

Survey of Harmonic Distortion in Indian Railway Electric Supply System: Results and Remedial Actions.

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ABSTRACT

Harmonic distortion has become a main concern in electric distribution system during the last few years. Many electric utilities are experiencing harmonic distortion related problems on their networks. Waveform distortion is always present to some extent in electric power system. However there is growing concern for this problem because of increasing use of nonlinear sensitive electric and electronic equipments. These problems are of concern to both customers and utilities. Railway electric supply system in India is fed from various state utilities at 132 kV/25 kV. The electric supply system of railway is at 25 kV, 50 Hz single phase system. The aim of this research work is to study the harmonic distortion caused by electric locomotives on utility supply network. Measurements are performed at 132 kV voltage levels and 25 kV level to determine level of individual voltage and current harmonics present and percentage total harmonic distortion in current and voltage. Particularly during this survey in addition to harmonic distortion other power quality problems present in railway electric supply system are monitored and analyzed. The results of this survey at site feeding the railway electric supply system are presented with remedial action.

KEYWORDS

Harmonic Analysis, Power Quality, Interharmonics, Unbalance, Harmonic Distortion.

1. INTRODUCTION

The power quality problem is defined as any problems manifested in voltage, current or frequency deviations that results into failure or malfunction of customer equipment. The various power quality issues are harmonic distortion, voltage sag, voltage swell, flicker, momentary interruptions, frequency variations, unbalance and transients are listed in various literature [12-13]. Harmonic distortion is one of the major power quality issues where percentage of nonlinear load is high. Harmonics can be defined as sinusoidal components of the periodic wave or quantity having frequency that is integral multiple of the fundamental

frequency. The various sources of harmonic, and the analysis of their effects on various equipments are listed in various literature [1-4]. The total harmonic distortion in voltage at PCC depends on system impedance and total current harmonic distortions. The effect of harmonic on various devices depends on symmetrical components of harmonics [9]. Harmonic distortion is load sensitive and harmonic currents generated by nonlinear load interact with power system impedance and give rise to harmonic voltage distortion. This distortion if exceeds the IEEE 519-1992 recommended limits [10], can cause motors, transformers, cables, capacitors and neutral wire overheating.

The harmonic distortions caused by electric locomotive in railway electric supply system is also a major issue. The objective of performing harmonic survey of railway electric supply system is to a) Identify the harmonic distortion levels in currents and voltage of railway electric supply system b) To identify the major harmonic current and voltage harmonics exceeding IEEE 519-1992 recommended limits c) Current and voltage interharmonics levels d) To study other power quality issues e) to provide cost effective mitigation solution.

2. EXPERIMENTATION

In Indian railway, electric locomotives are fed from 1 phase, 25 kV, 50 Hz supply system. The electric power to the railway electric network is fed from 132 kV / 25 kV Scott connected transformer. The drives used in electric locomotives are dc, but now a day 3 phase squirrel cage induction motor are used on large scale. The single phase 25 kV, 50 Hz supply is converted into dc by converter and then to 3 phase ac by inverter to feed 3 phase squirrel cage induction motor. Each section of supply system of railway is fed from 1 phase, 25 kV, 50 Hz system. The load on every section is intermittent and is decided by the length of the section, railway locomotive density. Power quality measurement was carried out with the help of four channel HIOKI 3196 power quality analyzer. Power quality analyzer was connected at 132 kV transformer primary side through metering CT and PT. The results

of harmonic measurement at 132 kV (i.e. primary side) of transformer and 25 kV (i.e. secondary side) of transformer are presented in next section.

2.1 HARMONIC MEASUREMENT RESULTS AT 132 KV (PRIMARY) SIDE OF SCOTT CONNECTED TRANSFORMER

The results of harmonic measurement at 132 kV primary side of a Scott connected transformer Feeding 25 kV electric railway network to study the impact of railway locomotives on harmonic supply voltage distortion was carried for 1 day.

Figure 1.0 (a) shows % total voltage harmonics distortion variation time plot of CH1 and CH2. From measurement result, it is clear that the total harmonics distortion in voltage is less than 2.5% IEEE 519-1992 recommended limit. Table 1 shows IEEE 519-1992, recommended voltage distortion limits.

| Bus Voltage at PCC | Individual Voltage Distortion (%) | Total Harmonics Distortion (THD %) |
|------------------------|-----------------------------------|------------------------------------|
| 69 kV and below | 3.00 | 5.00 |
| 69001 V through 161 kV | 1.50 | 2.50 |
| 161,001 V and above | 1.00 | 1.50 |

Table 1: IEEE 519-1992 Std.: Voltage distortion limits

Table 2 shows individual voltage harmonics measured at 132 kV primary side of transformer.

| Harmonic Order | Ch No. | Max. | Ave. | Min. | Harmonic Order | Ch No. | Max. | Ave. | Min. |
|----------------|--------|------|------|------|----------------|--------|------|------|------|
| 3 | 1 | 0.54 | 0.30 | 0.17 | 5 | 1 | 0.73 | 0.57 | 0.45 |
| | 2 | 0.46 | 0.18 | 0.05 | | 2 | 0.49 | 0.42 | 0.28 |
| | 3 | 0.37 | 0.13 | 0.02 | | 3 | 0.66 | 0.56 | 0.42 |
| 7 | 1 | 0.13 | 0.08 | 0.02 | 9 | 1 | 0.11 | 0.06 | 0.01 |
| | 2 | 0.24 | 0.12 | 0.07 | | 2 | 0.13 | 0.03 | 0.00 |
| | 3 | 0.20 | 0.12 | 0.06 | | 3 | 0.09 | 0.04 | 0.01 |
| 11 | 1 | 0.42 | 0.30 | 0.12 | 13 | 1 | 0.45 | 0.34 | 0.16 |
| | 2 | 0.47 | 0.33 | 0.17 | | 2 | 0.49 | 0.33 | 0.21 |
| | 3 | 0.35 | 0.22 | 0.12 | | 3 | 0.40 | 0.27 | 0.12 |
| 15 | 1 | 0.15 | 0.05 | 0.02 | 17 | 1 | 0.32 | 0.09 | 0.02 |
| | 2 | 0.16 | 0.05 | 0.02 | | 2 | 0.24 | 0.09 | 0.03 |
| | 3 | 0.11 | 0.05 | 0.02 | | 3 | 0.33 | 0.12 | 0.04 |

Table 2

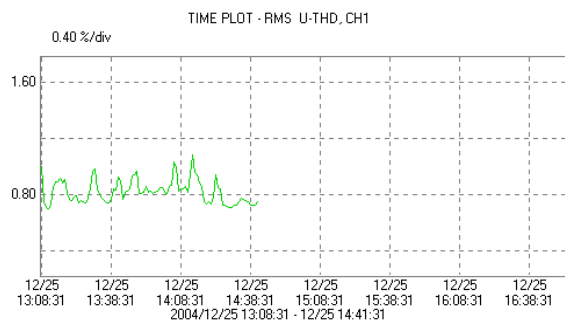


Figure 1(a): % Voltage THD Variation Time Plot Ch1
Max.Val.:1.08% Avg.Val.:0.83% Min.Val.:0.71%

Harmonics value after 17th are very less. The individual harmonic voltage distortion level at 132 kV side is below the recommended individual voltage distortion by IEEE 519-1992. Figure 2(a) shows the percentage voltage unbalance time plot and Figure 2(b) shows percentage current unbalance time plot.

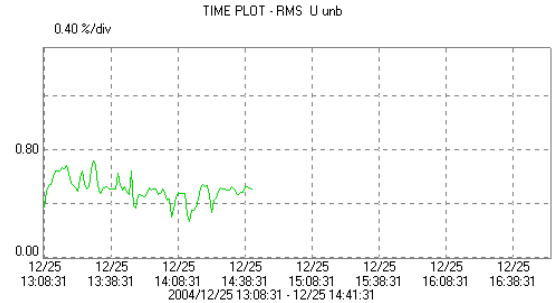


Figure 2 (a): Percentage Voltage Unbalance Time Plot
%Voltage Unbalance Variation Time Plot

Max.Val.:0.72% Avg.Val.:0.51% Min.Val.:0.27%

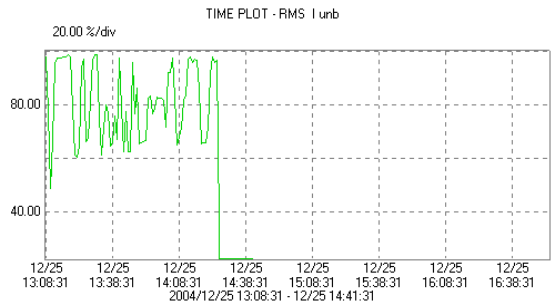


Figure 2 (b): Shows percentage current unbalance time plot. %Current Unbalance Variation Time Plot

Max.Val.:0.72% Avg.Val.:0.51% Min.Val.:0.27%

Because of use of Scott connected transformer to feed 25 kV, 1 phase, 50 Hz, railway electric supply, the value of percentage voltage and current unbalance value is less.

The measurement result of percentage total harmonic distortion in current measured at 132 kV side of CH1 and CH2 are presented in figure 3(a).

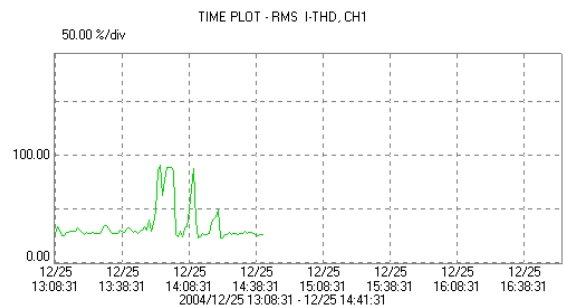


Figure 3 (a): % Current THD Variation Time Plot Ch1
Max.Val.:90.53% Avg.Val.:35.87% Min.Val.:23.20%

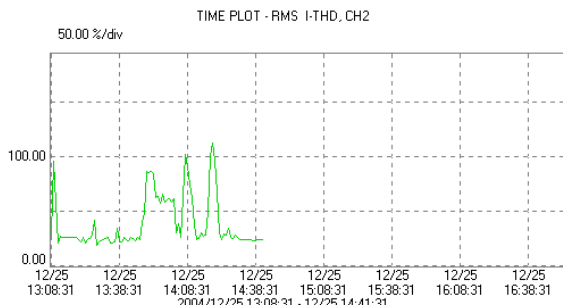


Figure 3(b): % Current THD Variation Time Plot Ch2
Max.Val.:112.35% Avg.Val.:40.06% Min.Val.:19.47%

The average value of % total current harmonics of channel 1 is 35.87%, channel 2 is 40.06%. The current

percentage total harmonics current distortion is above IEEE recommended limits shown in table 3. The I_{SC}/I_L ratio is 75 hence and TDD limit is 6.00.

| Maximum Harmonics Current Distortion in Percentage of I_L | | | | | | |
|---|----------|------------------|------------------|------------------|-------------|-------|
| Individual Harmonics Order (Odd Harmonic) | | | | | | |
| I_{SC}/I_L | $h < 11$ | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $35 \leq h$ | TDD |
| $< 20^*$ | 2.0 | 1.00 | 0.75 | 0.30 | 0.15 | 2.50 |
| $20 < 50$ | 3.5 | 1.75 | 1.25 | 0.50 | 0.25 | 4.00 |
| $50 < 100$ | 5.0 | 2.25 | 2.00 | 0.75 | 0.35 | 6.00 |
| $100 < 1000$ | 6.0 | 2.75 | 2.50 | 1.00 | 0.50 | 7.50 |
| > 1000 | 7.5 | 3.50 | 3.00 | 1.25 | 0.70 | 10.00 |

Even harmonics are limited to 25% of the odd harmonics limits above
 *All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L .
 Where I_{SC} = Maximum short circuit current at PCC
 I_L = Maximum demand load current (fundamental frequency component) at PCC

Table 3: IEEE 519-1992 Std: Current distortion limits for general subtransmission systems (69001 V through 161,000 V)

From the result of individual current harmonics distortion shown in table 4, is clear that individual harmonics (odd) from 3rd to 39th order are above IEEE recommended limit for I_{SC}/I_L ratio equal to 75. From the result, it is clear that the major current harmonics 3, 5, 11, 13, 17, 19, 21, 23, 25.

| Harmonic Order | Ch No. | Max. | Ave. | Min. | Harmonic Order | Ch No. | Max. | Ave. | Min. |
|----------------|--------|--------|-------|-------|----------------|--------|-------|-------|------|
| 3 | 1 | 78.72 | 27.64 | 78.65 | 5 | 1 | 25.68 | 12.21 | 6.03 |
| | 2 | 80.33 | 31.44 | 17.34 | | 2 | 27.63 | 9.83 | 3.72 |
| | 3 | 142.12 | 27.43 | 12.33 | | 3 | 39.19 | 9.95 | 3.10 |
| 7 | 1 | 6.79 | 2.29 | 0.58 | 9 | 1 | 5.60 | 2.37 | 0.99 |
| | 2 | 8.84 | 4.04 | 1.10 | | 2 | 5.90 | 3.01 | 1.03 |
| | 3 | 7.93 | 2.87 | 0.55 | | 3 | 10.01 | 2.73 | 0.99 |
| 11 | 1 | 16.24 | 6.10 | 1.77 | 13 | 1 | 12.01 | 6.38 | 1.82 |
| | 2 | 23.62 | 7.60 | 0.86 | | 2 | 21.91 | 6.42 | 1.45 |
| | 3 | 22.01 | 4.90 | 1.31 | | 3 | 20.99 | 4.32 | 1.22 |
| 15 | 1 | 4.30 | 2.10 | 0.58 | 17 | 1 | 10.70 | 3.94 | 1.70 |
| | 2 | 5.23 | 2.10 | 0.36 | | 2 | 9.25 | 2.71 | 0.81 |
| | 3 | 5.02 | 1.76 | 0.60 | | 3 | 15.18 | 3.32 | 1.06 |
| 19 | 1 | 14.84 | 5.91 | 2.26 | 21 | 1 | 21.30 | 6.10 | 1.74 |
| | 2 | 10.07 | 3.67 | 0.85 | | 2 | 8.79 | 3.49 | 0.97 |
| | 3 | 12.28 | 3.90 | 1.45 | | 3 | 9.28 | 3.11 | 0.98 |
| 23 | 1 | 20.43 | 6.44 | 0.88 | 25 | 1 | 14.48 | 3.62 | 0.66 |
| | 2 | 70.49 | 12.71 | 0.83 | | 2 | 31.30 | 5.82 | 0.70 |
| | 3 | 29.85 | 5.36 | 1.15 | | 3 | 31.95 | 6.24 | 0.73 |
| 27 | 1 | 2.12 | 1.02 | 0.42 | 29 | 1 | 1.53 | 0.60 | 0.26 |
| | 2 | 5.06 | 1.29 | 0.45 | | 2 | 3.64 | 1.16 | 0.32 |
| | 3 | 2.93 | 1.03 | 0.33 | | 3 | 5.17 | 1.15 | 0.24 |
| 31 | 1 | 1.08 | 0.55 | 0.17 | 33 | 1 | 0.82 | 0.43 | 0.11 |
| | 2 | 2.47 | 0.78 | 0.21 | | 2 | 1.26 | 0.51 | 0.14 |
| | 3 | 2.75 | 0.75 | 0.16 | | 3 | 1.67 | 0.41 | 0.11 |
| 35 | 1 | 1.53 | 0.60 | 0.26 | 37 | 1 | 1.08 | 0.55 | 0.17 |
| | 2 | 1.37 | 0.50 | 0.10 | | 2 | 1.52 | 0.47 | 0.07 |
| | 3 | 1.89 | 0.45 | 0.08 | | 3 | 2.27 | 0.46 | 0.06 |
| 39 | 1 | 0.82 | 0.43 | 0.11 | | | | | |
| | 2 | 1.29 | 0.43 | 0.05 | | | | | |
| | 3 | 1.73 | 0.34 | 0.04 | | | | | |

Table 4: shows the individual current harmonics distortion measurement result

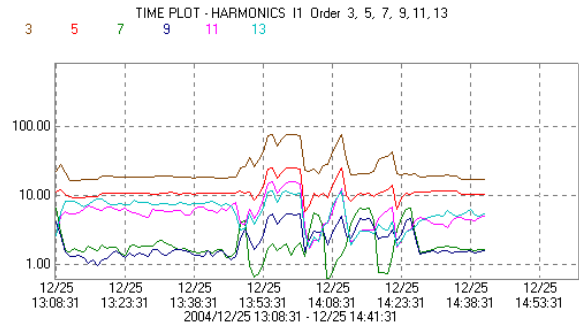


Figure 4(a): Ind. Current Harmonics Variation Time Plot Ch1

Figure 4 (a) shows individual current harmonics variation time plot of CH1 and CH2.

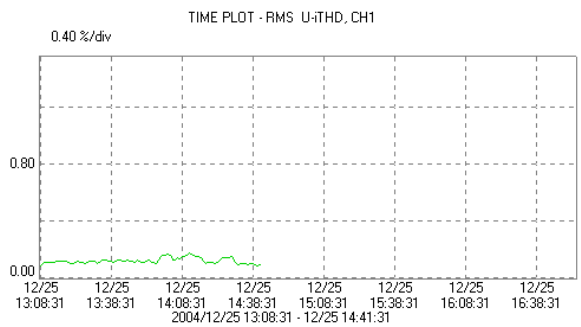


Figure 5(a): %Voltage Interharmonics Variation Time Plot Ch1

Max.Val:0.18% Avg.Val.:0.12% Min.Val:0.09%

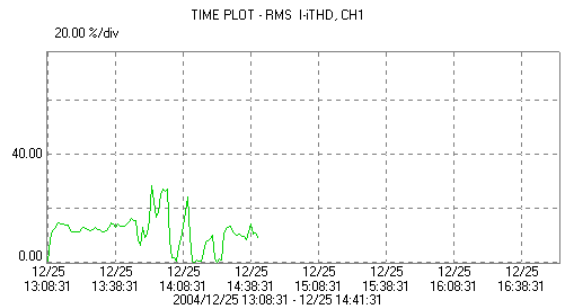


Figure 6 (a): %Current Total Interharmonics Variation Time Plot Ch1

Max.Val:28.38% Avg.Val.:11.60% Min.Val:0.34%

Figure 5 (a) shows percentage total voltage interharmonic distortion variation time plot of CH1 and CH2 respectively and Figure 6 (a) shows percentage total current interharmonic distortion variation time plot. From the result the total current interharmonics distortion in railway electric supply system is high and percentage voltage interharmonic distortion is very low.

2.2 MEASUREMENT RESULTS AT 25 KV SIDE

The railway electric supply system is a single phase 25 kV, 50 Hz. Harmonics measurement was carried out for 1 day at the secondary side of 132 kV / 25 kV Scott connected transformer.

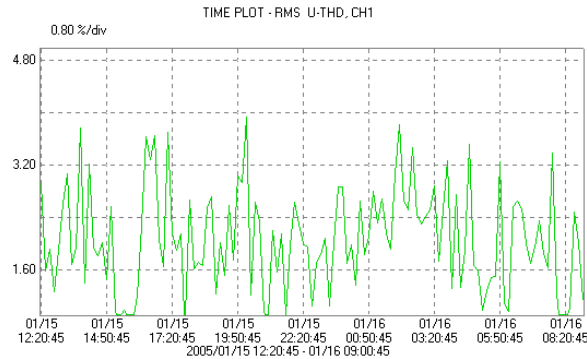


Figure 7(a)
Max.Val.:3.45% Avg.Val.:2.08% Min.Val.:0.78%

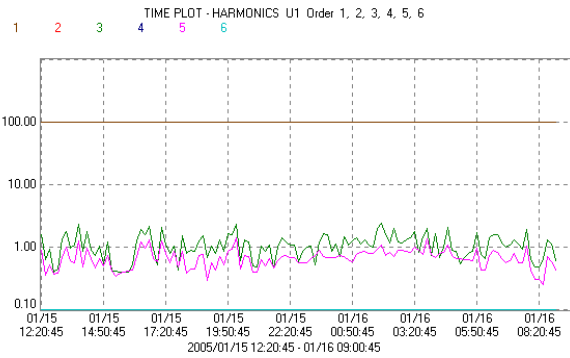


Figure 7 (b)

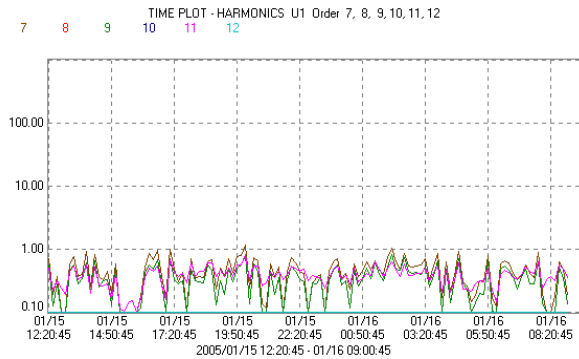


Figure 7 (c)

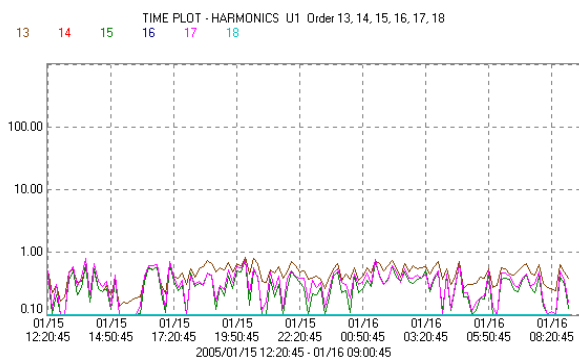


Figure 7 (d)

Figure 7(a), shows % total harmonics voltage distortion. The average value of the % total voltage distortion is 2.08% and is below 5% IEEE 519-1992 recommended limits for system voltage below 69 kV. Table 5 shows the measurement results of individual voltage harmonics.

| Harmonic order | Max. | Ave. | Min. |
|----------------|------|------|------|
| 3 | 2.46 | 1.13 | 0.40 |
| 7 | 1.20 | 0.46 | 0.05 |

| | | | |
|----------------|------|------|------|
| 11 | 0.85 | 0.40 | 0.10 |
| 15 | 0.79 | 0.30 | 0.02 |
| 19 | 0.97 | 0.37 | 0.07 |
| Harmonic order | Max. | Ave. | Min. |
| 5 | 1.43 | 0.70 | 0.25 |
| 9 | 0.83 | 0.34 | 0.01 |
| 13 | 0.83 | 0.46 | 0.14 |
| 17 | 0.82 | 0.34 | 0.05 |

Table 5: Measurement result of individual voltage harmonics

All the measured individual voltage harmonic levels are less than 3% level recommended by IEEE 519-1992 standard. Figure 7 (b, c, d) shows the individual voltage harmonics variation time plot.

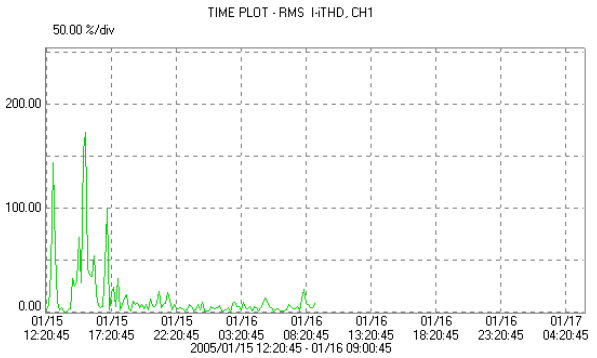


Figure 8

The results of % total current harmonics distortion is shown in Figure 8. The average % total current harmonics distortion is 32.89% and is above IEEE 519-1992 recommended limit for I_{SC}/I_L ratio equal to 75. Table 6 shows current distortion limit for general distribution system as per IEEE 519-1992 standard.

| Maximum Harmonics Current Distortion in Percentage of I_L | | | | | | |
|---|------|------------------|------------------|------------------|-------------|-------|
| Individual Harmonics Order (Odd Harmonic) | | | | | | |
| I_{SC}/I_L | < 11 | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $35 \leq h$ | TDD |
| < 20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.30 | 5.00 |
| * 20 < 50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.50 | 8.00 |
| 50 < 100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.00 |
| 100 < 1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.00 | 15.00 |
| > 1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.00 |

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L .

Table 6: Current distortion limits for general distribution systems (120V through 69,000 V)

Table 7 shows individual current harmonics measured values

| Harmonic order | Max. | Ave. | Min. |
|----------------|-------|-------|------|
| 3 | 52.77 | 22.89 | 8.24 |
| 5 | 21.72 | 8.62 | 3.35 |
| 7 | 12.67 | 4.11 | 1.29 |
| 9 | 7.95 | 2.86 | 1.19 |
| 11 | 11.20 | 3.14 | 0.83 |
| 13 | 12.53 | 3.35 | 0.78 |
| 15 | 4.54 | 1.68 | 0.53 |
| 17 | 6.94 | 2.21 | 0.57 |
| 19 | 14.56 | 2.98 | 0.57 |
| 21 | 14.96 | 2.44 | 0.49 |
| 23 | 46.24 | 5.17 | 0.93 |

| | | | |
|----|--------|------|------|
| 25 | 101.75 | 8.01 | 0.91 |
| 27 | 123.75 | 5.03 | 0.62 |
| 29 | 75.21 | 2.65 | 0.50 |
| 31 | 9.55 | 1.27 | 0.30 |
| 33 | 4.85 | 0.86 | 0.22 |
| 35 | 5.86 | 0.90 | 0.18 |
| 37 | 4.56 | 0.78 | 0.16 |

Table 7: Individual current harmonics measurement results at 25 kV

Individual current harmonics average value from 3 to 31 order are above IEEE 519-1992 recommended limit for I_{SC}/I_L equal to 75.

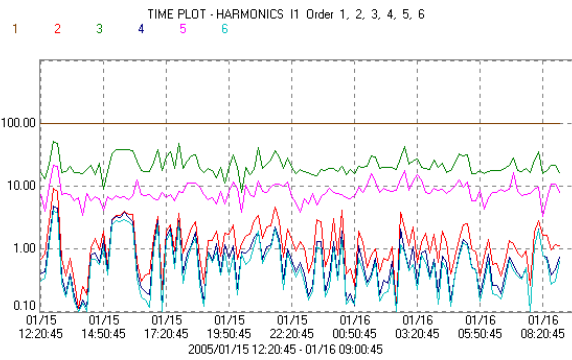


Figure 9 (a)

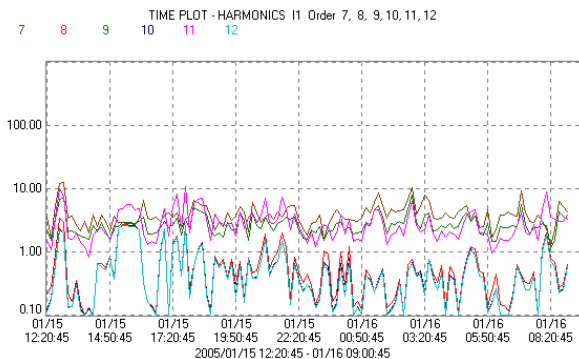


Figure 9 (b)

Figure 9 (a) and (b) shows individual current harmonics variation time plot.

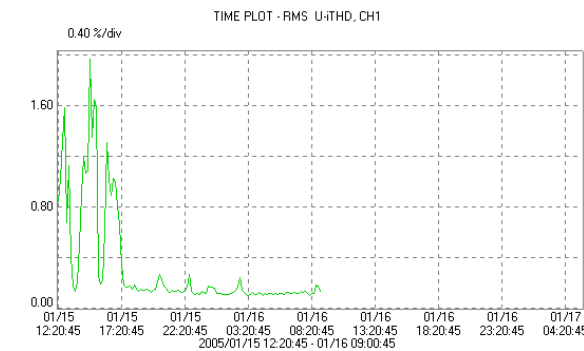


Figure 10 (a)

Max.Val:1.97% Avg.Val.:0.32% Min.Val:0.10%

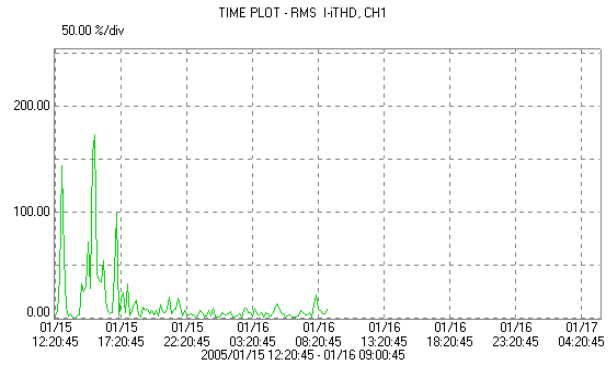


Figure 10 (b)

Max.Val:173.42% Avg.Val.:14.25% Min.Val:0.74%

Figure 10 (a) shows % total voltage interharmonics time plots and 10 (b) shows % total current interharmonics variation time plot. At 25 kV side also percentage total interharmonics voltage distortion is very less but percentage total interharmonics current distortion is high.

3. REMEDIAL ACTION TO LIMIT HARMONIC DISTORTION

The percentage current total harmonic distortion in railway electric supply system can be reduced by installation of multi tuned passive filters at appropriate points in place of power factor improvement capacitor. The drives used in electric a.c. locomotives should be 12, 18. There is a need to include limits on time varying harmonics and interharmonics in the revised harmonic standards.

4. CONCLUSIONS

The percentage total voltage harmonics distortion at 132 kV and 25 kV side of railway electric supply system is below IEEE 519-1992 recommended limits. The percentage total harmonics distortion in current at 132 kV side and 25 kV side of railway electric supply system exceed IEEE 519-1992 limit. The major current harmonics at 132 kV side are 3, 5, 11, 13, 17, 19, 21, 23 and 27 and 25 kV are 3, 5, 7, 11, 13, 17, 19, 21, 23, 25, 27 and 29. The individual current harmonics on 132 kV side and 25 kV side exceeds the IEEE recommended limits. To limit the harmonics distortion in railway electric supply system it is necessary to use multituned passive harmonics filters and 12, 18 pulse drive in electrical locomotives. The percentage total interharmonics current distortion at 132 kV and 25 kV is also high and there is a need to include limits on time varying and percentage total interharmonics voltage and current distortion in harmonics standards.

5. ACKNOWLEDGEMENT

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