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Cost reduction by interchanging the location of the windings in distribution transformers with HV copper winding and LV aluminum winding

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SUMMARY

According to the conventional winding configuration of distribution transformers, denoted as L-H, the low voltage (LV) winding is located internally and the high voltage (HV) winding is located externally. This paper proposes a new winding configuration, denoted as H-L configuration, according to which the location of windings is interchanged, that is, the HV winding is located internally and the LV winding is located externally. In the designs of transformer analyzed in this paper, the HV winding is manufactured with copper conductors and the LV winding with aluminum sheets. We have modified our transformer design program to analyze the new H-L configuration. Transformers ratings from 30 to 112.5 kVA are considered to show the cost reduction trend. The H-L and L-H configurations are compared on the basis of the following parameters: mean length of HV winding, mean length of LV winding, weight of HV conductor, weight of LV conductor, material cost, and total owning cost. As a result of the proposed design change, transformer manufacturers save material and reduce cost. Transformers cost reductions are especially important in the competitive environment of transformer companies around the world. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: transformer design; cost reduction; transformer windings; L-H configuration; H-L configuration; copper; aluminum

1. INTRODUCTION

In order to successfully compete in a global economy, transformer manufacturers need to continuously improve transformer design to save material and reduce cost. Because it is easier to insulate, traditionally the low voltage (LV) winding is placed closer to the core and the high voltage (HV) winding covers the LV winding [1–23]. In this paper, this conventional arrangement of windings is called L-H configuration. Authors of [1–23] use the L-H configuration for various purposes, which are not explicitly mentioned here for the sake of space. This is a list of references that could be substantially increased, but we just want to emphasize that there is not a single publication proposing the H-L configuration. Our paper proposes a design improvement capable of reducing the distribution transformer cost while ensuring the fulfillment of all constraints in three-phase distribution transformers using rectangular windings. In this paper, the HV winding is placed closer to the core, and the LV winding covers the HV winding. This arrangement of windings is called H-L configuration. In Figure 1, we can appreciate the differences between both winding configurations.

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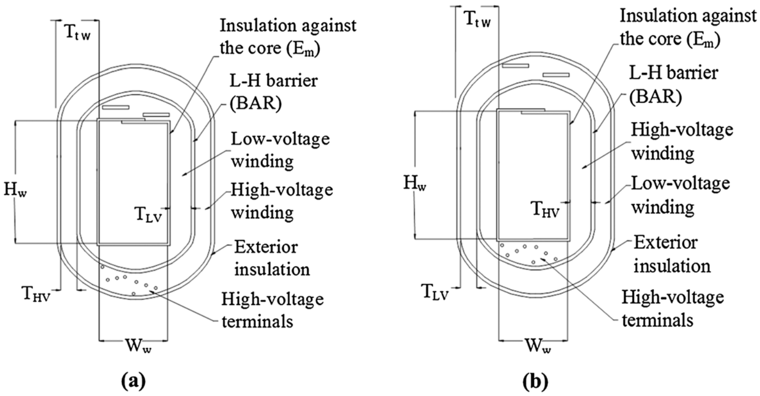

Figure 1. Rectangular windings: (a) L-H configuration, (b) H-L configuration. The letters L and H refer to low and high voltage windings, respectively.

In comparison with the conventional L-H configuration, the cost of the new H-L configuration is reduced because the mean length of the HV copper winding is reduced since the HV winding is placed close to the core. Copper material is more expensive than aluminum, and savings are obtained by reducing the mass of the HV copper winding at the cost of increasing the mass of the LV aluminum winding [23].

Furthermore, the distribution transformers with conventional L-H configuration have been designed in this paper using a field-validated transformer design computer program that has been utilized for many years in a mid-size transformer factory [1,21,22]. This noncommercial program was appropriately modified in the context of the research presented in this paper to design transformers with the proposed H-L configuration.

One distribution transformer has been actually built using the proposed H-L configuration, and this transformer has successfully passed all routine tests, according to international standards, with no failures reported [24]. This transformer, with the new configuration, has had a successful operation for more than 1 year, and no faults or dangerous overheated areas have been detected.

A common practice in many transformers companies is to re-design the transformers of their database, using their design computer programs, so as to try to reduce costs by at least 3% (minimum). If designers manage to achieve this goal, they then generate again all information to manufacture the transformer (drawings, list of raw materials, etc.).

The innovation proposed in this paper is that it exploits the price differences between copper and aluminum in order to reduce the cost of distribution transformers, manufactured with copper HV windings and aluminum sheet LV windings, by interchanging the location of the windings. This innovative design reduces the transformer cost from 6% to 10%, which constitutes a great improvement for the competitiveness of the transformer manufacturing industry.

2. CONVENTIONAL DESIGN BASED ON L-H CONFIGURATION

Figure 2 shows the rectangular windings with the L-H configuration, where the HV winding is manufactured with copper conductor and the LV winding is made of aluminum sheets.

The distribution transformers analyzed in this paper utilize a five-limbed core, three-phase shell-type distribution transformer (Figure 3). The cores are constructed to allow them to be inserted within coils. The joint configuration of cores is called step–lap joint [25]. The core laminations are in succession in order to obtain a higher mechanical stability. The joints have to be rigid and strong so as to prevent their removal under severe operation conditions and also to diminish the noise that emanates from their vibration during transformer operation.

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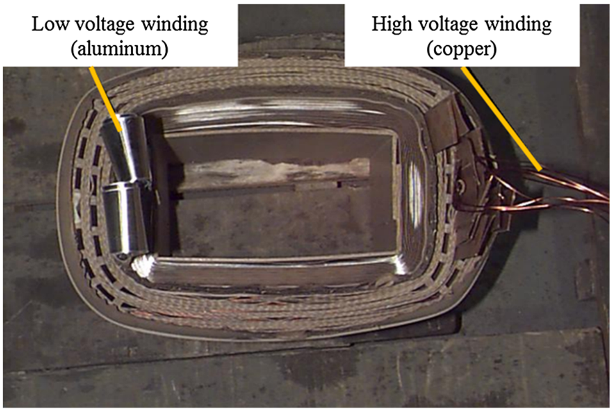

Figure 2. Rectangular windings with L-H configuration.

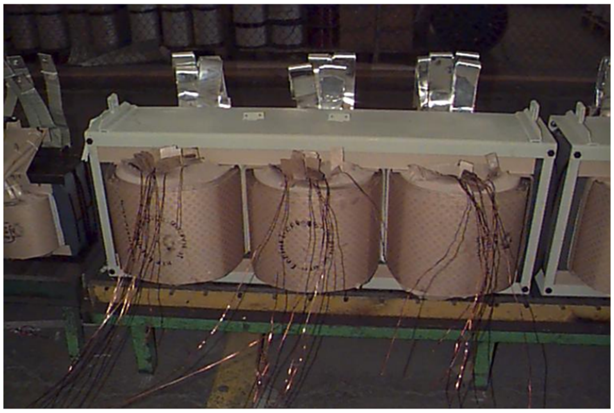

Figure 3. Three-phase shell-type transformer after the process of iron core-winding assembly. The proposed H-L configuration has been used.

For the conventional L-H configuration, the material weight of the LV and HV windings is computed as follows [22]:

$$W_{LV}^{c} = MLW_{LV}^{c} \cdot N_{LV} \cdot N_{\theta} \cdot S \cdot \rho_{Al} \cdot 10^{-6} \tag{1}$$

$$W_{HV}^{c} = MLW_{HV}^{c} \cdot N_{HV} \cdot N_{\theta} \cdot S \cdot \rho_{Cu} \cdot 10^{-6} \tag{2}$$

where

$$MLW_{LV}^{c} = \frac{\pi \cdot \left(A_1^c + B_1^c\right)}{2} \tag{3}$$

$$MLW_{HV}^{c} = \frac{\pi \cdot \left(C_1^c + D_1^c\right)}{2} \tag{4}$$

$$A_1^c = \frac{2 \cdot (W_w + H_w)}{\pi} + 2.2 \cdot E_m \tag{5}$$

$$B_1^c = A_1^c + 2.3 \cdot T_{LV} \tag{6}$$

$$C_1^c = B_1^c + 2.2 \cdot BAR \tag{7}$$

$$D_1^c = C_1^c + 2.2 \cdot T_{HV} \tag{8}$$

where S is the cross-section area of conductor, ρ_{Al} is the resistivity of aluminum, and ρ_{Cu} is the resistivity of copper.

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3. PROPOSED DESIGN BASED ON H-L CONFIGURATION

3.1. Overview

In devising any winding arrangement, the designer must choose the best combination of possible arrangements to obtain [1]

(a) adequate dielectric strength against various types of voltages,
(b) adequate cooling system,
(c) adequate mechanical strength, and
(d) minimal cost.

In this paper, the H-L configuration satisfies all the aforementioned requirements. In 2013, the authors in conjunction with the Mexican company Industrias IEM designed and manufactured a shell-type distribution transformer with the H-L configuration. This transformer passed all the factory tests, according to international standards [24]. Figure 4 shows details of the manufacturing of the rectangular windings with the H-L configuration.

3.2. Proposed H-L configuration

For the H-L configuration, the material weight of the LV and HV windings is computed as follows [22]:

$$W^p_{LV} = MLW^p_{LV} \cdot N_{LV} \cdot N_\theta \cdot S \cdot \rho_{Al} \cdot 10^{-6} \tag{9}$$

$$W^p_{HV} = MLW^p_{HV} \cdot N_{HV} \cdot N_\theta \cdot S \cdot \rho_{Cu} \cdot 10^{-6} \tag{10}$$

where

$$MLW^p_{LV} = \frac{\pi \cdot \left(C^p_1 + D^p_1\right)}{2} \tag{11}$$

$$MLW^p_{HV} = \frac{\pi \cdot \left(A^p_1 + B^p_1\right)}{2} \tag{12}$$

$$A^p_1 = \frac{2 \cdot (W_w + H_w)}{\pi} + 2.2 \cdot E_m \tag{13}$$

$$B^p_1 = A^p_1 + 2.3 \cdot T_{HV} \tag{14}$$

$$C^p_1 = B^p_1 + 2.2 \cdot BAR \tag{15}$$

$$D^p_1 = C^p_1 + 2.2 \cdot T_{LV} \tag{16}$$

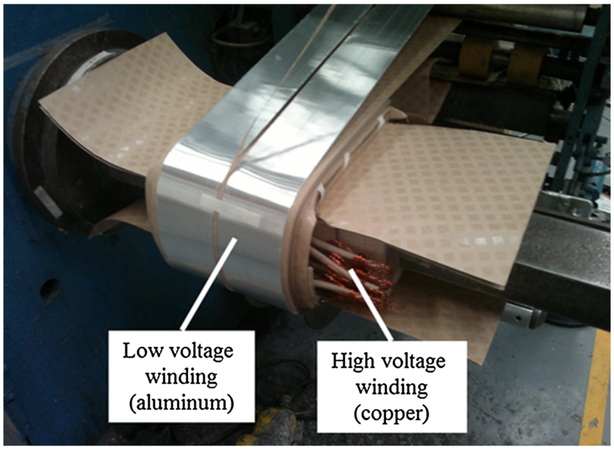

Figure 4. Rectangular winding with H-L configuration; high voltage winding is located internally and the low voltage winding is located externally.

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Equations (9)–(16) of the proposed H-L configuration have the same structure with the Equations (1)–(8) of the conventional L-H configuration. The main differences are $MLW_{LV}^{p} > MLW_{LV}^{c}$ and $MLW_{HV}^{p} < MLW_{HV}^{c}$.

4. TRANSFORMER DESIGN OPTIMIZATION

The transformer total owning cost (TOC) takes into account not only the transformer bid price but also the transformer losses throughout the transformer lifetime. The TOC is computed as follows [1,26–28]:

$$TOC = BP + CL = BP + A \cdot NLL + B \cdot LL \tag{17}$$

where

$$BP = \frac{MC + LC}{1 - SM} = \frac{TMC}{1 - SM} \tag{18}$$

where *TOC* (\$) is the total owning cost throughout the transformer lifetime, *BP* (\$) is the transformer bid price, *CL* (\$) is the cost of transformer losses throughout the transformer lifetime, *A* (\$/W) is the no-load loss cost rate, *NLL* (W) is transformer no-load loss, *B* (\$/W) is the load loss cost rate, *LL* (W) is transformer load loss, *MC* (\$) is the cost of transformer materials, *LC* (\$) is the labor cost to manufacture the transformer, *TMC* (\$) is the transformer manufacturing cost, and *SM* (%) is the transformer sales margin. Details on how the loss cost rates *A* and *B* are determined can be found in [1,26–28].

The objective of transformer design (TD) is to design the transformer so as to minimize TOC subject to several constraints: (a) constructional constraints and (b) the following operating constraints: maximum no-load losses, maximum total losses (minimum efficiency), maximum and minimum impedance value, and maximum limit on the magnetizing current. The design methodology is based on a multiple design method that assigns many alternative values to design parameters [1,21,22]. The TD results of this paper have been obtained with a field-validated TD program that has been used for many years in a mid-size transformer factory.

5. RESULTS AND DISCUSSION

5.1. Cost reduction

Table I shows a comparison of three-phase transformers, 60 Hz, with 13,200 V rated primary voltage, 220 V rated secondary voltage, delta-connected primary, star connected secondary, with the conventional and the proposed winding configuration. In Table I, the following parameter values are used: $A = 8.16$ US \$/W, $B = 4.02$ \$/W.

The following very interesting conclusions are drawn from Table I:

(1) The TOC of a transformer with the proposed H-L configuration is from 6% to 10% less expensive than the conventional L-H configuration.

Table I. Comparison of three-phase transformers with the conventional (L-H) and the proposed (H-L) configuration, 13,200/220 V at 60 Hz.

	75 kVA		112.5 kVA	
Design parameter	Conventional configuration	Proposed configuration	Conventional configuration	Proposed configuration
Flux density (T)	1.520	1.520	1.520	1.520
Mean length of LV winding (%)	100.00	149.20	100.00	140.92
HV conductor weight (%)	100.00	59.26	100.00	63.14
LV conductor weight (%)	100.00	155.2	100.00	141.68
Material cost (%)	100.00	71.50	100.00	85.34
TOC (%)	100.00	94.00	100.00	90.44

HV, high voltage; LV, low voltage; TOC, total owning cost.

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(2) The material cost of the proposed H-L configuration is 29% less expensive than the conventional L-H configuration.
(3) The proposed H-L configuration requires on average 39% less copper (in weight) than the copper weight of L-H configuration.
(4) An H-L configuration requires on average 48% more aluminum (in weight) than the aluminum weight of L-H configuration.
(5) The mean length of the LV winding of an H-L configuration is on average 42% larger than the mean length of LV winding of an L-H configuration.

The insulation papers (cardboard paper, crepe paper, and diamond dotted paper) used in typical windings of a distribution transformer represent only 2% of total material cost of a transformer. The cost of a typical tap changer is around 0.5% of the total material cost of a distribution transformer.

The improved transformer design (H-L configuration) is recommended for distribution transformers with primary distribution voltages ranging from 2300 to 34,500 V. On the other hand, it is not recommended to use the H-L configuration for voltages higher than 34,500 V, because the use of aluminum for the construction of the secondary winding (LV winding) will slightly increase the dimensions of the transformer tank.

5.2. *Short-circuit mechanical stress*

The radial and axial short-circuit mechanical stresses for the 112.5 kVA transformer with the H-L configuration were calculated during the design process [29], and the results are shown in Table II. It can be concluded from Table II that both L-H and H-L configurations comply with the restrictions of Table III for the maximum short-circuit mechanical stress [29]. Moreover, the L-H and H-L configurations show similar mechanical stress levels; however, the short-circuit mechanical stresses are all slightly lower for the proposed H-L configuration.

5.3. *Dielectric breakdown characteristics*

The maximum dielectric breakdown value depends on the thickness of the insulation paper. The breakdown voltage of an insulation system is that value of the voltage for which the dielectric either temporarily or permanently loses its insulating properties by way of a discharge process [30]. In order to determine this permissible value, experimental dielectric breakdown curves are typically used by designers. More specifically, dielectric breakdown curves for diamond dotted paper (made of kraft paper) immersed in transformer oil are used. Figure 5 shows the experimental dielectric breakdown curves for the insulation paper used in this research. Particularly, curve (a) of Figure 5 corresponds to the lightning impulse condition and curve (b) corresponds to normal voltage at 60 Hz [31].

Table II. Calculated short-circuit mechanical stress for the L-H and H-L configurations of the 112.5 kVA transformer of Table I.

Short-circuit mechanical stress (kg/cm^2)		
Direction	Conventional L-H configuration	Proposed H-L configuration
Radial	7.82	7.33
Axial	0.59	0.51

Table III. Maximum short-circuit mechanical stress for transformer.

Direction	Stress (kg/cm^2)
Radial	18.0
Axial	1.4

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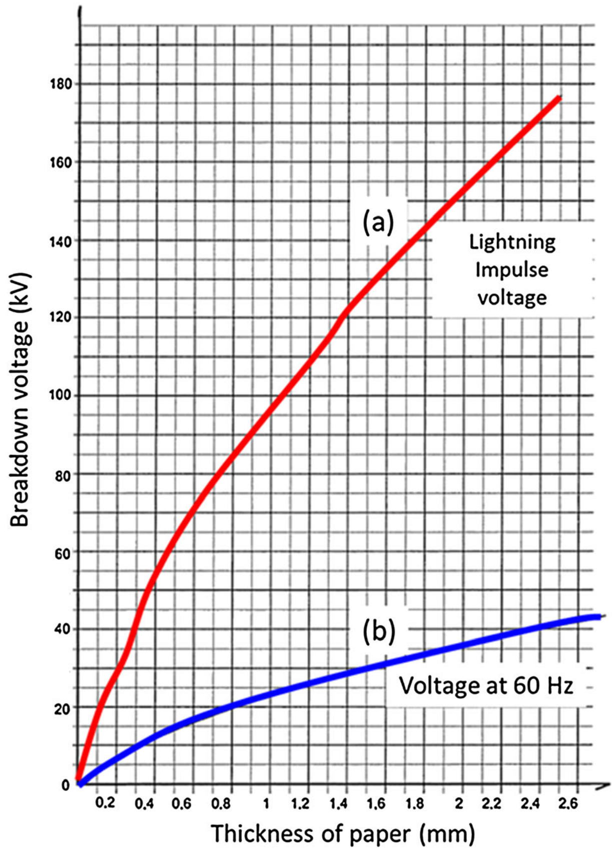

Figure 5. Dielectric breakdown curves for insulation paper: (a) lightning impulse condition, (b) normal voltage at 60 Hz.

The distribution transformers under study, with conventional L-H and proposed H-L configuration, have a paper layer with a thickness of 0.254 mm in the HV windings. It can be seen from the curve (a) of Figure 5 that for an insulation paper with a thickness of 0.254 mm, the maximum breakdown voltage for lightning impulse is 35 kV. In this case, a maximum dielectric stress of 137.8 kV/mm was calculated, which is the maximum dielectric stress that the insulation paper layer with a thickness of 0.254 mm can withstand.

In order to compute the maximum dielectric stress for lightning impulse condition in the configurations of windings studied in this paper, finite element simulations were carried out. A lightning impulse voltage of 95 kV was applied for both winding configurations (L-H and H-L) studied in this paper. This voltage was applied in the copper HV windings of transformers. The maximum dielectric stress was calculated in the HV windings. Figure 6 shows the results obtained by finite element simulations for both winding configurations.

For the conventional L-H configuration, a maximum dielectric stress of 57.60 kV/mm was calculated in the insulation paper. For the proposed H-L configuration, a maximum dielectric stress of 63.20 kV/mm was estimated. In both configurations, the values of dielectric stress calculated by the finite element simulations are much lower than the maximum value of the dielectric stress (137.8 kV/mm) that the insulating paper can withstand. This indicates that all the winding configurations studied in this paper do not present dielectric problems under impulse condition or under normal voltage at 60 Hz.

5.4. Generalization of results

The proposed winding design has been applied in a wide spectrum of actual transformers, of different voltage ratings and loss categories. In particular, four transformer designs were built and compared with the current practice and Figure 7 depicts the results. It should be noted that those experiments

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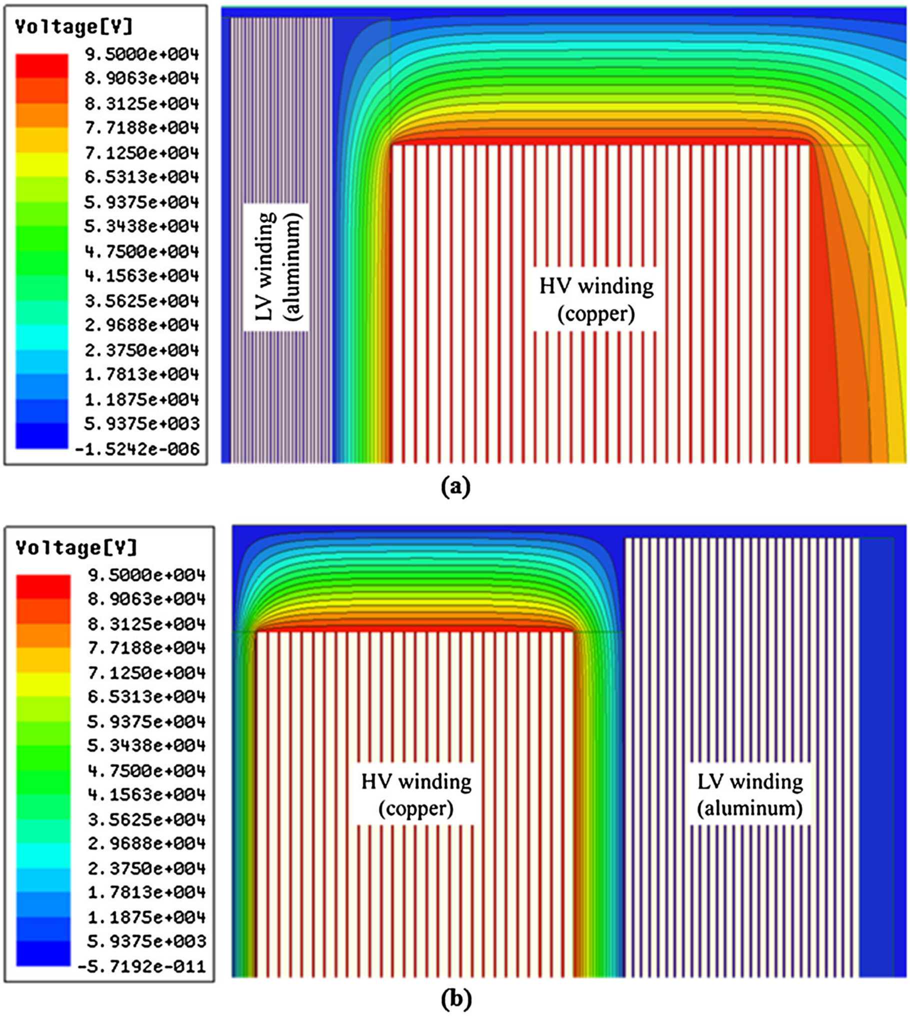

Figure 6. Voltage distributions in winding configurations: (a) conventional L-H configuration, (b) proposed H-L configuration.

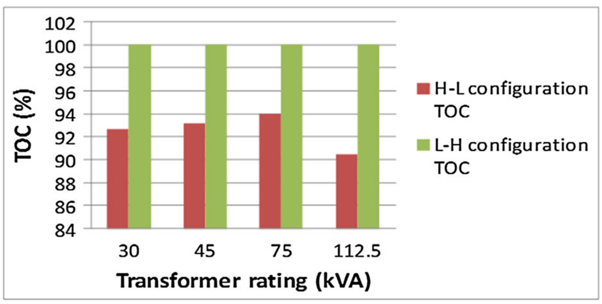

Figure 7. Total owning cost (TOC, %) difference between the H-L and L-H configuration considering four transformer ratings.

were carried out using the same levels of losses for each transformer rating. It has to be emphasized that there are already in operation several distribution transformers manufactured with the H-L configuration, and they have not experienced failures. The economical benefit with the proposed winding configuration is increased as the transformer rating increases. The reduction in the TOC is from 6% to 10% in transformers ranging from 30 to 112.5 kVA.

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In the near future, the authors are planning to compare H-L and L-H configurations in many design aspects, such as winding temperature comparison with fiber optic sensors [32], inrush currents [33], and geomagnetically induced currents [34].

6. CONCLUSION

This paper has presented a new winding configuration for distribution transformers, denoted as H-L configuration, according to which the HV winding is located internally and the LV is located externally. The proposed H-L configuration is compared with the conventional L-H winding configuration, where the LV winding is located internally and the HV winding is located externally. The comparison has been based on the minimization of transformer TOC. We have compared a wide range of distribution transformers with different power ratings, from 30 to 112.5 kVA.

Distribution transformers with the H-L configuration have smaller TOC for power ratings from 30 to 112.5 kVA. The TOC of a transformer with the H-L configuration is from 6% to 10% less expensive than the conventional L-H configuration.

The main idea of our improvement is the following: the cost of H-L configuration is reduced because the mean length of the HV copper winding is reduced. Copper is more expensive than aluminum and savings are obtained by reducing the mass of copper at the cost of increasing the cost of the less expensive material (aluminum).

In the TOC calculations, we assumed that transformers with the L-H and the H-L configurations have a useful life of 25 years. In the near future, when information is available for long-term failure statistics of this new configuration (H-L), the useful life of this new design can be better estimated and the TOC calculations repeated.

It should be noted that the H-L configurations did not present mechanical or dielectric problems in the analyses of this paper or in the operation of the distribution transformers manufactured with this new winding configuration.

7. LIST OF SYMBOLS AND ABBREVIATIONS

TOC	total owning cost
LV	low voltage
HV	high voltage
L-H	conventional configuration of windings where the LV winding is located internally and the HV winding is located externally as in Figure 1(a)
H-L	proposed configuration of windings where the HV winding is located internally and the LV winding is located externally as in Figure 1(b)
W_{LV}^{c}	total weight of the three phases of the LV winding for the conventional (L-H) configuration
W_{LV}^{p}	total weight of the three phases of the LV winding for the proposed (H-L) configuration
W_{HV}^{c}, W_{HV}^{p}	total weight of the three phases of the HV winding for the conventional and the proposed configuration of windings, respectively
MLW_{LV}^{c}, MLW_{LV}^{p}	mean length of the LV winding for the conventional and the proposed configuration of windings, respectively
MLW_{HV}^{c}, MLW_{HV}^{p}	mean length of the HV winding for the conventional and the proposed configuration of windings, respectively
A_1^c, A_1^p	exterior diameter of the section of insulation to core for the conventional and the proposed configuration of windings, respectively
B_1^c, B_1^p	exterior diameter of the section of LV for the conventional and the proposed configuration of windings, respectively
C_1^c, C_1^p	exterior diameter of the section of barrier between the LV and HV for the conventional and the proposed configuration of windings, respectively

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D_1^c, D_1^p	exterior diameter of winding for the conventional and the proposed configuration of windings, respectively
BAR	barrier between the LV and HV
E_m	insulation between the HV coil and core
W_w	window width of the winding
H_w	window height of the winding
T_{HV}, T_{LV}	HV winding thickness and LV winding thickness
N_{HV}, N_{LV}	number of turns of HV and LV winding
N_{θ}	number of phases
S	cross-section area of conductor
T_{tw}	total thickness of the winding

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