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Investigation of Power Quality Disturbances in an Electric Arc Furnace

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***Abstract* - Stochastic performance of an electric arc furnace (EAF) has drawn researcher's attention due to power quality problems introduced by EAF operation. In this paper, Electric arc furnace is modeled to investigate power quality problems. Voltage flicker, harmonics and inter-harmonics are the main power quality disturbances that arise in the electrical network as a result of arc furnace operation due to the non-linear nature of EAF. A time domain model is derived to study the behavior in various operating conditions (melting and refining). The characteristic modeling of an EAF is carried out in MATLAB (Simulink).**
***Keywords:* Electric Arc Furnace(EAF), Power Quality, Voltage Flicker**

I. INTRODUCTION

Now-a-days steel production by Electric arc furnace is widely increased (About 56% of total steel is made using electric route. Out of this 56%, 22% steel is made on Electric Arc Furnaces (EAF) and rest on Induction Furnace (IF), etc.) due to its several advantages like scrap is used for making steel rather than ores and flexibility, but these advantages are overshadowed by the power quality disturbances introduced by the arc furnace in the system like voltage flicker , harmonics, low power factor. Due to time varying behavior of Electric arc furnace it introduces voltage fluctuations at Point of common coupling & disturbs customers by causing flicker of bulbs and lights. It is stated that a small voltage fluctuation of less than 0.5% in the range of frequency 5-10Hz can cause visible flicker.

EAF is an Unbalanced and periodically varying load, which introduces several disturbances to power system quality. These problems should be dealt and appropriate measures should be taken to mitigate it. The major threats to the power quality are the long and short duration voltage variations, harmonics, inter harmonics etc.

To investigate the harmonic and voltage flicker introduced by an Electric arc furnace in the electrical network, Arc furnace is modeled based on its characteristics and its different stages of operation.

Figure 1 puts forward the typical line-voltage fluctuations generated by the operation of an arc furnace. The voltage fluctuation altogether introduces a typical phenomenon termed as "flicker."

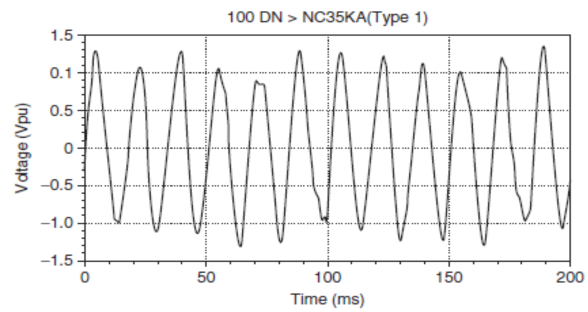


Fig. 1 Voltage flicker curve

Due to the distortion of arc furnace currents, as a result voltage also distorts, which is a serious issue because of their common usage. The modern day Electric arc furnaces are operated at poor power factor. The distortion of current is highest during the melting period, whereas it is reduced in the further stages of operation (air refining and refining). A typical amplitude spectrum of the current – during melting is shown in Figure 2.

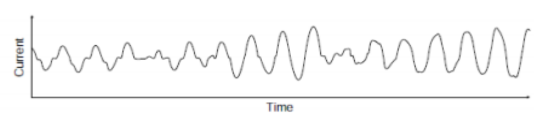
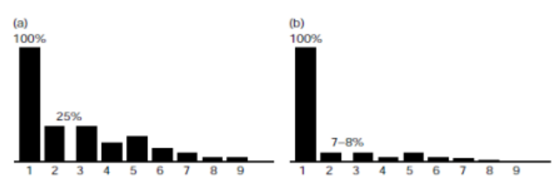


Fig. 2 Arc furnace current

Figure 3 is the spectrum that exhibits the characteristics and non-characteristics harmonics under different stages of EAF operation.



(a)Melting Period (b) Refining Period
Fig. 3 Harmonic spectrum of arc furnace current

II. ELECTRIC ARC FURNACE

Electric arc furnace is used in Steelmaking has emerged as an important steelmaking process in recent years. One of the methods is through production of electric arc which gives an arc temperature between 3000C to 3500C. Arc is the flow of current through an air gap between two electrodes.

The arc furnace has subsequent operations:

1. Furnace charging
2. Melting
3. Refining
4. De-slagging

The first step of operation cycle is "charging” the scrap and the electrodes are lowered to strike an arc on the scrap. This commences the melting portion of the cycle. The melting stage is the main part of EAF operation, melting is started by supply of energy to the arc furnace (electrical or chemical).graphite rod, is major contributor in melting process, through which the electrical energy is transmitted. The nature of arc is highly unpredictable and unstable during the initial stages of melting process. Large variations in the arc currents are visualized along with fast variations in the position of electrodes.

Further it is observed that, the arc stabilizes as the temperature in the furnaces has been increased, and once the charge gets melted forming a molten pool, the arc becomes stable and the average power input increases and then refining process starts.

The energy required for this process is very large and is dependent on the requirement of steel or scrap to be melted. The transformer loads may reach as high as 100MVA.

The steel making process using Electric arc furnace is chaotic in nature. The variations of voltage both with respect to magnitude and frequency are the characteristics of voltage flicker, and the injection of integral and fractional multiples of fundamental frequency components of supply voltage is termed as voltage harmonics and voltage inter harmonics.

The arc resistance of an EAF is highly variable making the V-I characteristic be non-linear, thereby introducing harmonic currents, resulting in voltage harmonics due to circulation of harmonic currents in an electrical network.

III. MODELING OF ELECTRIC ARC FURNACE

Detailed electrical operations of an EAF have been outlined in the preceding sections. As evident, the EAF is unbalanced, highly non linear, periodically varying load. Since such random behavior is difficult to be realized on a simulator, many researchers have published various models that can be used to simulate the characteristics.

The modeling is described based on the solution of non linear differential equation which closely approximates a practical arc furnace, In this part, to study the arc furnace behavior the modeling is done based on V-I characteristics of the EAF. Various time domain models are derived.

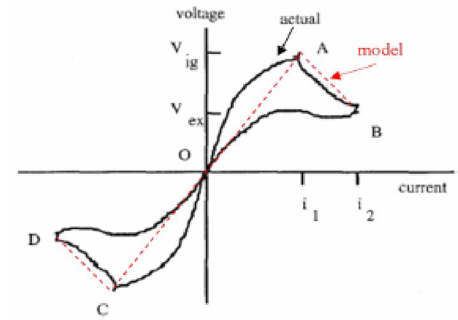


Fig. 4 Actual & approximated (linear piece wise) V-I characteristics of EAF

A. Hyperbolic model

In this model, the arc current and voltage are expressed with the relationship given by below equation.

$$V = \left\{VT + \frac{Ci,d}{Di,d}\right\} sign(I) \qquad (1)$$

VT: Arc voltage threshold value, when the arc current tends to increase. (VT=200)
I= Arc current
V= Voltage

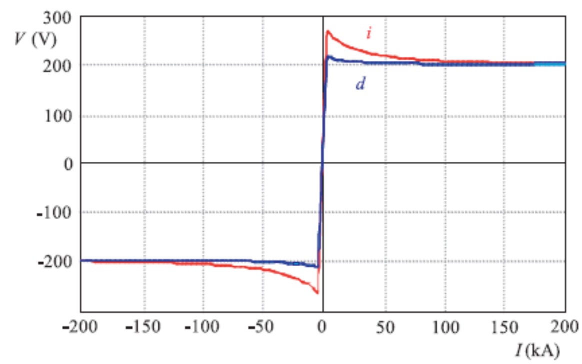


Fig. 5 Actual VI characteristics of hyperbolic model in static state

B. Exponential Model

In this model, the Voltage-current characteristic of the arc is articulated as an exponential function. The relationship between arc current and voltage in this model is given by below equation 2.

$$V = Vat\left(1 - e^{\frac{-|I|}{I0}}\right) sign(I)$$

Vat: arc voltage threshold value, when the arc current tends to increase.
$Vat = 200$
I= Arc current
V=Voltage
Io: constant current used to model the sheerness of negative and positive currents.

The above two models (Hyperbolic and exponential) can combined to a single model by significant evolution function in the combined model, voltage follows hyperbolic model characteristic during low arc currents and follows exponential model characteristic during high arc currents.

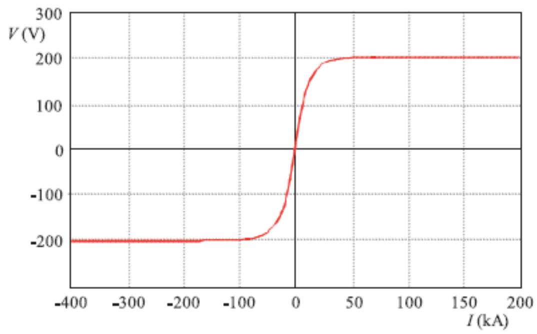


Fig. 6 Actual VI Characteristic of Exponential model in the static state

C. *Exponential-Hyperbolic Model*

The Voltage-Current characteristic of the above proposed model is given by equation 3:

$$V = \begin{cases} VT + \dfrac{C}{D+I} & \dfrac{dI}{dt} \geq 0, I > 0 \\ VT * \left(1 - e^{\frac{-|I|}{I0}}\right) & \dfrac{dI}{dt} < 0, I > 0 \end{cases} \quad (3)$$

The above proposed model has the ability to describe the Electric Arc Furnace behavior in time domain. The above model explains the different working stages of EAF like melting, refining stage. The melting stage introduces voltage flicker and refining stage introduces harmonics in current and voltage at PCC.

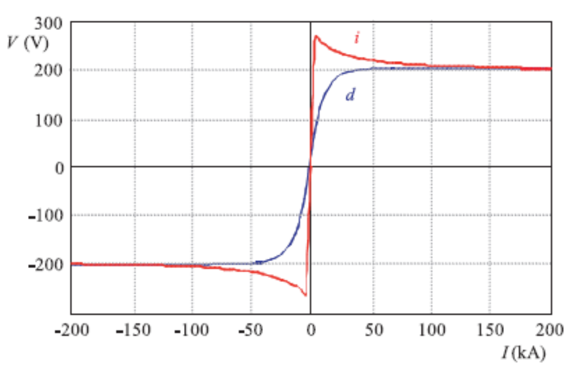


Fig. 7 Actual VI Characteristic of Proposed model

IV. RESULTS AND DISCUSSION

The characteristics of different time domain arc models can be studied by considering an EAF in single phase circuit. The EAF system arrangement is as shown in figure 8. The source impedance is represented as Zs and the source side transformer represents PCC and the EAF bus represents the secondary side of transformer having impedance as Zt. The electric arc furnace model can be implemented using the MATLAB function block.

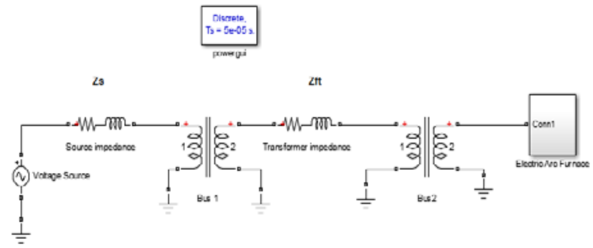


Fig. 8 Single Phase Test circuit of EAF

The specifications of the source, system impedance, and parameters of EAF are mentioned in the table I.

TABLE I SYSTEM SPECIFICATIONS

Items	Parameters
System	V=566V , f=50Hz Zs=0.0568+j0.468mΩ Zt=0.3366+j3.22mΩ
Hyperbolic Model	Melting stage Ci=190kW Di=5000A
	Refining stage Cd=39kW Dd=5000A

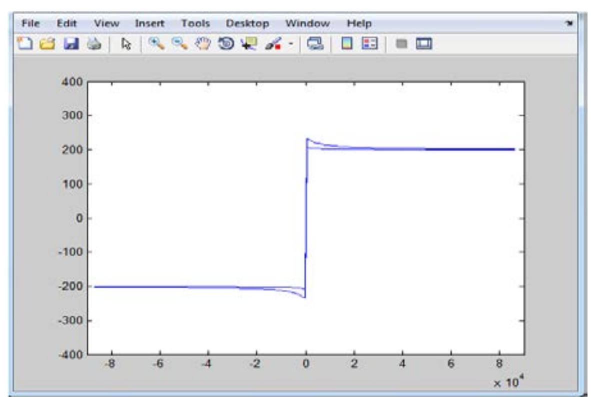


Fig. 9 VI-characteristics of hyperbolic model in static state

The static V-I Characteristics of Hyperbolic model is as shown in the figure 9. It is observed that the arc voltage is a hyperbolic function of an arc current and the characteristic curve has two curves forming the three zones of operation of an EAF, the curves for increasing and decreasing values of arc current with different constants under various operating conditions are simulated. This model nearly resembles the actual V-I Characteristics of an EAF model.

Figure 10 displays the V-I Characteristics of an exponential model in static state. The characteristic curve shows the exponential behavior of the arc voltage with respect to the arc current and the characteristic curve has two regions consisting of a linear and exponential regions.

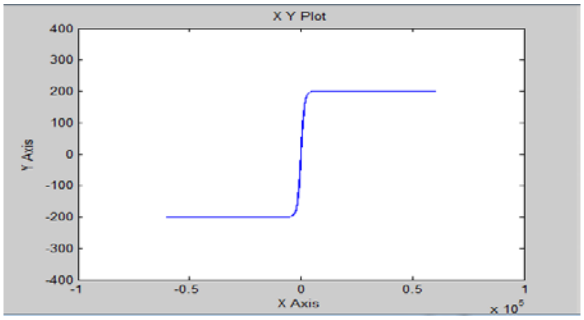


Fig. 10 VI-characteristics of Exponential model in static state

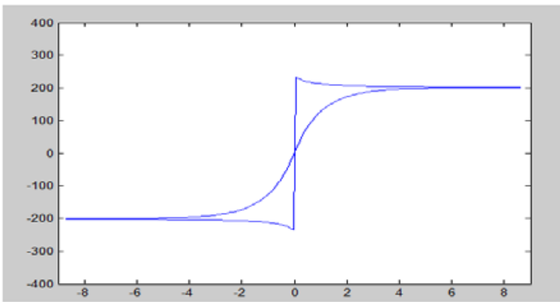


Fig.11 VI-characteristics of Exponential- Hyperbolic model in static state

The static characteristics of Hyperbolic-Exponential models are as shown in the figure 11.The characteristic curve displays both the exponential and hyperbolic nature of the arc voltage with respect to variation in arc current and the characteristic curve has three working phase.

V. HARMONIC BEHAVIOR OF EAF SYSTEM

The Three phase Test circuit of EAF connected supply system developed in Simulink is displayed in Figure 12. A three phase voltage source with suitable line impedance is used to couple the EAF to power system. The electric arc furnace model can be implemented using the MATLAB/SIMULINK function block and a sinusoidal block.

Each electric arc furnace MATLAB Function block represent each electrode at each phase; therefore, three MATLAB function blocks are required for each phase. The sinusoidal is used to model the flicker frequency and magnitude variation.

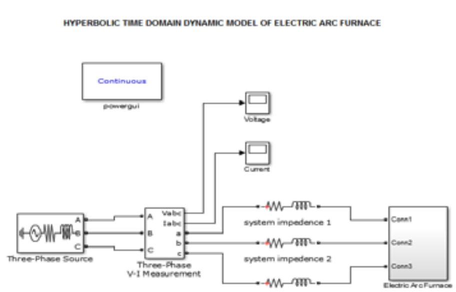


Fig. 12 Three phase Test circuit of EAF connected supply system

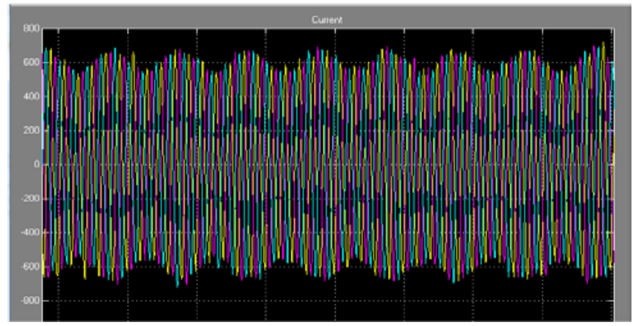


Fig.13 Three phase Arc current Waveform during Melting stage

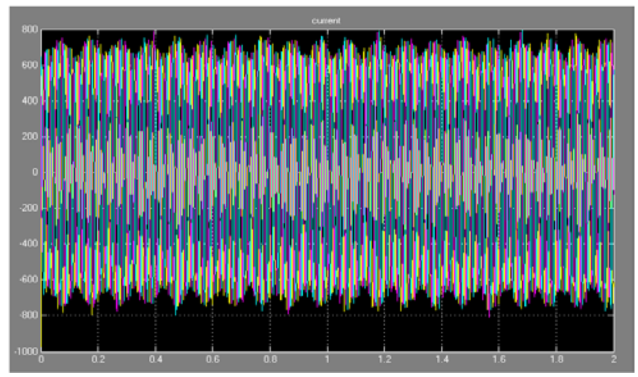


Fig. 14 Three phase Arc current Waveform during refining stage

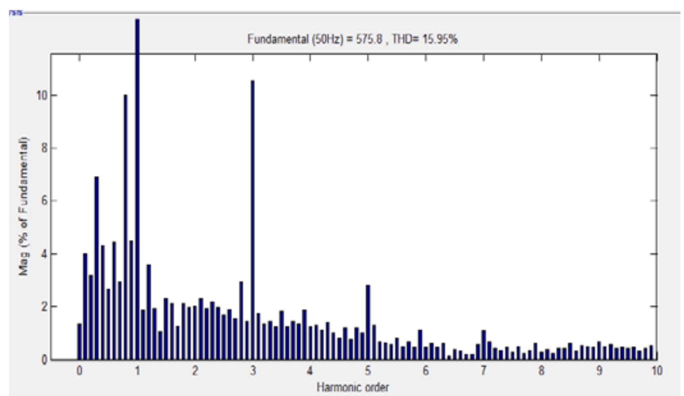


Fig.15 Arc furnace current harmonic spectrums during Melting

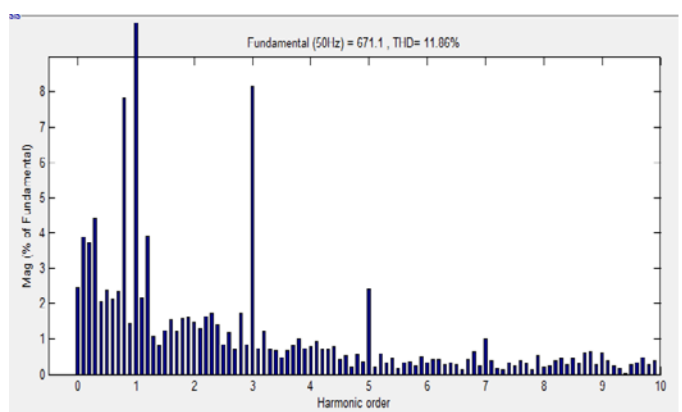


Fig.16 Arc furnace current harmonic spectrums during Refining

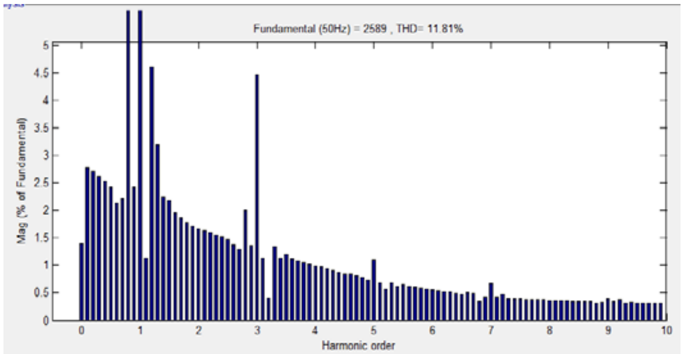


Fig.17 Arc furnace current harmonic spectrum in Exponential model

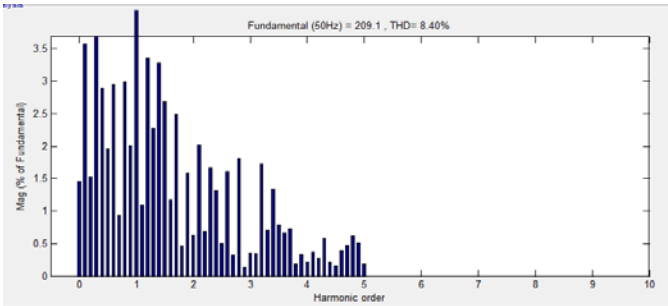


Fig. 18 Arc furnace current harmonic spectrum in Exponential-Hyperbolic model

TABLE II HARMONIC COMPONENT COMPARISONS OF DIFFERENT STAGES OF OPERATION

Harmonic order	Hyperbolic		Exponential Model	Exponential-Hyperbolic Model
	Melting stage	Refining Stage		
3rd (%)	10.53	8.15	4.47	0.35
5th (%)	2.81	2.40	1.10	0.18
7th (%)	1.10	1.01	0.66	-
9th (%)	0.69	0.60	0.40	-
THD (%)	15.95	11.86	11.81	8.40

Table II puts forward the harmonic distortion of an arc furnace current of the above time domain models. As discussed earlier, since the arc is unstable during the melting process, the non linearity is high under this condition ,hence the presence of the lower order harmonics results to the higher distortion levels in hyperbolic model, as the arc stabilizes in refining period the non linearity reduces comparatively hence resulting in lower THD during refining process.In both the exponential and Exponential-Hyperbolic model of an EAF, as the characteristics are linearized, the presence of the harmonics is relatively low compare to hyperbolic model.The harmonic spectrum of arc current of different models shows the significant presence of inter-harmonics which altogether contributes to the increased Total harmonic distortion of the system.Table III provides the information regarding the voltage flicker levels of different time domain models of an EAF, it is observed that the voltage flicker is high is case of hyperbolic-exponential model than the others.The mathematical equations and definitions for the voltage flickers are described in [6].

TABLE III VOLTAGE FLICKER of DIFFERENT TIME DOMAIN MODELS

Model	%Voltage Flicker
Hyperbolic- Melting stage	1.54
Hyperbolic- Refining stage	2.01
Exponential	10.85
Exponential-Hyperbolic	23.45

VI. CONCLUSION

EAF is a highly non linear, timely varying load with chaotic behavior introducing several power quality disturbances to the system. The static behavior of the Various Electric arc furnace models is studied and the results obtained indicate the existence of voltage flicker in the system. Hyperbolic and exponential model are studied in detail and a new model is derived. The new model exhibits characteristics for both increasing and decreasing currents. This model clearly indicates voltage and current unbalanced situation, voltage flicker when connected to power system and clearly resembles the Electric arc furnace. From the simulated results, the harmonic distortions and the voltage flicker of the arc models are exceeding the IEEE standards. These power quality problems cause disturbances to in the system. Hence, these issues with respect to arc furnace must be mitigated.

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