PROTECTION OF TRANSPORT NODES AND RESISTIBILITY OF PIPELINE SYSTEMS

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ABSTRACT

The analysis has been carried out and the laws of occurrence of emergency threats at pipeline transport facilities associated with the sequential damage of structural elements have been established. When an emergency situation develops, blocking of a separate system node is associated with simultaneous transition to a state of inoperability of all pipelines converging into the zone of that node. Such damage to the point element of the network structure prevents product flows from passing through that point. The ability of a system to withstand a progressive blocking depends on its composition, structure, and is characterized by an indicator of persistence, the value of which is calculated using a simulation method. An example of the use of cluster schemes in solving the problem of structural synthesis and the selection of the best protection option for a pipeline transport system has been considered.

Keywords: *system, pipeline, structure, transport nodes, clusters, protection, damage, resistance.*

Background. *Pipeline transport systems are widely used in various sectors of industrial production. Their operation ensures delivery of the target product to consumers in specified volumes and under specified conditions. Guaranteed product delivery is of particular importance for continuous technological processes and when servicing facilities that are not allowed to be disconnected from the source of the product [1, p. 14; 2, p. 4].*

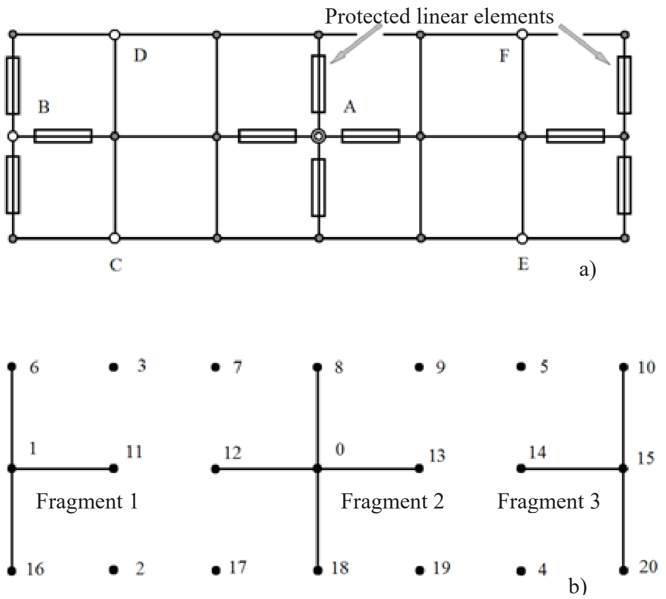
At the same time, functioning of the transport system may be associated with the occurrence of abnormal situations. The transition of individual elements of the system to a state of inoperability observed in this case can significantly limit its operational capabilities or be accompanied by the disconnection of individual consumers. The causes of damage to structural elements are usually explained by development of corrosion, hydraulic shocks, appearance of some resonant phenomena, seismic activity, formation of landslides, etc. [3–8].

Blocking of an individual node means the impossibility for a transport flow to pass through it and is considered as the result of simultaneous transition to an inoperative state of all the pipelines that converge here.

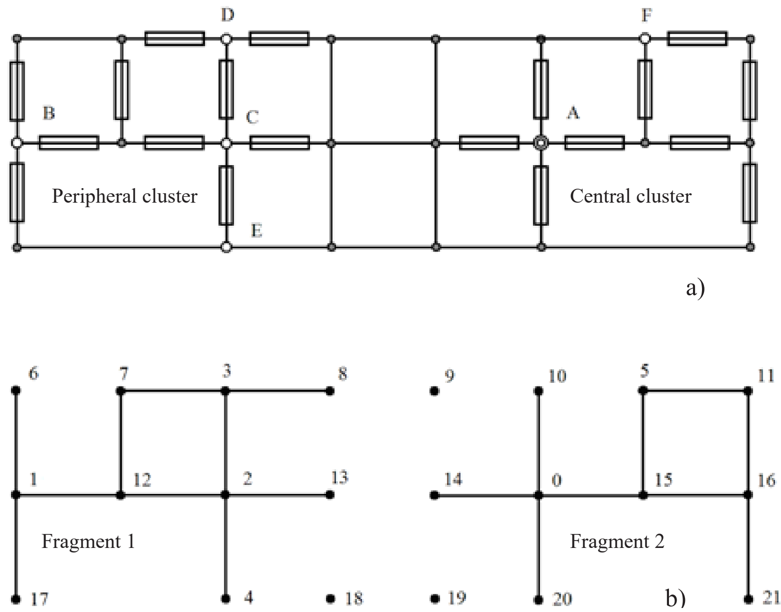
Due to the presence of redundant links in the system and alternative ways of delivering the product, blocking a separate node, as a rule, does not lead to disconnecting all consumers from the source. The real danger is the process of progressive blocking, when the transport nodes go into the blocking state sequentially and randomly. This type of damage to the network structure is accompanied by a rapid degradation of the properties of the system. The development of the process finally results in disconnection from the source of all consumers of the target product.

It is possible to increase resilience of the system to development of progressive damages by ensuring protection of individual transport nodes and clearly recognizing the criteria for evaluating occurring events.

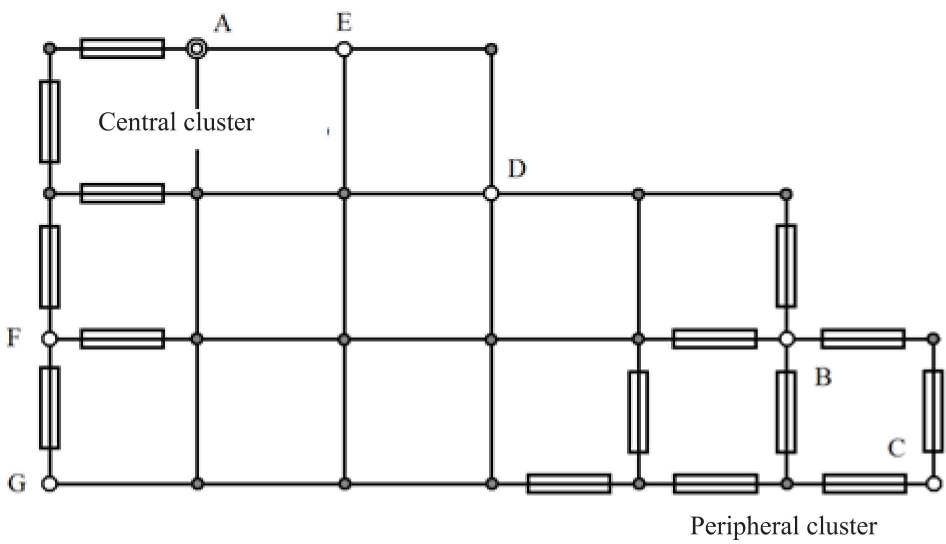
Objective. *The objective of the author is to consider the issues related to protection of*



Pic. 1. The block diagram of the system with isolated protected nodes (a) and a marked graph of this system after completion of the procedure of progressive blocking of nodes (b).



Pic. 2. Block diagram of a system with two protected clusters (a) and a marked graph of this system after the completion of the progress of progressive blocking of nodes (b).



Pic. 3. Block diagram of the pipeline system with eight protected nodes integrated into two clusters.

transport nodes in case of progressive blocking and to explore methods to assess and ensure durability of pipeline systems.

Methods. *The author uses general scientific and engineering methods, simulation, modeling, comparative analysis, structural analysis and synthesis, methods of percolation theory.*

Cluster scheme features

The protected transport node of the system is further considered as a structural element that is not damaged under any variant of the progressive blocking process. At the same time, a different, alternative view of protection of a single point element is also fair. Thus, it is quite correct to present blocking of a protected node as an event characterized by the simultaneous loss and subsequent instantaneous recovery of all the pipelines converging into it, which in these conditions turn out to be protected linear elements.

Since transition of protected pipelines to the state of inoperability is impossible, blocking a protected node does not lead to changes in the mode of operation of the entire transport system.

Let's consider the structural features of the transport system with three nodes protected from blocking (Pic. 1a).

These nodes (source A, consumer B, and distribution node) perform different functions and are isolated, since they are not interconnected by protected transport routes. In addition, only protected

Table 1

Quantitative composition of structural elements of the pipeline system

Name of system element	Quantity in the system	Note
Transport node	24	Including product source
Damageable node	16	Including border nodes
Product consumer	6	
Switchable consumer	4	B, C, D, E
Central cluster	1	
Peripheral cluster	1	
Consumer node in the central cluster	2	F, G
Consumer node in the peripheral cluster	2	B, C
Protected consumer	2	F, G
Border node in the central cluster	4	Including product source A
Border node in the peripheral cluster	3	

linear elements converge in each of them. The development of the process of progressive blocking will result in the fact that the system containing isolated nodes will break up into fragments torn apart from each other (Pic. 1b).

If the protection of nearby nodes leads to formation of a set of interrelated protected linear elements, then a protected fragment is formed in the system that can significantly affect its readiness to resist the development of progressive damage.

So, Pic. 2a shows a block diagram of a system consisting of two protected parts, each of which contains four protected nodes.

After the process of progressive damage is fully completed, formation of two unrelated fragments consisting of intact linear elements of the system will occur (Pic. 2b).

In percolation theory, a subset of interconnected nodes of a complex network is usually called a cluster [9, p. 48]. In this case, a set of interconnected protected transport nodes should be considered as some kind of protective cluster, the presence of which affects resistance to damage of the entire network object. If there is a source node in the protective cluster, then such a cluster is called central, otherwise it is considered as peripheral. It is obvious that in the transport system there can be only one central cluster.

In addition, consumer nodes within the central cluster are protected and cannot be disconnected from the source of the product due to progressive blocking. The same set includes border nodes belonging simultaneously to the cluster and the unprotected part of the system. Taking into account the aforementioned peculiarity, blocking of a border node is accompanied by transition to the state of inoperability of only a certain part of the pipelines converging to this node.

In the general case, protection of point elements of the network structure of transport systems is associated with possible formation of a certain number of:

- *protected consumers that cannot be disconnected from the source of the product under progressive blocking conditions;*
- *damageable nodes that can change their state when they are blocked;*
- *protective clusters, which may include both the source and consumers of the target product.*

Let's consider, for example, a block diagram of a pipeline system shown in Pic. 3. Data on the quantitative composition of the individual structural elements of the system are given in Table 1.

The analysis showed that as the process of progressive blocking of nodes develops, the order of disconnecting from the system is usually the following: first, consumers B and C lose the source (jointly), then consumer D and last of all consumer E are disconnected.

Network structures resistance index

The completion of the process of progressive blocking of damageable nodes always leads to a complete rupture of connections with the source of all disconnected consumers of the product. However, in real conditions development of an emergency situation usually ends at the initial stages of damage to the network structure. In this case, the consequences of an unfavourable scenario of events turn out to be less significant for systems that have a higher level of resistance to damaging effects.

The following notation is used to describe the dynamics of the process of progressive blocking of transport nodes of systems with protected point elements:

U_0 – total number of consumers of the product, which can be disconnected in an emergency;

u – number of consumers disconnected from the source of the product at the current system time;

Q_0 – proportion of the total number of consumers disconnected from the source at the current system time ($Q_0 = u/U_0$);

R_y – total number of damageable, unprotected transport nodes (including border nodes), which blocking is possible;

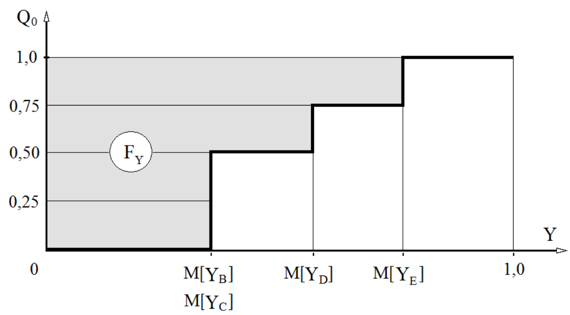
r_x – current number of blocked nodes during development of the process of progressive damage;

Y – degree of damage to the unprotected part of the network structure observed at the current system time ($Y = r_x/R_y$).

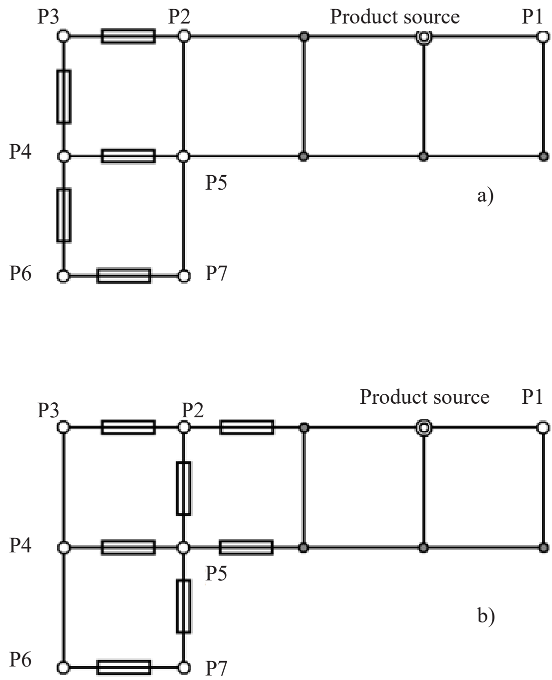
Evaluating the block diagram in Pic. 3, it should be noted that it has a peripheral cluster with two consumers of product, namely B and C. These consumers are connected to each other by protected linear elements and can only be disconnected from the source of the product jointly.

The consequence of this structural feature is coincidence of the values of the mathematical expectations of the corresponding degrees of damage $M[Y_B]$ and $M[Y_C]$ in the diagram, which is shown in Pic. 4.

Let's determine the indicator of resistance of the network structure to development of the progressive



Pic. 4. Diagram of damage to the network structure.



Pic. 5. Block diagrams of pipeline systems with configurations STR1 (a) and STR2 (b).

Table 2

Composition and properties of network structures of pipeline systems

Network structure designation	Number of structural elements			The most probable disconnection sequence of product consumers	Resistance index F_Y
	Disconnectable product consumers	Damageable nodes	Disconnectable consumers from the peripheral cluster		
STR1	8	9	6	Consumers P2, ... P7 (jointly), then consumer P1	0,361
STR2	8	9	6	Consumers P2, ... P7 (jointly), then consumer P1	0,416

blocking process as the area F_Y of the resulting stepped figure (Pic. 4):

$$F_Y = \frac{M[Y_B]+M[Y_C]+M[Y_D]+M[Y_E]}{U_0}.$$

That is, the indicator of resistance to development of a process of progressive blocking of nodes represents the arithmetic average of the mathematical expectations of the degrees of blocking corresponding to all possible phase transitions in the system [10].

The developed indicator of resistance $0 \le F_Y \le 1$ can also be considered as the average proportion of damageable nodes of the transport system, blocking of which leads to termination of delivery of the target product to switchable consumers.

Thus, F_Y is an important structural characteristic of a network object with protected point elements, which makes it possible to evaluate the ability of the system to withstand development of an emergency situation according to the scenario (algorithm) of progressive blocking of transport nodes. The method of simulation modeling, the essence of which is described in [11, p. 8], is quite suitable for calculating the values of the index of resistance.

Let us also note that network objects with protected point elements in a situation of progressive blocking of nodes are considered comparable if there is a fundamental possibility of combining their damage diagrams. It is established that such a combination is possible when the analyzed systems have:

- *the same number of consumer nodes, which can be disconnected from the source of the product as a result of development of the blocking process;*
- *the same total number of damageable nodes;*
- *the same number of peripheral clusters with two or more consumer nodes and the same number of such nodes in each of them;*
- *the same sequence of disconnection from the source of both individual consumers and peripheral clusters with an equal number of product consumers.*

If at least one of the listed conditions is not met, then a correct comparison of the established values of the system resistance indices is impossible.

Comparative analysis of resistance

Protection of pipeline system nodes can be implemented using various organizational and technical methods. At the same time, substantiation and selection of the most effective design solutions are of practical interest. Among other things, there is the problem of structural synthesis, which has a solution if the compared network structures are comparable [12, p. 41].

Let us suppose that the transport system is characterized by the block diagram STR1 shown in Pic. 5a. It includes a peripheral cluster with consumers P2, … P7, as well as a separate consumer of the target product P1. Characteristics of the structural composition of the system are shown in Table 2.

Let's change the protection conditions of the point system elements, taking as an alternative the diagram in Pic. 5b. Characteristics of the alternative structure STR2 are also listed in Table 2.

Taking into account the comparability conditions listed above and Table 2, we can conclude that the network structures STR1 and STR2 satisfy all the designated criteria, and the set values of the persistence indicators can be correctly compared with each other.

The calculated F_Y values established for these systems are given in the table. The analysis shows that changing the protection conditions during transition from the structure STR1to the structure STR2 leads to an increase in the system resistance index values to a progressive blocking of nodes by approximately 15 %.

This means that in order to completely break the links between the source and consumers of the target product, in the first case it is necessary to block on average about 3,25 nodes, and in the second – about 3,75 nodes.

Thus, from the considered alternative schemes of protection of the pipeline system, the variant in Pic. 5b has the best characteristics.

Conclusions.

1. The developed indicator of resistance of a pipeline system to the process of progressive blocking of nodes represents the average proportion of damageable nodes of the transport system, blocking of which in random order leads to disconnecting from the source of all consumers of the target product.

2. Correct comparison of the resistance indicators of various network structures to the progressive blocking process is possible only if the established conditions for their comparability are observed.

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