Improving the Efficiency of HPP and PSHPP Participation in the Electricity Market of Ukraine

Ihor Blinov, Dmytro Olefir, Euvgen Parus, and Olexander Kyrylenko

Abstract The main requirements for the volume of ancillary services in the IPS of Ukraine, in particular, the frequency containment reserve and frequency restoration reserves are considered. The influence of renewable energy sources (RESs) on the balance of production and consumption of electricity is shown. The place of hydroelectric power plants in the modern conditions of functioning of the IPS of Ukraine and the structure of the market of ancillary services is considered. It is shown that with the existing structure of production capacities in the IPS of Ukraine, in fact, only HPP and PSHPP units are able to balance the fast-changing load schedule of renewable energy sources due to their high maneuverability. Features of operation of HPP units in normal and emergency modes are provided. The plan of HPPs/PSHPPs operation in the electricity market is provided, which takes into account the indicators of the forecast balance of the IPS of Ukraine (monthly electricity production volumes of each HPP), water management constraints, current marks of the levels of HPP reservoirs, specific consumption of hydro resources, etc. Prospects for the development of ancillary services in the IPS of Ukraine are identified. According to the results of the operation feature analysis of the IPS of Ukraine, the need for updating the regulatory framework is set out, in particular as for updating the requirements for the minimum required reserves volumes to adjust frequency and active capacities in the IPS of Ukraine given the growing share of unregulated RESs in the production capacity structure. Certain measures are provided to increase the level of operational security of modes in the conditions of further development of RES and plans for synchronization of the IPS of Ukraine with ENTSO-E energy systems. Measures are provided to correct the situations related to the imbalance of HPP hydro modes. The model of optimal distribution of production capacities of the HPP cascade by

I. Blinov (✉) · E. Parus · O. Kyrylenko
Institute of Electrodynamics of the NAS of Ukraine, Kyiv, Ukraine
e-mail: blinovihor@gmail.com

D. Olefir
"Ukrhydroenergo" PJSC, Kyiv, Ukraine

I. Blinov
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kiev, Ukraine

O. Kyrylenko et al. (eds.), *Power Systems Research and Operation*, Studies in Systems, Decision and Control 220, https://doi.org/10.1007/978-3-031-17554-1_3

segments of the electricity market under the conditions of observance of the predetermined balance of hydro resources is provided. Using the provided model allows to maximize the economic effect of HPPs/PSHPPs operation in the electricity market.

Keywords Electricity market · Power system · Hydroelectric power station · Hydraulic power plant · Frequency containment reserves · Frequency restoration reserve · Ancillary services

1 Introduction

Since 2019, a liberalized electricity market has been operating in Ukraine [1, 2]. While the launch of organized segments of the electricity market [3–6] of Ukraine took place in July 2019, the start of the ancillary services market [7–9] was delayed due to the long-term procedure of certification of power plant units to provide certain types of ancillary services. Therefore, the first trading in this market segment took place in March 2020. At the same time, the Transmission System Operator (TSO) in Ukraine ("Ukrenergo" NPC) has repeatedly introduced technological constraints on both generation volumes (in particular, for renewable energy stations—RES) and in terms of electricity import/export. However, according to retrospective information published on the official website of "Ukrenergo" NPC, the share of trading in the balancing market not often exceeds 5%, which indicates a sufficiently high level of forecasting the balance of production and consumption of electricity. Therefore, the essence of the problems of balancing modes of the IPS of Ukraine is primarily in the mismatch of available resources of ancillary services with the actual needs of maintaining the operational security of modes of the IPS of Ukraine.

The Transmission System Code (hereinafter referred to as the TSC) [9] approved by the Regulator (the National Commission for State Regulation of Energy and Utilities—NCSREU) defines the volumes of frequency containment reserves, frequency restoration reserves and replacement reserves for different modes of operation of the integrated power system (IPS) of Ukraine, in particular, for isolated operation mode, synchronously with the ENTSO-E [10, 11] energy union or synchronously with the CIS and Baltic countries. The requirements of the TSC for defining the volume of frequency restoration reserves (for secondary regulation) were formed based on the normative document SOU-N E NEC 04.156:2009 "Basic Requirements for Frequency and Power Regulation in the IPS of Ukraine" (see Table 1), and did not take into account significant increase in the balance of capacity of the power system of Ukraine of the share of power plants operating on renewable energy sources (see Fig. 1). Thus, in accordance with the requirements of Chap. 8 of Sect. 5 of the TSC, the frequency containment reserve (FCR) should be ±1000 MW for the mode of operation of the IPS of Ukraine separated from other power systems. At the same time, the TSC assumes that in the isolated mode of operation of the power system of Ukraine, the value of 1000 MW may be the total volume of FCR and frequency restoration reserves (FRR). This requirement is due to the economic feasibility of

Table 1 Requirements for the volumes of reserves in accordance with SOU-N E NEC 04.156:2009

Type of reserve		Required volume of reserve, MW	
		IPS of Ukraine	"Burshtyn TPP Island"
Frequency containment reserve	Loading	119 ÷ 190*	8
	Unloading	119 ÷ 190*	8
Frequency restoration reserve	Loading	1000	200
	Unloading	500	100
Replacement reserve	Loading	1000	200
	Unloading	500	100

Note *—depends on the mode of operation of the IPS of Ukraine with neighboring energy associations

maintaining the FCR. Subject to synchronous work with the CIS and Baltic Energy Union or ENTSO-E, the volume of FCR is accordingly calculated and approved by the TSO. For the IPS of Ukraine, this volume may be about ±140–190 MW. Therefore, it is not feasible to keep larger volumes of FCR for the isolated mode. With regard to the requirements for the volume of FRR and replacement reserves (RR), the TSC regulates 1000 MW of reserves for loading and 500 MW for unloading.

Calculations carried out at the request of the Transmission System Operator in 2012 demonstrated that the volume of renewable generation should not exceed 2500–3000 MW. However, the capacity of RES power plants has increased almost 9 times within 3 years. Therefore, at the time of approval of the TSC, the volumes of frequency restoration reserves were no longer sufficient to meet the needs of the energy system of Ukraine.

According to the register of ancillary service units published on the official website of "Ukrenergo" NPC on September 22, 2021, 18 power plants may participate in auctions for purchasing ancillary services in the IPS of Ukraine [12]. These include eight HPPs, eight TPPs, one TPS and one NPP. As of September 22, 2021, the

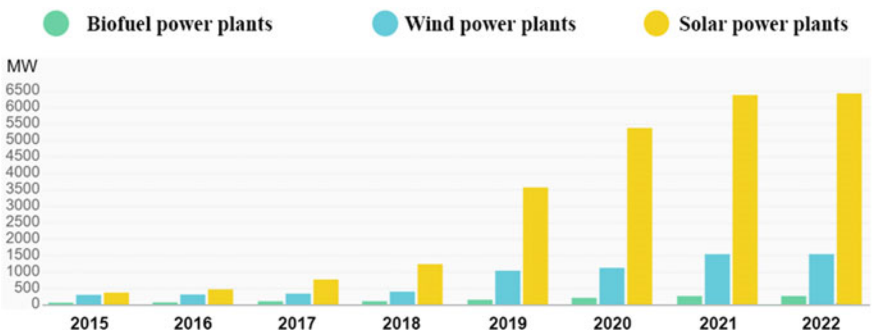

Fig. 1 The growth of RES in the IPS of Ukraine during 2015–2022

total volume of certified FCRs was ±270 MW, automatic FRRs (aFRRs) 1714 MW (±978 MW), manual FRRs (mFRRs) 4091 MW (−4040 MW) and RR 4840 MW.

These requirements do not take into account changes in the structure of production capacities of the IPS of Ukraine, especially the increase in the share of RES and their impact on imbalances in the IPS of Ukraine [13, 14].

2 Influence of RES on Electricity Production/Consumption Balances

In the period of 2018–2021, the determined capacity of solar plants (SPP) and wind plants (WPP) increased from 1100 to 8250 MW [15] (Fig. 1). Over the last three years, there has been a significant imbalance in the IPS of Ukraine due to the fast and uncontrolled commissioning of RES, especially SPP and WPP.

A significant increase in the determined capacity of RES results in an increase of fluctuations in unregulated electricity supply in the IPS of Ukraine [16–19]. Already in 2018, according to "Ukrenergo" NPC, the deviation of actual capacity values from the planned ones for solar and wind power plants was about 450 MW (Fig. 2).

Not sufficient attention was paid to the development and increase of quick-acting power reserves in the power system.

This is confirmed by the fact that the Report on Compliance Assessment (sufficiency) of the Generating Facilities to meet projected electricity demand and provide for the required reserve in 2020 [20] states that in order to increase electricity production by RES power plants without applying constraints by the dispatcher of "Ukrenergo" NPC (decreasing the load of RES power plants), the IPS of Ukraine should include at least 2 GW of highly maneuverable facilities. Thus, the TSC needs to be

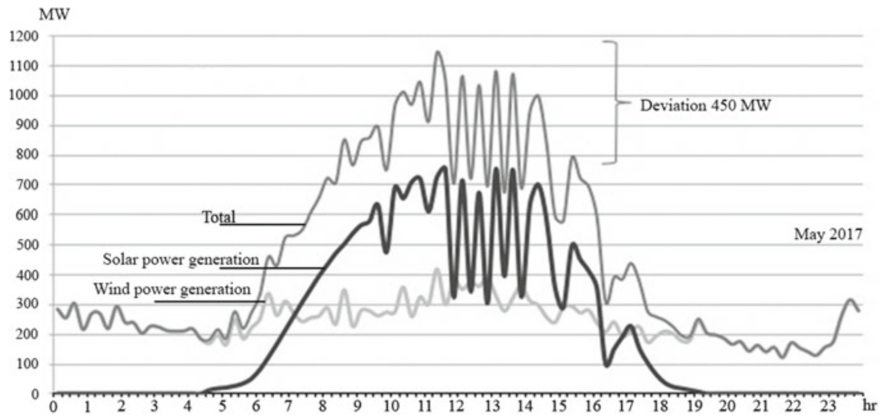

Fig. 2 Fluctuations in the volumes of generation from RES in 2017

Fig. 3 An example of the actual operation of the SPP

revised in terms of determining the minimum required reserve volumes for frequency and power regulation in the IPS of Ukraine.

An example of the actual operation of a solar power plant with a determined power of 18 MW in the period 1200 ÷ 1300 06/29/2021 is shown in Fig. 3. As seen from the diagram, the change in power within 2–3 min is almost 60% of the determined power of the SPP [21], the minimum load value of this SPP was 3 MW, and the maximum was 14.5 MW. Within 2–3 min, the change in power was 10.5 MW.

According to the retrospective information on daily schedules of electricity production/consumption in the IPS of Ukraine published by "Ukrenergo" NPC (see Fig. 4), in the period from 12:00 (pm) to 13:00 (pm) on 06/29/2021, the total RES capacity was 3149 MW, of which the dominant share in this hour of the day belongs to the SPPs themselves. Even taking into account the mutual compensation of power fluctuations of individual SPPs in different parts of the IPS of Ukraine, the change in RES power in adjacent intervals of real-time units can reach 1000 MW. Appropriate in-depth studies are needed to more accurately estimate RES generation fluctuations in the IPS of Ukraine.

It should be noted that fluctuations in RES power occur at intervals of several minutes. Thus, the problem of compensation for fluctuations is solved by the services of the FRR, which leads to a corresponding increase in the requirements for the FRR volumes.

It should also be noted that the requirements of the TSC on the volumes of frequency containment reserves (for primary regulation) are not adequate for different modes of operation of the IPS of Ukraine. Thus, the TSC states that "the value of the required total normalized primary reserve for the regulation area of the IPS of Ukraine for operation as part of ENTSO-E is ±3000 MW, and for operation as part of the energy union of the CIS, Baltic countries and Georgia is ±1200 MW." In fact, such volumes of frequency containment reserves should be provided for in total by all energy systems that are part of the respective energy union.

Analysis of the requirements of the Report on Compliance Assessment (sufficiency) of the Generating Facilities to cover the projected demand for electricity and provide for the required reserve in 2020 shows that:

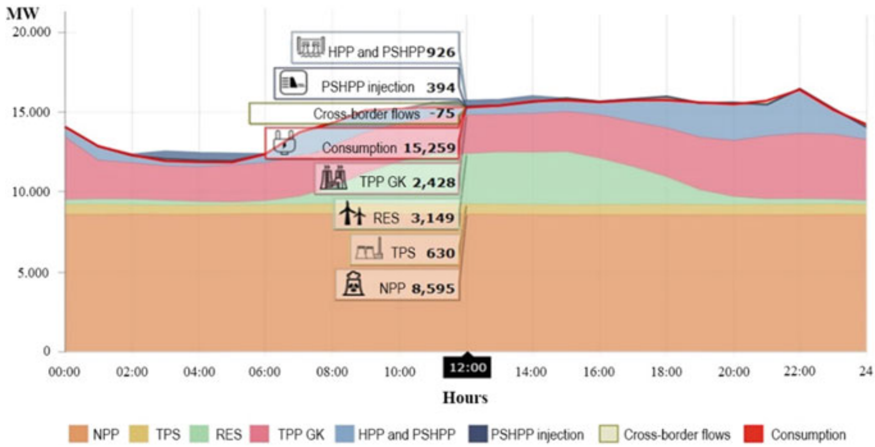

Fig. 4 Production of electricity by power plants of Ukraine on June 29, 2021

- "to maximize the production of electricity by power plants using RES by minimizing their involvement in the provision of services to reduce the load, high-maneuvering facilities should be at least 2 GW";
- "without the involvement of RES in the regulation or forced constraint of NPP capacities, the need for electricity storage systems may increase to 2 GW."

The above data suggest that the requirements of the TSC in terms of determining the volumes of frequency containment and restoration reserves should be adjusted, especially taking into account the planned synchronization of the IPS of Ukraine with the energy union ENTSO-E.

3 The Importance of Hydropower Plants in the Structure of Ancillary Services

The actual volumes of power reserves certified by the Transmission System Operator located at TPP, NPP power units, and HPP units are listed in Table 2. Lack of auctions for replacement reserves in the presence of significant delays in paying balancing services in the balancing market can result in disruptions in the operation of TPPs, especially in the conditions of global crisis in the coal market.

The data in Table 2 may indicate that the IPS of Ukraine has sufficient power reserves.

Another important issue that needs careful study is the allocation of power reserves at different types of power plants.

Some experts argue that HPPs and PSHPPs should be involved in providing ancillary services to provide for frequency containment reserves [22, 23]. However, dependence on hydro resources, change of available power depending on pressure,

Table 2 Actual power reserves in the IPS of Ukraine

PSE	Type and volume of reserve (MW)			
	Frequency containment reserve (FMR)	Automatic frequency restoration reserve (aFRR)	Manual frequency restoration reserve (mFRR)	Replacement reserve (RR)
"Ukrhydroenergo" PJSC	0	1219 (±608)	3193	3340
"DTEK SKHIDENERGO" LLC	±130	250 (±125)	250	420
"Kharkiv TPS-5" PJSC	±27	180 (±90)	90	180
"DTEK DNIPROENERGO" JSC	±63	310 (±155)	307	551
"DTEK ZACHIDENERGO" JSC	±10	0	251	349
"Energoatom" NNPC SE	±40	0	0	0
"Burshtyn TPP" Island	±20	290	290	450
Total on the IPS of Ukraine	±270	1956 (±978)	4091 (−4040)	4840

presence of inertia of directing devices, etc. do not allow to ensure compliance with the requirements of the TSC for frequency containment reserves by HPP and PSHPP units. It is feasible to use HPP and PSHPP units for secondary and tertiary regulation (for frequency restoration reserves and replacement reserves, accordingly).

NPPs operate in the around-the-clock mode, so it is feasible to involve NPP units in the provision of frequency containment reserves. In fact, after the completion of the certification of NPP power units, their reserves will be sufficient to cover the required volumes of FCR in the IPS of Ukraine.

As for TPPs and TRSs, it is feasible to involve them in providing all types of reserves. At the same time, it is feasible to provide frequency containment reserves only by means of those power units that will operate in the around-the-clock mode. TPS power units will be able to provide ancillary services for frequency and power regulation only during the autumn-winter period (in the heating period), as their operation on gas is very expensive [24–26].

Regarding the participation of energy storage systems (except for PSHPPs), their participation in tertiary regulation is infeasible due to technical constraints and high cost of such systems [27–30] (Table 3).

As NPPs cover the base load and RES power plants do not have balancing mechanisms, the main load to maintain the balance between electricity production and

Table 3 The feasibility of placing power reserves on different types of generation

Type of power plant	Frequency containment reserve (FCR)	Automatic frequency restoration reserve (aFRR)	Manual frequency restoration reserve (mFRR)	Replacement reserve (RR)
NPP	YES	NO	NO	NO
TPP	YES	YES	YES	YES
TPS	YES	YES	YES	YES
HPP	NO	YES	YES	NO
PSHPP	NO	YES	YES	YES
Other CHEs	YES	YES	YES	NO

consumption in the event of sudden changes in RES capacity rests with TPPs and HPPs (PSHPPs). It should be noted that the change in load on TPP units is carried out at a rate of 3–5 MW per minute and to compensate for fluctuations in RES power and to reliably compensate for fluctuations in RES capacity in the IPS of Ukraine must hold up to 3000 MW of FCR capacities, which is currently physically impossible. The problem of significant shortage of FCR in the IPS of Ukraine is currently solved mainly by significant volumes of FCR service, which is provided primarily by HPPs and PSHPPs. Therefore, with the existing structure of production facilities in the IPS of Ukraine, only HPP and PSHPP units are able to balance the fast-changing schedule of SPP loads due to their high maneuverability (change of power at HPP and PSHPP units lasts from several tens of seconds to several minutes).

In recent decades, the company has been carrying out large-scale modernization and reconstruction of existing equipment at HPPs and PSHPPs, as well as building new facilities, in particular, at the Dniester PSHPP.

The main tasks of the company include:

- at the request of the Integrated Power System of Ukraine, providing for coverage of peak loads, providing mobile reserves for frequency regulation and power balancing in the power system;
- maintaining optimal hydrological modes of water reservoirs in order to provide water to all water users (urban water supply, recreation, flood passages, water saving in summer time, sanitary water passages, etc.).

The availability of mobile power reserves allows "Ukrhydroenergo" PJSC to take an active part in the balancing market and the market of ancillary services.

As of January 1, 2021, the company has certified units of Kyiv, Kaniv, Kremenchuk, Middle Dnipro, Dnipro and Kakhovka HPPs. The number of certified units and regulating ranges for each HPP are provided in Table 4.

Units of HPPs and PSHPPs provide participation in automatic and manual secondary regulation of frequency and power and, with sufficient hydro resources present, in tertiary regulation.

Table 4 Certified HPP equipment of "Ukrhydroenergo" PJSC

Series No.	SE provision unit	Pmax, Pmin of the certified GUs	MW	Number of the certified GUs	Total number of GUs
1	Kyiv HPP	Pmax	336	16	20
		Pmin	160		
		Regulating range	176		
2	Kaniv HPP	Pmax	264	12	24
		Pmin	120		
		Regulating range	144		
3	Kremenchuk HPP	Pmax	234	4	12
		Pmin	92		
		Regulating range	142		
4	Middle Dnipro HPP	Pmax	300	6	8
		Pmin	135		
		Regulating range	165		
5	Dnipro HPP1	Pmax	495	7	10
		Pmin	390		
		Regulating range	105		
6	Dnipro HPP2	Pmax	479	4	8
		Pmin	280		
		Regulating range	199		
7	Kakhovka HPP	Pmax	312	6	6
		Pmin	120		
		Regulating range	192		

The difficulty of planning the operation of HPPs and PSHPPs in the balancing market and ancillary services [7, 31] market is that HPP water reservoirs are cascaded on rivers (see Fig. 5), and their hydro modes depend on weather conditions, rainfall, accuracy of water resources forecasting, a certain water reservoir functioning, water management constraints (water reservoirs marks, sanitary and ecological water passages, flood passages, etc.). The operation of each water reservoir depends on the condition of other reservoirs.

A peculiarity of HPPs operation is the fact that each of them has different types of hydraulic units (horizontal capsule, rotary blade, radial axial ones, etc.) with different determined power, different restricted areas, and as a result, different specific water consumption and different power ranges for regulation (see Tables 5 and 6).

Table 5 shows that the specific water consumption at the Kyiv HPP is 3.3 times higher than at Dnipro HPP. At the same time, the data in Table 6 shows that during the operation of four units at Kyiv HPP and Dnipro HPP-1, their determined capacities differ by 3.5 times, and power ranges for automatic control differ by 2 times.

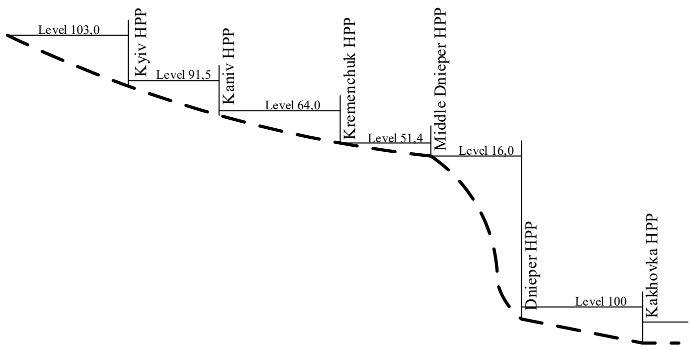

Fig. 5 Cascade of water reservoirs on the Dnipro River

Table 5 Hydropower indicators of hydropower plants

Power plant	Daily water consumption plan, m^3/s	Specific water consumption m^3/kW*h	HPP energy, plan per day, MW*h
Kyiv HPP	250	38.4	563
Kaniv HPP	320	38.0	728
Kremenchuk HPP	335	26.2	1105
Middle Dnipro HPP	405	32.4	1080
Dnipro HPP1	400	11.6	439
Dnipro HPP2		11.5	2562
Kakhovka HPP	500	26.2	1649
Dniester HPP	110	8.7	1092

Table 6 Regulating ranges of individual HPP units

Name of HPP	GU power, MW	Number of GU	Total power, MW	Regulating range, MW
Kyiv	22	4	88	$12 \cdot 4 = 48$
Dnipro	72	4	288	$24 \cdot 4 = 96$

This means that when planning the operation of HPP units in different segments of the ancillary services market, it is necessary to take into account a significant amount of output data: current water reservoir bief marks, sanitary water passage volumes, unit specific costs, determined powers and regulation ranges, etc.

4 Planning of HPP/PSHPP Operation in the Electricity Market

Planning of work in the electricity market consists of several steps. On the first step, the indicators of the forecast balance of the IPS of Ukraine (monthly volumes of electricity production by each HPP), water management constraints, current level marks of HPP waters reservoirs, specific costs of hydro resources, etc. are taken into account.

Based on this data, in the month preceding the month of delivery, volumes are planned for the sale of electricity on the market of bilateral agreements (usually these volumes include water volumes of HPPs which operate in the around-the-clock mode), and contracted volumes are included in the daily schedule of electricity production of each HPP. Based on monthly volumes of water discharges and volumes of electricity production, daily volumes of water discharges and volumes of electricity production are formed.

The planned volumes of water discharges through HPP turbines and daily volumes of electricity production at HPPs determine the volumes of electricity for trading on the day ahead market (DAM) and intraday market (IDM) [32, 33], volumes for trade of ancillary services (reserves for frequency and power regulation) on the auction platform, and, as a consequence, forming the daily schedule of loads of HPPs and PSHPPs.

However, the actual operation of HPPs and PSHPPs in the electricity market may differ significantly from the planned operation due to electricity production in the balancing market according to the commands by a dispatcher of "Ukrenergo" and the automatic testing of commands by the central regulator of the System of Automatic Regulation of Frequency and Power (SARFP) in the IPS of Ukraine.

Simplified activities of "Ukrhydroenergo" PJSC in the electricity market is shown in Fig. 6.

Under normal operating conditions of the IPS of Ukraine, the actual daily volumes of electricity production are equal to the planned ones, and, accordingly, the actual daily water discharges are equal to the planned ones. At the same time, there may be a slight imbalance of the hydro modes of HPPs water reservoirs due to testing the commands by the central regulator in the IPS of Ukraine and executing the commands by the dispatcher "on operational safety" when the actual daily volumes of water discharges by the company are equal to the planned ones, and there is an unintentional redistribution of volumes of hydro resources between different water reservoirs of HPPs.

In case of an emergency situation in the IPS of Ukraine due to a power imbalance (both toward shortage and toward surplus), the actual daily electricity production volumes differ significantly from the planned ones, and, accordingly, the actual daily water discharges differ significantly from the planned ones. Under such conditions, there is a significant imbalance in the hydro modes of HPPs water reservoirs, which can lead to violations of water management constraints (bief level marks, mandatory discharges of water, etc.).

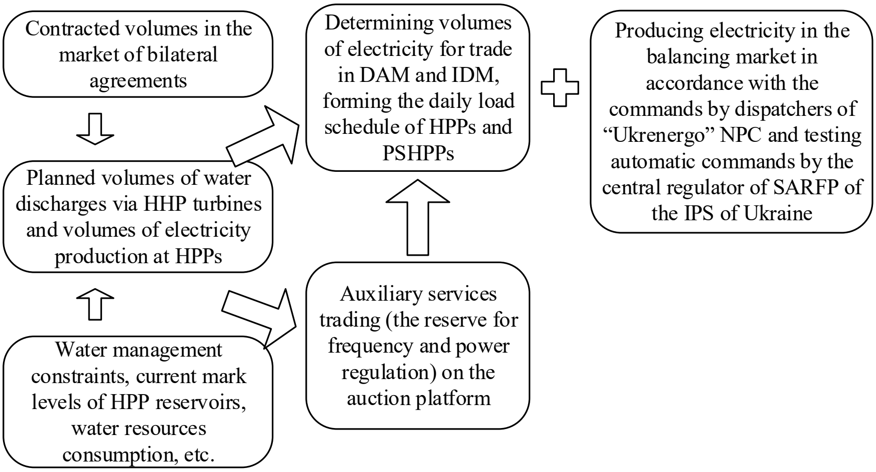

Fig. 6 Simplified block diagram of activities of "Ukrhydroenergo" PJSC in the electricity market

Especially negative emergency situations in the IPS of Ukraine are noted in the periods of floods or other limited periods.

For example, in the first decade of December 2020 (Fig. 7), because of a power shortage associated with the emergency shutdown of a number of thermal and nuclear power units, there was a significant unplanned initiation of HPP resources, which resulted in violations of the upper bief marks of HPP water reservoirs established by the Interdepartmental Commission on coordinating modes of operation of the Dnipro and Dniester water reservoirs. Thus, starting from December 11, 2021, at Kyiv and Kremenchuk HPPs, the lower set limits have been violated, while at Kaniv and Kakhovka HPPs, the upper set limits have been violated, i.e., there was an imbalance of the agreed mode of operation of the water reservoirs cascade.

Prior to the start of operation of the liberalized model of the electricity market in Ukraine in the spring, HPPs usually operated in a basic mode in order to prevent overflow of water reservoirs, further boost water discharges and prevent "idle" water discharges. However, in May 2021, a different situation was observed. During the flood occurring on the Dnipro River, there was a gradual filling of water reservoirs. The significant increase in electricity production by RES power plants in the spring of 2021 necessitated the unloading of HHPs to zero based on the commands by a dispatcher of "Ukrenergo" NPC. In order to prevent damaging to hydraulic engineering structures, hydromechanical equipment of the dam, to reduce the forcing of water reservoirs and other negative consequences, 47 emergency applications were submitted to "Ukrenergo" NPC in April–May 2021 (11 applications in April and 36 applications in May). Table 7 shows the data on the violation of water management constraints by HPPs water reservoirs in May 2021.

In August 2021, the opposite situation was observed, when in the low-water period there was an unplanned initiation of hydro resources at the HPPs. Table 8 includes

Table 7 Violation of water management constraints at HPPs water reservoirs

Number of the day of the month name of HPP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Kyiv HPP	102	102	102	103	103	102	102	102	102	102	102	102	102	102	102
Kaniv HPP	91	91	91	91	91	91	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**
Kremenchuk HPP	80	80	80	80	80	80	80	81	81	81	81	81	81	81	81
Middle Dnipro HPP	63	63	**63**	**63**	**63**	**63**	63	63	63	63	63	63	63	64	64
Dnipro HPP1, HPP2	51	51	51	51	51	51	51	51	51	51	51	51	51	51	51
Kakhovka HPP	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Dniester HPP	119	119	119	119	119	119	119	119	119	119	119	119	119	119	119
Number of the day of the month name of HPP	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Kyiv HPP	103	103	103	103	103	103	103	103	103	103	103	102	**103**	**103**	**103**
Kaniv HPP	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	**91**	91	91
Kremenchuk HPP	81	81	81	81	81	81	81	81	81	81	81	81	81	81	**81**
Middle Dnipro HPP	64	64	63	**63**	**64**	**64**	64	63	63	63	63	63	**63**	64	64
Dnipro HPP1, HPP2	51	51	51	51	**51**	**51**	51	51	**51**	51	51	51	51	51	51
Kakhovka HPP	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Dniester HPP	119	119	119	119	119	119	119	119	119	119	119	119	119	119	119

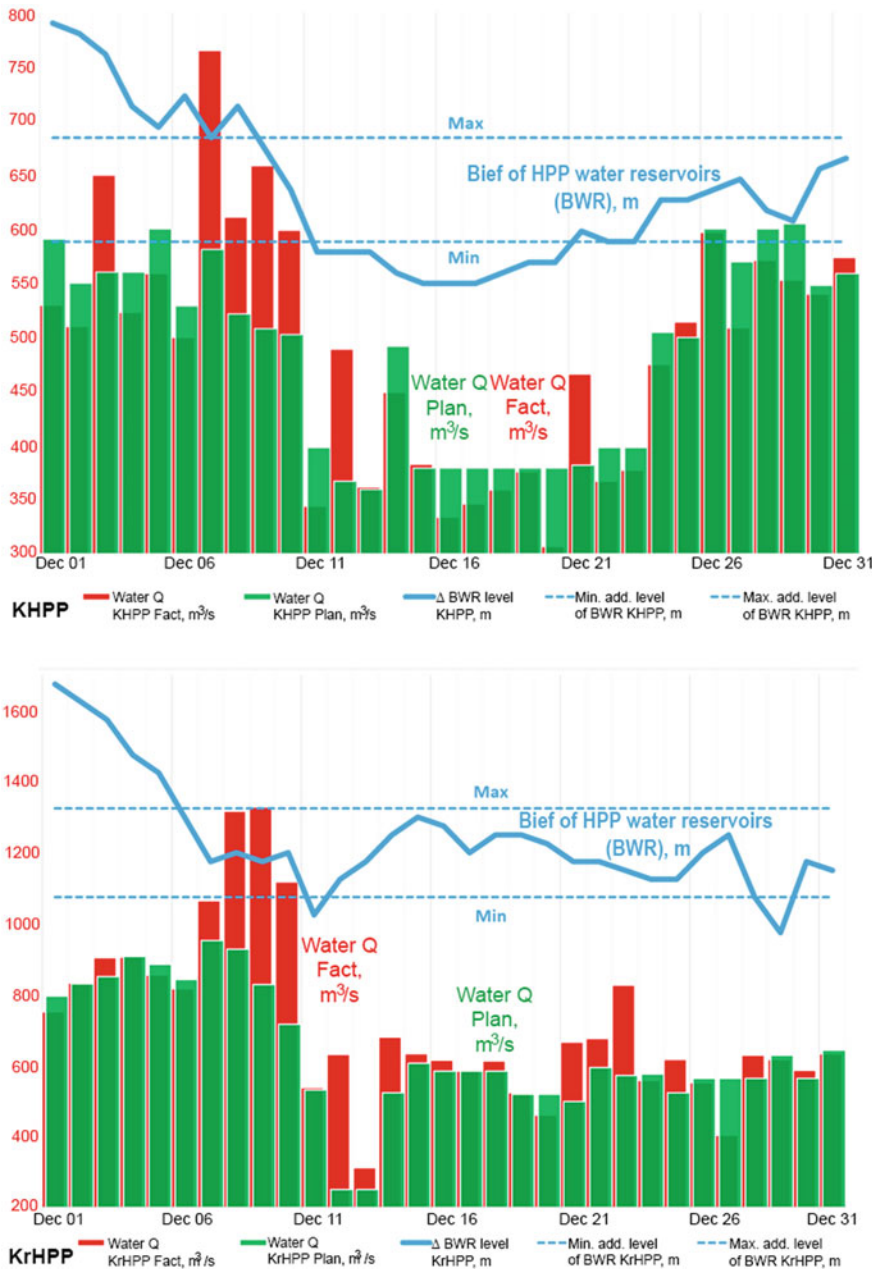

Fig. 7 Violation of hydro modes of HPP water reservoirs in December 2020

the data which shows that, for example, on August 2, the planned discharges of water through the Kremenchuk hydro unit should have been equal to 470 m^3/s.

According to the results of bidding in all segments of the electricity market, the planned water discharges had to be 486 m^3/s. However, according to the results of work on the balancing market, the actual discharges of water through the Kremenchuk HPP amounted to 1098 m^3/s, which was 2.37 times higher than planned.

Table 8 Operation of hydro resources in August 2021

Date	Power plant	Updated plan D-1 (hydro resource), m^3/s	Trading schedule (sales of PSO, BC, DAM, IDM), m^3/s	The fact of el. production, m^3/s
08/02/2021	Kyiv HPP	300	300	398
08/02/2021	Kaniv HPP	350	348	461
08/02/2021	Kremenchuk HPP	470	486	1098
08/02/2021	Middle Dnipro HPP	417	408	973
08/02/2021	Dnipro HPP	400	409	965
08/02/2021	Kakhovka HPP	500	476	894
08/02/2021	Dniester HPP	125	125	230
08/02/2021	Total:	2562	2552	5019
08/03/2021	Kyiv HPP	300	241	364
08/03/2021	Kaniv HPP	400	310	454
08/03/2021	Kremenchuk HPP	500	562	913
08/03/2021	Middle Dnipro HPP	408	470	830
08/03/2021	Dnipro HPP	400	462	806
08/03/2021	Kakhovka HPP	500	318	643
08/03/2021	Dniester HPP	120	110	182
08/03/2021	Total:	2628	2473	4192
08/04/2021	Kyiv HPP	300	265	340
08/04/2021	Kaniv HPP	400	334	437
08/04/2021	Kremenchuk HPP	500	535	989
08/04/2021	Middle Dnipro HPP	408	443	810
08/04/2021	Dnipro HPP	400	435	864
08/04/2021	Kakhovka HPP	500	410	696
08/04/2021	Dniester HPP	120	120	204
08/04/2021	Total	2628	2542	340

In order to correct the situations related to the imbalance of HPPs hydro modes, specialists are currently taking the following measures:

- decreasing/increasing in sales of aFFR and mFFR at auctions (decreasing/increasing in the number of units involved in automatic and manual secondary regulation), or redistributing reserves volumes between HPPs;
- changing in sales volume of the reserve type: symmetric, asymmetric (for loading/unloading) depending on the need to fill or initiate the water reservoir;
- certifying additional power reserves in the volume of 525 MW (including at PSHPPs), as well as implementing the project to introduce hybrid systems for electricity production with a total volume of 250 MW;
- diversifying sales at the expense of other segments of the electricity market: selling electricity at bilateral contracts market (BCM), DAM or IDM.
- improving the accuracy of forecasting hydro resources (by building mathematical models, timely receipt of forecasts of hydrometeorological conditions and actual bief marks of water reservoirs, analysis of the IPS of Ukraine and the electricity market operations, etc.). In the future, it is planned to introduce an automated system, Water Management System;
- putting constraints on the operation of HPPs and PSHPPs in case of violation of water management constraints or technological capacities of PSHPPs.

5 Modeling of HPP/PSHPP Operation in the Electricity Market

The main goal of the HPP cascade functioning is to maximize the profit from the sale of electricity and services in market segments:

$$\sum_i (Prof_i - Cost_i) \to \max,$$

where $Prof_i$ is profit from the sale of electricity or services in the i-th market segment; $Cost_i$ is costs related to the production of electricity or provision of related services.

The main activities of "Ukrhydroenergo" in market segments are shown in Table 9.

Detailed balance of production capacities in the target function for a separate calculation period of time, *h*:

$$\sum C_h^{XX} \cdot V_h^{HPP(XX)} \to \max,$$

where XX is a segment of the electricity market of Ukraine from the list given in Table 9, under the contracts, in which the corresponding volumes of generation $V_h^{HPP(XX)}$ are allocated at the price, C_h^{XX}, formed in the segment.

The target function is complemented by a system of equality and inequality constraints, which determine the technical and economic characteristics [34], as

Table 9 Activities of "Ukrhydroenergo" PJSC in market segments

BCM	Sale of mandatory volumes of electricity under PSO
	Commercial sale of electricity
DAM	Commercial sale of electricity
IDM	Buying/selling electricity to reduce imbalances
	Commercial sale of electricity
BM	Sale of services of loading/unloading of power units
ASM	Reservation of capacities for the provision of ancillary services
	Actual provision of ancillary services

well as the equation of the balance of hydro resources consumption, from water consumption for a single generator to water flow for the entire HPP cascade. The structure of the mathematical model of optimization of hydro resources of the HPP cascade is shown in Fig. 8. Consider components of the mathematical model shown in more detail in Fig. 8.

Models of market segments are used to derive the values of prices of electricity or services, C_h^{XX}, in certain market segments, *XX*. In most simulation problems, it is permissible to assume without compromising the accuracy of calculations that there is no impact of the volumes of electricity proposed by the HPP cascade on the prices in the relevant market segments. In this case, it is possible to use retrospective data on prices and tariffs in the electricity market for calculations. If necessary, the impact of the supply volumes of electricity or services on market prices shall be modeled by relative means of simulating pricing processes in the relevant market segments.

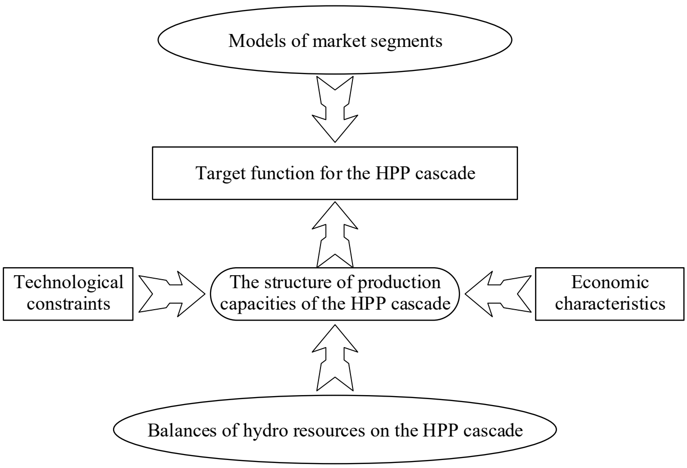

Fig. 8 The structure of the model of optimal resource allocation of the HPP cascade

The system of technological constraints determines the possibilities of actual operation of individual hydro generators and power plants in terms of electricity generation for the calculation period. Thus, for an individual hydrogenerator, the constraint of the minimum and maximum load levels at any time, t, shall be determined:

$$P_{\min}^{HG} \le P_t^{HG} \le P_{\max}^{HG},$$

where $P_{\min}^{HG}$, $P_{\max}^{HG}$ is, accordingly, the minimum and maximum levels of the hydrogenerator loading.

The above constraint applies only to the technological characteristics of the hydrogenerator and does not depend on the time of day or the peculiarities of the modes of Ukrainian power systems.

For a power plant, the technological constraint of the maximum load level, P_h^{HPP}, for a particular calculation period, h, shall be determined as follows:

$$P_h^{HPP} \le P_{\max,h}^{HPP},$$

where $P_{\max,h}^{HPP}$ is a maximum allowable level of the HPP loading during the calculation period, h.

In the general case, the technological maximum of the HPP loading shall be calculated as the sum of technological maxima available for operation during the calculation period, h, of hydrogenerators:

$$P_{\max,h}^{HPP} = \sum_i P_{\max}^{HG(i)},$$

where $P_{\max}^{HG(i)}$ is a technological maximum of the i-th hydrogenerator available for operation.

The value of the maximum level of the HPP loading for the calculation period, h, may be further limited by the maximum level of electricity supply, $P_{\max,h}^{EM}$, given the mode constraints of the power systems of Ukraine:

$$P_{\max,h}^{HPP} \le P_{\max,h}^{EM}.$$

The most important component of the model of optimal participation of the HPP cascade in the electricity market is the system of equations of the hydro resources balance. The system of equations of the hydro resources balance connects technical and economic characteristics of technological equipment at levels from an individual hydrogenerator to the HPP cascade.

The volume of electrical energy for the calculation period, h, for the i-th hydrogenerator is provided for by water consumption in accordance with technical characteristics of the respective generator:

$$V_{h,i}^{HG} = \frac{\Psi_{h,i}^{HG}}{\Upsilon_{h,i}^{HG}}(MW \cdot h),$$

where $\Psi_{h,i}^{HG}$ is a given water inflow for the HPP (m^3) for the calculation period, *t*; $\Upsilon_{h,i}^{HG}$ is technological water consumption for the production of electricity for the *i*-th hydrogenerator ($m^3/(MW \cdot h)$).

The planned balance of water consumption for the *i*-th hydrogenerator for the calculation period, *h*, shall be defined in the following way.

The planned water balance in the target function for the calculation period, *h*, for one hydrogenerator is as follows:

$$\Psi_{h,i}^{HG} = \sum_i V_{h,i}^{(XX)} \cdot \Upsilon_{h,i}^{HG},$$

where $V_{h,i}^{(XX)}$ is volumes of electricity produced by the *i*-th hydrogenerator for the calculation period, *h*, which are put up for auction in the market segment, *XX*, in accordance with the list provided in Table 9.

The volumes, $V_{h,i}^{(XX)}$, presented in the market segments, *XX*, are free variables of the optimization problem, which shall be taken into account directly in the target function.

At the level of the *j*-th HPP, the water balance shall take into account the total water consumption of all involved hydrogenerators:

$$\Psi_{h,j}^{HPP} = \sum_i \Psi_{h,i}^{HG}$$

The water balance at the level of the *j*-th HPP shall be formed based on the overall balance of the "HPP—water reservoir" system:

$$\begin{cases} \Psi_{\min,j}^{WR} \le \Psi_{h,j}^{WR} + \Psi_{h,j}^{WI} + \Delta\Psi_{h,j}^{WRF} - \Psi_{h,j}^{HPP} \le \Psi_{\max,j}^{WR} \\ \Psi_{h,j}^{san} \le \Psi_{h,j}^{HPP} \end{cases},$$

where $\Psi_{h,j}^{WI}$ is given water inflow for the *j*-th HPP (m^3) for the calculation period, *h*; $\Psi_{h,j}^{WR}$ is the initial water volume in the water reservoir of the *j*-th HPP (m^3) for the calculation period, *h*; $\Psi_{\min,j}^{WR}$ is the minimum allowable volume of filling of the water reservoir of the *j*-th HPP (m^3); $\Psi_{\max,j}^{WR}$ is the maximum allowable volume of filling of the water reservoir of the *j*-th HPP (m^3); $\Psi_{h,j}^{san}$ is sanitary water runoff for the calculation period, *h*, for the *j*-th HPP (m^3); $\Psi_{h,j}^{HPP}$ is estimated water consumption for the *j*-th HPP (m^3) for the period, *h*; $\Delta\Psi_{h,j}^{WRF}$ is the volume of increase/decrease of the water reservoir filling level for the *j*-th HPP (m^3) planned for the end of the calculation period, *h*.

Optimization of the operation of an individual HPP for the calculation period, h, shall be performed in compliance with the volume of filling of the water reservoir for the j-th HPP planned at the end of the calculation period. However, HPPs actively provide significant volumes of ancillary services. At the same time, the volumes of actual activation of services may differ significantly from those previously reserved. As a result of the discrepancy between the planned and actually provided volumes of ancillary services, as well as due to the active participation of HPPs in the Balancing Market segment, the difference between the planned and actual volumes of filling of the HPP water reservoir increases over time. As a result, there is a need to solve an additional problem of optimizing the operation of the HPP cascade in terms of compensating for the difference between the planned and actual volumes of filling of the water reservoir, which arose when providing the services on operational security support of Ukrainian power systems. Then the formulation of the optimization problem shall be carried out by determining the corrective volume of changes in the filling of the water reservoir, $\Delta\Psi_{h,j}^{WRF}$:

$$\Psi_{h,j}^{WR} - \Psi_{h,j}^{HPP} = \Delta\Psi_{h,j}^{WRF}.$$

In the considered problem for i generators of the j-th HPP, the planned water balance of water consumption in the target function for the calculation period, h, shall be defined as:

$$\Psi_{h,j}^{HPP} = \Delta\Psi_{h,j}^{WRF} + \sum_{i} V_{h,i}^{(XX)} \cdot \Upsilon_{h,i}^{HG}.$$

The water balance at the level of the HPP cascade reflects a sequential chain, the nodes of which are "water reservoir + HPP" systems. For each node of the "water reservoir + HPP" system, intermediate water extraction for the economic needs of the surrounding areas and additional inflow of water from smaller rivers are additionally taken into account, as shown in Fig. 9.

The system of water balance equations for the cascade with J HPP for the calculation period, h, has the following form:

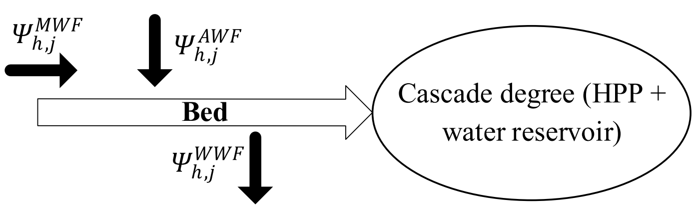

Fig. 9 Water balance of an individual stage of the HPP cascade

$$\begin{cases} \Psi_{h,j}^{WF} = \Psi_{h,j}^{MWF} + \Psi_{h,j}^{AWF} - \Psi_{h,j}^{WWF} \forall j \in J \\ \Psi_{h,j}^{MWF} = \begin{cases} 0 : j = 1 \\ \Psi_{h,j-1}^{HPP} : \forall j > 1 \end{cases} \end{cases},$$

where $\Psi_{h,j}^{MWF}$ is the main water flow for the *j*-th HPP (m^3) set for the calculation period, *h*; $\Psi_{h,j}^{AWF}$ is the additional water flow for the *j*-th HPP (m^3) set for the calculation period, *h*; $\Psi_{h,j}^{WWF}$ is intermediate withdrawal of water flow for the *j*-th HPP (m^3) set for the calculation period, *h*; $\Delta\Psi_{h,j}^{WRF}$ is the volume of increase/decrease of the water reservoir filling level for the *j*-th HPP (m^3) planned for the end of the calculation period, *h*.

The system of water balance equations for the HPP cascade is formed based on the following principle. The volume of water flow along the riverbed for the *j*-th HPP shall be made equal to the water consumption of the HPP of the previous $j-1$ degree: $\Psi_{h,j}^{MWF} = \Psi_{h,j-1}^{HPP}$. According to this concept, the volume of water flow along the riverbed for HPPs of the initial (zero) degree in the cascade shall be made equal to zero: $\Psi_{h,0}^{MWF} = 0$.

The main tasks solved using the written model include:

- planning of economic operation of the HPP cascade in compliance with the projected balance of hydro resources for the calculation period of time (day, week, decade, month, etc.);
- adjusting economic operation of the HPP cascade to eliminate water balance deviations from the planned indicators.

The main reasons for the water balance deviations from the planned indicators include:

- inaccuracy of the forecast of water flows along the main and additional beds;
- inaccuracy of forecasts of water use by settlements and commercial enterprises;
- discrepancy between the reserved and actually activated volumes of ancillary services (inaccuracy of the forecast of the use of operational security resources of the IPS of Ukraine);
- inaccuracy of the forecast of volumes of demand for resources of balancing of electricity in the Balancing Market.

In addition, the deviations of the actual results of economic operation of the HPP cascade due to the inaccuracy of the forecast of prices and tariffs in the segments of the electricity market of Ukraine should be taken into account.

Thus, the adequacy of the calculations performed using the model described is determined primarily by the adequacy of the solution of the relevant forecasting problems. Accordingly, improving the accuracy of planning the economic operation of the HPP cascade is achieved primarily by improving the quality of forecasting the above factors.

6 Conclusions

According to the results of the analysis of the IPS of Ukraine, the need is determined for updating the Transmission System Code in terms of updating the requirements for the minimum required reserves volumes to regulate the frequency and active power in the IPS of Ukraine given the increasing share of unregulated RESs in the production capacities structure, which results in the need to increase the resources volumes of the modes regulation. It is noted that HPPs and PSHPPs actually dominate in the segment of ancillary services of Ukraine, as the only source of highly maneuverable (peak) capacities in the IPS of Ukraine and, in particular, PSHPPs provide for smoothing of electricity consumption schedule, and, recently, compensation for electricity supply by RESs. Reconstruction of existing HPP and PSHPP facilities and construction of new ones is a necessary condition for maintaining the operational safety of the modes, as well as increasing the opportunities for synchronization of the IPS of Ukraine with the ENTSO-E energy union. Given the uncontrolled volumes of water resources of rivers, it is also feasible to introduce additional resources to regulate the modes for increasing the reliability of functioning of the IPS of Ukraine. Said measures will help increase the level of operational security of the modes in the conditions of further development of RESs and plans for synchronization of the IPS of Ukraine with ENTSO-E.

A model of optimal distribution of production capacities of the HPP cascade is provided. The model is designed to solve problems of planning and adjusting the balance of hydro resources in water reservoirs along the riverbed. The condition of adjusting the balance of the hydro resources in the water reservoirs allows to determine the volume of production capacities required for the implementation of this balance for each HPP. The calculated volumes of production capacities are distributed among the segments of the electricity market in order to maximize the profit obtained from the sale of electricity and/or services of regulation of the modes of the IPS of Ukraine. The use of the provided model allows to maximize the economic effect of the HPP cascade operation with the containment within the allowable levels of filling of the water reservoirs.

References

1. On Electricity Market: The Law of Ukraine. No. 2019-VIII of 13.04.2017
2. NEURC's Resolution "On Approval of Market Rules" No. 307 dd 14.03.2018
3. NEURC's Resolution "On Approval of Day Ahead Market and Intraday market" No. 308 dd 14.03.2018
4. Blinov, I.V., Parus, Y.V.: Congestion management and minimization of price difference between coupled electricity markets. Tekhnichna elektrodynamika **4**, 81–88 (2015)
5. Blinov, I., Kyrylenko, O., Parus, E., Rybina, O.: Decentralized market coupling with taking account power systems transmission network constraints. In: Power Systems Research and Operation. Studies in Systems, Decision and Control, vol. 388. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-82926-1_1

6. Kyrylenko, O.V., Blinov, I.V., Parus, Y.V., Ivanov, H.A.: Simulation model of day ahead market with implicit consideration of power systems network constraints. Tekhnichna elektrodynamika (5), 60–67 (2019). https://doi.org/10.15407/techned2019.05.060
7. Kyrylenko, O.V., Blinov, I.V., Parus, Y.V.: Operation evaluation of power plants in the provision of ancillary services of primary and secondary frequency control in the Ukrainian power system. Tekhnichna elektrodynamika **5**, 55–60 (2013)
8. Blinov, I.V., Parus, Y.V., Ivanov, H.A.: Imitation modeling of the balancing electricity market functioning taking into account system constraints on the parameters of the IPS of Ukraine mode. Tekhnichna elektrodynamika **6**, 72–79 (2017). https://doi.org/10.15407/techned2017.06.072
9. NEURC Resolution "On Approval of Transmission Network Code" No. 309 of 14.03.2018
10. Pavlovskyi, V., Steliuk, A., Lenga, O. and Hrechko, V.: Frequency stability of the bulk isolated power system with high share of renewables and nuclear generation. In: Power Systems Research and Operation. Selected problems, p. 180. Springer (2021). https://doi.org/10.1007/978-3-030-82926-1_8
11. Pavlovsky, V.V., Stelyuk, A.O., Lukyanenko, L.M., Lenga, O.V.: Analysis of frequency change in the IPS of Ukraine under conditions of disconnection of the power unit of a nuclear power plant. Tech. Electrodyn. 2018(4), 89–94 (2018)
12. Register of ancillary service units for IPS of Ukraine // NEC «Ukrenergo». 2021. https://ua.energy/wp-content/uploads/2021/09/Reyestr-vid-22.09.2021.pdf
13. Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage, White paper. IEC., p. 102 (2020)
14. Kyrylenko, O.V., Basok, B.I., Baseyev, Y.T., Blinov, I.V.: Power industry of Ukraine and realities of the global warming. Tekhnichna elektrodynamika (3), 52–61 (2020). https://doi.org/10.15407/techned2020.03.052
15. Analytical report on the development of wind power and solar power plants within the IPS of Ukraine. NEC «Ukrenergo», p. 11 (2020)
16. Basok, B.I., Butkevych, O.F., Dubovskyi, S.V.: Technical and economic aspects of decarbonisation prospects assessing of the interconnected power system of Ukraine. Tech. Electrodyn. **5**, 55–62 (2021). https://doi.org/10.15407/techned2021.05.055
17. Butkevich, O.F., Yuneeva, N.T., Gureeva, T.M.: On the issue of placement of energy storage in the Ukrainian UES. Tekhnichna elektrodynamika **6**, 59–64 (2019) (Ukr). https://doi.org/10.15407/techned2019.06.059
18. Ivanov, H.A., Blinov, I.V., Parus, Y.V., Miroshnyk, V.O.: Components of model for analysis of influence of renewables on the electricity market price in Ukraine. Tekhnichna elektrodynamika (4), 72–75 (2020). https://doi.org/10.15407/techned2020.04.072
19. Kulyk, M., Zgurovets, O.: Modeling of power systems with wind, solar power plants and energy storage. In: Systems, Decision and Control book series, SSDC, vol. 298, pp. 231–245. Springer (2020). https://doi.org/10.1007/978-3-030-48583-2_15
20. Zaporozhets, A.: Photovoltaic technologies: problems, technical and economic losses, prospects. In: Zaporozhets, A., Sverdlova, A. The 1st International Workshop on Information Technologies: Theoretical and Applied Problems 2021. CEUR Workshop Proceedings. vol. 3039. p. 166–1811. http://ceur-ws.org/Vol-3039/paper19.pdf
21. Report on compliance assessment (sufficiency) of the generating facilities. NEC «Ukrenergo». p. 122 (2020)
22. Kulyk, M.M., Kyrylenko, O.V.: The state and prospects of hydroenergy of Ukraine. Tech. Electrodyn **4**, 56–64 (2019). https://doi.org/10.15407/techned2019.04.056
23. Intelligent power systems: elements and modes: under the total ed. of acad. of NASU AV Kyrylenko. The Institute of Electrodynamics of the NASU, p. 408 (2014)
24. Popov, O., Iatsyshyn, A., Kovach, V., Artemchuk, V., Kameneva, I., Radchenko, O., Nikolaiev, K., Stanytsina, V., Iatsyshyn, A., Romanenko, Y.: Effect of power plant ash and slag disposal on the environment and population health in Ukraine. J. Health Pollut. **11**(31), 210910 (2021). https://doi.org/10.5696/2156-9614-11.31.210910

25. Iatsyshyn, A., Artemchuk, V., Zaporozhets, A., Popov, O., Kovach, V.: Mathematical approaches for determining the level of impact of ash-slag dumps of energy facilities on the environment. In: Babak, V., Isaienko, V., Zaporozhets, A. (eds.) Systems, Decision and Control in Energy I. Studies in Systems, Decision and Control, vol. 298, pp. 1–13 (2020). https://doi.org/10.1007/978-3-030-48583-2_1
26. Zaporozhets, A.O.: Correlation analysis between the components of energy balance and pollutant emissions. Water Air Soil Pollut. **232**(3), 114 (2021). https://doi.org/10.1007/s11270-021-05048-9
27. Electrical Energy Storage. White paper. IEC, pp. 79 (2019)
28. Kyrylenko, O.V., Blinov, I.V., Tankevych, S.E.: Smart grid and organization of information exchange in electric power systems. Tekhnichna elektrodynamika **3**, 44–54 (2012)
29. Kyrylenko, O.V., Blinov, I.V., Parus, E.V., Trach I.V.: Evaluation of efficiency of use of energy storadge system in electric networks. Tech. Electrodyn. **4**, 44–54 (2021). https://doi.org/10.15407/techned2021.04.044
30. Blinov, I., Trach, I., Parus, Y., Khomenko, V., Kuchanskyy, V., Shkarupylo, V.: Evaluation of the efficiency of the use of electricity storage systems in the balancing group and the small distribution system. In: 2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek), pp. 262–265 (2021) https://doi.org/10.1109/KhPIWeek53812.2021.9569981
31. Blinov, I., Parus, E.: Approach of reactive power pricing for ancillary service of voltage control in Ukraine. In: 2014 IEEE International Conference on Intelligent Energy and Power Systems (IEPS), pp. 145–148 (2014). https://doi.org/10.1109/IEPS.2014.6874167
32. Saukh, S.; Borysenko, A.: (2019) Representation of transmission and distribution networks in the mathematical model of the electricity market equilibrium. In: 2019 IEEE 20th International Conference on Computational Problems of Electrical Engineering (CPEE) (2019). https://doi.org/10.1109/CPEE47179.2019.8949116
33. Lin, J., Magnago, F.: (2017) Electricity markets: theories and applications. IEEE Press Series on Power, pp. 352 (2017)
34. Momoh, J., Mili, L.: Economic market design and planning for electric power systems. Institute of Electrical and Electronics Engineers, pp. 277 (2009). https://doi.org/10.1002/9780470529164