Синтезовано алгоритм контролю технічного стану генераторів водню, який включає: формування вихідних даних, визначення значень фазо-частотної характеристики генератора в контрольних точках, порівняння апріорі заданих і виміряних значень фазо-частотної характеристики генератора водню в контрольних точках у відповідності з обраним критерієм.

При описі динамічних характеристик генератора водню на основі гідро реагуючих складів використовується комплексна передаточна функція, для якої одержаний аналітичний вираз. Із врахуванням властивостей комплексної передаточної функції генератора водню обґрунтований вибір контрольних точок, в яких визначаються вихідні дані для побудови алгоритму контролю генератора водню. Контрольні точки характеризуються тим, що в цих точках алгебраїчні складові комплексної передаточної функції генератора водню співпадають по модулю або кожна із них обертається в нуль. В якості критерію для визначення технічного стану генератора водню, згідно з алгоритмом контролю, використана система нерівностей, яка побудована для контрольних точок.

В систему нерівностей входять апріорі задані значення фазо-частотної характеристики генератора водню і її значення, які виміряні, за умови використання реакції генератора на тест-вплив у вигляді стрибкоподібної зміни площі його вихідного отвору. Розв'язання тест-задачі показало, що методична відносна похибка визначення фазо-частотної характеристики за таких умов не перевищує 3,7 %. Параметром контрольних точок є частота.

Показано, що значеннями цих частот є розв'язки системи алгебраїчних рівнянь, параметрами якої є постійні часу генератора водню

Ключові слова: генератор водню, алгоритм контролю генератора, фазо-частотна характеристика генератора водню, контрольні точки, тест-вплив, гідро реагуючий склад

UDC 661.961; 861.968
DOI: 10.15587/1729-4061.2018.131020

THE SYNTHESIS OF CONTROL ALGORITHM OVER A TECHNICAL CONDITION OF THE HYDROGEN GENERATORS BASED ON HYDRO-REACTIVE COMPOSITIONS

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1. Introduction

The use of hydrogen as a working body is one of the promising directions for improving energy systems [1]. A special role among such energy systems belongs to onboard power plants for which it is essential to ensure prolonged functioning under autonomous mode at minimal weight and size characteristics. Such systems primarily include a system for storing hydrogen in a chemically bound state, specifically based on hydroreacting compositions. A hydrogen generator in such systems acts as the basic element that determines the level of safe operation of the system in general [2]. Safe operation of hydrogen storage and supply systems of this type requires such values for parameters and characteristics, which warrant compliance with the requirements of regulatory documents [3]. In this connection, it is an important task to ensure conformity of technical characteristics with the regulatory requirements with respect to one of the basic elements of hydrogen storage and supply system through the implementation of appropriate control algorithms of their technical condition.

2. Literature review and problem statement

Paper [4] outlines promising methods for obtaining hydrogen from substances in which it is in a chemically bound state. It is shown that when receiving H_2 from water using Al, modified with ceramic oxides, the H_2 yield can reach values of the order of 4.8 % by weight. It should be noted that the reported data were derived from laboratory studies at which control over hydrogen generation process was executed indirectly. The results of control were used to study hydrogen generation processes only and are not meant to address diagnosing tasks. Paper [5] gives information about hydrogen storage systems based on metal hydrides and intermetallic compounds. Such systems are employed in space engineering, transportation vehicles, military naval applications, due to their compatibility with the fuel elements of the proton exchange membrane (PEM). The paper gives detailed descriptions of structural solutions for tanks considering thermolysis and hydrolysis. A given work left out technical solutions aimed to control the processes of thermolysis and electrolysis. Results of determining certain thermodynamic characteristics of the process of hydrogen sorption (constants of reaction rate, the activation energy, etc.) are reported in [6]. However, information on such characteristics is not used to form control algorithms over hydrogen sorption processes. Authors of [7] describe a procedure for the estimation of efficiency of a hydrogen generator, which includes a water electrolyzer. They proposed an algorithm for determining thermodynamic and economic characteristics of the installation “Electrogas”. These characteristics were determined depending on the extent of using energy produced in the installation, as the ratio of the amount of energy, directed for storing, to the annual volume of electricity generated in the installation. The specifications considered are not meant to determine the technical condition of a hydrogen generator and reflect to the greater extent its commercial properties. To describe the processes that occur in hydride systems, authors of [8] employ isothermal charts. The use of such models in order to generate control algorithms does not make it possible to consider dynamic properties of hydrogen generators. Paper [9] notes that obtaining hydrogen by hydrolysis can yield large quantities of heat – up to 15.0 MJ/kg. Such a mode of operation can predetermine a possibility of the occurrence of an emergency [10]. To ensure safe operation of hydrogen generators, information is used about the results of measuring temperature [9] or hydrogen concentration [10]. Typically, such sensors possess a static relay characteristic that predetermines the implementation of trivial control algorithms over their technical condition based on the principle “pass – no pass”. In [11], attention is drawn to the fact that when using hydrogen in transport as a working body, an effective system for its safe operation is missing. Specifically, hydrogen generation equipment monitoring is implemented in a trivial way. Article [12] considers one of the promising options for creating nano-satellites using the hydrides and borohydrides of aluminum as combustible components. However, this work failed to tackle issues related to control over technological processes. Industrial designs of hydrogen generators typically realize control over one or two parameters of technological process for generating hydrogen [13]. Most often control is executed over such parameters that characterize the local properties of hydrogen generators of a given type. Authors of [14] propose control algorithm over a technical condition of hydrogen generators based on hydro-reactive compositions. Such a technical solution was patented [15] as a technique to control technical condition of the generator for a system of hydrogen storage and supply. A special feature of such an algorithm is the use of its amplitude-frequency characteristic at a fixed frequency. Such an approach to the formation of a control algorithm over technical condition of hydrogen generators does not provide information about its state throughout the entire range of frequencies. In this context, the issues related to the tasks on ensuring safe operation of hydrogen storage and supply systems include a problem on the organization of control over technical condition throughout the entire range of its working frequencies.

3. The aim and objectives of the study

The aim of present study is to synthesize control algorithm over a technical condition of hydrogen generator, which is based on the use of its phase-frequency characteristics.

To accomplish the aim, the following tasks have been set:

– to justify the choice of a criteria for determining a technical condition of the hydrogen generator based on the results of its control;

– to state a problem on the identification of parameters at control points of frequency characteristics of the hydrogen generator;

– to solve the problem on the identification of parameters at control points;

– to develop an indirect method for determining phase-frequency characteristics of the hydrogen generator employed to construct a hydrogen generator control algorithm.

4. Development of control algorithm over a technical condition of the hydrogen generator

4. 1. Dynamic characteristics of hydrogen generator

Dynamic properties of the generator for a hydrogen storage and supply system are defined by its transfer function. This transfer function takes form [10].

$$W(S)=K(1-\tau_1 S)\left[(\tau_2 S+1)(\tau_3 S+1)\right]^{-1}, \tag{1}$$

where K is the transfer coefficient; τ_i, $i=\overline{1,3}$ are the time constants; S is the integrated variable.

Such a transfer function of the hydrogen generator will be matched with an integrated transfer function or an amplitude-phase frequency characteristic

$$W(j\omega)=K(1-j\omega\tau_1)\left[(1+j\omega\tau_2)(1+j\omega\tau_3)\right]^{-1}, \tag{2}$$

where ω is the circular frequency; j is the imaginary unit.

Upon multiplying the numerator and denominator of fraction (2) by the integrated function of form

$$1-\omega^2\tau_2\tau_3-j\omega(\tau_2+\tau_3), \tag{3}$$

expression for $W(j\omega)$ can be represented in the form of two additive components

$$W(j\omega)=M(\omega)+jN(\omega), \tag{4}$$

where

$$M(\omega)=K\left[1-\omega^2(\tau_1\tau_2+\tau_1\tau_3+\tau_2\tau_3)\right]\times \\ \times\left[1+\omega^2(\tau_2^2+\tau_3^2+\omega^2\tau_2^2\tau_3^2)\right]^{-1}; \tag{5}$$

$$N(\omega)=-K\left[\omega\left(\sum_{i=1}^{3}\tau_i-\omega^2\prod_{i=1}^{3}\tau_i\right)\right]\times \\ \times\left[1+\omega^2(\tau_2^2+\tau_3^2+\omega^2\tau_2^2\tau_3^2)\right]^{-1}. \tag{6}$$

Fig. 1 shows a graphical dependence for amplitude-phase frequency characteristic *W*(*j*ω); Fig. 2 – for frequency characteristics *M*(ω) and *N*(ω). These characteristics are given for the case when the generator of a hydrogen storage and supply system based on hydro-reactive compositions has responsive surfaces arranged vertically. In this case, the ratio of a hydrogen generator outlet opening area to the surface area of gas release is equal to 0.02, and the hydrogen flow rate is $4\cdot10^{-4}$ kg·s^{-1}. For such working conditions of the hydrogen generator parameters of transfer function (1) are equal to

$$K=1{,}33\ \text{kg}\cdot\left(\text{m}^3\text{s}^{-2}\right)^{-1};$$

$$\tau_1=7{,}9\ \text{ms};\ \ \tau_2=6{,}5\ \ \text{ms};\ \ \tau_3=14{,}4\ \ \text{ms}.$$

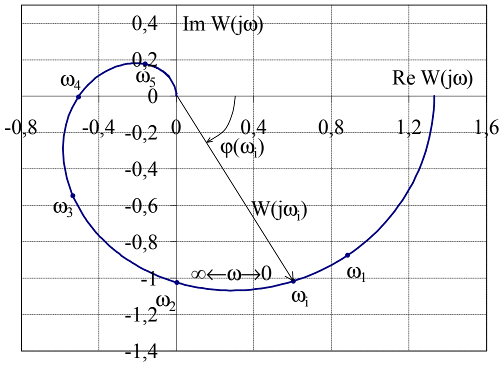

Fig. 1. Amplitude-phase frequency characteristic of hydrogen generator

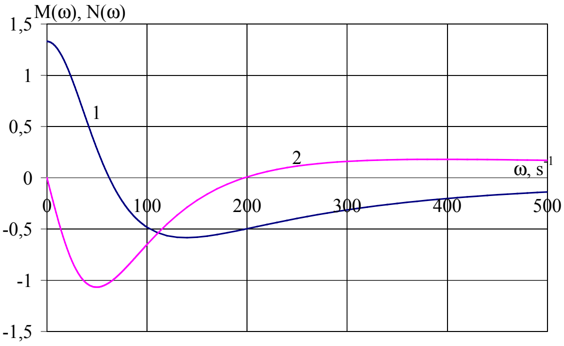

Fig. 2. Frequency characteristics of hydrogen generator: 1 – M(ω); 2 – N(ω)

The graphical dependence that determines performance of the vector *W*(*j*ω) hodograph at the complex plane is parametric. Frequency ω is the parameter of a given dependence. This circumstance predetermines the selection of control points when constructing a control algorithm over technical condition of the generator of a hydrogen storage and supply system.

4. 2. Selection of control points and a control algorithm over technical condition of the hydrogen generator

It is appropriate to choose as control points i the points that belong to the vector *W*(*j*ω) hodograph, which are matched with frequency values $\omega_i,\ i=\overline{1,n}.$ It should be noted that each *i*-th control point will be also matched with angular coordinate φ(ω$_i$) – Fig. 1. This angular coordinate acquires a meaning of the phase-frequency characteristic of hydrogen generator φ(ω).

If we *a priori* assign n values of frequency ω$_i$, as well as their corresponding angular coordinates φ$_i$, it is appropriate then to use, as a criterion for determining technical condition of the hydrogen generator, a set of inequalities

$$\left|\phi(\omega_i)-\phi_i\right|\le\varepsilon, i=\overline{1,n}, \tag{7}$$

where φ(ω$_i$) is the measured value of a phase-frequency characteristic of the hydrogen generator at frequency ω$_i$; ε is a small number.

A technical condition of the hydrogen generator is taken to be compliant with the requirements of normative documents if for all *n* control points of the *W*(*j*ω) hodograph conditions (7) are met.

The character of change in the frequency characteristics (4) to (6) allows us to specify the procedure for selecting parameters ω$_i$ and φ$_i$. It follows from an analysis of dependences shown in Fig. 1, 2 that when

$$\phi_i=-\frac{i\pi}{4},\quad i=\overline{1,5} \tag{8}$$

the following relations will hold

$$i=1,\ \ M(\omega_1)=-N(\omega_1);$$

$$i=2,\ \ M(\omega_2)=0;$$

$$i=3,\ \ M(\omega_3)=N(\omega_3);$$

$$i=4,\ \ N(\omega_4)=0;$$

$$i=5,\ \ -M(\omega_5)=N(\omega_5). \tag{9}$$

Relations (9) with respect to expressions (5) and (6) are transformed into a system of algebraic equations whose roots are the frequency ω$_i$ values at control points $i=\overline{1,5}.$ This system takes the form

$$i=1;5,\quad \begin{matrix}\omega_i^3\prod\limits_{k=1}^{3}\tau_k-\omega_i^2\left(\tau_1\tau_2+\tau_1\tau_3+\tau_2\tau_3\right)-\\ -\omega_i\sum\limits_{k=1}^{3}\tau_k+1=0;\end{matrix} \tag{10}$$

$$i=2,\ \ \omega_2^2\left(\tau_1\tau_2+\tau_1\tau_3+\tau_2\tau_3\right)-1=0; \tag{11}$$

$$i=3,\quad \begin{matrix}\omega_3^3\prod\limits_{k=1}^{3}\tau_k+\omega_3^3\left(\tau_1\tau_2+\tau_1\tau_3+\tau_2\tau_3\right)+\\ +\omega_3\sum\limits_{k=1}^{3}\tau_k-1=0;\end{matrix} \tag{12}$$

$$i=4,\ \ \omega_4^2\prod_{k=1}^{3}\tau_k-\sum_{k=1}^{3}\tau_k=0. \tag{13}$$

It should be noted that $\omega_1\le\omega_5$ (Fig. 1). Therefore, the parameter ω$_1$ is matched with a smaller positive root of algebraic equation (10); and the parameter ω$_5$ – a larger positive root of a given equation.

For the example under consideration, algebraic equation (10) to (13) have the following solution

$$\omega_1=27{,}8\,s^{-1};\ \ \omega_2=61{,}2\,s^{-1};\ \ \omega_3=110{,}4\,s^{-1};$$

$$\omega_4 = 196{,}5\, s^{-1};\quad \omega_5 = 435{,}2\, s^{-1}. \tag{14}$$

There is another possible technique to derive the values for parameters ω_i, $i = 1{,}5$, which is based on solving transcendental equations of the form

$$\phi(\omega) + \frac{i\pi}{4} = 0,\quad i = \overline{1{,}5}. \tag{15}$$

In this equation, a phase-frequency characteristic φ(ω) is determined in the following way:

$$\phi(\omega) = \arctan\left[N(\omega)\left[M(\omega)\right]^{-1}\right]. \tag{16}$$

Fig. 3 shows a graphical interpretation for solving the transcendent equation (15). Points 1–5 are matched with values for parameters ω_i, $i = \overline{1{,}5}$.

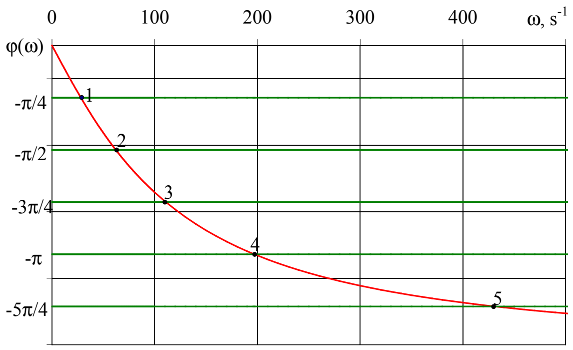

Fig. 3. Determining parameters ω_i, $i = \overline{1{,}5}$

The results obtained make it possible to represent an algorithm for determining technical condition of the generator for a hydrogen storage and supply system in the form of a sequence of the following procedures:

– formation of an array of initial data – ω_i, φ_i, ε;

– measurement of (determining) the values for a phase-frequency characteristic of the generator at control points – $\varphi(\omega_i)$;

– comparison of $\varphi(\omega_i)$ and ω_i at control points in accordance with criterion (7);

– making a decision on a technical condition of the hydrogen generator.

4. 3. Determining a phase-frequency characteristic of the hydrogen generator

In order to implement a control algorithm, it is required to ensure obtaining information about the values of a phase-frequency characteristic of the hydrogen generator $\varphi(\omega_i)$ at i-th control points. A search for such information, based on the measurement of phase difference between pressure in the cavity of the hydrogen generator and the area of its outlet opening at the harmonic law of its change with a frequency of ω_i, may prove to be too difficult to implement. A main difficulty here is associated with a change in the area of an outlet opening of the hydrogen generator in line with a harmonic law at frequencies of the order of (200.0÷450.0) s^{-1}.

The need to form such a harmonic influence on the hydrogen generator can be eliminated if the frequency characteristic φ(ω) is determined indirectly. One of the techniques for determining the frequency characteristic φ(ω) was considered in [16].

To determine a frequency characteristic φ(ω) in accordance with [16], one changes the area of an outlet opening according to expression

$$F(t) = B\cdot 1(t), \tag{17}$$

where B=const; $1(t)$ is the Heaviside function.

Fig. 4 shows the way pressure $P(t)$ changes in the cavity of a hydrogen generator. Function $P(t)$ can be represented in the following form

$$P(t) = \sum_{k=0}^{n} \Delta_k \cdot 1\left(t - (k+0{,}5)\tau\right), \tag{18}$$

where τ is the interval of discreteness; Δ_k is the pressure increment in a hydrogen generator cavity over time interval $(k+1)\tau - k\tau$

$$\Delta_k = P_{k+1} - P_k. \tag{19}$$

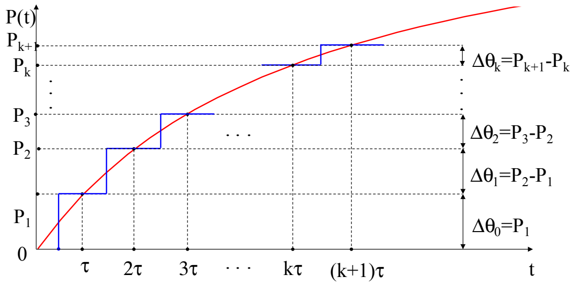

Fig. 4. Determining a phase-frequency characteristic of the hydrogen generator

Interval of discreteness τ is derived according to the Kotelnikov-Nyquist-Shannon theorem, that is

$$\tau = 0{,}5 f_m^{-1}, \tag{20}$$

where f_m is the maximum value of spectrum frequency of function $P(t)$.

If one applies an integral Laplace transform to expression (18), the following occurs

$$P(S) = S^{-1}\sum_{k=0}^{n} \Delta_k \exp\left[-S(k+0{,}5)\tau\right] = S^{-1}BW(S). \tag{21}$$

The expression for an amplitude-phase frequency characteristic of the hydrogen generator follows from (21)

$$W(j\omega) = B^{-1}\sum_{k=0}^{n} \Delta_k \exp\left[-j\omega(k+0{,}5)\tau\right] =$$

$$= B^{-1}\sum_{k=0}^{n} \Delta_k \left[\cos\left[\omega(k+0{,}5)\tau\right] - j\sin\left[\omega(k+0{,}5)\tau\right]\right], \tag{22}$$

according to which the expression for phase-frequency characteristic φ(ω) will take the form

$$\phi(\omega) = -\arctan\left[\left[\sum_{k=0}^{n} \Delta_k \sin\left[\omega(k+0{,}5)\tau\right]\right]\left[\sum_{k=0}^{n} \Delta_k \cos\left[\omega(k+0{,}5)\tau\right]\right]^{-1}\right]. \tag{23}$$

For a such method of identification of frequency characteristic φ(ω) an algorithm for determining a technical condition of the hydrogen generator comes down to the following:

– formation of an array of initial data – ω_i, φ_i, ε, *B*;

– formation of a test influence on the hydrogen generator in the form of a jump change in the area of its outlet opening – in accordance with expression (17);

– identification of phase-frequency characteristic of the hydrogen generator φ(ω) – in accordance with expression (23);

– determining the values for a phase-frequency characteristic of the generator at control points – φ(ω);

– comparison $\varphi(\omega_i)$ and φ_i at control points using criterion (7);

– making a decision about a technical condition of the hydrogen generator.

Fig. 5 shows graphical dependences for phase-frequency characteristics of the hydrogen generator, which are derived from expressions (16) and (23). The same figure shows a chart for misalignment error Δφ(ω) between these frequency characteristics.

We accepted, as the function *P*(t) that was used for the approximation with expression (18), the following function

$$P(t)=L^{-1}\left[W(S)F(S)\right], \tag{24}$$

where L^{-1} is the Laplace inverse transform operator; *F(S)* is the Laplace image of function *F(t)*.

With respect to expressions (1) and (17), expression (24) takes the form

$$P(t)=KB\left[1+\left(\tau_3-\tau_2\right)^{-1}\left[\left(\tau_1+\tau_2\right)\exp\left(-\frac{t}{\tau_2}\right)-\left(\tau_1+\tau_3\right)\exp\left(-\frac{t}{\tau_3}\right)\right]\right]. \tag{25}$$

This expression describes a reaction of the hydrogen generator to a test influence in the form of a jump change in the area of its outlet opening by the magnitude *B*.

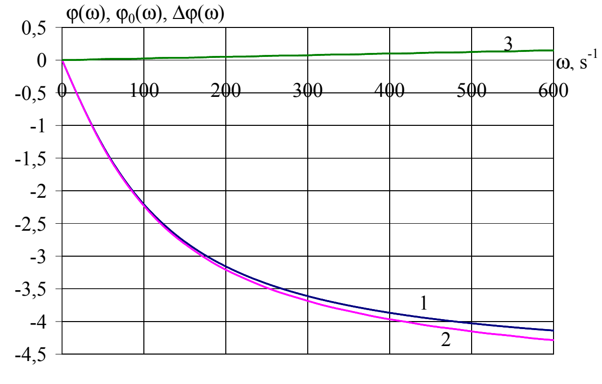

Fig. 5. Phase-frequency characteristics of hydrogen generator and a misalignment error: 1 — φ(ω) according to (16); 2 — φ(ω) according to (23); 3 — Δφ(ω)

It follows from an analysis of dependences shown in Fig. 5 that when τ=0.5 ms at frequency ω=600 s^{-1} the magnitude of a relative misalignment error does not exceed 3.7 %. The magnitude of the relative error of determining a phase-frequency characteristic of the gas generator is calculated by dividing the difference of expressions (16) and (23) by expression (16).

5. Discussion of results of the synthesis of control algorithms for hydrogen generators

A character of change in the amplitude-phase frequency characteristic of a hydrogen generator and its algebraic components predetermines the ideology of control algorithm over its technical condition. To construct such an algorithm, we introduce the concept of a "control point". Each control point is characterized by two parameters – frequency ω_i, $i=\overline{1,n}$ and angular coordinate $\varphi(\omega_i)$ at the complex plane. The angular coordinate has a meaning of the phase-frequency characteristic of a hydrogen generator.

Use the information at control points of frequency characteristics of the hydrogen generator makes it possible to formulate the criteria that characterize its technical condition. Such criteria represent a system of inequalities, which include the *a priori* assigned parameters and the measured values of phase-frequency characteristics of the hydrogen generator at fixed frequencies.

A transition to the application of phase-frequency characteristics of the hydrogen generator, in contrast to employing amplitude-frequency characteristics, as shown in [14], makes it possible to improve the reliability of the result of control over a technical condition. Improving the reliability of the result of control over a technical condition of the hydrogen generator is ensured by obtaining information in terms of phase-frequency characteristic at n control points. Unlike the approach under consideration, ref. [14] employs a one-time measurement of the amplitude-frequency characteristic of a hydrogen generator at the single, *a priori* assigned frequency.

To select the control points, we applied the hypothesis on that at each successive control point the value of a phase-frequency characteristic of the hydrogen generator differs from the preceding one by 45°. This allows reducing determining the values of frequencies at control points to solving a system of algebraic equations. The parameters of such a system of algebraic equations are the time constants, included in the structure of a transfer function of the hydrogen generator.

The proposed control point selection ideology implies that their number is not less than five.

It should be noted that the control algorithm over a hydrogen generator implies acquiring information about the values of its phase-frequency characteristic $\varphi(\omega_i)$ at *i*-th control points. Obtaining such information by measuring a phase shift angle between pressure in the generator cavity and the area of its outlet opening at the harmonic law of its change at frequency ω_i could prove difficult. The main difficulty here is associated with a change in the area of an outlet opening of the hydrogen generator in line with a harmonic law at frequencies (200.0÷450.0) s^{-1}.

The need to build such harmonic test influences on the hydrogen generator can be eliminated if the frequency characteristic φ(ω) is determined indirectly. Such a technique for determining the φ(ω) characteristic was proposed in [16] and is based on using information about a reaction of the hydrogen generator on the test influence described by the Heaviside function. A phase-frequency characteristic of the hydrogen generator is identified analytically based on the results of measuring pressure gains in its cavity with an interval of discreteness, which is derived from the Kotelnikov-Nyquist-Shannon theorem. To verify such an approach, we solved a test problem, in which we employed, as a function that describes a change in the pressure in the cavity of a hydrogen generator, its transient function. When solving a given problem, we have shown that a methodical error when determining phase-frequency characteristics of the hydrogen generator does not exceed 3.7 %.

A special feature of the proposed control algorithm over a technical condition of the hydrogen generator, compared to the one described in [14], is that we employ, as a test influence, a jump change in the area of its outlet opening. For the previously developed algorithm, a test influence is a change in the area of the outlet opening in line with the harmonic law at a frequency of the order of $(80.0 \div 100.0)$ s^{-1}. To create such a test influence, one requires an additional device while there is no need for it in the proposed variant.

The proposed control algorithm implies the absence of an inertial component in the reaction of a hydrogen generator to a test influence in the form of a jump signal. In this regard, further development of the algorithm should be aimed at estimating the impact of an inertial component on the change in pressure in the generator cavity, predetermined by the difference of the test influence from a jump-like form. In addition, it is appropriate to solve a problem on forming a test influence on the hydrogen generator without the use of external devices.

6. Conclusions

1. It is shown that it is appropriate to use as a criterion for determining a technical condition of the generator for a hydrogen storage and supply system a system of inequalities, which characterizes position of figurative points along a phase-frequency characteristic of the hydrogen generator for the *a priori* assigned frequencies whose number does not exceed five.

2. It is substantiated that the choice of parameters at control points of frequency characteristics of the hydrogen generator is reduced to solving a problem on the identification of frequencies at whose values algebraic components of the integrated transfer function of the hydrogen generator coincide by modulo, or each of them becomes zero.

3. Solving a problem on the identification of parameters at control points of frequency characteristics of the hydrogen generator is reduced to solving a system of algebraic equations whose parameters are the time constants of a hydrogen generator. The solution to the problem is obtained for typical characteristics of the generator for a hydrogen storage and supply system, from which it follows that the maximum frequency value does not exceed 450.0 s^{-1}.

4. We have developed an indirect method for determining phase-frequency characteristics of the hydrogen generator used to generate its control algorithm that eliminates the need for the formation of harmonic test influences throughout the entire range of changes in frequencies and is based on using information about a reaction of the hydrogen generator to the test influence in the form of a Heaviside function.

5. The result of solving a test problem has shown that a methodical error when determining phase-frequency characteristics of the hydrogen generator does not exceed 3.7 %.

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UDC 681.5.017
DOI: 10.15587/1729-4061.2018.132229

ANALYSIS OF INFLUENCE OF TECHNICAL FEATURES OF A PID-CONTROLLER IMPLEMENTATION ON THE DYNAMICS OF AUTOMATED CONTROL SYSTEM

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В умовах інтенсифікації, максимізації рентабельності та забезпечення технологічної безпеки виробництва виникає проблема регулювання, оптимізації, вдосконалення структури систем автоматичного управління. Незважаючи на довгу історію розвитку та наявність великої кількості патентів, розробок, публікацій, на сьогоднішній день залишається багато актуальних проблем, пов'язаних з практичною реалізацією ПІД-регулятора: уніфікація структури ПІД-регулятора, реалізація диференціальної складової, інтегральне насичення та безударна передача параметрів і режимів роботи.

У статті досліджується вплив нелінійностей, шуму, перешкод, функцій та особливостей ПІД-регулятора на динаміку системи автоматичного керування. Показано, що для максимальної ефективності реалізації ПІД-регулятора для керування інерційними об’єктами з транспортним запізнюванням потрібно застосовувати комплексний підхід: обмеження швидкості зростання збурення по завданню та умовного інтегрування для усунення інтегрального насичення; одночасне застосування експоненціального фільтра виміряної величини та диференціатора з фільтром високих частот для мінімізації впливу шумів та завад на перехідні процеси; відслідковування поточного стану системи дозволяє запобігти "удару" при зміні режимів роботи ПІД-регулятора; введення зони нечутливості регулятора потенційно забезпечить триваліший період експлуатації виконавчого механізму.

Здійснено математичне моделювання системи автоматичного регулювання розрідження у топці котлоагрегату з врахуванням запропонованого комплексу рішень. Наведені рекомендації дозволяють реалізувати ПІД-регулятор, придатний для практичного застосування з врахуванням стохастичності, нелінійності, квазістаціонарності та обмежень технологічних процесів.

Комплексна оцінка та врахування даних проблем сприятимуть підвищенню ефективності та надійності роботи обладнання, зменшенню споживання енергії та часу досягнення заданої цілі в процесі автоматичного регулювання, без зміни структури системи управління

Ключові слова: ПІД-регулятор, інтегральне насичення, фільтрація шумів, диференціатор, безударна передача

1. Introduction

Under conditions of intensification, maximization of profitability and ensuring technological safety of production, certain problems emerge related to the adjustment, optimization and improvement of the structure of automated control systems. Despite the emergence and gaining popularity of advanced control methods, such as Model Predictive Control, Fuzzy Logic, controllers based on the proportional-integral-differential (PID) law of regulation are the most popular at present, with a share of up to 90 % [1].

The operation and adjustment of regulation system is the major problem today. Thirty percent of the controllers used in industry are incorrectly adjusted [2] because natural nonlinearities of technical implementation have not been taken into consideration. In many PID controllers, differential component is shut down. The main causes of shutdown include complexity of adjustment and insufficient knowledge of the dynamics of control process. The result obtained is the incorrect adjustment of parameters leading to worsening efficiency of a technological process control and performance of a unit in general.