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ADAPTIVE CONTROL OF PULSE CURRENT GENERATOR CHARGER FOR DISCHARGE-PULSE INSTALLATIONS

АДАПТИВНЕ КЕРУВАННЯ ЗАРЯДНИМ ПРИСТРОЄМ ГЕНЕРАТОРА ІМПУЛЬСНИХ СТРУМІВ РОЗРЯДНО-ІМПУЛЬСНИХ УСТАНОВОК

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Abstract. *The aim of the work* is to study the charging device of the pulse current generator for discharge-pulse installations as a control object and to build a model of an adaptive control system that provides optimal operating modes with variable parameters of the control object during the charging process.
Method. The charging device of the pulse current generator for discharge-pulse installations as a control object refers to multidimensional discrete-continuous normal stochastic systems with output coordinates in the form of random non-stationary functions. The synthesis of control systems for objects of this class is a complex multi-criteria task, therefore, the decomposition method, stochastic modeling and neurotechnology were used in the study.
Results. The effective information coordinates and their adjustment ranges were determined. The algorithms for charging capacitive storage devices of the pulse current generator were analyzed. An adaptive information signal filter was developed, the optimality criterion of which is the accuracy of the information coordinate estimation. Also, the filter structure was determined. The coefficients of a two-level recursive filter are calculated for different values of the expected mean value of the output coordinates that determine the position of the control object in the state space. A model of an adaptive control system using neurotechnologies is constructed.
Scientific novelty. It is proven that the optimal value of the filter coefficients depends on the rate of change of the average value and the dispersion of the information signal. A filter adaptation mechanism is developed that takes into account the shift in the evaluation of the information signal. It is established that the state space of the control object is significantly multidimensional, which requires the use of parallel information processing algorithms. The use of two control structures based on neural systems is proposed, which are more effective for this type of tasks.
Practical importance. The use of the proposed adaptive control model in the synthesis of control systems for the charging device of the pulse current generator of discharge-pulse installations will ensure the optimal operating mode, increase the stability and energy efficiency of promising discharge-pulse technologies.
Key words: discharge-pulse installation; charging device; pulse current generator; information coordinates; stochastic systems; adaptive control system; neurotechnology.

Анотація. *Метою* роботи є дослідження зарядного пристрою генератора імпульсних струмів для розрядно-імпульсних установок як об’єкта керування та побудова моделі адаптивної системи керування, яка забезпечує оптимальні режими роботи при змінних параметрах об'єкта керування в процесі зарядки.
Методика. Зарядний пристрій генератора імпульсних струмів для розрядно-імпульсних установок як об'єкт керування відноситься до багатовимірних дискретно-неперервних нормальних стохастичних систем з вихідними координатами у вигляді випадкових нестаціонарних функцій. Синтез систем керування об'єктами такого класу є складним багатокритеріальним завданням тому при дослідженні використовувався метод декомпозиції, стохастичне моделювання та нейротехнології.
Результати. Визначено ефективні інформаційні координати та діапазони їх регулювання. Проведено аналіз алгоритмів заряджання ємнісних накопичувачів генератора імпульсних струмів. Розроблено адаптивний фільтр інформаційного сигналу, критерієм оптимальності якого є точність оцінки інформаційної координати, визначено структуру фільтра. Розраховано коефіцієнти дволанкового рекурсивного фільтра для різних значень

математичного сподівання вихідних координат, що визначають положення об'єкта управління в просторі станів. Побудовано модель адаптивної системи керування з використанням нейротехнологій.
Наукова новизна. Доведено, що оптимальне значення коефіцієнтів фільтра залежить від швидкості зміни середнього значення та дисперсії інформаційного сигналу. Розроблено механізм адаптації фільтра, який враховує зсув оцінки інформаційного сигналу. Встановлено, що простір станів об'єкта керування є суттєво багатовимірним, що потребує застосування алгоритмів паралельної обробки інформації. Запропоновано використання двох структур керування на основі нейросистем, які більш ефективні для даного типу завдань.
Практична значимість. Використання запропонованої адаптивної моделі керування при синтезі систем керування зарядним пристроєм генератора імпульсних струмів розрядно-імпульсних установок забезпечить оптимальний режим роботи, підвищить стабільність та енергоефективність перспективних розрядно-імпульсних технологій.
Ключові слова: розрядно-імпульсна установка; зарядний пристрій; генератор імпульсних струмів; інформаційні координати; стохастичні системи; адаптивна система керування; нейротехнології.

STATEMENT OF THE PROBLEM

Discharge-pulse installations use electro-explosive energy conversion in a channel of high-voltage discharge in fluid as a source of condensed dosated impact with high specific energetic characteristics in a defined local volumes. Those installations are widely used in different technological processes, such as: metal processing under pressure, demolition of rock materials and fragmentation of oversized materials, treatment of welded seams, intensification of metal crystallization, treatment of heading zones of water, oil and gas boreholes, etc. [1–7]. The advantages of these installations are efficiency, ecological cleanliness, controllability and possibility of automation. The implementation of main advantage – controllability, requires studying of discharge-pulse installation as an object of control. As per results of systems analysis of electro-explosive energy conversion inside channel of high-voltage discharge in fluid as an object of control, it was classified as multidimensional discrete-continuous normal stochastic system with random functions as output coordinates, which are nonstationary by expected mean value [8–10]. An effective control of objects of such class is a complex multicriteria task. It requires a decomposition in order to break it into several independent tasks of different level, all of which has its own optimality criterion and implementation algorithm. As a result, control system for discharge-pulse installation is a complex hierarchical structure, which contains several levels of control and several relatively independent subsystems. The operation of each subsystem must be synchronized by time, spatial coordinates and technological parameters. The higher-level system must perform optimal decision-making.

Based on the analysis, the following structural subsystems of the discharge-pulse installation are identified:

– auxiliary technological mechanisms, the operation algorithms of which are specified by technological cyclograms and change during the transition from one technology to another;

– the discharge circuit of the gas generator includes, in addition to the permanent elements of the discharge circuit, a discharge channel formed between the electrode and the processing object, in which an electro-explosive energy conversion occurs with the generation of a pressure wave that provides the necessary parameters of the technological impact;

– the movable electrode system, which provides the necessary localization of technological impact when processing objects of complex shape;

– charging device (charger) of the pulse current generator (PCG).

In order to develop control algorithms of all subsystems it is necessary to create adequate control models on all levels.

The high-voltage pulse current generators are the energy sources in discharge-pulse installations [11, 12]. One of the particular control tasks of autonomous sublevel is an adaptive control of charging process for high-voltage (30–50 kV) capacitive storages (2–8 μF) of PCG.

The charging device of the pulse current generator has a complex structure. Multidimensional nonlinear processes of charging capacitive storage devices take place in it. During charging, an intermediate frequency conversion occurs. The processes that occur in the charger when charging capacitors also have uncertainties: the quality factor of the charging circuit changes during the charging process; the resonant frequency depends on the load, which also changes during the charging process of the storage device.

The aim of this research is to build a model of adaptive control system of charging devices for PCG, which provides optimal operating modes of charging device under varying parameters of control object during charging process.

RESEARCH OBJECTIVE

The aim of this research is to build a model of adaptive control system of charging devices for PCG, which provides optimal operating modes of charging device under varying parameters of control object during charging process.

MAIN PART

The charging model of the storage battery of PCG capacitors is nonlinear, multidimensional, with variable parameters, has a dependent time coordinate (the charging time is limited by the rate of the discharge pulses) [13, 14]. The problem of synthesizing control systems for objects of this class cannot be effectively solved by traditional methods and requires the use of neurotechnology.

The task of adaptive control of the charging process of a PCG storage is to ensure its energy efficiency. This involves determining a particular criterion for the optimality of the system and synthesizing a control law, which is then implemented in software. In the optimization space, the qualitative picture of the system's behavior has several bifurcations, which are determined by parameters that depend on the specific design of the charger of the PCG, as well as the parameters of the technological mode of electro-pulse processing. The existence of several qualitative patterns of system behavior on the phase plane is due to reasons independent of the automatic control system and arising from the results of parametric optimization of the charging device design. Optimal PCG chargers have a high Q-factor of the oscillating circuit, which can be considered a bifurcation parameter. Therefore, for each phase portrait of the system's behavior, there will be its own Pontryagin maximum in the control space.

Thus, in order to build an effective control system for the PCG charger, it is necessary to use not just one law of optimal control, but a space of laws Ω, the choice of which should be carried out at the highest level of the hierarchical automatic control system, implemented according to the principle of deviation. The highest level task is to select the optimal trajectory in the space of optimal implementations. Obviously, the automatic control system must be combined (programmable control and deviation control) and adaptive. Expressions for control laws can be combined into a control vector, which we denote by $U \in \Omega$. The functional block diagram of the automatic control system of the PCG charger is shown in Fig. 1.

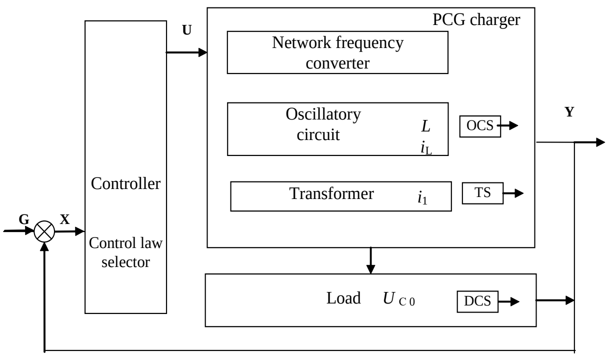

Fig. 1. Functional block diagram of the automatic control system for PCG charger

Control adaptation is carried out by a control law selector, which sets the specific structure of the control system depending on the coordinates of the input vector **X**, determined by the mismatch between the coordinates of the output vector **Y** and the reference vector **G**. The coordinates of the output vector **Y** are the output signals of the control object coming from the oscillatory circuit sensors (OCS), transformer sensors (TS) and discharge circuit sensors (DCS), which control the provision of a given technological mode and are fed to the controller input as feedback.

The effectiveness of an automatic control system is determined (among other factors) by a set of coordinates of the output vector of the control object, depending on the energetic, static, and dynamic characteristics of the mode.

To choose an effective output information coordinates, a study of the PCG charger as a control object was carried out. Analysis of the results showed that the output coordinates can be divided into instantaneous and integral characteristics of processes in the PCG charger. The range of regulation of the output coordinates is set by limiting characteristics determined by both safety requirements and technological necessity.

Instantaneous characteristics include: the current in the oscillatory circuit i_L (OCS), the threshold value of which should be the I_{Ltr} value, determined by the permissible current density in the inductor; the harmonic composition of the current in the primary winding of the transformer i_1 (TS), the limit values of which are the permissible values of the amplitudes of higher harmonics; temperature in the inductor (OCS) and transformer (TS), the maximum permissible values of which are determined by the classes of insulating materials, and the current values are determined from differential heat balance equations.

The integral characteristics include the nominal charging voltage U_{C0} and the pulses frequency f_p of capacitive storage discharges C_s to the load. These values are specified by technological requirements and can be considered initial conditions that must be stabilized by means of automatic control systems. As follows from the physics of charging processes, the integral characteristics in the general case depend nonlinearly on the instantaneous characteristics.

In order to determine the space of control laws, a study of the processes occurring in the PCG charger was carried out. There are several optimal algorithms for charging capacitive storage devices of the PCG (current stabilization mode, power stabilization mode, hybrid mode) [11]. The control system must ensure the shape of the charging current curve in accordance with a given algorithm, which is formed according to various optimality criteria depending on the state of the control object. In this case, one of the parameters that determines the transition from one control law to another is the voltage U_C on the capacitive energy storage device C_s. The formation of the charging current curve is carried out programmatically according to the Polzunov-Watt principle or according to the Poncelet principle. When controlling by deviation, either the current time t_i for the formation of the i-th stage U_{Ci}, or the current value U_C, or the current value of the current in the oscillatory circuit i_L can be used as the output coordinate. Regulation of all these outputs is possible (separate or combined control).

Thus, the state space of the system is multidimensional. A special case of the implementation of a automated control system for a PCG charger assumes a four-dimensional state space: U_C – the charge voltage of the capacitive storage; i_L – the current value of the current in the oscillatory circuit; i_{1H} – harmonic composition of the current of the primary winding of the transformer; t_C – the time of charging the capacitive storage to the specified value U_{Cs} (Fig. 2). The fourth coordinate, the charging time t_C of the capacitive storage device to a given value U_{Cs}, is not shown in the figure, but can be taken into account mathematically (dimensionless dependencies between U^*_C and t^*_C were obtained [13]).

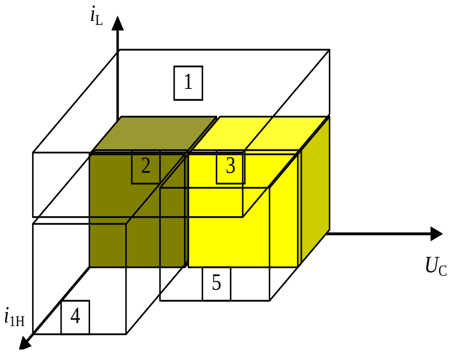

Fig. 2. Functional mapping of state space to control space

The control space is discrete-continuous, i.e. consists of areas with clear or fuzzy boundaries, within which controls are continuous. Fuzzy boundaries are due to the presence of bifurcations when the quality factor of the circuit changes (both during the manufacture of the charger and during the charging process). Five such areas have been identified, each of which has its own control laws. The mapping of the state space X onto the control space W is functional, but the problem of determining the mapping operators has been solved so far only for special cases of implementing an automatic control system for the PCG charger. This is one of many problems that can be solved efficiently and quickly using neural systems [15].

Omitting a thorough analysis of the four-dimensional state space, we present the rationale for the choice of these coordinates. The oscillatory circuit current iL determines the charging current of the capacitive energy storage device. Therefore, its value is limited from below, for example, by the condition of achieving a given rate of discharge pulses, and from above – by the permissible value of the current through the inductor. For this parameter it is convenient to use PWM control. However, operation in a near-resonance mode with a high q-factor of the oscillatory circuit, which is ensured by the results of parametric optimization of the charger, in the presence of bifurcations depending on the q-factor and the phenomenon of changing the q-factor during charging, leads to the need to change the control algorithm (for example, the introduction of PFM control). The harmonic composition of the current in the primary winding of the transformer, designated i1H, depends on the specified frequency at the input of the oscillating circuit. From below it is limited by an increase in losses in the transformer core, and from above by an increase in losses in its winding. At the same time, the phenomenon of changing the quality factor of the circuit during the charging process remains valid. Therefore, it is also necessary to use combined control here. To provide optimal charging algorithms for capacitive storage devices of the PCG charger, the control system must ensure the shape of the charging current curve in accordance with a given algorithm, which in the shown particular case is determined by the voltage UC on the capacitive energy storage device Cs. Thus, for areas 2 and 4 in Fig. 2, the charging current stabilization mode should be provided, for areas 3, 5 – power stabilization mode, for areas 2 and 3 – PWM regulation, for areas 4, 5 – PFM regulation, for area 1 – removing the charger from a dangerous mode (for example, turning off all transistor switches of the power frequency converter and turning on current protection).

In reality, the state space has a much larger dimension. The phase coordinates should include the temperature in the inductor (OCS) and the transformer (TS), the first derivative with respect to the current in the oscillatory circuit iL (OCS) and the first derivatives of the higher harmonic components of the current of the primary winding of the transformer i1 (TS), which will make it possible to more accurately determine the proximity of the processes oscillatory circuit to the resonant mode. Thus, the state space is essentially multidimensional, which requires the use of parallel information processing algorithms, for example, neural ones, which are more effective for this type of problem.

To effectively manage the charger, it is possible to use two fundamental control structures based on neural systems. In the first option, control functions are performed by a neural system based on a Hamming network. The neural network forms the control input of the control law selector. The output coordinates of the vector Y (from sensors OCS, DS, DCS) and the coordinates of the control action vector G are supplied to the network input. At the network output, a vector of control action numbers UN, of dimension n, is formed, which controls the selector of control laws U. The software implementation of such control involves storage in the memory of the matrix of control action parameters (coordinates of the vector U), which has a dimension of n×kk, where kk is the number of control keys, and n is the number of algorithms. Algorithms are deterministic. The disadvantage of this implementation is that combined algorithms (intermediate between the given ones) cannot be used without first saving to memory. Algorithms are formed during the training process of the system. A disadvantage can be considered that the learning process is hardware-separated from the control implementation process, which limits the possibilities for the development of an adaptive control system for the PCG charger.

In the second option, the neural system is part of the automatic control system by deviation as a device for assessing the state of an object, and is implemented on the basis of a Hopfield network. When implementing a control system based on a neural system, which is part of the automatic control system by deviation as a device for assessing the state of an object (information filter), a number of possibilities open up. To synthesize a control system for a PCG charger, it becomes possible to use the separation principle, which allows you to independently create an optimal controller and an optimal filter of information coordinates of the output vector Y. At the output of the neural network, vector Y0 is formed, which is a filtered image of the real control object, with dimension m (the number of output coordinates). The meaning of the transformation is that the vector Y is mapped into Y0, in the state space 0 with clear boundaries. Control is carried out according to the classical laws of PID-control. Unlike the previous option of the automatic control system implementation (with a limited number of control algorithms n), it is possible to create an infinite number of control algorithms.

CONCLUSION

As a result of the analysis of discharge-pulse installations from the point of view of controllability, several control levels and several relatively autonomous subsystems were identified. The class of particular problems of controlling discharge-pulse installations of an autonomous sublevel includes adaptive control of the process of charging the battery of high-voltage (30–50 kV) capacitive storage devices (2–8 μF) of a pulse current generator (PCG), which is the energy source of the installation. A study of the charger of PCG as a control object was carried out, as a result of which the coordinates of the multidimensional state space were determined. Instantaneous and integral output coordinates and the range of their regulation were highlighted. A study was carried out of the processes occurring in the PCG charger and the charging algorithms for capacitive storage devices, as a result of which the space of control laws was determined. A functional mapping of the multidimensional state space of a control object into the control space has been constructed.

Two options for adaptive control of the charger based on neural systems are proposed. In the first option, control functions are performed by a neural system built on the basis of a Hamming network. Algorithms are formed during the system training process and the training process is hardware-separated from the control implementation process. In the second option, the neural system is part of the automatic control system by deviation as a device for assessing the state of an object, and is implemented on the basis of a Hopfield network.

An analysis of the proposed options for implementing control systems has shown that for chargers of PCG for discharge-pulse installations, the use of the second option is more effective, since it allows: to take into account the gradients of system behavior, does not separate the hardware processes of training the system and implementing the control algorithm, does not limit the future development of the system.

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