Energy Conservation by Low Loss Distribution Transformers Adapted to Load Characteristics

T. Kefalas, A. Kladas, M. Tsili, E. Amoiralis, P. Georgilakis, G. Loizos, and A. Souflaris

Abstract-- **The importance of distribution transformer no-load loss on the operation of modern electrical grids is often underestimated. Internationally, distribution transformer no-load loss constitutes nearly 25% of the transmission and distribution losses of electrical grids. The losses in European Union distribution transformers are estimated at about 33 TWh/year whereas, reactive power and harmonic losses add a further 5 TWh/year. In the Greek electrical grid the no-load losses of 140,000 distribution transformers are estimated at about 490 GWh/year. This paper has two goals: The first one is to illustrate the significance of distribution transformer no-load loss in periods of high electric energy cost. The second goal is the presentation of a novel numerical methodology for wound core transformers no load loss analysis, enabling to determine the economically and technically optimum transformer for every use, which has been developed in the frame of the respective research project.**

Index Terms--**Computer aided analysis, finite element methods, magnetic cores, nonlinear magnetics, numerical analysis, power transformers, magnetic losses.**

I. Introduction

THE Transformer losses can be categorized into two components, no-load losses and load losses. No-load loss result from the energy required to maintain the constantly changing magnetic flux in the core and is practically independent of the transformer load. Load loss is mainly Joule losses in the transformer windings and is proportional to the square of the load.

No-load loss is the most important operating parameter of transformers, since the transformer is continuously energized in contrast to load losses, which occur only when the transformer is operating under load. Thus, while no-load loss is a fraction of the load losses in nominal load, the energy consumed in the magnetic cores of typical distribution transformers during a year is 300% higher than the energy consumed in the windings [1]. Given that the lifetime of a typical distribution transformer is more than thirty years, operating costs due to no-load loss far exceed the first cost of the transformer [2]. The effect of no-load loss of distribution transformers are the following:

– Increase in operating cost of the transformer.
– Greenhouse gas emissions due to the combustion of fossil fuels to offset no-load losses of the transformers installed in the distribution grid.
– Wasting of fossil fuels and raw materials.

As a result, the reduction of no-load loss of distribution transformers has attracted in recent years the interest of researchers, transformer manufacturers, and electrical utilities.

The reduction of no-load losses and the consequent minimization of operating and manufacturing costs of transformers can be achieved by methods of forecasting no-load losses during the design phase of the transformer. The exact calculation of no-load losses during the design phase is very important for transformer manufacturers and helps to reduce safety margins for no-load losses, avoid the payment of no-load losses penalties, and reduce transformers delivery time [3].

Fig. 1. Typical wound core.

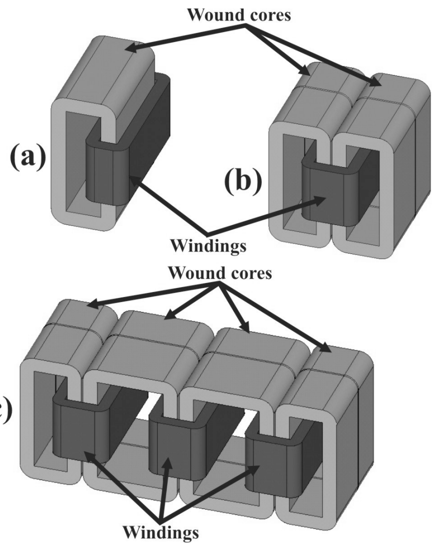

Fig. 2. Wound core transformer. (a) 1-phase core type. (b) 1-phase shell type. (c) 3-phase shell type.

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In this work, an innovative method of computing no-load losses of wound core transformers has been developed [1] [2]. A typical wound core, Fig. 1, consists of hundreds of steel sheets of grain-oriented steel. Wound cores are mainly used in the construction of distribution transformers with rated apparent power that ranges from 25 kVA to 2500 kVA. One-phase and three-phase transformers are made by winding the cores around prefabricated windings as shown in Fig. 2.

II. Losses in the Electrical Grid

High efficiency distribution transformers constitute a technology that is capable of reducing network losses due to the following reasons [4]:

- Distribution transformers represent the second major component of losses in the network.
- Replacement of transformers is easier than changing high and medium voltage cables or lines.
- There are significant margins for reducing transformer losses, as there are nowadays technologies capable of reducing losses up to 80% during the lifetime of a transformer.

On this basis, it becomes clear that there are several reasons for using high efficiency distribution transformers as a technology for improving the efficiency of the electricity grid.

In the next two paragraphs statistical data on losses of international, European, and Greek electricity grids are given.

A. International and European Statistical Data

In recent years, studies in European and international level, involved the recording of installed transformers and distribution losses. Among them is the Leonardo energy program, conducted by the European Copper Institute.

According to Leonardo energy program, losses in the electricity network worldwide are estimated to about 1.279 TWh, or 9.2% of total electricity generated. The network losses are significant for several reasons [5]-[8]. They represent a global economic loss of 61 billion U.S. dollars [9], and they increase significantly the cost of electricity. Also, more than 700 million tones of greenhouse gas emissions may be associated with these losses. Typically, one third of transmission and distribution losses occur in transformers, and two thirds in the rest of the system, while almost 70% of the losses occur in the distribution network.

In the European Union (EU-27), according to Strategies for development and diffusion of Energy Efficient Distribution Transformers (SEEDT), losses of distribution transformers are calculated at 33 TWh / year [8]. In addition, the reactive power losses and higher harmonics contribute a further 5 TWh / year, resulting in total losses of about 38 TWh / year [1], [8]. Due to the loading conditions of the EU-27 distribution transformers, the ratio of no-load losses to load losses is equal to three. This means that 75% of total losses of distribution transformers are due to no-load losses and only a 25% is due to load losses.

B. Greek Statistical Data

The number of installed distribution transformers in Greece is estimated to about 155,000 units. The public power corporation of Greece (PPC) owns about 140,000 units, with a mean no load loss of 400 W per transformer which results to electricity power requirements of 56 MW or to energy requirements of about 490 GWh / year due to no-load losses, [3]. By contrast the electricity consumption in 2006 on both lines of Athens Subway was 90 GWh. The remaining 15,000 units are used for industrial and commercial purposes.

Every year for the replacement of existing transformers and the expansion of the existing distribution grid, PPC installs approximately 7,300 new distribution transformers, and 630 new transformers are installed for industrial and commercial use. These numbers concern only oil-immersed distribution transformers, which constitute the majority of the distribution transformers in Greek and international level.

Most of the installed distribution transformers are of low efficiency, since they were designed to have a minimum manufacturing cost instead of high efficiency, and a large number of them installed in the public grid have exceeded its lifetime.

The replacement of all distribution transformers by new energy efficient transformers is not practical and it is uneconomic. However, newly installed transformers must be energy efficient, since the benefit is twofold. The use of efficient transformers on the one hand helps in the effort of reducing greenhouse gas emissions through energy conservation, and on the other hand purchasers of these transformers will have major economic benefits as they will be able to reduce energy consumption and avoid additional greenhouse gas emissions that might be required to pay due to the Kyoto Protocol.

III. No-Load Loss Evaluation

This section briefly analyzes the conventional and the proposed method of predicting no-load losses of wound core distribution transformers.

A. Conventional Method

The conventional procedure for evaluating no-load losses is the separation of losses into three components and the calculation of each component by using appropriate models. No-load losses are conventionally divided into the following components:

- Classical eddy current losses.
- Hysteresis losses.
- Anomalous or excess losses.

Hysteresis losses and anomalous losses are more difficult to estimate as no accurate physical model has been developed so far. The models that usually are applied are phenomenological models, i.e. mathematical models. Although they give useful results in many applications, their accuracy is not satisfactory and this is the main reason for not being applied in industry.

The usual practice in industry is to calculate transformer no-load losses by using experimental loss curves, which in turn require a large number of measurements in order to investigate the influence of all parameters that affect no-load losses [2]. This method has very good accuracy in the case of standard transformers and electrical steels for which there is sufficient industrial experience. But when non-standard designs are taken into consideration or if new electrical steels are used, the aforementioned method is hardly sufficient. Nevertheless, the use for each electrical steel of a specific core loss curve expressed as a function of peak flux density is a good first approach in determining the no-load loss of wound cores, as specific core loss curves can be determined experimentally with great precision. What needs to be investigated is the development of a systematic technique for calculating the local distribution of flux density and the experimental determination of local specific core losses, in order to develop a general method for calculating the no-load losses of wound cores regardless of their geometrical parameters.

B. Proposed Method

In this work the calculation of no-load losses is achieved through a combination of the locally-computed peak flux density distribution with the experimentally determined local specific core losses [1], [2]. In this fashion the resulting error in predicting no-load losses is kept to a minimum regardless of the geometry of wound cores. Therefore this methodology is suitable for application in the transformer manufacturing industry. The determination of the local peak flux density distribution is performed using the finite element method, which consists of four main stages shown in Fig. 3. The authors have developed a systematic numerical iterative method by which the evaluation of the peak flux density distribution is achieved using only magnetostatics analysis. As a result the aforementioned method results in low computational cost and improved precision in contrast with conventional techniques which are widely used like the finite element harmonic or the finite element transient analysis.

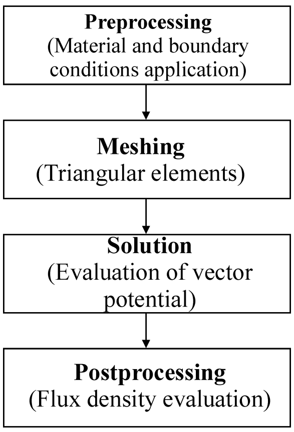


Fig. 3. Flowchart of finite element method.

Another problem to be resolved was the proper representation of wound cores. A typical wound core consists of hundreds of steel sheets. To precisely calculate the flux density distribution by conventional finite element method one would have to model all the steel sheets and the air-varnish composite between them. The resulting finite element model would have a very large computational cost and the solution would be very difficult or impossible to obtain. The technique developed in this paper considers the wound core as being constructed by a bulk material that has certain properties. For the representation of this material the authors developed an anisotropic elliptic model suitable for modeling the steels sheets of the wound core. With the abovementioned technique a good accuracy in calculating the local peak flux density distribution and a minimum computational cost is achieved. Local specific core losses are determined by an experimental setup implemented in the laboratory of Electrical Machines at the National Technical University of Athens. The specific experimental setup involves the usage of search test coils, a sampling card and appropriate computational analysis of measured data using LabVIEW software.

The proposed finite element method provides predictability of transformer no-load losses in the design phase with satisfactory accuracy regardless of the geometry of the wound core or the magnetization level. Also, because the proposed methodology has very low computational cost, it can be incorporated into the existing design methodology used by transformer manufacturers and also it can be combined with deterministic and stochastic optimization algorithms [3], which are necessary to determine the optimum technically and economically transformer.

IV. Results and Discussion

A. Comparison of computed and experimental results

Fig. 4 shows the results obtained from the proposed finite element method for a one-phase wound core shell type transformer. Fig. 4 (a) shows the geometry of the finite element method. Only a quarter of the overall geometry is modeled due to the symmetry of the problem. Fig. 4 (b) and (c) shows the vector distribution of the magnetic field intensity and flux density respectively. Finally, Fig. 4 (d) shows a contour plot of the magnetic vector potential.

The comparison between calculated and experimental local peak flux density in two different positions (at the corner and at the leg of the wound core) and two magnetization levels (1.55 T and 1.86 T) is shown in Fig. 5. The convergence between the calculated and experimental peak flux density distribution is satisfactory as can be seen from Fig 5. The aforementioned comparison was carried out for nine magnetization levels, three different core positions, and for a large number of wound cores. The results were similar to those of Fig. 5 in all cases.

As mentioned in Section III, in the proposed no-load loss evaluation method, the calculated peak flux density distribution is combined with the experimentally defined local specific core losses in order to obtain the no-load losses of wound core transformers.

In the case of analytical calculation of no-load losses for a given magnetization level, the mean peak flux density in the core is determined and then using the specific core loss curve the no-load loss is evaluated. Fig. 6 (a) shows the measured and calculated no-load loss of wound cores using the analytical method for various values of the rms voltage of the coil excitation.

The resulting error ranges between 3.5% for flux density values from 1.3 T to 1.8 T, and -4% for small and large values of flux density (<1.3 T, > 1.8 T). Also, the error tends to increase as the values of flux density decreases i.e., when it is much lower than 1 T, and when the magnitude of flux density is larger than 1.8 T.

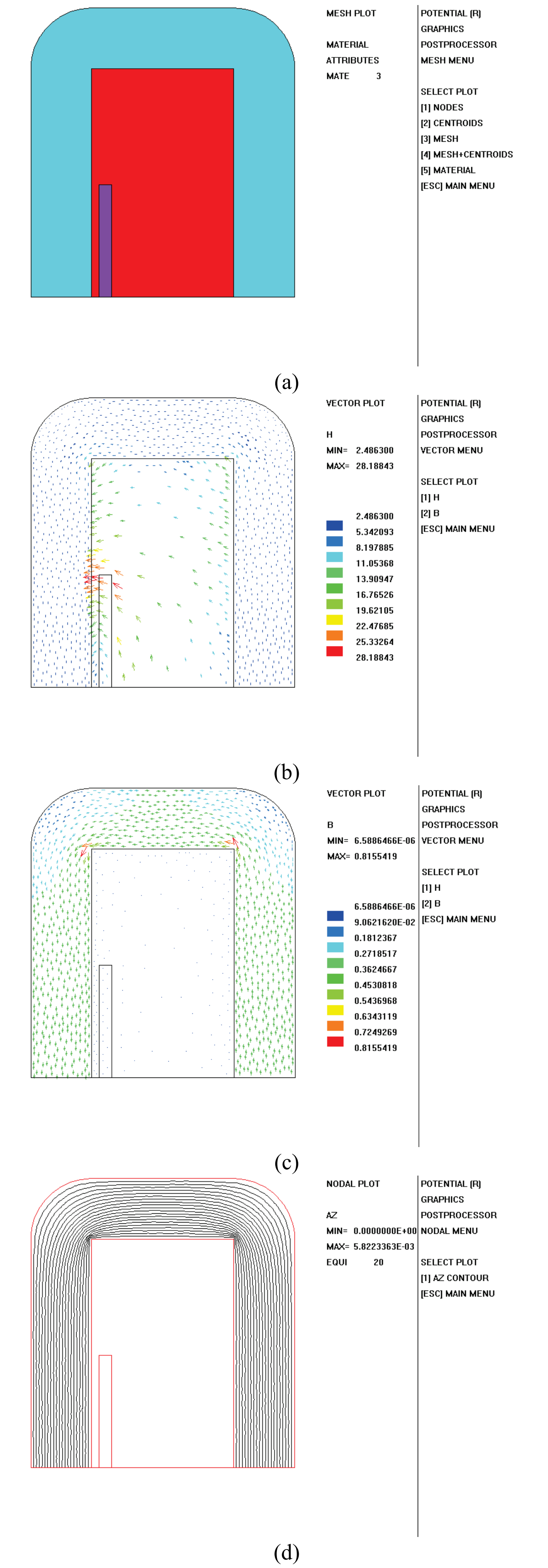


Fig. 4. 1-phase wound core transformer shell type. (a) Finite element model. (b) Magnetic field intensity distribution. (c) Flux density distribution. (d) Magnetic vector potential contour plot.

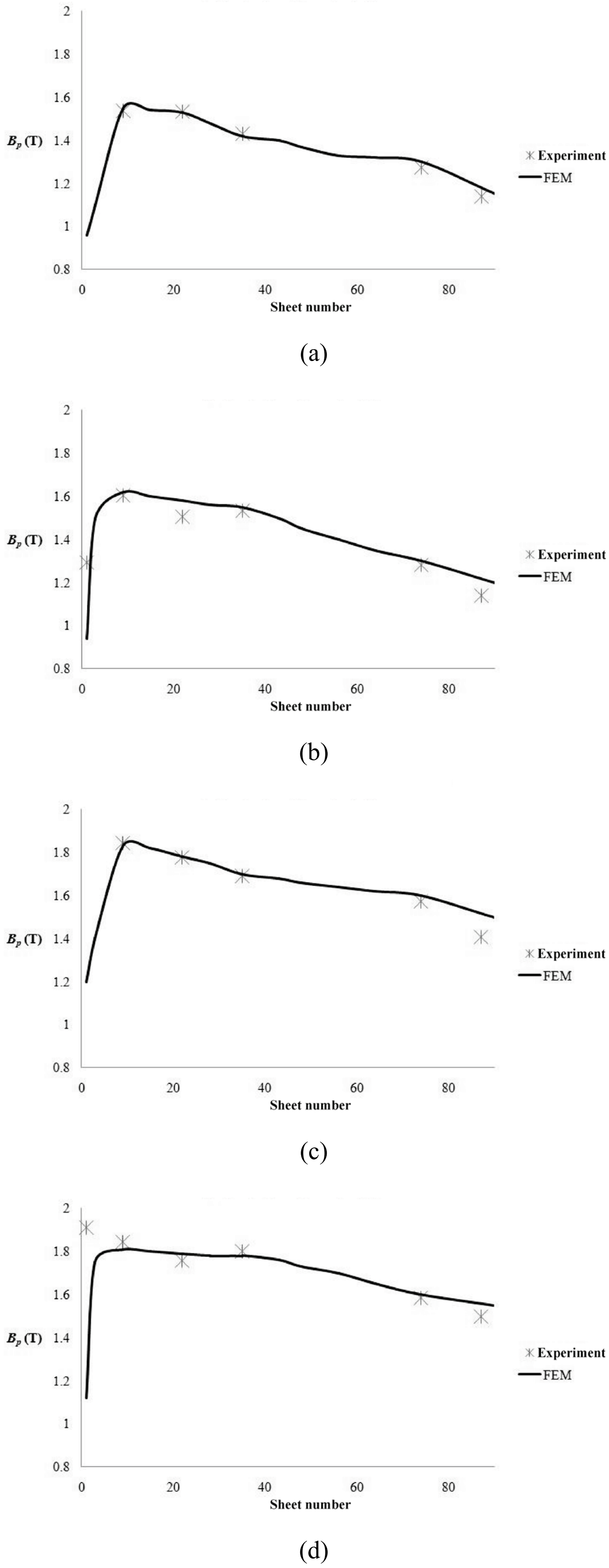
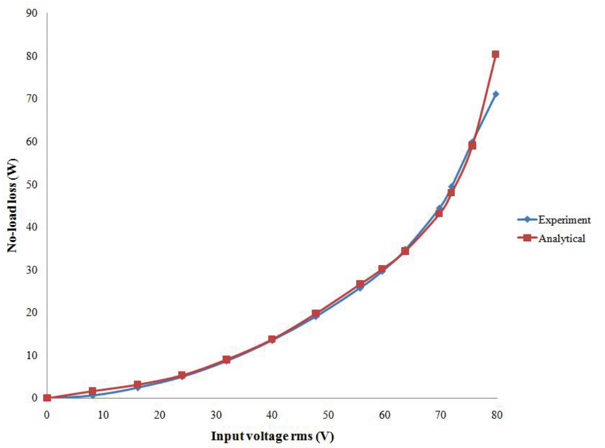


Fig. 5. Comparison of computed and experimental local flux density distribution. (a) Core corner, 1.55 T. (b) Core leg, 1.55 T. (c) Core corner, 1.86 T. (d) Core leg, 1.86 T.

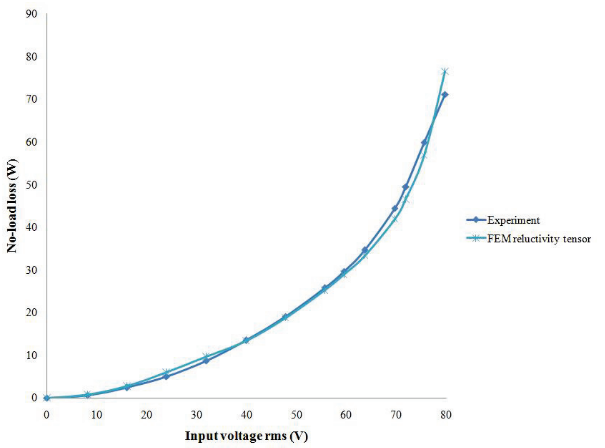
While the precision resulting from the analytical method is satisfactory for the case of conventional wound cores, this is not the case with three-phase transformers where the error is significantly larger. Also the error is not kept constant when the geometric dimensions and design parameters of the core are changing i.e., there is a significant degree of error dispersion. For the aforementioned reasons, the proposed numerical analysis of Section III is adopted for the calculation of distribution transformer no-load losses.

The proposed finite element analysis uses successive nonlinear magnetostatics analysis for various values of input excitation current and each time the excitation coil flux linkage is determined and from the latter the rms input voltage. This is repeated until the appropriate value of input current that ensures a specific voltage input is determined. Finally by using a postprocessor code and the resulting peak flux density distribution the no-load losses are evaluated.

In this method the macroscopic representation of the core material is chosen, using the magnetic reluctivity tensor and the elliptical anisotropic model. The reason for selecting the description of the core material using the reluctivity tensor is that the core consists of a large number of steel sheets so that the magnetic reluctivity is lower in the tangential direction of the steel sheet than in the normal direction of the steel sheet. As a result, the local flux density distribution of the core is different from that obtained considering a finite element analysis without using the tensor. The abovementioned is confirmed experimentally by the experimentally determined local flux density distribution of the core by using search coils as shown in Fig. 5. Fig. 6 (b) shows the measured and calculated no-load losses using the finite element method and the reluctivity tensor. The error ranges between 4% and 1% for all magnetization levels.



(a)



(b)

Fig. 6. Comparison of computed and experimental no-load loss. (a) Analytical method. (b) Proposed numerical method.

B. *Optimization of Transformer Design*

The optimization of the wound core transformer design is carried out by combining the no-load loss evaluation methodology with the branch and bound optimization procedure [3]. Initially, the proposed optimization method was compared with the conventional heuristic methodology used in the transformer manufacturing industry [3] to optimize the design of wound core distribution transformers rated at 160 kVA, 400 kVA, 1000 kVA and 1600 kVA in two different losses categories, BA' and AC'. The results are shown in Fig. 7. In all cases, the proposed optimization method results in transformer designs of lower manufacturing and operational cost than the corresponding designs obtained using the conventional method of optimization.

Then the proposed distribution transformer optimization methodology was compared to the existing methodology used by the industry for about another 200 study cases. For the objective comparison of the two methodologies the comparison must be carried out using the following data:

- Guaranteed no-load losses and load losses, as well as their corresponding percentages
- Prices of eight key materials
- Low and high voltage winding material
- Voltage value of the windings
- High and low voltage winding connection
- Low and high voltage winding material (copper, aluminum)
- Current density of high and low voltage winding
- Frequency
- Magnetic materials
- Joint ranges of the design variables (Low voltage winding turns, core width, core height, and flux density)

Taking into consideration the aforementioned input data as a common reference point, 200 design optimizations were carried out. Specifically, there were 14 designs at 1600 kVA, 24 designs at 1000 kVA, 20 designs at 800 kVA, 48 designs at 630 kVA, 28 designs at 400 kVA, 16 designs at 250 kVA, 24 designs at 160 kVA, and 14 designs at 100 kVA. Fig. 8 shows the average cost difference between the optimal designs obtained using the existing methodology and the proposed optimization methodology. As shown in Fig. 8, the proposed methodology leads to optimal designs which are of lower manufacturing and operational cost than those obtained by the conventional methods, by 1.60% for all 188 designs. It is worth noting that the specific average cost is achieved without affecting the quality of the optimal solutions provided by the optimization methodology proposed, in terms of compatibility with the design constraints, deviation from the guaranteed price losses and short-circuit voltage, and other performance characteristics.

V. Conclusion

The paper addresses the problem of wound core transformer no-load losses evaluation and the development of new methods to minimize their manufacturing and operating cost. The development of the proposed methods has led to the reduction of the manufacturing and operating costs of wound core distribution transformers. This in turn led to significant economic and environmental benefits and improvement of transformer efficiency.

An accurate prediction of no-load losses during the design phase is very important for transformer manufacturers since it contributes to the following.

- The reduction of safety margins for no-load losses.
- Avoid payment of no-load loss penalties.
- The reduction of delivery time of newly manufactured transformers.

The aforementioned have resulted in a significant reduction of the manufacturing and operating cost of wound core distribution transformers. Finally, because the purchase of transformers from utilities is based on the total cost of ownership, the manufacturing as well as the operating cost is taken into consideration, and as a result transformer manufacturers that will be able to offer transformers with certain specifications and minimized total ownership cost, are going to increase their market share.

On the other hand, the reduction of no-load losses is very important for distribution transformer owners since the no-load losses of the distribution grid and thus the cost of losses is very high due to the large number of distribution transformers installed in the distribution network.

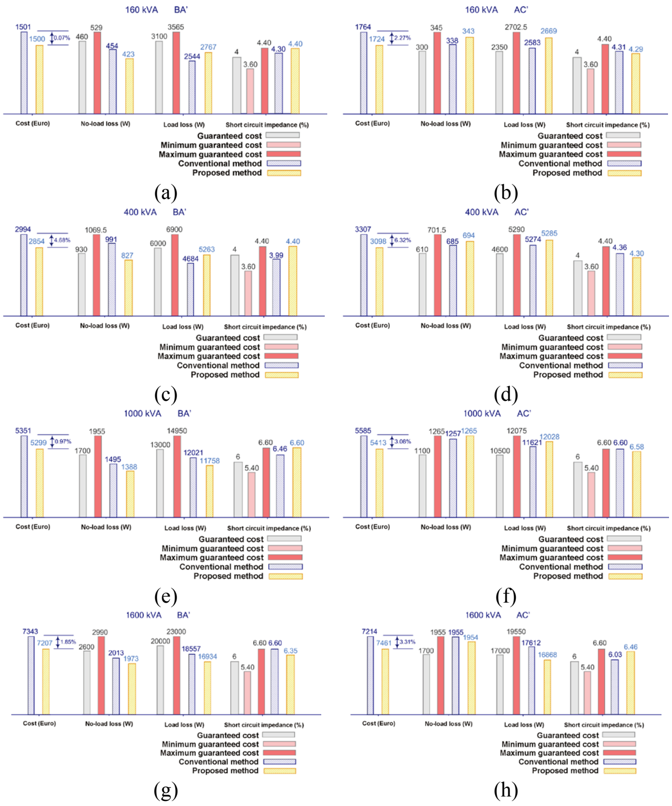


Fig. 7. Comparison of both methods for distribution transformer of nominal capacity (a) 160 kVA, BA’ loss class, (b) 160 kVA, AC’ loss class, (c) 400 kVA, BA’ loss class, (d) 400 kVA, AC’ loss class, (e) 1000 kVA, BA’ loss class, (f) 1000 kVA, AC’ loss class, (g) 1600 kVA, BA’ loss class, (h) 1600 kVA, AC’ loss class.

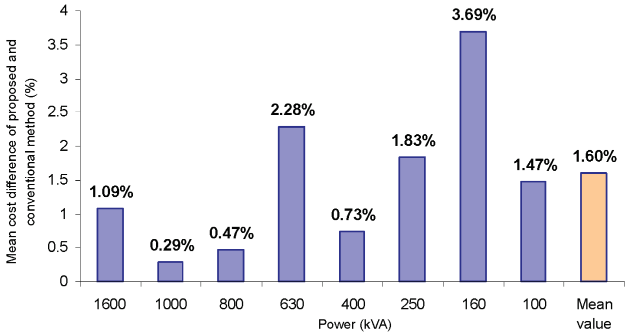


Fig. 8. Cost percentage difference between optimum design of the conventional and proposed methodology per transformer nominal capacity.

VI. Acknowledgement

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