Proportional regulator-based approach for a three-phase electric arc furnace

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Abstract. The paper presents a proportional regulator-based control strategy for a three phase electric arc furnace. This regulator is used in order to obtain the maximum or a desired active power of the electric arc by modifying the speed and the direction of the electrodes from an electric arc furnace. The simulations are carried out in the Matlab / Simulink environment and are illustrated the responses of the system for a stationary regime or a dynamic one. In the case of the dynamic regime are illustrated the responses of the system for the variation of the reference parameter in a specific domain or for the case that disturbances are occurring in the process. Also, it is presented how was tuned the proportional gain of the regulator. The process is modeled using a model that is based on the representation of the voltage-current characteristic of the electric arc. The system is tested in a closed-loop and the responses of this system illustrate the performance of the system for the cases taken into consideration.

1. Introduction

Steel is the most important iron alloy, the main component being carbon in a concentration of maximum 2.11% by weight. Using the alloying elements can be changed the main properties of steels: hardness, elasticity, strength, flexibility, corrosion resistance, flow resistance, acid resistance. If there is more than 2.11% of carbon, steel becomes harder, but even more rigid than iron (becomes cast iron).

One of the equipment that is used in order to produce steel by melting scrap using an electrical supply as the main energy input is the electric arc furnace (EAF). Most of the EAFs currently in use are fed to alternating voltage and are of high and very high power [1]. These types of furnaces are nonlinear, unbalanced, time-varying and which generally cause power quality problems [2]. These include: the occurrence of harmonic currents, asymmetry on the three phases, reactive power of significant value, voltage gaps (flicker effect) [3]. The increased concern about the power quality has led to the need to take measures to reduce these effects. In these conditions, it is important to study the behavior of the electric arc because, being a nonlinear circuit element [4], this is the main cause of the disturbances produced by the EAF in the power systems.

Over time, technological improvements have been made, in particular regarding the elaboration time of steel, but still exists problems in influencing the power quality. Current concerns are related in obtaining reduced energy consumption, but also in rejecting disturbances that may affect other consumers which are connected to the same power network [2], [5].

EAF taken into consideration in this paper is a three-phase one with direct action, so, the electric arcs appear between each of the three electrodes and the metal that will be melted. These electrodes
are supported by the electrode arms which are mounted on a hydraulic system that allows obtaining different arc lengths by changing the position of the electrodes.

In order to reduce the energy consumption and to melt the metals loaded in the furnace tank it is necessary to optimize the delivered power to the furnace. Arc power can be influenced in two ways: by modifying the position of the electrodes (during a melting stage) or by modifying the power delivered by the transformer to the EAF (changing the melting stages) [6].

2. Modeling of the Electric Arc Furnace

In order to analyze the operation of the EAF it is necessary to model the electric arc so that it is reflected as faithfully as possible the real arc behavior [7]. To analyze the behavior of the electric arc in the scientific literature are considered many types of models. The most used method for static and dynamic modeling of the electric arc behavior from the three-phase EAF is the method based on the voltage-current characteristic of the electric arc [8], [9] because this method is simple and direct and provides enough information regarding the operating of the technological installation taken into consideration. The method based on the voltage-current characteristic of the electric arc uses a numerical analysis procedure, which has the role of solving the differential equation which describes the behavior of the electric arc within the furnace [10].

The operating mode of the EAF can be defined by: electric arc current, electric arc voltage, voltage in secondary side of the furnace transformer, electrical resistance and circuit reactance through which is fed the EAF [11].

In this paper is used an exponential arc model illustrated in equations (1), model which was proposed and validated by the authors of this paper in [6].

In Figure 1 is presented the voltage-current characteristic of the EAF that will be obtained with the arc electric model. In this model, the voltage-current characteristic of the electric arc is divided in five sections in order to obtain a characteristic similar with the one from the real installation. In Figure 1 $v_{ig}$ represents the ignition voltage, $v_{ex}$ is the extinction voltage, $v_{av}$ is the average between the ignition and the extinction voltage of the arc, $v_{arc}$ is the voltage of the electric arc, $i_1$ is the current of the electric arc corresponding for the $v_{ig}$, $i_2$ is the current of the electric arc corresponding for the $v_{av}$, $i_3$ is the current of the electric arc corresponding for the $v_{ex}$ and $i_{arc}$ is the current of the electric arc [6]. $R_1$, $R_2$ and $R_3$ represents lines slope for the linear section of the voltage-current characteristic.

![Figure 1. Voltage-current characteristic divided by sections](image-url)

In the five sections of the voltage-current characteristic can be mentioned the followings:

- **1st section**: the voltage magnitude increases from extinction voltage to ignition voltage (EAF acts as a resistor);
- **2nd section**: the beginning of the arc melting process (exponential voltage drop across the electrodes);
- **3rd section**: the normal arc melting process;
• 4th section: stabilizing the voltage to a specific value;
• 5th section: changing the polarity of the supply voltage.

In the model from (1) were chosen values for the model parameters in order to accurately represent the voltage-current characteristic of the electric arc, $R_1 = 0.05$, $R_2 = -0.0007$ and $R_3 = -0.0003$. Limit $i_1$ is computed as presented in (2), limit $i_2$ is computed as presented in (3), limit $i_3$ is computed as presented in (4), limit $i_4$ is computed as presented in (5) and voltage $v_m$ is computed as presented in (6).

\[ v = \begin{cases} 
-v_{ex} + (i_1 - i_4) \cdot R_4, & i < -i_4 \text{ and } di/dt \geq 0 \\
-v_{ex} + (i + i_1) \cdot R_3, & i \in [-i_4, -i_1) \text{ and } di/dt \geq 0 \\
R_1 \cdot i, & i \in [-i_1, i_2) \text{ and } di/dt \geq 0 \\
v_{ex} + (v_{ig} - v_{ex}) \cdot e^{(i_3-i_1)/i_3}, & i \in [i_2, i_3) \text{ and } di/dt \geq 0 \\
v_m + (i - i_3) \cdot R_2, & i \in [i_3, i_4) \text{ and } di/dt \geq 0 \\
v_{ex} + (i_4 - i_1) \cdot R_3, & i > i_4 \text{ and } di/dt \geq 0 \\
v_{ex} + (i_4 - i_1) \cdot R_3, & i > i_4 \text{ and } di/dt < 0 \\
-v_{ex} + (v_{ex} - v_{ig}) \cdot e^{(i_4+i)/i_4}, & i \in [-i_3, -i_2) \text{ and } di/dt < 0 \\
-v_m + (i + i_3) \cdot R_2, & i \in [-i_4, -i_3] \text{ and } di/dt < 0 
\end{cases} \tag{1} \]

where:

\[ i_1 = \frac{v_{ex}}{R_1} \tag{2} \]
\[ i_2 = \frac{v_{ig}}{R_1} \tag{3} \]
\[ i_3 = 2 \cdot i_2 \tag{4} \]
\[ i_4 = \frac{(v_m - v_{ex} + i_1 \cdot R_3 - i_3 \cdot R_2)}{(R_3 - R_2)} \tag{5} \]
\[ v_m = \frac{(v_{ig} + v_{ex})}{2} \tag{6} \]

3. Control Strategy of the Electric Arc Furnace

In this paper is proposed, designed and implemented a proportional regulator-based control strategy for a three-phase EAF. This regulator is used in order to obtain the maximum or a desired active power of the electric arc by modifying the speed and the direction of the electrodes from an electric arc furnace. The simulations are carried out in the Matlab / Simulink environment and are illustrated the responses of the system for a stationary regime or a dynamic one. In the case of the dynamic regime are illustrated the responses of the system for the variation of the reference parameter in a specific domain or for the case that disturbances are occurring in the process.

In Figure 2 is presented the block diagram of the proposed control closed-loop. In this block diagram $I_{ref}$ is the reference arc current, $e_i$ is the error computed as the difference between the reference value and obtained value of the arc current, $c$ is the command for the hydraulic actuator in
order to move the electrode up or down with a corresponding speed, \( x \) is a value that will be added in the position of the arc in this way obtaining the value of the reference current, because arc length influence the electric arc current. \( I \) is the current of the electric arc obtained by the model of the electric arc. \textit{Controller} block stands for the proportional controller. \textit{Electric arc} block is the process in the control loop and the \textit{hydraulic actuator} is the execution element.

![Figure 2](image.png)

**Figure 2.** Block diagram of the proposed control closed-loop

4. **The Control System in the Stationary Regime**

In this case the input and output quantities are constant over time. The reference arc current is set to 56500 A and the response of the system should reach the setpoint value and remain in the stable area.

The process is represented by the operating mode of the EAF which can be defined by: electric arc current, electric arc voltage, voltage in secondary side of the furnace transformer, electrical resistance and circuit reactance through which is fed the EAF (Figure 3).

In Figure 3 \textit{ARC} block stands for the model of the electric arc that was presented in (1). \( R_t \) is the source resistance and \( R_{fc} \) is the flexible cables resistance. \( L_t \) is the inductivity of the source and \( L_{fc} \) is the inductivity of the flexible cables. These flexible cables are used to connect the transformer to the electric arc furnace. The \textit{RMS block} will return the effective value of the response of the control system which is an electric arc current. This block is necessary in order to make comparison between the setpoint and the response of the system. \textit{EE} is the execution element which is the hydraulic actuator in real plant and it is represented in the block diagram as a \textit{PT1} system having time constant of 0.75 seconds. \textit{EE} executes the commands received from the regulator which represents values that modify the arc length. The proportional regulator is represented by using of a gain block from Simulink.

Taking into account the block diagram presented in Figure 3 was obtained the response of the system in the stationary regime. It can be observed that the response of the control system reaches the value of the setpoint and after 0.2 seconds the response is stable.

4.1. **The Tuning of the Proportional Gain of the Regulator**

In order to tune the proportional gain (\( K_p \)) of the regulator was used the block diagram illustrated in Figure 3. The value of the \( K_p \) factor was chosen according to numerous tests performed by the authors of this paper. The tests have been made for negative and positive values of \( K_p \).

The increase of the \( K_p \) determines the decrease of the stationary error of the system, having an important role in ensuring adequate amortization, implicitly on the system stability.
Figure 3. Simulink bloc diagram for the control system in the stationary regime

Figure 4. Reference and response of the system in the stationary regime

In Figure 5 are presented some of the tests results for negative values of the proportional gain.

If $K_p = -5$ it can be noticed that the response obtained at the output of the process has a large overshoot and a residual oscillation around the reference.

Also the response does not stabilize for $K_p = -5e-01$. For $K_p = -5e-02$ the overshoot remains high, but the response stabilizes after 0.4 seconds. For value $K_p = -5e-03$ the overshoot becomes acceptable and the response stabilizes after about 0.25 seconds. For $K_p = -5e-04$ it can be observed that overshoot is small, but the response stabilizes only after approximately 0.75 seconds.
Following the analysis of the results presented in Figure 5, another set of tests was carried out with values of $K_p$ around the value $-5e-03$, the results being shown in Figure 6.

**Figure 5.** Obtained responses for using different negatives values of the proportional gain

**Figure 6.** Obtained responses for using different negatives values of the proportional gain around the value $-5e-03
The analysis of the results led to a choice of the proportional gain of $K_p = -5e-03$, taking into account the overshoot and the response time.

Arc current and voltage waveforms for the chosen $K_p$ are illustrated in Figure 7 and these corresponds to the ones from the scientific literature.

In order to choose a positive value for $K_p$, another set of tests was carried out for values of $K_p$. Some of the results obtained are shown in Figure 8. Analysis of all the results led to the conclusion that for $K_p$ cannot be chosen positive values.

![Figure 7. a) Arc current waveforms, b) Arc voltage waveforms for $K_p = -5e-03$](image1)

![Figure 8. Obtained responses for using different positive values of the proportional gain](image2)
5. The Control System in the Dynamic Regime

In the case of the dynamic regime are illustrated the responses of the system for the variation of the reference parameter in a specific domain or for the case that disturbances are occurring in the process.

5.1. Step Variation of the Reference

In Figure 9 is presented the Simulink bloc diagram for the step variation of the reference in a specific range. A change of the reference value is obtained by using of a step type signal at \( t = 0.5 \text{ sec} \), leading to an increase of the reference current from 56.5 kA to 59.5 kA.

In Figure 10 a) is presented the setpoint and response of the system and in Figure 10 b) is illustrated the corresponding arc length variation. It can be noticed that after about 0.2 sec after applying the step signal the response of the system manages to follow the reference value.

![Simulink bloc diagram for the step variation of the reference](image)

**Figure 9.** Simulink bloc diagram for the step variation of the reference

5.2. A Sequence of Step Variation of the Reference

In Figure 11 is illustrated the Simulink bloc diagram for a sequence of step variation of the reference. Multiple changes of the reference value are obtained by using of a Slider Gain component which allows changing the reference value in the form of step signals applied at random times, leading to an increase or a decrease of the reference current. The initial reference value is 56500 A.

Figure 12 a) shows the variation of the setpoint and the response of the system and Figure 12 b) illustrates the corresponding variation in the length of the arc. Two variations of the reference value were considered which are modified in a step form.

It can be noticed that the response of the system follows the value of the reference parameter. When decreasing the value of the reference it can be observed an increase in the length of the arc and when increasing the value of the reference it can be observed a decrease in the length of the arc.
Figure 10. a) Setpoint and response of the system, b) Arc length variation

Figure 11. Simulink bloc diagram for a sequence of step variation of the reference
5.3. *Step Disturbance in the Process*

In Figure 13 is presented the Simulink bloc diagram for the step disturbance in the process. A disturbance is injected in the process by using of a step type signal at $t = 0.5$ seconds while the setpoint is kept constant at $56500 \, A$, leading to a decrease of the arc length which corresponds in real plant to a changing in position of the metals from the furnace tank.

In Figure 14 a) is presented the corresponding arc length variation and in Figure 14 b) is illustrated the setpoint and response of the system. It can be noticed that after about $0.25$ seconds after injecting the disturbance the arc length is approximately restored to the initial value.

![Figure 12](image1.png)

**Figure 12.** a) Setpoint and response of the system, b) Arc length variation

![Figure 13](image2.png)

**Figure 13.** Simulink bloc diagram for a step disturbance in the process
Figure 14. a) Arc length variation, b) Setpoint and response of the system

In Figure 15 a) is represented the arc current waveforms and in Figure 15 b) is illustrated the arc voltage waveforms for the presented case in Figure 14.

Figure 15. a) Arc current waveforms, b) Arc voltage waveforms
5.4. A Sequence of Step Disturbance in the Process

In Figure 16 is illustrated the Simulink bloc diagram for a sequence of step disturbance in the process. Multiple disturbances are injected in the process by using of a Slider Gain component which allows modifying the arc length in the form of step signals applied at random times, leading to an increase or a decrease of the arc length. The initial reference value is 31 cm.

In Figure 17 a) are illustrated the variation of the arc length when are injected disturbances in the process in the form of successive steps at random times.

It can be noticed that the control system compensates the effect of these disturbances, the system returning each time to the initial arc length of 31 cm (Figure 17 a), respectively at the reference current value of 56.5 kA (Figure 17 b).

It can be observed that the response of the system is stable and does not have oscillations.

![Simulink bloc diagram for a sequence of step disturbance in the process](image)

**Figure 16.** Simulink bloc diagram for a sequence of step disturbance in the process

![Arc length variation and Setpoint and response of the system](image)

**Figure 17.** a) Arc length variation, b) Setpoint and response of the system
6. Conclusions
In this paper was used an exponential model of the electric arc for an electric arc furnace. The model is based on the voltage-current characteristic of the electric arc. This model is used in the implementation of the control strategy used in the current control of the electric arc.

It was proposed a proportional regulator-based control strategy for a three phase electric arc furnace. This regulator was used in order to obtain the maximum or a desired active power of the electric arc by modifying the speed and the direction of the electrodes from an electric arc furnace.

It was presented how was tuned the proportional gain of the regulator. The simulations were carried out in the Matlab / Simulink environment and were illustrated the responses of the system for a stationary regime or a dynamic one.

In the case of the dynamic regime were illustrated the responses of the system for the variation of the reference parameter in a specific domain or for the case that disturbances are occurring in the process.

By using the electrode system regulation it is reduced the energy consumption, it is avoided the appearance of damages caused by the breakage of the electrodes and it is compensated the effect of disturbances which influence the process.

Starting from the presented control strategy others control strategies can be implemented.

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