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An Approach to Short-Term Control of Integrated Energy Systems with Load-Controlled Consumers

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Abstract. Modern cities and industrial centers boast a developed energy infrastructure including fuel, electric, heating, and cooling systems. The integration of many separate system into a single technological complex can provide new functional capabilities, the application of more advanced technologies for operation, and the establishment of integrated energy systems. Such systems have a multidimensional structure of functional features and properties of development. The control of integrated energy systems with load-controlled consumers represents an urgent and a rather challenging task. The paper is concerned with an approach to short-term control of integrated energy systems with load-controlled consumers. Planning the daily electricity and heat loads is performed for an integrated energy system, including energy storage systems and electric water heaters, electrical shiftable loads of individual consumers as well as power generation by additional electricity and heat sources (PV systems, wind turbines, heat pumps). The optimal daily profiles are obtained based on the initial profiles of electricity and heat loads, photovoltaic generation and optimal profiles of using electricity and heat storage systems and shiftable load. Optimal daily electricity and heat load profiles differ greatly from the initial ones, which provides a reduction in the energy costs for the consumer.

1 Introduction

Modern energy sector represents a complex infrastructural system including fuel, electric, heating and cooling systems. Despite various types of services they render, their common goal it to create comfortable working and living conditions for the population, and to effectively facilitate the development of the national economy. To perform their functions, each of them has their production, transportation and distribution structure connecting them with consumers. They often overlap and compete in the market for energy services. This, in particular, refers to the electric, heating, gas and other systems. Being functionally independent, these systems can interact with one another under normal and emergency conditions, through the interchange of primary energy and use of energy carriers. All this is indicative of their natural integration which is growing increasingly stronger with the establishment and expansion of intelligent information and communications systems. Jointly, they represent a new structure, i.e. the intelligent integrated energy system. This structure combines certain independence of the systems involved with their coordinated participation in the accomplishment of the main goal of providing social and economic activities. The information system represents an infrastructural framework for the integrated energy system.

The properties expected to be acquired by the integrated energy system are:

• Flexibility, i.e. the capability of a system to adapt to a current level of energy consumption, variation in the ambient temperature, considering general changes in the urban infrastructure system, and adequately respond to internal and external impacts;

• Intelligence, i.e. the capability of the system to respond to the consumer needs (reduce or increase energy generation).

• Integration, i.e. the system is integrated into an urban environment, both in terms of the city planning and allocation of energy facilities and in terms of interaction among all systems of life support services of a city (electricity, heat water, fuel systems; sewerage, etc.).

• Centricity, i.e. control based on a distributed communications network where each component of the system can interact with any other component. Telecommunications network underlies the control.

• Efficiency, i.e. the equipment used meets all the modern requirements of energy efficiency. The maximum efficiency of the system is ensured by an optimal combination of technologies, including the maximum involvement of local energy resources.

• Competitiveness, i.e. the technologies are cost effective and energy resources are available to the population. Consumers can manage their energy consumption to reduce payment for it.

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• Reliability, i.e. the system meets a growing demand for energy, in particular, by using renewable resources and local fuels.

The integration of many separate systems into a single technological complex ensures the implementation of new functional capabilities, the use of more advanced technologies in operation, and the construction of integrated systems with coordinated control of their operation, as well as active participation of the consumer in the energy supply process [1-5]. In such energy systems, the end user is considered as a partner of energy entities in terms of ensuring reliable operation of the energy system, acquires the status of an active one and becomes one of the main elements in the energy system [6]. These consumers can independently set the requirements of the amount of energy to be received, its quality and consumer properties, and energy services [7-10].

2 Literature review

Various energy supply systems, such as electric, gas, heating and other systems were normally designed and operated independently of one another. The advances in technologies and equipment, the emergence of new conditions and opportunities, however, make the interaction between different types of energy systems much stronger, which leads to a considerably increasing interest in the research on joint operation of these systems. A widely applied approach to study the integrated systems is based on consideration of such systems in the form of an energy hub. For example, in [8] the authors suggest a method for optimal energy generation and conversion in the integrated energy system with different energy carriers, which involves the energy hub conception. This method is widely applied in the studies related to optimal operation and design of integrated energy systems [9, 10].

The problem of an optimal load of generating equipment lies in obtaining an optimal schedule of generating equipment startup and shutdown to meet the expected demand, given costs and constraints of a system. In the context of the integrated energy systems, this refers to the optimal startup and shutdown of each generating unit to meet the demand for several types of energy. The authors of [11] propose a solution to the problem of optimal loading of generating equipment based on the energy hub conception. For solving this problem, it is very important to consider the energy storage possibility. The authors in [12] consider planning of electricity and heat storage as part of the problem of optimal loading of generating equipment. The authors of [13] present a comparison of energy approach and exergy-based approach to solve the problem of optimal use of generating equipment.

The problem of the integrated energy system control can also be solved by determining optimal power flow. The determination of optimal power flow is reduced to the load distribution among energy sources, which meets the constraints of the energy transmission system in terms of cost minimization. Solving the problem of optimal power flow in the integrated energy system requires the consideration of the need for several energy types which is met by using several energy sources and devices for energy conversion, and satisfaction of the transportation system constrains for each energy carrier. The optimal power flow in an integrated electric and gas system was investigated in [14]. For solving this problem, the authors developed a mathematical model in which the objective function is determined by a set of points for various components that are characterized by the minimum operation cost of the electric and gas systems and do not violate the constraints of the electric and gas transportation system. A method for calculation of optimal power flow for the integrated electricity, gas and heating system is presented in [15]. The method is focused on the power flow and optimality condition of Kuhn-Tucker for the case with several energy resources.

The problem of the optimal power flow calculation for several periods of time is related to the planning of the energy system operation for a set time horizon. In [16], the authors present modeling of an optimal power flow coordinated in time for electric and gas system for the case of distributed energy resources. Due to relatively slow flow speeds and specific features of storage in the gas and heating systems, it is important to take into account the dynamic behavior of these energy systems during several periods of time to solve the problems of control and scheduling of the systems. The authors of [17] study a method for calculation of optimal power flow and scheduling for integrated electric and gas systems with a transient model for the natural gas flow. The calculations were performed to compare the solutions obtained with stationary and transient models of natural gas transmission systems. A model of optimal power flow for several time periods was developed to study combined electricity and gas networks in Great Britain [18, 19].

Some of the studies aim to investigate the control of integrated systems with focus on centralized and decentralized control. In [20], the authors present the findings of the research into the centralized control, which involves an approach to the control with projection models for integrated energy systems. Central controller determines the actions for each energy hub to ensure better efficiency in terms of stability of the transportation system, use of storage devices and forecasts of loads and prices. In [21], the authors propose a hierarchical centralized control of an integrated microgrid. Controller receives the data on transient characteristics of the natural gas flow and operation of energy converters. To take into consideration the dynamic characteristics of different systems, the controller was divided into three layers: slow, medium-speed and fast. The study is focused on the control of executive mechanisms when the renewable generation fluctuates, start of a conditioner, start of a microturbine, demand response and filling of energy storage. Further, the results of this research were extended to the control of an integrated energy system [22].A strategy of real-time control of the integrated electric and heating system was proposed in [23]. The strategy of control has a hierarchical centralized architecture and is designed to maintain frequency of power supply system at a level of 50 Hz and a temperature of district heating water equal to 1000C. An approach to solving the scheduling problem is presented in [24], where optimization is performed for a time period of 24 hours, and a strategy of real-time control compensates for a gap between a scheduled load and a real load by control actions.

Although, the centralized architecture of control can provide the best total energy system performance, its complexity limits its wide practical application. The distributed control architecture divides the common optimization and control problem into subproblems that are solved with individual models. The local control action to be performed, however, depends on the actions of neighboring controllers and should be coordinated. In [25], the authors propose a distributed control system for combined electricity and natural gas systems. The system consisting of several interrelated energy hubs was controlled by corresponding control agents. In [26], these results were extended to the studies of distributed control based on projection models and the use of storage devices in gas systems.

The integration of electric and heating systems is most pronounced in cities and populated areas, and manifests itself: in combined electricity and heat generation; the use of energy storage systems to ensure flexibility of cogeneration operation; and the use of electric equipment for heat production, transport and distribution. The joint operation and scheduling of electric and heating systems based on cogeneration is discussed in [27]. The interaction between electric and heating systems in the view of the need to ensure the required demand response was considered in [28]. Various electricity and heat supply options were compared when solving the problems of operation and scheduling in terms of techno-economic and environmental indices in [29, 30].

The sources of combined electricity and heat generation interconnect electric, heating and gas systems. In [31], the authors applied Sankey diagrams to illustrate energy flows through the electricity-heat-gas networks when considering several scenarios for the involvement of cogeneration power plant and heat pumps. The research was also focused on the impact of different technologies on operation of each network. The implications of switching from hydrocarbon fuel to renewables in the electric system for the district heating systems and gas network were studied in [32, 33].

Design of the load-controlled consumption systems, including heterogeneous energy sources and storage devices usually involves solving a mixed integer linear programming problem [34-35]. Some researchers [36-39] use multi-criteria optimization to consider not only the investment and operational costs in the design of energy systems, but also compensation for the energy generation-related emissions of pollutants.

The switch to the intelligent energy industry based on a customer-oriented approach generates the need to develop a methodological support for the study of prosumer consumption, which is a pressing scientific problem of great importance for the national energy development. In this paper, we propose an approach to short-term control of integrated energy systems with load-controlled consumers. This approach makes it possible to meet the consumer needs for various types of energy, given its transport.

3 Statement of the problem

Planning the daily electricity and heat loads is performed for an integrated energy system, including energy storage systems (batteries) and electric water heaters, electrical shiftable loads of individual consumers (dryers, washing machines, etc.) as well as power generation by additional electricity and heat sources (PV systems, wind turbines, heat pumps).

The procedure for constructing optimal daily electricity and heat load profiles includes the following three steps.

The first step: calculate the initial feasible power flow in the electrical and heat networks for the specified standard or projected daily load profiles of individual electricity and heat consumers subject to technological constraints. The software developed at the Melentiev Energy Systems Institute SB RAS is used to calculate the power flow in electrical and heat networks taking into account daily electricity and heat rates.

The second step: optimize daily electricity and heat load profiles for each individual consumer by solving the mixed integer linear programming problem. The set parameters include: a set of electricity sources I ; a set of heat sources J ; a set of cooling energy sources D ; a set of combined heat and power plants (CHPP) $CHP = (I, J)$; the cost of primary energy resources to produce electricity $S_{t,i}^{\mathrm{EL}},\, i \in I$, heat $S_{t,j}^{\mathrm{HE}},\, j \in J$ and cooling energy $S_{t,d}^{\mathrm{CO}},\, d \in D$ at time t; demand for electricity C_{EL}^{t} , heat C_{HE}^{t} and cooling energy C_{CO}^{t} at time t; distance to the source of electricity $l_i^{\mathrm{EL}},\, i \in I$, heat $l_j^{\mathrm{HE}},\, j \in J$ and cooling energy $l_d^{\mathrm{CO}},\, d \in D$. Solution to the problem should include: electricity generation $\mathbf{w} = (w_1,\dots, w_i)^{\mathrm{T}}$; heat generation $\mathbf{h} = (h_1,\dots, h_j)^{\mathrm{T}}$; cooling generation $\mathbf{q} = (q_1,\dots, q_d)^{\mathrm{T}}$. It is necessary to minimize the function of total costs of the load-controlled consumer energy system that has the form:

$$Z(w, h, q) = \sum_{t=1}^{p} \left\{ \begin{array}{l} \sum_{m=1}^{i} \Big[Z_t^{\mathrm{EL}}\left(w_m, S_{t,m}^{\mathrm{EL}}\right) + Z_t^{\mathrm{S\_E}}\left(w_m\right) + \\ + Z_t^{\mathrm{N\_E}}\left(w_m, l_m^{\mathrm{EL}}\right) \Big] + \sum_{n=1}^{j} \Big[Z_t^{\mathrm{HE}}\left(h_n, S_{t,n}^{\mathrm{HE}}\right) + \\ + Z_t^{\mathrm{S\_E}}\left(h_n\right) + Z_t^{\mathrm{N\_E}}\left(h_n, l_n^{\mathrm{HE}}\right) \Big] + \\ + \sum_{r=1}^{d} \Big[Z_t^{\mathrm{CO}}\left(q_r, S_{t,r}^{\mathrm{CO}}\right) + Z_t^{\mathrm{S\_E}}\left(q_r\right) + \\ + Z_t^{\mathrm{N\_E}}\left(q_r, l_r^{\mathrm{CO}}\right) \Big] \end{array} \right\} \to \min \tag{1}$$

$$\mathbf{w} = \left(w_1,\dots,w_i\right)^{\mathrm{T}}, w \in \mathbb{R}^{i}, \mathbf{h} = \left(h_1,\dots,h_j\right)^{\mathrm{T}}, h \in \mathbb{R}^{j}, \mathbf{q} = \left(q_1,\dots,q_d\right)^{\mathrm{T}}, q \in \mathbb{R}^{d}, S_{t,m}^{\mathrm{EL}} \in \mathbb{R}^{m\times p},$$
$$S_{t,n}^{\mathrm{HE}} \in \mathbb{R}^{n\times p}, S_{t,r}^{\mathrm{CO}} \in \mathbb{R}^{r\times p}, l_m^{\mathrm{EL}} \in \mathbb{R}^{i}, l_n^{\mathrm{HE}} \in \mathbb{R}^{j}, l_r^{\mathrm{CO}} \in \mathbb{R}^{d}, t = \overline{1,p},\ m = \overline{1,i},\ n = \overline{1,j},\ r = \overline{1,d}.$$

Subject to:

$$w_i = w_{i0} K_i^{\mathrm{TR}} K_i^{\mathrm{EF}} \lambda_i,\ i \in I;\ \ h_j = h_{j0} K_j^{\mathrm{TR}} K_j^{\mathrm{EF}} \lambda_j,\ \ j \in J;$$
$$q_d = q_{d0} K_d^{\mathrm{TR}} K_d^{\mathrm{EF}} \lambda_d,\ d \in D; \tag{2}$$

$$C_{\mathrm{EL}}^t \le \sum_{m=1}^{i} w_m^t;\; C_{\mathrm{HE}}^t \le \sum_{n=1}^{j} h_n^t;\; C_{\mathrm{CO}}^t \le \sum_{r=1}^{d} q_r^t; \tag{3}$$

$$w \ge 0;\; h \ge 0;\; q \ge 0; \tag{4}$$

$$\underline{w} \le w_i \le \overline{w},\; i \in I;\;\; \underline{h} \le h_j \le \overline{h},\; j \in J;\;\; \underline{q} \le q_d \le \overline{q},\; d \in D; \tag{5}$$

$$\underline{\eta} \le \frac{w_v}{h_v} \le \overline{\eta},\; v \in I, v \in J; \tag{6}$$

where $Z_t^{\mathrm{EL}}\left(w_m, S_{t,m}^{\mathrm{EL}}\right)$, $Z_t^{\mathrm{HE}}\left(h_n, S_{t,n}^{\mathrm{HE}}\right)$, $Z_t^{\mathrm{CO}}\left(q_r, S_{t,r}^{\mathrm{CO}}\right)$ – calculated costs of electricity, heat and cooling, respectively; $Z_t^{\mathrm{S\_E}}\left(w_m\right)$, $Z_t^{\mathrm{S\_E}}\left(h_n\right)$, $Z_t^{\mathrm{S\_E}}\left(q_r\right)$ – calculated operational costs of the source of electricity, heat and cooling, respectively; $Z_t^{\mathrm{N\_E}}\left(w_m, d_m^{\mathrm{EL}}\right)$, $Z_t^{\mathrm{N\_E}}\left(h_n, d_n^{\mathrm{HE}}\right)$, $Z_t^{\mathrm{N\_E}}\left(q_r, d_r^{\mathrm{CO}}\right)$ – calculated operational costs of the network from the source of electricity, heat and cooling , respectively, to the consumer; p – period of time; K^{TR} – the conversion factor of the primary energy resource to the required energy type; K^{EF} – source efficiency; λ – energy transmission losses in the energy system components; w_{i0} – primary energy resources; η – generated electricity to heat ratio at CHPP.

The above generalized statement was reduced to solving the problem of mixed integer linear programming.

The third step: calculate feasible power flow for each electrical and heat network for the obtained optimal total daily electricity and heat load profiles. To solve this problem, the software developed at ESI SB RAS is also used.

4 A case study (an example of a digital model of planning the integrated energy system operation)

The operation of the algorithm is illustrated by a numerical example in which daily electricity and heat load profiles of an individual household consumer are optimized by the criterion of the minimum energy costs for a given profile of daily electricity and heat rates. The test scheme of the integrated energy system is shown in Fig. 1. The 10 kV electrical network and the heat network contain six nodes, one of which is the source, and the remaining nodes are connected to electricity and heat consumers. The consumers have renewable energy sources (photovoltaic systems), heat and electricity storage systems, as well as electrical shiftable loads with their turn-on time determined by economic reasons. Each consumer is connected to the centralized power system. The consumer knows the electricity and heat rates during the day time. A characteristic electricity and heat load profile is assigned as an initial approximation for each consumer.

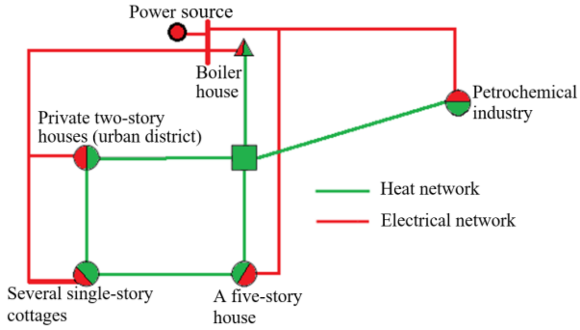
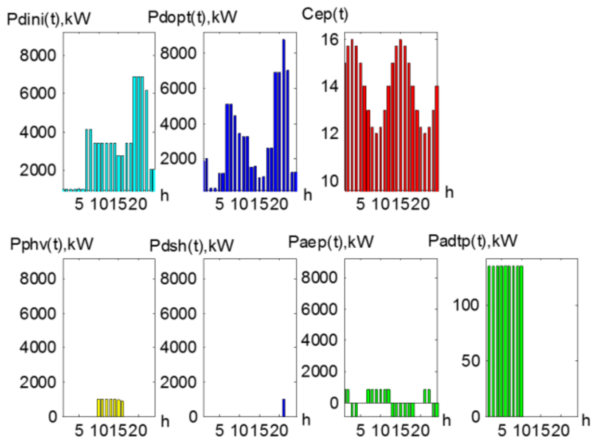


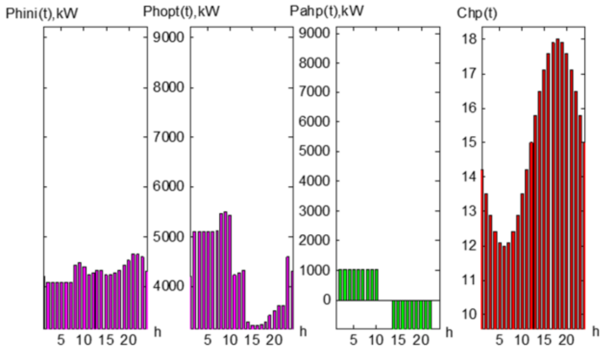
Fig. 1. Integrated energy system test scheme.

For the test system, the optimal daily electricity and heat load profiles were calculated for each consumer. Figures 2 and 3 present the calculated optimal daily heat and electricity load profiles for one node. Figure 2 shows the initial and optimal daily electricity load profiles, electricity rates and the profiles of daily photovoltaic generation, optimal switching of the shiftable load, operation of energy storage device and electricity consumption by heat storage system. Figure 3 shows the daily initial and optimal load profiles, the optimal profiles of heat storage operation and a profile of heat rates. The daily rate profiles are assumed to be sinusoidal to verify the correctness and operability of the algorithm for obtaining optimal daily electricity and heat load profiles.



Pdini(t) – initial daily electricity load profile; Pdopt(t) – optimal daily electricity load profile; Cep(t) – daily electricity rate profile; Pphv(t) – daily PV-based power generation profile; Pdsh(t) – daily shiftable load profile; Paep(t) – daily electricity storage profile; Padtp(t) – Daily profile of electricity consumption by thermal energy storage; h – hour.

Fig. 2. Daily active power load profiles.



Phini(t) – initial daily heat profile; Phopt(t) – optimal daily heat profile; Pahp(t) – daily heat storage profile; Chp(t) – daily heat rate profile; h – hour.
Fig. 3. Daily heat load profiles.

The optimal daily profiles are obtained based on the initial profiles of electricity and heat loads, photovoltaic generation and optimal profiles of using electricity and heat storage systems and shiftable load. Optimal daily electricity and heat load profiles differ greatly from the initial ones, which provides a reduction in the energy costs for the consumer.

5 Conclusions

In integrated energy systems, the end user is considered as a partner of energy entities in terms of ensuring reliable and efficient operation of the energy system. By acquiring the status of an active participant in the technological process, the consumer becomes one of the main active components in the energy system. In the context of expanding consumer opportunities in the energy sector, the control of integrated energy systems, taking into account the behavior of load-controlled consumers, is becoming very important. This paper describes an approach to short-term control of integrated energy systems with load-controlled consumers. This approach allows us to determine the optimal self-generation load to meet the current level of energy demand and create rational behavior with respect to both self-generation and the centralized systems to which the consumer is connected.

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