JOURNAL OF CRITICAL REVIEWS

ISSN- 2394-5125 VOL 7, ISSUE 15, 2020

OPTIMIZATION OF LOADING SCHEDULES OF CONSUMERS WITH OWN STATIONS ON THE BASIS OF RENEWABLE ENERGY SOURCES

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Received: 16 March 2020 Revised and Accepted: 17 June 2020

Abstract
Currently, many enterprises are installing their own stations for generating electricity based on solar and wind energy, which may have batteries. At the same time, part of the consumed electricity by the enterprise during the day can be taken from the electric power system (EPS). Changing the electricity tariff during the day sets the task of determining the optimal load schedules of such consumers relative to EPS. In the existing literature, mathematical models and solution methods which can be used to determine the optimal schedules of power consumption from EPS and power output by the own station, taking into account their characteristics are not found. In this paper, we propose a mathematical model and an algorithm for solving the problem of optimization of load schedules for consumers with their own stations based on renewable energy resources, taking into account the capabilities of batteries. The results of evaluation the effectiveness of proposed model and algorithm are given.
Keywords: Optimization, renewable energy source, power station, load schedule, mathematical model, cost of electricity, load schedule.

1. Introduction

High rates of energy consumption in all spheres of human activity, limited reserves of fossil fuels and increased need to protect the environment from harmful emissions determine the importance of increasing the level of electricity generation in power stations using renewable energy resources, in particular, solar and wind energy.
In recent years, numerous of publications devoted to the development of electricity production technologies based on solar and wind energy, their rational use by consumers, and their optimal integration into electric power systems have appeared. They are important for developing of research and practical works in this direction. At the same time, the development of technologies for the rational use of stations operating on renewable energy resources, taking into account all the influential and limiting factors, remains not perfect. One of these problems is associated with the determination of optimal load schedules for consumers which have own power stations using renewable energy resources, relative to EPS.
Currently, many enterprises around the world are widely introducing generating installations that operate on solar and wind energy. The generated power schedule are determined by the weather conditions. For the rational use of energy received from such installations, batteries that serve to accumulate energy during hours of excess and give them out during hours of minimum or absence of generated power can be used [1-3]. On the other hand, the use of batteries leads to a sharp increase in the economic costs associated with the construction and operation of such installations. Therefore, the feasibility of using the batteries in such installations is determined on the basis of solving the corresponding optimization problems [1, 2, 4-6].
In order to increase the reliability of power supply, the rational use of such stations and obtain economically advantageous, such enterprises are also connected to electric power systems (EPS), where the tariff of transmitted electricity, in general, changes during the day. In such cases, the task of determining the optimal schedules of the power output by the own station and the load schedule relative to the EPS at minimum total cost of generating and purchasing electricity in the enterprise per day is ensured. Since in some hours (or characteristic intervals) of a day, it may turn out to be more profitable to receive power from an EPS, than to generate it by its own station, taking into account the capabilities of the energy storage system. Such a problem, in the general case, is a complex optimization problem with many simple, functional, and integral constraints in the form of equalities and inequalities.
In the existing literature, rigorous methods and algorithms for solving such problems based on the use of appropriate mathematical models are not found. In [3], the problem of optimizing an autonomous power supply system based on

ISSN- 2394-5125VOL 7, ISSUE 15, 2020

solar and wind energy is considered. In works [4, 5], mathematical models and methods for solving the problems of optimization of location site and parameters of solar photovoltaic stations with batteries in distributed electric networks were proposed. However, their direct use for the effective solution of the problem considered in this paper presents corresponding difficulties. In [7], an algorithm for optimization of consumer load schedules under the conditions of providing the possibility of regulating the loads in individual intervals for a day in a certain range without changing the amount of electricity required for this period is described. It can be used to solve the problem in question only in special cases. Therefore, the development of a mathematical model and an algorithm for solving the problem of optimization of load schedules of consumers with their own power stations operating on renewable energy resources, taking into account all the influencing and limiting factors, remains an important task.
In this paper, we propose a mathematical model and a method for solving the problem of optimization of daily load schedules of own generating unit and relative to the EPS a consumer's with stations operating on renewable energy sources.

2. Mathematical model and method of solution

The station using renewable energy, in addition to energy conversion modules, includes additional equipments such as controllers for maximum power take-off of modules, inverters that convert direct current to alternating current, a monitoring system to monitor the parameters of the station's operating mode. It may also include batteries for the rational use of electricity generated by the station. In this paper, we consider consumer's own station with a battery. The figure 1 shows a schematic diagram of a consumer with a station that uses renewable energy (SRE), which is connected to the EPS.

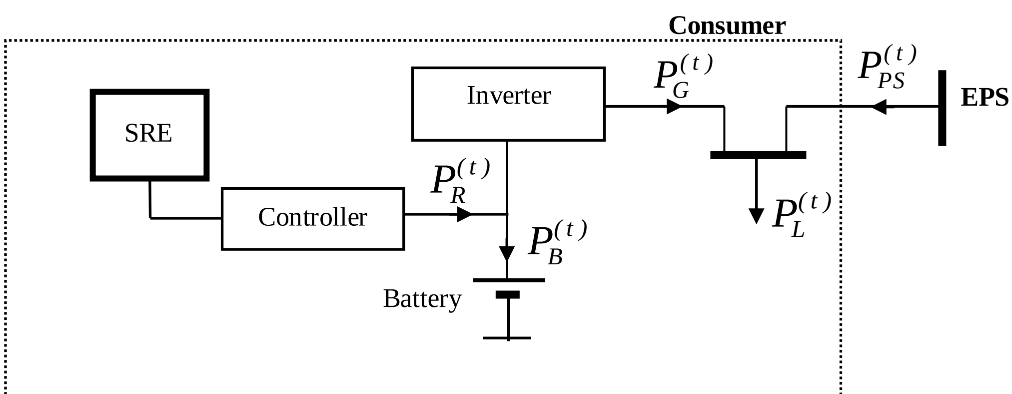

FIGURE 1: Schematic diagram of a consumer with own station using renewable energy.

In this problem the electric capacity of the battery W, consumer load schedule for the planned day $P_L(t)$, schedule of power output of a station using renewable energy $P_R(t)$, minimum and maximum boundary power of charging (discharging with a negative sign) of the battery are known. The optimal schedules of the power output by the consumer own station $P_G(t)$, the power received from EPS $P_{PS}(t)$ and the charging/discharging of the battery $P_B(t)$ are determined. The schedule for power output of own station depends on weather conditions. Therefore, it is determined in advance as a result of processing by appropriate methods of the accumulated statistical data during its operation.

The objective function, which is minimized, is the sum of the costs of the received and generated by own station during the day:

$$З = \sum_{t=1}^{24} \left[C_t P_{PS}^{(t)} + \beta P_G^{(t)} \right] \rightarrow min\,. \tag{1}$$

The limitations are:
consumer power balance equation for each hour of the day

$$P_{PS}^{(t)} + P_G^{(t)} = P_L^{(t)}, \quad t = 1, 2, ..., 24\,; \tag{2}$$

the equation of the balance the active power of own station, charging the battery and inverter for each hour of the day

$$P_R^{(t)} - P_B^{(t)} = P_G^{(t)}, \quad t = 1, 2, ..., 24\,; \tag{3}$$

inequality on the maximum possible charging power (discharge with a negative sign) of the battery

$$-P_{B.max} \le P_B^{(t)} \le P_{B.max}, \quad t = 1, 2, ..., 24\,; \tag{4}$$

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inequality on the minimum and maximum possible generated power for each hour of the day, determined by the ability of the inverter

$$0 \le P_G^{(t)} \le P_{G..max}^{(t)}, \quad t = 1, 2, ..., 24; \tag{5}$$

inequality on battery capacity

$$W_{bal} + \sum_{k=1}^{t-1} \left[P_R^{(k)} - P_G^{(k)} \right] \le W, \quad t = 2, 3, ..., 24; \tag{6}$$

inequality on the possibility of charging and discharging the battery in every hour of the day

$$-P_B^{(t)} \le W_{bal} + \sum_{k=1}^{t-1} \left[P_R^{(k)} - P_G^{(k)} \right] \le W - P_B^{(t)}, \quad t = 2, 3, ..., 24; \tag{7}$$

where C_t is the unit cost (price) of electricity in tth hour of a day; β is the unit cost of electricity generated by own station; $P_G^{(t)}, P_{PS}^{(t)}$ are the active power generated by the consumer and received from the EPS at tth hour of the day; $P_R^{(t)}$ is the power generated by own station in the tth hour of the day; $P_L^{(t)}$ is the total active load of the consumer at tth hour of the day; $P_{B..max}$ is the maximum possible battery charging/discharging power; $P_{G..max}^{(t)}$ is the maximum possible generated power by the consumer at tth hour of the day; W is the electric capacity of the battery; W_{bal} is the residual electricity in the battery from the previous day.

In this model, the unit cost of electricity generated by own station, which includes operating costs, is assumed constant regardless of the generated power.

To simplify the obtained problem, substituting expressions for $P_G^{(t)}$ to the objective function (1) and constraints (5), (6), (7), we can exclude these variables and equations (3).

The resulting problem is a linear mathematical programming problem. Therefore, the use of a simplex method for its solution is proposed.

3. Results and discussions

The effectiveness of the proposed mathematical model and the algorithm for solving the problem under consideration is studied by optimization the load schedule of a small enterprise with its own station that uses renewable energy. The daily schedules of consumer loads and power delivery by the own station, as well as a change in the electricity tariff during the day are given in Table 1. The electric capacity of the battery is W = 300 kWh. The residual energy in the battery from the previous day is W_{bal} = 0. The maximum allowed charge/discharge power of the battery is $P_{B.max}$ = 50 kW. The unit cost of generated electricity by own station, which includes operating costs, is β = 0.088 $ /kWh.

TABLE 1: Daily schedules of consumer loads and station power output.

t, h.	1	2	3	4	5	6	7	8	9	10	11	12
$P_L^{(t)}$, kW	80.0	75.0	70.0	70.0	75.0	85.0	90.0	100.0	110.0	125.0	130.0	120.0
$P_R^{(t)}$, kW	0.0	0.0	0.0	0.0	0.0	5.0	15.0	20.0	35.0	60.0	70.0	90.0
C_t, $/kWh	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.12	0.12	0.12	0.12	0.12
t, h.	13	14	15	16	17	18	19	20	21	22	23	24
$P_L^{(t)}$, kW	115.0	110.0	125.0	145.0	165.0	170.0	180.0	180.0	160.0	130.0	105.0	90.0
$P_R^{(t)}$, kW	100.0	100.0	100.0	90.0	70.0	60.0	35.0	10.0	0.0	0.0	0.0	0.0
C_t, $/kWh	0.12	0.12	0.12	0.12	0.14	0.14	0.14	0.14	0.14	0.12	0.09	0.09

Table 2 shows the optimization results using the proposed mathematical model and simplex method, which are the optimal schedules of the power output by the own station P_G(t), the power received from the EPS P_{PS}(t) and the charging/discharging of the battery P_B t). In it, the battery charging power is represented by positive, and the discharge by negative signs. The daily total cost of the electricity generated by the own station and received from the EPS is $ 295.48.

TABLE 2: Daily schedules of consumer loads and power output of the station having a battery.

t,h	1	2	3	4	5	6	7	8	9	10	11	12
$P_G^{(t)}$, kW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0	35.0	50.0	55.0	40.0
$P_{PS}^{(t)}$, kW	80.0	75.0	70.0	70.0	75.0	85.0	90.0	85.0	75.0	75.0	75.0	80.0
$P_B^{(t)}$, kW	0.0	0.0	0.0	0.0	0.0	5.0	15.0	5.0	0.0	10.0	15.0	50.0
t,h	13	14	15	16	17	18	19	20	21	22	23	24
$P_G^{(t)}$, kW	50.0	50.0	50.0	40.0	120.0	110.0	85.0	60.0	50.0	50.0	0.0	0.0
$P_{PS}^{(t)}$, kW	65.0	60.0	75.0	105.0	45.0	60.0	95.0	120.0	110.0	80.0	105.0	90.0
$P_B^{(t)}$, kW	50.0	50.0	50.0	50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	0.0	0.0

To compare the optimization results, table 3 shows the schedules of these power gained at the absence of a battery. In this case, the daily total cost of the generated by own station and received from EPS electricity is $ 301.08.

TABLE 3: Daily schedules of consumer loads and power output of the station without a battery.

t, h	1	2	3	4	5	6	7	8	9	10	11	12
$P_G^{(t)}$, kW	0.0	0.0	0.0	0.0	0.0	5.0	15.0	20.0	35.0	60.0	70.0	90.0
$P_{PS}^{(t)}$, kW	80.0	75.0	70.0	70.0	75.0	80.0	75.0	80.0	75.0	65.0	60.0	30.0
t, h	13	14	15	16	17	18	19	20	21	22	23	24
$P_G^{(t)}$, kW	100.0	100.0	100.0	90.0	70.0	60.0	35.0	10.0	0.0	0.0	0.0	0.0
$P_{PS}^{(t)}$, kW	15.0	10.0	25.0	55.0	95.0	110.0	145.0	170.0	160.0	130.0	105.0	90.0

Thus, in the considered example, the economic efficiency from using the proposed mathematical model and optimization the load schedule of the consumer having his own station using renewable energy is 2%. Such a small efficiency in the considered example is associated with a small range of changes in the electricity tariff during the day.

In the considered example, the schedule of the generated power of the station using renewable energy was accepted as deterministic. In general, such schedules are probabilistic or partially indefinite. In such cases, the problem is solved using the mathematical model proposed here and the optimization method, taking into account the nature of the load schedules by the algorithms described in [8-11]

4. Conclusion

A mathematical model and a method for solving the problem of optimization the load schedules of consumers with their own power stationts using renewable energy resources are proposed. It is shown that in conditions of change the electricity tariff during the day it will be possible to achieve a significant economic effect by optimization the load schedules of own stations and EPS.

In terms of a probabilistic nature and partial uncertainty of the initial information, the proposed mathematical model and solution method can be used taking into account this nature of the data by existing algorithms.

The proposed mathematical model and method for solving the problem can be used for optimal planning of short-term operation of consumers with their own stations.

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