This paper reports the synthesis of the main processes for the basic control over a complex technical vessel system. The issue related to the semantics of the description and the method for decomposing management tasks has been proposed to resolve in the context of the synthesis of the program to coordinate control over vessel technical systems and complexes with a sophisticated structure. An example of a five-unit ship's automated electric power system (SAEPS) for the predefined level of generated power, taking into consideration the efficiency criteria, was used to synthesize the algorithms that execute transitions from one level to another while taking into account the pre-emergency and emergency states of SAEPS. The organization of the sequential process of enabling/disabling generator units (GUs) implies developing a program for managing the coordinator's supervisor as part of a distributed two-level hierarchical structure of SAEPS control when the load changes. The sequence of operations to launch, synchronize, transfer the loading, and stop GU is based on the formation of GU optimal composition, the distribution of loads among GUs running in parallel, and the implementation of the program for optimizing the primary engine of the power plant.

The reported principles for constructing GU composition control procedures based on the principle of "rigid and flexible" thresholds have made it possible to build a diagram of adjustment of the time delay in enabling GU dependent on the demanded power. It has been proven that the proposed technique improves the reliability of SAEPS operation as it eliminates possible emergency modes when false control combinations are assigned. Databases on the quantity of GUs, their technical condition, loading, fuel consumption, and environmental parameters have been built. The synthesis of control over a five-unit SAEPS has made it possible to determine the algorithmization procedure based on using an extended data array and simplify the functioning algorithm involved in the operations of choosing the structure for a five-unit SAEPS

Keywords: efficiency, technical operation, quality, control system, complex

SOLVING A TASK OF COORDINATED CONTROL OVER A SHIP AUTOMATED ELECTRIC POWER SYSTEM UNDER A CHANGING LOAD

Vitalii Budashko
Doctor of Technical Sciences,
Associate Professor
Department of Fleet Technical Operation*
E-mail: bvv@te.net.ua
Valerii Shevchenko
PhD, Associate Professor
Department of Ships Technical Operation*
E-mail: vash4891@gmail.com
*National University
«Odessa Maritime Academy»
Didrikhsona str., 8, Odessa, Ukraine, 65029

1. Introduction

Global practices show that the research into sophisticated technical systems and complexes (STS and C) as the control and automation objects ultimately results in the acquiring of semantic information in the form of requirements for the scope of functions and a list of control tasks. It is obvious that the more *a priori* information is available about objects the fuller and more accurately the properties of the object are reproduced. This is achieved by a certain redundancy of information, the existence of specific data, parameters, etc. Primary and secondary semantic information is used to describe the tasks and functions of control. Obtaining secondary semantic information is considered to be a continuation of the knowledge about an object, which involves the following:

a) the identification of the most robust and characteristic features;

b) the results of the analytical-synthetic and logical conversion of primary semantic information, which is reproduced by symbols. Basically, the development of such symbol-based systems (thesaurus) is in the plane of designation of descriptors within it, which carry not only a load of meaning but also facilitate the reading of model semantic information.

On the other hand, devising methods for effective control over the technological processes on a vessel and operation of marine vehicles of various types is generally limited to a significant set of contradictory and, in some cases, mutually exclusive situations. Research and design of compound STS and C necessitate improving energy transmission processes based on the principles of dynamic control and stabilization of a vessel's power system while minimizing inevitable losses.

Given this, the designations of the main descriptors are supplemented with the symbols of international designation and indexing of SAEPS elements, as well as the technological process, for example, *ST* (*start*), *SP* (*stop*), *STQ* (*start-quickly*), *EM* (*emergency*), etc. To extract and generate information about membership, many auxiliary characters are used, related to the root of the descriptor $\varepsilon=(N, i, j, l...)$, where $N=\{N_{BAS}\}$ is a set of natural numbering N_{BAS}, in which the descriptor $\underline{BAS}$ denotes the basis of numbering. For example, $N_m=\overline{1,m}$ is the numbering of

GU set $GA(N_m)=\overset{m}{\underset{}{\cup}}GA(i)$; m – SAEPS assembly; i, j – each number in a set. Descriptors can include double numbering, for example, $EM(i, j)$, $i \in N_m$, $j \in N_{TRD}$, which indicates a signal about GU failure with the i-th serial number for the j-th parameter. A full set of emergency signals, in this case, is denoted $EM(N_m \times N_{TRD})$. Proposed thesaurus are constantly supplemented with descriptors as the tasks are solved, and individual descriptors are entered into the texts of requirements for automated control systems.

Thus, to summarize, the existing techniques to improve the reliability of SAEPS operation require the formation of coordinated control algorithms, which would minimize possible emergency modes when assigning false control combinations.

There are also errors in the sequence of enabling GU related to the incompleteness of the specified combination, an unspecified sequence, the indication of one GU several times in one sequence, and the coincidence of binary sets of different combinations in a sequence. Therefore, solving the tasks of coordinated control over SAEPS under a changing load is a relevant scientific and technical issue for the maritime industry.

2. Literature review and problem statement

Modern research is advanced towards improving the principles for synthesizing the systems that can effectively control the synchronization processes involving generator units (GUs) as part of compound technical systems and complexes (STS and C) [1]. Based on the application of resultant functions, the stages in solving the tasks of controlling the synchronization of frequency fitting in a hierarchical sequence [2] are determined. The functioning of STS and C control elements is analyzed using integrated optimization criteria and dual control principles [3].

In accordance with the requirements stated in [4], control over the structure of generator units (GUs) under a changing load should be carried out by selecting the *PRSEL* reserve and forming commands to start *ST(i)* or stop *SP(i)*. GU is enabled/disabled when the load reaches the upper *PH(l)* or lower *PD(l)* load thresholds for l parallel operating and backup GUs in accordance with the valid order $SQ(i) \in SQ(N_{SQ})$. Similarly, *PRST* start-up programs or *PRSP* stop programs, *PRSY* synchronization, *PRSH* distribution, or *PRUNL* load transfer are executed [5].

Hence, it follows that the coordinator program, after each technological cycle o T_{TC}, should determine the number of GUs connected to the main switchboard (MSB). That implies executing a subroutine of *SBCNT* counting, which generates a predicate *WRK(l)=I*, if l GUs are in operation, and calculating the required number of GUs according to the load. *PRNRY* program generates predicates *NRY(l)=I*, *NRY(l+1)=I*, *NRY(l−1)=I* for, respectively, l, l+1, l−1 parallel operating GUs to select a backup GU using the *PRSEL* program to start *PRST* or stop *PRSP* [6]. The upper loading thresholds are determined on the basis of calculating a load P_L permissible under the technical conditions per a single GU and the required supply of generated power $\nu_1 P_L$, $0 < \nu_1 < 1$. The lower thresholds are determined from calculating the power reserve $\nu_2 P_L$, based on economic expediency, $0 < \nu_2 < 1$. In this case, the generation of predicates *PH(l)*, *PD(l)* are written as the following rules:

while *PRNRY* do: $\sum_{i=1}^{l} P_G(i)$

if $\sum_{i=1}^{l} P_G(i) \geq \left(\sum_{i=1}^{l} P_D(i) - \nu_1 P_D \right)$,

then *PH(l)* else

if $\sum_{i=1}^{l} P_G(i) \leq \left(\sum_{i=1}^{l} P_D(i) - \nu_2 P_D \right)$ (1)

then *PD(l)* else if do,

where $P_G(i)$ is the current load on the i-th GU. The power $P_G(i)$, depending on the specifications, would vary within:

$$\left(1 - \frac{1+\nu_2}{l} \right) P_D \leq P_G(i) \leq \left(1 - \frac{\nu_1}{l} \right) P_D, \quad P_D = P_N K_{RCL}, \quad (2)$$

where K_{RCL} is the power conversion coefficient when changing environmental conditions; $\left(1 - \frac{1+\nu_2}{l} \right)$ is the load factor; P_N is the GU rated power. Expression (2) shows that an increase in the number l of GUs running in parallel leads to an increase in the load factor. Fig. 2 displays a diagram of GU structure control based on the principle of "rigid" loading thresholds at $\nu_1=0.2$ and $\nu_2=0.4$ regarding the control over a 4-unit SAEPS.

It follows from the analysis of (1), (2) that one can change the loading thresholds of SAEPS by varying the parameters ν_1, ν_2, P_L, separately or in different combinations. That is, it is possible to implement many ways to control SAEPS based on the principle of "flexible" loading thresholds for units. However, these techniques would not be exhaustive because they imply control over generated power only. If we take into consideration the possibility of load control (by disabling/enabling part of consumers and prohibiting enabling them at a certain peak of loading), as well as provide for the use of electricity storage devices, the scope of control tools could be significantly expanded. In this case, it is necessary to set a task on the time delays in starting a backup GU.

In order to filter short-term load emissions associated with the start or repeatedly short-term work of consumers, the techniques for the time distribution of emissions are used, and, to coordinate the GU overload characteristics – time delays (a method of amplitude-time division).

The random time function $p=x(t)$ most fully describes changes in the power consumption by SAEPS. It is assigned by the mathematical expectation $M_x(t)$, variance $\sigma_x^2(t)$, and a correlation function $K_x(\tau_r)$. As follows from some experimental data processing [7], the random process of changing the load under the running and stationary modes is characterized by a correlation relation, which decreases sharply as the τ_r interval increases. Therefore, already in the region $\tau_r > 1$, a random process can be considered ergodic, and a change in load is characterized by a random value $\bar{x}$. That is why the energy forecast $\bar{S}$, necessary to provide for an additional, higher than x_{PH}, load in the time intervals after t_{PH}, requires that formulae for performing calculations should be derived.

Thus, to summarize, the existing ways to improve the reliability of SAEPS operation do not completely eliminate but only minimize possible emergency modes when assigning false control combinations. In addition, there are errors in the sequence of enabling GU if the specified combination is incomplete, the sequence is not set, one GU is included several times

in the same sequence, and when the binary sets of different combinations of the sequence coincide.

The tasks related to SAEPS control based on the principle of "flexible" loading thresholds, considered in [8], necessitate a detailed elucidation of optimization tasks regarding the minimization of fuel consumption. SAEPS that are operated on modern vessels are characterized by a low load factor of installed capacity [9], and, as a result, low efficiency. That is explained not only by the existing principles of SAEPS configuration but also by the imperfect organization of its operating modes. The tasks considered are typically solved by means of approximate procedures, seeking to improve only one criterion – excessive redundancy of energy under the basic modes of vessel operation [10]. When calculating the required power and permissible load values of SAEPS, they consider the average or limit values of unmanaged variables (request for loading, temperature, pressure, humidity, etc.) not taking into consideration the possible range of their change [11]. That leads to a decrease in the technical and economic indicators of STS and C. Pay special attention to the need to account for weather conditions when calculating the upper levels of loading the diesel engines in order to avoid thermal overloads [12]. It is known that the maximum load of vessel diesel engines begins to decrease with an increase in ambient air temperature exceeding 27 °C, humidity – exceeding 60 %, and with a decrease in barometric pressure below 101.3 kPa [13]. The influence of these factors in modern systems is taken into consideration selectively while they act interdependently.

The manufacturer "*Wartsila-Sulzer*" [14] indicates in its diesel engine specifications that the normal parameters of the environment are the atmospheric pressure of 720 mm Hg, the air temperature of 20 °C, and humidity of 70 %. It is relevant to warn that any deviation from these values, especially the temperature of the suction air and pressure, significantly impairs the characteristics of the engine. The most characteristic changes, when sailing a vessel in the tropics, is a decrease in power, an increase in the specific fuel consumption and temperature of the exhaust gases, caused by a decrease in the weight charge of the air and an increase in its initial temperature [15]. That is explained by the fact that a decrease in the weight charge of air ρ_k leads to a decrease in the coefficient of excess air $\alpha = k\eta_v\rho_k g_C$, , where η_v is the coefficient of filling the cylinder, and g_C is the cycle fuel supply. In turn, a decrease in α would cause a decrease in the indicative coefficient of efficiency η_i and, as a result, in the effective efficiency of the engine $\eta_e = f(\alpha)$. As a result, the torque of the diesel engine would begin to decrease while the rotation frequency controller, in order to stabilize the frequency of the generated current, would begin to increase the fuel supply g_C, which could lead to overload in terms of mean indicative pressure. At the same time, the temperature of the exhaust gases would start to increase. Excessive increase in the temperature of the exhaust gases forces to reduce the cycle fuel supply, which leads to a total decrease in the GU generated capacity.

A study into the operating modes of a 6-unit SAEPS on the vessels of type "*Marco Polo*" reported in [16] showed that typical fluctuations in external conditions were within the following ranges: t, °C=20÷45; φ=60÷85 %; P_a=750÷780 mm Hg. This leads to a change in the maximum permissible, in terms of thermal load, power – from 735 to 604 kW (by 18 %). Frequent fluctuations in load and environmental parameters over 24 hours make it difficult for service personnel to solve the task of determining the optimal GU configuration. Therefore, in order to avoid the risks of thermal overload, it is necessary to main-

tain an excess supply of generated capacity. For example, under a running mode, instead of the possible four, there are five GUs operated at low and medium loads [17]. That leads to a decrease in mechanical efficiency, and, as a result, a decrease in the effective efficiency $\eta_e = \eta_i\eta_m$. Analysis of the operating conditions of diesel generators (DG) [18] reveals that the average load of SAEPS is 25–30 % of the total rated power of generators. On ships, certain types of DG, during almost all working hours (90 %), are loaded by less than 50 %. There are cases of failure of butterfly and frame bearings of engines due to long-term operation under small loads [19]. For example, when a single DG is operated with a load of 270 kW instead of two DGs running in parallel with a load of less than 50 % N_{enom}, the daily savings in fuel reach 0.8 tons and 10 liters of circulation oil. Thus, the elimination of these shortcomings makes it possible to obtain a significant technical and economic effect. Resolving this issue is associated, first, with the development of algorithms for estimation and continuous control of permissible loads for diesel engines, and, second, with the development automatic control system (ACS) of such engine which take into consideration changes in environmental parameters.

In this case, the mode of operation of the diesel engine can be adjusted by reducing fuel consumption per value ΔG_T by redistributing loads among the GUs running in parallel *PRSH*. By connecting the drives *ONACC*, disabling secondary *OFCNS* for a given mode of the consumer or reducing the temperature of the supercharged air T_S by increasing the cooling water inflow in the cooling system [20]. It should be noted that the $\alpha_C(i) > \alpha_{opt}$ zone is also undesirable since an increase in α_C leads to a deterioration in the combustion process, an increase in heat losses coming with gases, and a decrease in the indicative efficiency [21].

Some studies, for example [22], have made it possible to synthesize the optimization algorithm *PRORT* for the diesel engine modes of operation, provided a condition is accepted that the system contains all the necessary sensors $\{P_S, P_i, T_S, G_T, \varphi, t^G\}$, where φ is air humidity, t^G is the exhaust gas temperature. The controlling elements $\{SMW, SMF\}$ are the servomotors, which would adjust water supply *SMW* to cool the supercharged air and fuel supply *SMF*.

A technique chosen to organize the work of programs similar to PROPT is an interruption procedure with a sampling period T_{CO} predetermined by the dynamic properties of the super-air cooling system and diesel engine. To facilitate the procedure of logical programming, the PROPT program is represented as a set of PROPT=$\{SBHTP, SBALF, SBSM, SBCNT\}$ subroutines. Namely, subroutines *SB* for the control of high temperature *SBHTP*, calculations of deviations of the coefficient of excess air *SBALF*, control of servomotors *SBSM*, and calculations of the duration of enabling a servomotor C*NT* [23]. In this case, the rules of the system operation are re/presented in the form of instructions:

$$\text{while } T_{TC} \text{ do } PROPT, SBALF, SBHTP,$$
$$SBSM, SBCNT \text{ do}$$
$$\text{while } SBALF \text{ do:} \left(t_i^G - t_{dop}^G = \Delta t^G\right)$$
$$\text{if } \Delta t^G > 0 \text{ then } HTP$$
$$\text{go to } SBHTP \text{ else} \tag{3}$$
$$\text{do:} \left(\alpha_C(i) = f\left(P_S, P_i, T_S, G, \varphi\right), \Delta\alpha_C(i) - \alpha_{opt}\right)$$
$$\text{if } \left|\Delta\alpha_C(i)\right| > \Delta\alpha_{dop}$$
$$\text{then go to } SBSM \text{ else if do,}$$

that is, the implementation of the *SBALF* subroutine always begins with the control of the temperature of exhaust gases t^G and, if it is above the norm (HTP=1), then the transition to *SBHTP* is carried out. Otherwise, $\alpha_C(i)$ is calculated; it is compared with the optimal α_{opt} value, if the deviation exceeds the permissible one, there is a transition to *SBSM*, otherwise – the end of the program.

The BHTP subroutine is executed according to the following rule:

$$\text{while } SBHTP \text{ do if } HTP\,\&\,\overline{WVOPN} \text{ then}$$
$$ONSMW(INC)\,\text{do}\,B_W = f\left(\Delta t^G\right) \text{go to } SBCNT \text{ else}$$
$$\text{if } HTP\,\&\,WVOPN\,\&\,DCF \text{ then } ONSMF(DEC) \text{ do} \qquad (4)$$
$$B_F = f\left(\Delta t^G\right) \text{go to } SCBNT(BF) \text{ else if do,}$$

that is if the temperature of exhaust gases is higher than the norm (HTP=1) and the valve of the super-air cooling system is not completely open $\overline{WVOPN}$, then the *SM* servo motor is turned on *ON* to increase the *INC* supply of cooling water *ONSMW(INC)*. At the same time, the time of its operation B_W is calculated depending on the temperature exceeded and a transition to the *SBCNT* countdown program of servo motor operation is carried out. If at the raised temperature of gases, the water valve appears completely open *WVOPN* and, at the coordinator level, the decision *DCF* to lower the temperature of gases is made, the servomotor of the *SMF* controller is enabled *ON* to decrease fuel supply *ONSMF(DEC)*. The time of its operation B_F is calculated; a transition to the subroutine of the time interval $SCBNT(B_F)$ is executed, otherwise – the end of the subroutine.

Other {*SBSM, SBCNT*} routines are executed according to the following instructions:

$$\text{while } SBSM \text{ do if } \left(\Delta\alpha_c(i)<0\right)\&\,\overline{WVOPN}$$
$$\text{then } ONSMW(INC) \text{ do } B_W = f(\Delta\alpha) \text{go to}$$
$$SBCNT(B_W) \text{ else if } \left(\Delta\alpha_c(i)>0\right)\&\,\overline{WVCLS}\,\&\,\overline{HTP}$$
$$\text{then } ONSMW(DEC) \text{ do } B_W = f(\Delta\alpha) \text{go to}$$
$$SBCNT(B_W) \text{ else if } \left(\Delta\alpha_c(i)<0\right)\&$$
$$WVOPN\,\&\,DCF \text{ then } ONSMF(DEC) \text{ do } B_F =$$
$$= f(\Delta\alpha) \text{go to } SBHTP \text{ else if do;}$$

$$\text{while } SBCNT(B_W) \text{ do: if}\left(\Delta B_W(t+1)-1(CNT)=0\right)$$
$$\text{then } OFSMW \text{ else if do;}$$

$$\text{while } SBCNT(B_F) \text{ do: if}\left(\Delta B_F(t+1)-1(CNT)=0\right)$$
$$\text{then } OFSMF \text{ else if do,} \qquad (5)$$

that is, in case of deviations in the total coefficient of excess air from the optimal one, servo motors are enabled in the appropriate direction if it is possible to adjust. If not, when the valve is already fully open, control is carried out influencing the fuel supply if a coordinator approves of this (*DCP*=1). When the temperature of exhaust gases is exceeded, the process is sent to the *SBHTP* subroutine.

The implementation of *SBCNT* subroutines is carried out by comparing the result of subtracting the number from the remaining ones that reflects the size of the time interval $\Delta B(t+1)$, unit $1(CNT)$ of the account, which is usually equivalent to the duration of the main stroke T_{TC}.

Thus, for each additional $P(i)$, finding $\min F_{\Sigma}^{E}\left(P_{\Sigma}\right)$ is reduced to determining, by Lyapunov method [24], a global minimum of the function $F_i\left(P(i)\right)+F_{\Sigma-i}\left(P_{\Sigma}-Pi\right)$, and can be determined by simple sorting. Simultaneously with the choice of the GU configuration, the optimization of load distribution is solved.

In the process of operating a vessel's SAEPS under a static mode, or during the period of change in its structure under the conditions of load optimization, emergencies and pre-emergencies may occur, caused by the run-out of controlled parameters beyond the maximum level. For these cases, the study must provide for the algorithms that would form commands to enable a backup GU and disable a failed GU, taking into consideration the assigned sequence.

3. The aim and objectives of the study

The aim of this study is to establish operating rules for the algorithm of optimal control over SAEPS when changing the load, GU technical condition, and environmental conditions. This would make it possible to avoid errors in the sequence of enabling GU when the specified combination is incomplete, the sequence is not set, when one GU is included several times in one sequence, and when the binary sets of different combinations of sequence coincide.

To accomplish the aim, the following tasks have been set:
– to analyze the load characteristics of the units, decompose control tasks, and build databases that would determine the number of working GUs, their technical condition, load, fuel consumption, and environmental parameters;
– to determine the total load on SAEPS, analyze equivalent characteristics of fuel consumption, select the optimal one according to the criterion of the minimum fuel consumption, the GU configuration taking into consideration restrictions on the upper and lower loading thresholds;
– to determine the power conversion coefficient k_{RCL} and adjust the upper and lower load thresholds, the optimal load distribution in terms of technical condition and meteorological conditions;
– to optimize the operations of starting, synchronizing, transferring a load, and stopping GU, related to the formation of GU configuration under the conditions of optimality $F_{\Sigma}\min(P_{\Sigma})$. To improve the PROPT programs for optimizing primary GU engines, which implements the criterion$(\alpha_C-\alpha_{opt})\rightarrow\min$.

4. Materials and methods for synthesizing basic algorithms for the higher levels of SAEPS control

Determining the current value of the upper loading threshold for SAEPS implies considering the influence of meteorological conditions of a vessel's voyage. We determined the dependence of change in indicative power according to a procedure recommended by the International Congress of Motor Builders that employed K. Zinner's formulae [25]:

$$k = \frac{N_{iT}}{N_{iN}} = \left(\frac{D-P_P}{99}\right)^m \left(\frac{293}{T}\right)^n \left(\frac{293}{T_w}\right)^q, \qquad (6)$$

where N_{iT}, N_{iN} is the indicative power under the current and normal conditions, respectively; D is the barometric

pressure, kPa; P_P is the partial pressure of water vapor, kPa; T, T_w is the air temperature at suction and cooling water, respectively, K.

Managing the sequential process of enabling/disabling GU taking into consideration the emergency states of GU and control influences from the operator. We propose a sequence of synthesizing the algorithms for the program that controls the supervisor of the control system coordinator with a distributed two-level hierarchical structure.

Procedures for the transition from one level of generated power to another, taking into consideration the efficiency criteria, are executed taking into consideration the pre-emergency and emergency states of SAEPS and control influences from the operator. The structure and information connections of the control system, taking into consideration the requirements for the examined SAEPS, are strictly related to the principle of concentrating system control functions associated with the properties of adaptation and optimization.

The partial pressure is determined from the i-d diagram of moist air (Fig. 1) [26] as a function of temperature and humidity of the environment; the indicators of the extent of m, n, q are determined depending on the normal values of the total coefficient α_C of excess air [27]:

$$m = \begin{cases} 0.1, \text{if } 1.7 < \alpha < 2.1, \\ 0.3, \text{if } \alpha < 1.7; \end{cases}$$

$$n = \begin{cases} 0.2\eta_M, \text{if } \alpha > 2.1, \\ 0.35\eta_M, \text{if } 1.7 < \alpha < 2.1, \\ 0.55\eta_M, \text{if } \alpha < 1.7; \end{cases}$$

$$q = \begin{cases} 0.2\eta_M, \text{if } \alpha > 2.1, \\ 0.3\eta_M, \text{if } 1.7 < \alpha < 2.1, \\ 0.6\eta_M, \text{if } \alpha < 1.7. \end{cases} \qquad (7)$$
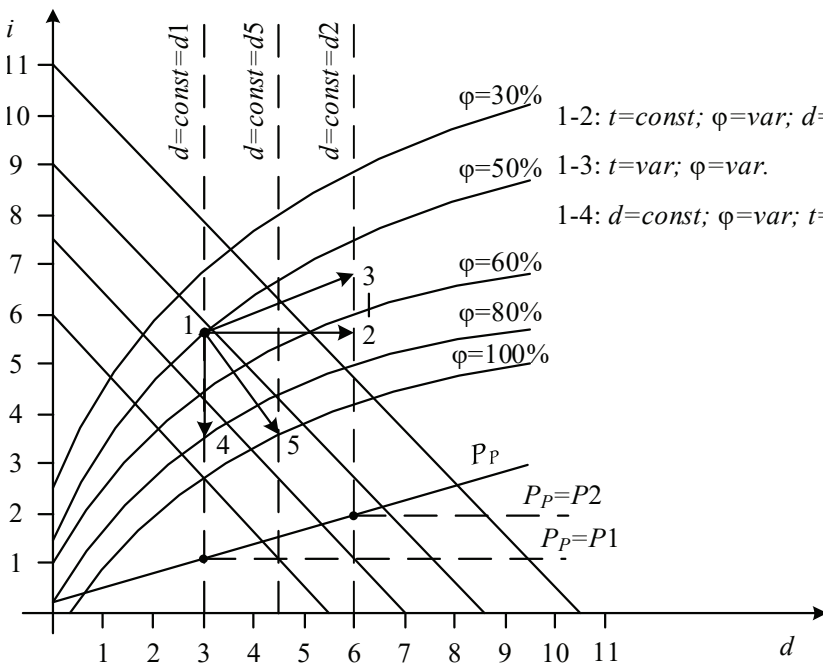

Fig. 1. Effect of relative humidity change on the partial pressure P_P

This relationship can be represented in the form of a nomogram (Fig. 2) [27] where the consumption of humid and dry air is related via the following ratio:

$$\frac{G_{BC}}{G_{BB}} = \frac{1}{1+1.61d_i}. \qquad (8)$$
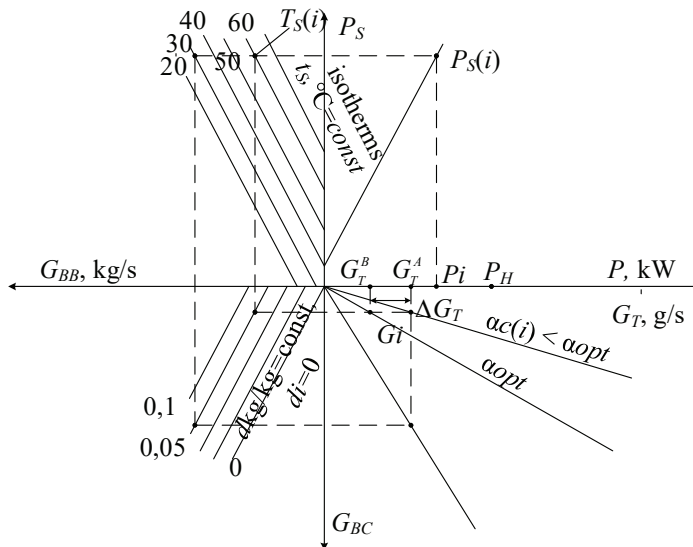

Fig. 2. Dependences of wet and dry air consumption on power

A value of d_i is found by using wet air tables or an i-d diagram. The nomograms in Fig. 2 demonstrate that when the load of DG is $P(i)$ and the fuel consumption is G_T^A, other operating parameters would be characterized by the set $\{P_S(i)$, $T_S(i)$, $d_i\}$, then the total coefficient of excess air would equal $\alpha_C(i) < \alpha_{opt}$ less than the optimal value. The consumption of dry air is ΔG_{BC} less than the norm, which would worsen the combustion process and lead to an increase in the temperature of exhaust gases.

Maintaining the optimal operation mode of each DG by adjusting α_C helps α_C solve the task of minimizing fuel consumption, but, for the current value of the system load, it is difficult to ensure the normal thermal mode of the diesel engine and the maximum value of its efficiency (Fig. 3) [27].

However, in general, for SAEPS, the objective function of total fuel consumption may not have a global minimum:

$$F_\Sigma = \sum_{i=1}^{l} F(i) \to \min,$$

$$F(i) = g_e(i) P_D(i),$$

$$F_\Sigma = g_{e\Sigma} P_{D\Sigma}; \; g_{e\Sigma} = \sum_{i=1}^{l} (i) g_e(i); \quad (9)$$

where F_Σ, $F(i)$ is the fuel consumption per hour of SAEPS operation and the i-th GU; $g_{e\Sigma}$, $g_e(i)$ is the specific fuel consumption by SAEPS and the i-th GU; P_Σ and $P_D(i)$ are the loads of SAEPS and the i-th GU; $\lambda(i) = P_D(i)/P_\Sigma$ is the load share of

the i-th GU; the prerequisite for the existence of a minimum of F_Σ is the equality to zero of the full differential $dg_{e\Sigma}$ (Fig. 4) [27]:

$$dg_{e\Sigma} = \sum_{i=1}^{l} \frac{\partial g_{e\Sigma}}{\partial P_D(i)} dP_D(i) = 0. \qquad (10)$$
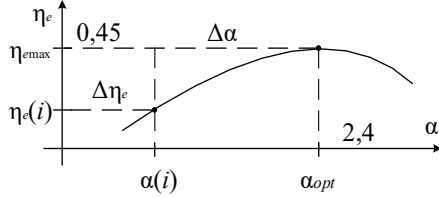

Fig. 3. Dependence of the diesel engine efficiency on the coefficient of excess air at 65 %
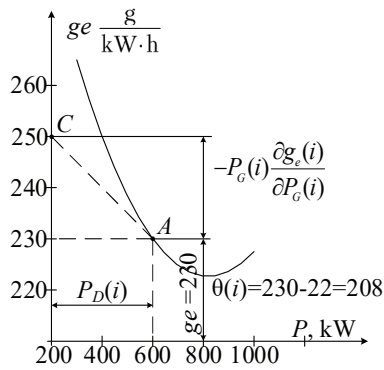

Fig. 4. Determining the parameter g_e

At the next stage, in accordance with the GU loading diagram in Fig. 5, it is necessary to consider issues related to the logical module *SBCNT*, which gives rise to a predicate:

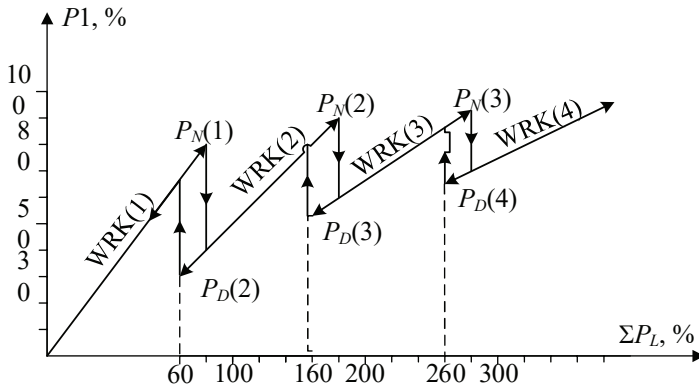$$WRK(l) \in WRK(N_l), \ l \in N_l, \ N_l = \overline{0,m}, \ |N_l| = m+1, \quad (11)$$

Fig. 5. Diagram of control over GU configuration based on the principle of "tough" loading thresholds

To find an extremum of the function $g_{e\Sigma}$, a load distribution method is used so that the values $\theta(i)$ for each GU at the points of the predefined mode accept equal values, that is,

$$\theta(1) = \theta(2) = \ldots = \theta(i) = \ldots = \theta(l),$$

where

$$\theta(i) = \frac{\partial \left(P_D(i) g_e(i) \right)}{\partial P_D(i)} = g_e(i) + P_D(i) \frac{\partial g_e(i)}{\partial P_D(i)}. \qquad (12)$$

In this case, a sufficient condition for optimal load distribution is the $g_{e\Sigma} \to \min$ minimum requirement, which is met at $d^2 g_{e\Sigma} > 0$. If GUs have the same load characteristics, then, in order to satisfy the required condition, it is necessary to distribute the load evenly at the points of SAEPS operation modes. To meet the condition of sufficiency, the following conditions must be satisfied:

$$\left\{ 2\frac{\partial \theta}{\partial P_D(i)} > 0; \ 3\left(\frac{\partial \theta}{\partial P_D(i)}\right)^2 > 0; \ldots; \ l\left(\frac{\partial \theta}{\partial P_D(i)}\right)^{l-1} > 0 \right\}, \quad (13)$$

this is achievable if all derivatives from $\left(\dfrac{\partial \theta}{\partial P_L(i)}\right)$ are positive.

This position is extremely important since it makes it possible to calculate, under optimality conditions, the lower load thresholds of SAEPS (Fig. 6) [27]. In this case, according to Fig. 6, the region of generators' operation, limited by valid boundaries, may increase, then formula (2) is simplified to take the following form:

$$P_{PD} \leq P_G(i) \leq \left(1 - \frac{\nu_1}{l}\right) P_L. \qquad (14)$$

However, during operation, the load characteristics of engines change [28], which can lead to their significant scattering and setting the task of optimizing the operation modes of SAEPS taking into consideration the actual load characteristics [29].

To solve the problem in such a statement, a method of dynamic programming [30] is used, which makes it possible to choose the most likely (quasi-optimal), for a certain region of operation mode, GU configuration in compliance with all restrictions. To perform the dynamic programming algorithm [31], equivalent characteristics $F_\Sigma^E(P_\Sigma)$, must be constructed, which are the dependences of the minimum fuel consumption by assemblies on their total power, that is:

$$F_\Sigma^E(P_\Sigma) = \min\left\{ F_i(P(i)) + F_{\Sigma-i}(P_\Sigma - Pi) \right\}. \qquad (15)$$

Accounting for the mechanical efficiency η_M, the power conversion coefficient k_{RCL} is determined from the formula $k_{RCL} = (k - 0.7(1-k)/\eta_M)$, and the permissible power P_{Di} of the i-th DG – from expression $P_{Di} = k_{RCL} \cdot P_N$ [32]. It is obvious that when the air temperature changes from 27 to 62 °C, the k_{RCL} value varies from 0.96 to 0.88, and when the three parameters change (T, D, φ) – from 0.93 to 0.85. In the analysis, it is accepted that the temperature of the cooling water varies within $25 \div 35$ °C [33]. Thus, the law is established for determining k_{RCL} whose application in algorithms (1) renders flexibility in the generation of predicates $PH(l)$, $PD(l)$. This law makes it possible to operate GU in regions as close as possible to the barrier characteristics while ensuring reliability and safety, and thereby improve a SAEPS load factor [34].

There is another way to improve control over SAEPS by maintaining the optimal mode of operation of the main engine if we accept as a criterion for assessing the mode the stability of the value for the total coefficient of excess air [35]. That is, $\alpha_C - \alpha_{opt} \Rightarrow \min$, where α_C is the current value, α_{opt} is the optimal value of the coefficient for a given mode of the diesel engine operation, at which the maximum possible power is achieved at the minimum fuel consumption

and the permissible temperature of exhaust gases [36]. In the nearest approximation, the total coefficient of excess air can be determined [37] from the readings of measuring devices, using the following expression:

$$\alpha_C = A_1 \frac{P_S}{T_S G_T}\left(\frac{1}{1+1.61 d(i)}\right), \tag{16}$$

where $A_1 1$ is the coefficient that takes into consideration the structural features of the diesel engine at the constant product of the filling and blowing coefficients; P_S and T_S are the air pressure and air temperature in the turbocharger; G_T is the fuel consumption per unit of time; $d(i)$ is the air humidity content under the i-th static mode.

At this stage, there is a need to generate primary predicates $P_N(N_l)$ and $P_D(N_l)$, which identify that the load has reached the upper and lower loading thresholds for GU.

In this case, emissions should not be taken into consideration if their duration is shorter than the specified time interval $t_{PN}(min)\pm\Delta\tau_{PN}$, where $\Delta\tau_{PN}$ is the time interval that corrects the instability of emission duration (Fig. 8).

In the case when $t_{PN}(min)$ is over and the ejection value $P_N(l)=1$, then the value for the second delay time interval is selected depending on the established amount of power ΔP_N, in accordance with the load characteristics of GU, for example, as follows

$$t_{PN} = \begin{cases} t_{PN}(min), \text{ if } \Delta P_{PN} \geq \Delta P_{PN}(max), \\ k_1(\exp(-\Delta P_N)), \\ \text{if } \Delta P_{PN}(min) < \Delta P_{PN} < \Delta P_{PN}(max), \\ t_{PN}(max), \text{ if } 0 \leq \Delta P_{PN} < \Delta P_{PN}(min), \end{cases} \tag{17}$$

or, as shown in Fig. 7, to count the delays $t_{PN}(min)$ and $t_{PN}(j)$, one should predict the subroutines of the timer $PR1TM$ and $PRTM$, giving rise to their corresponding predicates $T1PN$ and TPN according to the following rule:

if $P_N(l)$ then $PR1TM$ else $f(i)$

while $PR1TM$ do procedure: B_{PN}^{min}, $B_{PN}^{min} - r_{CNT}$ do;

if $B_{PN}^{min} - r_{CNT} = 0$ then $T1PH$ else $PR1TM$ fi;

if $P_N(l)$ & $T1PN$ then $PRTM$ else if do;

while $PRTM$ do procedure: B_{PN}, $B_{PN} - r_{CNT}$ do;

if $B_{PN} - r_{CNT} = 0$ then TPN if, $\tag{18}$

where $B_{PN}^{min} = t_{PN}^{min}/\Delta t_{PN}$ and $B_{PN} = t_{PN}/\Delta t_{PN}$ are the numbers that reflect the values of time intervals in the specified single interval Δt_{PN}; r_{CNT} is a number corresponding to the ordinal number of the current single interval, that is, the current time value t along the segment t_{PN}, $t=r_{CNT}\Delta t_{PN}$.

Under the conditions of uncertainty in a change in the load, it becomes necessary to prohibit the change towards a decrease (from a certain valid number) in GUs running in parallel even if the predicate $PD(l)$ is generated when assessing the load. This is achieved by assigning the minimum permissible (l_{min}) quantity of GUs. We shall link by the mutually unambiguous relationship the sets of these tasks with the set of predicates $MIN(l)$, and such that, if $MIN(l)=I$, then the minimum permissible number of GUs would be l_{min}. Thus, we have defined the rules to form a group of basic predicates $WRK(l)$, $PH(l)$, $PD(l)$, TPH, TPD,

$MIN(l)$, $NOTACC$, $NOTCNS$. This allows us to write the resultant functions RFU_{NRY} that give rise to these predicates:

$$RF\cup_{NRY}(l) \cong \begin{pmatrix} WRK(l) \& \overline{PH}(l) \& \\ \& \overline{PD}(l) \& \overline{MIN}(l_{min}>l) \end{pmatrix} \to NRY(l);$$

$$\cup_{NRY}(l+1) \cong \begin{pmatrix} WRK(l) \& PN(l) \& \\ \& TPN \& \overline{ACC} \& \\ \& \overline{CNS} \vee MIN(l_{min}>l) \end{pmatrix} \to NRY(l+1);$$

$$RF\cup_{NRY}(l-1) \cong$$
$$\cong \begin{pmatrix} WRK(l) \& PD(l) \& \\ \& TPD \& OFACC \& \\ \& ONCNS \vee \overline{MIN}(l_{min} \geq l) \end{pmatrix} \to NRY(l-1). \tag{19}$$

The next task arising in the study of the rules for operating the converter $WRK(l) \to NRY(l\pm1) \to WRK(l\pm1)$ is to determine a procedure for setting the order of enabling/disabling GU.

We believe that the system has a setter using can assign any sequence (order) $SQ(f)\in SQ(N_{SQ})$, taken from an ordered, numbered set $SQ(N_{SQ})$ of all possible sequences. Then, if there are m $|GU|=m$ generators installed in SAEPS, the set of sequences would be $|SQ(N_{SQ})|=m!|$, that is, with the growth of m, the order increases in factorial. Modern SAEPS do not seek to obtain the entire dimensionality $m!$ as this is an excessive complication of synthesis. In this regard, when selecting elements of a subset $SQ(f)\in SQ(N_{SQ})$, it is advisable to be guided by ensuring that each GU is able to be set in any turn. To this end, it would suffice to have a sequence of limited volume $|SQ(f)|=m$ within the state predicates' system

$$\begin{Vmatrix} SQ(1) \\ SQ(2) \\ SQ(3) \\ .... \\ .... \\ SQ(m-1) \\ SQ(m) \end{Vmatrix} \cong \begin{Vmatrix} 1 & 2 & 3 & ... & ... & ... & m \\ 2 & 3 & 4 & ... & ... & m & 1 \\ 3 & 4 & 5 & ... & m & 1 & 2 \\ ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... \\ m-1 & m & 1 & 2 & ... & ... & m-2 \\ m & 1 & 2 & ... & ... & m-2 & m-1 \end{Vmatrix}. \tag{20}$$

The synthesis of the sequence assignment algorithm (20) is much simpler than the synthesis of a full-size algorithm since it is possible to choose the current $SQ(i)$ sequence among m sequences.

We defined a set of the critical and non-critical controlled accidents for each GU and in SAEPS in general in the following way:

$$X_{CR}(i) = \bigcup_{i=1}^{c} x_{CR}(i), \quad i \in N_{CR} = \overline{1,c}, \quad |N_{CR}| = c, \tag{21}$$

where $X_{CR}(i)$ is the set of controlled and numbered N_{CR} accidents for each GU represented in the form of signals at the logical level {0, 1} from measuring transducers acquired from sensors i;

$$X_{NCR}(i) = \bigcup_{i=1}^{n} x_{NCR}(i), \quad i \in N_{NCR} = \overline{1,n}, \quad |N_{NCR}| = n \text{ is the set}$$

of signals {0, 1} representing non-critical accidents for each GU;

$$X_{EM}(i) = X_{CR}(i) \bigcup X_{NCR}(i) = \bigcup_{j=1}^{n+c} x_{EM}(j),$$

$j \in N_{EM}, |N_{EM}| = n+c$ is the set of all signals representing accidents for each i-th GU;

$$V_{EM} = \bigcup_{f=1}^{n+c} x_{EM}(f) = GA(N_{GA}) \times X(N_{EM}) =$$

$$= \bigcup_{i=1}^{m} GA(i) \times \bigcup_{j=1}^{n+1} x_{EM}(j) = \bigcup^{m(n+c)} (GA(i) \times X(N_{EM})) =$$

$$= \bigcup_{i,j=1,1}^{m(n+c)} x(i,j) = X(N_{GA}, N_{EM})$$

– is the set of all controlled SAEPS accidents, and, as follows from these transformations, the power of all controlled accidents is $|V_{EM}| = |N_{GA} \times N_{EM}| = m(n+c)$.

Fig. 6. Determining the permissible lower load limit of SAEPS based on the optimal load distribution condition

Fig. 7. Power delay time adjustment diagram

Regarding the information component of the SAEPS model. Information on the state and functioning of SAEPS` ACS should be presented to the operator both in the generalized, integrated form and in detail. Its form and structure must meet ergonomic and ergatic requirements. The efficiency of perception of the information model is increased by using optimal sign alphabets, special signals (color, flicker), graphical frames of the process. Thus, the system must be provided with some converter $X(N_{GA}, N_{EM}) \xrightarrow{PR} SMB(N_{GA}, N_{EM})$, that performs semantic analysis $X(N_{GA}, N_{EM}) \$ SMB(N_{GA}, N_{EM})$ in order to render the content of the accident in the natural or some formalized semantic language:

$$\cup_{SMB} \begin{pmatrix} PR, X(N_{GA}, N_{EM}), SMB(N_{GA}, N_{EM}) \cong \\ \cong X(N_{GA}, N_{EM}) \$ SMB(N_{GA}, N_{EM}) \end{pmatrix} \rightarrow$$

$$\rightarrow SMB(N_{GA}, N_{EM}). \tag{22}$$

The tasks of determining the optimal information model and information encoding techniques, the development of individual frames belong to the class of ergatic tasks and tasks of ergonomics. Therefore, here we move on to the further study of the converter. For the recording of the resultant functions $\cup_{ST}$, $\cup_{SP}$, which were defined by the family of predicates $\cup_{ST}$, $\cup_{SP}$, the relationships between the elements of the set of input signals and internal states are as follows,

$$\cup_{ST}(i)(PR, X_{ST}) \cong PR(\nu_{ST}) \rightarrow STA(i);$$

$$\cup_{SP}(i)(PR, X_{ST}) \cong$$
$$\cong PR(\nu_{ST}) \rightarrow SPA(i);$$

$$\nu_{ST} \cup \nu_{SP} =$$
$$= \begin{pmatrix} WRK(i), NRY(i), \\ SQ(m), EM(N_{GA}) \end{pmatrix}. \tag{23}$$

The model of this converter largely depends on the structure and properties of the setter of the order for enabling/disabling GU. Consider some research results on determining the structure and properties of the order setter (as regards a 4-unit SAEPS). In this case, the converter takes the following form

$$\begin{Vmatrix} K(1) \\ K(2) \\ K(3) \\ K(4) \end{Vmatrix} \cong \begin{vmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \\ 3 & 4 & 1 & 2 \\ 4 & 1 & 2 & 3 \end{vmatrix} \xrightarrow{PR} \begin{Vmatrix} SQ(1) \\ SQ(2) \\ SQ(3) \\ SQ(4) \end{Vmatrix} = SQ(\overline{1,4}). \tag{24}$$

Converter (23), considering (24) for $ST(1)$ and $SP(1)$, is described as follows

$$\cup_{ST}(1) \cong \begin{pmatrix} \overline{SWG}(1) \& \overline{EM}(1) \& \\ \& \overline{MST}(1) \& (WRK(0) \& \overline{VLT}) \end{pmatrix} \vee$$

$$\vee \begin{pmatrix} WRK(1) \& \\ \& \begin{pmatrix} \overline{SWG}(1) \& \overline{EM}(1) \& \\ \& \overline{MST}(1) \end{pmatrix} \& (WRK(0) \& \overline{VLT}) \end{pmatrix} \vee$$

$$\vee (WRK(1) \& NRY(1) \& SQ(4) \& EM(4)) \vee$$

$$\vee (SQ(3) \& EM(3 \& 4)) \vee (SQ(2) \& EM(2 \& 3 \& 4)) \vee$$

$$\vee (WRK(1) \& NRY(2) SQ(4)) \vee$$

$$\vee (SQ(3) \& EM(3 \& 4)) \vee \vee$$

$$(SQ(2) \& EM(i \& k \in \mathrm{mod}_{2-2}(2,3,4))) \vee$$

$$\vee (WRK(2) \& NRY(3) \& SQ(2)) \vee$$

$$\vee (SQ(3) \& EM((2 \& 3 \& 4) \vee WRK(3))) \&$$

$$\& (NRY(4) \& SQ(2)) \rightarrow STA(1), \tag{25}$$

where $WRK(0)$ is the de-energized mode EES; $EM(3\&4)$ should be understood as $EM(3)\&EM(4)$; $EM(3\vee4)=EM(3)\vee EM(4)$;

$$EM\left(i\&k\in\mathrm{mod}_{2-2}(2,3,4)\right)=EM(2)\&EM(3)\oplus$$
$$\oplus EEM(2)\&EM(4)\oplus EEM(3)\&EM(4);$$

$MST(1)$ is the GU start memory.

The predicate $SP(1)$'s description is considered for 4 cases:
1) $CR(1)=1-GU(1)$ a critical accident;
2) $WRK(2)\&NRY(1)$;
3) $WRK(3)\&NRY(2)$;
4) $WRK(4)\&NRY(3)$.

As the strongest prerequisite to form $SP(1)$, in addition to cases 2–4, we shall attribute the $GU(1)$ state, the last in line, or which is an accident, if other GUs are in a non-accident state. If not, then SAEPS has other GUs in a state of emergency, $SP(1)$ should not be formed, at least without the intervention of the operator. With these conditions in mind, one can describe $\bigcup_{SP}(1)$ as follows:

$$\bigcup_{SP}(1)\cong\left(SWG(1)\&CR(1)\right)\vee WRK(2)\&NRY(1)\&$$
$$\&\left(SQ(2)\vee EM(1)\right)\&\left(SWG(1)\&CR(1)\right)\vee$$
$$\vee WRK(2)\&NRY(1)\&\left(SQ(2)\vee EM(1)\right)\&$$
$$\&SWG(i\in2,3,4)\&\overline{EM}(i)\vee SQ(3)\&SWG(i\in3,4)\&$$
$$\&\overline{EM}(i)\vee SQ(4)\&SWG(4)\&\overline{EM}(4)\vee WRK(3)\&$$
$$\&NRY(2)\&\left(SQ(2)\vee EM(1)\right)\&$$
$$\&SWG\left(i\&k\in\mathrm{mod}_{2-2}(2,3,4)\right)\&\overline{EM}(i\vee K)\vee$$
$$\vee SQ(3)\&SWG(3\&4)\&$$
$$\&\overline{EM}(3\vee4)\vee WRK(4)\&NRY(3)\&$$
$$\&\left(SQ(2)\vee EM(1)\right)\&\left(\overline{EM}(2\vee3\vee4)\right)\rightarrow$$
$$\rightarrow SPA(1)\oplus SPQA(1), \qquad (26)$$

where $SPQA(1)$ is the command to stop a DG immediately, due to the critical accident $CR(1)$.

However, such models with homogeneous Boolean functions are more suitable for building devices with hard logic and are not quite effective in the development of programmed control systems. This is explained by the fact that with the growth of the established number of GUs in SAEPS, the dimensionality of programs increases significantly, and the tasks associated with the automation of ACS of the STS and C of a given class are significantly complicated. We shall solve the specified problem by searching for more compact Boolean functions, the main of which are the identifiers of data sets. Thus, the generalized functions $STA(i)$ and $SPA(i)$ at some values of indexes m, l, i, and others, demonstrate undefined identifiers that require the introduction of additional conditions and transitions when programming. This is the task of simplifying the operation of algorithms (26) and reducing their volume.

5. Results of synthesizing basic algorithms for the higher levels of SAEPS control

5. 1. Semantic decomposition of control tasks

The formulated tasks in accordance with the analysis of the requirements by international classification societies [38] regarding the structure, functions, and components of SAEPS and the purpose of improving control with information support have contributed to the decomposition of control tasks.

According to the specified dependences (6), (8)–(10), and the characteristic diagrams (Fig. 1–4), the method of decomposing the tasks of control over SAEPS, GU, and shaft generator unit (SGU) was used to determine the operational characteristics; the results are given in Tables 1–3. The resultant decomposition is represented in the form of a generalized converter structure to control the configuration of SAEPS, GU, and SGU, which corresponds to the formulated control tasks in Tables 1–3 (Fig. 6).

Table 1

Decomposition of SAEPS control tasks

Control function	Tasks solved during control
SAEPS control under normal, emergency, and pre-emergency modes	Coordination of the levels of generated power and the power required at present
	Transition from one level of generated power to another, taking into consideration efficiency criteria
	Control over the configuration of GU with the accounting of pre-emergency and emergency states of SAEPS and controlling influences from the operator
	Organization of the sequence of enabling/disabling GU, taking into consideration the emergency states of GU and controlling influences from the operator

Table 2

Decomposition of GU control tasks

Control function	Tasks solved during control
Hot reserve control	Processing signals from the switch that sets the type of control (automatic/manual) over lubrication, lubricant heating valve, lubricant pressure sensor.
	Formation of lubrication cycles with adjustable (variable by an operator) time intervals.
	Formation and control of signals for enabling/disabling a lubrication pump. Registration of emergency signals "No pumping", "No warming up"
Start process control	Processing of signals coming from the local coordinator, buttons "Start", "Emergency start", "Stop", "Emergency stop", from sensors of position of a rail, oil pressure, oil temperature, slow turn, speed sensor, block contact of generator machine.
	Formation (changeable by the operator) of time intervals of control: successful starting pumping of oil; slow turning; enabling an air valve; shutdown (pauses at repeated attempts of start) of the valve of starting air; enabling the servomotor of a controller; disabling blocking on oil pressure; emergency start; confirmation; successful excitation.
	Formation and control of execution of enabling/disabling signals: the pump of oil pumping; the servomotor of a controller; a working stop device; a slow turning device; a starting valve; unlocking of the generator machine.
	Formation of signals of process of start and ALARM: "Start", "Emergency start", "Fault", "No start", "No pumping", "No revs", "Ready to accept loading", "Warms up", "Synchronized", "Load enabled", "Accident"

Continuation of Table 2

Stop process control	Processing of signals coming from the local coordinator, buttons "Stop", "Emergency stop", from speed sensors, the position of the rail of fuel pumps, a generator automatic switch. Formation of variable (by operator) time intervals of control: enabling a working stop device, enabling an emergency stop mode. Formation and control of execution of signals on the shutdown of the generator automatic machine, enabling a working stop device, enabling/disabling a servomotor, closing the valves that cool seawater and fresh water. Formation of signals for a stop process and ALARM: "Stop", "Emergency stop", "Fault", "No stop", "Hot reserve enabled", "Diesel fuel", "Accident". Formation of the warning alarm system from gauges: Oil pressure; Water pressure; Oil temperature; Water temperature; Exhaust gas temperature; Overload; Rupture of fuel pipes: Presence of shavings in oil; Water in the collector; Starting air pressure
Protection and blocking control	Processing signals from the "Protection disabled" switch and the "Reset" button. Organization of time delays and formation of protection signals: – due to excessive speeds of the diesel engine without delay; – due to loss of oil pressure with a delay of 0÷15 s; – due to loss of circulation of cooling water with a delay of 0÷15 s; – due to an increase in the temperature of cooling water with a delay of 0÷30 s; – due to the reverse power with an adjustable power setting of 0÷15 % of the rated power P_N and the actuation time of 0÷15 s; – due to full-current overload with adjustable current setting 0÷1.5 from I_N and a time delay corresponding to time-current characteristic; – due to phase breakage and improper alternation of phases; – due to voltage deviation with adjustable deviation setting (from 0.01 to 70 %) and a time delay from 0.01 to 15 s; – due to frequency deviation up to 10 % of the rated value and a delay of up to 15 s. Formation of a generalized signal "Accident" and a signal deciphering the type of accident. Blocking the start-up when protection is triggered
Synchronization process control	Measurement and voltage control of synchronized GU. Measurement and frequency control of synchronized GU. Formation of signals for fitting the frequency of synchronized GU. Calculations of advance time for enabling a generator switch. Calculations of the intensity of change in the frequency of synchronized GU. Implementation of optimal synchronization process control according to the criterion of performance and minimum error of measurements
Control of the process of measuring electricity parameters	Implementation of multidimensional method of measuring electricity parameters: – frequency measurement; – measurement of amplitude and current values of linear voltages in a three-phase network; – measurement of load angle; – measurement of power direction; – measurement of amplitude and current values of phase currents of loading a three-phase network

Table 3

Decomposition of SGU control tasks

Control function	Tasks solved during control
Control over the processes of enabling/disabling SGU	Processing signals coming from the local coordinator, from the sensors of the clutch position, the speed of GD, the block-contact of the generator machine, buttons "Start" ("Clutch of SGU coupling"), "Stop" ("Disconnection of SGU coupling"). Control of the processes of clutching and disconnecting an SGU coupling. Formation and control of signals for enabling/disabling clutch valves and disconnecting an SGU coupling. Formation of signals of the process for enabling/disabling ALARM "Start", "Stop", "No stop", "Coupling in gear", "Coupling disconnected", "Ready to accept the load", "Synchronization", "Load enabled", "Malfunction", "Accident", "Pressure of working oil of SGU coupling", "Temperature of SGU windings"

The generalized structure of the converter to control the configuration of GU, which corresponds to the formulated control tasks in Tables 1–3, takes the form shown in Fig. 8.
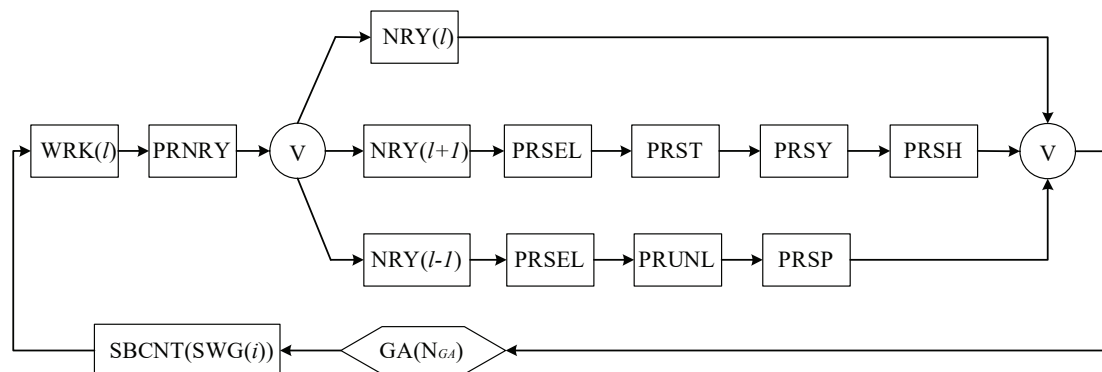

Fig. 8. Generalized structural diagram of the converter

Thus, the set of GUs installed in SAEPS is determined by the ratio $GA(NGA) = \overset{m}{\bigcup} GA(i)$.

5. 2. Iterative adjustments of the capacity redistribution coefficient in accordance with the upper and lower load thresholds

In accordance with the loading diagram of GU (Fig. 5), consider the issues related to the logical module *SBCNT*, generating a predicate (11). As input information, we accept signals $SWG(i) \in SWG(N_{GU})$, coming to the controller from state signalers (on/off) of generator circuit breakers $SWG(N_{GU})$, $|N_{GU}|=m$, forming at the input of the input device in each technological cycle T_{TZ}, m is the bit binary word $S_{SWG}(i) \in S_{SWG}(N_S)$ with the number of possible different combinations of values of variables predetermined by the expression $2^m = |N_S|$.

Since $|N_l| \neq |N_s|$, then one can set the functional correspondence between $WRK(N_l)$ and $S_{SWG}(N_S)$ in the form of Boolean functions [39]:

$$WRK(l) = \overset{c_m^l}{\underset{j=1}{\vee}} k_j^l, \qquad (27)$$

where k_j^l is the conjunction, a constituent unit that includes l non-inverse and $(m-l)$ inverse variables $S_{SWG}(i)$; $\vee$ is the disjunction that combines all possible conjunctions of full length.

The result is the correspondence in tabular form (Table 4) for a 4-unit (m=4) SAEPS [40].

Table 4

Combinations of GUs in a four-unit SAEPS

Vari-ables	$S_{SWG}(N_S)$				
	0	1 2 4 8	3 5 6 9 10 12	7 11 13 14	15
$SWG(1)$	0	1 0 0 0	1 1 0 1 0 0	1 1 1 0	1
$SWG(2)$	0	0 1 0 0	1 0 1 0 1 0	1 1 0 1	1
$SWG(3)$	0	0 0 1 0	0 1 1 0 0 1	1 0 1 1	1
$SWG(4)$	0	0 0 0 1	0 0 0 1 1 1	0 1 1 1	1
$WRK(l)$	$WRK(0)$	$WRK(1)$	$WRK(2)$	$WRK(3)$	$WRK(4)$

In this case, the technique to form an algorithm of functioning of the *SBCNT* module implies the arithmetic addition of the values of input variables with the result selected as a valid predicate according to the following rule:

while *SBCNT* do: $\sum_{i=1}^{m} SWG(i)$,

if $\sum_{i=1}^{m} SWG(i) = l$ then $WRK(l)$ if do. (28)

The input word $\overset{m}{\bigcup} SWG(i)$ is used as the address of a valid predicate, and unambiguous groups of address words would match non-extreme predicates. For example, the predicate $WRK(1)$ is generated by the following rule:

if $\vee \begin{pmatrix} S_{SWG}(1), S_{SWG}(2), \\ S_{SWG}(4), S_{SWG}(8) \end{pmatrix}$ then $WRK(1)$ $f(i)$. (29)

The next stage of the study is associated with the *PRN-RY* module, which generates predicates $NRY(l)$, $NRY(l+1)$, $NRY(l-1)$ for the individually operated, or running in parallel, GUs (depending on the specified load).

5. 3. Analysis of equivalent characteristics and selection of optimal GU configuration according to the criterion of minimum fuel consumption

The generation of primary predicates $P_N(N_l)$ and $P_D(N_l)$, identifying that the load has achieved the upper and lower GU loading thresholds, should not take into consideration emissions if their duration is less than the specified time interval $t_{PN}(min) \pm \Delta\tau_{PN}$. $\Delta\tau_{PN}$ is the time interval that corrects the instability of emission duration (Fig. 7).

In the case when, after $t_{PN}(min)$ is over, the emission value $P_N(l)=1$, then the value for the second delay time interval is selected depending on the amount of the established power ΔP_{PN}, in accordance with the load characteristics of GU (17). Or, as shown in Fig. 7, to count the delays $t_{PN}(min)$ and $t_{PN}(j)$, one should provide for the subroutines of the timer $PR1TM$ and $PRTM$, generating their corresponding predicates $T1PN$ and TPN according to rule (18).

We would like to emphasize that this approach to determining the time delay is fair for the established emission [41] when the probability of further increase in load is low over time t_{PH}. At the same time, as practice shows [42], at some levels of SAEPS loading there are significant fluctuations in the standard deviation σ_x relative to its mean values. Failure to consider these fluctuations can lead to engine overload during the delay, which is a significant drawback [43]. The disadvantage is eliminated by comparing the values of the produced, up to the time r_{CNT}, energy W_T with the permissible energy W_D along the section $t_{PN} = B_{PN} \cdot \Delta t_{PN}$, obtained by the results of measuring the power in a zero cycle $\Delta P_N(0)$ (Fig. 9). That is, we can conclude that the delay time would be over at a time point when:

$$W_T - W_D \geq 0; \ W_T = \sum_{j=1}^{r_{CNT}} \Delta P_{PN}(j), \ W_D = \Delta P_{PN}(0) B_{PN}. \quad (30)$$

In this case, the delay time control procedure is reduced to the following rule:

if $PH(l)$ then $PRTM$ else if;

while $PRTM$ do

procedure CTM: $\Delta P_{PH}(0)$, t_{PH}, Δt_{PH}, B_{PH}

while CTM do: $\sum_{j=1}^{r_{CNT}} \Delta P_{PH}(j) - \Delta P_{PH} B_{PH}$ if

$\sum_{j=1}^{r_{CNT}} \Delta P_{PH}(j) - \Delta P_{PH} B_{PH} > 0$

then TPH else $PRTM$ if.

The *CTM* procedure based on $\Delta P_{PN}(0)$ defines t_{PN}, calculates B_{PN}, and counts the timer program. After the time t_{PT} is over, if $\Delta P_{PT} > 0$, it is possible (in order to preserve the current GU configuration according to the criterion of technical and economic feasibility) to provide measures for their unloading. For example, by disabling secondary consumers (*CNS*) or enabling a power storage device. Naturally, the break in the power supply to secondary consumers, as well as the time of the return of electricity by storage devices, are limited. And, if, after this time is over, the deficit of generated power is unchanged, then the use of these techniques is impossible [44]. Therefore, there is a need to assess the load forecast of SAEPS after t_{PN}.

We provide a special program to perform the procedure of calculating $\overline{CS}$ and evaluating the predicted energy $\overline{S} < S_{ACC}$ by comparing it with the possible available energy

of the storage device S_{ACC}, as well as generating a *SWACC* predicate that algorithmizes enabling the storage devices:

if *PH* & *TPH* then *PRACC* else if;

while *PRACC* do procedure $C\overline{S}$: M_x, x_{PN},

$\sigma_x, k_x(\tau_r), \sigma_x, \Phi(z_r), \overline{S}$,

if $\overline{S} < S_{ACC}$ then *SWACC* else *NOTACC* if do, (31)

where N*OTACC* is the predicate, which indicates that the energy storage device is not able to solve the task of SAEPS unloading [45].
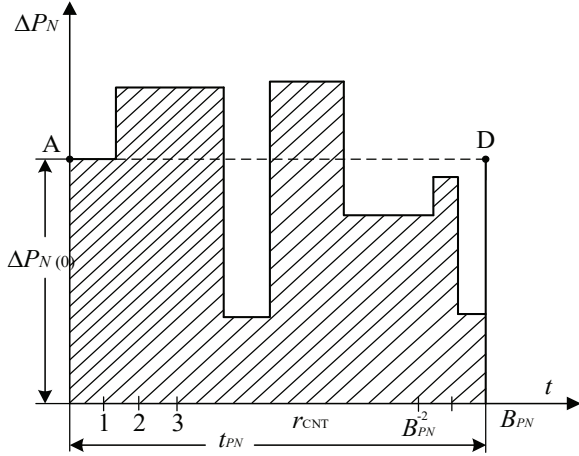
Fig. 9. SAEPS load: permissible — line A–D; actual —dashed region

The structure of the *PRCNS* program, which forms the predicate *OFCNS* to disable secondary consumers, is similar to the *PRACC* program.

5. 4. Improvement of operational operations under optimal conditions

Solving the task of synthesizing the sequence algorithm (20) is a continuation of the study of the properties of the converter (1), (2), its subroutine *PRSEL* (Fig. 8).

The *PRSEL* program structure is linked to the two resultant functions U_{ST} and U_{SP}, the weakest post-conditions of which would be the predicates $ST(i)$ and $SP(i)$. The prerequisites for these functions are the result of the work of the *PRCNT* and *PRNRY* programs, as well as a certain set of predicates from the database that characterizes the technical condition of GU. Set the following sets' predication:

– $EM(N_{GA}) = \bigcup_{i=1}^{m} EM(i)$, $i \in N_{GA}$ – a set of predicates

on the generalized state of emergency $GU(i)$?*GU*, <u>and</u>, if $EM(i)=1$, then $GU(i)$ experiences an accident, $N_{GA}=\overline{1,m}$ – GU numbering;

– $CR(N_{GA}) = \bigcup_{i=1}^{m} CR(i)$ – a set of predicates on the techni-

cal nature of the accident, requiring an emergency stop $GU(i)$, and, if $CR(i)=I$, then $GU(i)$ experiences a critical accident;

– $NCR(N_{GA}) = \bigcup_{i=1}^{m} NCR(i)$ – a set of predicates on the

noncritical *GU* accidents, with $NCR(i)=1$ if $GU(i)$ experiences a non-critical accident.

According to the description of the state predicates (19), we shall establish the properties and relations among the predicates on the emergency states of GU. Assume $EM(N_{GU}) \neq \emptyset$ if

at least one of the sets $CR(N_{GU})$ or $NCR(N_{GU})$ is non-empty. In addition, we establish for these sets the following, mutually unambiguous, correspondences $\left| EM(N_{GA}) \right| = \left| CR(N_{GA}) \right|$ and $\left| EM(N_{GA}) \right| = \left| NCR(N_{GA}) \right|$. Thus, the abstract model of the converter, which forms, for each $GA(i)$, a predicate on a generalized accident, takes the following form:

$$\bigcup_{EM} \left(PR, CR(N_{GA}), NCR(N_{GA}, t) \right) \cong$$
$$\cong \left((CR(i) \vee NCR(i)) \& TEM \right) \rightarrow EM(i), \quad (32)$$

where *TEM* is the predicate on ending the time delay of a generalized accident signal.

The accepted designation of the elementary emergency signal $x(i,j) \in X(N_{GU}, N_{EM})$ (21) is more expressive compared to $x_{EM}(f)$, since the symbol $x(i,j)$ carries the information about a membership to a certain GU – $GU(i) \in GU(N_{GU})$, $i \in N_{GU}$, as well as a membership to a completely certain accident, since $j \in (N_{CR} \vee N_{NCR})$. Thus, the predicates EM, CR, *NCR* are expressed in the form of the following correspondences:

$$\bigcup_{EM} \left(PR, X(N_{GA}, N_{EM}) \right) \cong$$
$$\cong \left(\bigvee_{i,j=1,1}^{m,(n+c)} x(i,j)=1 \right) \rightarrow EM(N_{GA}, N_{EM});$$

$$\left(\bigvee_{i,j=1,1}^{m,(n+c)} x(i,j)=1 \right) \rightarrow EM(N_{GA}, N_{EM});$$

$$\bigcup_{CR} \left(PR, X(N_{GA}, N_{EM}) \right) \cong \left(x(i,j) \& (j \in N_{CR}) \right) \rightarrow CR(i);$$

$$\bigcup_{NCR} \left(PR, X(N_{GA}, N_{EM}) \right) \cong$$
$$\cong \left(x(i,j) \& (j \in N_{NCR}) \right) \rightarrow NCR(i);$$

where $EM(N_{GU}, N_{EM})$, unlike EM(i), is a generalized accident signal for the entire SAEPS.

We shall demonstrate the transformation and translation from a semantic language into natural for the basic emergency signals of the i-th DG (22):

– $X(i,1)\$SMB \rightarrow LBP(i,1)$ – reduced oil pressure in the i-th GU, *NCR*;

– $X(i,2)\$SMB \rightarrow LBP(i,2)$ – no oil pressure, *CR*;

– $X(i,3)\$SMB \rightarrow WTP(i,1)$ – reduced pressure of cooling water, *NCR*;

– $X(i,4)\$SMB \rightarrow TP(i,2)$ – no cooling water pressure, *CR*;

– $X(i,5)\$SMB \rightarrow IBT(i)$ – oil high temperature, *CR*;

– $X(i,6)\$SMB \rightarrow GST(i)$ – exhaust gas high temperature, *NCR*;

– $X(i,7)\$SMB \rightarrow OVL(i)$ – DG overload, *CR*;

– $X(i,8)\$SMB \rightarrow VLD(i)$ – load voltage, *CR*;

– $X(i,9)\$SMB \rightarrow VLH(i)$ – high voltage, *CR*;

– $X(i,10)\$SMB \rightarrow PQD(i)$ – low frequency, *CR*;

– $X(i,11)\$SMB \rightarrow PQH(i)$ – high frequency, *CR*;

– $X(i,12)\$SMB \rightarrow OVS(i)$ – extremely high rotations, *CR*;

– $X(i,13)\$SMB \rightarrow PWR(i)$ – reverse power, *CR*.

Building such a model with homogeneous Boolean functions suitable to a greater extent for the construction of devices with hard logic is not quite effective in the development of programmable control systems. This is explained by the fact that with an increase in the established number of GUs in SAEPS, the dimensionality of programs grows significantly while the tasks associated with the automation of the ACS of STS and C of a given class are significantly complicated. Solving the specified task by searching for more compact

Boolean functions would cause certain difficulties, the main of which is the identification of data sets. Thus, the generalized functions $STA(i)$ and $SPA(i)$ at some values of indexes m, l, i and others reveal undefined identifiers that require the introduction of additional conditions and transitions when programming. This is what complicates the program, which increases its volume.

To eliminate these shortcomings, an algorithmization technique was used, based on the use of a special extended data array (Table 5).

The use of this data array makes it possible to record the functioning algorithm in the following form,

$$NRY(j) = \left(WRK(j)\,\&\,\overline{PD}(j)\,\&\,\overline{PH}(j)\right)\vee$$

$$\vee WRK(j+1)\,\&\,\left(PD(j+1)\,\&\,\overline{PH}(j)\right)\&$$

$$\&\,TM1\vee\left(WRK(j+m-1)\,\&\,PH(j+m-1)\right)\&$$

$$\&\,TM2\vee WRK(j+m-1)\&$$

$$\&\left(OVL(j+m-1)\vee MIN(j)\right)\&\overline{MIN}(j+1)\&$$

$$\&\ldots\&\overline{MIN}(j+m-1)\,\&\,STA(j)=AUT(j)\&$$

$$\&\overline{EM}(j)\,\&\,\overline{SWG}(j)\,\&\left(\overline{VLT}\vee NRY(1)\right)\&$$

$$\&\,SQ(j+m-1)\&$$

$$\&\,EM(j+m-1)\vee SQ(j+m-2)\&$$

$$\&\,EM(j+m-2)\,\&\,EM(j+m-1)\vee\ldots\vee$$

$$\vee SQ(j+1)\,\&\,EM(j+1)\&\ldots\&$$

$$\&\left(EM(j+m-1)\right)\vee\ldots\vee NRY(l)\left(\underset{i=j+m-l+1}{\overset{j+m-1}{\vee}}SQ(i)\right)\vee$$

$$\vee SQ(j+m-l)\&\left(\underset{i=j+m-l}{\overset{j+m-1}{\vee}}EM(i)\right)\vee$$

$$\vee SQ(j+m-l-1)\&\left(\underset{i=1}{\overset{C_{l+1}^{2}}{\vee}}\Pi_{l+1}^{2}\right)\in$$

$$\in\left(C(j+m-l-1)\ldots C(j+m-1)\right)\vee$$

$$\vee SQ(j+m-l-2)\&\left(\underset{i=1}{\overset{C_{l+2}^{3}}{\vee}}\Pi_{l+2}^{3}\right)\in$$

$$\in\left(EM(j+m-l-2)\ldots EM(j+m-1)\right)\vee\ldots\vee$$

$$\vee SQ(j+1)\&\left(\underset{i=1}{\overset{C_{m-1}^{m-2}}{\vee}}\Pi_{m-1}^{m-2}\right)\in$$

$$\in\left(EM(j+1)\ldots C(j+m-1)\right)\vee$$

$$\vee\ldots\vee NRY(m-1)\left(\begin{array}{c}\underset{i=j+2}{\overset{j+m-1}{\vee}}SQ(i)\vee\\ \vee SQ(j+1)\\ \&\,\&\left(\underset{i=j+1}{\overset{j+m-1}{\vee}}EM(i)\right)\end{array}\right)\vee NRY(m);$$

$$SPA(j)=AUT(j)\,\&\,SWG(j)\&$$

$$\&\left(\underset{i=1}{\overset{m-1}{\vee}}NRY(i)\right)\&\,SQ(j+m-i)\&$$

$$\&\,\Pi_{j+m-1}^{j+m-1}\in\left(EM(j)\vee CR(j)\vee NRY(j)\right)\&$$

$$\&\left(\underset{i=1}{\overset{m-1}{\vee}}WRK(j+1)\right)\&\left(\overline{PH}(i)\right)\&$$

$$\&\overline{MSP}(j+1)\&\ldots\&\overline{MSP}(j+m-1). \tag{33}$$

Table 5

Extended data array

Argument values for the resulting numeric index	Calculated numeric index by an argument									
	1	2	...	$m-1$	m	$m+1$	$m+2$	...	$(2m-1)$	$2m$
	NCR1	NCR2	...	~(m−1)	~m	NCR1	NCR2	...	~(m−1)	~m
	CR1	CR2	...	~(m−1)	~m	CR1	CR2	...	~(m−1)	~m
	EM1	EM2	...	~(m−1)	~m	EM1	EM2	...	~(m−1)	~m
	WRK1	WRK2	...	~(m−1)	~m	WRK1	WRK2	...	~(m−1)	~m
	SQ1	SQ2	...	~(m−1)	~m	SQ1	SQ2	...	~(m−1)	~m
	AUT1	AUT2	...	~(m−1)	~m	AUT1	AUT2	...	~(m−1)	~m
	SWG1	SWG2	...	~(m−1)	~m	SWG1	SWG2	...	~(m−1)	~m
	STA1	STA2	...	~(m−1)	~m	STA1	STA2	...	~(m−1)	~m
	PH1	PH2	...	~(m−1)	~m	PH1	PH2	...	~(m−1)	~m
	OVL1	OVL2	...	~(m−1)	~m	OVL1	OVL2	...	~(m−1)	~m
	0	PD2	...	~(m−1)	~m	0	PD2	...	~(m−1)	~m
	0	MIN2	...	~(m−1)	~m	0	MIN2	...	~(m−1)	~m

The data of the array of the converter (25) are valid at $j=1, 2,\ldots, m$ while meeting the conditions reflected in the extended data array. For example, for $NRY(j)$ function at $j=1$, the conjunction $WRK(j)\,\&\,\overline{PD}(j)\,\&\,\overline{PH}(j)$ takes the form of $WRK(1)\,\&\,\overline{PH}(1)$, because the value of the OVL argument is determined by the table and equals 0.

It is obvious that the capacities of the set of physical ordinal GU numbers and their ordinal numbers in the N_{QU} queue are equal, that is, $|N_{GU}|=|N_{QU}|=m$. And, for this task, we fix $N_{QU}=1,m$ strictly, while we have the right to perform any permutations over N_{GU}. Then each permutation $SQ(k\in m!)$ would be associated with N_{QU} via a certain functional relationship $Q\cup$: $N_{QU}\rightarrow N_{GU}$ and a set of predicates: $Q\cup\left(N_{QU},N_{GA}\right)=\underset{1,1}{\overset{m,m}{\bigcup}}Q\cup(j,i)$, and $Q\cup\,(j,i)=1$, if the j-th queue includes the i-th GU, $j\in N_{QU}$, $i\in N_{GU}$. That is, the following sequence is set for a five-unit SAEPS

$$Q\left(N_{QU},N_{GA}\right)=Q\cup(1,5)\quad Q\cup(2,4)$$
$$Q\cup(3,2)\quad Q\cup(4,1)\quad Q\cup(5,3),$$

and three GUs ($l=3$) are in operation, an $EM(4)$ accident occurred, so GU No. 2 is set on manual control $MNL(2)$.

In this case, the QU converter must, through the shift operation $MVE(N_{GA})$, put GU Number 2 first in the queue, and the emergency converter – the third, that is, the last one among those operated (Table 6).

Table 6

An example of setting a sequence of GUs for a five-unit SAEPS

N_{QU}	1	2	3	4	5
N_{GA}	5	4 EM	2 MNL	1	3

After disconnecting $G(4)\neq I$ from the bus, $GU(4)$ must be put last in the general queue. As a result, we obtain: $N_{GA}=25413$ – before disabling $G(4)$, and $N_{GA}=25134$ – after disabling. In a general case, the converter takes the following form:

$$\cup_{QU}\left(PR,Q\cup\left(N_{QU},N_{GA}\right),EM(N_{GA})MNL(N_{GA})\right)\cong$$
$$\cong MVE\left(N_{GA}\right)\rightarrow Q\cup\left(N_{QU},N_{1}\right), \tag{34}$$

where $MVE(N_{GU})$ is the predicate that is valid at the end of N_{GU} number shift operations.

Based on the properties of the new QU converter, the predicates $STA(i)$, $SPA(i)$ are described in a general form as follows

$$\bigcup_{SP}(i) \cong SWG(i)\,\&\,CR(i) \vee \overline{WRK}(1)\,\&\,WRK(l)\,\&$$
$$\&\,NRY(l-1)\,\&\,Q\cup(j=l,i) \vee$$
$$\vee SWG(i)\,\&\,CR(i) \vee \overline{WRK}(1)\,\&\,WRK(l)\,\&$$
$$\&\,NRY(l-1)\,\&\,Q\cup(j=l,i) \vee$$
$$\vee \overline{PH}(l-1)\,\&\,EM(i)\,\&\,\overset{l-1}{\underset{k=1}{\vee}}\overline{EM}(k) \rightarrow SPA(i), k\in N_{QU};$$

$$\bigcup_{ST}(i) \cong \overline{SWG}(i)\,\&\,\overline{MST}(i)\,\&\,\overline{EM}(i)\,\&$$
$$\&\,WRK(0) \vee WRK(l)\,\&\,NRY(l+1) \vee$$
$$\vee NRY(l)\,\&\,PH(l-1)\,\&\,\overset{l}{\underset{k=1}{\vee}}EM(k)\,\&$$
$$\&\,Q\cup(j=l+1,i) \rightarrow STA(i), \qquad (35)$$

where $\overset{l}{\underset{k=1}{\vee}}EM(k)$ is the disjunction of the predicates EM(k), valid if at least one of the l working GUs is in a state of emergency; $\overset{l}{\underset{k=1}{\vee}}\overline{EM}(k)=1,$ if none of the l-1 (except the i-th) GUs experiences an accident.

Predicates $STA(i)$, $SPA(i)$ are the prerequisites for the system to execute the programs to start $PRST$, stop $PRSP$, and synchronize $PRSY$.

6. Discussion of results of synthesizing basic algorithms for the higher levels of SAEPS control

After analyzing the load characteristics of GU and completing the decomposition of control tasks, we have defined control functions and those tasks that are solved in the process of control (Tables 1–3). Based on these results, a generalized structure of the converter to control the configuration of GU was developed, which corresponds to the formulated control tasks (Fig. 8).

In accordance with a GU loading diagram (Fig. 5), a structure of the logical module $SBCNT$ was determined, which generates a predicate (11). On this basis, depending on the input signals $SWG(i)\in SWG(N_{GU})$, entering the controller from the state detectors of circuit breakers, we obtained the possible combinations of values for the variables defined by expression $2^{m=|N_S|}$. In addition, according to the combinations of GUs given in Table 4, we suggested a procedure to form the algorithms of functioning of the $SBCNT$ module based on a valid predicate and a rule (20). The technique makes it possible to use the input word as the address of a valid predicate corresponding to non-extreme predicates of unambiguous groups of address words (21).

To determine the power conversion coefficient k_{RCL}, adjust the upper and lower load thresholds and optimal load distribution, according to the description of state predicates (20), the properties and relations among the predicates on the emergency states of GU have been established. Namely, based on a case where $EM(N_{GU})\neq\emptyset$, it was found that at least one of the sets $CR(N_{GU})$ or $NCR(N_{GU})$ is non-empty. In addition, the following, mutually unambiguous, correspondences $|EM(N_{GA})|=|CR(N_{GA})|$ and $|EM(N_{GA})|=|NCR(N_{GA})|$.

are established for these sets. Thus, the abstract model of the converter, forming, for each $GA(i)$, a predicate on a generalized accident, has acquired the following form

$$\bigcup_{EM}\left(PR,CR(N_{GA}),NCR(N_{GA},t)\right)\cong$$
$$\cong\left((CR(i)\vee NCR(i))\,\&\,TEM\right)\rightarrow EM(i),$$

where TEM is a predicate about the end of the time delay in a signal of a generalized accident.

However, it was found that the sets of critical and non-critical controlled accidents for each GU and in SAEPS in general are predetermined by the sets of measuring transducers

$$X_{CR}(i)=\bigcup_{i=1}^{c}x_{CR}(i),\quad i\in N_{CR}=\overline{1,c},\quad |N_{CR}|=c,$$

where $X_{CR}(i)$ is the set of controlled accidents N_{CR} numbered for each GU. Therefore, the display of signals at the logical level {0, 1} from the measuring transducers acquired from sensors i is possible only if the following sets are defined,

$$X_{NCR}(i)=\bigcup_{i=1}^{n}x_{NCR}(i),\quad i\in N_{NCR}=\overline{1,n},\quad |N_{NCR}|=n$$ – the sets of signals {0,1} reflecting non-critical accidents for each GU;

$$X_{EM}(i)=X_{CR}(i)\bigcup X_{NCR}(i)=\bigcup_{j=1}^{n+c}x_{EM}(j),$$

$j\in N_{EM},|N_{EM}|=n+c$ – the sets of all signals reflecting accidents for each i-th GU;

$$V_{EM}=\bigcup_{f=1}^{n+c}x_{EM}(f)=GA(N_{GA})\times X(N_{EM})=$$
$$=\bigcup_{i=1}^{m}GA(i)\times\bigcup_{j=1}^{n+1}x_{EM}(j)=\bigcup^{m(n+c)}\left(GA(i)\times X(N_{EM})\right)=$$
$$=\bigcup_{i,j=1,1}^{m(n+c)}x(i,j)=X(N_{GA},N_{EM})$$

– the sets of all controlled accidents in SAEPS. These conditions impose restrictions on the conversion and determining the power of all controlled accidents, which can be calculated according to the rule $|V_{EM}|=|N_{GA}\times N_{EM}|=m(n+c)$.

The accepted designation of an elementary emergency signal $x(i,j)\in X(N_{GU},N_{EM})$ is more adequate compared to $x_{EM}(f)$ since the symbol $x(i,j)$ carries information about a membership to a completely certain GU. Therefore, the rules of the set $GU(i)\in GU(N_{GU})$, $i\in N_{GU}$ of a membership to a completely certain accident would be fulfilled under the condition $j\in(N_{CR}\vee N_{NCR}$. Thus, the EM, CR, NCR predicates can be represented in the form of the following correspondences

$$\bigcup_{EM}\left(PR,X(N_{GA},N_{EM})\right)\cong$$
$$\cong\left(\overset{m,(n+c)}{\underset{i,j=1,1}{\vee}}x(i,j)=1\right)\rightarrow EM(N_{GA},N_{EM});$$

$$\bigcup_{CR}\left(PR,X(N_{GA},N_{EM})\right)\cong$$
$$\cong\left(x(i,j)\,\&\,(j\in N_{CR})\right)\rightarrow CR(i);$$

$$\bigcup_{NCR}\left(PR,X(N_{GA},N_{EM})\right)\cong$$
$$\cong\left(x(i,j)\,\&\,j\in N_{NCR}\right)\rightarrow NCR(i),$$

where $EM(N_{GA},N_{EM})$, unlike EM(i), is the signal of a generalized accident for the entire SAEPS.

We have optimized the operations of starting, synchronizing, transferring a load, and stopping GU under optimality conditions $F_\Sigma \min(P_\Sigma)$ by improving the program PROPT that controls the primary motors of GU, which implements the criterion $(\alpha_C - \alpha_{opt}) \to \min$. It should be noted that in the data array (Table 5) most of the arguments at numerical indexes 1 and $(m+1)$, 2 i $(m+2)$ coincide. However, the task of minimizing the functions (25) and (26) is not exhausted. The most effective way to reduce functions is to design a rational converter $K(N_1) \to SQ(N_1)$. Function analysis reveals that the main increase in their length is given by the correspondence $SQ(N_{GA}) \times EM(N_{GA})$, especially in cases where $|SQ| = m!$. The reduction is possible through the development of a self-adjustable converter, the output sequence $SQ(i)$, by setting a part of GU to manual MNL and remote control and reconfiguring the order specified by the operator depending on the pre-emergency and emergency situations $EM(N_{GU})$.

6. Conclusions

1. Using an example of the analysis of load characteristics of a five-unit automated SAEPS, the levels of generated power and the power required at a certain point in time have been established. It is proved that the procedure of transition from one level of generated power to another, taking into consideration the efficiency criteria, takes place considering the pre-emergency and emergency states of SAEPS and controlling influences by the operator. For example: a pause from 30 to 60 minutes and an operation of 1…10 minutes. The program enables automatic reset of the cycle pause when changing the configuration of operating GUs, as well as when disrupting the specified law of load distribution. The duration of the processes to start $TM(ST)$ and synchronize $TM(SY)$ is controlled and can be configured from 10 to 180 s. In case of the unsuccessful synchronization of DG $EM(i,SY)$, the latter is stopped as a failed GU. A warning emergency signal is formed at a failed SGU synchronization.

2. We have proposed a sequence of the synthesis of algorithms in the control program for the supervisor of the control system coordinator with a distributed two-level hierarchical structure. The task of coordinated control over SAEPS with changes in load has been solved. A generalized structure of the converter to control the configuration of SAEPS GUs has been given; the principles for constructing control procedures based on the principle of "rigid and flexible" thresholds have been described. Taking into consideration the time delay adjustment diagram for enabling GU dependent on the demanded power, a technique to improve the reliability of SAEPS operation was proposed, by eliminating possible emergency modes when erroneous control combinations are assigned. The load transfer process is controlled by the predefined value $SWGOP$, for example, no more than $(0.1\ P_H)$, and time $SWGOT$, for example, from (1 to 180 s). It is possible to set the time delay for an emergency stop $ESTD$ from 1 to 10 s according to the limit values of parameters such as the pressure and temperature of lubricant and cooling water, exhaust gas parameters, return power, low/high voltage, and frequency.

3. ACS of SAEPS has been proposed subject to minimum fuel consumption and taking into consideration meteorological navigating conditions. The coefficient of recalculation of the dependence of change in the indicative power k_{RCL}

accounting for mechanical efficiency has been determined. We have synthesized algorithms for optimizing the diesel engine operation modes by using the necessary sensors (air humidity, exhaust gas temperature, signals from the controlling elements of water supply control for cooling supercharged air, fuel supply, etc.). The sensors of analog signals determine the following: GU phase currents $AMP(N_m, N_I)$, N_I is the phase numbering; linear voltages $VLT(N_m, N_U)$, N_U is the linear voltage numbering; excitation current $IEX(N_m)$; the temperature of cooling fresh water (0…160 °C) $WTT(N_m)$; oil temperature (0…160 °C) $LBT(N_m)$; exhaust gas temperature (0…900 °C) $GST(N_m)$; the temperature of oil entering a GU bearing (0…160 °C) $BRT(N_m)$; GU winding insulation resistance (0…100 MOhm) $ISL(N_m)$; the GU frequency of rotation $TAH(N_m)$; the position of the rail of fuel pumps $FLRK(N_m)$; fuel consumption (0…1000 l/h). We have considered the possibility of determining the lower load thresholds of SAEPS according to the conditions for its optimal distribution.

4. Based on the analysis of loading characteristics of GU and the formation of a database for calculating the mode optimization, the coefficients of power conversion and adjustment of the upper loading thresholds dependent on the conditions of the technical state and meteorological conditions have been determined. The sequence of executing the operations of starting, synchronizing, transferring a load, and stopping GU is given. This sequence is associated with the formation of the optimal GU configuration, the distribution of loads among GUs running in parallel according to the conditions $F_\Sigma \min(P_\Sigma)$ and the execution of the program to optimize the primary engine of the power plant, which implements the criterion $(\alpha_c - \alpha_{opt}) \to \min$. When synthesizing control over a five-unit SAEPS, a procedure of algorithmization has been proposed, based on the use of an extended data array, which makes it possible to simplify the algorithm of functioning in the operations of selecting the configuration for a five-unit SAEPS. As a result, time delays were optimized taking into consideration protective signals: from ultra-high diesel engine speed without a delay; from oil pressure loss with a delay of 0÷15 s; from loss of circulation of cooling water with a delay of 0÷15 s; from an increase in the temperature of cooling water with a delay of 0÷30 s; from the reverse power with an adjustable power setting of 0÷15 % of the rated power P_H and the actuation time of 0÷15 s; from full-current overload with adjustable current setting 0÷1.5 from I_H and a time duration corresponding to a time-current characteristic; from phase breakage and improper alternation of phases; from voltage deviation with adjustable deviation setting (from 0.01 to 70 %) and a time delay from 0.01 to 15 s; from frequency variance up to 10 % of the rated value and a delay of up to 15 s.

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