Analyzing Electric Power Quality in Arc Furnaces

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Abstract The paper presents the analysis of the results carried out at Lloyds Steel Industries, Wardha, Maharashtra State, India. The various electrical quantities like voltages, currents, frequency, and flicker *etc*. regarding power quality are measured and recorded at different voltage buses; the same are compared with power quality standards. The AC Electric arc furnaces generate harmonics. Power quality disturbances such as harmonics, snapshots, and transients are investigated and found to be high.

Keywords

Harmonic current, Voltage sag, Flicker, Wild Phase, Flicker Severity Index

1. Introduction

The measurements about power quality are carried out on 220 kV incoming lines, 33 kV lines on two electric arc furnaces with capacitor bank switched off and switched on. The on line measurements of quantities affecting power quality are recorded. The harmonics are analyzed with power analyzer that could record waveform and give the spectrum and magnitude of waveforms.

The increased concern for power quality has resulted in significant advances in monitoring equipment that can be used to characterize disturbances and power quality variations. This paper discusses the information obtained from power analyzer measurements and compared with power quality standards.

Electric arc furnaces are known to produce voltage fluctuations or " Flicker" in the range of 0.5 to 30 Hz during random arc behavior during meltdown of the charge [1-2].

Extensive studies have shown that voltage variations as low as 0.5% in the frequency range of 6-10 Hz can cause objectionable light flicker from ordinary incandescent lamps. The two AC Electric arc furnaces being non-linear load produce harmonics and voltage flicker [3]. Non - sinusoidal voltage and current waveforms may result in overheating of conductor or transformers, capacitor failures, inadvertent circuit breaker tripping or malfunction of electronic equipment.

The Behavior of Electric Arc Furnace:

The voltage across an electric arc, which is relatively independent of current magnitude, consists of three components, anode drop, cathode drop and arc column component; which amounts to about 12 volts/cm of arc length. Typical values of arc voltages are in the range of 150-500 volts. Since the arc is extinguished at current zero, the power factor plays an important role on arc reignition. The figure 1 shows how arc voltage, power factor, input power; arc power and reactive power vary with arc current for a particular tap setting on the furnace transformer. The furnace is normally operated near maximum arc power, which corresponds to a power factor of 70%.

The three basic changes in operating states of an electric arc furnace, which can produce distinguishable voltage disturbances on power system, are open circuit condition, short circuit condition and the normal operation. The measurable data of interest for an electric arc furnace load include the following three phase quantities: supply voltage, real and reactive power, flicker, frequency and total harmonic distortion in respective phases. Because of the non-linear resistance, an arc furnace acts as a source of current harmonics of the second to seventh order, especially during the meltdown period. Voltage fluctuations are produced in this way through impedance on the value of harmonic currents supplied and the effective impedances at the harmonic frequencies.

The harmonic current I_v of the arc furnace forms a parallel tuned circuit consisting of capacitor C with reactive power and mains inductance, resulting from the mains short circuit power. When this tuned circuit resonates at a harmonic frequency, its reactance is high and a harmonic voltage arises, which is damped by the resistance of the resistive component of the supply system consumers' equipment. The Q factor of this tuned circuit is low at times of full load, and no resonant peaks occur. But in slack periods with combinations of low load with high resistance and Q factor values, harmonic voltages are expected at levels sufficient to cause appreciable interference [4].

2. Power Quality Standards

The IEEE Standard 519-1992 includes the limits for harmonic content generation by customers with utility being responsible for limiting harmonic voltage distortion to specified levels. The application of this standard is generally done at the point of common coupling (PCC). Two IEEE Power quality standards are considered.

i) 519-1992: harmonic voltage limits for power producers;
ii) 1547: Interconnecting Distributed resources with electric power system.

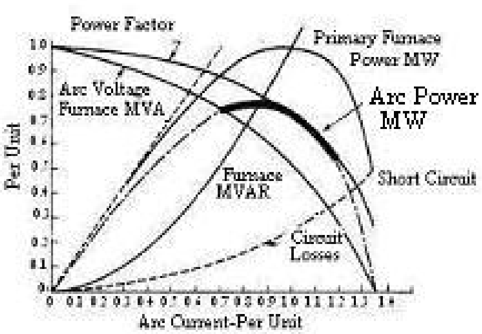


Figure 1: Electrical Characteristics of Electric Arc Furnace

3. Experimentation

A study is conducted to analyze electric power quality in arc furnace operation in steel plants with respect to power quality standards. For which an experimental work was conducted at Lloyds Steel Industries, Wardha. Measurements of quantities related to power quality in two AC electric arc furnaces;

i) MDH make, Germany, 50 Tonne, 40 MVA, 33 kV/545-150 volts
ii) Indomag, India, 50 Tonne, 40 MVA, 33 kV/ 545-150 volt, was carried out.

The current during arcing was 30-40 kA. Coal and oxygen firing in the furnace was at a pressure of 8 kg/cm^2. The impurities can be removed by the addition of fluxes. For a steel melting shop, the input in electric arc furnace is scrap mix. Hot Bricketted Iron (HBI) or Direct Reduced Iron and 30% scrap is used as charge for the furnace. The time required for arcing and melting is 70 minutes average.

The wild phase is still a problem in operation today even in modern furnaces. One reason is that the accurate measurement of individual arcs and radiation factor is involved. Another reason is that the pattern of heat damage in an arc furnace is governed by non-electric factors, for example by the location of the refractory lining. Because the radiation factors become unavoidably asymmetrical. If the radiation factors are equal, then the current in only one phase can be fully utilized. The aim of balancing should be to achieve symmetrical electric values in all three arcs. For arc furnaces equipped with co-planar conductors, this can be achieved by balancing the reactance or by using asymmetrical transformer voltages. Measurements on input side 220 kV is also carried out.

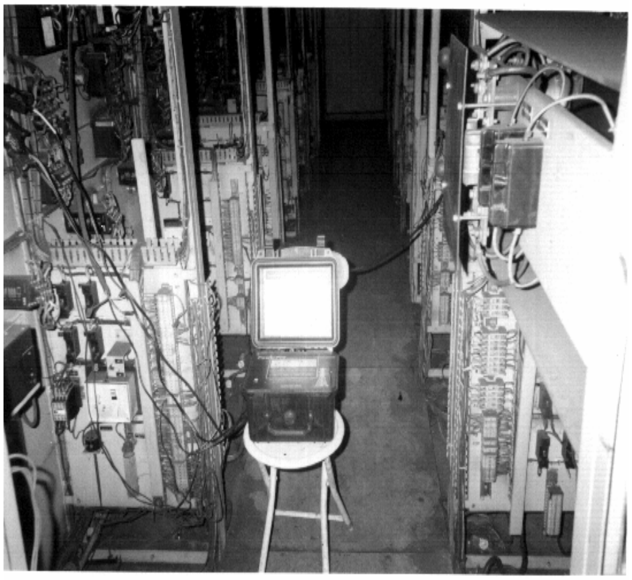
The three-phase power analyzer (Candura make, Power Pro model) was used for the analysis of power quality with compatible software named Power view data analysis. The following quantities were measured. Voltage, current, flicker (IEC 68, IEC 61000-4-15-PST and PLT), THD, waveform snapshots and harmonics up to the order of 64, frequency, transient events. This is 8-channel power analyzer with sampling of 256 samples/cycle. It has large graphical display. It displays harmonic bar charts in real time, waveform display. The analyzer has powerful features such as current inrush, voltage transient and energy costing analysis. Simple user interface makes the logger intuitive to use [5].

The strategy of measurements was to carry out recordings on Electric arc furnace-1 with all harmonic filters in on condition. Initially capacitor bank of fourth harmonic was switched off. After 5 minutes, another harmonic filter of third order was switched off for 10 minutes. Then Third harmonic filter was made on. After 5 minutes, fourth order harmonic was also switched on. The recordings of various quantities like RMS voltage, RMS current, flicker, frequency, THD voltage, THD current, current and voltage waveforms, powers kW, KVAR, kVA, power factor, voltage and current vectors were made for 13 hours. The similar measurements were also carried out on Electric arc furnace- 2 for 12 hours.

Measurement on 33 kV Side Section II, EAF-1 Bus:

MDH Germany make, 33 kV, AC furnace is fed from 33 kV bus section II of switchyard. It was observed that at 9-55 AM, Fourth harmonic filter was switched off. After 5 minutes, Third harmonics filter was switched off. Thus both filters were switched off for 15 minutes. The effect of switching off capacitor banks is studied. It was observed that the frequency increases from 50.1 Hz to 51.4 Hz and current decreases from 0.7 kA to 0.5 kA.

The photograph 1 shows the set up used for measurement and data analysis at 33 kV bus bars at section 2 and section 3 for electric arc furnaces 1 and 2 respectively.



Photograph 1. Set Up At 33 kV Bus for EAF-1

For EAF-1, it was noticed that the harmonics were maximum at the beginning of the heat cycle, which approximately comes after one hour. At the initiation of melting and during melting of cold scrap, it was found that the voltage and current waveforms were severely distorted. The harmonics are generated. The current harmonics of third, fourth and fifth order exceeds 3%. The current is resuming its sinusoidal nature after 5-8 minutes. The current refers to charging and meltdown of cold scrap. The flicker level is also very high. Figure 2 shows the sample waveform with severe distortion in each phase. The frequency recorded was 49.92 Hz. The values of RMS voltages for three phases and currents were noted.

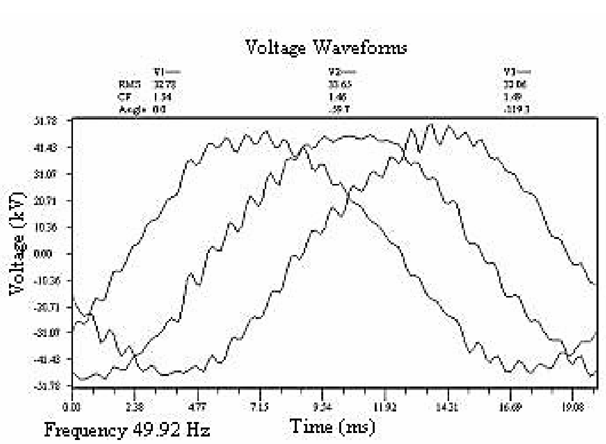


Figure 2. Voltage as a Function of Time For EAF-1

Voltage waveform is distorted for all three phases due to superimposition of Second order, Third order, Twenty sixth and Twenty seventh order harmonics predominantly on fundamental wave. This phenomenon is at the start of heat cycle. When cold scrap is charged and arc strikes, the current waveform is severely affected [6].

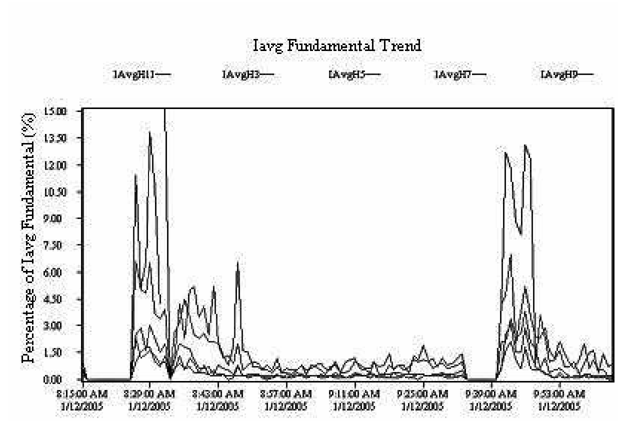


Figure 3. Percent of Current Average Fundamental as a Function of Time

Figure 3 shows one heat duration of EAF-1 from 8-27 AM to 9-42 Am. At 8-29 AM, after arc striking the current distortions were noted. The values of Current average fundamental for various harmonic orders were as follows. I_{H3}= 13.8%; I_{H5}= 6.5%; I_{H7}= 3%; I_{H9}= 1.6%; I_{H11}= 1.8%. The similar results were obtained for next charging. At the instant of striking of arc and beginning of melting, recorded values were I_{H3}= 11.18%; I_{H5}= 7.0%; I_{H7}= 3.4%; I_{H9}= 3.4%; I_{H11}=3.1%.

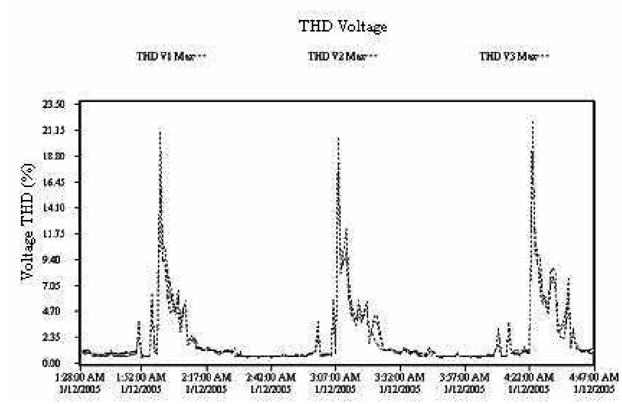


Figure 4. THD Voltage For EAF-1

At 1-59 AM, THD V_1= 20.9%, THD V_2=17.1%, THD V_3=15.4%; Corresponding I_1=0.51 kA, I_2=0.52 kA, I_3=0.72kA. After one heat cycle, which is about 70 minutes duration at 3-08 AM, THD V_1= 20.4%, THD V_2=17.8%, THD V_3=17.1%; Corresponding I_1=0.54 kA, I_2=0.45 kA, I_3=0.53 kA. Total Harmonic distortion is higher than power quality standards. Also there is unbalance in current for three phases. The non-uniform peaks in voltage indicate erratic behavior of arc (Figure 4).

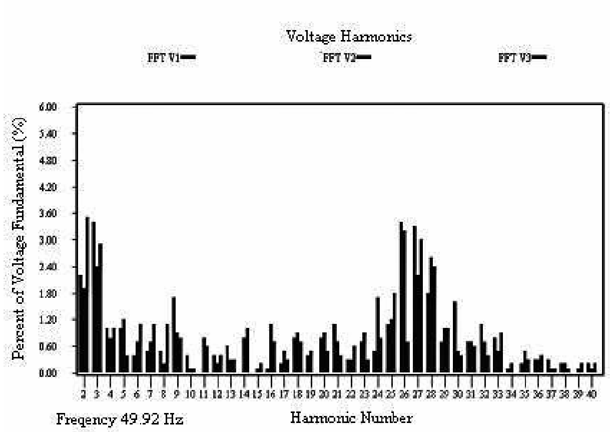


Figure 5. Percent of Voltage Fundamental as a Function of Harmonic

Voltage harmonics of Second order, Third, Twenty sixth and Twenty seventh are more than 3%. Voltage harmonics are produced in this way through impedance of the mains supply; the amplitude depends on the value of the harmonic currents supplied and the effective impedances at the harmonic frequencies.

Because of the non-linear arc resistance, an arc furnace acts as a source of current harmonics of the order Second, Third, Fourth, Fifth, Sixth, Ninth; their individual magnitude is more than 3%. All mentioned harmonics exceed the limits consisting of capacitor C with reactive power, and mains inductance from the mains short circuit power. Another harmonic current producing source is the energization of scrap metal and ladle furnace transformers.

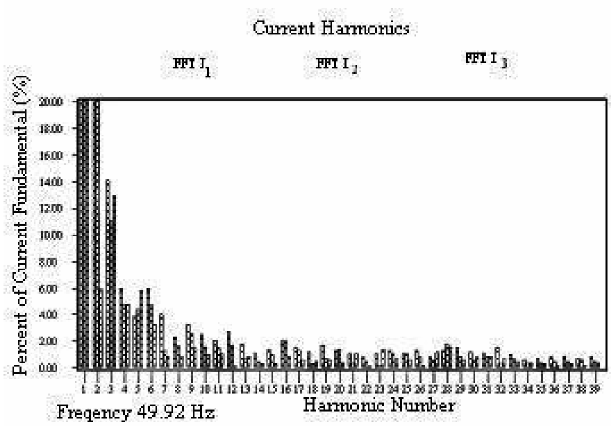


Figure 6. Percent of Current Fundamental as a Function of Harmonic

The dynamic inrush current waveform associated with transformer energizing operation includes both even and odd harmonics, which decay with time until the transformer magnetizing current reaches steady state (Figure 6). The most predominant harmonics during transformer energization are 2nd, 3rd, 4th, and 5th in descending order.

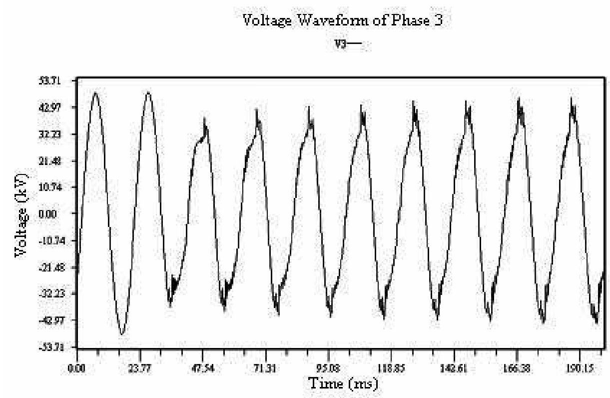


Figure 7. Voltage When Voltage Sag Lasted For 6.5 Cycles

The figure 7 shows voltage sag phenomenon, which lasted for 6.5 cycles. It is observed that oscillatory transients exist at the top and bottom peaks. The oscillations are multifrequency. Main circuit oscillations are induced by one or more arc voltage discontinuities and having energy sources in capacitances of cables, lumped inductances of the supply side and load side networks. They often cause chopping of voltage waveform at peaks due to switching in of major capacitor banks, unloaded line and cable transients, which lasted for several hundred milliseconds [6].

Current waveform during voltage sag is severely distorted. It contains double frequency transients. Voltage sags are followed by high currents, which in turn cause voltage drop at PCC. Asynchronous periodic current waveform is observed (Figure 8).

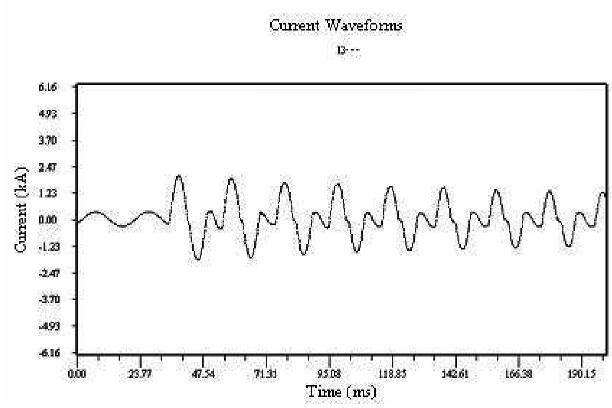


Figure 8. Current When Voltage Sag Lasted For 6.5 Cycles

Figure 9 shows that short term flicker severity index (P_{st}) is more than 1, which exceeds IEC standards. Also long term Perception (P_{lt}) is more than 0.74 [7]. Both these values are greater than standards. The voltage flicker is predominant at the beginning of heat cycle when arc strikes and melting starts.

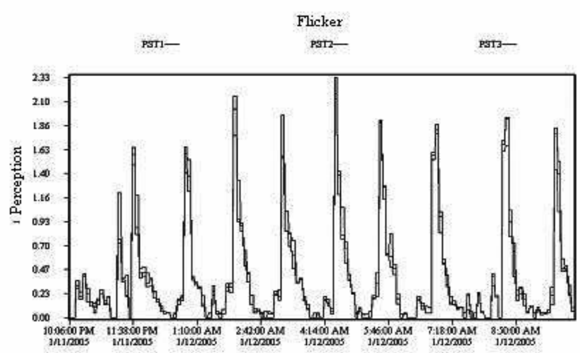


Figure 9. Flicker of EAF-1

From figure 10, it is noticed that supply frequency to arc furnace is not constant but varying randomly because of nonlinear behavior of arc and load is not constant.

The frequency peak of 50.26 hz is observed at 10.12 am, the dip in frequency is noticed 49.10 hz at 11.19 am after heat period. It was noticed that the variation in frequency is continuous and has no specific pattern. The load on the furnace is not of fixed pattern due to nonuniform loading of scrap, composition of scrap. The lowest frequency recorded was 48.92 hz at 6.57 am. The changes beyond the permissible limits may cause maloperation of electronic equipments.

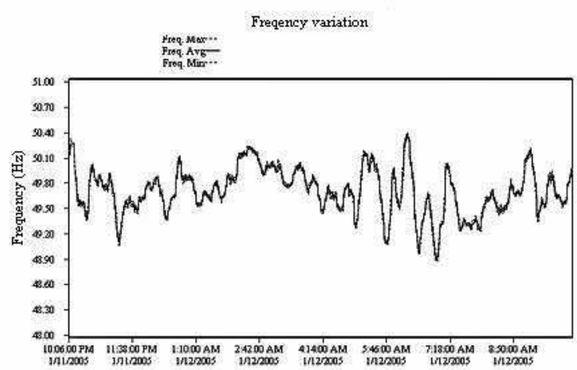


Figure 10. Frequency Variation For EAF-1

There are 4 events of voltage sag captured from 11-1-2005, 11-14-05 pm to 12-01-2005 5-28-07 AM. The table shows the details.

Table I

Events of Voltage Sag

Event	Start time/ Stop time	Duration (Cycles)	Type	Magnitude	Limits
1	11/14/05 PM	6.5	Voltage 3 sag	24.79 kV	28.05/36.3 kV
2	3-07-42 AM	4	Voltage 1 sag	26.31 kV	28.05/36.3 kV
3	4-22-16 AM	5	Voltage 3 sag	26.13 kV	28.05/36.3 kV
4	5-28-07 AM	5.5	Voltage 3 sag	25.78 kV	28.05/36.3 kV

4. Conclusion

The instability and non-linearity are greatest during melting down of cold scrap. The delay and erratic process of striking the arc and resulting gaps in the current are conspicuous.

As melting down progresses, the striking becomes more stable, but the current can still contain low-frequency fluctuations. The temperature and heat of the arc are high with a liquid steel bath, and the thermal conduction is low. So that the arc characteristics begin to approach the linear behavior of an ordinary resistance.

The non-sinusoidal arc voltage waveform is not entirely adopted by the supply current. Since inductance in the circuit gives rise to inductive reactance, this increases with frequency and therefore resists harmonics. The current waveform then becomes almost sinusoidal. The noticeable harmonic current causes increase in reactive power and with a higher reactance.

Flicker measured for short duration and long duration are more than the limits specified in IEEE Standards. Voltage sags on one of the lines has produced voltage and current unbalances.

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