Power Quality Issues of Electric Arc Furnace and their Mitigations -A Review

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Abstract— *Electrical Power quality is used to determine the health of the electrical power system that connects the consumer's devices. It is concerned with voltage quality, current quality, reliability of service, quality of power supply etc. Actually the power quality refers to maintaining the sinusoidal waveform of power distribution bus voltage at rated voltage magnitude and frequency. Voltage flicker and harmonics are the main types of power quality problems that are very common to the power system containing electric arc furnace (EAF). Utilities connecting electrical arc furnaces are highly concerned regarding these disturbances and try as far as possible to minimize them. In this paper, EAF is presented for the study of power quality problems and their mitigation. Analysis regarding power quality indices related to both AC and DC type arc furnace has been presented.*

Keywords— Electric Arc Furnace (EAF), Flicker Harmonics, Melting and Refining, Power quality.

I. INTRODUCTION

In the past few decades, the use of electric arc furnace has been increased for the production of steel and its alloy throughout the world. Steel production by electric arc furnace route in 2007 was 36% of the total steel production and this share is expected to be increased up to 50 % by 2030. The reason behind is increased use is due its reduced capital cost and less energy required for the production of the steel. The electric arc furnace is either AC or DC operated. It transfers the electric energy to thermal energy (electric arc) to melt the scrap material held by the furnace. The arc produced between the electrodes low voltage and high current supplied by the furnace transformer.

The operation of electric arc furnace can be divided in into intervals namely melting and refining periods. The refining period is further divided in several stages. During the melting stage, the electrode is lowered through a hydraulic actuator system to maintain the stable arc. The furnace draws active power in this condition. More and more buckets of scrap material are added into the furnace during the melting stages. During the refining stage, a long arc is established. The factors involved during the operation of the furnace are electrode position, electrode arm control scheme, supply voltage, operating reactance and the materials used for melting and refining. The installations of both AC and DC electric arc furnace [1] have been shown in figure 1(a) and figure 1(b) respectively as shown.

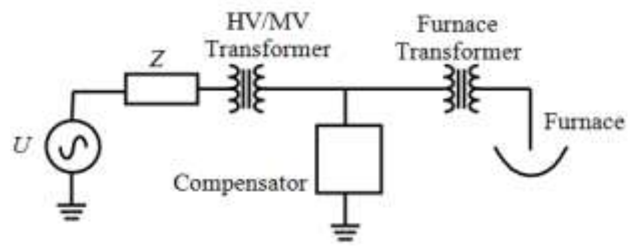

Fig:1(a)

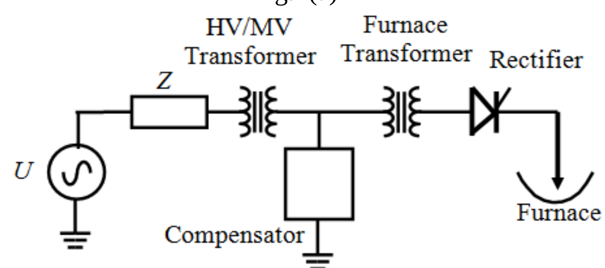

Fig: 1(b)

Fig.1: Installation of Electric Arc Furnace Arc Furnace (a) Installation of AC Arc Furnace (b) Installation of DC Arc Furnace

II. COMMERCIAL USE OF ELECTRIC ARC FURNACE

The electric arc furnace with its high thermal efficiency is suitable for melting down scrap. The electric arc furnace uses about 30% less energy for the same process that the blast furnace and the basic oxygen steelmaking plant. More over in the electric arc furnace scrap can be replaced up to 100% by unreduced iron ore (sponge iron). Electric arc furnace accounts for 51% of the total span of the three basic raw materials (scrap, pig iron and sponge iron), while open hearth furnace take about 17% and basic oxygen converters take about 9%.The growing availability of sponge iron increases the economics significance of the electric arc furnace. Electric arc furnaces are extremely flexible and can be used in changing circumstances and production levels. It can be used as smelting and refining mode. The electric power can be used in controlled way as per the demand. The electric arc furnace also can be combined with oxygen fuel burner when making special steels.

III. POWER CONVERSION – ELECTRICAL TO HEAT ENERGY

The AC arc furnace is either single phase system or three phase system fed by ac supply system with relatively high reactance. When electrodes are lowered, an arc is produced by high current from electrodes to the scarp held by the furnace. The heat generated by the arc at the temperature up to 3000ºC is utilized for melting and refining the scrap held by the furnace.

A DC arc furnace typically consists of graphite electrode (cathode) vertically mounted through an opening in the middle of the furnace roof. The anode connection is in the hearth of the furnace. The anode is in the direct contact of the scrap material to melt. The arc is generated between the tip of the cathode and the upper layer of the scrap held in the furnace. A very high temperature (1500 ºC) is generated which is utilized to melt and refine the scrap.

IV. PRINCIPLE OF ARC FURNACE OPERATION

A transformer directly energizes furnace electrodes in a high current circuit in AC arc furnaces, whereas dc furnaces employ a controlled rectifier to supply dc to the furnace electrodes. Arc furnace operation may be classified into stages, depending on the status of the melt and the time lapse from the initial energization of the unit. During the melting period, pieces of steel create momentary short circuits on the secondary side of the furnace transformer. These load changes affect the arc characteristics, causing fluctuations of current. The current fluctuations cause variations in reactive power, which cause a momentary voltage drop or flicker, both at the supply bus and at nearby buses in the interconnected system. The arc currents are more uniform during the refining period and result in less impact on the power quality of the system. Arc furnaces also create harmonic load currents and asynchronous spectral components. Harmonics represent an important power quality issue, because they may cause undesirable operating conditions.

V. DEFINITION OF POWER QUALITY

According to IEEE 1100 standard [2], the power quality is "the concept of powering and grounding sensitive electronic equipment in manner that is suitable to the operation of that equipment and compatible with the premise wiring system and the other connected equipment." It also understands for the supply reliability, service quality, voltage quality, current quality, quality of supply and the quality of utilizing the electrical power. There are kinds of classifications power quality issues. A few of them classify the events as "steady state" and non steady state phenomena. Duration of the event is the most important factor in ANSI C84.1 standard. IEEE-519 USES the wave shape (duration and magnitude) of each event to categorize the power quality problems. IEC-61000-2-5 standard use the frequency range of the event for the classification of the power quality. As per IEEE-1159 classification, there are three different types of short duration events namely instantaneous, momentary and temporary. Further each category is divided into interruption, sag and swell. Categories and Characteristics of Electromagnetic Phenomena in Power System as defined by IEEE-1159 standard have been shown in appendix.

VI. COMMON DISTURBANCES IN POWER SYSTEMS

The common disturbances in an electrical power system [3] are

a. Voltage sag
b. Voltage swell
c. Momentary interruptions
d. Transients
e. Voltage unbalance
f. Harmonics
g. Flickers
g. Voltage fluctuation

VII. ARC FURNACE POWER QUALITY PROBLEMS AND ITS MITIGATION – A REVIEW

J. D. Lavers *et al* [4] describes the detail performance including the harmonic analysis by using a method of data acquisition and analysis of an electric arc furnace. The above method suggested by the author was implemented on a single user minicomputer (a PDP 11/40) and on a large mainframe (IBM 3033). The author proposed harmonic method of analysis by using two software package namely FURNC (create furnace data) and FURNA (analyze furnace data). FURNC utilizes fast Fourier transform methods to compute the current and voltage harmonics. The harmonics produced by FURNC are processed by FURNA to analyze the specific parameter. The author in his paper presents the two arc furnaces supplied by 33 kV supply by individual 65 MVA on load tap changer furnace transformer. Each arc furnace is fitted with 65 MVAr SVC along with filter circuit (2nd, 3rd, 4th, 5th, and 7th. The results are obtained by the furnace during the operation the furnace current harmonics were found to be to the order of one to five percent with second, third and fifth dominating. The harmonic components were found negligible during pellet operation.

Aurelio García-Cerrada *et al* [5] has compared the performance of TCR based and VSI based flicker compensation experimentally from the arc furnace installation. An electrical arc furnace is a stochastic non linear load [6].The author has proposed a model for an arc furnace by assuming that whenever there is current, the voltage drop is constant for fixed for fixed arc length.

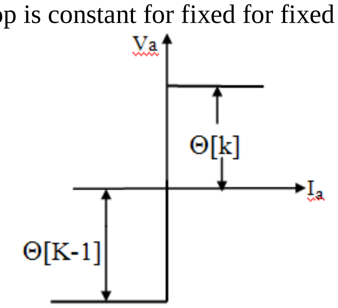

Fig.2: Electric arc I-V characteristic curve

In an arc furnace, the arc length varies with time due to the movement of the electrode and simultaneously the movement of scrap under the electrode. The time varying arc length of the arc length can be modeled as the stochastic process and consequently the proposed arc furnace model is

$$V_a\left(I_a, \Theta[k]\right) = \Theta[k] * sign\left(I_a\right) \qquad (1)$$

where Va and Ia are the voltage and current in the arc and $\Theta[k]$ is the parameter directly related to the arc length. The parameter $\Theta[k]$ take different value every time when the electric arc is started hat is every time Ia crosses zero. The index k is the counter of the discrete time signal $\Theta[k]$ whose sampling period is Ts = 0.01 sec which is the time of half cycle of 50 Hz system. Such a stochastic model of electric arc furnace generates harmonic voltage in the distribution system. The voltage fluctuation of the fundamental component is the origin of flickers [1] in the system. Flicker is due to the variations of the voltage as low as 0.3% and frequencies around 8%. The author used the data collected from the primary of the furnace transformer. The strategy of using TCR and its comparison with PWM-VSI control for flicker compensation was evaluated and it was found that PWM-VSI was superior.

Z. Zhang *et al* [7] has explained how to measure the flickers produced by the arc furnace and its compensation. The author explained the first Static VAr Generator (SVG) made by the EPRI and Westinghouse in 1986. The performance of SVG was investigated for flicker compensation due to its fast response. SVG has been taken into the circuit to replace the conventional SVC (Static Voltage Compensator) due to its long response time, costly and large in size. It was developed in late 1960s for the compensation of large fluctuating industrial loads. The working of SVG is different from the working of SVC. The SVC can operate selectively connecting passive element with the power line but the SVG is a controlled ac voltage connected to the power line by a reactor. For an arc furnace the response time of SVG is 1ms and for the SVC it is 4-5 ms. The flicker reduction by SVG is 90% where as by using SVC is of the order of 75%.Harmonic compensation is better for SVG with the same capacity. Size of SVG is reduced by 50% as compared to SVC.

C. S. Chena *et al* [8] has explained the voltage fluctuation problem and proposed the mitigation of such voltage fluctuation by using SVC. The SVC consists of passive harmonic filter to provide the required amount of reactive power and one TCR for susceptance control. The voltage fluctuation is a big problem during the steel production and for the other industrial customer. The voltage fluctuation problems are generated in the industrial power system containing electric arc furnace due to transient current absorbed by the arc furnace during its early stages of operation. To mitigate the voltage fluctuation, the author proposed the installation of SVC. It is found that that the voltage fluctuation is reduced by 0.8% to 0.21% by using SVC.

Omer Ozgun *et al* [9] has explained that the voltage flickers and harmonic load current are the examples of adverse effects produced by the arc furnace while in operation especially in early stages. The impact of such highly non linear time varying load needs to be investigated. The author proposed to present an arc furnace model in two stages: Dynamic and multivalve voltage – current characteristics of the electrical arc in the first part and generation of low frequency chaotic signal by the simulation of Chua circuit to obtain the voltage fluctuation in the latter part.

The differential equation which represents the dynamics of arc model is based on principle of energy conversion. The following differential equation is given as [10].

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$$k_1 r^n + k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} i^2 \qquad (1)$$

Here "r" stands for the arc radius which is chosen as the state variable instead of the arc resistance or the arc conductance. The arc voltage is given as

$$v = \frac{i}{g} \qquad (2)$$

where "g" the arc conductance and is given by

$$g = \frac{r^{m+2}}{k_3} \qquad (3)$$

The parameters are chosen as m = 0 and n = 2 for refining stage in the electric arc furnace. The second part of the electric arc furnace is to generate the chaotic signal of the arc voltage. The chaotic component of the arc furnace voltage is supplied from chaotic circuit of Chua [11], [12] which is implemented in Power System Block sets of MATLAB.

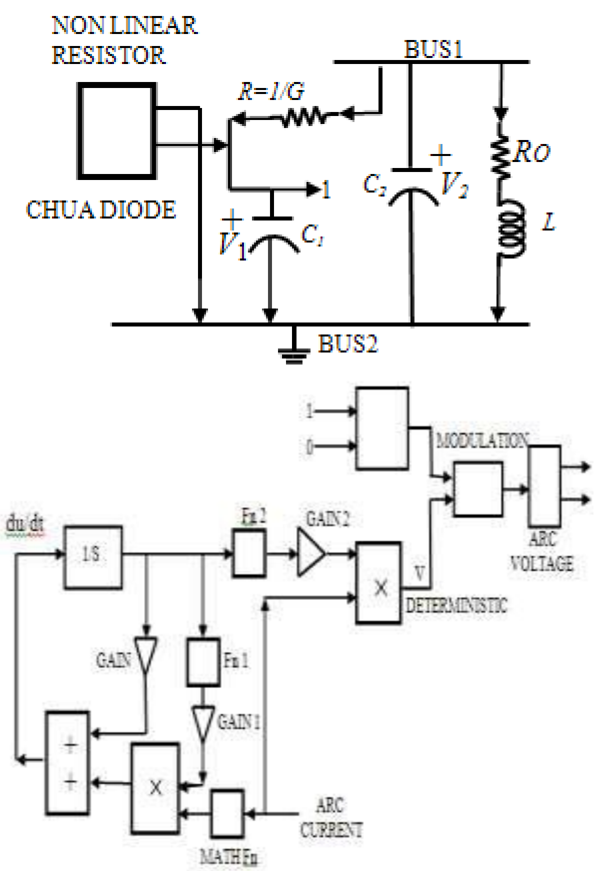

Fig.3: Matlab Implementation of Proposed Arc Furnace

The flicker generated by the simulated voltage waveform at the PCC is calculated by using flicker meter which is presented in IEC 1000-4-15 International Standard [13].

The model of IEC Flicker meter is implemented digitally in MATLAB which basically consists of five blocks as shown in the figure 4. The block 5 executes the online statistical analysis of the statistical analysis of the instantaneous flicker level. In this block, both the short term and long term flicker severity level indices are calculated and the results are displayed.

The output of this block is divided into 64 subclasses according to the instantaneous flicker level.

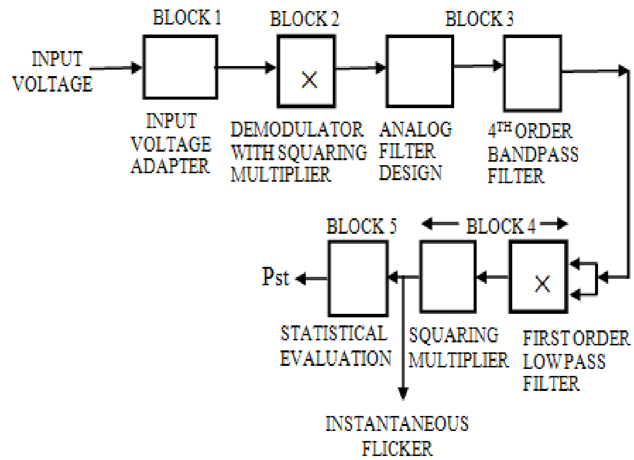

Fig.4: IEC Flicker meter model

Initially the probability distribution function (PDF) is formed by accumulating the number of elements at each level of flicker the cumulative probability function (CPF) can be formed by integrating flicker distribution over the flicker range. The short term flicker P_{st} can be calculated by using the following expression

$$P_{st} = \sqrt{\sum_{i=1}^{n} k_i P_i} \qquad (4)$$

Where k_i is the weighing coefficient and Pi the flicker level these P_i are taken from cumulative distribution curve.

$$P_i = CPF\left(\eta_i\right) \qquad (5)$$

Where η_i is the particular percent of the observation period. At least five points are normally taken while evaluating short term flicker severity. The short term flicker Pst is found to be 1.377 which is a value exceeding 1.00 which indicate that the customer complaint is likely to register.

M.Pamiani *et al* [14] has presented the benefits of the dynamic reactive shunt compensation by SVC in steel factory. Higher efficiency is the prime importance for the steel industries and to improve the efficiency of the system, the custom devices such as SVC or STATCOM are used. The author investigated the simulated result of the SVC which eliminates the supply reactance. Additional active power is delivered to the arc furnace when the SVC is in the circuit. Voltage variation is also observed to be low as compared to without SVC in the circuit. Flicker severity level is also calculated by using flicker meter of UIE/IEC type (The Pst is a 10 min integrated value)

$$P_{st99\%} = K_{st} \times \frac{Ssc_{EAF}}{Ssc_{PCC}} \quad (6)$$

Where Kst is the characteristic emission coefficient for Pst and its value is in between 45-85. SscEAF is the short circuit power at the tip of arc furnace electrode and SscPCC is the short circuit power at PCC. The author also proposed the oversized transformer or use of more transformers which reduces the short circuit impedance between the EAF and network. Pst99% increases at the PCC as the short circuit power increases at the PCC. In this condition the SVC at the arc furnace is the solution. In this condition, the maximum active power transferred is increased but the voltage variation from no load to full load remains the same.

Tongxin Zheng *et al* [15] has proposed an adaptive arc furnace model of arc furnace. According to the author the model is considered to be flexible and accurate. The difference between the proposed model and the existing model is that the control system is included in the model proposed which has been shown in the figure 5.

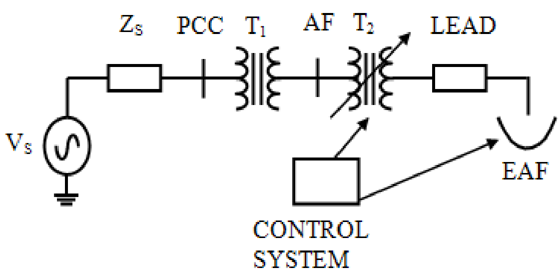

Fig.5: Arc furnace system configuration

As per the author, the adaptive arc furnace model is composed of two parts, the non linear arc model and the controller model. The arc is represented by a non linear current controller resistor. The pattern of the arc generated is determined by the arc length which is controlled by the controller.

The interaction among three components namely supply system, the arc furnace load and the control system constitutes the adaptive arc furnace model. The figure 6 shows the analysis scheme of the adaptive model of the electric arc furnace.

The supply system is assumed to be balanced, the furnace transformer assumed to be an ideal transformer with ratio tp:1 with zero phase shift and the arc furnace load is considered to be operated in balanced condition. Three phase arc voltage are identical with 120º phase shift.

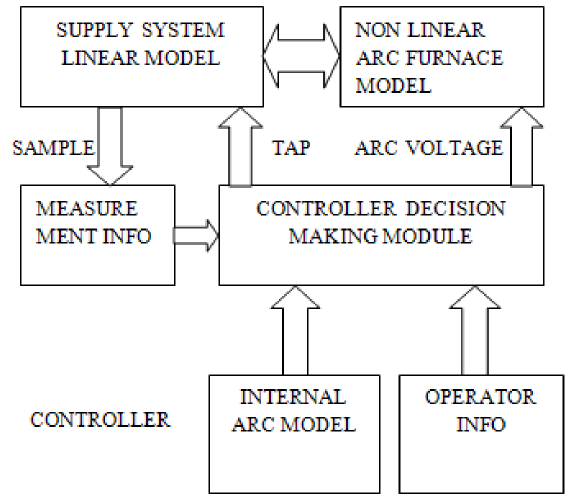

Fig. 6: Adaptive arc furnace model

The arc melting process can be divided into three periods. In the first period the arc begins to reignite from extinction, the arc is established and in the thirds period the arc begins to extinguish. The arc furnace control basically monitors the electrical and thermal parameters to make the arc furnace operation safe and efficient. The proposed controller is different from the actual controller. Some assumptions are made for the proposed controller.

(i) Only electrical parameters such as current , voltage and active power are monitored instead of thermal parameters.

(ii) The controller is assumed as an ideal controller without time delay and response dynamics.

(iii) The control scheme generates its output every cycle that is every 16.67ms while in actual control system the response time is normally in seconds.

The author has presented only fifth, seventh and eleventh component of harmonics are produced. The current harmonics shows the different characterizations in melting and refining stages. It is found that the contribution of harmonics increases more during melting and reduced in refining stages. The fifth component of harmonic is the greatest component of harmonic and changes with the power input. The voltage harmonic components are found more during refining stage. There is no big change for 5th, 7th and 11th harmonics during refining stage. In first case

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the white noise is added to the operating parameter to realize the flicker and in the next case it is observed that the random movement of melting material may change the electrode position which contributes the dynamic phenomena like voltage flicker. The harmonic components of each case are summarized in the Table2.

Table.2: Harmonic component of each four cases

	Harmonics	Case 0	Case1	Case2	Case3
Arc voltage	Fund	275.01	274.62	268.19	273.82
	3rd	N/A	33.33	32.65	32.63
	5th	N/A	20.00	18.83	18.75
	7th	N/A	14.29	12.44	12.28
	9th	N/A	11.11	8.92	8.75
	11th	N/A	9.09	6.60	6.42
Arc current	RMS (KA)	62.84	64.38	64.69	62.81
	Fund (KA)	62.75	64.28	64.60	62.71
	5th	4.70	4.67	4.86	5.07
	7th	2.36	2.39	1.82	1.89
	11th	N/A	0.97	0.80	0.82
Voltage at AF	RMS (V)	379.00	378.08	376.36	377.14
	Fund	378.00	378.08	376.36	377.14
	5th	N/A	1.89	1.41	1.48
	7th	N/A	1.28	0.69	0.71
	11th	N/A	0.89	0.75	0.74

G. Chang *et al* [16] explained that due to the uncontrolled nature of the steel melting process, current harmonics are produced by the arc furnace in a random and unpredictable manner. During melting process in the arc furnace, the arc length (the gap between tip of the electrode and scrap) varies. When the arc length is increased, the oscillation begins to occur due to rapid procession of arc jet around the attachment point on the electrode surface. As the arc length increases further, the arc current produces another transition in temporal behavior from regular oscillation to random and unpredictable motion of the arc. The author has described the power system of electric arc furnace in which the source reactance is small. The utility transformer HV/MV connects the high voltage bus to the medium voltage bus. The furnace transformer MV/LV connects the medium voltage bus to the arc furnace electrodes. An arc furnace produces wide range of harmonics due to current chopping and ignition in each half cycle of ac supply. It is observed that the interharmonics are also produced besides the integer harmonics. The author proposes to install SVC or filter near the arc furnace to reduce 3rd, 5th and higher order harmonics.

Ahmad Esfandiari *et al* [17] discussed the use of Unified Power Quality Conditioner (UPQC) to improve the power quality of the power system connected with electric arc furnace. Series capacitor, series inductor, SVC, passive filter and custom devices such as DVR or DSTATCOM are few compensating devices to improve the power quality of the power system. These devices are having their limitation in their performance. The UPQC consists of series and shunt active filters on a common DC link.

It is used to mitigate the voltage disturbance and compensate the reactive power, harmonics and interharmonics. Since voltages at the point of common coupling (PCC) contain low frequency interharmonics, conventional methods cannot be used for extracting voltage reference signals. The real simulation on a three phase arc furnace of capacity 60 MVA by using UPQC. Voltages found at the PCC before the compensation by using UPQC for 10Hz and 110Hz were found 0.13% and 1.12% whereas after compensation they were found to be reduced by 0.01% and 0.009% respectively.

C. Sharmeela *et al* [18] explained that the voltage flicker is generated in the industrial power system due to large and rapid industrial fluctuating load. Power quality in the electrical power system is affected by the voltage and current harmonics, voltage fluctuation and power factor. Harmonics are generated due to the use of power electronics devices and voltage fluctuation due to the presence of large nonlinear lads such as arc furnace. The author presents the effect of 11kV/0.566 kV, 4Ton AC EAF by installing SVC near the arc furnace. The harmonics and voltage flicker are evaluated with and without the installation of SVC and recorded.

Table.3: Total Harmonic Distortion Voltage and Total Harmonic Distortion Current with Operating Power Factor

	THD-V	THD-I	Power Factor
Without SVC	4.78%	4.975%	0.656
With SVC	2.21%	4.954%	0.857

The voltage flicker at the PCC without SVC is found to be 2% which is more than the permissible limit. After connecting the SVC, the voltage variation is 0.005%. The result shows that there is significant decrease in the voltage variation when the SVC is installed.

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M.P. Donsión *et al* [19] has presented the measurement of flicker and its mitigation with SVC on a iron and steel industry containing an AC arc furnace of 83MW (173Ton) with a furnace transformer 120MVA connected by 220 Volt line with power substation where there are other network connected with industrial and domestic consumer. In this paper, arc furnace is considered as an unbalanced, time varying and non linear load which produces many power quality problems such as harmonics, flicker and unbalance in the power system. During the arc furnace operation, the random behavior property of arc melting and its control cause serious power quality problem with the supply system.

Wang Yongning *et al* [20] presented the model of an improved time variant, non linear, three phase electric arc furnace which is based on the stochastic characteristics of arc length and real arc furnace condition. The actual arc furnace installation is not fitted with compensation devices. The arc furnace is a typical load in the power system which injects numbers of harmonic components in the power system whose magnitude changes with the varying loads. The author proposed the system identification technique to estimate the stochastic characteristic. The dynamic arc current and the wave form of bus bar current are obtained which are 22.7% for Ph-A; 12.7 for Ph –B and 21.0% for Ph-C. The total Harmonic Current Distortion at 110kV bus was also found to be 15.9%.

J. Sousa *et al* [21] presented in his paper the guide lines for the estimation for harmonics and flickers produced by the electric arc furnace. Disturbance in form of harmonics and voltage flickers namely are propagated into the distribution system when the electric arc furnace is operated. The cause of components of harmonics are due to the non linear behavior of the current voltage of the electrical arc and the voltage flicker is due the fact that arc length changes during the melting of the scrapes. The author presents 80MW electric arc furnace connected with 30kV/1.1kV, 120MVA furnace transformer, delta star transformer which is connected with utility transformer rated 230kV/30kV, 120MVA. In this paper, the author has evaluated harmonic distortion by using a distributed constant parameter model where as the voltage flicker simulation, nominal pie model is proposed. The voltage THD at PCC and arc furnace bus are obtained as 0.25% and 35.23% respectively and the current THD at PCC and arc furnace bus are found to be 2.08% and 13.26% respectively. The flicker severity index (Pst) at the PCC and arc furnace bus are 2.1 and 4.7 respectively.

I. Vervenne *et al* [22] has shown that the arc furnace converts electrical energy into thermal energy in form of an electrical arc which is used to melt the scrap material held in the furnace. The arc produced between the electrode and the material kept in the melting bath is characterize by the low voltage and high current delivered by the furnace transformer. The author has proposed an arc furnace model based on the power quality point of view. Since the electric arc furnace is responsible to propagate the disturbance in the high voltage network due to its dynamic behavior in melting stage of the operation. Hence such model was required to evaluate the harmonics and the flicker which are the most pronounced and major power quality problems in the power system. The perturbation produced by the arc furnace is of the random nature whether the furnace is supplied by AC or DC. The flicker produced by the arc furnace is variable from one cycle to another and especially during the melting stage the flickers are of high peaks. The flickers are dependent on quantity and quality of scrap, amount of oxygen used during the melting and the crumbling of scrap during melting.

Due to the variable arc length, harmonics are produced. The third harmonic is predominantly produced in such furnace during early stage of the melting. Upper limits of such generated harmonics are given table below.

Table.4: Upper limits of generated harmonics

Harmonics	Melting	Refining
2nd	5	2
3rd	20	10
4th	3	2
5th	10	10
6th	1.5	1.5
7th	6	6
8th	1	1
9th	3	3
11th	2	2
13th	1	1

DC arc furnace has totally different impact on the power system grid. These furnaces have considerably less flicker. The use of power electronic converter compile with the non linear characteristic DC load produces the harmonics.

E. O'Neill-Carrillo *et al* [23] presented the chaotic dynamics to explain the operation of electric arc furnace which is a non linear load in the power system. The author in this paper has shown the chaotic behavior in the arc furnace current. The Lyapunov Exponent which is the measure of chaotic behavior has been proposed in this

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paper. The Lyapunov Exponents are the measure of the rate of divergence (convergence) of state trajectories whose initial conditions are infinitesimally close together. A positive Lyapunov Exponent indicates a net average divergence from initial conditions. This shows the sensitive dependence on the initial conditions and presence of the chaos.

In general there are k Lyapunov Exponents associated with a dynamic process in a k dimensional phase space. The k^{th} exponent is defined as

$$\lambda_k = \ln\left[\underset{\longrightarrow}{\lim}\left(s_{n,k}\right)^{\frac{1}{n}}\right] \qquad (1)$$

Whenever the limit exists, $s_{n,k}$ can be regarded as the length of the k^{th} semi axis of the n^{th} iterate of an infinitesimally small ellipsoid of initial condition. The magnitude of largest positive Lyapunov exponent determines the time scale over which the system dynamics becomes unpredictable.

The largest positive Lyapunov exponent λ_1 can be estimated by using Wolf's algorithm [24] and is given by

$$\lambda_1 = \frac{1}{t_M - t_O}\sum_{k=1}^{M}\log_2\frac{L'(t_k)}{L'(t_k - 1)} \qquad (2)$$

Simulated data was compared with actual arc furnace data to validate the model. The author suggests two perspectives of chaotic dynamics of the arc furnace. The first one explains the detection problems [25] in which the operating level of the EAF is determined by the time series management of the load signals. The second perspective suggests with the modeling of the arc furnace that deals another dynamics of the arc furnace. The author experimentally identified the chaos during the operation single phase electric arc furnace. The Lyapunov Exponent (LE) was used to study the arc furnace data. Table 5 presents the calculation of the currents in the arc furnace. An arc furnace of the capacity 60MVA which is connected with 13.8kV bus is under the consideration and in each case the largest computed exponent is positive between 8 and 12bits/ seconds depending upon the parameters used in Wolf's algorithm.

Table.5: Lyapunov Exponent for 60 MVA EAF

Dimension	Delay (No. of Steps)	Lyapunov Exponent (bits/sec)
4	24	10.78
5	24	10.96
6	24	11.55
7	24	8.53

Table.6: Power Quality Indices for Actual and Modeled data

Index	Actual	Model
THD%	14.11	11.05
K-Factor	1.060	1.061
Zero Peak Flicker factor	0.714	0.646
Crest Factor	1.605	1.578
Lyapunov Exponent	16.89	15.26

Pedro E. Issouribehere *et al* [26] presented the power quality at PCC where an electric arc furnace supplied with alternating current. The quantities measured are current and voltage harmonic, power factor, active power, reactive power and flicker. The power quality is evaluated by comparing the contemporary International and Argentinean standard. Electric arc furnace produces serious electrical disturbances in the power system. Flicker and harmonics are the major power quality issues observed with an arc furnace of 75MW for steel melting was connected at 132kV voltage in the transmission system in Argentina. As per Argentinean regulation, the utility or the power system operator have got the responsibility to ensure the electromagnetic compatibility of the whole system and equipments connected to it. A summary of Flicker Compatibility for LV, MV and HV network [27] is given in the table 7.

Table.7: IEC Flicker Standard

Standard		IEC 61000-3-7[28]	IEC61000-3-7[29]
Purpose		Planning level for controlling emission	Compatibility level for MV network
Objectives at MV	Pst	0.9	1
	Plt	0.7	0.8
Objectives At HV-EHV	Pst	0.8	NA
	Plt	0.6	NA

The minimum required period for assessment is suggested one week and the Pst99% and Plt99% values resulting from the measurement is compared with the allowed 99% or 95% emission limits. The following relationship is considered.

Pst99% = 1.25 Pst95%

Plt99% = 0.84 Pst95%

The Pst measurement summary is given in the Table 8. Flicker level as per the Argentinean regulation is recorded in Table 9.

Table.8: Pst measurement summary

	MV Network	LV Network	HV Network
Scc MVA	905	2800	------
Flicker Level Pst95%	7.83	2.58	2.01

Table.9: Flicker level as per the Argentinean regulation

MV& HV (1<U≤220Kv) $K2=S_L/S_{SC}$	Individual Emission Limit
K2≤0.005	0.37
0.005<K2≤0.01	0.46
0.01<K2≤0.02	0.58
0.02<K2≤0.03	0.67
0.03<K2≤0.04	0.74
0.04<K2	0.79

Reference level of voltage harmonic and current harmonic according to ENRE and IEEE and measured and recorded in Table 10 and Table 11 respectively..

Table.10: Reference level of voltage harmonic according to ENRE and IEEE and measured voltage harmonics

	THD	H3	H4	H5	H7	H11	H13
ENRE limit	3	1.5	1	2	1.5	1.5	1.5
IEEE limit	2.5	1.5	1.5	1.5	1.5	1.5	1.5
Pst95 %	1.72	.69	.30	.70	.30	.24	.19

Table.11: Reference level of current harmonic according to ENRE and IEEE and measured current harmonics

	THD	H3	H4	H5	H7	H11	H13
ENRE limit	12	7.5	3.8	6	5.1	2.9	2.2
IEEE limit	4	3.5	0.9	3.5	3.5	1.75	1.75
Pst95 %	4.12	2.1	.88	.86	.46	.27	.25

Table.12: The result of harmonic content of arc furnace current at by IEEE 519 and the result obtained from the measurement

Furnace condition		Harmonic current				
		I_2	I_3	I_4	I_5	I_7
Initial melting	Theoretical	7.7	5.8	2.5	4.2	3.1
	Measured	8	7	2.8	3.8	1.4
Refining	Theoretical	--	2.0	--	2.1	--
	Measured	4	2.2	1.2	1	0.5

The flicker level measured in the steel factory is high and more than the reference level at the PCC.

Alfonso Alzate Gomez *et al* [30] presented an arc furnace model based on V-I characteristics which is obtained by the differential equation [31]

Some studies have been suggested to simulate the arc furnace which is based on deterministic [32], [33], Stochastic [34], [35] and chaotic assumptions [36], [37], [38].

The deterministic model of the arc furnace is proposed by modulating the arc radius with sinusoidal signal in form of equation (1)

$$r_S = r[1 + m_S.\sin(\omega t)] \qquad (1)$$

Where r_s is the arc radius for the deterministic mode of the arc furnace, r is the arc radius, modulation factor m_s. At a constant frequency of 10Hz and if the value of m_s is 0.025, Pst is close to 1at PCC.

In stochastic model, the arc length is close to Gaussian distribution and therefore a random signal with such a distribution is used to modulate the magnitude of the arc radius r_s as obtained from equation (1) is presented in (2)

$$r_g = r_s[1 + m_g.\varsigma_n] \qquad (2)$$

where ς is the standard deviation from the mean value of a Gaussian distribution which is modulated with factor m_g. For standard distribution values (20%-30%) for each phase and m_g being 0.16, the Pst is 1.0 at the PCC.

In chaotic assumption of the arc furnace model, the magnitude modulation of r_g (a random dynamic) of arc radius with chaotic signal c_h is presented as

$$r_d = r_g.[1 + m_c.c_h] \qquad (3)$$

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Where the term m_c is the modulation index and c_h is the chaotic normalized signal with low frequency. When m_c is equal to 0.08, the Pst is 1.0 for the voltage at PCC.

Table.13: Harmonic Analysis of the arc furnace current

Component	Peak(%)		
	Ph-A	Ph-B	Ph-C
Fund	100	100	100
2nd	8.02	7.37	6.36
3rd	7.36	6.71	7.74
4th	8.37	7.46	8.15
5th	4.67	4.47	4.29
THD	13.47	11.82	11.37

Table.14: Pst Comparison between real and simulated values

Component	Ph-A	Ph-B	Ph-C
Modeled	1.75	1.57	1.70
Pst99%	1.72	1.78	1.64

The author suggests that this model of electric arc furnace is helpful in the planning stage of new arc furnace on the new distribution system.

G.C. Lazaroiu *et al* [39] presented the power quality problems in a DC arc furnace on a real case application. The author proposed and implemented an ac dc converter control system for power quality improvement by considering flicker and harmonics at the point of common coupling. Two different models of DC furnace are considered in this paper: The deterministic model with sinusoidal disturbance of 10Hz and the random model with a white noise behavior of the disturbance. Proportional Integral Controller is used to minimize the impact of power quality in the AC network. The PCC is maintained at 220 kV line to line, short circuit power is 3500 MVA and the rated power of the DC furnace. The author introduced different power quality indices as follows.

$$THD_I = \sqrt{\sum_{K=2}^{40}\left(\frac{I_K}{I_1}\right)^2} \times 100$$

$$THD_V = \sqrt{\sum_{K=2}^{40}\left(\frac{V_K}{I_1}\right)^2} \times 100$$

$$TIHD_I = \sqrt{\sum_{K=2}^{40}\left(\frac{I_i}{I_1}\right)^2} \times 100 \quad TIHD_V = \sqrt{\sum_{K=2}^{40}\left(\frac{V_i}{V_1}\right)^2} \times 100$$

$$TD_I = \sqrt{THD_I^{\,2} + TIHD_I^{\,2}} \quad TD_V = \sqrt{THD_V^{\,2} + TIHD_V^{\,2}}$$

where V_1, I_1 are the fundamental value of RMS value of the voltage and current and V_K, I_K are the voltage and current on k_{th} harmonic order. Vi, Ii are the voltage and current on i-th interharmonic order. Without the optimized control the Total Harmonic Voltage Distortion is 8.28% and Total Harmonic Current Distortion is 41.06%. The Pst (50%) is 3.72%.

Tongxin Zhang *et al* [40] presented that the fundamental component of the current drawn by the electric arc furnace produces the fluctuation of the voltage in the local substation. Theses fluctuations are the responsible for the generation of flicker. The voltage varies as much as 0.3-1% with the frequencies between 2 and 8 Hz. The author proposes the SVC with TCR as the compensating device for the improvement of power quality. The controller of SVC is based on controlling of shunt susceptance which is controlled by changing the firing angle of the thyrister. The presence of controller is to maintain the desired voltage at the bus. In the steady state, the SVC provides steady state voltage to maintain the high voltage bus at the predetermined level. However in case of sudden increase of the load, the voltage of the bus begins to fall below its set point. In such a condition the SVC injects the reactive power into the bus to maintain the voltage of the bus at the desired level. The electrical circuit of the arc furnace supply from substation is shown in the figure 6.

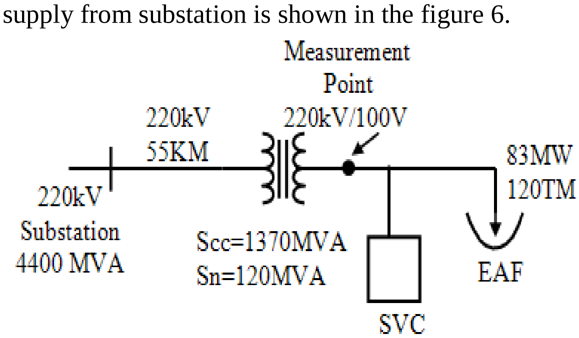

Fig.7: Electrical circuit of the arc furnace supply from Substation

A summary of measured flicker Pst95% at the Steel factory transmitted to substation 55 KM away with and without SVC is presented in the tables given below

A. Flicker measurements without SVC

Table.A.1: Flickers Pst95% at the measurement point

Date	D9	D10	D11	D12	D13
Phase1	0.125	6.031	6.313	6.031	5.938
Phase2	0.156	5.750	6.313	6.375	5.781
Phase3	0.125	5.688	5.625	5.688	5.188

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Table.A.2: Pst95% Flicker transmitted to substation

Date	D9	D10	D11	D12	D13
Phase1	0.039	1.878	1.965	1.878	1.849
Phase2	0.049	1.775	1.965	1.985	1.800
Phase3	0.039	1.771	1.751	1.771	1.615

B. Flicker measurements with SVC

Table.B.1: Flickers Pst95% at the measurement point

Date	D16	D17	D18	D19	D20
Phase1	0.156	2.906	3.281	3.313	3.280
Phase2	0.156	2.844	3.281	3.313	3.219
Phase3	0.188	2.750	3.031	3.156	3.094

Table.B.2: Pst95% Flicker transmitted to substation

Date	D16	D17	D18	D19	D20
Phase1	0.049	0.905	1.022	1.031	1.021
Phase2	0.049	0.885	1.022	1.031	1.002
Phase3	0.058	0.856	0.944	0.983	0.963

J. L. Guan *et al* [41] has presented in this paper that the criteria to estimate the severity of EAF voltage flicker are Maximum Reactive Power Fluctuation Method (MRPFM) [42], [43]. The voltage flicker is calculated by two methods round the world when electric arc furnace AC or DC is operated in the power system. The first flicker meter of IEC standard and established by UIE and the other is ΔV_{10} meter which is established by Japanese Technical Committee. ΔV_{10} method is used by Taiwan Power Company (TPC).The degree of voltage flicker, namely Short Term Flicker Severity (Pst) and 10 Hz equivalent value ΔV_{10} are measured conventionally to characterized the severity of flicker. The investigation carried on AC and DC furnaces reveals that the estimated value of ΔV_{10} measured by conventional method is significantly lower than the surveyed value [44], [45]. The difference between the estimated value and the actual value is quite large.

The author proposed in this paper the maximum complex apparent power fluctuation method (MCAPFM) to overcome the disadvantages of the conventional method. The revised method is based on the fact that the estimated value of ΔV_{10} cannot ignore the effect of active power variation. This method yield more accurate value of ΔV_{10} than the traditional method. During one of the case in a factory, the ΔV_{10} value is in between 0.073% ~ 5.71% while the ΔV is in between 0.107% ~ 12.543% in the primary side of the furnace transformer at 34.96Kv. In an another case, the ΔV_{10} value is in between 0.138% ~ 6.767% while the ΔV is in between 0.315% ~ 17.081% in the primary side of the furnace transformer.

Douglas Andrews *et al* [46] has explained that when the electric power is maximized, it affects the productivity of the electric arc furnace operation. Due to the non linear property of electric arc, the significant amount of harmonic current flows in the utility power system. These harmonic current in the power system results the voltage distortion. The author proposed an analytical technique to correct the power factor in a steel factory by field measurement, harmonic analysis and filter design to minimize the harmonic distortion. Power system harmonic was carried out in North Star Steel plant Beaumont, Texas at 13.8kV and 34.5kV voltage level in the power system. Scrap metal and Ladle furnace harmonics have been shown in Table 19.

Table.19: Typical scrap-metal and ladle furnace harmonics

Harmonics	Scrap Furnace	Ladle Furnace
2^{nd}	5%	2.0%
3^{rd}	20%	10.0%
4^{th}	3%	2.0%
5^{th}	10%	10.0%
6^{th}	1.5%	1.5%
7^{th}	6%	6.0%
8^{th}	1%	1 .0%
9^{th}	3%	3.0%
11^{th}	2%	2.0%
13th	1%	1 .0%

The voltage THD was found 1.51-8.17% at 13.8% and the current THD in the range of 3.45-9.86%. The voltage THD was found in the range of 0.53- 6.30% during the operation. During extreme sporadic condition of arc furnace, the voltage THD was found to be 19.18%. The current THD was in the range of 3.14-16.08%. The harmonic analysis was carried out by installing the line reactor and 4.7^{th} harmonic filter and it was found that the voltage THD and current THD were 2.63% and 3.83% respectively.

G. W. Chang et al [47] presented the classic and advance models of AC electric arc furnace which is based on the actual recorded data. Electric arc furnace, now days are designed for very large power and due to erratic as well as non linear nature of electric arc, harmonics, flickers and interharmonics are injected in the supply system. Therefore, an accurate model is required for the effective solution of

PQ problem in the power system. The author reviewed two classic models of electric arc furnace such as harmonic current injection model (HCIM) and Harmonic Voltage Source Model (HVSM) and Fast Fourier Transform (FFT) is used to calculate the harmonic component of EAF voltage and EAF current. Due to certain drawback, two advance models of electric arc furnace are proposed by the author namely Cubic Spline Interpolation Method (CSIM) and an improved neural network based method. CSIM is fit to explain the dynamic behavior of the EAF where as the RBFM not only is the accurate model but also describe the dynamic characteristics of the EAF loads.

Arash Dehestani Kolagar *et al* [48] presented the advantages of multiphase transformer in DC arc furnace power supply instead of three phase transformer. By utilizing multi phase transformer, power quality is improved. The transformer has three phases at the primary and multi-phases at secondary. The following Tables 20 and Tables 21 are for three and five phase system and Case-1, Case-2, Case-3 and Case-4 denote the thyristor based power supply with constant current control, DC–DC converter based power supply with constant current control, thyristor based power supply with constant power control and DC–DC converter based power supply with constant power control respectively.

Tables.20: Line current THD values in three phase systems

Feeding Topology	Variable	Min	Max	Mean
Case-1	THDa	0.02025	0.4766	0.2439
	THDb	0.1936	0.4952	0.2218
	THDc	0.1641	0.4807	0.1942
	ITHD	0.1899	0.4842	0.2177
Case-2	THDa	0.1151	0.3108	0.1325
	THDb	0.1151	0.3221	0.1331
	THDc	0.1149	0.3012	0.1321
	ITHD	0.1150	0.3115	0.1326
Case-3	THDa	0.2115	0.5187	0.2554
	THDb	0.2063	0.5325	0.2464
	THDc	0.1805	0.5173	0.2226
	ITHD	0.2008	0.5229	0.2419
Case-4	THDa	0.1069	0.3310	0.1190
	THDb	0.1060	0.3359	0.1187
	THDc	0.1051	0.3073	0.1177
	ITHD	0.1063	0.3250	0.1185

Tables.21: Line current THD values in five phase system

Feeding Topology	Variable	Min	Max	Mean
Case-1	THDa	0.1233	0.4514	0.1588
	THDb	0.1252	0.4551	0.1578
	THDc	0.1173	0.4491	0.1442
	ITHD	0.1225	0.4519	0.1538
Case-2	THDa	0.0381	0.2809	0.0561
	THDb	0.0379	0.2944	0.0570
	THDc	0.0377	0.2715	0.0560
	ITHD	0.0379	0.2824	0.0564
Case3	THDa	0.1351	0.4995	0.1865
	THDb	0.1332	0.4939	0.1818
	THDc	0.1270	0.4950	0.1732
	ITHD	0.1320	0.4961	0.1807
Case4	THDa	0.0403	0.3106	0.0609
	THDb	0.0406	0.3262	0.0615
	THDc	0.0401	0.2935	0.0599
	ITHD	0.0403	0.3104	0.0608

From the above result it is clear that level of harmonic distortion from DC- DC converter based power supply are significantly less than the thyristor power supply.

G. Carpinelli *et al* [49] discussed the problems of the compensation of disturbance of produced by the DC arc furnace while in operation. In previous years, the DC arc furnace is used for the scrap melting and it is replacing the traditional AC arc furnace. The unstable arc causes very rapid change in power absorbed with voltage fluctuation which is responsible for the voltage flicker even if the control system is present. Several compensating devices for the power quality improvement are adopted. The author proposed the active filter, the decoupled compensator and STATCOM are used to comply power quality limit. The following global indices related to power quality in the power system have been considered.

- THD_I And THD_V are the total harmonic distortion factors of current and voltage.
- $THDI_I$ And $THDI_V$ are the total interharmonic distortion factors of current and voltage.
- K-factor
- Pst

Power Quality Indices without and with compensators have been shown in Table 22 and Table 23.

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Table.22: Power Quality Indices without compensators.

Power quality indices (%)	Without compensators
THD I	8.45
THD V	11.43
$THDI_I$	4.10
$THDI_V$	4.34
K-factor	2.02
Pst	2.07

Table.23: Power Quality Indices with compensators

Power quality indices (%)	Active Filter	stat com	Active Filter& stat com	Decoupled Compen sator
THD I	1.41	6.76	3.08	1.41
THD V	2.07	9.42	3.96	2.51
$THDI_I$	2.86	3.28	2.05	1.87
$THDI_V$	1.48	4.43	2.19	1.06
K-factor	1.04	1.97	1.16	1.07
Pst	2.53	0.89	0.66	0.37

From the result obtained in Table 23, it is found that active filter is capable to compensate the waveform distortion and STATCOM is efficient for voltage fluctuation. The decoupled compensator reduces all the power quality indices effectively.

Chi-Jui Wu *et al* [50] has presented the load characteristics of a DC arc furnace steel factory in which the variation of active power and reactive power is high. The author has proposed the statistical method to understand the load characteristics of DC arc furnace steel factory in Taiwan. The furnace is supplied by a 161kV line. There are three main transformers and the 100MVA transformer supplies the 12 pulse rectifier for 50 Ton DC arc furnace. Four numbers of harmonic filters are at the furnace bus at 33kV. Out of four filters, two are single tune filter and the other two are C- type high pass filter. 2.5% and 97.5%cumulative probability are taken as the maximum and minimum value respectively. The degree of voltage unbalance is the ratio of negative sequence voltage and positive sequence voltage. It is found that the apparent power is in between 60.47~115.27MVA, active power in between 37.95~109.04MW, reactive power between -47.41~38.43MVAR, voltage between 156~163.25 kV, current between 215.76~426.19 Ampere, Voltage flicker between 0.212~0.941%, total voltage harmonic distortion 0.741~1.09% and the voltage imbalance V^-/V^+ between 0.590~1.06%.

Horia Andrei *et al* [51] described the electric arc furnace which is used for melting and refining iron metal in steel factory. AC and DC arc furnaces are the most disturbing load in the sub transmission and transmission electric power system. These arc furnaces are characterized by violent change in power that happens during initial stage of melting. The voltage and current characteristics of the electric arc is non linear which results in harmonic current in the power system. The author proposed to use the three phase power analyzer for the power quality analysis and the following quantities are important to be measured such as voltage , current , flicker (IEC 68, IEC 61000-4-15-P_{ST} and P_{LT}), wave shots , THD and harmonics up to the order of 64. Total Harmonic Distortion of voltage and current during melting and refining are presented in Table 24 and Table 25.

Table.24: Harmonic analysis of voltage during melting

	Phase A	Phase B	Phase C
THD V(%)	3.01	2.0	2.92
THD I (%)	10.01	10.73	10.07

Table.25: Harmonic analysis of voltage during refining

	Phase A	Phase B	Phase C
THD V(%)	1.72	1.83	2.0
THD I (%)	4.40	4.74	4.66

In different stages of operation of electrical arc furnace, the THD–I vary between 1-21% for the current and 1-6% for the THD–V. Comparing the value with the international standard; it is observed that the arc furnace does not match with either national or international standard.

H.M. Petersen *et al* [52] presented that the two models of the electric arc furnace to simulate the arc furnace flicker which is one of the power quality problem in the electric power system. The flicker is severe particularly during the initial bore down period [53]. The above two models present the stochastic values of arc resistance and arc voltage based on the assumption that the arc parameter are closely Gaussian [54].The author also suggested the compensation arrangement such as SVC and synchronous machine.

These are arc voltage and other is the arc resistance and are modeled by using probability technique. The arc voltage depends mainly on the arc length and is given by

$$V_{arc} = \overline{E} + \sigma\left(\sqrt{-2\ln\left(\text{rand}1\right)}\right)\cos\left(2\pi\ \text{rand}\,2\right) \quad (1)$$

Where rand 1 and rand2 are the uniformly distributed numbers between 0 and 1.

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The arc resistance model of the electric arc furnace can be given by

$$R_{arc} = R' + \sigma\left(\sqrt{-2}\ln(\text{rand}\,1)\right)\cos(2\pi\ \text{rand}\,2) \qquad (2)$$

Where the σ is the variance and R be the mean resistance. The author has investigated 33kV arc furnace installation. The furnace is supplied from 275 kV utility networks by two transformers. At 132 kV PCC a HV/MV transformer feeds the furnace transformer which is delta connected secondary from 229 V to 426 V (tap 13). The furnace is simulated for the both the models at the highest tap during bore down period. Measured and Simulated values Flicker without compensation and with compensation are presented in Table 26 and Table 27.

Table.26: Measured and Simulated Flicker values without compensation

Model	Pst Measured	Pst Simulated
Arc Voltage	1.30	1.36
Arc Resistance	1.30	1.33

Table.27: Simulated Flicker values with compensation

Device	Pst Simulated	Reduction Factor/%
40MVA SVC	0.81	1.68/40%
40 MVA Sync. Machine	0.96	1.38/28%
25MVASync. Machine	1.04	1.26/22%

A. Khalik *et al* [55] presented that the electric arc furnace causes the disturbance in the distribution power system due to the distortion in voltage and current due to generated harmonics, flickers, voltage fluctuation and unbalance of voltages. The electric arc furnace suffers from unequalization of three phases due to unbalance arc resistance and inductance of feeding conductors. The author introduced an 80MVA, 20kV/22.5kV/22.5kV,Y/Y/Δ, main transformer that supplies two electric furnaces of a steel factory through 0.5km cable for Arab Company for special steel. The voltage and current harmonic value were measured for the both the transformers on low and high side during 8 days. Two filters are installed at 22.5kV bus of 12.81MVAR and 15.88 MVAR respectively. Also the TCR of 0.28MVAR is also installed at the bus. The voltage odd harmonic and current odd harmonic value at PCC without filter are tabulated in Table 28 and Table 29. The phase voltage THD and phase current THD at the bus are presented in Table 30 and Table 31.

Table.28: The voltage odd harmonic value at PCC without filter

Odd Harmonic	Max Fund (%)	IEEE-519-992 Max. Limit	Even Harmonic	Max Fund (%)	IEEE -519-992 Max. Limit
3	1.37	3.0	2	1.15	1.5
5	1.73		4	0.50	
7	1.29		6	0.43	
9	0.37		8	0.31	
11	0.66		10	0.30	
13	0.54		12	0.31	
15	0.43		14	0.21	
17	0.50		16	0.20	
19	0.4		18	0.19	
21	0.28		20	0.17	
23	0.27		22	0.19	
25	0.35		24	0.18	

Table.29: The current Odd harmonic value at PCC without filter

Odd Harmonic	Max Fund (%)	IEEE -519-992 Max. Limit	Even Harmonic	Max Fund (%)	IEEE -519-992 Max. Limit
3	58.19	12	2	38.19	3
5	135.12	12	4	12.34	3
7	54.85	12	6	5.56	3
9	4.4	12	8	2.75	3
11	3.32	5.5	10	2.5	3
13	11.36	5.5	12	2.23	1.375
15	1.97	5.5	14	1.91	1.375
17	8.87	5	16	1.4	1.375
19	5.25	5	18	1.24	1.25
21	1.87	5	20	1.28	1.25
23	2.46	2	22	1.45	1.25
25	3.92	2	24	1.41	0.5

Table.30: The phase voltage THD at the bus

Phase	Max THD %	Min THD %	IEEE 519 Max permitted THD %
R	3.7	0.8	5.0
S	3.9	0.8	5.0
T	4.0	0.7	5.0

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Table.31: The phase current THD at the bus

Phase	Max THD %	Min THD %	IEEE 519 Max permitted THD %
R	130	1.2	5.0
S	127	1.4	5.0
T	120	1.4	5.0

The author suggests that for the improvement of power quality due to the arc furnace load, a new 5th tuned filter should be connected in addition of already installed 2nd and 3rd filter.

Le Tang *et al* [56] has proposed to develop an EMTP based arc furnace model regarding the generation of flicker in a large steel plant with one or two arc furnace in operation . The dynamic arc presentation is proposed by the author in the initial stage of the melting which is the worst condition of the flicker generation. The author introduces Bayou Steel Company which is supplied by Entergy's Little Gypsy 230kV switchyard through a 2.5 mile 230 kV transmission line. Initially the company has only one 57 MW arc furnace and in the second phase the company has started another 57MW arc furnace. Due to this proposal the equivalent system strength is reduced from the present 21576-18015 MVA to 13568-10196 MVA. Flicker was measured with one furnace and found to be 0.2 to 0.3%. The author presents the report of the flicker when both the furnaces were put in operation. The prediction of flicker for a single furnace as per the supply system in Europe [57].

The flicker for the single furnace as per Europe [57] is given by

$$Pst(99) = \frac{60}{SCR} \qquad (1)$$

Where $Pst(99)$ is the Pst level that exceeds 1% of the time. SCR is the short circuit ratio at the point of common coupling. For more than one furnace, equivalent Pst level may be given by

$$\text{Pst total} = \sqrt[\alpha]{\sum_i {P_{sti}}^{\alpha}} \qquad (2)$$

Where $\alpha = 3$; $Pst\ total$ is total Pst resulting from all the furnaces; $Psti$ is due to ith furnace. As per the empirical relationship, for the same size of the electric arc furnace the flicker level for both the furnace must be 26% more than the flicker level of the single furnace. Summary of simulated flicker level at the

Little Gypsy 230 kV bus is presented in Table 32

Table.32: Summary of simulated flicker level at the Little Gypsy 230 kV bus

	One Furnace		Two Furnace	
Fault MVA	□V /V (%)	Unweighted rms Flicker (%)	**ΔV/V** (%)	Unweighted rms Flicker (%)
21576	0.28	0.28	0.36	0.43
18015	0.26	0.29	0.41	0.49
15664	0.30	0.33	0.47	0.57
13568	0.35	0.39	0.60	0.75
12203	0.38	0.43	0.68	0.75
10196	0.45	0.52	0.76	0.92

The calculated value of the flicker level at the Little Gypsy (PCC) has been presented in two categories. First in the peak value of the ΔV/V and the other in unweighted RMS flicker. The maximum value of the acceptable unweighted RMS flicker is 0.5%.

E. A. Cano Plata *et al* [58] has proposed the new idea to present the electrical behavior of the electric arc furnace by the measurement of electric power in stationary and transient imbalance. The new technique adopted in characterizing the behavior the arc furnace is by using time frequency domain. The actual measurement made in the iron and steel company was compared by the electromagnetic transients ATPDraw. Voltage harmonics produced by the arc furnace is recorded in Table 33 below

Table.33: EAF voltage harmonics

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

The author in this paper presents an power quality indices namely Total Demand Distortion (TDD) of the current which is the ratio of short circuit current (Isc) and load current I_L and is accepted by IEEE- 519 standard. Total Demand Distortion of the current (ITDD) is recorded in Table 34. Total Voltage Harmonic Distortion flicker propagation in different position (actual conditions) are recorded in Table 35 and Table 36.

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Table.34: Total Demand Distortion of the current (ITDD)

Indicator	THD Ia	THD Ia3	THD Ia5	THD Ia7
Average	8.40%	0.86%	7.18%	4.05%
Std Deviation	3.52%	0.36%	3.49%	1.67%
Min Value	2.02%	0.18%	0.80%	0.61%
Max. Value	12.58 %	4.19%	24.02%	13.45%
Acceptable THD	15%	12%		

Table.35: Total Voltage Harmonic Distortion

Indicator	THD Va	THD Va 3	THD Va 5	THD Va 7
Average	1.1%	0.3%	0.7%	0.5%
Std Deviation	4.6%	0.1%	0.3%	0.2%
Min Value	0.3%	0.1%	0.1%	0.1%
Max. Value	6.1%	0.7%	1.8%	0.9%
Acceptable THD	5%	3%		

Table.36: Summary of flicker propagation in different position (actual conditions)

Measurement Point	Pst	Plt
Arc 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

Warsaw BROCIEK *et al* [59] presented the model of three phase arc furnace considering that the arc is non linear and non linearity that also appears in the windings of the furnace transformer. Voltage and Current distortion is the crucial parameter that describes the power quality. The voltage and current harmonics and the total harmonic distortion in the primary and secondary sides of the arc furnace transformer 30/0.75 kV are evaluated. The utility is at 110 kV and fault MVA level is 500MVA. The PCC is at 30 kV at the fault MVA is 200MVA. The furnace is connected with 30/0.75kV, 75MVA furnace transformer. The values of the current harmonics at PCC, the values of the current harmonics in secondary winding of furnace transformer, the values of the current harmonics at electrodes , the values of the voltage harmonics at PCC, The values of the voltage harmonics in secondary winding of furnace transformer and the values of the voltage harmonics at electrodes are recorded in Table 37, 38, 39, 40, 41 and 42 respectively.

Table.37: The values of the current harmonics at PCC

Harmonic order	Primary Winding		
	Phase A	Phase A	Phase A
1	1129	1713	1825
3	422	218	211
5	89	236	211
7	22	30	46
9	74	36	82
11	16	62	53
13	10	13	13
15	17	21	36
17	6	14	15
19	8	10	15
21	3	10	14
23	4	5	9

Table.38: The values of the current harmonics in secondary winding of furnace transformer

Harmonic order	Secondary Winding		
	Phase AB	Phase BC	Phase CA
1	18812	28545	30414
3	7037	3640	3519
5	1334	3935	3523
7	364	501	773
9	1234	607	1358
11	267	1037	891
13	170	212	211
15	284	355	606
17	95	231	255
19	139	172	258
21	57	174	230
23	68	70	144

Table.39: The values of the current harmonics at electrodes

Harmonic order	Electrode		
	Phase A	Phase B	Phase C
1	41750	37582	55909
3	10515	10637	1324
5	3592	4702	7342
7	1100	411	1252
9	2523	1392	1705

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11	808	1226	1915
13	319	321	388
15	878	213	925
17	308	244	477
19	377	176	416
21	287	118	404
23	211	170	210

Table.40: The values of the voltage harmonics at PCC

Harmonic order	Primary Winding		
	Phase A	Phase A	Phase A
1	23849	24277	23377
3	1593	824	796
5	503	824	796
7	192	265	408
9	837	412	922
11	222	860	739
13	167	208	207
15	321	401	686
17	122	296	327
19	199	264	369
21	90	275	365
23	118	132	249

Table.41: The values of the voltage harmonics in secondary winding of furnace transformer

Harmonic order	Secondary Winding		
	Phase AB	Phase BC	Phase CA
1	1412	1428	1373
3	96	50	48
5	30	89	80
7	12	16	25
9	50	25	55
11	13	52	44
13	10	12	12
15	19	24	41
17	18	20	17
19	15	22	7
21	5	17	22
23	7	8	15

Table.42: The values of the voltage harmonics at electrodes

Harmonic order	Electrode		
	Phase A	Phase B	Phase C
1	789	968	693
3	159	67	116
5	37	24	110
7	29	18	17
9	67	31	55
11	26	18	47
13	11	12	21
15	23	9	28
17	17	12	10
19	7	8	21
21	9	4	13
23	11	4	6

The results obtained for the harmonics estimation determine the propagation of voltage and current in the electric power system.

VIII. CONCLUSION

The associate problems and the issues related to the Power Quality in an electric power system that a customer encounter depends how the wave form of the voltage and current are distorted. There are numbers of power quality problems mentioned the review above namely voltage and current harmonics, flickers, voltage imbalance, transients, interharmonics, sag, swells etc. Among them harmonics and flickers are the most important power quality issues are found in the power system containing electric arc furnace. Major power quality indices are found to be more than the standard limit set by recognized international standard agencies especially during the melting stage of the operation. The information of the power quality indices related to the arc furnace obtained will be helpful to understand the mitigation technique.

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APPENDIX

Categories	Typical Spectral Content	Typical Duration
1.0Transients		
1.1 Impulsive		
1.1.1Nanosecond	5 ns rise	<50 ns
1.1.2Microsecond	1 µs rise	50 ns–1 ms
1.1.3Millisecond	0.1 ms rise	>1 ms
1.2 Oscillatory		
1.2.1LowFrequency	<5 kHz	0.3–50 ms
1.2.2MediumFrequency	5–500kHz	20µs
1.2.3High Frequency	0.5–5MHz	5 µs
2.0 Short-duration variations		
2.1 Instantaneous		
2.1.1 Sag		0.5-30cycles
2.1.2 Swell		0.5-30cycles
2.2 Momentary		
2.2.1 Interruption		0.5-30cycles
2.2.2 Sag		30 cycles–3s
2.2.3 Swell		30 cycles–3s
2.3.1 Interruption		
2.3.2 Sag		3 s–1 min
2.3.3 Swell		3 s–1 min
3.0 Long-duration variations		
3.1 Interruption, sustained		>1 min
3.2 Under voltages		>1 min
3.3 Overvoltage		>1 min
4.0 Voltage imbalance		Steady state
5.0 Waveform distortion		Steady state
5.1 Dc offset		
5.2 Harmonics	0–100 Hz	
5.3 Interharmonics	0–6 kHz	
5.4 Notching		
5.5 Noise Broadband		
6.0 Voltage fluctuations	>25 Hz	Intermittent
7.0 Power frequency variations		<10 s