ELECTRIC POWER QUALITY RECOGNITION FOR DISTRIBUTION FEEDERS: A REAL TIME STUDY

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Abstract: *Power Quality (PQ) issues are bringing more challenges to the large scale and medium scale industries.The usage of power electronic converters causes vulnerable PQ disturbances at Point of Common Coupling (PCC). When running theheavy equipment, the disturbances (harmonics, RMS variations, and switching transients) level is very high as well as the power factor (PF) is poor. Due to this poor PF, reactive power consumption in load increases accordingly total power increases. An electronic device such as LED lights, fluorescent lamps, computers, copy machines, and laser printers also disturbs the supply voltage. We are very well known that every PQ problem plays a considerable role of the economic aspects. Many researchers investigated PQ audit over a three decades. However these studies and its analysis are in simulation level. Hence, the PQ analyzer based study is required to find out the PQ issues at distribution feeders. It will be a valuable guide for researchers in the domain of power quality mitigation for further improvement in terms of reducing the THD as well as reduce the effect of sags and swells. Therefore, in this paper, the measurement has been carried out at different intervals during load condition and analyzed all types of disturbances. Also, this paper gives a brief real time PQ measurement using PQ analyzer HIOKI PW3198 at distribution feeders and it gives an idea to the researcher to optimize problem-related to PQ with respect to the high rated and low rated electric machinery of different feeders at PCC level. This study further extended to analyze the grid disturbances and forward to looking optimization methods for each individual PQ disturbance.*

Key words:*power quality, monitoring, disturbances, and results*

1. Introduction

Power quality becomes an important issue in both utilities and consumers due to increase of power electronic equipment in the industry as well as domestic applications. This non linear load acts as harmonic source results in considerable voltage and current harmonics in the electric distribution systems. The power quality is affected mainly due to the current harmonics generated by non linear loads. Current harmonics induces voltage harmonics, finally leads to voltage distortion in the distribution network [1]. The steady-state distortion on voltage and current due to harmonics will affect the operation of equipment connected in the distribution system. This power quality (PQ) issues will leads to increase in power losses and affect the communication system due to electromagnetic interference in the distribution system. The PQ disturbances may result in overheating of motors, transformers, cables, continuous tripping of power factor improvement capacitor, motor winding failures and mal operation of protection devices. [2]. our human life is collaborated with electrical equipment and electronic gadgets by the increased technology at its growth. At the earlier days the PQ disturbances were not that much issue but over the past decades, the use of electronics and the converter based drive system and variable frequency drives which are controlled by semiconductor switches are dominantly increased. So, the non-linear characteristics of this kind of load creating enormous PQ issues to the consumer. The major PQ issues cover sudden and short duration variations such as harmonics, three phase unbalance, flicker, voltage sags, short interruptions, oscillatory and impulsive transients as well as steady-state deviations [3]. The subject of PQ has been changed a lot due to raise of size and capacity of the power system, which become intricate and heading towards reduced reliability. Voltage interruptions and voltage sags are most commonly originated by faults in the power system network, which causes tripping of sensitive loads [4]. These disturbances have direct economic impact on industrial consumers. To avoid the economic losses and to protect the plant, industrial consumers install mitigation equipment. Some loads (like converter load) draws commutated current that disturbs the source. The diode bridge rectifiers are a major source of producing harmonics into the power system network and the concerns are varying from electrical components overheating and interference in communication lines [5]. Many industrial consumers concerning about Power Quality [6].

In the current scenario, the utilization and consumption of power are going very high. Meanwhile, the significance of PQ is playing a dynamic role for an uninterruptable and effective power supply. According to central electricity authority govt. of India (CEA), the total installed capacity has reached 278733.62 MW in India as on 30th September 2015. This intends a massive number of electrical installations are being newly deployed in the power system network, which challenges the reliability and quality of power in the power system network. Unfortunately, some non-linear characteristic equipment which creates the distort voltage at the supply side and leading to poor power quality [7]. PQ determines the health of electrical power to the consumer equipment and the overall concept of PQ depends on the consumer.

Different consumers have faced distinct disturbances that are polluting the voltage waveform from its purity. PQ issues are causing due to continually increasing load which disturbs the supply [8]. PQ is a blend of current quality and voltage quality but we cannot control over the currents because current depends on the load. If we are succeeded to maintain the voltage within the tolerable limits then we get good quality of power. In brief, power quality disturbances may cause equipment malfunction, memory malfunction of sensitive loads such as a computer, programmable logic controller controls; protection and relay equipment; and erratic operation of electronic controls [9]. So, this is obligatory to do monitoring because demand goes on increasing as suggested in [10-12] and monitoring standards also available from [13]. Several techniques provide the cost effective solution and impact of poor power quality such as harmonics, voltage dips and swells [14]. This paper presents a review of the performance analysis and comparison of various PQ detection techniques, and the power circuit topological aspects of power quality improvement techniques. Based on the review of over 200 publications 46 research works are analyzed and classified into four major categories. The first category [1-16] comprises of working, performance analysis, detection and classification techniques of power quality events. Second category [17-25], describes the power quality improvement using filters. These filters are further classified into passive filters, active filters and hybrid filters. Distribution static compensator (D-SATCOM), dynamic voltage restorer (DVR), unified power quality conditioner (UPQC) are the custom power device are utilized in distribution system for the power quality improvement are presented in third category [26-38].The fourth category [39-44] comprises of disparate PQ improvement techniques such as, power electronic converters, distributed generation, feeder reconfiguration, and energy storage. Different mitigation methods and techniques are demonstrated in chapter – II, for the improvement of power quality. There is a necessity to investigate the various power quality disturbances by extracting the waveform from PQ analyzer are demonstrated in chapter -III.

2.1. Classifications and mitigation methods of PQ disturbances.

Mitigation of PQ issues is achieved by using passive filter, active filter and hybrid filters**.** Generally**, c**urrent-based compensation and voltage-based compensation schemes for nonlinear loads have been carried out for the power quality improvement in the distribution system. By adopting this schemes mitigation of voltage sags, swells, notches, harmonics, spikes, flickers, and voltage unbalance the required quality of power is ensured. The conventional passive filter provides a cost effective solution with simple design are utilized to yield an economic solution for some industries and domestic customer, where the PQ is not much concerned [15]. Connecting a passive filter in parallel with the distribution system changes the network impedance and the performance of passive filter gets affected. Higher order harmonics current flows into the filter, series and parallel resonance occurs due to the interaction of filter impedance and source impedance which amplifies the harmonic current, having the impact of overload the filter [16]. A passive filter based power quality solutions has been presented by many researchers [17-25]. A three-phase harmonic power flow method using graph theory, injection current and sparse matrix techniques for unbalanced radial distribution systems is proposed [17].The optimal design method for passive power filters (PPFs) and its components in order to obtained the desired performance [18-23]. A passive filter can able to mitigate the telephone interference issues by using zero-sequence harmonic filters as well as it can be expanded to expand to create a double-tuned filter [24].The active power filters (APF) are recent devices used to mitigate and provides the optimal solution for all PQ issues. Active filters are classified into shunt and series active filter based on the way of connection. In general active filter comprises of voltage source inverter or a current source inverter with passive elements. [19]. Inclusion of power electronic components and complex control schemes the active power filter becomes more expensive. The hybrid filters (HF) overcome the deficiency of passive filter, provides better solution for PQ improvement without compromise the cost effectiveness [20].

Distributed flexible alternating current transmission (D-FACTs) is the modern devices deployed for the power quality improvements. This D-FACTs devices comprises of power-electronics switching devices, storage and passive elements which control the distribution system parameters there by mitigating for PQ issues. Dynamic voltage restorer (DVR) is series connecting custom power devices used for retains the required magnitude of voltage values at the point of common coupling (PCC) at the network. Many researches have been carried out with respect to DVR. The major components of the DVR are voltage source inverter (VSI), filter components and digital controller. Also, the estimation of the parameters is also plays a vital role on the performance of the DVR systems. In this connection, few literatures have been reviewed [26-31]. A single-phase dynamic voltage restorer (DVR) using direct ac/ac converter which compensates voltage disturbances such as voltage sags, swells, harmonics and flickers [26]. The new DVR topology has high efficiency and the ability to improve the quality of voltage [27]. A time-varying and constant switching frequency based sliding mode control (SMC) methods for three-phase transformerless dynamic voltage restorers (TDVRs) which employ half-bridge voltage source inverter (VSI) is developed [28]. A DVR which employs a cascaded multilevel inverter with capacitors as energy sources and this configuration does not require a storage elements and series injection transformer [29]. A multilevel cascaded-type dynamic voltage restorer (MCDVR) with fault current limiting function is presented [30]. DVR control system using recursive variable and fixed data window least error squares (LES) method implemented using a simple and low cost processor [31].

Distribution static compensator (D-STATCOM) is a parallel connected device used for current compensation, minimize the current harmonics and load unbalancing in distribution network [32]. In the past decade, many topologies and control schemes were developed in distribution static compensator (DSTATCOM) for distribution systems. A D-STATCOM is implemented for control of a distributed power generating system using a proposed composite observer based control technique is employed for fundamental components extraction of distorted load currents. [33]. An D-STATCOM topology employing predictive current control algorithm tracks reference current effectively and makes source current sinusoidal and also in-phase with voltage at the point of common coupling in both steady state and transient conditions [34]. A three phase D-STATCOM using adaptive neuro fuzzy inference system least mean square (ANFIS-LMS) based control algorithm for compensation of current related power quality problems[35]. Combination of DVR and D-SATCOMhas been introduced in form of unified power quality conditioner (UPQC) has the function of both of DVR and D-SATCOM [36-38]. An optimal size of the UPQC system is developed, which determines the fundamental ratings of the shunt converter, series converter, and series transformer. A data-driven control based controller is developed using the variable phase angle control method to realize the implementation of the designed UPQC system under the different compensating conditions [38]. The tuned filters are more expensive due to addition of additional components like inductor as mentioned [25]. The implementation and control of the active filters requires an advanced digital controller like DSP [31, 33], dSPACE controller or FPGA [34, 36]. Finally, the implementation active filters results in complexity in implementation and highly expensive [31-36]. Therefore, these methods are more suitable for high performance applications. For small distribution networks with more numbers of domestic consumers, a passive filter may yield the required power quality by using a passive filter. The small distributions systems mainly supplying domestic and a portion of industry and agriculture loads, a passive filter may result in economic solution to improve power factor and mitigate the harmonic problem to a required value.

Also, the incorporating the renewable energy in the distribution systems plays the major role in contributing power in modern society, but their integration to distribution system constitutes the power quality technical issues [39]. Their main advantage of compensating increasing load demand, mitigates harmonics, provides clean environment, reduces the usage of fossil fuels and can be able to support the distribution system even in remote areas [40]. The mostly used renewable energy sources are photovoltaic, wind power and hydroelectric power. A portion of distribution system integrated with multiple distribution generators (DGs), energy storage system (ESS) and active loads forms microgrid [41].

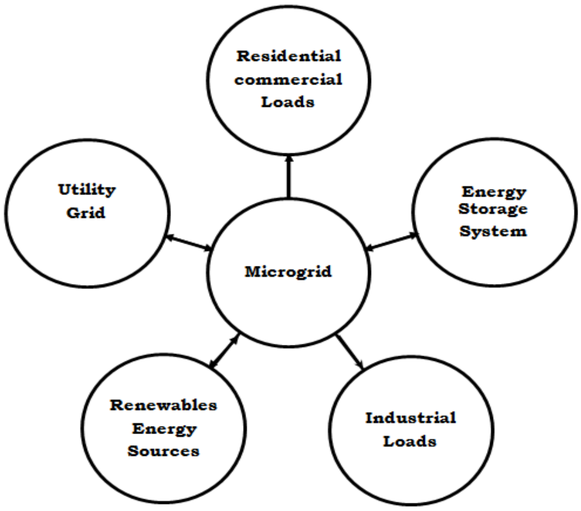

Fig. 1. Components of Microgrid

Fig 1: shows some of components of microgrid integrated with grid. The connection of microgrids in distribution networks with the power electronics techniques can improve the power quality and decreases losses thus increasing the performance enhancement and reliability of the distribution system [42]. Energy storage system and renewable energy sources with the advancement of power electronics devices, control of power flow is possible to and from the utility in the microgrid connected system [43]. The inclusion of FACTs device will provides as power flow control and voltage regulation to improve the efficiency of the network along with the protective relays and circuit breakers [44].

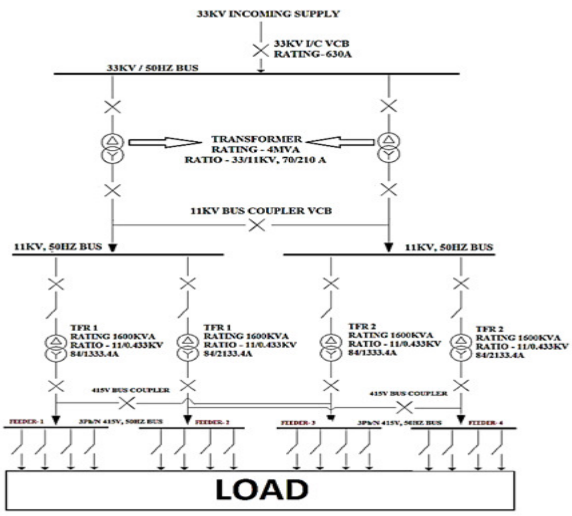

Fig. 2. Single line diagram of a distribution network

Fig 2.Representing the single line diagram of the distribution network having the ratio 33/11kV and 11/0.433kV to the load. This distribution network connected to the various feeders of the different load.In this, the complete measurement is done by HIOKI PW 3198 power quality analyzer and used software HIOKI PQA-HIVIEW PRO 9624-50 for the analysis which is very helpful and makes the process ease to find out the disturbances. Some of the disturbances play a key role in the quality of power which is frequency, harmonics, voltage sags/swells, interruption, transients, and flicker. Harmonics are caused by non-linear loads which might cause damage to the electrical devices. Many standards are available for classification of harmonic levels in the distribution system as specified by different standards such as IEC 61000-3-2, IEEE-519 and IEC 61000-4-30 [46]. These power quality standards are verified and referred while analyzing and monitoring the system.

2.2. Different Power Quality disturbances & Issues

Here the PQ monitoring and study deals with three different types of distribution feeders which are PMTC-CVD (feeder-1), SIC-PCC (feeder-2) and LDB-1A (feeder-3). These feeders are connected to the non-linear characteristics of the load which are primarily causing the different power quality problems. Fig. 2 represents feeder connections to the load and also represents the distribution structure. The disturbances are monitored and analyzed over the weeks with the help PQ analyzer. This data helps the PQ study to analyze the disturbances. These disturbances are creating some issues within the power system network. Some disturbances are playing a key role which is clearly mentioned in results and discussions. All the PQ disturbances and problems caused by those PQ disturbances are mentioned as follows.

- Frequency fluctuations: these are due to line disconnection caused by changes in supply stability or some circuit issues and these fluctuations change the speed of a motor.
- Voltage sag (Dip): Short duration under-voltages are called “Voltage Sags” or “Voltage Dips [IEC]”. Starting of large loads causes voltage dip.
- Voltage swell: turning off of heavy load in the network and heavy capacity capacitor bank switched off causes swell.
- Transient overvoltage (surge or impulse): Transients can generate either in utility and load side. Originates by switching on and off the power factor improvement capacitor or high capacity non-linear loads. They represent about 12 to 15% of all power line problems [47]. Due to this power is exceptionally damaged and losing the wiring.
- Flicker: it consists of voltage fluctuations outcome from sources such as thyristors control loads, arc welding, and blast furnace. It causes the light bulb to flicker.
- Interruption: interruptions occur from few milliseconds to 1 to 2 seconds due to opening and closing of protecting devices. If the durations of interruption are greater than 1 to 2 seconds leads to power failure in distribution system.
- Harmonics: these are originated by non-linear. It causes overheating of transformers, motors, and cables. It overloads the power factor correction capacitors and it is a source to fuse blown, relay trip and meter misoperation.
- Unbalance: improperly connected single phase loads in the three-phase network causes unbalance.
- Inrush current: when large electric equipment turned on, inrush current that flows momentarily.

Table 1.
IEEE Harmonic Standards 519-1992

	Special Applications	General system	Dedicated system
Notch depth	10%	20%	50%
THD (Voltage)	3%	5%	10%

Table 2.
IEEE Harmonic Standards 519-1992

Value	Observation Interval	Limiting Value
P_{st}	10 min	1.0
P_{lt}	2 hr	0.8

Table 3.
IEC Flicker Standards IEC 61000-2-2

Bus Voltage	Individual V_b (%)	THD V (%)
V < 69 kV	3.0	5.0
69 ≤ V < 161 kV	1.5	2.5
V ≥ 161 kV	1.0	1.5

IEEE 519-1992 provides guidelines for an allowable limit of voltage harmonic distortion on the utility system. Table. 1 shows the maximum individual harmonic component and for the total harmonic distortion (THD). Many industrial consumers are following these IEEE standards which are allowable level. The compatibility level of voltage distortion on MV and LV systems specified in IEC 61000-2-2 is 8%. These standards permit the same procedure by the customers at different locations but the current limit values vary in these cases. Table 2. Shows the notch depth and THD (Voltage) limits at different applications according to the IEEE 519-1992.

The flicker intervals and the limiting values for Pst and Plt are specified according to the IEC 61000-2-2 standard is shown in Table 3. These standards provide several guidelines to all kind of industrial consumers.

3.Problem Identifications for Different Distribution Feeders

The three feeders Feeder-1 (PMTC-CVD), Feeder-2 (SIC-PCC) and Feeder-3 (LDB-1A) having a different type of load. The Feeder-1 connected to the CVD (chemical vapor deposition) furnace which is operated and controlled by micro-processor based programmable controllers. Feeder-2 connected to the large rated equipment like induction furnaces, hot press, chillers and hanging cranes. Feeder-3 connected to the total lighting. The feeder's structure is shown in Fig. 2. The Fig.3. Shows the PQ monitoring and measurement at Feeder-1. The PQ analyzer helps ease to find all kind of disturbances.

Fig. 3. Power Quality Monitoring at Feeder-1

Fig. 4 shows the voltage and current waveforms at Feeder-1 during no-load condition. At no-load condition, the voltage waveform is perfect without any disturbance. When the load is turned on, the voltage waveform changes are shown in Fig. 5. The load is drawing distorted current. Due to this distorted current, the notch is forming in the voltage waveform is shown in Fig. 5. The load is disturbing the supply voltage by drawing the distorted current and the voltage waveform has lost its purity.

Fig. 6. Shows the harmonic bar graph at Feeder-2. The harmonic distortion shows up as the bar graph of 50 Hz frequency. Part of this noise is the cause of light flicker. According to the IEC standard of measurement of harmonic distortion (IEC-61000-4-30) should be below 5% but the THD value crossing the 5% limit. The individual harmonics second, third and fifth are crossing the individual harmonic limit 3% according to the IEEE standards [45]. These harmonics are mitigated by using the Harmonic Filters [47].

Fig. 6 shows the RMS variations in the total measurement period. The load creating large voltage fluctuations (sag and momentary interruptions), these are causing flickering is shown in Fig. 9. Due to large fluctuations, the flicker (Pst and Plt) values exceeded the IEC flicker standard. When the interruption happens the voltage goes to zero and after the interruption the load is drawing momentary inrush current is shown in Fig. 8. The voltage dips are mitigated by using static series compensator or static transfer switch [47] and the flicker is mitigated by static var compensator (SVC) or D-STATCOM [47].Fig. 10. Shows the frequency variations at Feeder-3 which is a lighting load. This load creates the large frequency variations in the supply. The oscillatory transients or momentary transients are caused by power factor correction capacitors switching. The oscillatory transient event is shown in Fig. 11.These disturbances are monitored by using the HIOKI PQA PW-3198 and the analysis has been done by HIOKI PQA-HIVIEW PRO 9624-50. For harmonic limits, IEC and IEEE use two different approaches.

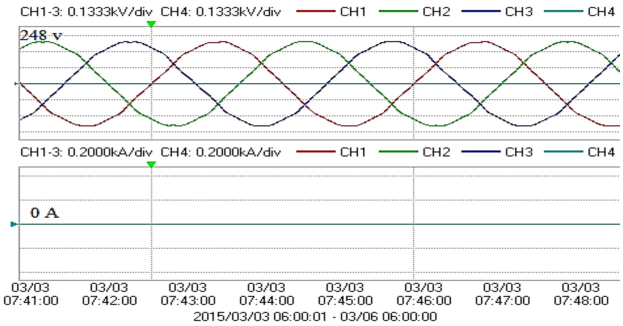

Fig. 4. Voltage waveform during no-load condition at Feeder-1 measured over 3 days period

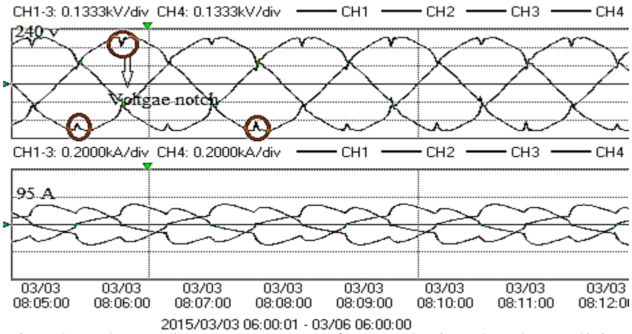

Fig. 5. voltage & current waveforms during load condition at Feeder-1 measured over 3 days period

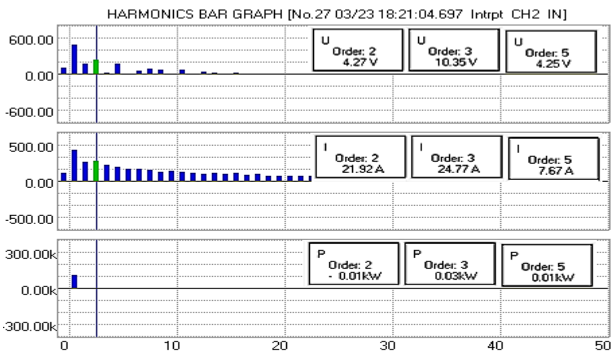

Fig. 6. Harmonic bar graph at Feeder-2 measured over 4 day period

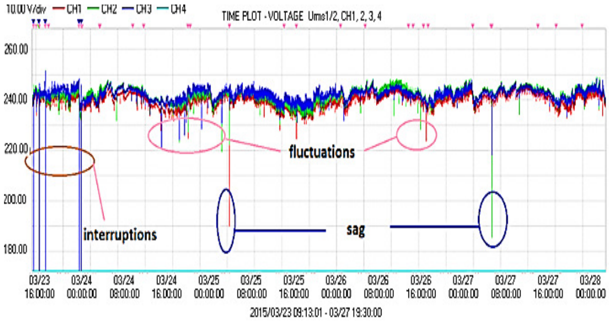

Fig. 7. RMS variations at Feeder-2 measured over 4 days period

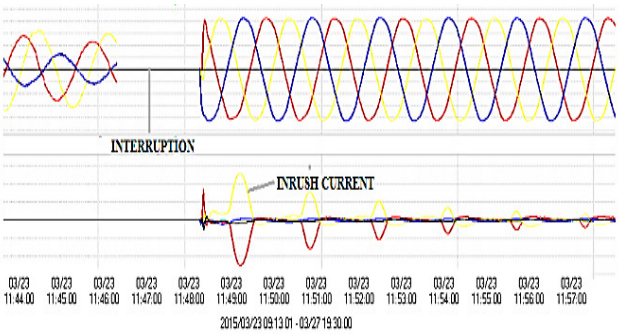

Fig. 8. Interruption period (inrush current) at Feeder-2

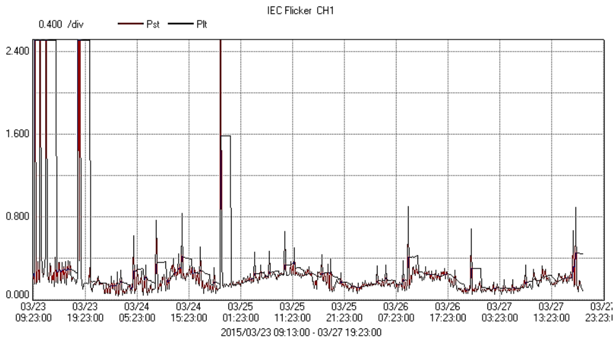

Fig. 9. Flicker (voltage fluctuations) at Feeder-2 measured over 4 days period

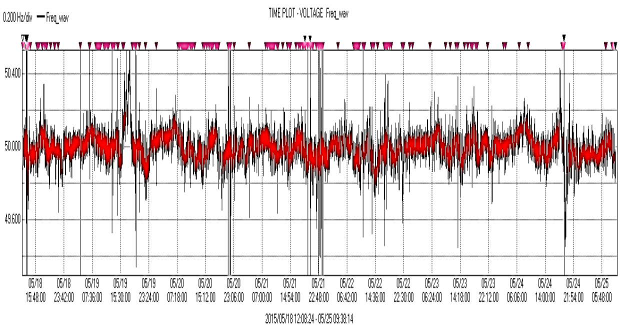
Fig. 10. Frequency variations at Feeder-3 measured over a week period

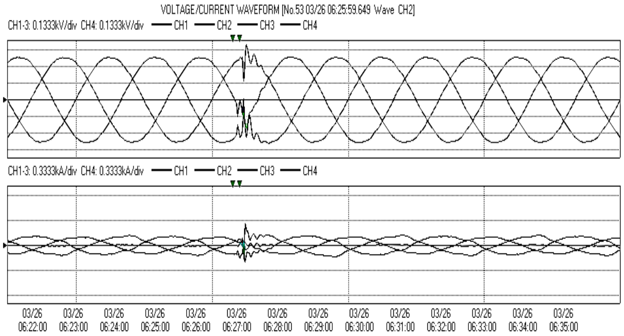
Fig. 11. Oscillatory transient event at Feeder-3 measured over a week period

Table 4. Represents the disturbance level and disturbance events which have occurred at the different feeders. Very high THD value appears at SIC-PCC (Feeder-2), it is not obeying the IEC 61000-4-30 standard. During the load period, a very bad PF value appears at PMTC-CVD and SIC-PCC, it increases the total RMS current. Some of the disturbances are mentioned each Feeder wise is shown in Table. 4.

Table 4. Power Quality disturbance events and values

Feeder		PMTC-CVD	SIC-PCC	LDB-1A
THD		2.81%	6.2%	1.72%
PF		0.6	0.5	0.9
Interruptions (momentarily)		✓	✓	✓
Sag/Swell		✓	✓	✓
Transient (oscillatory)			✓	✓
Voltage Notch		✓		
Individual Harmonics (%)	3	1.31	2.17	2.09
	5	3.55	3.55	2.32
	7	2.59	2.00	2.07
	9	0.4	1.17	0.72
	11	3.59	1.47	0.69

Most of the research here on finds the disturbances at distribution feeder level with the help of power quality monitoring have been done. Further measurements are required to test various networks and loads. Various type of loads creating various disturbances. So, the further study requires more monitoring results. The obtainability of increasing amount of monitoring equipment makes study ease. The discussions ongoing about how much disturbance level may occur formerly serious problems occur. However, the disturbances level at this point causes serious problems. So, we are trying to mitigate those disturbances as early as possible. As mentioned before, we are trying to find out all the disturbances level at each load point and we try to mitigate those disturbances.

4. Conclusion

In this paper, an overview of power quality is presented. Also, the real-time monitoring results have been given and various power quality issues and mitigation method are discussed at the medium voltage level. Unfortunately, the load is disturbing the supply system enormously and the power demand goes on increasing. More importantly, the physical effect on the equipment is a loss of productivity, misoperation of sensitive equipment and downtime. Consequently, the wide range of technology and software's now available, monitoring is highly effective to find problems and solutions. The power quality monitoring is prerequisite to design a digital controller for PQ mitigation.

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