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Electric Arc Furnace Model in Distribution Systems

E. A. Cano-Plata, Senior Member, IEEE, A. J. Ustariz-Farfan, Member, IEEE
O. J. Soto-Marin, Student Member, IEEE

***Abstract* -- This paper presents a new technique to characterize electrical arc furnaces through the measurement of electric power, stationary and transient states, and the imbalance of these systems. The non-stationary behavior of the voltage and current signals in electric arc furnaces are considered and analysis techniques of power quality in the time domain are used. The ATPDraw -Electromagnetic Transient Program- was used to validate the characterization of the electric arc furnace and the simulation results were compared with the measurements taken in a local steel manufacturing facility.**

***Index Terms*—Arc resistance, Arc stability, Electric arc furnace, Flicker, Flicker measurement, Furnace transformer, Harmonic analysis, Power quality, Total demand distortion, Total harmonic distortion.**

I. Introduction

The main objective in the operation of an Electric Arc Furnace (EAF) is to produce the maximum tonnage of steel at the lowest cost using simple equipment. Operators should use the maximum power available in the shortest time possible. Production loss should be avoided or minimized.

Due to the non-linear and stochastic nature of the EAF, furnace parameters such as voltage and current, real and reactive power, and resistance and reactance exhibit significant variations especially during fusion. These variations cause *flicker* and harmonic problems in the point of common coupling (PCC). Increasing the capacity of short circuit current in the PCC or using flicker and harmonics compensators can diminish these problems.

Arc stability helps reduce this difficulty and decreases overvoltage problems which could cause damage to a large number of the components of the system. The system parameters and especially the parameters of the EAF transformer should be adjusted properly to obtain a stable operation.

Fig. 1 shows a single line diagram of the EAF power system. The simulations yielded stability in the arc and a continuous transference of electrical energy with reactors of 2.9 Ω. The transformer should have the following specifications.

- To set the "tap-to-tap time" operation cycle on a new furnace in a Colombian iron and steel company.
- To operate the EAF at a high power factor (*pf*) with long arcs in order to decrease electrode consumption.

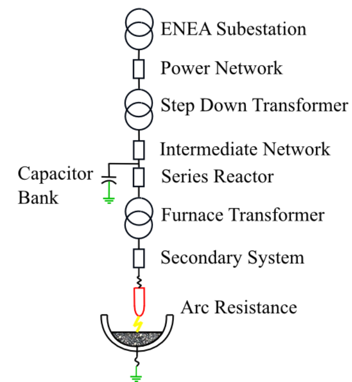

Fig. 1. EAF Single line diagram

II. Phases for the Specification of the Whiting 30T EAF

The first step is to gather the basic characteristics of the components in order to analyze the optimal power flow.

A. Furnace Transformer Specification

A clear specification of the type of burner to be fed is crucial in order to identify the type of transformer needed for the fusion.

1) Configuration and Capacity:

Given the diameter of the furnace Φ = 3.81m, and taking into account the following configurations:

- Cylindrical: Liquid steel capacity of 30 T (Nominal)
- Oval: Liquid steel capacity of 38 T (Change # 1)
- EBT: Liquid steel capacity of 35 T (Change # 2)

Three possible scenarios are presented for the analysis of the voltage to be supplied.

2) Maximum Voltage on the Secondary:

Based on the experience of the production team of the iron and steel company under study, and the information gathered from plants with similar operations [1] plus taking into account two probably options:

- Cylindrical tank: Vmax = 600V (with a possibility to increase at 700V checking refractory erosion and refrigerated panels during operation).
- Changing the original tank to an Oval or EBT: Vmax = 700V.

3) Operation Modes:

EAF will be used initially for Fusion and Prefining and in later stages (with Ladle Furnace) only for fusion and prefining. Panels will be designed and manufactured in accordance with requirements.

4) System Operating Voltages:

Experience in the operation of EAF is a high reliability factor. Experts demonstrate how to manipulate a molten pool using the tap changer of the system. The iron and steel company under study estimated the operation Table I and also proposed the impedance correlation. Table II shows the operation conditions intended.

TABLE I
RECOMMENDED OPERATING VOLTAGES

Voltages (V)	Operation
700	Operation with Oval Furnace or EBT in fusion
600	Operation with cylindrical furnace in fusion
500	Normal fining or prefining
400	Complicated fining

TABLE II
SPECIFICATION OF THE TRANSFORMER ACCORDING TO THE PROCESS STAGES AND THE POSITIONAL RELATIONSHIP OF THE TAPS

Stage	Voltage	Z%	First	Second	Third
1	700	6.2			Fusion
2	660	6.125			Fusion
3	620	6.05		Fusion	
4	580	5.975	Fusion		Fining
5	540	5.9		Fining	
6	500	5.825	Fining		
7	460	5.75			
8	420	5.675			
9	380	5.6	Complicated finings	Complicated finings	Complicated finings

5) Fusion Stage:

There are three important features in this stage. First, cold scrap is drilled, then the arc is stabilized and finally the best transfer is expected. Thus, the considered times are [2-3]:

6) Fusion Time at 30 MVA:

Step transformer power 28MW-24MW=$P_{\text{Furnace transformer}}$. Therefore, burners (4MW) on the top of the gas furnace are expected. Burners with operating points with a power factor of 0.8 and with an energy transfer of 28MW/3600s= 466kWh/60s, give W_{scrap} = 33 T, scrap weight.

Specific energy (Specific: 400kWh/T) required for fusion without burners gives an estimated total power (1):

$$E_{total} = W_{scrap} * E_{specific} \quad (1)$$

$$E_{total} = 33T_{scrap} * 400 \, kWh/T = 13200kWh$$

Therefore, 33 T of scrap for the first puddle of 30T, thus times will be:

$$t_{fusion} = \frac{13200kWh}{466kWh/60s} = 1700s \quad \text{with burners}$$

$$t_{fusion} = \frac{13200kWh}{400kWh/60s} = 1980s \quad \text{without burners}$$

Information from the production department of the iron and steel company under study was used to get the Tap-to-Tap operation times that are presented on Table III.

$$t_{Tap-to-Tap} = \sum t_{operation} \quad (2)$$

TABLE III
TAP TO TAP TIMES – OPERATION TAP

	S (MVA)	t_{fusion} (s)	t_{load} (s)	$t_{casting}$ (s)	$t_{prefining}$ (s)	t_{delays} (s)	t_{total} (s)
Ladle furnace	30	1980 (1700*)	720	600	420	600	4320 (4020 *)
	28,5	2040	720	600	420	600	4380
	27	2160	720	600	420	600	4500
Initial stage without Ladle furnace	30	1980 (1700*)	720	600	420	600	4920 (4620 *)
	28,5	2040	720	600	420	600	4980
	27	2160	720	600	420	600	5100

* With burners

III. EAF POWER FLOW TEST CIRCUIT – ACERIA DE CALDAS

The power system of ACASA [4] the PCC is with La Central Hidroeléctrica de Caldas (CHEC) the utility of the region and is coupled to the system through the substation; shown in figure 1. Connection details and the approach for assessing the power flow in the system are presented below.

A. Electric Arc Furnace Circuit

Fig. 2 shows the description of the system. The nomenclature described below is used to perform the circuit and flow calculations.

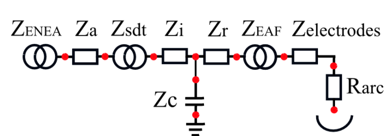

Fig. 2. ATP circuit diagram

- ENEA Substation (ZENEA): The utility of the region and is coupled to the system through the ENEA substation.
- Power network (Za): Power network chosen by the short-circuit power and its X/R relation.
- Step down transformer (Zsdt): Step transformer chosen by its power, impedance, and X/R relation.
- Intermediate network (Zi): Intermediate network

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represented by its impedance, resistance and reactance.

- Capacitor bank (Zc): bank of capacitors to offset the load, the bank nominal voltage and power.
- Series reactor (Zr): Series reactor with reactance X/R.
- Furnace transformer (Z_{EAF}): Furnace transformer with primary and secondary voltage relation, power, and impedance X/R.
- Secondary System (Zss): Secondary system with delta closure resistance and reactance, cooled cables, tubular bars, electrode mast arms, and electrodes.
- Refurnace (Rarc): Arc resistance varying between zero (short circuit electrodes in the bathing) and infinite (open).

B. Equivalent System of the Power Network

Power systems might be simulated based on the supply source. Therefore, it is important to determine the characteristics of the short circuit current of the system. The central national office characterized the ENEA Substation (SE) of 115kV with the following parameters [2].

Short circuit current: $I_{SC} = 8300A$

Short circuit power: $S_{SC} = \sqrt{3} * V_{LL} * I_{SC}$ (3)

$$S_{SC} = \sqrt{3} * 115kV * 8300A = 1653MVA$$

and the typical relation of distribution systems is *X/R=10*. The transformer of the iron and steel company under study has the following information

S=30MVA, 115/13.8kV

Z%=10.27 a 25MVAbase

X/R=10

Intermediate network is the network that connects the step transformer to the furnace transformer (EAF).

$$I_{SEC\_std} = \frac{S_{std}}{\sqrt{3} * V_{LL}} \quad (4)$$

$$I_{SEC\_std} = \frac{28MVA}{\sqrt{3} * 13.8kV} = 1171A$$

After applying the corrections proposed in the EAF electric design, $I_{sec\_std}=452A$ per conductor. Furthermore, 3 conductors with 452A each will be used in each phase. The conductors characteristics are: 3x500 AWG, Cu, 90 º C, XLPE of 15 kV with conductor length 163m, reference text [5] introduce the following parameters for this type of conductor: R=0.1031mΩ/m, X=0.129mΩ/m, X_{eq}=4.3E-2mΩ/m, R_{eq}=3.4366E-2mΩ/m. Therefore, for a conductor length of 163m, R_{eq}=5.6mΩ, X_{eq}=7mΩ. Regarding to Capacitor bank, Using 100% of the EAF transformer load (30 MVA), P_{carga}=21MW, Q_{carga}=21MVAr and *pf*=0.707 Considering an operation critical power factor, the desired power factor is 0.92. The power needed for the capacitor to achieve this factor is calculated using the power factor triangle as follows [6].

$$MVA = \frac{\quad}{0.92} = 22.83MVA$$

$$MVAr_{new} = \sqrt{22.82^2 - 21^2} = 8.96 \approx 9MVAr$$

Therefore, the new capacitors bank should be of 12MVAr and Vc=17kV, the capacitor bank selected is of 20MVAr. Voltage transient effects and the power to specify the capacitors reagents taking into account harmonic phenomena are chosen from this level.

The series reactor to be taken into account has a fixed impedance of 2.9 Ω referred to the EAF transformer primary. This reactor should be internal to the transformer given the favorable stability conditions in the arc. The following are the parameters of the furnace transformer.

$$S = 30MVA$$

$$U_{prim} = 13.8kV$$

Voltage on the secondary and impedances in percentage were changed to carry out the calculations. See Table IV.

TABLE IV
SECONDARY VOLTAGE WITH RESPECTIVE PERCENTAGE IMPEDANCES

TAP	1	2	3	4	5	6	7	8	9
Base voltage (V)	700	660	620	580	540	500	460	420	380
Base power (MVA)	30	30	30	30	30	30	30	30	30
Zcc%	6.2	6.125	6.05	5.975	5.9	5.825	5.75	5675	5.6
Zcc (mΩ)	1.013	0.889	0.775	0.670	0.573	0.485	0.406	0.334	0.270
Zr%	45.8	51.5	58.4	66.7	77	89.8	106.1	127.2	155.4
Zr (mΩ)	7481	7481	7481	7481	7481	7481	7481	7481	7481
Ztotal%	52	57.64	64.43	72.69	82.86	95.59	111.81	132.9	161.02
Ztotal (mΩ)	8.493	8.37	8.256	8.151	8.054	7.966	7.886	7.814	7.75

Notes:

Z_r, Reactor impedance: with a value of 7.481 mΩ in the secondary and of 2.9 Ω in the primary.

Z_{sc}, transformer short-circuit impedance.

Reactance-resistance relation for this transformer *X/R=40.*

C. Equivalent System to the EAF Transformer Secondary

For datails see the reference [4].

Fig. 3 shows the equilateral configuration of the cooled cables and following the parameters for this type of configuration are shown in the Table V.

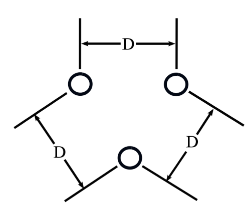

Fig. 3. Configuration of cooled cables

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TABLE V
PARAMETERS OF COOLED CABLES

Parameter		Value
Area	(mm^2)	5500
I	(A)	27500
GMR*	(mm)	7.75
R_{dc}	(μΩ/m)	3.31
R_{AC}**	(μΩ/m)	3.37
Length	(m)	7
R_{AC}	(μΩ)	23.633

* Geometric mean radius (GMR)
** With R_{AC} 2% greater than Rdc [7]

Now, understanding that the reactive impedance is obtained from:

$$X_L = 4*\pi*f*10^{-7}*\ln\left(\frac{D}{D_S}\right)\left[\frac{\Omega}{m}\right] \tag{5}$$

where
D = Distance between cables, 850m
D_s = GMR 73.4 mm
f = 60 Hz

Its value is

$$X_L = 4*\pi*f*10^{-7}*\ln\left(\frac{850}{73.4}\right) = 0.1825469*10^{-3}\left[\frac{\Omega}{m}\right]$$

$$X_L = 1.27783*10^{-3}\Omega$$

The specifications of tubular busses are:

TABLE VI
PARAMETERS OF TUBULAR BUSSES CONDUCTOR

Parameter		Value
Transportable current	(A)	48526
R	(mΩ/m)	489.8277E-04
Length $_{Major}$	(m)	2
R	(mΩ)	0.000979655
R_{eq}	(mΩ)	489.8277E-04

The specification of the electrode mast arms are shown on table VII:

TABLE VII
ELECTRODE MAST ARM PARAMETERS

Parameter		Value
Transportable current	(A)	50219
R	(mΩ/m)	1.993563E-04
Length	(m)	0.3
R	(mΩ)	0.0598E-03

Graphite electrodes, the specifications are shown on the following Table:

TABLE VIII
GRAPHITE ELECTRODES PARAMETERS

Parameter		Value
Diameter	(mm)	400
R	(mΩ/m)	6
Length	(m)	2515
R	(μΩ)	15.09

Total impedance of the Secondary:

$$R_{total} = 0.874466+23.6334+0.48983+0.0598+15.09$$
$$R_{total} = 40.1475\mu\Omega$$
$$X_L = 1.27783*10^{-3}\Omega$$

D. *New model of Electric Arc Furnace*

The Monte Carlo method is used to evaluate the characteristics of the Arc using the physical principles of O. Mayr [8-9]. The variable arc resistance, the total demand and the harmonic distortion vary as a function of time in this stochastic process. In other words, the arc, the load, and the harmonics of the electric arc furnace are randomly modeled using a bandwidth between 30Hz and 3500Hz.

Ignition resistance (R_{ig}) is obtained from the random variations of the noise frequency band as specified in equation (6). The Arc Resistance (R_{Arc}) described by equation (7) takes into account the initial active power corresponding to the area under the curve. Figure 4 shows a diagram of model blocks.

$$R_{ig} = \frac{V_{ig}}{WBN(RANDOM((t))} \tag{6}$$

$$R_{Arc} = \frac{P}{\dfrac{V_{ig}}{WBN(RANDOM(t))} + WBN(RANDOM((t))} \tag{7}$$

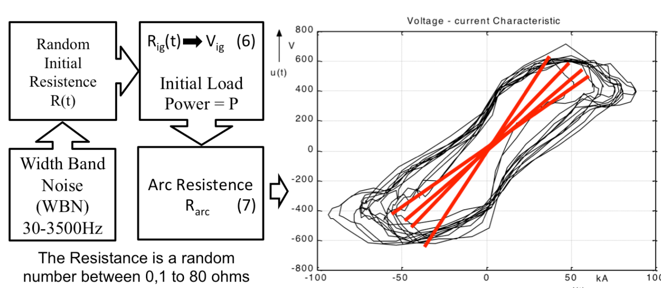

Fig. 4 Model of an Electric Arc Furnace

V_{ig} is the arc ignition voltage [10] in equations (6) and (7), WBN is a function of spectrum limitation between 30 and 3500Hz, and Random is a function of random number generation.

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This box is associated to the distribution system in a Montecarlo process for maximum simulation time in ATP / EMTP. Fig. 5 shows the simulation results.

Figures 4 and 5 show that the model is a dynamic modification of the traditional concepts taken in the characteristic of plane VI. [2-3],[10-11].

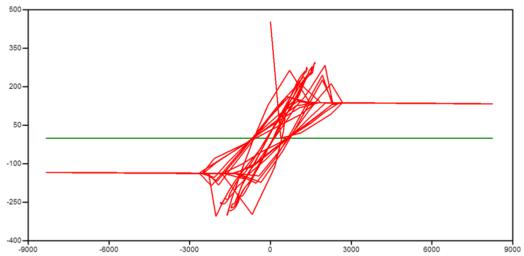

Fig. 5. Simulation results

Arc resistance can vary between zero and infinite. The values of the Table IX were considered. These are subject to oscillatory fluctuation over a sinusoidal range using the ATP software.

TABLE IX
ARC RESISTANCE

R_{arc} (mΩ)				
0.1	2.5	10	13.25	16.36
0.5	3.3	11.25	14	18
0.8	4.5	12	14.5	23
1.3	6	12.5	15	38
1.8	8	13	15.5	80

Calculation of Arc voltage:

$$V_{arc} = R_{arc} * I_{arc} \tag{8}$$

Arc length

$$L_{arc} = \frac{V_{arc} - 40}{C} \tag{9}$$

where L_{arc} is in centimeters and C = 11.5 V/cm. Basic model [2]

- This flow is verified in a spreadsheet. It was possible to implement a methodology in EXCEL to determine the operating point of the system.
- Fig. 4 shows the results of the spreadsheet.
- The characterization of the furnace during simulation has allowed the identification of the basic operating conditions of the power distribution system.

The Fig. 4 has the following nomenclature:

Parc: The arc power.

Q1: Reactive power at fundamental frequency.

P1: Active power at fundamental frequency.

Varc: Arc voltage.

pf: Power factor measured in the transformer secondary of the EAF.

Larc: Arc length.

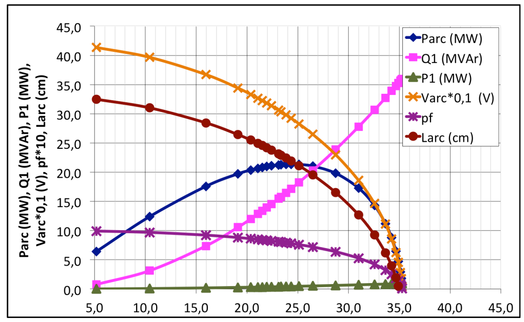

Fig. 6. Simulation results using the power flow diagram

The dynamics of the furnace will be enriched by voltage on the tap changer.

E. Harmonics Produced by Arc Furnaces.

The non-linearity of the behavior of electric arcs and the variability of the parameter values of the furnace generate harmonics with magnitudes and categories difficult to be predetermined.

The spectrum of an arc furnace is continuous. The dominant harmonics are 3,5,7,9,11… which decrease in magnitude as they increase in category; the arc furnace might even produce DC levels and harmonic. The greatest difficulty in predicting the harmonic spectrum is its stochastic nature, particularly in the fusion stage in which the production of harmonics increases.

The current in an arc furnace is more sinusoidal than its voltage, which is characterized by square waves (simplified arc model). The arc furnace might then be considered a source of voltage harmonics; a detailed description of the EAF is presented in [10]. Values resulting from various measurements in arc furnace installations are presented below. See Table X.

F. Voltage Fluctuation and Load Imbalance

Continuous load imbalance between stages and voltage fluctuations are present during the operation of the furnace; especially in the fusion stage. These are mainly due to:

- Movements of scrap.
- Bubbling of the melting materials.
- Magnetic repulsion between arcs.
- Movement of flexible conductors.

TABLE X
EAF VOLTAGE HARMONICS (MEASUREMENTS)

Harmonic	Worst case % fundamental	Typical % fundamental
2	17.0	5.0
3	29.0	20.0
4	7.5	3.0
5	10.0	10.0
6	3.5	1.5
7	8.0	3.0
8	2.5	1.0
9	5.0	3.0

1) Load Imbalance:

The largest imbalances occur when one or two phases are short-circuited and the other is in open circuit. Conductors in older installations are arranged in the same plane, which causes imbalance in the reactance because the mutual impedances are not equal. Small differences between the phase reactance take on major importance in voltage imbalances due to the high currents handled by the furnace. Imbalances cause a change in the voltage applied to the electrodes, thus developing different powers in each electrode. The arc furnace is an imbalanced load for the power system.

2) Voltage Fluctuations:

Voltage fluctuations are mainly due to the variable reactive power consumption. The severity of these fluctuations is higher in weaker networks. The system strength is measured in terms of its ability to short circuit at the PCC with the network.

Research on arc furnaces has shown that the subtransient short circuit force in power systems (in the PCC) must be at least 80 to 100 times the nominal power of the furnace to be able to tolerate the disturbances produced by the furnace. This requirement might be reduced by half in furnaces with compensation; that is 40 times the nominal power of the furnace [11-14]. Voltage fluctuations are stochastic in nature. The voltage at the PCC might be simulated as a voltage of 60Hz imposed on a white noise signal.

G. Simulation in Arc Furnaces with ATP

It is recommended to simulate the operation of the furnace in a predefined point in the absence of a clear arc furnace model that reflects its stochastic nature. The importance of having an appropriate model is to be able to predict the flicker produced by these furnaces.

References [15-17] outline the first approaches to a stochastic model arc furnace along with its ATP implementation.

1) Measurement in the Simulated System and Analysis of Power Quality in PCC:

Measurements of power quality obtained in 4 busses radially connected from the furnace to the 115kV ring circuit are made based on international standards defined by IEEE 519 [18] (limits of harmonic distortion), the IEEE 1159 standard (evaluation of transient events) and also the EN 50160 standard [19]. The Colombia´s standard, based largely on the above mentioned standards, is taken as reference to calculate power quality indicators as well as their acceptable limits.

The harmonic and flicker events will be analyzed in this study.

This paper introduces short circuit currents generated in [1], which are implemented in the ATP system. The demand current (I_L) has been obtained from measurements made in the iron and steel company under study for a week, taking the maximum demand average value at a fundamental frequency. The I_{sc}/I_L relation is presented in the IEEE 519 standard and will define the distortion limits of acceptable demand in the Total Demand Distortion (TDD) of the Current.

A detailed analysis of the harmonic distortion indices of current and voltage in the common connection point is presented below.

The analysis of results shows harmonic distortion in the current through the TDD. Voltage distortion measurements will be performed using the THD and harmonic distortion limits, acceptable by the IEEE 519 standard [18], will be checked.

2) Total Demand Distortion of the Current (I_{TDD}):

Fig. 7, Fig. 8 and Table XI shows the statistics of distortion indices of total demand simulated with ATP using the Monte Carlo model.

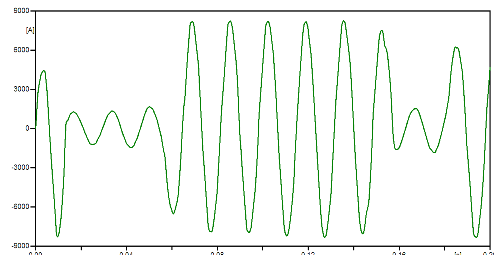

Fig. 7. Current of EAF substation (low voltage side)

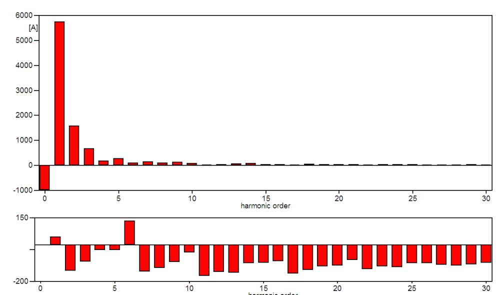

Fig. 8. I_{TDD} of EAF substation (low voltage side)

The values of total demand distortion are within the ranges of the standard IEEE-519 [18].

TABLE XI
TOTAL DEMAND DISTORTION

Harmonic	Amplitude	Harmonic	Amplitude
0	-221.43	6	162.97
1	6835	7	205.33
2	1651.8	8	81.221
3	640.16	9	109.72
4	468.74	10	108.13
5	483.86	11	108.28
TDD		28.52%	

3) Total Harmonic Distortion of the Voltage (V_{THD}):

Fig. 9, Fig. 10 and Table XII shows the statistics of total

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harmonic distortion indices of voltage. These results are also obtained with ATP using the same Monte Carlo model. The values of voltage total harmonic distortion are within the ranges of the standard IEEE 519 [18].

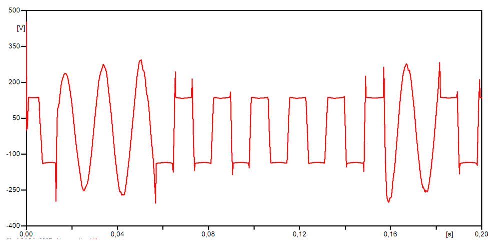

Fig. 9. Voltage of EAF substation (low voltage side)

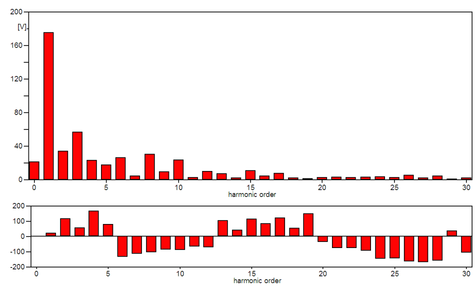

Fig. 10. VTHD of EAF substation (low voltage side)

TABLE XII
TOTAL HARMONIC DISTORTION

Harmonic	Amplitude	Harmonic	Amplitude
0	21.025	6	26.221
1	175.08	7	44.486
2	33.822	8	30.198
3	56.528	9	94.086
4	22.96	10	23.268
5	17.607	11	2.461
THD	50.73%		

4) Flicker:

Table XIII shows the summary of flicker propagation in the different system busses under current conditions. The methodology used for the calculations follows the EN50160 standard, which indicates that the flicker is calculated as 95% of the measurements taken during a week; Pst every 10 minutes and Plt every 2 hours. Under this standard Pst values should be less than 1 and Plt values should be less than 0.8. It can be noted that none of the inner busses meet the limits set by the above named standard. However, the busses are adjusted to limits well below 0.8. in order to replace the transformer of the furnace bay in the 115kV Substation. Figure 11 shows the detailed behavior in the Enea Substation. The change of the transformer in this substation will help comply with the limits set by the EN50160 standard [19].

TABLE XIII.
SUMMARY OF FLICKER PROPAGATION IN DIFFERENT BUSSES (ACTUAL CONDITIONS).

Measurement point	Pst	Plt
Fusion furnace	13.59	12.0
EVOLIS Substation	1.7929	1.9
115kV ACASA Substation	1.2566	1.2
La Enea Substation	1.1548	1.1

The propagation on the busses in the Enea Substation shows no flicker attenuation after connecting the furnace transformer to the transformer of 115kV.

Table XIV shows the summary of flicker propagation on the different system busses under the conditions proposed with the change of the transformer in the furnace bay. There is a strong Pst attenuation due to impedances from the fusion furnace transformer and the new 55/65 MVA transformer. This impedance change will decrease the Pst from 16.1 measured in the fusion furnace to 0.7627 measured at the ENEA Substation, this is due to the new filter bank and the new series inductance involved in the system it is showed in the table XIV, they are a significant enhancement.

TABLE XIV.
SUMMARY OF FLICKER PROPAGATION ON DIFFERENT MODEL BUSSES WITH A NEW TRANSFORMER.

Measurement Point	Pst
Fusion furnace	16.1068
EVOLIS Substation	1.3141
115kV ACASA Substation	0.8056
La Enea Substation	0.7627

Fig. 7 shows the temporal trend for current and proposed conditions with the transformer change in the furnace bay.

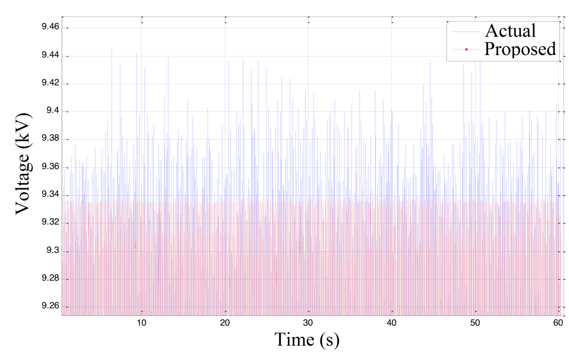

Fig. 11. Voltage peak oscillation in the Enea Substation

CONCLUSIONS

Table XV shows average indices of power quality found in the study reported in [4]. Both, voltage harmonic distortion indices and total demand distortion indices are within required limits I_{TDD}, V_{THD}.

TABLE XV
SUMMARY OF POWER QUALITY INDICES ON THE MEASURED BUSSES

Bus	I_{TDD}	V_{THD}	Pst
EVOLIS Substation	4.2%	1.137%	1.3141
115 ACASA Substation	4.1%	1.132%	0.8056
La Enea Substation	4.1%	1.099%	0.7627

The analysis shows that there is a high level of flicker throughout the circuit. Thus, the iron and steel company under study currently fails with the Pst and Plt values of the EN50160 standard, the same for the Colombian regulation office (CREG).

The installation of the new transformer will constitute a mitigation measure to the flicker phenomenon observed.

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Eduardo A. Cano-Plata (S'96, M'98, SM'15) was born in Neiva, Colombia, in 1967. He received the B.Sc. and Specialist Engineering degree in 1990 and 1994 from Universidad Nacional de Colombia, Manizales, both in Electrical Engineering. He received the Doctorate degree in Engineering in 2006 from the Universidad de Buenos Aires. Since 1994, he has been a full professor at the Universidad Nacional de Colombia, Manizales branch. His research interests include Power Quality, Power Electronic, Power Systems Grounding and Smart Grids. He is the current director of the Transmission and Distribution Network group – GREDyP.

Armando J. Ustariz Farfán: (S'08, M'12) was born in Urumita (Colombia) in 1973. He received a bachelor's degree in Electrical Engineer in 1997, and a Master's in Electric Power in 2000 from the Universidad Industrial de Santander. He received the Ph.D. degree in Electrical Engineering at the Universidad Nacional de Colombia, in 2011. He is a researcher and associated professor with the Electrical, Electronic and Computer Engineering Department, at the Universidad Nacional de Colombia, Manizales Branch. His research interests include Power Definitions Under Non-sinusoidal conditions, Power Quality, and Power Electronic.

Oscar J. Soto Marin: (S'15) Oscar was born in El Cairo (Colombia), in 1977. He received the B.Sc. M.Sc (Laureate thesis) in 2005 and 2015 respectively from Universidad Nacional de Colombia, Manizales Branch, both in Electrical Engineering. He is currently a PhD student in the Electrical Engineering program at the Universidad Nacional de Colombia, Manizales Branch. His research interests include Power Quality and Power Systems Grounding.