Rapid identification of the technical condition of a marine electric power system

A Saushev¹, N Shirokov¹ and A Butsanets¹
¹ Admiral Makarov State University of Maritime and Inland Shipping, Dvinskaya Str., 5/7, Saint Petersburg, 198035, Russia

E-mail: SaushevAV@gumrf.ru

Abstract. The article is devoted to the development of approaches to the rapid identification of the technical condition of marine electric power systems. It is shown that the means of technical diagnostics used on modern ships are used only for maintenance and repair of power equipment and are not adapted to provide preventive control in abnormal operating modes. The definition of rapid identification of a technical state as a process of technical diagnostics of a marine electric power system for the purposes of preventive and emergency control of its technical condition is given. The statement is substantiated that the means of technical diagnostics should not only identify the inoperative state of the system elements, but also predict the mode of its operation after disconnecting the inoperative generator set, provide the information necessary to ensure a trouble-free transition of the electric power system to a partially operable state. It is shown that, in contrast to the existing approaches to diagnosing the technical state of the ship's electric power system, it is necessary to take into account the rate of change of the controlled parameter, as well as to determine the probable time of its reaching the maximum permissible value. The necessity of identifying an inoperative element of the system and the implementation of control actions to exclude an emergency until the moment of overloading of the operable generating sets, their shutdown by protection and power outage is substantiated. This information in each specific case will allow the decision-making system of the marine electric power system to formulate recommendations for the maintenance personnel and the preventive protection system on the necessary impacts on the control object in order to avoid an emergency. The main reasons for overloading the marine electric power system have been formulated, algorithms have been developed for the practical solution of the problem of rapid identification of the technical state of the system for cases associated with overloading of serviceable electrical machines due to disconnection of inoperative generator sets.

1. Introduction
One of the most important directions of increasing the efficiency of operation of various electrical systems is the introduction of methods for managing their technical condition (TC) [1]. The practical implementation of this strategy is impossible without the use of technical diagnostics systems that have found their application in various fields of technology, including marine transport [2, 3]. The most important technical system of a modern ship is its marine electric power system (MEPS), on the performance of which the safety of the ship itself and the crew members largely depends. This circumstance determines the use of increased requirements for the reliability of the MEPS functioning, which is one of the determining factors of its accident-free operation. In order to ensure high reliability of the MEPS, the fleet continues to widely use the classical method of functional and hardware
redundancy. In this regard, a characteristic feature of the operation of the marine power plant, which is the most important component of the MEPS, is the mode “with provision of power reserve”, in which the number of operating generating sets (GS) exceeds the number required for efficient power supply to consumers. This approach leads to a contradictory situation arising during the operation phase. On the one hand, the parallel operation of an additional source of electrical energy provides a decrease in the load on operating electrical machines, which in practice leads to a noticeable increase in the specific consumption of fuel and lubricating oil, increased wear and decreased residual life of the power plant equipment. On the other hand, in the event of failure of one of the GSs, there will be no overload of the network and no power outage of the vessel. To the greatest extent, these contradictions are manifested during the operation of vessels of the technical fleet, for example, floating drilling platforms in the drilling and dynamic positioning mode. In this case, one has to choose between high operating costs and an increase in the reliability of the MEPS operation due to redundancy and installation of additional GSs. A possible solution to this contradiction is the use of special technical means in the fleet that increase the safety of the MEPS in abnormal modes caused by the failure of a GS or the control system (CS). In this regard, the development of methods and means of operational identification of the MEPS TC is an urgent task, the solution of which will improve the reliability of the ship's power supply, as well as eliminate the operating costs due to the presence of reserve GSs.

2. Results
The rapid identification (RI) of the MEPS TC is understood as the process of technical diagnostics, the result of which is the receipt of information about the technical condition of the MEPS, intended for the formation of control actions. These influences are necessary to ensure the trouble-free operation of the MEPS in the event of an emergency situation caused by the failure of the MEPS element or an error of the service personnel. Thus, with RI, the results of diagnostics are used not for the restoration of the vehicle, but for the structural or parametric adaptation of the MEPS to the arisen malfunction in order to preserve its correct functioning, carried out with preventive control [4]. In this case, the most important task is to obtain information about the operable or inoperative state of the MEPS. To solve this problem, one should use the information about the boundary of the operability area [5]. An electrical system will be in an operable state if the point \( S(\bar{X}) \) characterizing its technical state belongs to the operability area \( G \), that is, the following condition is met:

\[
S(\bar{X}) \in G
\]  

(1)

The area of operability \( G \) is understood as the set of admissible values of the primary parameters \( \{X\} \) at which all the requirements for the output parameters of the system \( \{Y\} \) and the output parameters of its functional blocks \( \{Z\} \) are fulfilled. Set \( G \) can be thought of as the intersection of sets \( D_x \), \( M_z \) and \( M_y \):

\[
G = D_x \cap M_z \cap M_y
\]  

(2)

where \( D_x \) is the tolerance region of the primary parameters, which has the shape of a bar and in Euclidean space can be described as \( D_x = \bigcap_{k=1}^n D_k \), \( D_k = D_{k\min} \cap D_{k\max} \), corresponds to the internal operability condition; \( M_z \) is the area described by mapping in space primary parameters \( \Phi_{xz} : D_z \rightarrow M_z \), \( M_z = \bigcap_{r=1}^p M_{xz} \) of the tolerance region of the parameters of system's functional blocks \( D_z = \bigcap_{r=1}^p D_{jr} \), corresponding to the internal operability condition; \( M_y \) is the region described by
mapping in space primary parameters $\phi_{M}: D_y \rightarrow M_y$, $M_y = \bigcap_{i=1}^{n} M_i$ of the tolerance region of MEPS output parameters $D_y = \bigcap_{i=1}^{n} D_i$ that corresponds to the external operability condition [6].

The options for the impact on the MEPS, which is in an abnormal operation mode, are very limited and boil down to the possibility of shutting down an inoperative unit or a group of electricity consumers. This circumstance determines the depth of diagnosis at the GS level, which in this case is an element of the system. In this regard, as shown in [7], for control purposes, it is expedient to use phase variables $\{\tilde{Z}\}$, which are functions of parameters $\{\tilde{X}\}$, as controlled parameters. Within the framework of this consideration, GSs are both functional blocks and elements of MEPS at the same time. Therefore, for this case, it is convenient to consider the operability region of MEPS in the space of the GS output parameters.

In general, a MEPS is a self-regulating system that, in normal operation, realizes structural adaptation to the value of the network load. At the same time, this load in the normal mode of MEPS operation forms a control action. Thus, in the event of failure and shutdown of one of the GSs, a situation of overload and shutdown of operable electrical machines is possible. The RI tools must anticipate the MEPS operation mode, characterized by the achievement of the controlled parameters of its limiting value, and carry out operational forecasting, the results of which are used to make a decision by the preventive control system (PCS). For these purposes, it is necessary to take into account the current value of the load value of the consumer network. As shown in [4], it is possible to construct a operability region that takes into account the constraints on control actions characterized by space $M_u$. We will call such an area the area of efficient functioning and denote it as $H$.

$$H = D_z \cap M_y \cap M_u,$$

where $D_z$ is the tolerance region of output parameters of the MEPS ($\{\tilde{Z}\}$), which corresponds to the internal operability condition, has the shape of a bar and in the Euclidian space can be described as $D_z = \bigcap_{k=1}^{n} D_k$, $D_k = D_{k_{\min}} \cap D_{k_{\max}}$; region $M_y$ characterizes external operability conditions of the system under consideration and is represented by the reflection of the output parameters of the MEPS ($\{\tilde{Y}\}$) in the space of parameters $\{\tilde{Z}\} \phi_{M}: D_y \rightarrow M_y$, $M_y = \bigcap_{y=1}^{n} M_y$; region $M_u$ characterizes the space of system's controlling actions [8] and is the reflection of the space of control signals ($\tilde{U}$) in the space of output parameters of functional blocks $\{\tilde{Z}\} \phi_{uc}: D_u \rightarrow M_u$, $M_u = \bigcap_{c=1}^{n} M_c$; the region of operable functioning $H$ characterizes the multitude of permissible values of internal and controlling parameters of a MEPS at which all the requirements to its output parameters are met [5].

Interestingly, a sudden failure of the MEPS and an emergency on a ship caused by a power outage often occur as a result of a faulty GS, the parameters of which change gradually. In this regard, a situation with a failure of the diesel lubrication system is typical, in which the value of the lubricating oil pressure can decrease from the nominal to the minimum permissible value over several minutes, after which the protection is triggered and the GS stops. At the same time, until the inoperative GS is turned off, it continues to supply the network with electricity of the required quality and its failure does not in any way affect the output parameters of the MEPS. After opening the automatic switch of a failed GS, the generated power of the ship's power plant decreases sharply, which can cause an overload of the remaining operable GSs, their disconnection from the network and a sudden failure of the MEPS, accompanied by a power outage of the vessel.

On the other hand, the gradual failure of the MEPS can be caused by a sudden loss of performance of one of the GSs, for example, due to a rupture of a pipe for transferring fuel to a diesel engine. In
this case, the GS supply from the supply tank will stop, but due to the residual fuel, the operation of the GS prime mover will continue for some time. In this case, a redistribution of the load between the operating GSs will occur: the inoperative GS will be unloaded, and the load of the remaining engines will increase. As a result, there will be an imbalance in the loads between the parallel operating GSs and loss of performance of the MEPS. Thus, a sudden failure of one of the GSs will lead to a gradual failure of the MEPS.

It can be seen from the examples given that there is a certain time interval from the moment of the appearance of a defect in the GS until the moment of MEPS failure and the de-energization of the vessel \((t_{em})\). This interval characterizes the inertia of the system in terms of its response to the loss of performance of at least one of its elements. This indicator must be taken into account when developing diagnostic support for MEPS, including RI tools. In this regard, of interest is the time interval from the moment of occurrence of a malfunction to its detection, called in [5] the quick search of the defect \((t_{qsd})\). To use the diagnostic results, the following condition must be met:

\[
    t_{qsd} + t_{sp} < t_{em},
\]

where \(t_{sp}\) is the time required to make a decision, select and implement the impact on the system in order to prevent an emergency.

Due to the fact that the inertia of MEPS in relation to various types of faults of its elements is different, two fundamentally different approaches are used to organize preventive control. The first of them is based on providing the maintenance personnel with information about the deviation of the monitored parameters from the set value and issuing recommendations on the advisability of performing certain operations in emergency situations. The technical means that implement the tasks of this group are passive in terms of responding to operator actions. They do not interfere with its work, carrying out auxiliary management functions, providing information on the ways of solving the problem and the most likely results of the control action. In this case, the maintenance personnel, on the basis of their experience and technical intuition, but taking into account the data obtained, makes a decision on the control action on the control object. Moreover, this decision does not necessarily coincide with the recommendations received from technical devices. In this case, the interaction of the operator and technical devices is considered as a man-machine complex [9, 10], which in practice is presented in the form of decision support systems (DSS). Such equipment includes ship-to-ship collision avoidance systems [11], which inform the ship driver about the most preferable actions, for example, for safe separation in the port water area. At present, the first DSSs have appeared in the fleet that solve the problems of identification of the TC of main engine vehicles [12, 13] on the basis of a wide set of monitored parameters and analysis of the deviation of their values from a given value. In this case, the most important is the task of obtaining diagnostic information in order to carry out maintenance, repair and prevent the evolution of a defect.

In contrast to the existing diagnostic systems, the goal setting of the MEPS RI dictates the need to take into account such an important factor as the rate of change of the controlled parameter and the determination of the probable time for reaching this parameter of its maximum permissible value. This information in each specific case will allow the MEPS DSS to formulate recommendations for the maintenance personnel on the necessary actions on the system in order to avoid an emergency. Based on operating experience and technical intuition, the operator can, instead of the recommended consumer, turn off for a short time another consumer that creates a similar load, but belongs to critical devices of the first category. Stopping this equipment may result, for example, in loss of propulsion and control of the vessel and cannot be recommended by DSS.

The time interval from the moment the controlled parameter reaches the warning value until the moment it reaches the emergency value can be so small that the operator, purely physically, will not have time to make the correct decision. In this regard, within the framework of the PCS, the second approach seems to be the most promising, i.e., the preventive protection of MEPS, which does not cancel the use of the DSS. The preventive protection system (PPS) of the MEPS performs all the functions implemented by the DSS, but at the same time takes on the responsibilities of a human operator in choosing and forming a control effect on the system. This circumstance allows
implementing the scenario of an accident-free transition of the MEPS to a partially operational state even in cases in which the value is very small and does not exceed one second. An important advantage of the PPS is its independence from the human factor, due to which the majority of accidents occur in electric power systems [14–15]. In this regard, it seems possible for the PPS to assess in advance the consequences of possible erroneous actions of the service personnel, to make timely decisions and carry out the necessary operations to neutralize them. In this case, the diagnostic tools that carry out the RI of the MEPS TC will consider the unlawful actions of the operator as a malfunction of the system.

Despite the fact that the reasons for the failure of a GS can be of a different nature and refer to different elements of the GS and its control system, the number of parameters characterizing its technical condition is small. In this regard, it is possible to define a set of faults leading to a strictly defined sign of an inoperative state of a MEPS element and causing the use of a specific control action on the system, as a certain cluster of defects (CD). Such malfunctions, for example, include: sticking of the button adjusting the decrease in the fuel supply to the diesel engine, shorting the active load sensor to the supply voltage, welding the contacts of the contactor of the diesel fuel regulator thus reducing the fuel supply, failure of the fuel pump and rupture of the fuel line. Each of the listed malfunctions has its own characteristic feature used when searching for defects for the purpose of restoring the system operability in accordance with eqs. (1) and (2). Moreover, they all have one common feature (corresponding to the CD)— uncontrolled unloading of the GS:

\[ X_i \rightarrow Z_i \rightarrow F_i \land U_i \rightarrow Y_i, \]  

where \( X_i \) is the event corresponding to the occurrence of the failure of GS in the \( i \)-th CD; \( Z_i \) is the event corresponding to the occurrence of the \( i \)-the indicator of the inoperable state (phase variable in eq. (2)) of the GS; \( F_i \) is the event corresponding to the triggering of protection relating to the \( i \)-th indicator of the inoperable state of the GS or its failure; \( U_i \) is the event corresponding to the presence of a certain combination of external actions at the moment of event \( F_i \); \( Y_i \) is the event corresponding to the emergency situation connected with ship power outage.

Following eq. (5), an emergency situation will occur only in the presence of certain external conditions \( U_i \). For MEPS, this condition is the total load of the network, which exceeds the generating capacity of the system after a failure or protective shutdown of one of the GSs. Consequently, the PPS after signal \( Z_i \) must assess the presence of an event and, before the protection is triggered, exclude it from the logical chain, that is:

\[ X_i \rightarrow Z_i \rightarrow F_i \land \overline{U_i} \rightarrow \overline{Y_i}. \]  

In this regard, the means of the RI of MEPS TC must determine and provide the PPS with information on the presence of a diagnostic sign of an inoperative state of the GA (\( Z_i \)) and the required amount of change in external actions on the system, at which event \( \overline{U_i} \) will occur at the time of event \( F_i \). At the same time, the TC RI provide information and means of protection that provide emergency control of the GS, aimed not at preventing an emergency, but only at mitigating its consequences [8]. In this case, the diagnostic results are usually limited to determining the moment at which the monitored parameter reaches its maximum permissible value. Thus, the TC RI can be defined as the process of technical diagnostics of MEPS for the purposes of preventive and emergency control of its technical state.

In contrast to the task of identifying the MEPS TC in order to carry out effective management in the field of maintenance and repair, the TC RI operates with a small number of parameters, which are determined, as a rule, by the system protection means. The work [16] considers the MEPS failures associated with abnormal operating modes, which are caused by the shutdown of the protection of at least one of the GSs operating in parallel.

3. Discussion
With the development of highly integrated control systems for the technological processes of the vessel, the reliability of the results obtained by the RI of MEPS TC will improve. In this regard, it is of
interest to use the information transmitted from the means of navigation and other technological systems that determine the operation mode of the MEPS. This circumstance will make it possible to more effectively use the PCS in emergency situations of MEPS operation, especially on ships of the technical fleet, floating drilling platforms, ships of the navy, or on unmanned vessels in the future [17–18].

4. Conclusion
1. The means of technical diagnostics used on modern ships are intended only for the implementation of effective maintenance and repair of power equipment. They are practically not adapted to provide rapid information about the technical state of MEPS, suitable for providing preventive control in abnormal operating modes.
2. The means of rapid identification of the MEPS TC should not only identify the inoperative state of the system elements, but also predict the mode of its operation after the inoperable GS is turned off, provide information to the PCS about the necessary correction of external conditions to ensure an accident-free transition of the MEPS to a partially operable state.
3. The proposed algorithms for the rapid identification of the technical condition allow for preventive control of the MEPS in the event of a failure of its elements.

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