

# Power Quality Analysis of Non- Linear Loads for Industrial Power System

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**ABSTRACT :** Power quality is becoming a more concern of today's power system due to rapid growth of non-linear loads in distribution network. This project mainly considering the highly nonlinear and time varying loads like electric arc furnaces. Electric arc furnaces (EAF) is one of the typical industrial non-linear loads responsible for deteriorating the power quality in the distribution network by introducing harmonics, annoying, voltage flicker and causing unbalance in voltages and currents. Hence EAF modeling is needed to study and analyze the power quality in the distributed network especially at connection point (pcc). This project modeling of electrical arc furnace is done based on V-I characteristics. Validation of the proposed model is performed by comparing the simulation results. Mitigation of voltage flicker can be done by using different facts devices and comparing the results.

**KEYWORDS:-**Electric arc furnaces, furnace modeling, flicker analysis, MATLAB/SIMULINK.

## I.INTRODUCTION

Electric Arc Furnaces (EAF) converts electrical energy into thermal energy and are widely used in to melt the metal in iron and steel industry. Nowadays, 40% of the steel produced is provided by EAF and this proportion is expected to rising 50% until in 2050. In addition to Electric Arc Furnaces are the most elements that use the electrical energy industry. Therefore, efficiently use of energy in EAF systems is one of the important problems in nowadays.

Electric arc furnaces are nonlinear and time-varying loads, and cause many problem of power quality such as imbalances, odd and even harmonics, inter harmonics, voltage drops and flicker in power systems. The main factors in this power quality deterioration is disturbances in waveform which generated by stochastic behavior of electric arc furnace[1]. Electricity producers and customers are tried to minimize as much as possible these negative effects caused by electric arc furnace. For minimizing power quality effect caused by EAF is required define the behavior of electric arc furnace load. The modeling of arc furnace load which have stochastic and non -linear features is quite difficult. The main issue in the modeling of electric arc furnace is to define of electrical arc. There are many methods used to approximate modeling of the electrical arc. Time and frequency domain modeling of electric arc can be shown in between these methods [2, 3]. In the modeling of electrical arc are benefited time domain methods which used as the basis for Cassie and Marry differential equations [4]. In addition to, in order to the analysis of EAF are used different methods such as varied linearization methods of nonlinear equations [5, 6], frequency response [7] and current-voltage characteristics [8]. Used this methods allow to study the static and dynamic characteristics of EAF. In the static characteristic conditions obtained with constant arc length does not occur the voltage flicker. However, due to the changes in the length of the arc during melting because of nonlinear characteristic of EAF constantly changes the arc current and cause to voltage flicker problem. In examinations is known that voltage flicker changes between the range of 4-10 Hz and this changes is disturb to people by perceived with the human eyes. In the time domain analysis, the parameters are determined using the harmonic source voltages and the unbalanced three phase currents [9,2,10]. When the EAF model in the time domain is compared with the model in the frequency domain, it can be concluded that modeling in the time domain is more efficient in studying the arc furnace elements and the EAF performance. However, the frequency domain models are more suitable for harmonic analysis of the external network. The external

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network is the model of a linear system at each harmonic. In the above explained methods, there are some limitations such as need to initial conditions for solving the differential equations, balanced operating condition of the three phases of the EAF and use of sophisticated mathematical equations for the estimation of the arc model. Considering the mentioned limitations, this study presents a new model for the EAF in the time domain. The main aspect of the new model is modeling of the proposed method with a good approximation without need to the initial conditions of the EAF performance. Also, the proposed method can be used to describe the different operating conditions of the EAF and . 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 and sinusoidal noise is employed to establish a new model of the furnace load. Then, unbalanced situation of the currents and voltages, the effects of the furnace load and voltage flicker are studied in the new model.

## II. TEST SYSTEM

Figure 1 shows the electric diagram of a source which supplies an EAF. In order to change the active input power of the arc furnace, a furnace transformer,  $T_F$  is used. This transformer is connected to point of connection, PC. This transformer is equipped with a tap changer located at the secondary winding. This tap changer varies the voltage of the furnace. The arc furnace is also connected to the point of common coupling, PCC, through the substation transformer,  $T_S$ . The simplified diagram of ps is shown below.

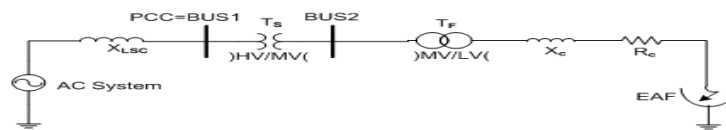


Fig. 1: Circuit Diagram Of An Eaf Connected To Rest Of Power System

In Fig. 1,  $X_L$  is the utility reactance.  $T_S$  is step down transformer of 132/30 kV, it's acts as pcc point and  $T_F$  is furnace transformer of 30/(0.7-1.9) kV The elements of  $X_c$  and  $R_c$  (neglect) are the reactance and resistance of line between furnace electrodes and  $T_s$  [11]. This impedance is the dominant part of the total impedance seen by the arc furnace.

TABLE I

Per unit values of circuit elements

Element	X p.u
Line	0.315
Transformer( $T_s$ )	0.13
Line2	0.445
Transformer( $T_f$ )	0.10
Furnace reactance	0.003

## III. MODELING OF ELECTRIC ARC

For the modeling of electrical arc is benefit from the Current-Voltage (V-I) characteristics that formed by the electrical arc. Actual V-I characteristic of electrical arc measured in the case of static progress is shown in Figure 2.

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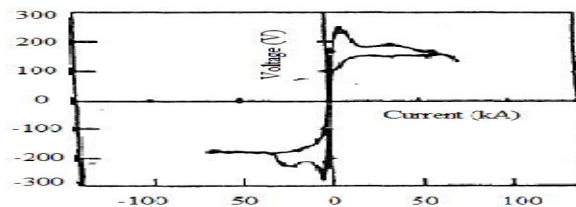


Fig 2. Actual V-I Characteristic Of Electrical Arc Measured In The Static Progress

As mentioned above, the operation of arc furnaces have stochastic properties and arc length is variable with time. Therefore, arc current changes. Variation of the arc current cause voltage drop and voltage flicker. Because of this reason, dynamic characteristic of EAF should be used in the modeling. For the creation of dynamic characteristic of EAF is benefited from static characteristic. As a result of, the simulation results has been compared with the real-time measurement and the most appropriate model for indentify to arc characteristic of EAF has been determined.

**Model 1: Hyperbolic model:** In this model the VIC of the EAF is considered to be in the form of  $V_a = V_a(I_a)$  and it

can be described as:

$$(1) \quad V(I) = V_{at} + (C/(D+I))$$

where, I and V are arc current and voltage of phase a. Also  $V_{at}$  is the threshold magnitude to which voltage approaches as current increases. This voltage depends on the arc length. The constants C and D are corresponding to the arc power and arc current ,respectively. These constants can take different values which depend on the sign of the derivative of the arc current. Since Eq. 1 has a behavior similar to hyperbolic function, it is called hyperbolic model. There are two paths to increase or decrease of current. first path is related to the increasing state of the current and the second path is associated with decreasing state of the current. In this regard, the constants C and D are classified into two groups. The constants for the first group (or first path) are  $C_a$  and  $D_a$ . Also constants of the second group (or second path) are  $C_b$  and  $D_b$ .

**Model 2: exponential model:** In this model the VIC of the EAF is approximated by an exponential function as follows:

$$(2) \quad V(i) = \begin{cases} V_m(1 - e^{-i/\tau}), & i \geq 0 \\ -V_m(1 - e^{-i/\tau}), & i < 0 \end{cases}$$

In the Eq. 2, the current time constant ( $\tau$ ) is used to describe the positive and negative currents. The exponential function is also used to model the VIC of the arc. This model can be used in optimization and stability issues of the EAF.

**Model 3:Proposed model: Exponential-hyperbolic model:** In this model the VIC of the EAF described using the following equations:

$$(3) \quad V(i) = \begin{cases} V_m + \frac{C}{D+i} & \frac{di}{dt} \geq 0, i > 0 \\ V_m(1 - e^{-i/\tau}) & \frac{di}{dt} < 0, i > 0 \end{cases}$$

In above equation,  $\tau$  is the current time constant in kA. As can be seen as in from this equation, for the positive current and regarding the hysteresis property of the arc, there are two cases. To increase and decrease the current of the EAF, the hyperbolic equation and exponential form of the equation are used, respectively. The proposed method has the capability of describing the EAF behavior in time domain using differential equation [5].

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### IV. DYNAMIC ELECTRIC ARC MODEL

**The Unbalanced situation in the proposed method:** In order to discuss the unbalanced condition we assume electric arc in two types of flicker 1) sinusoidal flicker 2) random flicker

#### A. THE MODELING OF SINUSOIDAL FLICKER EFFECT

The effect of the sinusoidal flicker is determined by the mathematical expression in equation (4).

$$V_{at(t)} = V_{at} \cdot (1 + m \cdot \sin(w_f \cdot t)) \quad (4)$$

In this equation,  $V_{at}$  is threshold voltage depended on the arc length.  $m$  is modulation index and  $w_f$  is flicker frequency.

#### 4.2. The Modeling of Random Flicker Effect

Random flicker is modulated as a random signal having zero mean of the frequency band between 0-12 Hz frequency range. Random flicker is determined by mathematical expression in equation (5).

$$V_{at(t)} = V_{at} \cdot (1 + m \cdot N(t)) \quad (5)$$

In this equation,  $V_{at}$  is threshold voltage depended on the arc length,  $N(t)$  is band limited white noise signal and  $m$  is modulation index [8].

### V. COMPENSATION TECHNIQUES

#### A. DYNAMIC VOLTAGE RESTORER

Switching off a large inductive load or energizing a large capacitor bank is a typical system event that causes swells. Then, a simple control based on dqo method is used to compensate voltage sags/swell. At the end, MATLAB/SIMULINK model based simulated results were presented to validate the effectiveness of the proposed DVR. Voltage sag is the most sever power quality problem faced by industrial customers. Voltage sag/swell is common reasons for malfunctioning in production plants.

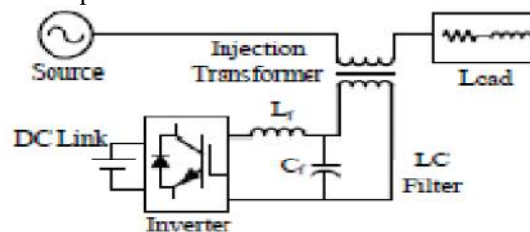


Fig.3. Basic Components Of A Dvr

During voltage sag, the DVR injects a voltage to restore the load supply voltages. The DVR needs a source for this energy. Two types of system are considered; one using stored energy to supply the delivered power as shown in Fig.3, and the other having no internal energy storage. There are a number of voltage sag/swell mitigating methods available but the use of custom power service is considered to be the most efficient method. This paper introduce basic concept of DVR (Dynamic Voltage Restore). DVR inject an appropriate voltage magnitude with an appropriate phase angle dynamically. Dynamic compensating signals are determine based on the difference between desired and actual values. Main components of DVR are voltage source converter, injecting transformer, passive filter, and energy storage device. The performance of DVR depends on the efficiency control technique of switching of voltage source inverter (VSI).

#### B. UPQC

According to the basic idea of UPQC, it consists of back-to-back connection of two three-phase active filters (AFs) with a common dc link. The point of common coupling (PCC) could be highly distorted, also the switching ON/OFF of high rated load connected to PCC may result into voltage sags or swells on the n the PCC has been discussed.

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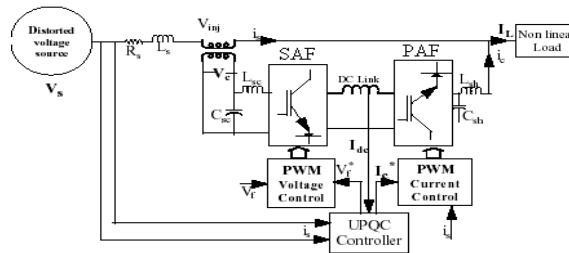


Fig.4 Power Circuit Configuration Of Upqc

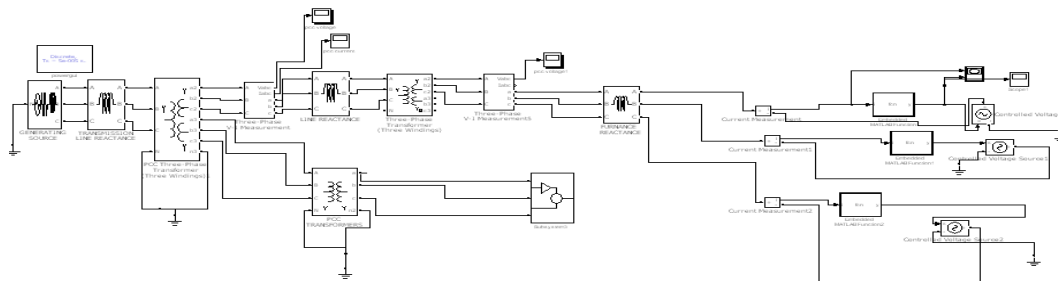
Fig.4 shows the general power circuit configuration of UPQC. This system consists of a PAF and a SAF. The control circuit of UPQC generates the currents and voltages of PAF and SAF in instantaneous and simultaneous manner, respectively. The series active filter connected in series through an injection transformer is commonly termed as series filters (SAF). It acts as a controlled voltage generator. It has capability of voltage imbalance compensation, voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). In addition to this, it provides harmonic isolation between a sub-transmission system and a distribution system. The second unit connected in parallel with load, is termed as Shunt Active Filter (PAF). It acts as a controlled current generator. The shunt active filter absorbs current harmonics, compensate for reactive power and negative sequence current injected by the load. In addition, it controls dc link current to a desired value. In power line conditioner one more element is a dc link inductor, which acts as energy storage device. A small amount of dc power supply is required to operate active power filter for harmonic compensation. The dc link inductor functions as dc power supply sources and hence does not demand any external power source. However, in order to maintain constant dc current in the energy storage element, a small fundamental current is drawn to compensate active filter losses.

## VI.SIMULINK MODEL&RESULTS

### A. STEADY STATE CHARACTERISTICS

**Comparison the different models of the furnace load :** In order to compare the proposed exponential- hyperbolic model with the other models, firstly the results of simulations hyperbolic load model are presented. In Model 1, the parameters of EAF characteristics are chosen as:  $V_{at}=250$  V,  $C_a=190000$  W,  $C_b=39000$  W,  $D_a=D_b=5000$  A

Simulink model of EAF connected to power system is shown in fig. 5. Using these parameters, the VIC of the EAF is derived and shown of Fig. 6.



. Fig 5. Simulink Model Of Eaf Connected To Power System

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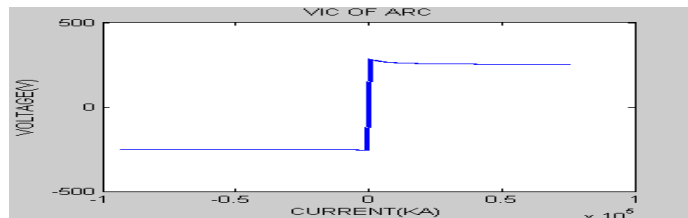


Fig6. VIC Of Arc In The Hyperbolic Model

The second simulation is associated with exponential model. This model is formed based on Eq. 2. The constant parameters in this model are chosen as:  $V_{at}=250$  V,  $T = 10$ KA. With the above values for the parameters, the VIC of the arc is obtained as shown in Fig. 7

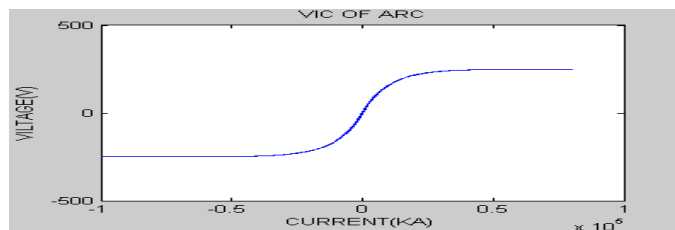


Fig 7. VIC Of Arc In The Exponential Model

**Results for the proposed exponential-hyperbolic method:** In this part, the results for the proposed exponential-hyperbolic method are studied. In the proposed exponential-hyperbolic model, the parameters are a combination of hyperbolic and exponential. The derived VIC of the arc is depicted in Fig. 8. At the points of this characteristic where the length of the arc is not varied with time, this characteristic is assumed to be constant. Based on comparison of VIC characteristics of 3 models with fig 2 we conclude exponential-hyperbolic model is suitable from actual VIC characteristics(hysteresis).

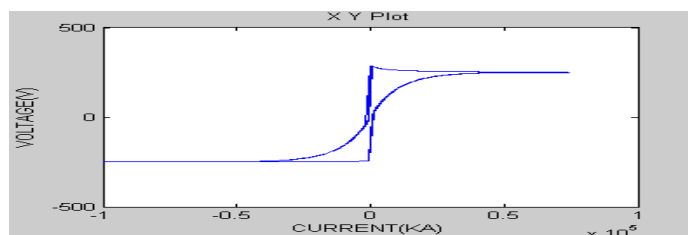


Fig 8. VIC Of Arc In The Exponential-Hyperbolic Model

The voltage waveform of exponential-hyperbolic model is shown in fig 9.

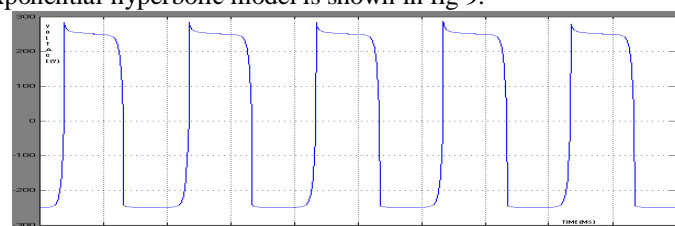


Fig 9. Waveform Of Voltage In Exponential-Hyperbolic Model

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## B.DYNAMIC CHARACTERISTICS

**Results for analysis of voltage flicker:** Arc length in the operation of the arc Furnace is variable. Therefore, identifying the dynamic characteristics of electrical arc is required for understanding the behavior of EAF. Steady-state characteristics are used for determine dynamic characteristic of electrical arc. In the simulation, Flicker effect is modeled with sinusoidal and random flicker effects in section 4. In the simulation, simulation parameters have been used to  $V_{at}=250\text{volt}$  and  $m=0.5$ .

**Sinusoidal flicker:** In this part, the simulation of the voltage flicker using the sinusoidal voltage is carried out based on Eq. 4. The values for the parameters used in Eq. 4 are:  $V_{at}=250\text{ V}$   $M=0.5$ .the VIC of arc is shown in fig 10 and voltage waveform of interconnected bus(pcc) is shown in fig 11

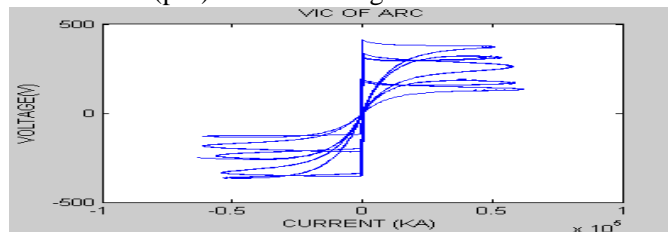


Fig 10.VIC Of Arc In Exponential-Hyperbolic Sinusoidal Flicker

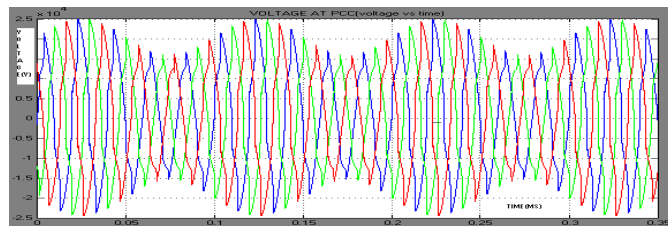


Fig 11.Pcc Voltage Waveform In Case Of Sinusoidal Flicker

**Random flicker:** In this part, the simulation of the voltage flicker using the random voltage is carried out based on Eq. 5. The values for the parameters used in Eq. 5 are:  $V_{at}=250\text{ V}$  and  $M=1$ . Also in Eq. 6,  $N_1(t)$ ,  $N_2(t)$  and  $N_3(t)$  are three white noise voltages with zero mean and variance equals 1 in the limited band (between 4-14Hz). The Vic characteristics are shown in fig 12.

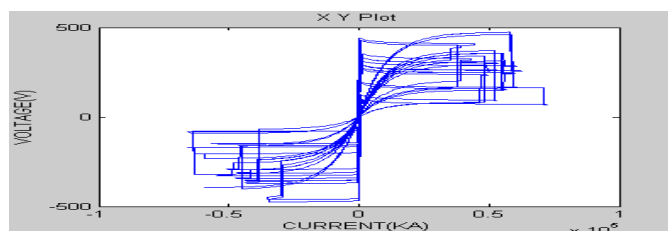


Fig 12.VIC Of Arc In Exponential-Hyperbolic Random Flicker

Voltage and current waveform at pcc, Therefore, arc current changes. Variation of the arc current causes voltage drop and voltage flicker at pcc is clearly shown in fig 13 and 14. due to flickers in voltage and current it injects harmonics in pcc is shown in fig 15. (Here, we assume source is free of harmonics)



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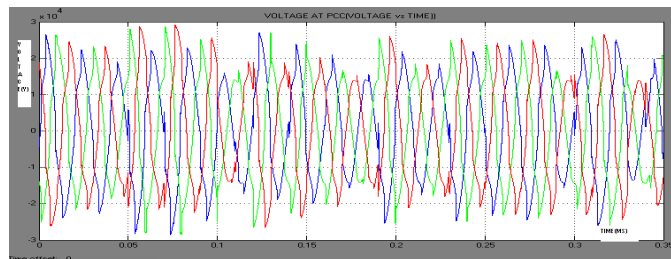


Fig 13.Pcc Voltage Waveform In Case Of Random Flicker

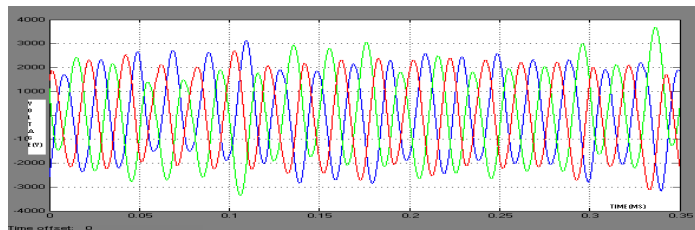


Fig 14.Pcc Current Waveform In Case Of Random Flicker

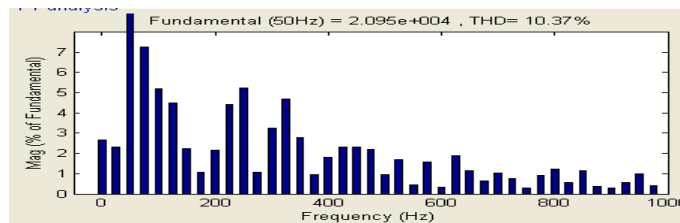


Fig 15. Fft Analysis Of Pcc Voltage In Power System

Based on above characteristics electric furnace connected to power system it create voltage sag/swell and inject harmonics into system. So, we want to mitigate this distortion by using suitable facts devices in order to get healthy power at PCC. Hence, this paper deals with series and series-shunt fact devices .

### C.RESULT OF COMPENSATION TECHNIQUES

**Case 1:** Proposed exponential-hyperbolic Model of Arc Furnace controlled by DVR.

By using dvr( series) to the above system we mitigate the voltage flicker at the PCC. But harmonic distortion decrease to 2% only in order improve voltage profile we further proceed into upqc fact device. Voltage waveform of exponential-hyperbolic model with random flicker connected dvr is shown in fig 16 and harmonic distortion at pcc with connected dvr is shown fig 17

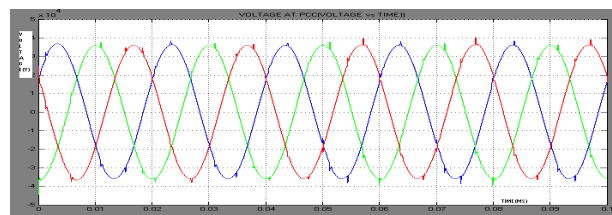


Fig 16.Pcc Voltage Waveform Of Model With Dvr



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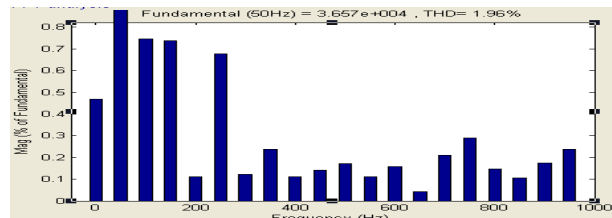


Fig 17.Fft Analysis Of Arc Model With Dvr

**Case 2:** Proposed exponential-hyperbolic Model of Arc Furnace controlled by UPQC

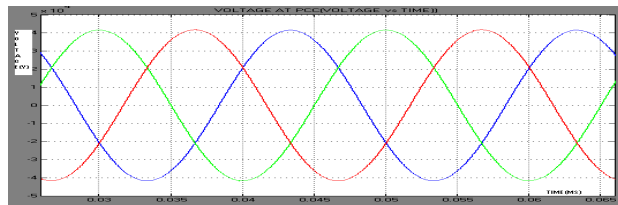


Fig 18. Pcc Voltage Waveform Of Model With Upqc

By using fact device like upqc( series-shunt) to the above system we mitigate the voltage flicker at the PCC and also harmonic distortion decrease to 0.08% . Voltage waveform of exponential-hyperbolic model with random flicker connected upqc is shown in fig 18 and harmonic distortion at pcc with connected upqc is shown fig 19

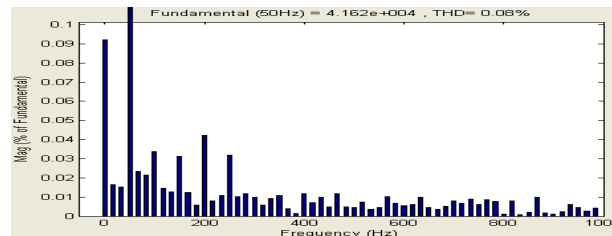


Fig 19.Fft Analysis Of Arc Model With Upqc

## VII.CONCLUSION

This study, firstly investigates the existing hyperbolic and exponential models for EAF. After that, the exponential-hyperbolic model is proposed. The proposed model has no limitation of the existing models and does not require any initial conditions or special needs for modeling of the arc. Most of the specifications of the EAF can be described by the proposed method. This study also proposes a three phase structure of the electric EAF which covers power quality aspects such as: voltage flicker and voltage and current unbalanced situation.

1. In all three models can be used to characterize of the arc furnace.
2. It is observed that voltage changes are periodic with sinusoidal flicker. But when arc furnace is melting, voltage is not periodically with time. Therefore sinusoidal flicker effect is not to identify exactly the RMS values of the voltage occurring in the common coupling point.
3. The exponential-hyperbolic model with random Flicker effect can be used to modeling the arc furnace load and identify the effect of flicker that occurs in an electric arc furnace. Thus, we obtain the examination opportunity for power quality problems caused by the EAF. Exponential-Hyperbolic model with random flicker effect can be used for determine to power quality problems caused by EAF loads.

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DVR and UPQC topology has been proposed in this paper, dvr have capability to mitigate voltage flicker but somewhat fail to decrease harmonic distortion. Upqc has the capability to compensate voltage sags, voltage swells and current harmonics at the pcc bus and also harmonic distortion

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