PUBLIC UTILITIES COMMISSION OF SRI LANKA

Investigation on Harmonic Content of Commercial Buildings

Influence on Power Quality

Corporate Plan Deliverable 2016 : CP16/INS/05

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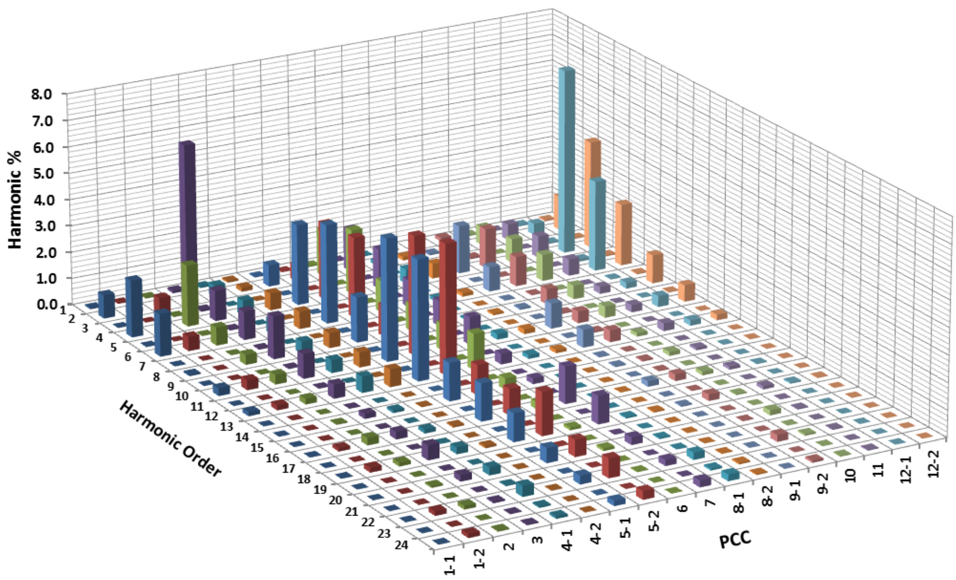

According to the section 6(2) of Sri Lanka Electricity Act No.20 of 2009, It is the duty of electrical inspectors to inspect, test and examine the electric lines and electrical plants belonging to persons authorized by a licence or exempted from the requirement of obtaining a licence to distribute or supply electricity. Accordingly, the PUCSL electrical inspectors have measured harmonic contents of several commercial installations (office complexes and shopping complexes) who have been exempted from having the requirement of obtaining the distribution licence, and evaluated the extent of distortion caused by harmonics, against the international standard IEEE 519–2014.

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1 Introduction

The Public Utilities Commission of Sri Lanka (PUCSL) in exercising of its powers to regulate electricity sector conferred by virtue of Section 10 of the Sri Lanka Electricity Act No. 20 of 2009, as amended, has issued exemptions to several commercial entities from the requirement of obtaining license for distributing and supplying electricity (Electricity Distribution Exemptions).

Aforementioned exempted parties purchase electricity in bulk and redistribute within the commercial premises concerned (eg: Office complexes, super markets) and provide electricity supply to consumers within the premises.

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.” In the power system of Sri Lanka the fundamental frequency is 50 Hz. Therefore harmonic frequencies of voltage and current signals are multiples of 50 Hz fundamental signals and for example the harmonic frequencies can be in 150Hz 350Hz, etc.

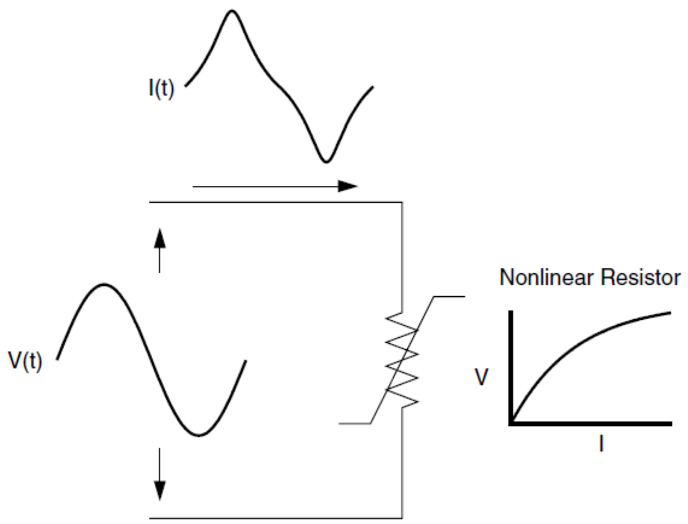
Presence of harmonics can cause damages to the equipment of the system users and will also affect the performance of the equipment connected to the power distribution system. With the introduction of equipment such as CFL, Air conditioning systems, Computers and Variable speed drives that use power electronic systems the electrical installations that are subjected to power quality issues cause by harmonics.

PUCSL has conducted harmonic measurement program covering 12 commercial entities that have been granted distribution exemptions. Selected installations are comprised of shops and offices. In general, commercial facilities are equipped with high-efficiency lighting with electronic ballasts, adjustable-speed drives for the heating, ventilation, and air conditioning (HVAC) loads, elevator drives, and electronic equipment, which can be considered as non-linear loads (impedance changes with the applied voltage). Even though these non-linear loads are very efficient in their operations they pose different threat by introducing harmonic currents and voltages to the power system.

The Commission conducted these harmonic measurements to assess the prevailing content of harmonic current and voltages in these commercial installations against the international standards (IEEE 519), so that the individual consumers connected and supplied by the respective commercial installations are not burdened with power quality issues backed by harmonics.

2 Harmonics - An Introduction

When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a harmonic of the fundamental. This waveform distortin caused by non linear loads, that is the impedence of the load is varies with the applied voltage.



Usually, the higher-order harmonics are negligible for power system analysis. While they may cause interference with low-power electronic devices, they are usually not damaging to the power system.

- Harmonics of order h 1, 7, 13,… are generally positive sequence.
- Harmonics of order h 5, 11, 17,… are generally negative sequence.
- Triplens (h 3, 9, 15,…) are generally zero sequence.

It is important to note that the every consumers who are connected with the same point where a harmonic producing sources are connected (PCC-point of common coupling), are subjected to the power quality problems caused by this distorted voltage and current waveforms produced by harmonic generating equipment or non-linear loads.

2.1 Negative Effects of Harmonics

Effects on Transformers : The eddy current losses, increase with the square of the harmonic number. In practice, for a fully loaded transformer supplying a load comprising IT equipment the total transformer losses would be twice as high as for an equivalent linear load. This results in a much higher operating temperature and a shorter life.

The triplen harmonics are effectively absorbed in the winding and do not propagate onto the supply, so delta wound transformers are useful as isolating transformers. Note that all other, non-triplen, harmonics pass through. The circulating current has to be taken into account when rating the transformer.

Neutral Conductor Over-Heating : Triplen harmonic currents are having an order that an odd multiple of three. These harmonic currents add in the neutral. Hence contribute to neutral conductor overloading.

Nuisance Tripping of Circuit Breakers : Residual current circuit breakers (RCCB) operate by summing the current in the phase and neutral conductors. Nuisance tripping can occur in the presence of harmonics. The RCCB, being an electromechanical device, may not sum the higher frequency components correctly and therefore trips erroneously.

Over-Stressing of Power Factor Correction Capacitors : Power factor correction capacitors are provided in order to draw a current with a leading phase angle to offset lagging current drawn by an inductive load such as induction motors. The impedance of the PFC capacitor reduces as frequency rises, while the source impedance is generally inductive and increases with frequency. The capacitor is therefore likely to carry quite high harmonic currents and, unless it has been specifically designed to handle them, damage can result.

Skin Effect : Alternating current tends to flow on the outer surface of a conductor. This is called skin effect and is prominent at high frequencies. Skin effect is normally ignored because it has very little effect at power supply frequencies but above about 350 Hz, i.e. the seventh harmonic and above, skin effect will become significant, causing additional loss and heating.

Problems Caused by Harmonic Voltages : Because the supply has source impedance, harmonic load currents give rise to harmonic voltage distortion on the voltage waveform. The source impedance of the supply network is very low so distortion levels are also relatively low. However, if the load is transferred to a UPS or standby generator during a power failure, the source impedance and the resulting voltage distortion in the installation will be much higher.

Induction Motors : Harmonic voltage distortion causes increased eddy current losses . further these harmonics is trying to rotate the motor at a different speed either forwards or backwards contributing to more losses.

Zero-Crossing Noise : Many electronic controllers detect the point at which the supply voltage crosses zero volts to determine when loads should be turned on. This is done because switching reactive loads at zero voltage does not generate transients, so reducing electromagnetic interference (EMI) and stress on the semiconductor switching devices. When harmonics are present on the supply the rate of change of voltage at the crossing becomes faster and more difficult to identify, leading to erratic operation.

EMI: Power cables carrying harmonic loads act to introduce in adjacent signal or control cables via conducted and radiated emissions. This "EMI noise" has a detrimental effect on telephones, televisions,

radios, computers, control systems and other types of equipment.

2.2 Sources of Harmonics

In general any non-linear load can be a source of harmonics. In commercial installations below mentioned harmonic sources are dominant.

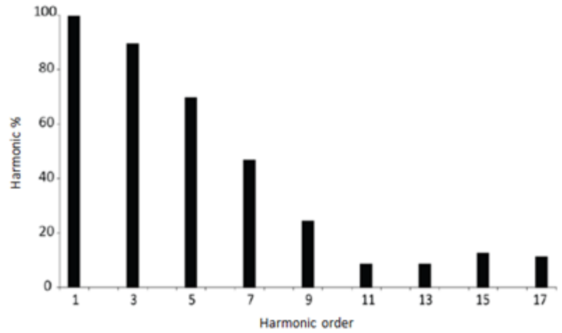
Single phase loads,

- Switched mode power supplies (SMPS) – virtually all electronic devices
- Electronic fluorescent lighting ballasts : Standard magnetic ballasts are usually rather benign sources of additional harmonics themselves since the main harmonic distortion comes from the behavior of the arc. Electronic ballasts typically produce current THDs in the range of between 10 and 32 percent.
- Small uninterruptible power supplies (UPS) units

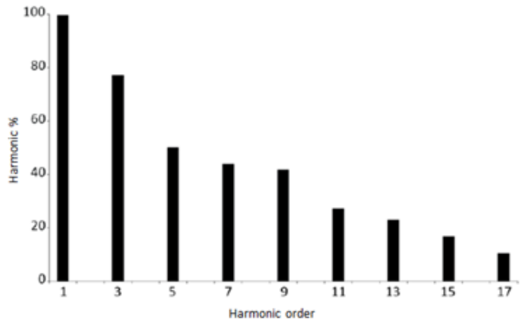
Three phase loads,

- Variable speed drives-VSDs (in HVAC systems, elevators) : Common applications of VSDs in commercial loads can be found in elevator motors and in pumps and fans in HVAC systems. In HVAC systems air flow and refrigerant flow is controlled by VSDs. A VSD consists of an electronic power converter that converts ac voltage and frequency into variable voltage and frequency.
- Large UPS units

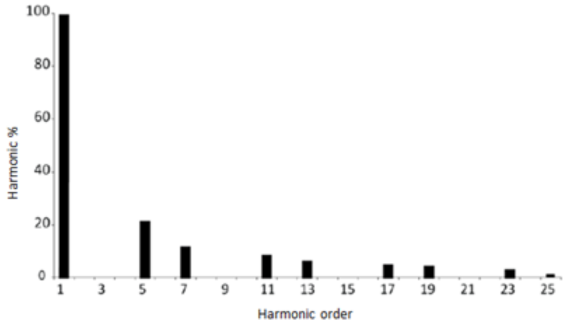
Generalized harmonic spectrums of typical loads in commercial installations are given below.



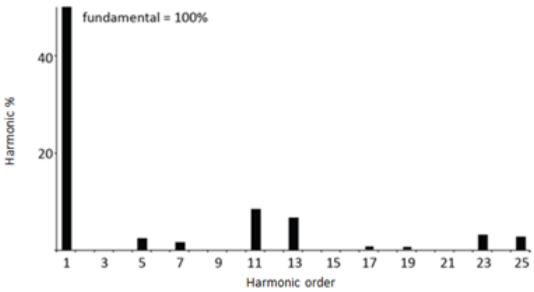
Personnel Computer



Fluorescent Lamp



Typical six Pulse Bridge



Typical Twelve Pulse Bridge

3 Harmonic Measurements

In doing measurement and analysis of harmonics following terms are important to understand.

- Harmonic (component): A component of order greater than one of the Fourier series of a periodic quantity. For example, in a 50 Hz system, the harmonic order 5, also known as the “fifth harmonic,” is 250 Hz sinusoidal voltage or current wave.
- Maximum demand load current: This current value is established at the point of common coupling and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12.
- point of common coupling (PCC): Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation.
- Short-circuit ratio: At a particular location, the ratio of the available short-circuit current, in amperes, to the load current, in amperes.
- Total demand distortion (TDD): The ratio of the root mean square of the harmonic content expressed as a percent of the maximum demand current.
- Total harmonic distortion (THD): The ratio of the root mean square of the harmonic content, expressed as a percent of the fundamental.

The international standard IEEE 519-2014 has recommended limits of harmonics (both current and voltages) according to the recommended methods of taking measurements. These recommended practices specify that measurements should be taken at the point of common coupling (PCC). PCC should be taken as the point in the electrical power system closest to the user , where other users are also connected. For the commercial users supplied through a common service transformer, the PCC is the LV bus of the transformer.

Considering the time constraints and resources, the “very short time harmonic measurement” method was selected as the optimum.

3.1 Very Short Time Harmonic Measurements

According to the IEE 519-2014, the very short time harmonic values are assessed over a 3-second interval based on an aggregation of 15 consecutive 10 cycle windows for 50 Hz power systems. Individual frequency components are aggregated based on an rms calculation as shown in following equation.

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^2}$$

F represents voltage (V) or current (I), n represents the harmonic order, and i is a simple counter. The subscript vs is used to denote "very short." In all cases, F represents an rms value.

3.1.1 Recommended Harmonic Limits

The daily 99th percentile values of each harmonic and THD at the PCC should be within following limits as recommended by IEEE 519-2014.

Voltage Limits

Limits for the line-to-neutral voltage harmonics in 400V system are as follows:

Individual Harmonic Limit (%)	THD Limit (%)
7.5	12

Current Limits

Limits for the current distortion by *odd harmonics* in 400V system according to the ratios of I_{SC} / I_L are as follows. Where,

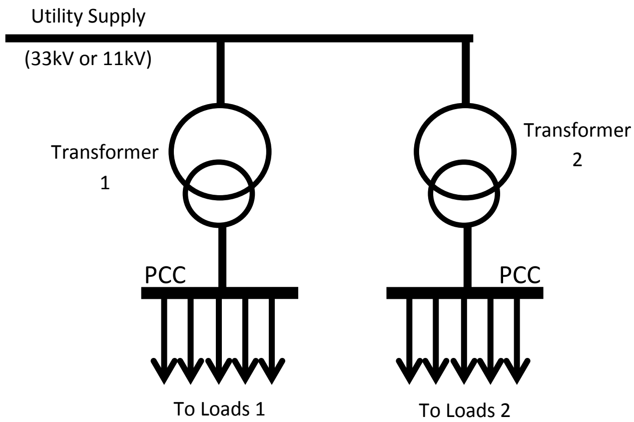
I_{SC} - Maximum short circuit current at the PCC

I_L - Maximum demand load current at the PCC under normal load operating conditions.

I_{SC} / I_L	Maximum Harmonic Current Distortion (odd harmonics) in Percent of I_L				
	3≤h≤11	11≤h≤17	17≤h≤23	23≤h≤35	TDD
<20	8.0	4.0	3.0	1.2	10.0
20<50	14.0	7.0	5.0	2.0	16.0
50<100	20.0	9.0	8.0	3.0	24.0
100<1000	24.0	11.0	10.0	4.0	30.0

4 Discussion on Results

Some of the commercial installations where the measurements were take,are supplied through single transformers while others are supplied with more than one transformer those are not operating in parallel. Hence, in the latter case such a commercial installations have more than one PCC to take measurements. For example, a facility which is supplied by two transformers (not in parallel) taken as two separate installations having separate PCCs on LV side. See the following figure for clarification. Reader should note that the harmonic values were recorded limited to a recording period of approximately 6 hours, because of the memory constraints in the loggers used to measure.



Recordings were taken up 25th harmonic and the results are summarized and discussed below.

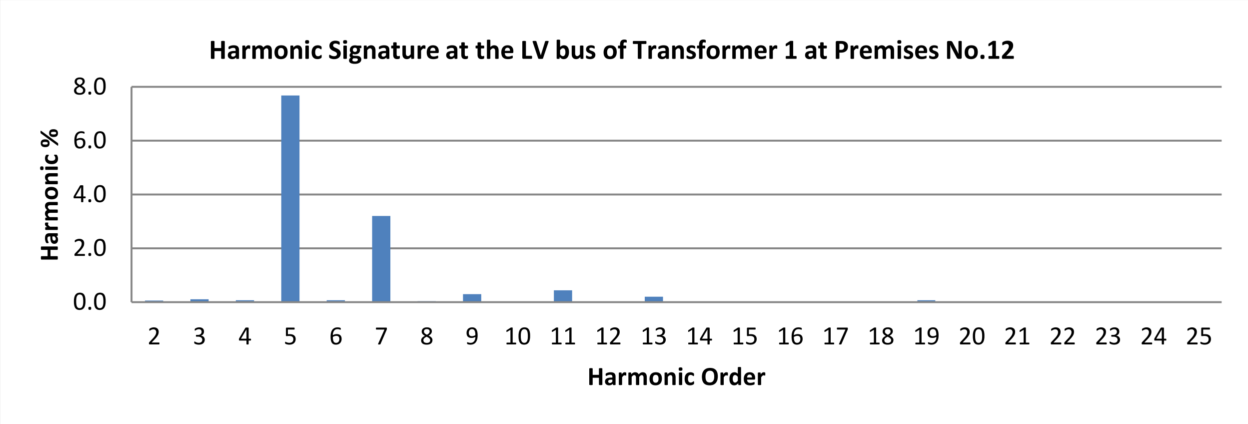
4.1 Results Obtained for Voltage Harmonics

According to our measurements it is observed that all relevant values are within the limits except for one user which is represented by premises no. 12. Here phase 2 of a one transformer is showing a value of 7.68 % for the 5th voltage harmonic component. Values are given in following table.

Facility		PCC (LV Bus)	Individual Harmonic Voltages (%) - 99th Percentile of very short time (3 s) harmonic values																								THD(Voltage)-99th Percentile
			h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	h25	
1	Transformer 1	Phase 1	0.06	1.01	0.01	2.02	0.03	1.46	0.00	0.03	0.00	0.28	0.00	0.17	0.00	0.00	0.00	0.03	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	2.30
		Phase 2	0.04	0.75	0.02	2.27	0.03	1.42	0.01	0.04	0.00	0.30	0.00	0.15	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	2.50
		Phase 3	0.05	0.91	0.00	2.15	0.01	1.91	0.00	0.10	0.00	0.28	0.00	0.13	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	2.70
	Transformer 2	Phase 1	0.03	0.08	0.00	1.24	0.00	0.58	0.00	0.00	0.00	0.39	0.00	0.17	0.00	0.00	0.00	0.12	0.00	0.16	0.00	0.00	0.00	0.17	0.00	0.13	1.40
		Phase 2	0.03	0.17	0.00	1.33	0.00	0.53	0.00	0.00	0.00	0.38	0.00	0.19	0.00	0.00	0.00	0.13	0.00	0.19	0.00	0.00	0.00	0.16	0.00	0.16	1.50
		Phase 3	0.03	0.11	0.00	1.28	0.00	0.49	0.00	0.00	0.00	0.38	0.00	0.20	0.00	0.00	0.00	0.12	0.00	0.19	0.00	0.00	0.00	0.17	0.00	0.16	1.50
2	Transformer	Phase 1	0.03	0.49	0.02	2.30	0.01	0.72	0.01	0.43	0.00	0.39	0.00	0.21	0.00	0.03	0.00	0.34	0.00	0.13	0.00	0.06	0.00	0.22	0.00	0.04	2.30
		Phase 2	0.04	0.33	0.03	2.48	0.03	0.71	0.01	0.37	0.00	0.42	0.00	0.18	0.00	0.05	0.00	0.24	0.00	0.16	0.00	0.07	0.00	0.07	0.00	0.05	2.50
		Phase 3	0.05	0.31	0.03	2.15	0.01	0.61	0.01	0.33	0.00	0.27	0.00	0.23	0.00	0.03	0.00	0.24	0.00	0.12	0.00	0.05	0.00	0.11	0.00	0.04	2.10
3	Transformer	Phase 1	0.11	6.09	0.08	0.95	0.04	0.94	0.03	1.57	0.03	0.91	0.02	0.34	0.02	0.17	0.00	0.30	0.00	0.34	0.00	0.10	0.00	0.02	0.00	0.01	6.30
		Phase 2	0.09	5.80	0.06	1.22	0.05	1.10	0.03	1.55	0.02	0.75	0.02	0.67	0.01	0.22	0.01	0.27	0.01	0.51	0.02	0.23	0.01	0.09	0.03	0.06	6.00
		Phase 3	0.08	6.07	0.05	1.25	0.03	1.18	0.04	1.69	0.03	1.09	0.02	0.57	0.02	0.17	0.00	0.26	0.00	0.80	0.01	0.37	0.01	0.06	0.02	0.02	6.40
4	Transformer 1	Phase 1	0.06	0.40	0.00	0.54	0.00	0.51	0.00	0.45	0.00	0.47	0.00	0.62	0.00	0.06	0.00	0.16	0.00	0.25	0.00	0.26	0.03	0.43	0.05	0.05	1.10
		Phase 2	0.05	0.47	0.00	0.50	0.00	0.58	0.00	0.46	0.00	0.49	0.00	0.58	0.00	0.11	0.00	0.14	0.00	0.25	0.00	0.28	0.02	0.42	0.05	0.08	1.10
		Phase 3	0.05	0.46	0.00	0.66	0.00	0.54	0.00	0.46	0.00	0.49	0.00	0.60	0.00	0.13	0.00	0.12	0.00	0.26	0.00	0.34	0.03	0.34	0.06	0.13	1.20
	Transformer 2	Phase 1	0.06	0.15	0.00	0.58	0.00	0.68	0.00	0.65	0.00	0.61	0.00	0.72	0.00	0.02	0.00	0.04	0.00	0.05	0.00	0.00	0.00	0.01	0.00	0.00	1.20
		Phase 2	0.08	0.15	0.00	0.74	0.00	0.59	0.00	0.51	0.00	0.53	0.00	0.65	0.00	0.03	0.00	0.07	0.00	0.10	0.00	0.00	0.00	0.03	0.00	0.00	1.20
		Phase 3	0.06	0.20	0.00	0.60	0.00	0.71	0.00	0.54	0.00	0.56	0.00	0.63	0.00	0.02	0.00	0.07	0.00	0.06	0.00	0.01	0.00	0.02	0.00	0.00	1.10
5	Transformer 1	Phase 1	0.03	0.77	0.00	3.01	0.00	3.98	0.00	1.45	0.01	4.60	0.01	4.92	0.00	1.43	0.00	1.38	0.00	1.14	0.00	0.54	0.00	0.28	0.00	0.16	7.90
		Phase 2	0.03	0.85	0.00	3.19	0.00	3.73	0.01	2.17	0.01	4.82	0.01	4.52	0.00	1.16	0.00	1.57	0.00	1.06	0.00	0.49	0.00	0.39	0.00	0.23	7.80
		Phase 3	0.03	0.84	0.01	2.93	0.00	3.47	0.01	1.49	0.02	4.38	0.00	4.15	0.00	1.69	0.00	1.27	0.00	0.97	0.00	0.63	0.00	0.28	0.00	0.19	7.10
	Transformer 2	Phase 1	0.03	0.58	0.00	2.92	0.00	3.36	0.00	1.02	0.01	4.72	0.01	5.30	0.01	0.98	0.00	1.09	0.00	1.79	0.00	0.51	0.00	0.49	0.00	0.36	8.10
		Phase 2	0.03	0.60	0.00	2.99	0.00	3.02	0.00	1.52	0.01	4.79	0.01	5.49	0.01	1.07	0.00	0.93	0.00	1.89	0.00	0.48	0.00	0.93	0.00	0.25	8.30
		Phase 3	0.03	0.58	0.00	2.73	0.00	2.77	0.01	0.97	0.01	4.00	0.00	3.93	0.00	1.35	0.00	0.96	0.00	1.20	0.00	0.90	0.00	0.75	0.00	0.33	6.60
6	Transformer	Phase 1	0.05	1.80	0.01	2.13	0.01	1.40	0.01	0.99	0.01	0.98	0.02	1.35	0.00	0.38	0.00	0.30	0.00	0.11	0.00	0.10	0.00	0.03	0.00	0.02	3.40
		Phase 2	0.05	1.65	0.00	2.63	0.01	1.11	0.02	1.18	0.02	1.15	0.02	1.44	0.01	0.43	0.00	0.27	0.00	0.11	0.00	0.10	0.00	0.01	0.00	0.01	3.70
		Phase 3	0.05	1.80	0.01	2.59	0.01	1.08	0.01	0.90	0.02	0.83	0.02	1.29	0.01	0.48	0.00	0.26	0.00	0.08	0.00	0.09	0.00	0.03	0.00	0.00	3.50
7	Transformer	Phase 1	0.04	1.75	0.00	1.63	0.00	1.07	0.00	0.95	0.00	1.27	0.00	0.30	0.00	0.14	0.00	1.46	0.00	1.19	0.00	0.28	0.00	0.21	0.00	0.24	3.40
		Phase 2	0.04	1.65	0.00	1.51	0.00	1.10	0.00	0.94	0.00	1.03	0.00	0.33	0.00	0.23	0.00	1.42	0.00	0.83	0.00	0.17	0.00	0.14	0.00	0.33	3.10
		Phase 3	0.03	1.37	0.00	1.41	0.00	0.94	0.00	0.97	0.00	0.87	0.00	0.55	0.00	0.26	0.00	1.27	0.00	1.12	0.00	0.40	0.00	0.32	0.00	0.18	2.90
8	Transformer 1	Phase 1	0.03	0.21	0.00	0.57	0.00	0.13	0.00	0.12	0.00	0.20	0.00	0.15	0.00	0.00	0.00	0.02	0.00	0.05	0.00	0.03	0.02	0.28	0.08	0.15	1.20
		Phase 2	0.03	0.05	0.00	0.55	0.00	0.11	0.00	0.03	0.00	0.20	0.00	0.13	0.00	0.00	0.00	0.01	0.00	0.07	0.00	0.06	0.02	0.28	0.06	0.31	0.90
		Phase 3	0.04	0.14	0.00	0.54	0.00	0.16	0.00	0.05	0.00	0.24	0.00	0.13	0.00	0.00	0.00	0.02	0.00	0.06	0.00	0.03	0.02	0.24	0.07	0.28	0.90
	Transformer 2	Phase 1	0.03	0.21	0.00	0.55	0.00	0.15	0.00	0.11	0.00	0.17	0.00	0.13	0.00	0.00	0.00	0.03	0.00	0.03	0.00	0.02	0.01	0.01	0.07	0.05	0.50
		Phase 2	0.03	0.05	0.00	0.56	0.00	0.12	0.00	0.03	0.00	0.17	0.00	0.11	0.00	0.00	0.00	0.02	0.00	0.07	0.00	0.00	0.01	0.02	0.06	0.03	0.50
		Phase 3	0.04	0.14	0.00	0.56	0.00	0.13	0.00	0.07	0.00	0.19	0.00	0.11	0.00	0.00	0.00	0.02	0.00	0.05	0.00	0.01	0.01	0.03	0.05	0.03	0.50
9	Transformer 1	Phase 1	0.04	0.04	0.01	1.79	0.01	1.00	0.02	0.04	0.01	1.13	0.02	0.46	0.03	0.00	0.00	0.15	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	2.20
		Phase 2	0.03	0.03	0.01	1.82	0.01	0.89	0.02	0.08	0.01	0.95	0.01	0.62	0.05	0.07	0.00	0.39	0.00	0.09	0.00	0.00	0.00	0.03	0.00	0.00	2.20
		Phase 3	0.03	0.12	0.01	1.84	0.02	0.89	0.03	0.07	0.01	0.76	0.02	0.96	0.01	0.05	0.00	0.08	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	2.20
	Transformer 2	Phase 1	0.15	0.17	0.03	1.46	0.01	1.18	0.03	0.55	0.02	0.47	0.04	0.39	0.01	0.07	0.01	0.29	0.01	0.19	0.01	0.03	0.00	0.22	0.00	0.08	1.90
		Phase 2	0.12	0.31	0.09	1.50	0.02	1.13	0.03	0.69	0.06	0.48	0.05	0.45	0.02	0.05	0.03	0.28	0.01	0.18	0.02	0.02	0.00	0.32	0.00	0.06	2.00
		Phase 3	0.14	0.35	0.06	1.53	0.02	1.05	0.03	0.51	0.04	0.39	0.05	0.49	0.01	0.04	0.02	0.17	0.02	0.36	0.00	0.01	0.00	0.23	0.00	0.11	1.90
10	Transformer	Phase 1	0.05	0.68	0.00	0.85	0.00	0.97	0.00	0.47	0.00	0.40	0.00	0.15	0.00	0.12	0.00	0.09	0.00	0.04	0.00	0.18	0.00	0.05	0.01	0.03	1.50
		Phase 2	0.05	0.68	0.00	0.93	0.00	0.98	0.01	0.54	0.01	0.37	0.01	0.09	0.01	0.15	0.01	0.12	0.01	0.03	0.01	0.18	0.01	0.06	0.02	0.01	1.50
		Phase 3	0.04	0.69	0.00	0.97	0.00	1.04	0.00	0.53	0.00	0.52	0.00	0.16	0.00	0.17	0.00	0.20	0.00	0.05	0.00	0.20	0.00	0.09	0.01	0.05	1.70
11	Transformer	Phase 1	0.03	0.52	0.00	0.71	0.00	0.56	0.00	0.22	0.00	0.36	0.01	0.29	0.00	0.04	0.00	0.07	0.00	0.14	0.01	0.02	0.00	0.03	0.00	0.03	1.00
		Phase 2	0.04	0.58	0.01	0.83	0.01	0.67	0.00	0.30	0.02	0.30	0.00	0.37	0.01	0.08	0.00	0.08	0.00	0.08	0.01	0.03	0.00	0.02	0.01	0.04	1.20
		Phase 3	0.03	0.71	0.01	0.96	0.00	0.65	0.00	0.28	0.00	0.18	0.00	0.22	0.01	0.16	0.00	0.18	0.00	0.15	0.00	0.06	0.00	0.06	0.00	0.03	1.30
12	Transformer 1	Phase 1	0.04	0.66	0.05	6.92	0.09	2.75	0.03	0.26	0.00	0.42	0.00	0.21	0.00	0.00	0.00	0.03	0.00	0.05	0.00	0.00	0.00	0.01	0.00	0.00	7.00
		Phase 2	0.06	0.11	0.07	**7.68**	0.07	3.20	0.03	0.30	0.01	0.44	0.00	0.20	0.00	0.00	0.00	0.03	0.00	0.06	0.00	0.00	0.00	0.01	0.00	0.01	7.80
		Phase 3	0.05	0.54	0.05	6.51	0.10	4.32	0.03	0.12	0.01	0.39	0.00	0.19	0.00	0.00	0.00	0.02	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	7.00
	Transformer 2	Phase 1	0.06	1.45	0.03	3.88	0.05	2.22	0.03	1.02	0.01	0.59	0.00	0.12	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	4.60
		Phase 2	0.05	1.30	0.04	4.16	0.04	2.47	0.03	1.03	0.03	0.77	0.00	0.29	0.00	0.02	0.00	0.01	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.00	4.90
		Phase 3	0.05	1.11	0.03	4.23	0.05	2.36	0.05	1.19	0.03	0.53	0.00	0.24	0.00	0.02	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	4.80

This particular building is an office complex. The concerned transformer has no consumers connected but common service loads such as lifts and fans. These lifts operated by DC motors hence rectifies are in operation. They have installed about 24 DC motors with power rating varing from 11kW to 30kW.

Even though not exceeded the limits, the 5th harmonic content in phase 1 and phase 3 of the same transformer LV bus has significant values 6.95% and 6.51% respectively. In the same bus the 7th harmonic components in each phases are having significant values (from 2.7% to 4.3 %). Harmonic profile is given in following figure. This 5th Harmonic could be a result of operation of 6-pulse rectifies used in AC to DC conversion.



In general harmonics generated by ***P*** number of pulse DC converters can be given as ***H=nP±1***. Accordingly 6-pulse rectifiers generate harmonics in 5th and 7th order while 12 pulse converter will give 11th and 13th harmonics mainly.

Problems from 5th Harmonic : Voltage distortion by 5th harmonic can cause problems for 3-phase motors. As it is a negative sequence harmonic and when supplied to an induction motor it produces a negative torque. It attempts to drive the motor in a reverse direction and slows down its rotation. So the motor draws more 50-Hz current to offset the reverse torque and regain its normal operating speed. The result is overcurrent in the motor, which either causes protective devices to open or the motor to overheat and fail. Therefore even no other consumers are connected with this concerned PCC of the transformer, the other 3 phase motors connected to this bus can be subjected to aforementioned drawbacks.

4.2 Results Obtained for Current Harmonics

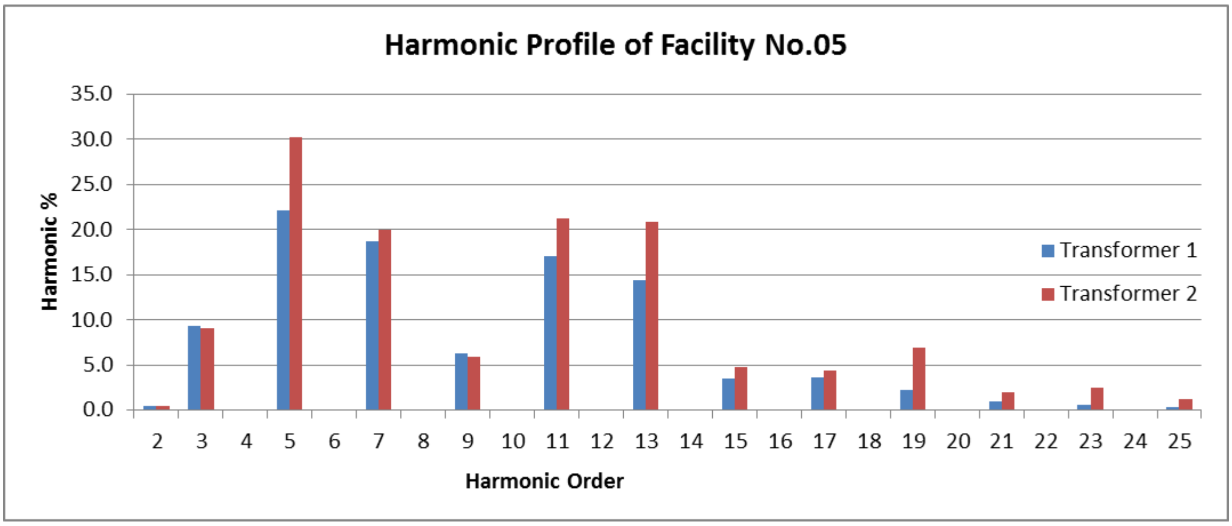
THD and individual harmonic currents upto 25th harmonic were recorded at each PCC. In below table the individual and THD values given as a percentage of fundamental current components. Values in RED color have exceeded the limits. Hence there is a possibility that THD and individual harmonic components in RED color, might also exceed the IEEE 519 limits when given as a percentage of Maximum demand current. Therefore further calculations required to verify the situation of harmonic components given in RED color.

Facility		PCC (LV Bus)	Relevant I_{SC}/I_L Range	Individual Harmonic Currents as a % of Fundamental - 99th Percentile of very short time (3 s) harmonic values																									Total Harmonic (THD)- 99th Percentile
				h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24	h25		
1	Transformer 1	Phase 1	20<50	0.5	1.0	0.0	2.7	0.0	1.3	0.0	0.0	0.0	0.7	0.0	0.6	0.0	0.0	0.0	0.3	0.0	0.4	0.0	0.0	0.0	0.4	0.0	0.3		3.40
		Phase 2		0.2	0.5	0.0	3.0	0.0	1.3	0.0	0.0	0.0	0.7	0.0	0.6	0.0	0.0	0.0	0.4	0.0	0.5	0.0	0.0	0.0	0.3	0.0	0.4		3.60
		Phase 3		0.2	1.2	0.0	2.9	0.0	1.3	0.0	0.0	0.0	0.8	0.0	0.6	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.4	0.0	0.4		3.70
	Transformer 2	Phase 1	20<50	0.7	11.3	0.1	7.3	0.3	8.1	0.1	0.3	0.0	0.5	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		14.80
		Phase 2		0.4	10.3	0.3	9.0	0.2	7.9	0.1	0.5	0.1	0.5	0.0	0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0		14.20
		Phase 3		0.6	9.2	0.1	7.8	0.2	10.1	0.1	0.5	0.0	0.5	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		14.20
2	Transformer	Phase 1	50<100	0.3	11.9	0.0	6.6	0.0	3.4	0.0	4.1	0.0	2.7	0.0	1.4	0.0	0.2	0.0	1.5	0.0	1.1	0.0	0.4	0.0	0.6	0.0	0.4		14.80
		Phase 2		0.3	6.7	0.1	6.2	0.0	3.0	0.0	2.7	0.0	1.2	0.0	0.9	0.0	0.4	0.0	0.6	0.0	0.6	0.0	0.5	0.0	0.2	0.0	0.2		10.00
		Phase 3		1.0	7.9	0.1	6.3	0.0	2.3	0.0	3.0	0.0	1.6	0.0	1.3	0.0	0.5	0.0	0.9	0.0	0.5	0.0	0.1	0.0	0.4	0.0	0.4		10.90
3	Transformer	Phase 1	50<100	1.1	7.0	0.1	1.9	0.1	2.0	0.1	1.3	0.2	3.4	0.1	1.3	0.0	0.2	0.0	0.5	0.0	0.3	0.0	0.5	0.0	0.1	0.0	0.1		7.20
		Phase 2		1.0	5.9	0.2	3.4	0.1	2.6	0.1	1.3	0.1	3.3	0.2	3.2	0.0	0.5	0.0	0.6	0.0	0.3	0.0	0.4	0.0	0.2	0.0	0.1		6.60
		Phase 3		0.9	5.3	0.2	3.5	0.1	3.6	0.1	2.1	0.2	3.0	0.1	2.6	0.0	0.3	0.0	0.8	0.0	0.5	0.0	0.4	0.0	0.1	0.0	0.1		6.50
4	Transformer 1	Phase 1	20<50	1.0	2.8	0.1	1.4	0.0	1.9	0.1	0.7	0.1	1.6	0.0	1.2	0.0	0.1	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.4	0.0	0.1		3.70
		Phase 2		1.0	3.3	0.2	2.0	0.1	2.6	0.1	0.8	0.1	1.6	0.0	2.6	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.4	0.0	0.1		5.00
		Phase 3		0.8	2.5	0.1	2.4	0.1	2.7	0.1	1.6	0.1	1.3	0.0	2.0	0.0	0.2	0.0	0.1	0.0	0.3	0.0	0.2	0.0	0.3	0.0	0.1		4.70
	Transformer 2	Phase 1	50<100	1.2	1.5	0.1	3.7	0.1	2.4	0.1	2.4	0.0	2.6	0.0	1.8	0.0	0.1	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.0		5.50
		Phase 2		1.5	1.2	0.1	4.3	0.1	1.9	0.1	1.8	0.0	2.1	0.0	1.2	0.0	0.2	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.0		5.40
		Phase 3		1.5	2.6	0.1	5.3	0.1	2.7	0.1	2.7	0.0	3.1	0.0	1.5	0.0	0.1	0.0	0.5	0.0	0.4	0.0	0.0	0.0	0.1	0.0	0.1		7.30
5	Transformer 1	Phase 1	20<50	0.4	8.0	0.0	**22.1**	0.1	**19.0**	0.1	5.0	0.1	**16.8**	0.1	**15.6**	0.0	3.2	0.0	3.4	0.0	2.5	0.0	0.9	0.0	0.5	0.0	0.3		**36.20**
		Phase 2		0.5	9.6	0.0	**22.4**	0.1	**18.7**	0.1	7.6	0.1	**17.3**	0.0	**14.1**	0.0	2.6	0.0	3.8	0.0	2.2	0.0	0.7	0.0	0.6	0.0	0.4		**35.50**
		Phase 3		0.4	10.3	0.0	**22.1**	0.1	**18.5**	0.1	6.2	0.1	**17.2**	0.0	**13.4**	0.0	4.6	0.0	3.5	0.0	2.2	0.0	1.1	0.0	0.5	0.0	0.3		**35.30**
	Transformer 2	Phase 1	20<50	0.5	8.2	0.1	**31.2**	0.1	**21.4**	0.1	5.0	0.1	**21.9**	0.1	**22.2**	0.1	3.6	0.0	**5.3**	0.0	**7.4**	0.0	1.4	0.0	2.0	0.0	1.4		**48.10**
		Phase 2		0.5	9.3	0.0	**29.9**	0.1	**19.3**	0.1	7.5	0.1	**22.1**	0.1	**22.6**	0.1	4.5	0.0	4.2	0.0	**7.6**	0.0	1.1	0.0	**2.9**	0.0	1.0		**47.30**
		Phase 3		0.5	9.6	0.0	**29.6**	0.1	**19.1**	0.1	5.3	0.1	**19.8**	0.1	**17.7**	0.1	6.1	0.0	3.5	0.0	**5.6**	0.0	3.2	0.0	**2.7**	0.0	1.3		**44.20**
6	Transformer	Phase 1	20<50	0.4	5.2	0.1	6.1	0.0	3.3	0.1	1.4	0.1	3.5	0.1	3.6	0.0	0.2	0.0	1.2	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0		8.90
		Phase 2		0.5	6.1	0.1	8.5	0.0	3.5	0.1	2.2	0.1	4.2	0.1	4.4	0.1	0.5	0.0	1.5	0.0	0.3	0.0	0.1	0.0	0.2	0.0	0.0		12.30
		Phase 3		0.4	6.0	0.1	6.5	0.0	3.7	0.1	0.9	0.1	2.5	0.1	3.7	0.0	0.4	0.0	1.1	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0		10.10
7	Transformer	Phase 1	50<100	0.2	12.2	0.0	4.6	0.0	5.0	0.0	2.5	0.0	4.4	0.0	1.7	0.0	0.7	0.0	5.4	0.0	3.5	0.0	0.9	0.0	0.7	0.0	0.8		15.20
		Phase 2		0.2	11.0	0.0	3.7	0.0	5.6	0.0	2.6	0.0	3.5	0.0	1.9	0.0	0.9	0.0	5.4	0.0	3.4	0.0	0.6	0.0	0.6	0.0	0.8		14.50
		Phase 3		0.2	11.7	0.1	6.1	0.0	6.0	0.0	2.9	0.0	2.6	0.0	2.6	0.0	1.1	0.0	4.4	0.0	4.1	0.0	1.3	0.0	0.9	0.0	0.8		15.50
8	Transformer 1	Phase 1	20<50	0.5	1.2	0.1	1.0	0.0	0.5	0.0	0.7	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.5	0.1	0.3		2.40
		Phase 2		0.4	0.9	0.1	1.1	0.0	0.7	0.0	0.6	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.1	0.1	0.6	0.1	0.5		2.10
		Phase 3		0.5	1.4	0.1	0.9	0.0	0.6	0.0	0.6	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.5	0.1	0.5		1.80
	Transformer 2	Phase 1	20<50	0.5	1.1	0.1	0.6	0.0	0.6	0.0	0.6	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.1		1.40
		Phase 2		0.4	0.8	0.1	0.7	0.0	0.7	0.0	0.5	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.1		1.20
		Phase 3		0.4	1.4	0.1	0.8	0.0	0.6	0.0	0.6	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1		1.64
9	Transformer 1	Phase 1	50<100	0.3	0.5	0.1	5.1	0.0	0.6	0.1	0.4	0.1	4.9	0.1	1.4	0.2	0.1	0.0	1.6	0.0	0.2	0.0	0.0	0.0	0.4	0.0	0.1		7.25
		Phase 2		0.5	0.9	0.2	4.2	0.0	0.9	0.1	0.2	0.1	3.0	0.1	1.9	0.2	0.5	0.0	2.0	0.0	0.2	0.0	0.0	0.0	0.5	0.0	0.1		5.70
		Phase 3		0.5	0.5	0.2	4.9	0.0	0.7	0.1	0.5	0.1	3.6	0.1	3.4	0.1	0.6	0.0	1.1	0.0	0.2	0.0	0.0	0.0	0.4	0.0	0.1		6.70
	Transformer 2	Phase 1	50<100	3.9	3.1	1.1	1.0	0.1	1.8	0.3	2.7	0.3	0.6	0.2	1.4	0.1	0.6	0.1	1.4	0.1	0.9	0.1	0.1	0.0	1.2	0.0	0.6		6.20
		Phase 2		3.4	4.7	1.7	1.5	0.1	2.2	0.2	3.3	0.5	0.6	0.3	1.8	0.1	0.5	0.2	1.3	0.1	0.9	0.1	0.2	0.0	1.5	0.0	0.7		7.60
		Phase 3		3.6	5.3	1.7	2.5	0.3	2.0	0.3	2.7	0.5	0.5	0.3	2.1	0.1	0.4	0.2	1.0	0.1	1.8	0.0	0.2	0.0	1.1	0.0	1.0		8.10
10	Transformer	Phase 1	100<1000	1.7	7.6	0.1	2.9	0.0	1.5	0.0	1.6	0.0	0.9	0.0	0.3	0.0	0.4	0.0	0.2	0.0	0.1	0.0	0.3	0.0	0.1	0.0	0.1		8.40
		Phase 2		2.1	7.5	0.2	4.8	0.0	2.9	0.0	2.4	0.0	1.5	0.0	0.1	0.0	0.7	0.0	0.4	0.0	0.1	0.0	0.4	0.0	0.2	0.0	0.0		9.70
		Phase 3		1.8	12.0	0.1	7.0	0.0	4.6	0.1	3.1	0.0	1.2	0.0	0.9	0.0	0.9	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.3	0.0	0.2		14.80
11	Transformer	Phase 1	50<100	0.2	3.8	0.1	1.8	0.0	1.0	0.0	0.5	0.0	0.8	0.0	0.6	0.0	0.0	0.0	0.5	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.1		4.00
		Phase 2		0.1	3.7	0.1	1.2	0.0	0.4	0.1	0.6	0.1	0.4	0.0	0.6	0.1	0.1	0.0	0.4	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.1		3.90
		Phase 3		0.2	3.4	0.1	1.8	0.1	0.9	0.0	0.8	0.0	0.5	0.0	0.6	0.0	0.3	0.0	0.5	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.1		3.80
12	Transformer 1	Phase 1	20<50	0.3	3.6	0.3	**31.7**	0.5	13.7	0.2	1.0	0.1	2.3	0.0	0.6	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.4	0.0	0.2		**32.66**
		Phase 2		0.4	1.3	0.4	**30.9**	0.4	**15.6**	0.2	0.9	0.1	2.2	0.0	0.6	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.4	0.0	0.2		**32.10**
		Phase 3		0.3	2.9	0.3	**30.1**	0.5	**18.9**	0.3	0.5	0.1	1.6	0.0	0.6	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.4	0.0	0.3		**32.00**
	Transformer 2	Phase 1	20<50	0.3	5.1	0.1	7.4	0.1	4.9	0.1	1.4	0.1	2.0	0.0	0.4	0.0	0.0	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.1		10.20
		Phase 2		0.2	5.0	0.1	8.2	0.1	4.9	0.1	1.0	0.1	2.4	0.0	0.6	0.0	0.0	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.1		10.70
		Phase 3		0.2	2.6	0.1	8.5	0.2	4.8	0.1	1.5	0.1	1.6	0.0	0.5	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.2		10.00

Harmonic values marked in red color in above table were further investigated to check whether they have actually exceeded the demand distortion limits specified in the IEEE 519-2014 standard. The following table depicts the facilities having exceeded limits (in red).

Demand Distortion (as a % of I_L)								
Facility No. 05								
Transformer 1	**h5**	**h7**	**h11**	**h13**	**h17**	**h19**	**h23**	**TDD**
Phase 1	20.3	17.4	15.4	14.3	3.1	2.2	0.4	33.2
Phase 2	21.6	18.1	16.7	13.6	3.7	2.1	0.6	34.3
Phase 3	20.2	16.9	15.7	12.3	3.2	2.0	0.5	32.4
Transformer 2	**h5**	**h7**	**h11**	**h13**	**h17**	**h19**	**h23**	**TDD**
Phase 1	26.7	18.3	18.7	19.0	4.6	6.3	1.7	41.3
Phase 2	27.4	17.7	20.2	20.7	3.9	7.0	2.7	43.4
Phase 3	25.1	16.2	16.8	15.0	3.0	4.8	2.3	37.5
IEEE 519™ - 2014 Limits	**14**	**14**	**7**	**7**	**5**	**5**	**2**	**16**
Facility No.11								
Transformer 1	**h5**	**h7**	**h11**	**h13**	**h17**	**h19**	**h23**	**TDD**
Phase 1	29.8	12.9	2.19	0.56	0.39	0.4	0.41	30.7
Phase 2	29.3	14.8	2.09	0.56	0.38	0.35	0.39	30.4
Phase 3	26.4	16.6	1.44	0.52	0.39	0.38	0.38	28.1

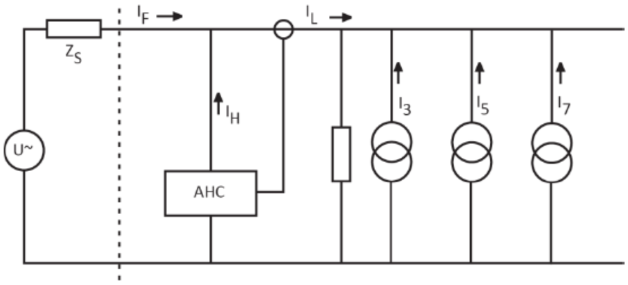
It can be seen that for the facility No. 05 the demand distortion mainly has caused by 5th, 7th, 11th and 13th harmonics. Following figure illustrates the harmonic profile.



In facility no.05, they have employed Air conditioning systems with variable refrigerant volume (VRV) technology. VRV Air-Conditioning Systems, mainly use variable speed drive technology. More harmonic current is caused by variable refrigerant volume (VRV) air-conditioning system than traditional air-cooled chiller unit and water-cooled chiller unit. There is a high probability that these odd harmonics are originated by 6-pulse and 12-pulse Ac to DC rectifies.

5 Common Methods to Mitigate Harmonics

Active filters and conditioners: The active filter measures wave shape of nonlinear load current waveform, which then fed to the controller to generate the corresponding compensation current, which is injected into the load in 180 degrees out of phase to compensate for the harmonic current. Following figure illustrates the operation of an active filter.

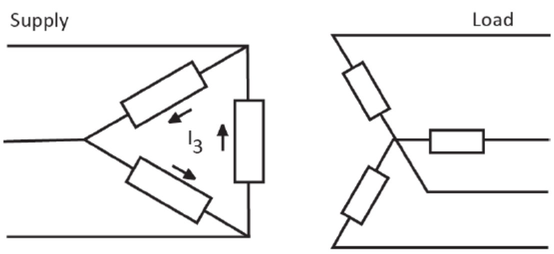


Phase Shifting of Harmonics : This is done through separating the electrical supply for harmonic generating loads to several phase shifted outputs. The amount of shift has to be selected according to the order of harmonic to be eliminated. So internally the relevant current harmonic will be shifted 180 degrees and cancel out.

- 60° is required between two three-phase outputs to cancel the 3rd harmonic currents
- 30° is required between two three-phase outputs to cancel the 5th and 7th harmonic currents
- 15° is required between two three-phase outputs to cancel the 11th and 13th harmonic currents

Reactors : Use of reactor is a simple and cost effective method to reduce the harmonics produced by nonlinear loads and is a better solution for harmonic reduction than an isolation transformer. Reactors or inductors are usually applied to individual loads such as variable speed drives .

Isolation Transformers : Balance triple-N currents in the form of 3rd , 9th, etc harmonics are circulate in the delta windings of transformers. It is beneficial to systems designers because it isolates triple-N harmonics from the supply. Following figure illustrates the circulation of 3rd harmonic current in the Delta winding.



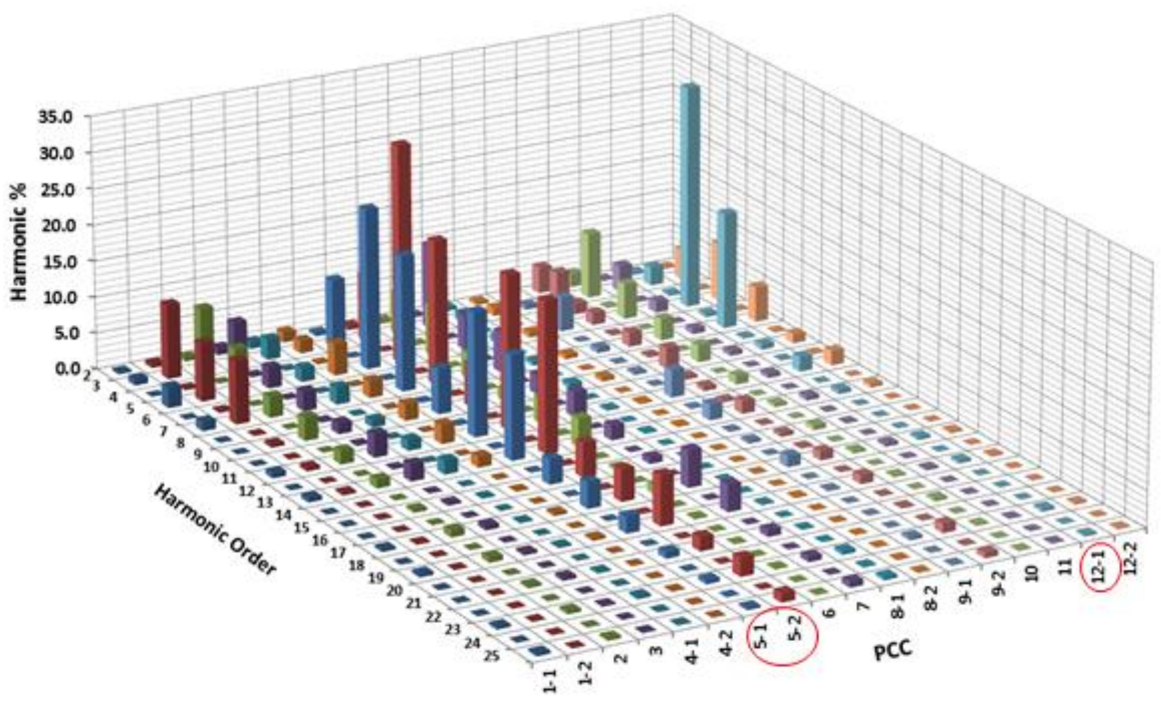
6 Conclusion and Recommendations

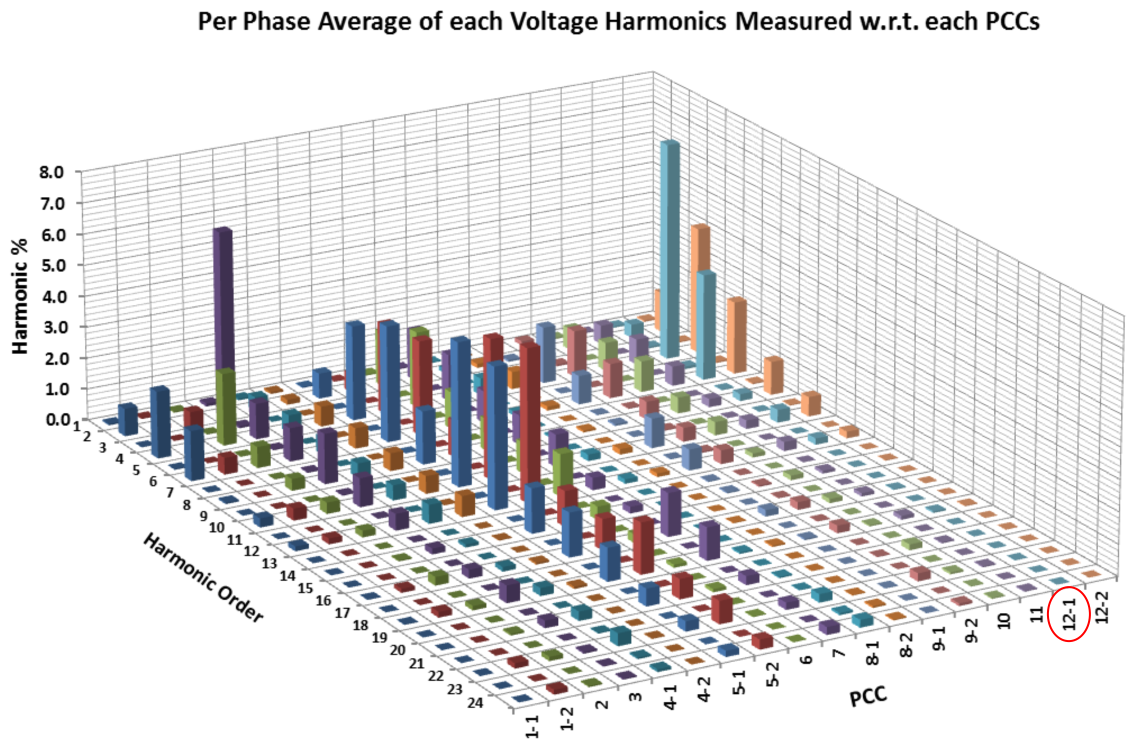
Majority of electrical loads which are connected to commercial installations are now non-linear. Loads have become non-linear since those are employed power electronic systems in order to improve the overall efficiency. Hence there is a tendency towards harmonic pollution in modern commercial installations unless there are migratory measures.

In this activity PUCSL has conducted harmonic measurements in twelve commercial installations These 12 facilities have granted exemptions for electricity distributions, by PUCSL in accordance with Sri Lanka Electricity Act No.20 2009. Except for 2 cases (circled Red in the following figures) other facilities has not exceeded the harmonic limits as specified in IEEE 519-2014 standard. Therefore consumers supplied by aforementioned exempted parties are not burdened with excessive harmonic currents and voltages presence at their respective points of common coupling.

As illustrated in the following figure, in this activity it has been found that two facilities have exceeded the prescribed limits for 5^{th},7^{th},11^{th} and 13^{th} harmonic components. Considering the general harmonic characteristics (harmonic signatures) of types of loads and power electronic control systems used in commercial installations, it can be deduced that AC to DC converting power electronics systems used to power DC motors in lifts and variable refrigerant flow – HVAC systems have caused the aforementioned harmonic distortions.

Per Phase Average of each Current Harmonics Measured w.r.t. each PCCs





Hence it is recommended to inform the respective facility managers in all twelve facilities where the measurements were taken, about the prevailing situation and inform them to use the results from this activity as a starting point for planning precautionary measures in order to improve the power quality at the respective points of common coupling. Further it is recommended to publish this this report in PUCSL website.

Recommended Regulatory Tool

Recommend preparing a guideline as a regulatory tool, covering commercial facilities where several consumers are supplied by a common electricity supply (such as shopping complexes and office complexes), to make such commercial facilities to comply with harmonic limits referred by international standards.

7 References

IEEE Recommended Practice and Requirement s for Harmonic Control in Electric Power System, IEEE Standard 519-2014

Application of IEEE Std 519- 1992 Harmonic Limits (Presentation) by Thomas Blooming, P.E., Daniel J. Carnovale, P.E., IEEE IAS Atlanta Section, September 17, 2007, IEEE IAS 52nd Pulp & Paper Appleton, Wisconsin June 19, 2006

Harmonics in power systems (White paper) Causes, effects and control Prepared by: Nikunj Shah, Design Engineering, Low-Voltage Drives Siemens Industry.

Application Note Harmonics: Causes And Effects, by David Chapman November 2011, European Copper Institute Publication No Cu0119, Available from www.leonardo-energy.org/node/1283

Application Note : Nuisance Tripping Of Circuit Breakers (True Rms Measurements) by David Chapman
March 2014, European Copper Institute Publication No Cu0110, Available From www.leonardo-energy.org

Harmonic Level Measurements and Analysis at Higher Education Buildings by Theofilos A. Papadopoulos, Georgios C. Christoforidis, Konstantinos Ch. Chatzisavvas and Grigoris K. Papagiannis T, 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion MEDPOWER 2012

Harmonic Analysis and Comparison, MCE Technical Publication, Motion Control Engineering, Incorporated Revised March 1999.