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ALGORITHM FOR ESTIMATION OF SHIP REFRIGERATION UNIT ENERGY EFFICIENCY USING FULL ORDER OBSERVERS

Annotation. *The article considers the construction of an algorithm for estimation the energy efficiency of a ship refrigeration unit using the minimum required number of sensors. It is established that the existing methods for diagnosing and monitoring the technical condition of ship refrigeration units are imperfect due to the presence of a large number of sensors and the necessity to suspend the unit. The choice of the refrigeration coefficient as an indicator of energy efficiency is justified. A method that allows determining the refrigeration coefficient in real time without the necessity to stop the operation of the ship's refrigeration unit and use pressure sensors is proposed. For this, the method supposes the calculation of the specific cooling capacity and compressor compression work, the mechanical power on the shaft and the mass flow rate of the refrigerant. The algorithm for determining the cooling capacity and compression work using only four temperature sensors is considered. This algorithm supposes the determination of enthalpies at characteristic points of the refrigeration cycle using the equations of the refrigerant state. A method for evaluating the mechanical power on the compressor shaft using full order adaptive state observers is proposed. A decision of using the electromagnetic torque of the compressor motor as a measured quantity is substantiated. A state observer is synthesized using a modal method based on a linearized model of the electric motor. An expression for calculating the geometric mean root and elements of the observer matrix is proposed. The resulting observer structure allows constructing it on the basis of a complete mathematical model of the electric motor and evaluating not only the speed, but also the load torque on the compressor shaft. In the environment of Matlab / Simulink, a simulation model of the compressor motor state observer is built. The obtained simulation results confirm the efficiency of the proposed method. An algorithm for determining the electromechanical parameters of a compressor for a given period of time using three voltage and current sensors is considered. A general algorithm for estimation energy efficiency, which can be the basis for creating a system for diagnosing and monitoring the technical condition of a ship refrigeration unit, is constructed.*

Keywords: *ship refrigeration unit; state observer; diagnostics, modeling, algorithm, energy efficiency*

Introduction. Development trends of the modern maritime industry show that the operation of ship mechanisms and units focuses on the diagnostics and timely detection of technological equipment malfunctions.

Ship refrigeration units (SRU) are the most common auxiliary marine power plants and are used in almost all types of marine and river vessels for food refrigeration and storage, preparation of cold water and ice, comfortable and technical air conditioning, gases liquefaction, carbon dioxide gas storage and in other applications [1].

Practice request of the modern navy of Ukraine forms quite strict requirements [2] for the SRU: besides improving consumer properties, high accuracy of temperature control in refrigerating chambers (RC), minimal electricity costs for cold production and higher reliability of operation at variable operating modes are required. These requirements for energy efficiency and reliability of SRU cause the need to find new ways of their technical condition diagnoses and monitoring.

The greatest effect of SRU faults diagnosing is achieved by using the Fault Detection and Diagnostics (FDD) approach with applying specialized microprocessor devices [3-4]. This approach involves the use of mathematical models of diagnosed SRU elements, which allow carrying out reliable estimation of their functioning basic parameters.

However, existing models of SRU elements mostly do not consider heat load fluctuations and the mutual influence of the elements on each other. In addition, there is a technical difficulty in identifying some important parameters of the SRU technical condition, such as the load torque on the compressor shaft [5]. Existing systems for the diagnostics and

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technical conditions monitoring require the installation of a great number of sensors in the SRU, which is often technically difficult. All this, as well as insufficient study of the processes occurring in the SRU in the variable modes, the absence of domestic manufacturers of systems for SRU diagnostics and technical conditions monitoring, the lack of schematic solutions scrutiny prevents the implementation of the FDD approach in SRU.

Therefore, the solving of the scientific and technical problem of improving the diagnostics and technical condition monitoring means by using the simulation models of the separate SRU elements is relevant.

Literature review

The development of information and communication technologies caused changes in approaches to the control algorithms and architecture of devices for the diagnostics and technical condition monitoring. In particular, in the last century, a system for refrigerated containers monitoring was proposed [6]. It included a data collection unit installed on each container controlled by the system and a central microcomputer system located at the container storage site, such as a container ship or land terminal. This data transmission system used only a wired network which is definitely a disadvantage.

The advent of the global Internet and wireless data communications has led to the ability of the SRU technical condition monitoring from anywhere on the planet. For example, work [7] proposes to use mobile networks, satellite communications and Wi-Fi to communicate the diagnostics and monitoring device of the refrigerator container with the operator. A GPS sensor is used to locate the container. Solar batteries are used for autonomous power supply.

Simultaneously with the development of technical means, the approaches and algorithms for SRU diagnostics and technical condition monitoring are changed. One of the most common approaches is FDD which involves the use of mathematical modeling and statistics methods. As stated in the introduction, the FDD approach has not been widely used in marine refrigeration. This is also evidenced by the relatively small number of papers that mainly consider the mathematical statistics methods in the construction of FDD systems for the SRU diagnostics and technical condition monitoring.

In particular, in works [8-9] the system of monitoring the SRU basic parameters by means of special radio frequency identification sensors, which are the so-called RFID tags, is considered. Data exchange between the information control system and RFID sensors is based on the extensible markup language XML. The authors of [10-11] propose diagnosing and detecting faults models of ship refrigerated containers on the basis of machine learning, which provides a high (over 97 %) recognition of non-nominal operating modes of the refrigeration unit.

The above solutions [8-11] have a significant drawback. It is the lack of SRU technical condition prediction and the assessment of its energy efficiency over the unit life cycle. In addition, the presence of a great number of sensors to monitor the SRU parameters significantly raises the system in price. This is partly solved by the installation of a modular control, monitoring and diagnostics system, which exclude the need for additional sensors [12]. However, the installation of such a system is only possible for refrigerated containers because of their standardized size, while for refrigerated holds, storage chambers, air conditioning systems this issue remains open.

In recent years, SCADA systems are widely used to optimize the control and prediction of ship refrigeration equipment failures [13-14]. Such systems, in addition to the functions of control, monitoring and diagnostics, allow to organize an automated workstation of the SRU operator with a graphical real-time display of the cooling process, the possibility of manual intervention in the operation of any device, storing statistics and graphical representation of historical trends [15]. The use of SCADA-systems allows fully automating the processes of SRU control, diagnostics and technical condition monitoring, but the issues of energy efficiency and thermodynamic parameters estimation and reliability of the unit in total remain unsolved.

In order to solve this problem, the authors of [16] propose to evaluate the SRU energy efficiency by indirectly determining the unit coefficient of performance (COP). However, the proposed method raises many questions about the accuracy of refrigerant mass flow rate determining and the losses in the drive. The authors of [17] propose the method of indirect determination of the household refrigerators energy efficiency, which can be applied to SRU, however, only for the comparative evaluation of existing models. It does not give the COP absolute value. The works [18-19] describe a method for determining the SRU refrigerating cycle basic thermodynamic parameters, but does not consider the mechanical and electrical parameters of the compressor, which significantly affect the unit reliability.

Summarizing the literature review [12-19], it can be noted that despite the many technical implementations of SRU control, diagnostics and technical condition monitoring systems, there is no single approach to assessing energy efficiency, reliability, timely diagnosis and detection of SRU failures. Existing technical solutions are aimed at automating the data collection and processing with the provision of diagnostic messages and the formation of control impacts. Moreover, a great number of SRU sensors is used and predictive diagnostics is not given much attention. The issues of SRU energy efficiency reliable estimation and reliability also remain unsolved.

These problems actualize looking for new approaches to the SRU diagnostics and technical condition monitoring with the use of mathematical modeling methods. It should be noted that the existing models of both separate units and SRU in general [19-22] do not take into account the variable mode of their operation, and the mechanical processes in the compressor are practically unmeasurable.

The purpose of the article. One of the main indicators of the SRU efficiency and reliability is the COP. It characterizes the degree of the refrigeration machine perfection and determines the energy costs of cold producing. Therefore, the system of SRU diagnostics and technical condition monitoring should be able to determine COP in real time and, if possible, to use a minimum of technical means. Thus, the purpose of this article is to develop a real-time algorithm for determining the SRU energy efficiency using the minimum required number of sensors.

Main part. Algorithm for determining the parameters of a SRU actual refrigeration cycle

The actual COP of any compression refrigeration unit is defined as:

$$\varepsilon = \frac{Q_0}{W_e}, \tag{1}$$

where: Q_0 – the amount of produced cold; W_e – the amount of consumed electricity.

Based on expression (1), we can conclude that the algorithm for determining COP can be divided into two parts: thermodynamic and electromechanical. First, we will consider the “thermodynamic” part of the algorithm, which involves determining the parameters of the SRU actual refrigeration cycle such as enthalpy at characteristic points (Fig. 1).

As we can see from Fig. 1, determining the enthalpies required calculating the compressor specific work and cooling capacity requires knowledge of the pressure values at the characteristic points of the SRU cycle. Many modern SRU especially ones with small and medium cooling capacity do not have the ability to connect external pressure devices, and depressurization of the system leads to the refrigerant emission into the atmosphere. This complicates the repair work. The proposed method considers the option of constructing the cycle with the possibility of installing only four temperature sensors without using pressure sensors.

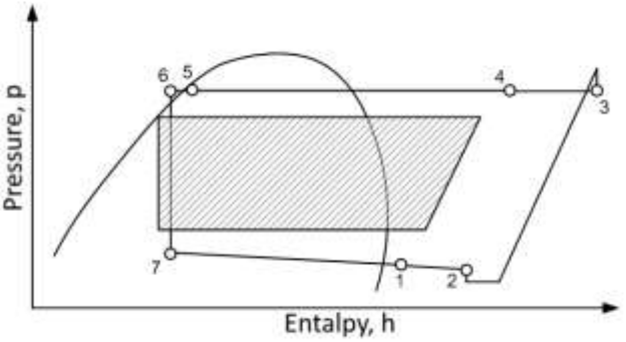


Fig. 1. Actual SRU refrigeration cycle

Thus, in order to calculate the cycle parameters and determine the technical condition of the SRU in operation, it is necessary to determine: the refrigerant condensation temperature T_k and the boiling point T_0 (Fig. 2); the compressor suction temperature T_2; the temperature of the supercooled liquid refrigerant behind the condenser before the thermostatic valve T_6; type of used refrigerant and compressor model. The temperature sensors locations are conditionally shown in Fig. 2.

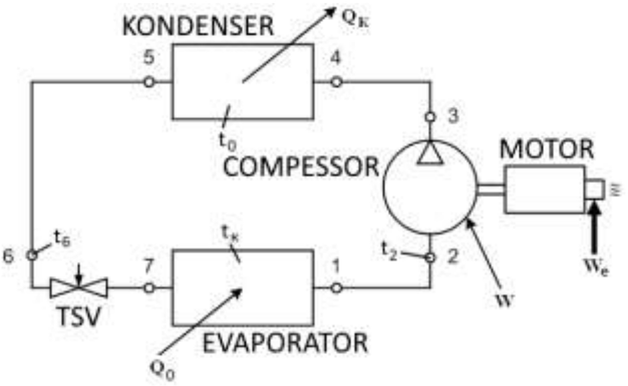


Fig. 2. SRU structural scheme

It is possible to use special tables or thermal diagrams of pressure – enthalpy and temperature - entropy to determine the SHU parameters in the single-phase field, but they are not always available to watch engineer. In addition, the use of thermal diagrams or tables reduces the calculations accuracy because using graphical or numerical interpolation methods. Taking into account the above, using a complex of simple equations based on experimental data and developed table of coefficients *B*, *C*, *D* of refrigerant state equations [18] is proposed. These equations provide sufficient accuracy for calculating enthalpy *h* as a function of the pressure *p* and the temperature *T*.

Below we consider the algorithm for determining the amount of cold Q_0 produced by SRU over a given period of time τ.

1. The measured values of T_k and T_0 determine the condensation pressure $p_к$ and boiling pressure $p_к$ by the expression

$$p = e^{D_0 + D_1 \cdot T + D_2 / T}. \qquad (2)$$

The pressure at points 1, 2, 7 is taken equal to p_0, and at points 3-6 is equal to $p_к$ (Fig. 1).

2. Enthalpy at points 1 and 2 is determined:

$$h = C_0 T + 50C \cdot \Theta^2 + C_1 + p\left(\frac{3B_3}{\Theta^2} - B_2\Theta^2\right), \qquad (3)$$

where: Θ = T/100.

3. The entropy at point 2 is determined:

$$s = \ln\frac{T^{C_0}}{p^R} + C \cdot \Theta + C_2 + \frac{p}{100}\left(\frac{2B_3}{\Theta^3} - 2B_2\Theta - B_1\right). \qquad (4)$$

The entropy at point 3 is assumed to be equal to s_2.

4. From equation (4) the compressor discharge temperature at point 3 is determined for known p_3 та s_3.

5. The enthalpy at point 3 is determined by expression (3) for known p_3 and T_3.

6. The enthalpy at point 6 is determined for known $p_к$ and T_6 and at point 7a for known p_0 and T_0 by the expression

$$h' = a_0 + a_1 \cdot \Theta + a_2 \cdot \Theta^5. \qquad (5)$$

7. The steam dryness at point 7 is determined

$$x_7 = \frac{h_6 - h_{7a}}{h_1 - h_{7a}}. \qquad (6)$$

8. The enthalpy at point 7 is calculated, taking into account the refrigerant parameters on the condensation and boiling lines

$$h_7 = h_6 + x_7\left(h_1 - h_6\right). \qquad (7)$$

9. The SHU specific cold capacity is determined as the enthalpy difference at the inlet and outlet of the evaporator

$$q_0 = h_1 - h_7. \qquad (8)$$

10. The compressor specific compression work is defined as the enthalpy difference on the suction and discharge lines

$$w = h_3 - h_2. \qquad (9)$$

11. The compression power of the compressor is determined by the pre-calculated mechanical power on the shaft P_m, taking into account the efficiency η_c for the given compressor model and the load

$$N = P_m \cdot \eta_c. \qquad (10)$$

The efficiency of the compressor η_c is generally determined by the geometric dimensions and the indicator diagram and can be calculated by the method [23].

12. The refrigerant mass flow through the compressor is determined for a specified period of time τ

$$m = \frac{N}{w}. \qquad (11)$$

13. The amount of produced cold over a period of time τ is calculated by integration

$$Q_0 = \int_0^{\tau}\left(m \cdot q_0\right)dt. \qquad (12)$$

The integration time value τ is determined depending on the dynamic properties of the SRU.

Technique for determining mechanical power on the SRU compressor shaft

The “electromechanical” part of the SRU COP determination algorithm, which involves real-time calculation of the consumed electricity W_e (1) and mechanical power on the compressor shaft P_m (10) is considered.

The determining the mechanical power on the compressor shaft P_m causes a number of difficulties, because it involves knowing the instantaneous values of the load torque M_l and the shaft rotational speed **Ω**.

The determining of Ω requires the speed sensor installation, which is practically impossible in hermetic and semi-hermetic compressors. Existing sensorless Ω detection systems [24] are imperfect because they require complex coordinate transformations and real-time differentiation operations.

It is almost impossible to measure the load torque on the compressor shaft. Indirect methods of calculating M_l [25] have a certain error and can only determine the mean value for one rotate of the compressor shaft. The accuracy of the indirect power determination method on the compressor shaft described in [16] also raises doubts because of a number of assumptions made by the authors.

These issues can be effectively solved by using adaptive observers of the compressor motor condition. When using observers, a mathematical model of an inductive motor (IM) is introduced into the diagnostics and technical condition monitoring system. This model evaluates the current value of the rotor rotational speed.

In the work [26], for this purpose, equations describing only electromagnetic processes in IM are used

$$\begin{aligned} &\frac{d}{dt}\begin{bmatrix} I_s \\ \Psi_r \end{bmatrix} = [A]\cdot\begin{bmatrix} I_s \\ \Psi_r \end{bmatrix} + [B]\cdot[U_s] \\ &I_s = [C]\cdot\begin{bmatrix} I_s \\ \Psi_r \end{bmatrix}, \end{aligned} \qquad (13)$$

where: I_s is the stator current vector; Ψ_r is the rotor flux vector; U_s is the stator voltage vector; *A* is the own matrix of IM; *B* is the control matrix; *C* is the output matrix.

In this structure of the model, the measured coordinates of the compressor electric drive state are the phase stator currents I_s, and the recovered coordinate is the rotor rotational speed Ω, which is determined by a special adaptation algorithm (Fig. 3).

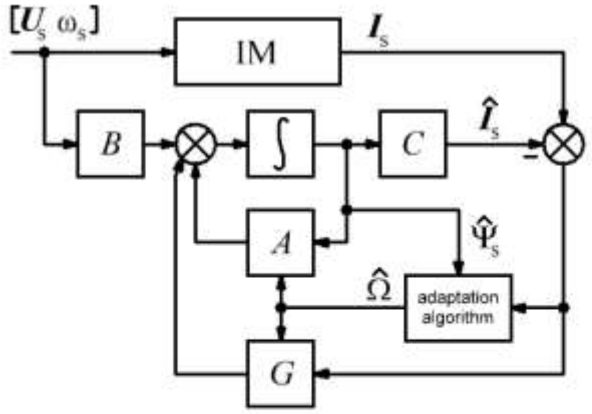


Fig. 3. The full order state observer of IM

This approach makes it quite simple to determine the values of Ω and the electromagnetic torque M_e, and therefore the power P_d that the motor produces. In the compressor steady operating mode, the use of the described method for determining P_m is justified because, if the losses on the motor shaft are neglected, $P_m \approx P_d$. But, as already mentioned, the SRU compressors operate in variable operation modes with a smooth or discrete control of the IM rotor rotation speed. In this case, the above equality is contravened and the task of identifying the load torque M_l on the compressor shaft arises.

As it will be shown below, this problem is effectively solved if the complete mathematical model of IM, which describes its electromagnetic and mechanical processes [24], applies in the structure of the compressor electric drive state observer. In this case, the IM electromagnetic torque can be used as the measured coordinate [27]. The proposed structure of the state observer is shown in Fig. 4.

In calculating the coefficients of the observer matrix *G*, the use of the IM mathematical model equations written in the canonical form [24] is directly difficult, because the electromagnetic torque M_e is determined by the productions of the stator current and flux vectors projections. However, this is unnecessary, because the coefficients of the matrix *G* are approximated determined on general recommendations or practical experience [26; 28] and influent only on the state coordinates identification rate by the observer. Therefore, it is permissible to use a linearized IM model [29].

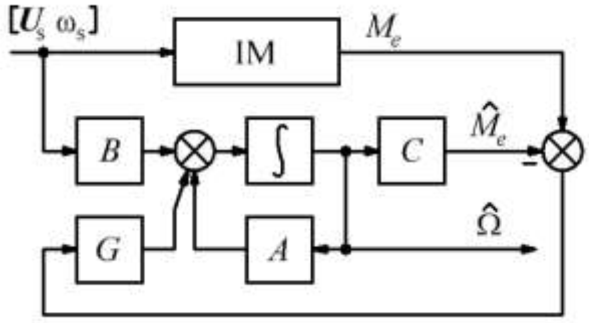


Fig. 4. The proposed structure of the IM state observer

Let's synthesize the IM state observer. For this we use the modal method [30].

System of differential equations of IM linearized mathematical model written in canonical form is

$$\frac{d}{dt}\begin{bmatrix} M_e \\ \Omega \end{bmatrix} = [A]\cdot\begin{bmatrix} M_e \\ \Omega \end{bmatrix} + [B]\cdot\omega_s + [F]\cdot M_l, \quad (14)$$

where: ω_s is the frequency of the IM current stator; *F* is the perturbation matrix.

Matrices of IM linearized model are

$$[A] = \begin{bmatrix} -\dfrac{1}{T_r} & -\dfrac{z_p\cdot\beta}{T_r} \\ \dfrac{1}{J} & 0 \end{bmatrix}$$

$$[B] = \begin{bmatrix} \beta/T_r \\ 0 \end{bmatrix}, \quad (15)$$

$$[F] = \begin{bmatrix} 0 \\ 1/J \end{bmatrix},$$

where: T_r is the electromagnetic time constant of the IM rotor; β is the mechanical characteristic stiffness; *J* is the total moment of inertia of the IM rotor and the compressor crank mechanism; z_p is the number of compressor IM pairs of poles. All these values are determined by the catalog data of the IM and the compressor.

Since the diagnostics and technical condition monitoring system provides for direct measurement of the IM electromagnetic torque M_e, the vector of the original (measured) variables is

$$Y = [C]\cdot\begin{bmatrix} M_e \\ \Omega \end{bmatrix} = [1\ \ 0]\cdot\begin{bmatrix} M_e \\ \Omega \end{bmatrix} = M_e. \quad (16)$$

The state observer for estimating the vector of state coordinates is constructed on the basis of the IM mathematical model (14) by supplementing it with a “stabilizing additive” [26-30]. Considering the perturbation is uncontrolled, and taking into account expressions (14) and (16), a linearized mathematical model of the full order state observer for the compressor IM will become as

$$\frac{d}{dt}\begin{bmatrix}M_e\\ \Omega\end{bmatrix}=[A]\cdot\begin{bmatrix}M_e\\ \Omega\end{bmatrix}+[B]\cdot\omega_s+\begin{bmatrix}G_1\\ G_2\end{bmatrix}\cdot\left(M_e-\hat{M}_e\right). \qquad (17)$$

where: *G* is the matrix of the full order state observer of dimension 2 × 1. The symbol ˆ in (17) and further indicates the estimated value of the corresponding value.

The checking of the IM observability condition is expressed by the requirement of the observation matrix *H* rank equality to the research object order [31]. According to equation (14) the order of the IM linearized model is 2. The observation matrix for the accepted object of study is

$$H=\left[C^T \vdots A^T C^T\right]=\begin{bmatrix}1 & -\dfrac{1}{T_r}\\ 0 & -\dfrac{z_p\cdot\beta}{T_r}\end{bmatrix}. \qquad (18)$$

The rank of the observation matrix *H* is 2, which satisfies the observation condition.

The elements of the matrix *G* are determined if the characteristic polynomial of the observer *D*(*s*) is equal to the normalized polynomial *N*(*s*):

$$|sE-A+GC|=s^2+A_1\cdot\Omega'\cdot s+\left(\Omega'\right)^2, \qquad (19)$$

where: *s* is the Laplace operator; *E* is a single matrix; Ω' is the geometric mean root whose value is selected from the condition of providing the required performance of the observer; A_1 is the shape factor whose value depends on the accepted root distribution of the characteristic polynomial.

The characteristic polynomial of observer *D*(*s*) taking into account (19) is

$$D(s)=s^2+\left(\frac{1}{T_r}+G_1\right)\cdot s-\frac{z_p\cdot\beta\cdot\left(J\cdot G_2-1\right)}{T_r\cdot J}. \qquad (20)$$

Equating the respective coefficients *D*(*s*) and *N*(*s*) we obtain

$$\begin{aligned}G_1&=A_1\cdot\Omega'-\frac{1}{T_r}\\ G_2&=\frac{1-\left(\Omega'\right)^2\cdot T_r\cdot J}{z_p\cdot\beta\cdot J}.\end{aligned} \qquad (21)$$

If the value of the geometric mean root is taken equal to $\Omega'=1/(A_1\cdot T_r)$, then finally the observer matrix is

$$G=\begin{bmatrix}0\\ \dfrac{A_1^2\cdot T_r-J}{z_p\cdot\beta\cdot J\cdot A_1^2\cdot T_r}\end{bmatrix}. \qquad (22)$$

In the expanded form equations of the linearized full order state observer of the compressor IM will be written as

$$\begin{aligned}\frac{d}{dt}\hat{M}_e&=-\frac{1}{T_r}\hat{M}_e-\frac{z_p\cdot\beta}{T_r}\hat{\Omega}+\frac{\beta}{T_r}\omega_s\\ \frac{d}{dt}\hat{\Omega}&=\frac{1}{J}\hat{M}_e+G_2\left(M_e-\hat{M}_e\right).\end{aligned} \qquad (23)$$

For the highest accuracy of the observer, it is preferably to implement it on the basis of a IM complete mathematical model. For this it is appropriate to transform equations (23) to the next form

$$\begin{aligned}T_r\frac{d}{dt}\hat{M}_e+\hat{M}_e&=\beta\cdot\left(\omega_s-z_p\cdot\hat{\Omega}\right)\\ J\frac{d}{dt}\hat{\Omega}&=\hat{M}_e+J\cdot G_2\left(M_e-\hat{M}_e\right)\end{aligned} \qquad .(24)$$

On the basis of equations (24) it is possible to construct a structural diagram, which is presented in Fig. 5.

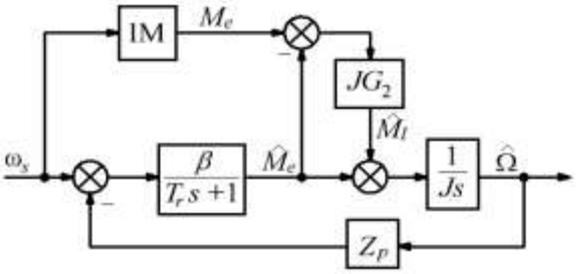


Fig. 5. Linearized full order state observer of IM

The analysis of equations (24) and the scheme in Fig. 5, indicates that the "stabilizing additive" actually represents the estimated value of the load torque on the compressor shaft M_l

$$\hat{M}_l=J\cdot G_2\left(M_e-\hat{M}_e\right). \qquad (25)$$

Therefore we build the full-order observer based on the complete mathematical model of the compressor IM

$$\begin{aligned}\frac{d}{dt}\begin{bmatrix}\hat{I}_s\\ \hat{\Psi}_r\end{bmatrix}&=[A]\cdot\begin{bmatrix}\hat{I}_s\\ \hat{\Psi}_r\end{bmatrix}+[B]\cdot[U_s]\\ \hat{M}_e&=\frac{3}{2}\cdot z_p\cdot k_r\cdot\left(\hat{I}_s\times\hat{\Psi}_r\right)\\ \frac{d}{dt}\hat{\Omega}&=\frac{1}{J}\hat{M}_e+G_2\left(M_e-\hat{M}_e\right)\end{aligned} \qquad ,(26)$$

where: k_r is the coefficient of electromagnetic coupling of the rotor. The elements of the matrices *A* and *B* can be taken from [26] and are determined by the parameters of the equivalent circuit.

Based on equations (26) in the Matlab/Simulink environment a simulation model of the compressor IM state observer is constructed (Fig. 6). For simplification, the stator currents were expressed through the appropriate fluxes and were excluded from the model in the explicit form. The passport data of the small cooling capacity SRU compressor HCV6 were used as model parameters and were taken from [25].

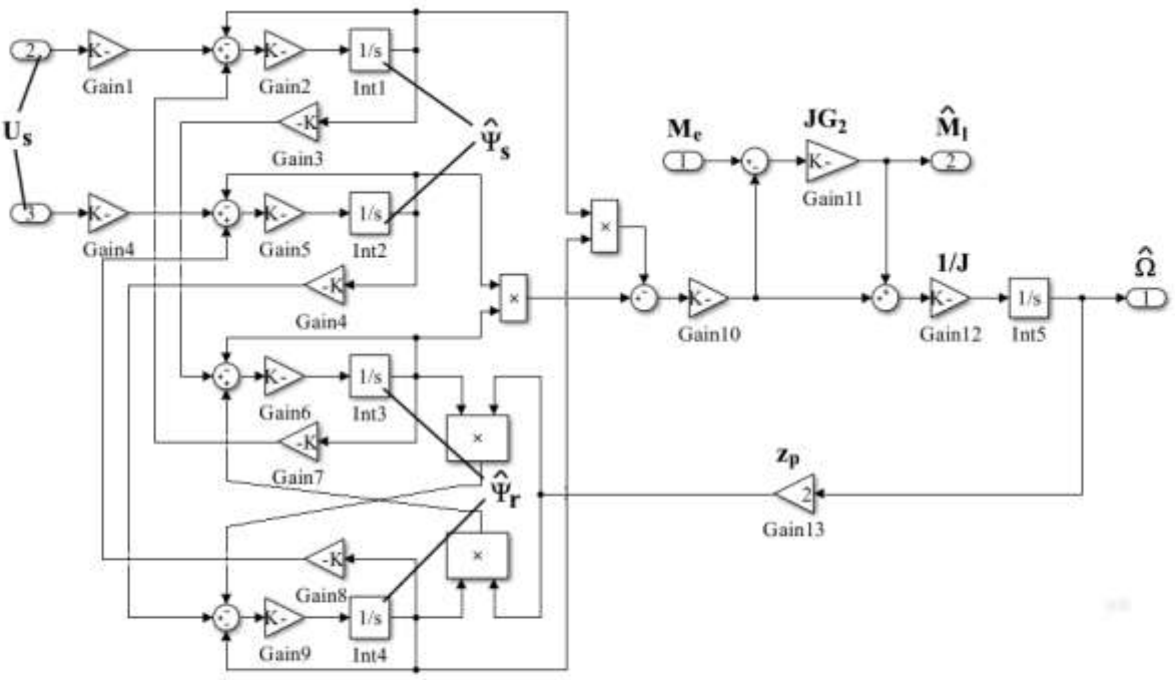
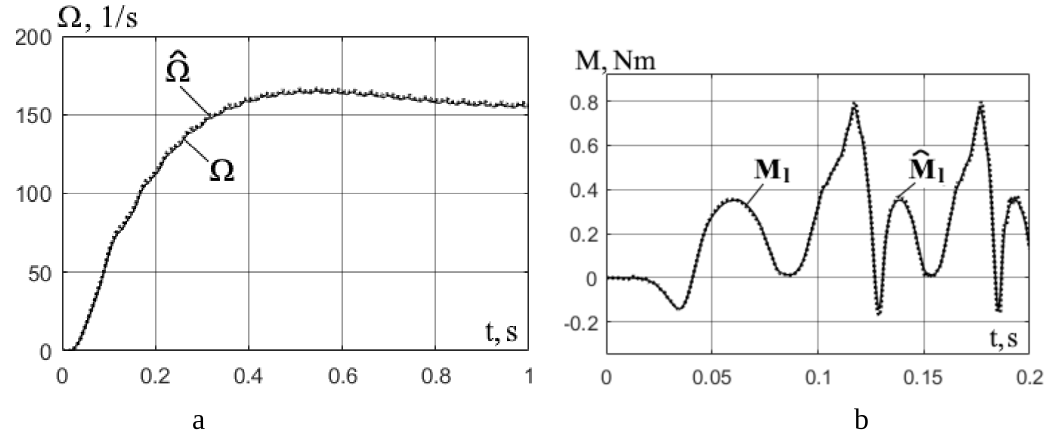


Fig. 6. The simulation model of the IM full order state observer

The moment of inertia of the compressor crank mechanism was assumed to be constant and equal to its maximum value. This assumption is valid because the change of the compressors total moment of inertia in one revolution of the shaft does not exceed a few percent.

As a result of the researching simulation model of the SRU compressor IM and the state observer when the signal of the stator voltage U_s was equal to 220 V, and the nominal compressor load, the average value of which was 0.3 N·m, graphs of the rotational speed Ω (Fig. 7a) and the load torque M_l (Fig. 7b) on the compressor shaft (shown by solid lines) as well as their estimates (shown by dots) were received at the output of the state observer. From Fig. 7, it can be seen that the estimated state coordinates of the compressor are quite close to their real values, and the observer error does not exceed 1.6 % of the rotational speed and 5.3 % of the load torque. This indicates the efficiency of the proposed method taking into account the assumed assumptions.



a b

Fig. 7. Graphs of the compressor rotational speed and load torque

Algorithm for determining the electromechanical parameters of the SRU compressor

The algorithm for determining the electromechanical parameters of the SRU compressor over a given period of time τ_e is considered.

1. The current value of the IM stator fluxes vector Ψ_s is calculated from the measured values I_s and U_s by the expression

$$\Psi_s = \int \left(U_s - R_s \cdot I_s \right) dt, \qquad (27)$$

where: R_s is the active resistance of the IM stator winding, which is determined from the passport data. For excluding the accumulation of additive measurement error that occurs during integration, it is possible to use the recommendations from [28].

2. The current value of the IM electromagnetic torque M_e is calculated by expression

$$M_e = \frac{3}{2} \cdot z_p \cdot \left(I_s \times \Psi_s \right). \qquad (28)$$

3. According to the passport data of the compressor IM AD the elements of the matrices *A*, *B* and *G* are determined.

4. The state observer determines the estimated instantaneous values of the load torque M_l and the rotational speed Ω of the compressor shaft. These values are averaged over a period of time τ_e.

5. The mechanical power on the compressor shaft is calculated by the average values of M_l and Ω:

$$P_m = M_l \cdot \Omega. \qquad (29)$$

The resulting value P_m is substituted into expression (10) to calculate the compressor compression power.

6. The amount of electricity consumed over a period of time τ_e is determined by integrating the voltage at the compressor motor stator clamps instantaneous values and the consumed current:

$$W_e = \int_0^{\tau_e} \left(I_s \cdot U_s \right) dt. \qquad (30)$$

Thus, for determination of W_e it is necessary to provide for the installation of the voltage and current sensors in the diagnostics and technical condition monitoring system (Fig. 2). The value of the period of time τ_e is assumed to be smaller than τ because the inertia of the processes occurring in the compressor is an order of magnitude smaller than that of the evaporator.

General algorithm for estimating the energy efficiency of SRU

The above provisions allow building a general algorithm for estimating the energy efficiency of SRU, the main indicator of which is the COP ε. This algorithm is presented in Fig. 8.

The analysis of the algorithm shows that it actually contains three subroutines that calculate specific cooling capacity and compressor compressing work, refrigerant mass flow through the compressor and mechanical power on the shaft in real time.

The most complicated solving process is the estimation of the mechanical power P_m by a synthesized full order observer. It is preferably that the integration step in the calculation of the equations was an order of magnitude smaller than the inertia of the observer

$$\Delta\tau \le \frac{1}{10 \cdot \Omega'}. \qquad (31)$$

It should be noted that with the on-off control of the SRU cooling capacity for processor time saving the P_m estimation subroutine and the W_e calculation can be started only when the compressor works, and only Q_0 can be calculated during the stop period.

Taking this into account the microprocessor part of the diagnostics and technical condition monitoring system is selected.

Conclusions. The conducted researches made it possible to achieve the set purpose, namely the algorithm of the real time SRU energy efficiency determination was developed.

The algorithm provides the energy efficiency estimation of the SRU as a whole and also separate elements such as compressor, motor and so on. All this makes it possible to apply the FDD approach in the design of the diagnostic system with specific recommendations for service staff.

The use of a full order adaptive observer in the SRU diagnostics and technical condition monitoring system allows making a reliable estimation of the compressor operational characteristics which are practically not directly measurable. In particular, the system is able to determine in real time the mechanical load and the rotational speed of the shaft for estimating possible malfunctions of the compressor mechanical part.

The implementation of this algorithm requires the installation of only 10 sensors. Among of them there are 4 temperature sensors, 3 current sensors and 3 voltage sensors. As temperature sensors, it is preferably to use semiconductor thermistors with the possibility of external connection to the information outputs. In this case, it is possible to create a mobile system for diagnosing and monitoring the technical condition of the SRU, which can be used by watch engineers.

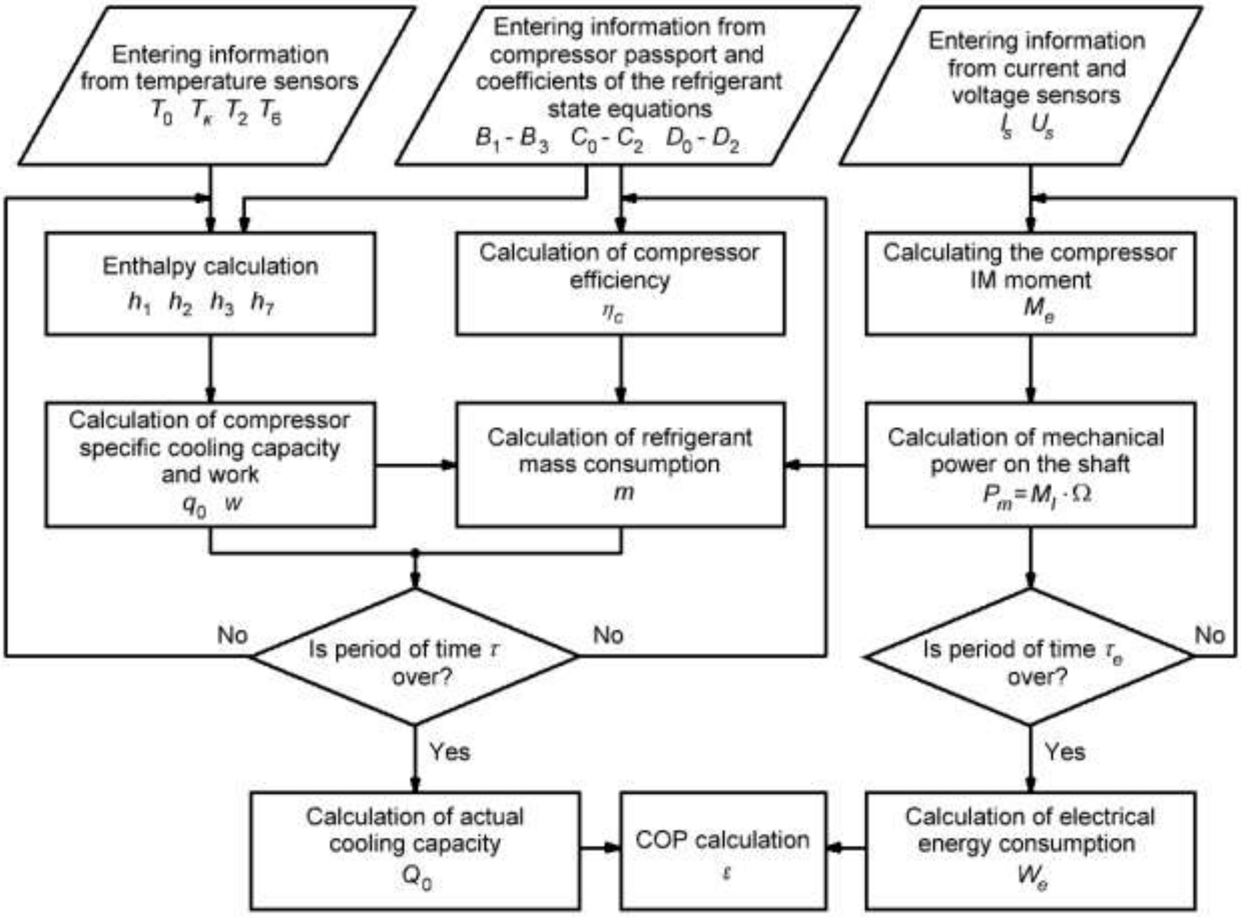


Fig. 8. Algorithm for SRU energy efficiency estimation

In general, the algorithm allows real time building the refrigeration cycle and in the presence of a “reference” cycle can be the basis for creating a system of the SRU diagnostics and technical condition monitoring, which requires further researches.

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АЛГОРИТМ ОЦІНКИ ЕНЕРГЕТИЧНОЇ ЕФЕКТИВНОСТІ СУДНОВОЇ ХОЛОДИЛЬНОЇ УСТАНОВКИ ЗА ДОПОМОГОЮ СПОСТЕРІГАЧІВ СТАНУ ПОВНОГО ПОРЯДКУ

Анотація. *Стаття розглядає побудування алгоритму оцінки енергетичної ефективності суднової холодильної установки з використанням мінімально необхідної кількості датчиків. Визначено, що існуючі методи діагностики та контролю технічного стану суднових холодильних установок недосконалі через наявність великої кількості датчиків та необхідність припиняти роботу установки. Обґрунтований вибір холодильного коефіцієнту в якості показника енергетичної ефективності. Запропонована методика, яка дозволяє визначати холодильний коефіцієнт в реальному часі без необхідності зупинки роботи суднової холодильної установки та встановлення датчиків тиску. Для цього методика передбачає обчислення питомої холодопродуктивності та роботи стискування компресора, механічної потужності на валу та масової витрати холодильного агента. Розглянутий алгоритм визначення холодопродуктивності та роботи стискування із застосуванням лише чотирьох датчиків температури. Даний алгоритм передбачає визначення ентальпій в* *характерних точках холодильного циклу з використанням рівнянь стану холодильного агента. Запропонована методика оцінки механічної потужності на валу компресора за допомогою адаптивних спостерігачів стану повного порядку. Обгрунтовано рішення в якості вимірюваної величини використати електромагнітний момент приводного електродвигуна компресора. Синтезований спостерігач стану із застосуванням модального методу на основі лінеаризованої моделі електродвигуна. Запропонований вираз для обчислення середньогеометричного кореня та елементів матриці спостерігача. Отримана структура спостерігача дозволяє будувати його на основі повної математичної моделі електродвигуна та здійснювати оцінку не тільки частоти обертання, а й моменту навантаження на валу компресора. В середовищі Matlab/Simulink побудована імітаційна модель спостерігача стану електродвигуна компресора. Отримані результати моделювання підтверджують працездатність запропонованої методики. Розглянутий алгоритм визначення електромеханічних параметрів компресора за заданий проміжок часу з використанням трьох датчиків напруги та струму. Побудований загальний алгоритм оцінки енергетичної ефективності, який може бути основою для створення системи діагностики та контролю технічного стану суднової холодильної установки.*

***Ключові слова**: суднова холодильна установка; спостерігач стану; діагностика, моделювання, алгоритм, енергетична ефективність*

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АЛГОРИТМ ОЦЕНКИ ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ СУДОВОЙ ХОЛОДИЛЬНОЙ УСТАНОВКИ С ПОМОЩЬЮ НАБЛЮДАТЕЛЕЙ СОСТОЯНИЯ ПОЛНОГО ПОРЯДКА

***Аннотация:** Статья рассматривает построение алгоритма оценки энергетической эффективности судовой холодильной установки с использованием минимально необходимого количества датчиков. Установлено, что существующие методы диагностики и контроля технического состояния судовых холодильных установок несовершенны из-за наличия большого количества датчиков и необходимости приостанавливать работу установки. Обоснован выбор холодильного коэффициента в качестве показателя энергетической эффективности. Предложена методика, позволяющая определять холодильный коэффициент в реальном времени без необходимости остановки работы судовой холодильной установки и использования датчиков давления. Для этого методика предполагает вычисление удельной холодопроизводительности и работы сжатия компрессора, механической мощности на валу и массового расхода холодильного агента. Рассмотрен алгоритм определения холодопроизводительности и работы сжатия с применением только четырех датчиков температуры. Данный алгоритм предполагает определение энтальпий в характерных точках холодильного цикла с использованием уравнений состояния холодильного агента. Предложена методика оценки механической мощности на валу компрессора с помощью адаптивных наблюдателей состояния полного порядка. Обоснованно решение в качестве измеряемой величины использовать электромагнитный момент приводного электродвигателя компрессора. Синтезирован наблюдатель состояния с применением модального метода на основе линеаризованной модели электродвигателя. Предложено выражение для вычисления среднегеометрического корня и элементов матрицы наблюдателя. Полученная структура наблюдателя позволяет строить его на основе полной математической модели электродвигателя и осуществлять оценку не только частоты вращения, но и момента нагрузки на валу компрессора. В среде Matlab / Simulink построена имитационная модель наблюдателя состояния электродвигателя компрессора. Полученные результаты моделирования подтверждают работоспособность предложенной методики. Рассмотрен алгоритм определения электромеханических параметров* *компрессора за заданный промежуток времени с использованием трех датчиков напряжения и тока. Построен общий алгоритм оценки энергетической эффективности, который может быть основой для создания системы диагностики и контроля технического состояния судовой холодильной установки.*

Ключевые слова: *судовая холодильная установка; наблюдатель состояния; диагностика, моделирование, алгоритм, энергетическая эффективность*

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