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Energy Hub Function Optimization Models During Ukrainian Energy Resources Market Liberalization

Yurii Veremiichuk[1*], Ivan Prytyskach[2], Olena Yarmoliuk[3], Vitalii Opryshko[4]
[1–4] *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine*

Abstract **– Analysis of energy supply systems that provide integration of self-organizing electricity and heat supply systems is conducted. The study considers the possibility of a model of energy hubs that combines disparate heat and electrical energy generation sources to meet the energy demand of consumers. The proposed models will allow to optimize energy consumption modes and integration of self-organizing electricity and heat systems built on the multiagent principle on the basis of smart technologies.**

Keywords **– Active consumer, distributed generation, energy hub, integrated power distribution systems, monitoring.**

I. Introduction

At present, Ukraine is actively adapting its energy policies to those pursued by the EU, namely, implementation of the Third Energy Package. This will provide opportunities for all European citizens to enjoy the benefits provided by a transparent and competitive energy market: freedom for consumers to choose suppliers, more competitive pricing, security of energy supply. Therefore, achievement of these goals includes:

- Separation of the functions of energy production and sales enterprises from transport functions, which enables the liberalization of the electricity and gas markets;
- Enhanced cross-border trade in the energy sector;
- Establishment of effective national regulatory bodies;
- Promotion of greater transparency of the activities of energy companies and others.

Taking into account the European experience and the reforms in Ukraine's energy sector, it is necessary to implement the requirements of modern integrated intelligent power supply systems (IIES), which are based on Smart Grid principles and primarily include achievement of their operational reliability and efficiency level, caused by the condition of main power systems equipment and active consumer behavior [1], [7], [9], [12]. However, IIES creation and management requires assessment of energy performance process conformity and the impact of energy facilities on IIES operation in the implementation of the Smart Grid concept with regard to active consumer behavior in energy consumption.

For the Ukraine energy sector, which is currently undergoing changes of its development paradigm, transition to new structures as IIES, which provide integration of self-organizing electricity and heat systems built on the multiagent principle based on smart technologies is urgent. The ideology and the creation and management of such systems is a major problem, which calls for active research.

II. Analysis of Recent Studies and Publications

Over the last decade, the problem of the development of intelligent power systems has been discussed widely [7]. In many countries, this is due to several key factors: the expected considerable expansion of the amount of renewable energy sources used, an additional demand for electricity related to the gradual transition to electric vehicles, development of information technologies that enable new high-quality monitoring and management of IIES [12]. As stated by the author of [1], intellectualization of energy networks is a leader in solutions and policy documents of governing bodies of leading countries, electricity organizations, companies and scientific journals.

Power companies of the European Union, the United States, Canada, Japan and other countries have already implemented large-scale pilot projects related to certain provisions of the Smart Grid fundamental concept. The policies of the developed countries, the principles of construction and operation of liberalized energy markets are aimed at promoting energy conservation and improving energy efficiency [2]. As an example, in the PJM energy market (United States), the ability to reduce consumer demand for electricity is considered equivalent to the ability of the manufacturer to increase electricity production. The rules of this market provide an opportunity for end users to sell resources from the demand side as energy efficiency resources or through demand management, thus creating competition for companies that produce electric power [4].

Compared with other countries, research in Ukraine is in its early stage [9]. It should be borne in mind that the concept of Smart Grid is based on a carefully coordinated, comprehensive solution of the energy sector restructuring problem and the features of the electric power system in our country must be taken into account [10].

The obtained results make it possible to move the focus of research to the formulation and development of the fundamentals of IIES. Developments are cropping up such as the "energy hub" – a fixed set of nodes, which is the specialized space for energy supply with various kinds of financial instruments [11].

[*] Corresponding author.
E-mail address: y.veremiichuk@kpi.ua

As a result of the integration of energy supply systems at the energy production and consumption levels, there is a need for joint consideration of the electrical, thermal and gas distribution networks for solving the optimization of flow in integrated power systems [8], optimizing the daily regimes in their scheduling [6], analyzing the energy supply security of integrated systems and other tasks.

The concept of energy hubs is developed in [3], [7], [13]. Here, mathematical models are presented for determining the optimal power consumption and energy generation.

III. Problem Definitions

The central problem is to increase the safety, reliability and efficiency of IIES operation in terms of integration of distributed generation sources, further development of electricity and heat supply with active involvement of the methodological fundamentals of effective management of energy consumers.

The functioning of integrated energy supply systems under the provisions of the energy hub has practically not been researched for the conditions of Ukraine. It is necessary to conduct deep analysis and adaptation of international experience to local conditions.

The aim of the present study is to analyze the process of creation, development and operation of integrated power supply systems under the Smart Grid and energy hubs conditions to improve their safety, reliability and operation efficiency and to ensure efficient management of electricity and heat supply with active participation of consumers.

To achieve this purpose, it is necessary to solve the following problems:

- Analysis and adaptation of the regulatory, technical and legal documents in order to facilitate the interaction of energy facilities to improve the efficiency of integrated energy systems;
- Development of the methods for using communication techniques in the management of power consumption for increasing energy self-saving, the reliability and efficiency of the operation of integrated power systems and development of complex evaluation system principles at various levels of the organizational structure of the energy sector;
- A complex analysis of the tasks related to the creation, development and operation of integrated energy supply systems in Ukraine;
- Development of theoretical fundamentals and practical methods to determine the power generated by alternative and renewable energy sources and different types of distributed generation in operation according to the available information and the actual level of uncertainty for assessing the energy potential;
- Problems related to distributed generation sources.

IV. Exposition of Basic Material

Formation of an energy hub is a promising process due to the implementation of the Smart Grid concept and the involvement of the active consumer and requires revision of the processes of construction and development of the Ukrainian energy systems according to the global tendency to increase energy independence, search for alternative sources and energy resource suppliers. These concepts need continued development and improvement, which in turn stimulates the country to implement the above-mentioned initiatives in the energy sector and the economy as a whole.

To achieve this goal and meet the challenges of research, expected is complex use of the mathematical and technical support provided by modern information and computer systems, of new theories that adequately take into account IIES construction, the automation metering and control systems, the developed methods, algorithms and software to evaluate and improve the efficiency of modern IIES.

Let us consider the structure of integrated intelligent power supply systems as shown in Fig. 1.

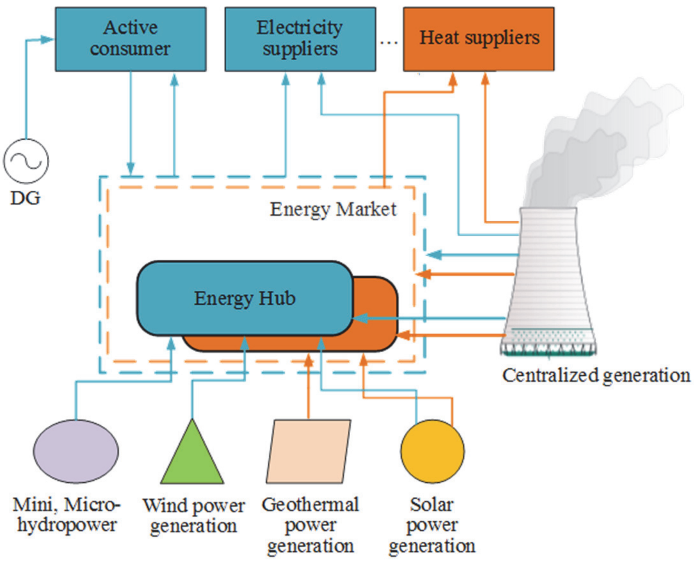

Fig. 1. The structure of integrated intelligent power supply systems.

Designing of separate energy hubs in a network makes it possible to formulate an optimization procedure that minimizes the total cost of energy saving and determines the optimal values of energy flow, primary and backup power generating and storage devices.

Let us consider the process of building an optimization function for an energy hub that is a complex of apartment buildings, using the energy hub model proposed in [5].

The optimization function formulated in [5] is

$$\min \sum_{k=0}^{T-1} \boldsymbol{c}(k)\boldsymbol{P}(k)$$

$$\mathbf{E}(k+1) = \boldsymbol{E}(k) + \mathbf{A}^{\mathrm{ch}}\mathbf{Q}^{\mathrm{ch}}(k) - \mathbf{A}^{\mathrm{dis}}\mathbf{Q}^{\mathrm{dis}}(k) - \mathbf{E}_{\mathrm{L}},$$

$$\mathbf{L}(k) = \mathbf{\Theta}\mathbf{P}(k) - \mathbf{Q}^{\mathrm{ch}}(k) + \mathbf{Q}^{\mathrm{dis}}(k),$$

$$\mathbf{P}(k)^{\min} \le \mathbf{P}(k) \le \mathbf{P}(k)^{\max},$$

$$0 \le Q_i^{\mathrm{ch}}(k) \le \delta_i^{\mathrm{ch}}(k) Q_i^{\max}(k) \qquad i = 1,\ldots,M,$$

$$0 \le Q_i^{\mathrm{dis}}(k) \le \delta_i^{\mathrm{dis}}(k) Q_i^{\max}(k) \qquad i = 1,\ldots,M,$$

$$\delta_i^{\mathrm{ch}}(k) + \delta_i^{\mathrm{dis}}(k) \le 1 \qquad i = 1,\ldots,M,$$

$$\mathbf{E}(k)^{\min} \le \mathbf{E}(k) \le \mathbf{E}(k)^{\max},$$

$$\mathbf{E}_0 = \mathbf{E}_T$$

where $\boldsymbol{c}$ – the row vector denoting the energy purchasing costs for each input power flow;

$\boldsymbol{P}$ – the column vector denoting the input power flow;

$\boldsymbol{L}$ – the column vector denoting the output power flow;

$\boldsymbol{\Theta}$ – the converter coupling matrix whose elements may be zeros, efficiencies or products of efficiencies;

$\boldsymbol{P}^{\min}$, $\boldsymbol{P}^{\max}$ – the column vector denoting the minimum and maximum capacity limits for the power flow;

$\mathbf{Q}^{\mathrm{ch}}, \mathbf{Q}^{\mathrm{dis}}$ – the column vectors denoting the power exchanged with the storing devices;

$\boldsymbol{A}^{\mathrm{ch}}$, $\boldsymbol{A}^{\mathrm{dis}}$ – diagonal matrices for the charging and discharging efficiency of each storing device;

$\boldsymbol{E}$ – the vector denoting the level of the energy stored in the storing device;

$\boldsymbol{E}_{\mathrm{L}}$ – the vector denoting the energy loss per unit of time in the storing device;

$\boldsymbol{E}_0$ – the vector denoting the level of energy stored in the storage devices at time $k = 0$;

$Q_i^{\max}$ – the capacity of the storage device;

$\delta_i^{\mathrm{ch}}, \delta_i^{\mathrm{dis}}$ – binary variables for each storage device ensuring that the storage device cannot be charged and discharged at the same time.

Let us consider the energy hub shown in Fig. 2. It consists of five converters, four streams of energy and storage devices. The converters are as follows: solar heating, a combined heat and power plant, a boiler, an electrical heating system and a solar power plant. The energy flows are as follows: solar electricity, natural gas, fuel pellets. Each of the five plants is characterized by its efficiency (the efficiency of converting one form of energy to another).

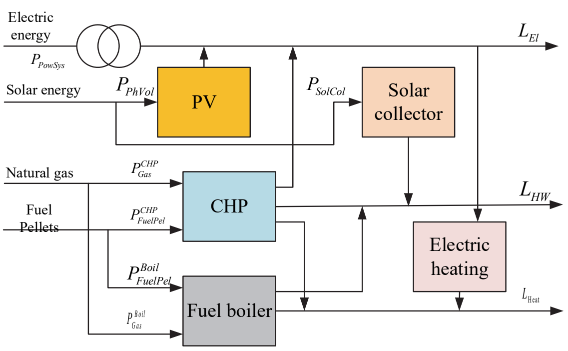

Fig. 2. Example of an energy hub for meeting the load of an apartment complex.

Let us analyze the possible sources of energy in an energy hub as well as the energy consumers. Electricity can flow from the grid through 10/0.4 kV step-down transformers and can be generated by solar panels and combined heat and power units based on gas and solid fuel. Heat for the boiler rooms within the heating system may be generated from gas and solid fuel as well as by the electric heating system. For the purposes of hot water supply, energy is generated by solar collectors and a combined heat and power unit based on gas and solid fuel. The energy consumers are household consumers of electricity, heating and hot water. The energy storage can be done by means of electric batteries. Hot water can be accumulated in heat-insulated tanks.

Let us construct matrix $\boldsymbol{P}$, $\boldsymbol{L}$, $\boldsymbol{\Theta}$, $\boldsymbol{Q}^{\mathrm{ch}}$, $\boldsymbol{Q}^{\mathrm{dis}}$, $\boldsymbol{A}^{\mathrm{ch}}$, $\boldsymbol{A}^{\mathrm{dis}}$ for the selected object, such as a complex of apartment buildings. Using the above considerations, the following matrix is obtained:

$$\mathbf{P} = \begin{bmatrix} P_{\mathrm{PowSys}} \\ P_{\mathrm{PhVol}} \\ P^{\mathrm{CHP}}_{\mathrm{Gas}} \\ P^{\mathrm{Boil}}_{\mathrm{Gas}} \\ P^{\mathrm{CHP}}_{\mathrm{FuelPel}} \\ P^{\mathrm{Boil}}_{\mathrm{FuelPel}} \\ P_{\mathrm{SolCol}} \end{bmatrix}; \qquad \mathbf{L} = \begin{bmatrix} L_{\mathrm{El}} \\ L_{\mathrm{Heat}} \\ L_{\mathrm{HW}} \end{bmatrix}.$$

The electricity is an input to the transformer and to the electric heating P_{PowSys}. The solar energy is an input to the photovoltaic panel P_{PhVol} and to the solar collector P_{SolCol}. The nature gas is an input to the combined heat and power generation system (i.e. the gas turbine) $P^{\mathrm{CHP}}_{\mathrm{Gas}}$ and to the fuel boiler $P^{\mathrm{Boil}}_{\mathrm{Gas}}$. The fuel pellets constitute an input to the cogeneration system $P^{\mathrm{CHP}}_{\mathrm{FuelPel}}$ and to the fuel boiler $P^{\mathrm{Boil}}_{\mathrm{FuelPel}}$. The consumers of the energy flows at the output of the power hub are domestic electricity consumers L_{El}, the hot water supply L_{Heat} and the heating system L_{HW}.

$$\boldsymbol{\Theta} = \begin{bmatrix} \eta_{\mathrm{Tr}} & \eta_{\mathrm{PhVol}} & \eta^{\mathrm{Gas}}_{\mathrm{CHP.El}} & 0 & \eta^{\mathrm{FuelPel}}_{\mathrm{CHP.El}} & 0 & 0 \\ \eta_{\mathrm{Tr}}\eta_{\mathrm{El.Heat}} & 0 & \eta^{\mathrm{Gas}}_{\mathrm{CHP.Heat}} & \eta^{\mathrm{Gas}}_{\mathrm{Boil.Heat}} & \eta^{\mathrm{FuelPel}}_{\mathrm{CHP.Heat}} & \eta^{\mathrm{FuelPel}}_{\mathrm{Boil.Heat}} & 0 \\ 0 & 0 & \eta^{\mathrm{Gas}}_{\mathrm{CHP.HW}} & \eta^{\mathrm{Gas}}_{\mathrm{Boil.HW}} & \eta^{\mathrm{FuelPel}}_{\mathrm{CHP.HW}} & \eta^{\mathrm{FuelPel}}_{\mathrm{Boil.HW}} & \eta_{\mathrm{SolCol}} \end{bmatrix}$$

A transformer is characterized by its electric efficiency η_{Tr}. The electric heating transforms electricity into heat for heating systems; it is characterized by electric-heating system efficiency $\eta_{\mathrm{Tr}}\eta_{\mathrm{El.Heat}}$. The photovoltaic panel transforms solar energy into electricity with efficiency η_{PhVol}, the value of which is approximately 0.1 to 0.18. The solar collector transforms solar energy into heat for hot water with efficiency η_{SolCol}, the value of which is approximately 0.68 to 0.91. The CHP system transforms the energy of natural gas into electricity, heat for heating systems and heat for hot water; it is characterized by gas-electric, gas-heating system and gas-hot water efficiencies $\eta^{\mathrm{Gas}}_{\mathrm{CHP.El}}$, $\eta^{\mathrm{Gas}}_{\mathrm{CHP.Heat}}$ and $\eta^{\mathrm{Gas}}_{\mathrm{CHP.HW}}$, respectively. The fuel boiler transforms the energy of natural gas into heat for heating systems and heat for hot water; it is characterized by gas-heating system and gas-hot water efficiencies $\eta^{\mathrm{Gas}}_{\mathrm{Boil.Heat}}$ and $\eta^{\mathrm{Gas}}_{\mathrm{Boil.HW}}$, respectively. The combined heat and power system transforms the energy of fuel pellets into electricity, heat for heating systems and heat for hot water; it is characterized by fuel pellet-electric, fuel pellet-heating system and fuel pellet-hot water efficiencies $\eta^{\mathrm{FuelPel}}_{\mathrm{CHP.El}}$, $\eta^{\mathrm{FuelPel}}_{\mathrm{CHP.Heat}}$ and $\eta^{\mathrm{FuelPel}}_{\mathrm{CHP.HW}}$, respectively. The value of the coefficient $\eta_{\mathrm{CHP.El}}$ is approximately 0.35 to 0.55, and the values of coefficients $\eta_{\mathrm{CHP.HW}}$ and $\eta_{\mathrm{CHP.Heat}}$ are approximately 0.18 to 0.55. The fuel boiler transforms the energy of fuel pellets into heat for heating systems and heat for hot water; it is characterized by fuel pellet-heating system and fuel pellet-hot water efficiencies $\eta_{\text{Boil.Heat}}^{\text{FuelPel}}$ and $\eta_{\text{Boil.HW}}^{\text{FuelPel}}$, respectively. The values of the coefficients $\eta_{\text{Boil.Heat}}$ and $\eta_{\text{Boil.HW}}$ are approximately 0.8 to 0.84.

$$\mathbf{Q}^{\text{ch}} = \begin{bmatrix} Q_{\text{El}}^{\text{ch}} \\ 0 \\ Q_{\text{HW}}^{\text{ch}} \end{bmatrix}; \quad \mathbf{Q}^{\text{dis}} = \begin{bmatrix} Q_{\text{El}}^{\text{dis}} \\ 0 \\ Q_{\text{HW}}^{\text{dis}} \end{bmatrix}.$$

Energy storage can take place in electric batteries $Q_{\text{El}}^{\text{ch}}$. Hot water can be accumulated in heat-insulated tanks $Q_{\text{HW}}^{\text{ch}}$. Accordingly, these can be used as the accumulated electricity $Q_{\text{El}}^{\text{dis}}$ and as accumulated hot water for the water supply system $Q_{\text{HW}}^{\text{dis}}$.

We also introduce a diagonal matrix $\boldsymbol{A}^{\text{ch}}$ for the charging efficiency of each storage device and a diagonal matrix $\boldsymbol{A}^{\text{dis}}$ for the discharging efficiencies:

$$\mathbf{A}^{\text{ch}} = \begin{bmatrix} \eta_{\text{El}}^{\text{ch}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \eta_{\text{HW}}^{\text{ch}} \end{bmatrix}; \quad \mathbf{A}^{\text{dis}} = \begin{bmatrix} \frac{1}{\eta_{\text{El}}^{\text{ch}}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\eta_{\text{HW}}^{\text{ch}}} \end{bmatrix}.$$

Optimization can be performed using standard optimization methods.

Phased implementation of solutions based on the results of the optimization will help primarily to ensure minimum costs of energy purchase from external sources and increase the power supply system efficiency by rationalizing energy consumption, minimizing energy loss, ensuring a high level of reliability and quality. This takes into account national electrical and thermal networks, the features of energy facilities, providing conflict-free implementation of the recommended solutions and ensuring their effectiveness.

For effective operation of an energy hub, its optimal functioning algorithms require most accurate information on the energy flow level, the possible levels of energy generation and the needs of the customers.

V. Conclusion

The analysis of world trends and experience of energy development shows the feasibility of establishing IIESs with complex usage of distributed generation, taking into account the possibilities of their implementation in the conditions of Ukraine.

The application of the results of the present study will ensure the creation of the scientific and technical basis for the implementation of development and control measures for the Ukrainian local energy system of the end user, which will help to attract foreign investment for energy efficiency projects for which there is an urgent need in Ukraine and expand the scope and volume of mutually beneficial cooperation between Ukraine and European Union countries.

In the future, the results will be used in solving a wide range of various tasks related to optimization of integrated electricity supply systems, identifying the most effective conditions of parallel operation of power systems, sources of distributed generation and micro-grids, emergence of energy hubs in the process of electricity market liberalization and formation of a gas market in Ukraine.

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