Problems of risk assessment in intersystem failures of life support facilities

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Abstract: The urbanisation process growing rapidly during the latest several dozens of years leads to proliferation of infrastructurally complex territories. At the same time, growing interaction of critical infrastructures in combination with the increased frequency and scales of anomalous natural processes result in the growth of the intersystem failures. The intersystem failures can be characterised by cascading processes and disastrous consequences. Such failures are characterised by a high level of social and economic impact affecting various critical infrastructures (energy supply, transport, water supply, telecommunications, finance, etc.), which requires development of the methods and models for assessment of their occurrence and progress. The given paper is devoted to the problems of classification and quantitative assessment of intersystem accident consequences including cascade failure process. Classification of intersystem accident is proposed based on topology of cascade process. Moreover, topology-based and flow-based approaches are used for modelling of intersystem accidents in power and gas supply systems.

Keywords: critical infrastructures; intersystem failures; cascading failures; classification; simulation.

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1 Introduction

The critical infrastructures comprise such main life support facilities as power supply (electricity, natural gas, petroleum products, and heat), transport, water supply and water disposal, telecommunications, etc. The systems listed above are interrelated by material, power engineering, and information flows.

The intersystem failure (ISF) is a development of abnormal processes when the initiating event in one system leads to negative consequences (such as equipment breakage, collapse of buildings and structures, inventory losses, damage to health or loss of life, deterioration in environmental quality, etc.) in other interrelated systems. The ISF risk means the anticipated summarised negative implications caused by intersystem development (including the cascading one) of the abnormal processes. One of the major tasks in ensuring safety and stability of interrelated critical infrastructures consists in identifying the places where disturbance propagation among the systems is possible. By this time, the topology of disturbance propagation among the interacting systems and within each system has not been studied as comprehensively as needed for the time being.

Simulation of cascading abnormal processes in separate critical infrastructures is considered to be one of the first steps in investigating the intersystem failures. The cascading failures of electrical power systems are investigated to the fullest extent possible. For several dozens of years the problems of simulating and managing the cascading failures were studied by a number of researches. A considerable number of findings on this problem are presented in the papers and books of Voropai and Efimov (Voropai, 2011). Special attention was paid to the issues of formation of mechanisms for ensuring reliability of the electrical power systems. At the same time, this publication did not consider the issues of the cascading intersystem failures simulation as well as the respective risk assessment.

A loading-dependent model (Dobson et al., 2005b) is another example of comprehensive analysis of the cascading failures in the electrical power systems. In these publications, the model of statistically distributed branching Galton-Watson processes was developed pertinent to the cascading failures in the electrical power systems. The authors used a classical definition of the cascading failures risk which is understood as the product of probability (frequency) of the cascading failures leading to power supply interruptions and the damage caused by interrupted electrical supply. The same electrical supply has made an attempt to expand the used models for description of the cascading failure in two interrelated critical infrastructures (Newman et al., 2005).

Noticeably less studies have been devoted to simulation of the cascading failures in the gas supply (Melnikov, 2007) and heat supply systems (Popyrin, 2000). A simple model approach for cascade accidents in transportation and telecommunication systems is presented in Crucitti et al. (2004).

The problem of risk assessment in interrelated critical infrastructures has been most comprehensively studied in the monograph (Hokstad et al., 2012). Despite the fact that the articles included into the monograph are of a methodological and qualitative nature, they present the fullest solution to the range of problems concerning interacting critical infrastructures. In particular, the publication has suggested the rating of interrelations (physical, informational, geographical, logical), analysed the models for risk assessment with allowance for interrelations of the systems, as well as analysed the statistical data on failures in interacting critical infrastructures. It should be noted that in this publication the risk assessment in interrelated systems was to a large extent targeted to vulnerability analysis. At the same time, the quantitative risk assessment has been made in this publication only for two interrelated infrastructures.

It is worthwhile to say that several software products, for instance (Bartels et al., 2012), have been developed by now making it possible to assess the consequences of the intersystem failures. A 3D simulation model for emergency interaction of major critical systems (power supply, gas supply, heat supply, water supply, ground transport) for the city of Berlin has been implemented within the framework of this project. The SIMKAS-3D Ð¡ model enables to reveal the places of physical concentration of the infrastructural systems and the abnormal process, including the damage assessment, by simulation. On the whole, this model makes it possible to conduct the risk assessment in the intersystem failures, but this is true only for the cases of physical effect of the infrastructural systems.

The methodological framework of studying the intersystem failures risk should be referred to the notion of 'system of systems' (Zio and Ferrario, 2013). In our opinion, further methodological development of these problems takes place within the framework of the notion of 'resilience'. Resilience as a comprehensive methodology also comprises such interdisciplinary researches as risk assessment and management, provision of security and protection of the critical systems as well as prevention of failures and catastrophes and elimination of their consequences (Klein and Kober, 2014).

The paper is focused on two problems in the intersystem accident risk assessment. The first problem concerns the extension of existing intersystem failures classification. The preliminary analysis of the intersystem failures shows that the failures affecting two and more life support facilities are the most hazardous ones and often cause disastrous consequences. The intersystem failures substantially differ by the sources initiating the ISAs, scenarios of the abnormal process development, duration of exposure to negative implications as well as the number and kind of the infrastructural systems involved and scale of consequences. In this connection it is expedient to classify the intersystem failures, which will make it possible to substantiate the approaches to simulation of the abnormal processes in the interacting infrastructural systems.

The classification of intersystem failures types offered in Rinaldi et al. (2001) is limited to three types: common causes, cascading, escalating. The analysis of the occurred intersystem failures as well as the qualitative analysis of possible topologies of the ISA scenarios made it possible to suggest extended classification of the ISA structures focused on branch (cascade) processes.

The second problem is connected to modelling the intersystem accident including cascades. Various approaches to a quantitative estimation of intersystem failures risk are under investigation. The fullest classification of used approaches is given in Ouyang (2014) where the basic types of models are empirical, agent-based, system-dynamic-based, economic-theory-based and network-based. In accordance with a number of criteria (level of a readiness of methods, the account of all types of interdependence between systems, resilience level estimation, etc.), the most preferable approach is network-based. This approach includes topology-based and flow-based methods. The both methods have been used for quantitative analysis of intersystem accidents risk.

Within the problem of intersystem failures modelling a particular interest and difficulties are connected to the description of cascade failures. The most detailed research has been done for electricity supply systems (for example, Dobson et al., 2005a; Newman et al., 2005). Cascade development of failures was also investigated with reference to abstract interdependency systems (Zio and Sansavini, 2011).

There is one more problem concerning an approach to the description of systems interaction during failures. Basically, general approach is connected with the use of financial flow as general equivalent. This approach, in particular is used in agent-based approach, for example, in input-output inoperability model (Setola, 2009). Within the proposed approach (network-based model) it is expedient to use a power equivalent for the interaction description.

2 Classification of intersystem failures

This part of the paper is devoted to the analysis of several interconnected systems interaction. Each system is structurally-complex and can be presented in the form of the connected directed or undirected graph. The interaction between systems can also be shown as a graph where knots interacting between systems are connected. In each i^{th} knot of system r the peak permissible load C_i can be presented as:

$$C_i^r(t) = \alpha_i(t) L_{i'}^r$$

where $L_{i'}^r$ – is a load (or short shipment, depending on system type) of a knot in the unperturbed system r, $\alpha_i(t) > 1$ – is the parameter generally dependent on failure duration and perturbation size the given knot is capable to withstand without full-functionality loss. The maximum load in knots of intersystem interaction can be similarly presented:

$$C_k^{l-m}(t) = \beta_k(t) L_k^{l-m}$$

L_k^{l-m} – is a load/short shipment at a knot in the unperturbed operation of systems l and m. $\beta_k(t) > 1$ – is the parameter of specifying perturbation size depending on perturbation time and which the given knot is capable to withstand without full-functionality loss.

Let us assume that in one system there is an initiating perturbing event (malfunction, accident) with duration t_1 at one of its knots. In this case on system knots r and knots of intersystem interaction $l - m$ have loads $\tilde{L}_i^r(t)$ and $\tilde{L}_k^{l-m}(t)$, $t \leq t_1$, respectively. If during time t_1 the perturbed load in a system knot $\tilde{L}_i^r(t)$ exceeds the maximum load $(\tilde{L}_i^r(t) > C_i^r)$ or, analogously, at a knot of gateway interaction $\tilde{L}_k^{l-m}(t) > C_k^{lm}$, these knots we will be considered disabled. $N^r(t)$ means a number of disabled knots of a system r at time t while N_{tot}^r means the total number of system r knots. Defeat of system r (damage level) is designated as $\xi^r(t) = \dfrac{N^r(t)}{N_{tot}^r}$. Accordingly, $N^{l-m}(t)$ is a number of disabled knots of intersystem interaction $l - m$ at time t, N_{tot}^{l-m} is the total number of knots of intersystem interaction $l - m$, $\xi^{l-m}(t) = \dfrac{N^{l-m}(t)}{N_{tot}^{l-m}}$ is the defeat of intersystem connection knots. During time of knot inoperability t_2 the load of the remained knots equals to $\hat{L}_i^r(t)$, where $t \subset t_1 \cap t_2$.

The peak values of parameters $\xi_r(t)$ and $\xi^{l-m}(t)$ at time $t \in (0, \max(t_1, \ldots t_p))$, allow to allocate the intersystem failures development into four types (Table 1).

Table 1 Classification of intersystem accident

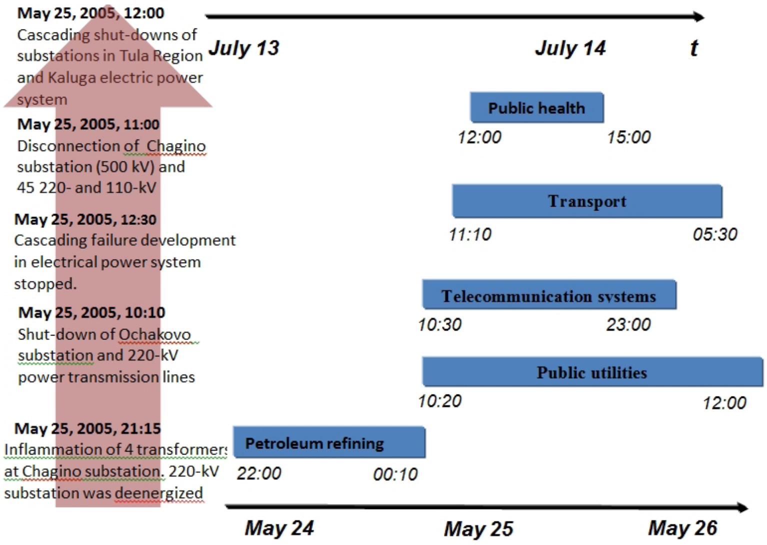
ξ^r	ξ^{l-m}	*Type*
$1/N_{tot}^r$	N_{tot}^{l-m}	Lack of branching
$1/N_{tot}^r < \xi^r \leq 1$	N_{tot}^{l-m}	Branching in systems
$1/N_{tot}^r$	$N_{tot}^{l-m} < \xi^{l-m} \leq 1$	Branching between systems
$1/N_{tot}^r < \xi^r \leq 1$	$N_{tot}^{l-m} < \xi^{l-m} \leq 1$	Branching in and between systems

The analysis of abnormal processes development structure in the suggested classification makes it possible to make some conclusions. Firstly, the failures without branching (Type I) are the most frequent cases of ISFs. Secondly, taking place rather frequently branching of the abnormal process in one of the interacting systems (Type II) leads to heavier consequences. Thirdly, in theory, the ISF can develop in such away that while the intersystem cascade (Type III) the cascading processes may not be observed in each of the interacting systems. Besides, feedback of abnormal processes may theoretically occur among the interacting systems. It is also necessary to underline that Type III needs more statistical evidence. Finally, the heaviest consequences appear when the abnormal processes branching is realised in the systems and between the systems (Type IV).

A great number of interacting components of the infrastructural systems results in a great number of possible ISF development scenarios. Figure 1 shows the example of realising the ISF development scenarios initiated by the failure in the electrical power systems.

A substantial difference in the failure running scenarios is clearly seen on the example of analysing ISF including the type, sequence, and duration of involvement of the interacting systems which should be reflected in simulation of ISFs.

Figure 1 Diagram of ISF development in electric power system of city of Moscow and Moscow Region in 2005 (see online version for colours)



3 Simulation of intersystem failures

The study has been divided into several stages. At the first stage the simple model of interaction of two diverse systems (electric and gas transmission networks) has been developed. The abstract gas-transport and electrical systems topologically close to corresponding systems of Great Britain have been used. Possible balance of each system's energy streams has been calculated under the condition of their interaction at the moment of operating mode diversion from the optimum in one of the systems. A possibility of use of underground storages of gas which let compensate originating diversions from an optimum operating mode of a gas-transport system has not been considered.

3.1 Gas transmission network model

In the gas transmission network model the main gas pipeline division is presented as a connected directed graph: $G = (V, E)$ where V is the vertex (knot) set, E is the oriented edge set. Graph vertexes $G(V)$ are the facilities of the gas transmission network which is essentially either the gas source, or its drain, or the node where the flow value is varying (for instance, intake for own needs of the gas-compressor station). It is necessary to assign the numbers to the network nodes in a gas flow direction. The network oriented edges are the line sections of the gas transmission network. The net gas value in the node is determined as a difference between the incoming and outgoing flows. The node is considered to be a source if the net gas value is positive or a drain if the net gas value is negative. If node i is neither drain, nor source, the flow conservation concept (continuity equation) is true for it:

$$\sum_{j\in\alpha_i} Q_{ij} - \sum_{j\in\beta_i} Q_{ij} = 0 \tag{1}$$

$$Q_{ij} \le C_{ij} \tag{2}$$

Here Q_{ij} is the gas flow, β_i is the set of all nodes related to node i by means of the incoming oriented edges, α_i is the set of nodes related to node i by means of the outgoing oriented edges, and C_{ij} is the throughput capacity of the oriented edge.

Gas motion over the oriented edge between the nodes is described in terms of the system of one-dimensional gas-dynamic divergence equations, which are due to the conservation laws. Solution of this system makes it possible to determine the value range of variables p, ρ, v, T for the unsteady gas flow where p, ρ, v, T is the density, pressure, speed, and temperature of gas, respectively. However, while considering the steady-state gas flow and equation of state expressed in terms of $p / \rho = zRT$ where z is the gas non-ideality factor, the equations can be simplified by neglecting the factors of the second order of smallness and determining the gas flow in the oriented edge (Aliyev et al., 1998):

$$Q_{ij} = K\sqrt{\frac{p_i^2 - p_j^2}{zT\lambda\Delta L_{ij}} D^5} \tag{3}$$

Here p_i, p_j are the initial and final pressures in the gas pipeline section, Δ is the specific density of gas, L_{ij} is the oriented edge length, and $K = 0.0385\ \frac{m^2 s K^{0.5}}{kg}$. Then in the i^{th} node with preset drain or source Q_i the pressure drop will amount to:

$$\Delta p = B_0 \frac{Q_i \lambda L_{i,i-1}}{D^5} \tag{4}$$

where $B_0 = zT\Delta / K^2$. If the i^{th} node is the gas-compressor station, its performance equation can be presented in terms of performance:

$$p_{out,i} = a_i p_{in,i} + b_i Q_i^2 \tag{5}$$

where a_i and b_i are the trial coefficients depending on the gas composition (z, R), gas temperature at the inlet of blower Tb, and the number of revolutions per minute is n (see Aliyev et al., 1998). Such approach for gas-transport system modelling allows considering the effects related to partial cutout of compressor stations engine installations.

The system of equations determined in this manner makes it possible, with allowance for the network topology, to calculate its mode of operation and determine the values of each Q_{ij} in the unified gas-dynamic system. The unperturbed gas-transport system is characterised by the given balances of gas flows at each knot. In case of defeat of compressor station in a knot of a gas-transport system, the stream on the edges of a graph related to this station impinges approximately $\sqrt{2}$ time as there is a necessity to adjust a pressure modification. The new operating mode of gas-transport system was further calculated. The requirement of a minimum diversion from the unperturbed operating mode was a measure for a new condition of operation selection.

Figure 2 Gas transmission network model (see online version for colours)

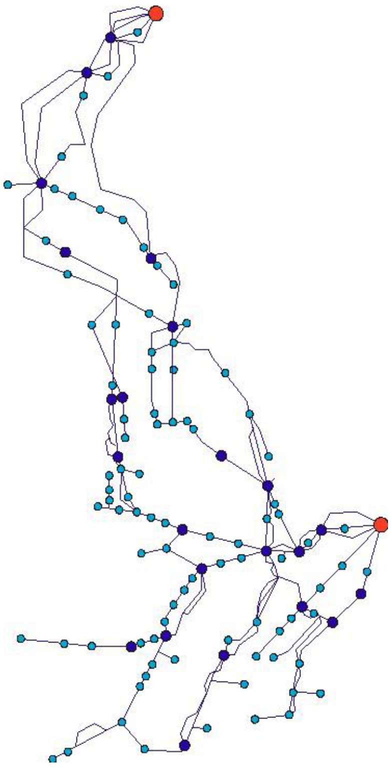


Figure 2 shows the gas transmission system model used in this publication. Red circles stand for sources while the blue and the dark blue ones represent drains and gas-compressor stations, respectively. The assumption is made for the network topology permanence, although, in general, the network topology may vary quite substantially depending on the operating procedures, scheduled repairs, operation modes of the underground gas storage facilities, etc.

3.2 Electric network model

The high-voltage (300–400 kV) electric network model is essentially undirected graph $G(V, E)$. Vertexes $G(V)$ of the graph are either the power plants (sources), or distribution substations of given power w_i. Oriented edges $G(E)$ of the graph correspond to the power transmission lines with given efficiency ϵ_{ij}. Each node of the network is connected to any related power source over the shortest (minimum) route in the network. Load L_i at the i^{th} node of graph G is determined as the number of minimum routes passing through this node multiplied by power w_j of final node j fed over this route (Goh et al., 2001; Newman, 2001). In each i^{th} node of graph $\tilde{G}$ maximum permissible load C_i is determined:

$$C_i = \alpha L_i \tag{6}$$

where L_i is the load upon the node in the unperturbed network, $\alpha_i > 1$ is the parameter indicating the perturbation size the given knot is capable to withstand without full-functionality loss.

If perturbation exceeding value C_i in one or several nodes occurs in the network, efficiency of the routes running through them changes, which leads to formation of new minimum routes. Hence, new efficiency of the graph's oriented edges can be determined as:

$$\epsilon_{ij}(t+1) = \begin{cases} \epsilon_{ij}(0)L_i / C_i & L_i(t) > C_i \\ \epsilon_{ij}(0) & L_i(t) \le C_i \end{cases} \tag{7}$$

The mean efficiency of the network is determined as (Asztalos et al., 2012; Simonsen et al., 2008):

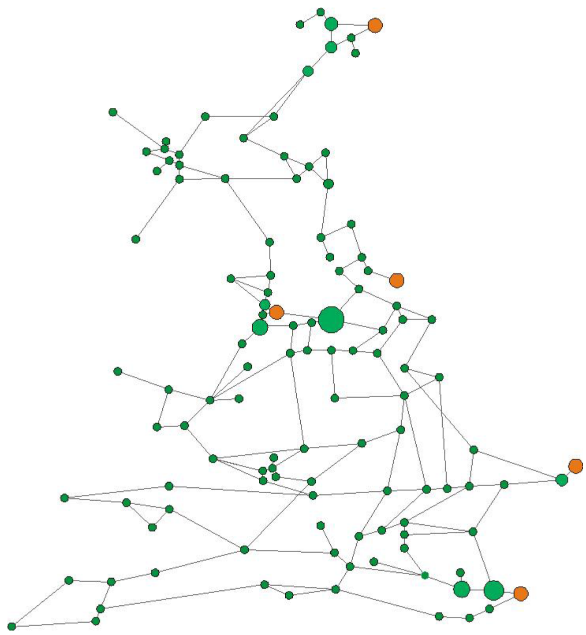
$$E = \frac{1}{N_s N_n} \sum \epsilon_{ij} \tag{8}$$

Here N_s is the number of source nodes, while N_n is the number of other nodes in the graph. Then, the damage to the network can be expressed through the mean efficiency loss (Kinney et al., 2005):

$$D(t) = \frac{E(G_0) - E(G_t)}{E(G_0)} \tag{9}$$

where $E(G_0)$ is the mean efficiency of the unperturbed network, $E(G_t)$ is the mean efficiency at time t.

Figure 3 High-voltage (300–400 kV) electric network model (see online version for colours)



Notes: Yellow circles – sources. Green circles – distribution substations.

Figure 3 shows the high-voltage electric network model used in this article. Yellow circles stand for sources. Green circles correspond to distribution substations. The size of a circle corresponds to the number of routes running through the node in the steady-state mode.

3.3 Interaction model

Interaction of two networks has been considered through a limited number of common nodes (see Figure 4). As the networks are heterogeneous, the fuel and energy balance of the networks was estimated pertinent to the fuel equivalent when allowing for their interaction (Table 2). This publication did not consider the situation when the electric network node was fully put out of action (for instance, as a result of the started fire).

Figure 4 Diagram of interaction between two networks (see online version for colours)

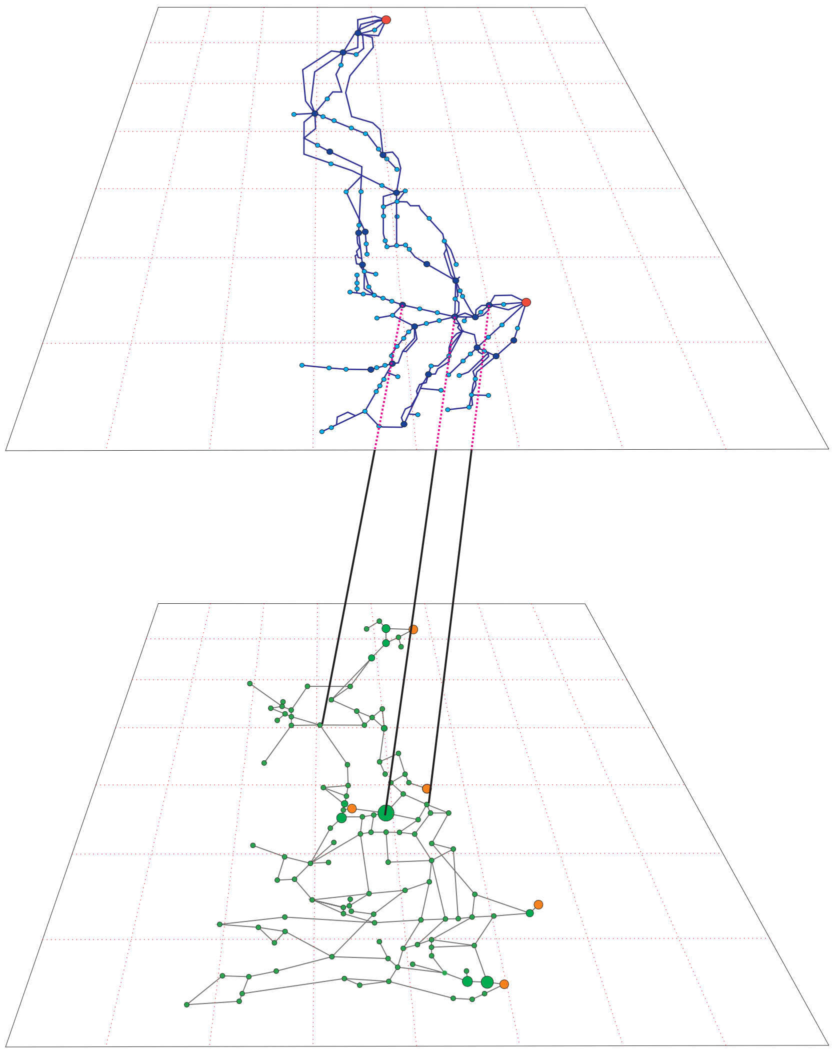


Table 2 Factors for estimation of fuel and energy balance

Fuel	*Measurement unit*	*Factor of conversion to fuel equivalent*
Combustible natural gas	Thou. cub. m.	1.154
Electric energy	Thou. kW·h	0.3445

The response of the electric network to gas shortfall in the common node were considered. This direction of interaction between the networks is related, above all, to the typical network perturbance times. The time of typical perturbance propagation in the gas network (the rate of gas flow in a pipe is about 10 m/s) considerably exceeds the time of perturbance propagation in the electric network: $\tau_{gas} >> \tau_{el}$. Therefore, pertinent to the typical times of perturbance propagation in the electric network the gas transmission network can be considered to be quasistationary.

The assumption of quasistationarity of gas transmission system breaks down if we consider a possibility of destruction or full disruption of functionality of the electric network node. In this case, we should rather consider the typical times of recovery of modes of operation than typical times of perturbance propagation.

In the considered model it is expected that the gas shortfall to the common node is fully compensated by the increased electric energy consumption. This assumption in the real situation is by no means always true, but enables us to describe interaction in case of a limited number of interacting networks.

3.4 Results of calculations

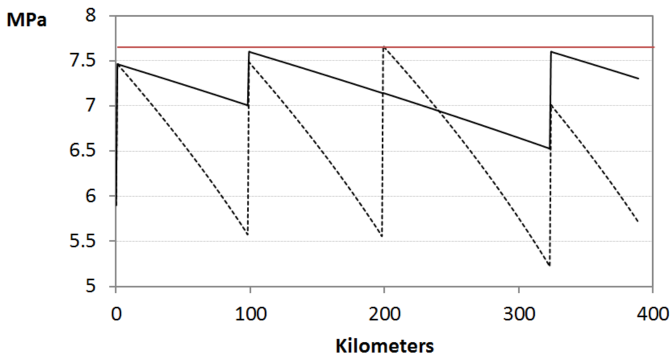
Full shutdown of the i^{th} gas-compressor station has been considered as the initial perturbation. In our publication we have used a simplified gas transmission network model. We have not considered a possibility of changing the gas production, availability of gas in the system of the underground gas storage facilities and other compensating mechanisms. In this case the shutdown of the gas-compressor station leads reduction of the capacity of the respective network division and, consequently, to the necessity of redistributing the gas flows. The pressure at the outlet of the $i - 1^{th}$ gas-compressor station starts rising, while the pressure at the inlet of the $i - 1^{th}$ gas-compressor station starts dropping. According to (1), this results in the pressure redistribution between the remaining nodes (see Figure 5) and, provided the gas transmission network integrity is retained, we have:

$$P_j < P_{crit}, (j = 1, i-1, i+1) \tag{10}$$

where P_{crit} is the critical pressure leading to the pipe rupture.

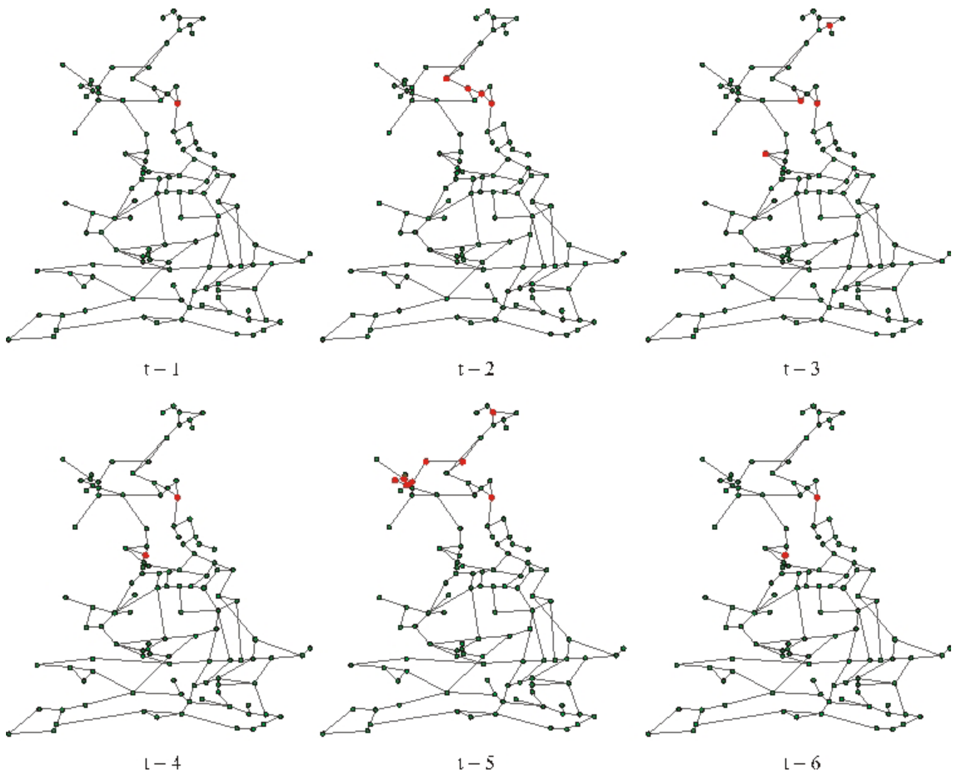
New values of the pressures in the system determine new values of the flow on the oriented edges of graph G. If obtained throughput C_{ij}^{*} on the cut of graph G is less than the gas consumption of this cut in the normal (failure-proof) mode, the gas shortfall takes place. Here one more definition has to be provided: a cut set of a graph is a set of edges whose exclusion would isolate connected by them nodes from the network.

Figure 5 Graph of pressure variation in case of improper operation of gas-compressor station in gas transmission network G along one of routes from source to user (see online version for colours)



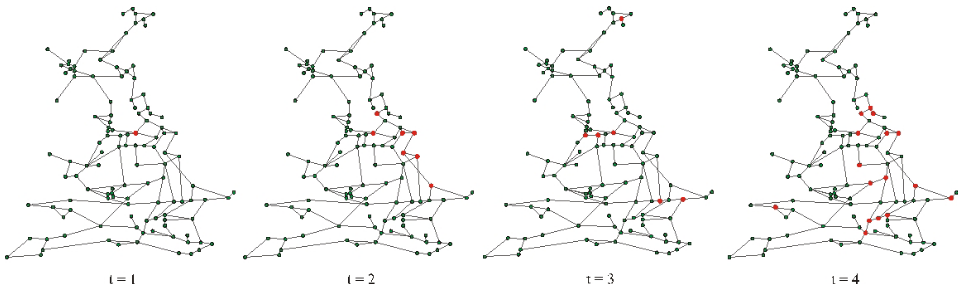
Notes: Dotted line – unperturbed mode. Solid line – mode with shut-off gas-compressor station. Red line denotes critical pressure of 7.6 MPa.

Figure 6 Development of overload in network $\hat{G}$ as a result of gas shortfall, which did not lead to cascading failure (see online version for colours)



Note: Overloaded ($L_i(t) > \alpha_i L_i(0)$) nodes are shown by red colour.

Figure 7 Development of overload in network $\hat{G}$ as a result of gas shortfall, which led to cascading failure (see online version for colours)



The response of the electric network to similar gas shortfalls in various nodes is different and depends on the network topology. Figures 6 and 7 show the dynamics of development of the perturbance that has begun in the electric network. Figure 6 shows that the perturbation coming from the gas network has caused just a local perturbation involving a small number of the network nodes. Figure 7 presents the way of development of the perturbation that has already been initiated in another node and involved a substantial part of the network as a result of the faults cascade development.

The size of the perturbation of network $\tilde{G}$ depends not only from its topology, but also on its ability to withstand the overload. In the model used by us each node of network $\tilde{G}$ has a common parameter α. Figure 8 represents the diagram of dependence of the fraction of normally functioning nodes of network $\tilde{G}$ on parameter α. As it can be seen, the higher the value of parameter α (i.e. the higher the ability of each node to withstand the overload) is, the less the damage caused by the external perturbation is.

Figure 8 Dependence of fraction of normally functioning nodes of network $\hat{G}(\alpha)$ on parameter indicating size of perturbance, which this node can withstand without loss of full functionality α (see online version for colours)

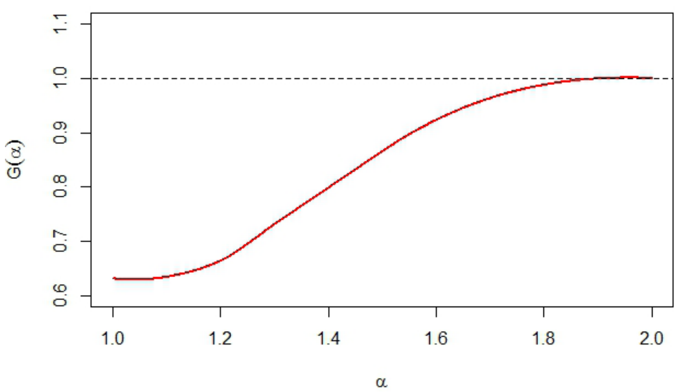
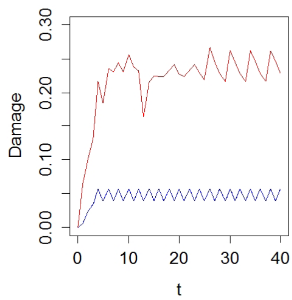


Figure 9 represents the graphs of damage caused to the gas network (shown in the figure with a blue line) and electric network (shown with a red line) in the case of cascading failure development. It can be seen from the figure that the gas network node significance is determined not only by the gas shortfall amount, but also by the impact of this shortfall on the adjacent electric networks.

Figure 9 Damage in networks G (blue line) and $\hat{G}$ (red line) during cascading failure development (see online version for colours)



4 Conclusions

The conducted research has made it possible to extend the classification of intersystem failures occurring in critical infrastructures using formal approach. Proposed classification suggests to view different types of scenarios of system and intersystem accidents taking into account a possibility of their cascade development.

The intersystem failure development is simulated on the basis of the simplified model of two networks interaction (gas supply and power supply systems). For interacting exposition between systems the energy equivalent is used. The system damages caused by interlocking a given node in the gas supply network have been estimated. It has been demonstrated that the damages to the networks can increase if allowance is made for interaction between the networks. This effect is particularly great if the cascading failure occurs in the electric network and those adjacent to it.

The offered model allows to reveal elements of systems ('bottlenecks') which can initiate intersystem accidents including those with the cascade development. It will allow to lower risk of intersystem accidents at the expense of precautionary and other provisions on revealed 'bottlenecks'. It is especially necessary for the infrastructurally complex territories where after effects of intersystem accidents are large-scale.

With allowance for the increasing actuality of the problem of risk assessment in intersystem failures, further studies will be aimed at the development of the interrelated systems models (transport, water supply, telecommunication, etc.) with due regard to the specific nature of emergency situations occurrence and development.

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