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CRITERION MODELLING OF THE PROCESS OF REDUNDANCY OF RENEWABLE ENERGY SOURCES POWER GENERATION INSTABILITY BY ELECTROCHEMICAL ACCUMULATORS

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Abstract: The paper analyzes the methods and ways for the redundancy of renewable energy sources (RESs) instability in electric power systems (PS). It is shown that these can be maneuverable capacities, in particular, thermal and hydropower plants, accumulators, hydrogen technologies, biogas plants. It is substantiated that, for various reasons, for the RESs to be developed and their capacity to be increased in power systems, electrochemical accumulators and highly maneuverable capacities existing in the PS are the most prepared for implementation. Mathematical models based on similarity theory and the criterion method have been developed for them. This approach is preferable due to the fact that with the minimum available information, it provides the opportunity to compare different ways of compensation of RESs generation instability, to assess their proportionality, as well as to determine the sensitivity of costs to the capacity of the redundancy methods. Criterion models which allow us to design dependences of the costs for the redundancy of RESs generation instability on the capacity of electrochemical accumulators, on the capacity of the system reserve, as well as on the capacity of power lines have been formed. Such dependencies make it possible to more reasonably choose certain methods of redundancy in accordance with the characteristics and requirements of PS.

Key words: power system, renewable energy sources, generation instability, redundancy, electrochemical accumulators, similarity theory, criterion method.

1. Introduction

The instability of RESs generation, caused by dependence on natural conditions, as well as their overestimated installed capacity connected to power systems (PS), lead to a decrease in the efficiency of the electric grid and deterioration in the quality of electricity supply services. This is especially true for photovoltaic plants (PVPs), the unit and total installed capacity of which in electric networks is growing every year. The instability of the PVPs operating modes has a negative impact on the balance reliability of the power system, as well as on the stability of its operation. It is possible to ensure the balance of capacity and electricity in a power system by comprehensively using the available maneuverable capacities, including thermal (TPP) and hydropower plants (HPP), as well as modern means (electric accumulators, hydrogen technology, biogas plants, coordination of electricity generation and consumption schedules, etc.). It would be optimal to use all these conditions in the developed automated control system (ACS) with a gradual transition to an automatic control system (ACS) based on the principles of SMART Grid.

The solution to the problem can be the creation of mathematical models, methods and automated control system for maintaining the balance in the power system with non-guaranteed energy sources such as photovoltaic plants. It is necessary to create favorable conditions not only for the design of RESs in electric networks of the power system but also for their optimal operation, minimizing the negative impact on technical and economic performance of the power system.

2. Analysis of scientific publications. Statement of the problem

If the criterion of optimality is taken as the total costs C_Σ of the redundancy of RESs generation instability, then, taking into account the really possible currently available methods of redundancy, the problem of minimizing C_Σ will be written [1-3]:

$$C_\Sigma = C_{ech}\left(P_{ech}\right) + C_h(P_h) + C_b(P_b) + \\ + C_s(P_s) + B_{tr}\left(P_{tr}\right) \to \min, \tag{1}$$

where $C_{ech}(P_{ech})$ is the redundancy costs by electrochemical accumulators; $C_h(P_h)$ is the costs of usage of hydrogen technologies; $C_b(P_b)$ is the costs associated with the use of biogas technology as a reserve; $C_s(P_s)$ is the costs of the use of the power reserve that is, in fact, compensation for maintaining the load reserve for TPP units operating on price bids; $C_{tr}(P_{tr})$ is the cost of increasing the power lines capacity, which is necessary for electricity to be transported from/to the place where the reserve capacity is connected to the power system; P_{ech}, P_b, P_h, P_s, P_{tl} are, respectively, the optimal values of power, which are determined from each of the redundancy methods.

Of course, the use of hydrogen technologies is relevant and promising but still expensive. Today, the widespread use of "green" hydrogen faces the following difficulties:

1. The production of hydrogen using low-carbon electricity is currently expensive. Research conducted by the International Energy Agency (IEA) found that the costs of hydrogen production from RESs could decrease by 30 % by 2030 as a result of reduced RESs costs and increased production of hydrogen. Fuel cells, gas station equipment, and electrolyzers (which produce hydrogen from electricity and water) are promising.

2. The development of hydrogen infrastructure is slow. Hydrogen prices for consumers strongly depend on how many gas stations there are, how often they are used and how much hydrogen is supplied per day. This task can be addressed through planning and coordination that brings together national and local governments, industry, and investors.

3. Hydrogen comes almost entirely from natural gas and coal. Hydrogen is already used commercially around the world, but its production is associated with CO_2 emissions. Therefore, it is necessary to repurpose the production of hydrogen using RESs.

4. Regulations limit the development of clean hydrogen energy. Government and industry must work in cooperation to ensure that current regulations do not discourage investment.

The use of biogas technologies as a reserve requires taking into account restrictions, for example, on the provision of raw materials – an economically feasible distance for the delivery of raw materials is a distance of up to 20 km for liquid raw materials and up to 50 km – for dry ones).

In order to choose one or another way of redundancy of RESs generation instability in the PS, it is necessary to take into account not only the costs of individual methods but also other factors that affect the process of their implementation and operation. Since all of the above methods, except for the system power reserve at TPPs and HPPs, are at different stages of development and readiness for large-scale implementation, one has to justify and select some of them. These are the methods whose production is debugged and offered on the market. Today, these are electrochemical accumulators and traditional methods of system redundancy. Actually, these are the very methods for the redundancy of the instability of RESs generation to be investigated in the first place. As for the other methods of redundancy, they should be considered at the next stage, when they will be technologically available and their cost to compensate for the instability of RES generation will be competitive.

Thus, the purpose of the article is to develop a mathematical model of the process of redundancy of the renewable energy generation instability by electrochemical accumulators in conjunction with the existing PS modes redundancy.

3. Mathematical model of the process of using electrochemical accumulators in electrical networks

According to the scenario that maneuverable capacities of the system and electrochemical accumulators are used in the power system to compensate for the instability of RES generation, problem (1) will be rewritten:

$$C = C_{ech}\left(P_{ech}\right) + C_s(P_s) + B_{tr}\left(P_{tr}\right) \to \min . \quad (2)$$

The costs of using the power system reserve, which is actually compensation for the maintenance of the load reserve for TPP power units operating on price bids, is determined by the formula:

$$C_{ps} = \begin{cases} P_{ps} \cdot (c_c^{ps} - dc_f), c_c^{ps} \rangle c_f \\ 0, c_c^{ps} \langle dc_f \end{cases} \quad (3)$$

where c_c^{ps} is the marginal price of the system, which is formed for the settlement hour on the wholesale electricity market; dc_f is the increased fuel price determined on the basis of the derivative function of fuel consumption for electricity generation by the level of load of the power plant unit and the costs of the required fuel;

A modified mathematical model of specific costs per 1 kW of redundancy in the scenario, which involves the use of electrochemical accumulators and takes into account the features of the power system, which requires power redundancy, can be written as the equation:

$$C = \frac{C_1}{P_{ech}} + C_2 P_s + C_3 P_{tr} + C_4 \frac{P_{ech}^2}{P_s^2 \cdot P_{tr}} \to min . \quad (4)$$

where C_1, C_2, C_3, C_4 are generalized constants containing the original data of the problem.

The first component of the equation takes into account the specific costs of the redundancy implementation using a system of electrochemical accumulators; the second, third, fourth components take into account the costs of electrical networks.

To analyze the system of redundancy of RESs generation instability, we will use the methods of similarity theory, in particular the criterion method [5–7]. The advantage of the chosen method is that it allows obtaining similarity criteria that link the same parameters of, in our case, different methods of redundancy, and creating conditions for analyzing the proportionality and sensitivity of calculation results in relative units with a limited amount of source information [8].

Problem (4) corresponds to the condition of canonicity when the degree of its complexity is

$s=m-n-1=0$, where m is the number of members of the objective function, n is the number of variables Pi. According to the criterion method, we write a system of orthogonal and normalized (orthonormal) equations for (4) [6, 9]:

$$\begin{cases} -\pi_1 + 2\pi_4 = 0 \\ \pi_2 - 2\pi_4 = 0 \\ \pi_3 - \pi_4 = 0 \\ \pi_1 + \pi_2 + \\ \pi_3 + \pi_4 = 1 \end{cases} \Rightarrow \begin{bmatrix} -1 & 0 & 0 & 2 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}. \quad (5)$$

With the degree of complexity of the problem of optimizing the methods of compensating for the instability of RES generation in form (4) being zero, it is simple to obtain the solution of this system of equations (5):

$$\pi_1 = \pi_2 = 2/6;$$

$$\pi_3 = \pi_4 = 1/6.$$

In accordance with the method of integral analogs [5], we write a system of equations in which the similarity criteria are related to the unknown Pi, taking into account (4) and the solutions to the system of equations (5):

$$\begin{cases} \pi_1 = \dfrac{2}{6} = \dfrac{C_1}{P_{ech}} \\ \pi_2 = \dfrac{2}{6} = C_2 \cdot P_s \\ \pi_3 = \dfrac{1}{6} = C_3 \cdot P_s \\ \pi_4 = \dfrac{1}{6} = \dfrac{C_4 \cdot P_{ech}^2}{P_s^2 \cdot P_{tr}} \end{cases}. \quad (6)$$

From the system of equations (6) we obtain the optimal values of the installations' capacities for the redundancy of the RESs generation instability:

$$P_{ech} = \left(\frac{C_1^4}{4C_2^2 \cdot C_3 \cdot C_4} \right)^{\frac{1}{6}};$$

$$P_s = \left(\frac{4C_1^2 \cdot C_3 \cdot C_4}{C_2^4} \right)^{\frac{1}{6}}; \quad (7)$$

$$P_{tr} = \left(\frac{C_1^2 \cdot C_2^2 \cdot C_4}{16 \cdot C_2^5} \right)^{\frac{1}{6}};$$

$$C = 3\left(4 \cdot C_1^2 \cdot C_2^2 \cdot C_3 \cdot C_4\right)^{\frac{1}{6}}.$$

In the criterion form, expression of costs (4) is written as:

$$C_* = \frac{\pi_1}{P_{ech*}} + \pi_2 P_{s*} + \pi_3 P_{tr*} + \pi_4 \frac{P_{ech*}^2}{P_{s*}^2 \cdot P_{tr*}}. \quad (8)$$

where $C_* = \dfrac{C}{C_{min}}$; $P_{ech*} = \dfrac{P_{ech}}{P_{ech\_opt}}$, $P_{s*} = \dfrac{P_s}{P_{s\_opt}}$, $P_{tr*} = \dfrac{P_{tr}}{P_{tr\_opt}}$, where P_{ech}, P_s, P_{tr} are the current and optimal values of the capacities of the redundancy methods, respectively. Taking into account the numerical values of the similarity criteria, (8) will be rewritten:

$$C_* = \frac{2}{6P_{ech*}} + \frac{2P_{s*}}{6} + \frac{P_{tr*}}{6} + \frac{P_{ech*}^2}{6P_{s*}^2 \cdot P_{tr*}}. \quad (9)$$

Let us select the component of the costs of redundancy by electrochemical accumulator (the first member of the optimized function) and the component that characterizes the costs of using the system reserve and the cost of increasing the margin of the capacity of transmission lines (the second member of the optimized function):

$$C_* = 0{,}333 \cdot P_{ech*}^{-1} + 0{,}667 \cdot$$
$$\cdot \left(0{,}5 \cdot P_{ech*} + 0{,}25 \cdot P_{tr*} + 0{,}25 \cdot P_{ech*}^2 \cdot P_{s*}^{-2} \cdot P_{tr*}\right). \quad (10)$$

According to accepted model (10), the costs B to compensate for the irregularity of the RES generation schedule by means of redundancy will be economically feasible if 2/3 of these costs are used to modernize networks and use the system reserve, and 1/3 of the costs of redundancy by electrochemical accumulators. The economically feasible values of similarity criteria do not depend on $C_1, \ldots, C_4$ and determine the proportionality of the model, ie the share of variable costs attributable to the elements of the redundancy system of RES generation instability. With regard to the generalized indicators $C_1, \ldots, C_4$, their impact on economically feasible values of capacity P_{ex*}, P_{ec*}, P_{en*} and costs B_* can be estimated by writing (7) as follows:

$$P_{eech*} = \left(\frac{C_{1*}^4}{4C_{2*}^2 \cdot C_{3*} \cdot C_{4*}} \right)^{\frac{1}{6}};$$

$$P_{es*} = \left(\frac{4C_{1*}^2 \cdot C_{3*} \cdot C_{4*}}{C_{2*}^4} \right)^{\frac{1}{6}};$$

$$P_{etr*} = \left(\frac{C_{1*}^2 \cdot C_{2*}^2 \cdot C_{4*}}{16 \cdot C_{2*}^5} \right)^{\frac{1}{6}};$$

$$C_{e*} = 3\left(4 \cdot C_{1*}^2 \cdot C_{2*}^2 \cdot C_{3*} \cdot C_{4*}\right)^{\frac{1}{6}},$$

where $C_{i*} = C_i / C_{ibas}$, $i = \overline{1,4}$.

Given that, as a rule, at the design stage additional values of C_i indicators are unknown, but their range $C_{i\,\min} - C_{i\,\max}$ is known, the base value should be taken as the average value of the price range [3].

From the expressions obtained, it is possible to estimate the impact of changes in, for example, C_1 on economically expedient values of all variables. Expressions (11) show that the economically feasible values of potential opportunities, which are determined from each of the redundancy capacities and the costs of their implementation, require the adopted scenario of the redundancy implementation. Therefore, economically feasible methods of redundancy and their potential, as well as the implementation parameters are selected taking into account their interaction in the system. Expression (10) also makes it possible to estimate the initial data impact on economically feasible values of costs and capacity, which are determined by different methods of redundancy, ie to investigate the sensitivity of costs to changes in capacity.

For example, if C_1 relative to the base value increases with constant C_2, C_3, C_4, the total cost C to compensate for the instability of RES generation by power redundancy increases by 44.2 %, and the capacity of electrochemical accumulators doubles (208 %), the capacity of the power lines increases by 44, 2 %, the capacity of a system reserve increases by 44.2 %.

Also, the criterion equation can determine the change in specific costs when changing one or another optimized capacity, ie to investigate the economic sustainability of costs to changes in parameters (Fig. 1). If the capacity of electrochemical accumulators P_{ech} increases by 50 %, the costs value will increase by 9.7 %, and if doubled – the costs value will increase by 33 %. If P_s increases by 50 %, the costs value will increase by 7.4 %. If P_{tr} increases by 50 %, the costs will increase by 2.8 %.

This analysis allows us to conclude that the cost allocation for the redundancy scenario under study is more sensitive to the choice of the capacity of electrochemical accumulators and the choice of system reserve capacity. Figs. 1 and 2 present an analysis of the specific cost sensitivity, both in the relative units and as a percentage, to the change in one of the influencing factors with the others unchanged; the costs are determined by formulas (10) and (11).

Fig. 3 shows the cost sensitivity depending on the simultaneous change in the capacity of the electrochemical accumulators and to the change in the capacity of the system reserve, with the capacity of the electrochemical accumulators decreasing in proportion to the increase in the capacity of the system reserve. With a RESs capacity being known, this seems obvious, because the required total reserve capacity must remain constant. A criterion sensitivity analysis makes it possible to determine the numerical characteristics of the relationship between the reserve capacity of electrochemical accumulators and the maneuverable capacity of the system reserve.

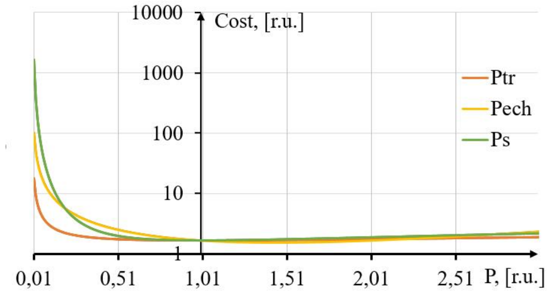
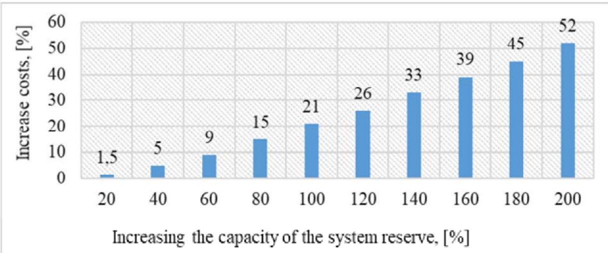
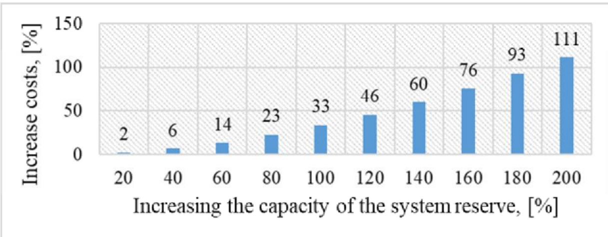


Fig. 1. Cost sensitivity: to changes in the capacity of electrochemical accumulators (green curve), to changes in the capacity of the system reserve (red curve), and to changes in the capacity of electric power lines (blue curve).



a



b

Fig. 2. Sensitivity of costs of change in the capacity of power redundancy: a) chemical type; b) system reserve capacity.

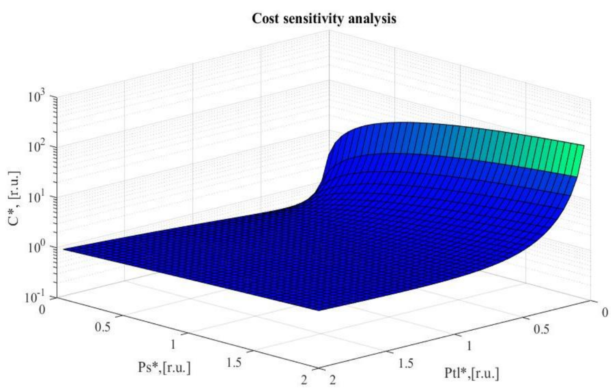


Fig. 3. Sensitivity of costs to simultaneous change in the capacity of electrochemical accumulators and the capacity of system reserve.

Fig. 4 shows the sensitivity of costs depending on the simultaneous change in the capacity of electrochemical accumulators and to the change in the capacity of electric power lines. Moreover, the capacity of electrochemical accumulators increases in proportion to the increase in the capacity of electric power lines. This dependence is obvious in principle because the construction of an electrochemical accumulator or increasing its capacity requires an increase in the capacity of power lines that connect it to the system, or you need to build a new line. The analysis of sensitivity of the costs of changing the power line capacity when changing the capacity of the accumulators of electrochemical type makes it possible to establish the corresponding numerical characteristics in relative units.

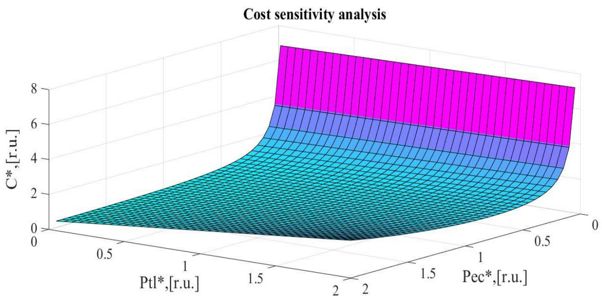


Fig. 4. Costs sensitivity to a simultaneous change in the capacity of electrochemical accumulators to change in the power line capacity.

4. Conclusions

For a pre-design analysis of the methods for redundancy of RESs generation instability during their development in power systems, it is advisable to use a criterion method based on the theory of similarity. This approach makes it possible in relative units to assess the benefits of a particular method of redundancy and to establish their optimal capacities for these cost characteristics. The optimization results obtained in this form allow us to analyze the proportionality and sensitivity of the components of the objective function, in our case, the ways of compensating for the uneven generation of RESs. The results of proportionality make it possible to rank the ways of compensating for the uneven generation of RESs in terms of costs, and the sensitivity – rationally, and to most efficiently use the power of different methods during operation.

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КРИТЕРІАЛЬНЕ МОДЕЛЮВАННЯ ПРОЦЕСУ РЕЗЕРВУВАННЯ НЕСТАБІЛЬНОСТІ ГЕНЕРУВАННЯ ВІДНОВЛЮВАНИХ ДЖЕРЕЛ ЕНЕРГІЇ ЕЛЕКТРОХІМІЧНИМИ НАКОПИЧУВАЧАМИ

Петро Лежнюк, Вячеслав Комар, Олена Рубаненко

В роботі аналізуються методи і способи резервування нестабільності генерування відновлюваних джерел енергії (ВДЕ) в електроенергетичних системах (ЕЕС). Показано, що це можуть бути маневрені потужності, зокрема теплові та гідроелектростанції, накопичувачі електроенергії, водневі технології, біогазові установки. Обгрунтовано, що з різних причин для розбудови і нарощування потужності ВДЕ в енергосистемах найбільш підготовленими для впровадження є електрохімічні накопичувачі та існуючі в ЕЕС високоманеврені потужності. Для них розроблено математичні моделі на основі теорії подібності і критеріального

методу. Надано перевагу такому підходу через те, що він за мінімально доступної вихідної інформації забезпечує можливість порівнювати між собою різні способи резервування нестабільності генерування ВДЕ, оцінювати їх співрозмірність, а також визначfти чутливість витрат до потужності способів резервування. Сформовано критеріальні моделі, які дозволяють побудувати залежності витрат на резервування нестабільності генерування ВДЕ від потужності накопичувачів електрохімічного типу, від потужності системного резерву, а також від пропускної здатності ліній електропередачі. Такі залежності дають можливість обґрунтованіше обирати ті чи інші способи резервування відповідно до характеристик і вимог ЕЕС.

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