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DEMAND MANAGEMENT IN MODERN ELECTRIC POWER SYSTEMS

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Annotation: *In recent years, due to the energy transition taking place in many countries around the world, processes of energy transition have also begun in Uzbekistan. This transition is associated with a shift toward green energy and the solution of the problem of diversifying energy sources, the development of market relations, as well as the digitalization and intellectualization of the energy sector. Under these conditions, at all stages of the transition, it is necessary to ensure the reliability of electricity supply to consumers and the stable operation of electric power systems (EPS) under various operating modes. Therefore, conducting research on the use of effective methods to reliably supply consumers with high-quality electric energy, including during the operation of wind and solar power plants with unstable operating modes, is highly relevant. One of such effective methods is operational demand management.*

Keywords: *Electric power systems, energy transition, wind and solar generation, demand management, deficit operating modes, operating mode balancing, contractual relations, prosumer consumers.*

INTRODUCTION

The global energy transition [1–3], which has been actively developing in many countries since the 2000s, has also stimulated transformation processes in the energy sector of the Republic of Uzbekistan. The need for an energy transition is driven by the depletion of fossil fuel reserves, environmental and climate changes, the rapid development of green energy, growing energy consumption, the introduction of digitalization and intelligent technologies, the deepening of market principles in the energy sector, and other factors.

The energy transition is understood as a significant structural change in the electric power system (EPS), during which the share of new primary energy sources increases and a gradual displacement of traditional sources occurs in the overall energy consumption [4,5], leading to changes in various processes within the EPS. All of these aspects are characteristic of the current situation in Uzbekistan’s energy sector.

The challenge lies in ensuring reliable and efficient operation of the EPS at all stages of the transition and in the long term, while integrating an increasing number of large-scale wind and solar power plants (WPPs and SPPs) characterized by variable and unstable operating modes. This necessitates scientific and applied research aimed at ensuring reliable supply of high-quality electric energy to consumers under energy transition conditions. International experience shows that one of the effective methods for improving EPS reliability is demand response; therefore, the analysis and justification of applying demand management methods (DM) to enhance the reliability and flexibility of EPS operating modes in Uzbekistan is highly relevant.

It should be noted that at present, a number of new-generation regulatory and legal documents related to the energy sector and the energy transition have been adopted and are being implemented in the Republic of Uzbekistan [6–8]. These include Law No. ZRU-939 "On Electric Power Industry" dated 07.08.2024, Law No. ZRU-940 "On Energy Saving, Its Rational Use and Improvement of Energy Efficiency" dated 07.08.2024, Resolution of the Cabinet of Ministers of the Republic of Uzbekistan No. 204 "On Additional Measures for the Introduction of Market Mechanisms in the Fuel and Energy Sector" dated 16.04.2024, and others.

Such documents signify an active shift of the national energy sector toward diversification of energy sources to enhance reliability and increase energy production, intensification of green (carbon-free) energy use, implementation of market principles, and adoption of advanced technologies. To ensure reliable supply of fuel and energy resources to consumers, these documents provide for a phased transition, the introduction of renewable energy sources (RES), wide application of energy-saving technologies, and a gradual transition to market-based pricing of energy resources.

This paper analyzes the application of demand management methods to improve the reliability, controllability, and efficiency of EPS operating modes, including during deficit situations that often arise due to the variable operating regimes of wind and solar power plants.

METHODOLOGICAL PART

Globally, the following interpretation of this process is given: demand management (or demand response) in electric power systems is a change in electricity consumption by end users relative to their normal load profile in order to reduce consumption during periods of high electricity prices in the wholesale market or when system reliability is under threat [2]. Demand management (DM) in electricity implies the planning and implementation of integrated activities both within the electric power system (EPS) and among its consumers, which influence the patterns of electricity generation and use, modify the configuration of the system load curve while maintaining the balance between generation and consumption [9,10].

Demand management can reduce electricity prices in the wholesale market, which in turn leads to lower prices in the retail market [11]. Worldwide, demand management has gained broad recognition as a means of ensuring reliability of power supply, integrating renewable energy sources, increasing competition in the electricity market, and expanding consumer participation opportunities [12]. DM is used as a tool for smoothing sharply fluctuating EPS load curves and for optimal management of deficit operating conditions of the EPS, among other applications.

Application of demand management in optimizing deficit operating conditions. Demand management (electricity consumption control) becomes particularly relevant during deficit and post-emergency operating conditions of the EPS. Deficit conditions may arise, for various reasons, either across the entire EPS or in its local areas due to maintenance of transmission lines and substation equipment, operational constraints on fuel resources (at thermal power plants) and water resources (at hydropower plants), as well as due to unstable operating modes of wind and solar power plants and other factors. During such periods, in order to ensure reliability and continuity of electricity supply, it is rational to apply demand management mechanisms based on contractual limitations with consumers, allowing optimization of operating conditions both for the EPS and for consumers during deficit periods.

These mechanisms are based on the fact that many consumers, including industrial ones, have the capability to reduce their electricity consumption by 3–20% or more of their load during certain time periods, participating in demand management without significant detriment to capital investments. This has a positive effect on the configuration of the aggregated EPS load curve; therefore, the system operator (or an aggregator) should conclude appropriate agreements with such consumers to utilize their regulating capabilities in demand management.

Issues of regulating electric load curves with the aim of their smoothing are directly related to the tasks of forecasting the operating modes of the electric power system (EPS), including short-term (operational) forecasts of wind and solar power plant (WPP and SPP) operating modes. Forecasting and subsequent optimization of operating modes consist in the fact that, based on the forecast of the aggregated load curve for the forthcoming time period (hours, days), an optimal distribution of load among all power plants of the EPS is carried out. When a forecast indicates a generation deficit during a certain period due to the variable operating modes of WPPs or SPPs, demand management measures are planned.

With the traditional approach to the problem of optimal control of EPS operating modes, the balance equation (without accounting for losses) has the following form:

$$\Sigma\left(P_i^{\text{reg}}\right) + \Sigma(P_j^{\text{nreg}}) = \Sigma\Pi_k; \tag{1}$$

where the right-hand side of the equation, $\Sigma\Pi_k$, is the total power of all consumers, k={1, r}, and r is the number of consumers; the left-hand side, $\Sigma\left(P_i^{\text{reg}}\right) + \Sigma(P_j^{\text{nreg}})$, is the sum of the capacities of all power plants in the EPS; $\left(P_i^{\text{reg}}\right)$ denotes the capacities of controllable (dispatchable) power plants; (P_j^{nreg}) denotes the capacities of non-controllable (non-dispatchable) power plants. The capacities of wind and solar power plants are included in the group of non-dispatchable plants; $\{i = 1, m\}$; where m is the number of dispatchable power plants; $\{j = 1, n\}$, where n is the number of non-dispatchable power plants.

Let us consider the right-hand side of the balance equation (1) by dividing it into two parts: controllable and non-controllable:

$$\Sigma\Pi_k = \Sigma\left(\Pi_k^{\text{reg}}\right) + \Sigma(\Pi_k^{\text{nreg}}) \tag{2}$$

Here, (Π_k^{reg}) is the controllable part of consumers' power demand, and (Π_k^{nreg}) is the non-controllable part of consumers' power demand.

Equation (1) then takes the following form:

$$\left(\Sigma P_i^{\text{reg}} + \Sigma P_j^{\text{nreg}}\right) = (\Sigma\Pi_k^{\text{reg}} + \Sigma\Pi_k^{\text{nreg}}); \tag{3}$$

where the left-hand side represents the sum of the load curves of power plants with controllable (P_i^{reg}) and non-controllable (P_j^{nreg}) capacities. The right-hand side consists of controllable (Π_k^{reg}) capacities used for demand management and non-controllable (Π_k^{nreg}) consumer capacities. Control actions can be applied to the controllable capacities on both the left-hand and right-hand sides of the balance equation (3). The ability to vary the components on both sides of the equation significantly increases the flexibility and efficiency of controlling EPS operating modes.

Contractual demand management measures with consumers are modern energy-saving approaches aimed at improving the energy efficiency of various operating modes, especially deficit ones. Demand management encompasses functions related to influencing consumers to regulate load schedules, which increases the operational flexibility of the power system and its ability to make flexible decisions when balancing consumption and generation capacities.

Relationship between Demand Management and Energy Efficiency. In demand management of electricity consumption, load is shifted from peak to off-peak periods, thereby improving energy efficiency through reduced electricity consumption during peak periods and increased utilization during off-peak periods. The introduction of more efficient equipment during off-peak periods and/or effective control of existing equipment, implemented in conjunction with demand management, can significantly enhance the energy efficiency of the electric power system. In addition, demand management can also contribute to a reduction in total energy consumption.

Methods of Involving Consumers in Demand Management. There are two main approaches to engaging consumers in load management [13]:

- Implicit demand management, based on the application of various types of time-differentiated electricity tariffs and/or behavioral incentives.
- Explicit demand management, which involves direct control of the consumer's load.

The use of differentiated tariffs is facilitated by AMR/AMI systems (automated systems for commercial electricity metering) equipped with electronic meters adapted to operate with various tariff schemes. The main type of differentiated tariff is the time-of-use (TOU) tariff, which предусматривает dividing the day into several (two or more) intervals ("zones"), each with a fixed electricity price. Other types of tariffs also exist, as well as discount schemes aimed at encouraging consumers to participate in demand management processes.

Direct control of a consumer's load can be carried out either by the consumer themselves or through automated or automatic load control via AMR/AMI systems from a dispatch center (by the system operator or an aggregator organization).

Types of Loads Participating in Demand Management. A wide variety of equipment used by industrial, agricultural, commercial, and residential consumers can participate in demand management. Industrial consumers exhibit the greatest diversity in the context of demand management; their participation is typically associated with shifting consumption schedules to periods of lower prices, as well as temporarily stopping or reducing the intensity of production processes. Demand management may involve full or partial shutdown of lighting, ventilation, and air-conditioning systems, as well as the use of on-site generation and/or energy storage systems.

Residential and commercial consumers also have opportunities for demand management, especially when AMR/AMI systems, smart home technologies, uninterruptible power supplies, energy storage systems, Internet of Things (IoT) solutions, and other innovations are implemented, enabling prompt and remote control of electricity consumption.

The widespread deployment of electric vehicles and charging infrastructure can also be effectively used for managing electricity demand.

Role of Aggregator Organizations. In the context of electricity market development, consumers with controllable loads may participate in demand management either independently or with the assistance of specialized load aggregator organizations. The emergence of such organizations is driven by the fact that retail consumers are not participants in the wholesale electricity market, are not connected to its infrastructure, and in most cases are unfamiliar with market rules. In addition, the individual capacity of a single consumer may be too small, while the number of consumers may be too large, for effective interaction with the market operator.

Aggregator companies organize and combine the controllable capabilities of individual consumers into larger aggregated blocks, acting as intermediaries between consumers and the electricity market infrastructure. Load aggregators may equip consumers with the necessary equipment to reduce consumption, provide consultations on load reduction technologies, develop optimal programs for consumer participation in demand management, and perform other related functions [14]. Energy supply companies or independent firms may act as load aggregators.

DISCUSSION

The results of the analysis show that demand management (DM) is effective for solving operational tasks of optimal control and balancing under market conditions, especially during deficit operating modes of the electric power system (EPS), which arise, among other factors, due to the stochastic and variable generation of large-scale wind and solar power plants (WPPs and SPPs).

Table 1.

Prospective structure of electricity demand management measures for the conditions of Uzbekistan

	Permanent implicit demand management measures
1	Implementation of differentiated tariffs and discounts
2	Design and construction of controllable consumers and energy storage systems
3	Improving the accuracy of forecasting models for large WPPs and SPPs
4	Subsidizing the deployment and use of energy storage equipment
5	Improving reactive power compensation in grids and at consumers
6	Administrative and organizational measures to increase load shifting and promote multi-shift operation
7	Development and implementation of demand management programs

8	Implementation of energy-efficient technologies and energy-saving methods
9	Periodic energy audits to assess demand management potential
10	Subsidizing consumer purchases of energy-efficient equipment
11	Promoting RES use and green procurement
12	Agreements on joint demand management with Central Asian power systems and consumers
13	State and legal support for demand management measures
	Operational load management measures during EPS deficit conditions
14	Demand management under consumer contracts using AMR/AMI systems
15	Balancing EPS capacity by adjusting controllable consumer loads
16	Allowable voltage and frequency reductions within standard limits
17	Public radio and TV appeals to switch off unused appliances
18	Rolling outages of Category III consumers during power deficits
19	Use of battery storage and pumped storage hydropower (PSH)
20	Connection of reserve capacity from Central Asian power systems
	Emergency measures
21	Activation of automatic underfrequency load shedding (UFLS)
22	Consumer disconnections during emergencies
23	Switching power from Central Asian and Russian power systems

The application of specific methods depends on many factors related to the parameters of the EPS, types of RES, consumers, and other conditions. For example, it depends on the category of consumers, their capacities, technological processes, and level of technical equipment; on the types and parameters of reserve facilities and EPS equipment; on the tariff schemes used; on the degree of deployment of local and renewable energy sources; on the time of day and season; and on climatic and geographical conditions, among others. Each power system, its individual elements, as well as consumers, possess unique characteristics that influence the selection and application of particular demand management methods.

International experience. Electricity demand management has today become a sought-after and significant tool for regulating the balance of supply and demand in electricity markets worldwide. In recent years, the electricity demand management market has remained stable and is expected to grow further in the future.

At present, North America remains the dominant market, while the Asia–Pacific region accounts for more than 10% of the global electricity demand management market; the increasing penetration of smart metering devices is a key factor supporting further growth.

In foreign power systems, the implementation of demand management mechanisms has made it possible to organize centralized control of consumer resources amounting to 2–6% of peak demand, or 0.5–14 GW of capacity (USA (PJM) — 13.9 GW; South Korea (KPX) — 3.2 GW; Ontario, Canada (IESO) — 0.7 GW; United Kingdom (National Grid) — 0.5 GW), enabling consumers to reduce electricity payments by 0.6–1.7% [2].

In addition, it should be noted that foreign demand management mechanisms provide various participation options, for example:

- **Direct demand control** (primarily used to enable the participation of residential consumers in demand management);
- **Guaranteed load shedding** (used for emergency demand management, activated as a last resort in cases of extreme necessity and therefore compensated at a reduced rate);
- **Fast reserve program** (used to ensure system frequency stability in the event of an unforeseen increase in demand or a reduction in supply and insufficient frequency regulation).

CONCLUSION

The energy transition of the Republic of Uzbekistan toward green energy with a predominance of wind and solar power plants (WPPs and SPPs) [17] requires the use of modern demand management methods, including those aimed at increasing flexibility in balancing both normal and deficit operating modes of the electric power system (EPS), which often arise due to the variability of wind and solar generation. Based on international experience, it can be concluded that the application of demand management methods is highly effective and cost-efficient for controlling deficit EPS operating modes, smoothing consumption load curves, and reducing electricity tariffs, especially under market conditions.

This study analyzes the tasks of demand management and develops and proposes various methods for controlling electricity consumption during Uzbekistan's energy transition.

The technical implementation of demand management in practice is carried out through the use of AMR/AMI systems, which incorporate differentiated tariffs and provide capabilities for limiting or disconnecting consumers. A transition is required from simple electricity metering and control toward mutually beneficial electricity consumption management for the EPS, consumers, and the state.

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