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Modelling of three-phase electric arc furnace for estimation of voltage flicker in power transmission network

Ana Tomasović Teklić[a], Božidar Filipović-Grčić[b,*], Ivica Pavić[b]

[a] Končar Electrical Engineering Institute, 10000 Zagreb, Croatia
[b] Faculty of Electrical Engineering and Computing, University of Zagreb, 10000 Zagreb, Croatia

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ABSTRACT

This paper presents a dynamic model of an electric arc furnace (EAF) developed in Matlab/Simulink environment. Model is based on simulating varying resistance of the electric arc in time-domain while taking into account its stochastic behaviour. The model was applied for estimation of voltage flicker in power transmission network at the point of common coupling caused by operation of EAF. Modelling and simulation of an International Eletrotechnical Commission (IEC) flickermeter were also performed in order to calculate voltage flicker from the simulated EAF voltage. In order to verify the developed EAF model, calculations of voltage flicker were compared to measurements obtained from various operating conditions of the EAF such as boring, melting and refining. Influence of short circuit power and switching operating condition of the transmission network on flicker levels at point of common coupling was investigated.

1. Introduction

Highly nonlinear time-varying loads, such as electric arc furnaces (EAFs), are widely used in the steel-making industry. Due to the process of melting and refining metals, mainly iron in the steel production, the EAF consumes large power which causes significant power quality (PQ) disturbances, such as harmonics and voltage fluctuations on the connected power network [1]. Disturbances produced by EAFs in electrical networks can significantly affect the voltage quality supplied by electrical power companies [2]. An EAF is a non-linear and time-varying load, which gives rise to harmonics, interharmonics and voltage fluctuations (flicker). The cause of harmonics is mainly related to the non-linear *U*–*I* characteristic of the electric arc, while the voltage fluctuations are due to the arc length changes that occur during the melting of the scrap. The current and voltage harmonic distortion may cause several problems in electric power systems such as premature ageing of equipment, incorrect operation of devices and additional losses in both transmission and distribution networks. The flicker phenomenon causes a physiological uneasiness in vision due to electric lightning flux fluctuations, which are particularly important with incandescent lamps. Therefore, it is of crucial importance to predict the flicker levels when an EAF is connected to a network or when an existing EAF is upgraded. In cases when flicker emission limits are exceeded, mitigation techniques should be considered in order to correct such disturbances. An extensive research which enables practical application of static synchronous compensators for improving PQ in EAF and flicker compensation applications was published in Ref. [3]. Obtaining an accurate model of EAF in time domain is thus important to study the impact of such load on the connected power system. For instance, the flicker assessment of EAF loads has to be calculated to check the compliance with the regulated standards [4,5]. Therefore, it is crucial to model these nonlinear loads for the PQ studies and mitigation designs.

Many models of the *U*–*I* characteristics have been proposed in the literature for both steady-state or dynamic operation of EAF. In Ref. [6] a controlled voltage source model for the EAF was proposed based on the piecewise linear approximation of the *U*–*I* characteristic. In Refs. [7,8] nonlinear time-varying resistance models for the EAF were proposed, where the arc length is dominated by periodic sinusoidal and band-limited white noise laws for flicker compensation purpose. In Ref. [9] the conductance model of the EAF for harmonic studies was proposed based on Cassie equation representing the single-phase *U*–*I* characteristic during refining stage. A time-varying resistance model was proposed in Ref. [10] for studying the early stage of melting cycle where the arc voltage is described by a linear function of arc length in random

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* Corresponding author. Fax: +385 16129890.
E-mail addresses: at.teklic@koncar-institut.hr (A.T. Teklić), bozidar.filipovic-grcic@fer.hr, bozofilipovic@gmail.com (B. Filipović-Grčić), ivica.pavic@fer.hr (I. Pavić).

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variation. Several chaotic systems were shown in Refs. [11,12] in order to describe the EAF operating behaviour and dynamics. Stochastic approaches were proposed in Refs [13–17], either with or without modelling the linear approximation of the *U–I* characteristic, in order to predict EAF voltage and current relationship in next few cycles or reactive power consumptions for compensation improvement. One of the greatest difficulties of stochastic approaches is prediction and modelling of the EAF stochastic nature, particularly in the initial boring stage of operation. The problem is how to take into account both non-linear and stochastic behaviour of the electric arc for different operation modes of EAF, which is especially important for estimation of voltage flicker levels. Despite the importance of stochastic representation of EAF to achieve real and accurate model in PQ studies, less attention has been paid to it in the literature. Because the arc melting process is a highly non-stationary stochastic phenomenon a deterministic or stochastic model for fully describing the EAF in different operating stages is usually very difficult to obtain.

Many new EAF models such as neural network-based types have been proposed recently. In Ref. [18] an accurate neural-network-based method was proposed for modeling the highly nonlinear *U–I* characteristic of an EAF. The neural-network-based model can be effectively used to assess waveform distortions, voltage fluctuations and performances of reactive power compensation devices associated with the EAF in a power system. Simulation results obtained by using the proposed model were compared with the actual measured data and two other traditional neural network models. It was shown that the proposed method yields favourable performance and can be applied for modelling similar types of non-linear loads for power engineering studies. In Ref. [19] the authors proposed a grey predictor model for the forecast of flicker levels produced by an EAF load. Actual measured data were adopted to implement the predictor model. Test results based on the proposed model were compared with two other neural network methods. It was shown that more accurate forecast is achieved for the flicker prediction based on the proposed method. In Ref. [20] a discrete wavelet transform (DWT) and radial basis function neural network (RBFNN)-based method was proposed for modelling the dynamic *U–I* characteristics of the EAF. The proposed method can also be applied to model other highly nonlinear loads to assess the effectiveness of compensation devices or to perform relative penetration studies. To model the multiple EAF operation stages more precisely, the authors extended the previous research of Ref. [20] by enhancing the model with including convergence check in the RBFNN training phase, an extended look-up table (ELUT) to save the RBFNN parameters (i.e. weights, centers, standard deviations, RMS value of input current data segment), and the criteria for identifying the four EAF operation stages obtained by DWT [21]. However, neural network approach requires significant training so issues such as learning speed, stability, and weight convergence remain as areas of research and comparison of many training algorithms.

Although many research papers described above have been published regarding modelling the EAF this problem still represents a challenging task, especially for PQ studies where accuracy of the model is of crucial importance. Therefore, in this paper a dynamic model of an EAF is proposed taking into account the stochastic behaviour of an electric arc. Model is developed for estimation of voltage flicker levels caused by EAF operation. Parameters describing stochastic behaviour of the electric arc for different operating modes of EAF are determined by matching the simulated short term flicker severity levels with the measured ones. The developed model is applied for estimation of flicker levels in the transmission network in case of different short circuit powers and switching operating conditions. The comparison between measured and calculated flicker values showed good agreement for various EAF operating modes. The aim of proposed approach is to introduce an accurate model of EAF which can be easily derived from field measurements of a particular EAF and applied in case of the flicker levels estimation at the point of common coupling.

This paper is organized as follows. In Section 2, the model of International Eletrotechnical Commission (IEC) flickermeter for estimation of voltage flicker from simulated voltage waveforms is described. The proposed dynamic model of an EAF based on simulating varying resistance of the electric arc in time-domain is elaborated in Section 3 while taking into account its stochastic behaviour. Model is applied for estimation of voltage flicker in the power transmission network. The verification of the developed EAF model is presented in Section 4 by comparing calculation results with measurements of voltage flicker obtained from various EAF operating conditions. In Section 5, proposed EAF model is used for estimation of voltage flicker at point of common coupling for two different switching operation conditions of the transmission network. The conclusions are given in Section 6.

2. Model of IEC flickermeter

In order to determine voltage flicker from simulated voltage waveforms an IEC flickermeter presented in Ref. [22] is modelled in Matlab/M-file. Functional diagram of IEC flickermeter shown in Fig. 1 consists of five blocks: 1 – voltage-adapting circuit scales the mean root-mean square (RMS) value of the input voltage to an internal reference level; 2 – squaring demodulator extracts the voltage fluctuation; 3 – two filters: the first one filters out the DC and residual ripple components of the demodulator output, while the second filter simulates the frequency response to a sinusoidal voltage fluctuation of a lamp and of the human eye; 4 – squaring multiplier to represent the nonlinear visual perception and a first-order low-pass filter with a time constant of 300 ms to represent the built up effect in the brain (the output of this block represents the immediate flicker sensation); 5 – online statistical analysis of the instantaneous flicker level. Flicker severity level indices are calculated both in short term and long term in this block, and the results are displayed. The output of block 5 is divided into suitable subclasses (at least 64 classes) according to the instantaneous flicker level. At first the probability distribution function (PDF) is formed by accumulating the number of elements at each level of the flicker. Afterwards, the cumulative probability function (CPF) is formed by integrating flicker distribution over the flicker range.

Finally, short term flicker severity P_{st} is calculated by using the following expression:

$$P_{st} = \sqrt{\sum_{i=1}^{n} k_i P_i}, \tag{1}$$

where k_i represents the weighting coefficient and P_i represents flicker level exceeded during a particular percent of the observation time. These P_i values were taken from the cumulative distribution curve:

$$P_i = CPF\left(\eta_i\right), \tag{2}$$

where η_i is a particular percent of the observation period. At least five points of the CPF should be used while evaluating the short-term flicker severity. All of the weighting coefficients and the corresponding time percentages can be found in Refs. [22,23]. In summary, the flickermeter model has two main parts: 1 – simulation of the response of the lamp-eye-brain chain; 2 – online statistical analysis of the flicker signal and displaying the results. The first task is accomplished by blocks 2–4, while the second task is performed in block 5. More detailed information about the IEC flickermeter can be found in Ref. [22–24].