Investigation of Voltage Quality in Electric Arc Furnace with Matlab/Simulink

Mustafa Şeker, Arif Memmedov

***Abstract*— Electric Arc Furnaces(EAF) are nonlineer and time-varying loads and grid in which they are bounded causes of some power quality problems such as harmonics, voltage flicker and inter-harmonics. Investigation of power quality problems that causes of the EAF is an important research topic. Nowadays, an advanced simulation program allows the modelling EAF loads and makes it the possible to examine the power quality problems caused by EAF. The most important issue in the modelling of EAF is the modelling of electrical arc. There are some different methods used for modelling the electrical arc in the literature. In this study, simulation model for a phase equivalent circuit of electric arc furnace(60 MVA) which is located in Sivas Iron and Steel Enterprises Inc.(SIDEMIR) has been created using Matlab/Simulink. The EAF in simulation has been modeled as nonlinear time-varying voltage controlled source and static and dynamic characteristics of EAF's has been studied by using the different time-domain analysis methods. In addition to HIOKI 3197 Power Analyser connected to common coupling point in transmission line which is feeding to EAF and real- time measurement values are obtained. Simulation results have compared with real-time measurement which is obtained with power analyzer and adherence has assessed.**

***Index Terms*— Arc Furnace, Power Quality, 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 [1]. 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 [2, 3]. 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 [4]. The main factors in this power quality deterioration is disturbances in waveform which generated by stochastic behavior of electric arc furnace [5,6,7]. 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 [8]. 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 [9, 10]. For the voltage flicker analysis in grids used the arc furnace is based on stochastic characteristic of EAF [11, 12]. In the modeling of electrical arc are benefited time domain methods which used as the basis for Cassie and Marry differential equations [5, 10, 13, 14]. In addition to, in order to the analysis of EAF are used different methods such as varied linearization methods of nonlinear equations [15, 18], frequency response [13] and current-voltage characteristics [19]. Used this methods allow to study the static and dynamic characteristics of EAF. Current-voltage characteristic is used the identify the static characteristic of the 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 this study, simulation model for a phase equivalent circuit of electric arc furnace (60 MVA) which is located in Sivas Iron and Steel Enterprises Inc. (SIDEMIR) has been created using Matlab/Simulink 2013. Static and dynamic characteristic of EAF are examined with various time domain methods which is used in the literature for modeling arc furnace load. In addition to, real time measurements with HIOKI 3197 power analyzer have been obtained from common coupling point which feeding the EAF system. Suitability of the applied simulation model has examined as compared simulation results and measurement results.

II. Equivalent Circuit of the Electricity System Supplying to Arc Furnace

A phase Equivalent circuit of the electricity system supplying to arc furnace is shown in Figure 1. Circuit parameters given in Table 1 have been used for the calculation of R and L values which are presented in the impedance of circuit section for SIDEMIR's electrical system. Equivalent circuit parameters have been calculated using specified methods in references [20-23].

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Table 1. Circuit parameters of the electricity system supplying to Arc Furnace

Utility	Short Circuit Power=7250 MVA Utility Voltage=380 kV
Stepdown Transformer(TEIAS)	Transformer Voltage Level=380kV/34,5Kv Transformer Power=100 MVA %z=15
EAF Transformer	Transformer Voltage Level=34,5kV/719V Transformer Power=60 MVA %z=4,9

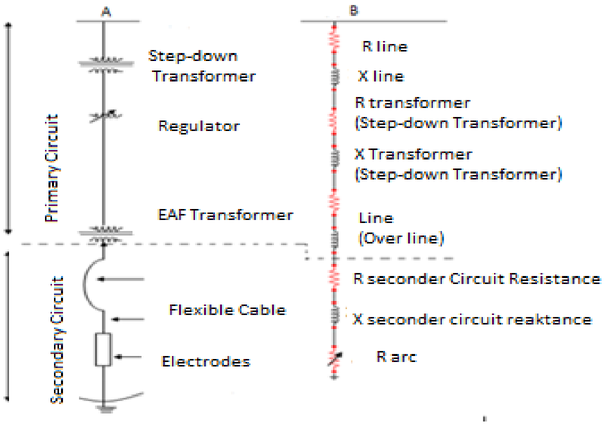


Fig 1. Single line equivalent circuit diagrams of the electrical system supplying to EAF

EAF transformer has 12 voltage levels and EAF transformer is operated at step 12. In this step, voltage level is 719 volt and these voltage levels are used as reference voltage for analysis. Resistance and inductance values for 719 volt reference voltage level take into the consideration the calculation parameters which is given Table 1 and reference [20-23] has been calculated and calculation results has been shown in Table 2.

Table 2. Resistance and inductance values of the system which is feeding the EAF for 719 volt reference voltage level.

	R(mohm)	L(mH)
Utility	0.071	0.027
Step-down Transformer	0.096	2.469
Line	0.004	0.010
EAF Transformer	0.527	1.343
Secondary Circuit	0.612	12.67

III. THE MODELLING OF ELECTRICAL ARC

For the modelling 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 of EAF[10] is shown in Figure 2.

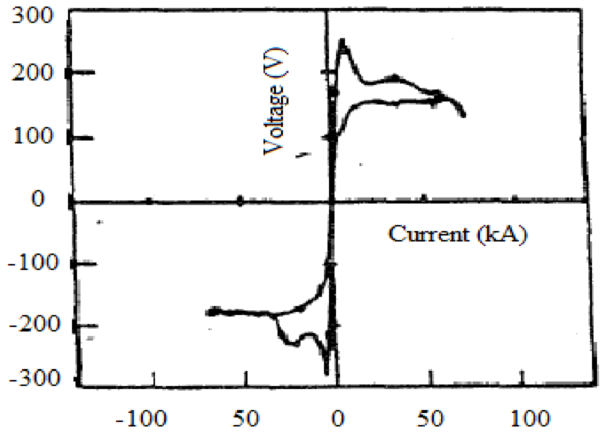


Fig 2. Actual V-I characteristic of electrical arc measured in the static progress with costant arc length

As mentioned above, the operation of electric arc furnaces have stochastic properties and arc length is variable with time. Therefore , arc current changes. Variation of the arc current causes voltage drop and voltage flicker. Because of this reason , dynamic characteristic of EAF should be used in the modelling. For the creation of dynamic characteristic of EAF is benefited from static characteristic. In this paper, static state characteristics graph presented in Figure 2 has been used for determining the static state characteristics of arc furnace for modelling the arc furnace and different time-domain analysis methods has been determined for the create to modeling of electrical arc in simulation. In addition to, HIOKI 3197 power analyzer is connected to common connection point of system feeding the EAF and real-time measurement with this analyzer has been obtained. 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.

3.1. Exponantial Model

In this model, V-I characteristics of electrical arc has been linearized as a exponatial function(1).

$$V(i) = V_{at}.\left(1 - e^{\left|\frac{i}{i_0}\right|}\right).signum(i) \qquad (1)$$

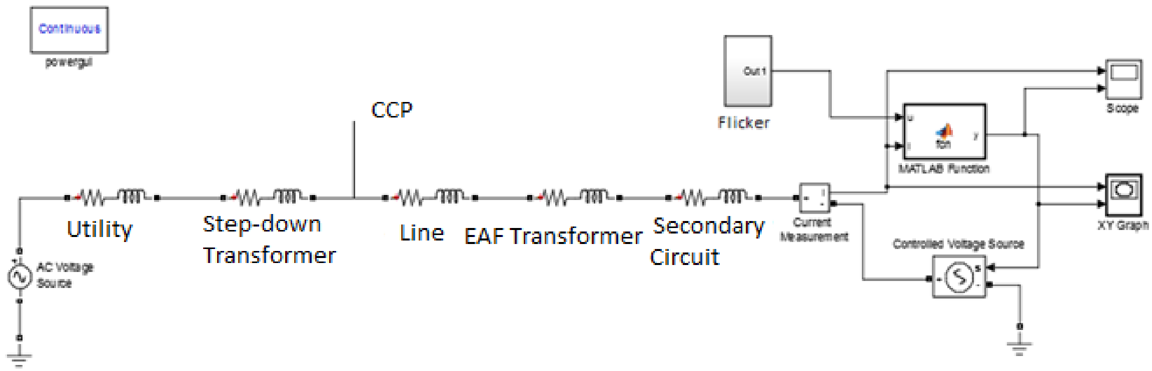
$İ_0$ in this equation is a constant values used to determine the steepness of positive and negative currents. This value is defined from the V-I curve of electrical arc using the static and dynamic characteristic. In this equation, V_{at} is threshold voltage depended on length of the arc length.

3.2. Hyperbolic Model

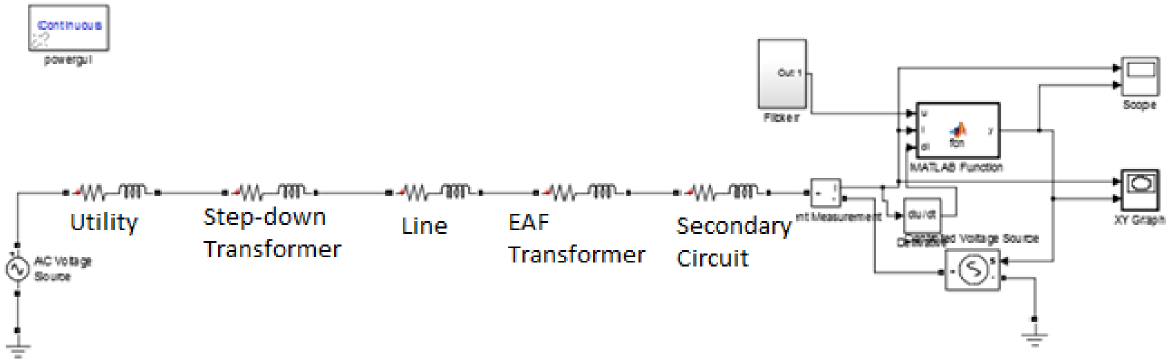
The characteristic of electrical arc in hyperbolic model is evaluated in the form V(i) and is linearized as in the Equation 2.

$$V(i) = \left[V_{at} + \frac{C_{i,d}}{D_{i,d} + |i|}\right].signum(i) \qquad (2)$$

In this equation, V_{at} is threshold voltage depended on length of the arc length. $C_{i,d}$ and $D_{i,d}$ are constant that determine to



(a)



(b)

Fig 3. A phase equivalent Matlab/Simulink system model used to the modelling of electrical arc
a) Exponential model, b) hyperbolic and exponential-hyperbolic model.

arc current and arc power respectively. i index represent the increase in the current and d index represent the decrease in the current.

3.3. Exponential-Hyperbolic Model

In this model, the combination of exponential and hyperbolic model, the V-I characteristic of electrical arc is defined mathematical expression in Equation 3.

$$V(i) = \begin{cases} \left[V_{at} + \frac{C_{i,d}}{D_{i,d}+|i|}\right].signum(i) & ,\frac{di}{dt} \geq 0 \text{ ve } i > 0 \\ V_{at}.\left(1 - e^{\left|\frac{i}{i_0}\right|}\right).signum(i), & \frac{di}{dt} < 0 \text{ ve } i < 0 \end{cases}$$

(3)

In this model, the increase of the current is defined as a hyperbolic function and the decrease of the current is defined as a exponential function. The relationship between arc length (l) and threshold voltage (V_{at}) explained by the expression given in the Equation 4.

$$V_{at} = A + B.l \qquad (4)$$

In this equation, A is a constant evaluated as the sum of voltage sag for anode and cathode and is approximately 40 Volts. B is defined as voltage sag depended on the arc length and empirically is acceptable as B=10 V/cm

IV. THE SIMULATION OF ELECTRICAL ARC

Matlab/Simulink 2013a simulation program has been used for the creation of EAF's simulation model and a phase equivalent circuit model which is shown in Figure 1 for EAF has been developed. Electrical arc has been modelled using nonlinear time-varying voltage controlled source and Matlab/Embedded function. Matlab/Simulink circuit model created for simulation is shown in Figure 4(a) and Figure 4(b). The substation called Flicker in these models is designed to detemine the effect of flicker. In the modelling of flicker effect is defined two models as sinusoidal flicker and random flicker. EAF mentioned in the study(SIDEMIR) is operated at 719 V voltage level for secondary voltage and arc length is approximately 24,3 cm for this voltage level. In this manner, V_{at} is calculated as; V_{at}=40+10x24,3 =283. $C_{i,d}$ and $D_{i,d}$ parameters are used in the calculate as C_i=190Kw , C_d=39kW and $D_{i,d}$=5000 A respectively.

4.1. The modelling of Sinusoidal Flicker Effect

The effect of the sinusoidal flicker is determined by the mathematical expression in equation (5).

$$Vat(t) = Vat.\left(1 + m.\sin(w_f.t)\right) \qquad (5)$$

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

4.2. The Modelling 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 detemined by mathematical expression in equation 6.

$$Vat(t) = Vat.\left(1 + m.N(t)\right) \qquad (6)$$

In this equation, V_{at} is thershold voltage depended on the arc length, N(t) is band limited white noise signal and m is modulation index. Flicker circuit models of equation (6) and (5) used in the simulation has been shown in Figure 4(a) and Figure 4(b) respectively.

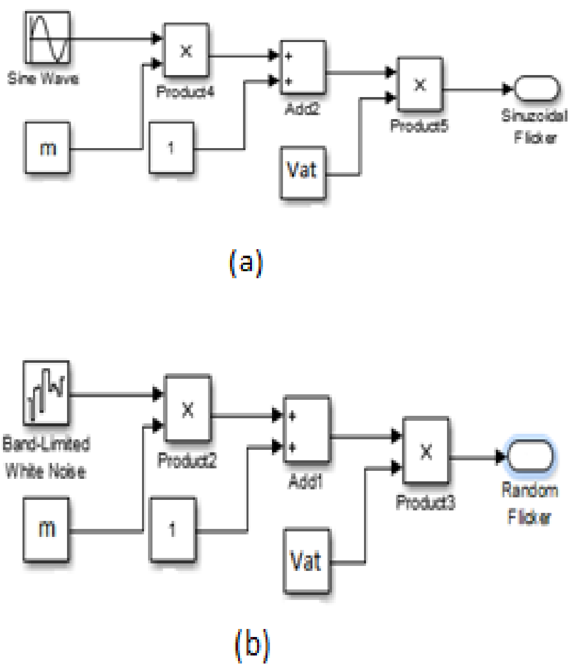


Fig 4. Matlab/Simulink subsystem model used for the flicker effect in simulation a) Sinusoidal Flicker effect, b) random flicker effect

V. STEADY-STATE CHARACTERISTIC OF ELECTRICAL ARC

Steady-state characteristic of electrical arc(Static characteristic) is seen in constand arc length but arc length is always variable because of the nonliear characteristic of EAF. Steady-state characteristic of electrcal arc is used for the determining of dynamic characteristic of electrical arc. Steady-state characteristic of electrical arc used to identify the dynamic characteristics. Simulation results obtained in the steady-state of electrical arc for different models has been shown in Figure 5,7, 9 respectively. In addition to arc current and voltage curves in steady-state of electrical arc has been shown in Figure 6,8 and 10.

5.1. Model 1: Exponantial Model

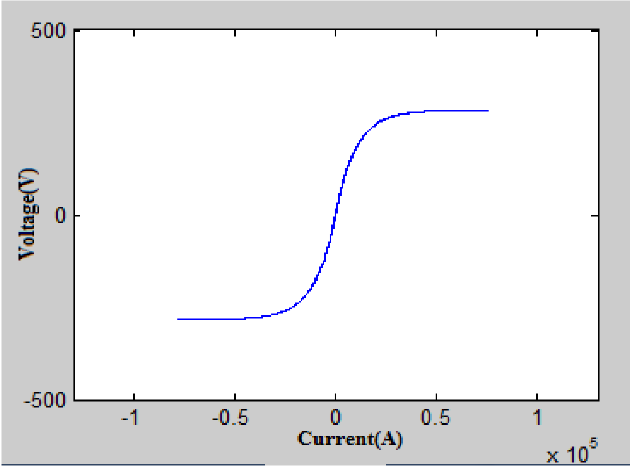


Fig 5. Steady-state current and voltage characteristic of electical arc for exponential model(V-I characteristic)

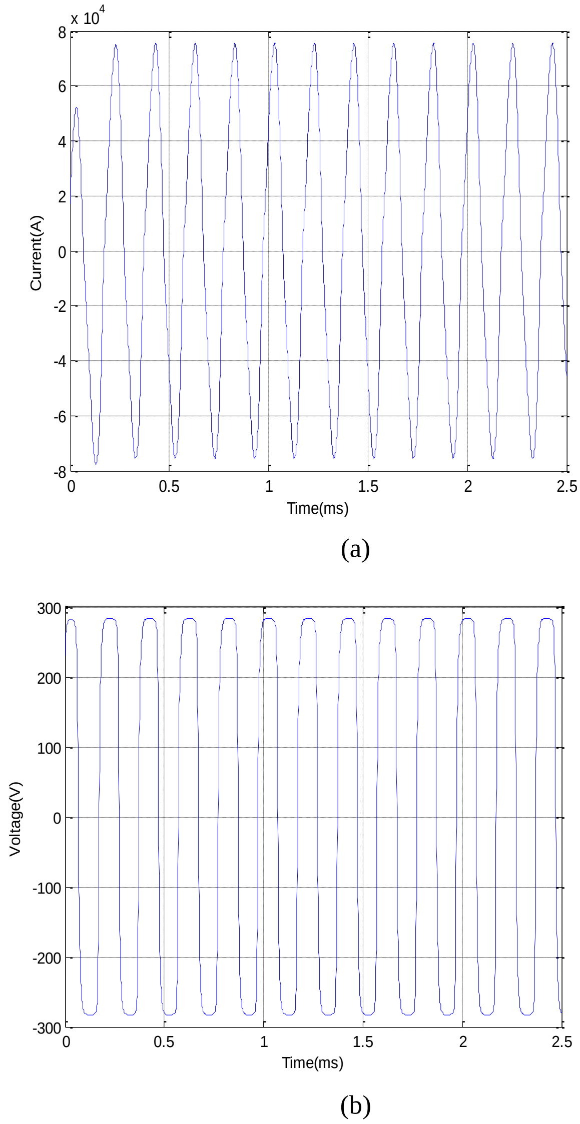


Fig 6. Current and voltage curves of electrical arc in steady –state for exponential model. a)The change of arc current, b) The change of arc voltage

5.2. Model 2: Hyperbolic Model

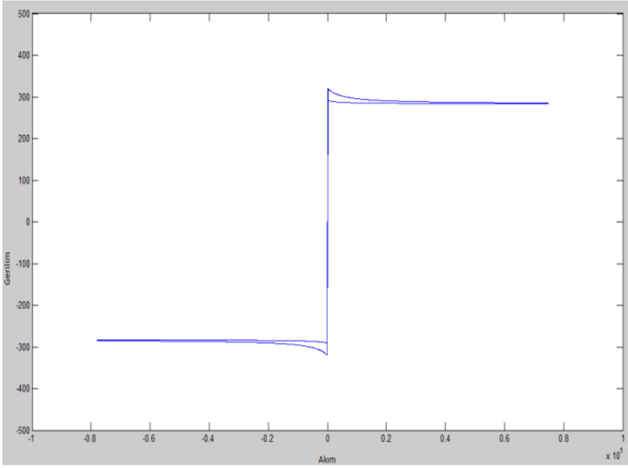
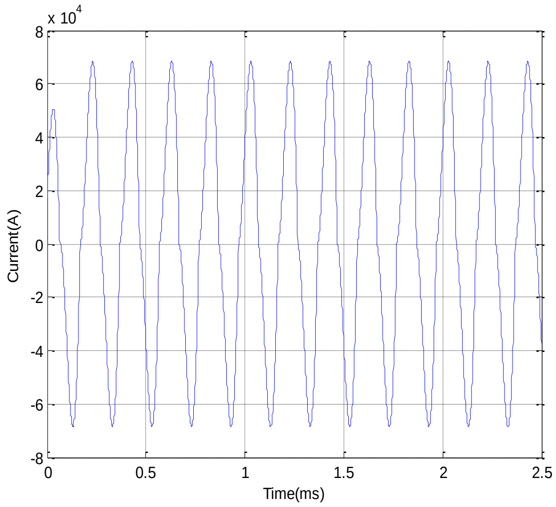
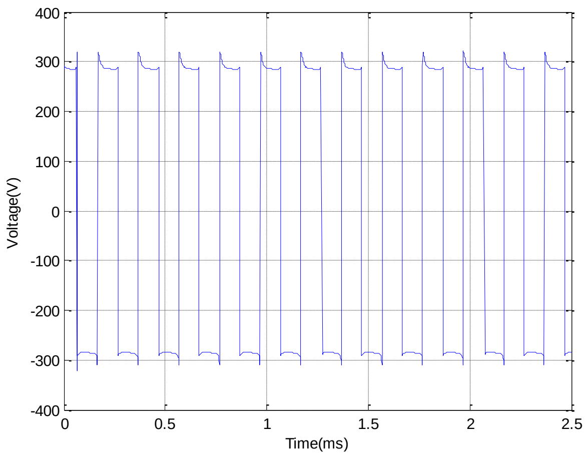


Figure 7. Steady-state current and voltage characteristic of electical arc for hyperbolic model(V-I characteristic)



(a)



(b)

Figure 8. Current and voltage curves of electrical arc in steady –state for hyperbolic model, a) the change of arc current, b) The change of arc voltage

5.3. Model 3: Exponantial- Hyperbolic Model

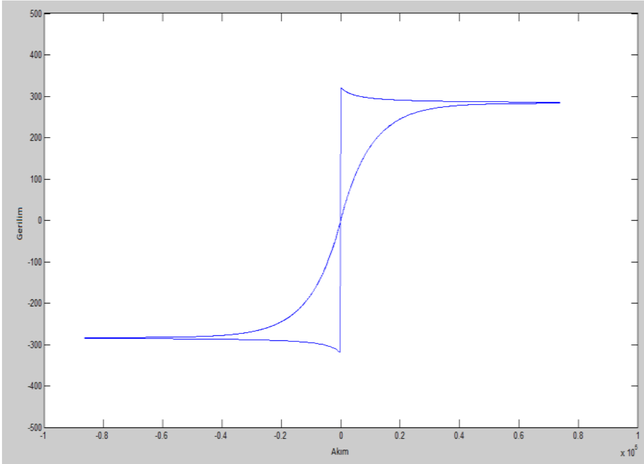
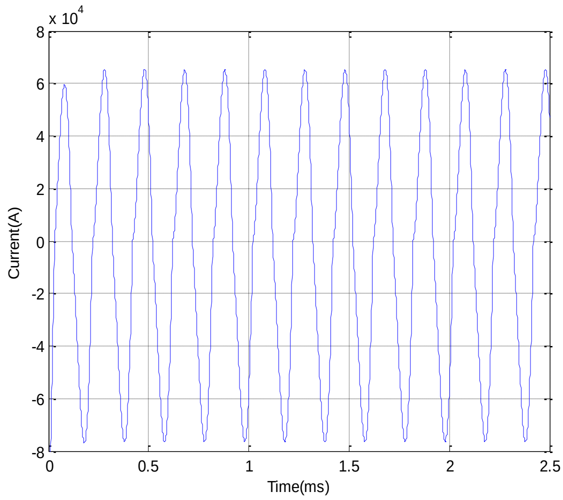
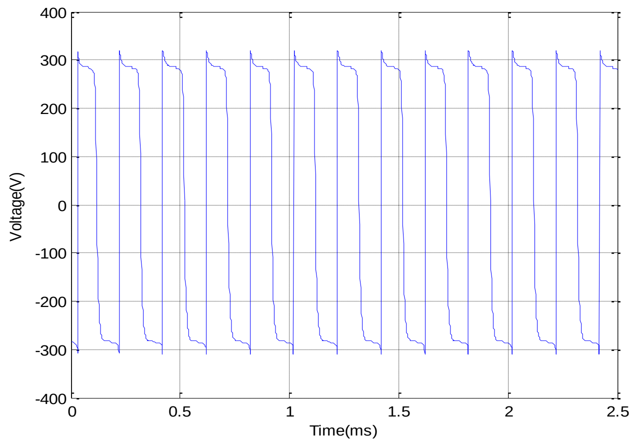


Figure 9. Steady-state current and voltage characteristic of electical arc for hyperbolic model(V-I characteristic)



(a)



(b)

Figure 10. Current and voltage curves of electrical arc in steady –state for hyperbolic model, a) The change of arc current, b) The change of arc voltage

VI. Dynamic Characteristic Of Electrical Arc

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 characterstics are used fort determine dynamic characteristic of electrical arc. In the simulation, Flicker effect is modeled with sinusoidal and random flicker effects. In the simulation, simulation parameters have been used to V_{at}=283 volt and m=0.5.

6.1.1. Exponatial Model with Sinusoidal Flicker Effect

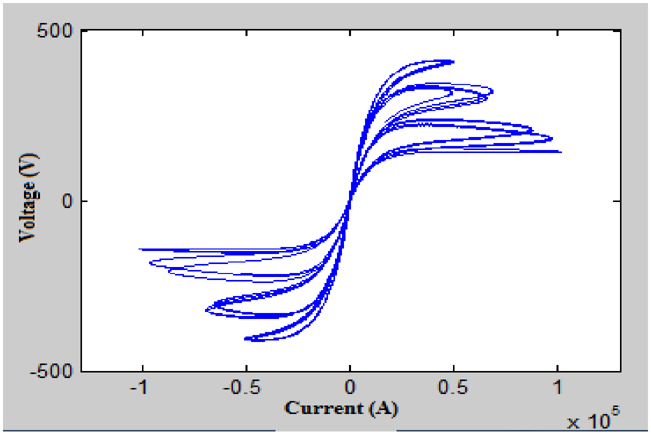
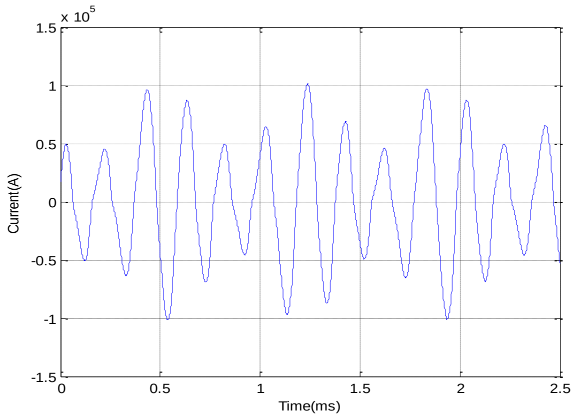
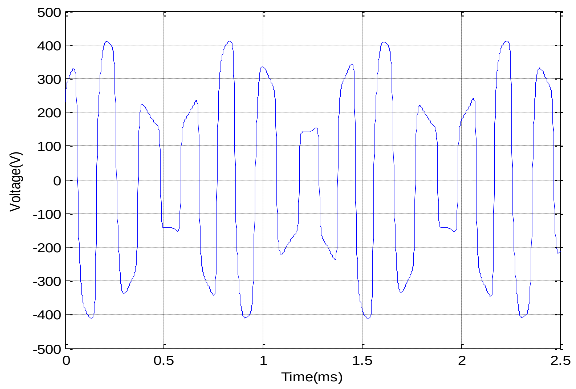


Figure 11. Dynamic current and voltage characteristic of electical arc for exponential model(V-I characteristic) with sinusoidal flicker effect.



(a)



(b)

Figure 13. Current and voltage curves of electrical arc in dynamic state for exponential model with sinusoidal flicker, a) The change of arc current, b) The change of arc voltage

6.1.2. Hyperbolic model with Sinusoidal Flicker effect

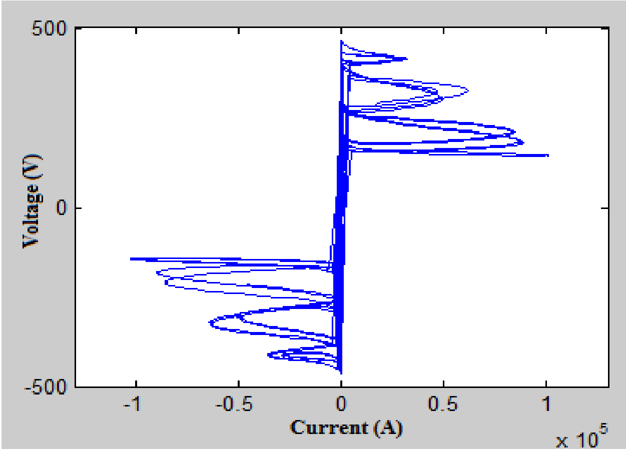
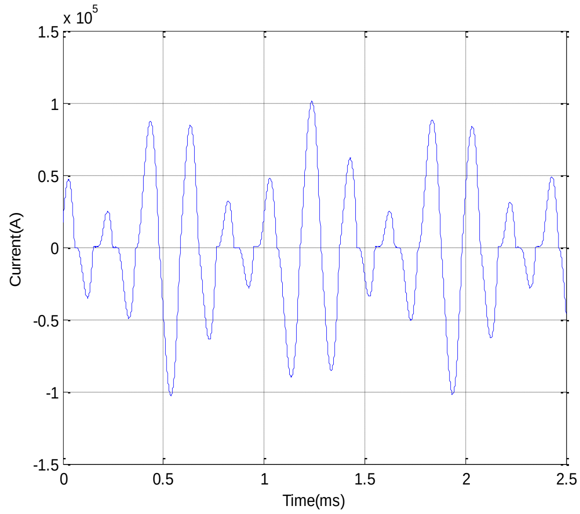
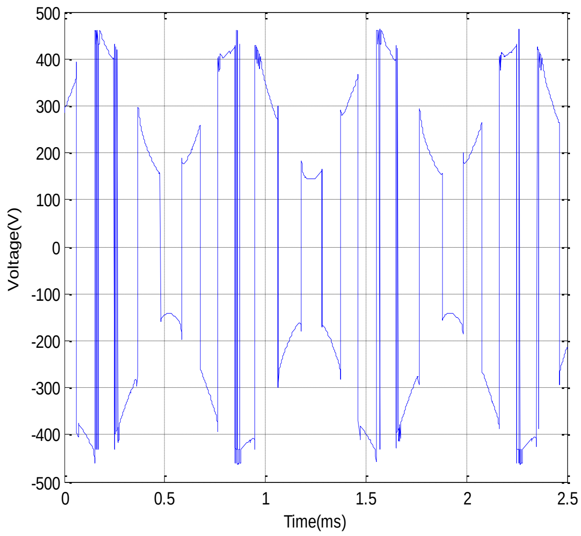


Figure 14. Dynamic current and voltage characteristic of electical arc for hyperbolic model(V-I characteristic) with sinusoidal flicker effect.



(a)



(b)

Figure 12. Current and voltage curves of electrical arc in dynamic state for hyperbolic model with sinusoidal flicker, a) The change of arc current, b) The change of arc voltage

6.1.3. Exponantial-Hyperbolik Model with Sinusoidal Flicker

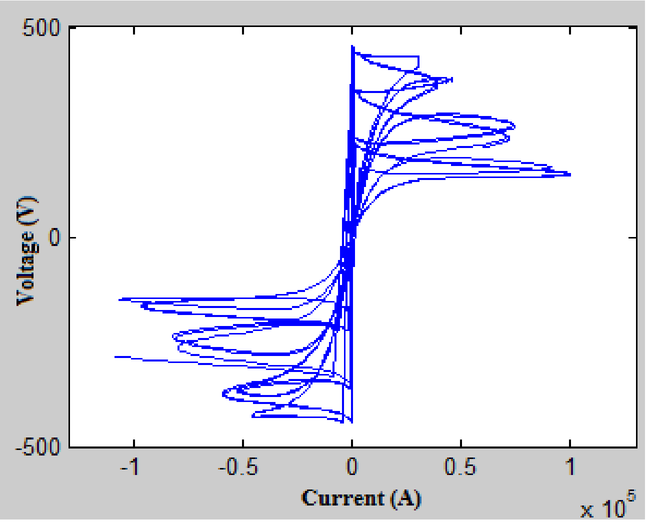
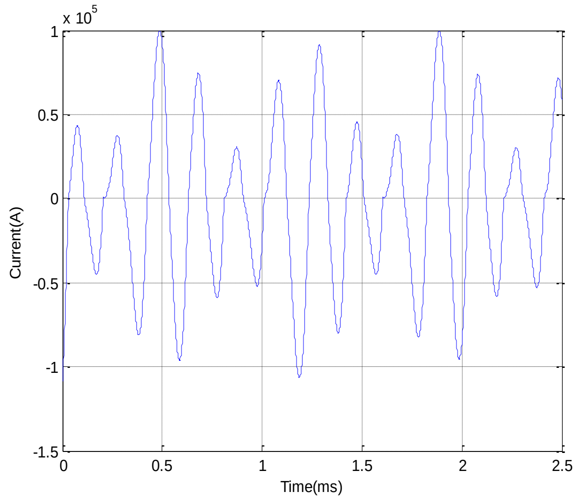
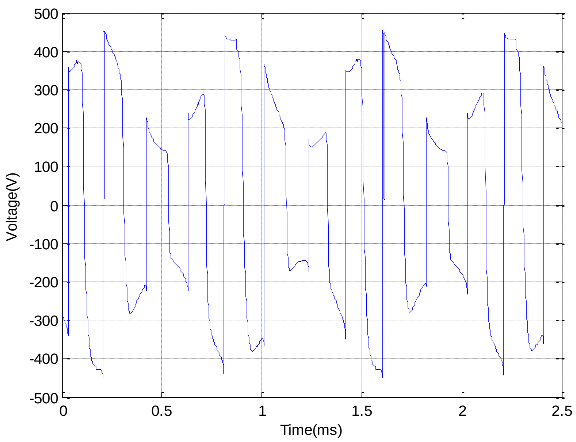


Figure 16. Dynamic current and voltage characteristic of electical arc for hyperbolic model(V-I characteristic) with sinusoidal flicker effect.



(a)



(b)

Figure 13. Current and voltage curves of electrical arc in dynamic state for hyperbolic model with sinusoidal flicker, a) The change of arc current, b) The change of arc voltage. Simulation parameters in random flicker effect have been used to V_{at}=283 volt and m=0.5

6.2.1. Exponential Model with random Flicker Effect

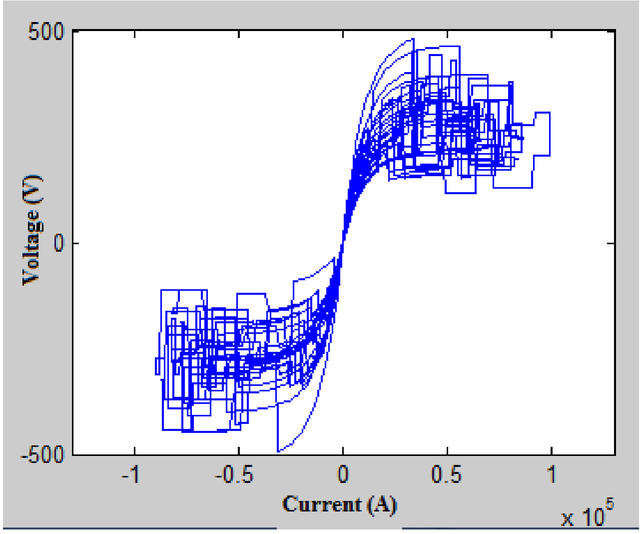
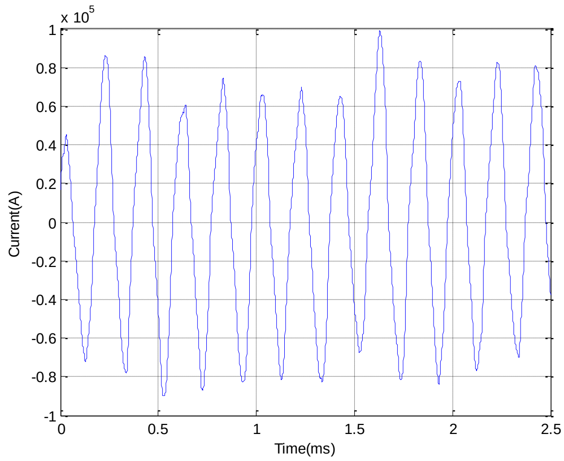
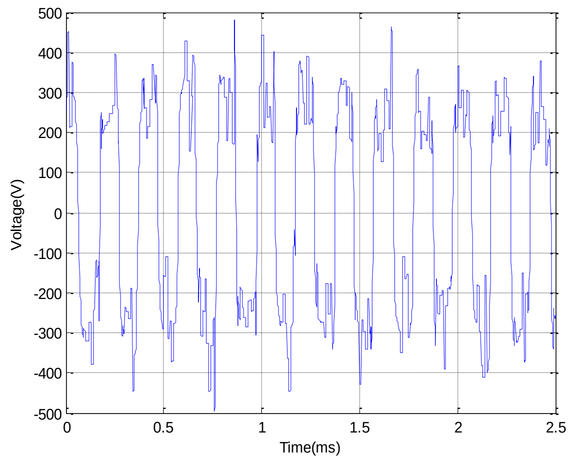


Figure 18. Dynamic current and voltage characteristic of electical arc for exponential model(V-I characteristic) with random flicker effect.



(a)



(b)

Figure 19. Current and voltage curves of electrical arc in dynamic state for exponential model with random flicker, a) The change of arc current, b) The change of arc voltage

6.2.2. Hyperbolic model with Random flicker Effect

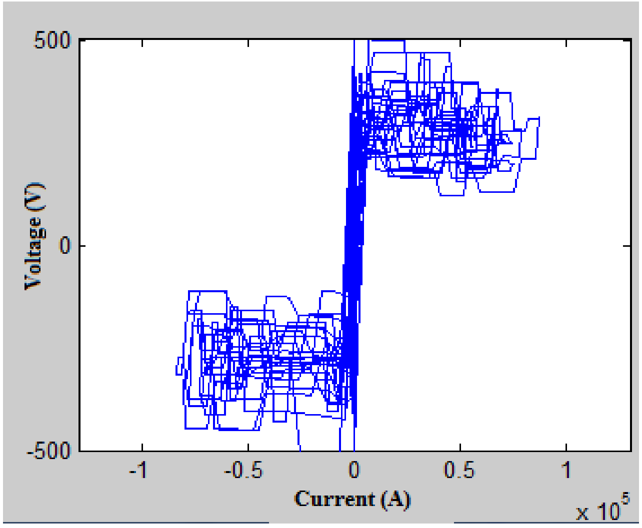
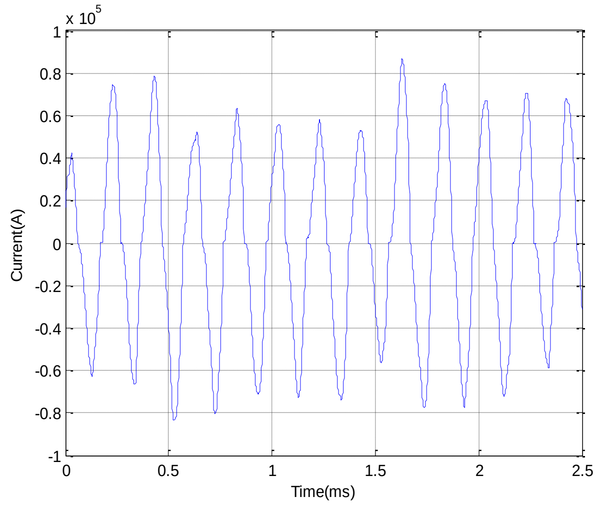
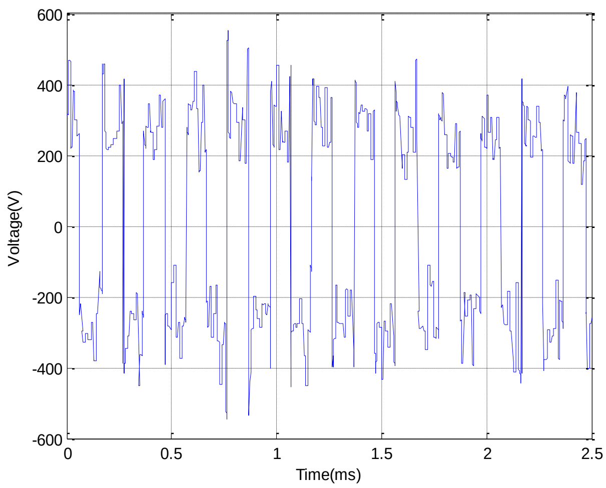


Figure 20. Dynamic current and voltage characteristic of electical arc for hyperbolic model(V-I characteristic) with random flicker effect.



(a)



(b)

Figure 21. Current and voltage curves of electrical arc in dynamic state for hyperbolic model with random flicker, a) The change of arc current, b) The change of arc voltage

6.2.3. Exponential- Hyperbolic model with Random Flicker

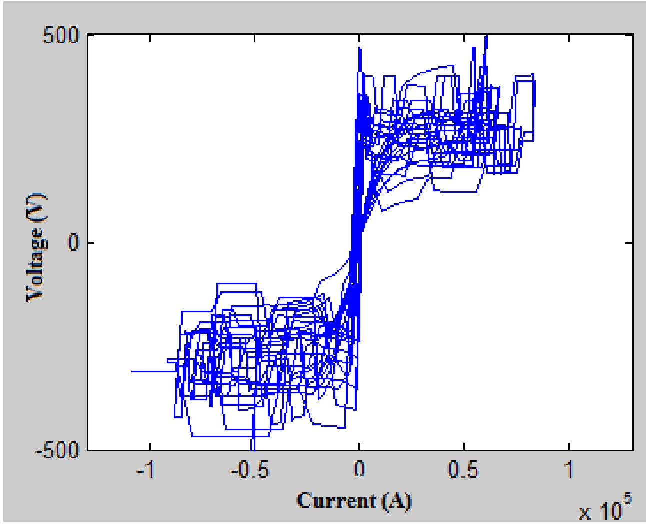
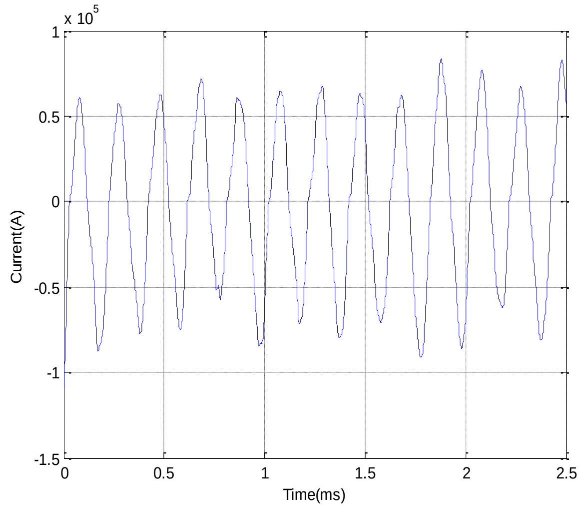
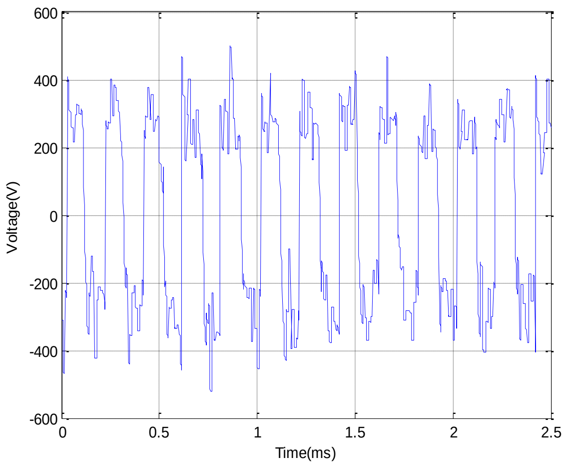


Figure 22. Dynamic current and voltage characteristic of electical arc for exponential-hyperbolic model(V-I characteristic) with random flicker effect.



(a)



(b)

Figure 23. Current and voltage curves of electrical arc in dynamic state for exponential-hyperbolic model with random flicker, a) The change of arc current, b) The change of arc voltage

VII. COMPORASION OF SIMULATION RESULTS WITH REAL TIME MEUSUREMENT

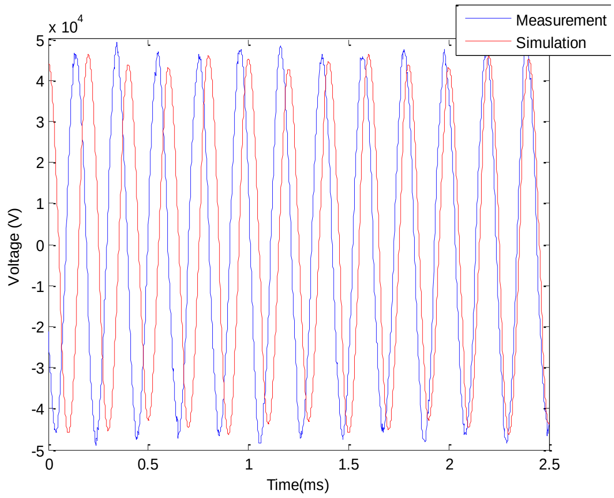


Figure 24. The change of voltage at a common connection point for exponential model with sinusoidal flicker effect (blue: measurement, red: simulation)

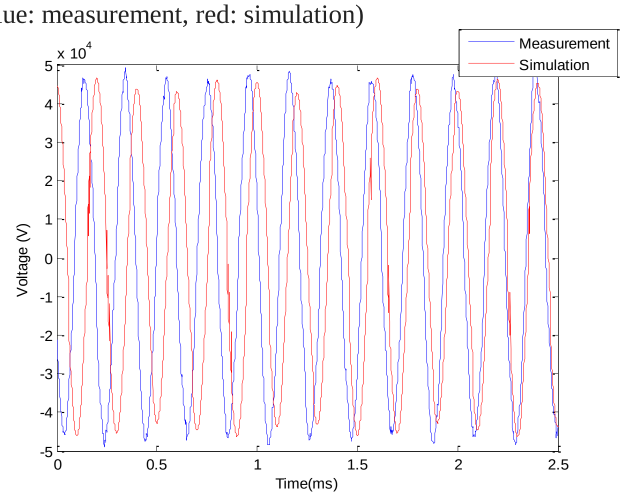


Figure 25. The change of voltage at a common connection point for hyperbolic model with sinusoidal flicker effect (blue: measurement, red: simulation)

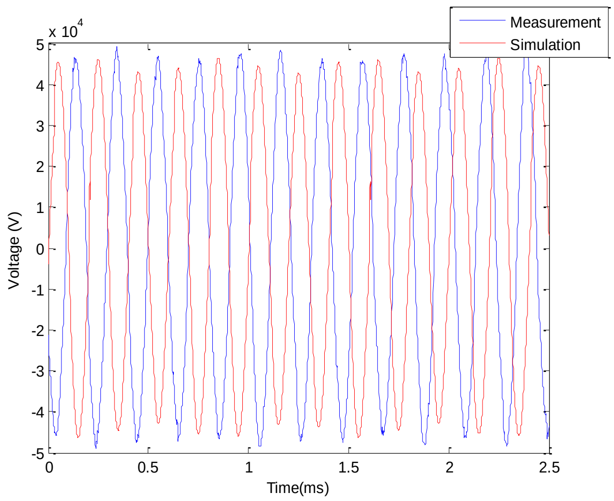


Figure 26. The change of voltage at a common connection point for exponential-hyperbolic model with sinusoidal flicker effect (blue: measurement, red: simulation)

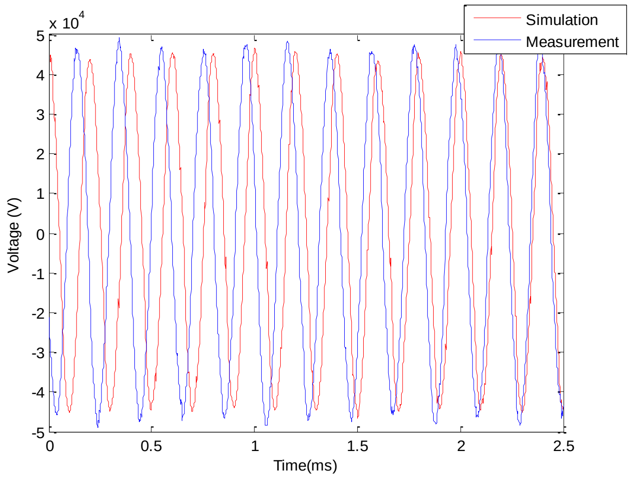


Figure 27. The change of voltage at a common connection point for exponential model with random flicker effect (blue: measurement, red: simulation)

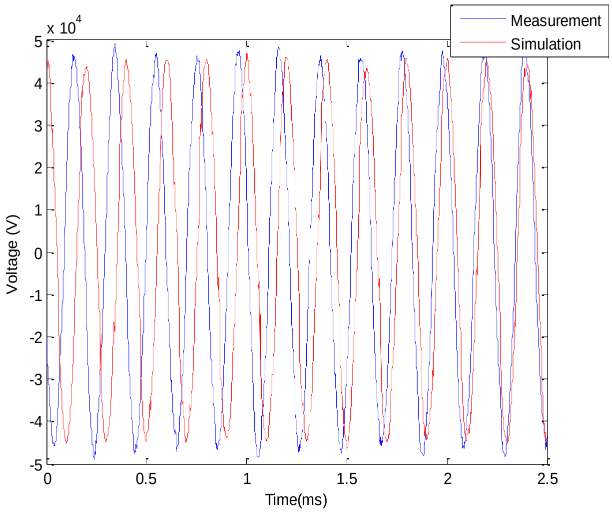


Figure 28. The change of voltage at a common connection point for hyperbolic model with random flicker effect (blue: measurement, red: simulation)

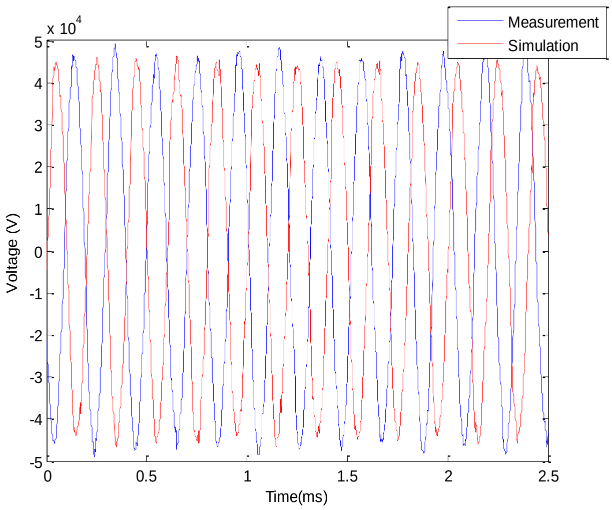


Figure 29. The change of voltage at a common connection point for exponential-hyperbolic model with random flicker effect (blue: measurement, red: simulation)

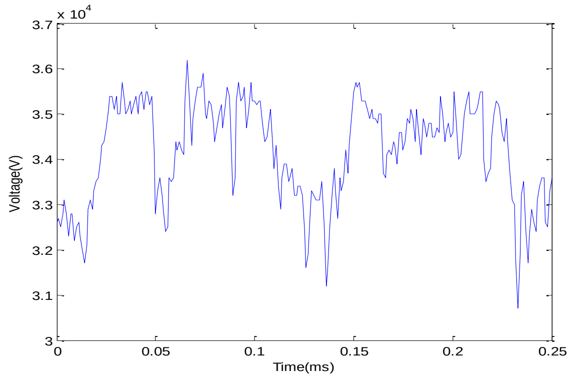


Figure 30. RMS voltage change in common coupling point with real time measurement.

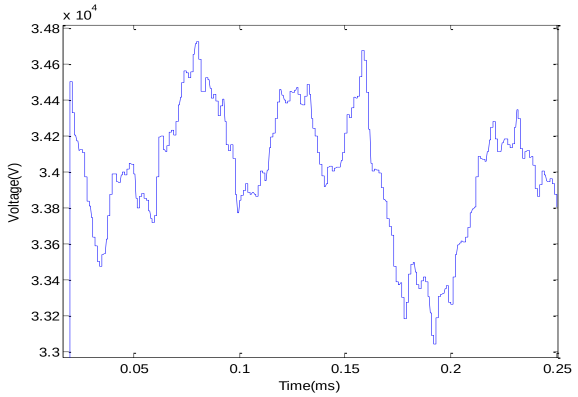


Figure 31. RMS voltage change in common coupling point for exponential model with random flicker

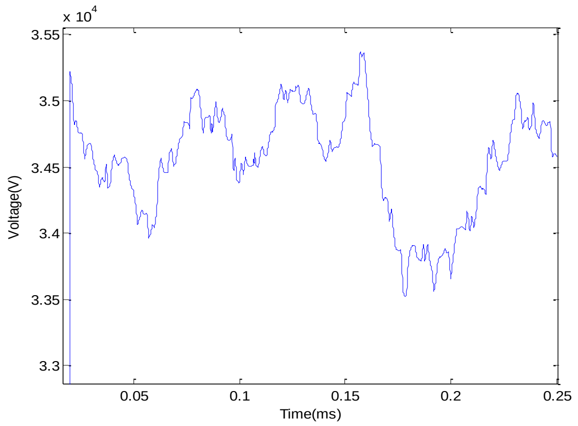


Figure 32. RMS voltage change in common coupling point for hyperbolic model with random flicker

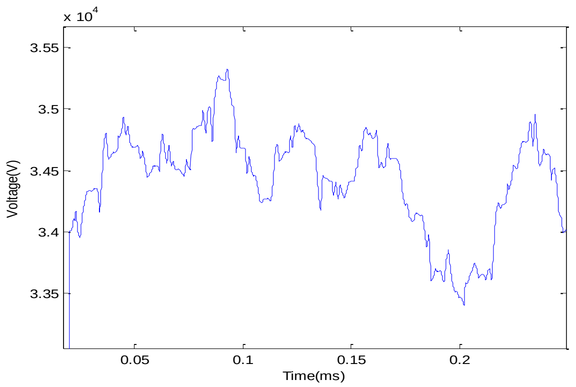


Figure 33. RMS voltage change in common coupling point for exponential-hyperbolic model with random flicker

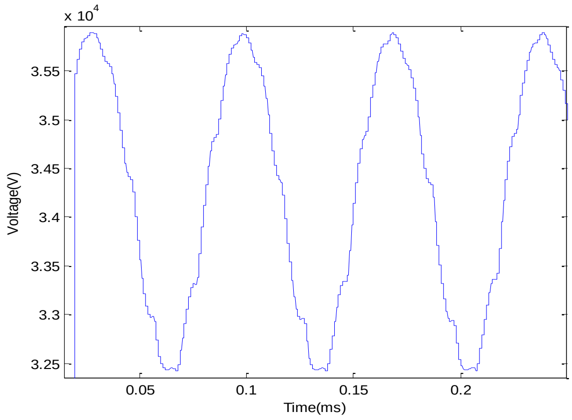


Figure 34. RMS voltage change in common coupling point for exponential model with sinusoidal flicker

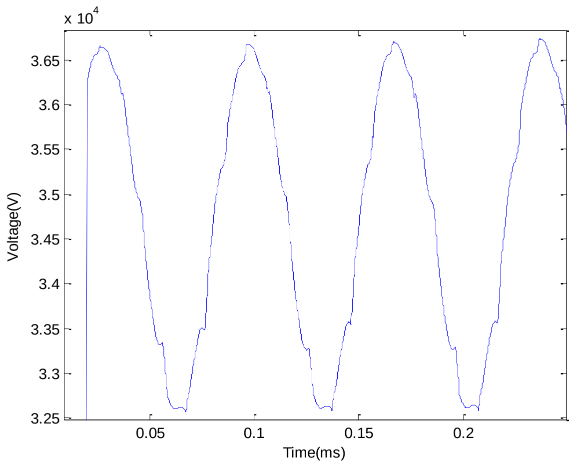


Figure 35. RMS voltage change in common coupling point for hyperbolic model with sinusoidal flicker

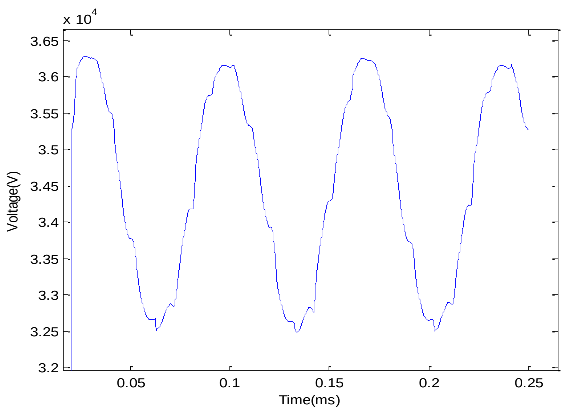


Figure 33. RMS voltage change in common coupling point for exponential-hyperbolic model with sinusoidal flicker

VIII. RESULTS

The behavior of EAF loads are necessary to identify for examination and investigation od power quality problems caused by electric arc furnace. In this paper, the behavior of EAF which is located in Sivas Iron and Steel Enterprises Inc.(SIDEMIR) has been tried to modeled with the aid of Matlab/Simulink. Different time-domain models presented in the literature are used to model the behavior of arc furnaces. When compared with actual measurement results obtained with HIOKI 3197 power analyzer in common coupling point and simulation results;

1. In all three models can be used to characterize of the arc furnace.
2. Compaired with the Simulation curves obtained with models and Real time measurement with power anayzer, exponential - the hyperbolic model seems to be more useful to the identify the behavior of the electric arc furnace
3. 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.
4. 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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