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Analysis of balanced, unbalanced, sinusoidal and nonsinusoidal three-phase systems through a Python developed tool

Análisis de sistemas trifásicos balanceados, desbalanceados, sinusoidales y no sinusoidales mediante una herramienta desarrollada en Python

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Abstract

This paper proposes a Python tool for the analysis of balanced, unbalanced, sinusoidal and nonsinusoidal three-phase systems based on the IEEE Std. 1459. The proposed tool was developed to be used by electrical engineers and professionals of related careers providing a free access for electrical power calculations that allows validation and power analysis in power systems. The proposed tool is available for use on a GitHub link and only requires voltage and current signals as inputs, making it possible to dispense expensive commercial network analyzers. The tool is made of two interfaces, one for making power calculations of sinusoidal three-phase systems and the other one for making calculations of nonsinusoidal three-phase systems; both interfaces can be accessed

Resumen

Este trabajo propone una herramienta en Python para el análisis de sistemas trifásicos equilibrados, desequilibrados, sinusoidales y no sinusoidales basada en la norma IEEE Std. 1459. La herramienta propuesta fue desarrollada para ser utilizada por ingenieros eléctricos y profesionales de carreras afines, proporcionando un acceso libre para el cálculo de la potencia eléctrica que permite validación y análisis de esta en los sistemas de potencia. La herramienta propuesta está disponible para su uso en un enlace de GitHub y solo requiere como entradas las señales de voltaje y corriente, por lo que es posible prescindir de costosos analizadores de redes comerciales. La herramienta está compuesta por dos interfaces, una para realizar cálculos de potencia de sistemas trifásicos

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through a main menu. The proposed tool facilitates decision-making in electrical system issues, which helps improving the efficiency and power quality of electrical systems.

Keywords: power quality, IEEE Std. 1459, Python, nonsinusoidal unbalanced three-phase systems.

sinusoidales y otra para realizar cálculos de sistemas trifásicos no sinusoidales; ambas interfaces son accesibles a través de un menú principal. La herramienta propuesta facilita la toma de decisiones en sistemas eléctricos, lo que ayuda a mejorar la eficiencia y calidad de la energía de estos sistemas.

Palabras clave: calidad de energía, IEEE Std. 1459, Python, sistemas trifásicos no sinusoidales.

1. Introduction

Ideally, three-phase electrical systems are expected to be balanced, sinusoidal, and with linear loads. In this way, generators would deliver energy with high power quality and efficiency standards. Nonetheless, real electrical systems exhibit a non-balanced and non-ideal behavior (Blasco et al., 2020). Voltage and current unbalance degrade power systems' efficiency since they increase power losses in transmission and distribution lines. They also lead to a non-ideal operation of motors, generators, transformers, and protection equipment. That is why the calculation of harmonic and unbalanced power components is of paramount importance for taking decisions and compensation strategies to increase power quality and efficiency in electric systems.

The calculation of power in balanced, unbalanced, sinusoidal and nonsinusoidal three-phase systems is a current study issue in the scientific community. In Blasco et al. (2018), a phasor formulation is proposed for quantifying apparent harmonic power components, where the proposed set of phasors helps to analyze the inefficiencies of the electrical network. New vector expressions are reported in Blasco et al. (2020), which quantify power unbalances aiming to design and build passive unbalance power compensators.

The authors in Qi et al. (2020), propose a scheme of reactive power control for defining the power injection of each inverter connected in an isolated AC microgrid. In Artale et al. (2021), new indicators are proposed for harmonic emission assessment, considering power ratio and conventional meters used in distribution networks. In Jopri et al. (2022), the authors identified the sources of harmonic distortion, using Short-time Fourier and Stockwell transform. As reported, identifying these sources is more efficient when incorporating an analysis in time and frequency domains, using the setup proposed in IEEE Std. 1459 (2010). In Kaur & Singh (2022), a three-phase network meter for vehicle-to-grid (V2O) was developed, providing a flexible and scalable solution for the measurement in charging stations.

Electrical parameters defined in the IEEE Std. 1459, were used through Fast Fourier Transform (FFT) in a three-phase network meter. In (Macedo et al., 2020) it is shown that commercial active power network meters are not standardized although they use IEEE Std. 1459. The commercial meters evaluated presented differences in their results although they measured the same voltage and current signals. In Li et al. (2020), a new methodology for evaluating economic losses due to harmonic distortion was reported, using IEEE Std.1459 equations. Similarly, this standard was used in (Graña-López et al., 2019) for calculating reactive power in three-phase non-linear and unbalanced systems.

The theoretical concepts on which this paper is based are found in the definitions of the IEEE Std. 1459. These definitions were used for programming the analysis of electrical power systems. The proposed tool was coded in Python programming language using Numpy, Matplotlib and Tkinter libraries and is available in a GitHub repository in (Juansuarezr, 2021). The software is composed of two sections: one for making power calculations of sinusoidal three-phase systems, and the other one for making calculations of nonsinusoidal three-phase systems. Research applications which require power calculations in unbalanced sources and loads, with harmonic distortion, may use the developed tool reported in this paper.

This paper is organized as follows: Section 2 discusses the main methodological aspects, Section 3 presents the results obtained through the proposed analysis tool, and Section 4 presents the conclusions considering the most relevant issues of the paper.

2. Methodology

This section shows the theoretical background for developing the proposed analysis tool, illustrating three main systems: balanced sinusoidal, unbalanced sinusoidal, and unbalanced nonsinusoidal three-phase systems. The equations and definitions used in this paper are based on the IEEE Std. 1459.

2.1 Balanced three-phase systems

Balanced three-phase sinusoidal systems are composed of three sinusoidal voltage sources connected to a load, whose electrical phase shift is 120° from each other with equal amplitudes. Three-phase sources and loads can be connected in delta or wye connection (also known as star) (Beig, 2016).

This paper uses a star-star connection to develop the deductions. Figure 1 shows the star-star connection, describing the three-phase source on the left and the load on the right; line currents and phase voltages are also denoted. It also illustrates the phase voltages, measured at terminals a, b, and c, referencing voltages to the neutral terminal n. Line currents are flowing through lines a, b, and c. The voltages of a balanced three-phase system are defined in the time-domain through equations (1), (2) and (3) (Beig, 2016).

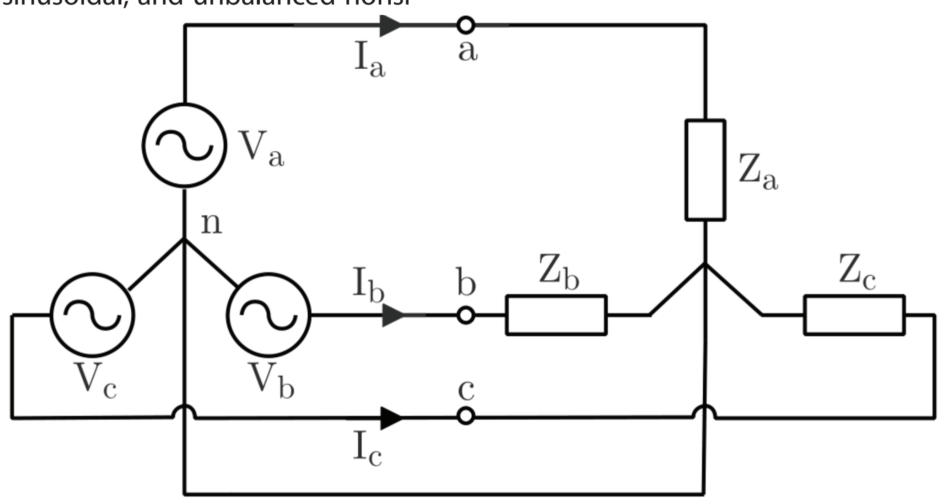

Figure 1. Wye-wye three-phase four-wire system.

$$v_a(t) = \Re\left(V_a e^{j(\omega t+\phi_a)}\right) = \sqrt{2}V_a cos(\omega t + 0 + \phi_a)$$

$$v_b(t) = \Re\left(V_b e^{j\left(\omega t-\frac{2\pi}{3}+\phi_b\right)}\right) = \sqrt{2}V_b cos\left(\omega t - \frac{2\pi}{3} + \phi_b\right)$$

$$v_c(t) = \Re\left(V_c e^{j\left(\omega t+\frac{2\pi}{3}+\phi_c\right)}\right) = \sqrt{2}V_c cos\left(\omega t + \frac{2\pi}{3} + \phi_c\right)$$

Similarly, line currents are defined in (4), (5) and (6).

$$i_a(t) = \Re\left(I_a e^{j(\omega t+\beta_a)}\right) = \sqrt{2}\overline{I_a} cos(\omega t + 0 + \beta_a) \quad (4)$$

$$i_b(t) = \Re\left(I_b e^{j\left(\omega t-\frac{2\pi}{3}+\beta_b\right)}\right) = \sqrt{2} I_b cos\left(\omega t - \frac{2\pi}{3} + \beta_b\right) \quad (5)$$

$$i_c(t) = \Re\left(I_c e^{j\left(\omega t+\frac{2\pi}{3}+\beta_c\right)}\right) = \sqrt{2} I_c cos\left(\omega t + \frac{2\pi}{3} + \beta_c\right) \quad (6)$$

Where V_k and I_k (k = a, b, c) are the RMS values associated to the sinusoidal waveforms of voltage and current, $\boldsymbol{V}_k = V_k e^{j\phi_k}$ and $\boldsymbol{I}_k = I_k e^{j\beta_k}$ are the phasors associated with the respective phases and $\omega = 2\pi f$ is the fundamental angular frequency of the system, defining frequency f in Hz. Moreover, ϕ_k and β_k are the initial phase angle of each voltage and current phasor, respectively.

A balanced three-phase system has three voltage phasors and three current phasors with identical magnitudes, which means that $V_a = V_b = V_c$ and $I_a = I_b = I_c$; it also has a shift angle equal to 120° among phasors, which is equivalent to $\phi_a = \phi_b = \phi_c$ and $\beta_a = \beta_b = \beta_c$ (Tleis, 2019).

2.2 Unbalanced three-phase systems

A three-phase system is unbalanced when the magnitudes of the phasors are not equal or the phase between any pair of phasors differs by $120°$. Fortescue's symmetric component decomposition can be applied to represent an unbalanced three-phase system as the sum of three balanced three-phase systems, which are called symmetric components of positive, negative, and zero sequence (Fortescue, 1918). Symmetric component sequences of an unbalanced three-phase system V_a, V_b and V_c can be calculated using (7), where α is defined as $1\angle 120°$, which offsets a signal by 120 degrees. Figure 2 represents the decomposition of an unbalanced three-phase system into its symmetrical components, where $\boldsymbol{V_a}^0$, $\boldsymbol{V_a}^-$ and $\boldsymbol{V_a}^+$ are the zero, positive and negative sequences, respectively. The same definition applies for currents.

$$\begin{pmatrix} \boldsymbol{V_a}^+ \\ \boldsymbol{V_a}^- \\ \boldsymbol{V_a}^0 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{pmatrix}\begin{pmatrix} \boldsymbol{V_a} \\ \boldsymbol{V_b} \\ \boldsymbol{V_c} \end{pmatrix} \quad (7)$$

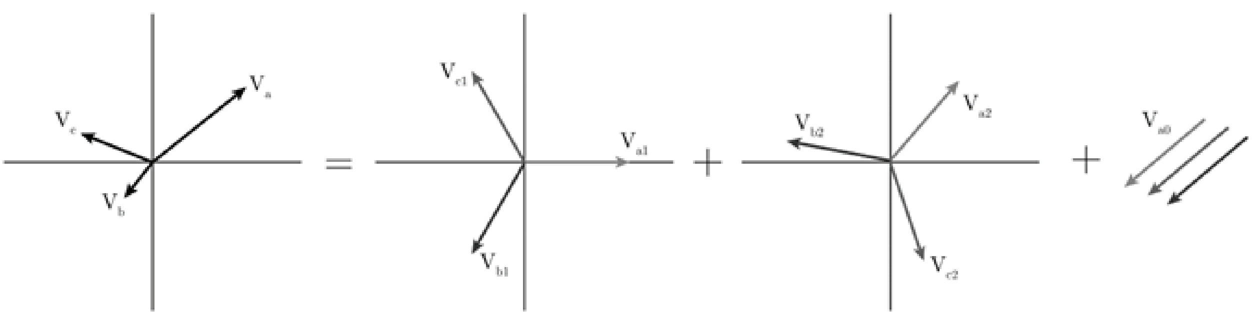

Figure 2. Decomposition of an unbalanced three-phase system into symmetrical components.

Symmetric components constitute a useful method for analyzing power in unbalanced three-phase four-wire systems (IEEE Std. 1459, 2010). The equations below use symmetric components for defining power in three-phase systems. For the following definitions V^+, V^- and V^0 are the RMS values of positive, negative and zero sequence components of voltage; I^+, I^- and I^0 are the RMS values of positive, negative and zero sequence components of current and, θ^+, θ^- and θ^0 are their respective phase angles between voltage and current phasors by each sequence.

Active power (P), also called real power, is the average value of the instantaneous power during the interval of a period. In terms of the symmetric components, active power is defined in (8) and (9), where P^k $(k = +, -, 0)$ represents the contributions of each symmetric component to the net active power (P).

$$P^k = 3V^k I^k \cos(\theta_k) \quad (8)$$

$$P = \sum P^k \quad (9)$$

Reactive power (Q) corresponds to the part of the power that cannot become useful work and that has a bidirectional flow between a source and a load. In terms of the symmetric components, reactive power is defined in (10) and (11), where Q^k $(k = +, -, 0)$ represents the contributions of each symmetric component to the net reactive power (Q).

$$Q^k = 3V^k I^k \sin(\theta_k) \quad (10)$$

$$Q = \sum Q^k \quad (11)$$

Apparent power (S) is defined in Emanuel (2004), as the maximum power transmitted to the load (or delivered by a source) while keeping the same line losses and the same load (or source) voltage and current. For unbalanced loads two apparent power definitions are prevalent: arithmetic apparent power and vector apparent power (Emanuel, 1999). The arithmetic apparent power is defined in (12), where $S_a = V_a I_a$, $S_b = V_b I_b$ and $S_c = V_c I_c$. The vector apparent power is defined in (13).

$$S_A = S_a + S_b + S_c \quad (12)$$

$$S_V = \sqrt{P^2 + Q^2} \quad (13)$$

The power factor (PF) is a number that indicates how much active power (P) is transmitted out of the maximum possible power (S) that will cause the same power loss in the supplying equipment and lines (Emanuel, 1998). A power factor is defined for both arithmetic and vector apparent powers; the arithmetic power factor is defined as $PF_A = \frac{P}{S_A}$ and the vector power factor is defined as $PF_V = \frac{P}{S_V}$.

Both power factors PF_A and PF_V are not accurate for nonsinusoidal waves or when the load is unbalanced (Emanuel, 2004). Hence a new definition for apparent power known as effective apparent power was suggested by F. Buchholz (Frank, 1992). The effective apparent power correctly reflects the power loss in the neutral current path as well as the effect of unbalance, which are not reflected properly by the arithmetic and vector apparent powers (Emanuel, 2004).

The concept of effective apparent power assumes a virtual balanced circuit that has the same line power losses as the actual unbalanced circuit. This equivalence leads to the definition of an effective line current (I_e) and an effective line-to-neutral voltage (V_e).

The effective current of a four-wire system is defined in (14). In this equation ρ is defined as the ratio $\rho = \frac{r_n}{r}$, where r_n is the neutral wire resistance and r is the line resistance. In case that the value of the ratio ρ is not known, it is recommended to use $\rho = 1.0$ (IEEE Std. 1459, 2010).

$$I_e = \sqrt{(I^+)^2 + (I^-)^2 + (1 + 3\rho)(I^0)^2} \quad (14)$$

The effective voltage is found by representing the load by three equivalent equal resistances R_Y, connected in star and three equal resistances R_Δ connected in delta. Using the ratio $\xi = \frac{3R_Y}{R_\Delta}$, the power equality between the actual load and the optimized system yields the expression for effective voltage, shown in (15) (Emanuel, 2004). If the value of the ratio ξ is not known, it is recommended to use ξ =1.0 (IEEE Std. 1459, 2010).

$$V_e = \sqrt{(V^+)^2 + (V^-)^2 + \frac{(V^0)^2}{1+\xi}} \quad (15)$$

The expression for effective apparent power S_e, in terms of the effective current and the effective voltage is shown in (16). The effective apparent power factor PF_e is defined as $PF_e = \frac{P}{S_e}$.

$$S_e = 3V_e I_e \quad (16)$$

2.3 Nonsinusoidal unbalanced three-phase systems

The effective apparent power of nonsinusoidal and unbalanced three-phase systems is calculated using equation (16). Expressions for calculating the effective voltage and the effective current for these systems are shown in equations (17) to (22), where the subscript 1 means fundamental (60Hz or 50Hz) and the subscript H the inclusion of all the harmonics (Emanuel, 2004). In equations (18) and (19) the subscripts ab, bc and ca represent the phase-to-phase voltages of the system.

$$V_e = \sqrt{{V_{e1}}^2 + {V_{eH}}^2} \quad (17)$$

$$V_{e1} = \sqrt{\frac{1}{18}\left(3\left({V_{a1}}^2 + {V_{b1}}^2 + {V_{c1}}^2\right) + {V_{ab1}}^2 + {V_{bc1}}^2 + {V_{ca1}}^2\right)} \quad (18)$$

$$V_{eH} = \sqrt{\frac{1}{18}\left(3\left({V_{aH}}^2 + {V_{bH}}^2 + {V_{cH}}^2\right) + {V_{abH}}^2 + {V_{bcH}}^2 + {V_{caH}}^2\right)} \quad (19)$$

$$I_e = \sqrt{{I_{e1}}^2 + {I_{eH}}^2} \quad (20)$$

$$I_{e1} = \sqrt{\frac{{I_{a1}}^2 + {I_{b1}}^2 + {I_{c1}}^2 + {I_{n1}}^2}{3}} \quad (21)$$

$$I_{eH} = \sqrt{\frac{{I_{aH}}^2 + {I_{bH}}^2 + {I_{cH}}^2 + {I_{nH}}^2}{3}} \quad (22)$$

The Total Harmonic Distortion (THD) is a measure that quantifies the nonsinusoidal property of a waveform (Asadi & Eguchi, 2020). The equivalent THD of the effective voltage and current are defined in equations (23) and (24), respectively.

$$THD_{eV} = \frac{V_{eH}}{V_{e1}} \quad (23)$$

$$THD_{eI} = \frac{I_{eH}}{I_{e1}} \quad (24)$$

The current distortion power, voltage distortion power, and harmonic apparent power are defined in equations (25), (26) and (27).

$$D_{eI} = 3V_{e1}I_{eH} \quad (25)$$

$$D_{eV} = 3V_{eH}I_{e1} \quad (26)$$

$$S_{eH} = 3V_{eH}I_{eH} \quad (27)$$

3. Results and discussion

This section shows the tool developed for analysis of balanced, unbalanced, and nonsinusoidal three-phase systems, as well as two examples that illustrate its use and scope. The software was developed in the open programming language Python, using theoretical background of the power equations described in the previous section, based on the IEEE Std. 1459; it has two main interfaces, the first one gives the possibility of analyzing time-domain waveforms, symmetric phasor components and the powers described in the section above; the second one relates to power in nonsinusoidal systems, in other words, harmonic analysis. The script code is shared in a GitHub repository (Juansuarezr, 2021).

3.1 Interface 1: three-phase sinusoidal unbalanced systems

Figure 3 shows interface 1, which makes power calculations of three-phase sinusoidal systems. The upper left part of the interface shows the time-domain plot of the three-phase system voltages, as well as the decomposition in symmetric components. The upper right part of the interface shows the same plots but for currents. The lower left part of the interface shows a bar plot with the values of active, reactive, apparent arithmetic, apparent vector, and apparent effective powers, while the lower right part shows the numeric values of these powers and their respective power factors. The interface has two set of sliders, which allow to set up the RMS values and their phases values of line-to-neutral voltages and line-to-line currents of the three-phase system.

To show the operation of this interface, the three-phase system of Figure 4 was used; this example was taken from Alexander & Sadiku (2012). The line currents flowing through the three-phase load are presented in (28), (29) and (30). Figure 5 and Figure 6 show the interface sliders fixed to the corresponding values of voltage and current of the example system analyzed.

$$I_a = 56.78\angle 0° A_{RMS} \quad (28)$$

$$I_b = 25.46\angle 135° A_{RMS} \quad (29)$$

$$I_c = 42.75\angle -155{,}1° A_{RMS} \quad (30)$$

Figure 3 shows the power analysis of the example system. Note that the phasor diagram of the voltages corresponds to the positive sequence of the symmetrical components, while the negative and zero sequences are null, which happens because the voltage supply of the system is balanced. In the time-domain plot of the currents it can be appreciated that these are not balanced, while their amplitudes are not equal, and the shift angles differ from 120°; moreover, the decomposition in symmetrical components show a significant contribution of the positive and negative sequences.

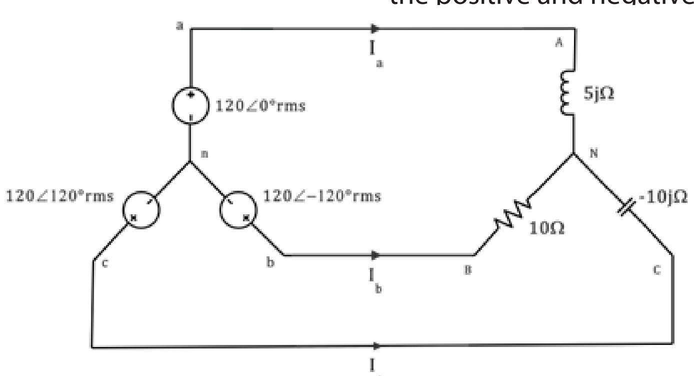

Figura 4. Example circuit.

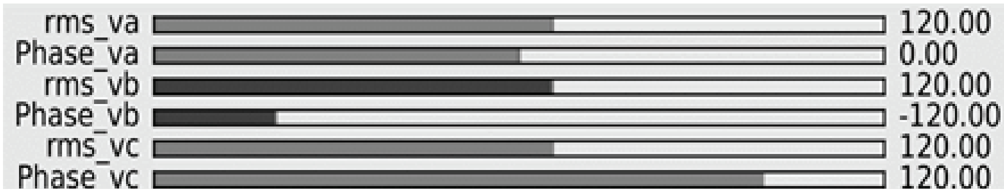

Figura 5. Voltage sliders.

Figure 6. Current sliders.

The values of active and reactive power calculated are the same as those obtained in (Alexander & Sadiku, 2012), and the relation S_A≤S_V≤S_e is fulfilled as mentioned in the IEEE Std. 1459.

3.2 Interface 2: three-phase nonsinusoidal unbalanced systems

Figure 7 shows interface 2, which makes power calculations of three-phase nonsinusoidal systems. The upper left part of the interface shows the time-domain plot of the three-phase system voltages, while the upper right part shows the same kind of plot but for currents. The middle part of the interface shows the frequency spectrum of the voltage signals of the system, and the lower part shows the frequency spectrum of the current signals.

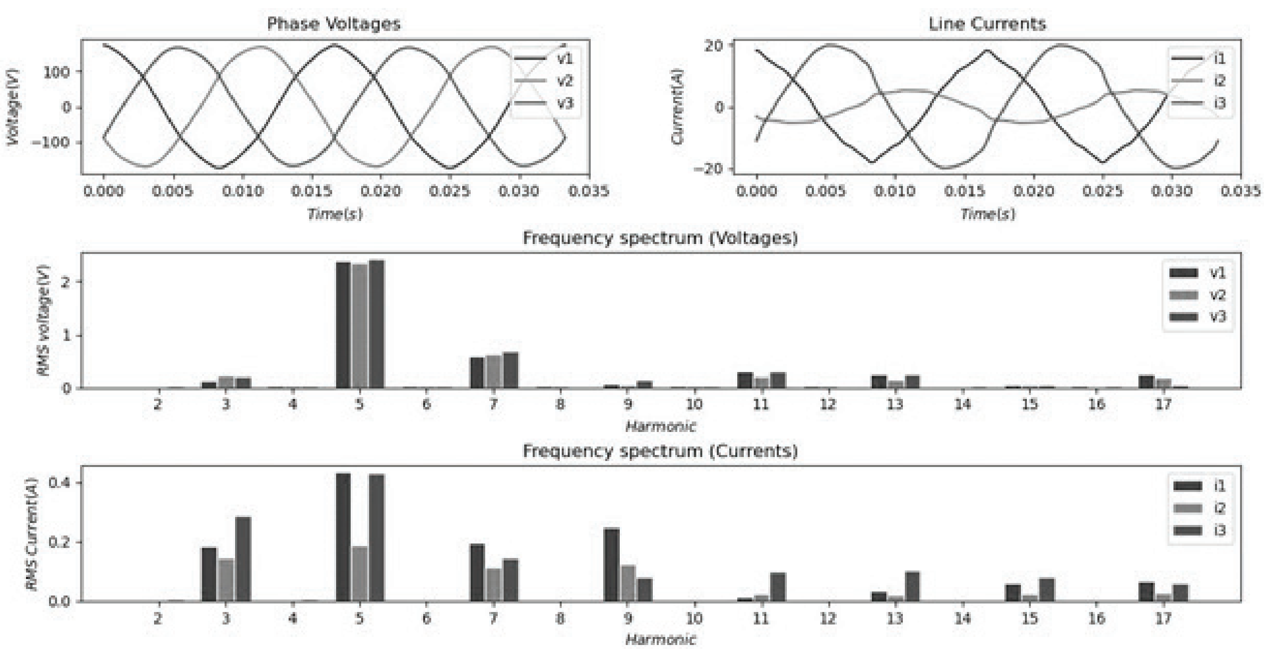

Figure 7. Interface 2: three-phase nonsinusoidal and unbalanced systems.

The program requires to load a csv file with the harmonics data of voltages and currents of the system. The csv file must have the structure shown in tables 1 and 2, where the first column corresponds to the harmonic order and the other columns correspond to the RMS values and shift angles of the line-to-neutral voltages and line currents of the system.

Table 1. Voltage harmonic data.

h	V_a	ϕ_a	V_b	ϕ_b	V_c	ϕ_c
1	119.12	0	120.14	120	118.99	-120
2	0.013	0	0.02	120	0.022	-120
3	0.135	0	0.238	120	0.203	-120
4	0.031	0	0.029	120	0.032	-120
5	2.391	0	2.338	120	2.424	-120
6	0.022	0	0.022	120	0.024	-120
7	0.585	0	2.338	120	2.424	-120
8	0.022	0	0.029	120	0.018	-120
9	0.071	0	0.048	120	0.146	-120
10	0.022	0	0.028	120	0.022	-120
11	0.319	0	0.215	120	0.316	-120
12	0.025	0	0.03	120	0.018	-120
13	0.257	0	0.148	120	0.245	-120
14	0.019	0	0.021	120	0.027	-120
15	0.043	0	0.055	120	0.061	-120
16	0.025	0	0.019	120	0.023	-120
17	0.248	0	0.185	120	0.058	-120

To show the operation of this interface, the data of Table 1 and Table 2 were used. The voltage and current data of these tables correspond to the measures of a lightning circuit in the laboratory building of the East Sectional of the University of Antioquia. The data were measured with a Metrel MI2892 power quality analyzer.

Table 2. Current harmonic data.

h	I_a	β_a	I_b	β_b	I_c	β_c
1	11.62	0	3.82	120	14.3	-120
2	0.004	0	0.002	120	0.006	-120
3	0.185	0	0.146	120	0.287	-120
4	0.002	0	0.002	120	0.005	-120
5	0.433	0	0.188	120	0.432	-120
6	0.002	0	0.001	120	0.003	-120
7	0.194	0	0.115	120	0.146	-120
8	0.003	0	0.001	120	0.003	-120
9	0.25	0	0.125	120	0.081	-120
10	0.002	0	0.001	120	0.004	-120
11	0.014	0	0.024	120	0.101	-120
12	0.002	0	0.001	120	0.003	-120
13	0.036	0	0.022	120	0.103	-120
14	0.002	0	0.002	120	0.103	-120
15	0.062	0	0.023	120	0.083	-120
16	0.003	0	0.001	120	0.003	-120
17	0.069	0	0.029	120	0.059	-120

Figure 7 shows the harmonic analysis of the example system. The time-domain plot of the voltages does not reflect a significant distortion caused by the presence of harmonics; on the contrary, current signals are affected in a considerable way by harmonics. The 5th harmonic RMS value of both voltage and current signals are the highest of all harmonics, which was expected since lightning loads usually have the higher impact in harmonic distortion in this harmonic order. Figure 8 presents the power analysis carried out by the analysis tool, which shows the calculated values of power parameters using the equations described in sections 2.2 and 2.3. It is necessary to emphasize that there is no reactive power in the previous analysis, since the shift angles between voltage and current signals were assumed to be zero for each harmonic; this is since the shift angles of the signals could not be measured with the equipment available.

	Variable	Value
0	Effective voltage	119.443889
1	Effective current	12.164174
2	Total Harmonic Distortion (V)	0.021025
3	Total Harmonic Distortion (I)	0.044268
4	Active power	3547.742932
5	Reactive power	0.000000
6	Fundamental effective apparent power	4353.581990
7	Current distortion power	192.723414
8	Voltage distortion power	91.535083
9	Harmonic apparent power	4.052055
10	Unbalanced power	4.052055
11	Effective apparent power	4358.808730
12	Arithmetic apparent power	3549.912852
13	Vector apparent power	3549.633375
14	Effective power factor	0.813925
15	Arithmetic power factor	0.999389
16	Vector power factor	0.999467

Figure 8. Output data of interface 2.

The calculation of power quantities using IEEE 1459 is a time-consuming activity; furthermore, the commercial power analyzers commonly used for such computations are expensive. The use of the proposed tool allows the calculation of power magnitudes when no power analyzer is available, only an oscilloscope or similar devices are required to obtain voltage and current waveforms which are the input of the developed tool. Figure 8 shows that the results are organized and can be used for further processing of the information for decision making.

4. Conclusions

An analysis tool for power calculations in three-phase unbalanced sinusoidal and nonsinusoidal systems was proposed. The developed tool facilitates the power calculations that uses a friendly and interactive environment for the user when performing power analysis in unbalanced sinusoidal and nonsinusoidal three-phase systems. The values calculated by the analysis tool in the example showed in section 3.1 are the same as those obtained in the source from which it was taken. Additionally, the different apparent powers show a decreasing behavior according to the relationship $S_A \leq S_V \leq S_e$ presented in the IEEE Std. 1459. With respect to the example showed in the section 3.3, the results are coherent with the kind of load analyzed, as it was seen in the 5th harmonic RMS values. The availability of the application on GitHub allows the reader to use a script and understand the intermediate stages used in the calculation of powers.

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