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Development of a MPC-based Control System for Electrical Discharge of Water Purification Plant

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The method of electrical discharge of water purification is a complex chemical-technological process. Under the influence of electrical discharges in the water purification plant, chemical processes such as the oxidation of the electroerosion products and precipitation of harmful impurities occurs due to iron oxides and hydroxides. The aim of this study is development of a control system for electrical discharge of water purification plant. The Model Predictive Control technique is selected. The developed control system allows reducing the energy costs for the process of water purification.

1. Introduction

Purification wastewater from harmful impurities is an urgent task. The study by Akter et al. (2017) is devoted to immobilization of heavy metals, which are contained in tannery sludge in high concentrations, under the subcritical water conditions by forming a particular crystalline mineral that captures heavy metals. In another recent article Delcolle et al. (2017) aims to develop and evaluate different processes to improve the quality of biodiesel wastewater to achieve legislation requirements for its final disposal. Today a large number of water purification methods are used: reverse osmosis, ion exchange, reagent coagulation, aeration, sedimentation, distillation, etc., each one with specific pros and cons. Lutchmiah et al. (2014) reviewed problems and prospects the use of reverse osmosis membranes for wastewater treatment. The main disadvantages dealing with these methods are: a large consumption of reagents, the need for periodic replacement of membranes, high costs of reagents and membranes, large areas needed for equipment installation and the ineffectiveness to clean water sources of toxic substances, like arsenic, and dissolved salts. Multistage technological schemes of water purification are being developed to reduce the impact of these shortcomings. For instance, Abdulgader et al. (2013) presented studies on using combined ion exchange and pressure driven membrane processes (ultrafiltration, nanofiltration and reverse osmosis) in water treatment. Also the study by Den et al. (2008) investigated the feasibility of electrocoagulation as a pretreatment process to remove silica from the source brackish water, since the presence of high silica concentrations in some brackish water, limits the application of reverse osmosis membranes desalination due to the potential formation of silica scales that irreversibly deteriorate the membrane material and performance. It was shown that interest on these hybrid processes has increased substantially in the last years from both industry and academia due to the need for higher efficiency, optimization and cost reduction of water treatment processes. More recently, researchers used electrical energy for water purification. For example, Rehman et al. (2015) has shown the effectiveness of Electro Coagulation Process (ECP) using aluminum and iron electrodes for the removal of heavy metals from industrial wastewater has been investigated, with particular attention to the effects of operating parameters on removal efficiency. One of such methods, based on the use of electric energy, is the water purification by using electroerosion process (EDM process) of metal balls. The electroerosion process of metal workpieces has been known for more than 70 years, but the use this method for water purification is a novelty. This new process of electroerosion for water purification has several advantages: it is based on cheap raw materials (metal balls) and characterized by low energy consumption.

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Despite what the literature proposes, this paper is aimed at optimizing the methods above by means of the development of an automatic control system.
Modern technological processes are inconceivable without automated control systems. Control systems are also being developed for the effective operation of modern water treatment plants. Article by Sobana et al. (2014) is devoted to the development of control systems reverse osmosis module using the centralized and decentralized techniques. In addition, a large number of works are devoted to the development of control systems for water treatment plants based on electrocoagulation. Demirci (2014) presented an experimental application of PID control to study the electrocoagulation process of textile wastewater. Due to the non-linear behavior of the process, the tuning of PID parameter was very complex, but results showed that PID control appropriately tuned is suitable for the electrocoagulation process. Again, Demirci et al. (2015) proposed the use of fuzzy logic to control both conductivity and pH during the electrocoagulation process, and applied this approach to the treatment of textile wastewater. Typically, the electrical conductivity of the treated water is a controlled variable for control of the electrochemical process of water purification. This parameter has a great influence on the performance of of water purification processes. Camcioglu et al. (2017) determined the effect of electrical conductivity; in his work, pH and temperature were maintained constant during the operations by means of an advanced control strategy based on chemical oxygen demand, color, turbidity and total suspended solids removal and energy consumption. The literature presents also several works related to the optimization and the development of control systems for electrical impulse generators, which can be used for electroerosion processing. The article authored by Behrens et al. (2003) introduced the electrical-discharge machining (EDM) process control system consisting of a Fuzzy gap-width controller adapted by a Neural Network. By combining a Neural Network with a Fuzzy controller in this way a learning process control system is achieved. However, as in the acquaintance of the authors, the development of a control systems for electrical discharge plant for water purification is still an open issue in the scientific literature.
The aim of this article is the development of a control system for electrical discharge of water purification plant based on MPC (Model Predictive Control) (Manenti, 2011; Rossi et al., 2017).

2. Process description

The electroerosion process for water purification is only one of the stages involved in the water purification process. The main aim of such a stage is to convert soluble salts into insoluble precipitate that can be easily removed from water. The scheme of water purification process is shown in Figure 1.

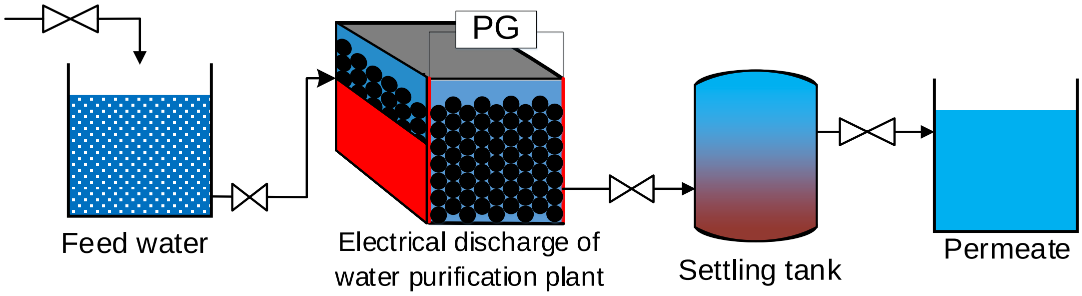


Figure 1: Possible technological scheme of the water purification plant

The technological scheme (see Figure 1) includes a tank with feed water, electrical discharge (electroerosion) of water purification plant, for treatment of contaminated water sources, a settler tank in which the electroerosion products deposited and products of chemical reactions. The electrical discharge equipment of water purification plant consists of electrical pulse generator (PG) and the tank-reactor. Two electrodes are located in the reactor-tank and connected to the PG. The interelectrode gap within the tank-reactor is filled with metal balls and purified water. Then, electrical impulses of short duration passed through the layer of metal balls. Electrical discharges arise between the balls when the electrical impulses pass. These discharges are characterized by high energy. As a result, electrical erosion process occurs on the surface of metal balls. The size of the dispersed particles is about 1-100 nm. The erosion products pass through the liquid phase with oxidation of water and dissolve therein oxygen. Active metal hydroxides and oxides, which are active coagulants, are formed in the oxidation:

$$\begin{aligned} & Fe + H_2O \rightarrow FeO + H_2 \uparrow \\ & 4FeO + O_2 + 2H_2O \rightarrow 4FeOOH \end{aligned} \qquad (1)$$

The process proceeds in three stages, which are represented in Figure 2.

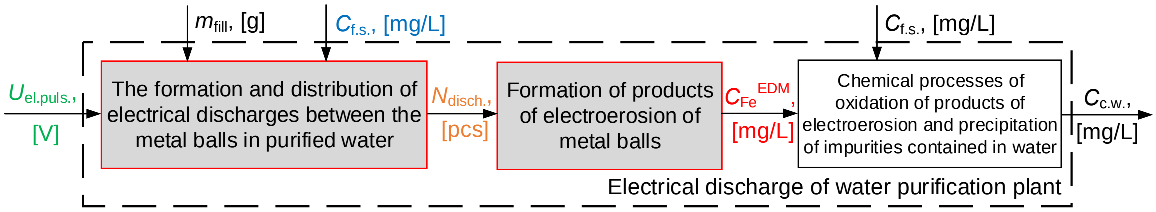


Figure 2: Information model of the electrical discharge of water purification plant

The rate and quality of water treatment depends on the number of formed electric erosion products resulting from one electrical impulse. Therefore, as the controlled variable, the concentration of the electric erosion products (C_{Fe}^{EDM}) in the plant was selected. This variable depends on the number of discharges occurring between the metal balls (N_{disch}) as a result of a single electric pulse. N_{disch} depends on the voltage (amplitude) of the electrical pulses ($U_{el.puls.}$), and also depends on the mass of metal balls fill in the plant (m_{fill}) and on the concentration of harmful impurities contained in water ($C_{f.s.}$). It is worth noting that the infinite increase in the voltage of the supplied electric pulses ($U_{el.puls.}$) does not lead to an infinite increase in the number of discharges (N_{disch}), since the surplus of energy unavoidably heats the aqueous solution. This leads to an inefficient use of electricity. Therefore, as the control variable, the voltage of the supplied electric pulses was selected ($U_{el.puls.}$).

3. Development of a control system

3.1 Mathematical model of the control plant

The mathematical model of the process is necessary for development of control systems based on MPC. Several papers are related to the modeling electrical discharge machining (EDM) of metal products by using machines, as well as to the modeling of the individual stages of the electric erosion process. Ming et al. (2014) proposed a hybrid intelligent process model, based on finite-element method and Gaussian process regression, for electrical discharge machining process. A model of single-spark EDM process has been constructed based on finite-element method, considering the latent heat, variable heat distribution coefficient of cathode, and plasma flushing efficiency, to predict material removal rate and surface roughness. However, these models are unsuitable for the simulation of electroerosion process for water purification since there is a gap in the distribution of the discharge energy and, as a consequence, in the products. In this regard, the mathematical model of the electrical discharge of water purification process, based on the application of probabilistic cellular automata, was developed earlier. Since the process proceeds in three stages, the mathematical model of the process is based on the models of each of the single stages. Nadezhdin et al. (2016) presented the mathematical model and the mechanism of formation of electroerosion holes and electroerosion products. In a subsequent work, Nadezhdin et al. (2017) presented a mathematical model of the distribution of electrical discharges between the metal balls in the aqueous solution. During the research was proposed a new approach to the modeling of the distribution of electrical discharges between the metal balls in the interelectrode gap in the water purification process. The proposed approach was based on the use of probabilistic cellular automata. The mathematical model of the control plant, based on the models developed earlier, was used to configure of the MPC.
The first stage of the electrical discharge of water purification process was described by a mathematical model based on probabilistic cellular automata. However, the use of this model to configuration the MPC controller has certain difficulties. Therefore, it is necessary to develop a simplified mathematical model for the first stage. To this end, full-factorial experiment was used. It is impossible to fix and calculate the number of electric discharges that formed between metal balls in the plant, since the balls fill the interelectrode gap in several layers. For this, the previously developed mathematical model was used (Nadezhdin et al. (2017)). As factors affecting the number of discharges occurring between the metal balls was determined: the voltage of the supplied electric pulses, the diameter of metal balls, the length of interelectrode gap, the electrical conductivity of aqueous solution. The following regression model describing the first stage of the process was obtained:

$$N_{disch} = 618.28 + 142.65 \cdot U_{el.puls} - 177.61 \cdot L_{pl} - 76.59 \cdot U_{el.puls} \cdot L_{pl} - 26.23 \cdot d_{ball} \cdot \gamma \qquad (2)$$

Where $U_{el.puls.}$ is the voltage of the supplied electric pulses (V); L_{pl} is length of interelectrode gap (m); d_{ball} is diameter of metal balls (mm); γ is electrical conductivity of aqueous solution (µS/m).

The mathematical model of the second stage of the process is presented in article Nadezhdin et al. (2016). The model describes thermos-physical processes, which occur on surface of metal balls that are processed with using electrical impulses. This stage is described by the following system of differential-algebraic equations:

$$\begin{cases} dC_{Fe}^{EDM}/dt = 0.001 \cdot m_{er.prod} \cdot \left(W_{pl} \cdot H_{pl} \cdot L_{pl} - \left(m_{fill}/\rho\right)\right)^{-1} \\ d\gamma/dt = k_{\gamma}^{-1} \cdot \left(C_{Fe}^{EDM} + C_{f.s.}\right) \\ m_{er.prod}(n) = \sum_{g=1}^{n} m_{Fe}^{EDM}(g), \text{ where } n = t \cdot f_{el.puls} \\ m_{Fe}^{EDM} = 2 \cdot N_{disch} \cdot V_{hole} \cdot \rho \\ V_{hole} = 0.5 \cdot \pi \cdot R_{hole}^{2} \cdot h_{hole} \\ R_{hole} = 0.5 \cdot \left[\left(73.96 \cdot d_{ball}^{2} - 930.1 \cdot d_{ball} + 3602\right) \cdot q_{chan}^{0.02309 \cdot d_{ball}^{2} - 0.4422 \cdot d_{ball} + 2.242} + \left(27.16 \cdot d_{ball}^{2} + 218.1 \cdot d_{ball} - 278.4\right)\right] \\ h_{hole} = q_{disch} \cdot \left(c_{ball} \cdot \left(T_{mel} - T_{0}\right) \cdot \rho\right)^{-1} \\ q_{disch} = 4.45 \cdot k_{ef} \cdot q_{el.puls} \cdot \left(N_{disch} \cdot \pi \cdot R_{hole}^{2}\right)^{-1} \end{cases} \tag{3}$$

where $m_{\text{er.prod}}$ is mass of electric erosion products accumulated in the plant (g); W_{pl} and H_{pl} is width and height of the interelectrode gap, respectively (m); m_{fill} is the mass of all balls loaded into the plant (g); k_{γ} is empirical coefficient, which determines the electrical conductivity of the aqueous solution as a function of the concentration of impurities in it; $f_{el.puls}$ is frequency of electrical pulses (Hz); t is operating time of the plant (s); m_{Fe}^{EDM} is mass of the metal released after the g-th pulse (g); V_{hole} is volume of erosion holes formed on the surface of metal balls (m^3); ρ is the density of the metal from which the balls are made (kg/m^3); R_{hole} is radius of the holes formed on the surface of the metal balls (m); h_{hole} is depth of the holes formed on the surface of the metal balls (m); q_{chan} is energy of the discharge channel arising between the balls (J); q_{disch} is energy spent for melting balls (J/m^2); c_{ball} is the heat capacity of the material from which the balls are made (J/(kg·K)); T_{mel} is melting temperature of metal balls (K); T_0 is initial temperature of balls in the plant (K); $q_{el.puls}$ is energy released as a result of a one electrical pulse (J); k_{ef} is empirical coefficient of the effective share of energy that goes to the melting of metal balls. The meanings of variables and parameters presents in Table 1.

Table 1: The meanings of variables and parameters of mathematical model

Variable/ parameter	d_{ball}, mm	W_{pl}, mm	H_{pl}, mm	L_{pl}, mm	$U_{\text{el.puls.}}$, V	$f_{el.puls}$, Hz	k_{γ}	ρ, kg/m^3	c_{ball}, J/(kg·K)	T_{mel}, K	k_{ef}
Value	6	100	125	100	500	700	0.65	7800	444	1808	0.06

The presented mathematical model was used to configuration the MPC controller.

3.2 Control system based on MPC controller

In the course of the work, a control system for the electrical discharge of water purification plant was developed. The scheme of the developed control system is shown in the Figure 3.

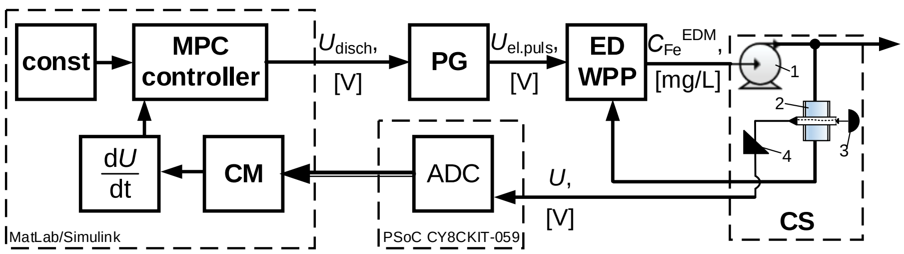


Figure 3: The scheme of the control system of the electrical discharge of water purification plant (EDWPP)

The principle of operation of the developed control system (Figure 3) is as follows. The pulse generator (PG) forms electrical pulses of a certain amplitude ($U_{el.puls}$). Electroerosion products are formed in electrical discharge of water purification plant (EDWPP) as a result of these impulses. The concentration of electroerosion products (C_{Fe}^{EDM}) formed in the process is determined by means of a concentration sensor (CS). The concentration sensor (CS) is based on the spectrophotometric method. Using a pump (1), the aqueous solution with electric erosion products is pumped through the measuring cuvette (2) and returned to the plant. From the source light (3) with a specific wavelength is passed through the measuring cuvette (2). As a result, light is absorbed by electric erosion products. The light flux passed through the solution is recorded with a photodetector (4). Then the signal from the photodetector (4) goes to the analog-to-digital converter (ADC). ADC is implemented using integrated circuit PSoC CY8CKIT–059. The interaction between the integrated circuit PSoC CY8CKIT-059 and the personal computer (MatLab/Simulink) is implemented by using the UART. A computational module (CM) is implemented in the MatLab package. In computational module (CM) the digital signal is processed and the absorption intensity is recalculated in the concentration values of the products of electric erosion, according to the Beer–Lambert–Bouguer law:

$$C_{Fe}^{EDM} = A \cdot \left(\varepsilon \cdot l_{cuv.}\right)^{-1} = \left(\varepsilon \cdot l_{cuv.}\right)^{-1} \cdot \log_{10}(I_0/I) \tag{4}$$

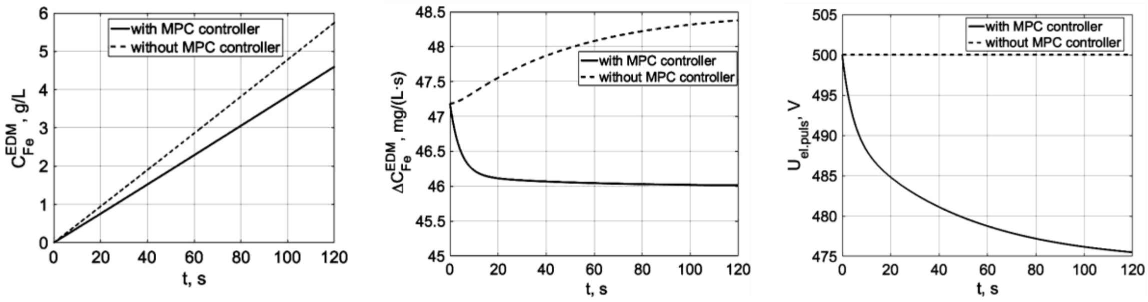
Where A is the amount of light of a certain wavelength that was absorbed by the products of erosion; ε is molar absorption coefficient (extinctions) (L·mol^{-1}·cm^{-1}); $l_{cuv.}$ is distance traveled by light in solution (cm); $I_0$is light intensity at the solution inlet (W/m^2); I is light intensity, at the solution outlet (W/m^2). Over time, the concentration of electroerosion products (C_{Fe}^{EDM}) increases in the plant. For the control, the derivative of the concentration (C_{Fe}^{EDM}) by time is used. This allows preserving the rate of formation of erosion products at the same level. The mathematical model of the process, described earlier (section 3.1), was used to configure the MPC. The MPC calculates the optimum values of the amplitude of electrical pulses (U_{disch}) while the rate of formation of erosion products is fixed at a certain level:

$$f = \begin{cases} U_{el.puls} \rightarrow \min \\ dC_{Fe}^{EDM}/dt = const \end{cases} \tag{5}$$

The calculated optimum value of the amplitude of electrical pulses (U_{disch}) is transmitted to the pulse generator (PG).

4. Results and discussions

The electrical discharge of water purification plant (EDWPP) operates by cycles of 120 s and, then, the treated water is drained into the settling tank. As a result of plant operations without MPC controller, graphs were obtained showing the changes of the concentration of electroerosion products in the plant (Figure 4a).



(a) Concentration of the electroerosion products in EDWPP

(b) The rate of change concentration of the electroerosion products in EDWPP

(c) Voltage (amplitude) of electrical pulses

Figure 4: The results of work of the electrical discharge of water purification plant (EDWPP)

As can be seen from the obtained graphs (Figure 4a), the concentration of electroerosion products in the plant is constantly increasing. At the same time, the rate of change concentration of electroerosion products (Figure 4b) increases (without MPC). This is explained by the fact that the electrical conductivity of the aqueous solution increases as a result of the formation of electroerosion products. Therefore, less energy is needed to form a discharge between the metal balls. But since the amplitude of the electric pulses does not decrease during the operation of the plant without a control system (Figure 4c), erosion products of sizes larger than 100 nm are formed. It has a negative effect on the water purification process. Since the electroerosion products of large sizes are oxidized only on the surface, accordingly, there is no effective use of the formed of electroerosion products. In this regard, the task of maintaining the rate of change concentration of electroerosion products in plant at a constant level has been achieved as well as the formation of highly disperse electroerosion products. Figures 4 presents the graphs broaching the operation of electrical discharge of water purification plant with the MPC-based control system. As can be seen from the graphs (Figure 4b), the developed control system will allow maintaining the rate of change concentration of electroerosion products at a constant level and, at the same time, the amplitude of electric pulses decreases (Figure 4c). As a result, there is a decrease in electrical costs for the process of water purification. At the same time, the efficiency of electrical discharge of water purification plant is maintained (Figure 4a).

5. Conclusions

A control system for electrical discharge of water purification plant was developed by basing on the MPC technique. The mathematical model of the process, already developed in previous works by the same authors, was used to implement the configuration of MPC. The developed control system allows reducing energy costs by 3.8 % for one cycle of water purification (120 s). The proposed control system can significantly reduce economic costs, since electrical pulses of high power (≈400-600 V) are required in the process of water purification. In addition, the highly dispersed electroerosion products obtained can significantly increase the rate of precipitation of harmful impurities contained in the water.

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