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Virtual Wide Area Power Quality Monitoring System for AEP Transmission using Energy Meters

P. KANSAL, N.R. DUNN, P.C. CAMBRAIA
American Electric Power (AEP)
USA

SUMMARY

Power Quality (PQ) has traditionally been a concern at distribution and sub-transmission levels where a majority of the customers are connected. Typically, most PQ issues are local issues at the customer site but with the increasing penetration of convertor-based technology at the transmission level, PQ at the bulk transmission level may get adversely affected. This can present a big planning and operational challenge and can affect many customers.

In this paper, we discuss an effort that AEP is undertaking to monitor harmonics at the transmission level using existing intelligent electronic devices (IEDs) and telecommunication infrastructure. The goal is to utilize existing infrastructure and develop a wide-area PQ monitoring system as a proof-of-concept to understand the state of PQ at the bulk transmission level and henceforth identify areas that may need PQ improvement.

KEYWORDS

Wide Area, Power Quality, Transmission, Energy Meters, Pi Display, Convertors, Flexible AC Transmission System (FACTS), High Voltage DC (HVDC) Transmission, Static VAR Compensator (SVC), Supervisory Control and Data Acquisition (SCADA), Communications, Harmonics, Flicker, Total Harmonic Distortion (THD), Intelligent Electronics Devices (IEDs), PQ Analytics.

1. Introduction

Until the last decade, the nature of loads and generations did not change much over time, and power quality issues were well understood with known solutions. Due to environmental concerns and availability of high-power switching devices, the generation and load mix is now changing rapidly. Convertor based devices are increasing in the system at all voltage levels. For example, at transmission level, renewable energy sources are increasing rapidly to meet the environmental targets and FACTS based devices like series capacitor, SVCs, battery

pkkansal@aep.com

storage, and HVDC are being installed to accommodate real and reactive power requirements of the new generation mix. Also, the use of high power electronics is steadily increasing at the distribution level in the form of electronics chargers, convertor based Photo Voltaic (PVs), and electric vehicles.

Unlike older PQ issues like arc-furnaces, rolling mills, capacitive transients, and grounding, the impact of new technologies on power quality is not well known. Therefore, it is crucial to monitor PQ issues, if any, of the Transmission system to determine if mitigation is necessary as we continue to integrate new technologies into the grid of the future.

Since utilities have many IEDs installed in their system and have telecommunication infrastructures in-place, it is worthwhile to understand if existing infrastructure can be used to measure system-wide power quality. This paper summarizes such an effort that we started at AEP Transmission. Section-2 discusses power quality, section-3 discusses AEP Transmission power quality standard, section-4 discusses IED selection and installation, section-5 discusses instrument transformer limitation, section-6 discusses PQ analytics, and section-7 concludes the project.

2. Power Quality

2.1 Power Quality Definition

Power quality, broadly speaking, measures the proximity of voltage signal, current signal, and power to their ideal behaviour. Ideally, voltage supply provided by the utility at the point of common coupling (PCC) should be of a fixed magnitude and fixed frequency (60Hz) and a customer should draw 60Hz current at unity power factor from the utility supply.

There are different PQ measurements like voltage harmonics, current harmonics, voltage unbalance, voltage sag or swell, transient overvoltage, voltage flicker, voltage regulation, communication interference, and power factor that quantifies the deviation of the current, voltage and power signal from their ideal behaviour. Further, there are a variety of standards such as ANSI, IEEE, NEMA, IEC, etc., that define the limits on these measurements that utility and customer should comply with for ensuring good power quality at PCC.

As described above, several PQ measurements are defined, but for the purpose of this project, we are only concerned about harmonics and flicker.

2.2 Harmonics and Flicker Impact

One of the key PQ measurements of concern is harmonics. As described in section-1, harmonics can be generated anywhere in the system. To meet the compliance requirements, each individual customer should mitigate the harmonics as described in subsection 2.3. Unfiltered harmonics flows back into the system to find a path of least resistivity to the ground. This can create high background harmonics in the places where filters are installed for other reasons. For example, uncompensated harmonics from a group of distribution stations can enter transmission system, creating background harmonics around a FACTS station which typically has filters for proper operation of the convertor controls. This can overload and trip the filter designed for FACTS convertors, creating major operational and planning issues for bulk electric transmission. Other bad impacts of harmonics are reduced insulation life, misoperation of some type of protection relays, increased system loses, overloaded neutrals, resonance, and communication interference. On the other hand, the major impact of voltage flicker is visible annoyance to eyes that can be very irritating to the customers. On rare occasions, voltage flicker can be severe enough to cause electronic loads to drop off-line.

2.3 Harmonics and Flicker Mitigation

The best place to mitigate harmonics is the place of its origin because an unmitigated harmonic can flow anywhere into the system to find the path of least resistivity. At the transmission level, a power system is meshed and it is very challenging and cost prohibitive to locate the source of harmonics far away from measurement point. To make the problem even more complex, different harmonics originating at one location will have different paths of least resistivity to ground.

Further, transmission system planning and operation studies typically assume that harmonics are not present at the transmission level. And, it is not very common to do a special harmonics studies for system expansion. So, it is a big modelling and studies challenge as well, to understand harmonics issues once they propagate away from their origin.

Harmonics [1] can electrically be eliminated or filtered at the point of origin using transformer winding connections or filters. Voltage flicker [2] issues can also be solved at the point of origin using SVCs [3]. If not rectified at the customer site, the flicker will be visible to all the nearby customers connected to the same system or adjacent system.

3. AEP Transmission PQ Standard

AEP has an in-house PQ standard which is largely based on IEEE-519 [1] and IEEE-1453 [2] standards. These standards are the basis for monitoring large industrial customers using dedicated PQ measurement system. As a part of the project, to minimize cost and to come up with proof-of-concept, we use existing transmission infrastructure to design a wide-area power quality system [Fig-1]. We surveyed various existing IEDs for their available PQ measurements and calculation methodology to find the device that most closely matches AEP standard requirements. The table below summarises the AEP PQ standard:

Table-1: Summary of AEP Transmission PQ standard

Measured Quality (per phase)	**Formula/Meaning**	**Threshold**	**Number of Analog Points**
Voltage Harmonics ($1\text{-}25^{th}$)	Percentage of Contract Demand	95% samples below IEEE 519 limits	75
Current Harmonics ($1\text{-}40^{th}$)	Percentage of Contract Demand	95% samples below IEEE 519 limits	120
Voltage Total Harmonic Distortion (THD_V)	$\frac{\sqrt{\sum_2^{25} {V_n}^2} \times 100}{V_1}$	95% samples below IEEE 519 limits	3
Current Total Harmonic Distortion (THD_I)	$\frac{\sqrt{\sum_2^{40} {I_n}^2} \times 100}{I_1}$	95% samples below IEEE 519 limits	3

Communication Interference (I*TIF) TIF: Telecomm Interference Factor	$\sqrt{\sum_{1}^{40}(I_n \times W_n)^2}$	95% samples below IEEE 519 limits	3
Short-term Voltage Flicker (P_{ST})	Visibly annoying voltage fluctuations	99% samples below IEEE 1453 limits	3
Long-term Voltage Flicker (P_{LT})	Visibly annoying voltage fluctuations	99% samples below IEEE 1453 limits	3

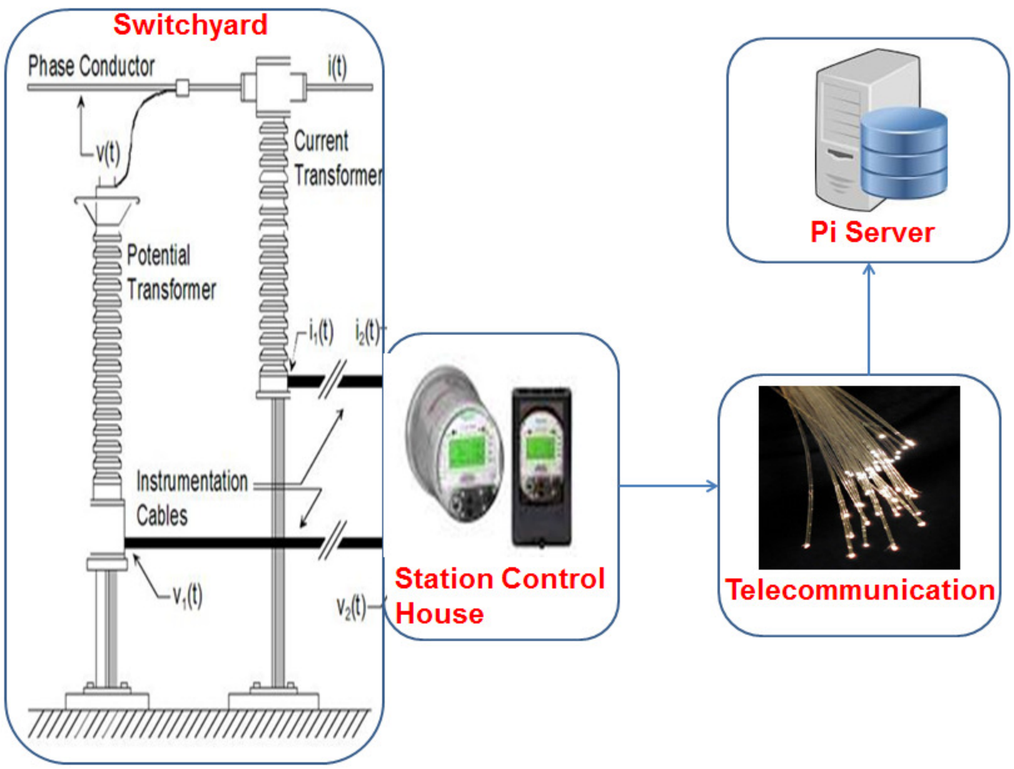

Figure-1: AEP's PQ Measurement System

4. IED Selection and Installation

4.1 IED Survey

For this project we evaluated our existing fleet of IEDs, including meters and relays, to see if they could be used to monitor harmonics and flicker across the bulk electric grid. The meters we considered for this project are the ION 8000 series meters and the SEL 734P meters. The rest of the meters in our fleet didn't do harmonic or flicker measurements, or didn't support the communication protocols and mediums required to collect data. Also, none of the relays in our fleet do harmonic and flicker measurements.

We focused on the ION 8600A, ION 8600B, ION 8560B and SEL 734P meters. A majority of our fleet is 8600B meters, but we moved to the SEL 734P and ION 8650B meters in the past couple of years. We only have a few ION 8600A meters.

Further, ION 8600B is only capable of measuring harmonics, so it is not evaluated. The ION 8600A, ION 8650B, and SEL 734P meters are all capable of measuring the harmonic and flicker quantities required. The comparison is as shown below:

Table-2: Survey of meters for PQ measurements

AEP Standard	**Energy Meters: ION-8650B**	**Energy Meters: ION-8600A**	**Energy Meters: SEL-734**
Harmonics and THD: 200ms[1] window averaged over 10s[2,3]	Available as per AEP standard	Available as per AEP standard	NA
Voltage flicker is required with 10 minutes (P_{ST}) and 120 minutes average(P_{LT})	Yes	Yes	Yes
THD_I and THD_V based on harmonics up-till 40^{th} and 25^{th} order only	Based on harmonics up-till 63rd order.	Based on harmonics up-till 63rd order.	Based on harmonics up-till 50th order.
Sampling Rate	1024 samples/cycle	256 samples/cycle	133.3 samples/cycle
I*T is Required	NA	NA	NA

Note 1: As per IEC 61000-4-30 [4]
Note 2: As per AEP standard
Note 3: 10 second averaging was done using Harmonic Evaluation Module in ION 8650B

We settled on the ION 8650B meter (0.2 Accuracy, Class 20) as it has the fastest sampling rate, and had the measurement modules that allowed us to measure the harmonics per our specifications.

4.2 Communications Requirement

As mentioned in Table-1 and Table-2, total 207 analog points (excluding communication interference), are required to be polled every 10 seconds. We chose to use Modbus to map these analog points as there are only 100 DNP analog points available in the meter while it has 320 MODBUS analog points.

ION 8650B meter supports MODBUS protocols over TCP, modem, and serial communication mediums. Due to the large amount of data to be polled from the meter we needed an Ethernet connection to make sure we would be able to get the data in a fast and reliable way. Also, we chose not to use cellular modem connections or meters behind a CIP firewall to prevent any lapses in communication and the collection of data. Further, we set up meter for direct polling of PQ data from a Pi server. This saves additional work and thecost of connecting a meter to remote terminal unit (RTU) and changing RTU Point Assignment (RPA) files.

4.3 Station Selection

Each station has different communication infrastructure depending upon their existing needs. The physical communication medium at station can be a phone line, ethernet, Very Small Aperture Terminal (VSAT) link, Multiple Address (MAS) Radio, or cellular connection.

Based on the discussion in above subsection, Ethernet, VSAT and MAS Radio are our only options. Further, MAS Radio does not talk to the station router, so the stations with Ethernet and VSAT are selected for this project. Ethernet connected stations can support large bandwidth usage whereas VSAT can support data usage in range of 1-4 kbps. The plot (captured and plotted using Wireshark) below shows the average bandwidth consumption (0.5 kbps) at one of the stations:

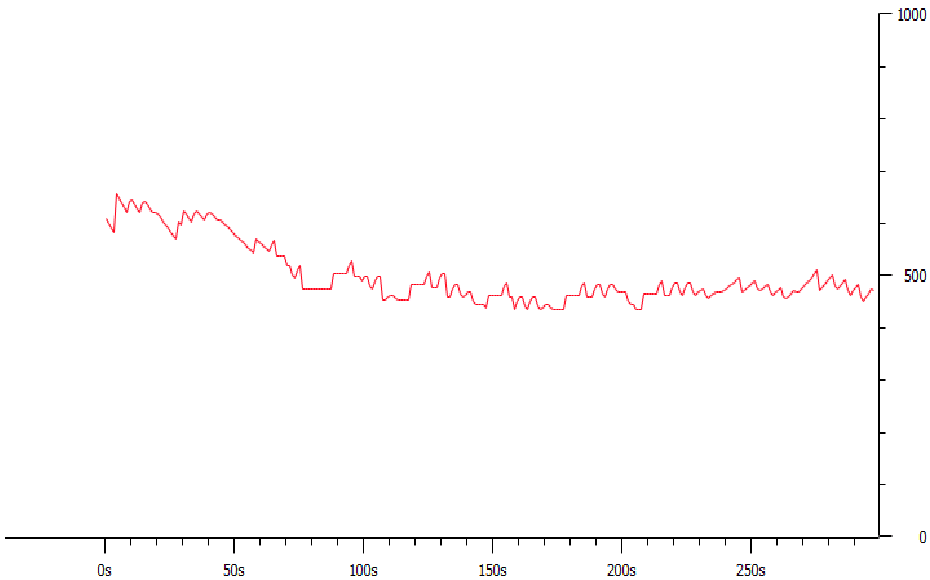

Figure-2: Average bandwidth usage (bps) Vs Time (s)

4.4 Template Installation

We made required changes in our meter template to enable PQ monitoring and created MODBUS maps. Since ION 8650 B meters are used as revenue meter, they are tested on an annual or bi-annual basis to make sure our measurements don't drift and that they remain accurate. To avoid any additional costs for the installation, we planned the installations as part of the testing plan. Since, meters are directly polled; no other changes are required other than template installation.

5. Instrument Transformer Limitations

Most of our new metering instrument transformers i.e. Current Transformer (CTs), Potential Transformers (PTs), and CVT (Capacitive Voltage Transformers) are 0.15 accuracy class transformers and some older CTs and PTs are 0.3 accuracy class transformers. Even though we use high accuracy metering transformers, they act as filters to the current and voltage signal at frequencies higher than fundamental. This can reduce the measurement accuracy of higher order harmonics in some cases. The actual frequency response of an instrument transformer is dependent on loading, secondary cable, and manufacturer. The table below shows the frequency response of some typical CTs and PTs tested at AEP. Clearly, CTs have good bandwidth characteristics for PQ. PTs can be some time limited to 13^{th} harmonics, and CVT has a very narrow frequency band.

Table-3: Instrument transformers approximate frequency response

Instrument Transformers	**Frequency Characteristics**	**Harmonics Measurement**	**Required Characteristics**
Current Transformers[1]	10000 Hz	40	2400 Hz
Potential Transformers[1]	800 Hz to 1700 Hz	25	1500 Hz
Capacitive Voltage Transformers[2]	200Hz to 600 Hz	25	1500 Hz

Note 1: Actual response will depend on loading, secondary cable, and manufacturer

Note 2: Based on [6]

6. PQ Analytics

There are two types of PQ analytics that we perform as discussed below in this section. One of the analytics is focused on a wide-area view while another analytic is a more focused detailed analytics for one particular station.

6.1 Wide Area PQ Analytics: Pi Display

In this project, we decided to store the meter data in an OSISoft PI data historian for further analyses and presentation. We configured an OSISoft MODBUS-Ethernet interface on a server within our DMZ (demilitarized zone) network, which can reach our meters via TCP/IP protocol. The MODBUS interface queries each meter every 10 seconds, takes a snapshot of the current values for each meter register (refer to the meter template) and stores the values in our PI data historian. The data historian is located outside the DMZ network, so corporate users can easily access the stored data via our custom display.

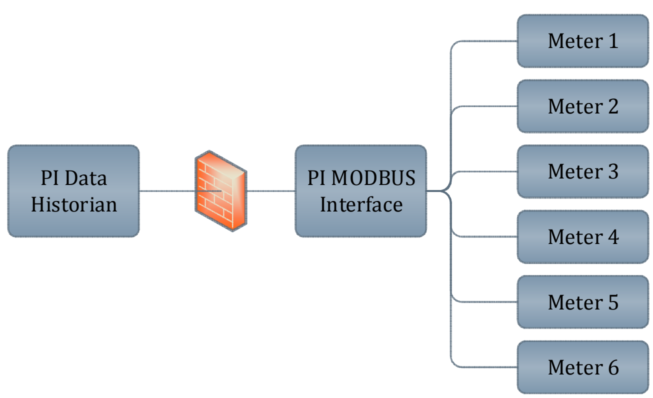

Figure 3: Pi data flow

Once the data is stored in our historian, we have a series of calculations performed at regular intervals. Some calculations are also triggered whenever we receive a new event for a given point. We opted to use OSISoft's PI-AF Analyses, which is an integral part of our data historian. We created a PI-AF template that matches the meter template. Our PI-AF template contains all PI tag mappings as well as the calculations we need to perform. We then created instances of each new meter based on our template. This approach keeps our PI data analyses consistent and any calculation changes can be applied only once at the template level. Changes made to the template are propagated to each meter instance.

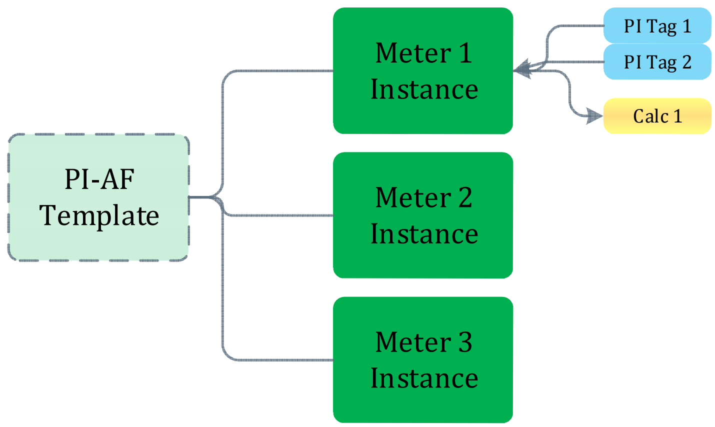

Figure 4: PI-AF template

The calculations and actual input tags are displayed on a PI-Process Book display specially built for this project. Users can see current values near real-time (updates every 10 seconds) or they can choose to display PI-AF analyses such as Max and Percentile for the following time periods (-1day,-7days, -30days, -90 days or -365 days). The display utilizes VBA (Visual Basic for Applications) behind the scenes and allows us to map to different PI-AF objects based on the user's selections in the drop-down boxes. The Figure-5 below shows the displays that we created.

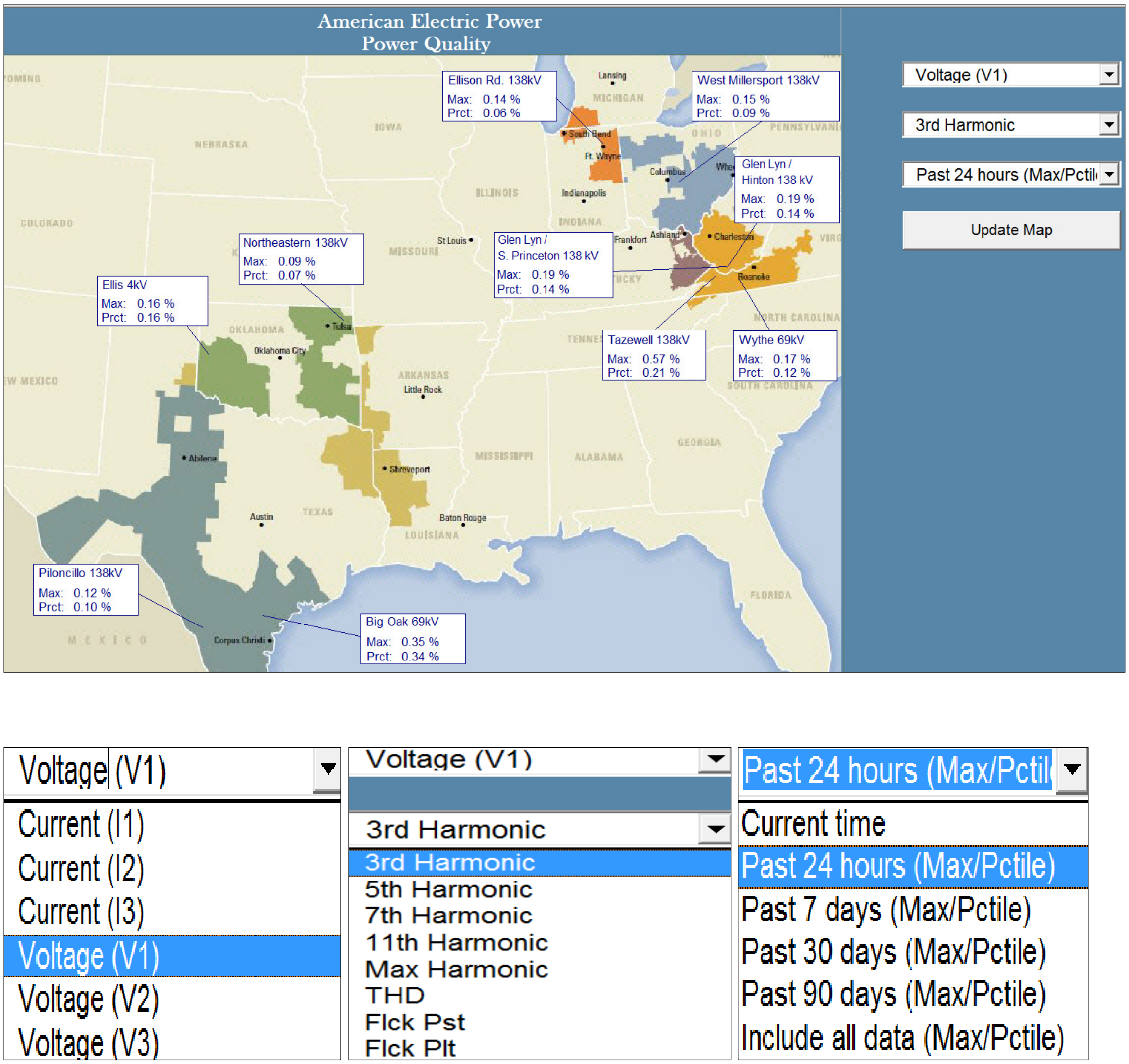

Figure 5: Wide Area Power Quality display and the available option menus

6.2. Detailed Analytics of One Station: MATLAB Scripts

Our display provides a good way to visualize our current data and some basic statistics. However, we have also made our PI tags available through PI-OLEDB provider, which allows other applications such as MATLAB to query our historical PI data using standard SQL statements. This gives us the ability to perform more in-depth analyses. Some of the plots showing in-depth analysis for a particular station are shown below in Figure 6-8 where blue trace represents maximum value and black trace represents percentile value.

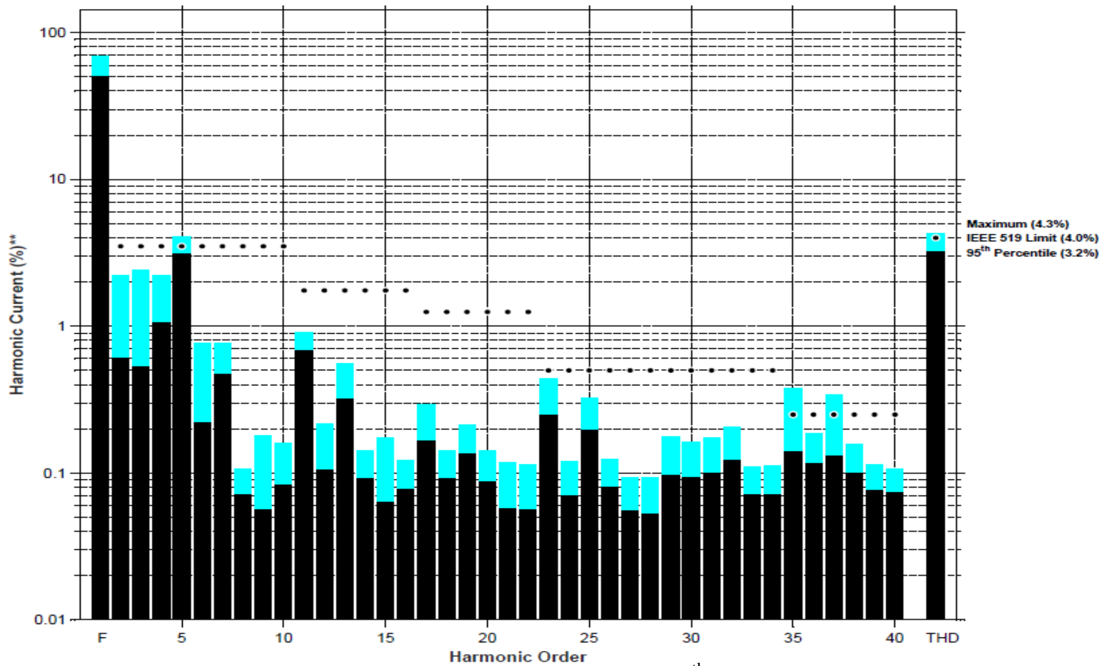

Figure 6: Current harmonics analysis with comparison of 95th percentile value to IEEE limits

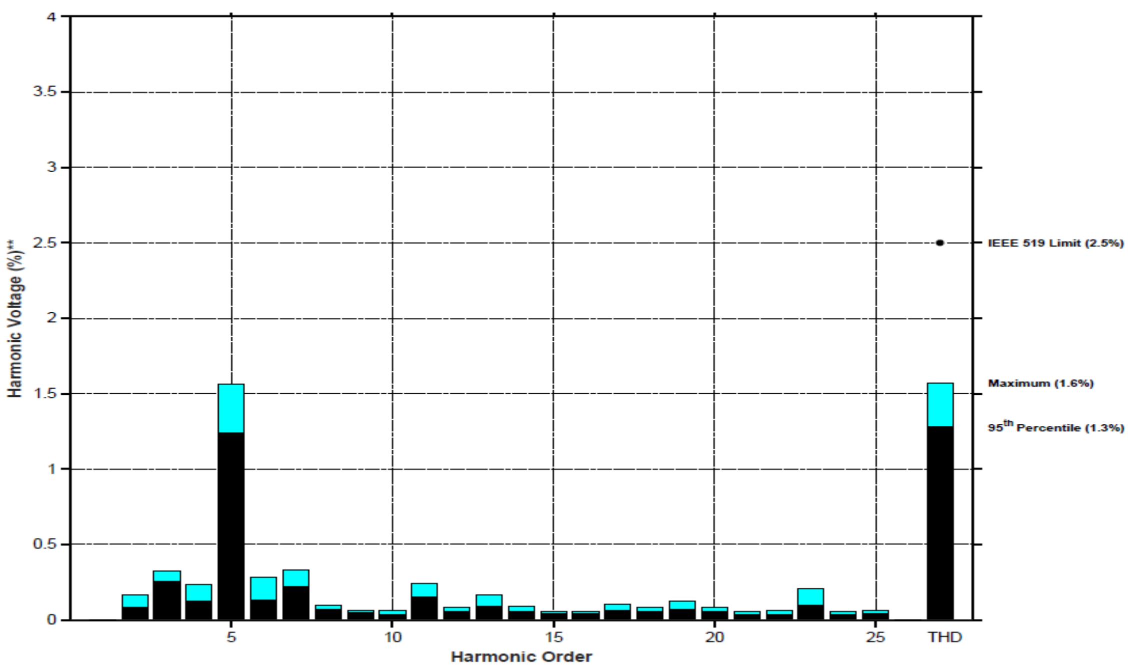

Figure 7: Voltage harmonics analysis with comparison of 95th percentile value to IEEE limits

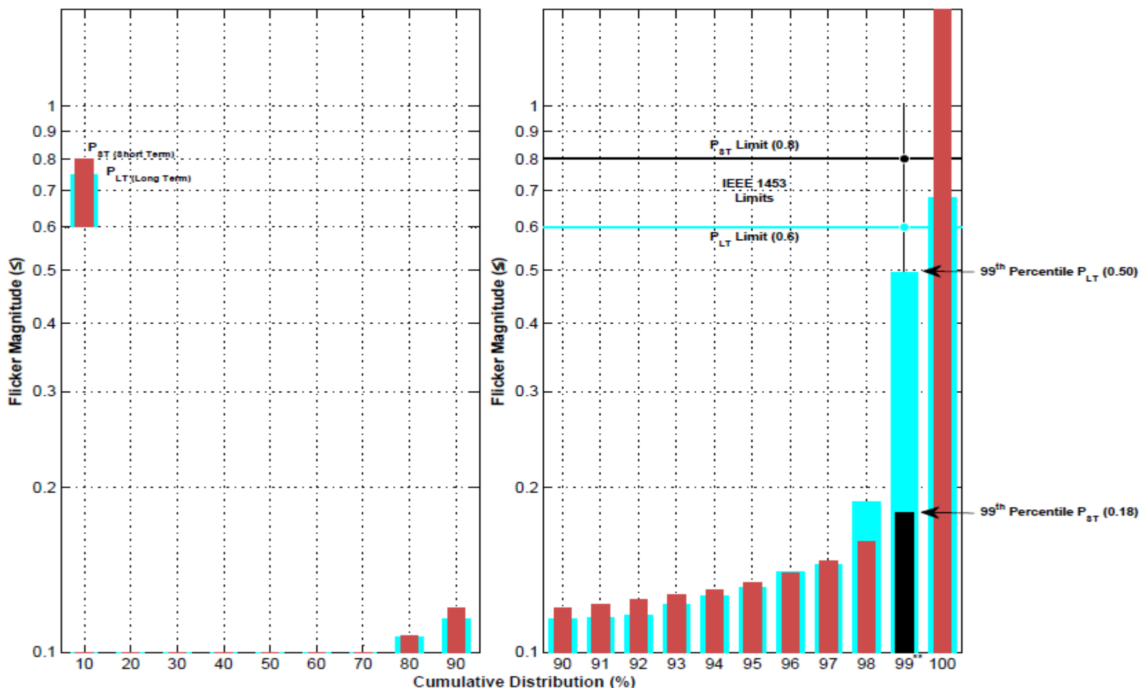

Figure 8: Voltage flicker analysis with comparison of 99th percentile value to IEEE limits

7. Conclusion

This paper discusses the virtual wide-area power quality system that we are developing at AEP using existing infrastructure to understand PQ issues at the bulk transmission level. We plan to expand this system and perform system-wide analytics to identify regions that might need improvements.

8. Acknowledgement

The AEP Power Quality standard and monitoring methodology was developed by Mr. Richard Gutman and the MATLAB program for plots shown in Figure-6-8 was developed by Mr. Sanjoy Sarawgi. Authors would also like to acknowledge Mr. Jeff Fleeman, Mr. Carlos Casablanca, Mr. Bradford Martin, Mr. John Mandeville, AEP Meter Operations group, and Schneider Team for their guidance thought this project.

BIBLIOGRAPHY

[1] IEEE-519-2014, IEEE Recommended Practices and Requirements for Harmonics Control in Power System

[2] IEEE-1453-2011, IEEE Recommended Practices- Adoption of IEC 61000-4-15:2010, Electromagnetic compatibility (EMC)-Testing and measurement techniques-Flickermeter-Functional and design specifications

[3] Virulkar, "Voltage flicker mitigation using STATCOM and ESS," POWERCON, October 2008

[4] IEC-61000-4-30, Testing and measurement techniques-Power quality measurement methods

[5] ION 8650 product manual

[6] IEEE Transaction on Power Delivery, "Equivalent circuit modelling of a capacitive voltage transformer for power system harmonic frequencies", Vol. 10, No. 4, October 1995