An Online Harmonics & Power Factor Assessment Tool

Rajen Mehta (Efficienergi Consulting Pvt Ltd) and Manas Kundu (International Copper Association India)

Abstract

Traditionally, the Power System used to serve majorly only linear loads on the receiving end.

However, with the advent of industrialization, to achieve better energy efficiency as well as clean power alternatives, the characteristics of the load which essentially used to have linear nature, gradually transitioned to a non-linear one.

The term Power Quality (PQ), which for a few decades post inception of electricity was perceived to be irrelevant, its significance has changed dramatically in contemporary world. The non-linear character of the load, for obvious reasons, is going to rise at more than exponential pace which validates the relevance of power quality and associated parameters more than ever.
To ensure high quality power for end consumers, it is important to identify the power quality issues and its effects along with the locations for deployment of mitigating solutions. Whilst various stakeholders such as OEMs of mitigating solutions, utilities through regulations continue to spread awareness on PQ, the need to have a quick reference on the impact of poor power quality especially harmonics and poor power factor (PF) is very much there. At the same time it needs to be very simple so that the discerning user can easily evaluate it and enable informed decision making faster.

In this direction, APQI (Asia Power Quality Initiative) has taken pioneering initiative to create and educate stakeholders on PQ , create baseline data repository & continues significant capacity building in this less understood but very important aspect.

1. Introduction

The cost of Power Quality is a topic which has been researched through numerous papers and case studies and surveys. On the economic front it can be classified as

- Loss of Revenue
- Tie up of equipment capacity
- Increased Electricity Bill
- Loss of Opportunities

At the same time it is also challenging to evaluate the same considering it comes from different areas such as

- Downtime – Revenue per hour and cost of production
- Equipment Problem – Troubleshooting the root cause and determining the actual costs
- Energy Cost – Actual power, reactive power (PF) penalties, and MD charge structure

The end consumer at present is more prone to the effects of power quality and related issues with the prominent ones apart from voltage related being harmonics and poor PF. The equipment has become much more sensitive to power quality problems than these have been earlier due to the use of automatic controls, power converters, which are highly sensitive to the quality of supply and other disturbances. The distribution system also gets badly affected by the non-linear loads especially critical network infrastructure such as distribution/power transformers and cables. These loads are responsible to inject harmonic currents in the main power supply which create chain reaction of undesirable events. Apart from generating harmonics, these non-linear loads need reactive power and thus creates unbalance which increases the severity and may cause additional problems like derating of cables/feeders, and may impact operating PF as well.

They may elevate the losses in transformers, cause equipment malfunction, oversaturate neutral, etc. These effects of harmonics and other PQ issues are well documented in many referenced papers and case studies.
The severity of PQ nationwide is buttressed from the study conducted by the Power Grid in 2015 which gives following statistics:

Zone	**% of time PF < 0.8**
North	24
East	22
South	10
West	6

Feeder (kV)	**% of time PF < 0.8**
220	20
400	37.5
765	55

Fig. 1 Statistical data deduced from Swachh Power Report-2015

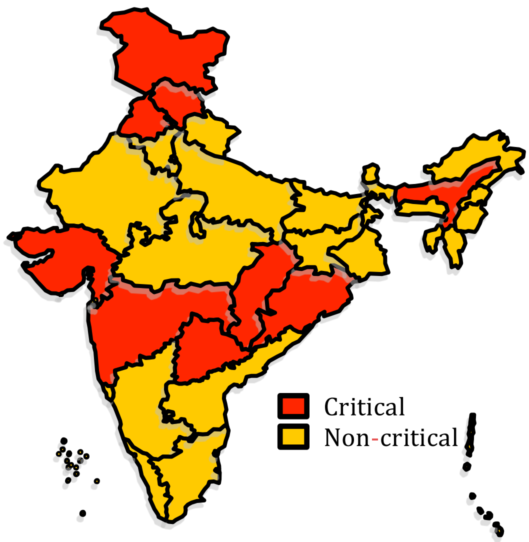


Fig. 2 Power Quality Map of India - Swachh Power Report-2015

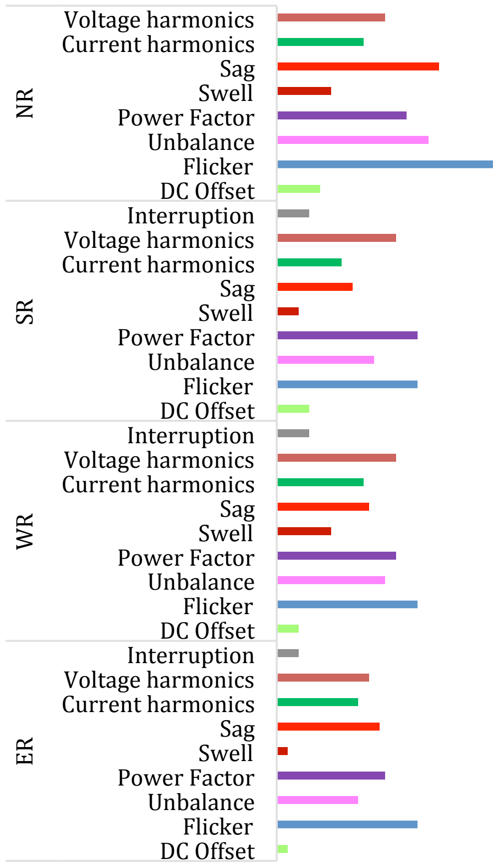


Fig. 3 Region-wise Power Quality Parameters observed across the country - Swachh Power Report-2015

The above study clearly summarizes that even with reactive power compensation being so widely promoted through incentive / penalty mechanisms by state distribution companies, still Power factor remains at a much lower level nation wide. It also highlights the criticality of the PQ nationwide which presumably has worsened further in the next 3-4 years after this study has been conducted.

The awareness related to harmonics and PF related problems has increased among the customers due to direct and indirect penalties enforced on them, which are caused by interruptions, loss of production, equipment failure, regulatory standards, tariff structures and so on. While the issue related to harmonics has become popular in past few years, huge efforts are still required to mitigate the associated impacts as quantification of the effects is not easy.

For the better addressal of the problems pertaining to the harmonics and PF, a tool, 1st of its kind, has been developed with support from Asia Power Quality Initiative APQI - a neutral platform working to build awareness & capacities on issues related to Power Quality so as to provide quantified metrics thus giving helping hand to resolve the unattended issues of the end-consumers. The tool addresses the issues of each and every stakeholder in a plant/facility related to harmonics and poor PF. While CXOs are concerned for extra incurred costs due to energy losses, the Plant Heads are focused to mitigate penalties/losses/repairs due to PF and harmonics. The tool is capable to suggest user by giving not only technical and business metrics but anti-punitive measures as well. It leverages state-specific norms and is in-line with latest relevant standards like IEEE 519-2014.

2. Key outputs from Tool

- **a)** Determine the KVAR requirement to reach optimum Power Factor and perceive achievable savings from avoidable energy costs.
- **b)** Estimate maximum allowable load capacity of the transformer based on harmonic derating.
- **c)** Identify the estimated compatibility to latest harmonic standards like IEEE 519-2014.
- **d)** Gauge cable and transformer losses due to harmonics.
- **e)** Obtain estimated budget for harmonic mitigation and PF improvement
- **f)** Estimate harmonic distortion with/without harmonic measurements

3. How to determine the KVAR requirement to reach optimum Power Factor and perceive achievable savings from avoidable energy costs?

Because of increase in fundamental and non-fundamental reactive power in electrical network, the equipment connected to that network will draw high currents from the electrical system.

In a non-harmonic system both the current & voltage are sinusoidal. The apparent power is the vector sum of the active and reactive power and represents the complete burden on the electrical system. But in a harmonic condition that is produced by nonlinear loads, the kW / kVAR spectra contain many of the harmonics in current.

To save on costs related to this invisible distortion component that affects both kwh and kVAh consumers, (although much significantly on kVAh consumers), we need to consider both fundamental and non-fundamental elements to calculate the total KVAR of network and the total additional KVAR required to get the optimum power factor of the system as follows

$$Total\ KVAR = \sqrt{KVAR^2 + KVARN^2}$$

Where KVAR is fundamental component and KVARN is non-fundamental component of the network.

This tool will calculate the required KVAR with help of load current and Power Factor as inputs to the tool. Since nowadays there is transition from the Displacement Power Factor to the True Power Factor, hence keeping that in mind the tool can accept either as input. The KVAR proposed by the tool is in sync with harmonic Mitigation proposed and not in isolation.

The tool also provides overview to the user for the losses before and after the installation of suggested filter. More details on those are explained in Section 5 below. Example of the same can be seen in the case study mentioned in the latter section of the paper.

4. How to check if you have compliance as per IEEE 519-2014?

Identifying the compatibility of harmonics in a power system is a big challenge now a days and this is considered as a joint responsibility involving all the stakeholders including the end-users. Harmonic limits are recommended for both voltages and currents. The underlying assumption of these recommended limits is to limit the harmonic current and voltage injected by end-users. In the event that limiting harmonic currents and voltages alone does not result in acceptable levels of distortion, end-users or operators should take action to modify system characteristics so that voltage distortion and current distortion levels are acceptable.

We can characterize current distortion levels with a THD value, but this can mislead the end user in the selection of harmonic filter. Small currents can have a high THD but cannot be a significant threat. For example, many adjustable-speed drives, pulse converters will exhibit high THD values for the input current while operating at light loads. This shouldn't be a concern, because the magnitude of harmonic current would be low in that instance, even though its relative current distortion is quite high. Responding to such scenarios, this tool will analyse fundamental of the *peak demand* load current rather than the fundamental of the present demand. As per guidelines of IEEE 519-2014, TDD and not THD serves as the basis for evaluating compliance. This tool will analyse the TDD where *IL* is the maximum demand load current over last 12-month average measured at the point of common coupling (PCC), which is usually at the customer's metering point. As it simply states that TDD is equal to the square root of the sum of squares of each of the maximum demand currents from the second harmonic to the maximum harmonic present, divided by the maximum demand load current at the fundamental. TDD is meaningful when monitored at the PCC over a period of time that reflects maximum demand of the customer as Per IEEE 519.

The main function of Tool is to design Harmonic filter for electrical network. It does so by including harmonic voltage limits and current distortion limits. **More importantly the size of the filter is guided by the compliance requirement of TDD as opposed to bulkier filter sizes that would be required if only THD-I was considered.** The measure of size is determined by a ratio called the "short-circuit ratio," or SCR, which is the ratio of the maximum *short-circuit* current at the Point of common coupling (PCC) to the maximum *load* demand current (IL) of the fundamental at the PCC. An attempt is made to calculate an estimated short circuit current at the PCC using different methods depending on the input data provided. In the first method this short circuit current can be calculated from the input data given by the user like short circuit MVA and Base KV with a formula as follows

$$Isc = \frac{Fault\ MVA}{\sqrt{3}\ *\ Base\ KV}$$

In absence of available short circuit MVA which is generally difficult to obtain alternatively Isc is calculated with help of line voltage drop and %Z.

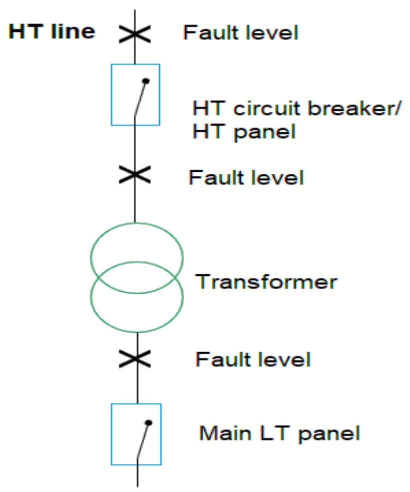


Fig. 4 A Typical Electrical System SLD

Isc calculations are done either for LT or HT network. In Fig 4 is simple SLD of the electrical network where fault MVA is unknown. LT cable between the HT line and LT breaker is taken into consideration. The tool itself calculate the %Z for that block with the help of R, X, cable parameters, and voltage drop. With help of the %Z, tool will calculate Fault MVA as follows.

$$Fault\ MVA = \frac{Base\ MVA}{\%Z}$$

Now to achieve these voltage harmonic and current harmonic limits, IEEE 519 sets limits on the amount of harmonic currents injected into the PCC, as a function of the size of the load. Following tables from IEEE 519-2014 are reproduced which are utilized for compliance verification by the tool.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Fig. 5 Voltage Distortion limit table from IEEE 519-2014

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]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 the PCC under normal load operating conditions

Fig. 6 Current Distortion limit table upto 69kV from IEEE 519-2014

Compliance results from the tool are obtained from values computed either by Reference Library data or Measurements entered by the end user.

With the help of the proposed filter current spectrum, projections on remaining harmonic distortion can be obtained.

The norms related to PQ are prevalent in US and European countries. While Indian sub-continent so far had focused mainly on availability of power, the upcoming trends and future projects mandates a similar regulation. The concerned bodies like BIS are working to introduce PQ regulation in coming days. By the time it is introduced, user can verify in advance whether their facility or part of their facility comply to relevant national/global standards or not.

5. What is your Cable and Transformer losses due to Harmonics?

The true power transferred to the load is a fundamental component of the system and whenever the current drawn by the load contains harmonics the total RMS current will be greater than the fundamental.

$$Irms = I_1 \sqrt{1 + THDi^2}$$

The above fundamentally explains that the total losses will be contributed by the sum of all the losses at all the individual frequencies.
These losses in the system increase the temperature in case of transformers and cables. In case of transformer generally losses in windings increase as the square of the THDi and that core losses increase linearly with the THD_u.In Utility distribution transformers, where distortion levels are limited, losses increase between 10 and 15% approximately.

The losses due to fundamental and non-fundamental currents in the transformer are as follows

$$Total\ losses = \sqrt{I^2 * R + In^2 * R}$$

Where in the above equation *I* is the fundamental component of current and *In* is the non-fundamental component of the current

Total load losses in the transformer will be represented as

$$P_{LL} = Pec + Posl + Pdc$$

Where

P_{LL} =Total load losses
P_{ec} = Eddy current losses in winding
P_{osl} = Stray losses in parts of transformer
P_{dc}= Ohmic losses

Ohmic losses are calculated by considering the winding impedance of transformer and connected load.

Pointing to eddy current losses these losses are produced due to time varying nature of magnetic flux in the transformer. Drawing upon IEEE C57.110 and assumptions using practical thumb rules such as.

$$Pec = 0.33\ Posl$$

for oil cooled transformers, the tool arrives at practical estimates of the additional losses due to non-sinusoidal quantities with minimal information. At the same time it also calculates the % of derating of transformer due to harmonics i.e. Factor-k. defined as weighting of the harmonic load currents according to their effects on transformer heating, as derived from ANSI/IEEE C57. 110.The higher the Factor-K, the greater the harmonic heating effects.

Cable losses are also additionally calculated based on cable data entered or assumed based on loading as well as minimum short circuit withstand capability. The additional losses due to non-sinusoidal currents play a bigger role and the active plus reactive power due to harmonics are calculated to arrive at these losses in cables as well.

To understand more in detail, we will see one of the case studies conducted by a textile mill located in the Maharashtra region using this tool.

6. Estimate harmonic distortion with / without harmonic measurements

If the user does not have harmonic data through measurements available, the tool has a capability to calculate and simulate the effect of total harmonic distortion based on the standard harmonics spectrum and inbuilt designed libraries for 6 pulse VFD drives, UPS and Lighting loads. These are simulated together to provide the combined effect at the PCC so that preemptive action can be taken at greenfield or expansion stage in terms of mitigation strategy to be planned. Work on augmenting the library remains a continuous process to be able to have more and more different kinds of non-linear loads as well as additional ratings, makes and models.

Case Study

The client belongs to *Textile industry* and relevant data like per unit energy rate, operating hours, L-L network voltage, type of conductor, size of conductor, voltage and current harmonic data, etc. was fed as input. The facility had a 2500KVA transformer and the maximum demand was about 1279KVA with voltage harmonic distortion at about 8% and current harmonic distortion at about 42% and following takeaways were obtained:

1. They found that the estimated harmonic compliance at PCC as per IEEE 519-2014 standard was above standard limits.[1]
2. The tool provided them key findings, corresponding impacts and recommendations along with projected monetary benefits.
   For e.g.
   a) They found that I-TDD% and V-THD% were above limits as per the estimated IEEE 519-2014 compliance[1].
   b) The tool also made them aware of possible impacts of the findings like possible regulatory penalties, possible overloading/overheating of network element, possible network resonance. It computed the total kW Loss: 17.23 kW, total kVA Loss: 50.71kVA, transformer

[1] The compliance is obtained by applying IEEE 519-2014 on a single timestamp measurement snapshot. However, for accurate compliance IEEE 519 requires data over extended period of time to ensure statistical significance of the outcomes

additional kW Loss: 6.164 kW.

c) Also, it gave them prioritized recommendation to come in-line with the compliance requirements as well as to save on losses in the facility

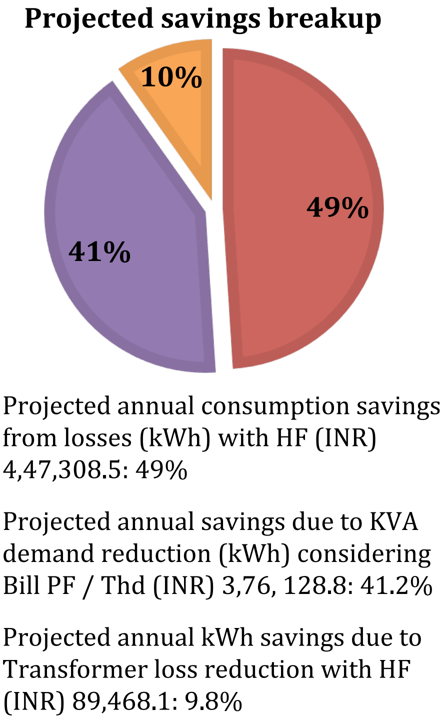
Phase-I:
Based on Measured/Bill PF, provide Additional 175 KVAR with 7% Series Detuned Reactor

Phase-II:
Provide 550 Amps Active Harmonics Filter (HF) to improve distortion PF.

d) The tool projected kVA Demand Reduction by improving PF (Billed / Measured) and Harmonics to be: **125.38 kVA** & Recoverable Total (Line/Load + Transformer) kWh Loss with Harmonic Filter and Caps ON to be: ***75924 kWh/Year***

3. Based on Factor-K calculations it suggested to derate the transformer to 91.9% of its full load capacity. So, in effect the 2500KVA transformer can be loaded only up to 2297.5KVA due to the harmonics present.
4. The tool also suggested the estimated annual savings of ***INR 9,12,906*** along with the ROI of ***2.7 yrs***[2] thus enabling the management to take an informed decisions of further detailing if required.

[2] The savings and ROI calculations are a guestimate based on some assumptions of the facility as well as benchmarked filter rates. The same are just provided to give an indication and are in no way an accurate estimate since savings as well as ROI depend on a number of factors apart from just losses



5. The tool also gives projection of achievable V-THD% and I-TDD% with HF which in this case were 1.9% and 7.4 % respectively.

Way Forward

The tool is first of its kind attempt especially by remaining extremely user friendly for a normal maintenance engineer and can succeed only with the active contribution from various stakeholders. This tool aims to bring down the resources spent on the Power Quality/PF studies only to give a better proposition in terms of tangible/in-tangible value to the end user and to provide as a quick decision tool to take action further and dive deeper if warranted. Much more can be done to enhance the accuracy and estimates from the tool by modeling additional system components as well as the recommendations thrown to incorporate more technologies as well as mirror real life cases better.

References

[1] Swachh Power – POWERGRID, Sep. 2015

[2] IEEE 519-2014 Recommended practice and Requirements for Harmonic Control in Electric Power Systems

[3] SECQR®
(https://secqr.efficienergi.com) – An online harmonics and Power factor assessment tool developed by Efficienergi Consulting Pvt Ltd with support from Asia Power Quality Initiative (APQI)