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Research Article

Observations on Harmonics Summation in Transmission Systems: Alternative Aggregation Estimation

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The aggregation of harmonic components from different sources is one of the critical and challenging assessments in electric power systems. Harmonic summation analysis and estimation is not a simple task since there will be variations because of the grid complexity, nonlinear sources, and unpredictable behaviour of harmonic currents that affect the results. An evaluation of harmonic summation using alternative methods to calculate the harmonic composition at any network point is suggested. A typical arrangement of transmission grids was modelled and used to simulate the results. This paper aims to highlight the results obtained by these alternative methods of harmonic summation and show the role of this type of analysis in transmission systems planning. The contributions are (a) illustrate how alternative methods of harmonic summation can be applied to investigate harmonic aggregation from different sources; (b) provide a case study that also discusses the harmonic aggregation effects with different locations of sources and component phase angle shifting; (c) show comparison and correlation between those alternative summations calculations with a standardized and firmly adopted method (proposed by IEC 61000-3-6). The software MATLAB/Simulink performs simulation and analysis. Finally, the work discusses the findings.

1. Introduction

Studies on harmonic distortions are usually necessary when measurements demonstrate a considerable harmonic level or when planning the connection of new loads and equipment sources of harmonic currents [1]. Harmonic contributions need caution because they can cause overheating in different equipment of the grid, failure in electronics, voltage stress in capacitors, etc. [2]. Transmission grids are especially vulnerable to harmonic resonances because of the circuits' low resistance values, so the resonances have high-quality factors [3]. For this reason, utilities often conduct measurement campaigns to determine the harmonic levels and assess their power quality condition [4]. Therefore, one should not neglect these distortions in the electric power systems, mainly in systems with multiple sources. The sum of different contributions should be estimated in harmonic studies.

The superposition principle is the basis for harmonic combination and been necessary for a phasorial composition for the proper use of the code [5]. However, due to the uncertainty associated with amplitude and harmonic phase, alternative expressions that consider impedance between sources are a reliable option. Alternative methods can estimate the resulting harmonic voltage if harmonic currents are known for a specific scenario. Simulation software uses sophisticated techniques to replicate practical situations. However, the absence of functional measurements to confirm the assumptions made by those tools is the primary concern in combining alternative methods of harmonic estimation. In contrast, simple techniques should be used to avoid estimation difficulties. These simple methods could be combined with site measurements and better understand how harmonics combine themselves.

Due to the uncertainty of the magnitude and angle of the phase, values less than the arithmetic summation of the maximum amplitudes will result from the aggregation of different harmonics sources [6]. If the harmonic study only considers the arithmetical sum as the total harmonic, this can cause costs and mitigation efforts beyond what is necessary [7]. Therefore, cancelling effect needs to be analysed, considering the variety of harmonic phase angles [8]. The resulting summation could be a challenge to estimate with precision.

The major existing standards on harmonic limits are based on fixed or strict values [9]. However, the literature and field measurements show the harmonics' nonstationary behaviour in different grid conditions. This variant nature requires detailed analysis and accurate measurements since using probabilistic methods applied to spectral analysis may not be the precise solution for all cases [10]. However, several scenarios and experiments have been developed to analyse the summation of harmonics. Until today these approaches are discussed and re-evaluated by several studies. A description of some methods and experiments is presented to give a better idea of the problem.

In [11], the author used a uniform probability density, applying magnitude and phase angle. It was concerned with the aggregation of random phasors, assuming that each harmonic load acts as a distorted current source. On the other hand, the study in [12], on the other hand, performed experiments to verify the behaviour of the arithmetic sum for different orders considering sources of harmonics of nonlinear loads. In [13], the authors used arithmetic summation and root square summation (RSS), considering each method regarding low and high harmonic orders. On the other hand, [14] proposed a variation factor related to a probability not exceeding the arithmetic aggregation. Another proposed method was based on the sum of sine waves [15], considering constant amplitudes and phases varying with uniform probability. With this result, it was possible to demonstrate that for some harmonic orders, random variations of the phase angle of different sources significantly decrease the likelihood of occurrence of the arithmetic sum value [16].

The method proposed in [17] worked with desultory probability features related to the summation of harmonic components. To evaluate the harmonic magnitudes, the authors used the summation method together with harmonic load flow and made a comparison with a Monte Carlo assessment for validation. In [18], an improved way for assessing harmonic levels caused by domestic load areas and an alternative bottom-up type approach was presented. The proposed model uses a typical spectrum and correlates with other operation scenarios based on different regions. The vectorial sum results were obtained by probabilistic functions and compared with actual field measurements.

The paper in [19] investigated how the bivariate normal distribution model could describe the harmonic summation from different sources. The loads considered are AC/DC static power converters with power fluctuation conditions. An extension of this investigation was also proposed [20], using the generalized Gamma distribution model to the magnitude using the method of moments. In [21], the authors proposed a method for describing a mathematical model and a statistical technique that assess various contributions of variable speed air conditioners on domestic harmonic levels. The review in [22] was presented as a discussion and an essential material in the literature for harmonic aggregation. It also has probabilistic calculation and statistical distribution tools applied to harmonic emissions from multiple random harmonic sources. Also, in [23], a solution was demonstrated for the density probability function to amplitude from different sources. In this case, it was shown that even though the current harmonic components varied randomly, the ranges are the same for additional orders, requiring only the arithmetic and geometric sum to define the function's parameters.

A case study [24] included a discussion on the aggregation of harmonic currents within a wind farm, 10 MW, and the results are compared with methodologies provided by International Electrotechnical Commission (IEC). An examination of the harmonic summation models defined in IEC 61000-3-6 is made by [25], illustrating the application of the general summation law based on measured data from electric arc furnaces sites. In [26], the proposed summation method aimed to adjust the methodology proposed in IEC 61400-21 since measurements suggested significant errors, using only the harmonic current sources magnitudes.

The analysis of [27] proposed an algorithm to calculate the probability of two harmonic voltages exceeding the vectorial summation magnitude. The authors then suggested another summation method for multiple harmonic sources distinct from the IEC 61000-3-6 standard. Another study stated that the proposed summation method of the IEC 61000-3-6 standard could lead to improper results regarding the sum of harmonics for grid code compliance since the phase angle of harmonic orders is not considered. The method proposed in [28] aimed to understand better offshore wind power plants harmonic emissions based on whether the phase angle behaviour tends to be deterministic or stochastic. Other works addressed this critical topic regarding wind parks [29, 30].

In [8], a study was carried out to analyse the summation of harmonics in industrial installations based on field measurements. In addition to the exciting results, from the probabilistic studies view, considerations about measurements were pointed out. The contribution in [31], on the other hand, proposed a deterministic methodology for harmonic modelling in a medium voltage (MV) and low voltage (LV) distribution network using aggregated harmonic source models based on measurements. Methods were used according to IEC 61000-3-4 summation law and using complex phasors. Other recent works still deal with the theme of summation of waveform distortions also focused on problems such as supraharmonics [32, 33]. Lastly, a study case [34] regarding a harmonic aggregation analysis in a Brazilian actual transmission system model was conducted using a similar approach of alternative summation laws proposed by this work.

This paper explores alternative expressions to calculate harmonic summation, revisiting and exploring further the contributions from [35]. The MATLAB/Simulink software performs transmission system modelling using typical transmission parameters and simulation. In addition, to observe the aggregation results in different scenarios and configurations, the study also compares the alternative summation methods with the summation method proposed by IEC 61000-3-6 [36]. This paper aims to illustrate how those alternative estimation methods can be used to bring a range of information about harmonic aggregation from several harmonic sources for different cases. The specific contributions are listed as follows:

(i) Illustrate how alternative methods of harmonic summation can be applied to investigate harmonic aggregation from different sources, which can be applied in transmission planning studies. The results also aim to provide another way to interpret the expressions, including showing a possibility of uncertainty factors.

(ii) Provide a case study that also discusses the harmonic aggregation effects with different locations of sources and source phase angle shifting. Also, illustrates the potential application based on probabilistic analysis.

(iii) Show a comparison and correlation between those alternative summations calculations with a standardized and strongly adopted method (proposed by IEC 61000-3-6).

The paper is organized as follows: Section 1 introduces and presents the objectives. Section 2 details the methodology adopted in this work. The results and discussions are presented in Section 3. Section 4 presents the conclusion.

2. Methodology

2.1. Approach Adopted. The assessment aims to evaluate the aggregation methods for several scenarios. Harmonic penetration studies are performed to calculate the vectorial summation and estimate the alternative calculations. Therefore, the work aims to perform harmonic injection from different sources in a transmission system model with instantaneous spectra based on the characteristic waveform. In addition, evaluate the resultant summation in the harmonic levels of the system buses. This procedure can provide helpful information about the individual harmonic levels that may occur at any point in the system. Besides the vectorial composition, the following alternative methods have been chosen to give a broad spectrum of the degree of variation and, consequently, the probable values:

(i) Root-Square-Sum (RSS): the benefit of this value is that it corresponds to a significant amplitude with a high probability of occurrence.

(ii) Arithmetic: it expresses the maximum amplitude that can occur but with a very low probability of occurrence.

(iii) Random: expressions for random phase (RP) and random phase and magnitude (RPM) are thought to complete the probable values' picture. When there is only a random phase, the corresponding expression provides a value with a probability of exceeding the RSS of 37%. In contrast, the random phase and magnitude have a 5% probability of exceeding the RRS.

A summary of the alternative methods expressions is shown in Table 1. Here, $I_{k,h}$ is the h current harmonic order at the busbar k, and $I_{i,h}$ is the h current harmonic order contribution of harmonic source i. Similarly, for the calculation of the harmonic voltage $V_{k,h}$ on the k bus, the component $I_{i,h}$ is multiplied by the transfer impedance between the harmonic source and the busbar, $Z_{i,k}$. In addition, n is the number of harmonic sources. Due to some harmonic sources, these methods are used to calculate the resulting harmonic current. The use and interpretation of these numbers should always be used in conjunction with practical information about the harmonic sources present in the power system. Note that, all the harmonic currents are specified by the magnitude and phase angle on a three-phase basis.

The IEC 61000-3-6 is the standard for assessing harmonic distortion limits the connected loads can meet, either at high or medium voltage levels. As shown in equation (1) [36], the standard also addresses a general summation law for harmonic emissions coming from multiple loads. Here, α is a coefficient of the summation, with corresponding values for different harmonic orders [37]. For harmonic orders less them 5^{th}, α is equal to 1. From 5^{th} harmonic up to 10^{th}, α is equal to 1.4. In addition, for higher orders, it assumes α is equal to 2. In this study, the IEC 61000-3-6 summation approach is compared to the alternative methods prior described.

$$I_{k,h} = \sqrt[\alpha]{\sum_{i=1}^{n} \left|I_{i,h}\right|^{\alpha}}. \quad (1)$$

2.2. Study Procedures. As described above for multiple harmonic sources, the proposed method of investigation is illustrated in this section using some examples. Figure 1 illustrates the simulated transmission system for the tests. The configuration shown is a simulated network but uses typical parameters for the 230 kV CHESF system [35], and it was modelled on Simulink. The transmission lines were modelled as distributed line parameters [38], the equivalent transmission model is assumed for the rest of the transmission grid, and the harmonic sources as ideal current sources.

The harmonic injection by nonlinear loads can be represented as current sources. This method has low computational effort, and the solution is obtained directly. Besides the magnitude, the current sources may or may not have the typical current lag to the applied voltage, also called phase angles [1, 39]. The harmonic current waveform, shown in Figure 2, composed of the fundamental and harmonics 5, 7, 11, and 13, is used to simulate the harmonic injection in busbars 1, 2, and 3. The phase angles and amplitude for cases 1 through 4 are in Table 2, resulting from equation (1). The

Table 1: Summation methods adopted (equations from [35]).

Method	Composition
Vectorial	$I_{k,h} = \sum_{i=1}^{n} I_{i,h}$
Arithmetic	$I_{k,h} = \sum_{i=1}^{n} \lvert I_{i,h}\rvert$
RSS	$I_{k,h} = \sqrt{\sum_{i=1}^{n} \lvert I_{i,h}\rvert^2}$
RP	$I_{k,h} = \sqrt{(\pi/2)\sum_{i=1}^{n} \lvert I_{i,h}\rvert^2}$
RPM	$I_{k,h} = \frac{1}{2}\sqrt{(\pi/3)\sum_{i=1}^{n} \lvert I_{i,h}\rvert^2}$

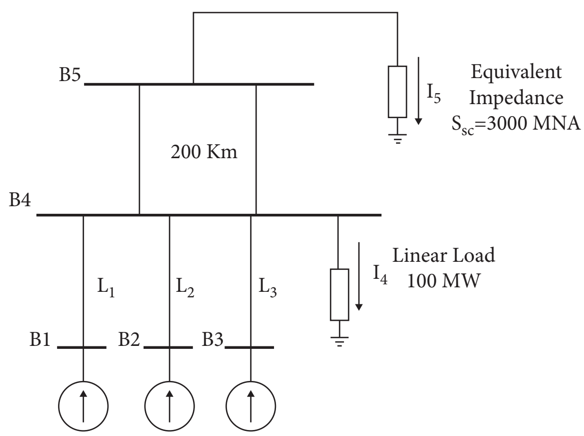

Figure 1: Transmission system summation test.

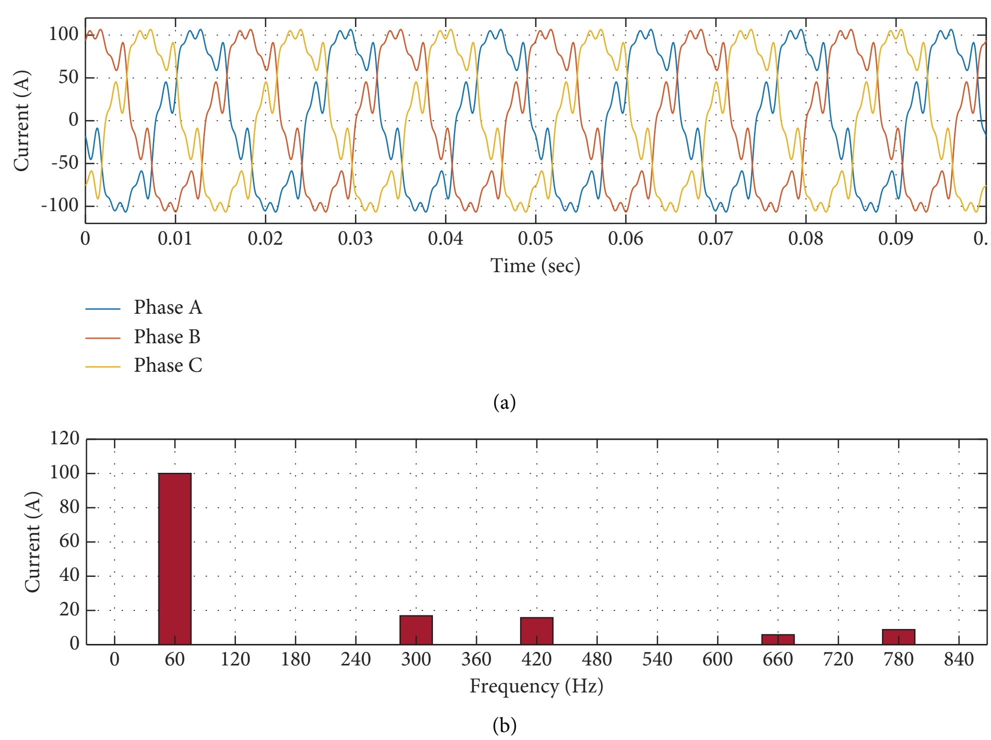

Figure 2: Injected waveform (a) and its spectrum (b).

Table 2: Typical phase angle spectrum-phase A.

Harmonic order	$\% I_{\text{nom}}$	$\theta_{h\text{-spec}}$	$\theta_{1_{\text{spec}}} = 30^{\circ}\theta_h$	$\theta_{1_{\text{spec}}} = 60^{\circ}\theta_h$
5	16.86	80.64	−69.36	−219.36
7	15.74	86.67	−123.33	−333.33
11	5.78	−95.35	−425.35	−755.35
13	8.77	−96.36	−486.36	−876.36

typical spectrum is related to the injected current waveform. In possession of the typical spectrum information, it is possible to calculate the set of harmonic current phase angles, as shown in equation (3). In which θ_h is the phase angle of the current source harmonic order h, and θ_{h_spec} is the phase angle of the current harmonic source for a typical spectrum. θ_1 is the phase angle for the fundamental frequency current obtained by a load flow, and θ_{1_spec} is the typical phase angle for the fundamental frequency current.

$$\theta_h = \theta_{h\text{-spec}} + h\left(\theta_1 - \theta_{1\text{-spec}}\right). \tag{2}$$

An equivalent impedance, shown in Figure 3, represents the remainder of the transmission system connected at busbar 5 for each phase. No typical impedance can be used in any system without question but measurements. However, inspections of impedance characteristics show that a T circuit can be assumed as an accurate method when the necessary data are available [35]. Basically, the harmonic impedance of a transmission system is determined by several parameters like fault level, system loads, capacitances (lines and cables), etc. The equivalent model can reproduce the prominence of the first two resonance frequencies, parallel and series.

The L_1, L_2, and C parameters are calculated using the following from equations (3) to (5). In those equations, V_f represents the nominal voltage in kV, S_{sc} the short-circuit level in MVA, ω_p the first parallel resonance, and ω_s is the first series resonance. Figures 4 and 5 compare the impedance measurements in busbar 4 and 5, respectively, when the line lengths vary. It is possible to observe that a line length variation causes changes in the number of resonance peaks and their magnitudes.

$$L = L_1 + L_2 = \frac{V_n^2}{S_{sc}.\, 2\pi f}, \tag{3}$$

$$L_1 = L\frac{{\omega_p}^2}{\omega_s}, \tag{4}$$

$$C = \frac{1}{\omega_p.L_2}. \tag{5}$$

The Total Harmonic Distortion (THD) [40] and harmonic voltage components are calculated using different methods when the injected currents' variations are assumed. This analysis aims to bring this approach through software widely used for the simulation and study of power systems and validate the reproducibility [35]. The four cases described below highlight some aspects of harmonic summation.

(i) Case 1: the currents injected in busbars 1, 2, and 3 are the same, with the length of the lines L1, L2, and L3 equal to 100 km.

(ii) Case 2: there is a phase shift between the injected currents. The injected current at busbar 2 has a 30° phase shift, and the one at busbar 3 has a 60° phase shift. The line lengths L1, L2, and L3 are equal to 100 km.

(iii) Case 3: the currents injected are the same as in Case 1, but the lines L1, L2, and L3 are 50, 100, and 250 km.

(iv) Case 4: the currents injected are the same as in Case 2, but the lines L1, L2, and L3 are 50, 100, and 250 km.

(v) Case 5: perform a probabilistic analysis to generate 1000 samples of scenarios in which the uncertain element of the model is the ideal harmonic source. For each round simulated, the individual harmonic order assumes a value magnitude with a uniform distribution, and the phase angles can take any value between 180° and −180°, also with uniform distribution. The amplitude is uniformly distributed between 10 A and 20 A for the 5th and 7th orders, 4 A to 10 A for the 11th order, and 7 A to 14 A for the 13th order.

3. Results and Discussion

3.1. Harmonic Distortion. This analysis highlights harmonic current values obtained in buses 4 and 5 for each proposed configuration about the aggregation's vectorial composition. Thus, the THD for quantitative analysis and the effects explored in the aggregation of harmonic sources can be observed. Figure 6 shows the values of harmonic currents resulting in the buses for case 1. Comparing the values found for the buses, Busbar 4 has slightly lower current values than busbar 5 for the 7th and 13th harmonics. For the 5th harmonic, the current value is considerably lower, 18.98 A, while at busbar 5, the value is 42.81 A. Unlike the 11th harmonic, which presents 24.60 A for busbar 4 and 19.0 A in busbar 5.

Figure 7 shows the values of harmonic currents resulting in the buses for case 2. In case 2, it is possible to observe a decrease in harmonic currents provoked by the effect of the shifting phase angle between the sources. This decrease occurred mainly for the 5th and the 7th, concerning the values obtained in case 1. However, the comparison between buses does not show differences attested previously. It indicates that the mismatch between sources produces a favourable effect on reducing harmonic distortion. The THD in busbar 4 and 5 is 2.64% and 2.50%, respectively, in case 2, less than those obtained in case 1, 4% and 5.68%.

Figure 8 shows the values of harmonic currents resulting in the buses for case 3. Considering the effects of the system configuration, that is, the relative position of the harmonic

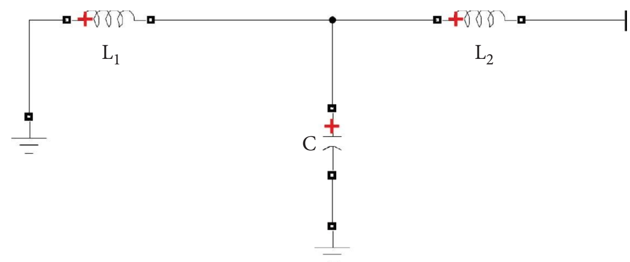

Figure 3: Transmission system equivalent model for each phase.

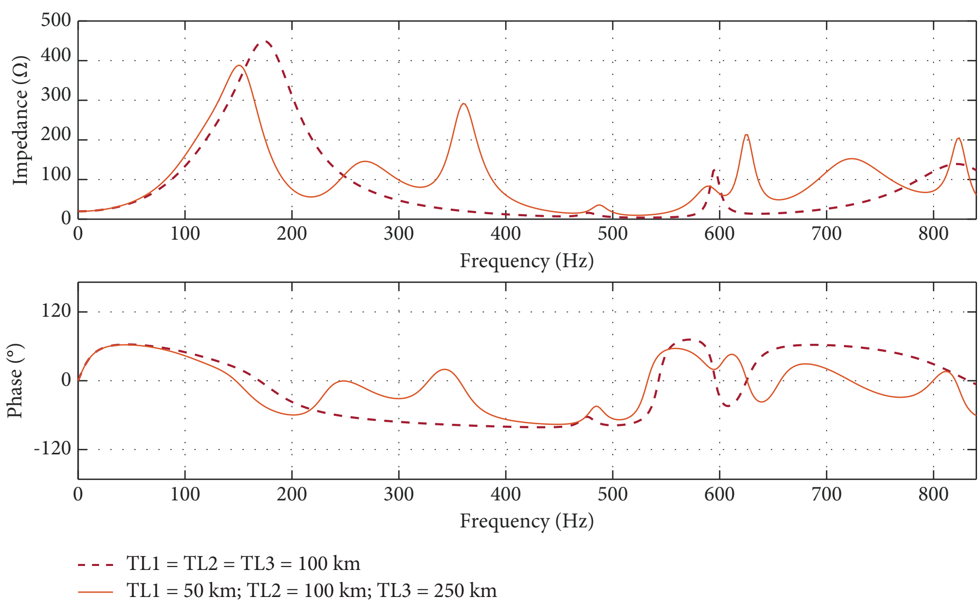

Figure 4: Impedance measurement at busbar 4.

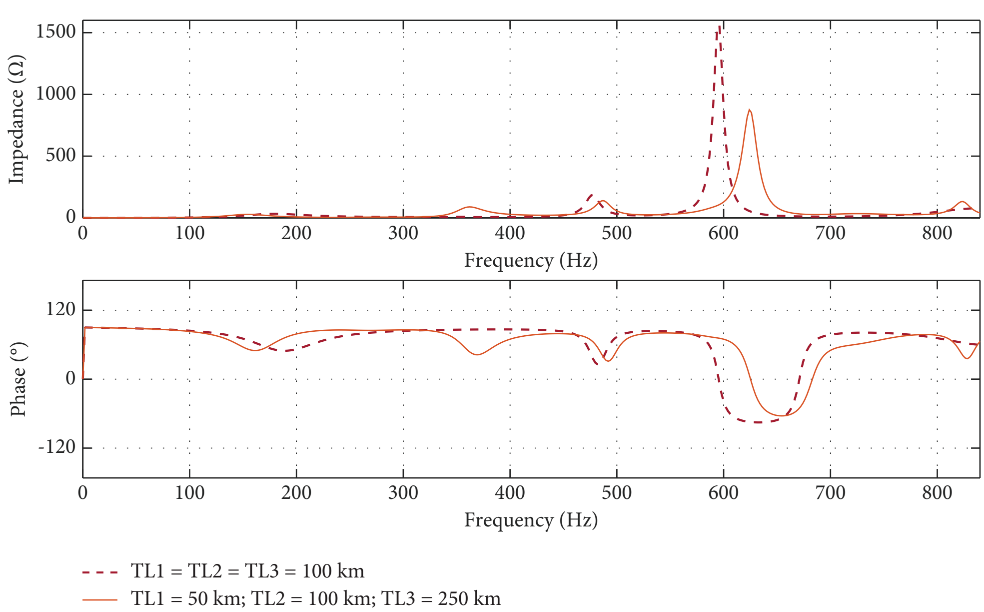

Figure 5: Impedance measurement at busbar 5.

sources. For that, compare cases 1 and 3. They show that the distortion is reduced in busbar 4 and 5 when different line lengths are used. It shows that varying position of the sources causes comparatively little cancellation at remote points. The THD reduce to 3.44% in busbar 4, case 3, compared to 4.00% in case 1. As the relative position of the

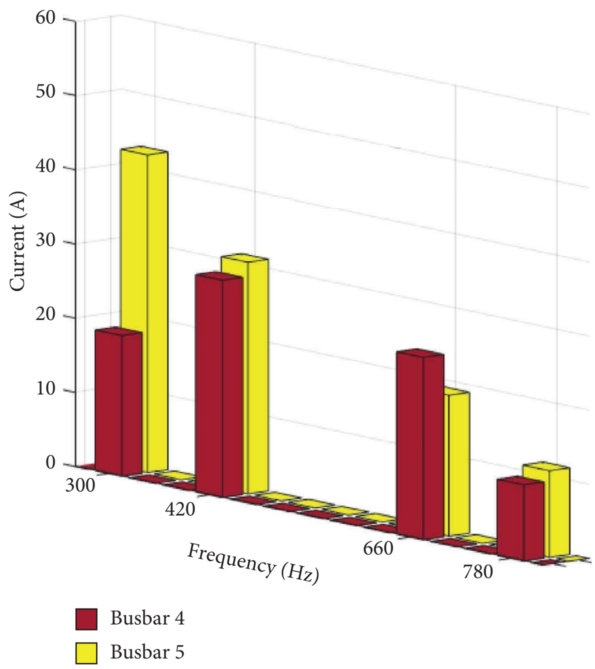

Figure 6: Case 1-Harmonic Current Spectrum in busbars 4 and 5.

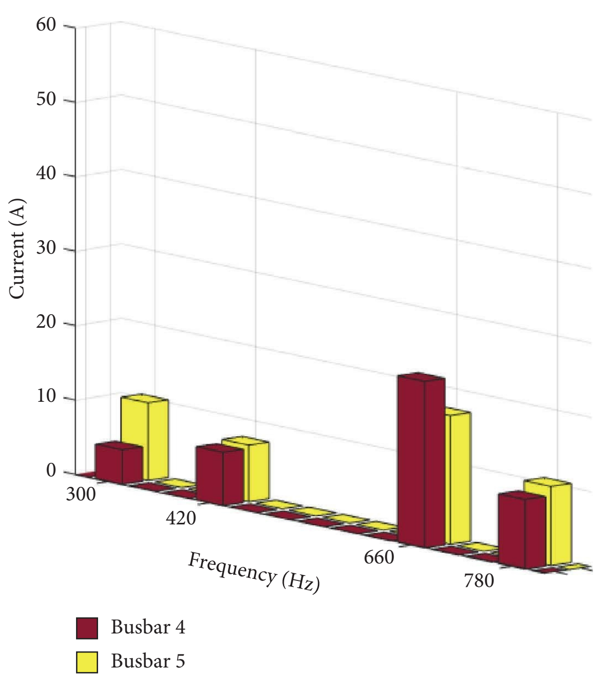

Figure 7: Case 2-Harmonic Current Spectrum in busbars 4 and 5.

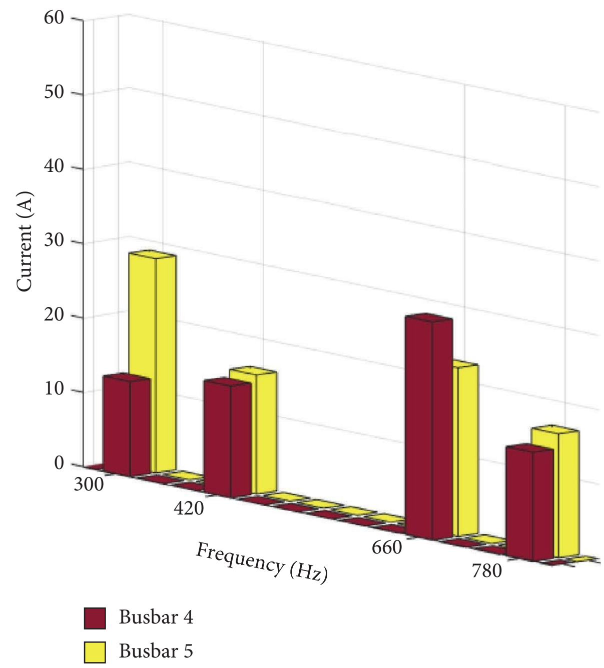

Figure 8: Case 3-Harmonic Current Spectrum in busbars 4 and 5.

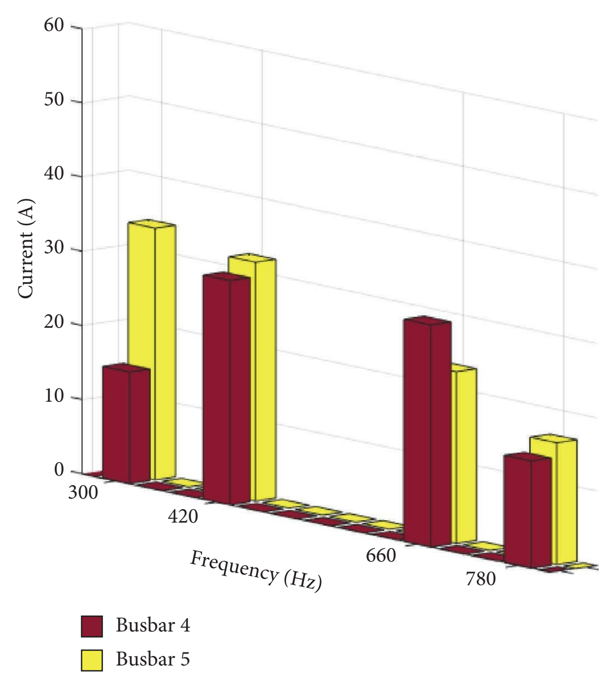

Figure 9: Case 4-Harmonic Current Spectrum in busbars 4 and 5.

harmonic sources is, in general, an uncontrollable parameter, the critical fact here is that phase angles of the harmonic currents injected from steady sources could be used to reduce the harmonic content. In comparison, it is possible to observe the 5th and 7th fall around 10 A. For example, the 5th harmonic dropped to 12.76 A at busbar 4 and 28.79 A at busbar 5. On the other hand, the 11th and 13th increased slightly.

Figure 9 shows the values of harmonic currents resulting in the buses for case 4. Case 4 is analysed to investigate the combined effect of the phase angles with the relevant source's position. Consider busbar 4 and 5. There was an amplification of the 7th harmonic. Thus the combined effect created a favourable combination at the 7th harmonic. For busbar 5, there was an increase in the 5th current harmonic, from 28.79 A to 33.83 A. Alternatively, the resulting current appeared unaltered at the 11th and 13th harmonics. Although it is well known that changes in the phase angles can reduce the harmonic content caused by many nonlinear

Table 3: Total harmonic distortion summary.

Case	Bus 4 (%)	Bus 5 (%)
1	4.00	5.68
2	2.64	2.50
3	3.44	4.12
4	4.53	5.47

sources. Another consequence of combined resonance at the 7th harmonic, the THD was increased at busbar 4 and 5 for Case 4, compared to Case 3. Table 3 details the THD values for each Case.

3.2. Alternative Methods Summation. In case 1, busbars 4 and 5, the vectorial and arithmetic composition should present the same value as the currents have the same phase angles (TL1, TL2, and TL3 have the same length). Three should multiply the harmonic voltage produced by one source if a single-phase was used. However, the mutual coupling terms are added arithmetically (for the Arithmetic sum) in the total distortion for three-phase analysis. Thus, the arithmetic summation represents the maximum harmonic voltage possible. Case 1 highlights another critical point. At busbars 4 and 5, the harmonic voltages are not attenuated because of the relative position of the sources. The vectorial sum is more significant than the random expressions and RSS. Figure 10 illustrates the results for cases 1 and 2.

In case 2, the phase shift's effect reduces the harmonic voltages calculated by the vectorial composition in busbars 4 and 5 for the 5th and 7th harmonic. Hence, the combined effect of the phase angles of the injected currents and system impedance can reduce the harmonic voltages at specific frequencies while increasing them at others. Also, from case 2, the vectorial sum stays close to the arithmetic sum for the two highest frequencies in busbars 4 and 5. In busbar 5, the 13th harmonic vectorial sum is equal to 1.11%, compared with the arithmetic sum of 1.72% (the practical value of the arithmetic sum should be 1.63% as in case 1).

Thus, the phase shift between sources is shown to reduce the harmonic composition at lower frequencies. The effect is less pronounced at higher frequencies. The vectorial of the 5th harmonic in busbar 4 reduced from 0.83% in case 1 to 0.21% in case 2, while the 13th reduced from 0.83% to 0.79%. Except for the vectorial composition, the other alternative methods have the same values in cases 1, and 2 since the injected currents' phase angles are only varied. In busbar 4, the 7th vectorial sum is 0.74% compared with 1.76% (RSS); 4.31% (arithmetic); 2.21% (RP) and 0.90% (RPM).

Therefore, these alternative methods can be beneficial in indicating how accurate the vectorial composition is in the comprehension of the harmonic variations. In busbar 5, the vectorial sum of the 13th harmonic approaches the arithmetic sum. Thus, implying the correct value is likely to be lower than the vectorial sum prediction for some time, i.e., the vectorial sum would be a pessimistic estimation. The interpretation of these results depends on the knowledge of the harmonic sources' behaviour and the engineer's experience. Figure 11 shows the results of cases 3 and 4.

The effects of moving the harmonic sources and varying the phase angles are observed in cases 3 and 4. It is possible to keep exploring only the harmonic source's position. In case 3, compared to case 1, the 7th harmonic decreased its vector value for both buses. However, the alternative summation values show that this harmonic can still assume greater values in these conditions than in case 1. Even in case 3, for both buses 4 and 5, the vectorial sum values are only more significant than the random phase magnitude method. In case 4, the combination of proposed effects causes an increase in the vectorial value of the 7th harmonic, as was observed in the previous subsection. The estimates resulting from the alternative methods are very similar to case 3. However, the vectorial summation has a value very close to the RSS method for all frequencies in the two busbars.

The results of case 5 confirm that the value of the vector summation of the harmonic contributions can present different values during the aggregation of amplitudes and random angles for the harmonic orders. After running the probabilistic analysis simulation, the probability density function (pdf) of the results for each summation method was calculated. Figure 12 shows the pdfs of each technique for the four harmonic orders explored in this work. In the latter case, it is clear that each aggregation method may indicate an overestimated or underestimated tendency of the resulting harmonics by different sources. However, these results can provide a range or even knowledge about the assumed values of the vectorial result. Moreover, although each harmonic order needs an evaluation, looking at the pdfs, it is clear which results are more representative concerning the vectorial summation for generalized results.

Therefore, the results have shown that using alternative expressions to combine the harmonic voltages proves useful for analysing harmonic summation. These methods of evaluation incorporate the system characteristics and possible harmonic variations. Although the examples use typical system parameters data and harmonic currents, they may represent likely system behaviour. These results obtained may vary according to the systems and characteristics of the network due to direct resonances that can be seen. However, these alternative summation results allow a broader estimate of the system's behaviour in different configurations and variations according to the frequency.

3.3. Comparison with IEC 61000-3-6. This analysis means to compare the explored results based on alternative methods with the one proposed by IEC 61000-3-6. The idea is to highlight the similarities and expectative with a standardized calculation as a reference, which indicates the applicability and reliability of computation. Using the exponents proposed by the standards, the calculations lead to that for harmonic frequencies greater than order 10, the numerical value obtained corresponds to the RSS (alternative method). However, these results can vary for another range and may not present a straightforward correspondence. Looking at the results is an opportunity to visualize such differences.

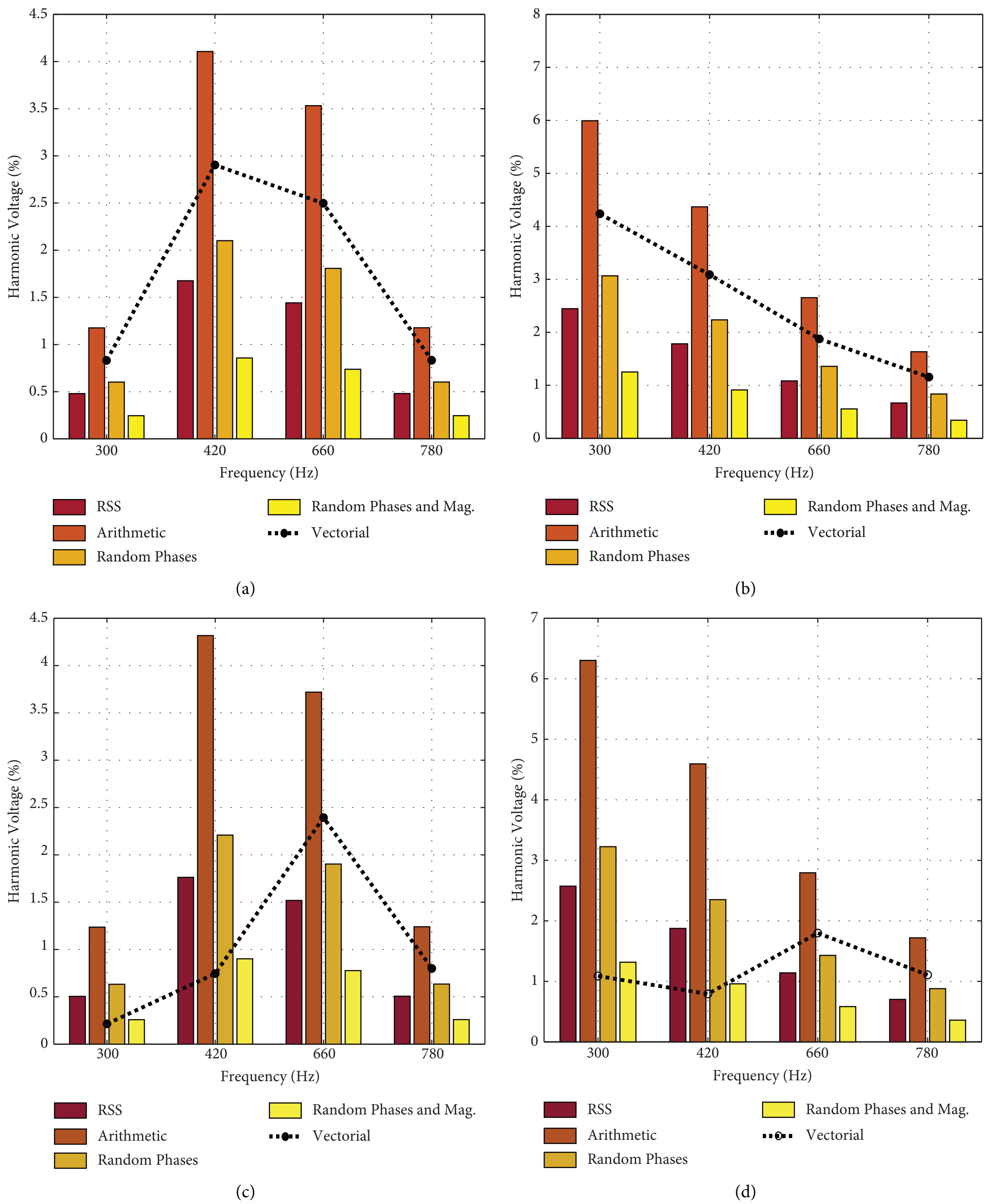

Figure 10: Summation results for Case 1 at busbar 4 (a) and busbar 5 (b), and Case 2 at busbar 4 (c) and busbar 5 (d).

Only the results for case 2 proposed in the methodology were considered to simplify the presentation, measured in busbars 4 and 5. The harmonic orders chosen for analysis were 5th for the intermediate class ($\alpha = 1.4$) and 13th for higher frequencies ($\alpha = 2$). This choice highlights the difference between the coefficients proposed by the IEC standard. The IEC method for busbar 4 has the value of 9.81 A and 22.12 A in busbar 5. Looking at RSS values, they

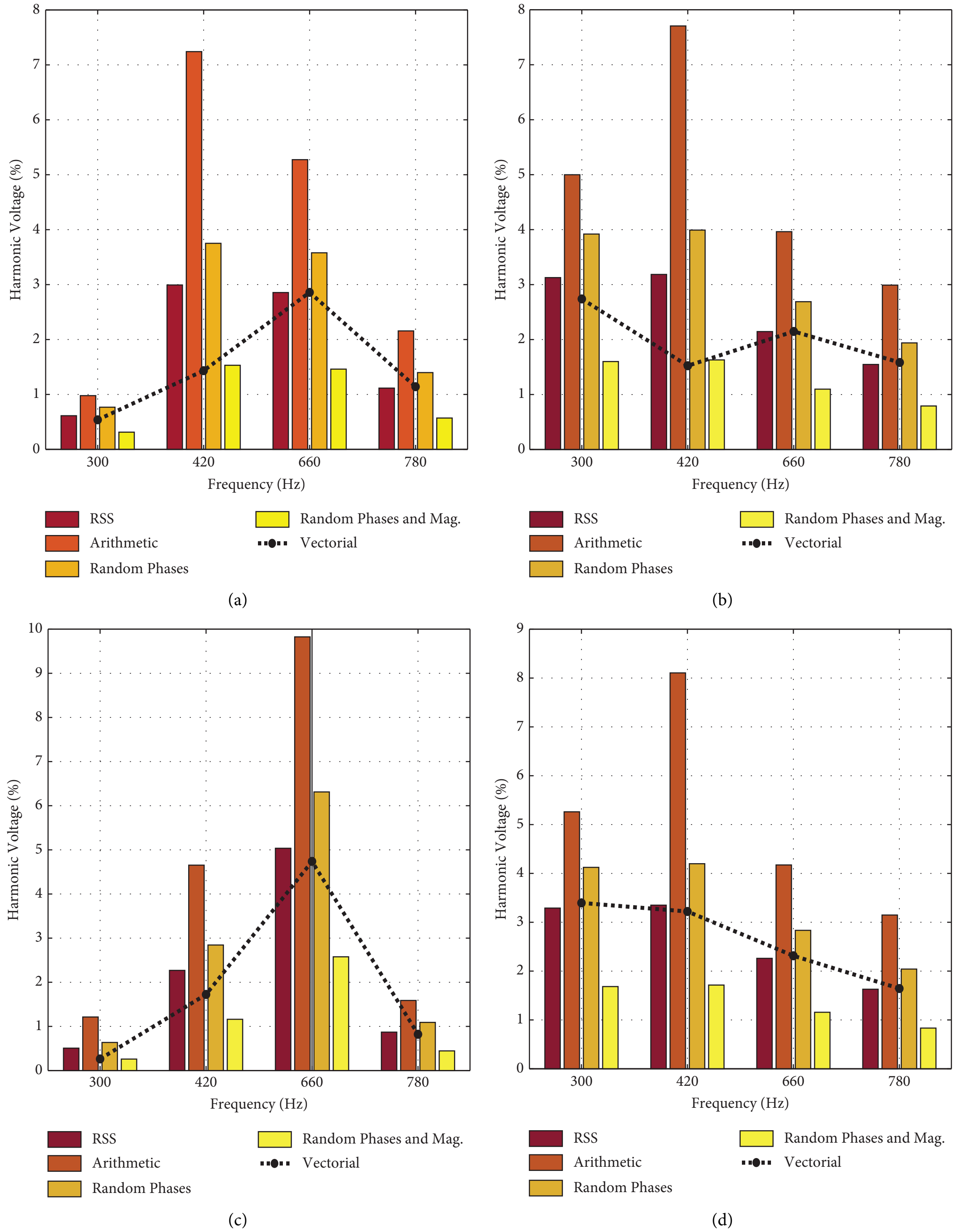

Figure 11: Summation results for Case 3 at busbar 4 (a) and busbar 5 (b), and Case 4 at busbar 4 (c) and busbar 5 (d).

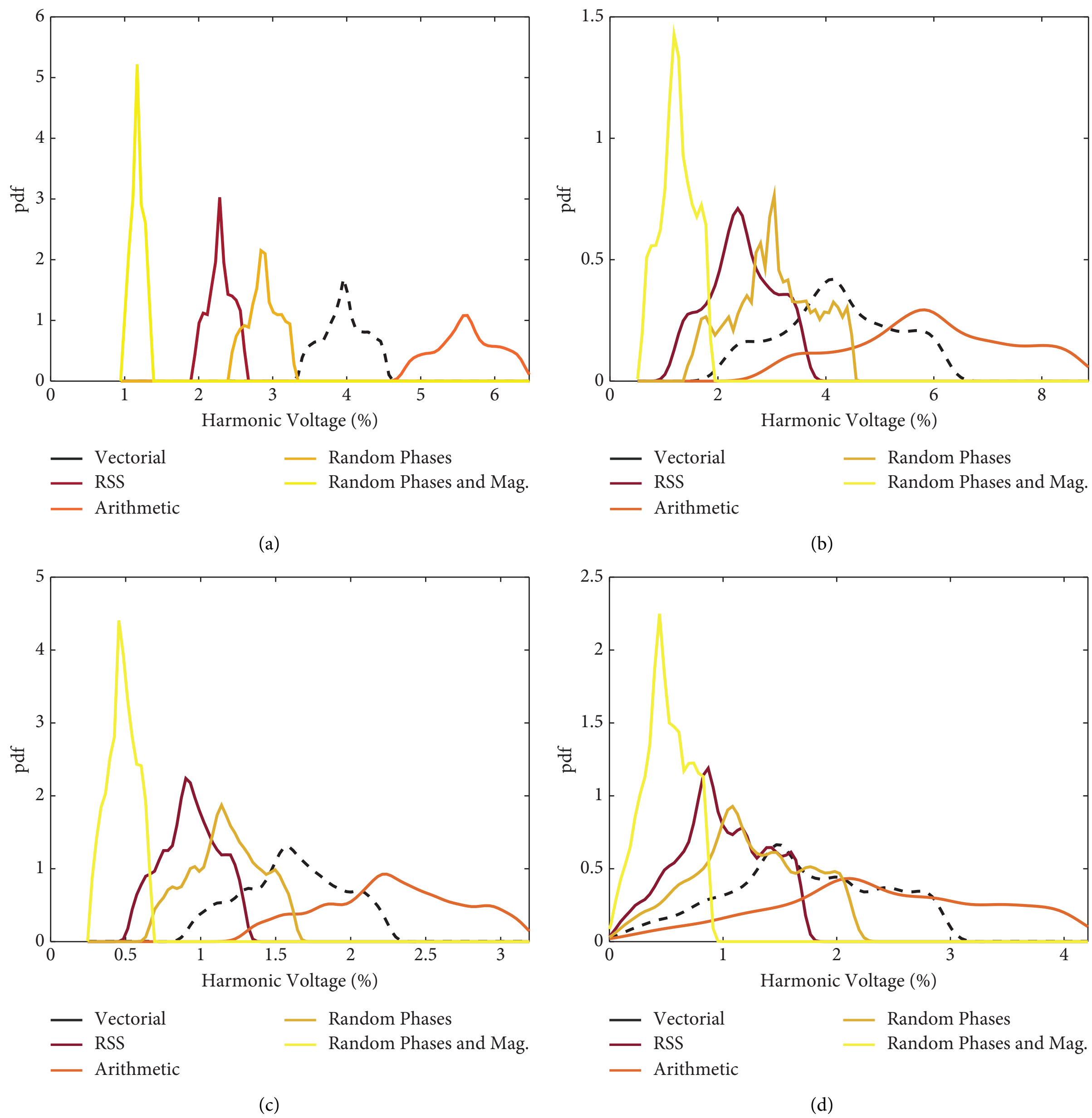

Figure 12: Summation methods pdfs for Case 5 at busbar 5 for 5th harmonic (a), 7th harmonic (b), 11th harmonic (c), and 13th harmonic (d).

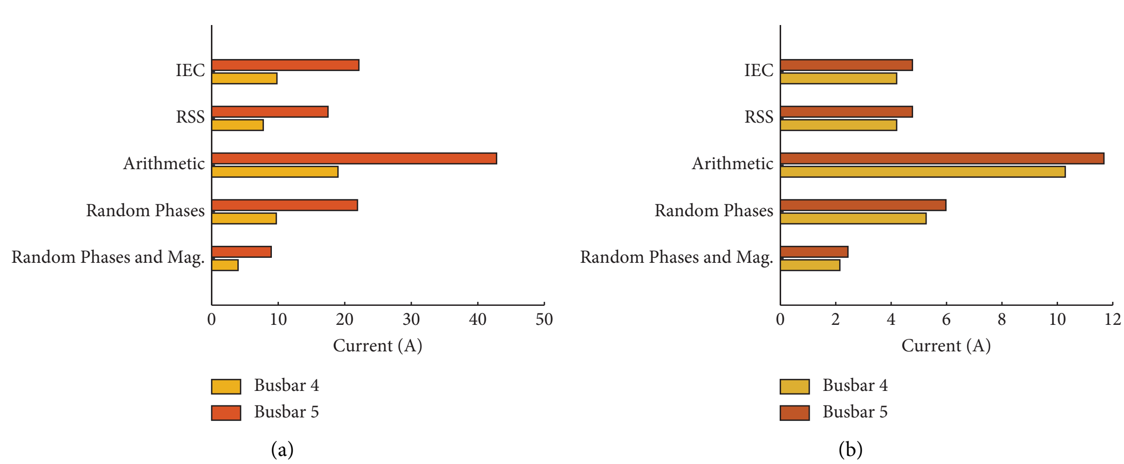

Figure 13: IEC results for 5th (a) and 13th (b) harmonic for Case 2.

are, respectively, 7.75 A and 17.48 A for RSS. The IEC results for this case are still the second largest among the methods, surpassing the RP method, which assumed current values of 9.71 A for bus 4 and 21.91 A for bus 5. Figure 13 shows the results of the IEC comparison for case 2. These results show the relationship between standard and alternative methods, highlighting that it is possible to obtain broader estimations using different estimations. In other words, using those aggregation methods with the standardized one, it is possible to provide more values for comparison that will reflect in reality, amplifying the scope of inference on the harmonic analysis.

4. Conclusion

The reliable evaluation of the different harmonic contributions combination from various sources becomes increasingly complicated due to the variability of the magnitudes and phase angles of the harmonic currents injected into the power systems. However, simple alternative summation methods can be used to predict probable values. Relative comparison between the vectorial and other expressions provides valuable information about the resulting voltage.

The approach suggested incorporates the system impedance by combining the harmonic voltages caused by each source at the transmission system busbars. There was no intention to discuss the theoretical and practical implications of the alternative expressions, e.g., random phase angles. They are intended to provide an alternative value that should be interpreted comparatively and based on the behaviour of harmonic sources. Using these simple expressions in conjunction with site measurements may prove very useful in investigating the harmonic combination without excessive complication. Rather than the individual harmonic components, the total harmonic distortion needs to be considered.

When comparing alternative methods with the method proposed by IEC 61000-3-6, it was possible to confirm relationships between the methods and the variation of the standard proposed coefficients. It also demonstrates that it is possible to find a broader estimate of the harmonic distortions in the planning stage when using different methods. In addition, the results showed that the current phase shit benefits the reduction of harmonic summation for those lower frequencies.

Furthermore, the results and discussion of this paper can be explored for a better assessment of transmission systems harmonic aggregation and by works that aim to discuss alternatives to standardized investigations in harmonic studies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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