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ADAPTIVE PID REGULATION METHOD OF UNINTERRUPTIBLE POWER SUPPLY BATTERY CHARGE CURRENT BASED ON ARTIFICIAL NEURAL NETWORK

Andriy Palamar; Mariia Stadnyk; Mariia Palamar

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *The paper considers the issue of improving the methods of uninterruptible power supply intelligent control based on adaptive algorithms with the use of artificial neural network technologies. An adaptive PID regulation method of the UPS battery charge current is proposed. A neural network based control scheme with adjustment of PID regulation coefficients has been developed. The simulation modeling was used to search for the artificial neural network topology, which would be the most effective according to the criteria of the battery charge current regulation accuracy. The use of artificial neural networks in the uninterruptible power supply control system made it possible to obtain more effective results for maintaining a stable battery charge current in the transient processes when the battery parameters are changed and in the stochastic load changes conditions.*

Key words*: control system, PID control, uninterruptible power supply, rechargeable battery, artificial neural network.*

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Statement of the problem. Telecommunications systems belong to the critical infrastructure of any country, therefore ensuring their reliable operation is an important task. A necessary condition is the use of industrial uninterruptible power supply (UPS) systems, which are designed to maintain the proper quality of electricity supply for a long time. The use of UPS for critical application systems places increased demands on energy efficiency, reliability of their operation, and power quality in all operating modes [1].

One of the most important components of modern UPS is the control and monitoring system, which is responsible for measuring electrical parameters, remote condition monitoring, operation modes control of rectifier modules and electricity quality supply in general. One of the main functions of the UPS control module is to regulate the rectifier modules output voltage with the simultaneous charge current adjustment of the storage batteries in accordance with the recommended modes of their operation, in particular, regarding the limitation of the charge current value [2]. It is especially important to control the voltage of the rectifier modules in transient modes during battery storage switching. It is necessary to prevent a significant current surge in the battery circuit, which negatively affects it, leading to a reduction in its service life [3].

In typical UPS, the proportional-integral-differential (PID) regulation algorithm is used to control the rectifier modules output voltage to protect the battery storage from significant current surges during its switching. In this case, the UPS control module is a component of a closed loop control system with current feedback in the battery storage electric circuit [4].

Most of the known methods and algorithms for PID controllers self-regulation involve the use of many new system parameters, which complicates algebraic calculations. For complex systems with multidimensional interconnected dynamic components, the mathematical model and the synthesis process of the optimal control system are significantly complicated. In the control system of such components, it is difficult to obtain the optimal parameters values of the

Corresponding author: Andriy Palamar; e-mail: palamar.andrij@gmail.com

regulator, which are built according to classical methods, in particular PID control, to achieve the required accuracy of regulation in all possible operating ranges. As a rule, adjustment coefficients are chosen experimentally, depending on the parameters and operating modes of a particular UPS.

The PID controller provides excellent control quality only with certain stable system parameters. In dynamic processes with variable parameters, non-linearity and disturbances that occur in the UPS, it is quite difficult to choose the optimal coefficient values for all operating modes of the system, therefore the PID regulation quality is significantly reduced. The power supply system of telecommunication equipment usually operates under conditions of uncertainty and stochastic changes in electricity consumption, which lead to a change in the operation mode of the UPS, and therefore require frequent correction of PID coefficients.

The use of traditional methods of automatic control theory does not make it possible to ensure the full adequacy of the developed control system dynamic characteristics with the reference model. One of the alternatives to classical methods is a control model based on the use of artificial neural networks (ANN). Therefore, an important task is to improve the UPS control subsystem based on adaptive PID controllers using neural network technologies.

Analysis of available investigations results. In computerized devices designing for complex systems managing, a development trend toward control process intellectualization appeared. Intelligent control and information processing systems are most often associated with the use of artificial neural networks. Various studies in the field of UPS control using neural network technologies by leading scientists and specialists were carried out [5–7].

In the paper [8], the controller of the power supply system based on artificial intelligence was modeled and developed using a fuzzy logic for the intelligent UPS control in the Microgrid system. The disadvantages of the proposed approach include the complexity of implementing such a system and its relatively high cost.

The papers [9, 10] present intelligent UPS monitoring and control systems based on Internet of Things technologies and the CloudMQTT cloud service, which provide the opportunity of remotely monitoring the status and parameters of the UPS. The disadvantages of such systems include the lack of remote software microcontrollers update.

In [11], General Electric VH series UPSs are considered, which are equipped with a unique technology of intelligent battery management. This technology makes it possible to increase the battery service life and improve their operational characteristics. The disadvantage of this model is the lack of a modular structure, which reduces the UPS reliability.

In the paper [12], methods and approaches are given that make it possible to automatically control the process of autonomous power supply in uncertain conditions. The authors proposed to use a fuzzy logic mathematical apparatus with neural network adaptation for forecasting and coordination of power supply and energy consumption processes.

As a result of the review and critical analysis of existing UPS control methods, it was found that at the moment no solution has been implemented that would allow the providing of UPS parameters adaptive regulation for optimal operation under conditions of stochastic load changes.

Objective of the paper. The purpose of this paper is to improve the methods of UPS intelligent control based on adaptive algorithms with the use of artificial neural network technologies.

Statement of the problem. The designing intelligent computerized systems task consists of determining the necessary structure of ANN, methods of its training for performing activity in the object control process. After that, it is necessary to create hardware and software that will control the uninterruptible power supply system using the intelligence algorithms [13, 14]. Their implementation requires the use of new approaches to the design process of UPS computerized control and monitoring system.

The artificial intelligence methods implementation is aimed at improving the technical characteristics of the designed uninterruptible power supply system. Only under this condition, the intelligence of the computerized system as a means of control and monitoring is ensured. A necessary condition for the intelligence of the system is its adaptability, that is, the ability of the system to changes adapt in the surrounding environment in order to improve its functioning in accordance with certain specified criteria [15].

The ability to learn according to certain rules and algorithms is one of the main advantages of artificial neural networks. To do this, it is necessary to provide the right set of training data and choose an adequate neural network structure. This property makes it possible to apply the ANN to solve the specific problem of PID coefficients adjusting for adaptive battery current control of the uninterruptible power supply.

The task of neural network synthesizing consists of two subtasks:

1. Selection of the optimal ANN structure.
2. Obtaining optimal weight coefficients.

Description of the method. The authors proposed an adaptive PID regulation method of the UPS battery charge current. In order to adapt the PID controller law for use in a discrete UPS control system, the classical PID control formula was reduced to a form that is convenient to implement on a microcontroller:

$$u_t = u_{t-1} + A_P \cdot i_t + A_I \cdot i_{t-1} + A_D \cdot i_{t-2}, \tag{1}$$

where A_P, A_I, A_D – are the coefficients of the proportional, integral and differential components, respectively.

$$A_P = K_P \cdot \left(1 + \frac{T_0}{2 \cdot K_I} + \frac{K_D}{T_0}\right), \tag{2}$$

$$A_I = -K_P \cdot \left(1 - \frac{T_0}{2 \cdot K_I} + \frac{2 \cdot K_D}{T_0}\right), \tag{3}$$

$$A_D = \frac{K_P \cdot K_D}{T_0}. \tag{4}$$

The discrete transfer control function of the PID controller for regulating the UPS charge current was reduced to the expression:

$$W_P(z) = K_P \left[1 + \frac{T_0 \cdot (1 + z^{-1})}{2 \cdot K_I \cdot (1 - z^{-1})} + \frac{K_D}{T_0} \cdot (1 - z^{-1})\right]. \tag{5}$$

where K_P, K_I and K_D – are proportional, integral and differential coefficients, respectively, T_0 – is the quantization period, which can be changed by software.

The coefficients have to be changed depending on the UPS battery type and condition, the parameters of the rectifier modules, the load value, etc. All these coefficients require optimal adjustment.

To control the UPS, which is characterized by functioning in the conditions of stochastic load changes, a scheme of neural control with adjustment of PID control coefficients is proposed, which is shown in Fig. 1.

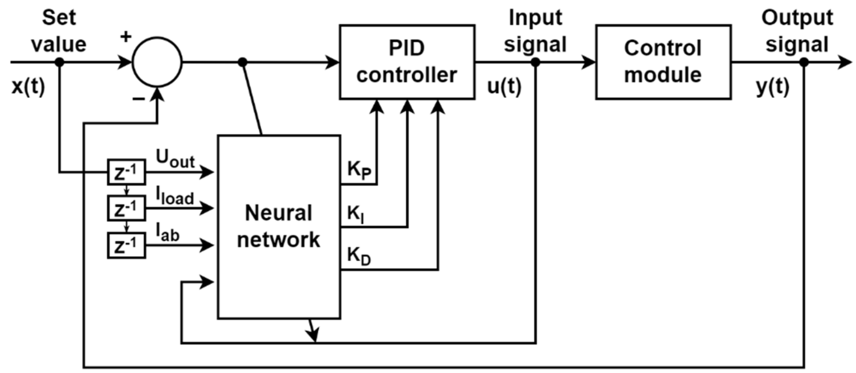

Figure 1. Structural scheme of neural control with PID coefficients adaptive adjustment

Artificial neural network simulation model. The quality of ANN training and, accordingly, the adjustment error are affected by the configuration of the neural network architecture and the choice of the activation function. In the process of choosing an ANN architecture, the hidden layers number and the input and output neurons number are important.

For the UPS control system, simulation modeling was used to search for the ANN topology, which would be the most effective according to the criteria of the battery charge current regulation accuracy. During the synthesis of the artificial neural network, its architecture was chosen to correctly reproduce the UPS components properties (Fig. 2). For this purpose, the number of ANN layers and the connections between them, the number of neurons for each layer, and the type of activation functions were determined. In order to take into account the nonlinearity of the control object, an ANN was chosen with different activation functions – nonlinear for the intermediate layer and linear for the output. At the first stage, the initial neurons number in each of the layers was set. Later, analyzing the ANN effectiveness training of the selected structure, its modification was gradually carried out.

The synthesis and research of ANN was performed using the Matlab Neural Network Toolbox component library. This tool was chosen because it has all the necessary tools for simulating neural networks using popular learning algorithms. In this software, an artificial neural network was synthesized and its possibilities for the optimal selection of PID coefficients for the task of regulating the UPS batteries charge current were studied.

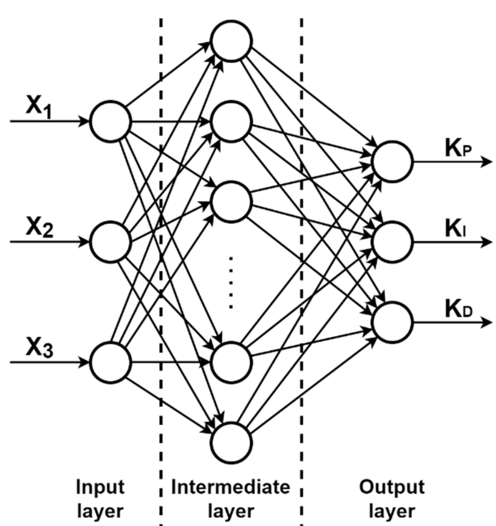

Figure 2. The structure of the neurocontroller neural network

As a result, a simple ANN with direct signal propagation (feed-forward) and reverse error propagation was used to solve the task of controlling the UPS battery charge current (Fig. 3). The input layer contains three neurons, and the intermediate layer contains ten. For the intermediate layer of the designed ANN, the hyperbolic tangent activation function (Fig. 4) was used, as it amplifies small signal values. For the output layer a linear function was used. The use of non-linear activation functions in intermediate layers ANN makes it possible to solve problem with significantly non-linear constraints, which includes the task of adjusting the PID coefficients of the UPS control system. The output network neurons form the scaled coefficients of the designed PID regulator K_P, K_I and K_D.

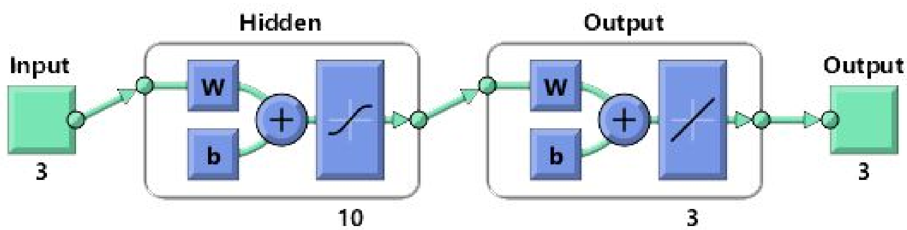

Figure 3. The structure of the neurocontroller neural network in Matlab

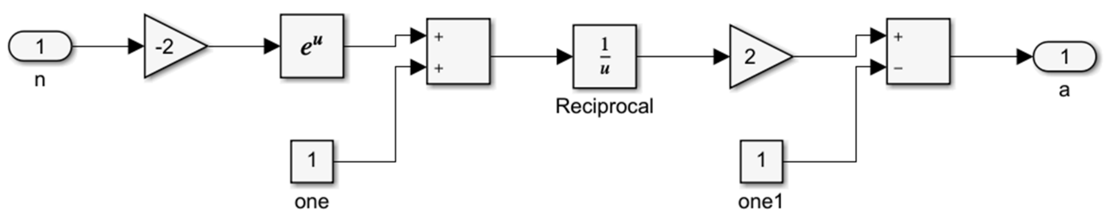

Figure 4. Model of the hyperbolic tangent activation function for the hidden layer neurons of the designed ANN

Artificial neural network training process. One of the most difficult tasks in the design of a PID controller based on ANN was the process of its training. It involved the use of input and output values sets obtained experimentally. Training sequences representing the values of the UPS electrical parameters were sent to the ANN inputs:

– output voltage U_{out};
– output load current I_{load};
– battery charge current I_{ab}.

In fact, the weight coefficients of the synthesized artificial neural network were obtained during the training process, using data from a real UPS. Based on the input sequence, the neural network created its set of output signals, which were compared with the expected output values. If there was a difference between the actual and the desired result, then the weight coefficients were changed in such a way that this difference decreased.

In order to increase the artificial neural network efficiency, in its training process, training sequences were applied, which not only reproduce the UPS operation modes to obtain the corresponding values of the output PID coefficients, but also took into account its actions aimed at compensating random influences and disturbances.

In the implementing process of the ANN learning algorithm, the mean squared error function E was used to evaluate the quality of the learning process. The function E, which must be minimized, is calculated by the formula:

$$E = \frac{1}{N_D} \cdot \sum_{k=1}^{N_D} (x(k) - y(k))^2, \quad (6)$$

where N_D – is the number of examples in the training sample, $y(k)$ – is the neural network output, $x(k)$ – is the target value from the training sample.

The fastest descent method was chosen for training the neural network. The values of the UPS electrical parameters (U_{out}, I_{load}, I_{ab}) were used as a training sequence. They were stored in the non-volatile memory of the UPS control module at certain intervals. The PID coefficients were also stored in the flash memory of the microcontroller and were selected experimentally depending on the type of battery storage and UPS configuration. This information was transferred to a computer through a serial port using developed specialized software, which provides the possibility of exporting it to a separate file in tabular format. Subsequently, the data from this file was used to train the synthesized ANN after being imported into the Matlab Neural Network Toolbox environment. As can be seen from Fig. 5, 395 epochs were sufficient for training the proposed ANN.

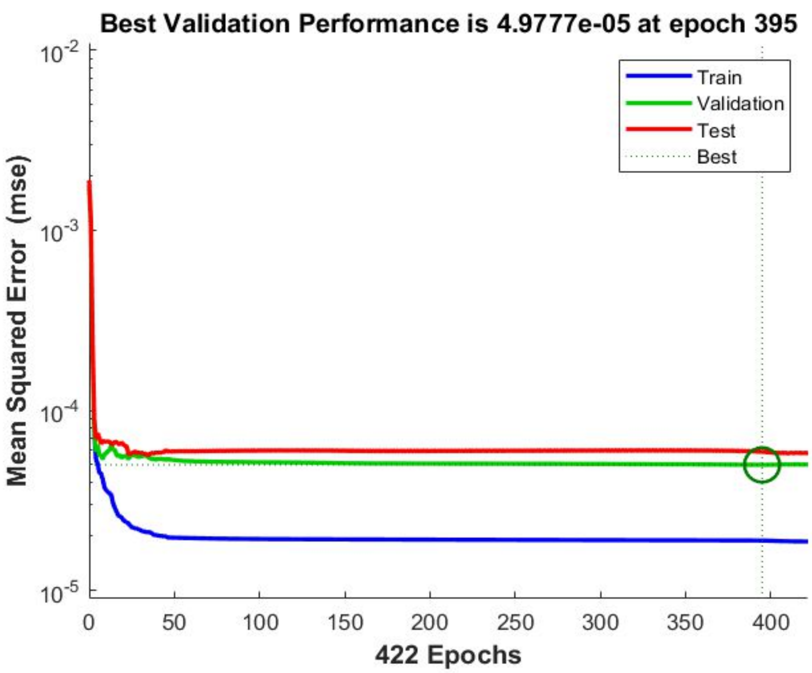

Figure 5. Dependence of the mean squared error on the number of the ANN training epochs

Experimental results and discussion. The developed software with output signals graphic visualization for remote monitoring of the uninterruptible power supply made it possible to assess the quality of the control system PID coefficients adjustments. The comparative results of regulating the battery charge current at the moment of supplying the UPS input voltage by the PID regulator (curves 1, 3) and the proposed adaptive PID regulating method of coefficients selection using ANN (curves 2, 4) are shown in Fig. 6.

It is clear from the graph that the regulation error of the battery charge current I_{ab} is insignificant, both for the optimized PID regulator (curve 1) and for the adaptive regulator based on ANN (curve 2). However, when the battery parameters are changed and in the stochastic load changes conditions, the PID regulator shows a much larger regulation error (curve 3) compared to the adaptive regulator based on the ANN (curve 4).

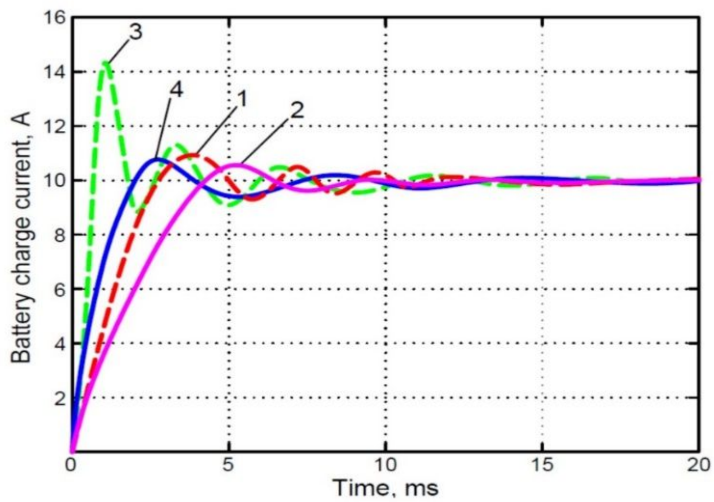

Figure 6. Transient processes during regulation of the battery charge current using: 1, 3 – PID regulator; 2, 4 – adaptive regulator based on the ANN

As a result of the conducted research, it was found that the proposed ANN of direct signal propagation allows obtaining optimal PID coefficients values with sufficient accuracy. Therefore, the use of artificial neural network in the uninterruptible power supply control system made it possible to obtain more effective results for the maintain a stable battery charge current in the transient processes when the battery parameters are changed and in the stochastic load changes conditions.

Conclusions. The control system built based on the proposed ANN adapts to changes in the controlled object parameters, while in control system based on the PID regulator, the regulation quality depends on the dynamics of the input signal changes. The use of ANN in the UPS control system provides an advantage over traditional systems also because the implementation of such a control system does not require an exact mathematical description of the control object. The results of experimental studies of the synthesized ANN showed that it provides a higher regulation quality of the battery charge current compared to programmed algorithms, but this depends on the quality and quantity of training data obtained experimentally.

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МЕТОД АДАПТИВНОГО ПІДРЕГУЛЮВАННЯ СТРУМУ ЗАРЯДУ БАТАРЕЇ ДЖЕРЕЛА БЕЗПЕРЕБІЙНОГО ЖИВЛЕННЯ НА ОСНОВІ ШТУЧНОЇ НЕЙРОННОЇ МЕРЕЖІ

Андрій Паламар; Марія Стадник; Марія Паламар

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Використання джерел безперебійного живлення для систем критичного застосування ставить підвищені вимоги до енергоефективності, надійності їх функціонування та якості електроенергії в усіх режимах роботи. Розглянуто питання удосконалення методів інтелектуального керування модульними джерелами безперебійного живлення на основі використання адаптивних алгоритмів з застосуванням технологій штучних нейронних мереж. Запропоновано метод адаптивного ПІД-регулювання струму заряду акумуляторної батареї джерела безперебійного живлення. Розроблено схему нейронного управління із налаштуванням коефіцієнтів ПІД-регулювання. Для системи керування джерелом безперебійного живлення засобами імітаційного моделювання Matlab виконано пошук топології штучної нейронної мережі, яка була б найефективнішою за критеріями точності регулювання струму заряду акумуляторної батареї. В результаті, для вирішення завдань управління струмом заряду батареї джерела безперебійного живлення використано штучну нейронну мережу з прямим розповсюдженням сигналу та зворотним поширенням помилки. Однією з найскладніших задач при проектуванні ПІД-регулятора на основі штучної нейронної мережі був процес її навчання, що передбачав використання послідовності з наборів вхідних і вихідних значень, які отримані експериментальним шляхом. Застосування штучної нейронної мережі в управлінні системою безперебійного живлення дозволило отримати ефективніші результати регулювання перехідних процесів для підтримки стабільного струму заряду батареї при зміні параметрів налаштувань та в умовах стохастичної зміни навантаження. Успішне вирішення поставленої задачі дослідження з використанням штучної нейронної мережі стало можливим завдяки застосуванню репрезентативного набору навчальних послідовностей, отриманих експериментальним шляхом.*

Ключові слова: *система керування, ПІД-регулювання, джерело безперебійного живлення, акумуляторна батарея, штучна нейронна мережа.*

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