Optimal Planning of Daily Modes of Electric Power Systems Containing Energy Storage Devices

Tulkin Gayibov[1, a)], Boburjon Murodov[2], Alisher Shanazarov [1]

[1] *Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan*
[2] *The joint-stock company "National Electric Grids of Uzbekistan", 100084 Tashkent, Uzbekistan*

[a)] *Corresponding author: tulgayibov@gmail.com*

Abstract. The development of electric power systems (EPS) all over the world at the present stage is characterized by the introduction of various power plants operating on renewable energy resources. Under these conditions, the rational use of generated energy and reliable operation of the electric power system sometimes require the installation or construction of various energy storage devices. While energy storage devices installed directly at renewable energy power plants are used to smooth out sudden fluctuations in their generated power, storage devices installed at locations separate from the power plants ensure optimal operation of the power system. Ensuring such optimal operation requires preliminary planning of daily operation modes using appropriate mathematical models and algorithms, which are currently not sufficiently sophisticated. Therefore, this paper proposes a mathematical model and algorithm for optimizing the daily operation modes of complex power supply systems incorporating energy storage devices. The results of examining of their effectiveness are presented using the example of optimizing the daily operation mode of the central part of the power system of the Republic of Uzbekistan, with storage batteries installed at four substations. The results of the study revealed that optimal regulation of battery modes throughout the day can provide significant economic benefits by aligning the load schedules of thermal power plants.

INTRODUCTION

The development of modern energy system throughout the world is characterized by the widespread introduction of various types of power plants operating on renewable energy resources into them. In such energy systems, for the rational use of generated and to ensure reliable operation of the EPS, often use installation or construction of various energy storage devices. While energy storage devices installed directly at renewable energy power plants are used to smooth out sudden fluctuations in their generated power, storage devices installed at locations separate from the power plants can ensure optimal operation of the power system, which can allow to obtain an additional economic effect by align the load schedules of existing thermal power plants (TPPs). Currently, the existing literature contains a number of works devoted to modeling and solving the problems of optimizing EPS modes containing adjustable storage devices. Such works can include, in particular, [1-9]. They undoubtedly made a great contribution to the development of the theory and practice of solving the problem under consideration. At the same time, they cannot be directly used to solve problems of optimizing EPS modes taking into account the regulatory capabilities of storage devices. In [1], a battery energy management system for optimal distribution of energy during the day in a distributed generation environment of DC networks is proposed. The objective function of optimization is the total cost of electricity received from the external grid. In [2], a method for optimizing a power supply system including a dynamic load, a wind turbine, batteries, a photovoltaic installation and a diesel generator is proposed. The objective of the proposed approach is to minimize the total cost, the cost of energy and maximize the benefit-to-cost ratio, maximize the use of renewable energy resources and minimize the operation of the diesel generator. In [3], the results of a study of various power management schemes in microgrids containing batteries are presented. In [4], an analysis of the costs and benefits of optimal battery management is carried out. The advantages of increasing the reliability of the battery system at the planning stage are considered. In [5], the issues of increasing reliability and efficiency due to energy storage in a distributed generation system and microgrids are studied. A literature review in [6] found that energy storage devices offer significant potential for maximizing energy efficiency in distribution networks. The work in [7] is devoted to optimization issues in a hybrid distribution system consisting of photovoltaic modules, wind turbines, and batteries. A mathematical model and an algorithm for solving the problem of minimizing the total active power losses and the deviation of node voltages from their nominal values are presented. In [8], a two-layer optimization strategy is proposed for an energy storage system (battery) for implementing primary grid frequency regulation in order to solve the problem of frequency fluctuations caused by the dynamic power imbalance between the power system and the load when connecting a large number of new energy sources to the grid. In [9], a general model is proposed for capturing the changing rate of charge change as a nonlinear function of the charging/discharging power. Since they are designed mainly to optimize the operating modes of storage batteries as part of hybrid, distribution or autonomously operating systems.

In connection with the above-mentioned conditions, the development of models and algorithms for optimizing the modes of EPS containing storage devices in the direction of further increasing their efficiency remains relevant.

This paper proposes a mathematical model and algorithm for solving the problems of optimizing the modes of EPS containing adjustable storage batteries when planning their short-term modes.

MATHEMATICAL MODEL AND OPTIMIZATION ALGORITHM

The mathematical model of the problem of optimizing the mode of the EPS containing storage devices for the period *T* can be formulated as follows:

minimize the objective function, which is a function of the total fuel costs in TPPs.

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

taking into account constraints:

- on active power balance for each of time interval *t*.

$$\sum_{i=1}^{n} P_i^{(t)} + \sum_{j=1}^{m} P_{ES.j}^{(t)} = P_L^{(t)}, \quad t = 1, 2, ..., T \ ; \tag{2}$$

- on the minimum and maximum permissible capacities of the stations participating in the optimization

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

- on the minimum and maximum charging and discharging powers of the storage devices

$$- P_{ES.j}^{ch.\max} \le P_{ES.j}^{(t)} \le P_{ES.j}^{dch.\max}, \quad j = 1, 2, ..., m; \quad t = 1, 2, ..., T \ , \tag{4}$$

- on the minimum and maximum permissible amounts of energy stored in devices

$$\alpha W_{ES.j} \le W_{ES.j}^{bal} - \sum_{i=1}^{t} P_{ES.j}^{(i)} \le W_{ES.j} , \quad j = 1, 2, ..., m; \quad t = 1, 2, ..., T \ ; \tag{5}$$

where *n, m*- amounts of TPP and storage devices, which participate in optimization; $P_i^{(t)}$, $P_{ES.j}^{(t)}$ - powers of *i*-th TPP and *j*- th energy storage device at *t*-th time interval; $P_L^{(t)}$ - the total load of the power system in the *t*-th time interval, which also includes the total losses of active power in electrical networks; $W_{AB.j}^{bal}$ - the amount of balance energy in the *j*-th storage device at the beginning and at the end of the period under consideration *T*; $W_{ES.j}$ – capacity of *j*-th storage device; *α* – depth of discharge coefficient of the *j*-th storage device. In the adopted model, the positive sign at $P_{AB.j}^{(t)}$ corresponds to the discharge mode, and the negative sign corresponds to the charge mode of the storage device.

This optimization model takes into account hydroelectric power plants participating in the optimization by reducing them to the category of fictitious thermal power plants by multiplying their energy characteristics by a coefficient representing the fuel equivalent of water consumption, which is defined as in [12]. And the capacity of power plants operating on renewable energy resources for each time interval is included as components in the power balance condition (2).

In the proposed algorithm for solving the resulting problem, the integral constraints (5) are represented by two constraints and the are taken into account by penalty functions expressed in quadratic form as in [10-13]:

$$PF_{\max.j}^{(t)} = \beta\left(-\sum_{i=1}^{t} P_{ES.j}^{(i)} - W_{ES.j} + W_{ES.j}^{bal}\right)^2, \quad j = 1, 2, ..., m; \quad t = 1, 2, ..., T; \tag{6}$$

$$PF_{\min.j}^{(t)} = \beta\left(\sum_{i=1}^{t} P_{ES.j}^{(i)} - W_{ES.j}^{bal} + \alpha W_{ES.j}\right)^2, \quad j = 1, 2, ..., m; \quad t = 1, 2, ..., T, \tag{7}$$

where β is a penalty coefficient, the value of which is taken as a small positive number that does not cause sharp fluctuations at the beginning of the iterative calculation process. To prevent violation of restrictions due to insufficient penalties, a sequential shift of the boundaries of the admissible region is used in subsequent iterations [11-13].

Constraint (2) is taken into account by allocating the capacities of the balancing station (for example, the 1st station) in all time intervals as dependent variables.

$$P_1^{(t)} = P_L^{(t)} - \sum_{i=2}^{n} P_i^{(t)} - \sum_{j=1}^{m} P_{ES.j}^{(t)}, \quad t = 1, 2, ..., T. \tag{8}$$

Constraint (3) for the balancing station is also taken into account by penalty functions $PF_{\min.1}^{(t)}$, $PF_{\max.1}^{(t)}$, represented as (6) and (7).

In this case, to take into account functional constraints in the form of inequality, the quadratic form of the penalty function is used. Therefore, before performing each iteration, a check for the constraint fulfillment is made. If it is fulfilled, the next iteration is performed without taking it into account. Otherwise, i.e., provided that the constraint is fulfilled, at the next iteration it is taken into account by the corresponding penalty function.

Thus, the solution to the problem is reduced to minimizing the generalized objective function.

$$F = \sum_{t=1}^{T}\sum_{i=1}^{n} B_i^{(t)}\left(P_i^{(t)}\right) + \sum_{t=1}^{T}\sum_{j=1}^{m} PF_{\max.j}^{(t)} + \sum_{t=1}^{T}\sum_{j=1}^{m} PF_{\min.j}^{(t)} + \sum_{t=1}^{T} PF_{\max.1}^{(t)} + \sum_{t=1}^{T} PF_{\min.1}^{(t)} \to \min \tag{9}$$

taking into account restrictions (3) (except for the balancing station) and (4).

At each k-th step of the iterative process, the capacities of all stations participating in the optimization (except for the balancing station), as well as the capacities of the storage batteries, are determined using the gradient method (for example, if we take the 1st station as the balancing station) as:

$$P_i^{(t)(k)} = P_i^{(t)(k-1)} - h_i^{(t)(k)} \cdot \frac{\partial F}{\partial P_i^{(t)}}^{(k-1)}, \quad i = 2, 3, ..., n; \quad t = 1, 2, ..., T; \tag{10}$$

where $h_i^{(t)(k)}$ - a step towards the minimum of the function F on active power of the i-th station in the t-th time interval and the k-th iteration, which is determined on the conditions, presented in [12, 13, 15, 16].

The capacities of the batteries at each iteration and in each time interval $P_{ES.j}^{(t)(k)}$ are determined in the same way as in formula (10). The capacities of the balancing station at the corresponding iteration and time interval are found by (8).

The generalized objective function (9) is a complex function of the capacities of all stations and storage batteries. Therefore, the derivatives with respect to these variables are calculated as follows (for example, with respect to the capacities of the stations):

$$\frac{\partial F}{\partial P_i^{(t)}} = \frac{\partial \overline{F}}{\partial P_i^{(t)}} + \frac{\partial \overline{F}}{\partial P_1^{(t)}} \cdot \frac{\partial P_1^{(t)}}{\partial P_i^{(t)}}, \quad i = 2, 3, ..., n. \tag{11}$$

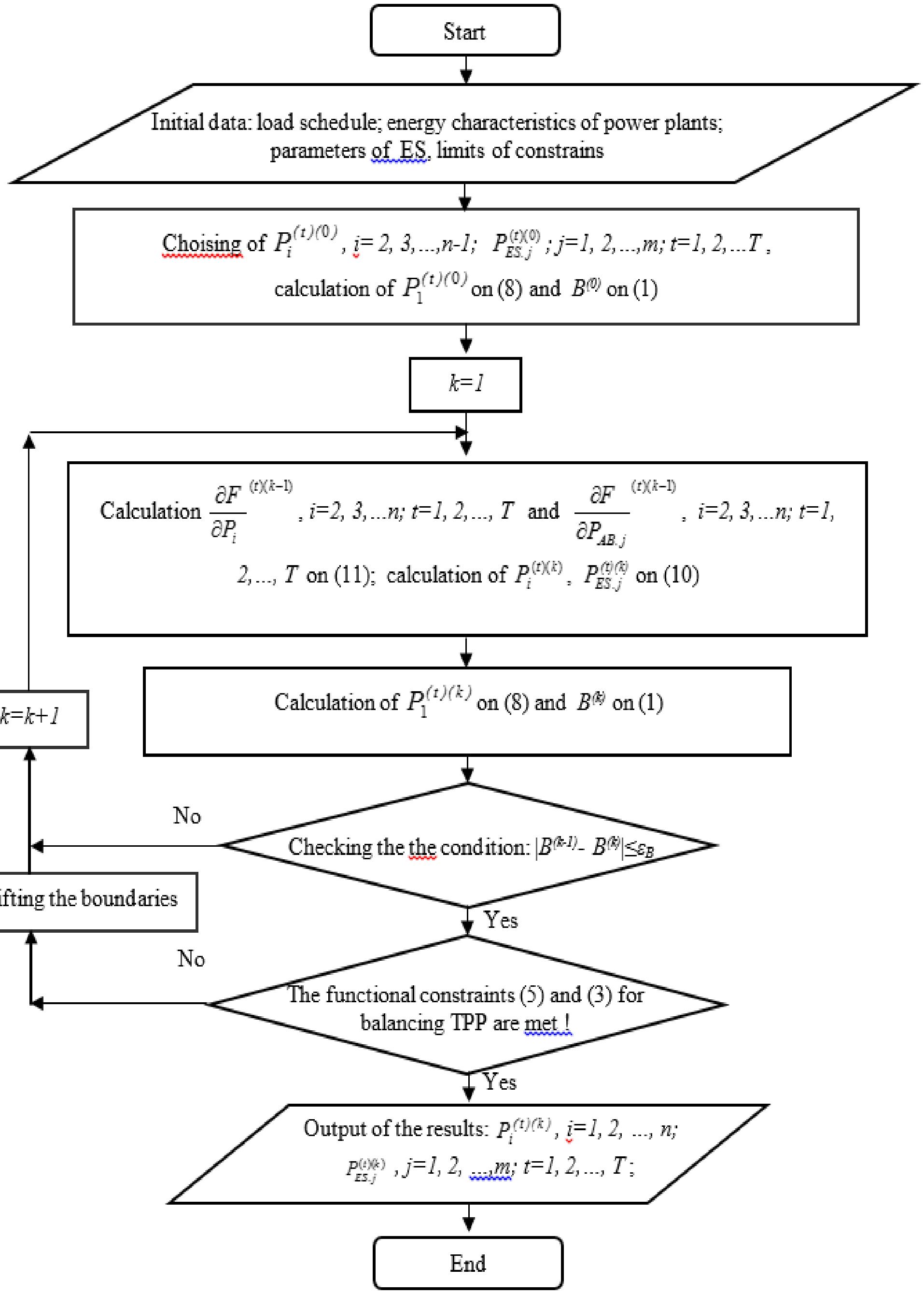

FIGURE 1. Enlarged block diagram of the optimization algorithm

Figure 1 shows a enlarged block diagram of the developed algorithm for optimizing the modes of the power system containing storage devices.

RESEARCH RESULTS

The efficiency of the proposed mathematical model and algorithm is studied using the example of optimization of the mode of the Central part of the EPS of the Republic of Uzbekistan.

The daily cycle is represented by 8 characteristic time intervals. The graph of the total loads of the power system is given in Table 1.

TABLE 1. Graphs of daily total loads

Parameter	Time intervals, t							
	1	2	3	4	5	6	7	8
$P_L^{(t)}$, MW	2590,0	2980,0	3340,0	2985,0	2795,0	3075,0	3545,0	2940,0

Optimization is carried out for the active capacities of the thermal power plants located in nodes 3, 14, 15, 21, 28 and storage batteries with a capacity of 200 MWh at substations in nodes 5, 19 and 27, as well as 500 MWh in node 4. The maximum permissible charging and discharging powers of storage batteries with a capacity of 200 MWh are 100 MW and 200 MW, respectively. And for a 500 MWh storage battery - 200 MW and 334 MW.

The consumption characteristics of equivalent fuel for the thermal power plants participating in the optimization are presented in quadratic form as (in tons of equivalent fuel/hour – t.f.e./h.)

$$B_i = a_i + b_i \cdot P_i + c_i \cdot P_i^2,$$

the coefficients of which are given in Table 2.

TABLE 2. Coefficients of thermal power plant consumption characteristics

№	TPP	a_i	b_i	c_i	P_i^{min}, MW	P_i^{max}, MW
1	TPP-28	29,537	0,2413	0,0000587	450	900
2	TPP-21	29,537	0,2413	0,0000587	450	900
3	TPP-3	45,146	0,2348	0,0000729	560	1120
4	TPP-15	19,707	0,2412	0,0000882	300	600
5	TPP-14	9,877	0,2409	0,0001770	150	300

The Syrdarya TPP with units operating on a 500 kV bus was selected as the balancing station.

To compare the results, the electric power system mode was first optimized without taking into account the storage batteries. The results are shown in Table 3.

Table 4 shows the results of the optimization of the electric power system mode taking into account the storage batteries at all four substations based on the use of the proposed mathematical model and calculation algorithm.

TABLE 3. Graphs of optimal daily loads of thermal power plants in the absence of storage batteries (in MW)

No	Power sources	Time intervals, t								Fuel consumption per cycle, t.e.f.
		1	2	3	4	5	6	7	8	
1	TPP-28	669,20	771,82	867,07	773,13	723,14	796,81	900,00	761,29	2037,43
2	TPP-21	667,93	770,28	865,87	771,59	721,73	795,21	900,00	759,78	2034,10
3	TPP-3	583,66	666,33	743,08	667,39	627,12	686,47	845,00	657,85	1923,70
4	TPP-15	446,06	514,38	575,19	515,25	481,97	531,12	600,00	507,37	1357,06
5	TPP-14	223,14	257,19	288,79	257,63	241,04	265,49	300,00	253,70	678,88
Total load of TPP		2590,0	2980,0	3340,0	2985,0	2795,0	3075,0	3545,0	2940,0	2590,0
Total fuel consumption, t.e.f./h.		858,52	985,60	1107,08	987,26	924,73	1017,27	1178,37	975,35	8031,17

TABLE 4. Graphs of optimal daily loads of thermal power plants and charge-discharge power of storage batteries

No	Power sources	Time intervals, *t*								Fuel consumption per cycle, t.e.f.
		1	2	3	4	5	6	7	8	
1	TPP-28	838,94	778,80	810,94	779,75	813,18	792,43	780,54	745,32	2061,37
2	TPP-21	772,26	772,37	835,65	773,33	725,32	786,45	835,20	740,14	2028,59
3	TPP-3	687,87	637,87	720,95	674,64	697,44	684,87	702,19	646,78	1924,66
4	TPP-15	487,32	517,99	546,09	518,62	492,01	526,89	546,26	495,50	1342,42
5	TPP-14	267,73	258,98	259,80	259,29	253,72	263,45	239,21	247,79	665,93
Total load of TPP		3054,12	3002,01	3173,43	3005,67	2981,67	3054,09	3103,40	2875,53	-
6	АБ-5	-94,50	-5,50	41,56	-5,16	-34,23	5,23	76,51	16,12	-
7	АБ-19	-94,50	-5,50	41,56	-5,16	-34,23	5,23	76,51	16,12	-
8	АБ-27	-94,50	-5,50	41,56	-5,16	-34,23	5,23	76,51	16,12	-
9	АБ-4	-180,63	-5,50	41,90	-5,16	-84,00	5,23	212,07	16,12	-
Total power of BSS		-464,13	-22,00	166,58	-20,64	-186,69	20,92	441,60	64,48	
Total fuel consumption,t.e.f./h		1010,59	992,91	1050,44	994,12	986,50	1010,27	1027,04	951,10	8022,98

In these results, the positive sign before the battery power corresponds to its discharge mode, and the negative sign - to the charging mode. In the calculations, it is assumed that at the beginning and end of the day the battery storage system contains energy corresponding to the maximum depth of discharge (in this case, equal to 50% of the nominal capacity).

As a result of the conducted research work, it was revealed that with the existence of storage batteries with a capacity of 200 MWh at three substations with a maximum charge power of 100 MW and discharge of 200 MW, as well as at node 9 with a capacity of 500 MWh. with a maximum charge power of 200 MW and a discharge of 300 MW, the total fuel consumption in them per control cycle (in this case, 8 hours) decreases by 8.19 t.e.f. If we take the duration of each of the characteristic intervals of the day to be equal to 3 hours, then the savings per day are 24.57 t.e.f.

The reduction in the total fuel consumption in thermal power plants per control cycle occurs due to the alignment of load schedules, due to ensuring optimal charging and discharging modes of storage batteries. Table 4 and Fig. 2 show the graphs of the total loads of all thermal power plants and storage batteries. They clearly show the alignment of the graph of the total load of the thermal power plant with the existence of storage batteries at substations.

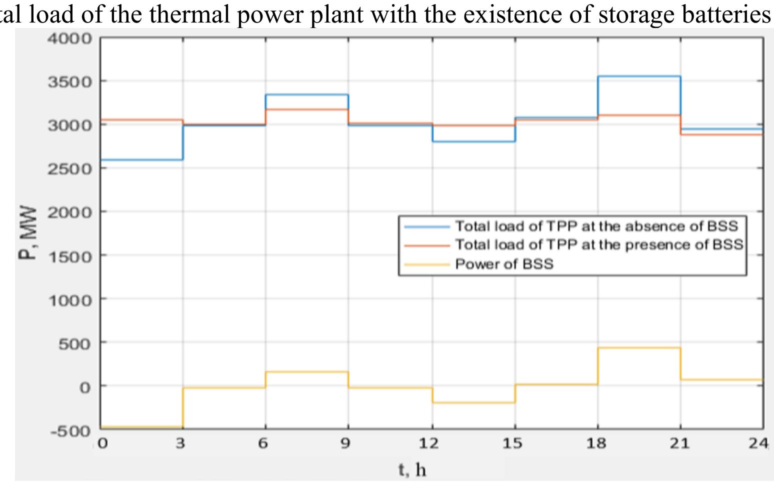

FIGURE 2. The schedules of total loads of TPP at absence and presence of battery storage systems.

Thus, in this case, the alignment of the schedule of total loads of thermal power plants due to the provision of optimal modes of charging and discharging batteries leads to a significant reduction in fuel consumption in thermal power plants.

CONCLUSIONS

1. A mathematical model of the problem of optimizing the modes of electric power systems containing battery storage system is proposed.
2. An algorithm for solving the problem of optimizing the modes of electric power systems containing adjustable storage batteries is proposed.
3. It is established that leveling the schedule of total loads of thermal power plants by ensuring optimal charging and discharging modes of storage batteries allows to significantly reduce the total fuel costs in them.

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