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Analyzing power quality issues in electric arc furnace by modeling

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ABSTRACT

Rapid growth of non-linear loads in distribution network has attracted power system engineers' attention from power quality point of view. Electric arc furnace (EAF) is one of the typical industrial non-linear loads responsible for deteriorating the power quality in the distribution network by introducing harmonics, propagating voltage flicker and causing unbalance in voltages and currents. Therefore, the EAF model is required to be studied and the power quality required to be analyzed in the distribution network. This paper presents a novel time domain EAF model to study power quality problems. The proposed model is a combination of two previous EAF models called-exponential and hyperbolic model-using transition functions. The functioning of the proposed model has been validated by comparing its various performance characteristics with the existing Cassie-Mayr's EAF model and with real measured data available. Current harmonics, voltage harmonics along with voltage flickers are considered as power quality problems for study and analysis. Simulation is carried out in SIMULINK/MATLAB environment.

1. Introduction

An EAF load is inherently non-linear, time-variant in nature which results into power quality problems such as-current harmonic, voltage harmonics and voltage flickers. The EAF operation generates odd and even current harmonics. These current harmonics, when circulated in the electric network, interact with the system impedance and generate voltage harmonics. These current and voltage harmonics together can affect other consumers connected in the distribution network. The EAF is also an inherent large source of voltage flicker. The voltage flicker is defined as the sensation that is experienced by a human eye when subjected to changes in the illumination intensity in the frequency range of 5–15 Hz [1,2]. The voltage flicker can causes large voltage fluctuation in the connected distribution network which in turn affects operation of other connected loads in the distribution network. The institute of Electrical and Electronics Engineers (IEEE) has set limits to the permitted voltage distortion and current distortion at the point of common coupling (PCC) of the utility-plant interface in IEEE 519-2014 [24]. Therefore an EAF is required to be studied and to be analyzed from power quality point of view w. r. t. IEEE 519 regulations. Hence, EAF modeling has attracted power system engineers to solve these power quality issues.

Simulation of an electric arc is an important issue in EAF modeling. Several methods describing the electric arc are available in the literature [1–7]. On the basis of actual measured samples of an electric arc in several functioning cycles of EAF, different operating points are generated in the quantitative form of statistical probability, corresponding to hidden Markov theory in Ref. [3]. This requires actual measurement of an electric arc. The time domain model utilizing differential equations are presented in Ref. [4]. Variation of power transmitted to the load by the arc furnace during the cycle of operation is considered in Ref. [5]. Balanced steady state equations are used in Ref. [6]. Comparisons of the time domain and frequency domain EAF models emphasize use of time domain models [1,7]. Frequency response and voltage current characteristics (VIC) are taken into account to analyze the EAF behavior in Ref. [7]. These methods impose limitations such as prior knowledge of initial conditions in case of the differential equations, consideration of balanced three phase currents, use of complicated mathematics and actual arc measurement for the EAF modeling. This paper presents a novel time domain approach in EAF modeling validated by simulation and by comparing its various performance characteristics with that of existing Cassie-Mayr's EAF model in MATLAB environment and that of available real measured data. The main features of the proposed EAF model are good mathematical approximation, no need of initial conditions, and no need of measurements of arc voltage, arc current, etc. in actual arc and

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consideration of unbalanced three phase currents. The proposed model can be used to describe various operating cycles of electric arc furnace and its impact on the connected electric network from power quality point of view. Finally, the proposed method presents a suitable model with a very good approximation for the VIC. In order to increase the accuracy of the load model, a random noise is employed to establish a new model of the furnace load.

2. Modeling of EAF as non-linear load

Typical VIC of an EAF is found to be exponential and hyperbolic in nature [3]. Complete VIC can be obtained by combining the hyperbolic and the exponential nature of the characteristics. Efforts have been made to combine these characteristics in Refs. [2,6]. These characteristics can also be combined using transition function suggested in Refs. [4,8]. In this paper the same transition function is used for combining the exponential and hyperbolic model characteristics and thus to propose a novel EAF model. A brief detail of exponential and hyperbolic model along with the detailed proposed model is as follows:

2.1. Model 1: hyperbolic model

VIC of hyperbolic EAF model is described as [2,6]:

$$v_{hyp}(i) = V_{at} + \left(\frac{C}{D+i}\right) \tag{1}$$

In equation (1) variable v_{hyp} is arc voltage given by hyperbolic EAF model and variable i is arc current per phase. Variable C is arc power and variable D is arc current. These constants can take different values which depend on the sign of the derivative of the arc current and can be obtained in steady state. It can be easily understood that arc voltage v_{hyp} increases as arc current i decreases. V_{at} is the voltage threshold magnitude to which the arc voltage v_{hyp} approaches as EAF current increases. This voltage is dependent on the arc length. In equation (1) Table 1 shows typical values of various parameters of EAF models. The values of arc power (C) and maximum arc current (I_o) are obtained from M/S Maithan Alloys Limited, Byrnihat, Meghalaya, INDIA by M/S Ohm Encon (P) Limited, whereas V_{at} and D can be decided arbitrarily.

Table 1
EAF model 1 and 2 parameters.

V_{at}(V)	C(kW)	D(kA)	I_o(kA)
200	23	5	10

Table 2
Sinusoidal and Random variations Parameters.

V_{at0}(V)	m	ω_f (Hz)	$N(t)$ (Hz)
200	0.8	4	4–14

2.2. Model 2: exponential model

VIC of exponential EAF model is described as [2,6]:

$$v_{exp}(i) = V_{at}\left(1 - e^{\left(i/I_o\right)}\right) \tag{2}$$

In equation (2) I_o is a current constant employed to model the steepness of positive and negative phases of arc currents. A typical value of I_o is tabulated in Table 1.

2.3. Model 3: proposed model

Exponential and hyperbolic models can be combined into single model by defining a transition function$O(i)$, which is a function of arc current and is given by:

$$v_{com}(i) = \underbrace{[1 - O(i)]}_{Higher\ \ Current} \cdot v_{exp} + \underbrace{O(i)}_{Lower\ \ Current} \cdot v_{hyp} \tag{3}$$

In equation (3), v_{hyp} and v_{exp} are the arc voltages given by equations (1) and (2) respectively. A satisfactory form of $O(i)$ used in this combination is given in Refs. [4,5]:

$$O(i) = e^{\left(-\frac{i^2}{I_t^2}\right)} \tag{4}$$

In equation (4) I_t is the transition current.

Substituting equations (1), (2) and (4) in equation (3), one can get:

$$\begin{aligned}
v_{com}(i) &= \left[1 - e^{\left(-\frac{i^2}{I_t^2}\right)}\right] \cdot V_{at}\left(1 - e^{\left(i/I_o\right)}\right) + e^{\left(-\frac{i^2}{I_t^2}\right)} \cdot \left[V_{at} + \left(\frac{C}{D+i}\right)\right] \\
&= \left(V_{at} - V_{at} \cdot e^{\left(i/I_o\right)}\right) \cdot \left[1 - e^{\left(-\frac{i^2}{I_t^2}\right)}\right] + e^{\left(-\frac{i^2}{I_t^2}\right)} \cdot V_{at} + e^{\left(-\frac{i^2}{I_t^2}\right)} \cdot \left(\frac{C}{D+i}\right) \\
&= V_{at} - V_{at} \cdot e^{\left(i/I_o\right)} - \underline{\underline{V_{at} \cdot e^{\left(-\frac{i^2}{I_t^2}\right)}}} + V_{at} \cdot e^{\left(i/I_o\right)} \cdot e^{\left(-\frac{i^2}{I_t^2}\right)} + \underline{\underline{V_{at} \cdot e^{\left(-\frac{i^2}{I_t^2}\right)}}} + e^{\left(-\frac{i^2}{I_t^2}\right)} \cdot \left(\frac{C}{D+i}\right) \\
&= V_{at} - V_{at} \cdot e^{\left(i/I_o\right)} + V_{at} \cdot e^{\left(i/I_o\right)} \cdot e^{\left(-\frac{i^2}{I_t^2}\right)} + e^{\left(-\frac{i^2}{I_t^2}\right)} \cdot \left(\frac{C}{D+i}\right)
\end{aligned} \tag{5}$$