Machinery & Energetics
Vol. 14, No. 2. 2023

Journal homepage:
https://technicalscience.com.ua/en

UDC 621.316.1.05
DOI: 10.31548/machinery/2.2023.23

Viktor Kaplun*
Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-7040-9344

Oleksandr Gai
PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-5460-7260

Petro Stetsyuk
Doctor of Physical and Mathematical Sciences, Senior Researcher
V.M. Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine
03187, 40 Academician Glushkov Ave., Kyiv, Ukraine
https://orcid.org/0000-0003-4036-2543

Andrii Ivlichev
Leading Software Engineer
V.M.Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine
03187, 40 Academician Glushkov Ave., Kyiv, Ukraine
https://orcid.org/0009-0005-2823-6204

Provision of optimal dispatching scenarios for regional power systems in the face of uncontrollable power shortages

Abstract. As of 2023, substantiation of the criteria for optimal load balancing of territorial energy islands in the face of uncontrolled power shortages due to unpredictable failure (destruction as a result of military bombardment) of the upper (trunk) level energy infrastructure is relevant. The research aims to substantiate approaches to ensuring the controlled operation of regional power systems under conditions of power shortages. The study applied the theory and methods of mathematical analysis of complex multicomponent systems in the form of mixed Boolean linear programming. A Mathematical Programming Language and modelling methods of the NEOS server based on the Gurobi solver were used to describe the modes of operation of power grids. A proportional power distribution method between load nodes of the post-emergency network configuration was used to determine the direction of electricity transit with the least losses. An algorithm and a program for solving the problem of addressing flows and power losses in multi-node regional power systems are proposed. The optimisation problem is formulated in the form of a mixed Boolean linear programming model with the criterion of minimising the power momentum, considering balance constraints and upper limits on the power between supply and load nodes. The developed transport matrix made it possible to find the optimal power distribution for emergency and post-emergency modes according to the criterion of minimum network losses. Algorithms and scenarios for the response of dispatching services were formed, considering the capacity of power grids and determining temporary power supply schemes, the configuration of which will ensure the "survivability" of energy islands. The levels of efficiency of the Boolean linear programming model associated with the connectivity of the cycles of the transport problem and

Article's History: Received: 30/12/2022; Revised: 03/04/2023; Accepted: 26/04/2023.

Suggested Citation:
Kaplun, V., Gai, O., Stetsyuk, P., & Ivlichev, A. (2023). Provision of optimal dispatching scenarios for regional power systems in the face of uncontrollable power shortages. *Machinery & Energetics,* 14(2), 23-33. doi: 10.31548/machinery/2.2023.23.

*Corresponding author

the order of traversal of its vertices for test examples depending on the constraints imposed on the components of the network structure are established. The process of tracking electricity flows will allow for establishing routes connecting specific electricity supply nodes with load nodes and determining their shares in covering the energy island's demand under conditions of power shortage

Keywords: moment minimisation criterion; energy island; transport matrix; Boolean linear programming; load balancing

INTRODUCTION

The basic chain of functioning of the current integrated power system of Ukraine consists of generation facilities, a transmission system (trunk power grids), a distribution system (distribution networks of lower voltage classes) and end consumers. Disruption of this basic pathway of electricity supply in wartime and in the context of the russian aggressor's bombing of the energy infrastructure leads to disruption of existing electricity supply schedules, power shortages due to reduced generation and the impossibility of its transportation through trunk and distribution networks.

Some of the generating capacities are destroyed, shut down or located in the occupied territories. Power plants located near the frontline under artillery fire have a special mode of operation. All this leads to a power shortage and a limited electricity consumption schedule compared to peacetime.

Following A. Izvoshchikova (2022), the amount of damage to the electricity infrastructure reaches 40-50% of power facilities. This indicates an existing systemic problem, which is a shortage of capacity due to damage not only to power plants but also to trunk grids. It is the transmission system that has suffered the most damage. In this situation, the problem of energy supply needs to be addressed at the network level. To a large extent, distribution system operators cannot transport electricity through trunk grids which is the main reason for the power shortage and leads to the introduction of electricity consumption limits in regional grids.

Since the damage is uneven and random, outage plans are formed accordingly. This circumstance greatly complicates the work of distribution system operators' dispatch services. The situations described above require not only a limited allocation of capacities permitted by the upper dispatch level but also changes (in most cases) in the configuration of the distribution network. This, in turn, leads to abnormal grid operation modes and incorrect operation of relay protection and automation.

H. Nosova (2022) noted that the most famous blackouts in history were in the United States (New York, 1977) and Brazil (1999). In recent years, the most famous mass blackouts have occurred in the United States – in California (2019) and Texas (2021).

X. Zhu *et al.* (2020), J. Naughton *et al.* (2021) and S. Bruno *et al.* (2022) devoted their research to the issues of ensuring optimal scenarios for the dispatching of regional power systems, in which they revealed this problem to a certain extent, but without considering the conditions of uncontrollable power shortages. As for the analysis of studies indirectly related to the issue of substantiating approaches to ensuring the resilience of regional power systems under conditions of power shortages, the material of Y. Jiang *et al.* (2018), R. Rai & K. Nagasaka (2018), H. Shang *et al.* (2020) indicates the expediency of a detailed consideration of the formation of algorithms and scenarios for the response of dispatch services, taking into account the capacity of power grids and the definition of temporary power supply schemes, the configuration of which will ensure the "survivability" of energy islands.

J. Xu *et al.* (2020) pointed out that extreme weather events cause power outages in active distribution systems and proposed a multi-stage switching strategy based on dynamic programming (DP), taking into account both islanding and fault reconfiguration and found a trade-off between minimising the overall power deficit and minimising the number of switching operations throughout the duration of the event, However, they did not track the power flows to establish the routes connecting specific power supply nodes to load nodes and determine their share in covering the energy island's demand under power shortage conditions.

V. Hosseinnezhad *et al.* (2018) formed an optimal systematic strategy for restoring the distribution network after emergencies due to serious failures and developed a two-stage solution procedure using graph theory and adjusting the results but did not consider the proportional distribution of power between load nodes of the new (post-emergency) network configuration, which allows determining the direction of electricity transit with the least losses.

Therefore, the issue of ensuring optimal scenarios for the dispatching of regional power systems in the face of uncontrollable power shortages is relevant.

The research aims to develop and substantiate approaches aimed at ensuring the controlled operation of regional power systems in cases of power shortages. For this goal, it was necessary to create algorithms and scenarios for the response of dispatch services that consider the capacity of power grids and determined temporary power supply schemes.

MATERIALS AND METHODS

The theory and methods of mathematical programming are used to provide optimal scenarios. The optimisation problems are formulated in the form of mixed Boolean linear programming problems. The AMPL modelling language was used to describe them. The Gurobi solver (n.d.) with NEOS Server (n.d.) was used to solve the optimisation problems.

The study used the proportional division method. The method is based on the fact that power flows and total losses between nodes are divided equivalently to power moments P_iL_i. The disadvantages of this method are that it ignores the unfair distribution of losses between the nodes of the trunk network and the distribution system, in particular, the imbalance of losses of the base and balancing nodes.

A network consisting of n nodes and m branches was considered. Figure 1 shows a generalised block diagram of the distribution of power flows in a regional power system.

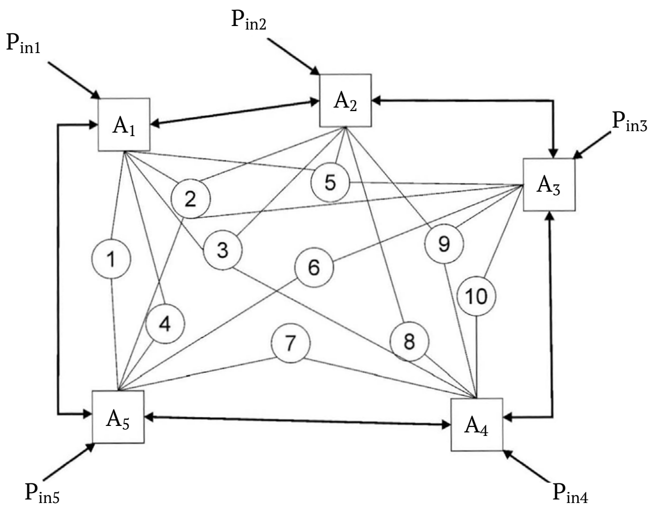

Figure 1. Generalised block diagram of power flows distribution in the energy island network
Source: compiled by the authors

To solve the problem of distributing power flows, it was necessary to record the initial data to be used in the calculation, namely the columnar incident matrices M specify the power of the nodes of set A, the demand of the load nodes of set B and the value of the power transmitted in each branch of the graph, otherwise, the values are zero. In this study, several incident matrices M were considered for five nodes of set A, each of which can be a balancing node and thus form a new (temporary) configuration of the power grid, and ten load nodes of set B. Incident matrices M establish the relationship between nodes and branches of a directed network graph. The notation used is that each element of the M_{is} matrix is located at the intersection of the i-th row (corresponding to the i-th node) and the s-th column (corresponding to the (i-j)th branch).

The optimisation problems (Bila *et al.,* 2022) were solved using the Gurobi solver available on the NEOS server. To describe the models of linear Boolean programming problems (Fourer *et al.,* 2003), we used the modelling language AMPL (A Mathematical Programming Language).

Figure 2 shows a graphical interpretation of the configuration of the possible distribution of power flows in the model power system, described below.

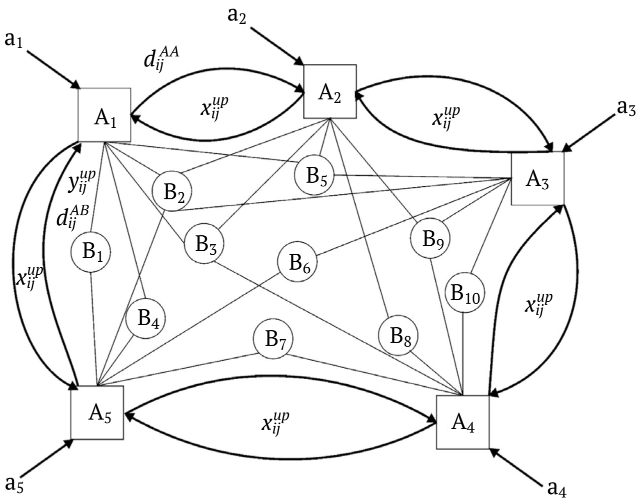

Figure 2. Graphical interpretation of the possible distribution of power flows in a model power system
Source: compiled by the authors

To solve this problem, the power grid is represented as a directed graph, which is a set of nodes and branches connected. Tracing the power transmission paths between the nodes of set A (the backbone network) can be performed in two directions: using the main power supply scheme (forward tracing) and using temporary schemes (backward tracing). Power transfers between the nodes of set A and the load nodes of the energy island (set B) are allowed in any direction, provided that the 1st Kirchhoff law is fulfilled, and the grid capacity is not exceeded.

The initial data and corresponding notation for the mathematical model are:

- a set of nodes of a higher voltage class (supply nodes) A;
- a set of nodes of a lower voltage class (load nodes) B;
- the set of links (branches of edges) of "supply nodes – supply nodes" $E_{AA} \subset A \times A$;
- the set of links (edge) of "supply nodes – load nodes" $E_{AB} \subset A \times B$;
- the level of the capacity limit of "supply nodes" a_i, $\forall i \in A$;
- load nodes' demand b_i, $\forall i \in B$, $\sum_{i \in A} a_i \leqslant \sum_{i \in B} b_i$;
- lengths (branches of network) of "supply nodes – supply nodes" d_{ij}^{AA}, $\forall (i,j) \in E_{AA}$;
- lengths (branches of network) of "supply nodes – load nodes" d_{ij}^{AB}, $\forall (i,j) \in E_{AB}$;
- upper limits of flows along the edges of the supply nodes-supply nodes network x_{ij}^{up}, $\forall (i,j) \in E_{AA}$;
- upper limits of flows along the edges of the supply nodes-load nodes network y_{ij}^{up},, $\forall (i,j) \in E_{AB}$.

Instead of an undirected graph, an oriented graph was considered, as shown in Figure 2.

The unknown (variable) flows along the branches for the edges of the supply nodes – supply nodes network are represented as follows:

$$x_{ij}^{+} \geqslant 0,\ i \in A,\ j \in A,\ (i,j) \in E_{AA},$$
$$x_{ij}^{-} \geqslant 0,\ i \in A,\ j \in A,\ (i,j) \in E_{AA},$$

and unknown (variable) flows along the branches for the edges of the supply nodes – load nodes network:

$$y_{ij}^{+} \geqslant 0,\ i \in A,\ j \in B,\ (i,j) \in E_{AB},$$
$$y_{ij}^{-} \geqslant 0,\ i \in A,\ j \in B,\ (i,j) \in E_{AB}.$$

Accordingly, the Boolean variables (1 – open branch, 0 – closed branch) will have the form:

$$X_{ij}^{+} \geqslant 0 \vee 1,\ i \in A,\ j \in A,\ (i,j) \in E_{AA},$$
$$X_{ij}^{-} \geqslant 0 \vee 1,\ i \in A,\ j \in A,\ (i,j) \in E_{AA},$$
$$Y_{ij}^{+} \geqslant 0 \vee 1,\ i \in A,\ j \in B,\ (i,j) \in E_{AB},$$
$$Y_{ij}^{-} \geqslant 0 \vee 1,\ i \in A,\ j \in B,\ (i,j) \in E_{AB}.$$

Reconciliation of the power deficit by adjusting power flows in the energy island to find optimal flow distribution points and aims to determine the conditions for meeting the demand of load nodes while minimising power moments and considering the connection between nodes with zero power (idling):

$$M^{*} = \min_{x,y,X,Y} \{ \sum_{(i,j) \in E_{AA}} d_{ij}^{AA} (x_{ij}^{+} + x_{ij}^{-}) + \sum_{(i,j) \in E_{AB}} d_{ij}^{AB} (y_{ij}^{+} + y_{ij}^{-}) + \sum_{(i,j) \in E_{AA}} \varepsilon (X_{ij}^{+} + X_{ij}^{-}) + \sum_{(i,j) \in E_{AB}} \varepsilon (Y_{ij}^{+} + Y_{ij}^{-}) \}. \quad (1)$$

under the following limitations:

- supply nodes must use the entire capacity limit (A-balance);

$$\sum_{j:(i,j) \in E_{AA}} (x_{ij}^{+} - x_{ij}^{-}) - \sum_{j:(j,i) \in E_{AA}} (x_{ji}^{+} - x_{ji}^{-}) + \sum_{j:(i,j) \in E_{AB}} (y_{ij}^{+} - y_{ij}^{-}) = a_i, \forall i \in A, \quad (2)$$

- demand at load nodes may not be fully met (B-imbalance):

$$\sum_{i:(i,j) \in E_{AB}} (y_{ij}^{+} - y_{ij}^{-}) \leq b_i, \forall j \in B. \quad (3)$$

Flows can only be sent along the edge branches E_{AA} in one direction without violating the set limit:

$$x_{ij}^{+} \leq x_{ij}^{up} \times X_{ij}^{+}, i \in A, j \in A, (i,j) \in E_{AA},$$
$$x_{ij}^{-} \leq x_{ij}^{up} \times X_{ij}^{-}, i \in A, j \in A, (i,j) \in E_{AA}, \quad (4)$$
$$X_{ij}^{+} + X_{ij}^{-} \leq 1, i \in A, j \in A, (i,j) \in E_{AA}.$$

Similarly for edge branches E_{AB}:

$$y_{ij}^{+} \leq y_{ij}^{up} \times Y_{ij}^{+}, i \in A, j \in B, (i,j) \in E_{AB},$$
$$y_{ij}^{-} \leq y_{ij}^{up} \times Y_{ij}^{-} 0, i \in A, j \in B, (i,j) \in E_{AB}, \quad (5)$$
$$Y_{ij}^{+} + Y_{ij}^{-} \leq 1, i \in A, j \in B, (i,j) \in E_{AB}.$$

In the objective function (1), a small number ε is used to consider the connection between nodes with zero power (idling) (in the calculations the $\varepsilon = 0.001$ is used).

The algorithm for distributing active power flows includes several stages:

- drawing up a replacement scheme for the power supply system;
- generating information on the nodes of sets A and B (generation limits and demand of the energy island's load nodes) and branches (distances between nodes and the value of the design capacity of the networks);
- creating incident matrices based on the targeting of nodal supply and demand;
- calculation of options for power distribution, considering the constraints;
- analysis of the results obtained justification of the choice of the optimal solution and response scenario of the dispatch service to ensure the survivability of the energy island.

For the numerical implementation of the mathematical model for the power grid scheme of the energy island shown in Figure 1, the initial data given in Table 1 were used.

Table 1. Parameters of the power scheme segment

Node designation	A_1	A_2	A_3	A_4	A_5					
Capacity, MVA	800	700	650	500	450					
Node designation	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}
Capacity, MVA	250	630	400	250	160	160	250	250	500	250
Nodes	A_1A_2	A_2A_3	A_3A_4	A_4A_5	A_5A_1	A_1B_1	A_1B_2	A_1B_3	A_1B_4	A_1B_5
Lengths L_i, km	85	90	110	140	95	13	7	9	15	20
Nodes	A_2B_2	A_2B_3	A_2B_5	A_2B_8	A_2B_9	A_3B_2	A_3B_5	A_3B_6	A_3B_9	A_3B_{10}
Lengths L_i, km	12	15	5	20	15	22	15	20	6	11
Nodes	A_4B_3	A_4B_7	A_4B_8	A_4B_9	A_4B_{10}	A_5B_1	A_5B_2	A_5B_4	A_5B_6	A_5B_7
Lengths L_i, km	25	18	6	17	10	7	17	3	18	13

Source: compiled by the authors

From the nodes of the higher voltage class A_i, a certain power P_{ini} is transferred from the grid to the load nodes of the energy island B_i. It is worth noting that in the above example, the demand of load nodes B_i is set as the value of the total reduced load connected to one network class with the length L_{AiBi} and the average electrical distance from the nodes' vertices A_i to the point of flow distribution.

RESULTS

Normal modes are managed following the dispatch schedule. This should ensure the required reliability of power supply to consumers, power quality and maximum efficiency. An integrated power system allows for the full use of dispatch management tools for electricity production and consumption, and the transfer of excess energy production from one region to another, although this is not the only reason why the system should be unified. If the integrity of the power system is compromised, there is a need to ensure the survivability of individual energy islands that are formed around existing generation facilities or trunk grid substations.

The resilience of regional power systems should be understood as a rather complex task, namely, to comply with the power consumption levels of energy islands, considering the power limit of the generation system and considering the capacity of the networks involved in the region's power supply.

In 2020-2022, many studies use both matrix and graph algorithms for solving transport problems. A solution to the addressability problem using a matrix approach was obtained by V. Kaplun & V. Osypenko (2020). The solution to the problem of optimal resource allocation allows tracing the paths of power transmission from power supply nodes (substations of trunk grids) to load nodes of the energy island (regional distribution system network) by using the proportional method.

The worst-case scenario for an uncontrolled increase in the power deficit is a partial or complete breakdown of the power system. For example, as a result of one or more system failures, automation is triggered, a large number of consumers are cut off almost simultaneously, and load volumes are sharply reduced. This, in turn, leads to the shutdown of some power plants that are technologically unable to instantly reduce their generation levels. The shutdown of generating capacities causes the next group of consumers to be disconnected, as the frequency in the power system decreases. This process is chain-like and leads to a complete blackout of consumers. In the best-case scenario, it is possible to preserve energy islands with power plants that have gone offline as a result of timely separation from the grid.

Configuring distribution system circuits and determining the duration of connection of load nodes (energy islands) to the grid is a non-trivial task of balancing microgrid systems with an individual set of end users. Damage to power equipment as a result of terrorist attacks requires a non-standard set of real-time solutions from dispatch services. It is in such circumstances that the development of scenarios to ensure the resilience of microgrid systems and the "survivability" of energy islands by optimising algorithms for dispatch services to respond to uncontrollable power shortages due to unpredictable failure of the backbone energy infrastructure is extremely relevant.

Several realisations of the mathematical model allowed us to obtain directional graphs of the distribution of energy flows and the value of the efficiency of this distribution, provided that the studied structure operates normally ($M^* = 40020$). These calculations do not consider the power losses in the cross-sections of the wires, but the study of the objective function is based on the criterion of the minimum power moment in the branches, which is proportional to the losses.

The simulation results under normal operating conditions of the structure under study between nodes A_i and load nodes B_i are shown in Table 2 and Table 3, respectively.

Table 2. Results of modelling power flow between A_i nodes

Node	Node	x_{ij}^{+}, MW	x_{ij}^{-}, MW	X_{ij}^{+}, MW	X_{ij}^{-}, MW	x_{ij}^{up}, MW	d_{ij}^{AA}, km
A_1	A_2	0	0	0	0	800	35
A_2	A_3	0	0	0	0	800	70
A_3	A_4	0	0	0	0	800	50
A_4	A_5	0	0	0	0	800	25
A_5	A_1	0	0	0	0	800	65

Source: compiled by the authors

Table 3. Results of modelling power flow between nodes A_i
and load nodes B_i under normal operating conditions of the studied network structure

Network A note	Network B note	y_{ij}^{+}, MW	y_{ij}^{-}, MW	Y_{ij}^{+}, MW	Y_{ij}^{-}, MW	y_{ij}^{up}, MW	d_{ij}^{AB}, km
A_1	B_1	180	0	1	0	180	13
A_1	B_2	180	0	1	0	180	7
A_1	B_3	180	0	1	0	180	9
A_1	B_4	180	0	1	0	180	15
A_1	B_5	80	0	1	0	180	20
A_2	B_2	180	0	1	0	180	12
A_2	B_3	180	0	1	0	180	15
A_2	B_5	80	0	1	0	180	5
A_2	B_8	80	0	1	0	180	20
A_2	B_9	180	0	1	0	180	15
A_3	B_{10}	170	0	1	0	180	11
A_3	B_2	140	0	1	0	180	22
A_3	B_5	0	0	0	0	180	15
A_3	B_6	160	0	1	0	180	20
A_3	B_9	180	0	1	0	180	6
A_4	B_{10}	80	0	1	0	180	10
A_4	B_3	40	0	1	0	180	25
A_4	B_7	70	0	1	0	180	18
A_4	B_8	170	0	1	0	180	6
A_4	B_9	140	0	1	0	180	17
A_5	B_1	70	0	1	0	180	7
A_5	B_2	130	0	1	0	180	17
A_5	B_4	70	0	1	0	180	3
A_5	B_6	0	0	0	0	180	18
A_5	B_7	180	0	1	0	180	13

Source: compiled by the authors

An alternative representation of the modelling results for optimising flows through given network sections is shown in Figure 3. In this case, the optimal power flow distribution was obtained with the value of the objective function $M^{*} = 40020$. It is worth noting that in this case, the balance between the power flows entering the nodes A_i from the power system trunk grids and the flows transmitted to the distribution system operators' networks B_i. The levels of transmitted capacities are indicated on the corresponding edges of the graph (Fig. 3).

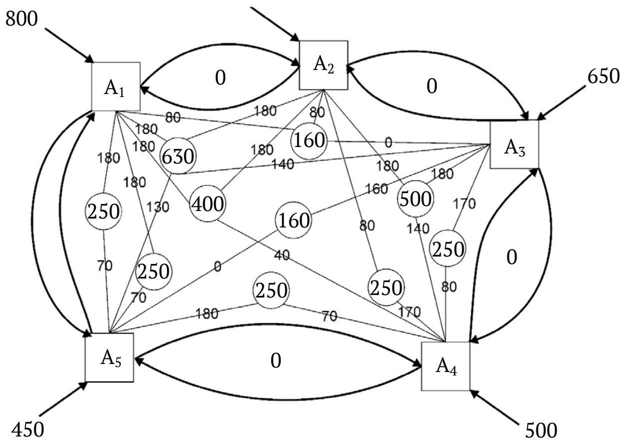

Figure 3. Results of mathematical modelling under the condition of the normal operation of networks
Source: compiled by the authors

The variant with a complete de-energisation of the input lines supplying a certain node A_1, but with preservation of its operating state, while keeping the limits of other nodes A_i, unchanged, is shown in Figure 4. The optimal flow distribution with the value of the objective function $M^* = 26590$ is obtained. It is worth noting that in the absence of a power supply to a certain node A_i, an imbalance between supply and demand of the studied segment of the power system arises (shown in red in Fig. 4).

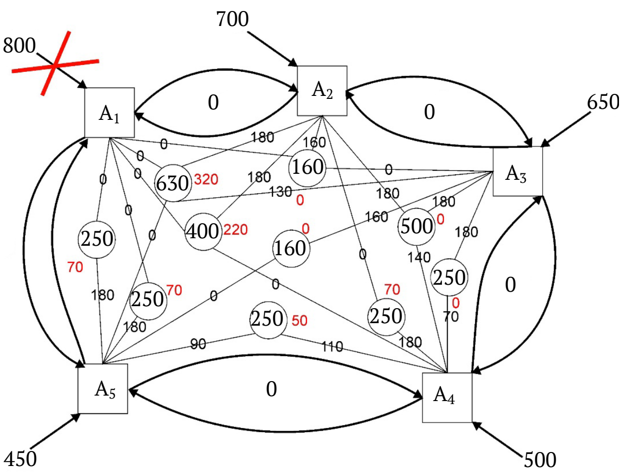

Figure 4. Results of mathematical modelling under the condition of limiting the power of node A_1
Source: compiled by the authors

The variant of the mathematical model implementation with complete de-energisation of the input lines of the energy island supplying a certain node A_i while maintaining its operating state and the condition of proportional change in the power of other nodes of the main grid is shown in Figure 5.

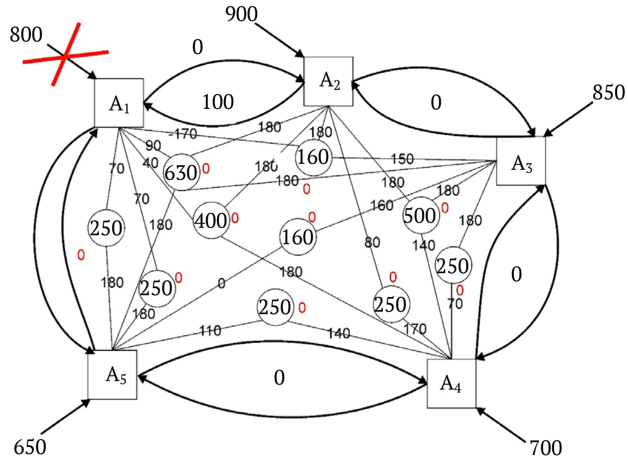

Figure 5. The results of mathematical modelling under the condition of limiting the power of node A_1 and determining the power flows between other nodes A_1
Source: compiled by the authors

The resulting value of the objective function for this case is $M^* = 49790$. It is worth noting that in the absence of a power supply to a certain node A_i and a proportional increase in the power of other nodes of the trunk grid, there is a complete satisfaction of demand from the load nodes. The proposed mathematical model does not consider approaches to the optimal distribution of upper (trunk) level flows, provided that the flow in a node is limited by the minimum loss criterion. At the same time, a proportional increase in the capacity of all operable nodes by the capacity of the node that is out of service was assumed.

DISCUSSION

N. Cai *et al.* (2012) proposed a model that, due to short-term energy shortages in extreme conditions such as earthquakes, tsunamis and hurricanes, flexible dispatch through an efficient energy transmission network, which focuses on the minimum energy recovery time by optimising energy dispatch based on the developed MILP (mixed integer linear programming) model under uncertainty of the initial information, but this model does not consider the efficiency of the selected supply in terms of minimum losses.

A. Ranjan & L. Hughes (2014) investigated the relationship between energy security and the diversity of energy flows in the power system using a set of energy security indicators and the Shannon-Wiener diversity index but did not propose an algorithm and program to solve the problem of addressing flows and power losses in multi-node regional power systems. T. Kulko *et al.* (2017), V. Bodunov *et al.* (2018), and A.F. Zharkin *et al.* (2021) solved a topological problem with variable parameters in the form of a Pareto-optimal region but did not consider the possibility of the presence of a closed mode of operation of the electric power system in the structure.

G. Fotis *et al.* (2023) conducted a similar analysis, which pointed to the possibility of a large-scale blackout in a country of the United European electricity transmission system or, even worse, a blackout in a large area of the European continent, especially given the energy crisis due to the war in Ukraine in the winter of 2022-2023. The authors also investigated how to avoid such a situation and compiled a list of reactions of the system operator in the event of a blackout. In contrast to the proposed approach, a fast and reliable restoration strategy based on the A* algorithm is used, and the effectiveness of the proposed solutions was tested using the classic IEEE-39 and IEEE-68 circuits.

The study of H. Bila *et al.* (2022) describes mathematical programming problems and numerical methods for solving them using NEOS Server based on various solvers, which are further used to solve linear Boolean programming problems for the well-known m-travelling salesman problem and a multi-extreme nonlinear programming problem. The Gurobi solver is available on the NEOS Server and the AMPL modelling language is used for computations.

A.V. Prakhovnik *et al.* (2010) analysed the national power system of Ukraine and pointed out the inefficient generation and distribution infrastructure and proposed a radically new approach to developing a strategy for meeting the demand for dispatchable electricity production, namely traditional centralised generation, decentralised and alternative energy sources, as well as the use of so-called manoeuvrable loads, such as electric heating systems. The authors used game theory and elements of fuzzy set theory as mathematical methods to solve the problem, taking into account the uncertainty of information and the multi-criteria nature of the problem, but it should be noted that this approach is suitable for solving problems of optimising the structure and increasing the efficiency of electricity supply under normal operation of the electricity system and allows finding solutions for situations of rapid emergency changes in the mode parameters to a limited extent.

Based on the material of E. Rosales-Asensio *et al.* (2022) proposed a new approach to power system resilience, which consists in describing and implementing operating modes in the form of transactional power systems, which aim to increase resilience to disasters and failures, while at the same time making it possible to supply electricity to the largest number of consumers. The authors pointed out that when analysing the power system structure for resilience, it is necessary to consider the needs of its critical users (such as control centres, fire stations and hospitals). To assess the resilience of the power system, they introduced "bonus points" for those systems that should continue to provide electricity to their critical users under any circumstances and assessed the resilience indicators taking into account these innovations, but it should be noted that the introduction of the so-called "bonus points" can significantly distort the operation of a particular power system and requires high expertise of the specialists responsible for their distribution.

A. Van Deventer *et al.* (2010) presented an analysis of cost-effective dispatching of emergency reserves with a particular focus on matching supply and demand. The demand is proposed to be balanced by the electricity market and the supply by the use of open-cycle gas turbines. As the reserve stock decreases and demand increases annually, this problem is growing. Reserves are designed to meet failures in the power system to ensure normal frequency. The categories of reserve according to auxiliary requirements are instantaneous, regulatory, ten-minute, additional and emergency, but the article pays little attention to the formation of the optimal structure of the power system according to the minimum cost criterion.

The study of B. Zhang *et al.* (2018) proposed an integrated intelligent monitoring platform for the operation of a dispatch service centre with a cloud server as the brain and land, sea, aviation and thematic services as the end services. In the context of the study, the Internet of Things technology, wireless sensor network technology and radio frequency technology are applied to realise the interaction between devices to complete automatic data collection and automatic remote transmission. The service centre based on cloud computing performs intelligent control, decision-making and tasks such as scheduling, distribution, data processing, data publishing and platform authorisation, which the research on this platform will provide some suggestions for future intelligent monitoring, but it is not indicated how monitoring of parts of the system will ensure the integrity of the power system structure in an emergency and optimise energy flows.

X. Zhou *et al.* (2015), the authors investigated the indicators of quantifying the risk of the emergency reserve allocation scheme and proposed a coordination method for allocating emergency reserves in the power grid, which considers the cost-benefit ratio. The proposed method first analyses the impact of factors such as regional cost-benefit ratio, probability of an outage and cost of reserve on the allocation of emergency reserve in the power grid, as well as the risks caused by the allocation of emergency reserve and insufficient reserve. The effectiveness and feasibility of the proposed allocation method are tested using the standard IEEE 118 scheme, and it should be noted that the proposed mechanism should be used in the normal operation of the power structure since in a critical state it is desirable to allocate the available reserves to eliminate a possible situation of loss of power system stability.

The proposed method of finding optimal points of power flow distribution for normal and limited modes and its implementation for typical cases of power supply of energy islands proves that this approach can be used as an additional tool of the decision-making system in the operational dispatch control of regional power systems.

CONCLUSIONS

The system of operational dispatch control in the face of unforeseen damage to the energy infrastructure requires a long time to develop adequate responses and scenarios to ensure the resilience of regional power systems. This imposes significant limitations on the development of timely management decisions by central and regional dispatching systems.

A mathematical model of optimisation based on mixed Boolean linear programming is proposed according to the criterion of minimising the power momentum, considering balance constraints and upper limits of the power of supply nodes and loads. The possibilities of solving the optimisation problem using the Gurobi solver available on the NEOS server are investigated using examples. The levels of efficiency of the Boolean linear programming model are established following the selected characteristic cycles of the transport problem under the specified restrictions on the components of the network structure.

Given the same cross-sections, the optimal values of the objective function may be achieved with different distributions of flows through the cross-sections of the network wires. As a rule, this will occur in cases where there is no balance between the energy flows from supply and load nodes. In this case, it will be necessary to modify the mathematical model by considering the proportional distribution of capacities in the energy island network according to the criterion of minimising losses from power outages for the relevant categories of consumers.

This model does not consider the idle mode for a particular section of the network (setting the correct minimum flow on a branch). This can be considered in the further improvement of the software implementation of the model by introducing restrictions that guarantee non-zero lower limits of power flow, considering the network capacity.

An important area for further research is the adaptation of the described transport problem to analyse the total flows in the oriented edges of the graph and to control the addressability of flow distribution between any nodes of the upper (backbone) and lower levels.

ACKNOWLEDGEMENTS

The authors would like to thank the Volkswagen Foundation (grant No. 97775).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Bila, H., Korchynskyy, O., Stetsyuk, P., Khomiak, O., & Shekhovtsov, S. (2022) Using the NEOS server for solving two classes of optimization problems. *Cybernetics and Computer Technologies*, 4, 56-81. doi: 10.34229/2707-451X.22.4.5.

[2] Bodunov, V., Kulko, T., Prystupa, A., & Gai, A. (2018). Topological task of distributed generation placement using a pareto optimization. In *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS)* (pp. 183-188). Kharkiv: IEEE. doi: 10.1109/IEPS.2018.8559502.

[3] Bruno, S., Giannoccaro, G., Iurlaro, C., Scala, M.L., & Menga, M. (2022). Predictive optimal dispatch for islanded distribution grids considering operating reserve constraints. In *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)* (pp. 518-523). Palermo: IEEE. doi: 10.1109/MELECON53508.2022.9842967.

[4] Cai, T., Zhao, C., & Xu Q. (2012). Energy network dispatch optimization under emergency of local energy shortage. *Energy*, 42(1), 132-145. doi: 10.1016/j.energy.2012.04.001.

[5] Fotis, G., Vita, V., & Maris, T.I. (2023). Risks in the european transmission system and a novel restoration strategy for a power system after a major blackout. *Applied Sciences*, 13(1), article number 83. doi: 10.3390/app13010083.

[6] Fourer, R., Gay, D., & Kernighan, B. (2003). *AMPL, A modeling language for mathematical programming*. Belmont: Duxburry Press.

[7] Gurobi optimization. Gurobi optimizer reference manual. (n.d.). Retrieved from http://www.gurobi.com.

[8] Hosseinnezhad, V., Rafiee, M., Ahmadian, M., & Siano, P. (2018). Optimal island partitioning of smart distribution systems to improve system restoration under emergency conditions. *International Journal of Electrical Power and Energy Systems*, 97, 155-164. doi: 10.1016/j.ijepes.2017.11.003.

[9] Izvoshchikova, A. (2022). *In Ukraine, about 50% of the critical energy infrastructure was damaged – Kubrakov*. Retrieved from https://suspilne.media/335756-v-ukraini-poskodzeno-blizko-50-kriticnoi-energoinfrastrukturi-kubrakov/.

[10] Jiang, Y., Li, L., & Liu, Z. (2018). A multi-objective robust optimization design for grid emergency goods distribution under mixed uncertainty. *IEEE Access*, 6, 61117-61129. doi: 10.1109/ACCESS.2018.2875786.

[11] Kaplun, V., & Osypenko, V. (2020). Energy efficiency analyses in polygeneration microgrids with renewable sources. In *2020 IEEE 7th International Conference on Energy Smart Systems* (pp. 139-143). Kyiv: IEEE. doi: 10.1109/ESS50319.2020.9160346.

[12] Kulko, T., Bodunov, V., Prystupa, A., & Gai, A. (2017). Placement of distributed generation considering topology. In *2017 IEEE International Young Scientists Forum on Applied Physics and Engineering (YSF)* (pp. 32-35). Lviv: IEEE. doi: 10.1109/YSF.2017.8126587.

[13] Naughton, J., Wang, H., Cantoni, M., & Mancarella, P. (2021). Co-optimizing virtual power plant services under uncertainty: A robust scheduling and receding horizon dispatch approach. *IEEE Transactions on Power Systems*, 36(5), 3960-3972. doi: 10.1109/TPWRS.2021.3062582.

[14] NEOS Server. (n.d.). Retrieved from https://neos-server.org.

[15] Nosova, H. The biggest blackouts in history: What it was like (2022). Retrieved from https://tsn.ua/svit/nayvidomishi-blekauti-v-istoriyi-2222854.html.

[16] Prakhovnik, A.V., Popov, V.A., & Nakhodov, V.F. (2010). Risk and uncertainty assessment in the development of strategy for forming the potential of dispatchable generation in the national power system of Ukraine. *International Journal of Global Energy*, 34(1-4), 132-138. doi: 10.1504/IJGEI.2010.037400.

[17] Rai, R., & Nagasaka, K. (2018). Analysis of ELD and OPF for a large-scale power system under emergencies. *International Journal of Renewable Energy Research*, 8(4), 2257-2265.

[18] Ranjan, A., & Hughes, L. (2014). Energy security and the diversity of energy flows in an energy system. *Energy*, 73, 137-144. doi: 10.1016/j.energy.2014.05.108.

[19] Rosales-Asensio, E., Elejalde, J., Pulido-Alonso, A., & Colmenar-Santos, A. (2022). Resilience framework, methods, and metrics for the prioritization of critical electrical grid customers. *Electronics*, 11(14), article number 2246. doi: 10.3390/electronics11142246.

[20] Shang, H., Lin, H., Li, Z., Zhao, H., Chen, M., Yang, Z., & Wen, F. (2020). Robust optimal scheduling of mobile emergency power sources considering uncertainties. *Dianli Jianshe/Electric Power Construction*, 41(8), 111-119. doi: 10.12204/j.issn.1000-7229.2020.08.013.

[21] Van Deventer, A., Chowdhury, S., Chowdhury, S.P., & Gaunt, C.T. (2010). Management of emergency reserves dispatching in electricity networks. In *2010 International Conference on Power System Technology* (pp. 1-5). Zhejiang: IEEE. doi: 10.1109/POWERCON.2010.5666078.

[22] Xu, J., Zhang, T., Du, Y., Zhang, W., Yang, T., & Qiu, J. (2020). Islanding and dynamic reconfiguration for resilience enhancement of active distribution systems. *Electric Power Systems Research*, 189, article number 106749. doi: 10.1016/j.epsr.2020.106749.

[23] Zhang, B., Tang, K., & Guo, H. (2018). Research on the unmanned intelligent monitoring platform of geographical conditions. *Proceedings of SPIE – the International Society for Optical Engineering*, 2018, article number 10835. doi: 10.1117/12.2503981.

[24] Zharkin, A.F., Novskiy, V.O., Popov, V.A., & Yarmoliuk, O.S. (2021). Improving the efficiency of distribution network control under the conditions of application of distributed sources generation of electrical energy and means of its accumulation. *Technical Electrodynamics*, 3, 37-43. doi: 10.15407/TECHNED2021.03.037.

[25] Zhou, X., Li, W., Tang, J., Wang, Q., Yu, J., & Zhang, C. (2015). Risk quantification based coordinative allocation of emergency reserve. *Dianwang Jishu/Power System Technology*, 39(7), 1927-1932. doi: 10.13335/j.1000-3673.pst.2015.07.025.

[26] Zhu, X., Yang, J., Li, G., Dong, X., & Liu, S. (2020). Optimal dispatching strategy of regional integrated energy system considering virtual energy storage system. *Electric Power Construction*, 41(8), 99-110. doi: 10.12204/j.issn.1000-7229.2020.08.012.

Віктор Володимирович Каплун
Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-7040-9344
Олександр Валентинович Гай
Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-5460-7260
Петро Іванович Стецюк
Доктор фізико-математичних наук, старший науковий співробітник
Інститут кібернетики імені В.М. Глушкова НАН України
03187, пр. Академіка Глушкова, 40, м. Київ, Україна
https://orcid.org/0000-0003-4036-2543
Андрій Володимирович Івлічев
Провідний інженер-програміст
Інститут кібернетики імені В.М. Глушкова НАН України
03187, пр. Академіка Глушкова, 40, м. Київ, Україна
https://orcid.org/0009-0005-2823-6204

Забезпечення оптимальних сценаріїв диспетчеризації регіональних енергосистем в умовах некерованого дефіциту потужності

Анотація. Станом на 2023 рік важливим є обґрунтування критеріїв оптимальності балансування навантаження територіальних енергоостровів в умовах некерованого дефіциту потужності внаслідок непередбачуваного виходу з ладу (руйнування внаслідок воєнних бомбардувань) енергетичної інфраструктури верхнього (магістрального) рівня. Метою дослідження було обґрунтування підходів щодо забезпечення керованого функціонування регіональних енергосистем за умов дефіциту потужності. В роботі було застосовано теорію та методи математичного аналізу складних багатокомпонентних систем у формі змішаного булевого лінійного програмування. Для опису режимів роботи електромереж було використано мову моделювання A Mathematical Programming Language та методи моделювання NEOS-сервера на базі солвера Gurobi. В дослідженні застосовано метод пропорційного розподілу потужності між вузлами навантаження післяаварійної конфігурації мережі для визначення напряму транзиту електроенергії з найменшими втратами. Запропоновано алгоритм і програму для розв'язування задачі адресності потоків і втрат потужності у багатовузлових регіональних енергосистемах. Сформульована задача оптимізації у формі моделі змішаного булевого лінійного програмування з критерієм мінімізації моменту потужності при врахуванні балансових обмежень та верхніх границь на потужності між вузлами постачання та навантажень. Розроблена транспортна матриця дозволила знаходити оптимальний розподіл потужності для аварійних та післяаварійних режимів за критерієм мінімальних мережевих втрат. Сформовано алгоритми та сценарії реагування диспетчерських служб з урахуванням пропускної здатності електричних мереж та визначення тимчасових схем електропостачання, конфігурація яких дозволить забезпечити «живучість» енергоостровів. Встановлено рівні ефективності моделі булевого лінійного програмування, пов'язаних зі зв'язністю циклів транспортної задачі та порядком обходу його вершин для тестових прикладів в залежності від обмежень, які накладаються на компоненти структури мережі. Процес відстеження потоків електроенергії дозволить встановлювати маршрути, які зв'язують конкретні вузли постачання електроенергії з вузлами навантаження, і визначати їх частки у покритті попиту енергоострова за умов дефіциту потужності

Ключові слова: критерій мінімізації моменту; енергоострів; транспортна матриця; булеве лінійне програмування; балансування навантаження