at which the reactive power in the «PMSM-AC» system is maintained equal to zero. Calculation of power characteristics of the electric drive at optimum control is carried out according to equations obtained from geometrical relations of the vector diagram.

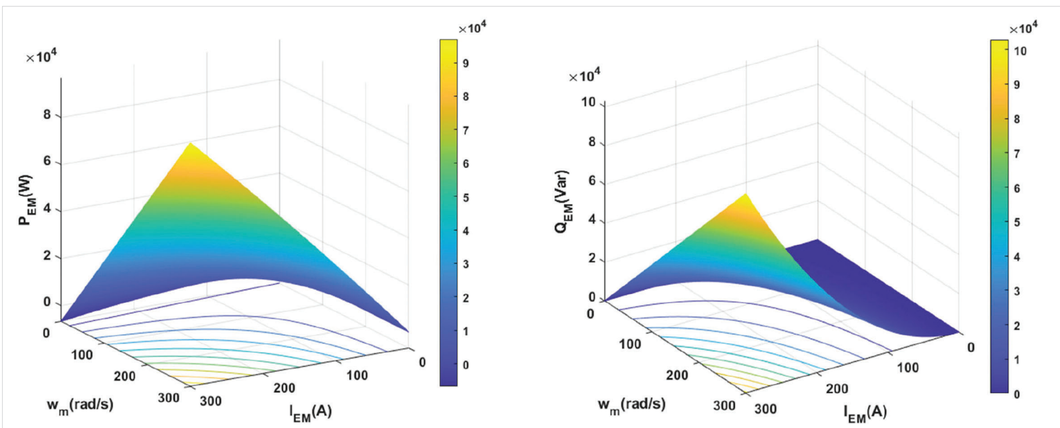

Figure 7 Energy characteristics (P_{EM}, Q_{EM}) of the PMSM-AC system of the SHMS with FOC control
Slika 7. Energetske karakteristike (P_{EM}, Q_{EM}) PMSG-AR sustava SHMS-a s FOC kontrolom

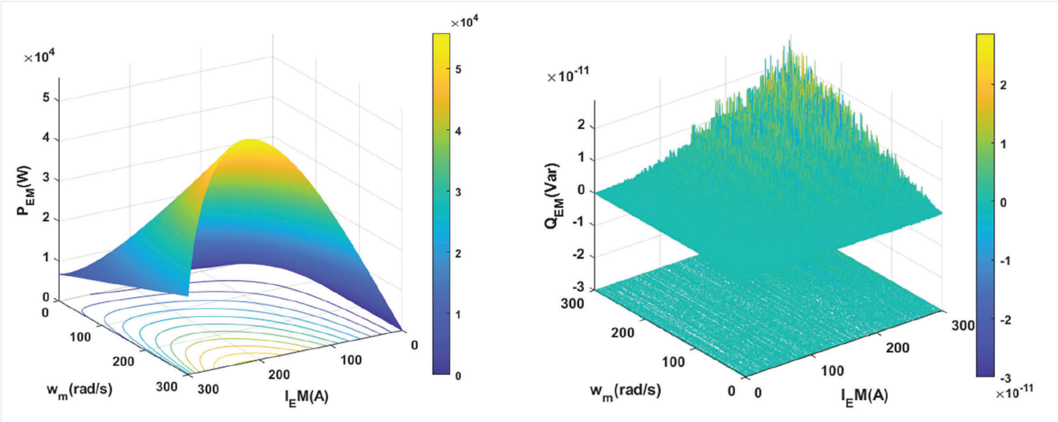

Figure 8 Energy characteristics (P_{EM}, Q_{EM}) of the PMSM-AC system of the SHMS with optimal control
Slika 8. Energetske karakteristike (P_{EM}, Q_{EM}) PMSG-AR sustava SHMS-a s FOC kontrolom

$$
\begin{aligned}
&\varphi_m = \arcsin\frac{x_m I^*_{EM}}{E_{EM}},\\
&I^*_d = -I^*_{EM}\sin\varphi_m, I^*_q = I^*_{EM}\cos\varphi_m,\\
&U_d = r_m I^*_d - x_m I^*_q, U_q = E_{EM} + r_m I^*_q + x_m I^*_d,\\
&P_{EM} = 1.5\left(U_d I^*_d + U_q I^*_q\right),\\
&Q_{EM} = 1.5(U_q I^*_d - U_d I^*_q).
\end{aligned}
\qquad (12)
$$

Calculated by equations (12) and plotted energy characteristics of the electric drive in spatial coordinates under optimum control are shown in Fig. 8, from which it follows:

- Under optimum control of electric drive of PMSM-AC the active electromagnetic power grows with the increase of speed. As the current increases, the active power first increases and then decreases. Such a characteristic in a closed-loop electric drive leads to non-linear self-oscillations at current (torque) corresponding to the supply section of the characteristic. This requires the drive control system to introduce a limitation at the input of the current relay regulator.
- Reactive power in the system with optimum control is equal to zero at any speeds and currents.

4. MODEL EXAMINATION OF SHMS / *Provjere modela SHMS*

The SHMS model examinations were carried out for the generating set and the electric drive with FOC and optimal control.

SHMS model (Figure 9) includes:

- The electric drive containing the ACCS control system Active Converter and AC-PMSM power part;
- The Generator set contains Control System Active Rectifier and PMSM-AR power part .

This model enables to test quasi-steady and quasi-dynamic electromagnetic and energy processes in SHMS.

The current and rotational speeds of the SHMS generator set are shaped by the Control block. The current of the PMSM drive is formed on the output of the PI controller, the set signal of which is the set rotational speed.

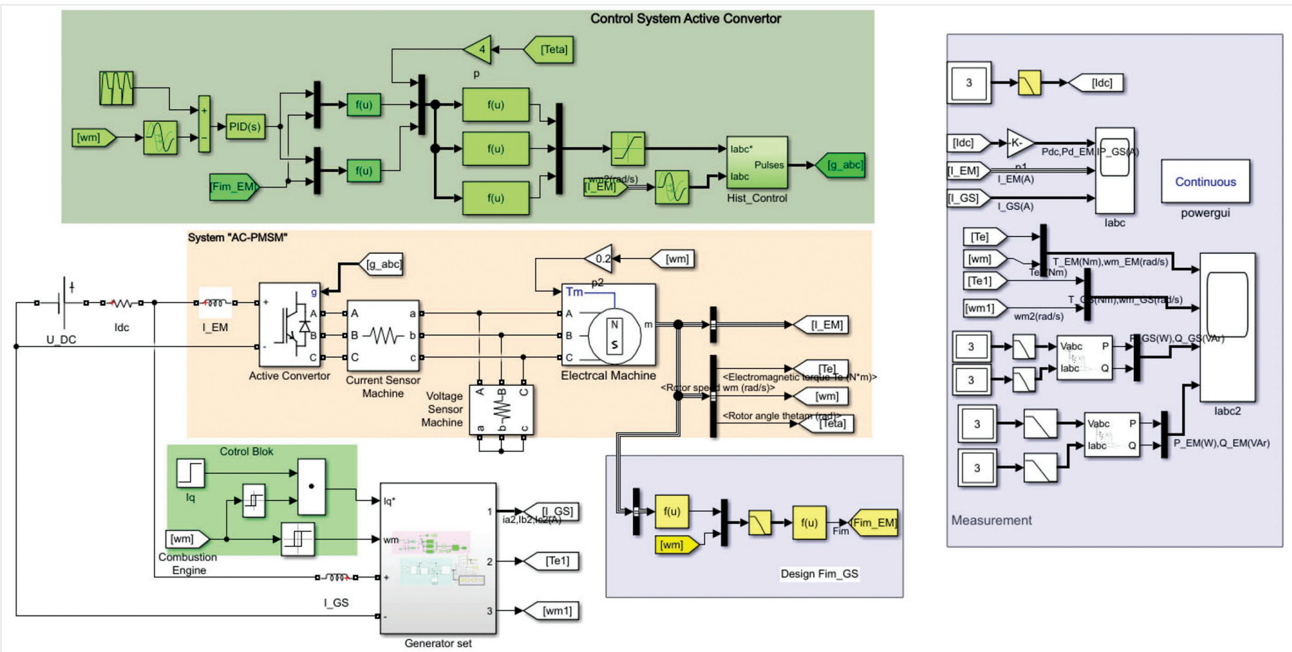

Figure 9 Virtual model in the SHMS system
Slika 9. Virtualni model SHMS sustava

Hist Control blocks are relay regulators that control the current in PMSG-AR and PMSM-AC systems.

Electromagnetic and energy processes in the hybrid mechatronic system of the electric drive were simulated in the following operating modes:

1. When starting the electric drive with current (torque) limitation, when the object is moving, and the PMSG is not working.
2. At a constant speed of the object and constant speed of the combustion engine.
3. At a constant speed of the object and constant rotational speed of the combustion engine
4. During deceleration of an object and then driving at a slower speed.

Switching between the modes mentioned above takes place in a step-by-step manner. This enables the observation of transition states in SHMS. Modeling in SHMS was carried out in a system with the FOC control and optimal control – both in the generator set and in the electric drive.

SHMS electromagnetic and energy processes (Figures 10, 11) are presented with the use of the following oscillograms:

- Torque and rotational speed of the drive motor ($T_{EM}(Nm), \omega_{m\_EM}(rad/s)$);
- Torque and rotational speed of the generator ($T_{GS}(Nm), \omega_{m\_GS}(rad/s)$);
- Active and reactive power of the converter ($P_{EM}(W), Q_{EM}(VAr)$);
- Active and reactive power of the generating set ($P_{GS}(W), Q_{GS}(VAr)$);
- Battery power supply ($P_{dc}(W)$);
- power supply in the drive's DC circuit ($P_{d\_EM}(W)$);
- power supply in the generator's DC circuit ($P_{d\_GS}(W)$);
- Phase currents of the electric motor ($I_{EM}(A)$);
- Phase currents of the generator $I_{GS}(A)$.

The torque on the drive motor's shaft is set proportionally to the rotational speed (proportionally to the object's speed).

The independent variable in oscillograms is the relative time $t(pu) = \omega_b t, \omega_b = 314(rad/s)$.

Figure 10 presents the complied oscillograms for FOC both in the drive and in the generator set.

In the first operating mode $t(pu) = 0 - 0.02pu$, the drive power is covered by the power (current) consumed only from the battery.

In the second and fourth operating modes, the generator supplies both the drive and the battery.

When decelerating $(t(pu) = 0.04 - 0.06pu)$, in the third operating mode, the generator and the drive supply energy to the battery.

Active and reactive powers in this control method are comparable in the generator set. The electric drive at all speeds and torques operates in modes close to optimum due to the presence of speed feedback.

Figure 11 presents electromagnetic and energy processes in SHMS with optimal control of both the generator set and the electric drive. By comparing Fig. 10 and Fig. 11, we can observe that the reactive power under optimal control (in both units) is equal to zero.

At time t = 0.02 (pu), the propulsion engine reaches nominal speed at nominal load (the ship's propeller is underwater). At time t = 0.04 (pu), the speed and load are reduced (the ship's propeller is overwater). The energy is returned to the accumulator. From the moment t = 0.06 (pu) the speed of the main propulsion engine and the load is lower than the

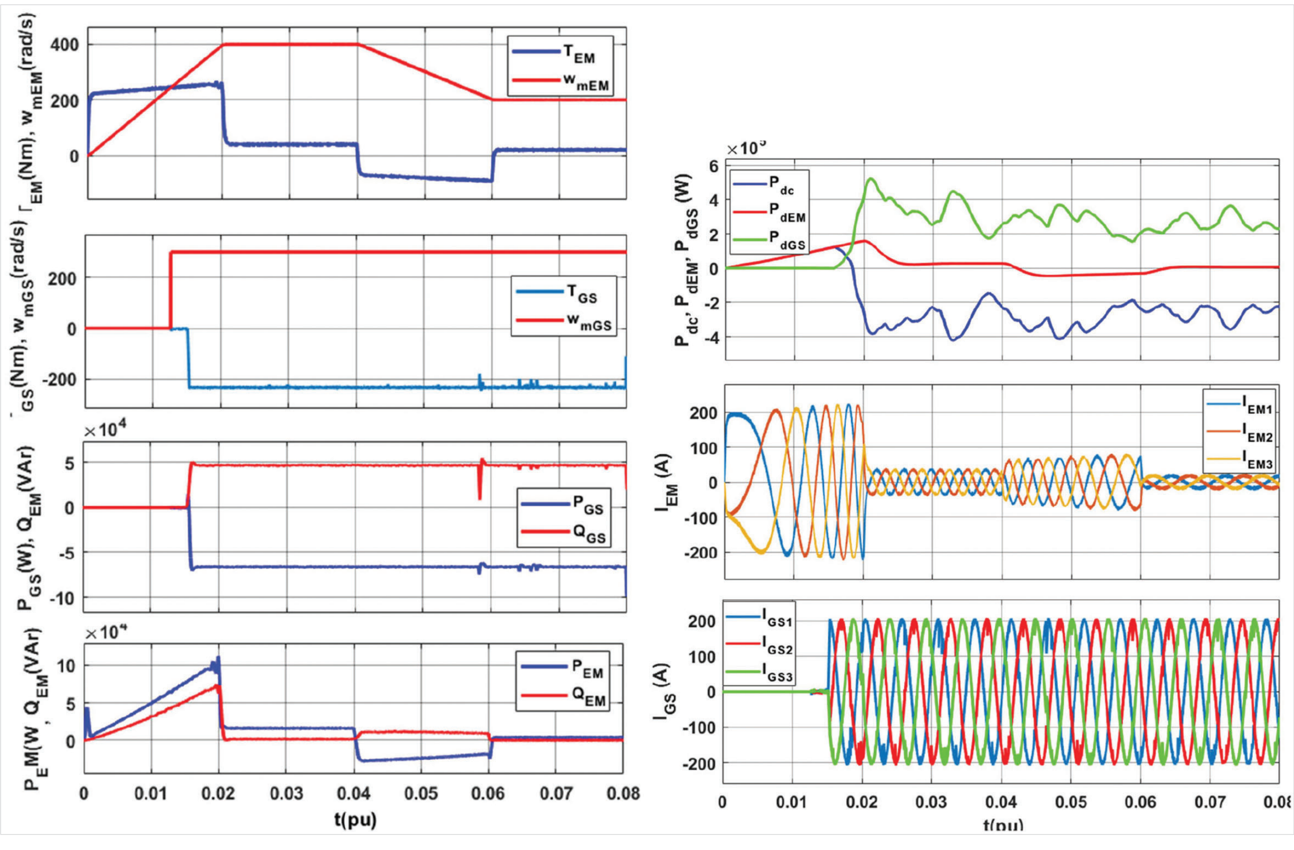

Figure 10 Energy and Electromagnetic processes in SHMS with FOC

Slika 10. Energetski i elektromagnetski procesi u SHMS s FOC-om

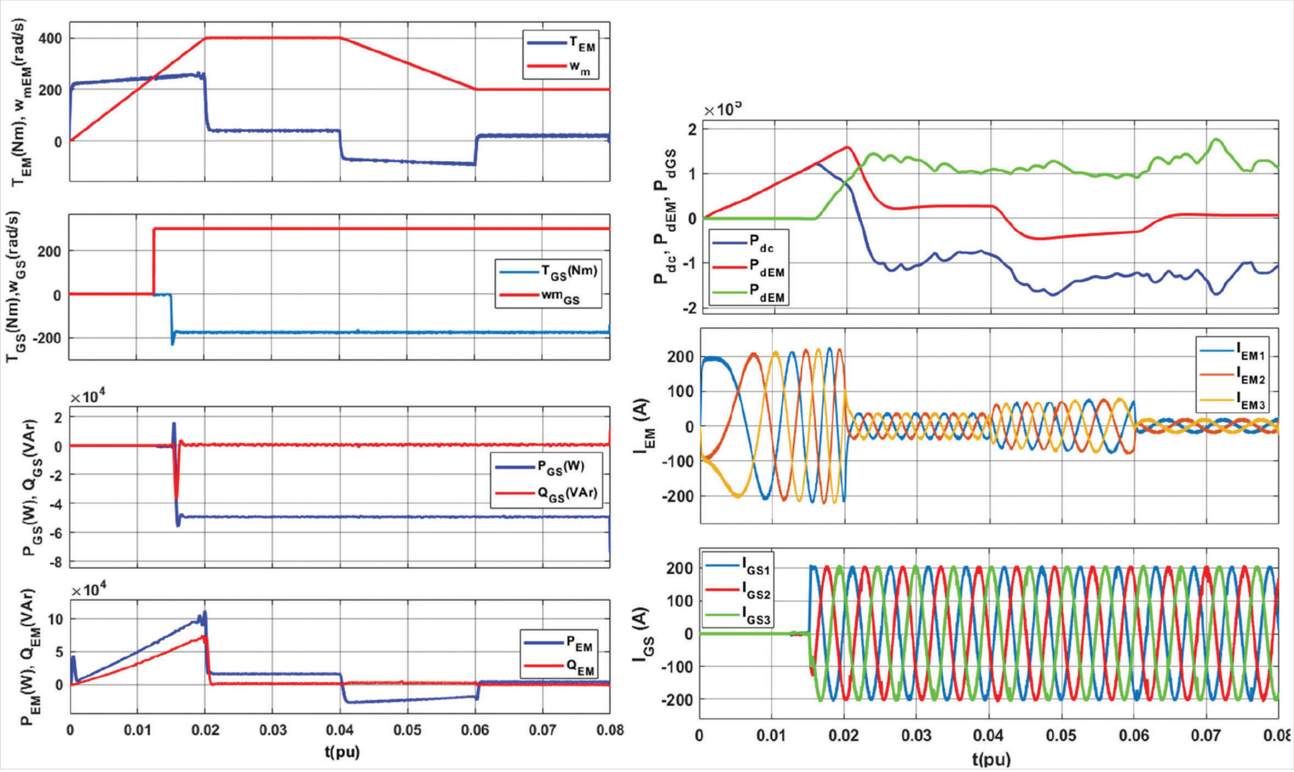

Figure 11 Energy and Electromagnetic processes in SHMS with optimal control
Slika 11. Energetski i elektromagnetski procesi u SHMS s optimalnom kontrolom

nominal one (the propeller of the ship propulsion is above the water surface). Diesel-Generator set is working (after start-up) with constant speed and load giving the same active power both at control with optimization (Fig.11.) and without energy optimization (Fig.10.).

In a series hybrid mechatronic system with selected parameters of electric machines, a significant improvement of the energy performance is achieved by optimizing mainly the generator set.

5. CONCLUSION / *Zaključak*

A great challenge for the shipping industry is environmental protection. IMO has set requirements for energy efficiency by introducing the Energy Efficiency Design Index [21]. Meeting the high rigor due to the increase of energy efficiency is associated, among others, with the reduction of losses in ship systems is. The method of eliminating reactive power in the electric propulsion system proposed in this paper increases efficiency by reducing losses in the power supply cables, applied to the electrical machine systems and power electronic systems of the propulsion system.

Power semiconductor converters in intelligent systems and networks (Smart Grid) enable to build separate current sources (slave mode) and connect them in parallel with one voltage source (master mode), thus eliminating processes of exchangeable oscillation between these sources. In the analyzed series hybrid mechatronic system, the battery acts as a voltage source for the electric drive. The PMSM electric motor has a speed controller and the CE-PMSG generator set at the input. They act as regulated power sources with a power connection for one-way (for the generator) and two-way (for electric motor) power connection.

The virtual model prepared and presented in the article enables to study all possible cases of power redistribution of two electric power sources (PMSG, energy storage battery) and, in addition, PMSM operation in generator mode - both in steady-state and transient states. For SHMS with selected parameters of electric machines, a significant improvement in energy performance is achieved by optimizing the generator set – both via the selection of the optimal rotational speed of the generator and the optimal control of the active converter. In the SHMS electric drive part, it is important to exclude non-linear oscillations. This is ensured by the selection of the current limit value in the control system. The reactive power in the machine-converter systems (AR-PMSG and AC-PMSM) has been (practically) limited to zero. Therefore, the loss current in transmission lines has been reduced.

By comparing the energy and electromagnetic characteristics of the propulsion control with energy optimization (Fig.11.) and without optimization (Fig.10.), it can be concluded that the proposed control did not deteriorate the mechanical and exploitation properties of the ship's propulsion.

The control method of the hybrid drive system proposed in this paper based on the analysis of the fundamental harmonic of currents and voltages allowed for energy optimization (reduction of reactive power in the system to zero) in the steady-state. This method does not provide energy conversion control in transients. The authors are currently working on a control synthesis for a hybrid drive system that will provide transient optimization while providing energy optimization in static states of system operation.

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