Optimal Planning of Short-Term Modes of Power Systems Containing Energy Storage Devices

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Abstract: The development of the electric power industry at the present stage throughout the world is characterized by an increased rate of introduction of power plants operating on renewable energy resources, primarily solar and wind power plants. The unevenness of the load schedules of electricity consumers is increasing. To reliably provide consumers with high-quality electricity at minimal economic costs, electricity storage devices are being introduced into such energy systems. Under such conditions, the tasks of optimal planning of short-term modes of electric power systems, which consists of determining for each time interval the optimal values of all regulated parameters, in particular loads, through the use of the regulating capabilities of storage devices, become much more complicated. At present, despite the existence of several models and algorithms for optimization of the energy storage devices as part of the power system, the issues of determining the optimal operating modes of power systems in a short-term cycle through the use of their regulatory capabilities based on the use of rigorous mathematical models and algorithms have not been sufficiently studied. This paper presents a mathematical model for the problem of optimization of the modes of a power electric system containing adjustable energy storage devices and the algorithm for aligning consumer load schedules. The results of a study of the effectiveness of the proposed optimization model and algorithm using the example of aligning the daily load schedules of the Central part of the electric networks of JSC "National Power Networks of the Republic of Uzbekistan" are given.

1 INTRODUCTION

The modern development of energy throughout the world is characterized by the widespread introduction of stations powered by renewable energy sources into power systems and an increase in the unevenness of consumer load schedules [1, 4, 11]. To reliably supply consumers with high-quality electricity at minimal costs, some energy systems use energy storage devices, which serve to cover electricity imbalances resulting from random changes in plant capacities and to level out consumer load schedules. Under these conditions, the tasks of optimal planning and operational control of the modes of electric power systems become much more complicated. At the same time, it is necessary to improve existing mathematical models and algorithms for solving the problem, taking into account the alignment of consumer load schedules through the use of the regulating capabilities of energy storage devices.

The existing literature presents the results of many developments devoted to the optimization of the configuration, characteristics and operating modes of energy storage devices in electric power systems, which undoubtedly made a significant contribution to the development of the general scientific theory in this direction. In particular, in [1-6] the results of the authors' research on the selection of optimal parameters of various types of energy storage devices in power supply systems are presented. In [7-14] the results of research on optimization of operating modes of various types of energy storage devices in energy systems are presented. In particular, in [7] the problem of optimization of operating modes of energy storage devices in power supply system of buildings taking into account the uncertainty of the load, source and mechanism of rough response to demand is considered. An interval mode optimization model based on shared energy storage and refined demand response is proposed. In [8], a general overview of works devoted to the optimization of the parameters of batteries when used for various purposes, in particular to ensure the quality of electricity, increase the efficiency of operation by regulating the required power, minimizing active losses due to accumulation and also forms of objective functions in implicit forms are given. In addition, the main approaches to using various heuristic and artificial intelligence methods to solve such a problem are presented. In [9], the results of studies on ensuring the quality of electricity through large-scale energy storage in power systems are presented.

An analysis of existing developments shows that the issues of determining the economical operating modes while ensuring the required reliability, quality of electricity and environmental protection of electric power systems with system energy storage devices based on the use of rigorous mathematical models have not been sufficiently studied. Most of these works do not study the issues of leveling the load schedules of power systems due to energy accumulation. Methods and algorithms proposed in some works for solving similar problems for electrical networks of enterprises [15, 16] and small autonomous systems cannot be directly used for large power systems. In this regard, the development and implementation of effective models and methods for optimization the modes of power systems containing large energy storage devices, taking into account all influencing factors, remains an urgent task.

In this regard, this paper presents the results of research on the development of a mathematical model and algorithm for solving the problem of optimization the modes of electric power systems, taking into account the regulatory capabilities of the system energy storage devices they contain.

2 MATHEMATICAL MODELING AND ALGORITHM OF OPTIMIZATION

The mathematical model of the problem of optimal mode planning for period T of a power system with energy storage devices can be formulated as follows:

- minimize the objective function, which is a function of the total costs associated with fuel consumption in thermal power plants (TPP):

$$B=\sum_{t=1}^{T}\sum_{i=1}^{n}B_i^{(t)}\left(P_i^{(t)}\right)\rightarrow \min \qquad (1)$$

taking into account the constraints;

- on power balance in each time interval of the period under consideration T

$$\sum_{i=1}^{n}P_i^{(t)}+P_{REN}^{(t)}+P_S^{dch(t)}=P_L^{(t)}+P_S^{ch(t)}, \quad t=1,2,..,T; \qquad (2)$$

- on permissible minimum and maximum power of thermal power plants:

$$P_i^{(t)\min}\le P_i^{(t)}\le P_i^{(t)\max}, \; ; \quad i=1,2,n;\; t=1,2,...,T \qquad (3)$$

- on permissible minimum and maximum charging and discharging power of energy storage device

$$0\le P_S^{ch(t)}\le P_S^{ch.\max}, \quad t=1,2,...,T; \qquad (4)$$

$$0\le P_S^{dch(t)}\le P_S^{dch.\max}, \quad t=1,2,...,T; \qquad (5)$$

- on permissible minimum and maximum energy (capacity) of charge and discharge of energy storage device

$$W_S^{\min}\le W_S^{(t)}\le W_S^{\max}, \quad t=1,2,...,T, \qquad (6)$$

where n is the number of thermal power plants participating in optimization; T is the number of time intervals during the period under consideration; $P_i^{(t)}$, $P_S^{ch(t)}$, $P_S^{dch(t)}$ - power of the i-th thermal power plant, charge and discharge of the storage device in the t-th time interval of the period under consideration, respectively; $P_{REN}^{(t)}$, $P_L^{(t)}$ - the total power of stations operating on renewable energy sources and the load of the power system in t-th time interval; $P_S^{ch.\max}$, $P_S^{dch.\max}$ - permissible maximum charge and discharge powers of the storage device; $W_S^{(t)}$, $W_S^{\min}$, $W_S^{\max}$ - the amount of energy in the storage device in t-th time interval, as well as its permissible minimum and maximum values.

In cases where a battery is used as an energy storage device, $W_S^{\min}$ represents the amount of energy corresponding to the greatest depth of its discharge. If it is accepted that the charge energy in the storage device at the beginning and end of the planning period is equal to $W_S^{\min}$, then the amounts of charge and discharge of the storage device during the planning period T must be the same, i.e. the following conditions must be met:

$$\sum_{t=1}^{T}P_S^{ch(t)}=\sum_{t=1}^{T}P_S^{dch(t)}=W_S^{\max}-W_S^{\min}. \qquad (7)$$

Integral constraint (6) can be replaced by the following constraints, expressed in terms of the unknown charging and discharging powers of the storage device:

$$\sum_{i=1}^{t} P_S^{ch(i)} - \sum_{i=1}^{t} P_S^{dch(t)} \le W_S^{\max} - W_S^{\min}, \;\; t = 1, 2, ..., T \,, \quad (8)$$

$$-\sum_{i=1}^{t} P_S^{ch(i)} + \sum_{i=1}^{t} P_S^{dch(t)} \le -W_S^{\min}, \;\; t = 1, 2, ..., T \,. \quad (9)$$

Optimal planning of the power system mode for period T involves determining for each time interval the optimal powers stations, which participate in optimization and the charging and discharging powers of the storage device, at which the objective function (1) has a minimum value and the above presented constraints are met. As a result, simultaneously with solving the problem within the given constraints, the total load schedule of consumers is leveled due to the regulating capabilities of the energy storage device. Therefore, the problem under consideration can be solved by dividing it into two stages. At the first stage, the problem of leveling the consumer load schedule is separately solved by using the regulating capabilities of the storage device. And at the second stage, the optimization of the power system mode using the equalized load schedule obtained as a result of the first stage, based on the use of traditional methods and algorithms is carried out. Below we will consider the problems associated with implementing the first stage.

In the problem of leveling the load schedule, the objective function is presented in the following form:

$$f = \sum_{t=1}^{T} \left(P_{L.p}^{(t)} - \sum_{i=1}^{T} P_L^{(i)} / T \right)^2 \to \min \,, \quad (10)$$

where is $P_{L.p}^{(t)}$ is the calculated load in t-th time interval, obtained as a result of leveling the schedule.

Minimization of the last function is carried out on $P_{L.p}^{(t)}$, $P_S^{ch(t)}$, $P_S^{dch(t)}$, taking into account constraints on power balance in each time interval

$$P_{L,p}^{(t)} + P_S^{ch(t)} - P_S^{dch(t)} = P_L^{(t)}, \quad t = 1, 2, ..., T \,, \quad (11)$$

permissible calculated loads

$$P_{L.p}^{(t)\min} \le P_{L.p}^{(t)} \le P_{L.p}^{(t)\max}, \quad (12)$$
$$t = 1, 2, ..., T \text{ and } (4), (5), (7), (8), (9).$$

The proposed algorithm for solving the resulting problem involves minimization the function (10) taking into account constraints in the form of equalities (11) and (7) by indefinite Lagrange multipliers, functional constraints in the form of inequalities (8) and (9) by penalty functions as in [20], and simple constraints (12), (4) and (5) through fixing at each iteration the variables that go beyond the permissible limits on the corresponding violated boundaries. Thus, the following generalized objective function is minimized

$$\begin{aligned} F = f &+ \sum_{t=1}^{T} \mu_1^{(t)} \left(P_{и,p}^{(t)} + P_S^{ch(t)} - P_S^{dch(t)} - P_{и}^{(t)} \right) + \\ &+ \mu_2 \left(\sum_{t=1}^{T} P_S^{ch(t)} - W_S^{\max} + W_S^{\min} \right) + \\ &+ \mu_3 \left(\sum_{t=1}^{T} P_S^{dch(t)} - W_S^{\max} + W_S^{\min} \right) + \\ &+ \sum_{t=1}^{T} Pf_1^{(t)} + \sum_{t=1}^{T} Pf_2^{(t)} \to \min \end{aligned} \,, \quad (13)$$

taking into account constraints (12), (4) and (5). Where $\mu_1^{(t)}, \mu_2, \mu_3$ are the undetermined Lagrange multipliers, taking into account the corresponding restrictions; $Pf_1^{(t)}$, $Pf_2^{(t)}$ – penalty functions that take into account functional restrictions in the form of inequalities (8) and (9), which have quadratic forms, as in [20].

The values of the undetermined Lagrange multipliers at each k-th iteration $\mu_1^{(t)}, \mu_2, \mu_3$ are found based on the sequential solution of the equations obtained by equating the following partial derivatives to zero:

$$\frac{\partial F}{\partial P_{L.p}^{(t)}} = 0 \,, \quad \frac{\partial F}{\partial P_S^{ch(t)}} = 0 \,, \quad \frac{\partial F}{\partial P_S^{dch(t)}} = 0 \,.$$

The optimal calculated loads, charging and discharging powers for each time interval at the kth iteration are calculated using the following formulas:

$$\left. \begin{aligned} P_{L.p}^{(t)(k)} &= P_{L.p}^{(t)(k-1)} - h_L^{(t)(k)} \cdot \frac{\partial F}{\partial P_{L.p}^{(t)}}^{(k-1)}, \\ P_S^{ch(t)(k)} &= P_S^{ch(t)(k-1)} - h_S^{ch(t)(k)} \cdot \frac{\partial F}{\partial P_S^{ch(t)}}^{(k-1)}, \\ P_S^{dch(t)(k)} &= P_S^{dch(t)(k-1)} - h_S^{dch(t)(k)} \cdot \frac{\partial F}{\partial P_S^{dch(t)}}^{(k-1)}. \end{aligned} \right\} \,, \quad (14)$$

where $h_L^{(t)(k)}$, $h_S^{ch.(t)(k)}, h_S^{dch.(t)(k)}$ are steps in the direction of descent to the minimum in k-th iteration, defined as in [20, 21].

The condition for the convergence of the iterative process is

$$\left| f^{(k-1)} - f^{(k)} \right| \le \varepsilon_F \,, \quad (15)$$

when all specified constraints are met. In cases where condition (15) is met under violated constraints, penalties for such constraints are increased and the calculation proceeds to the next iteration.

An enlarged block diagram of the proposed algorithm is shown in Figure 1.

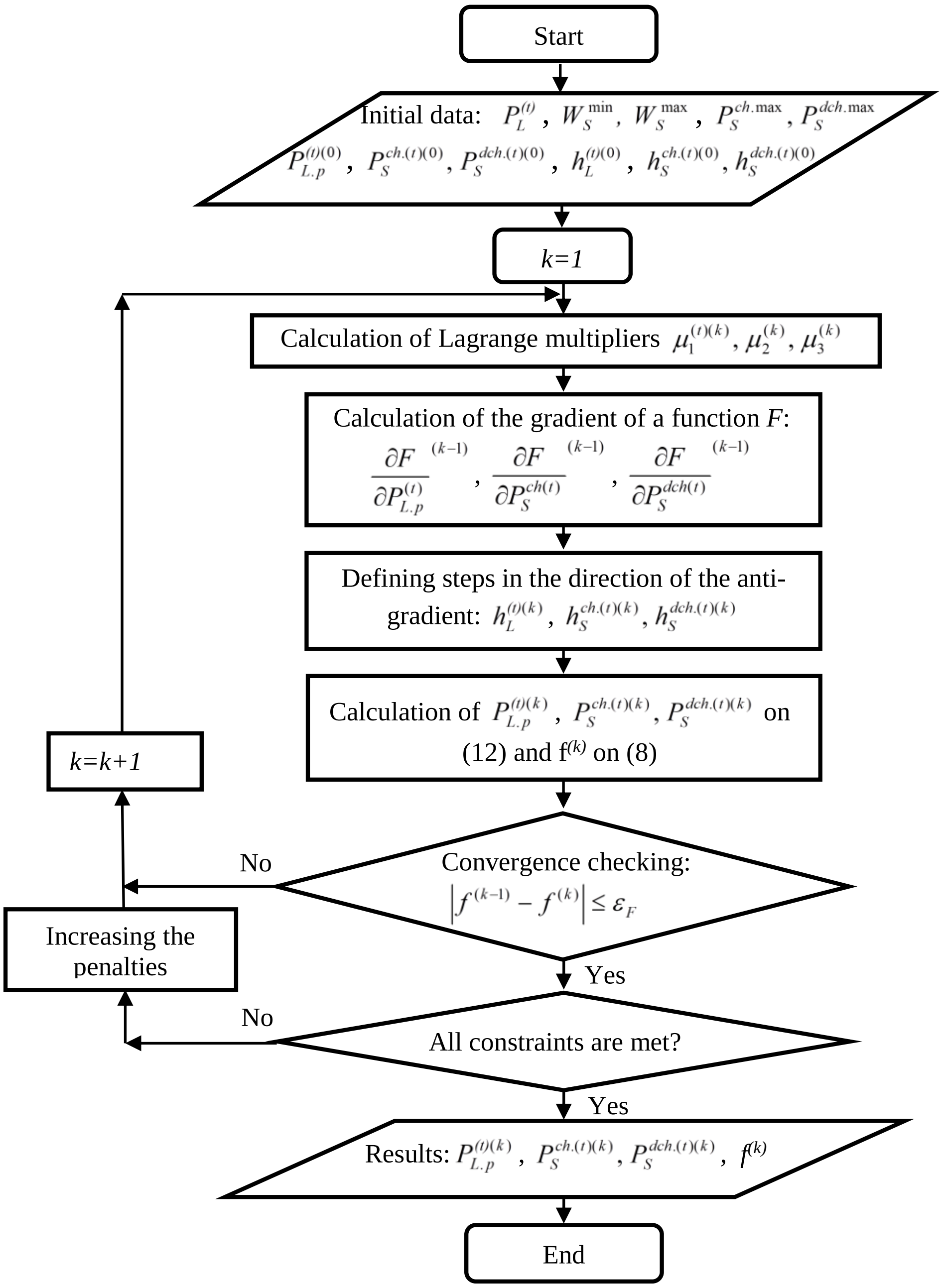

Figure 1: Enlarged block diagram of the optimization algorithm.

3 RESULTS

The effectiveness of the proposed mathematical model and optimization algorithm was studied using the example of leveling the daily schedules of total loads in the central part of the main electric networks of “National electric grid of Uzbekistan” JSC through the use of the regulatory capabilities of energy storage devices.

The day June 15.2022 for which the daily schedule of load is represented by eight characteristic time intervals (Table 1), was taken as an example.

As an example, an energy storage device with the following parameters was selected: $W_S^{\max}$ =800 MWh., $W_S^{\min}$ =160 MWh., $P_S^{ch.\max}$ =400 MW, $P_S^{ch.m\ i}$ =0, $P_S^{dch.\max}$ =400 MW, $P_S^{dch.\min}$ =0.

At the beginning of the day, the energy stored in the storage device is $W_S^{\min}$ = 160 MWh.

Table 1 shows the initial schedule of the total load $P_L\,(t)$ and optimization results: the calculated load after leveling using the storage capacity $P_{L.p}(t)$, charging $P_S^{ch.}(t)$ and discharging $P_S^{dch.}(t)$ power of the storage devices.

Figure 2 shows daily schedule of the initial and calculated total loads $P_L(t)$, $P_{L.p}(t)$, and in Figure 3 schedules of charging and discharging power of storage device. In this case, the discharge power is shown with a negative sign.

Table 1: Daily schedule of initial total loads of consumers and optimization results.

Number of the time interval	1	2	3	4	5	6	7	8
Durition of time interval, hours	0-4	4-8	8-10	10-14	14-16	16-18	18-22	22-24
$P_L^{(t)}$, MW	2196.0	2534.0	2965.0	3395.0	2965.0	2664.0	3300.0	2664.0
$P_{L.p}^{(t)}$, MW	2304.3	2585.7	2935.9	3264.1	2935.9	2980.0	3120.0	2664.0
$P_S^{ch.(t)}$, MW	108.3	51.7	0.0	0.0	0.0	320.0	0.0	0.0
$P_S^{dch.(t)}$, MW	0.0	0.0	29.1	130.9	29.1	0.0	160.0	0.0

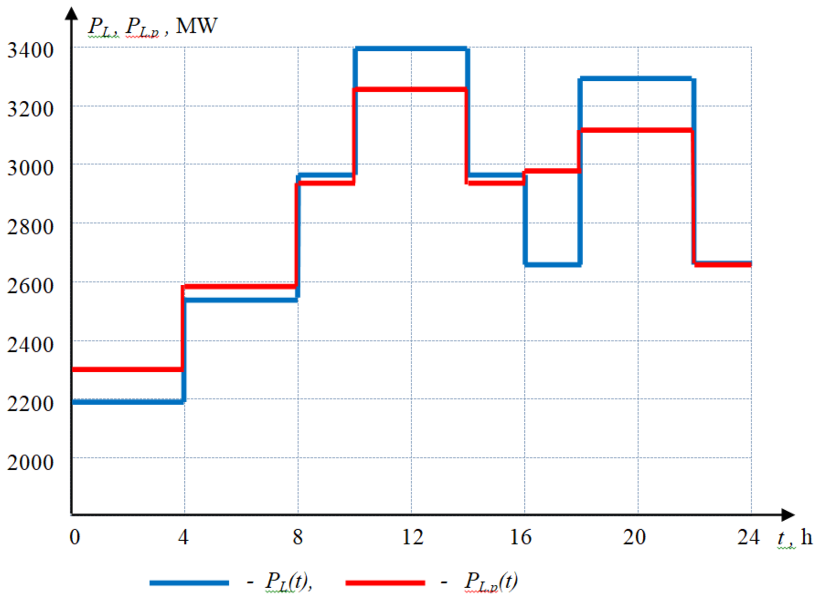

Figure 2: Daily schedules of initial and calculated loads.

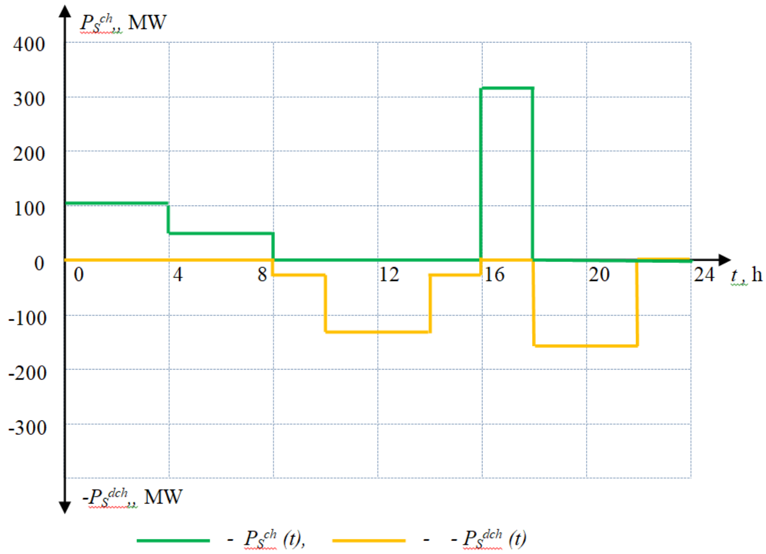

Figure 3: Daily schedules of charging and discharging the energy storage device.

The reliability of the results obtained is confirmed by comparing them with numerous results obtained based on a simple selection.

In the example considered, due to the regulating capabilities of energy storage devices, the daily load schedule of the power system is significantly leveled. In particular, the difference between the maximum and minimum total loads decreases from 1199 MW to 960 MW.

Analysis of the results shows that the use of the proposed mathematical model and optimization algorithm when planning short-term modes of power systems containing energy storage devices makes it possible to significantly align load schedules. This leads to a corresponding reduction in costs associated with the production of electricity at power plants due to the improvement of their operating modes, with the loss of electricity in networks due to their unloading. In addition, the regulatory capability of energy storage devices creates favorable conditions for the efficient use of power plants operating on renewable energy resources in the energy system.

4 CONCLUSIONS

The study addresses the optimization of short-term operating modes in electric power systems with energy storage devices. Based on the conducted research, the following key conclusions have been drawn:

1) A mathematical model for the problem of optimization of the modes of electric power systems containing energy storage devices when planning their short-term modes has been proposed.
2) An algorithm for leveling the consumer load schedules in electric power systems when optimizing their modes using the regulatory capabilities of energy storage devices is given.
3) Based on the research carried out using the example of the central part of the main electrical networks of the “National electric grid of Uzbekistan” JSC it was established that the use of the proposed model and algorithm makes it possible to significantly equalize load schedules through the use of the regulating capabilities of energy storage devices. This leads to a corresponding reduction in costs as a result of unloading elements of the electrical network and improving operating conditions of power plants.
4) The proposed mathematical model and optimization algorithm can be used when planning short-term modes of electric power systems containing energy storage devices.

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