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Research Paper

Harmonic aggregation techniques for power quality assessment a standard framework

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Abstract

A review on the existing methods for aggregation of harmonic currents including recommended method used in IEC 61000-3-6 standard is performed and different approaches are compared. Main advantages of each method are outlined and simulation studies are performed to assess each method. A simple technique is proposed to base future research and standardization on. The proposed technique is simple, reliable and realistic though requires experimental data to derive parameters.

Keywords: *Electromagnetic Compatibility; Harmonic Distortion; Harmonic Aggregation; Power Quality; Current Harmonics.*

1. Introduction

Although power quality has been an issue since far earlier, (for instance see [1]), Growing usage of nonlinear power electronic devices along with the increased utilization of sensitive electronic components such as computers, resulted in a growing attention to this area. An index for power quality is the harmonic distortion. [2] Harmonic distortion is a measure indicating how pure the sinusoidal waveform is is. [2]Harmonic pollution (i.e. levels of high order harmonics in the current/voltage waveform with a magnitude which causes unacceptable performance degradation) may cause compatibility problems between different components connected to a shared bus, distribution losses, damage to several components such as transformers, power switches and electric motors, accidental operation of remotely controlled switches and breakers(false tripping), equipment malfunction due to excess voltage, metering errors in power distribution and distributed measurement and control systems, fires in wiring, penalties on monthly bill units, generator failures etc. Permissible levels of harmonic pollution in IEC and IEEE international standards are provided as static indices measured at PCCs. [3], [4] However, since it is not always practical to measure power quality indices in PCCs, especially when the network behavior is time varying (e.g. inserting new loads, time varying components, etc.), some approximate methods are recommended in IEC 61000 series for evaluating the total harmonic distortion based on single component distortions. [3].

The importance of having a proper estimation of harmonic current based on individual harmonic currents is that one can determine whether it is possible to add new components without violating the THD requirements or not. If the new component violates the THD level requirements, it has to be integrated with a harmonic filter. Also in the situation when one or a few loads are to be provided with a harmonic filtering means to reduce THD, it is desired to be able to determine the harmonic level after adding the filter at the design stage. Also appropriate aggregation formulae will be useful for optimal placement of harmonic filters in a network. (I.e. whether to provide each load with its harmonic filter or to design a single filter for a group of loads consisting n loads, and to determine n to yield best results).

2. A review of the existing methods

The most pessimistic method to sum up individual harmonics is to add the harmonic currents magnitudes (peak or RMS) to estimate the aggregated harmonic current. This method, namely linear summation, presumes that all I_{hn}s are in phase as stated in equation (1). If the components (usually load currents) are in phase, a scalar summation would be accurate;

however this will lead to a conservative yet unrealistic approximation of THD [3]. It has been represented that in many cases, arithmetic summation is too pessimistic and actual harmonics cancels each other due to phase differences, resulting in a very smaller aggregated harmonic level. (See [6] and references therein.).
Another method is to vector-sum the harmonic currents which lead to an exact value for the aggregated harmonic current. This method is accurate, however the actual phases are not constant [6] and the so called vector sum may result inaccurate estimation if the phase angles are not measured for a long enough period. An approximate method is to use statistical methods as [6] which require a probability density function for harmonic phases or sums. The probability that a phase equals a specific value depends on switching time which is human dependant as well as internal circuitry of the device.
The third method is to establish formulae based on empirical data. IEC 61000-3-6 recommends to add up harmonics based on table 2 and equation 2, which is arithmetic summation for harmonic orders below 5 and a root of sums for higher orders.(2)

$$I_{hTOT} = \sum_{j=1}^{n} I_{hj} \quad (1)$$

In which the following notation is used:
I_{hTOT}: Aggregated harmonic current (order h) for all of components.
I_{hj}: Harmonic current (order h) for jth component.
The IEC 61000 recommended formulation is:

$$I_{hTOT} = \sqrt[\alpha]{\sum_{j=1}^{n} {I_{hj}}^{\alpha}} \quad (2)$$

In which:

Table 2: IEC 61000-3-6 Method for Harmonic Aggregation [5]

α	Harmonic Order
1	h < 5
1.4	5 < h < 10
2	h > 10

Using root sum of squares –RSS– is also possible, assuming 90 degrees phase differences. Other aggregation techniques include summation of vector components presuming random phase differences driven by probability densities of different types. These methods require experimental data to estimate phase angle difference PDF, from the experimental histograms. Statistical approaches are more logical to be applied especially when an appropriate density function is available. Actual PDFs can be modeled only through complicated analytical functions. [6] In addition, because of fixed limits recommended for THD levels [4], [9], it is more practical to derive conservative deterministic models based on statistical analysis. One approach is to define a percentile in the statistical model, not to be violated by the system. For instance [10] sets 5% limit for the THD (i.e. The THD level may not exceed 95% of the recommended limit) which is recommended by IEC as well. [3].

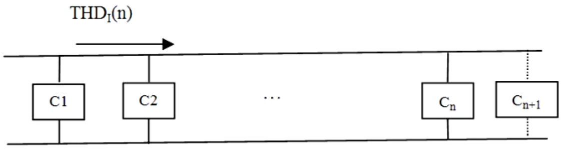

Fig. 1: An Array of Loads for Aggregated THD Evaluation

The recommended methods –namely harmonic aggregation techniques or methods of harmonic summation are not accurate due to the fact that harmonic components have different- usually time variant - phases. A statistical analysis of harmonic phases is performed in [7], in which probability density functions are estimated on the basis of simplifying assumptions. The PDF of harmonic phases is considered to be uniform in [7], [6], which are too optimistic. In fact, the statistical analysis of harmonics is valid only if experimental data for individual appliance harmonics is used to model phase behaviors. In this study, experimental data are drawn to model the phase behavior, examine the current aggregation method, evaluate the statistical assumptions of [7] and to derive statistical indices for THD levels which is optimistically considered to be in steady state in standards IEEE 519, IEC 61000 (CIGRE is one exception [6] which admits that permissible harmonics are to be time varying).
A major problem with the statistical aggregation methods is that it can't be guaranteed that a probability density function remains valid for any time. A small change in the load conditions may lead to large deviations in harmonic pollution state. Therefore a sensitivity analysis is to be performed on the effect of a change in a single load harmonic level on the entire harmonic level of a bus. As a result, any effective approach should include an aggregation method along with some tolerance levels for each kilowatt per load, which guarantees that the method remains valid in the future. This will be discussed in future sections.
The main pre-requisite of an effective statistical analysis is to provide a histogram of the random variable. The histogram may be drawn from experimental data or simply chosen by intuition. (e.g. a uniform or Gaussian distribution). It should be noted that since switching time may affect the phases, human factor must be considered in the modeling process. For mathematical analysis a simple density function may be fitted to the experimental histogram.

Consider N identical devices connected to a common line and operating in the steady state conditions. One may neglect the effect of harmonic voltage on harmonic current by presuming a sufficiently low voltage THD [6]. Therefore, the current THD is a vector sum of individual current harmonics. As a result one may deduce the following:

$$I_k \sim |I_k| \angle I_k = |I_k| e^{j\varphi_k} \rightarrow |I_k| \sim p_M(i), \angle I_k \sim p_p(\varphi)$$

In which I_k represents the k[th] harmonic current in steady state. (Because of the same principles applied to all harmonics, the harmonic indices are omitted.) It can be shown that if the phase and magnitude of harmonics are to be independent, the real and imaginary parts of the complex random variable I_k will be dependent. The total harmonic for order h is then computed as the vector sum for which follows:

$$I_{TOT} = \sum_{k=1}^{n} I_k \rightarrow |I_{TOT}| \sim p_{TOTM}(i), \angle I_{TOT} \sim p_{TOTp}(\varphi)$$

Since the magnitude of harmonic currents for all of the identical devices is almost the same, the magnitude of sum of harmonics can be computed as:

$$|I_{TOT}| = |I_k| \sqrt{\left(\sum_{k=1}^{n} \cos(\varphi_k)\right)^2 + \left(\sum_{k=1}^{n} \sin(\varphi_k)\right)^2}$$

It is complicated and unnecessary to compute the phase of I_{TOT}. In fact the magnitude of I_{TOT} is of the most concern. For different phases, the magnitude may vary as follows:

$$p_{TOTM}(i) = \begin{cases} p_M(i) & -I < i < I \\ 0 & \text{otherwise} \end{cases}$$

For uniform and Gaussian distribution of independent individual phases, the p_{TOTM} approaches a Gaussian form with shortened tails. This can be manifested by relaxing the constraint $-I < i < I$ and applying the central limit theorem.

3. Policies regarding harmonic control

To control harmonic pollution, two major companies may cooperate with each other; power distribution companies which are responsible for distributing the power efficiently and require power quality to assure customer satisfaction and low power losses during the distribution, and producing companies to produce electronic devices which emit low harmonics. [13].

A policy is to define a power quality measure determined for the whole power distribution system as in IEEE 518 and IEC 61000-3-6. This policy requires power distribution companies to guarantee the THD levels by utilizing harmonic filters, making the polluting loads to pay extra bills, optimizing the line characteristics and promoting companies to produce less polluting devices. Another approach is to force all producing companies to confine emitted current harmonics for power consuming devices and voltage harmonics for generators. This is specifically important because some harmonic requirements for electronic devices are based on safety aspects. The second approach requires that mostly contributing loads to harmonic pollution are identified and effective limits defined to result in overall acceptable levels, which requires sufficiently accurate aggregation calculation methods. For instance, a harmonics limit has been eliminated in the last version of some national and international standards related to electronic ballasts and lamps. (See two last versions of IEC-61000-3-2 and INSO 6195 for instances.)

It seems to the authors that a compromise between the two approaches is gradually forming, allowing the producers to increase economic benefits at the cost of slightly violating perfect requirements for harmonic pollution and letting the distribution companies to compensate the pollution with harmonic reduction techniques. Achieving this agreement requires consensus considering economic aspects, technical complexity and energy issues, which may be manifested in international/national standards.

All electronic devices may not require confining harmonic emission in the same level. As a rule of thumb, the more apparent power the device draws from the bus, the stricter will be its harmonics pollution requirements. To be more precise the following factors, determine the necessity of defining strict limits on harmonic emission of a load.

1) The overall power that these group of loads consumes as a portion of total power demand in a distribution system. For instance a single TV may not draw a significant current from the bus, however since the number of TVs is significant, a considerable portion of power may be consumed by TVs. As a result, significant harmonic pollution levels in TVs may result in the violation of THD requirements of a distribution system.
2) Technological factors: Some electronic/electric devices could be easily improved with respect to power quality measures. However, for some devices it may be technically complicated or impossible to enhance manufacturing technology in such a way that improves power quality indices, especially THD level. In these situations,

producing companies may use harmonic filters inside the device circuitry which results in extra engineering costs, decreased efficiency and increased production costs.

3) Duty Cycle: The duration, in which a device is on, is an important factor. Appliances which draw current 24 hr per day are to be limited with more strict conditions.
4) Concurrency: Devices which are usually draw current in the same duration of time; have greater effect on the THD of bus.

Taking the aforementioned factors into consideration, one may determine the severity of harmonic emission limits for each kind of load, as some devices may not need harmonic requirements. (IEC 61000-3-2 defines four classes, from A to D; each required a different level of THD.)

International standards may help making this decision by requiring/relaxing THD levels for each kind of device based on international consensus between all engaged parties. As an instance, harmonic requirements have been eliminated from IEC 60929:2011, for electronic ballasts, while they were included in the previous version of this standard.

4. Proposed frame work for harmonic aggregation

4.1. Random phases for N identical loads

The simplest method for introducing a summation formula is to estimate the phase mean value for each load; however it is not practical since individual phases cannot be measured at PCCs. An approximate method is to measure aggregated harmonic current and estimate a total coefficient for all components to result in the measured aggregated current.

$$\gamma = \frac{|I_{TOT}|}{|I|}\ ,\ |I_k| = I\ , \forall k$$

The relative aggregation coefficient is defined as:

$$\gamma_r = \frac{\gamma}{N}$$

Therefore one may deduce that:

$$|I_{TOT}| = \gamma_r N |I|$$

The proposed aggregation coefficient is due to temporal changes and may vary in general. Figure 1, shows the aggregation coefficient for different numbers of identical loads with the same amplitude and random phases uniformly distributed in [0, 2π). The coefficient doesn't exceed 120, even for 10000 loads.

Figure 2 and 4 depict the coefficient for a million experiments each with a random phase set, for 10 and a hundred loads.

Figures 5 and 6 depict the ratio between maximum possible value of aggregation coefficient (which is actually the number of loads; N) and its mean and maximum value for 1000 experiments and 10 to 1000 numbers of loads.

Figures 6 and 7 depict the same measure for normally distributed phases.

The following observations are to be mentioned:

1) The distribution of random phases is vitally important and only validated PDFs may be utilized to yield accurate results.
2) For normal distribution, mean value of the coefficient is about 0.6 of its maximum possible value and the coefficient rarely exceeds 0.8 of N.
3) Percentage of coefficients more than the 95% confidence interval is always less than 0.1%; therefore one may introduce this limit as an optimistic measure of aggregation coefficient guaranteeing that the probability of occurrence of a larger coefficient is less than 5%, which is a result of presumed normal distribution.

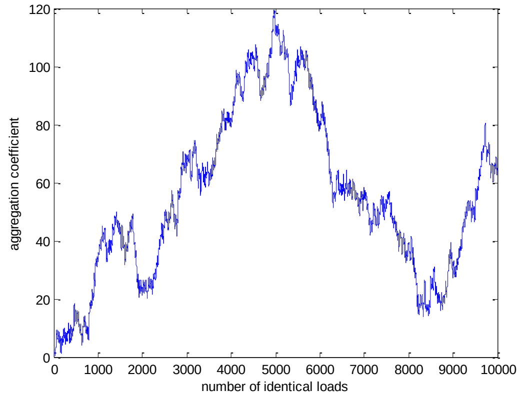

Fig. 1: Aggregation Coefficient For Identical Loads

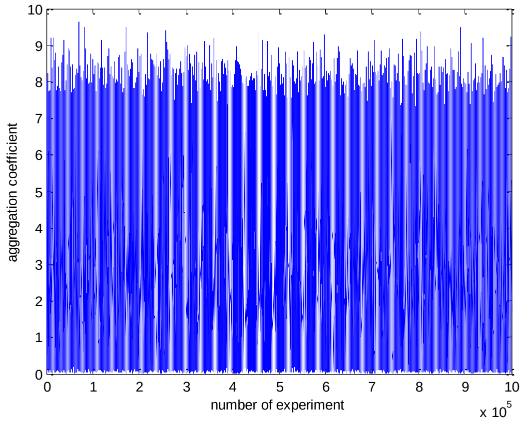

Fig. 2: Aggregation Coefficient In Different Experiments

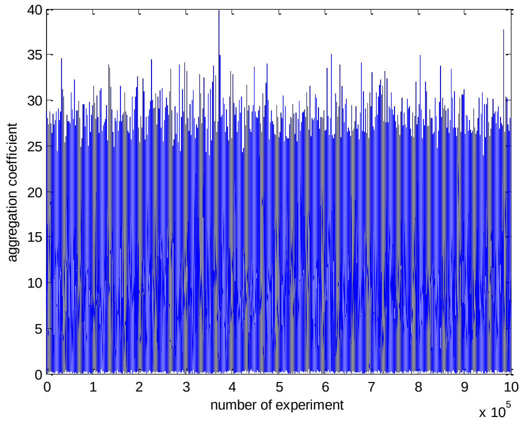

Fig. 3: Aggregation Coefficient

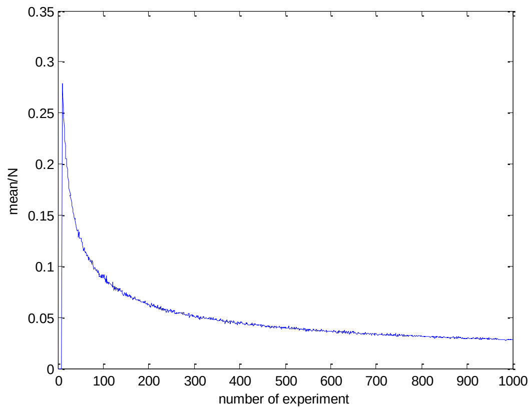

Fig. 4: Ratio Between Mean and the Maximum Possible Value of Current

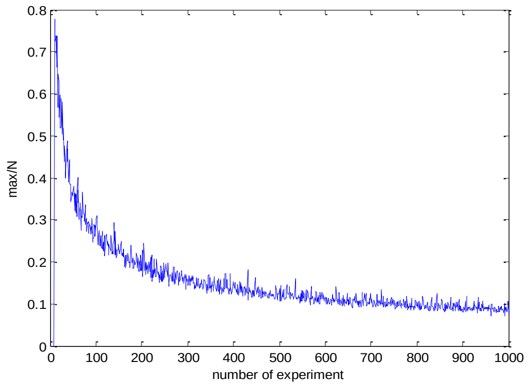

Fig. 5: Ratio Between Maximum Value Occurred and the Theoretical Maximum Value (N) for Uniform Phases

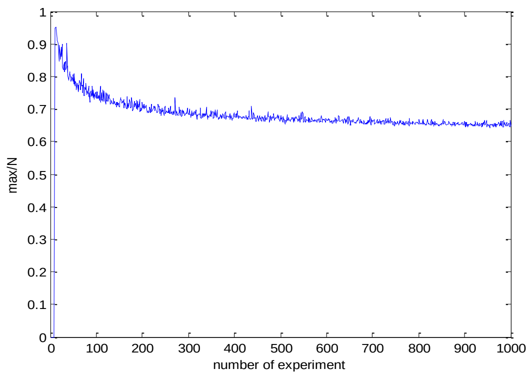

Fig. 6: Ratio Between Maximum Value Occurred and the Theoretical Maximum Value (N) for Normal Phases

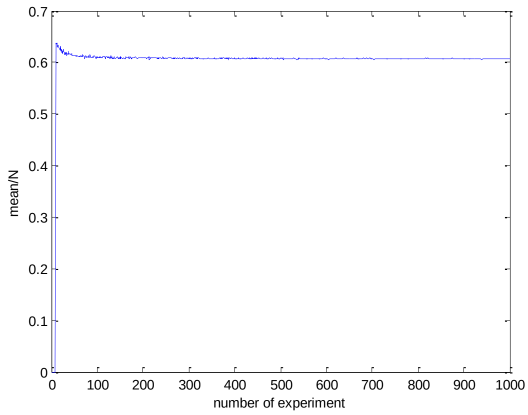

Fig. 7: Ratio between Mean and the Theoretical Maximum Value (N) for Normal Phases

4.3. Random magnitudes and phases

In general, the magnitude and phase of each load are arbitrary and may be modeled as random. Therefore a practical measure may be defined as follows. The first step is to find an arithmetic average of all currents.

$$I_{ave} = \frac{1}{N}\sum |I_k| \ , \forall h$$

Second, determine the relative coefficient as:

$$\gamma_r = \frac{|I_{TOT}|}{NI_{ave}}$$

In this way, one can easily estimate the total h^{th} harmonic current using the relative coefficient and rated currents of each load. The following figures depict the aggregation coefficient for the same set of simulation.

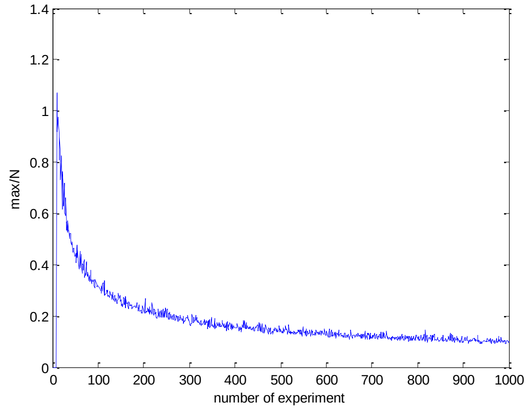

Fig. 8: Ratio Between Maximum and the Theoretical Maximum Value (N) for Normal Phases and Magnitudes

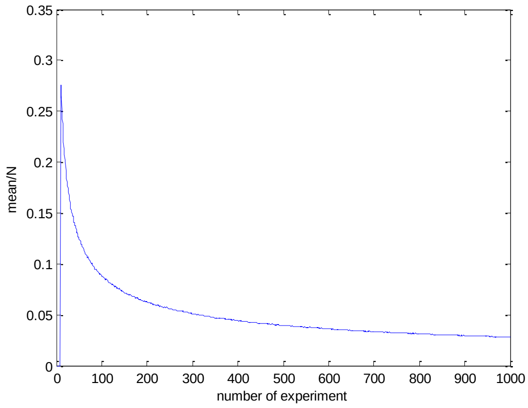

Fig. 9: Ratio Between Mean and the Theoretical Maximum Value (N) for Normal Phases and Magnitudes

It is observed that the random magnitude of harmonic currents makes the coefficient smaller, though in real situations, arithmetic summation is too pessimistic.

5. Evaluation and comparison

In this section the proposed method is compared to the existing ones in an experimental case study.

5.1. N identical loads (same current magnitudes)

The following figure depicts the aggregated current for 10 identical loads with the same current and random phases-normally distributed- which shows that the proposed method has advantage over arithmetic sum. The root square sum is not acceptable since it provides too optimistic estimations. The experiment is repeated 100 times.

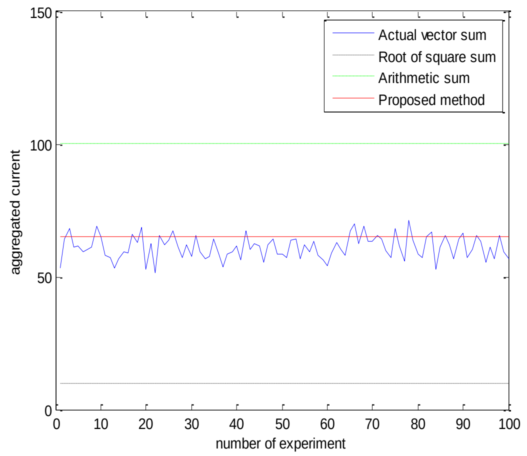

Fig. 10: Comparison of Different Estimates: Identical Loads

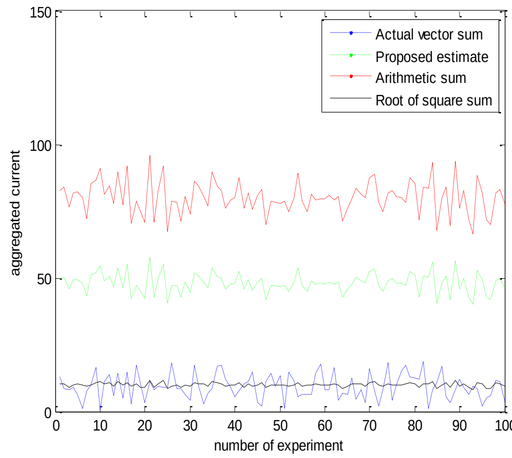

Fig. 11: Comparison of Different Estimates: Different Loads

5.2. N different loads (different current magintudes)

Figure 11 shows the aggregated current for 10 different loads in a hundred simulations with random phases and currents. It is shown that the proposed method provides more realistic estimate of aggregated harmonic current while the estimated aggregated current is always larger than the real value.

It is noted that IEC 61000-3-6 method is too conservative for low harmonic orders (arithmetic sum- dashed red line) and too optimistic for higher order harmonics (higher than 10) since the actual vector sum exceeds the estimate several times. The proposed estimate is between the two values, not violated by the actual vector sum. The proposed sum is independent of experiment (as the arithmetic and root of square sums) when the devices are drawing same currents; however the estimate of aggregated current depends on the experiment, when loads are considered to be different (i.e. drawing different currents in each experiment).

6. Conclusion

A review of the existing approaches for aggregation computation techniques is provided. Simulations illustrate that the existing formulas are too pessimistic. Therefore a simple frame work is proposed for standard calculation of the aggregated harmonic current. The simulation studies shown that any estimation method is extremely dependant on the experimental data and shall be examined using experiments. Pessimistic estimations may not require extensive simulation/experimental verification, however they are not accurate. A simple frame work is proposed which is essentially seeking a coefficient for certain situations to estimate the aggregated harmonic current. The proposed frame work requires extensive experimental data to define required parameters.

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