AC arc electrical load model for new power supply analysis

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***Abstract* — This paper describes a model of an AC arc electrical load for analysis of furnace operating in conjunction with high-speed semiconductor converter. The semiconductor converter is part of electric furnace circuit and generates the current that compensates for the inactive power components caused by electric arc load. A dynamic model of the electric arc is developed taking into account random factors. This is necessary to ensure that the converter control system is adjusted to the rapidly changing electrical parameters. This solution allows to reduce the negative load impact on the supply network, as well as increase the useful power and the furnace productivity.**

Keywords — nonlinear electrical load, nonparametric current source, power quality

I. Introduction. A review

The AC arc steelmaking furnace (electric arc furnace, EAF) is one of the most unfavorable receivers of electrical energy. We are talking about the electromagnetic compatibility problem of the supply network and the consumer [1]. On the other hand, it is necessary to ensure high performance for the process plant in order to be economically and environmentally efficient. Optimization of the electric mode control system of the arc steelmaking furnace solves the problem only partially, since all components of the total power are not compensated.

Currently, solutions to these problems are known. For example, in industry, controlled static converters are used in the low-voltage circuit of a furnace transformer [2]. However, such solutions have limitations due to its high cost, since the power supply is performed at full capacity of the furnace.

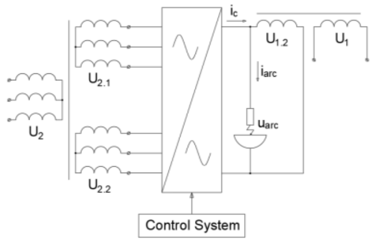

Fig. 1. Equivalent circuit of a power supply with static converter

To improve electromagnetic compatibility and ensure high energy performance of an AC arc furnace, it is proposed to consider the concept of a new power source with a static semiconductor converter operating as a nonparametric current source. To analyze the operation of such device, a corresponding model of an arc model has been developed.

II. Installation power optimization method

The single–phase power supply circuit is shown in Fig. 1, where U_2 is the primary voltage of the additional transformer winding, V; $U_{2.1\text{-}2.2}$ is the secondary voltages of the additional transformer windings, V; U_1 is the primary voltage of the furnace transformer winding, V; $U_{1.2}$ is the secondary voltage of the furnace transformer winding, V; U_{arc} is the arc voltage, V; i_{arc} is the arc current, A; i_c is the current of the semiconductor converter, A. As can be seen, compensation of inactive components of full power is carried out at low voltage. This solution allows to unload the furnace transformer from inactive power components.

The static converter can consist of three links: three-phase bridge rectifier, DC link, and three-phase chopper. Such solution is possible due to the appearance of particularly powerful semiconductor switches. The converter as a current source allows to compensate arc current harmonics. The reactive power component and the power component from current and voltage asymmetry can be reduced by adjusting the static converter control system.

III. Load model and results

To analyze the converter operation and configure its control system, a nonlinear arc load model is required. The most significant problem of modeling an AC electric arc is the random nature of arc burning.

The arc model is based on the solution of the nonlinear Cassie differential equation (1) obtained from energy balance equation and has the form

$$\theta_{arc} \frac{dg_{arc}(t)}{dt} = \left(\frac{u_{arc}^2(t)}{E_{arc}^2} - 1 \right) \cdot g_{arc}(t)\,, \tag{1}$$

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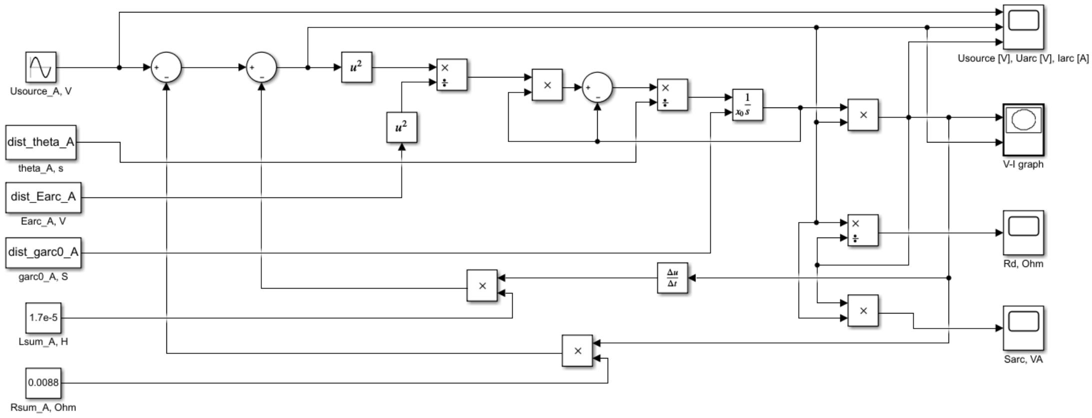

Fig. 2. Simulink scheme for solving the Cassie equation with random signal sources

where Θ_{arc} is the time constant, ms; g_{arc} is the arc conductivity, S; u_{arc} is the arc voltage, V; E_{arc} – counteracting arc EMF, V.

Firstly, this model takes into account the nonlinear V-I characteristic of the electric arc due to the introduction of the coefficient Θ_{arc}. Secondly, the described model simulates random nature of the electric arc burning. To simulate random distortions of the arc time constant, counteracting arc EMF, initial conductivity of the arc column g_0, sources of random step signals with a normal distribution law of values are used. The calculation scheme for solving the Cassie equation is shown in Fig. 2.

Table I shows the main parameters of the random signals used in phase A. Fig. 3 shows the dynamic V-I characteristic of the electric arc of phase A for the initial melting phase. This is the most unfavorable period of metal melting which corresponds to Θ_{arc} = 0.1-0.5 ms.

TABLE I. PARAMETERS OF THE RANDOM SIGNALS USED

Signal	Expected value, E [X]	Variance, Var [X]
$\Theta arc(t)$, s	$0{,}5\cdot10^{-3}$ s	$2{,}5\cdot10^{-8}$ s^2
Earc(t), V	526,6 V	$3\cdot10^2$ V^2
$g_0(t)$, S	86,2 S	$5\cdot10^2$ S^2

As can be seen from Table I, the electric mode corresponding to the beginning of melting is considered. The three-phase load is modeled by three independently burning arcs in phases A, B, and C. The arc steelmaking furnace receives power via a 150 200 kVA furnace transformer from a 35 kV network with an industrial frequency of 50 Hz [3].

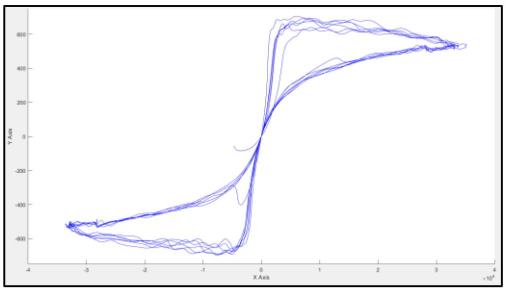

Fig. 3. V-I characteristic of the arc. X axis – I_{arc}, A; Y axis – U_{arc}, V

Expression for arc current

$$i_{arc}(t) = \sum_{k=1}^{\infty} I_{km} \cdot sin(kwt + \psi_k) + X_{i_{arc}}(t)\,, \qquad (2)$$

where k is the current harmonic ordinal number; I_{km} is the k-th current harmonic amplitude, A; ω is the angular frequency, rad/s; ψ_k is the initial phase of the k-th current harmonic, rad; $X_{iarc}(t)$ is the random component of current signal, A.

The results of frequency analysis of phase current signals are presented in Table II.

TABLE II. FREQUENCY ANALYSIS RESULTS

	Phase A	Phase B	Phase C
$I_{(5)}$, %	9,4	7,9	10,1
$I_{(7)}$, %	3,8	3,7	3,2
THD_I, %	10,7	9,1	10,8

IV. CONCLUSIONS

The described model of the AC arc simulates the arc current and voltage curves, as well as the dynamic V-I characteristics of the industrial EAF-180 with randomly changing parameters. This dynamic model can be used to synthesize and configure the control system of a high-speed semiconductor nonparametric current source that provides compensation for full power inactive components of the electric arc furnace. The purpose of this solution is to increase the useful power and EAF productivity, as well as their electromagnetic compatibility with the supply network.

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