Energy hub component models for multi-energy system

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Abstract. The paper presents the principles of constructing simulation models of the components of an integrated multi-energy system based on the energy hub concept. The application of the algorithms designed to develop simulation models of the components are given, the results of their implementation are verified with generally accepted theoretical approaches used to obtain the necessary characteristics depending on the set objective functions. The proposed approach offers a broad prospect for the study of many significant problems in integrated power systems with multiple carriers, including their properties, features of expansion and operation.

1. Introduction

Modern energy systems are complex infrastructure technical facilities. These systems have to meet ever increasing requirements for the reliability of energy supply to consumers, the quality of the energy supplied, as well as the efficiency of operation and expansion of the systems themselves. Currently, a comprehensive analysis of such systems is complicated by a number of factors. The main of them are:

- The creation and implementation of a great number of new technical solutions in the modern technological process of energy supply (highly efficient storage devices of various types of energy resources: heat, electricity, natural gas; new energy sources based on the renewable resources: wind, solar energy, biogas) and their integration into a single energy system.
- The ability to quickly and cost-effectively convert one type of energy to another.
- The growing role of the load-controlled consumer with self-generation that acts both as the consumer and as the generators.

The traditional end-user energy supply system consists of several energy flows which are practically independent of one another. The main energy resources for the end consumer are electricity, heat, and natural gas. The feasibility and effectiveness of their use was considered independently of each other. Consequently, modelling of the energy supply system was divided into several independent subproblems. Modelling of each of the energy supply channels was done by traditional mathematical methods, which were based on the equations of state that are characteristic only of a given type of energy carrier.

Thus, the modern energy supply system is a multifactorial energy object and the study of its operation efficiency by traditional methods becomes virtually impossible. Solving this problem calls for a new methodological approach providing joint modeling of energy objects of various nature on a single basis. The paper will present a methodological approach to the formation of simplified mathematical models of integrated energy systems based on the energy hub concept using simulation methods.
2. Current state of the research

The authors of [1] were the first to present the concept of multi-energy systems. They introduced a concept of an energy hub, proposed a functional diagram, and made an attempt to mathematically describe this class of systems.

Further development of the energy hub concept involved the study on joint work of three energy hubs [2]. The issues of economic feasibility and the selection of the optimization method come to the fore.

In subsequent studies [3, 4], the authors proposed an approach to combine the optimization of the related energy flows of different energy infrastructures, such as electricity, gas, and district heating systems. A stationary power flow model is presented, which includes the conversion and transmission of an arbitrary number of energy carriers. Connections between different infrastructures are explicitly taken into account based on the new concept of energy hubs.

In [4], the author describes the particular points of the conversion of one type of energy into another. A generalized mathematical model of the hub taking into account energy storage systems is obtained. The author of [5], considers the reliability of a system consisting of several hubs. A detailed mathematical description is given. Of interest is the study presented in [6]. The focus of this study is optimal operation of the integrated electricity and natural gas infrastructure. The connections between the electrical system and the gas system are modelled by the so-called energy concentrators, which are the interface between the loads and the transmission infrastructure. Further, the researchers [7-14, etc.] already consider the development of mathematical tools for modeling of the energy hubs. Traditionally, the mathematical model of the energy hub without storage devices and energy transfer systems is written in a matrix form [1, 15]. The main points of the energy hub concept were considered in [15].

Fig. 1 shows a simplified model of the energy hub consisting of N - inputs and N - outputs.

An analysis of the mathematical description is carried out under the following assumptions:

1. The system is in a steady state, transient processes are not considered;
2. Energy hub consists only of energy converters;
3. Energy is transmitted only from input to output;
4. Energy flows are characterized by power and efficiency.

In the mathematical description of this functional diagram, the relationship between the inputs and outputs of the energy channels is represented by a matrix of the system of equations.

In the case of three samples from the instantaneous values of current separated by equal sampling intervals, we obtain an actual value of the current at the time of the average sample, and its derivative:
where $p^\alpha_{\text{out}}, p^\beta_{\text{out}}, \ldots, p^\xi_{\text{out}}$ - vectors of energy channels outputs; $p^\alpha_{\text{in}}, p^\beta_{\text{in}}, \ldots, p^\xi_{\text{in}}$ - vectors of energy channels inputs; $C_{\alpha\alpha}, C_{\beta\alpha}, \ldots, C_{\xi\xi}$ - energy conversion matrix coefficients.

A more detailed description of the mathematical model of an energy hub with energy storage is presented in [3]. The analysis of the mathematical description of the energy hub is carried out in three stages.

1. The systems of energy conversion are considered;
2. The available energy storage devices and their interaction with the system for converting various types of energy into each other is considered;
3. The energy transmission systems for various channels are considered.

Since the concept of the multi-energy hub is widely used for MES, the energy flow modeling is of great importance. Moreover, the use of complex storage devices and energy converters makes the hub structure increasingly more complicated, and, as a result, the standard method becomes less and less applicable to modern systems.

The fundamental study on multi-energy systems [15] presents a mathematical description of the energy hub in a matrix form. This description however does not allow for energy storage devices and considers only conversion of one type of energy into another. The authors of [4] propose a method for optimization of operating conditions and give a numerical example. The proposed approach of the mathematical description of these systems is used in later studies. The energy hub concept found further development in [2]. In this study, the focus is on the joint operation of three energy hubs. The optimization methods of the system are given. This study gives consideration to the issues of economic feasibility and selection of an optimization method. The paper [16] presents the optimization model for multi-energy conversion systems based on game tree. In [17-19], the authors address the selection of optimization methods for the operation of multi-energy systems.

3. An algorithm of building simulation models of multi-energy hub components

To study the principles of this system operation with a view to its optimization according to one or other target criteria, it is necessary to obtain a mathematical model of an energy hub as a control object.

Functional diagram of the energy hub to be developed for the analysis of operation of an energy system with different energy carriers, should allow for their mutual influence and focus on the following:

• types of energy carriers (electricity, heat, gas, etc.);
• constraints imposed on energy carriers in terms of power, consumption, losses and non-linearity at energy transmission and conversion;
• different energy measurement units should be brought to a single measurement system;
• technical capability of converting one type of energy carrier to another;
• specific features of the technical implementation of the storage of various types of energy carriers;
• the exergy component of the energy balance in the case of heat generation;
• time limit for switching to another energy carrier.

The algorithmic implementation of the blocks for converting one type of energy into another or their energy storage is based on that the mathematical description of the output characteristics of these devices can be implemented with sufficient accuracy by a system of or one linear differential equation of the first or second order with constant coefficients.

To develop simplified models of components (elementary hubs) of a multi-energy system, it is necessary to consider the equipment and facilities of the system, and, based on the data obtained,
determine the necessary and sufficient parameters of the system components depending on the chosen objective functions.

In the generally accepted assumptions, the energy hub consists of energy storage devices, converters, and transmission systems. Depending on the objective, the energy conversion subsystems will be represented by:

1. A system that changes the characteristics of an energy channel without converting one type of energy into another, transformers, heat exchangers, etc.
2. The systems that convert one type of energy into another - electric heating boilers, systems that convert the energy of natural gas into electricity.
3. Energy storage systems, including energy storage systems, heat storage devices, gas storage facilities.
4. Energy transmission systems, including lines, pipelines, heat networks, and a gas supply structure.

Thus, a multi-energy system should be structurally divided into a number of functional blocks with respect to different energy channels. The input and output parameters of the blocks are consistent and interconnected.

The functional diagrams of various energy supply channels were considered in [17, 20-21]. A unified algorithm should be applied to build the internal structure of the hub components. Based on the proposed basic assumptions, the system of equations of state for energy supply channels cannot be used in the named units in simulation models. However, the mathematical tools that make it possible to correctly define almost all the operating conditions of elementary components of multi-energy systems are well developed and it is advisable to use them in the initial stage.

The algorithm consists of the following stages:

1. The relationship between the studied function and the load is built according to the equations of state in the named units or according to the graphs presented in the passport data of specific physical objects.
2. The graphs are built, processed and presented in the selected system of units (in this case, the Joule).
3. Based on the obtained graphical relationships, the polynomial characteristics are calculated by mathematical methods of discrete data processing (approximation, interpolation).
4. The obtained calculated relationships are verified with the initial data in a range of expected operating conditions.
5. The elementary hub component that satisfies the requirements imposed on it is implemented in software.

Fig. 2 presents an example of functional diagram for electricity supply channel of general energy hub simulation model taking into account the specifics of simulation modeling in Matlab/Simulink.

A study of load schedules, in order to optimize energy. Two cases are considered:

- The use of energy storage.
- Selecting the optimal load curve with the features of the tariff (applying differentiated tariffs depending on time).

In the study, a simulation model of Fig. 2 was used. The objective function in the study is as follows:

\[ C = (C_P + C_H) \rightarrow \text{min} \]

where \( C_P \) - payment for power consumption; \( C_H \) - payment for heat consumption.

Thus, the goal is to minimize payment through two energy supply channels.

4. An analysis of energy consumption of the building

The building under the study is situated in the city of Irkutsk. It is a four-storey building. Its total area is 1631m². The coordinates of the building are 52°15’29”N 104°15’46”E. The climate is very cold, average annual humidity is 72.6%. The cost of consumed heat and power electricity was calculated. An
analysis of power electricity consumption by month allowed us to identify periods of time when payment for electricity has the maximum value. This happened during peak hours in the system.

As mentioned above, for this study both options for the application of the proposed algorithm were considered. The results are presented in Fig. 3.

Figure 2. Simulation model of an energy hub on two power supply channels

Figure 3. Economic effect
From the analysis of Fig. 3, it follows that the accumulation of power electricity at night gives an economic effect of 2.5%. The conversion of electrical energy into thermal energy gives an effect of about 2%. Calculations were carried out for this particular facility based on current tariffs for power energy and heat. Obviously, for other conditions, the effect may be more or less.

5. Conclusions
The paper presents the principles of constructing simulation models of the components of an integrated multi-energy system based on the energy hub concept. The application of the algorithms designed to develop simulation models of the components are given, the results of their implementation are verified with generally accepted theoretical approaches used to obtain the necessary characteristics depending on the set objective functions. It is shown that the use of storage systems and conversion of power energy into heat significantly reduce the cost of energy.

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