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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.

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.

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.

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Nomenclature

$\overrightarrow{J}_S$	current density vector
$\overrightarrow{J}_{ei}$	eddy current density vectors
V	volume
T	period of the current
P_{skin}	losses due to skin effect
P_{prox}	losses due to proximity effect
δ	skin depth
R	conductor radius
D	conductor diameter
R_{ac}	AC resistance for the conductor
R_{dc}	DC resistance of the conductor
I_{rms}	current (true rms)
Q	distribution boxes
σ	electric conductivity
RR	profit
II	new investment
d	monthly operating days
m	months of annual operation
λ	price of electricity
ΔP	difference in cable losses
P	power
$\Delta P[k,i]$	difference in cable losses of the conductor of the output i of the distribution boxes K
$R[k,i]$	resistance of the conductor of the output i of the distribution boxes K
$I[k,i]$	current of the conductor of the output i of the distribution boxes K
N_i	initial investment
O_i	mean annual savings
SPBT	simple payback time
VAL	net present value
IRR	internal rate of return
I	current
DD	operation cost
a	annual interest rate

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 life cycle 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.

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 formulae that allow valid results and facilitate an analytical and computational analysis.

In an installation as referred to in Refs. [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 $\overrightarrow{J}_S$ and the induced eddy current density vectors $\overrightarrow{J}_{ei}$ 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:

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

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.