

Mathematical Modeling of Electric Arc Furnace to Study the Flicker

Goyal R. Awagan
Department of Electrical Engineering
Govt. College of Engineering,
Aurangabad (M.S.), India
goyal.5awagan@gmail.com

A. G. Thosar
Associate Professor,
Head of Electrical Engg. Dept.
Govt. College of Engineering,
Aurangabad (M.S.), India
aprevankar@gmail.com

Abstract- Electric arc furnaces (EAF) are used in the melting and refining of metals such as copper, lead, aluminium, high grade alloy steel, etc. The production of steel by EAF technology is increasing in emerging economies. Today, India ranks second in the world in EAF-based steel production. As the popularity and use of the EAF in the industry increase, so does the power quality problems as a result of this progress. The EAF operation causes harmonics, interharmonics, voltage flicker and strongly varying reactive power demand, which affect the power quality adversely. Utilities and customers are concerned about these effects and try to take precautions to minimize them. Therefore, obtaining the time response of an electric arc furnace becomes important in investigating the impact of these nonlinear, time varying loads on the power quality of the overall power system. Hence, developing an accurate and easy to use arc furnace model has been an important and quite a challenging task for several researchers in the past. This paper attempts to study the power quality issues related to EAF particularly flicker using the Cassie-Mayr arc furnace model.

Index Terms- Power Quality, Electric Arc Furnace, Flicker, Harmonics, Cassie-Mayr arc model, Sinusoidal variation, Random variation

1. NOMENCLATURE

v	Arc voltage (V)
i	Arc current (A)
g	Arc conductance (mho)
E_0	Constant steady-state arc voltage (V)
θ	Arc time constant (μ s)
P_0	Constant power loss (W)
V_{at}	Threshold arc voltage (V)
m	Modulation index
w_f	Flicker frequency (Hz)
$N(t)$	Band limited white noise (Hz)

2. INTRODUCTION

Electric arc furnaces are widely used in steel industry for melting and refining of iron. They are also used in the smelting of nonferrous metals. The principle of operation of EAF is that the air in the air gap gets ionized under the influence of electrostatic forces and becomes conducting medium on the application of high voltage across an air gap and the current flows in the form of a continuous spark, called the arc. Depending on the formation of arc, the EAFs are classified as direct arc furnace, indirect arc furnace and submerged arc furnace. Direct arc furnace is mainly employed for making alloy steels such as stainless, high speed steel. Indirect arc furnace is used for melting nonferrous metals. Submerged arc furnace is used for the production of Ferro-chrome and Ferro-manganese. Though the arc furnace is becoming popular in the metallurgical industry, it has become a cause for concern among the power system engineers. EAFs are characterized by rapid changes in absorbed powers that occur mainly in the initial stage of melting process, during which the critical condition of a broken arc may become a short circuit or an open circuit. Owing to the very complex arc phenomenon, the voltage-current characteristic of the arc is highly non-linear, which causes harmonic currents which in turn produce harmonic voltages when circulating by the electric network. Generation of harmonics results in further flicker problems. Thus, EAF is one of the responsible sources for deteriorating the power quality in the connected network.

With the increasing use of EAFs many power quality problems are introduced in the power system. In order to study the power quality issues related to arc furnace, there is a need to develop an accurate electric arc furnace model which can represent the furnace operation with accuracy. Literature review reveals some of the methods for modeling and predicting the behavior of electric arc furnaces. R.C.Dugan [1] developed an electronic arc model based on analog approach which simplified the study of harmonic phenomena in arc furnace power systems on a transient network analyzer (TNA). TNA is a special-purpose analog computer which is well suited for solving switching and harmonic transient problems. The arc model is based on the simplification of the v_i characteristic of the arc. The developed model is a primitive one and the time varying characteristic of the arc is neglected. Early EAF models based on explicit mathematical equations are reported in [2]. The differential

equation representing a general dynamic arc model is based on the principle of conservation of energy. This method makes use of empirical formulas that relate arc radius/length, arc voltage and current but did not directly incorporate the quasi-stochastic nature of EAF operation. S. Varadan [3] presents a time domain controlled voltage source model for an arc furnace. The model is based on the piece wise linear approximation of the v_i characteristic of the arc. Omer Ozgun [4] presents an arc furnace which is modeled using both chaotic and deterministic elements. The Chua's chaotic circuit is used to represent the flicker effect and a dynamic model is obtained using the differential equation. A review of the various power quality issues in the arc furnace using different arc models is discussed in [5]. However the above models deal with some properties of EAF. Some of them deal with single-phase model useful for the study of flicker effect other with static model useful for harmonic studies. Therefore, it is necessary to develop a mathematical model capable of representing both the static and dynamic behavior of the electric arc furnace load with enough accuracy.

This paper presents a Cassie-Mayr method to model the electric arc furnace that is formulated from the classical Cassie and Mayr models used in the past to study the arc phenomenon in high voltage circuit breakers. The structure of the paper is organized as follows. Section 3 deals with the principle of electric arc furnace. Section 4 describes the mathematical modeling of various electric arc furnaces. Section 5 describes the mathematical modeling of electric arc furnace using Cassie-Mayr method. Section 6 describes the simulated electric arc furnace model using the Cassie-Mayr equations. The static and dynamic characteristics of the arc furnace model are discussed in section 7.

3. PRINCIPLE OF ELECTRIC ARC FURNACE

The physical model of the electric arc furnace is shown in Fig.1 [6]. It consists of three electrodes that are moved vertically up and down with hydraulic actuators. The ore is melted with a huge power surge from the electrodes. The actual product is denser than the scrap and thus falls to the bottom of the furnace creating the matte. Above the matte lies the slag where the electrode tips are dipped. The tremendous heat created by these electrodes causes the ore to liquefy and separate. Thereupon more raw materials are placed in the furnace and the process repeats itself.

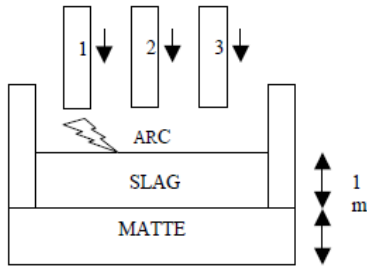


Fig.1 Physical model of arc furnace

The phenomenon of arcing takes place when the electrodes are moved above the slag. As the electrode approaches the slag, current begins to jump from the electrode to the slag, creating electric arcs. Depending on the magnitude of the input voltages of the electrodes, the arcing distance can vary. Usually, arcing occurs in a region within centimeters of the slag (approximately 10-15cm) [6].

Electric arc furnaces marked their beginning during the discovery of carbon arc by Sir Humphrey Davy [7]. The arc voltage waveform for carbon is shown in Fig.2 [1] and the corresponding $v-i$ characteristic is shown in Fig.3 [1].

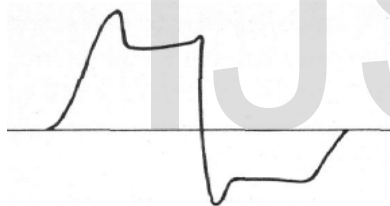


Fig.2. Typical carbon arc voltage

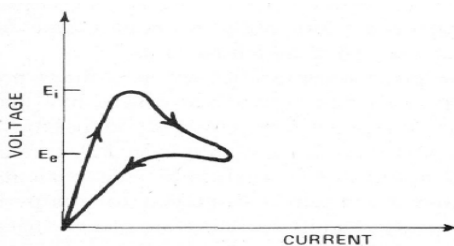


Fig.3. Typical carbon arc $v-i$ characteristic

The voltage is a multi-valued function of current. Just after the reignition of arc at a voltage E_i , a negative resistance is displayed until the arc extinguishes again when the arc voltage falls below E_e [1].

The differential equation representing a general dynamic arc model based on the principle of conservation of energy is found in [2]. The power balance equation for the electric arc is

$$p_1 + p_2 = p_3 \tag{1}$$

where

p_1 is the power transmitted in the form of heat to the external environment,

p_2 is the power which increases the internal energy in the arc, thus affecting its radius, and

p_3 is the total power developed in the arc and converted into heat.

It is assumed that the cooling effect is a function of the arc radius r only in equation (1). Therefore, p_1 is written as

$$p_1 = k_1 r^n \tag{2}$$

The cooling effect is also a function of the arc temperature. However, in order to keep the model simple, this dependence is assumed to be less significant and is therefore ignored. Thus, only the arc radius r appears as a state variable. If the environment surrounding the arc is hot, the cooling of the arc may not depend on its radius at all, so that in this case $n = 0$. If the arc is long, then the cooling area is mainly its lateral surface area, so that in this case $n = 1$. If the arc is short, then the cooling is proportional to its cross-sectional area at the electrodes, so that in this case $n = 2$.

The term p_2 is proportional to the derivative of the energy inside the arc which is proportional to r^2 ,

$$p_2 = k_2 r \frac{dr}{dt} \tag{3}$$

Finally,

$$p_3 = vi = \frac{k_3}{r^2} i^2 \tag{4}$$

In equation (3), the resistivity of the arc column is assumed to be inversely proportional to r^m , where $m = 0.2$, to reflect the fact that the arc may be hotter in the interior if it has a large radius.

Substituting equations (2), (3) and (4) into (1) gives the differential equation of the arc:

$$k_1 r^n + k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} i^2 \tag{5}$$

The arc voltage is given by

$$v = \frac{i}{g} = \frac{k_3}{r^{m+2}} i \tag{6}$$

where g is defined as arc conductance and is given by

$$g = \frac{r^{m+2}}{k_3} \quad (7)$$

For static arc model, equation (6) gives

$$r = \text{const} * i^{\frac{2}{m+n+2}} \quad (8)$$

So that in equation (6)

$$v = \frac{k}{i^q} \quad (9)$$

with

$$q = \frac{m+2-n}{m+2+n} \quad (10)$$

The values of q do not vary much with m . The static characteristic depends mainly on the cooling and little on the variation of resistivity with temperature.

4. MATHEMATICAL MODELING OF ELECTRIC ARC FURNACE

There are several approaches for modeling and predicting the EAF behavior. The methods of electric arc furnace modeling can be broadly classified as "time domain" and "frequency domain" methods. The frequency domain model represents the arc voltage and arc current by its harmonic components. The electrical arc is a time varying and nonlinear phenomenon. Therefore description of arc behavior is easier in time domain than frequency domain. Time domain methods are the basic methods for flicker study in EAF. Time domain methods can be further classified as v_i characteristic (VIC) and equivalent circuit method (ECM) [11]. VIC method utilizes the numerical analysis method to solve the differential equation with nonlinear VIC. This method is widely used for modeling the static and the dynamic operation of EAF. The ECM methods can be obtained from arc operation; the periodic variation of arc voltage and the resistance that arc shows can be used to develop the arc furnace model. Another method to analyze the arc model in the time domain is based on the Cassie-Mayr equation. In this method Cassie and Mayr equations are employed for the low and high current of the arc, respectively.

The previous studies reveal that most of the stochastic ideas are used to capture the time-varying, a-periodic, and nonlinear, behavior of arc furnaces [8]. The use of the chaos theory in arc furnace modeling is almost a new compared to the stochastic ideas. The electric fluctuations occurring

in the arc furnace were noticed to be chaotic in nature [9]. Therefore, chaos theory was used for modeling arc furnace. Some of the researchers used both chaotic and stochastic elements to model the arc furnace [4]. Most of the efforts were put to model the electric arc furnaces either from harmonics or from flicker point of view. The literature shows some models with the combination of both flicker and harmonics as well.

In [3], the arc furnace load is modeled as a controlled voltage source, and the model is based on a piece-wise linear approximation of the rated v_i characteristics of the load. Depending on the arc resistance variations, this model represents both static and dynamic characteristic. The random operation of the arc has been modeled by stochastically modifying its v_i characteristics. This model includes the power consumed by the arc furnace load as an input parameter. Fig.4. shows the typical v_i characteristic of an arc furnace load [1].

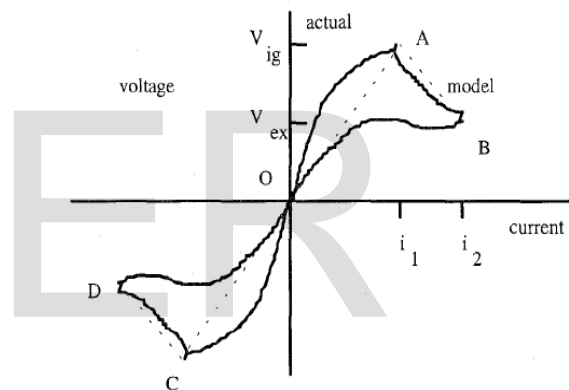


Fig.4. Actual and piece-wise approximation of v_i characteristics of an arc furnace load

The piece-wise linear approximation of the v_i characteristics can be defined in the first quadrant of the v_i plane as in equation (13) which is defined in terms of equation (11) and (12).

$$i_1 = \frac{V_{ig}}{R_1} \quad (11)$$

$$i_2 = V_{ex} - V_{ig} \left(1 - \frac{R_2}{R_1} \right) \quad (12)$$

$$v = \begin{cases} iR_i, & 0 \leq i \leq i_1 \\ iR_2 + V_{ig} \left(1 - \frac{R_2}{R_1} \right), & i_1 < i \leq i_2 \end{cases} \quad (13)$$

where, v is the voltage, i is the current, R_1 and R_2 are the slopes of segments OA and AB respectively, V_{ig} and V_{ex} are the ignition and

extinction voltage of the arc respectively, i_1 and i_2 are the currents corresponding to the ignition and extinction voltages respectively in the first quadrant of the v_i characteristic shown in Fig.4.

Since the power consumed by the arc furnace is equal to the area under the piece-wise linear v_i characteristics, the arc resistance R_1 , can be obtained in terms of the power consumed by the arc furnace load as

$$R_1 = \frac{V_{ig}^2}{\left(P + \frac{V_{ig}^2}{R_2} - \frac{V_{ex}^2}{R_2} \right)} \quad (14)$$

However, if we assume that the quantities V_{ig} , V_{ex} and R_2 do not change with the load operating conditions, then for any other given power consumption, P , it is possible to obtain a similar v_i characteristics with a different slope R_{1new} in terms of the new power P_{new} as in equation (14). The static load model for the arc furnace load can be obtained from the combination of equations (13) and (14) at any given power consumption given the rated v_i characteristics.

By considering the v_i characteristic of the arc in detail, a more accurate non linear approximation model is developed in Fig.5 [11].

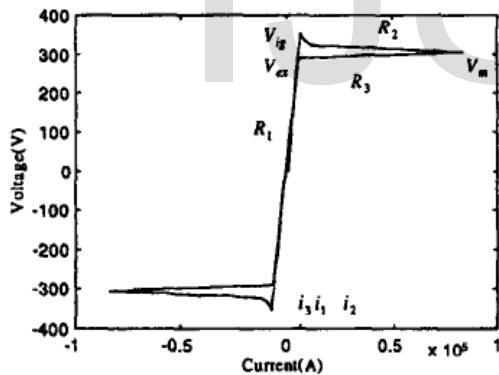


Fig.5. Nonlinear approximation of v_i characteristic

The arc melting process is broadly divided into three parts in this model. In the first part, the voltage magnitude increases from extinction voltage $-V_{ex}$ to ignition voltage V_{ig} . The arc acts as a resistor and the arc current changes its polarity from $-i_3$ to i_1 . In the second part, the arc begins to melt and the voltage across the electrode drops exponentially from V_{ig} to V_{st} and the arc current increases from i_1 to i_2 . In the third part, the normal arc melting process takes place and there is a linear, slow and smooth drop in voltage from V_{st} to V_{ex} . The mean value is assumed to be V_m as the melting cycle spans for most of the half cycle [11]

The dynamic load model takes into account both periodic and stochastic changes of the arc resistance about the value R_1 found in equation (14) for a given loading condition and not the arc radius as there is a direct relationship between the arc resistance and arc radius. This model is based on representation of the v_i characteristics using two different variations for the arc resistance about the value R_1 found in equation (14) i.e. sinusoidal variation and band limited white noise variation. The arc resistance in the case of sinusoidal variation is defined as

$$R_1(t) = R_1 [1 + \sin(\omega_f t)] \quad (15)$$

and in the case of band limited white noise variation is defined as

$$R_1(t) = R_1 + BLW \quad (16)$$

where

R_1 is a constant obtained in equation (4) for a given power consumption,

ω_f is the flicker frequency, and

BLW is band limited (4-14 Hz) [12] white noise with zero mean.

The expected value of $R_1(t)$ is equal to R_1 as in (17) over a period such that the total input power requirement of the arc furnace is satisfied.

$$\xi[R_1(t)] = R_1 \quad (17)$$

Depending on the type of study to be performed, the static or the dynamic load model can be used. Basically the static model is used for harmonic studies while the dynamic model is used for voltage flicker studies.

As an alternative to the stochastic models, in [9] deterministic chaos is used in the characterization of arc current's a-periodic behavior. Chaos, also called strange attractor, has no generally accepted precise mathematical definition. From a practical point of view, it can be defined as bounded steady-state behavior that does not fall into the categories of the other three steady-state behaviors, i.e., equilibrium points, periodic solutions and quasi-periodic solutions [13]. The arc furnace load is modeled using a dynamic and multi-valued v_i characteristic obtained by solving the corresponding differential equation (5), whose parameter is the arc length and the forcing function is the arc current [2]. In order to represent the flicker effect, a low frequency chaotic signal is modulated with the arc voltage. The model is connected to the system as a controlled voltage source [4, 10].

The chaotic component of the arc furnace voltage is supplied from the well known chaotic

circuit of Chua [14, 15]. In order for an autonomous circuit consisting of resistors, capacitors, and inductors to exhibit chaos, it has to contain the following [14]:

- i. At least one locally active resistor,
- ii. At least one nonlinear element,
- iii. At least three energy storage elements.

Chua's circuit [14, 15], is the simplest such circuit that satisfies the above conditions; moreover it is the only physical system for which the presence of chaos has been proven. These two properties of this circuit motivated its use as a chaos generator. One more useful property of this circuit is its ability to generate chaotic signal at any frequency by scaling the values of the energy-storage elements. Fig.6 shows the Chua's circuit that includes two capacitors (C1, C2), a resistor (R), an inductor (L) and a nonlinear resistor (NR) (a pair of negative resistors).

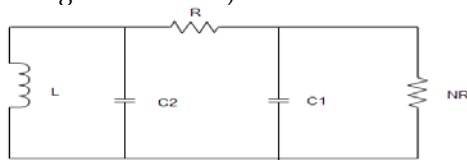


Fig.6. Chua's circuit

The electric arc voltage is obtained from the simultaneous solution of (8), and the low-frequency chaotic signal that is generated by the simulation of Chua's chaotic circuit. Modulation of these two signals produces the final arc furnace voltage, which is the output of the model. The current absorbed from the power system bus is injected as the input to the model. The model behaves as a controlled source, namely it takes the system current as an input and assigns the terminal voltage value at each time step.

5. MATHEMATICAL MODELING OF ELECTRIC ARC FURNACE USING CASSIE-MAYR METHOD

A Cassie-Mayr electric arc furnace model capable of representing both the static and dynamic behavior of the electric arc furnace load with enough accuracy has been studied in [16]. The relationship between the arc voltage and arc current is highly nonlinear due to the very complex arc phenomena. The characteristics of the arc depends on a number of factors such as electrode material, geometry of electrodes, separation between the electrodes, position of the electrodes, type of gas and the gas pressure. According to Nottingham, an atmospheric arc of

constant length could be represented by equation (18) as follows.

$$v = A + \frac{B}{i^n} \quad (18) \quad (18)$$

where,

v is the arc voltage,

i is the arc current,

n is the exponent which depends upon the absolute boiling point temperature of the anode and also on the type of gas in which the arc burns.

The vi characteristic of the arc can also be explained by taking into account the mode of heat loss from the arc. For this a simple arc model is considered with a constant current density and constant heat loss per unit area of the cylindrical surface of the arc. The circumference of the arc column and therefore the heat loss vi is proportional to the arc radius. For a constant current density, the arc radius is proportional to the square root of the arc current. The relationship between v , i and arc conductance g is given by equation (19) as

$$v \propto \frac{1}{\sqrt{i}} \quad \text{and} \quad g \propto vi^2 \quad (19)$$

This model gives the vi characteristic of the arc in the low-current range.

For the high-current range, the current density is kept constant. The loss is assumed to be proportional to the cross-sectional area of the arc. Here, v remains constant and the arc conductance is given by equation (20) as

$$g \propto i \quad (20)$$

This model represents the arc in the high-current range.

The Cassie model, which is a suitable representation of an arc for high currents, and the Mayr model, which yields good results for arcs with low currents are usually expressed in conductance rather than arc resistance because of the extremely low values for arc resistance. A qualitative understanding of the phenomena determining arc striking or extinction of the energy-balance type can be achieved by the simple Cassie and Mayr differential equation models, based on simplifications of principal power-loss mechanisms and energy storage in the arc column.

With the arc conductance g as the dependent variable, the Cassie equation is given by

$$g = \frac{vi}{E_0^2} - \theta \frac{dg}{dt} \quad (21)$$

where

E_0 is the constant steady-state arc voltage,

θ is the arc time constant= energy stored per unit

volume/ energy loss rate per unit volume

and the Mayr equation by

$$g = \frac{i^2}{P_0} - \theta \frac{dg}{dt} \quad (22)$$

where

P_0 is the constant power loss

The Cassie equation is more valid for higher current regions while the Mayr equation is more representative of zero and low-current regions, an arc may be simulated by the combination of (21) and (22). In order to combine (21) and (22) into a single arc model we have define a transition current I_0 such that the arc conductance is given by

$$g = \frac{vi}{E_0^2} - \theta \frac{dg}{dt}, \text{ if } i > I_0$$

$$g = \frac{i^2}{P_0} - \theta \frac{dg}{dt}, \text{ if } i < I_0 \quad (23)$$

In order to allow for smooth transition between (21) and (22), a transition factor $\sigma(i)$ is defined, which is a function of arc current such that the arc conductance is given by

$$g = [1 - \sigma(i)]g_C + \sigma(i)g_M \quad (24)$$

where g_C and g_M are the conductance given by (21) and (22), respectively.

$\sigma(i)$ varies between zero and unity and should be a monotonic decreasing function when i increases. The transition factor is given by,

$$\sigma(i) = \exp\left(-\frac{i^2}{I_0^2}\right) \quad (25)$$

When i is small, the value of σ is close to unity and g is dominated by Mayr conductance g_M . When i is large, the value of σ is negligible and, therefore g is dominated by Cassie conductance g_C .

However, when the arc is absent between any two electrodes there has to be a finite though very small amount of conductance, g_{\min} which depends on the distance between the electrodes, geometry of the electrodes, type of gas and temperature. Thus, the complete Cassie-Mayr arc model is given by

$$g = g_{\min} + \left[1 - \exp\left(\frac{-i^2}{I_0^2}\right)\right] \cdot \frac{v.i}{E_0^2} + \exp\left(\frac{-i^2}{I_0^2}\right) \cdot \frac{i^2}{P_0} - \theta \cdot \frac{dg}{dt} \quad (26)$$

and

$$i = gv \quad (27)$$

In general form, θ should be a function of i because when an arc is igniting or extinguishing, the energy stored per unit volume is large compared with the energy loss per unit volume. However, when the arc stabilizes, error of I is small and can be represented by

$$\theta = \theta_0 + \theta_1 \cdot \exp(-\alpha \cdot |i|) \quad (28)$$

where

$$\alpha > 0 \text{ and } \theta_1 \gg \theta_0$$

When the arc is igniting or extinguishing, i is small and $\theta \approx \theta_1$. When i is large, $\theta \approx \theta_0$. The seven parameters together with g_{\min} , I_0 , E_0 and P_0 characterize the arc furnace model. This model is in time domain and in addition to generating power quality parameters, can investigate the effect of different feed system designs on performance of furnace.

6. SIMULATION OF ELECTRIC ARC FURNACE MODEL USING CASSIE-MAYR METHOD

The three phase arc furnace simulated in this paper is modeled using the Cassie-Mayr model that has the real time modeling capability of the different states of the furnace. This model is helpful to study the static characteristics and also to simulate flicker disturbance caused by the electric arc furnace. Fig.7 shows complete simulation of three phase electric network supplying an EAF. The model consists of 115 kV, 100 MVA, 50Hz three phase source block feeding through a three phase transformer to an electric arc furnace. In order to provide an adequate voltage level to the arc furnace two step-down transformers are used. The EAF is connected to the utility through a (HV/MV) [110/13.8 kV] transformer (T1) and is fed by a (MV/LV) [13.2/0.55 kV] transformer (T2). Fig.8 shows three simulated equation sets of Cassie-Mayr for three phases. EAF is modeled as a non-linear time varying voltage controlled source using subsystem. The arc current is taken as the input parameter to this function and the output is non-linear time varying voltage. The XY graph is used to monitor the voltage-current characteristic of the arc. Fig.9 shows detailed simulation of Cassie-Mayr equations (26) to (28). Table 1 shows the values of parameters associated with Cassie-Mayr EAF model useful for the determination of arc static model [17]

TABLE 1
PARAMETERS FOR CASSIE-MAYR EAF MODEL

Parameter Description	Parameter	Value
Minimum arc conductance	g_{\min}	0.008
Transition current	I_0	10 A
Momentarily constant steady state arc voltage	E_0	250 V
Momentarily power loss	P_0	110 W
Time Constant	θ_0	110 μ S
Time Constant	θ_1	100 μ S
Constant	α	0.0005

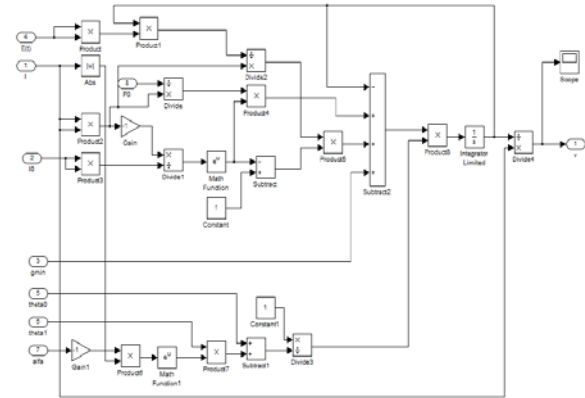


Fig.9. Cassie-Mayr EAF equation Simulation

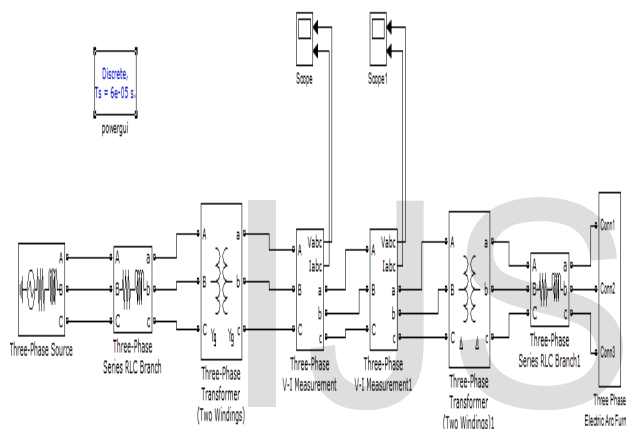


Fig.7. Complete SIMULINK model of three phase electric network supplying an EAF

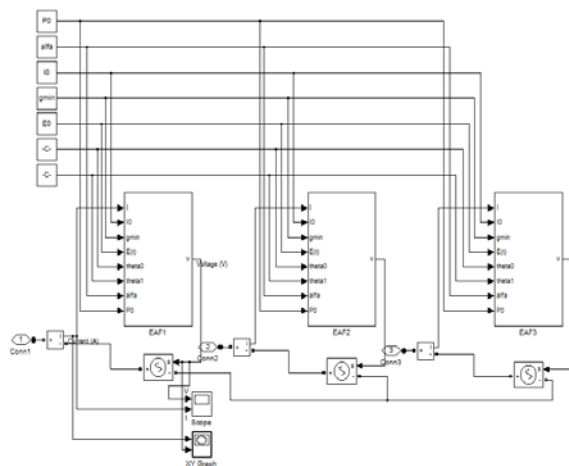


Fig.8. Three phase EAF Simulation

During the melting process, there are fast variations in the current which are connected with the arc-length variations caused due to metal-scrap adjustments, electrodynamic forces and arc-electrode variable displacement [8]. These current fluctuations causes a momentary voltage drop or flicker both at the supply bus and at nearby bus in the interconnected system. Thus, EAF exhibits dynamic characteristics during the melting cycle.

The arc currents during the refining period are more uniform and have a very less impact on the system. During the refining cycle the level of molted material is constant along with uniform rate of melting in the furnace. The arc length is almost constant during this cycle resulting into uniform v_i characteristic [9]. Thus, there is no flicker at the PCC. However, due to the intrinsic non-linearity of the arc characteristic, voltage and current harmonics are present at PCC. Thus, EAF exhibits steady state characteristic during the refining cycle.

The refining stage contributes harmonics in current and voltage, while scrap meltdown stage yields voltage flicker at PCC. Therefore, real time analysis of power quality demands dynamic model of EAF. In order to bring the stationary arc-model to give rise to voltage fluctuations, cause of flicker, the v_i characteristic must undergo time variations which correspond to a time dependence of the arc length as in equation (29) [8]

$$V_{at} = A + B \cdot l \tag{29}$$

where,

V_{at} is the threshold arc voltage

A is the constant representing the sum of anode and cathode voltage drops

B is the voltage drop per unit arc length

l is the arc length in centimeters

There are two time-variation laws for

simulating a flicker i.e. sinusoidal law and white-noise law. Some models apply these time-variation laws to the arc resistance for a given loading condition [3]. Some models incorporate both sinusoidal and stochastic time variation rules to vary the arc length by varying the arc voltage directly [8]. In order to represent the flicker effect, a low frequency chaotic signal is modulated with the arc voltage [4]. However in this paper, the impact of voltage flicker on EAF is explained using threshold voltage, V_{at} which is varied sinusoidally and randomly. In this regard V_{at} is modulated as follows:

Sinusoidal Variation

The sinusoidal variation is assumed as,

$$V_{at}(t) = V_{at0} [1 + m \cdot \sin w_f \cdot t] \tag{30}$$

where, m is modulation index
 w_f is a flicker frequency

The SIMULINK model for Sine Flicker is shown in Fig.10

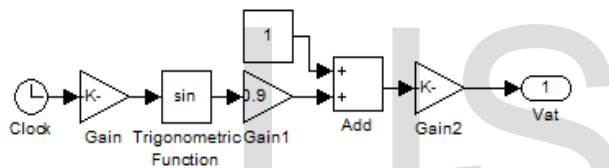


Fig.10. SIMULINK Model for Sine Flicker

Random Variation

The random variation is assumed as,

$$V_{at}(t) = V_{at0} [1 + m \cdot N(t)] \tag{31}$$

where, $N(t)$ is a band limited white noise with zero mean and unit variance

The SIMULINK model for Random Flicker is shown in Fig.11

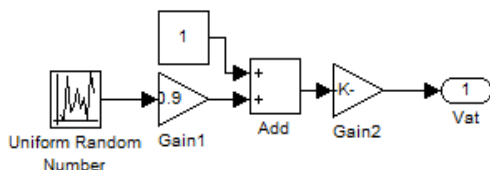


Fig.11. SIMULINK Model for Random Flicker

Table 2 shows the parameters utilized for sinusoidal variation and random variation [18].

TABLE 2

PARAMETERS USED FOR DYNAMIC CHARACTERISTICS

Sinusoidal Variation		
Parameter Description	Parameter	Value
Initial threshold voltage	V_{at0}	200 V
Modulation index	m	0.9
Flicker frequency	w_f	4 Hz
Random Variation		
Parameter Description	Parameter	Value
Initial threshold voltage	V_{at0}	200 V
Modulation index	m	0.9
Band limited white noise	$N(t)$	4-14 Hz

7. RESULTS AND DISCUSSION

The electric arc furnace is modeled using the Cassie-Mayr mathematical equations in MATLAB software. The static and dynamic vi characteristic of the arc along with the respective voltage and current waveforms are discussed. The dynamic arc characteristic are simulated using both the sinusoidal variation and band-limited white noise random time variation.

7.1 Static Characteristics of Arc

The Cassie-Mayr static arc model is simulated using the arc parameter $E_0 = 200V, \alpha = 0.0005, \theta_1 = 100\mu sec, \theta_0 = 110\mu sec$ Static voltage/ current characteristic of the arc is depicted in Fig.12. Corresponding arc voltage waveform and arc current waveform are shown in Fig.13 and Fig.14 respectively.

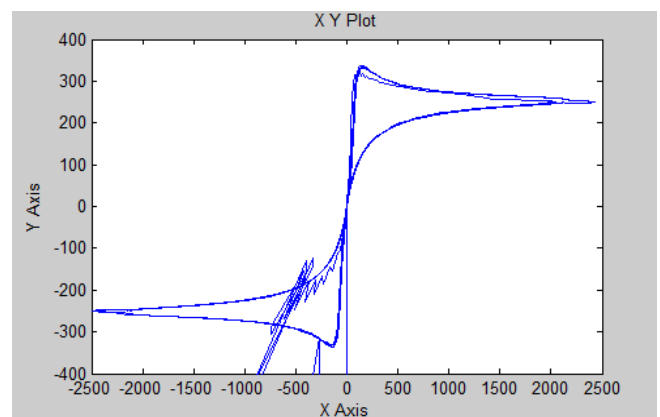


Fig.12. Voltage-current characteristics of arc

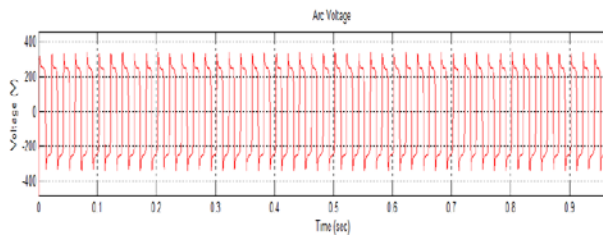


Fig.13: Arc voltage waveform

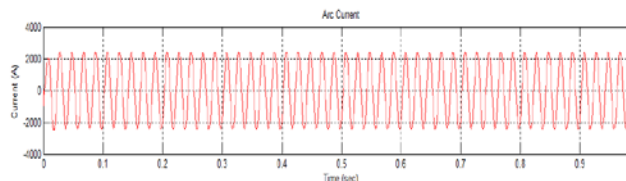


Fig.14: Arc current waveform

7.2 Dynamic Characteristics

7.2.1 Sinusoidal Flicker Generation

The results for the dynamic arc model simulation using the sinusoidal variation law for the arc effective voltage is shown in this section. The flicker frequency was randomly chosen to be 4 Hz. The corresponding voltage-current characteristic, arc voltage waveform and arc current waveform are shown in Fig.15, 16 and 17.

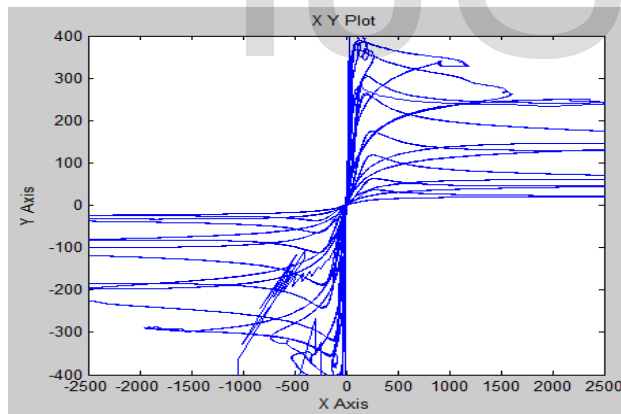


Fig.15: Voltage-current characteristics of arc

The simulation results obtained shows that if the arc furnace generates sinusoidal flicker, the arc voltage and current are varied sinusoidally with the flicker frequency. The flicker phenomenon is visible for the electrical bulbs that are rapidly changing the light intensity. Also, the side effects of the flicker are visible for the modern computation technique that could be damaged by the voltage variations.

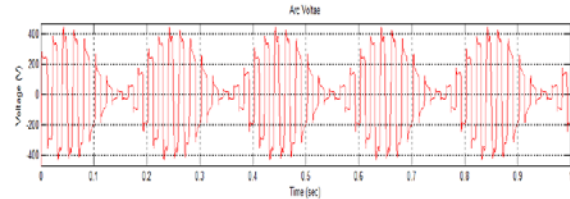


Fig.16: Arc voltage waveform

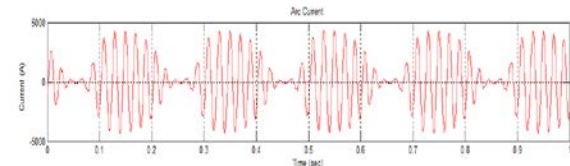


Figure.17: Arc current waveform

7.2.2 Random Flicker Generation

Results pertaining to the dynamic model with band-limited white noise random time variation are presented in this section. The voltage-current characteristic for random variation is shown in Fig.18. The corresponding arc voltage and arc current waveforms are shown in Fig.19 and 20 respectively.

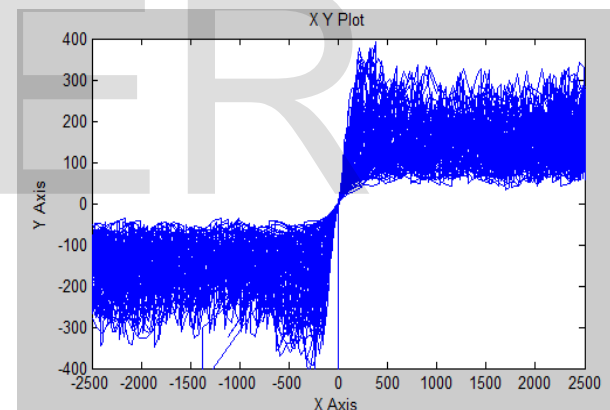


Fig.18: Voltage-current characteristics of arc

The results obtained for random variation of arc furnace shows that the arc voltage and current are varied randomly. Thus, we see that the furnace load flicker leads to a variation in the voltage of the bus supplying EAF and the nearby buses in the interconnected system.

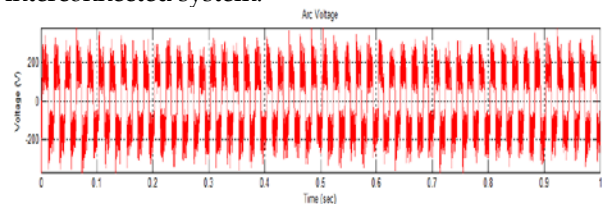


Fig.19: Arc voltage waveform

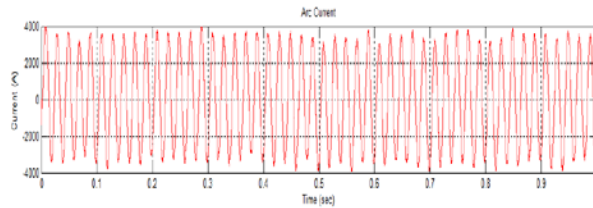


Fig.20: Arc current waveform

8. CONCLUSIONS

In this paper, an electric arc furnace is modeled using the Cassie-Mayr arc equations capable of representing the static and dynamic characteristics of the arc furnace load. There are current fluctuations in the EAF during the melting process which causes flicker phenomenon. The flicker effect is simulated using sinusoidal and random signals in this paper. The voltage-current characteristics corresponding to sinusoidal and random variations are shown in this paper.

The utilities are working on how to mitigate the flicker efficiently and economically. The fast response of the distribution static compensator (DSTATCOM) makes it efficient solution for improving the power quality in the distribution system. By using the adequate control strategy we can compensate the load reactive power variations, reduce the voltage flicker, improve the power factor and stabilize the voltage profile.

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