Design of day-ahead load profile to improve the efficiency of commercial and industrial microgrids

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Abstract. Commercial and industrial microgrids (CIM) are created to meet the needs of businesses and corporations. The creation of the CIM, where power is generated only from renewable energy sources (RES), has a positive effect on the environment. The CIM is a local energy cell connected to the power system by a power transmission line, and includes its power plants, network, and consumers. Special rules are developed to regulate the relationship between the CIM and the power system for the violation of which a fine is imposed. Compliance with these rules by the CIM requires the creation of a CIM management strategy aimed at avoiding a fine. Within the framework of this strategy, active consumers and energy storage systems play an important role in reducing fines and maintaining the power balance in the CIM. The study aims to explore the possibility of optimal functioning of an environmentally friendly CIM without violating obligations to the power system.

1 Introduction

As electricity tariffs continue to rise, connectivity issues persist, and digital technologies advance, an increasing number of consumers opt to disconnect from the power grid and establish their microgrids. This fact negatively affects the energy reliability of the power system, the quality of electric energy and pricing for consumers that remain in the system. The key difference between a microgrid and a power system is the expanded role of the consumer. The consumer requirements will shape the microgrid characteristics [1]. The paper [2] provides an overview of microgrid management schemes and ways to protect them. The Government of the Russian Federation issued a decree to optimize the microgrid management process in Russia. This document legalizes commercial and industrial microgrids (CIMs), but imposes certain requirements on them. The study [3] outlines the prerequisites for establishing CIMs in Russia, the requirements for microgrids, and the advantages of switching to this kind of systems.

Commercial and industrial microgrid is a local energy cell connected to the power system by a power transmission line. It includes its power plants, network, and the consumer. CIMs are created to meet the needs of businesses and corporations. Main incentives to establish

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CIMs involve enhancing the resistance to potential power outages and reducing energy costs. This means that their key function is to help make profits and minimize losses for commercial and industrial consumers. Such a microgrid can be located far from the main power system, but it must maintain a connection to it. The use of distributed generation also significantly reduces the cost of network infrastructure [4]. The paper [5] provides an overview of the current state of microgrids, starting with the concept and ending with the optimization of industrial microgrids. In [6], the effect of the distributed energy resources operating in an industrial microgrid is investigated, and the CIM model is presented. The paper [7] provides an overview of articles related to industrial microgrids in terms of environmental impact, optimization of energy consumption, design, forecasting and economic aspects.

Since fossil fuels used by power plants are not renewable, they pose a threat to energy stability of the system [8]. Fossil fuels also cause serious environmental problems, such as greenhouse gas emissions, which contributes to global warming [9]. However, the ability to combine renewable energy sources is an ideal alternative to conventional ones. Solar energy, like wind energy, is a frequently used renewable energy source. The most important disadvantage of the photovoltaic and wind systems is that the power generated depends on climatic conditions. The solar power plant may not generate electricity at night or even during cloudy times. Therefore, the photovoltaic system generates power periodically, which should be compensated by other power plants or energy storage systems (ESS) [10]. Wind power plants generate power only at a certain range of wind speed.

Energy storage systems serve as a reserve of energy. They absorb excess energy or supply power when generation is scarce to fulfil load demands and mitigate fluctuations in the power output of renewable energy sources. The combination of renewable energy sources and optimal management can become an alternative to diesel generators, which are usually used in off-grid or remote areas [11].

This study applies a storage control strategy, which involves maximum use of wind and solar energy. The ESS control strategy is described in detail in [12]. The paper [13] offers a comprehensive overview of the optimal planning of hybrid generation systems.

In order to regulate the relationship and maintain the optimal performance of the CIM and the power system, special restrictions on the flow of active power from power system are developed. Violations of these restrictions will incur fines. To ensure compliance with these rules, it is essential to develop a CIM management strategy aimed at avoiding fines and maintaining a power balance in the CIM. Managing power generation becomes increasingly complex when dealing with generating stations relying on renewable energy sources, as these stations do not have a constant schedule of power generation. In the management of these microgrids, consumer demand management strategies come to the fore. Active consumers (ACs) and energy storage systems (ESSs) play a crucial role in addressing these problems within demand management strategy. The basic concepts of demand management are described in more detail in [14]

The structure of the paper is as follows. The second and the third sections characterize the problem solved and give objective of the research respectively. The fourth and fifth sections present the algorithms for making decisions on microgrid management and for calculating the optimal operating state respectively. The sixth section presents the results obtained in the study. The seventh section serves as the concluding part.

2 Problem statement

The study aims to examine the possibility of optimal functioning of an environmentally friendly (power is generated only at wind and solar stations) CIM without violating obligations to the power system. The CIM is connected to the power system by one transmission line, for which the power value and the limits of power deviations are predetermined. Failure to comply with these limits is a breach of obligations to the power system. The resources of active consumers and battery resources are considered as a reserve. Active consumers are ready to change their power consumption, following the demand management program. The paper proposes a demand management program based on the "load shifting" strategy.

Optimal CIM operation is possible if there is an optimal strategy for CIM management. In this study, the CIM management strategy is considered optimal if, when fulfilling obligations to the power system, consumers are provided with electricity without upsetting the comfort level of active consumers.

The main idea of the developed CIM management strategy is as follows. We analyse h operating states, where h is the number of operating states per day. From *h* operating states *h1* (wrong) and h2 (easy) operating states are selected. Wrong operating states are understood as the operating states in which controlled parameters are violated. Easy operating states are those where the load can be changed without violating the limits of controlled parameters. To eliminate wrong operating states, the load curves of active consumers are adjusted. There are many options to adjust the curves, which represent different numbers and various sequences of wrong operating states to be processed. Further, a certain number and a certain sequence of wrong operating states is called a branch. In this study, an algorithm for creating a CIM management strategy has been developed, where the problem of choosing the optimal distribution of control actions (CAs) between the active consumers in each wrong operating state (Problem 1) and the problem of the optimal option for adjusting the load curves in the wrong and easy operating states (Problem 2) are solved as optimization problems.

This paper is concerned with the description of the problem of optimal distribution of control actions among active consumers in a particular operating state and the calculation of the indicator that characterizes this operating state.

3 Objective function and constraints

The problem of adjusting the load curves is solved as the problem of identifying the operating state with adjusted load curves a day ahead. In the study, the planned (forecast) load curves of the active consumer are adjusted. The adjustment involves shifting the load to other hours of the considered day, subject to the following conditions: to ensure maximum compensation for the delayed power and to guarantee the effective management of CIM.

The optimality criterion is written as follows:

$$\varphi_k = \sum_l^r \left(S_k^{sch} - S_k^{real}\right) \to min, \qquad (1)$$

where $\varphi_k$is deviation of the area under the planned daily load curve (S_k^{sch}) from the area under the actual daily load curve (S_k^{real}), *k* is a branch number. Condition (1) means that the deviation of the area under the planned load curve from that under the actual load curve should be minimal, or in other words, the delayed power must be compensated.

The objective function is formulated as follows:

$$\varphi_{k(C)} = \sum_{i=1}^{h1}\left(\sum_{l=1}^{r} \varphi_{l(i)}\, C_{l(i)}\right) b_i \to min, \qquad (2)$$

Subject to constraints (3) – (6) written below and subject to Ohm's and Kirchhoff's laws, where *l* is the active consumer number, *r* is the quantity of active consumers, $C_{l(i)}$is a payment to active consumer for participation in the demand side management program, *i* is the number of an operating state, and b_i is an optimization parameter. b_i=1, if operating state belongs to the branch, b_i=0, if operating state does not belong to the branch and, hence the operating state remains without any change (a planned one).

Optimal parameters are calculated subject to equality and inequality constraints that look as follows:

$$\varphi_{k(P)} = \sum_{i=1}^{h1}\left(\sum_{l=1}^{r} \varphi_{l(i)}\, b_i\right) < \Delta S^{max}, \qquad (3)$$

where $\Delta S^{max}$is the maximum values of delayed power per day, whose compensation is assumed to be not necessary.

Branch transfer capability constraint

$$P_{EPS}^{min} < P_{EPS} < P_{EPS}^{max}. \quad (4)$$

Power balance constraint

$$\Delta P_j = 0. \quad (5)$$

Power output constraints

$$P_i^{\min(CA)} < P_i^{CA} < P_i^{\max(CA)}, \quad (6)$$

where n is the number of nodes in the power system, P_{EPS} is the power flow from the power system, $P_i^{\min(CA)}$, $P_i^{\max(CA)}$ are minimum and maximum active power at the load nodes, P_{EPS}^{min}, P_{EPS}^{max} are minimum and maximum active power flow from the electric power system, ΔP_j is the active power balance at node j.

4 Description of an algorithm to be developed

To create an optimal CIM management strategy, first, an archive of steady operating states is formed with planned (forecast) load curves and generations with the dimension $[n \times h \times 1]$, where n is the number of state variables, h is the number of points per day. The archive is written to the database. The index that characterizes this archive is assigned a deliberately large number ($\varphi_b = 1000$). Then the archive of the steady operating state is preprocessed in the following order. Wrong operating states for the studied day are identified. The controlled parameter is the active power flow from the power system. The load curves of the active consumer and the profile of active power flow from the power system are analyzed. Based on the results of the analysis, the Lin array is filled in, where the hours (operating state numbers) to which the load can be shifted are indicated (total h2).

The algorithm is described below.

The objective function and constraints are set. The left side of constraint (1) (i.e., values $\varphi_{l(i)}$) is calculated (in function "constr_b"). The input data include b array, which consists of zeroes and ones. The b array is used to calculate the numbers of operating states that will be processed in the function constr_b (branch k is filled). The output data are the values $\varphi_{l(i)}$ for the operating states of the entire branch.

The following is an algorithm for processing the operating state in the order indicated in each branch k (constr_b):

1. Set initial conditions. Setting the initial conditions is understood as adding archive_k to the database, setting $\varphi_k = \varphi_b$.
2. Perform a cycle until the number of operating states in branch k reaches that $for\ l = 1{:}\,h3$.
3. Analyse the operating state. Calculate the control actions. Solve the optimization problem for one operating state with a view to determining the optimal distribution of control actions among active consumers.
4. Perform a cycle until the number of easy operating states reaches that $for\ j = 1{:}\,h2$.
5. Perform a cycle until the number of active consumers arrives at that $for\ i = 1{:}\,r$.
6. Shift load by one hour from array Lin.
7. Calculate the adjusted state variables in easy operating state.
8. Analyse the operating state obtained. Calculate φ_l using (1), check the constraints. If $\varphi_l < \varphi_{l-1}$ and the constraints are met, then the resulting operating state is recorded in the database (archive k), $\varphi_k = \varphi_l$, go to 9. Otherwise go to 9 without recording operating states in the database.
9. Check if all operating states in the branch have been considered? If not, go to 2. Otherwise, go to 10.

10. Stop the algorithm.

5 Description of a problem of optimal distribution of control action

This study is devoted to the description of the problem of optimal distribution of control actions among active consumers in a particular operating state and the calculation of the indicator that characterizes this operating state. The problem of the optimal distribution of control actions among active consumers (in other words, the problem of obtaining an optimal operating state) is formulated as an optimization problem with equality and inequality constraints. The indicator is calculated according to (1).

The optimization problem is solved to search for the optimal operating state, which will occur after certain actions of active consumers. The optimality criterion is minimization of the difference between the deviation of the value of the active flow from the power system from the limit (ΔP_{i-j}) and the size of the control action of active consumers (ΔP). Mathematically, it is written as follows:

$$C_i \Delta P_{i-j} - \sum_{l=1}^{r} C_l^{AC} \Delta P_l \rightarrow min. \qquad (7)$$

If the flow is surplus

$$\Delta P_{i-j} = P_{i-j} - P_{i-j}^{max}\, ; \Delta P_l = P_l - P_l^{opt}. \qquad (8)$$

If the flow is deficient

$$\Delta P_{i-j} = P_{i-j}^{min} - P_{i-j}\, ; \Delta P_l = P_l^{opt} - P_l, \qquad (9)$$

where r is the number of active consumers, ΔP_{i-j} is variation of the flow in the controlled line limited by nodes *i, j* with respect to the limit, ΔP_l is the variation of the active power at load node l with respect to the nominal behavior, C_i is the fine for violation of limits in the considered period, C_l^{AC} is a payment to active consumer for participation in the demand side management program.

Objective function is written as follows:

$$\alpha C_i P_{i-j} + \alpha \sum_{l=1}^{r} C_l^{AC} \Delta P_l \rightarrow min, \qquad (10)$$

where $\alpha = 1$ if the power flow from the power system is surplus, $\alpha = -1$ if the power flow is deficient.

The active power balances at all nodes of the microgrid and inequalities are used as constraints. The inequalities are responsible for meeting the limits of a set of state variables. They look as (4), (5), (6).

6 Case study

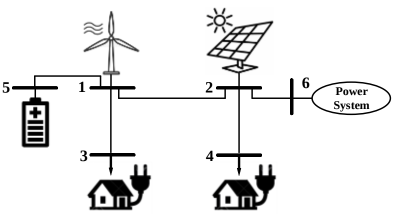

Fig. 1. Test schema.

Calculations are made for a circuit consisting of 6 nodes and 5 lines (Fig. 1). Nodes 3 and 4 are the active consumers. Node 1 represents a wind farm. Node 5 is a battery. Node 2 is a solar plant. Node 6 denotes the slack node, where power injection is the power flow from the power system. The scenario is formulated as follows: calculate the control actions for two active consumers. Consumers (nodes 3 and 4) have a control strategy of high and medium comfort, respectively. Control actions are aimed at returning the power flow from the power system to the specified limits, which look as follows:

$$4.1\text{MW} < \text{P}_6 < 5.9\text{ MW}, \tag{11}$$

where 4.1 and 5.9 are the given values, $P_6 = 5MW$.

The basic features of active consumers per day are presented in Table 1.

Table 1. Demand management program "Load shifting".

Node No.	Comfort level	Maximum, minimum	Shutdown (±)		Number of shutdowns	Response speed, min
		%	Total	One period	max	
3	High	±3.3	30	10	6	Less 15
4	Medium	±4.8	30	10	6	Less 15

6.1 Generation and analysis of operating states archive

On the basis of a simulation experiment, a 10-minute archive of the scheduled operating states with a depth of one day is compiled. Scheduled operating states are created in the same way as it was done in [15], the difference is node 2. Figure 2 shows the active power profiles at all microgrid nodes. The power profile of the wind generator (node 1) is calculated according to wind turbine characteristics with $v_{ci} = 5\ m/s$, $v_r = 10\ m/s$ and $v_{co} = 23\ m/s$, and the probability of wind speed modeled at $a = 9.8$ and $b = 10$, where a is the shape factor, b is the unevenness factor. The obtained archive is analyzed and areas under load curves are calculated (S_k^{sch}).

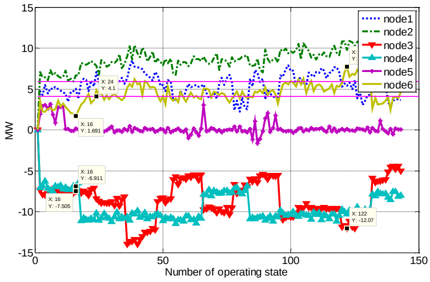

Fig. 2. Scheduled operating states (archive).

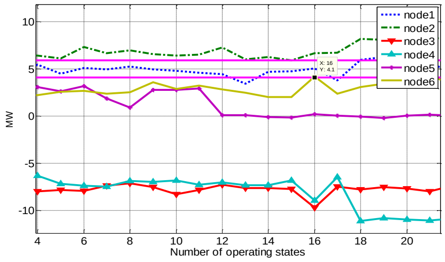

Fig. 3. Corrected operating states (part of archive).

Analysis of the power flow from the power system profile (Fig. 2, node 6) shows that constraint (11) is not satisfied in several operating states (for example, operating state 16, which we refer to below). In this case, firstly, the optimal operating state is calculated where the objective function is written as follows

$$\alpha\Delta P_6 + \alpha\Delta P_3 + \alpha\Delta P_4 \rightarrow min, \qquad (12)$$

where $\alpha = -1$.

To determine the equality constraints, the operating state variables are calculated. The inequality constraints are made up of extreme values of active power load at nodes 3, 4 (column 3, Table 1). Calculations results show that the load at nodes 3 and 4 increased to the following values: $P_3 = -9.7$MW, $P_4 = -8.9$MW.

Then, the control actions for both active consumers are calculated by the equation

$$P_l^{CA} = P_{l(sch)} - P_{l(opt)}, \qquad (13)$$

where $P_{l(sch)}$, $P_{l(opt)}$ are the values of active power at node l in the scheduled and optimal operating states, respectively. The control actions are $P_3^{CA} = -2.0$MW and $P_4^{CA} = -1.3$MW.

Then load profiles are corrected (the load equal to the control action is transferred to another operating state, for example, to operating state 122) and load flow solution is found. This means that operating state 122 has been fixed and as a result, two operating states (16 and 122) differ from the scheduled operating states. After that, S_k^{real} is calculated. Finally, φ_k is calculated by (1). $\varphi_1 = 1.2$MW.

Figure 3 shows active power profiles at all microgrid nodes after correction of load profiles. As seen, the power flow from the power system (node 6) in operating state 16 is no longer out of bounds.

7 Conclusion

The study focuses on the issue of managing CIM, where only renewable energy sources are used to generate power. CIM is connected to the power system by one transmission line. To regulate the relationship between the CIM and the power system, there is a rule developed to regulate the deviation of the power flow from the power system from its planned value.

A review of scientific papers is conducted. The authors mainly consider the general concept of microgrids, neglecting industrial microgrids. Studies are focused on the use of distributed energy resources in the form of renewable energy sources.

An algorithm is proposed to determine the CIM management strategy a day ahead. The strategy suggests adjusting load curves in wrong and easy operating states, which makes it possible to manage CIM without violating obligations to the power system. A block of the proposed algorithm is developed to provide optimal distribution of control actions among active consumers. To calculate the control actions, an optimization problem is solved with equality and inequality constraints.

Calculations are made on a 6-node scheme. The results show that with the correct adjustment of load curves, obligations to the power system will not be violated.

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