

Article

Procedure for Improving the Energy, Environmental and Economic Sustainability of Transformation Houses

Vicente León-Martínez, Elisa Peñalvo-López *, Clara Andrada-Monrós, Jorge Cano-Martínez , Amparo León-Vinet  and Laura Molina-Cañamero

Institute for Energy Engineering, Universitat Politècnica de València, 46022 Valencia, Spain; vleon@die.upv.es (V.L.-M.); claanmon@etsii.upv.es (C.A.-M.); jorcama2@etsii.upv.es (J.C.-M.); amleovi@etsii.upv.es (A.L.-V.); laumocaa@etsii.upv.es (L.M.-C.)

* Correspondence: elpealpe@upvnet.upv.es; Tel.: +34-96-387-59-35

Abstract: A procedure for improving the energy, economic and environmental sustainability of the transformation houses in low-voltage distribution networks is described in this paper. This procedure is based on the reduction of the transformer consumption, copper and core losses. Likewise, the procedure distinguishes between transformation houses with old and new transformers. The reduction of core losses, replacing transformers with others of lower power or that are more efficient, achieves significant improvements in energy and environmental aspects. The reduction of copper losses, and applying reactive compensation techniques, such as harmonic filtering and load balancing, applied in old and new transformation houses, have a greater impact on cost savings, especially when there are capacitive consumptions, as the Circular 3/2020 of the National Markets and Competition Commission of Spain determines. The procedure has been applied to an industrial transformation house, which has an old 1600 kVA transformer, resulting in significant economic savings and CO₂ reductions of more than 60%, after replacing the current transformer with a more efficient one.

Keywords: distribution transformers; copper losses; core losses; efficient transformers; capacitive penalizations; environmental assessment



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1. Introduction

The transformers of the electrical distribution networks, used in industrial, commercial and residential activities, have significant energy consumptions and give rise to high carbon dioxide emissions into the atmosphere. Consequently, these machines affect the energy and environmental sustainability of electrical systems [1–4]. The energy consumption of transformers is due to their copper and core losses, as is well-known [5–10]. A report carried out in 2008 for the project “Strategies for development and diffusion of Energy Efficient Distribution Transformers (SEEDT)” [11] estimated the percentage of energy losses caused by distribution transformers is a third of the total losses in the electrical networks. That same report counted more than 4.5 million transformers in the distribution networks of the EU-27, with energy consumption—caused by losses—of 33.4 TWh/year, of which 24.1 TWh/year corresponded to core losses, and 9.3 TWh/year was due to copper losses. The saving potential estimated by the report reached 12 TWh/year and a reduction in CO₂ emissions of up to 4 million tons/year of CO₂ in the year 2025 [12] and was the most favorable scenario for a rapid replacement of existing transformers for more efficient ones, which had only 49% losses in the core than current transformers.

Following the proposals presented by the SEEDT project, organizations [13,14] and companies in the electricity sector [15–18] have promoted changes in regulations [19–29] to favor the manufacture and use of efficient transformers [30,31].

Aware of the importance of reducing the transformers’ own consumptions, as a necessary step to promote the circular economy and guarantee energy and environmental

sustainability in the electricity sector, this paper describes a procedure to improve the sustainability of transformation houses in low-voltage distribution networks. This procedure is based on the reduction of transformer copper and core losses.

Actions to reduce copper losses were analyzed in a previous article [32]. These consist of minimizing the values of reactive, unbalanced and distortion currents, using well-known techniques, such as reactive power compensation and the use of harmonic filters. As a novelty, the minimization of unbalanced current is achieved using the active and reactive components of the unbalanced power vector $(\vec{S}_{uip}, \vec{S}_{uiq})$ [33]. These quantities provide sufficient information to network operators to obtain a more equitable distribution, in real-time, of the loads connected to the transformers. Copper loss reduction techniques are complementary to actions to reduce core losses and can be applied to both old, inefficient, transformers and efficient transformers.

The reduction of losses in the core is achieved in the procedure by replacing the old transformers with more efficient ones, of equal or lesser power. The use of efficient, lower-power transformers considerably improves the energy sustainability of transformation centers, larger than the improvement derived from the reduction of copper losses.

The procedure for sustainability improvement has been applied to a transformation house of the low-voltage distribution network of an industrial estate, which has a 1600 kVA transformer, 25 years old, from the manufacturer Ormazabal. The study has focused on energy, environmental and economic aspects. For the energy study, a measurement campaign has been carried out, using the FLUKE 435 Series II network analyzer, whose loss calculator allows for the copper losses due to each component of the secondary currents to be measured separately. The environmental effects caused by copper and core losses, that is, the amount of emissions of carbon dioxide and other gases, have been determined using the emission factor from Spain (0.241 kg CO₂/kWh), corresponding to the year 2019 [34], prior to which the measurement campaign was made. The economic effects have been obtained by applying Circular 3/2020 of the National Markets and Competition Commission of Spain [35]. The penalties for capacitive consumptions caused by two permanently connected capacitor banks $Q_{c1} = 3 \times 25$ kVar and $Q_{c2} = 3 \times 100$ kVar amount to tens of thousands of euros per year.

Finally, the energy, environmental and economic sustainability improvements resulting from the application of the procedure in the transformation house of the example are summarized in the conclusions.

2. Economic Costs of Transformer Losses and Charges for Capacitive Consumptions

Nowadays, the costs derived from energy losses in distribution transformers deserve special attention due to the high cost of energy. In Spain, these costs are obtained through the energy billing term [35],

$$FE = \sum_{p=1}^{p=i} Te_p \cdot W_p \quad (1)$$

being:

- FE = billed energy, in euros;
- Te_p = energy price in the hourly period p , expressed in EUR/kWh (Table 1), for the 6.1 TDA toll, where the transformation houses are included;
- W_p = energy lost by the transformer in the hourly period p , expressed in kWh;
- i = the number of hourly periods of the transmission and distribution tolls.

Table 1. Energy prices in Spain (Te_p), in EUR/kWh, for each hourly period of the 6.1 TDA toll.

Year	Hourly Periods					
	P1	P2	P3	P4	P5	P6
2020	0.032950	0.024407	0.013180	0.006590	0.004224	0.002636
2022	0.133862	0.115644	0.097066	0.08647	0.072677	0.065821
Increment (%)	406.26	473.81	736.46	1312.14	1720.57	2497.00

Table 1 shows the strong increase in energy prices, especially during off-peak hours (up to 25 times), the result of which has been a reduction in the difference in prices between peak, flat and off-peak hours.

The energy is supplied in the transformation houses according to the 6.1 TDA toll, with voltage values between 1 and 30 kV, as shown in Table 2.

Table 2. Voltage and power limits corresponding to each transmission and distribution toll.

	Transmission and Distribution Toll					
	2.0 TDA	3.0 TDA	6.1 TDA	6.2 TDA	6.3 TDA	6.4 TDA
Voltage (kV)	$V \leq 1$	$V \leq 1$	$1 < V < 30$	$30 \leq V < 72.5$	$72.5 \leq V < 145$	$V \geq 145$
Power (kW)	≤ 15	> 15	–	–	–	–

For the purposes of calculating energy costs, according to Equation (1), the prices of each hourly period in Table 1 must be applied to the supplies made at the times indicated in Table 3, based on the type of day. Five types of days are distinguished, in the peninsular territory of Spain, namely [35]:

- Type A: from Monday to Friday, excluding high season holidays (January, February, July and December);
- Type B: from Monday to Friday, excluding mid-high season holidays (March and November);
- Type B1: from Monday to Friday, except for mid-season holidays (June, August and September);
- Type C: from Monday to Friday, excluding low season holidays (April, May and October).
- Type D: Saturdays, Sundays, holidays and January 6.

Table 3. Hourly billing periods according to the type of day.

Hourly Period	Type of DAY				
	A	B	B1	C	D
P1	9 h–14 h 18–22 h				
P2	8–9 h 14–18 h 22–0 h	9–14 h 18–22 h			
P3		8–9 h 14–18 h 22–0 h	9–14 h 18–22 h		
P4			8–9 h 14–18 h 22–0 h	9–14 h 18–22 h	
P5				8–9 h 14–18 h 22–0 h	
P6	0–8 h	0–8 h	0–8 h	0–8 h	All day hours

Likewise, in order to ensure the quality of the electricity supply, Circular 3/2020, of the National Commission of Markets and Competition of Spain, January 15, establishes that the supplies made with the 6.1 toll:

- Will be penalized for all capacitive consumptions supplied under power factors (*PF*) less than 0.98, between 0 and 8 h, on working days, and 24 h on holidays;
- Will not be penalized for capacitive consumptions outside these periods, even when the power factor is less than 0.98, or when the power factor in said periods is greater than 0.98.

The value of the power factor is obtained by the electrical companies, in each hourly period, as:

$$PF = \frac{W_p}{\sqrt{W_p^2 + W_q^2}} \tag{2}$$

where W_p is the active energy (in kWh) and W_q is the net reactive energy (in kVAR-h), calculated as the difference between the inductive and capacitive reactive energy supplies in the hourly period.

The surcharge or penalty for capacitive reactive power supplies (*RCAP*) is calculated as [36]:

$$RCAP = 0.05 \cdot \Delta W_q \tag{3}$$

being:

$$\Delta W_q = W_q - 0.20306 \cdot W_p \tag{4}$$

the value of the net reactive energy supplies that exceed those corresponding to a power factor of 0.98 capacitive ($0.20306 W_p$). In other words, 20.306% of the capacitive reactive power supplies are not penalized.

3. Proposed Procedure for Improving Sustainability of Transformation Houses

Improving the sustainability of the transformation houses of the electrical distribution networks requires reducing the losses of the existing transformers in them. For this, the proposed methodology has two main steps (Figure 1): (1) the reduction of copper losses, and (2) the reduction of core losses.

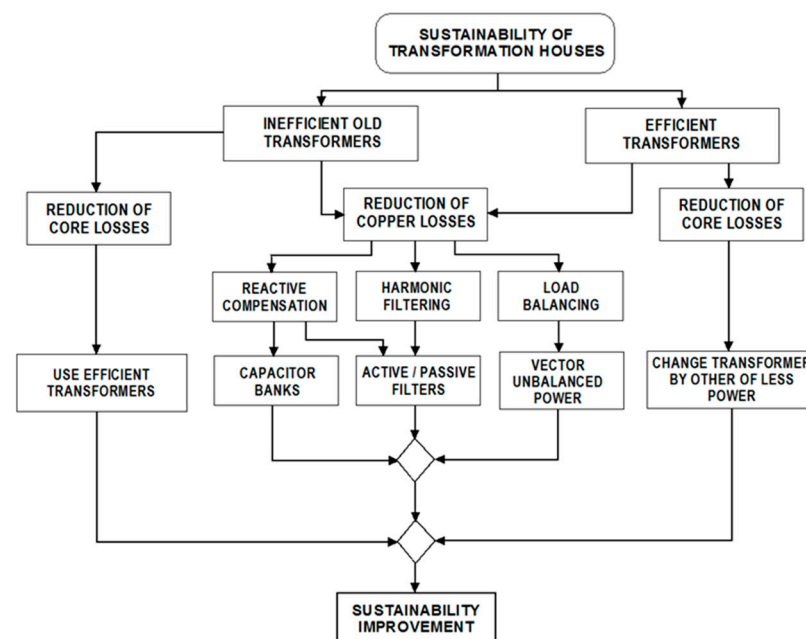


Figure 1. Organization chart of the procedure for improving the sustainability of transformation houses.

3.1. Reduction of Copper Losses

This consists of reducing the value of fundamental frequency currents, due to reactive power supplies and/or imbalances, as well as losses caused by non-fundamental frequency currents.

This step can be applied both in transformation houses with old (inefficient) and new (efficient) transformers.

3.1.1. Reduction of Copper Losses Caused by Reactive Currents

Losses caused by fundamental frequency reactive currents (P_{cr+}) are usually the main copper losses of transformers in distribution networks and on which the managers of these electricity networks have the greatest savings. These losses can be calculated from the fundamental-frequency positive-sequence reactive powers Q_+ and line-to-neutral voltages, as follows:

$$P_{cr+} = \frac{1}{3} r_{cc} \cdot \left(\frac{Q_+}{V_+} \right)^2 \tag{5}$$

measured in the secondary of the transformer, and the short-circuit resistance of the transformers, and is obtained by:

$$r_{cc} = P_{cN} \cdot \left(\frac{V_{20}}{S_N} \right)^2 \tag{6}$$

where V_{20} is the RMS value of the secondary line-to-line no-load voltages, P_{cN} is the rated copper power losses, determined according to IEC 60076-1 [37], and S_N is the transformer rated power.

Losses due to the reactive currents can be greatly reduced by using relatively inexpensive devices such as capacitor banks. In highly distorted electrical networks, capacitor banks can be replaced by harmonic filters, both active and passive, which are capable of jointly reducing load losses caused by reactive and distortion currents.

However, the use of non-variable compensation devices, both capacitor banks and passive filters, can be the cause of overcompensation, which usually increases the value of these losses in distribution transformers even above the existing values without reactive compensation devices. This case will be dealt with in more detail in the application case, in Section 4.

3.1.2. Reduction of Copper Losses Caused by Imbalanced Currents

Unbalances in the active power and reactive power supplies give rise to losses due to the load on the transformer, of value:

$$P_{cu} = 3 r_{cc} \cdot (I_-^2 + I_0^2) \tag{7}$$

where I_- and I_0 are, respectively, the negative and zero sequence components of the transformer secondary currents and r_{cc} is determined by (6).

Currently, devices are known [38–42] for reducing unbalanced currents, which also have the ability to compensate for reactive power (Q_+) and, therefore, can additionally reduce the losses due to reactive currents (P_{cr+}), defined by (5).

However, as indicated in Figure 1, the losses caused in the transformers due to unbalanced loads can be reduced, in industrial practice, by equitably distributing the active power and reactive power supplies between the secondary phases. To carry out this task, the managers of the electrical networks can use the representation of the angles (α_p and α_q) of the following vector quantities [33]:

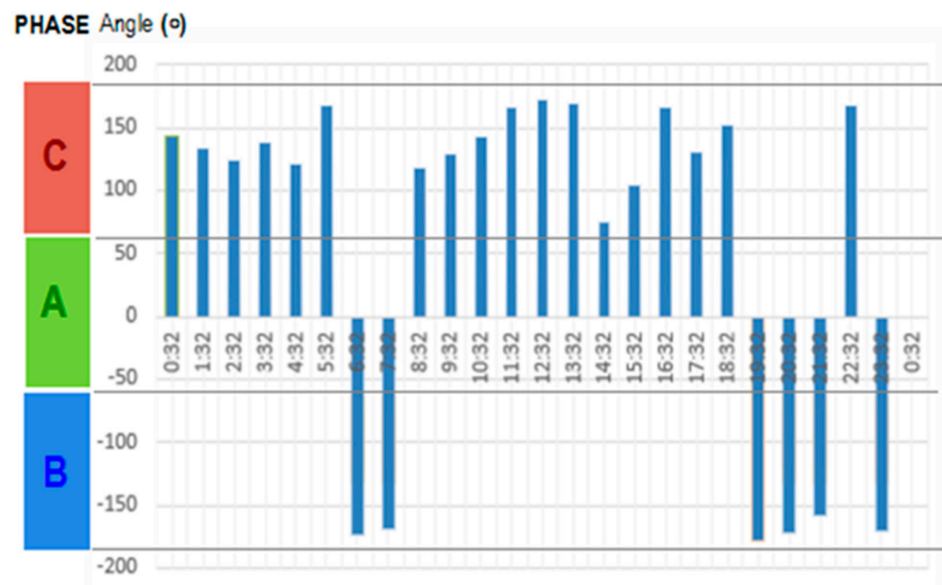
$$\vec{S}_{uip} \approx P_A + a^2 P_B + a P_C = S_{uip} \angle \alpha_p \quad \vec{S}_{uiq} \approx Q_A + a^2 Q_B + a Q_C = S_{uiq} \angle \alpha_q \tag{8}$$

The first one (\vec{S}_{uip}) measures the effects of active power imbalances (P_A, P_B, P_C) supplied in each phase ($z = A, B, C$) of the transformer secondary, where $a = 1 \angle 120^\circ$.

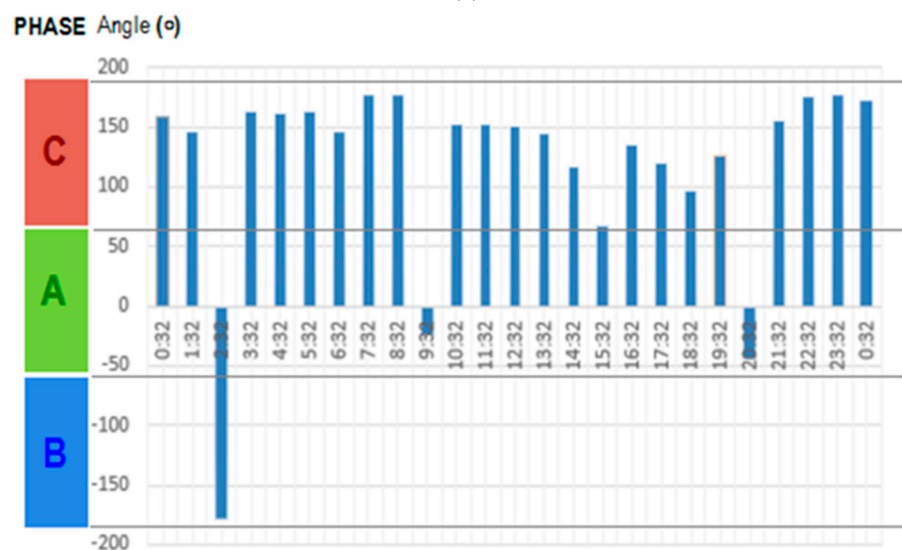
The second vector quantity (\vec{S}_{uiq}) determines the effects of unbalances in reactive power supplies (Q_A, Q_B, Q_C).

The angles α_p and α_q can have values between 0° and 360° , and each phase of a three-phase system occupies a spatial sector of 120° . Imbalances in phase A correspond to the values of the angles α_p and α_q between -60° and 60° . Imbalances in phase B give values of these angles between -60° and -180° and imbalances in phase C correspond to the values of α_p and α_q between 60° and 180° .

The ends of the segments represented in Figure 2a,b indicate the angular positions (α_p and α_q) of the components \vec{S}_{uip} and \vec{S}_{uiq} of the imbalance power vector. Therefore, these segments determine the phases of the transformer in which the imbalances caused by active loads (Figure 2a) and reactive loads (Figure 2b) have a greater value. These representations can be known in real-time and therefore help network operators to distribute loads more evenly.



(a)



(b)

Figure 2. Imbalances throughout a day in the distribution transformer of an industrial area, due to (a) active loads (α_p), and (b) reactive loads (α_q).

3.1.3. Reduction of Copper Losses Caused by Harmonic Currents

The losses due to the circulation of harmonic currents through the transformer windings are obtained by:

$$P_{ch} = r_{cc} \cdot \sum_{z=A,B,C} I_{hz}^2 = r_{cc} \cdot \sum_{z=A,B,C} \sum_{n \neq 1}^{\infty} I_{nz}^2 \quad (9)$$

where I_{nz} are the RMS values of the harmonic currents in each phase of the transformers ($z = A, B, C$), $n = f_n/f_1$ is the ratio between each harmonic frequency (f_n) and the fundamental frequency ($f_1 = 50 \div 60$ Hz) and r_{cc} is the short-circuit resistance, determined according to (6).

The reduction of these losses can be done using passive or active harmonic filters. The use of passive filters is recommended, due to their cheaper cost—if the harmonic pollution is not too high. The elimination of harmonics of a very high value can be carried out by passive filters of the first order, tuned to the frequency (f_n) of the harmonic to be eliminated. The series association of a coil, of inductance,

$$L_n = \frac{1}{(2\pi f_n)^2 \cdot C_n} \quad (10)$$

and a capacitor,

$$C_n = \left(1 - \frac{1}{n^2}\right) \cdot \frac{Q_{cn+}}{3 \cdot 2\pi f_1 \cdot V_+^2} \quad (11)$$

constitutes these passive filters, in which f_1 is the fundamental frequency, $n = f_n/f_1$, Q_{cn+} is the reactive power that the filter must compensate and V_+ is the effective value of the positive sequence voltage and fundamental frequency. Equation (10) is the resonance condition of a coil-capacitor series association at the tuning frequency f_n , whereas that of Equation (11) follows from the reactive power (at the fundamental frequency) of the three coil-capacitor series associations of a three-phase passive filter.

3.2. Reduction of Core Losses

The second step of the proposed procedure is implemented in two ways:

- a In transformation houses with old, inefficient transformers, the reduction of core losses requires the replacement of these transformers with other efficient ones, of equal or less nominal power (Figure 1);
- b In new transformation houses, in which efficient transformers have already been installed, the only option to reduce core losses is to replace them with other efficient transformers of lower nominal power, whenever possible (Figure 1).

The replacement of transformers by others of lower power can be carried out when the transformer in operation in the transformation house works with very low load rates. Under these conditions, the losses in the core are always much greater than the losses in the copper and, therefore, the energy savings that result from reducing the former can be high.

The previously described actions for core loss reduction are based on the fact of these losses decrease with the rated power of the transformer. However, in the case of equally efficient transformers, the value of the short-circuit resistance (r_{cc}) evolves in the opposite direction, that is, it increases as the rated power decreases. For this reason, when a transformer is replaced by another of lower-rated power, the decrease in core losses must be weighed against the increase in copper losses in the new transformer.

4. Application Example

The procedure was applied to improve the energy, economic and environmental sustainability of one of the transformation houses of the low-voltage distribution network of an industrial area, in which there are furniture manufacturing, vehicle repair, industrial spare parts stores, as well as a couple of cafes/restaurants, among other companies. The transformation house has an operating transformer from the manufacturer ORMAZABAL,

of 1600 kVA, whose primary is connected to the 20 kV medium voltage electrical network, with nominal features indicated in Table 4.

Table 4. Nominal features of Ormazabal distribution transformers.

Rated Power (kVA)	Copper Losses (W)	Core losses (W)	Short-Circuit Resistance (Ω)
1600	17,000	2600	0.011708

Connected to the secondary of this transformer, there is a three-phase non-variable capacitor bank, with a power $Q_{c1} = 3 \times 25$ kVAR. Likewise, after the first power measurements were made in the secondary of the transformer, the existence of a second three-phase non-variable capacitor bank was detected, with an estimated power $Q_{c2} = 3 \times 100$ kVAR. This second reactive compensator was not visible, as it was outside the transformation house, inside the companies.

To carry out the study, a measurement campaign was made between the months of October and December of the year 2020, using the Fluke 435 Series II network analyzer. This instrument has a loss calculator for the distribution lines (Figure 3), which can be adapted to measure the losses in transformers, introducing the value of the short-circuit resistance of the transformer instead of the resistance of the lines, and discounting the values of losses in the neutral conductor.

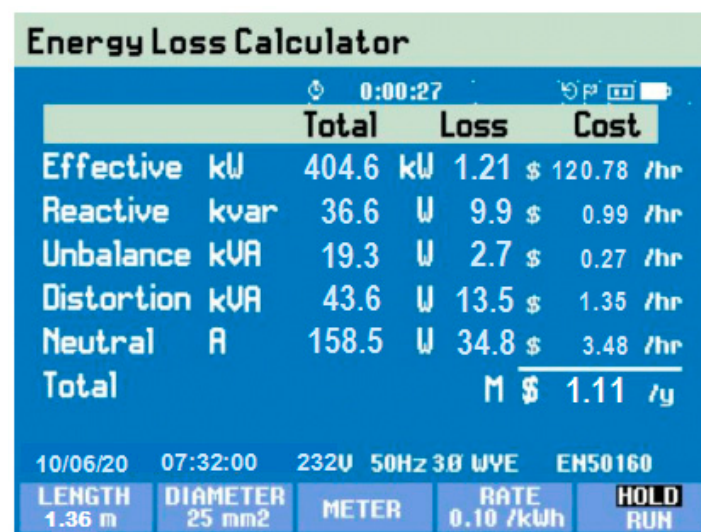


Figure 3. Loss calculator screen from the analyzer Fluke 435 Series II.

The economic costs derived from the operation of the transformer and the surcharges for capacitive consumption have been obtained by applying Circular 3/2020, of the National Commission of Markets and Competition of Spain, 15 January.

4.1. Energy Study of the Transformation House

The Fluke 435 Series II analyzer was connected to the transformer secondary terminals and measurements were made on working days and holidays. The values of the transformer copper losses, due to each component of the secondary currents, were measured by the Fluke 435 Series II analyzer, entering in the loss screen of this instrument (Figure 3) a value of resistance equal to the short-circuit resistance of the transformer, indicated in Table 4.

The active (P) and reactive (Q') powers recorded throughout the measurement campaign on working days and holidays remained (without significant changes) at the values represented in Figures 4 and 5, for working days and holidays, respectively.

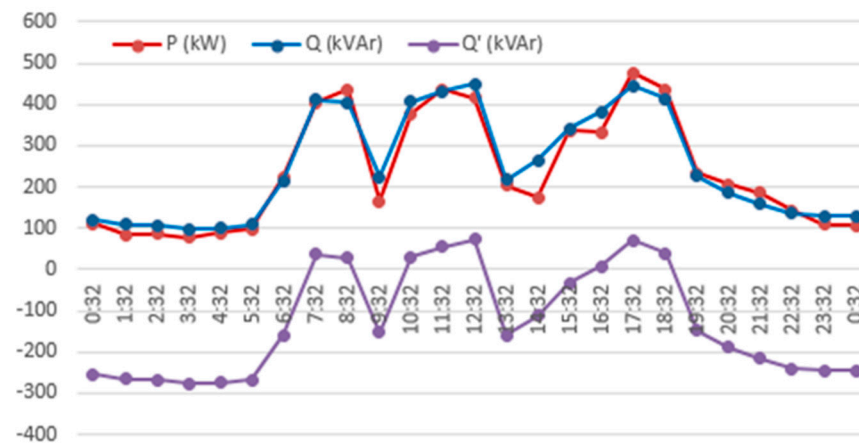


Figure 4. Active (P) and reactive (Q') powers delivered by the transformer on working days, as well as the reactive powers (Q) supplied without capacitor banks. (Negative sign indicates capacitive reactive powers).

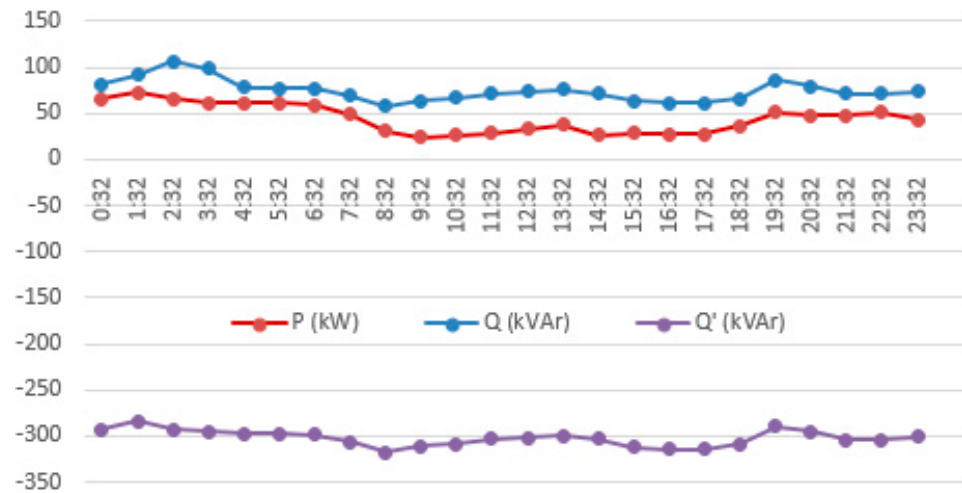


Figure 5. Active (P) and reactive (Q') powers delivered by the transformer during holidays, as well as the reactive powers (Q) supplied without capacitor banks. (Negative sign indicates capacitive reactive powers).

Based on the measured values of reactive power (Q'), represented in Figures 4 and 5, it was deduced that the capacitor banks (Q_{c1} and Q_{c2}) were permanently connected at all hours of working days and holidays, giving rise to the high values of capacitive reactive power (higher than 300 kVAr) during times of low activity of companies. The values of the reactive power absorbed by the installations fed by the transformer, without the effect of the capacitor banks, are those represented by Q in Figures 4 and 5.

The values of the transformer copper losses, due to the active and reactive currents (P_{ca} and P'_{cr}), are those represented in Figures 6 and 7, for working days and holidays, respectively. Likewise, these figures represent the losses that the reactive currents would cause if the capacitor banks (P_{cr}) were not connected. The comparison of the values of P_{cr} and P'_{cr} shows the impact produced by the capacitor banks on the copper losses of the transformer, which are especially important in periods of low activity of the companies. It can be noted in Figures 6 and 7 that transformer power losses caused by reactive currents have values between 500 and 700 W each hour in low activity periods, with capacitor banks, whereas these power losses reach only between 50 and 100 W each hour in these periods if capacitor banks were disconnected.

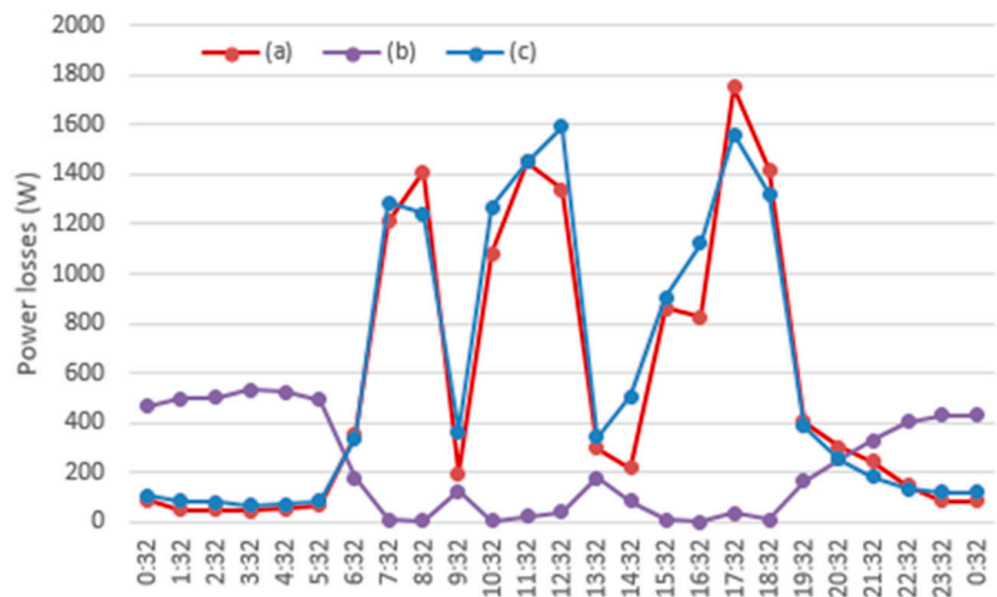


Figure 6. Transformer power losses in working days due to (a) active currents (P_{ca}); (b) reactive currents with capacitors (P'_{cr}); and (c) reactive currents without capacitors (P_{cr}).

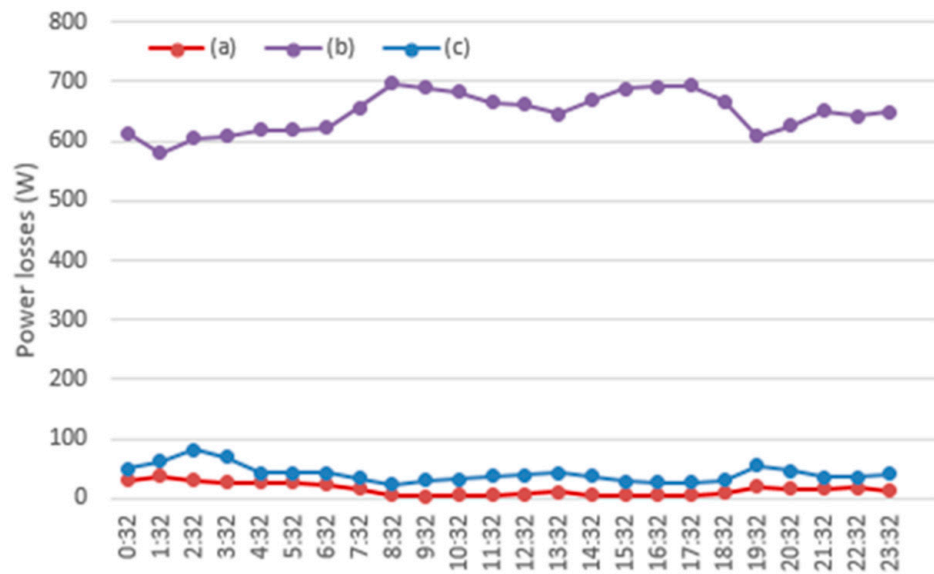


Figure 7. Transformer power losses in holidays due to (a) active currents (P_{ca}); (b) reactive currents with capacitors (P'_{cr}) and (c) reactive currents without capacitors (P_{cr}).

Likewise, the Fluke 435 Series II analyzer recorded the values of copper losses caused in the transformer by unbalanced currents (P_{cu}) and distortion currents (P_{ch}). These values are those indicated in Figures 8 and 9, for working days and holidays, respectively. It can be seen in these figures that the copper losses caused by the distortions were greater than those caused by the unbalances, undoubtedly due to the amplification of the distortion currents produced by the Ferranti effect in the presence of capacitive loads. However, the importance of losses due to imbalances and distortions is comparatively much less than those caused by capacitive reactive currents.

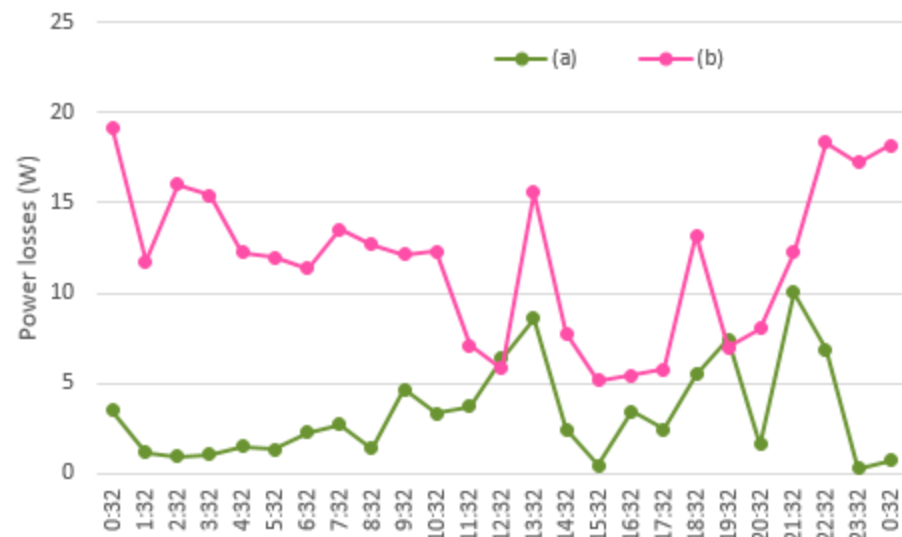


Figure 8. Transformer power losses, in working days, caused by (a) unbalanced currents (P_{cu}) and (b) distorted currents (P_{ch}).

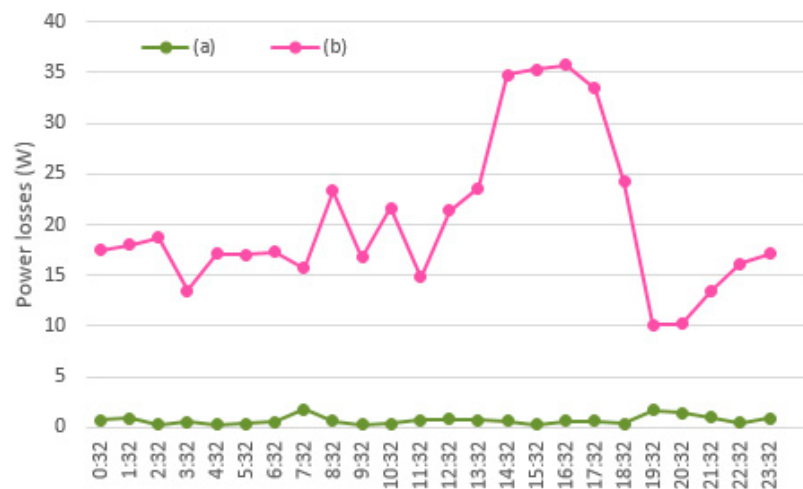


Figure 9. Transformer power losses, during holidays, caused by (a) unbalanced currents (P_{cu}) and (b) distorted currents (P_{ch}).

From the values of the powers and losses in the copper measured in the secondary of the transformer, an inefficient operation of the same is observed, whose cause is, mainly, in the inadequate operation of the non-variable capacitor banks, used for the compensation of the reactive power. These devices are responsible for high values of capacitive reactive power in periods of low activity in companies (Figures 4 and 5). Consequently:

- (1) There are significant copper losses in the transformer, caused by the reactive compensation equipment, which give rise to significant CO₂ emissions.

This fact can be seen in the energy losses on holidays in Table 5. The energy losses due to reactive currents on holidays amount to 1772.7 kWh/year. This value has been obtained by multiplying the losses caused by the reactive currents, each day (15.55 kWh, calculated based on the values in Figure 6), by 114 holidays in a one-year period, between September 2020 and August 2021. If the capacitor banks had not been connected, the reactive losses would have been only 113.92 kWh, on holidays (at a rate of only 0.9993 kWh/day). Likewise, CO₂ emissions, on holidays, are 427.21 kg each year compared to only 27,454 kg/year that would be produced without the capacitor banks. The CO₂ emissions indicated in Table 5 have been determined based on the 0.241 kg CO₂/kWh ratio, obtained from Red Eléctrica Española, in 2019 [34].

Table 5. Annual energy losses (W_{cr}) and CO₂ emissions caused by reactive currents in the operation of the transformation house.

	Operation with Actual Capacitor Banks		Operation with No Capacitor Banks	
	Energy Losses (kWh/year)	CO ₂ Emissions (kg/year)	Energy Losses (kWh/year)	CO ₂ Emissions (kg/year)
Working days (251)	1322.77	318.74	3737.39	900.63
Holidays (114)	1772.70	427.21	113.92	27.45

On the contrary, during the hours of greatest activity on working days, the capacitor banks work properly and achieve significant savings in losses and CO₂ emissions (Table 5).

- (2) There are high economic penalties for capacitive reactive consumptions, after the Circular 3/2020 of the National Commission of Markets and Competition of Spain was introduced. (Table 6).

Table 6. Measured and penalized capacitive energies each day and annual penalizations.

Type of Day	Penalization for Capacitive Energy			
	Penalization Period	Measured Capacitive Energy, W_q (kvar-h/day)	Penalized Capacitive Energy, ΔW_q (kvar-h/day)	Annual Penalization (RCAP) (Euros)
Working days (251)	0–8 h	1511.17	324.53	4072.93
Holidays (114)	24 h	7249.43	7032.61	40,085.90

In accordance with what is indicated in Section 2, not all the capacitive reactive energy (W_q), recorded each day in kVAR-h, is penalized, but only the net value (ΔW_q) that results from discounting the inductive reactive energy in the penalty periods and indicated in Table 6, for working days and holidays. Penalties for the capacitive reactive energy (RCAP) have been calculated based on Equations (3) and (4), for a period of one year, between September 2020 and August 2021. This period includes 251 business days and 114 holidays.

- (3) Copper losses and CO₂ emissions caused by unbalanced and distortion currents in the transformer windings are much lower than those due to reactive currents.

These energy losses have been obtained by adding the values of copper losses indicated in Figures 8 and 9, for each hour of the working days and holidays, and multiplying the resulting values by 251 working days and 114 holidays (Table 7). The carbon dioxide emissions, indicated in Table 7, have been calculated by multiplying the energy losses by 0.241 kg CO₂/kWh [34].

Table 7. Annual energy losses and CO₂ emissions caused by unbalanced (W_{cu}) and distorted (W_{ch}) currents in the transformer of the transformation house.

Type of Day	Imbalance		Distortion	
	Energy Losses (kWh/year)	CO ₂ Emissions (kg/year)	Energy Losses (kWh/year)	CO ₂ Emissions (kg/year)
Working days	20.19	4.866	69.37	16.72
Holidays	1.97	0.475	55.52	13.38

4.2. Energy and Environmental Effects Resulting from Improving the Sustainability of the Transformation House

The elimination of penalties for capacitive reactive energy, as well as a reduction in carbon dioxide emissions in the transformation center, can be carried out based on three actions, included in the procedure described in Section 3:

- (4) Optimization of the operation of the capacitor banks;
- (5) Reduction of copper losses caused by imbalances and distortions;
- (6) Replacing the transformer with a more efficient one, with less power.

The first of these actions is the one that can bring economic benefits, while the third provides, above all, energy and environmental benefits.

4.2.1. Optimization of the Operation of the Capacitor Banks

We have already indicated above that there are two banks of three-phase capacitors, fixed, connected to the secondary of the transformation center transformer. The first, $Q_{c1} = 3 \times 25$ kVAR is located in the transformation center itself. The existence of the second bank of capacitors, $Q_{c2} = 3 \times 100$ kVAR, was deduced after analyzing the registered powers.

The operation of the capacitor banks Q_{c1} and Q_{c2} is only efficient in the periods of greatest activity of the companies, in which the reactive power supplies are considerably reduced (Figure 2) and the power factor of the transformer is close to 1 (Figure 10). However, in periods of low activity, whether on working days or holidays, the capacitor banks supply large amounts of reactive power to the mains (Figures 4 and 5), with factors of capacitive power being very small, less than 0.3 capacitive (Figure 10).

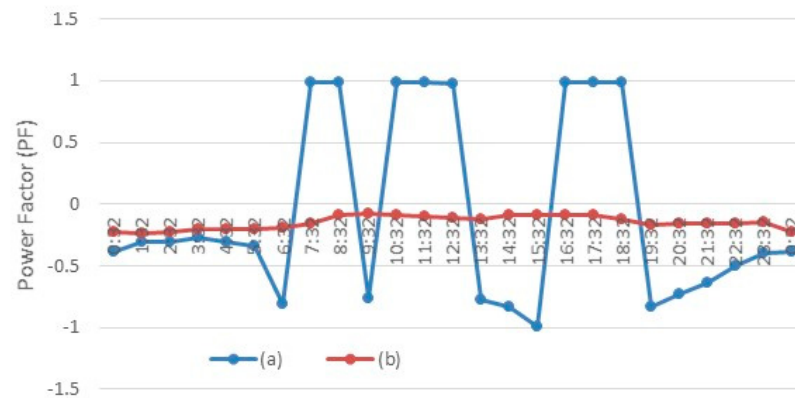


Figure 10. Transformer power factor on (a) working days and (b) holidays. (Positive values indicate inductive PF, whereas negative values signify capacitive PF).

The environmental and economic consequences of reactive power in the inefficient operation of the transformer are observed in Tables 5 and 6, respectively. To reduce their impact, it is necessary to optimize the operation of the capacitor banks. For this, it is proposed:

- a. Maintain the operation of the first capacitor bank (Q_{c1}), without disconnection, at any time of the day, every day of the year, both working days and holidays;
- b. Connect the second capacitor bank (Q_{c2}) only between 7:00 a.m. and 8:00 p.m. on working days, keeping it disconnected for the rest of the hours on working days and all hours on holidays. This solution can be applied, in a very economical way, by incorporating a switch with a programmable timer in this capacitor bank.

The energy effects of the limitation of the period of operation of the capacitor bank Q_{c2} are:

- (1) A significant decrease in the reactive power supplied, with very short capacitive periods, which are compensated by the inductive periods on working days and holidays (Figure 11), reaching power factors very close to unity (Table 8);

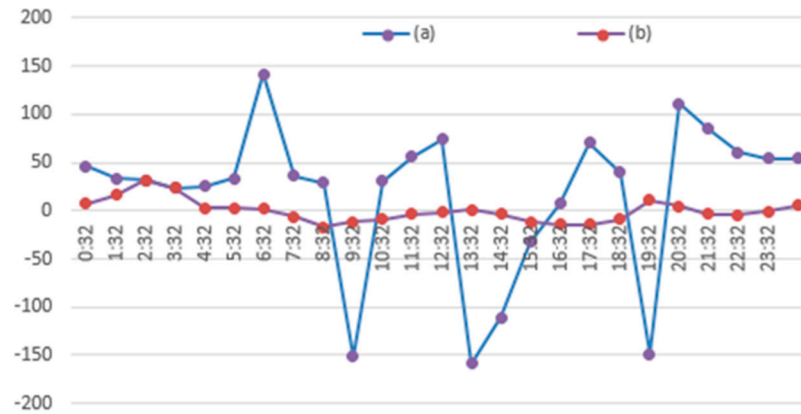


Figure 11. Transformer reactive powers, in kVAR, after applying actions for optimizing the operation of capacitor bank Q_{c2} : (a) working days, and (b) holidays.

Table 8. Power factor and reactive energies each day and annual penalizations resulting from applying the above actions on the second capacitor bank (Q_{c2}).

Type of Day	Power Factor	Total Reactive Consumptions Per Day, W'_q (kvar-h)	Penalized Capacitive Energy W'_q (kvar-h/day)	Annual Penalization (RCAP) (Euros)
Working days	0.99773 (ind)	394.51	0	0
Holidays	0.99998 (cap)	6.7998	0	0

- (2) The high reduction of transformer copper losses caused by reactive currents, especially on holidays (Figure 12), which, compared to those indicated in Table 5, represent energy savings of 2820 kWh/year and 679.58 kg/year, in CO₂ emissions (Table 9).

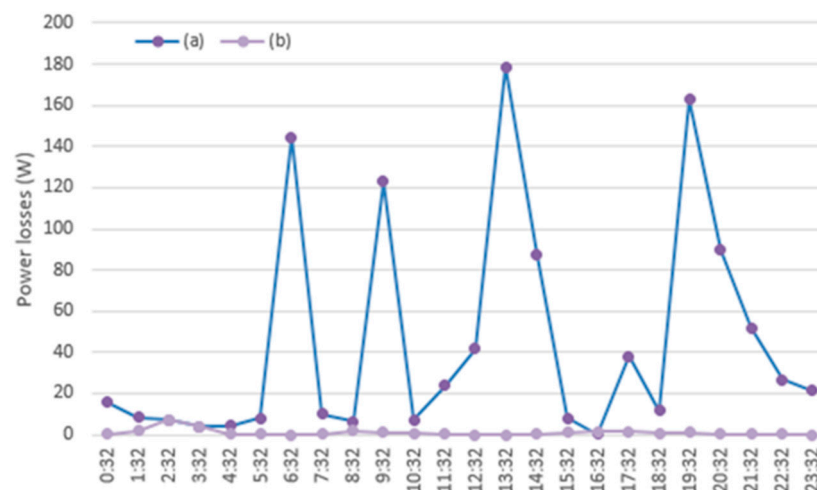


Figure 12. Transformer power losses due to reactive currents (P'_{cr}) after applying actions for optimizing the operation of the capacitor bank Q_{c2} : (a) working days, and (b) holidays.

Table 9. Annual energy losses (W'_{cr}) and CO₂ emissions caused by reactive currents and savings after optimizing the operation of the capacitor bank Q_{c2} .

	Losses and Emissions		Savings	
	Energy Losses (kWh/Year)	CO ₂ Emissions (kg/Year)	Energy Losses (kWh/Year)	CO ₂ Emissions (kg/Year)
Working days (251 days/year)	272.74	65.73	1050.03	253.01
Holidays (114 days/year)	2.65	0.64	1770.05	426.57

4.2.2. Reduction of Transformer Copper Losses Caused by Imbalance and Distortion Currents

The losses caused by current imbalances in the transformer are not affected by the operation of the capacitor banks, since these are balanced loads. Likewise, the values of these losses are very small, both working days and holidays (Figures 8 and 9). This is an indication that the loads are slightly unbalanced and, therefore, it will not be necessary to apply any specific action to reduce these losses, whose values will remain at those indicated in Table 7.

Regarding the phenomenon of distortion, the optimization of the operation of the capacitor banks has an additional beneficial effect, reducing the distortion currents and copper losses.

Indeed, the distortion of the currents is fundamentally caused by the amplifying effect caused by the capacitive loads. This fact is observed in Figure 13. During periods of low activity of the companies, in which there are high supplies of capacitive reactive power, the currents are highly distorted (Figure 13a), with THD% of 14.58%, while in the times of high activity of the companies, the currents are slightly distorted (Figure 13b), with THD% lower than 3.74%. Under these latter conditions, distortion copper losses have an average value of 5.5 W (Figure 8). In our opinion, this is the maximum value of the losses caused by the distortion of the loads, without the amplifying effect of the capacitors, in periods of low activity for the companies.

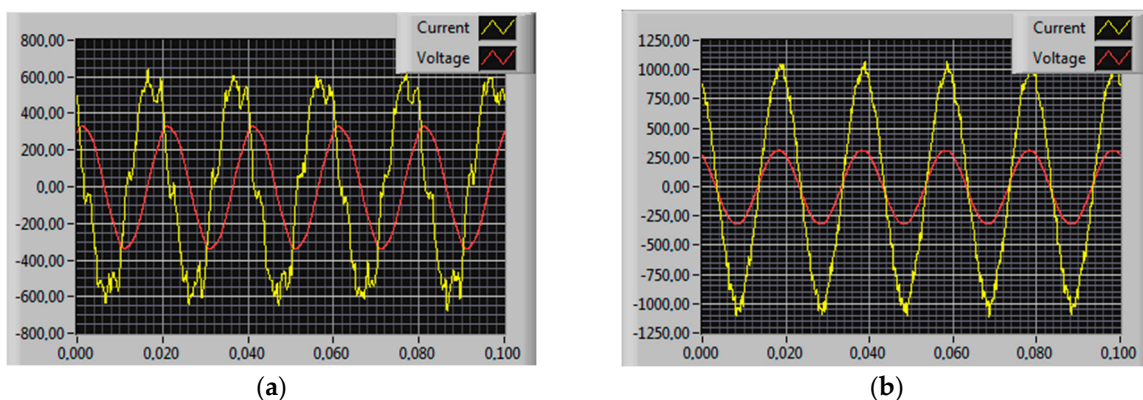


Figure 13. A-phase voltage and current waveforms registered in the secondary of the transformer in periods of (a) small power consumptions and (b) high power consumptions.

Consequently, the disconnection of the capacitor bank Q_{c2} , in the periods of low activity of the companies, gives rise to an additional reduction of the distortion currents and the losses caused by them. Considering that the value of losses due to distortion, without the effect of the capacitors, is the previously indicated 5.5 W every hour, it results in a 50% decrease in energy losses due to distortion currents, indicated in Table 7, for working days, and 75% for holidays. These reductions also extend, with the same percentage, to carbon dioxide emissions (Table 10). These important benefits make the additional installation of harmonic filters unnecessary, in our opinion.

Table 10. Annual energy losses (W'_{ch}) and CO₂ emissions caused by distorted currents and savings after the optimization in the operation of the capacitor bank Q_{c2} .

Type of Day	Losses and Emissions		Savings	
	Energy Losses (kWh/year)	CO ₂ Emissions (kg/year)	Energy Losses (kWh/year)	CO ₂ Emissions (kg/year)
Working days (251)	34.685	8.36	34.685	8.36
Holidays (114)	13.93	3.345	41.59	10.035

4.2.3. Replacing the Actual Transformer with a More Efficient One, with Less Power

The nominal values of the copper and core losses of efficient distribution transformers are indicated in Table 11. It is observed that the core losses of the transformers are smaller in the transformers of lower nominal power. This fact could justify the replacement of transformers with others of lower-rated power. However, it can also be seen in Table 11 that the short-circuit resistance (r_{cc}) evolves in the opposite direction, so the load losses will increase if lower-power transformers are used, since the currents maintain their value. For this reason, in the event of replacing the actual transformer with another of lower power, the most suitable replacement transformer must be the one whose total losses, obtained as the sum of the copper losses and the core losses, have the lowest value.

Table 11. Nominal features of 24 kV efficient distribution transformers according to Commission Regulation (EU) No 548/2014.

Power (kVA)	Copper Losses (W)	Core Losses (W)	Short-Circuit Resistance (Ω)
1600	12,000	1080	0.000826447
1000	7600	693	0.00134064
800	6000	585	0.001653704
630	4600	450	0.00204438

The comparison of the energy loss values in the copper of the 1600 kVA Ormazabal transformer ($W_c^{(1)}$), indicated in Table 12, and is measured by the Fluke 435 Series II instrument according to the equation:

$$W_c^{(1)} = W_{ca} + W_{cr} + W_{cu} + W_{ch} \tag{12}$$

denotes the impact of optimizing the operation of capacitor banks. The copper energy lost in the 1600 kVA Ormazabal transformer, with the optimized operation of the capacitors ($W_c^{(2)}$), is obtained as the sum of the losses due to the active currents (W_{ca}), to the reactive currents (W'_{cr} , Table 9), to the unbalanced currents (W_{cu} , Table 7) and the distortion currents (W'_{ch} , Table 10), determined after the optimization of the operation of the capacitors, i.e.:

$$W_c^{(2)} = W_{ca} + W'_{cr} + W_{cu} + W'_{ch} \tag{13}$$

The copper losses for efficient transformers ($W_c^{(3)}$) have been calculated based on the following expression:

$$W_c^{(3)} = W_c^{(2)} \frac{r'_{cc}}{r_{cc}} \tag{14}$$

where r_{cc} is the short-circuit resistance of the 1600 kVA Ormazabal transformer (Table 4) and r'_{cc} is the short-circuit resistance of the analyzed efficient transformers (Table 11).

The total losses of each transformer have been obtained by adding their copper losses ($W_c^{(1)}$, $W_c^{(2)}$ or $W_c^{(3)}$) to the core losses of each transformer (Tables 4 and 11).

The values of carbon dioxide emissions (Table 13) have been determined by multiplying the total energy lost for each transformation and operation of the capacitor banks, indicated in Table 12, by the emissions factor for the year 2019, in Spain, 0.241 kg CO₂/kWh.

Table 12. Annual copper losses ($W_c^{(1)}$, $W_c^{(2)}$ and $W_c^{(3)}$) and total losses (copper + core losses): ⁽¹⁾ current operation of capacitors; ⁽²⁾ by optimizing the operation of capacitors; and ⁽³⁾ using efficient transformers and optimizing the operation of capacitor banks.

Transformer	Total Copper Losses (kwh/year)		Total Losses (kwh/year)		
	Working Days (251)	Holidays (114)	Working Days (251)	Holidays (114)	Total (365)
Ormazabal 1600 kVA ⁽¹⁾	4909.54	1872.98	20,571.94	8986.57	29,558.52
Ormazabal 1600 kVA ⁽²⁾	3824.84	61.31	19,487.24	7174.91	26,662.15
Efficient 1600 kVA ⁽³⁾	2699.89	43.28	9205.81	2998.16	12,203.96
Efficient 1000 kVA ⁽³⁾	4379.68	70.20	8554.32	1966.25	10,520.57
Efficient 800 kVA ⁽³⁾	5402.42	86.59	8926.46	1687.16	10,613.62
Efficient 630 kVA ⁽³⁾	6678.71	107.05	9389.51	1338.25	10,727.76

Table 13. Annual carbon dioxide emissions, in kg/year: ⁽¹⁾ current operation; ⁽²⁾ optimizing operation of capacitors; and ⁽³⁾ using efficient transformers and optimizing the operation of capacitor banks.

Transformer	Working Days (251)	Holidays (114)	Total (365)
Ormazabal 1600 kVA ⁽¹⁾	4957.84	2165.76	7123.60
Ormazabal 1600 kVA ⁽²⁾	4696.42	1729.15	6425.57
Efficient 1600 kVA ⁽³⁾	2218.60	722.56	2941.16
Efficient 1000 kVA ⁽³⁾	2061.59	473.87	2535.46
Efficient 800 kVA ⁽³⁾	2151.27	406.60	2557.87
Efficient 630 kVA ⁽³⁾	2262.87	322.52	2585.39

Observing the total energy losses, indicated in Table 12, and the carbon dioxide emissions, in Table 13, it follows that the most suitable replacement transformer for the actual 1600 kVA must be an efficient transformer with a nominal power of 1000 kVA, since it is the one with the lowest total losses (Table 12) and carbon dioxide emissions (Table 13). Compared with the 1600 kVA inefficient transformer, annual energy savings of 19,037.95 kWh and annual savings in carbon dioxide emissions of 4588.14 kg are obtained.

4.3. Economic Effects of Improving the Sustainability of the Transformation House

The economic costs derived from the operation of each transformer are obtained by multiplying the value of its total energy losses (in the copper and in the core), for each hourly period (P1, P2, P3, P4, P5 and P6) and type of day (A, B, B1, C and D), according to Table 3, by the energy prices in each hourly period (Table 1). The effects of the increase in electricity prices from January 2020 to January 2022 have been considered in the study.

The economic costs corresponding to the total losses of the inefficient transformer of 1600 kVA, without optimizing the operation of the capacitor bank Q_{c2} , are indicated in the fourth column of Table 14. Likewise, the economic costs due to the total energy losses of the inefficient transformer of 1600 kVA and of the efficient replacement transformer of 1000 kVA, when the operation of the capacitor bank Q_{c2} has been optimized, are indicated in the sixth and eighth columns, respectively, of Table 14.

Table 14. Daily energies and annual costs for three analyzed transformers: 1600 kVA ⁽¹⁾ with no improvements, 1600 kVA ⁽²⁾ with capacitor bank improvements and 1000 kVA ⁽³⁾ efficient transformer, on working days ⁽⁴⁾ and holidays ⁽⁵⁾, corresponding to 2020 ⁽⁶⁾ and 2022 ⁽⁷⁾ energy prices.

Type of Day (n° Days)	Period	1600 kVA ⁽¹⁾		1600 kVA ⁽²⁾		1000 kVA ⁽³⁾	
		Energy kWh/Day	Costs (€/Year)	Energy kWh/Day	Costs (€/Year)	Energy kWh/Day	Costs (€/Year)
A (81)	P1	30.5063	129.96 ⁽⁶⁾	29.6519	126.00 ⁽⁶⁾	13.3958	57.80 ⁽⁶⁾
	P2	24.5555	560.79 ⁽⁷⁾	23.7021	543.53 ⁽⁷⁾	11.1513	249.7 ⁽⁷⁾
B (43)	P2	30.5063	45.93 ⁽⁶⁾	29.6519	44.55 ⁽⁶⁾	13.3958	20.38 ⁽⁶⁾
	P3	24.5555	254.19 ⁽⁷⁾	23.7021	246.38 ⁽⁷⁾	11.1513	113.16 ⁽⁷⁾
B1 (66)	P3	30.5063	37.22 ⁽⁶⁾	29.6519	36.10 ⁽⁶⁾	13.3958	16.50 ⁽⁶⁾
	P4	24.5555	335.57 ⁽⁷⁾	23.7021	325.23 ⁽⁷⁾	11.1513	149.46 ⁽⁷⁾
C (61)	P4	30.5063	18.59 ⁽⁶⁾	29.6519	18.03 ⁽⁶⁾	13.3958	8.26 ⁽⁶⁾
	P5	24.5555	269.76 ⁽⁷⁾	23.7021	269.76 ⁽⁷⁾	11.1513	120.09 ⁽⁷⁾
D 251 ⁽⁴⁾ +114 ⁽⁵⁾	P6 ⁽⁴⁾	26.8981	41.49 ⁽⁶⁾	24.2902	34.98 ⁽⁶⁾	9.5404	11.49 ⁽⁶⁾
	P6 ⁽⁵⁾	78.8296	1035.9 ⁽⁷⁾	62.9378	873.56 ⁽⁷⁾	17.2478	157.62 ⁽⁷⁾
TOTAL	ALL		273.19 ⁽⁶⁾ 2456.2 ⁽⁷⁾		259.66 ⁽⁶⁾ 2250.2 ⁽⁷⁾		114.43 ⁽⁶⁾ 919.45 ⁽⁷⁾

The third, fifth and seventh columns of Table 14 indicate the energy lost daily, in kWh, for each transformer at peak hours (P1-A, P2-B, P3-B1, P4-C), at low hours (P2-A, P3-B, P4-B1, P5-C), off-peak hours on working days (P6⁽⁴⁾) and 24 h a day on holidays (P6⁽⁵⁾), with the times indicated in Table 3 for each type of day of the year (A, B, B1, C and D). The daily values of the energy losses in the transformer have been obtained by adding the consumption at peak hours (9–14 h and 18–22 h), flat (8–9 h, 14–18 h and 22–24 h) and valley (0–8 h, on working days and 24 h on holidays). These hours are the same throughout the year, but the price of energy in each of these hours has a different value, depending on the type of day of the year (Table 1).

The results indicated in Table 14 show that improving the sustainability of the transformation house, optimizing the operation of the capacitor bank Q_{c2} and replacing the inefficient 1600 kVA transformer with an efficient 1000 kVA transformer, allows savings of 158.76 EUR/year, at 2020 energy prices. However, at energy prices of the beginning of the year 2022, these savings amount to the sum of 1536.75 EUR/year. The savings that would have been obtained without the replacement of the inefficient transformer, of 1600 kVA, reducing only its copper losses, would only be 13.53 EUR/year, at 2020 prices, and 206 EUR/year, at prices of principles of the year 2022. To the previous savings, in economic costs of the losses in the transformer, it would be necessary to add the savings in penalties for capacitive reactive energy, which amount to 44,158.83 EUR/year (Table 6), after the optimization of the operation of the bank of capacitors Q_{c2} .

4.4. Summary of Benefits derived from the Improvement of the Sustainability of the Transformation House

The application of the procedure for improving the sustainability of the transformation center used in the application example has allowed the energy, environmental and economic savings indicated in Table 15 to be achieved.

Table 15. Summary of energy, emissions and economic savings in the industrial transformation center: ⁽¹⁾ Optimizing only the operation of the capacitor banks and ⁽²⁾ replacing the inefficient transformer with an efficient one, with optimization of the capacitors.

	Energy and Environmental Savings		Economic Savings (at Prices from Early 2022)	
	Energy (kWh/year)	CO ₂ Emissions (kg/year)	By Energy Consumptions (€/year)	Reactive Penalties (€/year)
No transformer replacement ⁽¹⁾	2896.37	698.00	206	44,158.83
With transformer replacement ⁽²⁾	19,037.95	4588.14	1536.75	44,158.83

Reducing only the copper losses, without replacing the transformer with a more efficient one, by optimizing the operation of the capacitor bank Q_{c2} , the benefits obtained are as follows (Table 15):

- Losses caused by reactive and distortion currents have been considerably reduced, achieving energy loss savings in the transformer of 2896.37 kWh/year and savings in carbon dioxide emissions of 698 kg/year;
- Savings in economic costs derived directly from this energy consumption are very modest and amount to only 206 EUR/year, but the savings in penalties for capacitive reactive energy are very high, at 44,158.83 EUR/year;

In addition, if an efficient 1000 kVA transformer replaces the inefficient 1600 kVA transformer, the benefits derived from the full application of the procedure to improve the sustainability of the transformation house are as follows (Table 15):

- Savings in energy losses of 19,037.95 kWh/year (64.4%) and savings in carbon dioxide emissions of 4588.14 kg/year (64.4%);
- Decrease indirect costs of energy losses by 1536.75 EUR/year (58.11%) and savings from penalties for capacitive consumption by 44,158.83 EUR/year (100%).

5. Conclusions

In this paper, the economic, energy and environmental effects resulting from applying the proposed procedure to improve the sustainability of the transformation houses of the low-voltage distribution networks have been analyzed.

Reducing reactive currents, either through the use of suitable compensation devices or by optimizing the operation of existing ones, is usually a technique that achieves a greater reduction of copper losses in distribution transformers, greater than imbalance compensation and harmonic filtering.

However, the energy savings and reduced CO₂ emissions resulting from minimizing copper losses in older inefficient transformers are very small compared to the savings that can be achieved by reducing core losses, after replacing those transformers with other efficient ones. The combined utilization of current reduction techniques (copper losses) and the use of efficient transformers (core losses) in transformation houses allow for savings of between 55% and 70% in energy consumption and CO₂ emissions in transformation houses with old transformers. However, only between 10% and 20% of these savings are due to the application of copper loss reduction techniques.

The decrease in economic costs, resulting from the application of the proposed procedure to improve the sustainability of transformation houses, is more modest than its energy and environmental effects, especially if only actions are applied to reduce copper losses, such as can be seen in Table 15. However, the current energy shortage means that these cost savings can reach interesting amounts. The savings in penalties for capacitive consumptions are insignificant if the reactive compensators have been well chosen. Otherwise,

optimizing the operation of the reactive compensation devices allows significant savings to be achieved through penalties, as seen in the application example (Table 15).

The results in reducing CO₂ emissions and economic savings obtained in this paper can be extended to each country, simply by using the CO₂ emission factor and the energy prices of the corresponding country.

The procedure described in this paper is being applied to the monitoring of the transformation houses of the distribution network of a small city in collaboration with the electricity company Eléctrica de Vinalosa S.L.U. It is expected that the development of this project will lead to new lines of research that we will describe in future papers.

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Nomenclature

Acronyms

FE	Billed Energy
TDA	Transmission & Distribution Access
PF	Power Factor
RCAP	Reactive CAPacitive, penalty for capacitive reactive power consumptions
THD%	Total Harmonic Distortion, in percent

Greek symbols

α_p	angle of the S_{uiip}^{\rightarrow} component of the vector unbalanced power that measures active power imbalances
α_q	angle of the S_{uiiq}^{\rightarrow} component of the vector unbalanced power that measures reactive power imbalances

Superscripts

Superscript ⁽¹⁾	actual operation of capacitor banks in the transformation house
Superscript ⁽²⁾	optimized operation of capacitor banks
Superscript ⁽³⁾	optimized operation of capacitor banks and changing actual transformers by efficient ones
Superscript ⁽⁴⁾	number of working days in the annual period analyzed
Superscript ⁽⁵⁾	number of holidays in the annual period analyzed
Superscript ⁽⁶⁾	costs, in euros, calculated according to 2020 energy prices
Superscript ⁽⁷⁾	costs, in euros, calculated according to 2022 energy prices

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