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Optimization of Load Schedules of Enterprises with Hybrid Power Plants Operating on Renewable Energy Sources

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ABSTRACT: This article discusses the issues of optimal planning for the distribution of enterprises' loads between electric power systems and their own power plants operating on renewable energy sources. A mathematical model and an algorithm for solving the problem under consideration are proposed. Based on the presented research results, the effectiveness of the proposed model and calculation algorithm is shown.

KEYWORDS: Optimization, renewable energy, power station, load schedule, mathematical model, electricity price.

I. INTRODUCTION

At present, the issues of developing and improving the technologies of production of electricity based on renewable energy resources, as well as optimization of operating modes of their activity are important problem. One of the effective technologies involves the use of hybrid power plants, in which two or more types of primary energy resources are used to generate electricity. Such power plants can operate in autonomous - not connected to the main power system and connected to it electrical networks.

In the existing literature, a number of works are devoted to analyzing hybrid power plants. However, the work to study the optimal operating modes of such installations in a short-term control cycle cannot be considered sufficient. In particular, in [1-2] the issues of optimal design of the configuration of an autonomous system with power plants operating on renewable energy resources are considered. A mathematical model and an algorithm for determination the optimal solution, in which all consumers are reliably provided with high-quality electricity at a minimal cost, are proposed. However, in these developments, the issues of optimization of load schedules of such stations (in conditions of connection to it) were not considered. In [3-6], a simulation of optimization model of hybrid stations using renewable energy sources is proposed. However, the optimization of the load schedules of such plants using renewable energy sources was not considered in them. In this regard, the study of issues of optimizing the load schedules of power plants operating on renewable energy resources remains as a urgent problem. This paper proposes a mathematical model and an algorithm for solving the problems of optimization of load schedules for consumers of industrial enterprises to their own hybrid power plants and the power system.

II. OPTIMIZATION METHOD

A hybrid power plant based on renewable energy source installed at an enterprise may consist of solar panels, wind turbines, hybrid controllers, inverters, a monitoring system, and batteries. Figure 1 shows a schematic diagram of a consumer's power system with a hybrid power plant operating on renewable energy sources.

The composition of the initial data for the problem of optimization of consumer load schedule for power station and the power system includes battery capacity W_{Gib}, consumer's daily load schadule $P_L(t)$, combined power generation curve of solar panels and wind generator $P_{Gib}(t)$, minimum and maximum limiting battery charge/discharge power (discharge power is taken with a minus sign). As a result of solving the problem, the following are determined: output power graph (load schedule) of the hybrid power plant operating on renewable energy sources (taking into account the

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Vol. 10, Issue 2, February 2023

charge/discharge power of the battery) $P_{G.Gib}(t)$, the charge/discharge graphs of batteries installed in the hybrid power plant $P_{B.Gib}(t)$, and the load curve relative to the external power system $P_{PS}(t)$.

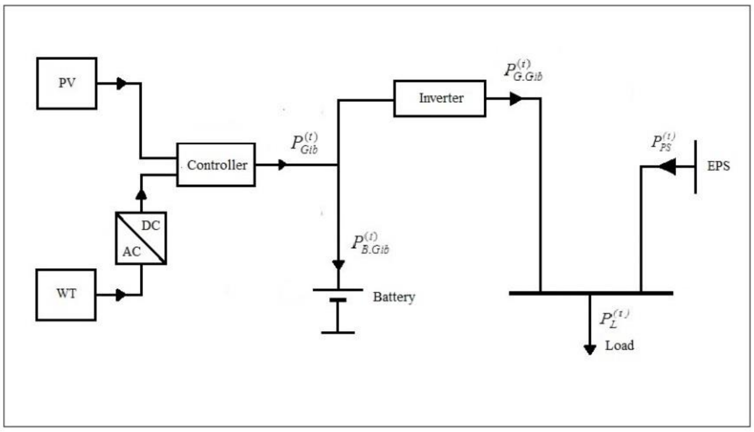

Fig 1. Schematic diagram of enterprise's power system with a hybrid power plant operating on renewable energy sources

The objective function is a generalized function of the daily cost of electricity generated by the hybrid power plant and received from the power system [7]:

$$З = \sum_{t=1}^{24}\left[C_t P_{\mathrm{PS}}^{(\mathrm{t})} + \gamma P_{\mathrm{G.Gib}}^{(\mathrm{t})}\right] \to \min$$

where $P_{G.Gib}^{(t)}$ – is the power received from the hybrid power plant operating on renewable energy sources at the *t-th* hour of the day; γ is the unit price of electricity generated by a hybrid power plant, which includes the costs of production, installation, operation and maintenance of solar paneles, wind turbines and equipments servicing them, as well as the costs associated with the agreed distribution of profits received by the manufacturer.

The constraints which have to be taken into account at optimization consist of following conditions:

The equation for the balance of active power generated by solar panels, wind turbines, and the entire hybrid power plant for each hour of the day:

$$P_{\mathrm{PV}}^{(\mathrm{t})} + P_{\mathrm{W}}^{(\mathrm{t})} = P_{\mathrm{Gib}}^{(\mathrm{t})}, \quad t = 1, 2, ..., 24$$

The active power balance in the enterprise for each hour of the day:

$$P_{\mathrm{PS}}^{(\mathrm{t})} + P_{\mathrm{G.Gib}}^{(\mathrm{t})} = P_{\mathrm{L}}^{(\mathrm{t})}, \quad t = 1, 2, ..., 24$$

The equation taking into account the charge/discharge power of the battery installed in the hybrid power plant:

$$P_{\mathrm{Gib}}^{(\mathrm{t})} + P_{\mathrm{B.Gib}}^{(\mathrm{t})} = P_{\mathrm{G.Gib}}^{(\mathrm{t})}, \quad t = 1, 2, ..., 24$$

Inequalities on the maximum possible charge/discharge power of the battery installed in the hybrid power plant (the discharge is taken with a negative sign) for each hour of the day:

$$-P_{\mathrm{B.Gib.max}}^{(t)} \le P_{\mathrm{B.Gib}}^{(\mathrm{t})} \le P_{\mathrm{B.Gib.max}}^{(t)}, \quad t = 1, 2, ..., 24$$

Inequalities for the maximum inverter power for each hour of the day:

$$0 \le P_{\mathrm{G.Gib}}^{(\mathrm{t})} \le P_{\mathrm{G.Gib.max}}^{(t)}, \quad t = 1, 2, ..., 24$$

Battery charge energy inequalities:

$$W_{bal.Gib} + \sum_{k=1}^{t-1}\left[P_{\mathrm{Gib}}^{(\mathrm{k})} - P_{\mathrm{G.Gib}}^{(\mathrm{k})}\right] \le W_{Gib}, \quad t = 2, 3, ..., 24$$

Inequalities on the possibility of charging/discharging the batteries for each hour of the day:

$$-P_{B.Gib}^{(t)} \le W_{bal.Gib} + \sum_{k=1}^{t-1}\left[P_{\mathrm{Gib}}^{(\mathrm{k})} - P_{\mathrm{G.Gib}}^{(\mathrm{k})}\right] \le W_{Gib} - P_{\mathrm{B.Gib}}^{(\mathrm{t})}, \quad t = 2, 3, ..., 24$$

where $P_{PV}^{(t)}$ – is the active power generated by the solar panel at the *t-th* hour of the day; $P_{W}^{(t)}$ – is the generated active power of the wind generator at the *t-th* hour of the day; $P_{Gib}^{(t)}$ – is the generated active power of the hybrid power plant at

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Vol. 10, Issue 2, February 2023

the *t-th* hour of the day; $P_L^{(t)}$ – is the total active load of consumers at the *t-th* hour of the day; $P_{B.Gib.max}$ – the maximum possible charging/discharging power of the battery; $P_{G.Gib.max}^{(t)}$ – permissible maximum power of inverter at the *t-th* hour of the day; W_{Gib} – is the electric capacity of the storage battery; $W_{bal.Gib}$ – the amount of electricity remaining in batteries from previous day.

According to the proposed algorithm of the mathematically described problem is solved by Cplex method.

III. RESEARCH AND RESULTS

The study of effectiveness of the described mathematical model of the problem under consideration and the algorithm for solving it was carried out for the scheme shown in Fig.1. The initial data is given in Table 1. It shows the daily load curves of the consumer, the generating capacity of the hybrid power plant operating on renewable energy sources, and the cost of electricity received from the power system by hours of the day.

The electric capacity of the storage battery is W_{Gib}= 600 kW. Remaining amount of electricity in battery from the previous day is $W_{bal.Gib}$=0. Maximum battery charge/discharge power is W_{Gib}= 100 kW. The unit price of electricity produced at a hybrid power plant operating on renewable energy sources, considering all costs is γ = 0.0705 $/kWh [9-10].

Table 1. Daily graphs of consumer loads and total power generated by solar panel and wind generator.

t, h	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$P_L^{(t)}$, kW	140	140	140	140	140	140	140	140	260	280	280	280
$P_{Gib}^{(t)}$, kW	7	7	13,7	13,7	13,7	53,7	77	97	113,7	153,7	173,7	217,7
C_t, $/ kW*h	0,09	0,09	0,09	0,09	0,09	0,09	0,225	0,225	0,225	0,16	0,16	0,16
t, h	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
$P_L^{(t)}$, kW	280	360	360	320	320	320	320	320	140	140	140	140
$P_{Gib}^{(t)}$, kW	256,3	280,1	280,1	260,1	240,1	230,1	176,3	126,3	33,7	23,7	13,7	3
C_t, $/ kW*h	0,16	0,16	0,16	0,16	0,225	0,225	0,225	0,225	0,225	0,09	0,09	0,09

Table 2 presents the optimization results based on the proposed mathematical model and the algorithm for its solution. In it the optimal active power received from the power system $P_{PS}^{(t)}$, the graph of the optimal load of the hybrid power plant $P_{G.Gib}^{(t)}$, the graphs of the optimal charge (positive sign) and discharge (negative sign) powers of the batteries installed in the hybrid power plant $P_{chgib}^{(t)}$ and $P_{dchgib}^{(t)}$ are showen.

The total daily cost of electricity received from the electric power system and hybrid power plants operating on renewable sources amounted to 537.67 US dollars.

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Vol. 10, Issue 2, February 2023

Table 2. Daily optimal load schedules.

t, h	1	2	3	4	5	6	7	8	9	10	11	12
$P_L^{(t)}$, kW	140	140	140	140	140	140	140	140	260	280	280	280
$P_{PS}^{(t)}$, kW	140	140	140	140	140	140	0	43	100,5	126,3	206,3	162,3
$P_{G.Gib}^{(t)}$, kW	0	0	0	0	0	0	140	97	159,5	153,7	73,7	117,7
$P_{ch.gib}^{(t)}$, kW	7	7	13,7	13,7	13,7	53,7	0	0	0	0	100	100
$P_{dch.gib}^{(t)}$, kW	0	0	0	0	0	0	-63	0	-45,8	0	0	0
t, h	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
$P_L^{(t)}$, kW	280	360	360	320	320	320	320	320	140	140	140	140
$P_{PS}^{(t)}$, kW	123,7	79,9	149,7	159,9	0	0	43,7	93,7	6,3	140	140	99,6
$P_{G.Gib}^{(t)}$, kW	156,3	280,1	210,3	160,1	320	320	276,3	226,3	133,7	0	0	40,4
$P_{ch.gib}^{(t)}$, kW	100	0	69,8	100	0	0	0	0	0	23,7	13,7	0
$P_{dch.gib}^{(t)}$, kW	0	0	0	0	-79,9	-89,9	-100	-100	-100	0	0	-37,4

To compare the obtained optimization results, the problem was solved for the case when the hybrid power plant does not have batteries. In this case the daily total cost of electricity received from the electric power system and hybrid power plants operating on renewable sources amounted to $582.89.

Thus, in the case under consideration, the economic efficiency from optimization the consumer load schedules for hybrid power plant operating on renewable energy sources and an energy system based on the use of the proposed mathematical model and calculation algorithm is 8.41%.

IV. CONCLUSION

1. A mathematical model and an algorithm for solving the problem of optimizatrion the daily load schedules of consumers of a manufacturing enterprise concerning its own hybrid power plant and power system are proposed.

2. It has been established that the regulation of the daily load schedules of the consumer in relation to a hybrid power plant operating on renewable energy sources and power systems in the presence of batteries makes it possible to obtain a significant economic effect.

3. The proposed mathematical model and algorithm for solving the problem under consideration can be used to optimize the daily load schedules of consumers of manufacturing enterprises of relatively own hybrid power plants and power systems.

ISSN: 2350-0328
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