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The Use of Energy Storage to Improve Controllability and Security of the Belarusian Power System

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Abstract — **The planned commissioning of the second unit of the Astravets nuclear power plant in the Republic of Belarus in 2023 will exacerbate the need to ensure controllability and security of both the entire Belarusian power system and its individual power generation centers. To address this issue effectively, it is crucial to flatten the load curves of electricity consumers, and energy storage systems (ESS) make this achievable. The Belarusian power system can use several types of ESSs, both system-wide and local. Li-ion-based ESSs have the best performance when used to smooth the load curves of individual substations. This paper assesses the efficiency of lithium-ion energy storage units. The assessment focuses on various factors such as leveling of the daily load curve of the consumer, decrease in power loss, and voltage regulation at the ESS installation site.**

***Index Terms*: Power system, nuclear power, energy storage system, daily load profile.**

I. INTRODUCTION

The fundamental concept driving the power system design is simultaneous and synchronized power generation and consumption. This condition makes it possible to maintain one of the most important operating parameters, which is AC frequency.

The daily load curve of both the entire Belarusian power system and its individual power generation centers is characterized by significant irregularity with pronounced daytime load peaks and demand troughs at night. The irregularity factor of the daily load curve is 0.65–0.7.

When the second unit of the Astravets NPP is put into commercial operation in 2023, the power of the two base load units operating in the Belarusian power system will amount to about 40% of the maximum load of the power system. The number of powerful flexible units of condensing power plants (CPPs) running in hot standby should be reduced to maintain the self-balancing state.

The introduction of ESSs into the power system will separate the power generation and consumption processes in time (provided that ESS efficiency is high) and smooth out the load curve of individual power generation centers and the power system as a whole. Addressing this problem will make ESSs a key component of the electric power industry in the context of “smart energy concept.”

Potential ESS applications in the power system also include voltage and frequency regulation, provision of spinning capacity, emergency power supply to prevent the unfolding of system accidents (in the event of power system islanding), restoration of the power system after an accident, and emergency power supply to the consumer. A unique benefit of using ESSs is that they can perform the above functions simultaneously [1].

It is worth noting that renewable energy sources (RES) have not be-come widespread in the Republic of Belarus (the share of renewable generation in the installed capacity of the Belarusian power system is about 3%). The use of

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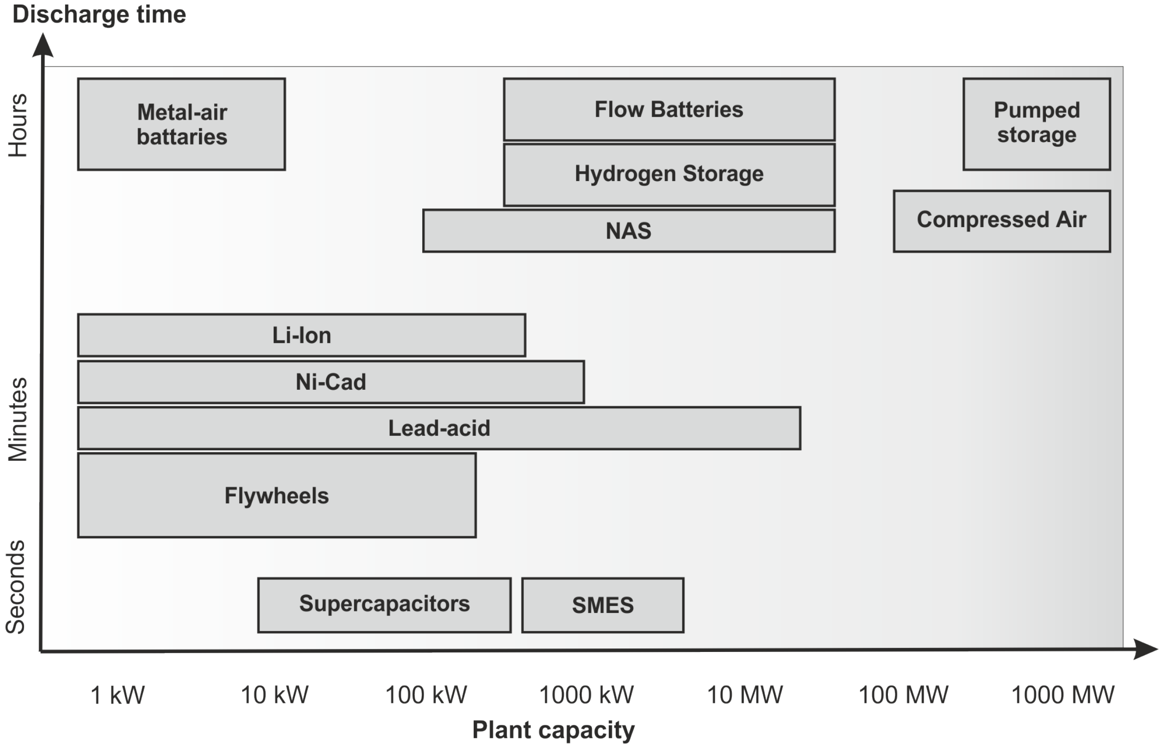

Fig. 1. Capacity and discharge time (duration) of various ESSs.

ESSs, however, is a key solution for efficient integration of renewables into the power system.

II. Review of the Worldwide Experience in the Use of ESSs

Energy storage systems have been used in the world for quite some time. For example, galvanic cells were invented in the 1800s and the first pump storage projects were introduced in the early 1900s.

Recently, the demand for ESSs has increased dramatically. This is due to the digitalization of control systems of the power system and its local power generation centers; higher electrification in various sectors of the economy, including transport; decentralization of electricity generation (large-scale use of distributed generation, including RES), and introduction of multifunctional energy facilities (cogeneration plants).

In the Belarusian power system, where installed capacity of the Astra-vets NPP is significant, an urgent task to be addressed by the use of ESSs is to flatten irregular daily load curves. ESSs can be used to supply consumers with electricity during the time of the day when power consumed exceeds power generated by the economically feasible generation equipment (NPPs, large units of TPPs). Another use of ESSs is to store electric energy during the periods when its generation at sources at issue exceeds consumption (which calls for the generation equipment shut-down). Furthermore, ESSs reduce the need for a steep increase or de-crease in the load of generation equipment in case of emergencies in the power system.

To assess the efficiency of ESSs utilization, one should factor in their energy capacity, maximum power output during the discharge period, dis-charge duration, and storage efficiency.

Known energy storage technologies can be divided according to the type of energy stored:
- mechanical (pump storage systems, flywheels),
- electrochemical (rechargeable cells, flow batteries),
- chemical (fuel cells),
- electrical (capacitors, supercapacitors, superconducting magnetic energy storage systems),
- thermal (use of molten salts and hot water).

Depending on the technology, the duration of energy storage can range from less than 10 hours (some battery storage systems) to weeks, months, and years (pump storage systems).

Figure 1 summarizes the data on capacity and discharge time (duration) of ESSs based on various technologies [2].

Table 1. Main Specifications of Major Energy Storage Technologies

Technology	Energy density, Wh/l	Power density, W/l	Nominal capacity, MW	Life cycle, number of charges and discharges	Storage time
Flywheels	20–80	5,000	<20	>100 000	ms – 15 min
Compressed air energy storage technology	12	0.2–0.6	100–300	>13 000	30 s – days
Pumped storage	0.2–2	0.1–0.2	100–5 000	>100 000	1 h – days, months
Capacitators	0.05–10	100 000	0.05	>50 000	ms – 1 h
Battery storage	15–1 673	10–10 000	0-100	1 000–20 000	s – days
Flow batteries	10–70	0.5–33.42	0.03-50	12 000	h – months
Superconducting magnetic energy storage	6	2 600	0,01-10	100 000	1 ms – 1 h
Hydrogen	600	0.2-20	<50	>1 000	s – days
Supercapacitors	10–30	40 000–120 000	0.01–1	>100 000	1 ms – 1.2 h
Fuel cells	500–3 000	>500	50	>1 000	s – days
Thermal energy storage	120–500	-	0.1–300	≈13 000	min – month

Table 1 presents main specifications of major energy storage technologies [2].

III. ESS TECHNOLOGIES IMPLEMENTABLE FOR THE BELARUSIAN POWER SYSTEM

Considering the level of development of ESS technology and maturity of the industrial prototypes in the CIS countries, we can conclude that only some of the ESSs mentioned above can be integrated in the Belarusian power system.

As already noted, the commissioning of the Astravets NPP has exacerbated the issue of peak shaving and valley filling in the daily electric load curve of the Belarusian power system, since the NPP units normally operate to meet the base-load demand. A conventional solution to this problem is to construct a pumped storage power plant (PSPP) together with the NPP. PSPPs are both highly flexible sources of peak power and serve as controlled loads. They prove effective when utilized:

- to do peak shaving;
- to provide multiple short-term pickups of the system load;
- to raise the nighttime load of TPPs to the level optimal in terms of their operational reliability;
- to ensure a fast-acting backup power for maintaining frequency and a short-term backup power during emergencies;
- to control the reactive power balance in the network.

In Belarus, due to the specific features of its terrain and the need to flood large areas, the unit capacity of PSPPs is limited to 400–570 MW. Therefore, the construction of several such plants is required to provide reliable backup power for two 1200 MW units of the Astravets NPP. Furthermore, this infrastructural solution requires significant capital expenditures and a long time to implement it, which is not feasible in the current context. The global power industry has shown a remarkable interest in utilizing lithium-ion batteries, as evidenced by the widespread adoption of ESSs because they have better

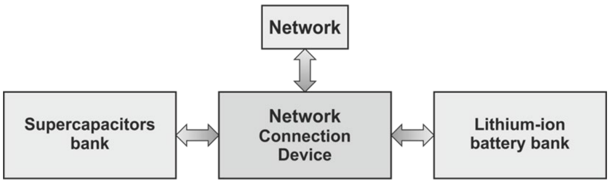

Fig. 2. Flowchart of a hybrid ESS.

performance compared to other storage battery technologies. Li-ion battery is gaining popularity in power generation and other sectors due to its long service life, high cell voltage, excellent performance in low temperatures, sufficient charge retention, and the desired depth of charge.

Another promising strand is the use of supercapacitors as part of "hybrid" ESSs together with storage battery [3].

Hybrid energy storage devices perform the following functions:

- flatten load curves in the network (by storing electric power during power-surplus periods and delivering it to the network during power-deficient periods);
- ensure increased steady-state and transient stability limits when coupled with modern power electronics devices;
- damp active and reactive power fluctuations, eliminate or significantly reduce irregular fluctuations in tie lines, and thus increase the transfer capability of the transmission line;
- ensure uninterrupted power supply to substations and electrical networks (auxiliaries), and to the essential consumers;
- provide stable and sustainable operation of decentralized and non-conventional sources operating both off-grid and as part of an IPS.

In hybrid ESSs, lithium-ion batteries are used as long-term energy storage, while banks of stacked-type supercapacitors are used as short-term energy storage.

Figure 2 shows the flowchart of a hybrid ESS.

In 2022, a draft "Concept of Application of Energy Storage Systems Based on Lithium-Ion Batteries in the Belarusian Power System" was developed. The document envisages commitment to a full-fledged adoption and use of ESS at Belenergo's generation sources, in electrical networks, and at power facilities of industrial enterprises and transport.

According to the draft Concept, the technically available potential for installation of ESSs in the Belarusian power system is estimated for the sites of location at:

- 1 200 MWh and 150 MW for thermal power plants;
- 500 MWh and 100 MW for distribution systems of industrial consumers;
- 500 MWh and 70 MW for renewable energy sources;
- 2 800 MWh and 300 MW for charging infrastructure for electric vehicles.

IV. THE USE OF ESSS IN 110 KV DISTRIBUTION NETWORKS OF THE BELARUSIAN POWER SYSTEM

In 2022, RUE Belenergosetproekt did research to assess the technical capacity and feasibility of installing lithium-ion energy storage units with a view to flattening daily load curves, reducing power loss, and regulating voltage at the point of ESS installation.

Several substations with transformer utilization rate close to 50% in normal operating conditions were selected as "standard" 110/10 kV substations (SS). It is worth noting that the share of substations with such a significant transformer load in the Belarusian power system is less than 5%, and they are located near the capital city, large regional centers, and in major industrial hubs of the Republic of Belarus. However, due to the policy of increasing electricity consumption for heating and hot water supply, which is pursued in the Republic of Belarus, the stated power of both residential and industrial consumers is expected to grow in the years to come. This will entail the need to address the problem outlined below. ESS performance was tested for two alternative options for the case of increased electrical load at the substations:

- reconstruction with transformer power increased;
- installation of ESS to shave daily load peaks and keep existing transformers in operation without overloading.

The input data included:

- reporting measurements obtained from automated metering system (half-hourly load snapshots) for transformer windings of a given substation during four representative days (winter/summer, weekday/weekend);
- electric loads according to the current technical conditions issued for power supply to consumers from this substation;
- flow diagram of the substation and feeding network.

The Korzyuki substation of RUE Minskenergo was chosen as a "standard" 110/10 kV substation with predominantly residential loads.

A notional substation was simulated as a "standard" substation with predominantly industrial loads.

Two 110/10 kV transformers with a capacity of 16 MVA each were in-stalled at the 110 kV Korzyuki substation.

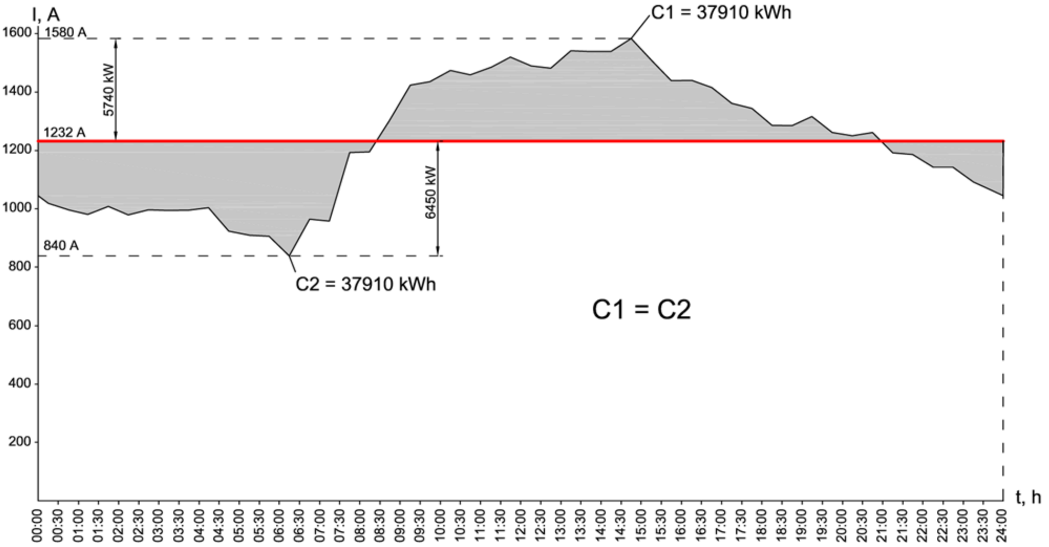

Fig. 3. Daily load curve (load current, A) of the 110/10 kV Korzyuki substation on a winter weekday, given the equality of ESS discharge/charge areas.

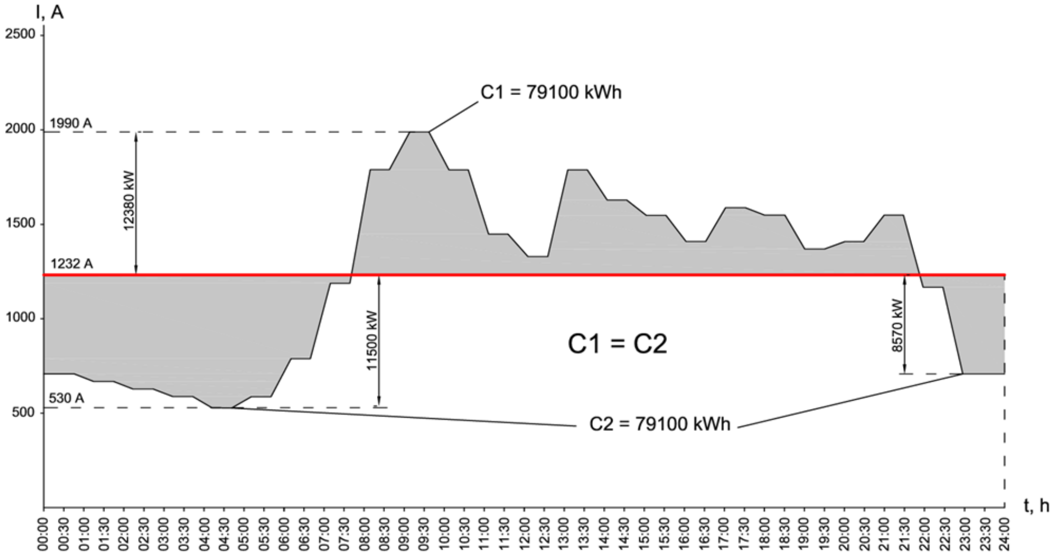

Fig. 4. Daily load curve (load current, A) of the 110/10 kV substation serving the woodworking industry on a winter weekday, given the equality of ESS discharge/charge areas.

Figure 3 shows the simulated daily load curve of a winter workday for this substation. This simulation factors in the increase in load under equal areas of battery discharge/charge that makes the application of ESS possible. The allowable maximum load exceeds the substation capacity limit by 28%. The required operating capacity of the battery should be about 38 thousand kWh and the nominal capacity should be 6.5 MW.

The horizontal line of the graph indicates the overload limit of the sub-station capacity (40% or 1 232 A) with one of the transformers removed from service for maintenance or shut down due to emergency.

The comparative calculations of costs for the options of modernization of the 110/10 kV Korzyuki substation (replacement of transformers versus ESS installation) demonstrated that capital expenditure incurred in the installation of the 10 kV ESS exceeds the cost of transformer replacement by a factor of 12.

This study does not consider 110/10 kV substations serving predominantly industrial loads and enterprises

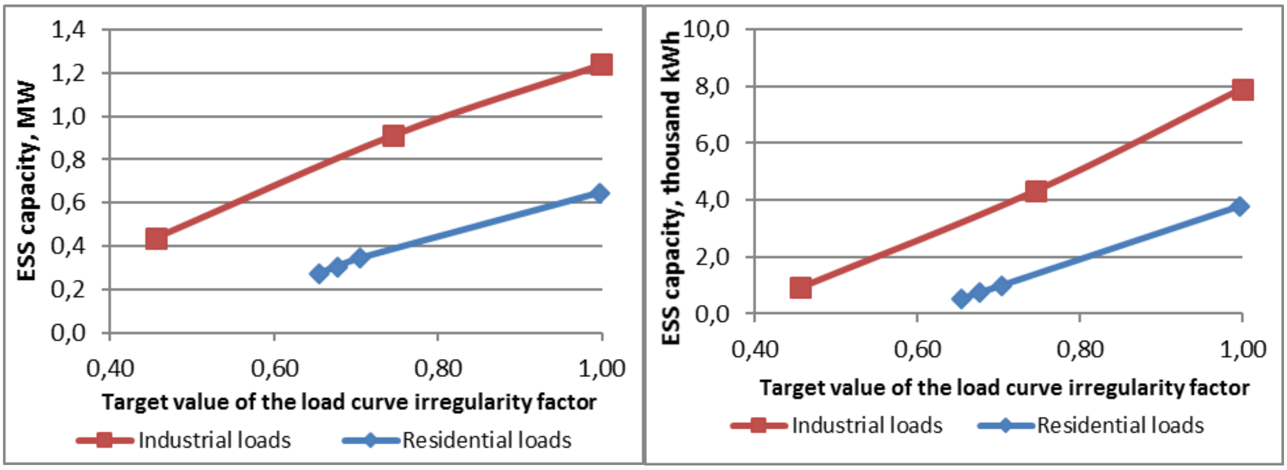

Fig. 5. Relationship between the required power and capacity of the ESS and the target value of the load curve irregularity factor.

operating continuously (oil refining, metallurgy, heavy engineering, etc.), since their daily load curve has no pronounced peaks and troughs in power consumption, during which the storage unit could be charged/discharged. Installing ESSs at such substations for reducing peak loads is not feasible. This does not preclude the installation of ESSs for the reasons of reliability of power supply to the essential units of the production process of this type of enterprises.

A 110/10 kV substation of the woodworking industry with two 16 MVA transformers was used in our case study as a substation serving predominantly industrial loads. Figure 4 shows the load curve for such a substation with equal areas of battery discharge/charge, at which ESS proves feasible.

The allowable maximum load exceeds the substation power limit by 62%, the required operating capacity of the battery is about 79.0 thousand kWh at the nominal capacity of 11.5 MW.

The comparative calculations of costs for the options of modernization of the 110/10 kV Korzyuki substation serving the woodworking industry (replacement of transformers versus ESS installation) show that capital expenditure incurred in the installation of the 10 kV ESS exceeds the cost of transformer replacement by a factor of 26.

We performed a series of calculations for substations with two characteristic load curves. The calculations indicated that to fully flatten the load curves, it will be necessary to install ESSs of sizable power and capacity: 12 MW and 80 thousand kWh, respectively (Fig. 5).

V. POWER LOSS IN THE NETWORK DUE TO ESS INSTALLATION

Assessment of the impact of ESS on power loss involved calculations of changes in power loss in the network of the Minsk power system with the voltage of 10 kV and more for the time frame covered by the options considered:

- Option 1: the use of an ESS and a transformer of a smaller power (16 MVA);
- Option 2: the use of a transformer of higher power (25 MVA).

The calculations were performed using the RASTRWIN software.

Additional annual power loss ΔW in the network of 10 kV and higher were determined by the equation

$$\Delta W = \Delta P \cdot \tau, \qquad (1)$$

where ΔP is additional added power loss in the network of 10 kV and above due to increased load (with no ESS); τ is time of maximum loss determined by the equation

$$\tau = (0.124 + T_{\max}/10000)^2 \cdot 8760. \qquad (2)$$

Here $T_{\max}$ is time of maximum load utilization, which was assumed to be equal to 5 000 h.

Power loss by transformers was calculated as follows:

$$\Delta W_T = \Delta P_{XX} \cdot 8760 + (S_{\max}/S_{\text{nom}})^2 \cdot \Delta P_{SC} \cdot \tau, \qquad (3)$$

where ΔP_{XX} is the no-load loss of the transformer; ΔP_{SC} is the short-circuit loss of the transformer; $S_{\max}$ is the highest value of the total power running through the transformer;

S_{nom} is nominal power of the transformer.

Power loss by the 10 kV ESS was determined based on the overall efficiency of lithium-ion energy storage units, which is about 85% according to the data of manufacturer. Analysis of the calculation results indicated that in the case of using ESSs, their power loss and the increase in load loss in transformers of smaller power under Option 1 were not offset by the reduction in no-load loss in transformers of smaller power under Option 2. Therefore, in general, power loss was greater with the installation of ESSs than without their use, which needs to be taken into account in the feasibility study.

VI. USE OF ESSS FOR VOLTAGE REGULATION

We calculated the effect of a 6.5 MW ESS on voltage levels in the 10 kV network of the 110 kV Korzyuki substation. 10 kV ESS inverters are selected so as to generate the necessary reactive power for voltage regulation in the 10 kV network. With a load power factor of 0.9, the power of the inverters will be about 7.2 MVA. According to the ESS nameplate data, the power factor control range is 0.1 to 1 per unit, provided the inverter is not loaded with active power. Thus, a 7.2 MVA inverter can control reactive power in the range of – 6.5 MVar to + 6.5 MVar.

A change in reactive power by 6.5 MVar on 10 kV busbars for the 110 kV Korzyuki substation leads to a change in the voltage level of the 10 kV network by 0.6 kV. When utilizing the full regulation range, the 7.2 MVA inverter can regulate the voltage over a range of 1.2 kV (about 12%).

The 10 kV ESSs are mainly used to avoid overloading of 110 kV substation transformers when one of two 110/10 kV transformers is shut down during the winter season while substation loads are significant. When operating two transformers during the same period or in the case of summer loads, the active power of ESS will not be fully used. This allows utilizing these devices as means of voltage regulation (generation/consumption of reactive power) in a 10 kV network when active power consumption/generation is below the nominal value of the plant.

The technical feasibility of reactive power generation/consumption can only be determined after calculating the required level of inverter loading with respect to active power for specific loading conditions of the substation. It is also important to highlight that for voltage regulation on the 10 kV side, 110/10 kV transformers are equipped with on-load tap changers (OLTC), therefore, the use of ESSs for 10 kV voltage regulation is not a top priority.

According to preliminary estimates, cutting down the ESS costs to be-low 200 USD/kWh can serve as a criterion of economic feasibility of large-scale adoption of ESSs in 10–110kV distribution systems of the Belarusian power system. In so doing, one should take into account such factors as ESS service life and degradation, and the payback period of ESS as an energy-saving measure should not exceed 10 years.

It is worth noting that the feasibility study of the ESS in 10 kV distribution networks of industrial enterprises should involve [4]:

- identifying special requirements for the reliability of process equipment in operation at the enterprise;
- clarifying estimates of the economic benefit based on additional terms of contractual relations with the power supply entity (payment for stated power, participation in demand response, frequency regulation, etc.).
- clarifying the costs of the devices planned for installation and their maintenance costs.

VII. CONCLUSION

1. The use of ESSs at the 110/10 kV substations offers a solution to balance daily variations in electricity demand. By compensating for daytime peak loads and boosting the nighttime minimum loads (load “valleys”) ESSs help level out the load curve and avoid the replacement of 110/10 kV transformers with higher power transformers.
2. ESSs can be used for voltage regulation in the 10 kV substation network, however, since 110/10 kV transformers with on-load tap-changers are used, the task is not of primary importance.
3. The cost of ESS installation significantly exceeds the cost of reconstruction of electrical network facilities, which precludes us from drawing a definite conclusion about the feasibility of large-scale adoption of ESS in 10 kV distribution networks.

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