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Multicriteria strategy of power managing system for ships power plants for combined propulsion complexes

Vitalii Budashko
National University "Odessa Maritime Academy", Odessa, Ukraine,

Abstract: *Increasing the efficiency of hybrid ship propulsion complexes (CPC) according to various criteria of energy management strategies.On the basis of classification of topologies of circuitry solutions of ship power plants (SPP) of the CPC, for mechanical, electric and hybrid types of engines, the flowchart of control strategies for the criterion of minimum energy consumption is defined. The change in the technical component of the traditional approach to the construction of hybrid CPC's power systems applies the principle of modifying the structure of the SPP with the integration of an additional static power supply as the dynamic reserve, which has allowed meeting the current energy efficiency requirements, vibration levels, noise and degradation effects produced for the SPP CPC in all energy fields for energy transfer to propellers. The simulation of energy transfer to propellers in MatLab/Simulink is carried out using optimization blocks and identifying markers. The result is to identify the main advantages and disadvantages of SPP CPC depending on the topology of energy distribution systems. In accordance with the chosen structure of the electricity distribution system, the principles of the transmission of electricity in the SPP of the CPC and energy systems and their management strategies in terms of improving efficiency and elimination of these shortcomings were obtained. Finally, the mathematical apparatus for researching energy transfer processes from the point of view of designing and managing the methods of designing and controlling the hybrid SPP of the CPC has been improved in order to reduce fuel consumption, emissions to the environment and increase the level of maintainability, flexibility and comfort. The originality of the proposed methodology is to improve the implementation of the SPP CPC by developing methods for identifying markers of degradation effects that affect the processes in the SPP CPC, and in implementing these methods in the calculation and information systems. The method involves the iterative optimization options of the SPP CPC; it can be used as an intellectual design tool, which is the result of the use of improved SPP CPC performance.*

Keywords: *ship power plants, combined propulsive complex degradation effects, effectiveness, functionality, decision support system.*

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I. Introduction

The development of the coastal shelf (the product of natural resources, the construction of wind and tidal power plants, pelagic fishing, etc.) involves the development of high-tech science-intensive sectors of the maritime industry, which involve the construction and operation of vessels for the provision of exploration, drilling, lifting and transport operations in various operating conditions (the so-called offshore fleet). Such vessels will be equipped with innovative combined propulsion complexes (CPCs) with ship power plants (SPPs), which are built on the principle of unified electric power systems [1, 2].

The problems of increasing energy efficiency caused by energy shortages and the desire to improve the environmental performance of the SPP CPC are underpinned by the requirements established by the International Maritime Organization in Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL) regarding the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Index (EEOI) within the framework of developing and implementing an energy management plan Ship Energy Efficiency Management Plan (SEEMP) in the process of improving the operation and operation of the vessel.

Thus, it is possible to formulate the actual scientific and technical problem in the field of transport, transport technologies and related infrastructure development: research, development and forecasting of methods for improving the operational characteristics of the SPP of the CPC, which would ensure the efficiency of their operation is impossible without establishing the regularities of changing parameters and introducing methods and means of diagnosing and predicting the technical state of the SPP of the CPC during operation [3, 4].

Hybrid SPP CPCs with alternative generating elements (AGE) that use the maximum efficiency of direct mechanical drive and the flexibility of combining the combustion power from the heat engine and the accumulated energy from the AGE are the most promising. At low power of a propulsion electric drive designed to bring the vessel in motion, propulsion electric motor (PEM) provides the necessary power, and excess power of the thermal engine can be used as the power supply of its own needs from the booster. The typical SPP CPC architectures are shown in [5]: Anchor Handling Vessel – Fig. B.1; Multipurpose Offshore Vessel – Fig. B.2; Anchor Handling and Offshore Construction Vessel – Fig. B.3, Fig. B.4; Rescue, Rescue and Guard Vessels – Fig. B.5; Offshore Construction Vessels – Fig. B.6; Fig. B.7; Oceanographic Research Vessels – Fig. B.8; Fisheries Research Vessel – Fig. B.9; Diesel-Electric Passenger Vessels – Fig. B.10; Fishing Trawlers – Fig. B.11; Fig. B.13; Pelagic Seiner/Pelagic Trawlers – Fig. B.12; Product/Chemical Tankers) – Fig. B.14; Fig. B.15; Twin Marine Lifter – Fig. B.16; Small Waterplane Area Twin Hull Technology – Fig. B.17; Cutter Suction Dredger – Fig. B.18; Seabed Logging Ship – Fig. B.19; Multifunctional Geotechnical & Soil Investigation Vessel – Fig. B.20; Offshore Subsea Construction Vessel – Fig. B.21; Multipurpose Field & ROV Support Vessel Multi-Purpose Vehicles (RV) – Fig. B.22; Cable Laying Cables – Fig. B.23; Seismic Research Vessel – Fig. B.24; LNG Car Ferry – Fig. B.25; Roll-on/Roll-off ships – Fig. B.26.

Effective distribution of capacities between AGE, battery storage power station (BSPS), SPP and other components of the SPP during the change of operating modes is possible due to the improvement of the strategy of controlling the hybrid SPP of the CPC on the criterion of minimum electricity consumption or by the criterion the maximum of obtaining alternative energy with the regulation of the charge level of batteries BSPS.

This can be accomplished by synthesizing a three-level multicriterion energy management strategy in the hybrid SPP CPC by integrating the classical power distribution control strategy with the medium speed diesel-generator (MSDG) control strategy and the AGE BSPS charge rate, which will differ from the existing higher efficiency of detecting the risk of deenergizing the SPPs, with greater reliability and the accuracy of determining the need for reducing the load and is fully integrated with the intrinsic regulators of the frequency of rotation of the thrusters and the power supply system. The purpose of the work is to develop the theory, methodology and technology in the field of increasing the efficiency of the functioning of SPP CPC.

In order to achieve the certain goal, it will be necessary to solve the problem of increasing the efficiency of hybrid SPP CPC by combining the criteria of power management systems strategies.

Depending on the type of CPC, one or another of the three known methods of its dynamic hold over the drill point is used. This, in turn, predetermines the use of the power management system (PMS). SPP CPC usually consists 6 ÷ 10 different types motors for THR, depending on the positioning on the vessel for positioning, which feed on 4 ÷ 6 high-voltage medium speed diesel-generator (MSDG).

MSDGs are distributed among the tires as the least two main switchboards (MSB) connected to each other by means of an integral switch. PMS functions are implemented in three independent control systems, namely, Dynamic Positioning (DP), DC drilling (DC), and Data Management Systems (DMS).

In such projects, the power management functions of each system operate independently and have special inputs for sensors from main electrical chain [5, 6].

Systems calculate the total power, depending on the total load. If the system total load exceeds certain limits set in advance, they decrease. The system will also reduce the load if the load on any individual MSDG will exceed the pre-set limit. Such a structure allows not to exceed the load on a separate MSDG even when the reciprocating power is affected by any MSDG or the failure of the sensor component.

At the present stage of technical maintains and operation of such systems are the following problems:

- compliance DP systems to the requirementsof Failure modes and effects analysis (FMEA), which are faced with the stage maintains and operation [7, 8];
- unification of PMS in the combination of functions in relation to other similar [9, 10];
- the independence of the components of the PMS from each other even to the level of sensors [11–13];
- not only the reduction of power in terms of the total estimated load, but also the load of the detached MSDG [14–16];
- compliance of the system with the conditions for increasing the load in terms of sufficiency to ensure normal work, depending on any abnormal regime and not overloading the SPP in general [17–21].

The development of strategies, methods and means for improving the efficiency of the SPP CPCs is limited to a substantial set of contradictory, conflict, and sometimes mutually exclusive factors and situations: the need to analyze the operation of the SPP CPC during exploration, drilling, hoisting and transport operations and loading different operating conditions; the need for analysis of processes at the intersections of energy flows in the SPP and the CPC with thrusters (THR) and the lack of methods for recording degradation effects that have a significant effect on these processes; the need to improve the methods of computational hydrodynamics for tracking degradation effects on propeller flow lines and the lack of physical models of registration components of the monitoring system for degradation effects on shaft line lines; the need for the synthesis of mathematical models of intrinsic regulators of the revolutions of the THR with simultaneous improvement of the mathematical apparatus in the modeling of energy processes in the SPP CPC in different operating modes;

formulation and association of criteria for choosing solutions based on the set of both SPP CPCs and operating modes in which they operate and the absence of formalized physical models of multifunctional SPCs taking into account situational environmental factors and identification factors of operating modes; the demand for power distribution management strategies in the SPP CPC and the lack of a methodology for the creation of mathematical models of ship automated power plants (SAPP) with multi-constructions, taking into account the hydrodynamic properties of the vessel with the ability to assess their impact on energy processes; the development of technology for the implementation of the decision support system (DSS) for the SPP CPC and the presence of intellectual, behavioral and cognitive limitations of the decision maker (DM).

Determination of criteria for applying energy management strategies

The control system (CS) of the SPP CPC distributes the power between the battery storage power station (BSPS), photovoltaic (PV) generation system (PVGS) and SPP according to the chosen energy management strategy:

- with state machine control strategy (SMCS);
- with classical PI control strategy and state-of-charge (SOC's) regulation of BSPS (CPICS);
- with frequency decoupling and state machine control strategy with SOC's regulation of BSPS (FDSMCS);
- with equivalent consumption minimization strategy (ECMS);
- with external energy maximization strategy with SOC's regulation of BSPS(EEMS).

The main purpose of BSPS as PVGS is shown in Figure 1 hybrid SPP CPC - commissioning of the SPP after exhaust and power support in maneuvering modes of the ship, one of which is DP mode. Depending on the chosen energy management strategy, the CS regulates the power of each power source in accordance with the given output voltage and maximum current of the BSPS, PVGS and power transducers (DC/DC converter, IN). Summary data on the analysis of advantages, disadvantages and criteria for the use of different types of SPP CPC are given in Table 1.

Table 1

Advantages, disadvantages and criteria of choice of engines and technologies of power supply SPP CPC

Technology	Advantages	Disadvantages and selection criteria
Electromechanical CPC	Low losses at rated power	Low efficiency with partial and peak loads
	Low emissions of CO_2 and NOx at rated power	High NOx emissions when reducing load
	Low energy conversion loss	Low reservation
		Increased noise level
		Overload of diesel engines
CPC	Overload Capacity	MSDG rotation speed constant
	Consistency of load with MSDG	Losses at rated power
	High visibility	The risk of constant instability of load capacity
	Reduced NOx emissions at low speeds Potentially low noise level	
Hybrid CPC	Low losses at rated power	MSDG rotation speed constant
	Overload Capacity	
	Matching load and PEM at low power	The complexity of the system
	Potentially low noise level PEM	
Hybrid CPC with AGE	Independence from the state of air	Limited power
	Reduction of emissions into the air	Insecurity
	High efficiency and low noise	Ability to upgrade
Hybrid SAPP	Independence from the state of air	Limited power
	Reduced emissions into the air and low noise	Insecurity
CPC with hybrid SAPP	Leveling the load	MSDG rotation speed constant
	Zero noise and harmful emissions	The complexity of the system
	Storage of regenerated energy	Danger of battery maintenance
	Backup power efficiency	The cost of the bats
	Possibility of switching on pulse power	The need to control the state of each of the bacteria
	Reduced fuel consumption and emissions into the atmosphere	Ability to disable batteries as a result of recharging
	No increase of NOx during load increase	Difficulty monitoring the status of batteries
CPC with hybrid SAPP DC	Variable speed of PEM and load	The complexity of the system
	Optimal load PEM	Cost and loss in power electronics
	Reduced noise and vibration of the engine	Increase NOx due to variable power
	Reduced fuel consumption and CO_2 emissions	Need to introduce energy saving with power reduction
	Possibility of switching on pulse power	Management complexity

The disadvantages of the given functional diagram of the hybrid SPP CPC are:
- inconsistency of MSDG parameters with other components, which leads to uneven regulation of magnetic fluxes and voltage amplitudes, which causes an additional increase in voltage pulsations at the output of converters and the emergence of equalizing currents in synchronous operation;
- elevated level of harmonics in the current of consumers of energy;
- reduced reliability, efficiency, increased dimensions and mass, which arise due to the use of elements of increased power and equipment kits to them;
- the lack of the possibility of balancing the three-phase system of supply voltage with uneven loading of the phases.

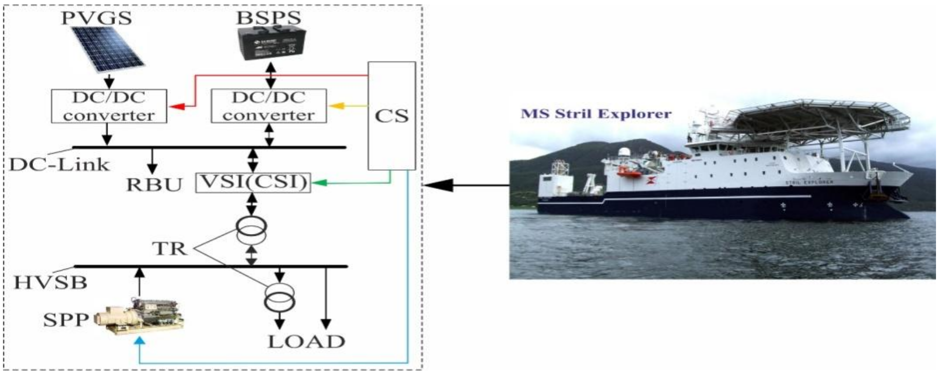

Figure 1 Structural functional diagram of hybrid SPP CPC: PVGS – photovoltaic (PV) generation system; BSPS – battery storage power station; CS – control system of the SPP CPC; RBU – resistor back unit; VSI – voltage source inverter or CSI – current source inverter; HVSB – high voltage switchboard; SPP – ships power plant with medium speed engine (MSDG); TR – voltage transformers; LOAD – to consumers of AC, in particular –propulsion electric motor (PEM), thrusters – (THR), low voltage switchboard (LVSB).

Analysis of Figure 1 allows us to conclude that the control of the hybrid SPP CPC is a very complicated process that requires consideration of the many quantity of factors of power and operational components. For example, a component of the hybrid SPP CPC, like BSPS, is based on the use of lithium-ion batteries (LIB) [22].

The variety of modes of the SPP CPC in the application of LIB determines not only the large range of manufactured capacities and standard sizes of batteries, but also wide ranges of voltages (from seven to several hundred volts) of batteries on their basis, necessary for the implementation of certain powerful, power and performance characteristics of BSPS [23, 24].

In the presence of dangerous external influences on BSPS, their constructive execution is complicated, as well as in the case of powerful batteries (especially for hybrid SPP CPCs), which require additional air or liquid cooling [25]. On Figure 2 is the structural functional diagram of the hybrid SPP CPC with fragmentation of BSPS.

When designing hybrid SPP CPC, the general requirements for all LIB are to ensure the safety and convenience of operation, as well as the achievement of the full discharge of all battery, in cyclic mode, rather than work on the schedule of the weakest element. This is achieved by introducing into the BSPS of the Battery Management System (BMS) of battery modular assemblies (BMA), which monitors the state and protects the battery from the occurrence of hazardous operating modes and provides information on its basic parameters [26-28].

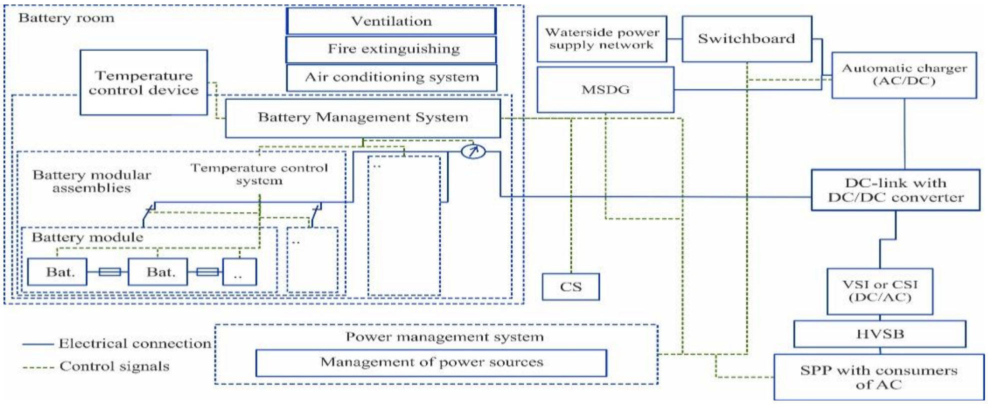

Figure 2. Structural functional diagram of hybrid SPP CPC with fragmentation of BSPS

Given the high power and high energy reserve, as well as the fire hazard used in LIB electrolyte, the main task of CS of battery modular assemblies can be considered the protection of battery in the event of hazardous operating modes. These include, above all, current overloads and short circuits of power circuits, overheating of battery, recharging and excessive discharge of LIB.

Protection against the occurrence of hazardous operating modes is carried out by leveling the imbalance of LIB stresses and the formation of control signals for changing the operating mode of external devices or for switching off the battery from external power circuits with the help of switching equipment, which is constructively placed both within and outside battery [29, 30]. Taking into account the foregoing, one can conclude that the development of the SPP CPC requires additional research in the field of improving the energy processes associated with the use of alternative energy sources in the SPP CPC. The latter require the development of modern local CS from the point of view of their integration into the CS of hybrid SPP CPC.

To protect the BSPS from overcharging and overloading, the local CS measure the voltage of each element in LIB. In this case, the measuring circuits of all batteries must be galvanically solved and designed for operation at a voltage corresponding to the maximum voltage of BSPS (Figure 2). For most applications, the accuracy of measuring the voltage of LIB should be no worse than ± 20 mV. When shaping the CS on the level of LIB voltage must take into account the voltage drop on their internal resistance and temperature.

Elemental temperature control of LIB is also required to protect the BSPS from overheating. Recently, for these purposes, temperature sensors with digital or analogue output are often used, relatively easy to use, providing accuracy of ±(1÷2)°C. Thermoresistors or thermocouples continue to be used for a number of special applications related to the operation of BSPS under extreme conditions or with restrictions on the use of the imported elemental base.

For measure current in BSPS, along with shunts, current-type current sensors are used, the wide range of which allows measuring currents in the range from 10 to 1000 A with an accuracy of ± 2% accuracy. In addition to calculating the charge and discharge capacities of LIB, the value of current is necessary for the calculation of corrective corrections to the measured values of the voltage of LIB. Current sensors can also be used to protect against current overloads of the BSPS power circuits along with fusible inserts or fuses that self-repair and protect LIB from short-circuit currents only and are not effective at relatively small (1,5÷2-times) current overloads.

The most difficult, in terms of implementation, the task is to ensure the efficiency of BSPS with failures (short circuit or breakdown) within LIB. The breakthrough in LIB is most dangerous when they are connected in the consistent manner in the BSPS, short circuit – with their parallel connection. In the parallel connection of LIB in addition to protect from the effects of internal short circuit consistently with each of them installed melting insert.

In order to maintain the efficiency of BSPS in the rejection of one of the LIB with their sequential connection it is necessary to withdraw it from the power circuit, while preserving its integrity. For this purpose, electromechanical or electronic bypass devices are used, which are controlled by the local CS, which are installed directly on the LIB for discharging the resulting heat [31].

An important function of the local CS is the hardware alignment of the charge level (leveling the voltage unbalance) of the individual LIB in the BSPS. The reason for the voltage disbalance is the difference in the degree of charge of batteries, which is due to differences in the rates of their self discharge, which is defined as leakage currents through external and internal electrical circuits of batteries, and electrochemical processes occurring on their electrodes. The hardware methods for leveling the voltage divergence, which are components of the DSS in the design of the SPP CPC, can be divided into the following:

- the most simple in implementation of the passive method, when the LIB with high voltage is discharged with the help of the resistor connected in parallel to it;
- active methods for balancing batteries voltage by redistributing energy between them;
- system methods that provide an individual (independent) charge mode for each LIB.

The simplest but fairly effective system method for leveling the imbalance in large and very large capacities of LIB is their charge with multichannel automatic chargers (AC/DC converter) (Figure 1). For low-voltage portable LIB, circuit-engineering solutions have been well-proven, providing automatic switching of LIB from the serial circuit to parallel with the connection to it of the specialized AC/DC converters [32, 33].

In active methods, transformer circuits of energy redistribution are implemented in LIB, or the "lagging" batteries is charged from one or more direct current sources supplied from the outlet of the batteries or from an external source of energy (eg, AC/DC converters, BSPS, other renewable energy source). Such devices, providing large flowing currents, allow not only to offset the imbalance of stresses in batteries, but also to provide their full discharge, and not to work according to the schedule of "worse" of LIB. High-voltage high-rise batteries are built on the modular basis, based on the requirements of providing electrical safety during installation and repair, as well as the possibility of their transportation and installation with minimal use of lifting-transport mechanisms. They use CS also built on the modular principle with 2-3 levels of control.

During design of powerful BSPSs for hybrid SPP CPCs, the safety requirements for their installation, operation, maintenance and repair are on the forefront. For backup batteries, an important requirement is long-term maintenance of the technical characteristics in the standby mode of connection to the load, guaranteed transition and provision of a given mode of discharge by command, whose arrival time is uncertain. The battery life of the standby mode can range from a few months to ten years or more. High-energy capacitive batteries can be constructed in sequential-parallel or parallel-sequential circuits [34-36].

The specified lifespan and continuity of work of LIB are achieved: by means of the use of component parts and materials with appropriate service life; at the expense of structural redundancy in batteries; due to the use of AC/DC converters and continuous monitoring of their condition (Figure 2), which allows to carry out the necessary regulatory and repair work on separate of LIB subsystems without removing the entire battery from the standby mode as soon as possible.

At the magnitude of the voltage at each LIB at the end of the discharge, it is concluded that their nominal capacity is reduced and the possibility of further operation of both LIB and AC/DC converters as the whole. According to the results of testing and available information on AC/DC converters work in the standby mode, the decision is made to carry out repair and restoration work on faulty sections. Defective AC/DC converters are disconnected from the output bus of the BSPS. All normal AC/DC converters after the end of the test discharge are connected to the charge from the AC to the voltage of 4,2 V on any LIB. Further charge for leveling the voltages on individual LIB is carried out with the help of internal recharging devices from the BSPS. In the case of the parallel connection of LIB in the power circuit, each of them should provide an element of protection against overcurrent (for example, fuse-link), which protects the AC/DC converters from short circuit within individual of LIB, and the local CS should provide control over their state.

3. Method of design of mathematical models of power systems with multi-constructions

Depending on the connection point, the spatial vector of the consumed PEM (induction–IM or synchronous – SM) current will be rotated in d,q coordinates with the frequency determined by the load phase, which, in turn, depends on the impedance difference at the point of connection and the nearest high-voltage bus MSDG (Figure 3).

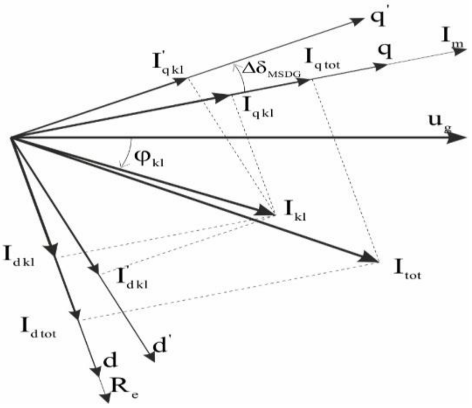

Figure 3. Vector diagram for the area kl (k, l – natural number) of the high-voltage bus with connected to it IM and MSDG: u_g – voltage on the bus, p.u.; I_{tot} – total consumption current of IM, p.u.; $\Delta\delta_{MSDG}$ – load angle; φ_{kl} – current phase of the stator of IM.

The equation of the MSDG model connected to the bus can be described by the system of equations:

$$\begin{cases} \dfrac{d\bar{\Psi}}{dt} = (W(n)+FX^{-1})\bar{\Psi} + Nu_g + gu_f \\ \dfrac{dn}{dt} = \dfrac{1}{t}(t_{m\_msdg} - \bar{\Psi}^t (M^t K M) X^{-1} \bar{\Psi}) \\ \Delta \dfrac{d\delta_{MSDG}}{dt} = \omega_N (n - n_1), \end{cases} \qquad (1)$$

where: $\bar{\Psi}$ – flux vector of the winding of the stator; u_f – excitation voltage, p.u.; n – speed of rotation, $[c^{-1}]$ shaft generator, p.u.; ω_N – nominal speed of rotation, [rad/s]; r_{ss} – resistance of the winding of the stator IM, p.u.; r_{lk} – resistance of the tire between points lk, p.u.; t_d, t_q – longitudinal and transverse components of the constant time of the damper winding of the MSDG, s; t_f – constant time of the winding of excitation, s; x_d, x_q – longitudinal and transverse components of the reactive resistance of the scattering of the windings of the stator, p.u.; $k_{\mu d}$, $k_{\mu q}$, $k_{\mu f}$ – longitudinal and transverse components of the coefficient of saturation of the damper and stator windings of the MSDG and the winding of excitation; μ_d, μ_f – coefficients of interinduction between the stator winding and the damping, between the winding of excitation and the damping.

$$W(n)=\begin{bmatrix} 0 & \omega_N n & 0 & 0 & 0 \\ -\omega_N n & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \quad N=\begin{bmatrix} \omega_N & 0 \\ 0 & \omega_N \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}; \qquad (2)$$

$$F=\begin{bmatrix} \omega_N(r_{ss}+r_{kl}) & 0 & 0 & 0 & 0 \\ 0 & \omega_N(r_{ss}+r_{kl}) & 0 & 0 & 0 \\ 0 & 0 & -1/t_d & 0 & 0 \\ 0 & 0 & 0 & -1/t_q & 0 \\ 0 & 0 & 0 & 0 & -1/t_f \end{bmatrix}; \qquad (3)$$

$$X=\begin{bmatrix} -x_d & 0 & 1 & 0 & 1 \\ 0 & -x_q & 0 & 1 & 0 \\ -(1-k_{\mu d})x_d & 0 & 1 & 0 & \mu_d \\ 0 & -(1-k_{\mu q})x_d & 0 & 1 & 0 \\ -(1-k_{\mu f})x_d & 0 & \mu_f & 0 & 1 \end{bmatrix}; \quad g=\begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{t_f} \end{bmatrix}^t \qquad (4)$$

Then, from expression Eq. (1), the vector of the flux coupling ψ MSDG is connected with the quantities that characterize the stator winding by the expression:

$$h(\bar\Psi)=\bar\Psi_s^t K i_s=\bar\Psi^t (M^t KM) X^{-1}\bar\Psi, \qquad (5)$$

where:

$$K=\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}; \quad M=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}; \quad M^T KM=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (6)$$

The common solution of Eq. (1)-(4) allows us to determine the constant integration that characterizes the setpoint of the MSDG PID-regulators in their parallel work. The regulators are tuned so that one of the regulators controls the frequency and voltage, and the other for the supply of active and reactive power with the settings set for the power of the first generator. In this way, the uniform load distribution is achieved:

$$c=x_d(\mu_f(\mu_d+k_{\mu d}-1)-\mu_d+1-k_{\mu d}+k_{\mu f}(k_{\mu q}-1)).$$

If the properties of load are represented by the graphs in the form of the implementation of any stochastic process of changing the load of the MSDG during the change in the operating mode of the CPC $I_i(t)$ and $\varphi_i(t)$ for i = 1, 2, ..., then the functional analogue of the single operator of the E_F must be with two controllable coordinates $I^m(t)$ and $\varphi^m(t)$, whose values correspond to:

$$\dot I^m(t)=\left[-\boldsymbol{R}^m_{(\Psi)F}\cdot I^m(t)+E^m_F(t)+\beta_x\cdot \boldsymbol{X}_F(t)+\beta_\delta\cdot\delta_F(t)+\beta_\varphi\cdot\boldsymbol{Y}_F(t)\right]/\boldsymbol{L}^m_{(\Psi)F} \qquad (7)$$

and
$$\dot\varphi^m(t)=c_I\cdot I^m_F(t)+c_U E^m_F(t)+c_{\varphi(U)}\cdot\delta_{(\varphi)F}(t)+c_{\varphi(I)}\varphi_F(t), \qquad (8)$$

where: R_m and L_m are the matrices of the active and reactive components of the equivalent electrical circuits for the replacement of load; β_x, β_δ, β_φ– weighted average constant constructive coefficients of the self-excitation system of MSDG, shock absorbers and amplifier-phase transformer; c_I, c_U, $c_\varphi(U)$, $c_\varphi(I)$ – weighted average constant constructive coefficients of current, voltage and feedback sensors VSI or CSI (see Figure 1, 2) by current and voltage respectively.

The values of the current of the stator, active (P) and reactive (Q) power are from the equation:

$$\begin{cases} i_s=MX^{-1}\bar\Psi \\ P=u_g^t i_s=u_g^t MX^{-1}\bar\Psi \\ Q=-u_g^t K i_s=-u_g^t KMX^{-1}\bar\Psi. \end{cases}, \qquad (9)$$

In the case of an increase in the total load, the generator connected to the parallel operation at an initial moment, proportional to the constant time of the MSDG, can automatically "take over" all the surplus demanded by power consumers. This is due to the fact that the rest of the generators operating in steady state will supply constant power depending on the settings, which can lead to an unexpected inconsistency of the load between the generators.

To avoid such inconsistencies, depending on the current consumption and the calculation of the difference between the power of the particular generator and the connected, the load distribution unit, by affecting the PID-regulators of the MSDG on the frequency of rotation and voltage, eliminates the inconsistency that arises.

Methodology of synthesis of multi-criterial strategies for managing power distribution

It is proposed to use an additional in the hybrid SPP CPC of the BSPS, which consists of electric double-layer capacitor (EDLC). Block diagram of the classical strategy of controlling the hybrid SPP CPC using EDLC for the criterion of minimum electricity consumption is shown in Figure 4.

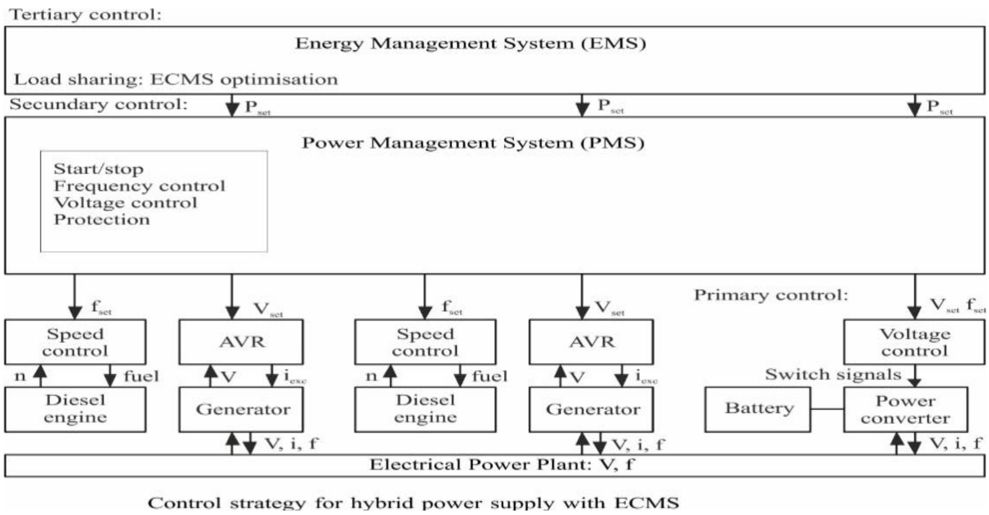

Figure 4. Block diagram of control of hybrid SPP CPC for the criterion of minimum power consumption: AVR – Automatic Voltage Regulator; X_{set} – setting; P – power; f – voltage frequency; V – voltage; n – speed of rotation of MSDG; i_{exc} – current of excitation of generators; I – current of MSDG.

Based on the developed method, the strategy of controlling of the SPP CPC according to the criterion of the Equivalent Consumption Minimization Strategy (ECMS) has been improved by introducing the criterion for obtaining the maximum energy of alternatives (External energy maximization strategy with SOC's regulation – EEMS) and regulating the degree of charge of the battery of BSPS using PVGS to minimize fuel consumption. Observance of other criteria, such as noise, vibration, emissions to the environment or maintenance of MSDG, primarily depends on the operating point of the MSDG (Figure 5) and PVGS [37] and is determined by the configuration of the electricity distribution control system. Thus, similar functions of costs depending on the mode of operation of MSDG can be obtained according to these criteria, and also the overall optimal power of the SPP CPC can be determined with the weighted function of costs for several criteria.

Thus, improving the strategy by the criterion of obtaining the maximum energy of alternative energy and regulating the degree of charge of batteries of BSPS using PVGS becomes the promising approach to increase the efficiency of SPP CPC in comparison with many functions for future developments.

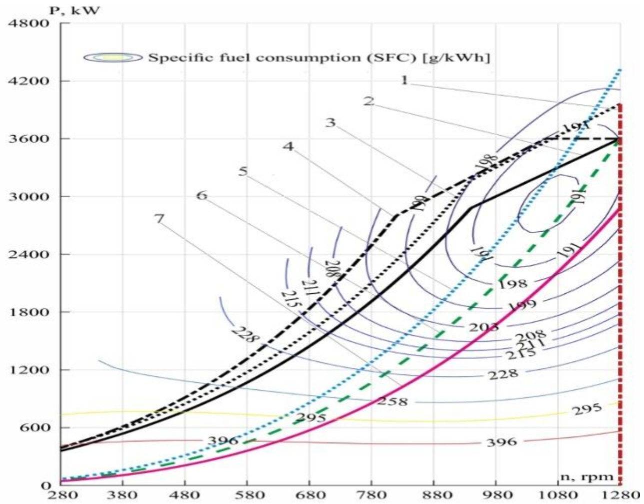

Figure 5. Dependence of specific fuel consumption on load on MSDG and characteristics of propellers: 1-4 – characteristics of MSDG; 1 – barrier; 2 – loading; 3 – load bearing with high rating; 4 – load with sequential turbocharger; 5-6 – characteristics of propellers; 5 – settlement; 6 – on free water; 7 – test.

Ultimately, further research should move through the integration of management strategies from the point of view of an integrated approach. The block diagram of one of the variants of the improved strategy of management of the integrated system with the hybrid SPP CPC and the so-called western system coordinating council (WSCC) in Figure 6.

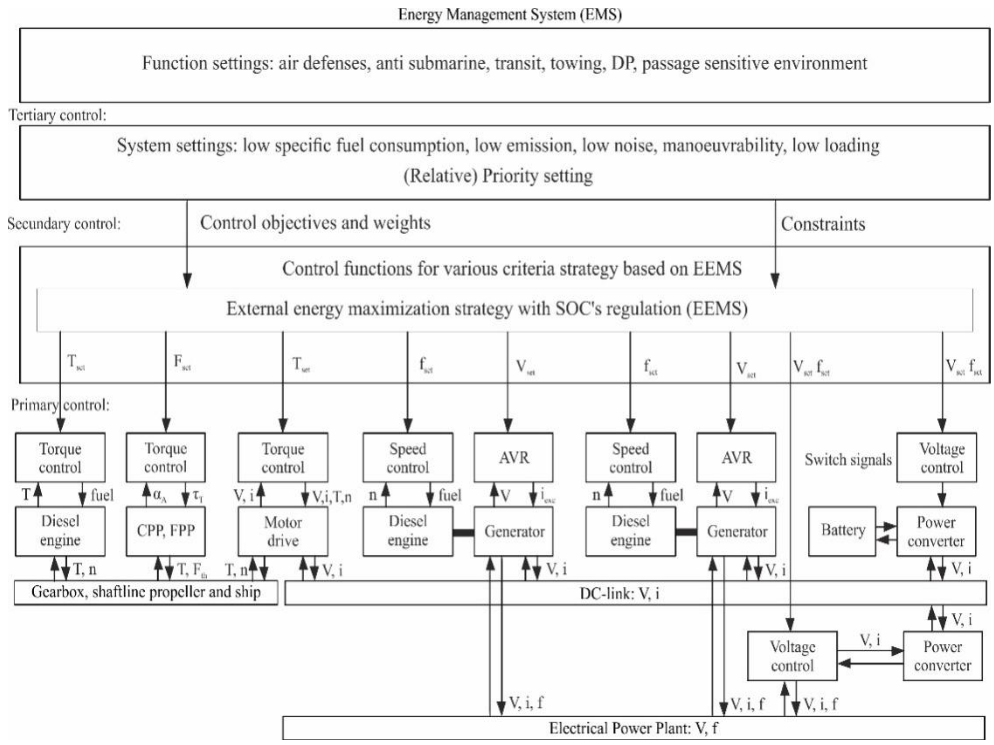

Figure 6. Block diagram of the control strategy of the SPP CPC for the criterion of the maximum of alternative energy and the regulation of the battery charge level BSPS: X_{set} – setting; T – thrust (moment); F – force of propeller; f – voltage frequency; V – voltage; n – speed of rotation of MSDG; i_{exc} – current of excitation of MSDG; i – current; τ_T – resultant projection of the vector of effort on the plane of the vessel; α_A – angle of position of the THRs

The block diagram of the proposed system for monitoring the state of EDLC for one of the hybrid CPCs, strategy of controlling of which is given in Figure 6, is presented in Figure 7.

The energy of the discharge of condenser modules (Figure 7) in the SPP of the CPC for the characteristics of the perturbing forces whose parameterization is determined by the equations (10) and (11), provided that all the thrusters in the coordinate plane of the direct control of the moment are determined by the (12) by estimating the integration of the total surface area of all EDLC modules under the galvanic discharge or charge curve.

$$\begin{cases} U_S(t)=I_S(t)\times Z_{SE}+t_{EM}\times\overline{\upsilon}_S(t), \\ F_S(t)=I_S(t)\times t_{ME}+Z_{SM}\times\overline{\upsilon}_S(t), \end{cases} \quad (10)$$

where Z_{SE} – Impedance of the converter on the electric side; Z_{SM} – Impedance of the converter on the mechanical side; t_{EM} – constant time of electromechanical transformation; t_{ME} – constant time of mechanical-electrical transformation.

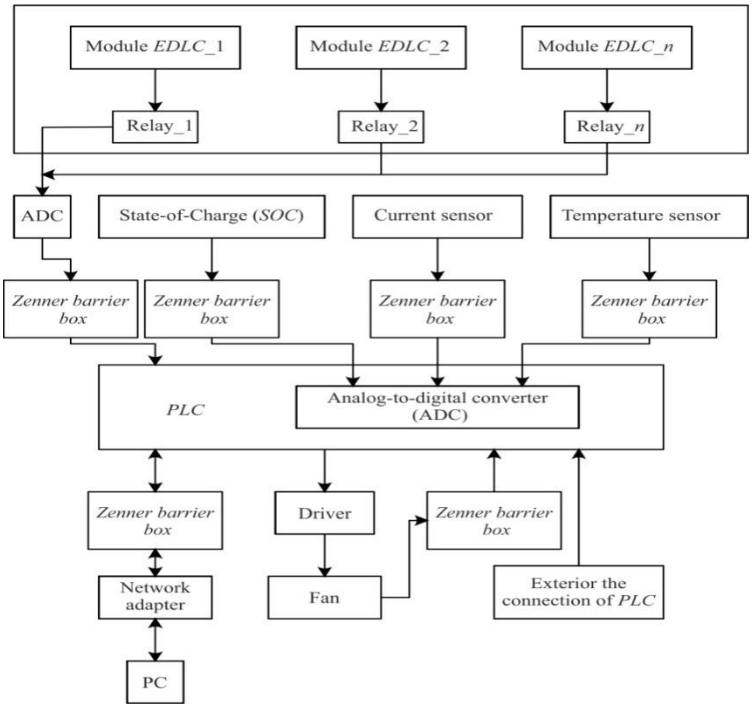

Figure 7. Block-diagram of EDLC state monitoring system for hybrid CPC: ADC - analog-to-digital converter; PC - personal computer.

Th e general solution for the system of equations (10) will be to find the coefficients of the polynomial for the steady-state behavior of the disturbing forces determined by the flow quality according to the certain sensor provided that the operational mode of the SPP of the CPC remains unchanged beyond the calculation interval:

$$\begin{cases} \overline{\boldsymbol{U}}_S(\boldsymbol{Z}) = \overline{\boldsymbol{I}}_S(t)\cdot \boldsymbol{Z}_{SE} + t_{EM}\cdot \overline{\upsilon}_S(t), \\ \overline{\boldsymbol{F}}_S(\boldsymbol{Z}) = \overline{\boldsymbol{I}}_S(t)\cdot t_{ME} + \boldsymbol{Z}_{SM}\cdot \overline{\upsilon}_S(t), \\ (m_{cS}+m_{ncS})\cdot \dfrac{d\,\overline{\upsilon}_S(t)}{dt} + \mu_S\overline{\upsilon}_S(t) + \mu_R\displaystyle\int_{\varepsilon_0}^{\varepsilon}\overline{\upsilon}_S(t)dt = \overline{\boldsymbol{F}}_S(\boldsymbol{Z}), \end{cases} \quad (11)$$

where $\mathbf{F}_S(\mathbf{Z}) = (\mathbf{F}_{S1}(\mathbf{Z}^1), \mathbf{F}_{S2}(\mathbf{Z}^2), \mathbf{F}_{S3}(\mathbf{Z}^3), \mathbf{F}_{S4}(\mathbf{Z}^4), \ldots, \mathbf{F}_{Si}(\mathbf{Z}^m))^{T_{matrix(i)}}$; the complex impedance is determined by the matrices of the active and inductive components of the circuit for replacing the complex load$\mathbf{Z}^m = \mathbf{R}^m + p_i j\mathbf{L}^m$(7), (8); $T_{matrix(i)}$ – matrix of the configuration parameters of the trimming devices, where (i = 0 ... k) is the number of the corresponding configurationCPC:

$$E_{int/SOC}(t) = I_{EDLC}\int_{U_{EDLC\_max}}^{U_{EDLC\_min}} U_S(t)dt \quad (12)$$

Results of simulation of energy processes in the hybrid CPC using of multi-criterial strategies for managing power distribution

The following analysis of the method of different operating modes of the SPP CPC in terms of energy consumption, has allowed to identify the main criteria for comparing the fuel consumption and the state of the charge BSPS (voltage to DC-link). The overall efficiency of the system and the voltage at each source of energy that may affect the parameters of the operating mode was evaluated using an approach based on the inverse wavelet transformation of their instantaneous capacities using the simulation model SPP CPC in MatLab/Simulink. On Figure 8-11 shows the obtained characteristics during modeling of energy processes in the hybrid CPC for 350 s in the MatLab/Simulink environment. The load profile was determined according to the system of equations (7), (8) for cosφ = 0,8.

At the beginning of the simulation (t = 0 s), the power supply is provided by the main MSDG and PVGS of hybrid CPC is included for the charge of BSPS and preparation for emergency mode. At t = 40 s, there is the blackout of the vessel. PMS switches the load supply to alternative sources. At this time, additional load power is instantly secured from DC-link, where "realized" the reset of energy from the main consumers who worked in the generator mode, since the power of the PVGS is increasing slowly.

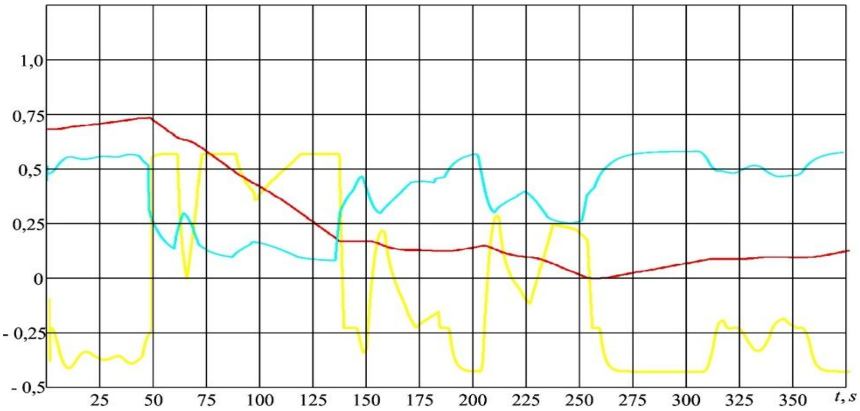

Figure 8. Energy characteristics of BSPS: – the maximum current matches to the value of 400 A; – the maximum voltage matches to the value of 48 V; the maximal charge matches to the value of 100%

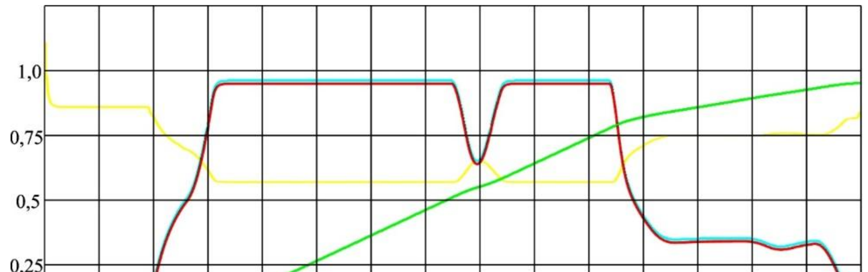

Figure 9. Energy characteristics of the PVGS: – the maximum voltage matches to the value of 170 V; – the maximum current matches to 250 A; – the maximum value of the ratio of the voltage on the PVGS to the idle speed matches to the value of 1; – the maximum temperature of the PVGS corresponds to a value of 60 ^{o}C

At t = 45 s, DC-link voltage reaches the lower setpoint (270 V) and the BSPS starts to feed the DC-Link bus up to 450 V, the voltage reaches the required level by 47 seconds and the BSPS allows it to slowly restrict its power to zero. PVGS provide total load power and continues to feed the bus DC-Link, which 55 seconds connect emergency users. At t = 62 s, BSPS is switched on to support the voltage of the DC-Link bus up to 450 V and to help the PVGS provide the required additional load power. At 80 seconds, the PVGS achieves its maximum power, which is limited to 10 kW via the DC/DC input voltage range, and additional power is provided by the BSPS, the maximum power of which is achieved at t = 120 s (20 kW) and the power supply is provided through the bus DC-Link.

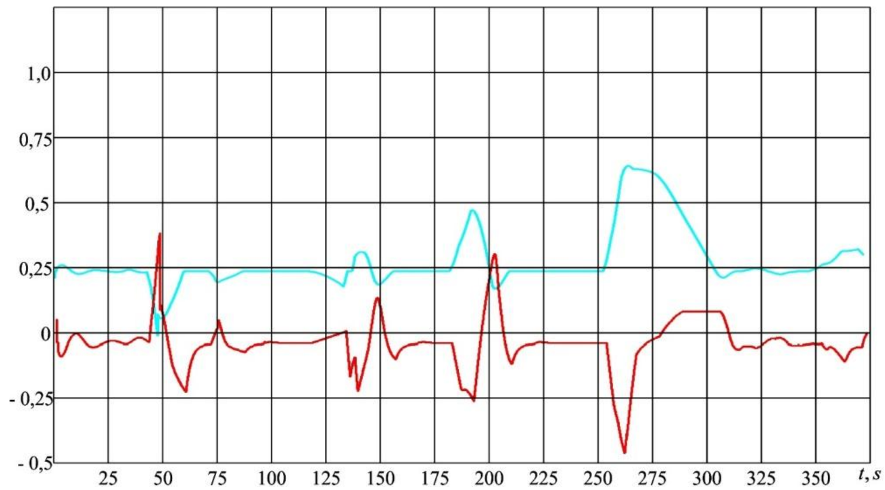

Figure 10. Dependence of voltage and current on DC-link: — the maximum voltage matches to the value of 450 V; — the maximum current matches to the value of 1000

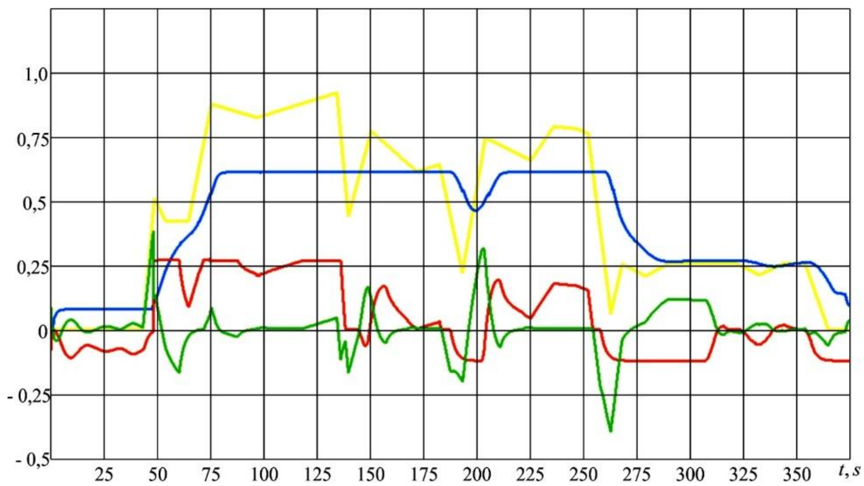

Figure 11. Characteristics of capacities at different sections of the SPP CPC: the maximum load power matches to the value of 1000 kW; – the maximum power at the PVGS matches to the value of 10 kW; – the maximum power at the BSPS matches to the value of 20 kW; – the maximum power for DC-link matches to the value of 300 kW

For 130 seconds, the effort is lower than the maximum power consumption. At the linkage with low dynamic characteristics of PVGS, the time of overriding processes should be changed to the DC-Link bus. When t = 135 s, the sponge on the DC-link busbar reaches the reach of 450 V, and the charge of the BSPS batteries drops to zero. For 140 seconds, a new mode is enabled for the SPP CPC mode and the algorithm of PMS for all living situations that are necessary for the similar person with t = 55 s. At t = 165 s, the load power falls below the maximum power of the PVGS and the additional power is provided by the BSPS and the DC-link bus. At 190 seconds, the sudden increase in load is due to the connection of consumers that provide the entry of the SPP CPC, and PMS quickly reacts, providing additional power load from the bus DC-Link, to which, to restore the voltage and support the PVGS with additional load power, for 195 seconds, the batteries of the BSPS are connected. At 250 seconds, the launch of the main MSDG of the hybrid CPC is taking place and the additional energy of the PVGS begins to accumulate in the BSPS and elements of the DC-link. At t = 260 s, the SPP CPC needs additional power due to the change in operating mode (eg, maneuvering the vessel) and the energy of the PVGS is again used to support the main MSDG. At 330 seconds the boat goes into running mode, and the load capacity decreases. PVGS are also slowly reducing their power to an optimal level and switching to the power of the BSPS batteries.

II. Conclusions

In the chapter, further development of resource-saving ecologically clean technologies of operation of the SPP CPC through the use of alternative generating elements in designing power supplies and increasing their speed when changing operating modes, which allowed to improve the strategy of controlling the hybrid SPP

CPC in terms of power distribution between BSPS, PVGS, SPP and other components of the SPP in accordance with the chosen energy management strategy. Namely: in the state machine control strategy; with PI-control and state-of-charge regulation (SOC), the classical PI-control strategy with the SOC regulation; with control of the frequency and state of the MSDG and frequency decoupling and state machine control strategy with SOC regulation (FDSMCS); equivalent consumption minimization strategy (ECMS); based on the criterion of obtaining the maximum of alternative energy and regulating the degree of charge of batteries. For the first time, a three-level multi-criteria strategy for managing energy distribution in the hybrid SPP CPC was synthesized by combining the classical power management control strategy with the control strategy for the MSDG state and the charge level of the PVGS of BSPS, which allows the design of flexible multifunctional power systems that integrate into the hybrid SPP CPC as an capacitive component, as well as parametrization of propulsion and power characteristics depending on the change of operating modes, hydrodynamics characteristics and environmental conditions. Important is the possibility of iterative optimization of the parameters of the SPP, which allows using the developed method as the means of intelligent design, the result of which is the improved performance of the SPP CPC. The proposed strategy compared to existing systems has the higher efficiency of detecting the risk of blackout of the SPP, greater reliability and accuracy in terms of determining the need for the reduction in load (within 150 milliseconds). The new concept is the fully integrated system with intrinsic controllers of the speed of rotation of the THRs and the power supply system.

For example, analyzing the obtained dependencies and the data in [39], we can conclude that the control of the frequency and state of the SODG with the regulation of the charge level of batteries BSPS , with all other equal conditions for operating mode, allows to reduce the quantity or power of the modules of the PVGS for 7 ÷ 10%, and management by using the criterion of obtaining the maximum of alternative energy and adjusting the level of the battery's capacity to use low-capacity rechargeable batteries in the range of 6 ÷ 8%. The concept of constructing the mathematical model of the SPP CPC [40-44], which takes into account the dynamics of all its objects, including vessels in the transmission modes of power from MSDG to propellers, is proposed, confirmed its working capacity with the help of DSS Ships_CPC [45].

The comparative analysis of simulation results can only be carried out for similar strategies. Since today the proposed strategy is original, it is not possible to perform such an analysis. The indirect indicators of the benefits of the proposed strategy are, above all, to exclude blackout of the SAPP.

The study of the influence of the parameters of the main regulators of the control system on energy processes in the SPP of CPC, confirmed the wide possibilities for the development and application of various effective strategies for the operation of the MSDG voltage stabilization systems. DSS Ships_CPC was developed using the Open System technology, which means its ability to reorganize, reconfigure and integrate into the technological processes of managing the energy system of the vessel of any complexity with the prospect of completion in the form of the universal structure.

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