

Influence of Cable Losses on the Economic Analysis of Efficient and Sustainable Electrical Equipment

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Abstract

Increasing energy needs are accompanied by environmental responsibilities, since nowadays electricity companies operate in a competitive and sustainable energy framework. In this context, any proposal for action on energy efficiency becomes important for consumers to minimize operational costs. In electrical installations, electricity consumption can be decreased by reducing losses in the cables, associated with the overall efficiency of the equipment, allowing a better use of the installed power. The losses must be analysed in conjunction with all loads that contribute to the currents in the sections of an electrical installation. When replacing equipment in output distribution boxes with more efficient ones, the current in those sections is reduced in association with the decrease in power losses. This decrease, often forgotten, is taken into account in this work for the economic analysis of efficiency and sustainable electrical equipment. This paper presents a new software application that compares and chooses the best investment in the acquisition of electrical equipment. Simulation results obtained with the new software application are provided and are then validated with experimental results from a real electrical installation.

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1. Introduction

In power production, transport, and distribution for final consumption, various aspects have been particularly highlighted: environmental and economically efficient dispatch [1,2], distributed generation and impacts on the operational characteristics of networks [3], customer satisfaction and profit making of the producer and distributor of energy [4], dimensioning of the section of cables to reduce energy consumption and optimize operating distribution systems [5–7], reduction of distribution losses by reducing reactive power optimization with capacitors placed in the distribution lines [8–10], layout optimization for radial distribution [11], and the use of superconducting power transmission [12,13].

Also noteworthy are the study and development of efficient and sustainable electrical equipment, in particular industrial induction motors [14–16], which are responsible for a large share of electricity consumption, as well as efficient lamps [17,18] for industrial and domestic use.

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At a time when global energy consumption is predicted to increase by 38.6% by the year 2030 [19], in association with growing environmental pressure around the industry, there is a need for the most efficient use of energy.

Moreover, in the near future the consumer is expected to stop being passive and to become an active element throughout the chain of production and consumption of energy. This requires that the consumer have action tools available that will help him or her make decisions taking into account the characteristics of the data and the installation.

In order to reduce the energy consumption in a domestic or industrial installation, the efficiency of real loads and all losses in the cables of the installation should be thoroughly studied to improve the energy efficiency. Indeed, energy efficiency and reduction of consumption in electrical installations and equipment represent an important line of research.

Hence, this paper provides consumers with a new software application that allows them to compare options and choose the best investment in the acquisition and installation of electrical equipment, aiming for both efficiency and sustainability. Two research aspects are connected in an original way: the influence of equipment and the losses caused by it in the installation, on the one hand, and the associated economic analysis, on the other hand.

The equipment choice focuses on multiple factors: cost/price, energy consumption, reduction of losses in the cables, useful life, and interest rate. The consumer can then make a decision in the light of all the parameters of the equipment and its electrical installation. The power losses in the conductors must be considered together with all loads that contribute to the current in the sections of an installation, which makes a real difference in the choice of efficient and sustainable equipment.

This study is based on a new way of thinking: from minimal investment cost to minimal lifecycle cost. The connection between optimal cables selection and the influence of efficient/sustainable equipment is also experimentally validated, in addition to the simulation results obtained using the new software application.

This paper is structured as follows. Section 2 presents the problem formulation. Section 3 explains the economic evaluation. Section 4 illustrates the software application. Section 5 provides the simulation results, validated with experimental results. Finally, concluding remarks are given in Section 6.

Nomenclature

\vec{J}_S	Current density vector	d	Monthly operating days
\vec{J}_{ei}	Eddy current density vectors	m	Months of annual operation
V	Volume	λ	Price of electricity
T	Period of the current	ΔP	Difference in cable losses
P_{skin}	Losses due to skin effect	P	Power
P_{prox}	Losses due to proximity effect	$\Delta P[k, i]$	Difference in cable losses of the conductor of the output i of the distribution boxes K
δ	Skin depth	$R[k, i]$	Resistance of the conductor of the output i of the distribution boxes K
R	Conductor radius	$I[k, i]$	Current of the conductor of the output i of the distribution boxes K
D	Conductor diameter	N_i	Initial investment
R_{ac}	AC resistance for the conductor	O_i	Mean annual savings
R_{dc}	DC resistance of the conductor	$SPBT$	Simple Payback Time
I_{rms}	Current (true rms)	VAL	Net Present Value
Q	Distribution boxes	IRR	Internal Rate of Return
σ	Electric conductivity	I	Current
RR	Profit	DD	Operation cost
II	New investment	a	Annual interest rate

2. Problem formulation

The losses in electrical installations are a known problem that cannot be eliminated, but it may and should be reduced. The objective of this study is to present a new software application that allows analysing the influence of cable losses on the economic analysis of efficient and sustainable electrical equipment, validating simulation results with experimental data.

The methodology used to develop this work shows how to calculate the losses in electrical conductors, identifying first the parameters of an electrical installation with the respective loads. The calculation methods used in the software application and the respective outputs are provided. An analysis is presented based on real laboratory measurements, with a wattmeter at the beginning and at end of the conductors to obtain the respective losses. Finally, the simulation results are compared with experimental results to validate the software application.

An electrical installation, whether large or small, produces heat in the conductors when in operation, which is associated with power losses. Industrial and domestic electrical systems operate mostly on alternating current, for which the influence of the skin effect and proximity of conductors should be considered, due to the creation of eddy currents and magnetic fields caused by the neighbouring conductors. The skin effect is the tendency of an AC current to become distributed within a conductor such that the current density is largest near the surface of the conductor and smaller at greater depths in the conductor. The electric current flows mainly at the "skin" of the conductor between the outer surface and a level called the skin depth. The skin effect causes the effective resistance of the conductor to increase at higher frequencies where the skin depth is smaller. Skin depth is due to the circulating eddy currents arising from a changing H field, cancelling the current flow in the centre of the conductor and reinforcing it in the skin.

If currents are flowing through one or more nearby conductors, the distribution of current within the first conductor will be constrained to smaller regions, so the resulting current crowding is termed the proximity effect. The proximity effect can significantly increase the AC resistance of adjacent conductors when compared to its resistance to a DC current. The losses in the conductors of an installation should thus consider the skin effect and the proximity to other conductors. Due to the nonlinearity of configurations and diversity of types of cables, the problem may become very complex in terms of analysis. Multiple studies have been done using programs for finite element analysis, simplification, and verification of semi-empirical formulas that allow valid results and facilitate an analytical and computational analysis.

In an installation as referred to in [20], it is assumed that the multiple phase conductors can be treated as infinitely long parallel wires, so the resulting magnetic field wraps around the conductors in the plane perpendicular to the conductor axis and the resulting eddy currents flow parallel or anti-parallel to the net phase current. The source current density vector \vec{J}_S and the induced eddy current density vectors \vec{J}_{ei} from various phase conductors can be added in each infinitesimal area of the conductor cross-section of interest, after which Eq. (1) can be applied over the cross-sectional area of the conductor to determine the total loss per unit length:

$$P_{total} = \frac{1}{T} \int_0^T \frac{1}{2\sigma} \int_{Volume} \left[\vec{J}_S + \sum_{i=1}^N \vec{J}_{ei} \right]^2 dV dt \quad (1)$$

where V is the volume variable, t is the time variable, σ is the electric conductivity of the conductor, and T is the period of the current wave.

The total losses are the sum of two components, the skin effect and the proximity effect, as given by:

$$P_{total} = P_{skin} + P_{prox} \quad (2)$$

The total losses can be analysed separately, making the overlap at the end.

The loss associated with the proximity effect results from the interaction of conductors that occurs when they are transversed by an electric current, which creates magnetic fields, changing the total distribution of current in the straight section in all conductors. This interaction is a function of the distance between conductors, the amplitude of the current, the phase angle, and the frequency and distribution of induced current.

For instance, in two adjacent conductors carrying AC current flowing in opposite directions, such as the ones found in power cables and bus bars pairs, the current in each conductor is concentrated into a strip on the side facing the other conductor. Since the current is concentrated into a smaller area of the wire, the resistance is increased. The additional resistance increases power losses, which can generate undesirable heating.

To determine the proximity effect losses of multi-conductor three-phase cables, several solutions have been presented as suggested in [20], proposing that when the conductor radius is larger than the skin depth, the power dissipation from the proximity effect is proportional to the conductor radius (Eq. (3)). As the conductor radius becomes less than the skin depth, the loss can be expressed by Eq. (4).

$$P_{prox} = (cR + d) \left(\frac{\mu_0 \mu_r I}{2\pi r} \right)^2, R \geq \delta \quad (3)$$

$$P_{prox} = aR^b \left(\frac{\mu_0 \mu_r I}{2\pi r} \right)^2, R < \delta \quad (4)$$

where $a = 2.605E^6$, $b = 3.968$, $c = 10.192$, and $d = -0.074$ for copper, $a = 1.485E^6$, $b = 3.951$, $c = 13.222$, and $d = -0.125$ for aluminium, R is the conductor radius, and δ is the skin depth, given by:

$$\delta = \sqrt{\frac{2}{\sigma \omega \mu_0 \mu_r}} \quad (5)$$

The contribution of skin effect losses can be calculated using finite element or analytical methods and semi-empirical random configurations for conductors. One approach to three-phase cable systems is presented in [20].

The skin effect increases conductor resistance with frequency as a result of the reduced cross-section through which the current flows. The AC resistance for a conductor with a diameter much greater than the skin depth can be computed from Eq. (6), where D is the conductor diameter:

$$R_{ac} = \frac{l}{\pi \sigma \delta (D - \delta)} \quad (6)$$

The skin effect losses P_{skin} can be calculated by:

$$P_{skin} = I_{rms}^2 R_{ac} \quad (7)$$

In cases where the conductor diameter is comparable to or less than the skin depth, the exact skin effect loss calculation formula, Eq. (8), should be applied, where R_{dc} is the DC resistance of the conductor, and I_0 and I_1 are the modified Bessel functions [21] of the first kind in the zero and first orders, respectively.

$$P_{skin} = \frac{I_{rms}^2 R_{dc}}{2} \operatorname{Re} \left[\gamma \frac{I_0(\gamma)}{I_1(\gamma)} \right] \quad (8)$$

with:

$$\gamma = \frac{(1+j)D}{2\delta} \quad (9)$$

This paper introduces hereafter a new analysis of existing electrical consumers, integrating the losses of conductors, the investment analysis, and the choice of efficient/sustainable equipment.

2.1 Identification of parameters

Three types of parameters are considered: physical, load, and operating parameters. The physical parameters correspond to:

- Distribution boxes (Q): The distribution boxes are numbered from number 1 (initial distribution boxes) to the total number of distribution boxes for the installation.
- Connections between distribution boxes: The connection of the distribution boxes is saved in a matrix that identifies the connection courses. The number contained in the matrix $[k,i]$ indicates the number of the respective output, where k indicates the distribution boxes that provide energy, and i indicates the distribution boxes that receive energy. Figure 1 shows an example of a connection matrix, where distribution box k 1 provides energy to distribution box i 2.

"See Fig. 1 at the end of the manuscript".

- Length and section of the output conductors in the distribution boxes: From the length and section, the resistance of the conductors is determined for all outputs. The values are saved in a resistances matrix, as illustrated in Fig. 2.

"See Fig. 2 at the end of the manuscript".

The load parameters correspond to:

- The power of the loads connected to the electrical installation.
- The efficiency and power factor of the loads.
- The daily load diagram.

The operating parameters correspond to:

- The operating time of the electrical installation.
- Monthly operating days (d).
- Months of annual operation (m).
- The price of electricity (λ).

2.2 Calculations

After the input of the parameters and load diagrams, the following calculations are made:

- Determination of the load diagram associated to the output distribution boxes, adding the corresponding load diagrams.
- Determination of the currents in all conductors of the electrical installation.

- Difference in cable losses (ΔP) in the conductors affected by the changed equipment:
- Profits from the variation of cable losses (G1), given by:

$$G1 = \sum_{j=1}^n [R[k,i](I[k,i]_1)^2 - R[k,i](I[k,i]_2)^2]_j d m \lambda \quad (10)$$

- Profits from the variation of power equipment (G2), given by:

$$G2 = \sum_{j=1}^n [(P1[k,i]_j - P2[k,i]_j)] d m \lambda \quad (11)$$

- Total profits, given by:

$$R = \sum_{j=1}^n [R[k,i](I[k,i]_1)^2 - R[k,i](I[k,i]_2)^2]_j d m \lambda + \sum_{j=1}^n [(P1[k,i]_j - P2[k,i]_j)] d m \lambda \quad (12)$$

3. Economic evaluation

The economic evaluation is conducted in accordance with the rational selection of a solution to be taken during the investment decision, which should be based on a number of comparisons and analyses. The methods can be grouped into static and dynamic methods, to be described hereafter.

3.1 Static methods

Static methods are applied for the assessment of the efficiency during the initial stage when the economic justification of an investment is examined. One of the most popular methods involves the payback period.

Simple Payback Time (SPBT) refers to a method that enables one to determine the overall period necessary for the cost of the expenditure to be returned and is expressed as the length of time needed for an investment to make enough to recoup the initial investment:

$$SPBT = \frac{N_i}{O_i} \quad (13)$$

where N_i is the initial investment, and O_i is the mean annual savings resulting from an investment.

3.2 Dynamic methods

Dynamic methods result in the verification of the credibility of the calculations due to the application of a discount account, considering the change in the time value of money and the total cash flow associated with an investment.

The following methods have found most extensive application: Net Present Value (VAL), Internal Rate of Return (IRR), and Payback Period (PP).

In this paper the VAL is used, which is computed from the sum of the annual cash-flows for a given annual interest rate.

The interest rate is indicated by the investor according to the desired profitability:

$$VAL = \sum_{k=0}^n \frac{RR_k - DD_k - II_k}{(1+a)^k} + \frac{V0}{(1+a)^n} \quad (14)$$

where RR is the net profit, DD is the operation cost, II is the new investment, n is the number of years of useful life, $V0$ is the residual value of the old equipment, and a is the annual interest rate.

4. Software application

The software is structured using matrices and vectors that allow the characterization of the electrical installations and respective loads. The load diagram and parameters of the installation are entered via the keyboard or may carry out data acquisition automatically. After the installation is characterized (physical parameters, load parameters, operating parameters), updating the data in all sections, it starts with the distribution boxes that do not feed other distribution boxes, with the diagram loads being the set of outputs.

Figure 3 provides a flowchart of the software application.

"See Fig. 3 at the end of the manuscript".

Figure 5 presents the results of the new software application for the installation shown in Fig. 4. The results compare an initial situation of a normal induction motor with two more efficient induction motors, to work 5 hours a day, providing the power losses in the cables, the VAL, and the best investment. These results are illustrative of the capabilities of the software application developed.

"See Fig. 4 at the end of the manuscript".

"See Fig. 5 at the end of the manuscript".

5. Case study

5.1 Simulation results

Figure 6 shows the scheme of a real installation with the respective parameters: heater [2,1]: 1000 W; lamps [2,2]: 3×100 W, 3×72 W, or 3×20 W; lamp [3,1]: 100 W; inductor motor [3,2]: 1000 W, to work 8 hours a day.

"See Fig. 6 at the end of the manuscript".

Fig. 7 presents the results of the new software application for the real installation shown in Fig. 6. The results compare an initial situation of a normal 3×100 W incandescent lamp with a 3×72 W halogen lamp and another 3×20 W fluorescent compact one.

"See Fig. 7 at the end of the manuscript".

5.2 Experimental validation

The experimental setup can be seen in Fig. 8, which corresponds to the scheme shown in Fig. 6.

"See Fig. 8 at the end of the manuscript".

Laboratory measurements were performed at the beginning and end of the cables identified in Fig. 6 as A and B. With 3×100 W lamps, losses of 6 and 1.4 W were obtained in cables A and B respectively. Considering the more efficient 3×20 W lamps (option 2), losses of 4 and 0.2 W were obtained in cables A and B respectively.

Figures 9 and 10 shows the measurements made at the beginning and end of cable B, respectively, considering the less efficient lamps. Figures 11 and 12 shows the measurements made at the beginning and end of cable B, respectively, considering the more efficient lamps (option 2).

"See Fig. 9 at the end of the manuscript".

"See Fig. 10 at the end of the manuscript".

"See Fig. 11 at the end of the manuscript".

"See Fig. 12 at the end of the manuscript".

From the experimental results a 43.2% decrease in total losses was observed, which is considerable. Thus, option 2 represents the best investment, validating the simulation results, which provided comparative VAL results.

Considering the operation over a year and large-scale electrical installations, the software application developed represents a valuable tool for assessing different alternatives, indicating the most efficient and sustainable ones.

6. Conclusions

The losses in electrical installations can make a considerable difference in the economic evaluation supporting the investment decision. The results presented confirm that the VAL is superior when the losses are included, and may even switch from negative to positive. The importance of the application of software in real situations was also demonstrated and validated with experimental results, making it possible to analyse and choose effective solutions from the point of view of economic profitability, making energy use more efficient and sustainable. The analysis of energy efficiency in industrial systems should include the whole life cycle and all the components and losses of the system for a proper assessment.

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Figure captions

$i \backslash K$	1	2	...	n
1	0	0	0	0
2	2	0	0	0
...	0	0	0	0
n	0	0	0	0

Fig. 1. Connection matrix.

$i \backslash K$	1	2	...	n
1	0.168	0,281	0	0
2	0.315	0,525	0	0
...	0	0	0	0
n	0	0	0	0

Fig. 2. Resistances matrix.

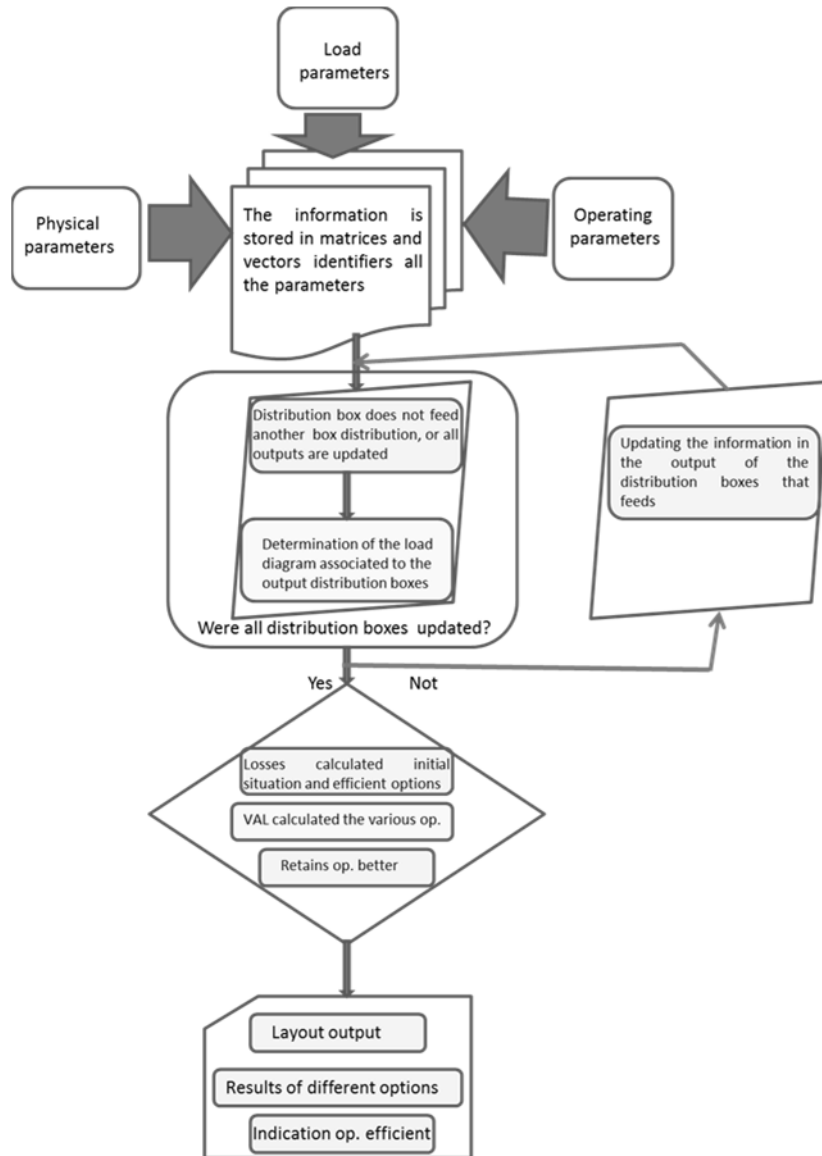


Fig. 3. Flowchart of the software application.

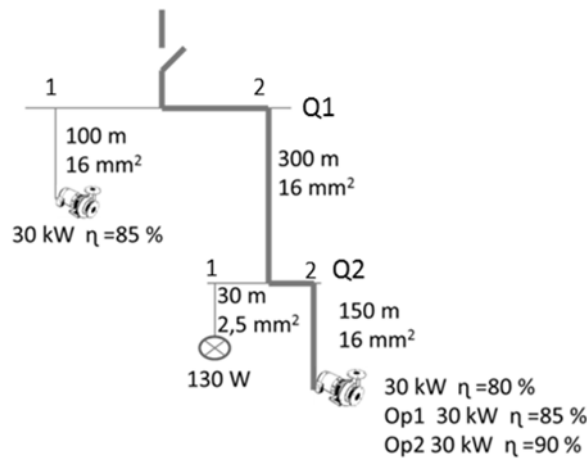


Fig. 4. Scheme of installation A.

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Initial situation:
Power loss in cables:1149.489967Euro/Year

WITH EFFICIENT PUMP option1:
Power loss in cables:1040.273465Euro/Year
UAL (present net value - WITHOUT LOSSES):-634.484
UAL (present net value - WITH LOSSES)165.579

WITH EFFICIENT PUMP option2:
Power loss in cables:946.700268Euro/Year
UAL (present net value - WITHOUT LOSSES):1029.621
UAL (present net value - WITH LOSSES)2515.153

THE BEST INVESTMENT IS:

option:2

WITH UAL(present net value):2515.153

```

Fig. 5. Results of the new software application for installation A.

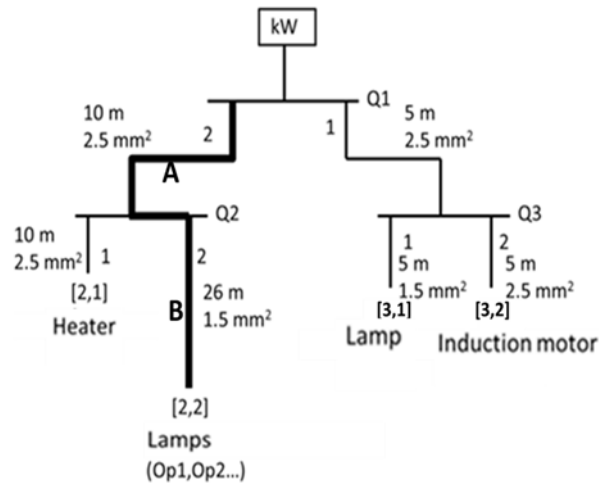


Fig. 6. Scheme of installation B.

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Initial situation:
Power loss in cables:5.416297Euro/Year

WITH EFFICIENT option1:
Power loss in cables:4.900713Euro/Year
UAL (present net value - WITHOUT LOSSES):229.223
UAL (present net value - WITH LOSSES)233.000

WITH EFFICIENT option2:
Power loss in cables:4.201117Euro/Year
UAL (present net value - WITHOUT LOSSES):660.209
UAL (present net value - WITH LOSSES)669.111

THE BEST INVESTMENT IS:

option:2

WITH UAL(present net value):669.111

```

Fig. 7. Results of the new software application for installation B.

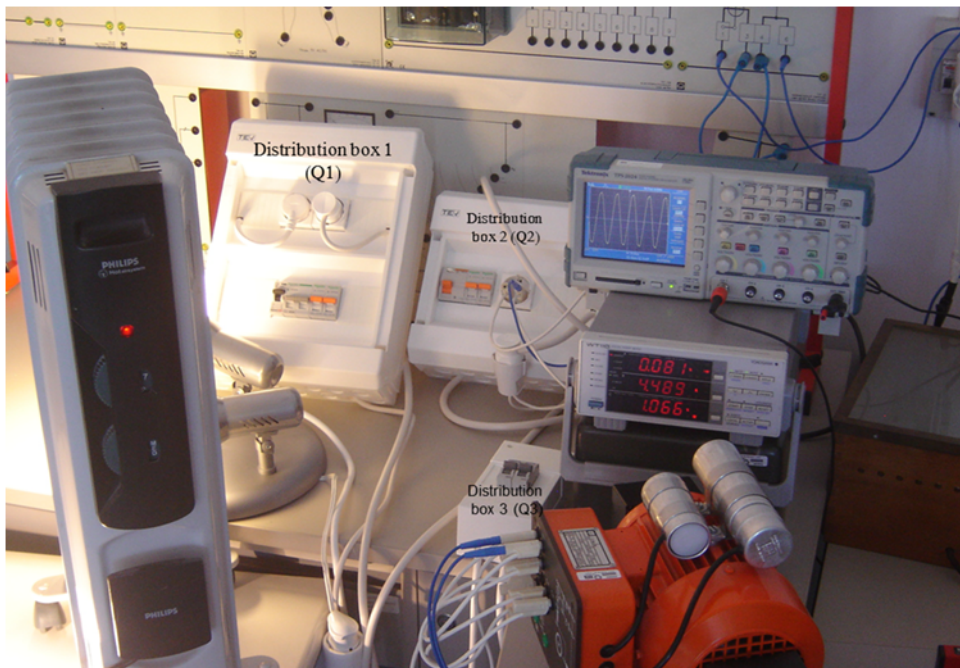


Fig. 8. Experimental setup.

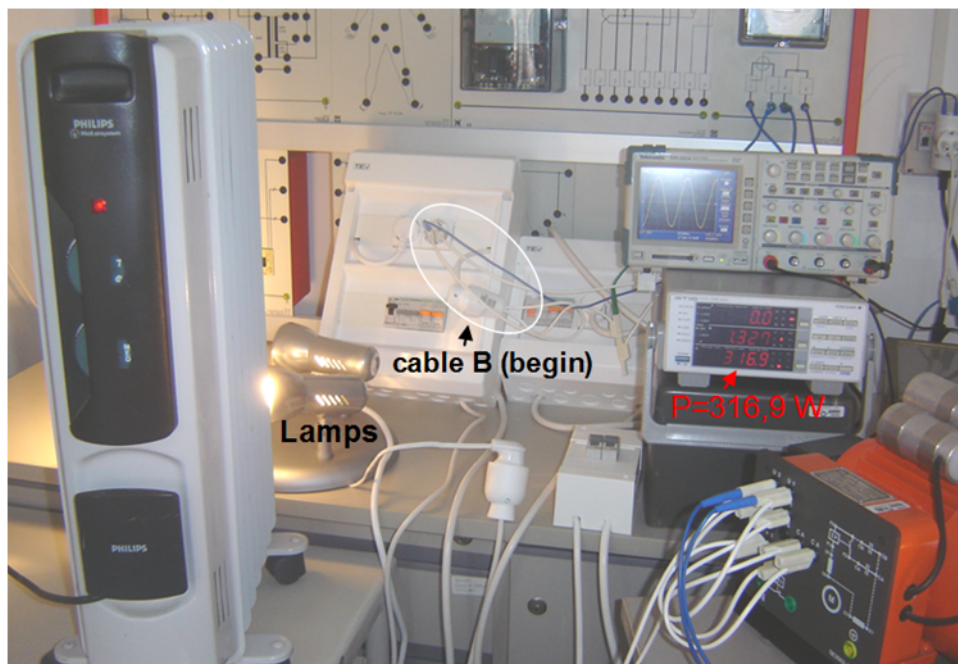


Fig. 9. Initial measure in cable B (begin).

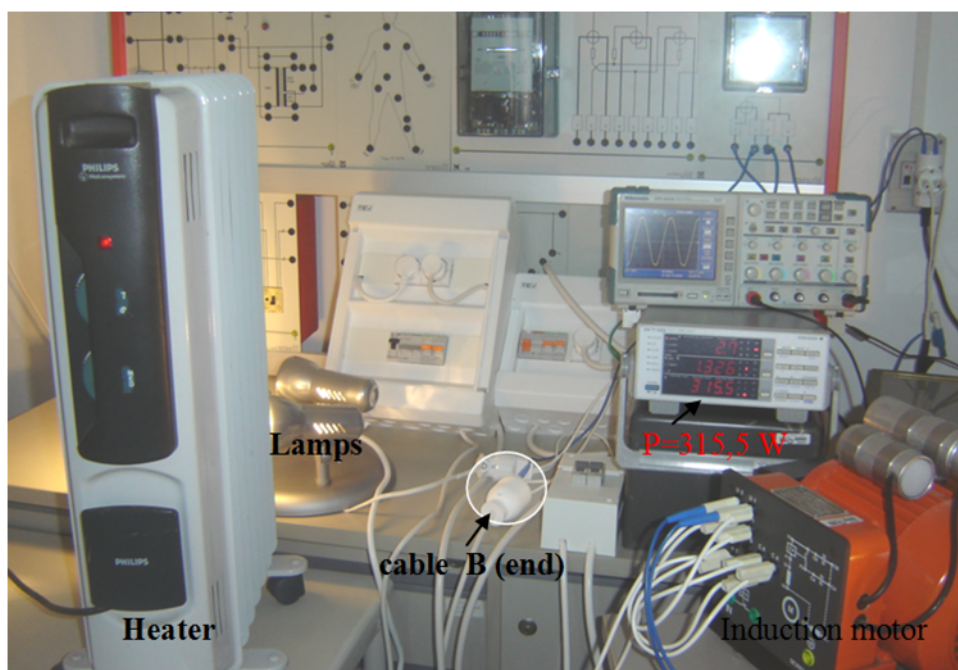


Fig. 10. Initial measure in cable B (end).

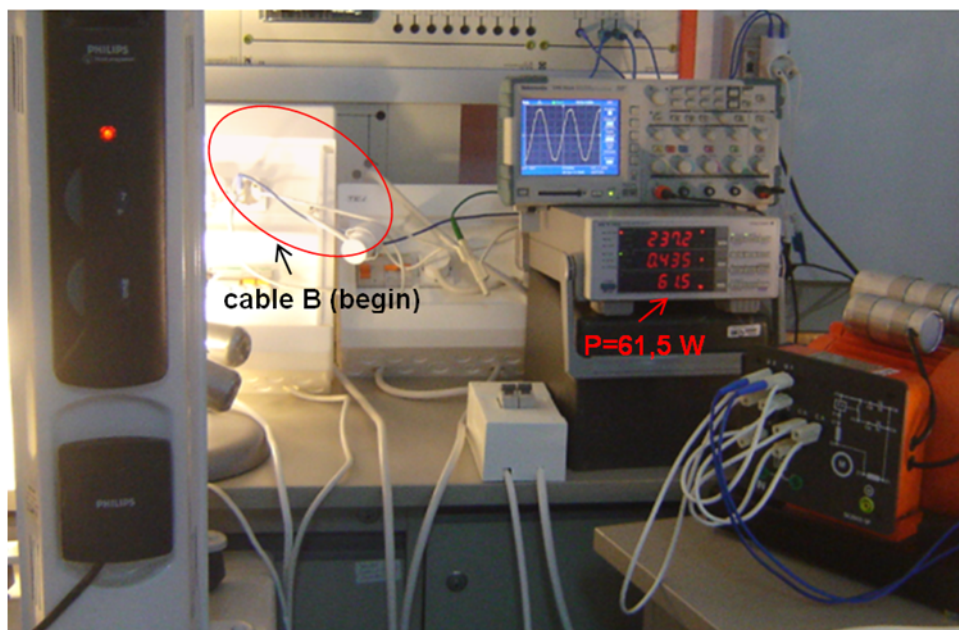


Fig. 11. Measure in cable B (begin), option 2.

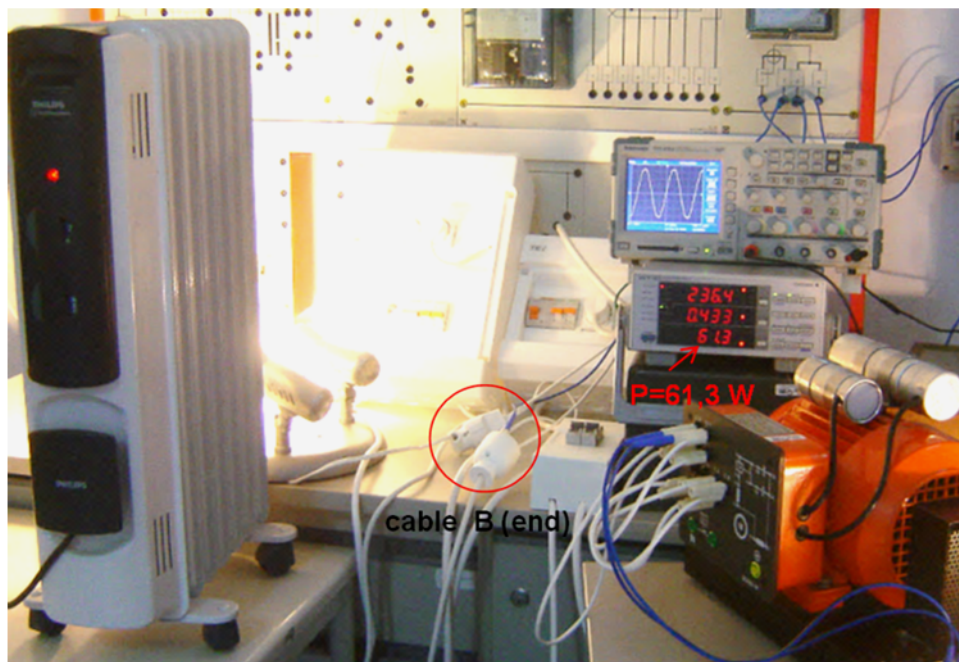


Fig. 12. Measure in cable B (end), option 2.