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OPTIMIZATION OF ELECTRICITY CONSUMPTION BY A GROUP OF MONOPOLAR ELECTROLYSIS PLANTS OF THE SAME TYPE

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Recently, more and more attention has been paid to environmental problems associated with excessive extraction of traditional energy resources. The transition to sustainable and renewable energy sources is becoming a key solution to overcome the depletion of natural resources and reduce the negative impact on the environment. One of the promising areas is the use of technology for obtaining hydrogen and oxygen through electrolysis. However, these days the mentioned technologies require large energy costs. Yet, in some of group operating modes, several electrolysis plants that operate simultaneously (in this paper, we are talking about monopolar electrolyzers with an active electrode) were used. At the same time, they might have a very negative impact on the elements of the electrical network that supplies this group of electrolysis plants. The optimization of the operation of a group of monopolar electrolysis plants of the same type in order to minimize their negative impact on the electrical network is considered in this paper. The results of the approximation of the function that describes the change in voltage for electrolysis with an active electrode, obtained from experimental data, using Fourier series were given. The optimization objective function was determined and the problem of finding the optimal sequence of starting a group of electrolysis plants was solved using stochastic methods. As a result of the calculations, it was established that the use of stochastic methods is appropriate, and based on the proposed solution, it is possible to create a prototype of a real control system for a group of similar electrolysis plants.

***Keywords**: electrolyzer, hydrogen, optimization, algorithm, function, current density.*

Introduction

The relevance of hydrogen technologies is determined by modern global challenges in the field of energy, ecology and economics. In addition, the increase in energy demand, the need to reduce greenhouse gas emissions and the commitment for sustainable development contribute to their active implementation, which, in turn, will allow to solve environmental problems, strengthen energy security and open up new economic opportunities.

Hydrogen technologies are also key to creating a sustainable energy system of the future. In view of this, the urgency of using hydrogen technologies is growing every day, especially with the strengthening of global environmental standards and the development of "green" energy. The most common method of obtaining hydrogen is the electrolysis of water, which requires sufficient amounts of electricity [1]. If there are not enough electricity sources, this can cause additional load on the energy system, especially during peak consumption periods [2, 3].

Relevance of the problem

Recent research in the field of green hydrogen indicates a significant interest in optimizing existing methods of its production and minimizing costs. In current papers, the improvement of hydrogen systems is considered from the perspective of:

– maximizing the profitability of electrolyzers when using solar panels as a power source by finding the best operating time and number of photovoltaic cells [4, 5];

– reducing costs in hydrogen logistics by choosing the optimal number of containers for its storage and transportation [6, 7];

– finding the best configuration of the hydrogen system (using different electrolyzer settings and different power sources) [8].

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It is worth noting that these papers consider hydrogen production systems based on a single electrolyzer and do not aim to assess the feasibility of using multiple plants.

The membraneless monopolar high-pressure electrolyzers have been developed in the Anatolii Pidhornyi Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine [9–11]. Unlike a bipolar electrolyzer, the electrodes in a monopolar electrolyzer are connected to the current source separately (in parallel), which simplifies their manufacture, installation and maintenance. In addition, in a bipolar electrolyzer the electrodes must simultaneously perform the functions of the anode and cathode, which requires more complex material processing. A monopolar electrolyzer with an active electrode operates in cycles consisting of two half-cycles – hydrogen and oxygen, with different half-cycles having different voltage polarity on the passive plates.

Fig. 1. Damaged turbine blades

The cyclical nature of electrolysis systems without optimization of the launch sequence can lead to a high load on the power system during hydrogen (oxygen) generation on an industrial scale. The appearance of turbine blades that failed due to mechanical shock caused by a sharp change in the load on the generator shaft is shown in Fig. 1.

Plant description

In industry, traditional electrolyzers with a liquid alkaline electrolyte, providing gas generation with a pressure of 0.05–1.6 MPa in the temperature range from 333 to 353 K and a current density of 1200–2500 A/m^2 are widely used. At the same time, energy consumption (depending on the process temperature, pressure, electrode quality, electrolyzer design and a number of other factors) varies from 4.3 to 5.2 kWh/m^3 of hydrogen (H_2).

In a monopolar high-pressure electrolyzer, the production of H_2 and O_2 during the decomposition of H_2O is spaced in time and forms hydrogen H_2 and oxygen O_2 half-cycles. This eliminates the need for a membrane. In this case, in the first half-cycle, hydrogen is released on the passive electrode in gaseous form and fed into the high-pressure line, and oxygen is chemically bound by the active electrode (forming a chemical compound). In the next half-cycle, electrochemical reduction of the active electrode with hydrogen occurs, which is accompanied by the release of oxygen on the passive electrode and its withdrawal into the external line.

A simplified functional diagram of the power supply system of the electrolysis plant (considered in this paper) is shown in Fig. 2.

This diagram shows that the same amount of electric current flows through the electrolytic cell over time, changing direction as it goes from one half-cycle to the next one. The element with the highest energy consumption in this diagram is the electrolytic cell. The potential U_e arises at the electrolytic cell terminals due to the flow of current I_{cur}. The electric energy W consumed by the electrolytic cell is the integral of the power $P(t)$ over time

$$W = \int_{t_1}^{t_2} P(t)dt\ ;\ P(t) = I_{cur} \cdot U_e(t)\,.$$

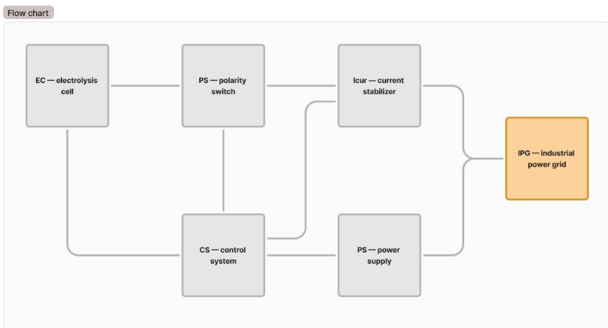

Fig. 2. Functional diagram of an electrolysis plant:
EC – electrolysis cell; PS – polarity switch;
I_{cur} – current stabilizer; CS – control system;
PS – power supply; IPG – industrial power grid

In accordance, $W = I_{cur} \int_{t_1}^{t_2} U_e(t)dt$, where $U_e(t)$ – is the law of voltage change at the electrolytic cell terminals.

The voltage change of the full cycle of hydrogen and oxygen release during electrolysis using a gas-absorbing electrode is shown in Fig. 3 and Fig. 4.

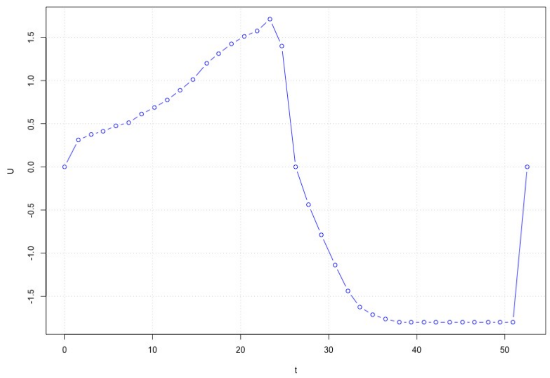

Fig. 3. Voltage change of the full cycle of hydrogen and oxygen release during electrolysis using a Fe (spongy) electrode assembly. Current density I=0.03 A/cm²

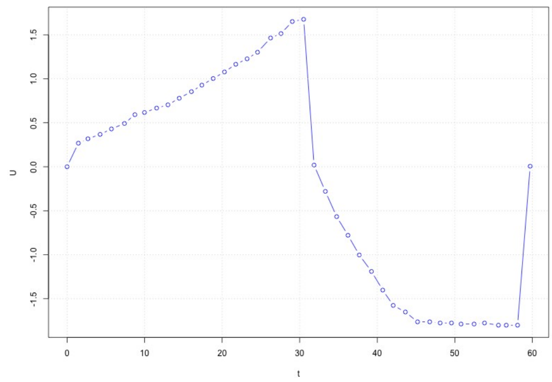

Fig. 4. Voltage change of the full cycle of hydrogen and oxygen release during electrolysis using a Fe (spongy) electrode assembly. Current density I=0.015 A/cm²

Description of expected optimization

Accordingly, the generation of gases with the simultaneous use of several devices creates a large electrical and mechanical load on the electrical system. Based on the schedule of the electrolyzer operation cycle, unevenly distributed power consumption can lead to an increase in peak power and the occurrence of shock mechanical loads on the energy system (which can cause a shock to the turbines of the generating plant and cause them to fail). The voltage change in the non-optimized operating mode of the 1st, 3rd, 5th electrolyzers simultaneously is shown in Fig. 5.

To avoid such scenarios, the plants need to have a control module (controller) that will manage the launch sequence in such a way as to minimize the amount of simultaneously used voltage and eliminate shock loads during the completion of the plant's operation cycles. In addition, optimization of the launch sequence of electrolyzers ensures stable and continuous hydrogen production, in contrast to the unoptimized activation of plants operating in a half-cycle mode. The change in the voltage of the optimal launch sequence of 6 identical electrolyzers is shown in Fig. 6.

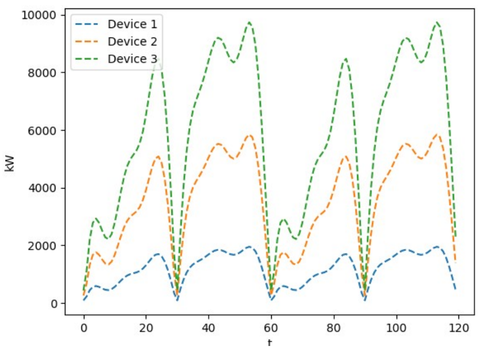

Fig. 5. Voltage change of non-optimized operating mode of the 1st (blue), 3rd (orange) and 5th (green) identical simultaneously running electrolyzers

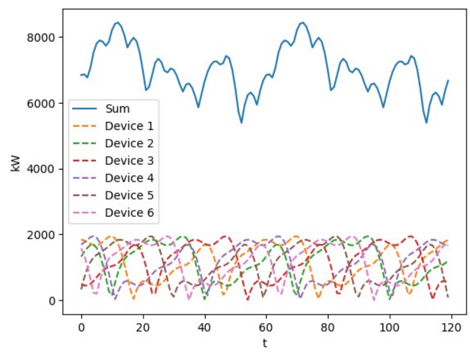

Fig. 6. Optimal launch sequence of 6 identical electrolyzers

Optimization of the electrolysis system

To clearly present the problem, an example in which it is advisable to apply optimization methods is considered. In particular, the scenario of replacing the traditional heating system of a residential area with a system based on hydrogen boilers is considered. The algorithms proposed below can be adapted to other areas, for example, to energy supply in the agro-industrial complex or in the field of hydrogen aviation.

In the given model, hydrogen production by electrolysis is carried out in parallel with the heating process. Depending on the type of power supply source, electrolyzers can create a significant additional load on the power grid. Thus, in the case of connection to a centralized power grid, the load on transformer substations increases, which, without appropriate optimization, necessitates the installation of additional transformers and an increase in the cost of their maintenance. If renewable energy sources are used, the problem of compensating for fluctuations in electricity generation arises, which requires additional batteries, transformers and photovoltaic panels.

The proposed optimization approaches allow to significantly reduce resource losses and ensure stable functioning of the system under conditions of variable load and unstable energy supply.

The required thermal energy for annual heating of a five-story building built in 1950–1970 was calculated

$$Q_0^{\text{year}} = Q_0^{\max} \cdot \frac{t_\text{i} - t_\text{o}^\text{a}}{t_\text{i} - t_\text{o}^\text{c}} \cdot n_0 \cdot 24 \cdot 3600 \text{ MJ/year;}$$

where $Q_0^{\max}$ – maximum heat consumption

$$Q_0^{\max} = \alpha \cdot q_0 \cdot V_\text{b} \cdot (t_\text{i} - t_\text{o}^\text{a}) \cdot 10^{-6};$$

α is the conversion factor; q_0 is the specific heating characteristic of buildings at the calculated outdoor air temperature and is a function of the purpose of the building and other factors; V_b is the external construction volume of the building; t_i – is the calculated indoor air temperature in heated rooms; t_o^a – average outdoor temperature during the heating period; t_o^c is the calculated outdoor air temperature for heating design is taken according to the application data [12] t_o^c= -30 ºC; n_0 is the duration of the heating period, days; 24 is the operating time of heating systems of residential and public buildings during the day, hours.

Let's say there are 15 typical Soviet-type houses in the block, each with a volume of 7800 m^3. In total, we need to heat 117.000 m^3 per season; t_o^c= -22 ºC; t_o^a= -0.1 ºC; n_0=17 days.

The following characteristics are used for residential buildings: t_i=18 ºC; q_0=0.42 (W/m^3)·K; α=1.134.

Maximum heat consumption

$$Q_0^{\max} = 1.134 \cdot 0.42 \cdot 117000 \cdot (18 - (-22)) \cdot 10^{-6} = 2.2289904 \text{ MW.}$$

The thermal energy for annual heating

$$Q_0^{\text{year}} = 2.228 \cdot \frac{18 - (-0.1)}{18 - (-22)} \cdot 176 \cdot 24 \cdot 3600 = 15337451.1273 \text{ MJ/year, or } 4260.40 \text{ MW/year.}$$

120–142 MJ/kg of thermal energy is released from 1 kg of hydrogen [13], or 33.33–39.44 kWh of thermal energy.

Hydrogen boiler efficiency

$$\eta = 1 - \frac{9 \cdot H \cdot [584 + C_p (T_f - T_a)]}{GCV},$$

where H is the hydrogen content in fuel; C_p is the specific heat of combustion of flue gases, Kcal/(kg ºC); T_f is the flue gas temperature, ºC; T_a is the ambient temperature, ºC; GCV is the total heat of fuel combustion.

The typical efficiency of a hydrogen boiler is 80–90% [14], calculated taking into account the use of hydrogen from fossil sources, where losses due to the amount of hydrogen in the fuel and the moisture contained in the fuel are greater. Since these losses are lower in fuel produced by an electrolysis system, the efficiency of a hydrogen boiler (95%) is used in the calculations.

The amount of hydrogen (kg) is determined by the formula

$$H = \frac{Q}{E} \cdot \eta = 42604030/33.33 \cdot 0.95 = 134673.718 \text{ kg,}$$

where Q is the heat demand per 1 m² per day (kWh); E is the energy density of hydrogen, 33.33 kWh/kg; η is the boiler efficiency (in fractions, for example, 0.95 for 95%).

Density of hydrogen under standard conditions

$$\rho = \frac{\text{Molar mass}}{\text{Volume of 1 mole}} = =2/2.414=0.08988 \text{ g/l,}$$

where molar mass of hydrogen is 2 g; volume of 1 mole of gas under standard conditions (0 °C, 1 atm) is 22.414 l.

Accordingly, volume of 1 kg of hydrogen

$$V = \frac{1000}{0.08988} = 11120 \text{ l} = 11.12 \text{ m}^3.$$

Thus, it is necessary to have 1497571.751 m^3 of hydrogen per year, 8508.930 m^3 of hydrogen per day, and 354.538 m^3 of hydrogen per hour. To produce 1 m^3 of hydrogen, our electrolyzer consumes 4.24 kW of electricity [9]. However, to produce 354.538 m^3 of hydrogen, it is necessary to consume 1503.244 kW of electricity, which is at least 1 additional transformer for 1600 kW, such as TM-1600.

In the following, we will consider the process of optimizing this peak load by balanced launch of several electrolyzers to obtain this amount of hydrogen.

Planning and optimization of the electrolyzer launch sequence

The most expensive and dangerous option for launching a system with several plants is to launch all electrolysis plants simultaneously. The result of the optimization is a delayed launch sequence for each electrolysis plant in the system with a minimization of energy consumption.

A system with several electrolyzers is defined by a vector of functions that describe the amount of power consumed for each electrolysis plant of the system with several electrolyzers, $\overline{A}_f$. An analytical function of the power consumed at a time $A_f(t)$ is set for each electrolyzer. During the practical application of the algorithm, the consumed voltage was given in tabular form and approximated by the program.

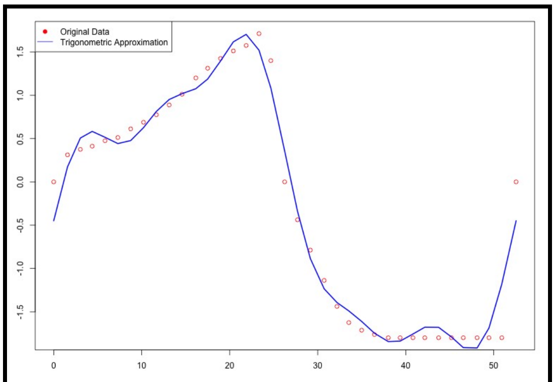

Fig. 7. Fourier series of 5 harmonic oscillations

Since the function describing the power consumed at a time is periodic and nonlinear, the approximation is carried out by Fourier series in the form of a sum of 5 harmonic oscillations (Fig. 7).

When minimizing, it is necessary to determine the amount of consumed power, since the restrictions on the network are set based on it. Due to this the consumed power will be used in the future. Function $S_f(t, \overline{A}_f, \overline{\varpi}, n)$ is the power consumed at time t for the electrolyzers. The configuration of the electrolyzer system is given by the vector of functions $\overline{A}_f$, launch sequence $\overline{\varpi}$, and the number of plants n.

The best launch sequence is the one in which the maximum power value during the operation of the electrolysis system is the smallest among all possible launch sequences.

Maximum power value during operation of the electrolysis system

$$h(\overline{A}_f, \overline{\varpi}, n) = \max_{t\in[0;2\pi]}\left(S_f(t, \overline{A}_f, \overline{\varpi}, n)\right).$$

Optimization objective function

$$C(\overline{A}_f, M, n, k) = \min_{i\in[0;k]}\left(h(\overline{A}_f, M_i, n)\right),$$

where M is the matrix of launch sequences for each plant or a function that generates launch sequences; k is the number of launch sequences.

It is precisely due to the need to generate launch sequences that this problem is not trivial and requires the right choice of a method. Using a direct search for possible shift operations is inefficient, as it generates a large number of options that need to be checked.

The number of possible combinations of launch time shifts of n plants with k shifts is the number of placements with repetitions [15] $A_n^k = n^k$. With a fixed step (the step was chosen to be 3 minutes) on the example of 3 electrolyzers, identical in characteristics and operating modes.

Accordingly, for 3 plants and 21 shift options (from 0 to 60 minutes with a step of 3) the number of combinations will be 21^3=9261, for 4 plants – 194481, and for 5 – 4084101, i.e. with changes in the quality and number of plants the complexity and execution time increase significantly. The complexity in this case is equal to $\Theta(\varphi) = n^k \cdot 360$, where 360 is the number of steps needed to find the evaluation function.

Therefore, one of the stochastic algorithms must be chosen. A genetic algorithm is taken to solve this problem.

The stochastic algorithm is chosen because traditional optimization methods rely on properties such as continuity, differentiability, smoothness, and convexity of the objective function and constraints (if any). The absence of any of these properties makes traditional methods incapable of solving such optimization problems [16]. The minimum objective function is not differentiable, since it can have a break at the minimum point when the evaluated sequence changes.

Genetic algorithm

Genetic algorithm is an evolutionary search algorithm used to solve optimization and modeling problems by sequentially selecting, combining, and varying the desired parameters using mechanisms that resemble biological evolution. A feature of the genetic algorithm is the emphasis on the use of the "crossover" operator, which performs the operation of recombination of candidate solutions, the role of which is similar to the role of crossover in living nature [17].

Basic steps of the genetic algorithm:

– *creating the initial population* – an initial group of solutions (chromosomes) is generated randomly or based on certain assumptions. Within the model of the electrolyzer system, it is assumed that random values are generated in the range of 0–60 minutes (equivalent to the interval 0–2π), the size of one solution group is equal to the number of electrolyzers, the number of solution groups is selected manually and increased if necessary to improve the search result;

– *calculation of the fitness function for individuals in a population* – for each chromosome, a fitness function value, which determines how well a given solution solves the problem, is calculated. To optimize the electrolyzer launch sequence, the fitness function is the maximum power value during the operation of the electrolysis system $h(\overline{A}_f, \overline{\varpi}, n)$.

Repetition until the algorithm's stopping criterion is met (the stopping criterion is the number of generations, or steps, that the algorithm runs through):

– selection of individuals from the current population. Chromosomes that will participate in the creation of the next generation are selected. In these calculations, tournament selection is used: several chromosomes are selected, and the best one is chosen from among them;

– crossover and/or mutation. In our implementation, we use both crossover and mutation. Crossover is the process by which new chromosomes are created from pairs of selected chromosomes. A universal type of crossover was chosen, in which each pair of corresponding genes (the shift of a particular device $\overline{\varpi}_i$) is crossed in proportion to a random value $\alpha \in [0;1]$

$$\overline{\varpi}_{ni} = \alpha \cdot \overline{\varpi}_{1i} + (1-\alpha) \cdot \overline{\varpi}_{2i} .$$

Mutation is the process of introducing a small random change to individual genes on a chromosome. For this optimization, Gaussian mutation was used with a random change in the gene value within the allowable range;

– formation of a new generation. A new population is formed from the offspring (results of crossover and mutation).

Numerical results

For daily heating of the block, 354.538 m^3 of hydrogen is required. To obtain this amount, 1503.244 kW of electricity must be spent.

If hydrogen is produced using a single electrolyzer, then at a voltage of 2 V and 1 A/cm^2, the electrolyzer has a total plate area of 751622 cm^2, which is equivalent to a plate measuring 1 m×7.51 m per plant, as shown in the corresponding graph (Fig. 9), with a peak power of 1463.652 kW. When using 5 identical electrolyzers, each of which has a plate area on the device of 150324.4 cm^2, after optimization we obtain that the optimal launch sequence is [7.048 min, 15.094 min, 51.793 min, 42.944 min, 29.906 min] with a peak power of 996.6641 kW (Fig. 10).

When using 3 identical electrolyzers, each of which has a plate area on the device of 125270.3 cm^2, and the 1st electrolyzer, which has a plate area on the device of 375811 cm^2, after optimization we obtain that the optimal launch sequence is [52.425 min, 34.925 min, 27.650 min, 11.123 min] with a peak power of 1054.1243 kW (Fig. 11).

Having calculated that when using 10 identical electrolyzers, each of which has a plate area of 75162.2 cm^2, after optimization we obtain that the optimal launch sequence is [1.756 min, 5.428 min, 43.759 min, 39.116 min, 15.594 min, 29.183 min, 9.565 min, 49.261 min, 26.891 min, 53.966 min], with a peak power of 953.4203 kW (Fig. 12).

Thus, an algorithm that reduces the maximum peak load by more than 500 kW, which allows balancing equipment costs and the load on the power grid, has been developed.

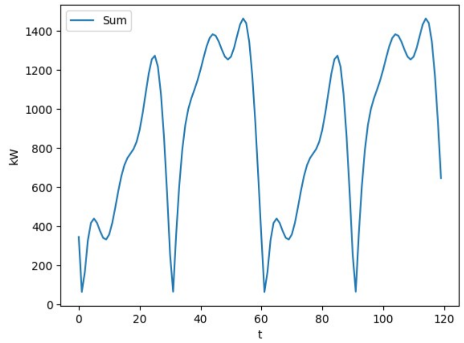

Fig. 9. Power when using one electrolyzer with an electrolysis cell area of 751622 cm² and peak power of 1463.652 kW

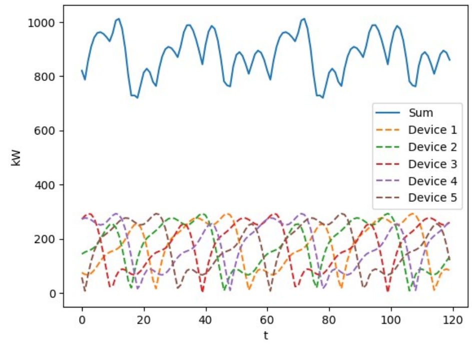

Fig. 10. Power when using 5 identical electrolyzers, each with an electrolysis cell area of 150324.4 cm² and a peak power of 996.6641 kW after optimization

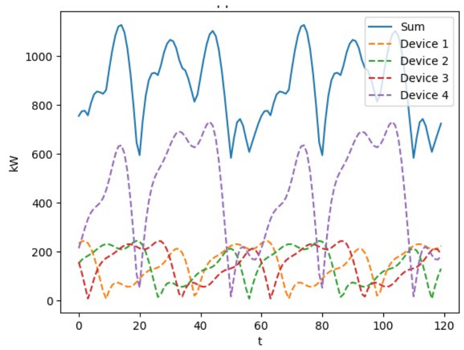

Fig. 11. Using 3 identical electrolyzers, each with an electrolysis cell area of 125270.3 cm² (orange, red and green lines), and the 1st electrolyzer, which has an electrolysis cell area of 375811 cm² (purple line) with a peak power of 1054.1243 kW after optimization

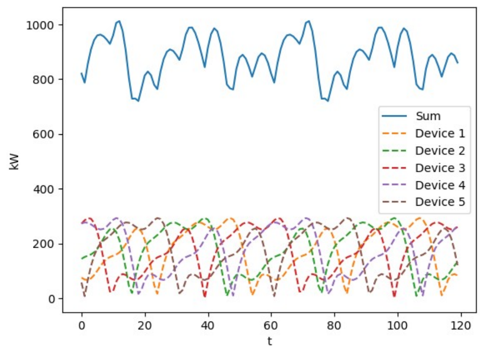

Fig. 12. Power when using 10 identical electrolyzers, each with an electrolysis cell area of 75162.2 cm² with a peak power of 953.4203 kW after optimization

Conclusions

In this paper, a solution to improve the use of membraneless monopolar high-pressure electrolyzers by simultaneously using several electrolyzers with an optimized launch sequence was proposed.

The optimization objective function was determined and the use of stochastic methods for optimizing the launch sequence of electrolyzers was argued. The use of a genetic algorithm allowed obtaining approximately optimal results for a fixed number of iterations.

The problem of replacing the traditional heating system of a residential block with a system based on hydrogen boilers was considered. The results proved the feasibility of optimization. As shown in the example of a problem with the placement of ten electrolyzers, the optimized launch sequence provided a reduction in peak energy consumption by more than 34%. At the same time, the computational complexity remained constant: 100 iterations were used on a set of 100 combinations, which is specified as a hyperparameter, in contrast to a complete search of 10^{60} possible options with a step of one minute.

The calculation results demonstrate that the problem of scaling a hydrogen system from monopolar electrolyzers can be successfully solved by stochastic methods, taking into account modern computing capabilities and the quality of the selected hyperparameters of the genetic algorithm. If necessary, this solution can be used as part of a control system and integrated into industrial hydrogen production problems.

For further improvement, it is necessary to develop a full-fledged control system. The control system should provide automatic creation of approximations according to the passport data of the electrolyzers for which calculations are performed, and provide convenient functionality for quality monitoring and system management.

The development of a control system based on a genetic algorithm contributes to increasing the efficiency of the functioning of the hydrogen energy system, reducing operating costs, optimizing work processes, and ensuring practical integration of optimization algorithms into real engineering solutions.

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Оптимізація споживання електроенергії групою однотипних електролізних установок монополярного типу

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Останнім часом дедалі більше уваги приділяється екологічним проблемам, пов'язаним із надмірним видобуванням традиційних енергетичних ресурсів. Перехід на стійкі й відновлювані джерела енергії стає ключовим рішенням для подолання виснаження природних ресурсів і зменшення негативного впливу на довкілля. Одним із перспективних напрямів є використання технології отримання водню й кисню за допомогою електролізу. Однак на сьогодні згадані технології вимагають великих витрат енергії. Проте в деяких режимах групової роботи використовуються декілька електролізних установок, які працюють одночасно (у даній статті мова йде про монополярні електролізери з активним електродом), при цьому можуть дуже негативно впливати на елементи електричної мережі, яка живить цю групу електролізних установок. У статті розглядається оптимізація роботи групи однотипних монополярних електролізних установок із метою мінімізації їх негативного впливу на електричну мережу. Наведено результати апроксимації функції, яка описує зміну напруги для електролізу з активним електродом, отриманого з експериментальних даних, за допомогою рядів Фур'є. Визначено цільову функцію оптимізації та розв'язано задачу пошуку оптимальної черги запуску групи електролізних установок за допомогою стохастичних методів. У результаті проведених розрахунків встановлено, що використання стохастичних методів є доцільним, а на основі запропонованого рішення можна створити прототип реальної системи управління групою однотипних електролізних установок.

***Ключові слова**: електролізер, водень, оптимізація, алгоритм, функція, густина струму.*

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