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Exergoeconomic methodology applied to energy efficiency analysis of industrial power transformers

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ABSTRACT

This work aims to develop a methodology based on exergoeconomic models to be used as a tool in the analysis of energy efficiency transformers arranged in distribution networks. The exergetic modelling method adopted is based on building of thermoeconomic functional diagram that will be used later as a reference for defining the allocation of costs associated with the transformer choose for analysis. The exergetic cost for each compound of transformer has a tendency to decrease because the value aggregated by device operation. Also exergetic production cost and final cost of power output have this same tendency. Finally these costs provide a payback period less than a year, which makes viable the investment in this system with operational set points.

1. Introduction

Transformers are devices of fundamental importance in electric power transmission and distribution. This importance is responsible for one third of total losses in the grid where it operates, according to Leonardo Energy Institute [1].

This typical framework encourages the analysis with focus on power quality and energy efficiency, with clear objective to minimise such losses. Mathematical or physical optimisation models have been widely used to find the best configuration of energy systems, particularly in proposals for energy cogeneration.

This work aims to develop a methodology based on exergoeconomic models to be used as a tool in the analysis of energy efficiency transformers arranged in distribution networks.

For this, concepts of heat and mass transfer have been consolidated in order to relate the appropriate equations to develop mathematical representations of the powers and energies involved in the transformation process in the equipment under study [2–6]. The application of such concepts to the analysis of oil transformers was presented in [7,8].

Theory of transformers was also consulted in order to obtain the equations relating to thermal losses in these devices [9–11]. The equivalence between thermal and electrical systems was also favoured by the literature, a great source of information for analysis proposed [12].

Some authors as [13] developed specific models with the clear purpose of relating the influence of the oil temperatures at the top and the hottest spot of winding in transformers of 2500 kV A.

Methods of costs analysis adopted for a technical–economic analysis of transformers had presented in related works [14,15]. These methodologies show most important parameters used in economical engineering adopted, which will be seen with greater attention when exergoeconomic analysis for transformers will be developed [16].

A distribution transformer modelling procedure had discussed by Gorman and Grainger [17,18]. The method presented in part I illustrated how transformer models are developed and how their parameters are estimated, and in part II how they are used in formation of Y_{BUS} and Z_{BUS} system models.

Several authors had developed works about transformers thermal modelling. A novel technique to identify the thermal parameters to be used for the estimation of the hot-spot temperature was presented by [19].

The original transient thermal model of transformers with ONAN cooling was developed by [20,21]. Two problems exist in the on-line application of the model: unknown starting hot-spot temperature and variation in the thermal parameters in a long-term transformer operation. Both are discussed in [22].

Mao et al. [23] used the hot-spot and top-oil temperatures measurements to derive equivalent linear dynamic thermal models yields performance.

An accurate temperature calculation method taking into account the finite element method (FEM) to estimate life of transformer form hot spot temperature had presented by [24]. Also Faiz et al. [25] had used finite element modelling of a typical

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Nomenclature

A	body area (m^2)
A_1	radiating surface area (m^2)
C	thermal capacity of a body (cal/°C or kW h/°C)
c	sensitive specific heat of body (cal/g °C)
c_{OMoil}	cost of operating and maintenance of oil tank (US$/kW h)
c_{OMrad}	cost of operating and maintenance of radiator (US$/kW h)
c_{OMwin}	cost of operating and maintenance of windings (US$/kW h)
c_{oil}	cost of transformer oil tank (US$/kW h)
c_{Pin}	cost of transformer power input (US$/kW h)
c_{Pout}	cost of transformer power output (US$/kW h)
c_{rad}	cost of transformer radiator (US$/kW h)
c_{win}	cost of transformer windings (US$/kW h)
EPC	exergetic production cost (US$/h)
f	annuity factor (–)
G_{Nb}	weight of core and coils of the transformer (kg)
G_{TA}	weight of the tank and accessories (kg)
H	operating time in a year (h)
h	coefficient of film (kcal/h m^2 °C)
I_{oil}	investment on transformer oil tank (US$)
I_{pu}	load current per unit (p.u.)
I_{rad}	investment on transformer radiator (US$)
I_{win}	investment on transformer windings (US$)
K_θ	correction of resistance due to change in temperature (–)
K	constant (cal/s cm °C)
L	body length (m)
m	mass of body (kg)
mn	exponent that defines the non-linearity for the winding hot spot (–)
nn	exponent that defines the non-linearity for oil on top (–)
P_{EC-R}	is the average of the eddy current (Foucault) losses where there is the highest temperature in the winding (p.u.)
R	receipt (US$/year)
Q	amount of heat given or removal of a body (J)
$\dot{q}$	heat flow (kcal/h)
T_1	radiating surface temperature (surface 1) (K)
T_2	radiating surface temperature (surface 2) (K)
V_O	volume of oil (L)

Greek

β	ratio between losses without load and with load (–)
ΔT	temperature variation (K or °C)
$\Delta\theta_{H-R}$	hottest temperature in the windings in relation to the top of oil (K)
$\Delta\theta_{O-R}$	top oil temperature in relation to the ambient one (K)
σ	constant of Boltzmann (4.88×10^{-8} kcal/h m^2 K^4 or 5.669×10^{-8} W/m^2 K^4)
τ_H	time constant winding hot spot (min)
τ_O	time constant of the oil on top (min)
θ_A	ambient temperature (°C)
θ_H	hottest temperature in the windings (°C)
θ_O	top oil temperature (°C)

transformer to indicate that the hot spot position is always on the top most part of the transformer, where temperature of winding depends on the load and the type of loading and is changed by loading.

A numerical method based on heat transfer theory using the finite element method and where only needed to solve heat conduction equation was proposed by [26].

There are many other works relating dynamic thermal modelling of power transformers, such as [27–32]. Specifically top-oil temperature evaluation models had proposed by [33–35]. Also models for prediction of liquid filled transformer loading capability [36] and of hottest spot temperature [37] had proposed.

Numerical modelling for transformer core and winding temperature evaluation had developed by several authors, such as [38–40].

Focus on alternative energy sources has provided new modelling techniques, more accuracy of generating systems, allowing for a more rigorous and clear technical–economical analysis. As an example exergoeconomic and thermoeconomic analysis models have been used as a powerful tool for energy systems optimisation. Exergetic production cost (EPC) is a new method developed for the analysis and optimisation design of thermal systems. The objective of this technique is the minimum (optimal) total operating costs of a plant assuming a constant rate of production and electrical power generation [41–47].

Thermoeconomics is today a powerful tool for studying and optimising an energy generation system. The application of this technique is important for the evaluation of utility costs as products or supplies of production plants, energy costs between process operations or of an energy transformation system. These costs may be applied in viability studies, in investment decisions, by comparing alternative techniques and operating conditions, in a cost-effective evaluation of the equipment during installation, in an exchange or expansion of an energy system [41,42,47].

Several works based on the development of methodologies to model and to optimise thermal energy systems have been analysed in order to obtain information about techniques used in these evaluations [48–61].

Development of models for thermoeconomic design and operation optimisation has also been evaluated. These models deal with thermoeconomic optimisation and the best way to obtain balance between exergy balance and energy production/generation costs [62–70].

Thermoeconomics has been presented in several works relating exergy balance analysis and costs minimisation. These works have played an important role for the establishment of basic fundamentals issues necessary for the development of the proposed methodology [71–78].

2. Methodology

The proposed work will be developed according to the following schedule:

- Relationship of the transformer equations (energetic, exergetic and cost).
- Development of an exergetic model.
- Development of an exergoeconomic model.
- Tabulation of data collected from industries.
- Application of models developed to typical values obtained from industries to validate this methodology.
- Results analysis.