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Mathematical Model of a Local Grid with Small Modular Reactor NPPs

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The technical and economic processes of the Local Grid, regional electricity system comprising small modular reactor nuclear power plants, renewable electricity generators, and electricity storage systems are investigated. Smart grid technologies are used in the management of such a system. In relation to the electricity system, the Local Grid acts as a consumer or producer of electricity depending on the price situation in the wholesale market and its own ability to balance the volume of electricity generation-consumption.

The Local Grid market is considered to be perfect, otherwise the wholesale electricity market is characterized by imperfect competition. The mathematical model of the Local Grid is offered. The presented model adequately reproduces the characteristics of the interaction between the local market and the wholesale market. The mathematical model is generated in the form of the commitment problem for small modular reactors and electricity storage systems. The model reflects the technological limitations for the loading modes of small modular reactors and units of the energy storage system, which operate in the modes of direct and reverse energy conversion. In particular, the model reflects the shunting modes and start-shutdown modes of small modular reactors and charge-discharge modes of energy storage system units, which together determine flexibility of the operation modes for the entire power system. The commitment problem of small modular reactors of a nuclear power plant, units of the electricity storage system, and transmission lines connecting the Local Grid with the power system is a mixed integer programming problem with an objective function of minimized system costs.

Cluster integer functions are used to reduce the dimensionality of the problems of mathematical modeling the loading modes of the Local Grid in the descriptions for the sets of the same type small modular reactors, as well as the same type energy storage units. The Local Grid model reproduces the modes of its disconnection from the system operator's network to increase nuclear safety in the event of a natural disaster or hostilities. The results of computational experiments on modeling the commitment modes of the local electrical grid are presented.

The experiments used standard data on the volume of electricity consumption and its production from renewable energy sources. The results of the computational experiment confirm the adequacy of the suggested mathematical model for the Local Grid. The presented model is suitable for the use both independently – to analyze Local Grid functioning - and in combination with the models of electric power industry - to determine the impact of the Local Grids on the electricity system.

The article is developed based on the results of the research carried out under target program “Support of State-Priority Research and Scientific and Technical (Experimental) Solutions of the Department of Physical and Technical Problems of Energy of the NAS of Ukraine for 2022 – 2023” with program expenditure classification code 6541230 (applied research).

Keywords: Local Grid, small modular reactor, electricity storage system, model, unit commitment problem.

Introduction

The analysis of present energy supply systems implies economic, environmental and safety studies.

Up-to-date integrated solutions to reduce the negative environmental impact of conventional power generation technologies are implemented by reducing fossil fuel production and introducing renewable and nuclear energy technologies.

SSTC NRS ДЕРЖАВНЕ ПІДПРИЄМСТВО ДЕРЖАВНИЙ НАУКОВО-ТЕХНІЧНИЙ ЦЕНТР З ЯДЕРНОЇ ТА РАДІАЦІЙНОЇ БЕЗПЕКИ

Over the last decade, the efficiency of solar and wind power generation technologies has improved significantly, and their implementation has become widespread. The rate of development of solar and wind power plant (SPP and WPP) capacity is now constrained by the variability of their electricity production due to changes in weather conditions. Balancing variable capacities in the power system requires the involvement of additional shunting generating units that run on fossil fuels, which leads to negative environmental consequences.

Conventional nuclear power industry uses powerful units that cover the base load. Nuclear units are predominantly not involved in capacity control. An additional constraint on the development of nuclear energy is the high requirements for production safety. Increased requirements are placed both for the reliability of power units and for the reliability of NPP connection to the system operator's grid.

The development of small modular reactors capable of participating in load regulation allows forming Local Grids that provide a cost-effective and environmentally friendly power supply to consumers in the region and are resistant to system faults.

The design of up-to-date small modular reactors provides a high level of nuclear safety, including simplicity of the design and minimum number of components, resistance to loss of connection with the external grid, and ability to work in the island mode [1].

Modular reactors are designed to participate in load regulation. This is achieved by shutting down one or more modules, maneuvering the load of individual modules, bypassing the steam turbine directly to the condenser [2].

When the Local Grid is disconnected from the power system, an NPP equipped with small modular reactors will automatically switch over to the power supply of the allocated area covered by the Local Grid.

The use of electricity storage systems in Local Grids provides additional operational flexibility of such systems.

This architecture also has the advantage of reducing power losses due to reduced power flows in the high-voltage transmission lines.

The development of efficient small modular reactor technologies, intensive development of renewable energy sources (RES), as well as grid equipment, smart metering, data transmission systems and control methods, all described by term Smart Grids, are leading to changes in the structure of the energy system and the interaction of agents in the energy market.

Local Grids, including consumers, small modular reactors, renewable energy sources and energy storage systems, are balanced energy systems of consumers-producers. Depending on the level of market prices, the level of domestic consumption, as well as the capabilities of generating capacity and storage systems, local grids can act as both consumers and producers.

In the wholesale electricity market, there may be imperfect competition [3], while in Local Grid, due to the closer connection of producers to consumers, effective pricing mechanisms are assumed to operate.

Research has paid considerable attention to the possibility of sharing nuclear and renewable energy sources, as well as to the interaction of local networks with the grid and the wholesale electricity market.

Prospects for the joint use of small modular reactor NPPs with renewable energy sources are investigated in [2]. However, the authors have not studied the operation modes of such a system and peculiarities of its interaction with the wholesale electricity market.

The possibility of decomposing an entire electricity market into a Top-Level Market and a set of lower tier markets operating within the boundaries of individual Local Grids has been investigated in [4].

In [5], the behavior and interaction of local network operators are studied using game theory methods. At the same time, the simplified representation of local grids as a system of the consumer and uncontrolled generators of the electric power is considered.

To reduce the dimensionality of mathematical modeling problems for commitment modes of the same type generating units of power systems in [6], cluster variables were used instead of traditionally used binary variables.

The unit commitment model of loading generating units on the cyclic forecasting horizon (UCC-model) has been proposed in [7]. The UCC model reproduces unit-loading modes on a cyclical weekly forecast horizon and does not require initial conditions, as it establishes a relationship between the states of generating units at the end and beginning of the forecast horizon.

The UCC model adequately reflects the loading modes for generating units of NPP, thermal power plants (TPP), powerful combined heat and power plants (CHP), hydro power plants (HPP) and energy storage systems, including powerful hydro pump storage plants (HPSP). The UCC model is a multi-node model and takes into account the limitations for the volume of electricity transmission by interconnection power lines. The UCC model takes into account system-wide requirements for the placement of primary and secondary power reserves on loaded units, including energy storage systems.

The UCC model is a tool to analyze the adequacy of shunting power in the tasks of medium- and long-term forecasting of power system development in terms of increasing electricity production of wind and solar power plants.

The mentioned research results were used to develop the model of functioning of the Local Grid in market conditions.

Consider the work of the Local Grid, which includes:

consumer;

NPP with small modular reactors;

uncontrolled RES generator;

electricity storage system.

Each of the listed members may represent a set of producers and/or consumers of a similar type. It also provides a link between the Local Grid and the Top-Level Market.

The work of the Local Grid is provided on the basis of the following provisions:

RES ensure the production of electricity with minimum variable costs with no emissions into the environment. The load of this producer (generator) is determined solely by weather conditions;

NPP with small modular reactors provides the main part of electricity production and participates in load regulation;

energy storage facility balances supply and demand, taking into account the technical limitations of the generating equipment, consumption schedules, and the price level in the upstream market;

if the Local Network lacks its own generation, electricity is sourced from the grid and the price of electricity for consumers on the Local Grid is the sum of the prices on the upstream market and the transmission price;

if the price on the upstream market rises significantly, it becomes feasible to supply electricity from the Local Grid to the wholesale market, with the price of electricity for Local Grid customers being set equal to the price on the external market.

At its core, the task of modeling the Local Grid including small modular reactors, renewable energy sources and an energy storage system is similar to the problem of optimal unit commitment [8-11].

The following is a mathematical model of the Local Grid, which reflects the technological constraints for the loading modes of the small modular reactors and energy storage system units. The model reproduces the shunting and start-shutdown modes of the small modular reactors, as well as the charge/discharge modes of the energy storage units.

The commitment problem of small modular reactors of NPPs, power storage system units, as well as transmission lines connecting the Local Grid with the power system is presented as a mixed integer programming problem with the target function of minimized system costs. To reduce the dimensionality of the tasks of mathematical modeling for loading modes of the Local Grid, cluster integer functions are used in the descriptions of the sets of single-type small modular reactors, as well as of the single-type energy storage units.

Mathematical description of Local Grid model

A. Model parameters:

t – the number of the time interval of the weekly forecast period

T – set of numbers t

z – the number of the weekly forecast period

Z – set of numbers z

N – the whole number of SMRs ready to operate in load mode

S – the whole number of ESS ready to operate in pump or generator mode

T_0 – the number of the extreme right time interval of the weekly period

c^{SU} – the cost of SMR startup

$\bar{C}$ – operating costs under minimum SMR load

$\tilde{c}$ – the coefficient of elasticity of operating costs to the load of the SMR

$\underline{P}$ – the minimum load of the SMR

$\bar{P}$ – maximum load of the SMR

c^{SD} – the cost of SMR shutdown

P^{SU} – the lower allowable load limit of the SMR during its startup

P^{SD} – the upper permissible load limit of the SMR before its shutdown

ΔP^{up} – the value of the maximum increase in load on the SMR

ΔP^{down} – the value of the maximum reduction of the load on the SMR

η^{P} – efficiency of ESS equipment operated in pump mode

η^{G} – efficiency of ESS equipment operated in generator mode

c^{P} – specific operating costs for ESS operation in pump mode

c^{G} – specific operating costs of ESS operation in generator mode

$\bar{q}$ – the maximum amount of energy that ESS can store

$\underline{q}$ – the minimum amount of energy that ESS can store

$\bar{p}^{P}$ – maximum ESS load under the operation in pump mode

$\bar{p}^{G}$ – maximum ESS load under the operation in generator mode

c^{RnW} – specific operating costs for the production of electricity from RES

Pr^{TL} – the prices in the Top-Level Market

Pr^{TSO} – the transmission price

H – the maximum allowable load of transmission lines connecting the Local Grid to the power system.

B. Model variables:

$\mathrm{Cos}t$ – operating costs for electricity production by the SMR

$\mathrm{Cos}t^{SU}$ – costs for SMR startup

$\mathrm{Cos}t^{SD}$ – costs for SMR shutdown

$\mathrm{Cos}t^{RnW}$ – operating costs for electricity generation from RES

$\mathrm{Cos}t^{S}$ – operating costs for ESS, which operates in generator mode

p – the load of the unit in generation mode

p^{RnW} – the load of RES

$\mathrm{Cos}t^{Ext}$ – the cost of electricity purchase in the Top-Level Market

Income – the income from electricity sale to the Top-Level Market

p^{Ext} – the load of purchase in the Top-Level Market

p^{Int} – the load of sale to the Top-Level Market

l – the load of consumption

$\tilde{p}$ – variable load of the SMR

u – integer function that characterizes the state of the G SMRs and takes a value $u \in \{0,1,\cdots,N\}$ if u SMRs are operated in load mode

x – integer function that characterizes the state of the G SMRs and takes a value $x \in \{0,1,\cdots,N\}$ if x SMRs are operated in shutdown mode

y – integer function that characterizes the state of the G SMRs and takes a value $y \in \{0,1,\cdots,N\}$ if y SMRs are operated in startup mode

p^P – the load of ESS operated in pumping mode

p^G – the load of ESS operated in generator mode

q – the amount of energy stored at the ESS

u^P – integer function that characterizes the state of the S ESSs and takes a value $u^P \in \{0,1,\cdots,S\}$ if u^P ESSs are operated in pump mode

x^P – integer function that characterizes the state of the S ESSs and takes a value $x^P \in \{0,1,\cdots,S\}$ if x^P ESSs are operated in the stop of the pump mode

y^P – integer function that characterizes the state of the S ESSs and takes a value $y^P \in \{0,1,\cdots,S\}$ if y^P ESSs are operated in the start of the pump mode

u^G – integer function that characterizes the state of the S ESSs and takes a value $u^G \in \{0,1,\cdots,S\}$ if u^G ESSs are operated in generator mode

x^G – integer function that characterizes the state of the S ESSs and takes a value $x^G \in \{0,1,\cdots,S\}$ if x^G ESSs are in the stop of the generator mode

y^G – integer function that characterizes the state of the S ESSs and takes a value $y^G \in \{0,1,\cdots,S\}$ if y^G ESSs are in the start of the generator mode

h_t – binary function, which takes a value of 0 when the load of purchase in the Top-Level Market occurred and a value of 1 when the load of sale to the Top-Level Market occurred.

C. The objective function of the UCC optimization problem

Operating costs of electricity production in the power system are minimized

$$\sum_{\forall t \in T} \begin{pmatrix} \mathrm{Cost}_t + \mathrm{Cost}_t^{SU} + \mathrm{Cost}_t^{SD} + \\ \mathrm{Cost}_t^{S} + \mathrm{Cost}_t^{RnW} + \\ \mathrm{Cost}_t^{Ext} - Income_t \end{pmatrix} \to \min. \quad (1)$$

D. Balance of electricity production and consumption

Balance of electricity production and consumption is represented by equations

$$p_t^{RnW} + p_t + p_t^G + p_t^{Ext} = l_t + p_t^P + p_t^{Int}, \quad \forall t \in T. \quad (2)$$

$$0 \le p_t^{Ext} \le h_t H, \quad \forall t \in T. \quad (3)$$

$$0 \le p_t^{Int} \le (1 - h_t) H, \quad \forall t \in T. \quad (4)$$

E. Operating costs for SMR

Operating costs for SMR

$$\mathrm{Cost}_t = \bar{C} u_t + \tilde{c}\, \tilde{p}_{t,}, \quad \forall t \in T, \quad (5)$$

$$\tilde{p}_t \le \left(\bar{P} - \underline{P}\right) u_t, \quad \forall t \in T, \quad (6)$$

$$p_t = \underline{P} u_t + \tilde{p}_t, \quad \forall t \in T. \quad (7)$$

F. The mode of SMR operation

The mode of SMR operation is described by the system of relationships between the binary functions of its state, which has the form

$$y_t - x_t = u_t - u_{t-1}, \quad \forall t \in T, \quad t \ne 1, \quad (8)$$

$$y_1 - x_1 = u_1 - u_{T_0}, \quad (9)$$

$$y_t + x_t \le N, \quad \forall t \in T, \quad (10)$$

$$u_t \le N, \quad \forall t \in T. \quad (11)$$

G. The cost of SMR startup

The cost of SMR startup is calculated by the formula

$$\mathrm{Cost}_t^{SU} = c^{SU} y_t, \quad \forall t \in T. \quad (12)$$

H. The cost of SMR shutdown

The cost of SMR shutdown is calculated by the formula

$$\mathrm{Cost}_t^{SD} = c^{SD} x_t, \quad \forall t \in T. \quad (13)$$

I. The current maximum attainable load of the SMR

The current maximum attainable load of the SMR is limited by the maximum installed capacity or its allowable load before shutdown

$$p_t \le p_{t-1} + \Delta P^{up} u_{t-1} + P^{SU} y_t, \quad \forall t \in T, \quad t \ne 1; \quad (14)$$

$$p_t \le p_{T_0} + \Delta P^{up} u_{T_0} + P^{SU} y_t, \quad t = 1. \quad (15)$$

The unit load is limited from the top by its current maximum achievable load

$$p_t \le \bar{P} u_t, \quad \forall t \in T. \quad (16)$$

J. The current minimum achievable load of the SMR

The SMR load is limited from the bottom by its current minimum achievable load

$$p_t \ge \underline{P} u_t, \quad \forall t \in T. \quad (17)$$

The current minimum achievable load of the SMR is limited by the technical capabilities to reduce its load during shutdown

$$p_t \geq p_{t-1} - \Delta P^{down} u_t - P^{SD} x_t, \quad \forall t \in T, \quad t \neq 1; \quad (18)$$

$$p_t \geq p_{T_0} - \Delta P^{down} u_t - P^{SD} x_t, \quad t = 1. \quad (19)$$

K. Description of ESS

Operating costs of ESS are determined by the formula

$$\mathrm{Cost}_t^S = c^P \left(1 - \eta^P\right) p_t^P - c^G \left(1 - \eta^G\right) p_t^G, \quad t \in T. \quad (20)$$

Energy balances of ESS are represented by equations

$$q_t - q_{t-1} = \eta^P p_t^P - \frac{p_t^G}{\eta^G}, \quad \forall t \in T, \quad t \neq 1. \quad (21)$$

Complemented by the conditions of weekly cyclicity of accumulated energy

$$q_0 = q_{T_0}. \quad (22)$$

The amount of stored energy is limited by the energy consumption of its storage systems

$$S\underline{q} \leq q_t \leq S\overline{q}, \quad \forall t \in T. \quad (23)$$

The operation of ESS in the mode of direct conversion of stored energy into electrical energy is described by the following relationships between the binary functions of the state of the systems:

$$y_t^G - x_t^G = u_t^G - u_{t-1}^G, \quad \forall t \in T, \quad t \neq 1, \quad (24)$$

$$y_1^G - x_1^G = u_1^G - u_{T_0}^G, \quad (25)$$

$$y_t^G + x_t^G \leq S, \quad \forall t \in T, \quad (26)$$

$$u_t^G \leq S, \quad \forall t \in T. \quad (27)$$

The operation of ESS in the mode of inverse conversion of electrical energy into another form of energy suitable for its accumulation and storage is described by the following relationships between binary functions of the state of the systems:

$$y_t^P - x_t^P = u_t^P - u_{t-1}^P, \quad \forall t \in T, \quad t \neq 1, \quad (28)$$

$$y_1^P - x_1^P = u_1^P - u_{T_0}^P, \quad (29)$$

$$y_t^P + x_t^P \leq S, \quad \forall t \in T, \quad (30)$$

$$u_t^P \leq S, \quad \forall t \in T. \quad (31)$$

The inability to operate ESS simultaneously in the modes of direct and reverse energy conversion is reflected in the limitations

$$u_t^G + u_t^P \leq S, \quad \forall t \in T. \quad (32)$$

Generating equipment of ESS, working in the mode of direct conversion of stored energy into electricity, has limited load, i.e.

$$p_t^G \leq u_t^G p^G, \quad p_t^G \geq 0, \quad \forall t \in T. \quad (33)$$

Load limitations of ESS are also taken into account during their operation in the mode of inverse energy conversion

$$p_t^P \leq u_t^P \overline{p}^P, \quad p_t^P \geq 0, \quad \forall t \in T. \quad (34)$$

L. Description of RES power generation systems

Operating costs for the production of electricity from RES are calculated by the formula

$$\mathrm{Cost}_t^{RnW} = c^{RnW} p_t^{RnW}, \quad t \in T. \quad (35)$$

The projected maximum volumes of electricity production from RES are determined on the basis of retrospective models of the respective power plants.

M. Purchase of electricity in the Top-Level Market system

The cost of electricity purchase in the Top-Level Market system

$$\mathrm{Cost}_t^{Ext} = \left(\mathrm{Pr}_t^{TL} + \mathrm{Pr}_t^{TSO}\right) p_t^{Ext}. \quad (36)$$

N. The sale of surplus electricity to the Top-Level Market system

The income from electricity sale to the Top-Level Market system

$$Income_t = \mathrm{Pr}_t^{TL} \; p_t^{Int}. \quad (37)$$

Peculiarities of Computer Simulation of Local Grid System and Results of Computer Experiment

To perform computational experiments, the proposed mathematical model of the Local Grid system as a mixed integer programming problem (1) - (37) was implemented in IBM ILOG CPLEX Optimization Studio Version 20.1 using the OPL optimization programming language. The following computer experiments were performed using the obtained computer model.

The simulation is carried out for a week period with hourly process detail under the following conditions.

The pattern of electricity consumption is standard for an average city and varies in the range from 83.1 to 197.2 MW.

The price of electricity on the Top-Level Market changes according to the formula:

$$\Pr_t^{TL} = 0.15 l_t - 12, \quad \forall t \in T.$$

The load of the RES varies depending on the weather conditions in the range from 2.2 to 103.9 MW, its cost of electricity generation is 5 $/MWh.

SMR and ESS characteristics are reflected in Tables I and II respectively.

The Local Grid has been simulated for two modes of operation:

operation under normal conditions, synchronous with the power system. Maximum allowable load of transmission lines that connect the Local Grid with the power system: H=75MW. Figure 1 presents the graph of electricity demand coverage in the Local Grid by various sources of generation and import for synchronous mode. The difference between the consumption and production curves corresponds to the capacity of the export and charge of the ESS;

operation under emergency conditions, in the island mode. During the operation in the island mode H=0MW, the curves of electricity consumption and RES production remain unchanged. Figure 2 presents the graph of electricity demand coverage for the island mode.

The simulation results of the Local Grid system for synchronous and island modes of the Local Grid are shown below in Figure 3 and Figure 4.

Figure 3 presents the changes in SMR load, power flow from the external energy system and to the external energy system.

The figure shows that the disconnection of the Local Grid from the power system leads to a certain destabilization of the SMR operation mode due to the cessation of external power flows.

Table 1 – SMR characteristics [1, 12]

N	2
c^{SU}	1093.1 $/StartUp
$\bar{C}$	835 $/h
$\tilde{c}$	3 $/MWh
$\underline{P}$	19.25 MW
$\bar{P}$	77 MW
c^{SD}	1337.5 $/ShutDown
P^{SU}	19.25 MW/h
P^{SD}	77 MW/h
ΔP^{up}	57.75 MW/h
ΔP^{down}	57.75 MW/h

Table 2 – ESS characteristics [12].

S	2
η^P	0.85
η^G	0.85
c^P	25 $/MWh
c^G	25 $/MWh
$\bar{q}$	75 MWh
$\underline{q}$	0 MWh
$\bar{p}^P$	20 MW
$\bar{p}^G$	15 MW

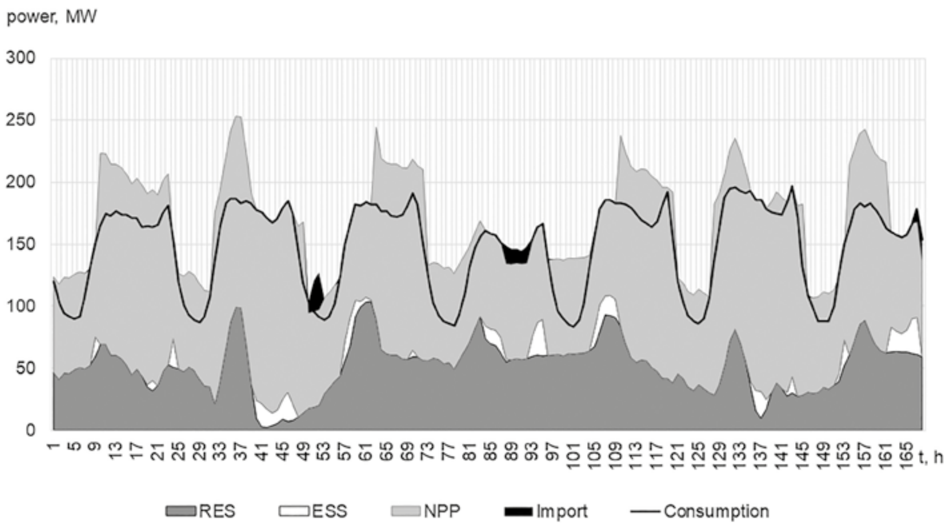

Figure 1 – Electricity consumption and production during the week in the Local Grid system for synchronous mode

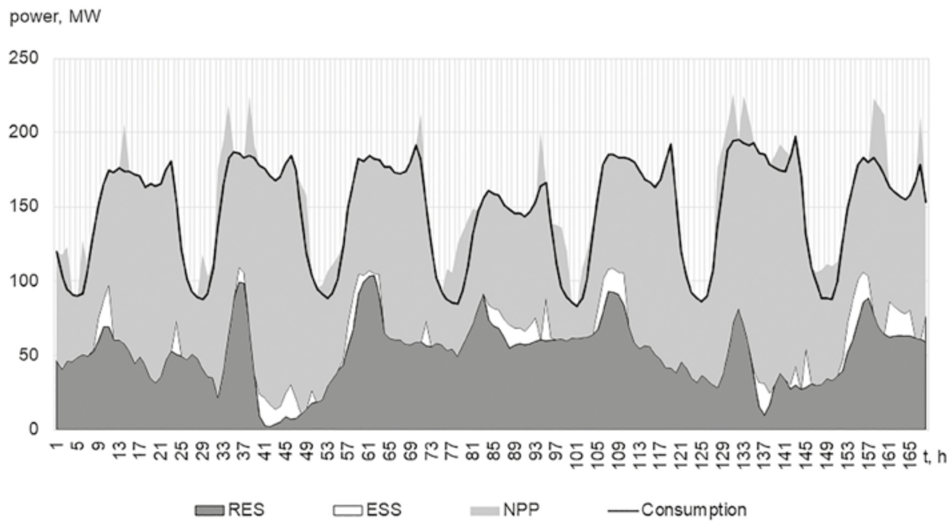

Figure 2 – Electricity consumption and production during the week
in the Local Grid system for the island mode

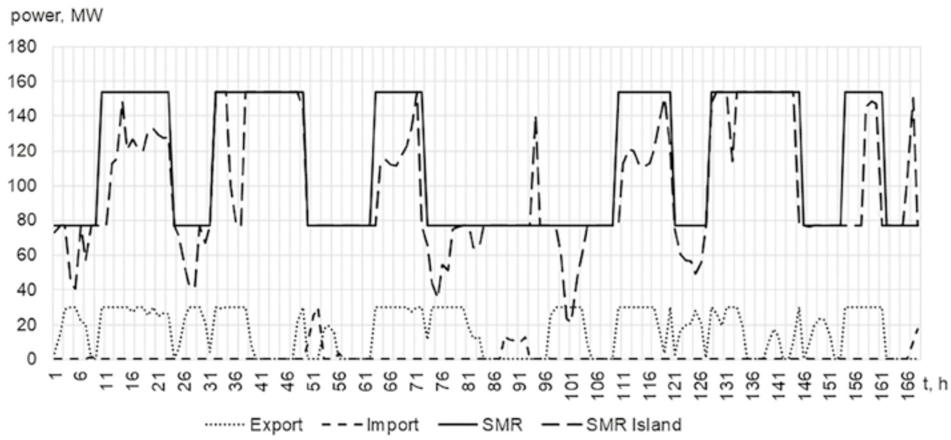

Figure 3 – Electricity production by the SMR, the supply of electricity
from the outside power system and supply to the outside power system

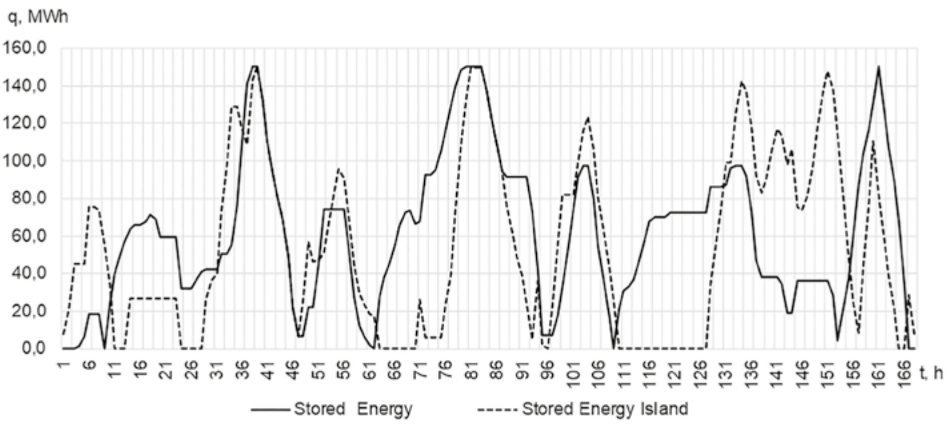

Figure 4 – Weekly graphs of the stored energy level in the Local Grid system

At the same time, if the installed capacity structure of the local grid is chosen reasonably, the schedules of the SMR meet the design requirements [1].

The value of ESS charge is shown in Figure 4. Obviously, when the local grid is disconnected from the power system, the instability of the storage system increases, but due to the limited operation time of the Local Grid in the island mode, this should not lead to a rapid depletion of its resource.

An analysis of the economic characteristics of Local Grid operation indicates the following. Under synchronous operation weekly costs are $318.6 thousand, at the same time, weekly revenues from electricity sales to the wholesale market are $38.9 thousand. Consequently, the value of the objective function is $279.7 thousand. Under the island mode of operation weekly, costs make up $304.3 thousand, with zero revenues from supply to the external market. That is, synchronous operation of the Local Grid is more efficient.

Conclusion

Reducing the environmental impact of power industry requires the development of renewable and nuclear power generation technologies. At the same time, the dependence of RES on natural conditions and increased safety requirements for nuclear power generation limit the combined generation of these technologies.

The development of small modular nuclear reactor technology has increased the safety of production at the plant level, has significantly reduced the requirements for the reliability of the NPP connections with the power system, while dramatically improving the maneuvering characteristics of nuclear power.

The combined use of small modular nuclear reactor technology, renewable energy sources and energy storage to supply power to consumers in a particular region provides:

efficient and environmentally friendly electricity generation;

increase of production safety at nuclear power facilities and security of power supply to consumers during local power grid outages.

reduction of network losses and simplification of power system recovery after system accidents.

Local Grids form a new class of participants, which, depending on external market price conditions and the supply-demand balance in the local grid, can act as a buyer or seller of electricity.

In order to account for the interaction of Local Grids with the wholesale market and to analyze the operation of local networks in isolated mode, the energy system is decomposed, with the wholesale market as the top level and the set of Local Grids as the lower level.

The mathematical model of the Local Grid is generated in the form of a load problem for small modular reactors and power storage systems, provides a comprehensive analysis of its operation modes in market conditions.

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Математична модель локальної мережі з АЕС на малих модульних реакторах

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У цій статті досліджуються техніко-економічні процеси функціонування «Локальної електричної мережі» – регіональної електроенергетичної системи у складі АЕС на малих модульних реакторах, генераторах електричної енергії, які використовують відновлювані джерела енергії, а також акумуляторів електричної енергії. В управлінні такою системою застосовуються технології «Розумних мереж» . Стосовно електроенергетичної системи «Локальна електрична мережа» виступає як споживач або як виробник електричної енергії, залежно від кон'юнктури цін на оптовому ринку та власної спроможності щодо балансування обсягів виробництва-споживання електроенергії.

Ринок «Локальної електричної мережі» вважається досконалим, а оптовий ринок електроенергії характеризується недосконалою конкуренцією. Запропоновано математичну модель «Локальної електричної мережі». Наведена модель адекватно відтворює особливості взаємодії локального ринку з оптовим ринком. Математична модель сформована у вигляді задачі завантаження малих модульних реакторів та систем акумулювання електроенергії. В моделі відображено технологічні обмеження на режими завантаження малих модульних реакторів і блоків системи акумулювання енергії, які працюють у режимах прямого та зворотного перетворення енергії.

Зокрема, модель відображає маневрові режими та режими пуску-зупинки малих модульних реакторів та режими заряджання-розряджання блоків акумулювання електроенергії, які сукупно визначають гнучкість режимів функціонування всієї енергосистеми. Задача завантаження малих модульних реакторів АЕС, блоків системи акумулювання електроенергії, а також ліній електропередачі, що поєднують «Локальну електричну мережу» з енергосистемою, є задачею змішаного цілочисельного програмування з цільовою функцією системних витрат, які мінімізуються.

З метою зменшення розмірності задач математичного моделювання режимів завантаження «Локальної електричної мережі» в описах множин однотипних малих модульних реакторів, а також однотипних блоків акумулювання енергії використано кластерні цілочисельні функції. Модель «Локальної електричної мережі» забезпечує відтворення режимів її від'єднання від мережі системного оператора з метою підвищення ядерної безпеки в умовах стихійного лиха або воєнних дій. Наведено результати обчислювальних експериментів з моделювання режимів навантаження «Локальної електричної мережі».

В експериментах, описаних у статті, використані типові дані щодо обсягів споживання електроенергії та її виробництва з відновлюваних джерел енергії. Результати обчислювального експерименту підтверджують адекватність запропонованої математичної моделі «Локальної електричної мережі». Наведена модель придатна для використання як самостійно – для аналізу функціонування «Локальної електричної мережі», так і в комплексі з моделями електроенергетики – з метою визначення впливу «Локальних електричних мереж» на електроенергетичну систему.

Стаття підготовлена за результатами досліджень, які виконуються за цільовою програмою «Підтримка пріоритетних для держави наукових досліджень і науково-технічних (експериментальних) розробок Відділення фізико-технічних проблем енергетики НАН України на 2022 – 2023 рр.» з кодом програмної класифікації видатків 6541230 (прикладні дослідження).

Ключові слова: локальна мережа, малий модульний реактор, система акумулювання електроенергії, модель, задача завантаження потужності.

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