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DC ARC FURNACE MODELLING FOR POWER QUALITY ANALYSIS

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Cuptoarele cu arc electric alimentate la tensiune continuă reprezintă surse importante de perturbații pentru rețelele de transport şi distribuție. În lucrare este studiată modelarea cuptorului cu arc electric alimentat la tensiune continuă şi este analizat sistemul de control a convertorului curent alternativ – curent continuu, ilustrând avantajele obținute în ceea ce priveşte îmbunătățirea calității energiei electrice. În acest studiu sunt considerate modelele aleator şi deterministic ale arcului electric, precum şi diferete structuri ale convertorului curent alternativ – curent continuu.

The dc arc furnaces are highly disturbing loads for transmission and distribution networks. The present paper deals with the study of the dc arc furnace modeling and analysis of the controller structure for the ac-dc converter, highlighting the advantages obtained regarding power quality improvement. In this study both deterministic and random models of the electric arc are considered together with different structures of the ac-dc converter unit.

Keywords: voltage flicker, dc arc furnace, power quality

1. Introduction

The dc arc furnaces are supplied from the power system through various ac-dc conversion topologies. The main advantage of the dc arc furnaces with respect to the ac arc furnaces is the possibility to regulate the output voltage of the converter. In this way, the control of the current supplied to the installation is allowed and a reduction of the light flicker can be determined. In addition, a fast operation control on the dc arc furnace, obtained with electronic devices, permits the introduction of sophisticated and efficient control techniques [1].

The operation with non linear power electronic devices also causes harmonics. The identification of the harmonics presence in the voltage waveform is possible by observing the profile of the measured parameters during the operation process. The voltage flicker level, sensed by the human eye as variations of the light sources flux is determined using the flickermeter, which considers the irritability sensation of the human eye when a certain level of the supply voltage variation is exceeded. To quantify the amplitude of such

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disturbance, reference is made to the instantaneous flicker sensation S(t). The value of S(t) is measured by means of an instrument, the so-called flickermeter. The setting-up of the flickermeter model is done in Simulink, the simulation tool, in the MATLAB environment. The flickermeter model, presented in detail in [2, 3], is a conventional analog one, in agreement with the models proposed in current standards that of the necessity to comparative analyses between innovative equipment and conventional architectures, whose disturbances were measured using analog instruments.

The present paper deals with the study and analysis of the controller structure for the ac-dc converter, highlighting the advantages obtained regarding power quality improvement. Various strategy of controls for the ac-dc converters in dc furnace applications have been presented in the past [4]. The main power quality indices regarding harmonics and flicker levels are reported in the paper with reference to IEEE standards.

2. DC arc furnace model

The ac-dc static conversion system is realized with a full controlled Graetz bridge that supplies the operation power of the dc furnace and stabilizes the current in the arc furnace [5].

The ac-dc conversion and the control-regulation systems have to reach the following objectives:

- the correct operation of the arc furnace: maintaining scheduled profile of energy, possibility of regulation, high speed answer of the system to variations of the reference value;
- the energy saving in the arc furnace process;
- the proper ac-dc conversion of the voltage, with small dc voltage ripple;
- commutations with minimum perturbation injections in the power system (compatible with the used devices and the operation conditions of the arc furnace);
- the stabilization of the controlled quantity (guaranteeing the reduction of power quality perturbances, without the use of expensive filtering systems and reactive power compensation);
- the maximum constructive simplicity (reducing the construction investments of the arc furnace and, once realized, simplifying maintenance and increasing the reliability).

In the following sections the ac-dc conversion and the control systems are analyzed in detail.

3. AC/DC conversion system

The common used systems for dc arc furnaces applications [5] are:

- for 6 pulses ac-dc converter: two-star configuration with coupling inductor or three phase Graetz bridge;

- for 12 pulses ac-dc converter: two series connected three phase bridge or two parallel connected three phase bridge.

Based on the objectives of constructive simplicity, regulation possibility, reliability and maintenance facility, the Graetz bridge solution is preferred. This choice reduces the complexity of the converter, allows an optimal control and reduces the investment costs.

In the present work the 6-pulse ac-dc converter model with firing angle control, with and without freewheel diodes, is implemented and simulated.

Fig. 1 shows the converter model without freewheel diodes.

The outputs of the conversion system are:

- the positive and negative terminals on the dc side;
- the reference current signal;
- the instantaneous value of the dc current absorbed by the load.

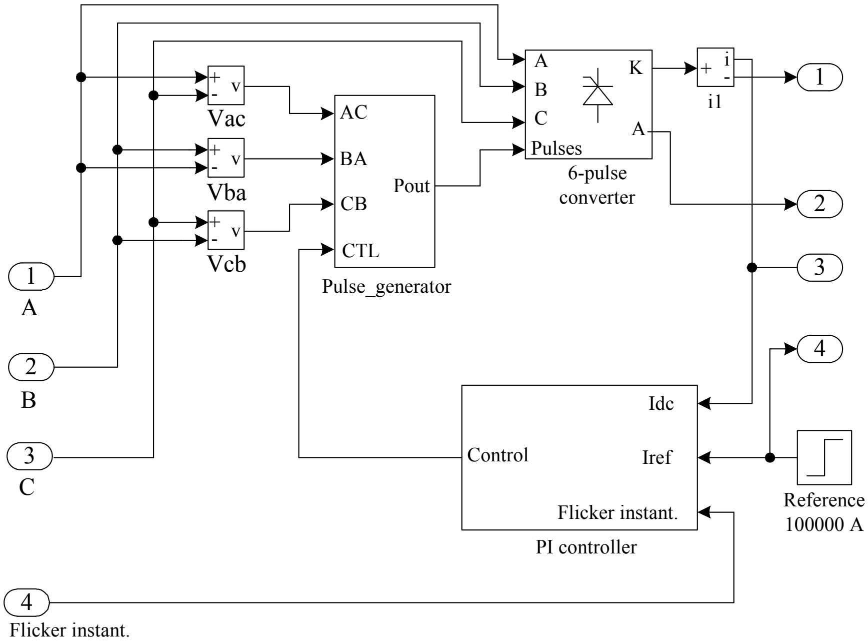

Fig. 1. Schematic diagram of the conversion system model without freewheel diodes implemented in Simulink

The model is composed by the following sub-blocks: “Pulse_generator”, “PI controller” and “6-pulse converter”.

The “Pulse_generator” sub-block automatically elaborates the firing pulses for each tyristor of the converter bridge, using the three phase line-to-line voltages and the signal from the “PI controller”.

The “PI controller” sub-block establishes the operation of the arc furnace. The control logic and the structure of this sub-block are explained in detail in the following section.

The “6-pulse converter” sub-block is the controlled 6-pulse Graetz bridge.

4. Control system

The control of the thyristor bridge firing angles is based on proportional integral (PI) regulation. For designing the control device it is necessary to know the transfer function of the load in the frequency domain. For this reason it is assumed that the electrical arc is modeled by an equivalent variable resistance.

Due to the time-varying nature of the load, in order to precisely size the PI controller a study of non linear systems, time-varying and periodic would be necessary. Such study introduces many difficulties, so it is preferred to realize an approximate sizing of the controller and to proceed, iteratively, to an experimental determination of its characterizing parameters. This can be done also providing to the feedback system a sufficiently large phase margin for giving the capability to absorb load fluctuations.

On the basis of the voltage and current measured on the arc furnace real case application during operation, the average value of the equivalent resistance for the electrical arc is deduced: R=0.004Ω. When the smoothing inductance, L=90 μH, is connected in series with the electrical arc, the ac-dc system “sees” globally a load, that in Laplace transformation, is characterized by the following impedance *Z*(*s*) and admittance *G*(*s*):

$$Z(s) = 0.004 + 9 \cdot 10^{-5} \cdot s \tag{1}$$

$$G(s) = \frac{1}{Z(s)} = \frac{1}{0.004 + 9 \cdot 10^{-5} \cdot s} \tag{2}$$

The parameters of the regulator are τ_{PI}=0.027, G_{PI}=0.021 and the transfer function of the PI controller is:

$$F_{PI}(s) = G_{PI} \cdot \frac{\tau_{PI} \cdot s + 1}{\tau_{PI} \cdot s} = 0.78 \cdot \frac{27 \cdot 10^{-3} s + 1}{s} \tag{3}$$

The above results have to be considered as an initial point for analyses more elaborated, in order to establish the parameters of the regulator that best guarantees the correct operation of the arc furnace. The used PI controller has three input parameters: the coefficient α for the proportional part, the coefficient β for the integral part and the coefficient γ that is a constant of the output signal translation. The values of these coefficients are set by an iterative simulation process on the dc arc furnace operation. The goal is to limit the power quality disturbances on the ac point of common coupling (PCC) and thus in the transmission and distribution networks. Both sets of parameters satisfy the operation requirements of the dc arc furnace: guarantee a good stabilization of the absorbed current, have a short time of response to the variations of the functioning parameters, and are stable to the variations of load and reference current.

The difference between the two sets of values consists in the different disturbances on the ac supply system. The first set reduces the power quality perturbation values in the ac network feeding the arc furnace. The second set of values considerably reduces the voltage flicker perturbation.

5. UIE Flickermeter

Since, from the point of view of analyzing the signal, the flicker is a low-frequency modulation of the network voltage at 50 Hz, the purpose of the flickermeter is to separate the carrier from the modulating wave, weight the effects of the latter based on human sensitivity to the disturbance, and return the instantaneous flicker sensation signal.

The structure of the flickermeter may be represented through the transfer functions contained in the block diagram in Fig. 2. This condenses all the signal manipulations required for obtaining in exit the trend of the instantaneous flicker disturbance in accordance with the information supplied by the current standard [3]. In addition, this diagram considers the steps necessary for setting up efficient electronic implementation.

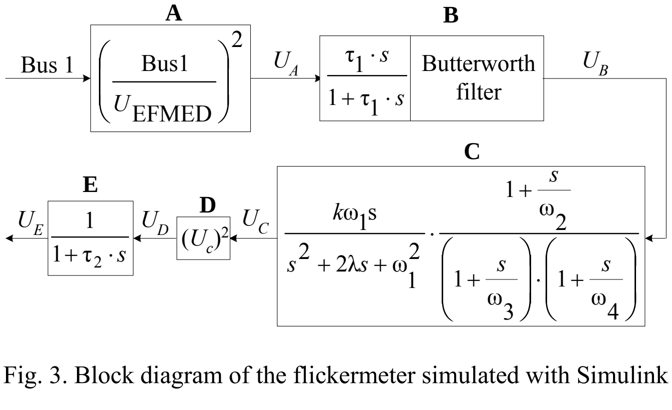

Fig. 3. Block diagram of the flickermeter simulated with Simulink

Block A has the dual function of expressing the instant input voltage as a p.u. value and that of simulating the behavior of the quadratic demodulator.

Block B has the job of cutting off the dc voltage component, eliminating the signal of the carrier wave and the high-frequency fluctuations found at the exit of the quadratic demodulator.

Block C simulates the response in the frequency of the human eye to the voltage fluctuations of an incandescent lamp supplied by a variable sinusoidal voltage.

Block D squares the signal exiting from Block C by simulating the non-linear perception of the flicker in the eye-brain chain.

Block E is a low-pass filter that performs the smoothing action.

Once we have obtained the trend in respect of the instantaneous flicker sensation, we have, from the latter, to calculate the indices that make it possible to evaluate the severity of the disturbance injected into the network [3].

6. Case studies

The goal of the case studied is mainly devoted to analyze the system control of the above described dc arc furnace system. Two different models of dc electric arc are considered: the deterministic model with a sinusoidal time varying disturbance at 10 Hz, and the random model with a white noise behavior of the disturbance representation. The operation of each control architecture is evaluated and tested. The system response at current reference value variation during arc furnace functioning is considered in order to evaluate the stability of the dc arc furnace at the furnace operation power variations. In this way the dynamic of the system is highlighted and the answer to usual operations conducted by an operator during real functioning is tested.

The case studied is referred to a real plant sited close to Bucharest, in Romania. The measurements were done using the device ION 7600 at the 110kV voltage level. At PCC the line-to-line voltage is 110 kV, the ac arc furnace has 60MVA (see Fig. 3). The ac power supply system (the ideal voltage source, the transmission line and the HV/MV and MV/LV transformers), the rectifying circuit, constituted by a three phase current controlled converter, and the dc arc furnace, behind a smoothing reactance, are illustrated in Fig. 3.

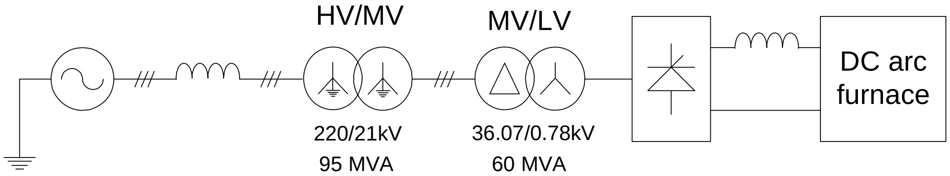

Fig. 3. Simplified diagram of the dc arc furnace power supply

For a dc electric arc with sinusoidal disturbance at 10 Hz, with voltage variation between 225 V and 600 V, the waveform of the dc current is shown in Fig. 4, where a variation on the reference current (I_{ref}) gives rise to a variation on the dc furnace current (I_{dc}) following the control dynamics. After the firing transient, the dc current varies between 95 and 105 kA, with an average value of 100 kA. The ac-dc conversion and the control systems contain current fluctuations in the range of ±5 % of the imposed value, while the error between the average value of dc current and the reference value is 0.68 %.

Simulation studies are performed on the above described system where every combination of the following factors is taken into account:

- arc model: deterministic or random one as reported in the technical literature ([6, 7]);

- control parameters: proposed values optimized for a reduction of the power quality perturbation values in the ac network and proposed values optimized for voltage flicker reduction on ac network.

Results are summarized in Table 1, where the main power quality indices are evaluated in each case on the basis of recommendation reported in [8, 9]. The short term flicker severity value at PCC is reported in Table 1. The values of the indices THD, TIHD (Total Interharmonic Distortion), TD (Total Distortion) (for voltage and current) measured at all voltage levels are reported in Table 2.

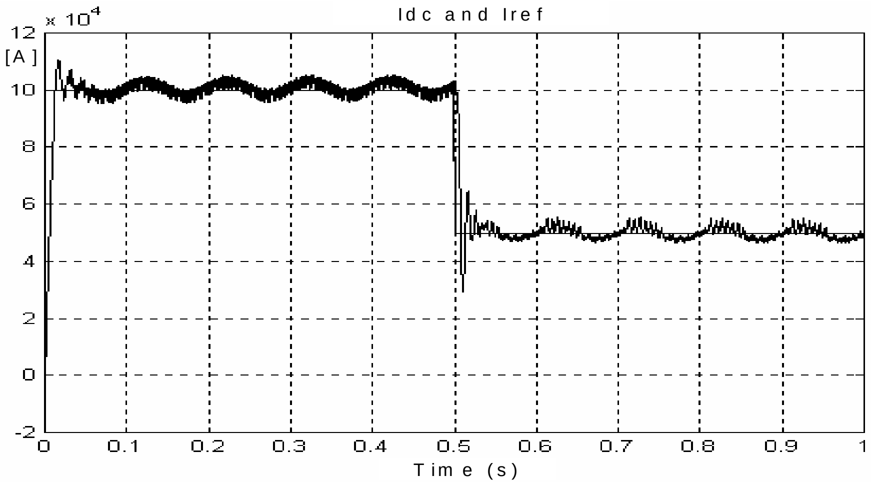

Fig. 4. Waveforms of the dc current and of the reference current during the power furnace regulation

Table 2

Power Quality Indices

CONTROL PARAMETERS	ARC MODEL		THD_V	TIHD_V	TD_V	THD_I	TIHD_I	TD_I
Optimized control for a good compromise between flicker and harmonics injected on ac network	Deterministic arc model	LV	7.28	7.77	10.65	9.55	1.94	9.75
		MV	3.72	3.99	5.46	9.57	2	9.78
		HV	1.36	1.47	2	9.57	2	9.78
	Random arc model	LV	7.11	7.81	10.56	5.55	3.03	6.33
		MV	3.65	4.01	5.42	5.64	3.05	6.41
		HV	1.34	1.47	1.99	5.63	3.05	6.4
Optimized control for an important reduction of the flicker on ac network, to the detriment of harmonic perturbations	Deterministic arc model	LV	9.39	5.11	10.69	9.54	1.94	9.73
		MV	4.83	2.55	5.46	9.48	1.98	9.68
		HV	1.76	0.93	1.99	9.54	1.94	9.73
	Random arc model	LV	8.76	6.09	10.67	5.57	3.02	6.33
		MV	4.5	3.05	5.44	5.62	3.02	6.38
		HV	1.64	1.11	1.98	5.61	3.02	6.37

The values of the P_{st} are within the maximum value limit for a single customer. This allows the connection of the plant without the necessity to introduce dynamic compensating systems for the reactive power control. Moreover, the distance between the P_{st} obtained values and the imposed limit allows to the proposed control system to operate with the parameter values devoted to a reduction of the power quality disturbances on ac networks. In this way, the harmonic distortion indices of the voltage at PCC are minimized.

7. Conclusions

The high capacity ac arc furnaces connected to the HV level can determine power quality perturbations in the transmission networks.

The present paper proposes and implements a control system, which is based on the flicker level on the ac network and chooses in real time the most convenient set of parameters for the PI controller.

This active control system is tested on the existing dc arc furnace facility considering two types of arc modeling (deterministic and random one) and two ac-dc converter with freewheel diodes. For all the cases investigated, the main power quality indices are computed and reported in the paper with reference to the current standards.

Table 1

Short term flicker severity Pst

CONTROL PARAMETERS	ARC MODEL		P_{ST}
Optimized control for a good compromise between flicker and harmonics injected on ac network	Deterministic arc model	LV	0.64
		MV	
		HV	
	Random arc model	LV	0.55
		MV	
		HV	
Optimized control for an important reduction of the flicker on ac network, to the detriment of harmonic perturbations	Deterministic arc model	LV	0.62
		MV	
		HV	
	Random arc model	LV	0.54
		MV	
		HV	

R E F E R E N C E S

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