

Ushkarenko O.O.<https://orcid.org/0000-0002-3159-330X>

Admiral Makarov National University of Shipbuilding

ANALYSIS OF AUTOCORRELATION PROPERTIES OF INFORMATION FLOWS IN DISTRIBUTED CONTROL SYSTEMS

The paper presents an analysis of the correlation characteristics of information flows in distributed control systems of autonomous power systems, including ship electric power plants, operating in real time. The distributed control system is represented as a microprocessor network modeled as a queuing system with multiple input flows, priority-based service, and intervals of service unavailability. It is shown that with increasing intensity of incoming flows and uneven loading of network nodes, overload conditions arise, leading to increased packet delays, queue growth and loss of information packets. Therefore, the primary focus of the paper is on researching the autocorrelation properties of the aggregate information flow formed by several input flows of varying intensity and priority. The conditions under which input flows can be approximated by Poisson flows were considered, and the influence of unavailability intervals of the queuing system on the flow structure was analyzed. To evaluate the correlation characteristics, an autocorrelation function is used, allowing one to determine the degree of dependence between successive packets over time. Stationary Poisson flows with varying intensities were modeled, and changes in correlation coefficients were analyzed for different service unavailability intervals. It was shown that increasing the duration of the unavailability interval leads to expansion of the zones of lack of correlation and distortion of the flow distribution, which negatively impacts network performance. It was found that with increasing incoming flow intensity, the impact of these distortions becomes more pronounced, leading to an increased probability of channel and network node load. The obtained results confirm the need to consider the correlation characteristics of information flows when analyzing and designing distributed control system networks. The considered approach can be used to improve the accuracy of performance models and develop effective flow control algorithms under conditions of limited resources and interval service unavailability.

Keywords: correlation analysis, information flows, distributed control system, queuing system.

Formulation of the problem. Modern distributed control systems for autonomous electric power systems (AEPS), including ship electric power plants (SEPP), are characterized by a high degree of integration between computing, communications, and control subsystems, interacting through intensive data flows. Data transmission in such systems is carried out through multi-level microprocessor networks, in which information packets pass through a series of switching and processing devices [1, p. 708]. The operation of these networks under conditions of random request incoming calls leads to the formation of queues and delays, which directly impacts the performance and reliability of the entire control system.

A significant feature of distributed control systems is the presence of time intervals when service resources are unavailable [2, p. 613]. These intervals are caused by both the specifics of flow management algorithms

and the limited computing and communication capabilities of network nodes. During these intervals, information packets are not serviced, leading to their loss or accumulation in queues [3, p. 1089]. This phenomenon becomes especially critical during a sharp increase in flow intensity or when the load is unevenly distributed among network nodes.

When operating communication nodes with interval-based access to resources, the structure of the total flow generated at the system input, as well as its autocorrelation properties, play a crucial role. Correlation between successive packets determines the likelihood of queues accumulating during periods of unavailability and significantly impacts the efficiency of flow processing. Therefore, analyzing the autocorrelation characteristics of information flows is a necessary step in the development and optimization of traffic management algorithms in distributed control systems.



Analysis of recent research and publications. Queuing theory [4, p. 111] is widely used to construct performance models for computing systems. Analysis of a SEPP distributed control system's microprocessor network as a queuing system allows us to determine the number of packets in the network at different stages of service, the waiting time in queues, the packet transmission time, and other characteristics of the flow processing process.

When the level of flows in the network of SEPP distributed control system increases sharply, congestion occurs, i.e., the incoming messages are blocked. One of the reasons leading to a decrease in productivity is the busyness of queue processing systems, which are queuing systems (QS). A request received at the input of the system "waits" in a queue for execution. This waiting time depends on such factors as the intensity of flows and the time it takes to process packets in the queuing system, which has the negative impact on the control quality. One approach to solving such problems is to optimize the use of all available network resources [5, p. 371]. In particular, it is desirable to ensure that network nodes are not overloaded, while similar nodes on alternative routes are underloaded. It is possible to use feedback algorithms [6, p. 14] that consider the presence and size of queues, packet arrival rates, and the interval between successive packets, using only information about input flows and saturation flows. This control mode, in which the servicing of request flows occurs strictly according to a predetermined law, is most often used in queuing systems with a high load, when the intensities of incoming requests for different flows are practically the same [7, p. 69]. However, if gaps appear in the flows, the cyclic control method is not practical: for some flows, the service device operates in idle mode, while for other flows there are queues of service requests.

Despite the large number of studies devoted to modeling distributed control systems based on queuing theory [8, p. 17; 9, p. 2], existing research has insufficiently explored the impact of correlation characteristics of information flows on their processing efficiency under conditions of interval-dependent unavailability of service resources.

In most known studies, input information flows are assumed to be Poisson or statistically independent [10, p. 551; 11, p. 49]. The analysis is limited to average values of intensity, delays, and queue lengths, while unavailability intervals of service nodes are either not considered at all or are considered in a simplified manner, without regard to the temporal structure of the flows.

In real distributed control systems of SEPP, information flows are generated by a set of local sources, exhibit temporal correlation and non-stationarity, and interact with service devices operating in modes with periodic or event-driven unavailability. Thus, existing studies lack an analysis of the correlation characteristics of total information flows in distributed control system networks, taking into account unavailability intervals of service resources. The influence of temporal correlation of flows on the efficiency of their processing and the probability of loss of information packets has not been sufficiently studied, which limits the applicability of existing performance models in the conditions of real operation of distributed control systems.

Task statement. This research is devoted to the assessment of the intensity of the total flow in SEPP distributed control system and the construction of an autocorrelation function in order to analyze the influence of the unavailability time interval during which flows are not serviced on the efficiency of their processing.

The solution to this problem will allow us to more adequately describe the flow processing processes, improve the accuracy of performance models, and develop more efficient methods for managing network resources aimed at reducing packet loss and improving overall system performance.

Outline of the main material of the study. The automated control system for a ship's electric power plant is considered as a set of microprocessor systems distributed across production areas. In terms of topology and control organization, the system is distributed [12, p. 21]. In Fig. 1 a structural diagram of the microprocessor network of the distributed control system is shown.

The following designations are used in the figure: DPM – Diesel Parameters Monitoring system; DCU – Diesel Control Unit; ES – Excitation System of the synchronous generator; CPR – Current Protection Relay; RPR – Reverse Power Relay; SCP – Short-Circuit Protection; LAR – Local Automation Router; RPD, APD – Reactive and Active Power Distribution devices; GS – Generator Synchronization block; FCR – Functional Complex Control Flow Router; AS – Emergency Alarm System; VCU – Voltage Control Unit; PRC – Power Reserve Control device; ICS – Integrated Control System; IM – Insulation Monitoring unit; PM – Power Monitoring unit; VM – Voltage Monitoring unit; FM – Frequency Monitoring unit.

For each network process, the following are assessed:

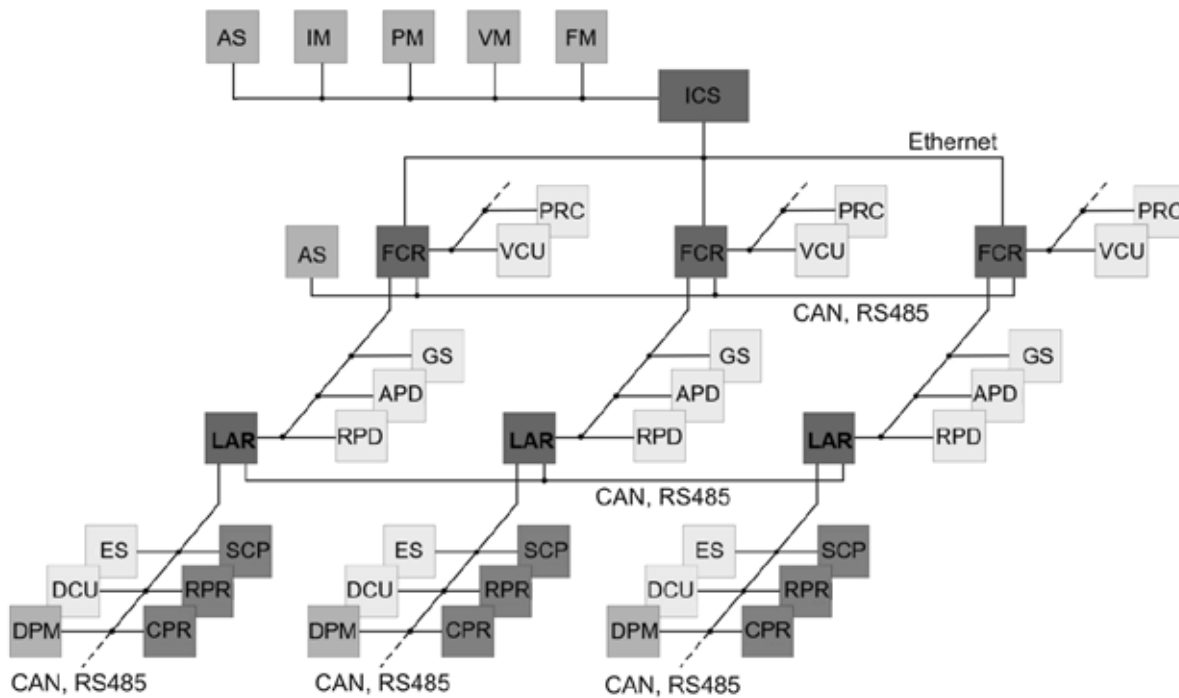


Fig. 1. The structure of the microprocessor network of a ship power plant distributed control system

- the volume of data transmitted for each service class;
- the uniformity of the data flow for each service class;
- the distribution of workload intensity depending on the power plant operating mode.

Distributed control systems operating in real time require strict and precise quality of service guarantees. Correct network design and flow classification into a small number of priority classes may be sufficient to ensure the normal operation of the control system. Ultimately, appropriate resource allocation during peak load periods or emergency situations, along with protection from lower-priority flows, will ensure the required level of service. The advantage of this solution is higher overall efficiency, as it allows for the transmission of a larger number of flows in a simpler manner and using simple data path management mechanisms [13, p. 3]. Figure 2 shows the functional diagram of the flow processing system.

Queuing systems can be divided into two types [14, p. 49] – systems with waiting and systems with losses. In the first case, a request received at the system input "waits" for processing; in the second, it is rejected due to the service channel being busy and is lost from the QS.

A flow is defined as a sequence of information packets entering a service system – a collection of queues and service devices (channels). Each packet

enters its own channel, where it undergoes service operations.

Input flows π_1, π_2, π_3 are generated by the automation equipment of the ship electric power plant, the state and operating mode of which determine the probabilistic structure of these flows. Requests for input flows are received in accumulators (queues) Q_1, Q_2, Q_3 with unlimited capacities. The following flow service classes can be defined [3]:

- π_1 is a low-intensity, information-rich, priority flow;
- π_2 is a low-intensity flow;
- π_3 is the highest-intensity priority flow.

If the environment is in state $e^{(0)}$, then the input flows are Poisson-type flows (flows of individual requests). For the environment state $e^{(1)}$, the input flows are not simplest. Next, the case when the system is in state $e^{(0)}$ is considered.

The information content of flow π_1 means that the dynamics of the queuing system take into account the presence of requests in storage Q_1 and the arrival of requests along this flow. Its priority is determined by the need to promptly service incoming requests. The priority of flow π_3 means that if there are no requests along flow π_1 (a gap), servicing along flow π_3 will continue.

A random input flow π_j is described by a vector random sequence $\{(\tau_i, v_i, \eta_{ji}), i \geq 0\}$, where η_{ji} is the number of requests of type v_i received during the time interval $[\tau_i, \tau_{i+1})$ along this flow. The request type is

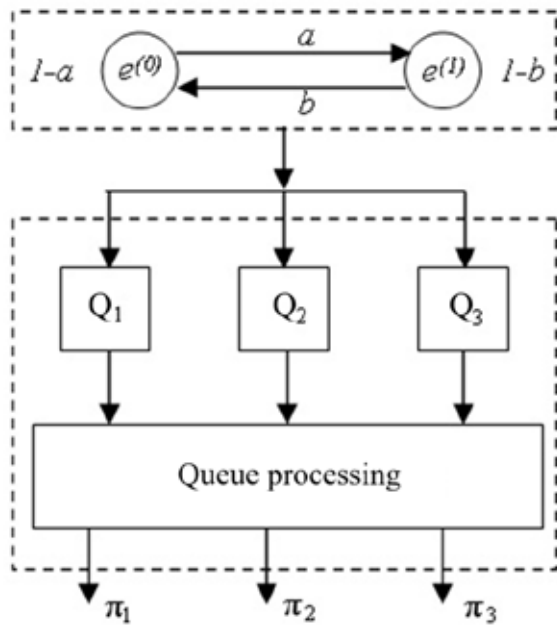


Fig. 2. The functional diagram of the flow processing system

determined by the label v_i (the state of the random environment).

For the simplest flow, which can be considered a flow from local control means arriving at the LAR flow router (Fig. 1), the number n of events falling within any time interval τ is distributed according to the Poisson law [15, p. 167]:

$$P(n, \tau) = \frac{(\lambda\tau)^n \exp(-\lambda\tau)}{n!}, n = 0, 1, 2, \dots \quad (1)$$

The probability that no event will occur during a time interval τ is:

$$P(0, \tau) = e^{-\lambda\tau}. \quad (2)$$

Then the probability of the opposite event is:

$$P(T < \tau) = 1 - e^{-\lambda\tau}. \quad (3)$$

To model a Poisson flow with intensity $\lambda(t)$, which determines the number of information packets received per unit of time, it is necessary to use a system of densities:

$$a_i(t_1, \dots, t_i) = \prod_{j=1}^i \lambda(t_j) \exp\left(-\int_{T_0}^{t_i} \lambda(x) dx\right). \quad (4)$$

The conditional probability density can be defined by the equation:

$$f_i(t_i/t_{i-1}, \dots, t_1) = \frac{a_i(t_1, \dots, t_i)}{a_{i-1}(t_1, \dots, t_{i-1})} \quad (5)$$

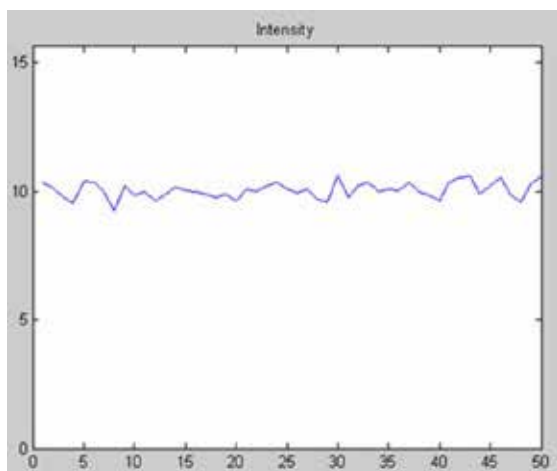
Substituting (1) into (2) we get:

$$d_i = 1 - \exp\left(-\int_{t_{i-1}}^{t_i} \lambda(t) dt\right). \quad (6)$$

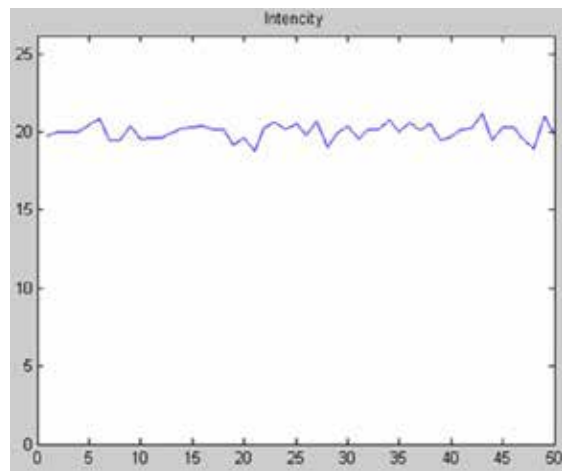
where t_1, \dots, t_i – moments of occurrence of flow events.

The given time points t_1, \dots, t_i constitute a Poisson flow. Two stationary Poisson flows with different intensities, $\lambda=10$ and $\lambda=20$, were analyzed. The intensity graphs for these flows are shown in Fig. 3, a, b, respectively.

To implement the flow, event occurrence times t_1, t_2, \dots of the flow with the required intensity were generated. The following algorithm was then executed:



(a)



(b)

Fig. 3. Flow intensity graphs: a – $\lambda=10$; b – $\lambda=20$.

1. The first event is recorded: $i_m=1, i=1$;
2. The event occurrence time is stored: $t_{im}=t_i$, and the event counter is incremented by one: $i_m=i_m+1$;
3. The event counter is incremented by one: $i=i+1$;
4. The condition $t_i-t_{mim}-1>\tau$ is checked. If it is met, proceed to step 2; otherwise, proceed to step 3.

The correlation function has two uses. It determines the degree of "similarity" between two flows at different time delays (cross-correlation). It is also used to determine the degree of correlation between a flow and itself depending on the delay time (autocorrelation) [16, p. 3]. Correlation is a normalized value with the interval value [-1,1]. To estimate a stationary flow, the autocorrelation function is used:

$$R_j = \begin{cases} i=1, \frac{1}{NWh^2} \sum_{j=1}^N v_j(v_j-1) \\ i \neq 1, \frac{1}{(N-i+1)Wh^2} \sum_{j=1}^{N-i+1} v_j v_{j+i-1} \end{cases}, \quad (7)$$

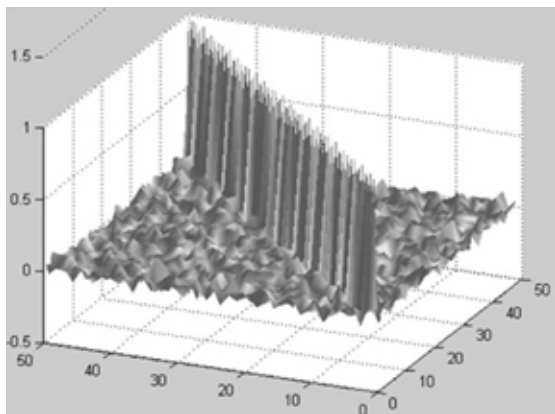
where N – the number of time intervals; v_m – the number of received packets during each time interval; W – the number of iterations of the process of the flow under study obtaining realizations; h – the time interval partitioning step.

When plotting the graph, the ordinate axis shows the value of R_j calculated using equation (7), and the abscissa axis shows the time interval numbers. Fig. 4, a, b, show the correlation coefficient matrices for flows with intensities $\lambda=10$ and $\lambda=20$, respectively.

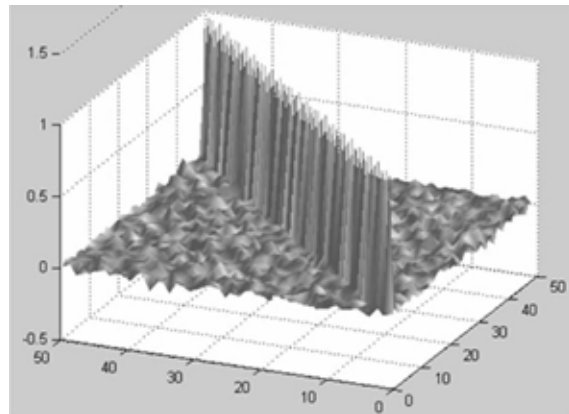
The effect of dead time with different values ($\tau=0.1$) was also analyzed. The results are shown in Fig. 5, a, b, respectively.

The figures show how the size of the “dead” zone to the right and left of the diagonal increases with the increase in the value of the information flow servicing system unavailability interval.

Conclusions. Modeling information flow processing systems allows to optimize system parameters, examine their operating principles, and

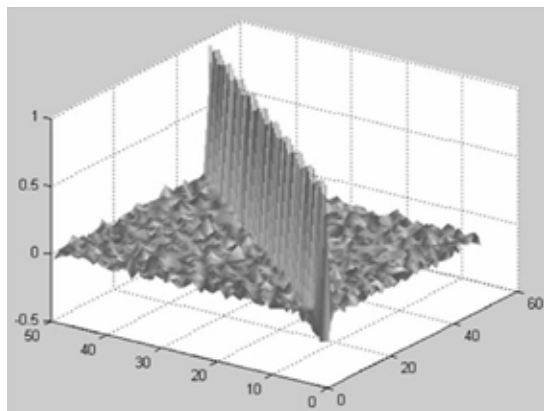


(a)

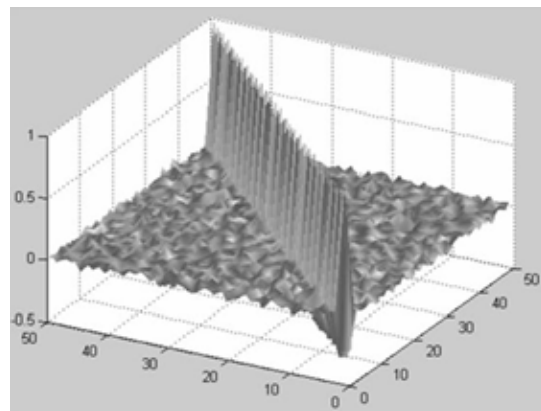


(b)

Fig. 4. Correlation coefficients at $\tau=0.01$: a – $\lambda=10$; b – $\lambda=20$



(a)



(b)

Fig. 5. Correlation coefficients at $\tau=0.1$: a – $\lambda=10$; b – $\lambda=20$

study and eliminate factors that lead to performance degradation. In this research, network flows have been analyzed within limited time intervals. The resulting relationships showed that the impact of the unavailability interval of the information flow

processing system significantly distorts the flow distribution. This leads to performance loss and overload of channels and network nodes. The greater the intensity of the input flow, the more noticeable these distortions are.

Bibliography:

1. Jin Z., Meng L., Guerrero J. M., Han R. Hierarchical Control Design for a Shipboard Power System With DC Distribution and Energy Storage Aboard Future More-Electric Ships. *IEEE Transactions on Industrial Informatics*. 2018. Vol. 14, No. 2. P. 703–714. DOI: <https://doi.org/10.1109/TII.2017.2772343>
2. Choinski Dariusz, Senik Michal. Distributed control systems integration and management with an ontology-based multi-agent system. *Bulletin of the Polish Academy of Sciences: Technical Sciences*. 2018. Vol. 66, No. 5. P. 613-620. DOI: <https://doi.org/10.24425/124277>
3. Ushkarenko O. O. Technique for analyzing data exchange processes in automated control of ship electric power systems. *Матеріали XVI міжнар. наук.-техн. конф. "Інновації в суднобудуванні та океанотехніці"*. Миколаїв : НУК, 2025. С. 1088–1091
4. Saghafian S. Queueing Theory and Resource Allocation. *Insight-Driven Problem Solving: Analytics Science to Improve the World*. Cambridge University Press. 2025. P. 111–139. DOI: <https://doi.org/10.1017/9781009379175.005>
5. Al-suod Mahmoud. Influence of Time Delays on Network-Controlled Diesel Generator Performance. *Journal Européen des Systèmes Automatisés*. 2023. Vol. 56, No. 3. P. 365–375. DOI: 10.18280/jesa.560302
6. Supiyandi Supiyandi, Hasanuddin Muhammad. Optimization of Computer Network Performance Using Heuristic Algorithms. *Journal of Computer Science Artificial Intelligence and Communications*. 2024. Vol. 1, No. 1. P. 12–17. DOI: 10.64803/jocsaic.v1i1.3
7. Tsitsiashvili G. Alternative Designs of High Load Queueing Systems with Small Queue. In: *Silhavy, R. (eds) Informatics and Cybernetics in Intelligent Systems. CSOC 2021. Lecture Notes in Networks and Systems*. Springer, Cham. 2021. P. 69–76. DOI: https://doi.org/10.1007/978-3-030-77448-6_8
8. Siddiqui Dr-Shadab. Modelling and Simulation of Queueing Models through the concept of Petri Nets ADCAIJ: Advances in Distributed Computing and. *Advances in Distributed Computing and Artificial Intelligence Journal*. 2020. P. 17–28. DOI: <https://doi.org/10.14201/ADCAIJ2020931728>
9. Pouhela F., Kiggundu A., Schotten H. D. Queueing Theory-Based Modeling and Optimization of a Publish/Subscribe IoT Communication System. *ICC 2025 – IEEE International Conference on Communications*, Montreal, QC, Canada, 2025. P. 1–7. DOI: <https://doi.org/10.1109/ICC52391.2025.11161937>
10. Okorogu Victor, Okafor Chukwunenye. EJSIT Improving Traffic Management in a Data Switched Network Using an Adaptive Discrete Time Markov Modulated Poisson Process. *European Journal of Science, Innovation and Technology*. 2023. Vol. 3, No. 4. P. 542–562.
11. Strilets Viktoriia, Doroshenko Maksym. Analysis and forecasting of computer network characteristics. *Bulletin of V.N. Karazin Kharkiv National University, Series «Mathematical modeling Information technology Automated control systems»*. Vol. 55. P. 49–57. DOI: <https://doi.org/10.26565/2304-6201-2022-55-05>
12. Рябенський В. М., Дорогань О. І., Ушкаренко О. О. Автоматизація процесів моніторингу параметрів та керування автономними електроенергетичними системами з дизель-генераторними агрегатами : монографія. Миколаїв : НУК, 2017. 175 с.
13. Yahyaoui Haythem, Aidi Saifeddine, Zhani Mohamed Faten. On Using Flow Classification to Optimize Traffic Routing in SDN Networks. *2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC)*, 2020. P. 1–6. DOI: <https://doi.org/10.1109/CCNC46108.2020.9045216>
14. Ibe Oliver. Markov Processes for Stochastic Modeling: Second Edition. *Elsevier*, 2013. P. 49–57. DOI: <https://doi.org/10.1016/B978-0-12-407795-9.00003-7>
15. Catak M., Allahviranloo T. Poisson Processes. In: *Discrete Random Processes. Studies in Systems, Decision and Control*. Springer, Cham, 2026. Vol 644. P. 167–176. DOI: https://doi.org/10.1007/978-3-032-08630-3_9
16. Hassani H., Royer-Carenzi M., Mashhad L. M., Yarmohammadi M., Yeganegi M. R. Exploring the Depths of the Autocorrelation Function: Its Departure from Normality. *Information*. 2024. Vol. 15(8), No. 449. P. 1–26 DOI: <https://doi.org/10.3390/info15080449>

Ушкаренко О.О. АНАЛІЗ АВТОКОРЕЛЯЦІЙНИХ ВЛАСТИВОСТЕЙ ІНФОРМАЦІЙНИХ ПОТОКІВ У РОЗПОДІЛЕНИХ СИСТЕМАХ УПРАВЛІННЯ

У статті розглядаються питання аналізу кореляційних характеристик інформаційних потоків у мережах розподілених систем керування автономними, в тому числі й судновими електроенергетичними системами, що функціонують у режимі реального часу. Розподілена система керування представлена у вигляді мікропроцесорної мережі, яка моделюється як система масового обслуговування. Показано, що при зростанні інтенсивності вхідних потоків та нерівномірному завантаженні вузлів мережі виникають перевантаження, що призводять до збільшення затримок та втрат інформаційних пакетів. Основну увагу приділено дослідженню автокореляційних властивостей сумарного інформаційного потоку, що формується кількома вхідними потоками різної інтенсивності та пріоритетності. Розглянуто умови, за яких вхідні потоки можуть бути апроксимовані пуассонівськими, а також проаналізовано вплив інтервалів недоступності системи масового обслуговування на структуру потоків. Для оцінки кореляційних характеристик використано автокореляційну функцію, що дозволяє визначити ступінь залежності між послідовними пакетами в часі. Проведено моделювання стаціонарних пуассонівських потоків з різною інтенсивністю та виконано аналіз зміни кореляційних коефіцієнтів за різних значень інтервалу недоступності обслуговування. Показано, що збільшення тривалості інтервалу недоступності призводить до розширення зон відсутності кореляції та спотворення розподілу потоків, що негативно позначається на продуктивності мережі. Встановлено, що при збільшенні інтенсивності вхідного потоку вплив зазначених спотворень стає більш вираженим, що призводить до зростання ймовірності навантаження каналів і вузлів мережі. Отримані результати підтверджують необхідність прийняття до уваги кореляційних характеристик інформаційних потоків при аналізі та проектуванні мереж розподілених систем керування. Розглянутий підхід може бути використаний для підвищення точності моделей продуктивності та розробки ефективних алгоритмів керування потоками в умовах обмежених ресурсів та інтервальної недоступності обслуговування.

Ключові слова: кореляційний аналіз, інформаційні потоки, розподілена система керування, система масового обслуговування.

Дата першого надходження статті до видання: 09.01.2026

Дата прийняття статті до друку після рецензування: 05.02.2026

Дата публікації (оприлюднення) статті: 08.04.2026