Analysis of Power Quality Disturbances in a Multi Utility System

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Abstract— Electrical power systems are subjected to different types of power quality disturbances. Investigation and monitoring of power quality are necessary to maintain accurate operation of the power system and sensitive equipment. Assessment of power quality requires the identification of any anomalous behavior on a power system, which adversely affects the normal operation of electrical or electronic equipment. A power quality assessment involves gathering data resources, analyzing the data (with reference to power quality standards) then, if problems exist, recommendation of mitigation techniques must be considered. Accordingly field power quality data is collected by power quality recorder and analyzed with reference to power quality standards to identify the power quality issue to suggest the favorable mitigation. In the paper, the factorial data related to power quality from various industries was collected and analyzed for the assessment of power quality issues. Accordingly, the data was collected from various Industries and power quality problems caused by various non linear devices were analyzed and mitigation techniques suggested.

Index Terms— Power quality analysis; mitigation techniques; power quality issues; power quality standards; capacitor bank; Variable frequency drives; Battery charger; Uninterrupted power supply.

1 INTRODUCTION

Power quality is defined as the ability to supply a clean and stable power supply that will always be available and has noise free pure sinusoidal wave shape and it is always within a voltage and frequency tolerance. The assessment of power quality has become very important nowadays with the emerging of sophisticated electronics and the widespread use of high-tech devices. These devices are not only sensitive to the effects of power quality but can also give a negative impact on the operation of the device. Poor power quality can also result in less productivity, lost or corrupted data, damaged equipment and poor efficiency. In case of momentary interruption in a process line in a factory it can result in breakdown of costly equipment and facility shutdown. It is this vulnerability of modern technology that has brought an increased awareness of power quality assessment thus it is very important to investigate these problems and their possible solutions.

1.1 Power Quality Issues:

There are a lot of power quality related problems that can result in malfunctioning of equipment and damaging sensitive equipments. The power quality problems are voltage sag, voltage swell, voltage fluctuations, voltage dips, voltage unbalance, flicker, harmonic distortion, frequency variations, long interruptions, short interruptions, electrical noise, under voltages, blackouts and brownouts.

A. Voltage Sag: Voltage sag means that the rms voltage is reduced for a very short duration. The rms voltage decreases between the 10 to 90 percent of the nominal voltage for a one half cycle to one minute. The major cause of voltage dips are fault in the system, starting of large loads, excessive network loading, loss of generation, incorrectly set transformer taps and voltage regulator malfunctions, causes under voltage which indirectly lead to overloading problems as equipment takes an increased current to maintain power output. Under voltages can create overheating in motors and can lead to the failure of non linear loads such as computer power supplies.

B. Voltage Swell: Voltage swell is the increase in the rms voltage level to 110% to 180% of the nominal rate and is characterized by the rms magnitude and also duration level. Voltage swell is normally associated with system fault conditions and when the load is suddenly thrown off raising the voltage at point of common coupling (PCC).

C. Voltage Fluctuations: Voltage fluctuations are the oscillated voltage value and modulated amplitude signal with particular frequency for example 0 to 30Hz. The main causes of voltage fluctuations are arc furnaces, often start and stop of electric motors and when the load is oscillating. The consequences of voltage fluctuation are flickering of lighting which gives an impression of unstable visual perception.

D. Voltage Unbalance: Voltage unbalance is the variation in three phase voltages, three phase magnitudes and also phase angle differences as they are not equal. The consequence of voltage unbalance existence of the negative sequence is harmful to all three phase loads and resistance loads.

E. Frequency Variations: Frequency variation involves the change in frequency from the nominal utility frequency 50Hz. The consequences are data loss problems, equipment failure in sensitive equipment or even complete shut down due to problems caused in generators.

F. Harmonics: Harmonics is defined as the multiple integer of the fundamental frequency. In a non linear load the current and voltage drawn is not perfectly sinusoidal. It's not giving perfectly sinusoidal waveform but contains harmonics. Harmonics causes problems such as insulating materials in motors, degrading of the conductors, transformers faces a lot of problems. Once the level of harmonics increases it will affect the loads associated with other equipment. The problems created like equipment failure, equipment heating, create an electromagnetic interference between the communication circuits.

G. Flickers: Repeatedly cause supply voltage variations and also will maintain it randomly. It is caused by arc furnaces, welding equipment and shredders.

H. Power Factor Variations: Power factor is defined as the ratio of real power to apparent power and is very important term in the electrical power system. In case of non linear loads, the apparent power is greater than the real power and thus gives low power factor. Poor power factor has various consequences such as increase the load current, larger KVA rating of the equipment, greater conductor size, larger copper loss, poor efficiency and poor voltage regulation. In case of high power factor, the useful power is transferred to the electrical system.

1.2 Solution to Power Quality Problems:

Many types of power enhancement devices has been developed to improve the power quality and also to protect the equipment. Few of them are transient voltage surge suppressors, types of filters such as noise filters, harmonic filters, voltage regulators, isolation transformers, dynamic voltage restorer, UPS, static VAr compensators, Unified Power Quality Conditioner (UPQC).

A. **Transient Voltage Surge Suppressors (TVSS)**: TVSS gives the simplest and more expensive way to condition the power. It is used as an interface between power source and also between different types of loads such that the transient voltage is diminished or clamped through the TVSS before this voltage reaches the load.

B. **Noise Filters**: Noise filters can be used to remove the unwanted voltage signals and current signals in the sensitive equipment. It can be carried out by using combination of capacitors and inductors to create a low impedance path to the fundamental frequency and also a high impedance path to the higher frequencies.

C. **Harmonic Filters**: Harmonic filters can be used to reduce the unwanted or undesirable harmonics. These are of two types mainly known as passive filters and active filters. Passive filters are the combination of resistors, inductors, capacitors whereas active filter comprises of amplifier along with passive elements.

D. **Isolation Transformers:** Isolation transformer is used to separate the sensitive load from the electrical system. The main structure of isolation transformer shield is grounded and will be made up of non magnetic foil and it is located between the primary and secondary. If any transient or noise is coming from the main sources it cannot pass through the load instead it will first go through the capacitance between the primary and pass through the ground. Isolation transformers effectively filter the noise.

E. **Voltage Regulators**: Voltage regulators are used to maintain the output voltage. There are three types of voltage regulators such as tap changers, constant voltage transformers and buck boost. Tap changers are used to adjust the input voltage automatically varying taps on the transformer. The advantages of tap changers are high efficiency, having high overload current capability, isolate the noise and disadvantage is the noise created when the tap changes. Constant voltage transformer is to maintain nearly constant output voltage during large input in size. Buck boost increases or decreases the magnitude of voltage to match with the output. The advantages of Buck boost are high efficiency, withstand high inrush currents.

F. **Uninterrupted Power Supply (UPS):** UPS is used to provide the protection and continuously supplies power during any power disturbance or power interruptions.

G. **Dynamic Voltage Restorer (DVR)**: It is connected in series with the load, and is similar to the voltage source. The DVR maintains the output voltage constant by using the stored energy to inject the active and reactive power.

H. **Static VAR Compensators**: Static VAR compensators are used to regulate voltage fluctuations by using a combination of capacitors, reactance and solid state switches.

I. **Unified Power Quality Conditioner (UPQC)**: UPQC is used to compensate the supply voltage and current and is related to the power quality issues in the power distribution systems.

1.3 Power Quality Standards in India:

In India IE rules 1956 defines the standard for voltage and frequency at clause as follows:

"54. Declared voltage of supply to consumer: Except with the written consent of the consumer or with the previous sanction of the State Government, a supplier shall not permit the voltage at the point of commencement of supply as defined under rule 58 to vary from the declared voltage:

(i) In the case of low or medium voltage, by more than 6 per cent, or;

(ii) In the case of high voltage, by more than 6 per cent on the higher side or by more than 9 percent on the lower side, or;

(iii) In the case of extra-high voltage, by more than 10 per cent on the higher side or by more than 12.5 per cent on the lower side.

55. Declared frequency of supply to consumer: Except with the written consent of the consumer or with the previous sanction of the state government, a supplier shall not permit the frequency of an alternating current supply to vary from the declared frequency by more than 3 percent."

The above standards have been observed by the utilities, mostly public and vertically integrated, in India since past few decades but with the introduction of the Electricity Act 2003 respective State Electricity Regulatory Commissions (SERC) are mandated to prescribe both 'Conditions of Supply' and 'Standards of Performance' for distribution utilities. Many of the state regulators have already issued such electricity supply code and standard of performance regulations which puts on the utility to observe not only the above qualities of supply but also various reliability indices like SAIDI, SAIFI, CAIDI, CAIFI etc in line with IEEE guidelines. Few progressive States also has prescribed standards for Harmonic distortion limits in line with IEEE 519 but halted from implementation due to absence of quality metering at cost effective point. Similarly at the transmission level or Grid level the central regulator (CERC) has prescribed various voltage distortion limits (see table 1 below), in line with IEEE 519 -1992 standard, under India Electricity Grid Code .

Table 1 IEEE Standard 519-1992 Harmonic Voltage Limits
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69kV and below	3.0	5.0
69.001kV through 161kV	1.5	2.5
161.001kV and above	1.0	1.5

The Central Electricity Authority (CEA) of India has prescribed

Central Grid Code which specifies the steady state voltage variation limits, maximum permissible values of voltage unbalance and harmonic standards as given below:

Table 2 Voltage Variation Limits and Harmonic Standards as in Central Grid Code

System Voltage (Nominal)-kV rms	Voltage Variation (%)	Voltage Unbalance (%)	Total Harmonic Distortion (%)	Individual Harmonics of any particular frequency (%)
765	+/-3%	1.5	1.5	1.0
400	+/- 3%	1.5	2.0	1.5
220	+/- 5%	2.0	2.5	2.0
132 and below	+/- 10%	3.0	3.0	2.0

The current distortion limits for general distribution systems are observed in line with IEEE standards as given in Table:

Table 3 Current Distortion Limits for General Distribution Systems (120V through 69kV)

Maximum Harmonic Current Distortion in Percent of IL						
Individual Harmonic Order (Odd Harmonics)						
Isc/IL	<11	11≤h≤17	17≤h≤23	23≤h≤35	35≤h	TDD
<20*	4	2	1.5	0.6	0.3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20
Even harmonics are limited to 25% of the odd harmonic 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.

TDD= Total demand distortion (RSS), harmonic current distortion in% of maximum demand load current (15 or 30min demand).

PCC= Point of common coupling.

1.4 Fluke Power Quality Analyzer:

Fluke Model 435-II 3-Phase Energy and Power Quality Analyzer was used for analyzing power quality problems at the visited places. These Analyzers help locate, predict, prevent and troubleshoot problems in power distribution systems.

Fig 1 Fluke Power Quality Analyzer

The Analyzer uses five different screen types to present measuring results in the most effective way.

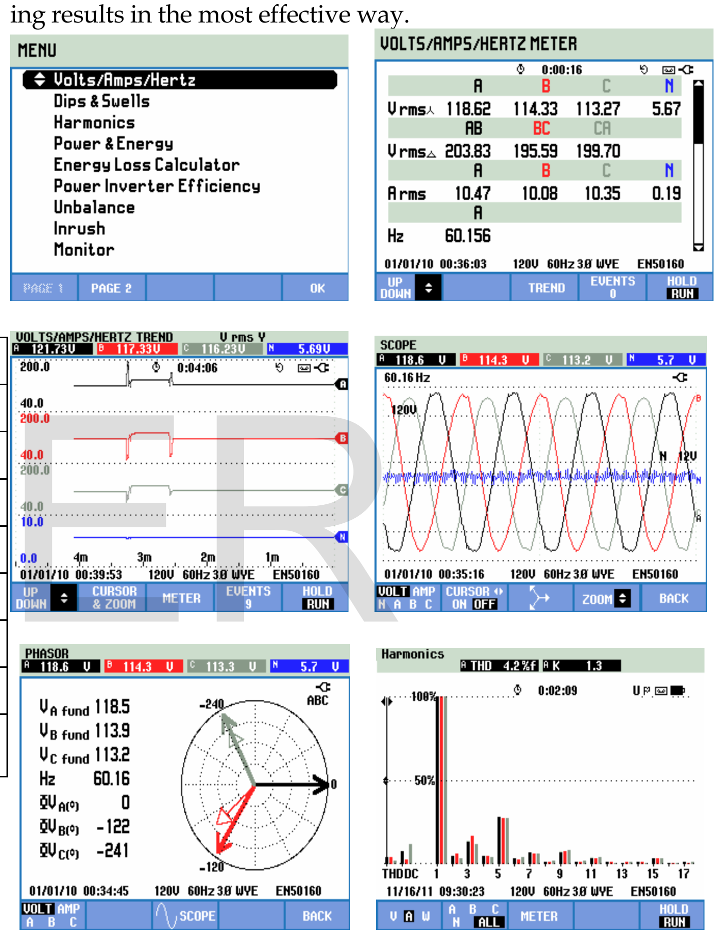

Fig 2 Survey of Display Types

The Meter screen gives an overview of voltages and currents in all phases. The rms voltages are shown neutral-to-line and line-to-line. Also frequency and Crest Factors are shown. The Crest Factor CF indicates the amount of distortion: a CF of 1.41 means no distortion and higher than 1.8 means high distortion.

During a dip the voltage drops; during a swell the voltage rises. In three phase systems a dip begins when the voltage on one or more phases drops below the dip threshold and ends when all phases are equal to or above the dip threshold plus hysteresis. The trigger conditions for dips and swells are threshold and hysteresis. Rapid voltage changes are quick transitions of the rms voltage between two steady-states. Rapid voltage changes are captured based on steady voltage tolerance, steady time, minimum step detected, and minimum rate (%/s).

When voltage changes cross the dip or swell thresholds, it is considered a dip or swell and not a rapid voltage change.

Harmonics measures and records harmonics and interharmonics up to the 50th harmonics. Related data such as DC components, THD (Total Harmonic Distortion), and K-factor are measured. Harmonics are periodic distortions of voltage, current, or power sine waves. A waveform can be considered as a combination of various sinewaves with different frequencies and magnitudes. The contribution of each of these components to the full signal is measured. The Bar Graph display shows the percentage contribution of each of the components related to the full signal. A signal without distortion should show a 1st harmonic (= the fundamental) at 100 % while the others are at zero: in practice this will not occur because there always is a certain amount of distortion resulting in higher harmonics. Unbalance displays phase relations between voltages and currents.

2 POWER QUALITY ANALYSIS CASE STUDIES

2.1 Industry I:

In Industry I it is was observed that there is a 15Kvar capacitor bank always fixed in the system and 5 banks of 25 kVAR each and 1 bank of 10 kVAR connected to Automatic power factor corrector which maintains the power factor unity by accordingly switching the capacitor banks. The power quality analyzer was connected at the PCC for readings.

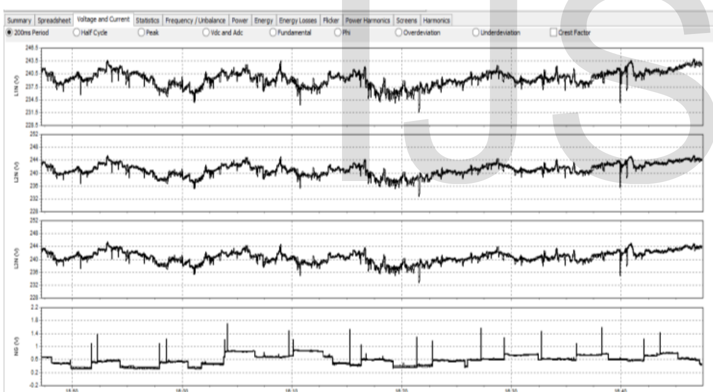

Fig 3 Current waveform

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. The distortion power factor and power factor was maintained unity at all times. The unbalance power was also less than the specified limits. The harmonics also were below the specified limits. Current spikes while switching 'ON' capacitor banks and unbalance current was noted, an unwanted high inrush current and transient overvoltage may appear during the energizing process. These transients lower the lifetime of the capacitor banks as well as can damage the electromagnetic switches such as circuit breakers in addition to the customers electrical apparatus might be damaged.

A pre insertion inductor can reduce the capacitor harmonic currents noticeably. A shunt inductor is provided across the circuit breaker as a bypass, which is closed before the capacitor bank is energized. It is arranged such that the moveable part of the circuit breaker makes contact with the shunt resistor first before contacting the fixed contact energizing the capacitor bank. The inductor provides damping and reduces the transient energy. Selection of 2-3% to that of capacitor bank ratings is recommended for the sizing of the pre insertion inductor.

2.2 Industry II:

In Industry II readings were taken from separate sections/ non linear equipments like Variable frequency Drives, Battery Charger, Uninterrupted Power Supply and Electrical Workshop which consisted of Crane, Welding machines and Lathe machines.

A. Variable Frequency Drive:

The primary purpose of a VFD is precise speed control so that motor speeds can be ramped up and ramped down and the connected load can be maintained at the required speeds, which only utilizes the energy required. Cage Mill 75kW, 1500rpm was the equipment connected to the VFD with rating of 110kW and make Schneider Altivar 71.

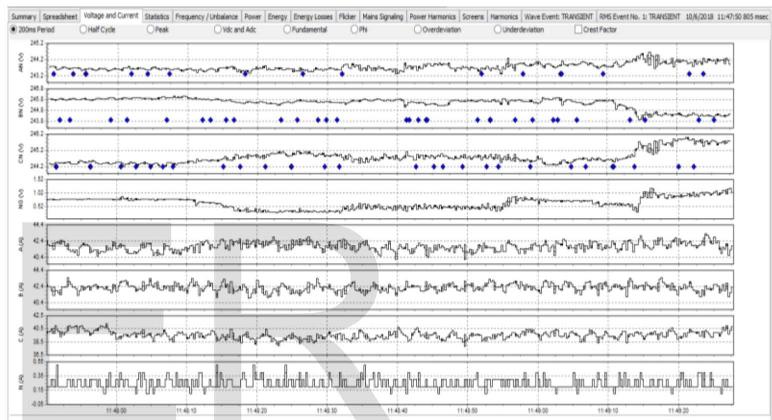

Fig 4 Voltage and Current waveforms

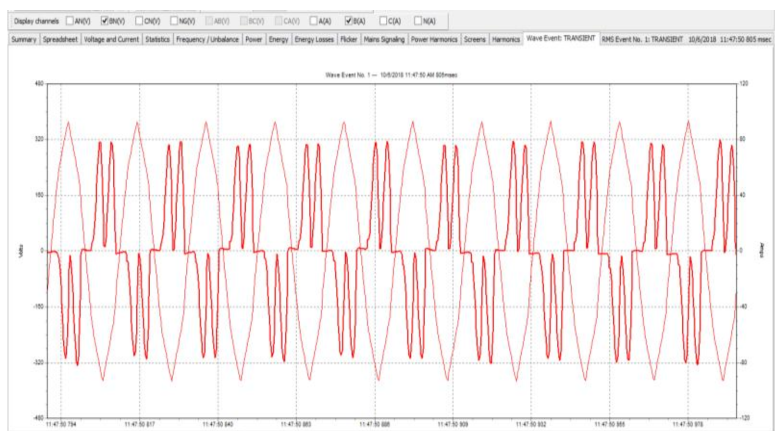

Fig 5 Transient Wave

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. The harmonics also were below the specified limits. Voltage transients were noted down.

The VFD consists of a diode rectifier which creates the transient waves as observed. Harmonic Filter can be used to make the curve sinusoidal. The suggestion is instead of the diode rectifier, the VFD should incorporate front end controlled convert-

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er or switch mode converter using IGBT so as to obtain a sinusoidal output.

B. Battery Charger:

A battery charger is a device used to put energy into a secondary cell or rechargeable battery by forcing an electric current through it. The battery charger can be used in two modes i.e. as Float charger and Float cum boost charger. Float charging is used where the battery rarely gets discharged. Float charging of a battery involves charging the battery at a reduced voltage. Whereas float cu boost charging involves a high current for a short period of time to charge the battery. It is generally if the battery has been discharged heavily. The battery charger rating is 220V/100AH for which readings were noted.

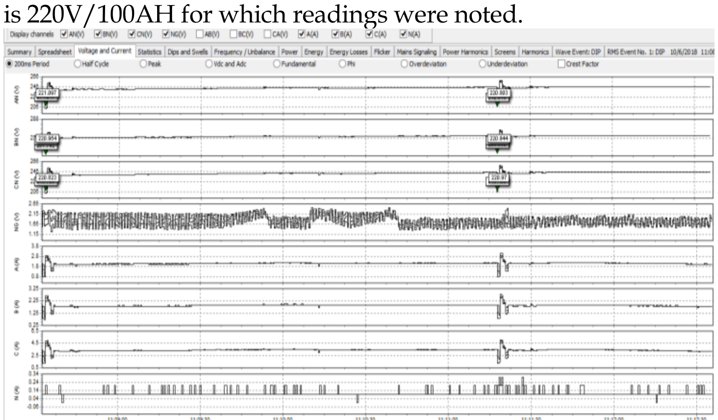

Fig 6 Voltage and Current Waveforms

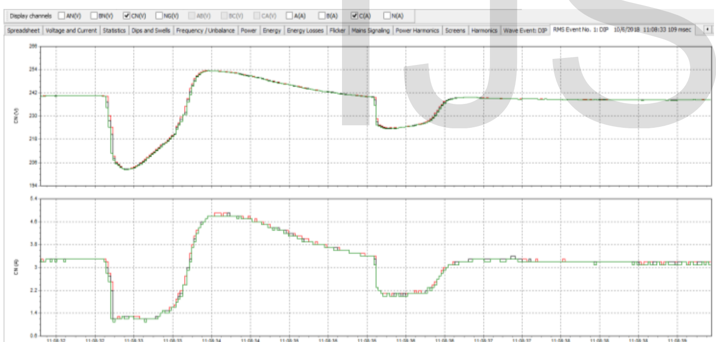

Fig 7 Voltage dip event

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. The harmonics also were below the specified limits. Voltage dips were observed. Thus constant voltage transformer was recommended for the voltage regulation and also provides a clean spike free output voltage.

C. Uninterruptible Power Supply:

UPS is an electrical apparatus that provides emergency power to a load when the input power source or mains power fails. 2x20Kva Parallel Redundancy is the rating of the UPS with an output voltage of 230V AC.

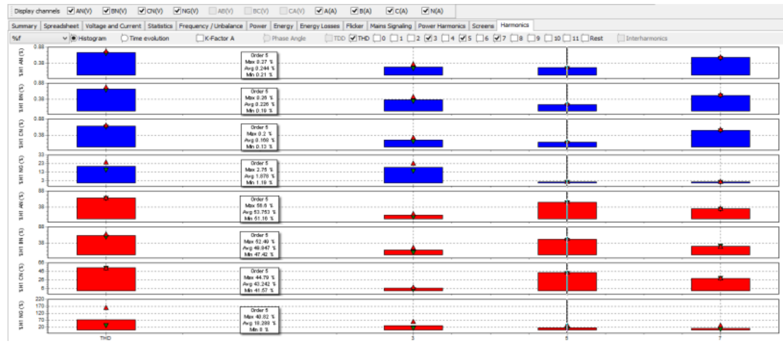

Fig 8 5th Order Harmonics

Fig 9 7th Order Harmonics

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. 5th harmonic was observed to be around 50% and 7th harmonic was around 30% to that of the fundamental. 5th and 7th harmonic filter was suggested to mitigate the observed harmonics.

D. Workshop:

The workshop comprised of Crane, welding machines and lathe machines.

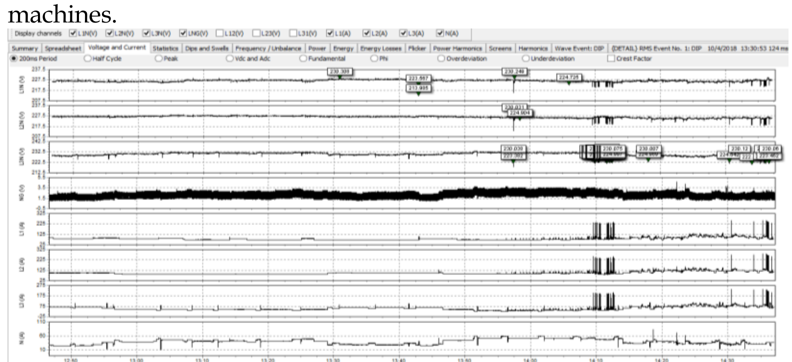

Fig 10 Voltage and Current Waveforms

Fig 11 Voltage dip event while using cranes

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. The harmonics also were below the specified limits. Voltage dips and current spikes were observed. Dynamic voltage restorer is recommended which is used to inject 3 phase voltage in series and in synchronism with the distribution feeder voltage in order to compensate for voltage sag.

2.3 Institutions:

A. Department 1:

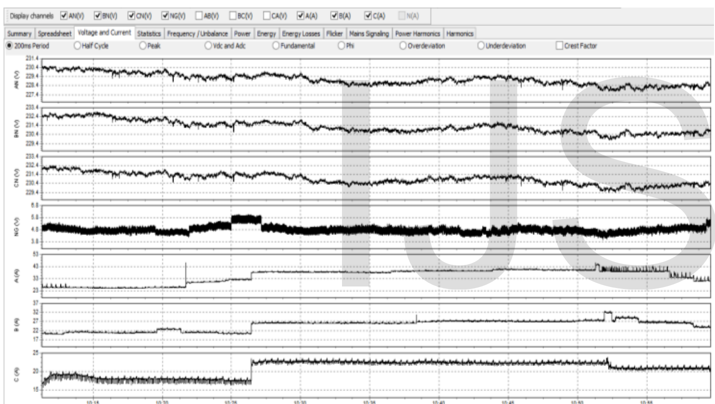

Fig 12 Voltage and Current waveforms

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. The distortion power factor and power factor was maintained unity at all times. The unbalance power was also less than the specified limits. The harmonics also were below the specified limits. Neutral current was observed which lead to voltage drop but was within the specified limits of 25A. Thus no mitigation technique was suggested as everything was within the specified limit.

B. Department 2:

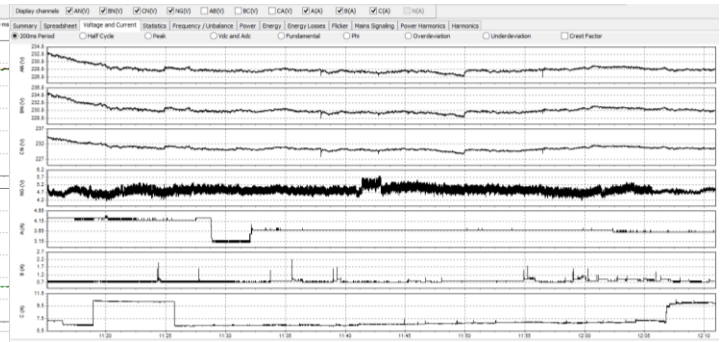

Fig 13 Voltage and Current waveforms

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. The distortion power factor and power factor was maintained unity at all times. The unbalance power was also less than the specified limits. The harmonics also were below the specified limits. Inrush currents were observed when starting a motor which lead to voltage sags. Use of soft starters is recommended for a controlled startup, improved efficiency as well as controlled motor acceleration.

2.4 Research Centre:

In the Research Centre the readings were taken into 3 sections i.e. Bus 1, Bus2 and Bus3.

A. Bus 1:

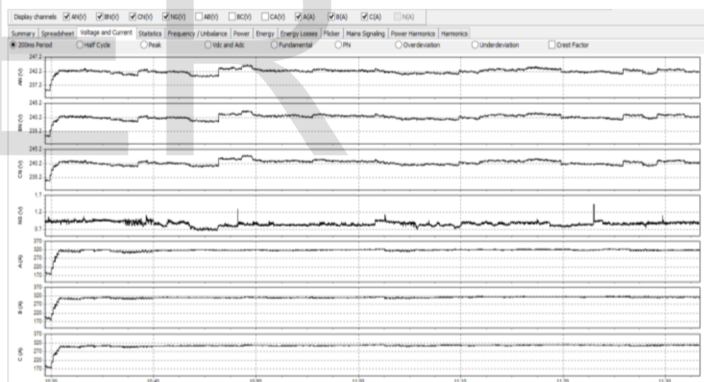

Fig 14 Voltage and Current waveforms

Fig 15 5th Order Harmonics

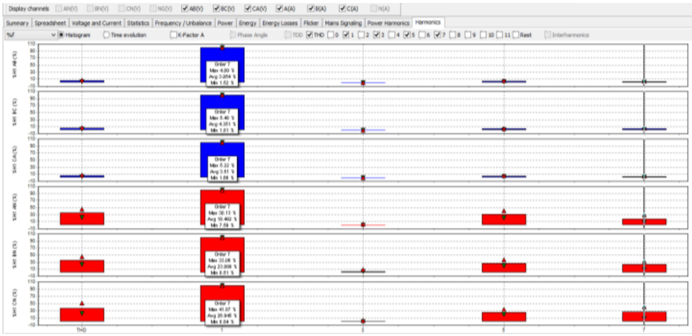

Fig 16 7th Order Harmonics

B. Bus 2:

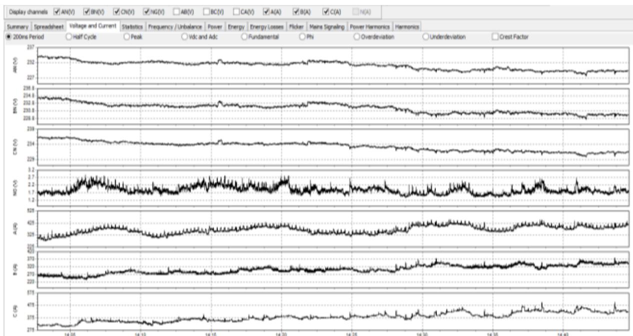

Fig 17 Voltage and Current waveforms

C. Bus 3:

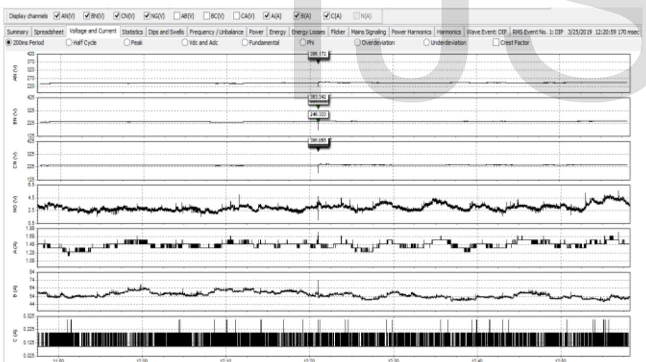

Fig 18 Voltage and Current waveforms

It was observed that the parameters like voltage, current, frequency, total harmonic distortion was within the specified limits. In bus 1, 5th harmonic was observed to be around 30% and 7th harmonic was around 25% to that of the fundamental. 5th and 7th harmonic filter was suggested to mitigate the observed harmonics.

3 CONCLUSION

The power quality of any industry should be within the specified limits for higher efficiency and also to maintain the utility power supply by not injecting in harmonics and affecting other consumers using the same feeder power. This review paper has presented different power quality problems in various industries caused by various non linear loads, which could be summarized and concluded as:

1. Capacitor bank while switching 'ON' and 'OFF' gives rise to current spikes which can be mitigated by using a pre insertion inductor.
2. Electrical machines department gave rise to inrush currents when starting motors which led to voltage drop and can be mitigated by using soft starter.
3. Variable frequency drive gave rise to transients and can be mitigated by upgrading from diode rectifier to a controlled rectifier.
4. Battery charger gave rise to voltage dips which can be mitigated by the use of a constant voltage transformer.
5. UPS gave rise to 5th and 7th harmonic filter which can be mitigated by using harmonic filter.
6. Voltage dips were observed in the Workshop which can be mitigated by using Dynamic Voltage Restorer**.**

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