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A promising way of preventive deloading of the vessel's electrical power system

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Abstract. The method of preventive protection of the ship power system in abnormal situations is considered. Existing devices are shown to form a command to unload electrical power sources after an emergency situation, often resulting in a power outage on the ship. A method of unloading the network, in which the automatic formation of the command to disconnect selected power consumers in the case where at least one of the parallel working genset units is already inoperable, but the quality indicators of generated electricity is still within acceptable limits, is proposed. It is marked, that the offered approach provides forecasting of a power condition of ship electric power system in case of reduction of its generating ability. The conditions under which deloading should be carried out are formulated and presented in the form of logical expressions. It is shown that the proposed approach has a universal character, as it does not depend on the number of generating sets working in parallel, nor on the number of defective machines, nor on the type of incident. The functional scheme of the original device for preventive unloading of the ship electrical power system is presented. It is noted that practical realization of the proposed method of ship electric power network unloading allows in case of at least one of the generating units working in parallel to realize in advance the structural adaptation of system to the arisen failure and to pass in a partially nonfunctional state, bypassing an emergency situation. In this case, there is no interruption in power supply to critical consumers, ensuring the safety of ship operation.

1. Introduction

Shipboard electrical power systems (SEPS) are responsible for generating and managing the flow of electrical power required to support the life of the vessel. At the stage of operation, the most important task is to ensure accident-free operation of SEPS, including in case of failure of at least one of the generating units (GA). The important place at the decision of the given problem belongs to ways of identification of a technical condition (TC) of system which are realized by methods of technical diagnostics [1-3]. In this article the issues of GA overload protection by means of SEPS unloading are considered. At present the algorithms of shutdown of various consumer groups at emergency operation modes of power sources are implemented by control systems (CS) of both coastal [4]-[6] and SEPS [7-9]. At that, in case of deviation of quality indicators of the generated electric power, coastal networks, as a rule, have inertia, sufficient for implementation of a complex of actions, aimed at their transfer into the field of admissible modes. In this case, a given sequence of control operations of the control system is formed, which usually include disconnection of different groups of consumers as the resulting impact [10, 11]. In autonomous power systems, which include SEPS, GA overload protection usually has two levels. At the first level, the SU forms a command to disconnect the secondary consumers, which is given after a certain time delay after the load of any of the GAs exceeds the permissible value. In this case, the SEPS load and the load of the overloaded GA is reduced. This operation can be carried out in several stages. In each step, a pre-selected group of consumers is deactivated after a preset time interval. Application of time delay for operation of the first level of GA overload protection allows to avoid errors of the first kind and to prevent erroneous unloading of the network at current surges during start-up of powerful electric motors [12]. If disconnection of consumers does not lead to reduction of GA load below the permissible value, the second level of protection disconnects the overloaded unit, which allows to keep operability of the generator, but, at the same time, can lead to interruption of ship power supply and create an emergency situation. The considered way of SEPS protection from overload is admissible in those cases, when electric power sources are in working condition, and overload occurs due to rapid increase of load.

Known SUs perform disconnection of different groups of consumers in cases when internal or output parameters of electric power system exceed permissible values. In this case, the controlling influence is aimed at stopping the further development of the emergency situation, at minimizing the possible damage, as well as at preventing more serious equipment failures and the possible death of the operating personnel. It is known that failure of one of two parallel operating diesel generators, functioning as part of SEPS with optimal load of 75-85%, practically always leads to power interruption and emergency situation on the vessel [12]. In order to prevent possible emergency situations, the method of SEPS preventive control was suggested in works [12-14], according to which control system forms control action in a form of warning signal till the moment of SEPS parameters output beyond admissible limits. In this case, the SEPS parameters determining its technical condition are only approaching their maximum permissible value, but it is possible to influence their values in such a way as to prevent the occurrence of an emergency situation due to structural adaptation of the system to the occurred malfunction [13].

2 Methods and materials

From the point of view of preventive control, the command to disconnect the different consumer groups to unload the SEPS must be generated before the system or at least one of its GAs is overloaded. In this regard, we can talk about preventive unloading of the power system in order to prevent an emergency situation during its transition to a partially operable state. As shown in [14], SEPS is operable and can perform its functions provided that the representing point, characterizing its technical state, belongs to the tolerance area, defined as the intersection of areas G_z and M_u.

$$H = G_z \cap M_u , \tag{1}$$

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where G_z defines SEPS serviceability area plotted in the GA monitored parameter space ($\overline{Z}$), and M_u is the area of control actions of the system. The SEPS operability domain will be understood as the set of admissible values of the monitored GA parameters, at which all requirements to the output parameters of the system are fulfilled [14]. At present, a number of methods for constructing the domain for various electrical devices and systems have been developed, described in [15], [16]. At the same time, in [14] the domain G_z is represented as an intersection of areas D_z, M_y:

$$G_z = D_z \bigcap M_y .$$

Given the constraints imposed by the control actions on the system, and in accordance with [13], the area H can be represented as follows:

$$H = D_z \bigcap M_y \bigcap M_u , \quad (2)$$

where D_z is a tolerance range of output parameters $\overline{Z}$ of GA.

These parameters include, for example, the coolant temperature and lubricating oil pressure of the diesel engine, the shaft speed and the power developed by the generating set. The range D_z has the shape of a hyperparallelepiped (bar) and in Euclidean space can be described as $D_z = \bigcap_{k=1}^{n} D_k$, $D_k = D_{k\,\min} \bigcap D_{k\,\max}$, which corresponds to the internal condition of operability. The range M_y characterises the external operating conditions of the system in question and is a representation of the output parameters $\overline{Y}$ SEPS to the parameter space of the state variables $\overline{Z}$. Herewith, $\Phi_{yz} : D_y \rightarrow M_y, M_y = \bigcap_{y=1}^{n} M_y$. Examples of such parameters are the frequency and voltage of the ship's network and the total power generated. Control area M_u is a mapping of the control signal space $\overline{U}$ into the output space $\overline{Z}$ of the function units: $\Phi_{uz} : D_u \rightarrow M_u$, $M_u = \bigcap_{c=1}^{e} M_c$ [14]. The control signals include such quantities as the frequency and voltage set points of the ship's mains, the SEPS variable load.

Preventive unloading of SEPS in the framework of preventive control should provide advance reduction of network load in case of failure of at least one of GA or its SU in order to avoid overloading and interruption in power supply of responsible consumers. In [14] it is shown that for this kind of tasks it is reasonable to consider as the most important indicator of quality of SEPS operation the value of generated power $N_{общ}$, developed by an autonomous generating system (AGS). In accordance with Article [13], an AGS will be understood as a set of GAs interconnected and designed to supply a ship with electric power of the required quality. In this case

$$N_{gen} = \sum_{i=1}^{n} N_i , \quad (3)$$

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where N_i is the power that can be generated by the i -th GA, n - is the number of operating GAs in the SEPS at a given point in time. If at least one of the units operating in parallel fails, condition (2) will no longer be fulfilled and the SEPS will enter an inoperative state. In this case, if, as a result of the warning control, the depictive point $S(\mathbf{Z})$, characterising the technical state of the SEPS will belong to one of the truncated areas of correct functioning w_j^q, then the transition of the system to a partially operable state will occur accident-free. In this case, as shown in [14], as a result of the control action the conditions will be fulfilled

$$S(\overline{Z}) \in w_j^q = D_x^q \cap M_y^q \cap M_u^q, \quad j = \overline{1, q}, \tag{4}$$

where $D_x^q \in D_x$; $M_y^q \in M_y$; $M_u^q \in M_u$.

Following the work of [14], truncated areas of correct functioning are (w_j^q) will be referred to as the areas resulting from the segmentation of the area H. According to [13], the truncated correct functioning areas corresponding to the correct functioning states of SEPS can be represented as follows:

$$\forall w_j^q \in H \text{ and } H = \bigcup_{j=1}^{q} w_j^q, \ j = \overline{1, q}.$$

The operable GAs will be operable in all operating modes of the SEPS, including the mode that occurs after the inoperable unit is shut down. Therefore, to ensure that condition (4) is fulfilled, it is necessary to check whether the set of input (control) signals satisfies the given requirements $D_u = \bigcap_{c=1}^{e} D_c$. In this case $e = 1$, the control signal is the active network load P_c [17]. The inequality must be satisfied

$$P_c \le N_{gen}^{nom\ pr} = \bigcup_{i=1}^{n-m} N_i^{nom},$$

where $N_{gen}^{nom\ pr}$ the predicted value of the nominal SEPS generation capacity that occurs after the outage of inoperable units; N_i^{nom} - the highest (nominal) power that a GA can develop, n - the number of operational GAs; - the number of non-operational GAs to be switched off.

The essence of the approach under consideration is that before the circuit breaker of each failed GA is tripped, the value of $N_{общ}^{ном\ пр}$ and its comparison with the network load P_c. The condition must be fulfilled for the selected consumers to form a signal to switch off:

$$\Delta P_c^{pr} = P_c - N_{gen}^{nom\ pr} \ge 0,$$

where ΔP_c^{pr} - the amount of excess SEPS load over the predicted amount of generation capacity.

Thus, the condition for preventive offloading of the grid in j mode (F_j) can be formulated as follows:

$$F_j = L_m^{sh\,d} \wedge (\Delta P_c^{pr} \geq 0), \tag{5}$$

where $L_m^{sh\,d}$ - an event consisting in the identification of inoperable units to be shut down. Or, given that in steady state $P_c = N_{gen} = \bigcup_{i=1}^{n} N_i$, we can write expression (5) as follows:

$$F_j = L_m^{sh\,d} \wedge \left\{ (\bigcup_{i=1}^{n} N_i - \bigcup_{i=1}^{n-m} N_i^{nom}) \geq 0 \right\}. \tag{6}$$

Based on the expression (6), a strategy can be constructed and algorithms for preventive SEPS offloading synthesised.

3 Results

According to the expression (6), to ensure preventive unloading of SEPS, it is advisable to perform the following operations:

- Identify the inoperable state of the GA (usually one unit fails, but in general the situation is possible when several, in general case m GAs, are inoperable at the same time);
- Determine the amount of power that can be generated by the ship's power plant after the faulty units have been shut down;
- Measure the power developed by each of the working GAs at a given moment in time and calculate the total generated power of the ship's genset at the given moment in time;
- Compare the total power generated at that point in time with the predicted maximum possible power that the ship's power plant will be able to deliver after the inoperable GAs have been switched off. If this power is less than required, then form a command for preventive unloading of the SEPS.

Thus, disconnection of the chosen groups of consumers will occur before shutdown of inoperable GA and after operation of protection the remained operable units will function without an overload and interruption in power supply of responsible consumers will not occur.

Practical realisation of the offered way of preventive protection SEPS can be carried out by means of the device of preventive unloading SEPS which functional scheme for the ship power station with three GA, is presented in Fig. 1.

The following designations are introduced in the figure: 1.1, 1.2, 1.3 - sensors of capacity of the first, second and third GA accordingly; 2.1, 2.2, 2.3 - control blocks of the corresponding GA operation; 3.1, 3.2, 3.3 - blocks of definition of a technical condition of the corresponding GA; 4 - addition block, 5 - block of definition of a mode of SEPS operation; 6.1, 6.2 - memory blocks, 7.1, 7.2 - controlled keys; 8 - comparison block, 9 - logic element "OR".

Each of the power sensors 1.1, 1.2, 1.3 generates a signal on its output which is proportional to the current power value of the relevant unit (N_1, N_2, N_3). The information received is summarised by unit 4 and a signal proportional to the total (total) power is generated at its output $N_{gen} = N_1 + N_2 + N_3 = \bigcup_{i=1}^{3} N_i$ and is fed to the first input of the comparison unit 8. Assume that the generators are of the same type and that the ship's power plant operates in a mode close to optimum in terms of fuel economy and $N_1 = 0.7N^{nom}$, $N_2 = 0.75N^{nom}$, $N_3 = 0.8N^{nom}$, where N^{nom} is GA rated power. The first input of the comparison unit will then receive a signal proportional to $N_{gen} = 2.25N^{nom}$.

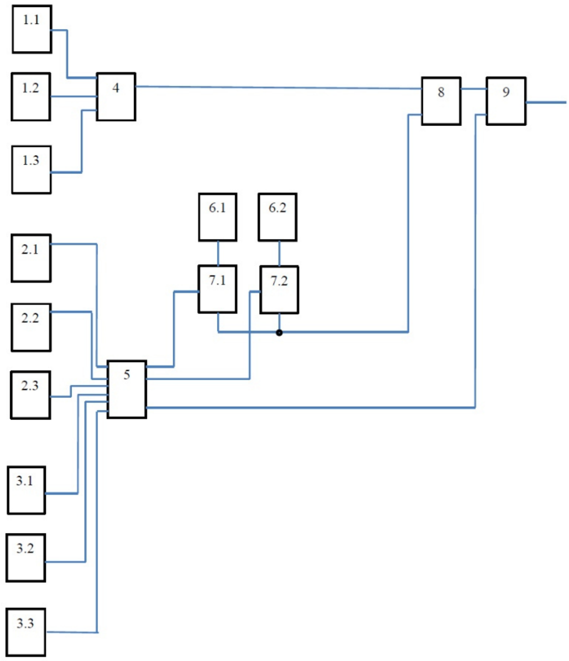

Fig.1. Functional diagram of the SEPS preventive unloading device.

As all units are operational, the first three inputs of the SEPS 5 operation mode detection unit will receive logic one signals. Assume that the lubrication system on the second GA diesel engine has failed and the lube oil pressure has dropped to the warning value. In this case, a logic one signal appears at the output of block 3.2 and is applied to the fifth input of block 5. A logical one signal appears at the second output of the mode definition block informing that only two GAs (GA1 and GA2) will operate as part of the AGS after the protection has tripped. This signal will be applied to the control input of the second controlled switch 7.2 and the signal proportional to $\bigcup_{i=1}^{n-m} N_i^{nom} = \bigcup_{i=1}^{2} N_i^{nom} = 2N_i^{nom}$ from the output of memory six will go to the second input of the comparison unit. Since the signal at the first input of block 6, exceeds the signal at its second input, the output of the comparison unit will form a logical unit signal and will go to the first input of the logic element "OR" 9, at the output of which there will be a signal to unload the SEPS. This will reduce the load on the mains and after the faulty GA has been switched off by the protection, the first and third unit will operate without overloading and there will be no interruption of power supply to the responsible consumers. If it turns out that all operating GAs are inoperative, the third output of the mode definition block will show a logic one signal and will go to the second input of the OR logic element, which will reduce the network load and, in some cases, increase the time of the monitored parameter change from the warning to the emergency value. During this time, the standby or emergency unit can start.

The proposed SEPS preventive protection approach is universal because, firstly, its use does not depend on the number of units working in parallel; secondly, its use does not depend on the number of failed GAs; thirdly, and most importantly, its use does not depend on the cause and nature of the failure that occurred. As follows from expression (6), the unloading command is given in the presence of the fact of occurrence of the defect and is not determined, by any of its signs. In [18], the process of SEPS technical state identification for the purpose of preventive control is called operational diagnosis. In this case, it is not important which defect has occurred, it is important which cluster of defects the defect belongs to. These faults can be faults characterised by a drop in lube oil pressure, as in the example above, or an increase in diesel engine coolant temperature which results in a sudden drop in the SEPS generating capacity as a result of an inoperative GA being switched off. In this case only the monitored parameters of the GA can be taken into account ($\overline{Z}_r^v$), which are phase variables and functions of the primary parameters of the system $\overline{Z}^v_{r\,\min} \le \overline{Z}^v_r \le \overline{Z}^v_{r\,\max}$ [14].

SEPS can have failures associated, for example, with a failure of the drive motor supply system, where the power output of the power plant decreases for a relatively long time, at least for a few seconds. In this case, fault identification can be carried out by considering the load variation of the operating units [17]. In this case

$$F_i = L_1 \wedge (L_2 > L_{\lim}) \wedge L_3 \,,$$

where F_i defines an inoperative state of the GA, the load of which decreases; L_1 is load-reducing condition of the *i*-th GA when the load of the remaining operating GAs is increased; $L_2 > L_{\lim}$ the event that the difference in active load of the generators is greater than the permissible value; L_3 determines an event corresponding to an increase in the unit load differential.

The versatility of the proposed approach means that it can be used in the preventive management of SEPS, and has a significant impact on improving its survivability.

4 Discussion

Modern SEPS protection systems do not fully meet the operating conditions. In this regard, the classic method of functional and hardware redundancy is still widely used when ships are operating in tight areas, areas with heavy traffic, and in adverse weather conditions. In this regard, a characteristic feature of shipboard power plant operation is the mode "with provision of power reserve", when the number of operating generating units (GPU) exceeds the number required for efficient power supply to consumers. This approach leads to a contradictory situation during the operational phase. On the one hand, the parallel operation of an additional source of electric power leads to reduction of loading of operating machines, that in practice leads to sharp increase in specific consumption of fuel and lubricating oil, coking of engine parts by residues of combustion products, increased wear and reduction of residual life of equipment. On the other hand, in case of failure of one of GA, there will be no network overload and vessel de-energizing [18].

Application of the offered approach together with other methods of preventive protection considered, for example, in [12], [14], [17], [18], will allow to avoid blackout of SEPS at failure of its elements and gradually to exclude operation of a vessel with excessive number of GA. This circumstance will eventually lead to a significant reduction in operating costs for shipping companies, especially those using the operation of floating drilling rigs.

5 Conclusion

The research carried out leads to the following conclusions.

1. The offered method of preventive protection provides decrease in a network load of ship power station before disconnection by protection of the failed GA, and also carries out transition of inoperative electric power system to a mode of correct functioning without a power outage of a vessel. Preventive protection is implemented in the form of SEPS preventive control.
2. The device the functional scheme of which is presented in work, allows simply enough to use the attribute (6) formulated in article, identifying expediency of forming of control action on unloading of SEPS network.
3. The developed approach has universal character both from the point of view of quantity of working and failed GA, and from the point of view of character and type of the arisen failures in SEPS.

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