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Simulation of losses in a three-phase bank of transformers in the presence of harmonic distortion

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ABSTRACT

The load losses of the transformers increase considerably with the presence of harmonic distortion in the currents. Its increase can be determined using an analytical method based on ANSI/IEEE Standard C57.110. On the other hand, when it comes to three-phase banks with transformers of different capacities, delta connections, or incomplete connections, the analytical method does not allow the losses to be accurately estimated, which is why digital simulation is necessary. This work presents an adjusted model to determine the load losses in a three-phase bank of three single-phase transformers with different connection schemes. The model allows for determining load and electrical losses and calculating total additional losses. It is also possible to decide on the load capacity of the bank's transformers, the power factor, and the efficiency with which they operate under these conditions.

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1. INTRODUCTION

Harmonics have undesirable effects in electrical distribution circuits [1]–[3] the most common products are that harmonics cause an increase in Joule effect losses in conductors and voltage drops in feeders, for example. The growing use of power converters in networks has fundamentally impacted power quality in distribution networks. In this voltage level, a fundamental element is the transformer, whose losses are charged to the secondary distribution [4], and these are only sometimes properly considered [5]. The distribution company needs to know the transformation losses since these form an essential part of the technical losses in distribution and, therefore, have a notable impact on the efficiency of these systems, the economy, and the CO_2 emissions [6]. On the other hand, clients need to reduce transformation losses. Transformation losses influence the helpful life of the transformer, but they also affect the efficiency with which it operates.

Transformers are affected by the circulation of currents with a high harmonic content. These currents cause an increase in losses and, therefore, in the working temperature, leading to the deterioration of the insulation and a reduction in the machine's useful life [7]–[11]. These problems caused by non-linear loads and their effect on the temperature increase of the transformer were presented at the IEEE Transformers Committee, approving the ANSI/IEEE Std. C57.110 [12] provides a procedure to determine the reduction of the capacity and permissible current of the transformer when working with non-sinusoidal currents.

From this standard, it is possible to establish a mathematical model that allows the losses in transformers to be determined when they supply non-linear loads. The ANSI/IEEE Std. C57.110 model requires data that manufacturers do not offer, so laboratory tests on transformers are necessary. On the other hand, there are the data that are used for the analysis in the presence of harmonics, so it is then required to carry out measurements on the secondary of the transformer using a recording instrument (network analyzer) and obtain the individual harmonic distortion spectrum of the currents in the distribution circuit [13].

In distribution networks, loads are unbalanced and non-linear. In Latin America, three-phase banks of single-phase transformers are expected to be used in wye–delta connection (when the three-phase load is greater than the single-phase load) or in an-open delta connection if this is not the case. In the case of three-phase transformers and three-phase banks with wye connections, the analytical method has been generalized to determine the losses in the presence of loads with harmonic content [14]–[17]. In these cases, the methodology is applied by determining the factors of copper, eddy currents, and other stray losses. This methodology yields precise values for banks with wye–wye connections. However, when the bank's transformers do not have equal capacity, or these transformers are not loaded in the same way (three-phase system with single-phase loads), the analytical method only offers the total three-phase losses of the bank [18], [19]. It is not accurate to determine each transformer individually.

This research aims to propose an adjustment to the analytical model of the ANSI/IEEE Std. C57.110 uses digital simulation to determine the load losses in a three-phase bank of three single-phase transformers with different connection schemes. To do this, we start by describing the analytical method provided by the standard for single-phase dry core or oil-filled transformers and based on the parameters of the bank transformers and the characterization of the non-linear load, obtain the currents and voltages that circulate through the windings of each machine that forms the three-phase bank. The advantage of the adjusted model lies in the possibility of being used in three-phase banks of single-phase transformers with any connection scheme, also determining the load losses with greater precision in these cases in which there is no direct correspondence between the currents of the feeders and those of the windings in three-phase distribution systems, unbalanced and with high contents of harmonic distortion of the currents. The practical importance of the study of power quality, especially of harmonic distortion and its influence on transformation losses, lies in relating the technical improvements that can be applied with technical impacts that result in economic benefits, both for the company supplier as well as for users and environmental results linked to the mitigation of the effects of polluting gases resulting from generation.

2. METHOD

2.1. Analytical method for estimating load losses in electric transformers

The level of harmonic distortion is described by the total harmonic spectrum using each component's magnitudes and phase angle [1]. The indicator frequently used to evaluate the harmonic distortion in the voltage and current waveform is the total harmonic distortion (THD). The THD represents a measure expressed as a percentage of the harmonic pollution level of a system, and its value can be calculated by (1) [20], [21].

$$THD = \sqrt{\left(\frac{RMS}{RMS_1}\right)^2 - 1} \cdot 100 \quad (1)$$

where, RMS is the measured actual rms voltage or current, RMS_1 is the effective voltage or current of the fundamental harmonic of the signal, and THD is the total harmonic distortion for voltage (THD_v) or for current (THD_i) expressed in percent.

In general, the total losses (p_T) in transformers can be included within the load and no-load losses of the transformer [7], [8], [10], [12].

$$p_T = p_{NLL} + p_{LL} \quad (2)$$

where, p_{NLL} are the no-load losses, and p_{LL} are the load losses.

No-load or core losses are due to flow variations that circulate through the core material over time. For values less than 8% of THDv, the no-load losses in the transformer are considered constant [7], [8], [10], [12]. Load losses, resulting from harmonics, can be divided into Joule effect losses, also called ohmic or copper losses, present in the copper of the transformer windings [8], [9], [11], [12], and into additional losses due to eddy currents. These losses will increase in a quadratic proportion with the load current and as the square of the frequency [9]. On the other hand, the load losses can be obtained practically from the machine's short-circuit test. This can be expressed in the following way: [7], [8], [10], [12].

$$p_{LL} = p_{JL} + p_{ECL} + p_{OSL} \tag{3}$$

where, p_{JL} are the electrical losses in the windings, p_{ECL} are the additional losses due to eddy currents, and p_{OSL} are other stray losses.

Additional eddy current losses, also called “Eddy Losses” are due to stray flux in the core, core clamp, tank wall, and other structural parts of the transformer. The other additional losses include “Eddy Current” losses in the winding conductors and losses due to the circulation of currents between parallel or isolated windings. By their nature, there is no practical procedure to measure them and to separate the additional eddy current losses from the other further losses. For this reason, the total additional losses (p_{TAL}), made up of the sum of with, are calculated from the difference between the load losses and the copper Joule effect losses, using the expression (4).

$$p_{TAL} = p_{ECL} + p_{OSL} = p_{LL} - p_{Cu} \tag{4}$$

where, p_{Cu} are the copper losses in the transformer. The copper losses will be calculated by expression (5).

$$p_{Cu} = I^2 R_{CD} \tag{5}$$

where, I is the effective value of the transformer load current, and R_{CD} is the direct current resistance of the winding.

From the theory of analysis of non-sinusoidal periodic signals, it is known that, in the presence of harmonics, the effective value of the signal is determined by expression (6).

$$I = \sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{6}$$

Then the electrical losses are determined according to [10] using expression (7).

$$p_{JL} = \sum_{h=1}^{\infty} I_h^2 \, R_{CD} \tag{7}$$

For its part, the losses due to parasitic currents of the transformer can be determined according to [12] through the expression (8).

$$p_{ECL} = p_{ECLn} \cdot \sum_{h=1}^{\infty} \left(\frac{I_h}{I_n}\right)^2 h^2 \tag{8}$$

where, p_{ECln} are the nominal eddy current losses of the transformer, and I_n is the effective value of the nominal current of the transformer.

According to the ANSI/IEEE C57.110 standard, it is established that the nominal value of the other stray losses (p_{OSLn}) is 67% of the total losses (p_{TAL}) for oil transformers and 33% for dry transformers [12]. Considering this criterion, it is proposed that the other additional losses will be determined according to (9).

$$p_{OSL} = p_{OSLn} \cdot \sum_{h=1}^{\infty} \left(\frac{I_h}{I_n}\right)^2 h^{0.8} \tag{9}$$

2.2. Harmonic loss factors (F_{HL})

The harmonic loss factor is established as a proportionality factor applied to the losses in conditions of harmonic distortion. It represents the relationship between the losses in the transformer with harmonics and these losses in nominal conditions, or that would be had with purely sinusoidal signals [12]. They are represented according to (10).

$$F_{HL} = \frac{p_H}{p_n} \tag{10}$$

where, p_H are the losses in the presence of harmonics, and p_n are the nominal losses.

In this way, the copper losses can be determined using (11).

$$F_{HJL} = \frac{p_{JL}}{p_{Cu}} = \frac{\sqrt{\sum_{h=1}^{\infty} I_h^2} R_{CD}}{I^2 R_{CD}} = \frac{\sqrt{\sum_{h=1}^{\infty} I_h^2}}{I^2} \tag{11}$$

Expression (12) is used to calculate eddy current losses.

$$F_{HECL}=\frac{p_{ECL}}{p_{ECLn}}=\frac{p_{ECLn}\cdot\sum_{h=1}^{\infty}\left(\frac{I_h}{I_n}\right)^2 h^2}{p_{ECLn}}=\sum_{h=1}^{\infty}\left(\frac{I_h}{I_n}\right)^2 h^2=K-factor \qquad (12)$$

For the other stray losses, expression (13) is used.

$$F_{HOSL}=\frac{p_{OSL}}{p_{OSLn}}=\frac{p_{OSLn}\cdot\sum_{h=1}^{\infty}\left(\frac{I_h}{I_n}\right)^2 h^{0.8}}{p_{OSLn}}=\sum_{h=1}^{\infty}\left(\frac{I_h}{I_n}\right)^2 h^{0.8} \qquad (13)$$

In the case of three-phase transformers and three-phase banks with wye connections, the analytical method has been generalized to determine the losses in the presence of loads with harmonic content [5], [9]. In these cases, the methodology is applied by selecting the factors of copper losses due to parasitic and additional currents as an average of them per phase of the bank [6], [9].

$$F_{HL}=\frac{p_{H\emptyset A}+p_{H\emptyset B}+p_{H\emptyset C}}{3} \qquad (14)$$

where, $p_{H\emptyset A}$, $p_{H\emptyset B}$, $p_{H\emptyset C}$ are the losses due to harmonics for phases A, B and C respectively. Finally, the three-phase losses of the transformer or bank are determined by multiplying the respective factors by the nominal three-phase losses.

2.3. Model for digital simulation of the three-phase bank of single-phase transformers

The basic model to determine the load losses in the transformer through simulation is based on the scheme in Figure 1. The system is based on the model of a transformer and its parameters, which correspond to the data of its equivalent circuit, which are obtained from laboratory tests. The transformer supplies power to a non-linear load, which is designed based on the values of the individual harmonics of the current.

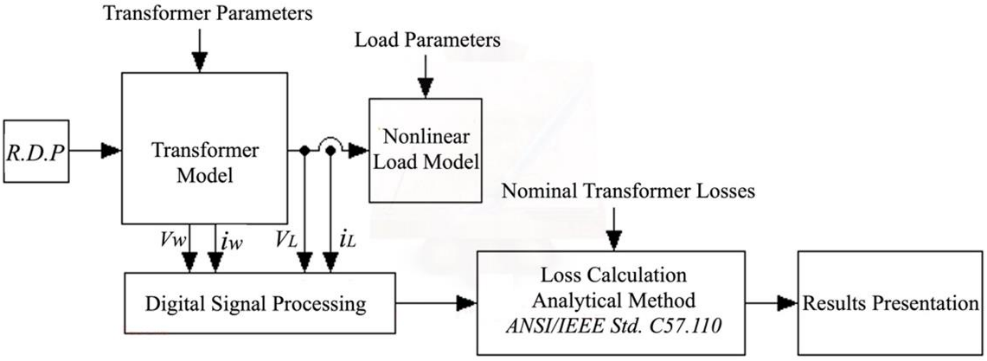


Figure 1. Model for simulation and adjustment of loss calculation

The simulation allows obtaining the discrete values of the voltages and currents at two points in the system, specifically, the voltages and currents in the transformer windings (v_w and i_w) and the voltages and currents in the line (v_L and i_L). The digital processing of the signals will allow obtaining the harmonic spectrum of the currents in the transformer windings, the THD value, calculating the electrical losses, and determining the active, reactive, distortion, and apparent powers for each of the windings of the transformer. Finally, the nominal data of the machine and the harmonic spectrum of the currents in the windings are used to determine the load losses using the analytical method of ANSI/IEEE Std. C57.110 [12].

From the energy diagnosis in electrical service, it is possible to measure the average values of the individual harmonic distortion of the line currents using a recording instrument (three-phase network analyzer). With these measurements, it is possible to build the nonlinear load model according to its development in the Fourier series.

$$i(t)=\sum_{h=1}^{\infty}\left[A_h cos(h\omega t+\varphi_h)\right] \qquad (15)$$

where, A_h is the amplitude of the h-order harmonic of the signal, and φ_h is the phase shift of the h-order harmonic of the signal. From the amplitude and phase spectrum of the line currents, it is possible to reconstruct the current signal as a sum of current sources of amplitude A_h with a phase shift angle φ_h as represented in Figure 2.

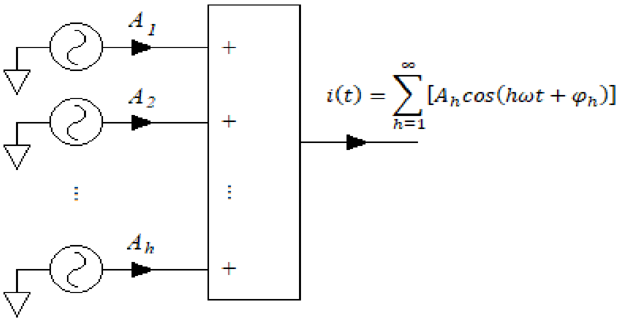


Figure 2. Nonlinear load model based on the individual harmonics of the currents

For the transformer simulation, the three-winding linear transformer, whose data comes from the Steinmetz model [7]. Obtained from the nominal values of the transformer and parameters of its equivalent circuit determined from the tests, will be used, Figure 3. This model element aims to obtain the voltages and currents in the machine windings.

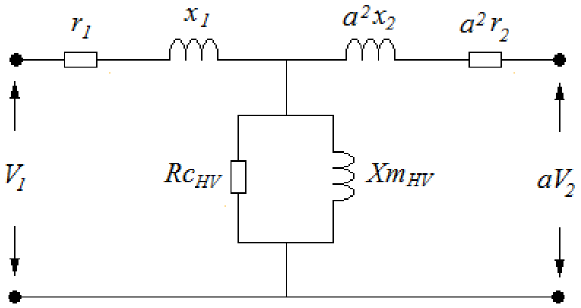


Figure 3. Exact equivalent circuit referred to the high voltage side

2.4. Practical implementation in a case study

The industrial electrical service of the soybean processing plant, belonging to the Cereals Base Business Unit of Santiago de Cuba, is part of a three-phase bank of three single-phase transformers, with a Y/Δ connection with a central tap grounded by the secondary. The capacity of transformer 1 is 75 kVA, and transformers 2 and 3 have a total of 100 kVA. The study was developed in conjunction with the Office for the Regulation and Rational Use of Energy (ONURE) in Santiago de Cuba as part of an energy diagnosis for this entity. The measurements were carried out using a Chauvin Arnaux C.A network analyzer 8333 4B.

Figure 4 shows the transformer bank and load configuration parameters using a graphical user interface designed in MATLAB. The load is configured from the harmonic amplitude distortion spectrum values for the line currents measured in the general distribution board of the service. The measurements showed high harmonic contamination, with a high content of harmonics in the line currents, mainly in odd harmonics, highlighting the harmonics of order 5th, 7th, 11th, and 13th. For the simulation of the transformer using MATLAB, the equivalent circuit parameters for transformers with standardized capacities of 100 kVA and 75 kVA, respectively.

The Simulink model of the three-phase bank and the voltage and current signals obtained in the windings of each transformer through digital simulation are presented in Figure 5. The model created for the digital simulation of the transformer bank, with wye–delta connection and non-linear loads on each feeder, shown in Figure 5(a), allows the currents and voltages in each winding of the transformers that make up the bank to be obtained, Figure 5(b). With these results, it is possible to determine all the operating parameters of the machines. In addition, the digital processing of these signals provides the harmonic spectrum of the currents for using the ANSI/IEEE Std. C57.110 analytical model.

Harmonic load design (Phase A)

Harmonic amplitude (A) [Press Enter to update value]

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
87.1000	0.9000	5.3000	0	16.3000	0.1000	12.2000	0.3000	4.8000	0.8000	14.2000	0.1000	6.7000	0	0.8000

I_rms (A): 91.1087

THDi (%): 30.6867

Harmonic load design (Phase B)

Harmonic amplitude (A) [Press Enter to update value]

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
114.5000	0.7000	6.9000	0	16.2000	0	8.2000	0.2000	4.8000	0.4000	8	0	4.8000	0	1.3000

I_rms (A): 116.619

THDi (%): 19.3278

Harmonic load design (Phase C)

Harmonic amplitude (A) [Press Enter to update value]

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
106.2000	1.1000	4.3000	0	21.1000	0	11.3000	0.1000	2.7000	0.4000	15.2000	0.1000	7.9000	0	0.8000

I_rms (A): 110.3295

THDi (%): 28.1568

Three-phase transformer bank design

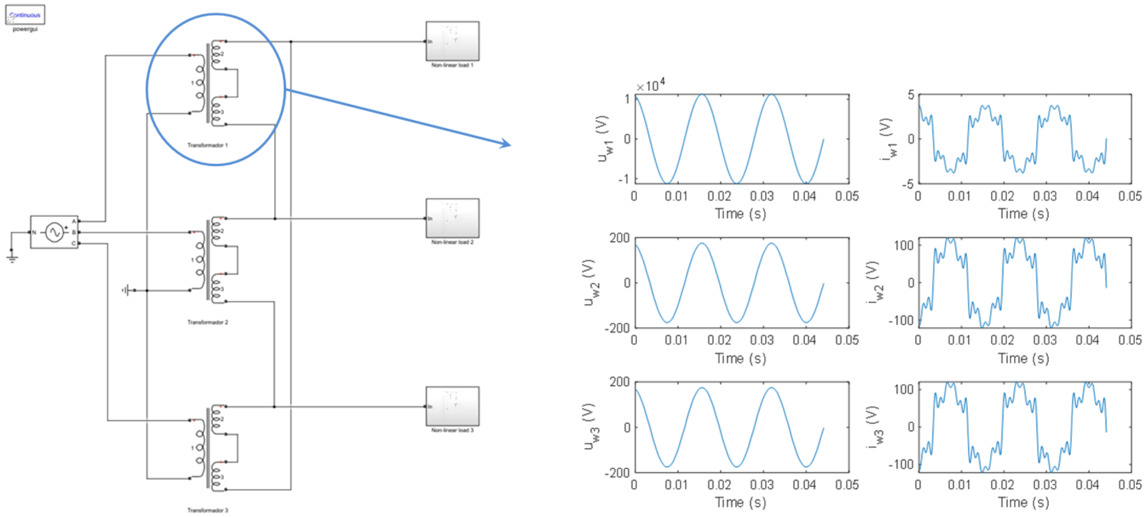
Connection scheme: Y - Δ

Capacity of T1 (kVA): 100

Capacity of T2 (kVA): 100

Capacity of T3 (kVA): 75

Figure 4. Graphical user interface for the configuration of the non-linear load and the transformer bank with the data of the soybean processing plant service

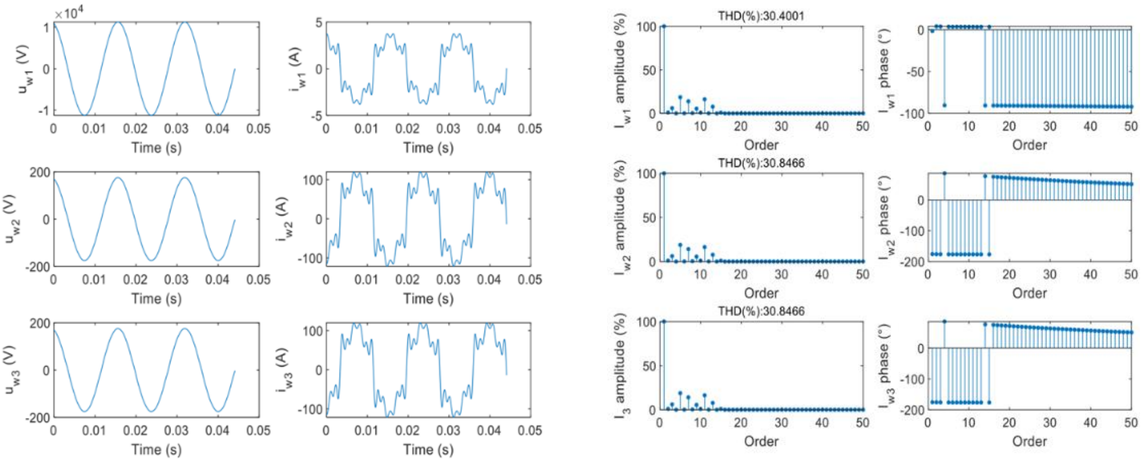


(a) (b)

Figure 5. Simulink model implementation of the three-phase bank of three single-phase transformers with Y/Δ connection. (a) model for the digital simulation of the three-phase bank and (b) example of the voltages and currents in each winding of transformer 1 of the bank

3. RESULTS AND DISCUSSION

From the simulation, it is possible to determine the load losses of each transformer, and from them, the total additional losses can be calculated. These operations are carried out by applying the expressions (5)-(8) through which it is possible to calculate the total additional losses (p_{TAL}) because of the difference between the load losses and the copper losses or electrical losses in each winding. Expression (16) is used to determine the electrical losses. Based on the discrete values of the currents in each transformer winding obtained in the simulation, it is possible to reformulate this expression, Figures 6(a) and 6(b).



(a) (b)

Figure 6. Example of simulation results for transformer 1 of the three-phase bank with non-linear load. (a) voltages and currents in each winding of transformer 1 of the bank and (b) harmonic spectrum of amplitude (% of the fundamental harmonic) and phase of the currents of the windings of transformer 1

$$p_{Cu} = \frac{\sum_{i=1}^{N}(I_i)^2 R_w}{N} \tag{16}$$

where, N is the number of data elements, I_i is the instantaneous current in each of the windings, and R_w is the resistance of the windings determined in the transformer model.

Based on the diagnoses carried out and using the model adjusted for the digital simulation of the three-phase banks of single-phase transformers, the operating parameters of each transformer are determined. To estimate the influence of harmonic distortion on load losses, transformer losses in the presence of harmonic distortion are calculated, and the loss values are compared with the loss values when the bank supplies a linear load. Table 1 lists the nominal values of each loss in the transformers that comprise the three-phase bank of three single-phase transformers. Table 2 shows the simulation results of the three-phase bank of three single-phase transformers using MATLAB.

Table 1. Nominal values of losses in single-phase distribution transformers

Magnitudes	Transformer 1 (75 kVA)	Transformer 2 (100 kVA)
No-load, p_{NLL} (W)	277.00	339.00
Nominal load losses, p_{LL} (W)	942.00	1315.00
Nominal total losses, p_T (W)	1219.00	1654.00
Total additional losses, p_{TAL} (W)	445.00	790.00
Nominal electrical losses, p_{JL} (W)	497.00	524.00
Nominal Eddy current losses p_{ECLn} (W)	147.00	260.00
Nominal other stray losses, p_{OSLn} (W)	298.00	530.00

In the cereal company Santiago soybean processing plant service, the transformation losses associated with harmonic distortion amount to 139.2 W. These losses represent 10.8% of the bank's total losses, for an average THDi of 14.8%. For this operating state, the bank has a power factor of 0.788, and the chargeability of the bank is 17.50%.

Among the advantages of using the adjusted model for digital simulation is the possibility of analyzing the losses in the three-phase bank of three single-phase transformers when it serves a linear load that demands a current equal to that of the fundamental harmonic. In this way, it is possible to determine the losses in the transformation, which are a product of the effect of harmonic distortion. Table 3 shows the results of both analyses using simulation.

Table 2. Simulation results of the three-phase bank of three single-phase transformers with Y/Δ connection

Magnitudes	Transformer 1 (75 kVA)	Transformer 2 (100 kVA)	Transformer 3 (100 kVA)
Power factor, *PF*	0.891	0.975	0.594
Total losses, p_T (W)	154.763	543.107	529.691
Electrical loss factor, F_{HJL}	0.039	0.244	0.210
Eddy current loss factor, F_{HED}	3.281	3.545	5.414
Other stray loss factor, F_{HOSL}	1.143	1.170	1.264
Load losses, p_{LL} (W)	91.763	204.107	190.691
Electrical losses, p_{JL} (W)	19.406	127.649	87.605
Eddy current losses, p_{EC} (W)	42.385	45.788	69.925
Other stray losses, p_{OSL} (W)	29.972	30.671	33.161
Transformer loadability (%)	3.941	24.664	20.514
Efficiency, η (%)	94.125	97.742	95.653
Harmonic current distortion on the high voltage side, $THDi_{w1}$ (%)	20.092	22.108	28.834
Harmonic current distortion on the low voltage side, $THDi_{w2}$ (%)	19.921	22.267	26.724

Table 3. Simulation results of the three-phase bank with Y/Δ connection, considering a linear load, with an effective value of the currents equal to the value of the fundamental harmonic in the case study

Calculated losses	With non-linear load			With linear load		
	Transformer 1 (75 kVA)	Transformer 2 (100 kVA)	Transformer 3 (100 kVA)	Transformer 1 (75 kVA)	Transformer 2 (100 kVA)	Transformer 3 (100 kVA)
Total losses for each transformer	154.8 W	543.1 W	529.7 W	123.6 W	504.1 W	460.7 W
Total bank losses		1227.6 W			1088.4 W	

As can be seen in Table 3, the total losses associated with the harmonic distortion of the currents in the load (Δp_T) for the service of the soybean processing plant amount to 139.2 W. Considering that the bank operates with a continuous regime throughout the year, the energy associated with the transformation losses due to harmonic distortion can be calculated according to expression (17).

$$\Delta Ep = \Delta p_T \cdot 24\ \frac{h}{day} \cdot 365\,\frac{day}{year} \tag{17}$$

The energy associated with transformation losses due to harmonic distortion will be 1219.4 kWh/year.

The billing cost for electricity consumption for state clients is regulated by resolution 66 of 2021 of the Ministry of Finance and Prices. By this resolution, to services located in medium voltage, if measurement equipment is installed that allows the consumption of each of the three periods of the day to be recorded, Rate M1-A is applied. The periods of the day for the application of rates are:

a. Day: from 5:00 a.m. to 5:00 p.m. For each kWh consumed during the day.

$$F_{day} = \left(1.5869\ \frac{CUP}{kWh} \cdot K + 0.8595\,\frac{CUP}{kWh}\right) \cdot Day\ consumption\ in\ kWh \tag{18}$$

b. Electrical peak: from 5:00 p.m. to 9:00 p.m. For each kWh consumed during peak hours.

$$F_{peak} = \left(3.1672\ \frac{CUP}{kWh} \cdot K + 0.8595\,\frac{CUP}{kWh}\right) \cdot Peak\ consumption\ in\ kWh \tag{19}$$

c. Early morning: from 9:00 p.m. to 5:00 a.m. the next day. For each kWh consumed in the early morning hours.

$$F_{em} = \left(1.0601\ \frac{CUP}{kWh} \cdot K + 0.8595\,\frac{CUP}{kWh}\right) \cdot Early\ morning\ consumption\ in\ kWh \tag{20}$$

K represents the adjustment for fuel price variations, whose value reflects the proportion in which the weighted average of all fuels used in generation varies, as well as the structure of these volumes and types of fuels used [22]–[26] and in correspondence with the master reports of the electric company, the value of the adjustment coefficient *K* for fuel price variations for the year 2022 varied between 0.9269 and 1.1058, averaging a value of 1.009 in the year, which will be used as a reference for calculating billing costs. Table 4 details the calculations of billing costs in each of the schedules, taking as reference the average values of actual demand (RD) and contracted demand (CD) in the year for this service, the programs established by rate M1-A.

Table 4. Calculation of costs for energy billing associated with losses resulting from the influence of harmonic distortion in the case study

M1-A rate schedules	Transformation losses in the bank associated with harmonic distortion (W)	Percentage of energy consumed by schedule (RD/CD)	Energy associated with losses by schedule (kWh/year)	Average K factor of the year 2022	Billing (CUP/year)
Early morning	139.2	47.6	193.5	1.009	373.32
Day		83.7	510.3		1255.78
Electrical peak		69.0	140.1		568.30
Total billing cost for the year, for energy associated with harmonic distortion losses (CUP/año)					2197.40

For the soybean processing plant service, the costs for energy billing associated with transformation losses amount to 2,197.40 CUP/year, which represents 0.18% of the annual costs for electricity billing for this service. To calculate the fuel used in electrical generation necessary to cover the energy associated with the transformation losses due to harmonic distortion in the currents, it is essential to consider the specific fuel consumption per unit of energy. This gross specific consumption fluctuates yearly at values close to 289 g/kWh. The calculation of fuel consumption is carried out using expression (21).

$$Cons_{comb} = CEB \cdot \Delta Ep \cdot 10^{-6} \tag{21}$$

The fuel consumption for electricity generation is 0.35 tons/year, equivalent to 103.21 USD/year, considering the price of the fuel used in the country's electricity generation, according to the Statistical Yearbook of Cuba for the year 2022. The use of this fuel for generation impacts the environment due to the emissions of polluting gases into the atmosphere. To determine this impact, the emission factors of each of the polluting gases are taken into account. The environmental impact of fuel use for energy generation associated with the losses due to harmonic distortion in this service is 0.9 tons/year.

4. CONCLUSION

The model is designed to adapt to ANSI/IEEE Std. C57.110 in the transformer is based on the processing of currents in the machine windings and not the system line currents. Therefore, it applies to single-phase transformers and three-phase banks of single-phase transformers in any connection scheme. It is easy to implement and does not require additional data besides quality diagnostics in distribution networks or industrial systems.

With the proposed model for digital simulation, it is possible to determine the load losses of each of the bank's transformers. Likewise, the digital simulation shows the power, power factor, load ability, and efficiency values with which each transformer operates. The analysis in a case study allowed us to estimate the influence of harmonic distortion on the company's billing costs due to fuel consumption for generation and the effect on the emission of polluting gases.

Expanding the case study in three-phase banks with wye–delta and open wye–open delta connections would allow for data sufficiently extensive to correlate the load losses in the single-phase transformers that are part of these banks with the values of individual harmonic distortion of the currents measured in the feeders on the low voltage side, as well as determining the influence of the harmonic distortion of the currents on the elevation of the working temperature of the distribution transformers and the shortening of their useful life.

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