Tuning proportional–derivative controller for a three-phase electric arc furnace

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Abstract. In this paper is presented a control system that is based on the proportional-derivative controller for modeling and simulation of the electric arc furnace focusing on the controller’s loop. The proposed controller is used to modify the position of the electrodes of the electric arc furnace in order to minimize the effect of the disturbances that can appear in the process during its functioning. With the proposed controller can be obtain the maximum power that can be used during functioning of the electric arc furnace. Also, the proposed control system can be used to obtain a specific active power for the electric arc that appears in the functioning of the electric arc furnace. In this paper are presented the steps used to tune the proportional and derivative gains of the controller. Used mathematical model of the electric arc is based on the voltage-current characteristic of the electric arc that simulates the functioning of the electric arc from the electric arc furnace. The model is integrated in the control system implementation. The simulations are implemented using Simulink toolbox from Matlab software. Taking into consideration obtained results during simulation are selected the best values for the gains of the proportional-derivative controller in order to obtain performance optimization of the electric arc furnace. For the selected gains of the proportional-derivative controller is presented the response of the system that is tested in a closed loop.

1. Introduction
In the present the steel is used in many domains. One of the equipment that is used to produce steel is electric arc furnace (EAF). EAF can be supplied by alternating current or direct current [1]. In this paper the EAF taken into consideration is supplied by alternating current. The metal that is loaded in the furnace tank can be direct reduced iron, steel scrap and hot metal [2].

At the beginning of the melting process the metal loaded in the furnace tank has different configurations and when the metal begin to melt the metal can modify its position and can break the electrodes of the EAF or the electric arc can extinguish [3].

The electrodes are moved by a hydraulic actuator in order to obtain different positions so maintaining constant the electric arc length [4-7].

In the functioning of the EAF the electric arc is the main cause of the nonlinearity of the EAF [8], that is why it is so important to design control strategies in order to maintain constantly the electric arc length.

In this paper the simulations are performed for a single phase network this meaning that the controller is used to modify the position of one electrode of the EAF at a moment of time.
2. Mathematical modeling of the electric arc

Used mathematical model of the electric arc is based on the implementation of the voltage-current characteristic of the electric arc. This model is used in the implementation of the proposed control system. Electric arc is the element which represents the main nonlinearities of the electric arc furnace installation.

Mathematical model used in this paper for modeling the behavior of the electric arc was proposed in [9] by the authors of this paper. This model is presented in (1) and illustrates the relationship between the voltage and the current of the electric arc. In order to represent the voltage-current characteristic of the electric arc with this model, the typical characteristic was divided in three zones for each of the half-period of the alternating current.

In relations (2) and (3) parameter \( i_f \) represents the value of the electric arc current that corresponds for the ignition voltage of the electric arc (\( v_{ig} \)); parameter \( i_2 \) represents the value of the electric arc current that corresponds for the extinction voltage of the electric arc (\( v_{ex} \)); parameter \( R_1 \) is the line slope obtained when the voltage-current characteristic is approximated with the line \( CA \) (Figure 1); parameter \( R_2 \) corresponds to the line slope obtained when the voltage-current characteristic is approximated with the line \( DC \) or \( AB \) (Figure 1).

\[
v_{arc} = \begin{cases} 
R_1 \cdot i_{arc}, & i_{arc} \in [-i_f, i_f] \\
R_2 \cdot i_{arc} + v_{ig} \cdot (1 - R_2 / R_1), & i_{arc} \in (i_f, i_2) \\
R_2 \cdot i_2 + v_{ig} \cdot (1 - R_2 / R_1), & i_{arc} > i_2 \\
R_2 \cdot i_2 - v_{ig} \cdot (1 - R_2 / R_1), & i_{arc} \in (-i_2, i_f) \\
R_2 \cdot (-i_2) - v_{ig} \cdot (1 - R_2 / R_1), & i_{arc} < -i_2
\end{cases}
\]  

(1)

where,

\[
i_f = v_{ig} / R_1
\]

(2)

\[
i_2 = v_{ex} / R_2 - v_{ig} \cdot (1 / R_2 - 1 / R_1)
\]

(3)

Figure 1. The voltage-current characteristic obtained with the model of the electric arc

Arc length can vary between \( \theta \) and a maximum value. Value \( \theta \) corresponds to the short-circuit regime and the maximum value has to be chosen in order to be fulfilled the conditions required to burn the electric arc [10].
3. Implementation of the proportional-derivative controller

In this paper is presented a control system that is based on the proportional-derivative controller for modeling and simulation of the electric arc furnace focusing on the controller’s loop. In the implementation of the proposed controller is considered that the execution element is a hydraulic actuator which has the transfer function corresponding to a dynamic behavior of a first-order controlled system (PT1). Time constant for this controller is 0.75 seconds. In plant the hydraulic actuator is used to modify the position of the electrodes of the electric arc furnace in order to reduce the effect of disturbances that can appear in the process during EAF functioning.

With the proposed control system can be obtain the maximum power that can be used during functioning of the electric arc furnace and also can be obtain a specific active power for the electric arc required in the functioning of the electric arc furnace.

In Figure 2 is presented the Matlab/ Simulink implementation of the proposed control system. In this control system the process is represented by the functioning of the electric arc furnace that includes the power supply voltage, the model of the electric arc, the system impedance and the transformer impedance of the EAF. The PD controller is implemented using two gain blocks, a derivative block and a sum block from Simulink. The gain blocks represent the proportional and derivative factors of the PD controller.

![Simulink implementation for the proposed control system](image)

**Figure 2.** Simulink implementation for the proposed control system

In can be observed in Figure 2 that the reference current (setpoint) is compared with the output of the system this being the actual arc current (response). Controller has two inputs: one input is represented by the error computed as the difference between the setpoint and actual value of the arc current and the second input is the derivative of the error. Taking into consideration the inputs the controller sends a command to the hydraulic actuator which is the execution element (EE). The output of the execution element represents a value that is used to modify the position of one electrode of the EAF. This value can be positive this meaning that the electrode will be moved up and be obtaining another position of the electrode. If the value is negative this means that the electrode will be moved down and if the value is approximately zero it means that the electrode should not be moved. By moving the electrode it will be obtained again the value of the setpoint, because arc current is influenced by the arc length.
3.1. Tuning the proportional gain of the controller

In order to obtain the best value for the proportional gain (Kp) were performed several tests, in the followings being presented the most representative cases. In all the figures below the setpoint is represented with blue colour and the response is represented with black colour. When tuning the proportional gain all the tests are performed for the stationary regime and was ignored the derivative part of this controller. For all the tests the setpoint is maintained constant at the value 56500 A.

In Figure 3 is presented the setpoint and the response of the system for Kp = -5 and Kp = -5e-01. It can be observed that for Kp = -5 the response could not reach the setpoint and it is not stable. Also, for Kp = -5e-01 one can notice that the response presents an oscillation and it is not stable.

In Figure 4 is presented the setpoint and the response of the system for Kp = -5e-02 and Kp = -5e-03. It can be observed that for Kp = -5e-02 the response presents an oscillation but after 0.4 seconds the response of the system became stable. Also, for Kp = -5e-03 one can notice that the response of the system presents an overshoot, but it is smaller than the overshoot obtain for the previous value of the Kp, after 0.2 seconds the response became stable and the error is small.

In Figure 5 are presented the setpoint and the response of the system for Kp = -5e-04 and Kp = -5e-05. It can be observed that for Kp = -5e-04 the response is not reaching the value of the setpoint. Also, for Kp = -5e-05 it can be noticed that the response of the system is not reaching the response of the system and the error increases. For Kp larger than -5e-05 the response presents a larger error.

Analyzing the results obtained in the tests presented before it can be noticed that best value for Kp is the value -5e-03.

Taking into consideration the results presented before another set of tests are performed for values of Kp around the value -5e-03.

![Figure 3](image3.png)

**Figure 3.** Response (black) and setpoint (blue) for Kp = -5 and Kp = -5e-01

![Figure 4](image4.png)

**Figure 4.** Response (black) and setpoint (blue) for Kp = -5e-02 and Kp = -5e-03

![Figure 5](image5.png)

**Figure 5.** Response (black) and setpoint (blue) for Kp = -5e-04 and Kp = -5e-05
Figure 6 illustrates the setpoint and the response of the system for $K_p = -1e-03$ and $K_p = -2e-03$. It can be observed that for $K_p = -1e-03$ the response of the system presents an constant error and the setpoint is not reached. In the case $K_p = -2e-03$ the response of the system presents a small overshoot and after approximately 0.15 seconds the response of the system reached the value of the setpoint and it is stable, the error being very small.

In Figure 7 is presented the setpoint and the response of the system for $K_p = -3e-03$ and $K_p = -4e-03$. It can be observed that for $K_p = -3e-03$ the response of the system presents an overshoot that is larger as compared with the value $K_p = -2e-03$ and after 0.2 seconds the response of the system reach the setpoint value and it is stable. When $K_p = -4e-03$ the response of the system presents a larger overshoot as compared to the previous case and after 0.2 seconds the response of the system became stable and reaches the value of the setpoint.

In Figure 8 are presented the setpoint and the response of the system for $K_p = -5e-03$ and $K_p = -6e-03$. It can be observed that for $K_p = -5e-03$ the response is not reaching the value of the setpoint and it is distinguished a constant error. Also, for $K_p = -6e-03$ it can be noticed that the response of the system is not reaching the response of the system and the error is also constant. For $K_p$ larger than $-6e-03$ the response presents a larger error.

Taking into consideration the results obtained in Figure 6-8 it can be observed that best value for the proportional gain of the PD controller is $K_p = -2e-03$.

Figure 6. Response (black) and setpoint (blue) for $K_p = -1e-03$ and $K_p = -2e-03$

Figure 7. Response (black) and setpoint (blue) for $K_p = -3e-03$ and $K_p = -4e-03$

Figure 8. Response (black) and setpoint (blue) for $K_p = -5e-03$ and $K_p = -6e-03$
In the followings is presented another set of tests for positive values of the $K_p$ gain.

In Figure 9 is presented the setpoint and the response of the system for $K_p=5$ and $K_p=5e-01$. It can be observed that for both of these values the response could not reach the setpoint value, the error being very large.

In Figure 10 is presented the setpoint and the response of the system for $K_p=5e-02$ and $K_p=5e-03$. It can be observed that for $K_p=5e-02$ the response of the system presents considerable error. For the value $K_p=5e-03$ the response presents an overshoot, but after 0.2 seconds the response could not reach the value of the setpoint, the error being also of considerable value.

In Figure 11 is presented the setpoint and the response of the system for $K_p=5e-04$ and $K_p=5e-05$. It can be observed that for $K_p=5e-04$ the response of the system begins to be closer to the setpoint value, but the error became larger as the time increases. One can noticed that for $K_p=5e-05$ the response of the system presents an error that is constant in time but the response of the system could not reach the value of the setpoint. For values over $K_p=5e-05$ the response presents the same error and the setpoint is not reached.

Taking into consideration the results obtained for positive values of $K_p$ it can be noticed that for the $K_p$ gain could not be chosen positive values.

![Figure 9](image1.png)
**Figure 9.** Response (black) and setpoint (blue) for $K_p=5$ and $K_p=5e-01$

![Figure 10](image2.png)
**Figure 10.** Response (black) and setpoint (blue) for $K_p=5e-02$ and $K_p=5e-03$

![Figure 11](image3.png)
**Figure 11.** Response (black) and setpoint (blue) for $K_p=5e-04$ and $K_p=5e-05
3.2. Tuning the derivative gain of the controller

In order to obtain the best value for the derivative gain ($K_d$) were performed several tests, in the followings being presented the most representative cases. In all the figures below the setpoint is represented with blue colour and the response is represented with black colour. When tuning the derivative gain all the tests are performed in the stationary regime, the setpoint being kept constantly at $56500 \, A$ and the proportional gain is maintained constant at the value $K_p = -2e-03$.

Figure 12 presents the setpoint and the response of the system for $K_d = -5$ and for $K_d = -5e-02$. One can notice that for $K_d = -5$ the response of the system did not reach the setpoint value. Also, for the value $K_d = -5e-02$ the response of the system do not reach the value of the setpoint.

In Figure 13 are illustrated the setpoint and the response of the system for the values $K_d = -5e-04$ and $K_d = -5e-05$. It can be observed that in both cases the response of the system do not reach the setpoint value.

In Figure 14 are illustrated the setpoint and the response of the system for the values $K_d = -5e-06$ and $K_d = -5e-07$. One can notice that in the case $K_d = -5e-06$ the response of the system presents a very small overshoot and after approximately 0.05 seconds the response of the system reach the setpoint value and remain stable, the error being very small. If $K_d = -5e-06$ it can be observed that the response of the system presents a larger overshoot as compared to the previous case, but the response reach the setpoint value and it is stable.

Analyzing the results obtained in Figure 12-14 it can be noticed that best value for $K_d$ is for the value $-5e-06$, taking into account the overshoot, response time and stability of the system.

Taking into consideration the results presented before another set of tests are performed for values of $K_d$ around the value $-5e-06$.

In Figure 15 are presented the setpoint and the response of the system for the values $K_d = -1e-06$ and $K_d = -2e-06$. It can be observed that for both cases the overshoot of the response of the system is small and it is stable and reach the setpoint value.

Figure 16 illustrates the setpoint and the response of the system for the values $K_d = -3e-06$ and $K_d = -4e-06$. It can be observed that for both cases the overshoot of the response of the system is smaller as compared to the previous two cases, it is stable and reach the setpoint value.
In Figure 17 are presented the setpoint and the response of the system for the values $K_d = -5e-06$ and $K_d = -6e-06$. It can be observed that the best value of the response of the system is obtained for the value $K_d = -6e-06$ taking into account the performance of the system.

![Figure 14. Response (black) and setpoint (blue) for $K_d = -5e-06$ and $K_d = -5e-07$](image)

![Figure 15. Response (black) and setpoint (blue) for $K_d = -1e-06$ and $K_d = -2e-06$](image)

![Figure 16. Response (black) and setpoint (blue) for $K_d = -3e-06$ and $K_d = -4e-06$](image)

![Figure 17. Response (black) and setpoint (blue) for $K_d = -5e-06$ and $K_d = -6e-06$](image)

4. Conclusions
This paper presented a control strategy that is based on a proportional-derivative controller for an electric arc furnace. The control strategy can be used to minimize the effect of the disturbances that can appear in the process during melting of steel, using electric arc furnace. Also, the control strategy can be used to obtain a maximum power of the electric arc or a specific active power of the electric arc. The controller send commands to the execution element and the execution element delivers to the electric arc model a value that can be positive or negative depending on the necessary moves of the
electrode. In the control system was included also the process that is given by the functioning of the electric arc furnace. The controlled parameter is the current of the electric arc.

The electric arc was modeled using a model based on the linearization of the voltage-current characteristic of the electric arc.

The simulations were performed using Simulink toolbox from Matlab software. The proportional-derivative controller was tuned by performing several tests with different values for the proportional and derivative gains. These factors were chosen taking into account the responses of the system while maintaining constantly the setpoint which is given by the current of the electric arc. First was chosen the proportional gain and then the proportional gain was maintained constantly and the derivative gain was chosen.

For the considered mathematical model of the electric arc the best value for the proportional gain of the PD controller is $-2e-03$ and the best value for the derivative gain of the PD controller is $-6e-06$.

Regarding the presented results it can be noticed the good evolution of the system taking into consideration the system performance given by the response time, overshoot and system stability.

Presented cases in this paper as well as the obtained results by simulation gives the present work a practical applicability character, opening new perspectives of research in the conversion field of electrical energy into thermal energy.

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