



PREDICTIVE CONTROLLER OF DC ARC CURRENT FOR ELECTRIC FURNACE/PLASMA HEATER SYSTEMS SUPPLIED BY THYRISTOR CONVERTERS

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Abstract: *A fast predictive current controller for dc electric arc furnace/plasma heater systems is presented in this paper. Compared to the conventionally used PI controllers, the proposed controller is more robust to the arc voltage changes. The unwanted reactive power variations (at the point of the system connection) due to the electrode short circuits and the electrical stress on the thyristors and the fuses are significantly reduced in the system with the proposed controller. The operation of the proposed controller is experimentally verified on a laboratory prototype. The simulation and experimental results demonstrated very good dynamic performance of the controller.*

Key Words: *ac-dc converters, predictive control, fast current control, rectifiers, thyristors, dc electric arc furnaces, plasma heaters*

1. INTRODUCTION

Direct current electric arc furnaces (dc EAFs) are high-power electric loads, whose active and reactive power can vary significantly during their operation. This is especially the case during the initial period of the operation of the high power dc EAFs (so-called bore-in period), when frequent electrode short-circuits occur [1]. As a consequence of the large active and reactive power variations, electric arc furnace can induce significant unwanted disturbances into the power system network in the form of voltage flicker. Currently, most of the dc arc furnaces are supplied through high-power thyristor rectifiers, and the arc current control is performed by adjusting the thyristor delay angle. The arc voltage is controlled electromechanically (or with the hydraulic valves) by means of electrode position control. Since the arc voltage control is significantly slower than the arc current control and its speed is limited by the lowest natural frequency in the positioning system, the only way to significantly improve the control of the furnace operation is to improve the arc current control by

implementing a fast, reliable and robust arc current controller.

High performance arc heater systems supplied from high power thyristor converters are used in aerospace industry for testing of the heat-repellent materials for space vehicles [2]. High pressure and high temperature conditions which occur during space vehicle reentry phase are simulated by these systems in plasma wind tunnels. Since the mass flow valves in these systems have slow response, the required dynamics can be achieved only with the fast and reliable control of the electric arc current [3].

2. REVIEW OF CURRENT CONTROL TECHNIQUES IN DC ARC FURNACE AND PLASMA HEATER SYSTEMS

Classically, a linear PI current controller has been used in dc EAFs and arc heater systems. However, since the filtering of the feedback current signal (in order to obtain the dc component of the arc current) produces a time-lag of the feedback signal, the classical PI current controller cannot compensate fast enough for the current overshoots occurring after electrode short-circuits. This is illustrated in [4] where a current overshoot of around 30% can be observed after the electrode short-circuit has occurred in a 140 MVA dc EAF. Also, the PI current controller cannot provide required disturbance rejection in arc heater systems [3]. On the other hand, the implementation of the fast model-based predictive current controllers is not feasible, because a precise electric arc model, which is at the same time suitable for implementation in predictive controllers, has not yet been developed.

Several control structures were proposed for the efficient current control in dc EAFs and plasma heaters. In order to reduce the negative influences on the power system network induced by the dc EAF operation, the control structure consisting of two PI current controllers connected in parallel was presented in [5]. The controller

with the first set of parameters guarantees the “good compromise” between the injected harmonics and the induced flicker. The controller with the second set of parameters reduces flicker but increases injected harmonics. Based on the measured instantaneous flicker, an auto-adaptive mechanism was used to choose the controller with the preferred parameter set. The simulation results showed that it takes about 30 ms for the system to reach a new steady state after the current reference was changed from 100 kA to 50 kA.

A control structure combining a PI controller and a feed-forward term was presented in [6]. The feed-forward term ensures fast response and the PI controller improves the static accuracy and the immunity to the disturbances. According to the authors, in order to retain the system stability, the influence of the feed-forward term was kept low and the overall system response was predominantly determined by the PI controller.

Large load current overshoots (around 50%) and long settling times were demonstrated in [7], where PI-controlled thyristor converter with was used in plasma torch applications.

An integrated commercial system for the electrode position and arc current control, ELREG, developed by ABB, was described in [8]. This system also uses classical PI controllers for both the electrode position control and the arc current control.

3. PROPOSED PREDICTIVE CONTROLLER OF DC ARC CURRENT

The fast predictive current controller for loads with slow-varying voltage (e.g., high-power battery banks, dc motors and electrowinning processes) was presented in [9]. Although an electric arc voltage can vary significantly and in a chaotic manner, it will be shown in this paper that the same predictive controller can be used to effectively control the current of the dc electric arc. The simplified block diagram of the proposed system was shown in Fig. 1.

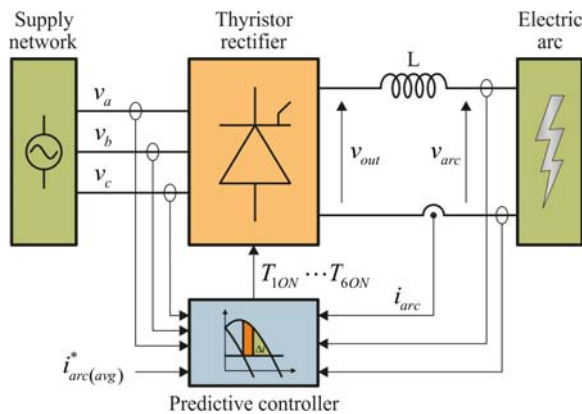


Fig. 1. Simplified block diagram of the proposed system.

Unlike the model-based predictive controllers, the proposed arc current controller does not rely on the dc arc model. That is a significant advantage of the proposed controller over model-based controllers, since a suitable dc arc model which is applicable in model-based predictive controllers has not yet been developed.

According to the principles described in [9], the electric arc current can be controlled by knowing the dc-side inductor voltage-time product, and the instantaneous arc current. Namely, the thyristors are fired (gating signals $T_{1ON} \dots T_{6ON}$ are generated) when the sum of the measured instantaneous arc current, i_{arc} , and the arc current rise, which is predicted from the remaining dc-side inductor voltage-time product, is equal to the arc current reference, i_{arc}^* . This way, an accurate current control is achieved just by knowing the dc-side inductor parameters and by measuring the line voltages, the instantaneous arc current, and the instantaneous arc voltage. Thus, in order to predict the arc current, the measurements of the network voltages, the dc arc voltage, and the instantaneous arc current need to be performed.

The proposed dc arc current controller is modeled in Simulink[®]. In the simulated system, the dc electric arc is represented by the simplified model, which is proposed in [10]. The obtained simulation results were experimentally verified on a laboratory prototype. The main part of the laboratory setup was shown in Fig. 2 (the power transformer and the PC were not shown in the figure).

4. SIMULATION AND EXPERIMENTAL RESULTS

The simulation results shown in Fig. 3 illustrate a response (to a reference change) of the system with the proposed predictive controller, compared to systems with classical PI controllers. The PI controllers' parameters were set for the fastest response to a reference change, with minimal overshoot. The second order Butterworth filter cut-off frequency was set to 1256 rad/s. The averaging window of the moving average filter was set to 1/300 s. The obtained simulation and experimental results of the proposed converter response to a reference step change from 3 A to 7 A were shown in Fig. 4 and Fig. 5, respectively. The experimental data were recorded as comma separated values, and then plotted by the MATLAB[®] *plot()* function. The obtained simulation and experimental results of the proposed converter response to a reference step change from 7 A to 4 A were shown in Fig. 6 and Fig. 7, respectively. Simulation results shown in Fig. 8 illustrate a superior performance of the proposed controller, in comparison with the PI controller with different feedback current signal filters, after a temporary electrode short circuit has occurred.

Simulation and experimental results of the proposed system response to electrode short circuit were shown in Fig. 9 and Fig. 10, respectively. Simulation and experimental results of the proposed system response after a short circuit is cleared were shown in Fig. 11 and Fig. 12, respectively. Figures 8–12 illustrate the ability of the proposed controller to effectively compensate for the electrode short circuits (as an extreme case of the arc voltage variations), and thereby to enable a reduction of unwanted variations of the reactive power at the point of the system connection, which are the main cause of the induced flicker phenomenon. Variations of the

"instantaneous" value of the active and the reactive power due to a short circuit, obtained by simulations and

corresponding to responses shown in Fig. 8, were shown in Fig. 13.

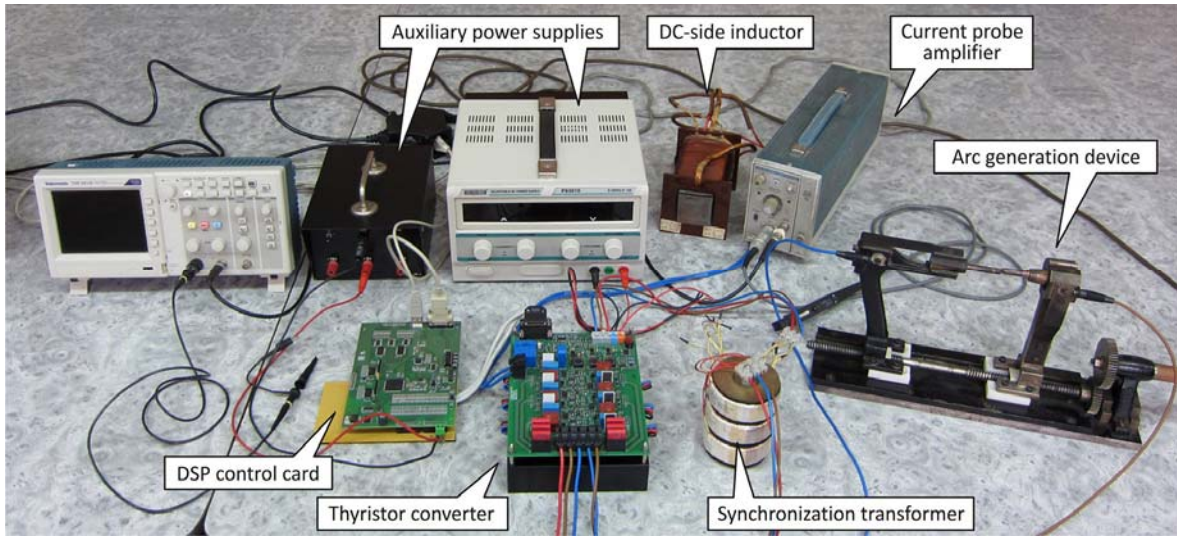


Fig. 2. The main part of the laboratory setup (the power transformer and the PC were not shown in the figure).

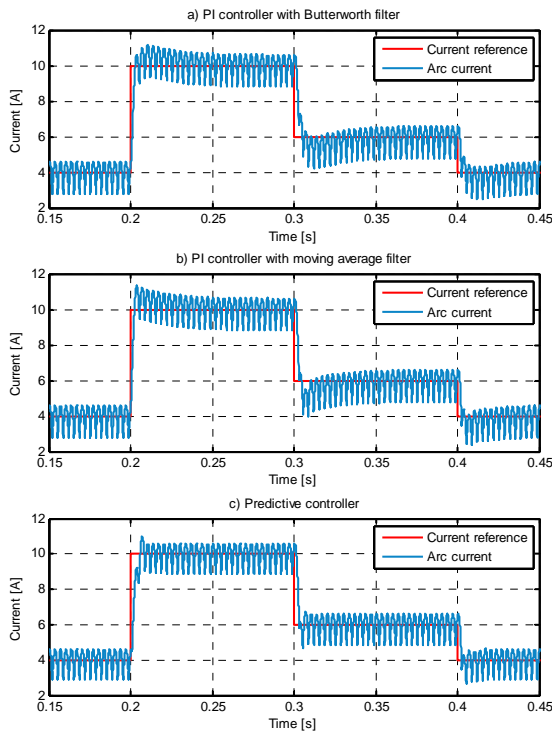


Fig. 3. Simulated response of the systems with PI controllers and the system with the proposed predictive controller, to a reference step change.

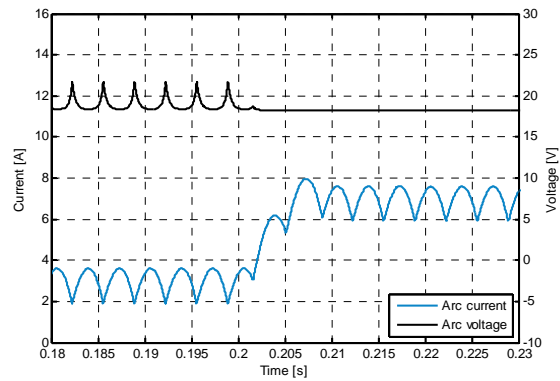


Fig. 4. Simulated system response to a reference step change from 3 A to 7 A.

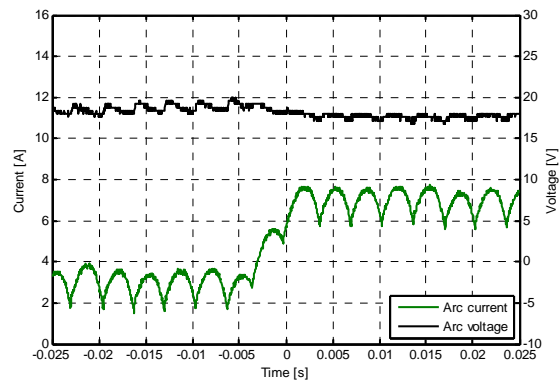


Fig. 5. Measured system response to a reference step change from 3 A to 7 A.

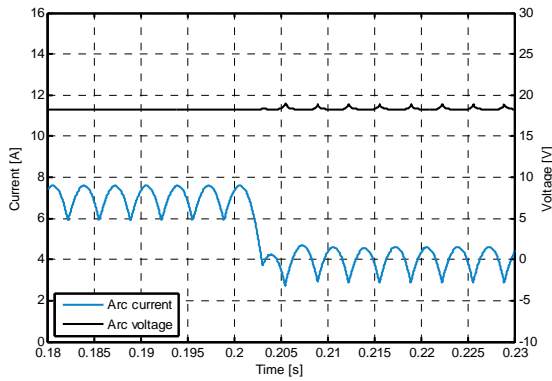


Fig. 6. Simulated system response to a reference step change from 7 A to 4 A.

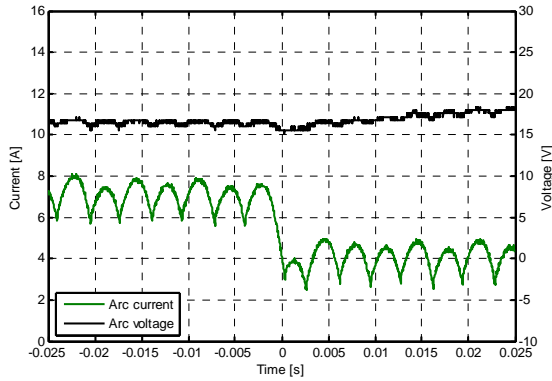


Fig. 7. Measured system response to a reference step change from 7 A to 4 A.

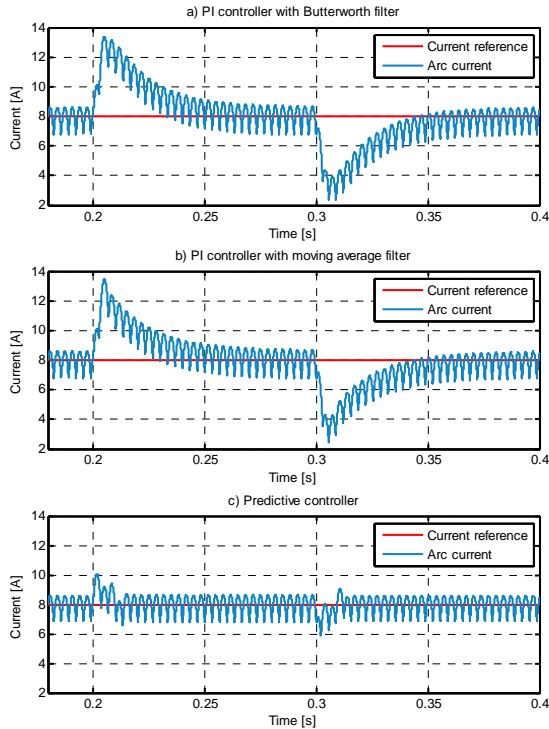


Fig. 8. Simulated response of the systems with PI controllers and the system with the proposed predictive controller, after a temporary electrode short circuit has occurred at $t = 0.2$ s and cleared at $t = 0.3$ s.

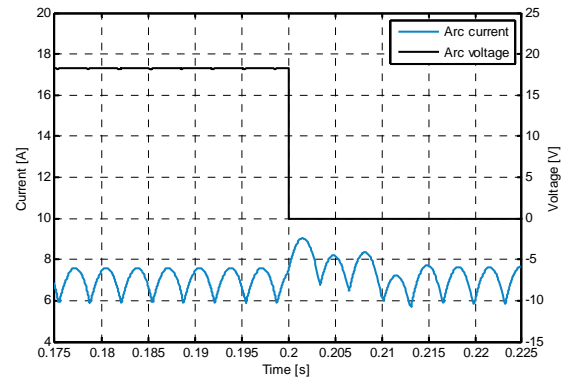


Fig. 9. Simulated system response to the electrode short circuit.

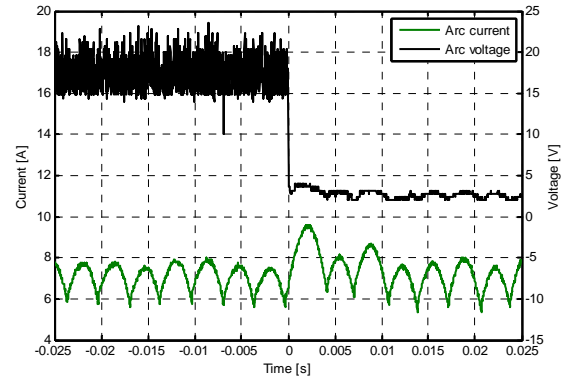


Fig. 10. Measured system response to the electrode short circuit.

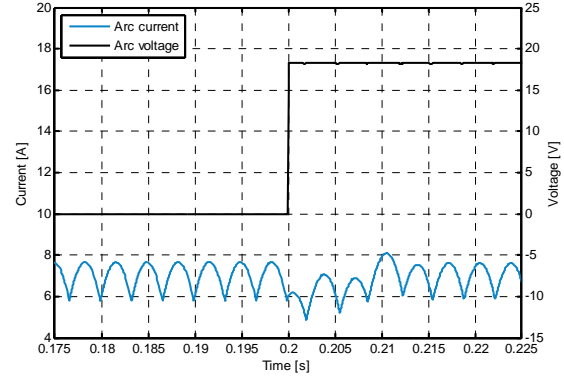


Fig. 11. Simulated system response after the electrode short circuit was cleared.

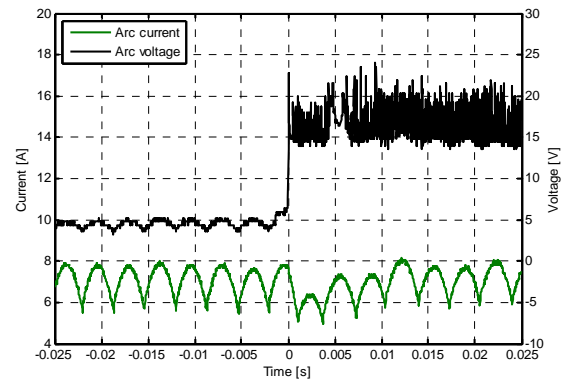


Fig. 12. Measured system response after the electrode short circuit was cleared.

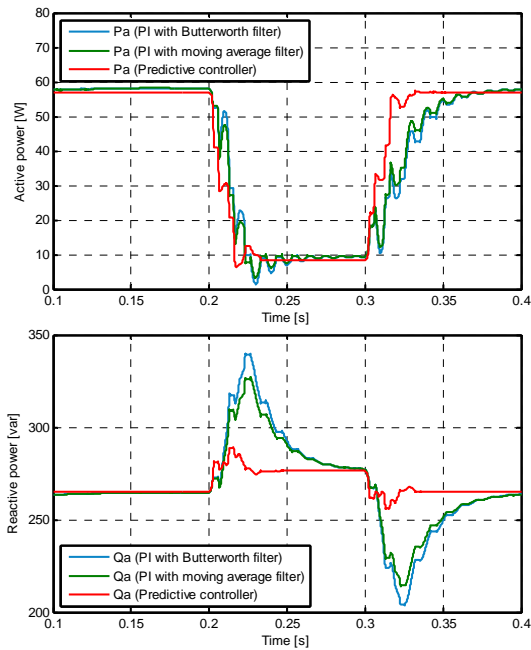


Fig. 13. Variations of the active and the reactive power due to the electrode short circuit.

As shown in Fig. 13, the reactive power variations due to the electrode short circuits are significantly smaller in the case of the proposed predictive controller, compared to the PI controller, while the active power variations are similar for all the simulated systems.

5. CONCLUSION

A fast predictive current controller for dc electric arc furnace/plasma heater systems is presented in this paper. Unlike a classically used PI current controller, the presented predictive controller does not require a filter for the current feedback signal, in order to obtain a dc component of the load current. Therefore, a significant time-lag of the feedback signal, which is induced by the filtering action, is avoided. As a consequence, the presented predictive controller is more robust to the arc voltage changes than the PI controller. Compared to the system with the PI controller, variations of the reactive power due to the electrode short circuits are significantly smaller in the case of a system with the proposed predictive controller. As a consequence of lower reactive power variations due to electrode short circuits in dc EAFs, less disturbance (in the form of flicker) to the power network can be expected in the case of a system with the proposed controller.

A very important advantage of the proposed controller, from a cost-effectiveness point of view, is less electrical stress on the thyristors and the fuses, due to the lower overcurrents after the electrode short circuits in electric arc furnaces, as shown in Fig. 8. Providing these lower overcurrents, a lower rate of thyristor failures, lower rate of unwanted fuse failures and therefore lower maintenance costs can be expected in a system with the proposed predictive controller. Also, the availability of the system is increased and, in the case of dc arc furnaces, the furnace productivity is increased as well.

6. REFERENCES

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