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FIELD INVESTIGATIONS INTO HARMONICS POLLUTION AFFECTING TRANSFORMERS

SUMMARY

Field investigations on harmonics caused by loads are essential to have a quantitative visualization and formation of premise of research. Field investigations have been carried out covering spectrum of loads and voltage levels right from generation to consumers, as at present. Investigations have revealed that low tension consumers form cluster of non-linear loads and are major contributors of current harmonics. Traction loads are another major category of harmonic pollutant. Industrial consumers do provide reactive compensation which helps to filter out current harmonics partially. However, in absence of any regulatory measure consumers keep polluting current harmonics into the system and also bear with the consequential disturbances. Voltage harmonics are significant only at leaf ends of distribution distribution system, where source impedance, seen by the harmonics generated by the load, is high. Tranasformer is the first major equipment in power system to intercept the harmonics. These harmonics caused accelerated ageing of transformers and even objectionable rise of temperature of cover-plate and turets.

Key words: Current Harmonics, Voltage Harmonics, Total Harmonic Distortion, Crest Factor

1. INTRODUCTION

Sinusoidal waveform is the most natural waveform and is ideal for generation of electricity through rotating machines. Nevertheless, practical limitation of creating sinusoidal flux distribution has been causing small distortion in the waveform of voltage generated by the rotating machines. Inventions for energy conservation, efficiency and process control have made loads non-linear. Presence of harmonic in power systems is mainly due to non-linearity of loads such as arc load, electronic loads, converter loads, process efficiency and control equipments, non-linear inductances and recurring transients. Various researcher have carried out harmonic survey. It is observed from the reported harmonics [S Jain, Patidar,Waware] that each of them cater to specific needs of the researcher. It was, therefore, considered essential to determine presence of harmonics prevalent across the power system covering various voltage levels right from generation upto distribution.

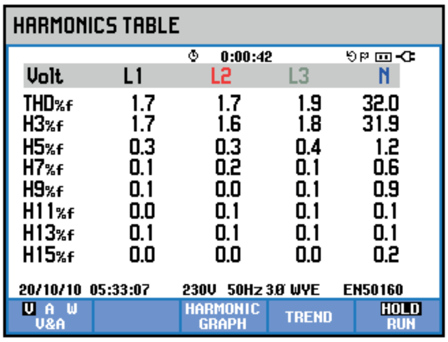
2. HARMONICS IN POWER SYSTEM

Transformer is a nodal element in the power network and an interface between loads and power supply system. Moreover, harmonics generated by load are intercepted by the transformers. Accordingly, measurement of harmonics across the power system were carried out and are classified as under –

i.	Harmonics at generation,	ii.	Harmonics at transmission level,
iii.	Harmonics on traction feeder,	iv.	Harmonics in Industrial area,
v.	Harmonics in commercial area,	vi.	Harmonics in residential area

2.1. Harmonics at Generator Terminals

Sanjay Gandhi Thermal Power Station (SGTPS), Birsinghpur, Madhya Pradesh, has total capacity of 1340 MW (2*2*210+1*500 MW units) and is the largest generating station in the state of Madhya Pradesh Power Generating Company Ltd. (MPPGCL) India, having total installed capacity of 3847.5 MW out of which thermal generation capacity is 2932 MW. In a power deficit utility it is difficult to schedule harmonic measurement on unloaded generator. Generating voltage of 500 MW unit and 210 MW units are 21 kV and 15.75 kV, respectively, which are stepped up through generation transformer to 400 kV and 220 kV, respectively. These units are inter connected at the station bus through 315 MVA 400/220 kV Inter-Connecting Transformers (ICTs). The presence of harmonics at generating point, shown in Fig. 1, though small and within permissible limits, is attributed to construction of alternator, having discrete slots to place windings. Amongst these low order harmonics, predominance of the third harmonics is due to non-linearity of magnetic material. Short Circuit Level (SCL) of the generating station is 5803 MVA and is quite high, while current harmonics are quite feeble, and thus voltage harmonics would be close to its no-load values. Neutral current of fundamental frequency is practically negligible, as compared to the line current, since currents of three-phases cancel out. However, the definition of THD and harmonics content is with respect to the magnitude of the fundamental and, therefore, THD and harmonic current in the neutral is high and shall be seen in practically all harmonic recordings presented in this chapter.


HARMONICS TABLE 0:00:42

Volt	L1	L2	L3	N
THD%f	1.7	1.7	1.9	32.0
H3%f	1.7	1.6	1.8	31.9
H5%f	0.3	0.3	0.4	1.2
H7%f	0.1	0.2	0.1	0.6
H9%f	0.1	0.0	0.1	0.9
H11%f	0.0	0.1	0.1	0.1
H13%f	0.1	0.1	0.1	0.1
H15%f	0.0	0.0	0.0	0.2

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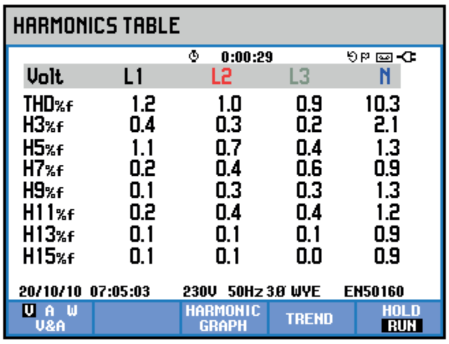
V A W V&A | HARMONIC GRAPH | TREND | HOLD RUN

A - Voltage Harmonics of 500 MW Unit


HARMONICS TABLE 0:00:29

Volt	L1	L2	L3	N
THD%f	1.2	1.0	0.9	10.3
H3%f	0.4	0.3	0.2	2.1
H5%f	1.1	0.7	0.4	1.3
H7%f	0.2	0.4	0.6	0.9
H9%f	0.1	0.3	0.3	1.3
H11%f	0.2	0.4	0.4	1.2
H13%f	0.1	0.1	0.1	0.9
H15%f	0.1	0.1	0.0	0.9

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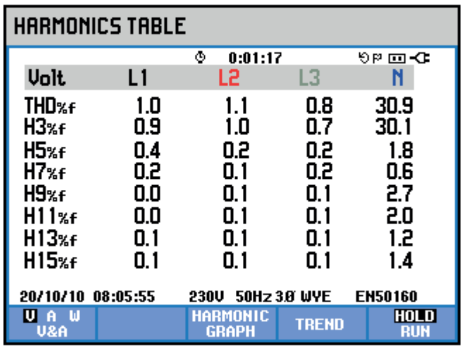
V A W V&A | HARMONIC GRAPH | TREND | HOLD RUN

B - Harmonic Voltages on 400 kV side of 400/220 kV ICT


HARMONICS TABLE 0:01:17

Volt	L1	L2	L3	N
THD%f	1.0	1.1	0.8	30.9
H3%f	0.9	1.0	0.7	30.1
H5%f	0.4	0.2	0.2	1.8
H7%f	0.2	0.1	0.2	0.6
H9%f	0.0	0.1	0.1	2.7
H11%f	0.0	0.1	0.1	2.0
H13%f	0.1	0.1	0.1	1.2
H15%f	0.1	0.1	0.1	1.4

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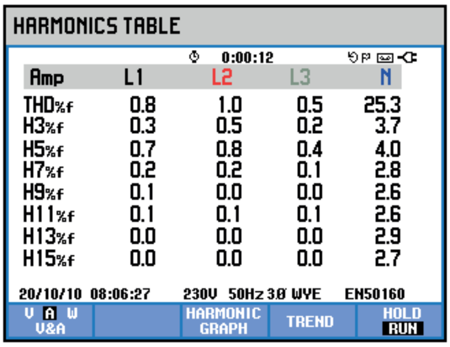
V A W V&A | HARMONIC GRAPH | TREND | HOLD RUN

C - Voltage Harmonics on 210 MW Unit 1


HARMONICS TABLE 0:00:12

Amp	L1	L2	L3	N
THD%f	0.8	1.0	0.5	25.3
H3%f	0.3	0.5	0.2	3.7
H5%f	0.7	0.8	0.4	4.0
H7%f	0.2	0.2	0.1	2.8
H9%f	0.1	0.0	0.0	2.6
H11%f	0.1	0.1	0.1	2.6
H13%f	0.0	0.0	0.0	2.9
H15%f	0.0	0.0	0.0	2.7

20/10/10 08:06:27 230V 50Hz 3Ø WYE EN50160

V A W V&A | HARMONIC GRAPH | TREND | HOLD RUN

D - Current harmonics in 220 kV generator

Figure 1: Measurement of Harmonics at SGTPS, Birsinghpur, MPPGCL, India

2.2. Harmonics at Transmission Level

Transmission lines are the medium for propagation of harmonics into the system, and they converge and diverge at substations. Accordingly, an EHV substation having three voltage levels 132, 33 and 11 kV was taken up for measurement of harmonics. Chattisgarh State Electricity Board (CSEB), India, has a large concentration of industrial loads predominantly metal processing. This is attributed to the existence of one of the largest plant of Steel Authority of India Limited (SAIL) at Bhilai. A 132/33/11 kV Gudiyari substation at Raipur, CSEB was chosen for measurement of harmonics since it is close to Bhilai. The substation has 2x40 MVA, 33/11 kV, YNyn0 Connection, transformers. They are operating on Normal Tap (i.e. tap number 5), percentage impedance at Normal Tap equal to 10.04%. One of the two transformers, having a mix of industrial and town feeders, was taken up for harmonic measurements. Short circuit levels (SCL) of the PCC, which have an impact on voltage harmonics, are also shown in Table 1. There is a consistent increase the short circuit level at the substation. This increase and is attributed to increase in generation and transmission infrastructure, to cater to the increasing load. The increase in short circuit level gives a respite in voltage harmonics (below 1%) and is substantiated in voltage harmonic recordings, despite the presence of current harmonics (about 4%), and below the permissible limit of 5% as per IEEE Std. 519.

Table 1: Trend of Short Circuit Levels (MVA) at 132/33 kV Substation, Gudiyari

S. No	Bus KV	07-08		08-09		09-10		10-11		11-12	
		3ϕ	1ϕ	3ϕ	1ϕ	3ϕ	1ϕ	3ϕ	1ϕ	3ϕ	1ϕ
1	132	2812	1780	3196	1948	3215	1958	3386	2059	4157	-
2	33	835	712	866	738	867	739	879	753	922	82

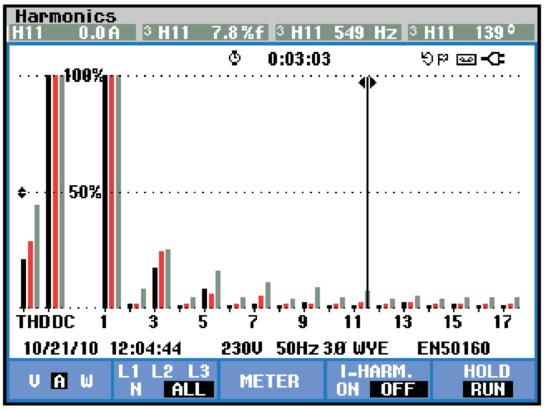
The order of harmonics is comparable on primary and secondary side of 40 MVA transformer and is attributed to its Y-Y connection. Moreover, mutual coupling between the harmonics transfers the harmonics from one side to the other. The Crest Factor (CF) in the recorded current waveform parameters, is as high as 1.75, and is indicative of predominance of 5^{th}, 9^{th}, and 11^{th} harmonic, with a difference of degree. The substation has two separate feeders, one is Industrial Feeder and the other is Town Feeder and its field observations are brought out in the foregoing paras. In the same substation a separate 10 MVA 33/11 kV transformer is on Town Feeder for supply to township and its harmonic recordings are also found to be below 5%.

2.3. Harmonics in Traction Feeders

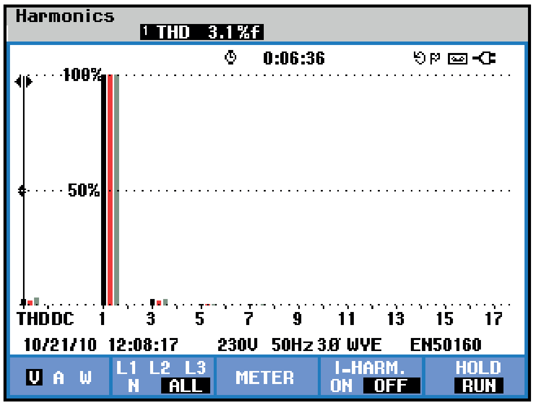
a) **220 kV Three Phase Traction Feeder** : Madhya Pradesh Power Transmission Company Limited, India (MPPTCL) has a dedicated 220 kV feeder emanating from 315 MVA transformer in 400/220 kV YNYn0D1substation at Katni. At down end the railways convert it into single phase feeders for use in traction. This substation is receiving supply from 400 kV switchyard of Power Grid Corporation of India Limited (PGCIL) at Satna, which in-turn is closely connected to power hub of NTPC at Vindhyachal Thermal Power station. Fault level at the feeding substation at Satna 400 kV Bus is 10116 MVA, while at 400 kV Katni bus is 4096 MVA. Harmonic measurements have been made at control panel. The harmonic recordings are shown in Fig. 2. It was seen that Phase A, B and C had 21.7%, 38.3% and 43.8% current harmonics, respectively, while voltage harmonics were 2.1%. 2.9%, and 3.1%, respectively. Despite, severe current harmonics, which is characteristic to traction loads the order of voltage harmonics is reasonably subdued. This is attributed to strong linkage of the substation to the power system.
Traction loads are Two Phase loads and they cause unbalanced loading on the transformer at the substation. Moreover, the K-Factor corresponding to the recorded harmonics varies from 1.3 to 2.11. Thus winding carrying highest current THD would age faster. This creates a need of review of ageing criteria based on the philosophy that “strength of the chain is that of its weakest link”. The THD_i in neutral current was observed to be above 500%, with individual harmonic components above 75%, and is obvious due to its definition and EHV circuit neutral current is only due to capacitive coupling with the ground.

b) **66 kV Three Phase Traction Feeder** : The 66 kV Ridge Valley substation, national capital Delhi, has a dedicated traction feeder. Railways have, however, at their end shifted load from this feeder on to another supply from Delhi Transco. In view of this, at the time of measurement, only allied loads were catered by railways from supply available on this feeder. Despite, the harmonic patterns on the feeder is shown in Fig. 3 presence of current harmonics is beyond permissible limits. Presence of 3rd, 5th and 7th harmonic is predominant. Dispersion of THD_i across phases is within 10% and is considered to be acceptable.

c) **25 kV Two Phase Metro Rail Feeder** : Measurements were taken at 66 kV substation, at Indira Gandhi International Air Port, Delhi. This substation receives supply from adjoining 132 kV substation of Delhi Transco. At the substation there are 2*30 MVA 66/33 kV transformers for airport supply. Supply to metro rail is made from this substation through 2*30 MVA 66/27.5 kV Two-phase to Single phase transformers. Observations on one of the traction feeder are brought out in Fig. 4. It is seen from the current waveforms that electrical system of metro rail is designed for harmonic correction. This is evident from 9.7% THD of current harmonics in Fig. 4-C. Though the THD_i is above permissible limit of 5%, it is quite low as compared to observations on 220 kV and 66 kV traction feeders. THD_i, during unloaded condition current 72.8%, Fig. 4.B, and on the face of it is enough to cause panic. However, the associated K-factors, at 98.6 is indicative of negligible fundamental component and accordingly the high THD_i is attributed to noise, which is quite high in air-port zone. Power transformer neither handle these spurious signals nor do the they affect it, and hence it is ignored. Similar observations are made in lightly loaded conditions shown in Fig. 4.D, where current THD is 45.9%. The power factor (*PF*) is seen to be 0.9 while the *cos*φ is 0.95 as seen in Fig. 4.E and waveforms shown in Fig. 4.A. This further substantiates corrective measures that have been put in place in the electrical systems of the Metro Rail. Voltage harmonics in Fig. 4.F are within acceptable limits due to vicinity of feeding substation.



A - Current Harmonics at Control Panel



B - Voltage Harmonics at Control Panel

Figure 2: Harmonics in 220 kV Traction Feeder at 400/220 kV Substation

HARMONICS TABLE

0:00:07

Amp	A	B	C	N
THD%f	11.3	10.6	11.7	11.1
H3%f	9.0	6.3	8.4	8.4
H5%f	5.8	5.2	7.3	6.3
H7%f	2.0	3.3	1.6	2.1
H9%f	1.7	1.5	1.1	0.9
H11%f	1.5	1.8	1.3	1.1
H13%f	0.9	1.3	0.7	0.7
H15%f	0.2	0.6	0.3	0.4

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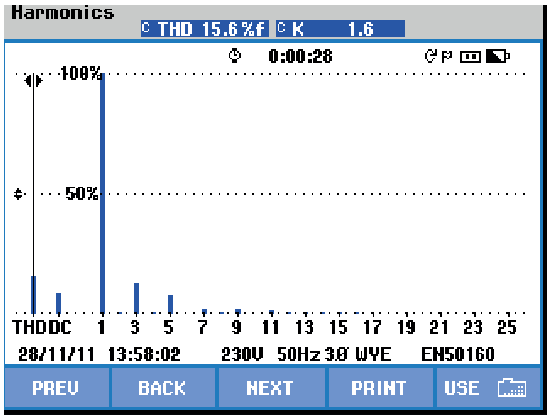
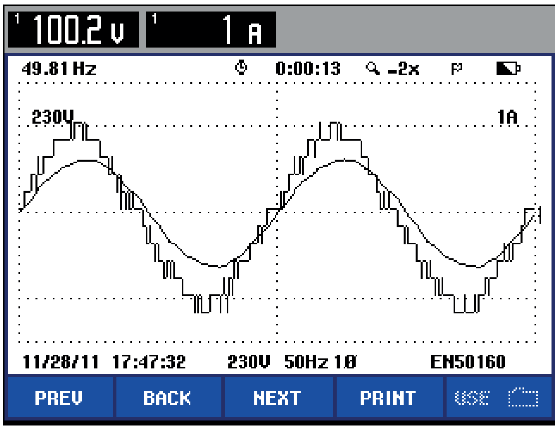
A. Current Harmonics in the Feeder

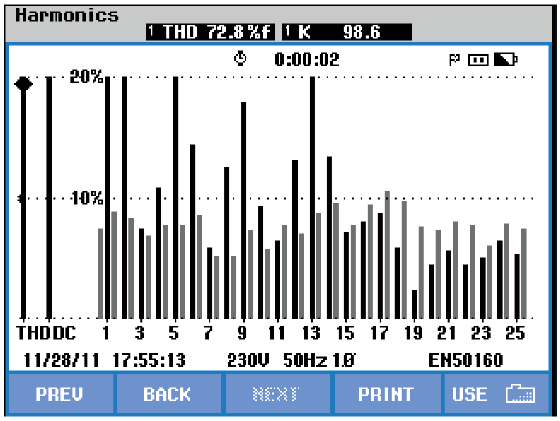


B. Harmonic Spectrum of Current Harmonics in B Phase.

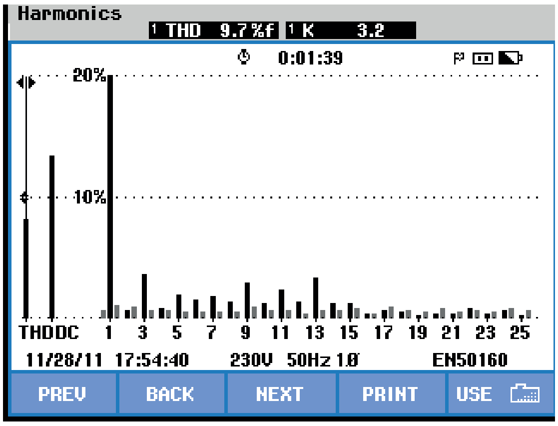
Figure 3: Current Harmonics measured on 66 kV Feeder from Ridge Valley Substation



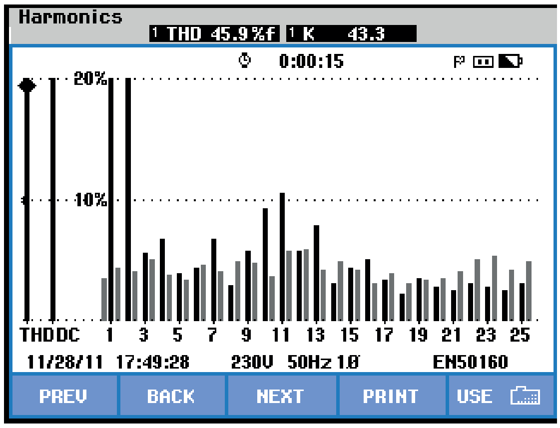
A. Voltage and Current Harmonics Waveform



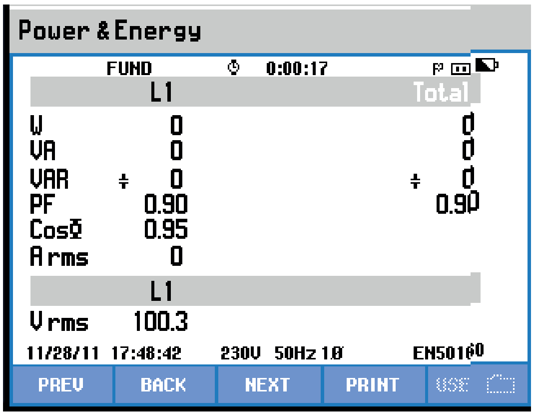
B. Spectrum of Current Harmonic –Feeder unloaded.



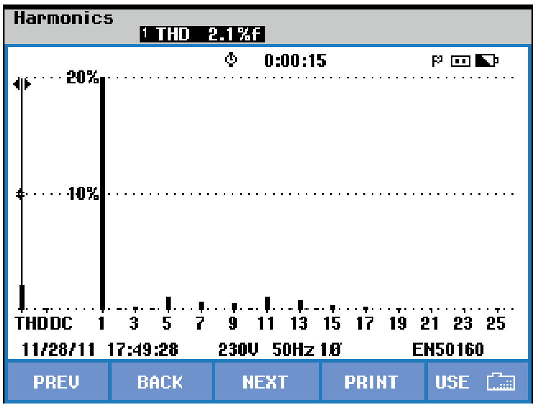
C. Spectrum of Current Harmonic –Loaded Feeder



D. Spectrum of Current Harmonic – Lightly Loaded Feeder



E. Power Measurements



B. Voltage Harmonics

Figure4: Observations on 27.5 kV Feeder of Metro Rail

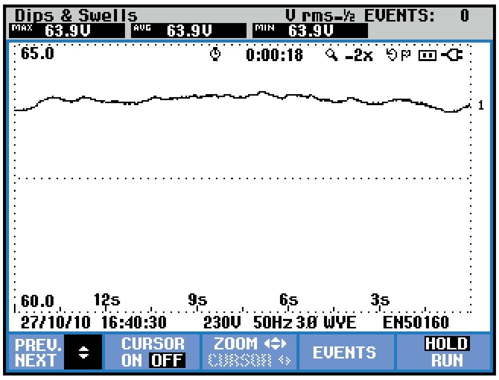
2.4. Harmonics in Industries

A mix of harmonic pollutant industries were taken up for measurement.

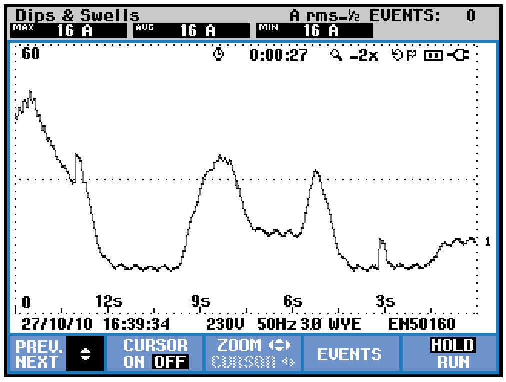
a) **Metal Processing Industry – Arc Furnace :** M/s 3D Innovations is a sponge iron plant where iron scraps are converted into ingots in arc furnace. It has contract demand of 1000 kVA having 2*500 kVA, 33/0.04 kV, YD coneected, 6.9% Z, arc furnace transformers. feeding two independent arc furnaces It receives power supply from Kabeer Nagar Feeder, emanating from 220/132/33 kV Urla S/stn. Frequent failures of 5/5 Amp CTs have been experienced at this location. Since, up-gradation of CT to 10/5 Amp, in Aug'11, failures have not been experienced. However, the harmonics at the time of recording were abourt 2% and well within IEEE limits. This was also validated with CF which was about 1.46.

b) **Metal Processing Industry – Induction Furnace :** M/S Goyal Pipes, Manufacturer of MS Ingots out of Pig Iron and Steel Scrap, Major load Induction Furnace. It uses 2*3900 kVA 33/0.9 kV three winding transformer with secondary and tertiary winding of equal ratings but Dd0 and Dy11with 4.12% Z for each of LV winding and 7.81% Z for primary. It has one The unit has contract demand of 6.4 MVA. It has another 1*950 KVA 33/0.4 kV transformer which caters to auxiliary loads and 2*350 Capacitor Bank for overall power factor correction. Despite this current harmonics, with predominance of 11th and 13th, was observed to be 10% Power factor at the industry was seen to be 0.99. This indicates that the industry has taken care of only reactive power compensation, to avert low power factor penalties, while harmonic compensation has been ignored in absence of any regulatory measures.

c) **Rolling Mill** : M/s Chattisgarh Steel Products, Urla, is a rolling mill, which manufacturer of steel sections using MS ingots. It receives supply from nearby 220 kV/132/33 kV substation, Urla, CSEB. Current harmonics have diversity across phase in the range of 13% to 17% with CF as high as 1.9. The industry is operating at PF=0.94 due to use of passive filters to compensate for reactive power absorption and thus to avail the benefit of tariff for evading low power factor penalty. But, the industry has not used active filters for harmonic compensation. This is evident from crest factor also. The necessity of active filter can be realized from load fluctuations observed in Fig.5.



A. Voltage Trend



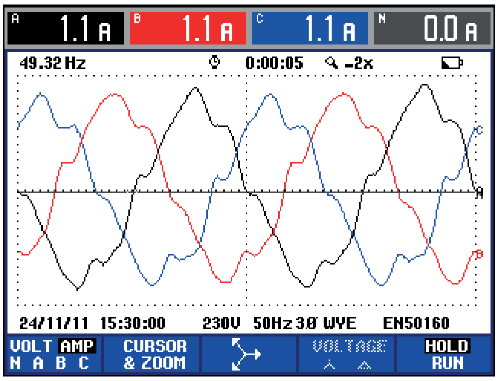
B. Current Trend

Figure 5: Dynamic Current and Voltages at M/s Chattisgarh Steel Products, Urla , Rolling Mill

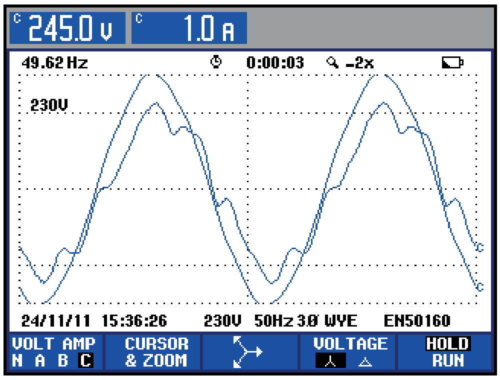
d) **Industrial Area** : An industrial area catering to small industries from a substation with 3*1000 kVA 11/0/.4 kV transformer was also taken up for measurement of harmonics. Transformers have 5% impedance and accordingly maximum current THD should be 5% as against significant harmonics upto 11th order are recorded as shown in Fig.-6-C. Further, presence of even current harmonics, seen in Fig 6-C is substantiated by loss of quarter symmetry in current waveforms in Fig. 6-A and Fig. 6-B.

2.5. Harmonics in Commercial Complex

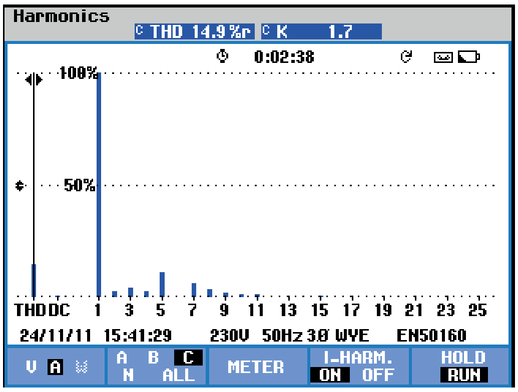
a) **Shopping Mall:** Select City Walk, biggest mall in Saket, South Delhi has connected load of 8 MVA having 4*2MVA, 33/0.415 kV transformers, with percentage impedance of 6%. The complex has generator back of equivalent capacity. They have installed 4*700 kVA detuned switched capacitor bank for reactive power compensation one with each of the transformers. Power factor, which attracts penalty, was seen to be exceptionally good at 0.997. Harmonic frecordings at the complex are shown in Fig. 7. Each of the transformers operates in radial mode with changeover facility during contingency. It is seen that harmonic recordings are as high as 11%. Inadequacy of harmonic mitigation, as against reactive power control, even at this organized complex, is attributed to absence of provision in the tariff to penalize for harmonic injection; it is unlike the penalty for low power factor. Only 3rd, 5th and 7th harmonics are found to be predominant.



A. Waveform of Three Phase Currents

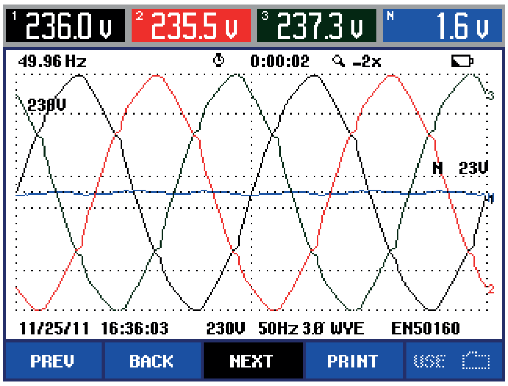


B. Current and Voltage Waveform of R-Phase

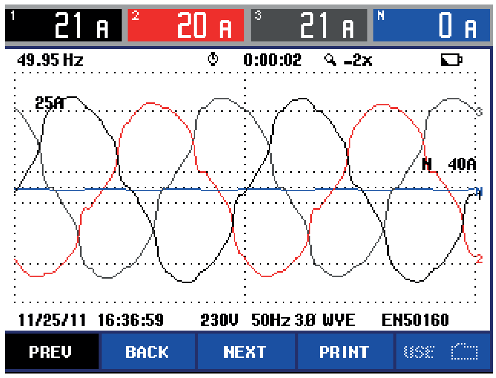


C. Current Harmonic Spectrum in R-Phase

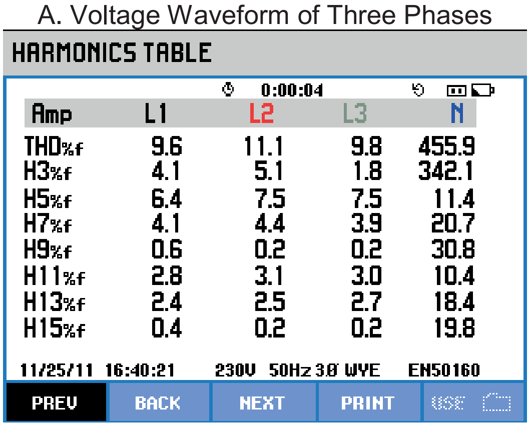
Figure 6: Harmonic Measurements on LT side of Transformer Feeding Cluster of Industries



A. Voltage Waveform of Three Phases



B. Current waveform of Three Phases



HARMONICS TABLE

0:00:04

Amp	L1	L2	L3	N
THD%f	9.6	11.1	9.8	455.9
H3%f	4.1	5.1	1.8	342.1
H5%f	6.4	7.5	7.5	11.4
H7%f	4.1	4.4	3.9	20.7
H9%f	0.6	0.2	0.2	30.8
H11%f	2.8	3.1	3.0	10.4
H13%f	2.4	2.5	2.7	18.4
H15%f	0.4	0.2	0.2	19.8

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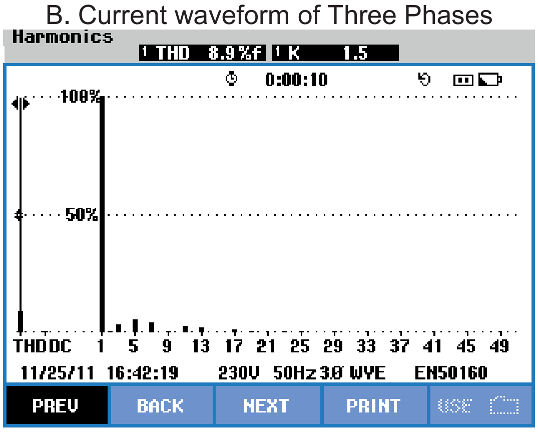
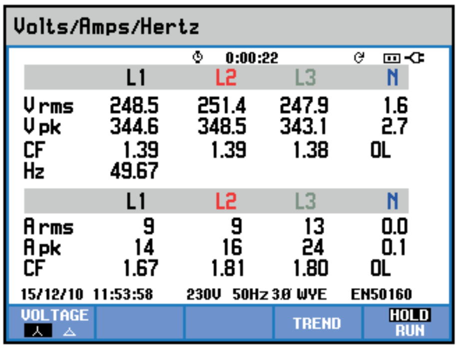
C. Harmonic Content in Current in Three Phases



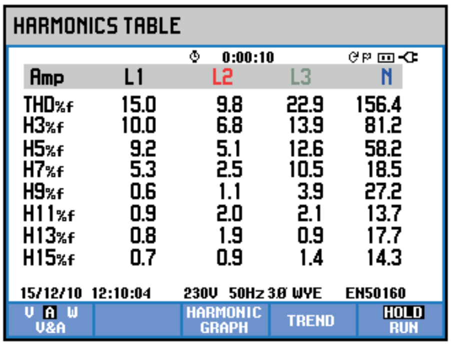
D. Harmonic Spectrum in A-Phase

Figure 7: Harmonics Recording at Shopping Mall, Delhi

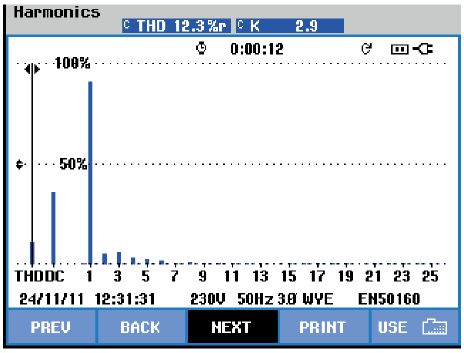
b) **Commercial-cum-Office Complex** : This shopping-cum-office complex is in a high rise building #96 at Nehru Place, Delhi. #96. Ground floor accommodates assorted shops, while all upper floors are offices with computers and A/Cs. The complex is supplied from 1*1000 kVA and 1*630 kVA transformers on ground floor. The observations were made on LT side of 1 MVA transformer and in Figure 2.14. The A phase had highest harmonic content predominant third, fifth, second seventh and ninth in descending order. Significant DC component was seen and is attributed to the nature of loads.



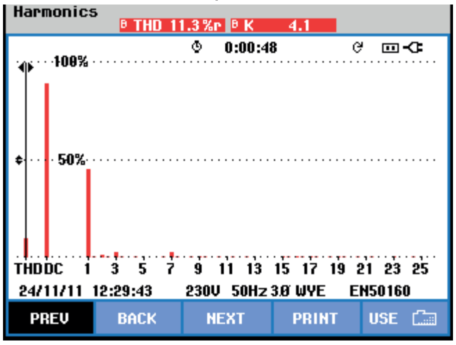
A. Current Harmonics in Three Phases



B. Current harmonics Spectrum in Phase A



C. Current harmonics Spectrum in Phase B



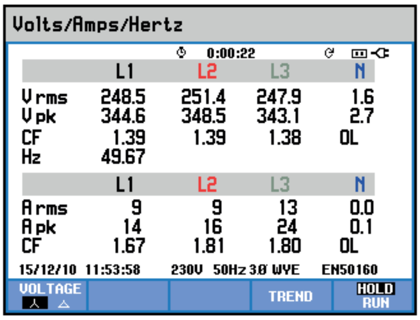
D. Current harmonics Spectrum in Phase C

Figure 8: Recording of Harmonics at Commercial-cum-Office Complex

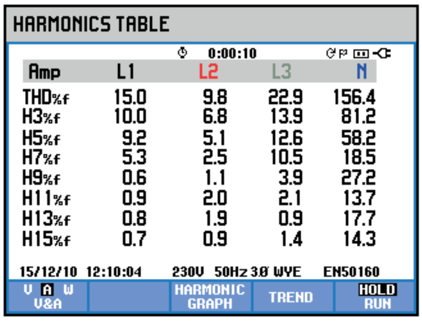
2.6. Harmonics in Residential Area

a) **Residential Area** : Indian Institute of Technology Roorkee, is the residential institute with extensive infrastructure to support academics, research and on the campus boarding. The non-linear loads in the institute include main computer center, laboratories of different departments, air conditioning, and compact fluorescent lamps (CFLs) alongwith high power LT machines with a total maximum load of 6 MVA. Though, all loads are of low voltage, but power supply to these low voltage loads is met through 10 number substations, which are connected in a grid on 11 kV. The grid receives supply from the state power utility on two feeders emanating from 33/11 kV substation, located on outskirts of the institute.
Saraswati Kunj substation is the major load center of the institute, having a mix of residential and institute loads, was preferred, amongst other sub-stations, for harmonic measurements. It has 2*800+1*630 kVA, 11/0.4 kv DY11transformers feeding separate set of feeders. Rrecording of harmonics on secondary side of one of the 800 kVA transformer are shown in Fig. 9. The effect of non-linear loads is visible in harmonic recordings in Fig 8. Almost all the loads are single phase and are responsible for predominance of 3^{rd}, 5^{th} and 7^{th} order harmonics (Fig 9.B), Voltage waveform, is almost unaffected and is seen from the CF of voltage (Fig 9.A) and is attributed to the vicinity of power source.
In continuation to this, reference to observations of harmonic and reactive power presence in various field observations, discussed abover is relevant. Residential uses of electricity suffer from severe harmonic disorder and high reactive power, and this can be attributed to lack of awareness amongst consumer which have a high diversity. As regards regulatory measures, through tariff it is seen to be a distant future, in wake of the fact that there are no penalty on harmonic violations even for bulk and organized power consumers.

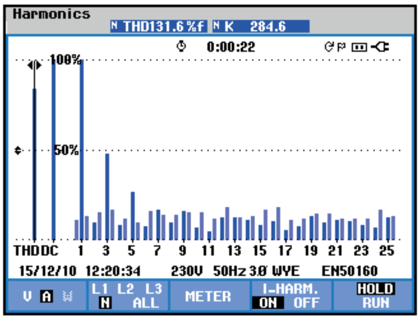
b) **High-Rise Residential Complex :** A high-rise (tweve storied) residential complex was taken up for harmonic measurement. It has 100% disel gereator backup. Though the voltage harmonics both of the diesel generator on no-load and utility supply were seen to be within limits, however current harmonics were seen to vary from 8% to 15% across the threwe phases. Thepower factor of the load was about 0.6%. The observations are brought out in Fig 10.



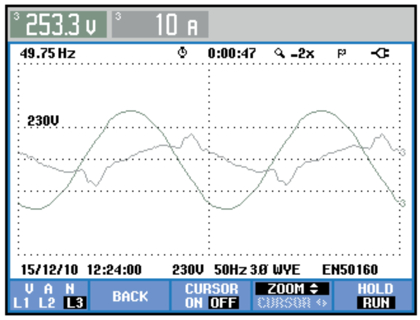
A. Waveform Parameters



B. Current Harmonics on LT Side

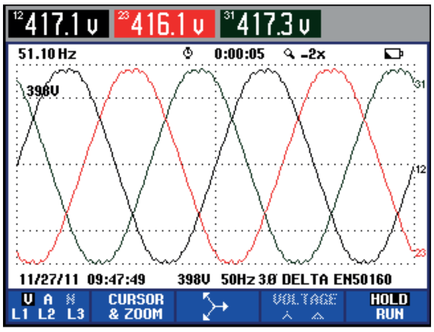


C: Harmonics in Neutral Current

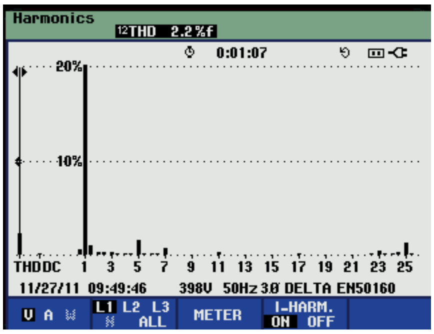


D. Current and Voltage Waveform

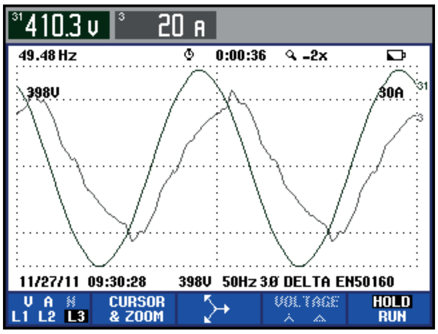
Figure 9: Harmonics at 11/0.4 kV Transformer at Sarswati Kunj



A. Voltage Waveforms



B. Harmonic Spectrum



C. Current and Voltage Waveforms of C-Phase

Figure 10: Harmonics Recorded on Captive power Generator of Residential Complex

S. K. Joshi, H. O. Gupta, P. Agarwal, G. Kumbhar, Field investigations into harmonics pollution affecting transformers, Journal of Energy, vol. 61 (2012) Special Issue, p. 160-169

3. CONCLUSIONS

Investigation into causes of harmonics is not the objective of this research work. However, harmonic survey across the power system is carried out to determine state of the harmonics prevalent in the system. Alternators, despite technological developments have constraints of placing armature coils in discrete slots and thus causing inception of voltage harmonics, though in small magnitude, right at the point of generation. Presence of current harmonics is predominant at distribution level with an exception of traction feeders which are either on HV or EHV. Consumers which exercise proper management of reactive power and harmonics have shown comparatively lower presence of harmonics. But, this is not true for all the industries. L.T consumers, commercial and residential loads, are individually small but their combined effect becomes quite severe. This is evident from the observations on harmonics in commercial and residential area. The future trend in this regard is of large and high rise complexes and is seen as an opportunity of effective harmonic management. Harmonics generated at consumer end are intercepted by the transformers and there is lot of diversity across phases in respect of harmonics. This diversity of harmonics cause heating of transformer windings, and the effect of heating of windings is in the order of harmonic content and causes accelerated ageing. Thus a criterion of ageing of transformer based on highest harmonic loading is important.. It is seen that some of organized consumers have taken suitable measures for power factor correction, however, measures of harmonic mitigation are found to be insufficient and current harmonics are seen to be beyond permissible limits, with a difference of degree, practically in all cases.

Further, heating of cover plate and turets for bsuhing, specially in high current current transformers has been been a matter of conccern. Use of non-magnetic inserts, and even non-magnetic cover-plate of transformer has been suggested by various reserachers to control the heating of cover-plate. This problem becomes more vulnerable in presence of harmonics. Separaetly this aspect has been invetigated by the authors and they have proposed a remedy using aluminum shield around the low voltage leads of transformer, specially feeding either non-linear loads or cluster of such loads.

Investigation into presence of has created a data set covering the spectrum of power system right from generation till distribution, spanning over various voltage levels and category of loads. Some of the load centers covered in the investigations are generally inaccessible. This papers, due to space limitations contains salient data. However, in case the dataset is a reasonable pointer to the state of harmonics that would inflence transformer.