Principles of system analysis for sustainable electric power supply to agro-industrial complexes operating in energy isolated territories

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Abstract. The article considers application of principles of system analysis while solving the problems of sustainable electric power supply of agro-industrial complexes operating on energy-insulated territories. The involvement of renewable energy sources in electricity generation is substantiated. The term “regionally isolated electrotechnical complex” is introduced. The principles of the theory of system analysis with regard to a regionally isolated electrotechnical complex - were considered: emergence, optimality and equifinality. It is proposed, when solving the problems of sustainable supply of electricity to agro-industrial complexes operating in energy-isolated territories, to proceed from decomposition approaches to assessing the sustainability of development by integral indicator of levelized cost of electricity LCOER.

1. Introduction
The concept of sustainable development proposed by the UN in 2015 [1], is based on strategies to achieve 17 global sustainable development goals (SDGs). One of them, SDG7, is Affordable and Clean Energy. As a result, there are subtasks with social, economic and environmental content. Works in the field of renewable energy sources as one of the responses to this challenge have intensified in the energy sector. The schemes for supporting implementation of energy resources of renewable energy sources (RES) built in a number of countries, resulted to a systemic reduction in the cost of electricity produced using RES. For 2010-2015 the electricity produced by solar panels reduced in price by more than two times [2], the forecast for a decrease by 2025 is about 57%. Wind power is being improved with systemic optimization, as by the wind generators itself, as by the energy-saving system of the wind farm infrastructure. The forecast of reduction in the cost of electricity produced with RES is expansion of its volume and geography, including in places where there are no pronounced natural and climatic conditions conducive to RES use.

The key characteristic of energy supply using RES is the continuity and mutual influence of "production and consumption of energy resources" [3]. Consideration of the stochastic nature of the energy produced by RES requires "transformation of the vector of development of electrical production complexes and consumption systems" [3], in terms of changing the principles of design, construction and management for all components interacting in the specified energy conversion process. With regard to the energy infrastructure of the Russian Federation, while SDG7 implementing there is an urgent need to “improve the efficiency of energy supply to remote and isolated areas” [4]. At the same time, the Energy Strategy of the Russian Federation for the period up to 2035 sets a trend
to “reduce economically feasible costs for the production of 1 kWh of electricity in the territories of
decentralized power supply” [4].

Involvement of renewable energy sources into the electric energy production becomes a tool that
optimizes the task of power supply to settlements located in the territories of decentralized power
supply. RES development is going in several directions, first of all, using of wind and solar energy.
Such types of RES as geothermal, tidal, wave are also developed. Although the total share of RES
energy consumed in the world is less than 2%, the last decade there is an intensive growth in the
installed capacities of both wind energy and solar energy, about 600%. Expected growth rates are 6.3-
8.3% per year up to 2040. In the long term “the most serious expected transformations of the world
and Russian energy systems are connected with further RES development” [5].

2. Problem statement

We introduce the definition: "regionally isolated electrotechnical complex (RIEC) is a separate set of
isolated power supply systems (IPS)" [6] which is characterized by the following main features [7]:

- Every IPS of the considered aggregate is an electrotechnical complex for generation and
  consumption of electrical energy (ETCG), while converting outer energies of various types:
  chemical, thermal, solar, hydraulic, ..., hereinafter called "external energy impact" (EEI) into
  electrical energy consumed by IPS;
- All IPSs included in the analyzed RIEC interact with each other only through mutual "weak
ties and weak interactions", including information and communication, hereinafter referred to as
  "external non-energy impact" (ENI);
- All IPS included in RIEC have a common ultimate goal and ensure the efficient and safe
  operation of the entire RIEC in a wide range of external impacts, both energy and non-energy;
- Mutual "weak ties and weak interactions" typical for the analyzed RIEC affect the quality of
  the RIEC functioning (including energy parameters) in a wide range of external impacts.

So “weak ties and weak interactions” are understood as non-energy impacts between IPSS:
informational, communicative, administrative, logistic, economic, environmental, social, legal and
others. Moreover, these weak links and weak interactions significantly affect the energy indicators of
individual IPS and RIEC: the quality of electrical energy, efficiency, energy efficiency, reliability of
power supply. At the same time, the cost of electric energy production, the level of environmental
friendliness of electric energy production, as well as the life cycle, efficiency and quality of
functioning of the entire complex as a whole depend on weak ties and weak interactions for the
considered IPS. As a consequence, the indicated "weak ties and weak interactions" must be considered
when analyzing and synthesizing the structure and principles of construction and operation of each
individual IPS included in the analyzed RIEC.

These are optimization problems arising in this case: technical, technological, production, design
and engineering, associated with the development and analysis of mixed or coupled models of devices
and systems that combine nodes and subsystems of different physical nature are often and successfully
solved using re-meshing [8]. As an example of the effective application of this approach, one can point
to problems of the "chain-field" type, where a combination of software, for example, ANSYS and
Matlab, is used. At the same time, these approaches are not focused on considering the revealed weak
ties and weak interactions which requires either using decomposition methods, with a natural change
in the degree of adequacy of modeling individual components of the system [9], or a specialized
approach is to be developed.

3. Theory

It follows from the RIEC introduced definition and its characteristic features: the ultimate aim of the
RIEC functioning, as a complex of IPS, is the reliable provision of consumers included in IPS with
electrical energy of the required quality. The actual production and transmission of electrical energy to
the consumer, as well as the management of these processes, is carried out through the interaction of physically heterogeneous components of the IPS components of the RIEC. At the same time, the quality of the IPS functioning is significantly influenced by the “weak ties and weak interactions” inherent in the considered RIEC. These include: geographic and climatic conditions, social and legal policy, science and technology policy, financial policy and economic priorities. The above-mentioned characteristic features of RIEC lead to the following statements [7]:

Statement 1. RIEC is “a complex production and technological system (CTS), which is a collection of interacting, functionally independent and physically heterogeneous subsystems designed to achieve a common (specific) aim” [10].

This statement is fully correlated with the concept of a complex system introduced in GOST 22.2.04-2012 [10], and with a number of definitions accepted in the world and local references [11-14], including the concept of a complex technical system. The corresponding enlarged structural energy diagram of the CTS RIEC from the standpoint of system analysis is shown in figure 1.

As a consequence of Statement 1, it is necessary to use system analysis method (SAM) in the analysis and synthesis of CTS RIEC [7]. Optimization problems for CTS RIEC, using SAM, lead to a weakly formalized choice of optimality criteria in a multidimensional space. Additionally, it is necessary to synthesize an algorithm for cutting off the set of optimal search alternatives. Note that the SAM approaches are quite deeply developed, including large power systems field [14-15]. However, shown above, CTS RIEC structural and functional features, as a specific complex technical system, lead to adapt SAM conceptual tool. First of all, the SAM basic principles: the principle of consistency, the principle of connectivity, the principle of hierarchy, the principle of optimality, the principle of emergence, the principle of equifinality.

Further formulations are of an integrative nature, taking into account the CTS RIEC definition adopted in this article and the theoretical provisions of a number of references [7; 11-18].

The principle of consistency. Here CTS RIEC is understood as a complex object consisting of a complex of interrelated and mutually influencing components of electrical complexes and systems. This principle requires the study of the CTS RIEC itself, but taking into account the interaction and
mutual impact with a larger system (supersystem), with which the complex technical system of RIEC interacts through weak links and weak interactions.

The principle of connectivity. When analyzing any CTS RIEC component, both internal connections between the components included in the CTS RIEC and interactions and interactions with the external environment (taking into account the impact of various external impacts) are identified and considered. In this case, CTS RIEC is primarily considered as an element of the supersystem.

The principle of hierarchy. Here CTS RIEC is considered as a hierarchical complex of physically heterogeneous subsystems. The division into subsystems is possible, both by the features of the physical boundaries of the components entering the system, and by the type of energy converted in the power channel, which is reflected by the energy structural diagram [19]. The assignment of a component, or a group of components to a certain hierarchical level, is determined by the purpose of the functioning of this level, which is set by a component or group of components of a higher level. In this case, the interaction of all components, regardless of their physical nature, is determined by the conservation laws.

Optimality principle. CTS RIEC is considered as a multi-parameter system, its performance and quality of functioning in various modes, with various external impacts throughout the entire life cycle, is set by an integral target indicator that meets the task of achieving a general (specific) aim. The CTS RIEC integral target indicator includes indicators of quality of electrical energy, energy efficiency, energy conservation, resource conservation, environmental damage, social effect, administrative and logistic resources considering weak ties and weak interactions inherent in the analyzed system. The best value of the integral target indicator of the CTS RIEC functioning is achieved by solving a multi-parameter optimization problem substantiating a set of technical, technological, economic, environmental and social criteria for decisions made in the design, creation, and operation of the analyzed system.

The principle of emergence. Here, CTS RIEC has integral properties, its individual components do not have them. When modeling, this circumstance leads to discrepancy between the local optima of the IPS target indicators included into the analyzed CTS RIEC, with the global optimum of the integral target of the entire CTS RIEC. The indicated mismatch increases with an increase in the number of levels and components of the system. Accordingly, to achieve global optimal results, it is necessary to make decisions and develop improvements of the system based not only on the analysis data of its individual components (as a rule, individual IPS), but also on the basis of the structural and parametric synthesis of the entire CTS RIEC and its optimization as a whole.

Equifinality principle. CTS RIEC can achieve the required performance and quality of functioning in various modes, with various external impacts, determined exclusively by its own characteristics of the system, the integral target indicator of the CTS RIEC functioning, under different initial conditions and in different ways. This circumstance leads to a multivariate approach in the development of efficient control algorithms. The proposed formulations of the main principles of SAM, as applied to CTS RIEC, allow, when solving the problems of managing the development of renewable energy sources and small-scale power generation [20], proceed from decomposition approaches to integral estimates of the following form:

$$\text{LCOER} = \frac{\sum_{t=1}^{T} \left[ \text{IRS}[t, G(WI), E(W)] + \text{ORS}[t, G(WI), E(W)] + \text{FRS}[t, G(WI), E(W)] \right]}{\sum_{t=1}^{T} \left[ \text{ERS}[t, G(WI), E(W)] \right]}$$

Where LCOER - Levelized Cost of RIEC Electricity;  
G(WI), E(W), IRS[t, G(WI), E(W)], IR[t, G(WI), E(W)], ORS[t, G(WI), E(W)], \text{FRS}[t, G(WI), E(W)], \text{FR}[t, G(WI), E(W)],  
\text{ERS}[t, G(WI), E(W)], \text{ER}[t, G(WI), E(W)] – functionals describing ROETC throughout the life cycle T, at a discount rate - r, in the current year - t.
4. Conclusion
Based on the above:

- The main characteristic features of RIEC are established;
- It has been established that RIEC is a complex production and technological system (CTS RIEC);
- With regard to CTS RIEC, the basic principles of system analysis have been adapted: the principle of consistency, the principle of connectivity, the principle of hierarchy, the principle of optimality, the principle of emergence, the principle of equifinality.

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