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Smart overload protection of the ship's electrical power system

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Abstract. Modern means of protecting ship's electrical power systems from overload are considered. It is shown that a promising approach is the implementation of preventive protection. This protection allows providing power supply to the most important consumers of the vessel through structural switching without going into an emergency state, in which a blackout of vessel will take place. Definitions of the main concepts used in the work are given and analyzed. The content of the concepts, state and survivability which are fundamental in the synthesis of algorithms for preventive protection of ship electrical power are disclosed. It is noted that the concept of survivability given in the standard requires clarification, and the concept of state is characterized by internal parameters of the object under study and is continuously changing. At the same time, it is possible to distinguish stable types of states that are fundamental in the synthesis of algorithms for preventive protection and unloading of ship electrical power systems. The functional diagram of the device providing preventive unloading of ship electrical power systems based on the ideas of smart control is considered. It is noted that control options are possible for independent and dependent tolerances that determine the area of operability of the equipment in the technical implementation of the unit for identification and the unit for monitoring the operating condition of the object under study. A structural diagram showing identification of the technical condition of the object under study is given. It based on fuzzy logic, which allows synthesizing elements of the device for preventive unloading of the ship's electrical power system based on smart protection methods. An example of the practical implementation of the proposed device for preventive unloading of a ship's power plant is considered. This power plant includes two generator units. A distinctive feature of the preventive unloading algorithm and the device implementing it is the ability to disconnect not only secondary but also important consumers of electrical energy.

Keywords: protection of the ship's electrical power system, preventive unloading device, reliability, survivability, condition, identification, fuzzy logic

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Научная статья

Интеллектуальная защита судовой электроэнергетической системы от перегрузки

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Аннотация. Рассматриваются современные средства защиты судовых электроэнергетических систем от перегрузки. Показано, что перспективным способом является реализация превентивной защиты, которая позволяет за счет структурных переключений обеспечить электроснабжение наиболее ответственных потребителей судна без перехода в аварийное состояние, при котором происходит обесточивание судна. Приведены и проанализированы определения основных используемых понятий. Раскрыто содержание понятий состояния и живучести, которые являются основополагающими при синтезе алгоритмов превентивной защиты судовых электроэнергетических систем. Отмечается, что понятие живучести, приведенное в стандарте, требует уточнения, а понятие состояния характеризуется внутренними параметрами объекта исследования и непрерывно меняется. При этом можно выделить устойчивые виды состояний, которые являются основополагающими при синтезе алгоритмов превентивной защиты и разгрузки судовых электроэнергетических систем. Рассматривается функциональная схема устройства, обеспечивающего превентивную разгрузку судовых электроэнергетических систем на основе идей интеллектуального управления. Отмечается, что при технической реализации блока идентификации и блока контроля рабочего состояния объекта исследования возможны варианты контроля по независимым и зависимым допускам, определяемым область работоспособности объекта. Приведена структурная схема идентификации технического состояния объекта исследования на основе нечеткой логики, которая позволяет синтезировать элементы устройства превентивной разгрузки судовой электроэнергетической системы на основе интеллектуальных методов защиты. Рассмотрен пример практической реализации предложенного устройства превентивной разгрузки судовой электростанции, в составе которой имеются два генераторных агрегата. Отличительной особенностью алгоритма превентивной разгрузки и реализующего его устройства является возможность отключения не только второстепенных, но и ответственных потребителей электрической энергии.

Ключевые слова: защита судовой электроэнергетической системы, устройство превентивной разгрузки, надежность, живучесть, состояние, идентификация, нечеткая логика

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Introduction

Modern protection devises in the electric power industry unload electrical grids at the moment of overload, which can lead to cascading and rolling blackouts of consumers [1-3] in practice. In ship electrical power systems (SEPS), this can lead to a break in the power supply and blackout of the vessel [4]. During an emergency, as a rule, there is no time to select the consumers to be disconnected, so they are determined in advance, based on the operating modes of electrical equipment and the importance of the functions they perform [5-7].

A completely different situation occurs in the case of preventive protection. Let us consider this circumstance using the example of preventive unloading of the ship's elecrical grids in the event of a sudden failure of the SEPS caused by a gradual failure of its elements [4]. A similar situation arises if a lubrication or a cooling system of a prime mover in a diesel generator (DG) is out of order. Before the shutdown, the DG generates electricity of the required quality and its malfunction does not affect the generating capacity of the power plant as a whole. The time interval between the formation of a warning and emergency signal informing about overheating of the coolant in the prime mover is at least several seconds. This time is quite sufficient for structural reconfiguration and to switch off a certain number of specific consumers, based on the actual load of the electrical grid at the moment. In this case, shutdowns can be implemented according to a specially developed algorithm based on the accepted optimality criterion. On the other hand, the work [8] shows how we can to determine in advance the DG, which in the near future (usually several seconds) will switch to the motor mode, for example, due to the failure of the diesel fuel system using the methods of operational identification of the technical condition of the elements of the SEPS. In this situation, the DG will continue to perform the functions assigned to it for a certain time. English This is due to the fact that even if the fuel supply is stopped, residues of fuel oil in the pipeline and filters will ensure the operation of the DG. Therefore, it is possible to plan in advance and implement a program for disconnecting consumers of electrical energy depending on the load they create at a given time and their importance in terms of meeting the needs of the SEPS and the entire vessel as a whole in the shortest possible time.

According to the work [9], operational identification of the technical condition of the SEPS means technical diagnostics aimed at obtaining information about its technical condition, which is intended to form control actions necessary for the trouble-free operation of the SEPS in the case of an abnormal situation caused by the failure of one of its elements or an error of the maintenance personnel. In this case, the aim of the study is not to restore the operability or serviceability of the object under diagnostic, but to reduce the likelihood of its dangerous and/or emergency state radically.

These circumstances are especially significant for SEPS that include groups of consumers whose operation cannot be predicted with great accuracy. For example, an electric stove, a food cooking boiler, an electric meat grinder, an electric frying pan and a dishwasher or only the emergency lighting and a fan may be working in the galley at the moment of shutdown. In this regard, research aimed at developing approaches that ensure unloading the electric grid before the shutdown moment of the faulty DG, taking into account the current load value, are relevant and have great practical significance for ensuring the safety of the vessel.

The aim of the work is to develop a method for preventive protection of SEPS from overload, the main provisions of which are considered in the work [10].

Methods and results of the study

It is necessary to have an unambiguous interpretation of the basic concepts to reveal the essence of the issues considered in the article. In this regard, we will provide definitions and a brief description of the most important terms. The object under study in the work is SEPS.

According to USS 22652-77, SEPS is a set of ship electrical devices, united by the process of production, conversion and distribution of electrical energy and intended to supply electric power to electrical receivers of a ship.

In a similar way, according to USS 18311-80, a marine electrical device is a set of interconnected electrical products that are in structural and functional unity, intended to perform a specific function for the production or conversion, transmission, distribution or consumption of electrical energy onboard vessel.

These definitions emphasize how important the functional purpose of the concepts under consideration is. Thus, the SEPS is not primarily a set of products that characterizes the material basis of the object of study, but a set of devices designed to perform a certain function.

In general, SEPS are designed to implement functions which are responsible for the generation and management of electrical energy flows necessary to ensure the survivability of the ship. At the same time, the most important properties of this system are the properties of reliability, safety and survivability.

According to USS R 27.102-2021, reliability is the property of the object under study to maintain over time the values of all parameters characterizing the ability of the object to perform the required functions in specified modes, conditions of use, strategies for maintenance, storage and transportation within established limits.

Reliability is a complex property that may include failure-free operation, durability, reparability and storability or certain combinations of these properties depending on the purpose of the object and the conditions of its use.

It is necessary to take into account all the listed properties during operation. For the SEPS, as an object under study, but the most important of them of these properties are the properties of failure-free operation and durability.

According to USS R 27.102-2021, safety is the property of an object not to pose a threat to the life and health of people, as well as to the environment in the case of a malfunction during manufacture and operation. Although safety is not included in the general concept of the reliability of an object, under certain conditions it is closely related to this concept, for example, if failures can lead to conditions harmful to people and the environment, exceeding permissible standards.

With regard to the SEPS considering only the operational stage, safety can be briefly defined as the property of the SEPS not to create a threat to the life and health of the ship's crew in the case of a violation of its operational state.

The concept of "survivability" occupies a borderline position between the concepts of "reliability" and "safety" of an object. According to USS, survivability is the property of the object consisting of its ability to withstand the development of critical failures from defects and damages with an established system of technical maintenance and repair or the property of the object to maintain operability under influences not provided for by the operating conditions or the property of the object to maintain operability in the presence of defects or damage of a certain type, as well as in the case of failure of some components. In this case, operability may not be complete. According to the standard, partially inoperative states are possible for complex objects, in which the object is capable of performing the required functions with reduced performance characteristics or is capable of performing only part of the required functions.

Failure is an event that disrupts the operation of an object. Criticality of failure is a set of features that characterize the significance of the failure consequences. Defect is each individual non-compliance of an object with the requirements established in the documentation. Damage is a disruption of the object operability while keeping its operational state. Defect and (or) damage may cause a partial or complete failure of an object. Hazardous state is a state of an object that corresponds to a high probability or high significance of adverse consequences for people, the environment, commodity and material valuables

It follows from the definition of survivability that this is a complex property that can be represented as the following properties: resistance to failures in a dangerous state of the object under study; durability in case of abnormal impacts on the object under study; durability in case of partially inoperative states of the object under study. At the same time, for complex objects under study, such as the SEPS, one should not talk about the property of the object to keep its operability in case of failure of some components, since if even one of the DG fails and switches off, the system is inoperative in any case.

Let us consider a situation where the SEPS has become partially inoperative as a result of the operability losses, but at the same time, in the steady-state operating mode, it fully supplies consumers with electrical energy who are currently implementing the safety and operation of the vessel. Such a partially inoperative state has an independent significance when considering preventive actions to maintain the survivability of the system. In this state, all requirements for the functioning of the system are met in relation to the selected, responsible consumers.

The paper considers one of the possible ways to ensure the survivability of the SEPS, providing for its preventive protection in case of possible overloads. Smart devices and means can be used for the technical implementation of such protection. The algorithm implementing the proposed approach includes the following main operations:

1) monitoring the load of electrical grid P_g, quantity m and system of operating DG;

2) monitoring the current load P_i of each operating electrical energy consumer SEPS;

3) assessing the technical condition of each operating DG;

4) determining the moment when at least one of the DG has become inoperative, but continues to function, without having a significant impact on the operation of the entire SEPS;

5) predicting the generation capacity of the power plant P_{for} after stopping inoperative DG:

$$P_{for} = \sum_{j=1}^{m-k} P_j ,$$

where P_j – load that can be taken by j DG without overload; k – the number of failed DG and compare the obtained value with the current value of the electricity load;

6) if the current electricity load turns out to be greater than the predicted value of the power plant generating capacity obtained in the item 5, then, taking into account the actual load of consumers, those of them are selected, the disconnection of which will lead to the fulfillment of the inequality $P_g < P_{for}$ and they turn off these consumers;

7) disconnecting inoperative DG after the condition is met $P_g < P_{for}$.

Fig. 1 shows the functional block diagram of the device that ensures preventive unloading of the SEPS based on the ideas of smart control. For greater clarity, we will assume that there are three DG (m = 3) and an arbitrary number n of groups of electricity consumers which can be disconnected. Fig. 1 shows the following symbols. Numbers *1.1-1.3* denote the active load sensors, each of which generates a signal proportional to the load of the corresponding generator. Numbers *2.1-2.3* denote identification units of technical condition of the DG, which generate a logic signal *1* when it loses its operability. Numbers *3.1-3.3* denote the units for monitoring the operating condition of the units, which generate a logic signal *1* if this DG is currently performing the functions assigned to it (DG is working). The rest ones are: *4* – a summing device that generates a signal proportional to the load of the electrical grid at the moment; *5* – the block predicting the generating capacity of the SEPS, which forms a signal proportional to the load that the ship's power plant will be able to take after an emergency shutdown of the inoperative DG; *6* – the subtraction block, which forms a signal proportional to the value of the load being disconnected. Numbers *7.1*-*7.n* designate the load sensors of the corresponding consumer groups, which form signals proportional to the load at the moment; *8* – the block for selecting consumers to be disconnected, which forms a logic signal *1* signal at the outputs corresponding to the consumer groups to be disconnected. The operating principle of its components is of great importance for the practical implementation of the device under consideration. If the sensors of active load are well known and implement the functional dependence between the output signal and the load value of a particular DG then the reliability of the assessment of the condition in which a given DG is, largely depends on the operating principle of the identification block of DG technical condition and the monitoring block of operating condition. The following options are possible, which we will consider using both blocks as an example.

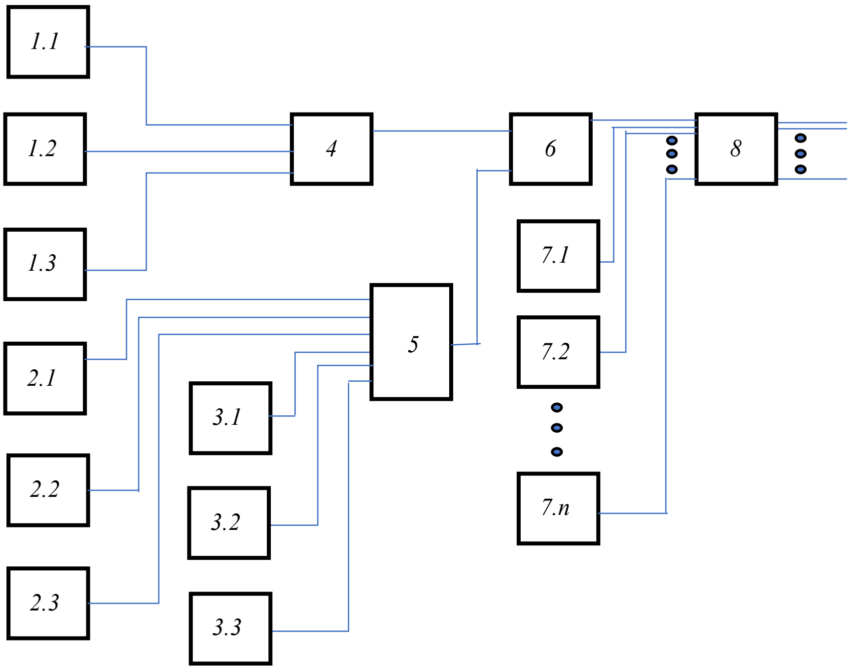

Fig. 1. Functional block diagram of the device for preventive unloading of the SEPS

Variant 1. The logic output signal of the unit for monitoring the operating condition is formed on the basis of independent prestart control, in which each variable determining the condition of the DG has specified limitations. When any variable goes beyond the permissible limits, it is considered that the DG has become inoperative and a logic signal *1* is formed at the output of the unit. This approach is the simplest and most common, but it has a significant drawback – a large method error, which largely depends on the number of controlled variables and their parameters [11].

Variant 2. The logic output signal of the unit monitoring operating condition is formed on the basis of dependent prestart control. In this case, the assessment of the DG condition is determined on using analysis of operating envelope. The reliability of the assessment increases significantly in this case. Currently, effective methods for determining such operating envelope and algorithms for determining the technical condition have been developed [11, 12]. In relation to the problem being solved, these issues are considered in [11].

Variant 3. The logic output signal of the unit for monitoring the operating condition is formed on the basis of independent or dependent prestart control. At the same time, smart methods for assessing the condition of the DG based on fuzzy logic are used. This approach can be used when it is not possible to determine the condition of the object under study accurately and it is necessary to rely on heuristic methods and fuzzy logic.

Methods and algorithms of parametric identification are used, as a rule, to solve the problems of preventive control. It is necessary to have diagnostic models of the object under study to solve the identification problem using these methods, but some individual parameters may be unknown in these models. Classical identification methods are used for a quantitative assessment of these parameters [13]. At the same time, situations are possible when there is no unambiguous relationship between the input and output of the object and it is impossible to draw a conclusion about the condition of the object in advance based on the available input information. The initial information is incomplete (fuzzy). In this case, it is possible to use expert systems [14]. The technical condition of the object can be established based on fuzzy logic methods. These methods assume that each a priori information is assigned a finite family of solutions that differ from each other in specific values of the conditional probabilities when making a given specific decision.

It is necessary to have an initial knowledge base, i.e. a priori information about the properties of the object under study for practical implementation of fuzzy logic methods. An expert system and a priori information about the object under study allow formalizing the procedure for identifying the technical condition of the object under study. A confidence probability of making the right decision can be specified in this case. Fig. 2 shows a possible algorithm for identifying the condition of the object under study based on the use of a priori information from the expert system. The operation of the identification block in the circuit of the device for preventive unloading of the SEPS can be built on the basis of this algorithm.

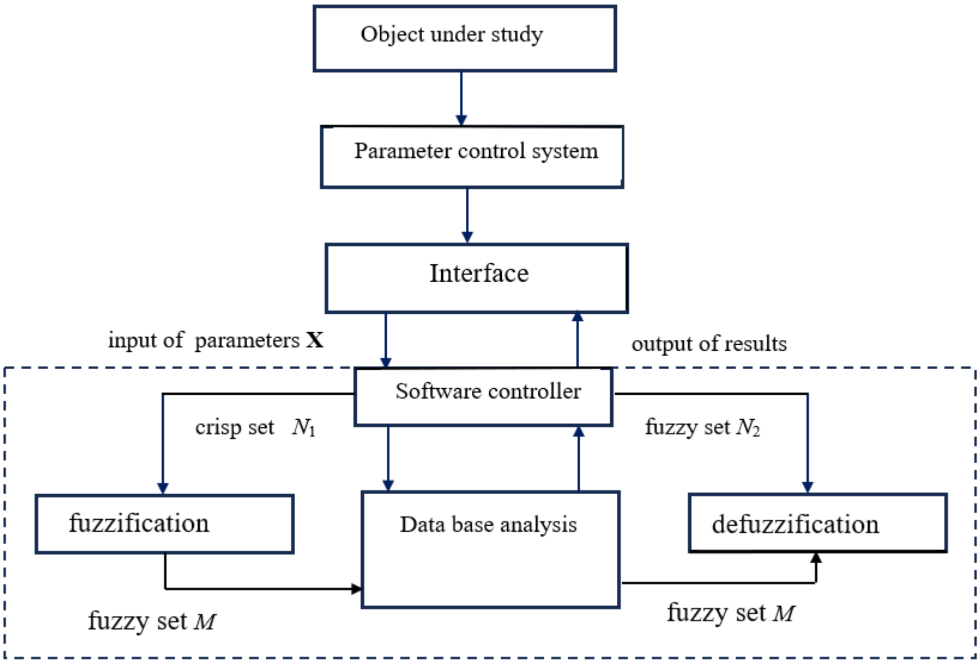

Fig. 2. Block diagram of the condition identification of the SEPS based on fuzzy logic

In [14], a similar structural diagram was used to develop module of expert system for identifying failures in the main diesel engine of the vessel. The object under study is considered as a dynamic system in a certain condition. It is important to understand the term "condition" correctly. Following [12], the condition will be understood as the internal certainty (substrate) of the object under study, characterized at a given moment of time by the features established by the technical documentation for this object, which are the initial conditions for the processes of their further change. It follows from this definition that the condition of the object under study is characterized by the internal properties of the object, which are quantitatively expressed by internal (primary) parameters. In addition, it records the features of the object at a specific moment in time and, above all, its quantitative characteristics that evaluate the functional properties of the object. The state of the object is constantly changing. At the same time, it is possible to distinguish stable, fundamentally different states, for example, operational and inoperative states, as two most important sets of conditions.

The control system of parameters (CSP) continuously records the input and output parameters of the object under study, which are fed to the interface device, which can be any automatic device or a person (operator), for example, the ship's electrical engineer. Then the data on the object under study are sent to the programmable controller (PC) or the microcomputer-based controller for their processing. Both PC and the microcomputer-based controller are parts of the expert system. At the fuzzification stage, the crisp set of input data $\mathbf{X} = (X_1, X_2, \ldots, X_n)$ is transformed into a fuzzy set $\mathbf{N_1}$, determined using the values of the membership functions, where n – is the number of diagnostic parameters of the object under study obtained in the CSP [13, 14].

Thus, at this stage, a correspondence is established between the specific values of the parameters of the object under study, which form the crisp set $\mathbf{N_1}$, in the form of the fuzzy set **M** of variables. This operation is carried out on the basis of the available values of the membership functions, which are recorded in the memory of the PC. Then, the inverse transformation of the fuzzy set M into the crisp set $\mathbf{N_2}$ is carried out, the elements of which $\mathbf{Y} = (Y_1, Y_2, \ldots, Y_m)$ are the probabilities of each malfunction, where m is the number of failures corresponding to the number of qualitatively different conditions of the object under study. The fuzzy set represents the dependence $\lambda(X) = N_1 \to N_2(Y)$ as a function of the output variable Y. In this way, the possible condition of the object under study is identified with an assessment of the probabilities of these conditions.

The rest elements of the functional diagram of the device are similar in terms of technical implementation of their functional purpose to sensors of active load. A special place here is occupied only by the block for predicting the generating capacity of the SEPS, which can also be built on the principles of smart control.

This article does not set the task of detailed development of the identification block based on Boolean or fuzzy logic. It only notes the fundamental possibility of identifying the technical state of the object under study using hard and fuzzy logic methods for developing control actions for preventive control, ensuring protection of the SEPS without the system going into an emergency condition.

Let's consider the operation of the proposed device for a specific example, in which the identification of the technical condition does not cause difficulties. Let's assume that the SEPS is in the mode in which DG1 and DG2 operate as a part of this system and they are loaded respectively by 75 and 70% of the nominal power P_n. In this case, $P_1 = 0{,}75P_n$, $P_2 = 0{,}7P_n$. If one of the units fails, for example, DG2, then a logical signal *1* will appear at the output of the technical condition identification unit *2.2* and unit *5* will generate a signal proportional to the value of P_n at its output. In this case, the signal at the output of the summing device will correspond to the value of $1.45P_n$, therefore the value of the disconnected load ΔP will be equal to $0.45P_n$. The inputs of block *8* will receive information about the value ΔP and magnitude of the load created at the moment by each of the groups of consumers, the disconnection of which will not lead to an emergency situation on the vessel $P_{load.1}$, $P_{load.2}$ …, $P_{load.n}$.

The choice of disconnected consumers, as noted above, can be made on the basis of available information on the importance of these consumers, which is stored in the memory of the PC in the form of weighting coefficients for each consumer or group of consumers. In this case, groups can be determined that create a load exceeding the value ΔP. A logical signal *1* which will initiate their disconnection is formed at the corresponding outputs of block *8*.

A distinctive feature of the algorithm under consideration is that, if necessary, not only secondary consumers can be switched off, but also some important consumers of electrical energy. For example, in a critical situation, the fan of the main engine can be switched off, possibly in combination with a decrease in the vessel's speed. Since the standby DG3 is warm standby, it will be able to start within one minute. The main engine will not overheat during this time, and the overload of the power plant and the blackout of the SEPS will definitely lead to its emergency shutdown.

Conclusion

Analysis of known systems for protecting the SEPS from overload showed that algorithms based on the ideas of preventive control should be used for increasing the reliability of the ship's power supply and the survivability of the entire system. In this case, if at least one of the operating DG becomes inoperative and is disconnected by standard protection, the condition of the SEPS can be characterized by the magnitude of the electrical grid load. Smart control ideas based on the use of fuzzy logic can be implemented to identify the condition of the DG when the relevant information is available. If, it turns out that $P_g > P_{for}$ as a result of reducing the number of operating DG, then the rest operational DG will run into emergency operation mode and will be disconnected by individual protective device or will fail. In this case, the probability of failure-free operation of the SEPS will be determined only by the probability of all operating DG performing their functions in unacceptable operating conditions and failure of protection devices. The probability of such an event in engineering calculations is assumed to be zero. In a similar situation, the use of preventive unloading means will allow promptly to reduce the electrical grid load, before the number of operating DG decreases. In this case, the influence of random factors on the emergency-free transition of the SEPS to a new, partially inoperative condition will be extremely small. Its numerical value will be determined by the probability of the start of preventive unloading devices, close to one.

The developed device for preventive unloading of the SEPS allows preventing its transition to an emergency state by means of structural reconfiguration, which is characterized by disconnection of specific secondary and important consumers of electric energy in accordance with the algorithm of preventive control. The proposed approach to protecting the SEPS from overload increases its survivability.

The device which was developed for preventive unloading of the SEPS allows preventing its transition to an emergency state by means of structural reconfiguration, which is characterized by disconnection of specific secondary and important consumers of electrical energy in accordance with the algorithm of preventive control. The proposed approach to protecting the SEPS from overload increases its survivability.

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