OPTIMAL DESIGN OF TRANSFORMERS FOR SUBTRANSMISSION AND DISTRIBUTION NETWORKS

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INTRODUCTION

Efforts aiming at achieving optimal designs are considered among the most important activities of transformer manufacturing companies. Obviously, such activities can only be successful provided that accurate and efficient simulation and computational tools are utilized. In this paper, the use of finite-element and integral-equations computational tools in several transformer design aspects is presented. Examples of advantages resulting from using the aforementioned tools in comparison with conventional design procedures are given and results are discussed.

OBJECTIVES OF AN OPTIMAL DESIGN OF TRANSFORMERS FOR SUBTRANSMISSION AND DISTRIBUTION NETWORKS

Considerable efforts are carried out with the objective of optimally designing network transformers. The objective functions to be extremized is usually the cost of the transformers either initial or total capitalized cost. The optimization is subject to operational constraints and without compromising the quality so that the reliability and the outage free service length is unaffected if not improved. The design variables for transformer optimization usually include the winding space factors, the core dimensions, the flux density, and the current densities. The operation constrains are either individual, such as current density or flux density, or in the form of functions of the design variables, such as the reactance, the no load losses, the load losses, the eddy current loss, temperature rise, dimensions, transport weight and external dimensions.

Among network transformers, distribution and sub-transmission network transformers have quantitatively different operational constraints (compared with each other). These differences include:-

(i) Distribution transformers (11-22/0.4 kV) are required to have a considerably lower percentage leakage reactance (4%-7%) than for the sub-transmission transformers (66/11 kV) which ranges between 11 and 13 %.

(ii) Distribution transformers have a lower iron loss as a percentage of copper loss to give maximum efficiency at low load factors. This could limit the maximum core flux density. Distribution transformers could have a flux density as low as 1.0T while for sub-transmission transformers it could be 1.6 T and higher.

(iii) Distribution transformers have a higher window aspect ratio (window height/window width=3-4) while for sub-transmission transformers the ratio is around 2.

(iv) Distribution transformers have a smaller eddy current loss as a percentage of the ohmic loss.

(v) Distribution transformers have a smaller ratio between the core cross section and the total conductor cross sectional area per window.

For the above reasons, designs of distribution and sub-transmission transformers have to be dealt with separately. There are two approaches to the solution of the optimization problem for distribution and sub-transmission transformers [1]. The approach followed here is the multiple design method [1] based on generating a number of alternative designs covering combinations of the selected key design variables.

MODELING OF THE TRANSFORMER

An accurate modeling of the transformer is required to predict its performance for a given design and given input conditions. This would require a complex nonlinear, 3-D, time varying and composite media field modeling, which can be time consuming and expensive. A complete model will account for the non-linearity and hysteresis in the magnetic material as well as the eddy currents in the core and in the windings.

Three approaches are considered in this paper. Namely, these approaches are:-

(i) The conventional approach based on equivalent circuit modeling and approximate formulas. This is the conventional approach followed by transformer manufacturing companies. It is based on years of experience and a large database coupled with regression analysis techniques. This approach allows the designers to quickly design the transformer and predict its performance. However, it is limited in applicability and if significant changes are made to the physical configuration of the transformer, computational results that differ significantly from test results may be expected. The range of validity needs to be confirmed by measurements or by accurate field modeling.

Integral equation approach. This numerical approach has been outlined in an earlier paper [2]. It is based on nonlinear volume integral equation formulation for the magnetization of the core. Dynamic effects and eddy currents in the windings are not considered initially. Once the core magnetization is solved for, the leakage magnetic field due to the winding currents in the presence of the core can be computed and this is used as incident field to compute the eddy current loss in the windings.

Finite elements approach. This formulation is based on the variational form or the weak form of the boundary value problem of the transformer [3,5]. It can also be a
composite approach in which the magnetic field distribution is first solved for neglecting dynamic effects and eddy currents. This is then used as a boundary condition to solve for the eddy currents in the windings [3,4].

OPTIMAL DESIGN OF SUB-TRANSMISSION TRANSFORMER

This paper deals with the design optimization of subtransmission (power) transformers as well as the distribution transformers since subtransmission is regarded as high voltage distribution in many unified systems. As previously stated, the design optimization is broadly targeted at the minimization the sum of the initial cost, the capitalized cost of losses over the transformer lifetime, in addition to any applicable penalty cost for probable design criteria not strictly met. These design criteria may include: no load losses, load losses, the percentage reactance as well as the maximum flux density and current density.

In general, the design process involves computations coupled to some safety factors and/or margins. Factors incorporated in a particular design approach should ensure that a manufactured transformer will conform to all design constraints. More rigorously, these factors are supposed to account for two main possibilities. First, they are supposed to account for any expected narrow manufacturing tolerances due to human errors, material quality tolerance, assembly undetected misshaps, …etc. Second, they serve as to portray worst-case computational scenarios for criteria that can not be precisely estimated.

As a result of the incorporation of such safety factors, it is very well possible to end up with a manufactured transformer that does not exactly conform with the design criteria constraints. On one hand, a transformer superior in performance to the constraints suggest that the incorporated factors were over estimated leading to a more expensive than needed design. On the other hand, a transformer that does not meet the constraints suggest that the factors were under estimated yielding a transformer that may end up as a sales burden.

While it is extremely difficult to estimate factors related to manufacturing tolerances, these factors may be roughly inferred from manufacturing practices and experiences for every manufacturing plant. As for factors related to computational aspects, more precise estimations may be achieved provided that more accurate computational approaches are used. Obviously, these accurate computational approaches would involve electromagnetic field analysis. It should be pointed out that using conventional design approach instead of electromagnetic field approaches may still work provided that the design problem is restricted within the limits of applicability of these formulas.

In order to demonstrate these points, a conventional design approach was used to estimate the no load loss for two different 25 MVA 66/11 KV transformer designs. Dimensional details of these two designs are given in Figure 1. Two electromagnetic field approaches, finite element approach[5] and integral equations approach[2], were also applied to the same designs for the same purpose. For these two approaches, tank losses were computed using methods discussed in [2] after obtaining the field distribution in the various tank parts. Comparison between results obtained from all three approaches are given in Figures 2-4. These figures reveal how computations obtained from the conventional approach may be misleading. A bold example is the conventional approach prediction of tank losses for the design #2 under consideration which exceeds 3 times accurate finite-element calculations (refer to Figure 3).

![Figure 1: Comparison between dimensional details of the two 25 MVA designs under consideration (normalized with respect to Design #1).](image1)

![Figure 2: Comparison between computed core loss for both 25 MVA designs (normalized with respect to finite-element results).](image2)

![Figure 3: Comparison between computed tank loss for both 25 MVA designs (normalized with respect to finite-element results).](image3)
OPTIMAL DESIGN OF SPACE CONSTRAINED SUBTRANSMISSION TRANSFORMERS

There is no doubt that the demand for electric power is increasing from one year to another. Whether residential or industrial loads are considered, expansion becomes a goal within every nation in order to fulfill economical growth plans. In fact, there are economical indicators that directly correlate electrical power consumption per capita to living standards.

As electricity consumption increases, good network planning necessitates the replacement of existing transformers with larger ones within substations that are in the immediate vicinity of load centers. Two challenges remain to be faced in such a case. The first is to try to maintain the footprint area of new transformers. This should avoid the need to expand the substation area which might be extremely costly especially in metropolitan areas and/or crowded cities having high population. The second challenge is to try to minimize, as much as possible, any increase in transformer weight. Meeting this requirement means making use of existing civil structures housing and/or supporting transformers with no additional enforcements.

Along the very same lines of reasoning, demands to replace existing 25 MVA power transformers with new 40 MVA ones in Egypt appear to be increasing. Efforts aiming at achieving a 40 MVA design comparable, both space wise and weight wise, to existing 25 MVA ones have been carried out. While these constraints may mean sacrificing some efficiency criteria, good as well as accurate optimization design measures should be taken to minimize this aspect as much as possible. Obviously, field computation packages become indispensable.

Design efforts to achieve the aforementioned goals have been carried out for 40 MVA transformers. In these efforts, the previously mentioned integral-equations approach has been utilized[2]. In order to demonstrate the effectiveness of the adopted optimization design approaches, three different transformer designs are compared. Namely, a space/weight constrained 40 MVA transformer design was compared to both an existing 25 MVA design and an unconstrained 40 MVA transformer design. Results of this comparison, normalized with respect to the existing 25 MVA transformer design, are shown in Figures 5 and 6. As can be seen from these figures a 40 MVA transformer design has been achieved, without sacrificing any of the existing 25 MVA transformer performance criteria, with a mere increase of 15% and 18% in volume and weight, respectively. The unconstrained design shown in the same figure also reveals that achieving better performance is possible with a larger and heavier transformer. Likewise, a 40 MVA transformer having identical (or smaller) dimensions and weight compared to the 25 MVA design is achievable at performance cost.
as a sub-optimization problem subject to the following assumptions:

(i) The type of the core lamination (for a given flux density $B$) will only affect the iron losses.

(ii) The selection of the lamination type can be based on the sum of the cost of the lamination and the capitalized cost of the iron losses.

(iii) Comparison is based on designs which meet all the operational constraints.

Although, as pointed out before, the large aspect ratio of the window can limit the applicability of conventional analysis approaches, this does not apply to the iron losses and the iron weight of distribution transformers in particular.

Figures 7-9 compare the sum of the cost of the silicon steel laminations plus the capitalized cost of the iron losses for H0 and M1 lamination-types. These figures show that it is more economical to use M1 lamination-type for distribution transformers at any flux density $B$. For 25 MVA and 40 MVA subtransmission transformers, however, it is found that it would be more economical to use M1 lamination-type for $B \leq 1.75T$ and $B \leq 1.6T$, respectively. Generally, it is also found that the difference in losses resulting from using both lamination types is small except for flux density values $B$ exceeding 1.85 T.

**CONCLUSIONS**

From the results presented and discussed in this paper, it is clear that the optimization of transformer designs have to be performed through the utilization of accurate computational approaches. These approaches should, somehow, be based on electromagnetic field analysis techniques. Only by adopting such approaches, it is possible to estimate the possible minimization estimates for a design loss, design volume or both.

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**REFERENCES**


