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Evaluation of reliability and corresponding financial implications of maintaining autonomous systems of energy supply / Ocena skuteczności i ekonomicznych korzyści z dywersyfikacji dostawy energii

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Abstract
The traditional and renewable sources are included in autonomous electrical power system for upgrading the power system and increasing the reliability. The reliability indexes of electrical sources, specific losses, time delays and system effectiveness are dependent on the choice of the autonomous electrical power system structure. The analysis of the results of modeling shows that the usage the sets of sources and reduces the specific cost of electricity of autonomous electrical power system.

Key words: **autonomous electrical power system, financial implications, independent and autonomous systems of energy economy, economics, econometrics**

At present the principal strategy of developing low capacity (independent or autonomous) systems of energy supply is in design of hybrid systems combining several sources of electricity including (in the first place) generation from renewable sources.

The utilisation of renewable energy sources of various nature allows providing energy needs (fully or to large extent) of stand-alone industrial, residential or other objects. The reliability of such systems is increased due to access of diversified sources (e.g. PV panels, wind generators, etc.). On the other hand the renewable sources are not always available due to variable nature factors. Therefore the autonomous electrical power system (AEPS) should include traditional sources of electricity generation or energy storages. For example, access to grid, diesel generators, batteries, etc.[1].

Noted above dictates the need to: (a) rational choice of capacities for each source, (b) design of the controlling algorithms to satisfy the pre-determined reliability of supply and optimise the costs of the system during certain period (e.g. life-time of the base equipment).

To characterise the reliability of electricity supply system one needs to define two random variables, time to failure T_F and recovery time T_R. Often it is more convenient to use instead of T_R the average time of interruption of supply t_1, which accounts not only for the recovery time, but also time required to organise the supply at the required level.

The relationship between t_i and T_r is:

$$t_i \approx (1{,}3 \div 2{,}2) \times T_R, \qquad (1)$$

For every technological process there is a characteristic known as allowable (critical) time of interruption . The time of critical interruption may be defined as:

$$T_A = t_i - T_C. \qquad (2)$$

For the analysis of AEPS we will use the graph theory,

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[1] V. Kozyrskiy, V. Kaplun, *Analysis of streams in local systems with distributed generation by methods of graph theory*, Annals of Warsaw University of Life Sciences – SGGW Agriculture, N57, 2011, pp. 109-112.

which is the most convenient tool of mathematical modelling of reliability of complex systems. Graph consists of two sets: (a) set of vertices and (b) set of edges. The reliability graph of AEPS each state of the system will be represented with a circle and an identification number in it. The transition from one state to another will be denoted by lines connecting the states. The mathematical theory of graphs can be used for numerical analysis of the reliability of AEPS.

The reliability analysis of AEPS may be performed using random graphs. Random graphs may model random failures of the system elements. For quantitative assessment of AEPS reliability we shall use reliability characteristics of individual elements (blocks). We shall assume that failures of the elements are statistically independent.

We shall also use the theory of Markov and semi-Markov processes. A Markov chain with n states is represented with a transition probabilities matrix[2]:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}. \qquad (3)$$

Each element p_{ij} represents probability that the system will move to state j from state i in one step. The diagonal elements p_{ii} is the probability that system will not change the state.

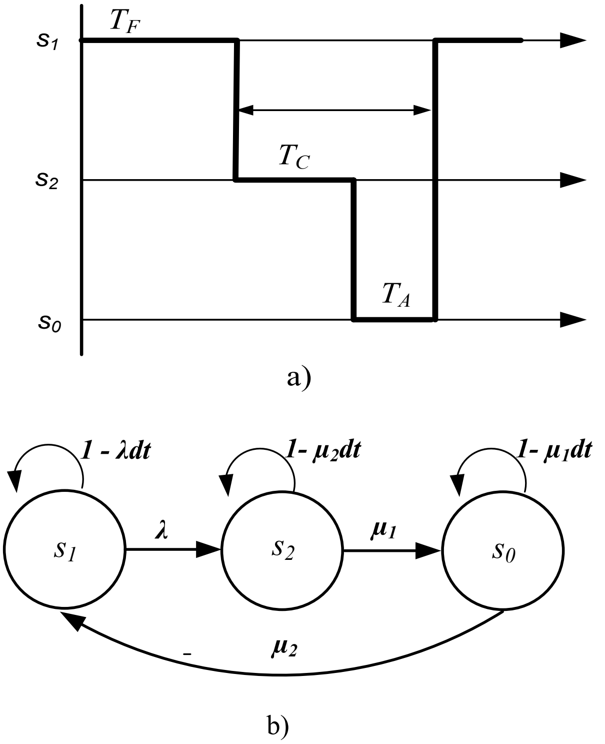
System transition from one state to another is described with a random variable having cumulative distribution function $F_k(t)$ for each state k. In case of Markov processes all distributions $F_k(t)$ are exponential distributions. Given transition probabilities p_{ij}, parameters, and distributions λ_1 of time that the process remains in state i, one may find the weight of each edge as: $\lambda_{ij} = p_{ij}\lambda_1$.

Semi-Markov process is defined with transition probabilities of inserted Markov chain p_{ij} and conditional distribution $F_k(t)$ of the time duration that the system remains in state i under condition that the system will move into pre-defined state j.

Hence, the graph representing semi-Markov process should picture on each edge transition probability p_{ij} and conditional distribution of time that the process remains in state corresponding state given transition along this edge.

Consider functioning of a single non-reserved element which may take one of three states: s_1 – the element is in order, s_2 – the element is out of order, however there is no need to supply disconnection and s_0 – the element is out of order and cannot perform its function (state of failure) (fig.1a). If the failure stream has intensity λ the element transits from state s_1 to state s_2 and from there, after certain time, with intensity μ_1 may transit into state s_0, from where it may restore to "in order" state with stream intensity μ_2. The transitions graph over certain time dt may be seen on figure 1b.

Figure 1. The time diagram of transitions of a single element from state to state (a) and the graph of states (b)



a)

b)

A Markov process may be represented by the following system of differential equations of states:

$$\frac{dp}{dt} = \sum_{j \in G_i^{'}} \lambda_{ij} p_j(t) - p_i(t) \sum_{j \in G_i^{''}} \lambda_{ij}\ , \qquad (4)$$

where G_i is the subset of states of the Markov process which allow transition into state i and G_i is the subset of states that may be entered from state i, finally λ_{ij} are intensities of the transitions.

The system (4) is linearly dependent and, therefore, we need to add another equation (normality equation) to make the solution unique:

$$\sum_{i=n}^{n} p_i = 1 \qquad (5)$$

To perform the Markov process analysis we will need

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[2] *Ibidem.*

impose the following assumptions and restriction, namely:

- tree of transitions will be assumed independent;
- all intensities of failures λ and recovers μ are constant;
- transition probabilities within short time are negligible;
- all processes are strictly Markovian with exponential probability distributions.

Consider a generalised structure of AEPS that combines three sources of electric power:

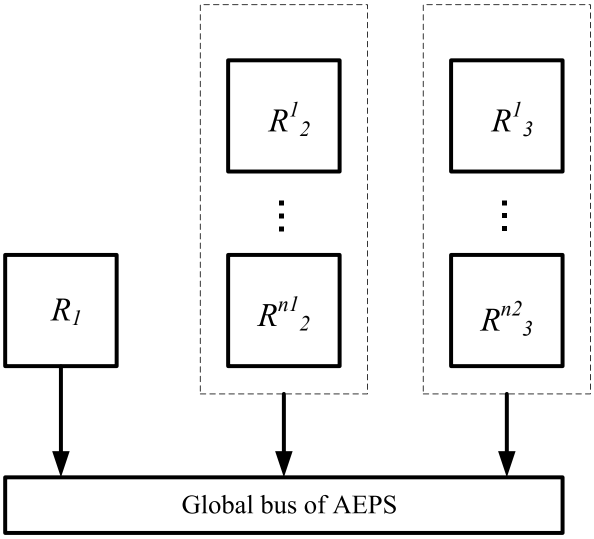
R_1 is the supply from the grid;

R_2 of sources of electric energy consisting of static converters with accumulative features and sources that use renewable and/or non-traditional primary energy. The static convertors have special functional characteristics that allow switching to the autonomous supply at shortest possible time typically without sine wave discontinuity.

R_3 is the set of sources using the internal combustion engines (gas/petrol, diesel, gas/diesel, biofuels, etc.). The specific of these sources is in the presence of automation features that provide required activation time (that is, time from transition from unloaded/cold reserve to working mode).

The figure 2 presents the general structure of such IRES with variable sources.

Figure 2. General Structure of the AEPS



From the probabilistic point of view the source R_1 is an alternating restoration process, that is, it is represented by two independent variables that come to effect in turns. These variables are identically distributed and are independent as a set.

To improve the electric energy quality and reliability the system includes two sets of sources R_2 and R_3, which allows meeting the strictest requirements in terms of quality as well as continuity of supply. The set has sources and the set has sources.

In the system under study one of the sources $R_2^1, \dots, R_2^{n_1}$ works in loaded reserve $(R_2^j \in R_2, j = \overline{1, n_1})$. Among $R_2^1, \dots, R_2^{n_1}$ we may have both traditional electrical energy sources (static converters with accumulation), and non-traditional/renewable. In the general case the processes behind $R_2^1, \dots, R_2^{n_1}$ are also alternating restoration processes.

The generators using renewable sources are also characterised by accessibility to the primary energy. This is caused by the natural factors, such as availability of wind, sunlight, etc. To include such states in the study we introduce the accessibility coefficient K_a.The coefficient will be defined as a probability that the source R_2 has access to the primary energy at certain remote moment of time (that is it will be able to convert this primary energy into electrical energy).

In case of a failure of source R_1 the energy supply will be secured by one of the operational and accessible sources from the set $R_2^1, \dots, R_2^{n_1}$. In general, the activation sequence of sources $R_2^1, \dots, R_2^{n_1}$ (if R_1 fails) is defined by the AEPS algorithm.

The sources of set R_3 are working in unloaded mode with time-delay (time required for activation). In case of a failure of source R_1 (assuming this source is always accessible), after some time delay one of the sources R_3 becomes the main source of the electricity (the time delay normally depends on the degree of automation) (reliving from this function one of the sources $R_2^1, \dots, R_2^{n_1}$) until R_1 restores or as per AEPS functioning algorithm.

The reliability indicators, relative losses, time-delay and respectively indicators of reliability and efficiency of the system depend on the configuration of the AEPS and sets of sources $R_2^1, \dots, R_2^{n_1}$ and $R_3^1, \dots, R_3^{n_2}$.

Hence, the problem in general may be stated as follows: to select from possible "candidates" of sources with given parameters select such that the structure of the system as whole is optimal in certain a sense. In this context it seems reasonable to consider one of two approaches in optimization:

- maximization of a certain reliability indicator (e.g. readiness coefficient, operational readiness coefficient) assuming that average specific losses satisfy some restrictions;

- minimization of average specific losses in the system under restricted reliability indicators;

To state formally the optimization problem (finding most rational use of the electricity sources) we need to account for special operational indicators of the autonomous system and conduct the following phases of the research:

Phase 1: Categorize the consumers of the electrical energy according to the requirements regarding continuity/reliability of electricity supply.

Phase 2: Define and substantiate levels of electricity supply quality for all categories of the consumers as per following steps:

- introduction of additional equipment (filters, stabilizers, chargers, etc.) as a quality improving subsystem;
- substantiating of design solutions for achieving higher levels of technical perfection for both electricity sources (e.g. overloading capacities), and other equipment such as automation system, commutation equipment, etc.)
- optimization of operation modes of the consumers.

Phase 3: Define, substantiate and analyse levels of reliability indicators for the consumers as per following steps:

- substantiate the optimal distribution of the electricity demand from selected sources.
- conduct analysis of economic indicators via introduction of the main optimization criteria – specific production cost of electrical energy.

To solve the optimization problem we need to minimize the function of expenses with respect to multiple variables satisfying a set of constraints.

Consequently, the traditional and renewable sources are included in AEPS for upgrading the power system and increasing the reliability. The reliability indexes of electrical sources, specific losses, time delays and system effectiveness are dependent on the choice of the AEPS structure. The analysis of the results of modeling shows that the usage the sets of sources and reduces the specific cost of electricity of AEPS.

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