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New Time Domain Electric Arc Furnace Model for Power Quality Study

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***Abstract*— Power quality is becoming a more concern of today's power system engineer due to rapid growth of non-linear loads in distribution network. 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. Hence electric arc furnace model is needed to study and to analyze the power quality in the distribution network. This paper presents a new time domain model of electric arc furnace 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 performance characteristics with the existing Cassie-Mayr EAF model. Simulation carried out in SIMULINK/MATLAB environment.**

***Index Terms*—Power quality, harmonic distortion, harmonic analysis**

I. NOMENCLATURE

i =Arc current
v =Arc voltage
g =Arc conductance
E_0 =Momentarily constant steady state arc voltage
θ =Arc time constant
θ_0 =Constant
θ_1 = Constant
α = Constant
P_0 =Momentarily power loss
I_0 =Transition current
$g_{\min}$ =Minimum conductance
THD_I =Total Current Harmonic distortion
THD_V = Total Voltage Harmonic distortion

II. INTRODUCTION

Electric arc furnace (EAF) is an inherently non-linear, time-variant load and it can cause power quality problems such as harmonics and voltage flicker. Odd and even harmonic currents are generated by EAF operation. These harmonic currents, when circulated in the electric network can generate harmonic voltages which in turn can affect other users connected in the distribution network. Flicker is the sensation that is experienced by human eye when subjected to changes in the illumination intensity. The maximum sensitivity to change in illumination is in the frequency range of 5 to 15 Hz [4, 5]. As an EAF is a large source of flicker, causes voltage fluctuation in the connected electric network which is a major power quality issue which affects operation of other connected load in the distribution network. Hence, modeling of EAF has attracted attention of power system engineers to solve these power quality issues pertaining to EAF.

The important issue in the modeling of the EAF is the simulation of arc. There are several methods used to describe the electric arc [1-4, 7-8]. On the basis of actual measured samples of an electric arc in several functioning cycles of EAF, different operating points are generated in the form of statistical probability, corresponding to hidden Markov theory in [1]. This requires actual measurement of an electric arc. The time domain methods based on the differential equations are also presented [2]. Variation of power transmitted to the load by the arc furnace during the cycle of operation is considered in [3]. Comparison of EAF modeling in time domain and frequency domain shows that he time domain is more useful in studying the EAF [4, 8]. The balanced steady state equations are used in [7]. Other methods such as frequency response, V-I characteristic are employed to analyze the behavior of the EAF [8]. The above methods suffer from limitations such as knowledge of initial conditions for the differential equations, balanced situation of thee phase currents, actual arc measurement and use of complicated mathematical equation for the modeling of EAF. This paper presents simulation of the EAF model in the time domain using MATLAB. The main feature of the proposed model is good approximation without need of initial conditions of the EAF. Also, the proposed method can be used to describe different operating situations of the EAF and its effect of the connected electric network.

III. EAF MODELING AS NON-LINEAR LOAD

A. *Model1:Cassie-Mayr EAF model*

Mathematical model of Cassie-Mayr EAF model expressed as in [1, 5]:

$$g = g_{\min} + \left[1-\exp\left(-\frac{i^2}{I_0}\right)\right]\cdot\frac{v\cdot i}{E_0^2} + \exp\left(-\frac{i^2}{I_0}\right)\cdot\frac{i^2}{P_0} - \theta\cdot\frac{dg}{dt} \quad (1)$$

$$\theta = \theta_0 + \theta_1\cdot\exp\left(-\alpha\cdot|i|\right) \quad (2)$$

$$v = \frac{i}{g} \quad (3)$$

Typical values of and E_0, θ_0 , θ_1, α, P_0, I_0, and $g_{\min}$ are tabulated in Table 1[4-6].

TABLE I. CASSIE-MAYR EAF MODEL PARAMETERS

Parameter Description	**Parameter**	**Value**
Mimimum arc conductance	$g_{\min}$	0.008
Tansition current	I_0	10 A
Momentarily constant steady state arc voltage	E_0	250 V
Momenttarily power loss	P_0	110 W
Time Consatnat	θ_0	110 µs
Time Consatnat	θ_1	100 µs
Constant	α	0.0005

B. *Model 2: Proposed EAF model*

Proposed EAF model is a combination of Hyperbolic and Exponential EAF models. The $v-i$ characteristic of hyperbolic EAF model is considered to be in the form of $v = v(i)$ and it can be described as [5, 7]:

$$v_{hyp}(i) = V_{at} + \left(\frac{C}{D+i}\right) \quad (4)$$

In (4) variable v and i are arc voltage and arc current per phase respectively. V_{at} is the magnitude of the voltage threshold to which the voltage approaches as current increases. This voltage is dependent on the arc length which is defined by constants C and D taking care of arc power and arc current respectively. Typical values of these constants are tabulated in Table I.

The V-I characteristic of exponential EAF model is approximated by exponential function as [4, 6]:

$$v_{exp}(i) = V_{at}\left(1-e^{\left(i/I_o\right)}\right) \quad (5)$$

In (5) current constant I_o is employed to model the steepness of positive and negative currents. A typical value of I_o is tabulated in Table 2.

TABLE II. PROPOSED EAF MODEL PARAMETERS

Parameter Description	**Parameter**	**Value**
Voltage threshold	V_{at}	200 V
Arc power condtant	C	19 kW
Arc current constant	D	5 kA
Current steepness constant	I_o	20 kA

Exponential and hyperbolic models can be combined into single model by many ways. One of the simplest methods is proposed in [14], in which hyperbolic EAF model equation is chosen to be operative for increasing part of current wave and that of exponential EAF model equation of decreasing part of current wave. Here these EAF equations are combined by defining a transition function $O(i)$, which is a function of arc current and is given by and main contribution of this paper:

$$v_{com}(i) = \underbrace{[1-O(i)]}_{Higher\,Current}\cdot v_{exp} + \underbrace{O(i)}_{Lower\,Current}\cdot v_{hyp} \quad (6)$$

In (6), v_{hyp} and $v_{\exp}$ are the arc voltages given by (4) and (5) respectively. A satisfactory form of $O(i)$ used in this combination is given in [2, 6]:

$$O(i) = e^{\left(-\frac{i^2}{I_o^2}\right)} \quad (7)$$

In (7) I_o is the transition current. When arc current $(i)$is small, value of $O(i)$ is approaching unity which yields arc voltage value v_{com} is dominated by v_{hyp} and when arc current value is large, $O(i)$ is approaching zero yields arc voltage value v_{com} is dominated by $v_{\exp}$. The combined model voltage follows exponential model characteristic during high arc currents and follows hyperbolic model characteristic during low arc currents.

Thus the V-I characteristic of the proposed model is described by following equation:

$$v_{com}(i) = \begin{cases} V_{at}\left[1-e^{\left(i/I_o\right)}\right] & \textit{for higher arc current} \\ V_{at} + \left(\frac{C}{D+i}\right) & \textit{for lower arc current} \end{cases} \quad (8)$$

The combined model has the capability of describing the EAF behavior in time domain. Also the combined model can explains various operating conditions of the EAF such as scrap meltdown stage, refining stage from power quality point of view. The refining stage contributes harmonics in current and voltage at point of common coupling (PCC) while scrap meltdown stage yields voltage flicker majorly.

IV. EAF Dynamic behavior

Dynamic EAF model is required for real time analysis of the effect of the arc. The dynamic arc characteristic is simulated by varying arc voltage. In general the variation is of random nature. However two types of variation are considered for the study-sinusoidal variation and random variation. In order to study the effect of voltage flicker on the power system of EAF, V_{at} is varied sinusoidally and randomly. In this regard V_{at} is modulated as follows:

A. A. The sinusoidal variation

The sinusoidal variation is assumed as [6-7],

$$v_{at}(t) = V_{at0}\left[1 + m \cdot sin(\omega_f \cdot t)\right] \tag{9}$$

In (9) m is modulation index and ω_f is a flicker frequency.

B. B. The random variation

The random variation is assumed as [6-7],

$$v_{at}(t) = V_{at0}\left[1 + m \cdot N(t)\right] \tag{10}$$

In (10) $N(t)$ is a band limited white noise with zero mean and variance of one. The parameters used for sinusoidal variation and random variation are tabulated in Table III.

TABLE III. Flciker generation Parameters

Parameter Description	Parameter	Value
Sinusoidal variation		
Arc voltage threshold	V_{at0}	250 V
Modulation index	m	0.8
Flciker frequency	ω_f	4 Hz
Random variation		
Time Consatnat	V_{at0}	240 V
Modulation index	m	0.7
Band limited white noise	$N(t)$	4-14 Hz

V. Voltage Flicker assessment

Voltage flicker assessment is also one of the important aspects of power quality study. The assessment of voltage flicker involves the derivation of system RMS voltage variation and the frequency at which the variation occurs. The voltage flicker usually expressed as the RMS value of the modulating waveform divided by the RMS value of the fundamental value, as follows [17-19]:

$$\%\,Voltage\ Flickr = \frac{V_{2P} + V_{1P}}{V_{2P} - V_{1P}} \tag{11}$$

Equation (4) is useful for estimating voltage flicker. A variety of perceptible/limit curves are available in published literature which can be used as general guidelines to verify whether the amount of flicker is a problem [17].

VI. EAF Modeling with Power System

Fig. 1 shows a simple single phase equivalent electric network of a source which supplies an EAF. It consists of voltage source, source impedance, furnace transformer impedance and EAF.

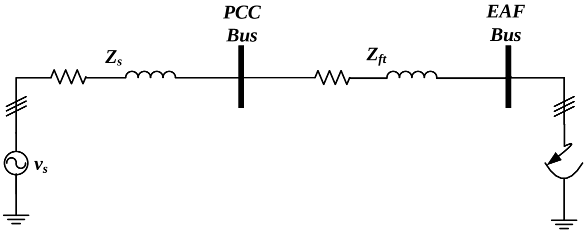


Figure 1. EAF connected in power system

In Fig. 1, the system impedance is represented as Z_s and the furnace transformer whose impedance is given by Z_{ft}. The system parameters along with proposed EAF Model are tabulated in Table IV [7].

TABLE IV. Power System Parameters

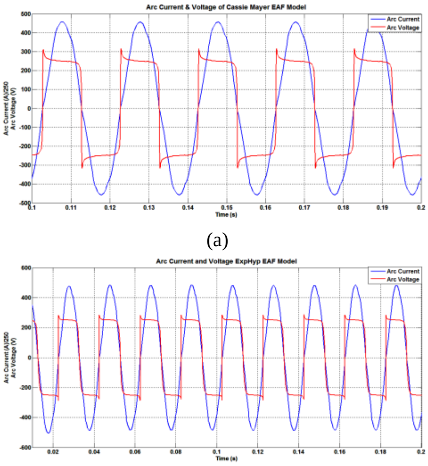
Parameter Description	Parameter	Value
Source voltage	V	415 V
Supply frequency	f	50 Hz
Source impedance	Z_s	(0.0528+j0.468) mΩ
Furnace transformer impedance	Z_{ft}	(0.3366+j3.22) mΩ

VII. Simualtaion Results

Simulated results are presented as a comparison of performance of Model 2 (Proposed-Exponential-Hyperbolic) with that of Model 1 (Cassie-Mayr). The performance of EAF includes various performance characteristics such as arc current, arc voltage, harmonic spectrum, arc conductance variation, arc voltage-current characteristic (VIC), variation in active & reactive power, etc. For better comparison, each performance characteristic of EAF model 1 and model 2 is presented together.

A. A. Steady State Characteristics

1) Arc Current and Arc Voltage



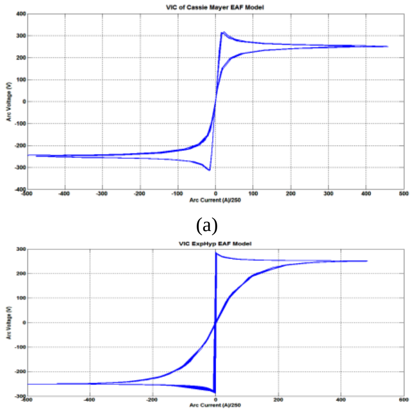
(a)

(b)

Fig. 2 Arc Current and Arc Voltage of (a) Model 1 (b) Model 2

Fig. 2 represents steady state characteristics of two models of EAF i.e. arc length is kept constant, which demonstrates refining condition of an EAF. In this condition, the level of molted material is constant and melting is uniform in the furnace. Hence behavior of V-I characteristic is also uniform. This condition does not produce any flicker at PCC but produces harmonics in voltage and current.

2) *Voltage-Current Characteristic (VIC)*

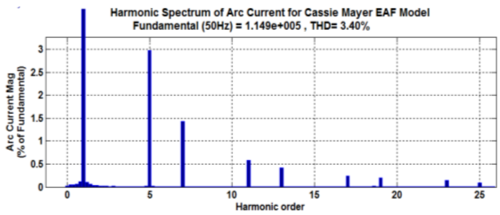


(a)

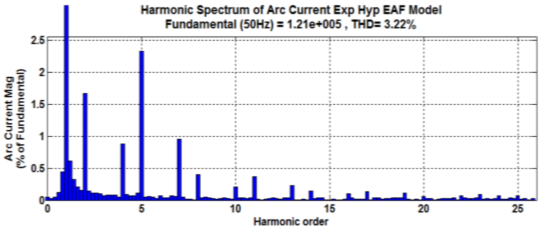
(b)

Fig. 3 VIC of (a) Model 1 (b) Model 2

3) *Current Harmonics at PCC*



(a)

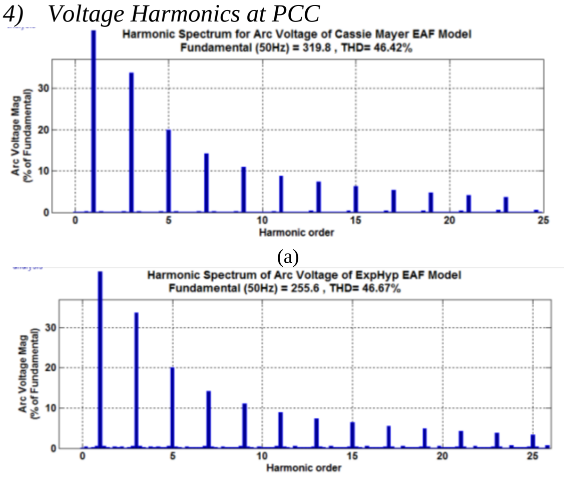


(b)

Fig. 4 Harmonic Spectrum of Current at PCC of (a) Model 1 (b) Model 2

It can be seen from Fig. 4 that total harmonic distortion (THD_I) observed in both the models is quite same (3.40 % for model 1 and 3.22 % for model 2). This shows validity of model 2 for refining cycle.

4) *Voltage Harmonics at PCC*



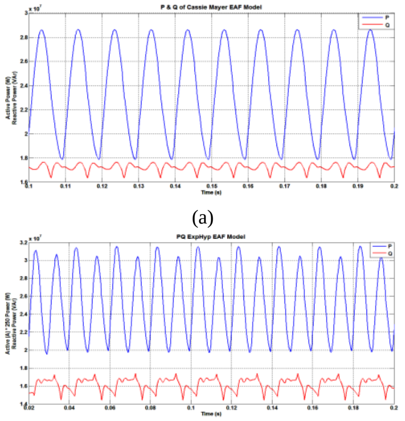
(a)

(b)

Fig. 5 Harmonic Spectrum of Current at PCC of (a) Model 1 (b) Model 2

Similarly, it can be seen from Fig. 5 that total harmonic distortion (THD_V) observed in both the models is quite same (46.42 % for model 1 and 46.67 % for model 2). This shows validity of model 2 for refining cycle

5) *Active and Reactive Power (P-Q)*



(a)

(b)

Fig. 6 Active (P) and reactive (Q) of (a) Model 1 (b) Model 2

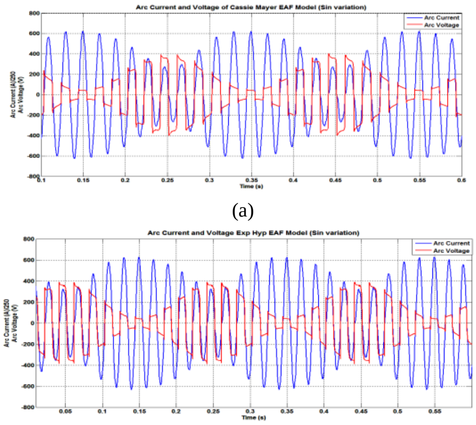
Fig. 6 shows active and reactive power consumption by EAF.

B. Dynamic Characteristics

Dynamic characteristic represents melting cycle of EAF. In this operation the furnace is charged with scrap, after that the electrodes could be lowered, each of which has its own regulator and mechanical drive. This operation exhibits severe voltage flickers. The effect of voltage flicker on the system with EAF can be studied using voltage variation with reference to time. As described in previous section, the effects of two types of flicker on the dynamic characteristic of the EAF are studied. Results of the simulation are obtained using (9) and (10) with values given in Table III.

C. Sinusoidal Flicker

Results for sinusoidal flickers are presented in Fig. 12, which show the variation of arc voltage and arc current. It can be seen that if the furnace load generates sinusoidal flicker, the arc voltage and arc current, are varied sinusoidally with the flicker frequency.



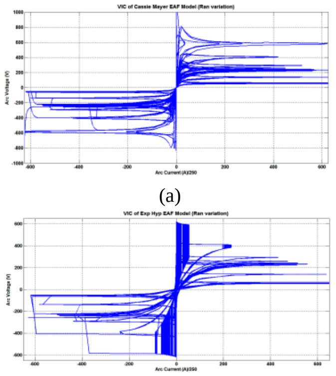
(a)

(b)

Fig. 7 Arc voltage and current of (a) Model 1 (b) Model 2 for Sinusoidal Flicker

D. Random Flicker

The simulation results for VIC for model 1 and model 2 under random flicker condition are presented in Fig. 8. The proposed EAF model 2 provides identical VIC as model 1.



(a)

(b)

Fig. 8 VIC of (a) Model 1 (b) Model 2 Random Flicker

VIII. COMPARISION AND ANALYSIS

Table V shows comparison of voltage harmonic analysis between EAF Model 1 and Model 2. Total harmonic distortion observed in Model 1 and Model 2 is 46.42 % and 46.67 % respectively, which is violating IEEE 419-1992 Limits of 5%. % Error observed in THD of Model 2 (Proposed) with respect to Model 1 is -0.54 %, which is less than 10 %. It makes Model 2 acceptable.

TABLE V. VOLTAGE HARMONIC ANALYSY @ PCC

Harmonics (% of Fund.)	**Model 1 (Cassie-Mayr)**	**Model 2 (Proposed)**	**% Error**	**% Error (Average)**
V_{peak} (V)	305	288	5.57	1.85
THD_V	46.42	46.67	-0.54	
3rd	33.69	33.64	0.15	
5th	19.98	20.07	-0.45	
7th	14.12	14.19	-0.49	
9th	10.99	11.05	-0.54	
11th	8.78	8.92	-1.57	
13th	7.3	7.41	-1.48	
15th	6.27	6.39	-1.88	
17th	5.36	5.54	-3.25	
19th	4.67	4.82	-3.11	
21st	4.16	4.29	-3.03	
23rd	3.65	3.82	-4.45	
25th	3.26	3.38	-3.55	

Harmonic distortion of each harmonic order is expressed as % of fundamental. Harmonic distortion observed in almost all harmonic orders (3rd to 25th) is more than IEEE 419-1992 Limit of 3 % for individual harmonic order. % Error for each harmonic order is calculated by taking Model 1 (Cassie-Mayer) to be the reference. Maximum error observed in model 2 with respect to model 4 is +0.15 % (3rd order) and -4.45 % (23rd order) on positive and negative side respectively. Average error observed is -1.86 % which is less than 10 %, which makes model 2 (Proposed) acceptable. % Error observed in the voltage magnitude at PCC of Model 2 with respect to Model 1 is 5.57 %, which again confirms validity of Model 2.

Table VI shows comparison of current harmonic analysis between EAF Model 1 and Model 2. % Error observed in THD of Model 2 (Proposed) with respect to Model 1 is 5.29 %, which is less than 10 %. It makes Model 2 acceptable.

TABLE VI. CURRENT HARMONIC ANALYSY @ PCC

Harmonics (% of Fund.)	**Model 1 (Cassie-Mayr)**	**Model 2 (Proposed)**	**% Error**	**% Error (Average)**
I_{peak} (kA)	117.5	120	-2.13	7.85
THD_I	3.4	3.22	5.29	
5th	2.98	2.79	6.38	

Harmonics (% of Fund.)	Model 1 (Cassie-Mayr)	Model 2 (Proposed)	% Error	% Error (Average)
7th	1.43	1.24	13.29	
11th	0.58	0.56	3.45	
13th	0.42	0.39	7.14	
17th	0.24	0.22	8.33	
19th	0.19	0.17	10.53	
23rd	0.14	0.13	7.14	
25th	0.09	0.08	11.11	

Harmonic distortion of each harmonic order is expressed as % of fundamental. % Error for each harmonic order is calculated by taking Model 1 (Cassie-Mayr) to be the reference. Average error observed is 8.07 % which is less than 10 %, which makes model 2 (Proposed) acceptable. % Error observed in the current magnitude at PCC of Model 3 with respect to Model 4 is -2.13 %, which again confirms validity of Model 3.

Table VII shows comparison of active power, reactive power and power factor between Model 1 and Model 2. % errors calculated are less than 10%.

TABLE VII. POWER ANALYSY @ PCC

Parameter	Model 1 (Cassie-Mayr)	Model 2 (Proposed)	% Error (w. r. t. model 1)
Active Power (P)	23280 kW	24900 kW	-6.96
Reactive Power (Q)	17250 kVAR	16130 kVAR	+6.49
Power Factor (PF)	0.574	0.606	-5.57

Table VIII shows comparison of sinusoidal flicker generated by Model 1 and Model 2. % Errors is +1.36 %, which is again less than 10%.

TABLE VIII. VOLTAGE FLICKER ANALYSY @ PCC

Parameter	Model 1 (Cassie-Mayr)	Model 2 (Proposed)	% Error (w. r. t. model 1)
Voltage measurement			
V_{1P} (Volts)	65	64	1.54
V_{2P} (Volts)	390	400	-2.56
Flicker Calculations			
% Voltage Flicker	1.40	1.38	+1.36

Comparison of various performance characteristics of EAF Model 2 (Proposed) with existing EAF Model 1 (Cassie-Mayer), as shown in Fig. 2 to Fig. 8, validates Model 2. Comparison of voltage harmonic analysis, current harmonic analysis, power analysis and voltage flicker analysis at PCC of EAF Model 2 (Proposed) with respect to EAF Model 1 (Cassie-Mayer) shows that the % error observed is less than 10 %. This again confirms the validity of EAF Model 2 (Proposed).

IX. CONCLUSIONS

This paper describes performance evaluation of composite filter for power quality improvement of electrical electric arc furnace distribution network. First of all, distribution network is simulated using Cassie-Mayr EAF model. The simulated EAF distribution network is used for power quality analysis including voltage-current harmonics, voltage flicker and voltage unbalance. Next, a control strategy for a composite filter, which is connected with the existing passive filter, is proposed for taking care of the unbalance, non-sinusoidal and randomly varying EAF. The control strategy is based on the dual vectorial theory of power. Finally, detail performance of composite filter is evaluated by comparing its performance with passive filter for various operation cycles of EAFs connected distribution network. Performance comparison shows that, the proposed composite filter performs better than the passive filter alone for harmonic compensation, voltage flicker mitigation, and for clearing voltage unbalance on EAF load side.

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