

Evaluation of the total owning cost of MV/LV for industrial distribution transformers with different loss levels

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1. ABSTRACT

Industrial distribution transformers are estimated to be approximately 40% of the total population on MV/LV distribution transformers. Most industrial users do not evaluate transformer losses and do not have a sufficient expertise to compare transformers with different loss levels.

The total owning cost of transformers having different energy efficiency has been calculated; the different solutions have been compared from an industrial consumer point of view.

2. INTRODUCTION

In 2000, in Italy, the total consumption of electrical energy by industrial and tertiary sector has been approximately 213 TWh¹. Industrial sector accounts for nearly 70% of the total consumption (142 TWh). The average growth rate of electrical energy demand in 2000 for industrial and tertiary sector has been approximately 5,4%².

Electrical energy supplied in MV can be estimated in approximately 90 - 100 TWh per year which means roughly 43 - 50% of the total electric energy consumed by industrial and tertiary sector³.

Industrial distribution transformers are estimated to be approximately 40% of the total population on MV/LV distribution transformers. Statistical records for industrial transformers are quite poor but available data allows to estimate the population ranging from 250.000 units to 300.000⁴; the total installed capacity can be estimated in approximately 100 GVA.

In evaluation of the total population is quite difficult, a tougher task is to determine the composition of the population in terms of rated power; from the data available, the average rated power should be approximately 400 kVA and such a composition should not be far from reality: 30% up to 100 kVA, 30% 160-250 kVA, 20% 400 - 630 kVA, 10% 1000 - 1250 kVA and 10% above 1250 kVA⁵.

3. BACKGROUND

3.1. Transformer losses and efficiency

Transformer losses may be no-load losses or load losses.

No-load losses⁶ are almost exclusively iron losses; they are a square function of voltage and they occur whenever the transformer is connected to the system, independently of the load value.

¹ Data from Gestore della Rete Nazionale; <http://www.grtn.it> .

² Data from Gestore della Rete Nazionale; <http://www.grtn.it> .

³ Data from ENEL (www.enel.it) and Autorità per l'Energia Elettrica e il Gas (www.autorita.energia.it).

⁴ Data from ANIE (www.anie.it).

⁵ Data from M. Agostini, A. Clò, G. Goldoni: Mercato dei trasformatori e risparmio energetico. Quaderni di Enegia n°1.

⁶ No-load losses are defined (CEI EN 60076-1:1998, art. 3.6.1) as *the active power absorbed when rated voltage at rated frequency is applied to the terminals of one of the windings, the other winding or windings being open-circuited.*

Load losses⁷ are mainly copper losses and they occur only when a load is connected to the transformer; they are a square function of the apparent power of the load.

Transformer efficiency can be evaluated by the following formula:

$$h = \frac{xP_r}{(xP_r + P_0 + x^2P_k)} \quad \text{Eq. 1}$$

where:

- x = transformer load factor (ratio between total actual output and rated output power);
- P_r = rated active power (kW)⁸;
- P_0 = no-load losses (kW);
- P_k = load losses at rated power (kW).

For a given transformer, maximum efficiency is reached for a load value at which no-load and load losses are equal, that is when:

$$x^2P_r = P_0$$

$$x = \sqrt{\frac{1}{r}} \quad \text{Eq. 2}$$

where r is the ratio between load losses at rated power and no-load losses and depends on the transformer design.

The load value at which maximum efficiency is reached is a function of the parameter r . The transformer ratio r is usually greater than 1⁹ which means that maximum efficiency can be reached only if the transformer is partially loaded¹⁰. As r increases the load factor x , at which maximum efficiency is reached, decreases.

From the analytical expression of transformer efficiency, it can be seen that there are two ways of selecting a more efficient transformer: the first and quite obvious is to choose a more efficient machine, which is a transformer with a lower level of no-load and load losses. The second way is to choose the rated power of transformer so that load factor (x) corresponds to the maximum efficiency value, which means basically to oversize the transformer.

These two approaches can be mixed to find an optimal solution.

All of these criteria are technical solutions to the problem of reducing transformer losses and do not take into account any economical and any other technical issues¹¹.

3.2. Total owning cost and capitalisation of losses for industrial transformers

3.2.1. Total owning cost

The total owning cost (TOC) for a transformer consists of several components. In general purchase price, value of total losses¹², installation, maintenance, repair and decommissioning costs must be taken into account when determining TOC.

⁷ Load losses are defined (CEI EN 60076-1:1998, art. 3.6.3) as *the absorbed active power at rated frequency and reference temperature, associated with a pair of windings when rated current is flowing through the line terminals of one of the windings, and the terminals of the other winding are short-circuited. Further windings, if existing, are open-circuited.*

⁸ Product of the rated power and average $\cos\phi$ of the load.

⁹ Typical values for transformer ratio r range from 5 to 7.

¹⁰ Maximum efficiency at rated power ($x = 1$) is a theoretical value as it can be reached only if the transformer ratio r is equal to 1 which is not a typical design criterion.

¹¹ For instance they do not take into account the short circuit duty of other electrical equipment.

¹² Total losses are defined as the *sum of the no-load loss and the load loss* (CEI EN 60076-1:1998, art. 3.6.4). The power consumption of the auxiliary plant is not included in the total losses.

Installation, maintenance, repair and decommissioning costs can be neglected when comparing two transformers of the same type, having the same rated value except for the losses value¹³.

3.2.2. Capitalisation of losses

When energy losses are taken into account in the process of purchase decision, their cost is to be evaluated in some way.

HD 428 [2] and HD 538 [3] propose a formula in order to determine the cost of no-load and load losses:

$$C_l = A \cdot P_o + B \cdot P_k \quad \text{Eq. 3}$$

where:

- A is the cost per rated watt of no-load losses;
- B is the cost per rated watt of load losses.

The determination of A and B factors is quite difficult.

Utilities go through extensive research and analysis in order to develop an accurate model for the capitalisation of distribution transformer losses.

Industrial transformer purchasers can use a simplified approach for evaluating the cost of no-load and load losses. In fact for industrial transformers:

- A depends basically on the demand rate and the energy rate the utility charges for the capacity cost and energy cost;
- B depends basically on the demand and energy rate but also on the load diagram of the transformer.

The cost of losses come into effect during the lifetime of the transformer. Cost of losses is therefore to be converted to the moment of purchase by assigning capital values. Moreover the trend of transformer load diagram and of the cost of energy is to be somehow forecasted in order to make an accurate evaluation of the total owning cost.

3.3. Reference values for industrial transformer losses in Italy

CENELEC has set limits for distribution transformers no-load and load losses in two main harmonisation documents (HD) [2], [3].

For oil filled distribution transformers the HD428 offers a choice between three different energy efficiency levels both for no-load and load losses. Therefore there are nine possible combinations among which HD defines five preferred combinations¹⁴.

The Italian Electrotechnical Committee¹⁵ has set limits that correspond to those prescribed by HD428 and has also specified two series of transformers, namely "normal losses" and "reduced losses", that comply with the values of no-load and load losses set by the HD428 for the preferred combinations A-A' and C-B' respectively.

¹³ Installation, maintenance, repair and decommissioning costs are independent on the transformer design.

¹⁴ HD428 preferred combinations are: A-A', B-B', C-B', A-C', C-C'.

¹⁵ CEI - Comitato Elettrotecnico Italiano.

Table 1 - Values of load losses (P_k) and no-load losses (P_o) set by the HD428 for oil filled distribution transformers

Rated power (kVA)	No-load losses (W)			Load losses (W)		
	A'	B'	C'	A	B	C
100	320	260	210	1.750	2.150	1.475
160	460	375	300	2.350	3.100	2.000
250	650	530	425	3.250	4.200	2.750
400	930	750	610	4.600	6.000	3.850
630 (4%)	1.300	1.030	860	6.500	8.400	5.400
630 (6%)	1.200	940	800	6.750	8.700	5.600
1000	1.700	1.400	1.100	10.500	13.000	9.500
1600	2.600	2.200	1.700	17.000	20.000	14.000
2500	3.800	3.200	2.500	26.500	32.000	22.000

Table 2 - Values of load losses (P_k) and no-load losses (P_o) set by CEI 14-13 for the "normal losses" series of oil filled distribution transformers

Rated power (kVA)	No-load losses (W)	Load losses (W)
50	190	1.100
100	320	1.750
160	460	2.350
250	650	3.250
400	930	4.600
630 ⁽¹⁾	1.300	6.500
1000	1.700	10.500
1600	2.600	17.000
2000 ⁽²⁾	3.200	22.000
2500	3.800	26.500

(1) The value of short circuit impedance is 4%

(2) This is not a preferred value of rated power for HD428

Table 3 - Values of load losses (P_k) and no-load losses (P_o) set by CEI 14-13 for the "reduced losses" series of oil filled distribution transformers

Rated power (kVA)	No-load losses (W)	Load losses (W)
50	150	850
100	250	1.400
160	360	1.850
250	520	2.600
400	740	3.650
630 ⁽¹⁾	900	5.600
1000	1.330	9.000
1600	2.090	13.000
2000 ⁽²⁾	2.400	16.000
2500	3.040	21.000

(1) The value of short circuit impedance is 4%

(2) This is not a preferred value of rated power for HD428

4. METHOD

The aim of the study was focused on the evaluation of the capitalised cost of losses and total owning cost of MV/LV oil filled distribution transformers for an industrial purchaser.

Seven standard industrial consumers have been selected among the nine set by EUROSTAT¹⁶. Only those supplied in MV have been considered¹⁷; these consumers are characterised in terms of annual consumption of electrical energy, maximum demand and annual utilisation (see Table 4).

Table 4 - The standard industrial consumers chosen for the calculations

<i>Code</i>	<i>Annual consumption (kWh)</i>	<i>Maximum demand (kW)</i>	<i>Annual utilisation (hours)</i>
lc	160.000	100	1.600
ld	1.250.000	500	2.500
le	2.000.000	500	4.000
lf	10.000.000	2.500	4.000
lg	24.000.000	4.000	6.000
lh	50.000.000	10.000	5.000
li	70.000.000	10.000	7.000

The rated power and the number of transformers owned by each standard consumer has been defined (see Table 5) assuming that:

- power factor ($\cos\phi$) is equal to 0,9 where the transformer is installed¹⁸;
- oversized by 20%.

Table 5 - Rated power and number of transformers owned by each standard consumer

<i>Standard consumer</i>	<i>Maximum demand (kW)</i>	<i>Cosϕ at maximum demand</i>	<i>N° of transformers</i>	<i>Rated power (kVA)</i>
lc	100	0,90	1,00	160
ld	500	0,90	1,00	630
le	500	0,90	1,00	630
lf	2500	0,90	3,00	1000
lg	4000	0,90	2,00	2500
lh	10000	0,90	5,00	2500
li	10000	0,90	5,00	2500

The total owning cost of the transformer(s) owned has been calculated for each standard consumer assuming that the transformer(s) belongs to the Italian "normal losses" series.

The total owning cost of the transformer(s) was then calculated considering:

- oversizing the transformer in order to achieve maximum efficiency;
- a Italian "reduced losses" transformer;
- the combination of the two above;
- a C-C' transformer;
- a D-D' transformer¹⁹.

¹⁶ Data from EUROSTAT - *Electricity prices for EU industry on January 2002*

¹⁷ The standard consumer coded lh can be considered a borderline consumer since he can a HV supply or a MV supply.

¹⁸ This is the same to say that power factor correction is centralised.

¹⁹ This hypothetical combination have no-load and load losses reduced by 15% respect to C-C' HD428 combination.

This case of the "normal losses" transformer has been assumed as the reference for the comparison of the different solutions; specifically:

- the total owning costs of the different solutions;
 - the balance between purchase cost increase and capitalised cost of losses savings;
 - the difference in capitalised cost of losses and total owning cost of the different solutions with respect to the base case;
- have been evaluated.

The total owning cost has been calculated on the basis of the formula given in HD428. The cost per rated watt of no-load losses (A factor) and the cost per rated watt of load losses (B factor) have been determined using the following formulas:

$$A = (12 \cdot C_d + 8760 \cdot C_e) \cdot F_c \quad (\text{€/kW year}) \quad \text{Eq. 4}$$

$$B = (C_e \cdot h) \cdot \left(\frac{S_L}{S_r} \right)^2 \cdot F_c \quad (\text{€/kW year}) \quad \text{Eq. 5}$$

$$F_c = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \quad \text{Eq. 6}$$

where:

- C_d is the demand rate (€/kW);
- C_e is the cost of energy (€/kWh);
- h is the annual utilisation (hours);
- S_L is the maximum apparent power of the load (kVA);
- S_r is the transformer rated power (kVA);
- F_c is the capitalisation factor.

Energy prices are those calculated by EUROSTAT; VAT-excluded energy price has been considered in the calculations. The demand rate was determined on the basis of the Italian tariff structure for MV customers.

In the basic scenario transformer life for industrial transformer have been assumed 10 years; calculations have been performed also for 15 and 20 years.

Energy prices and load profile have been considered constant over the transformer life.

5. RESULTS

The main results of the calculations are summarised in the figures of Chapter 8.

The basic findings can be summarised as follows:

- the "reduced losses" transformer solution seems to have the lowest TOC cost (see Figure 1 and Figure 2);
- oversizing the transformer in order to reach the maximum efficiency level is not a feasible approach with respect to TOC (see

Figure 3);

- the combination of the two approaches seems not to give any synergetic effect, on the contrary seems to be less attractive the "reduced losses" solution (see.);
- the "reduced losses" transformer solution seems to have the lowest simple payback of the increase in the purchase cost (see Figure 5);
- D-D' combination have a comparable value of TOC savings but longer payback of the purchase cost increase the reduced losses solution (see Figure 1 and Figure 5).

Figure 1 - Comparison between TOC savings achieved using a "reduced losses", C-C' and D-D' transformer instead of a "normal losses".

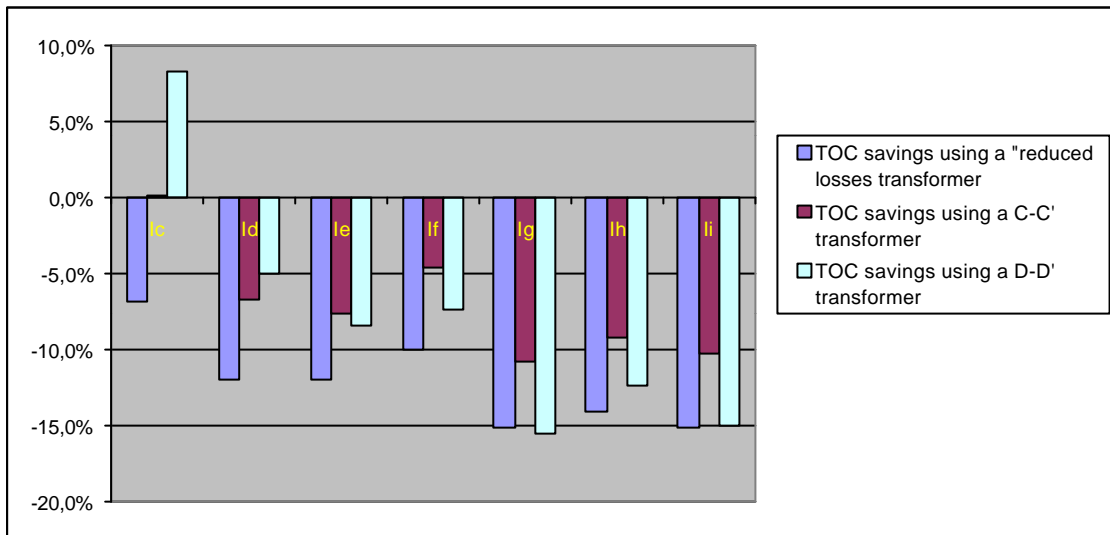


Figure 2 - Comparison between TOC savings achieved using a "reduced losses", C-C' and D-D' transformer instead of a "normal losses" (€)

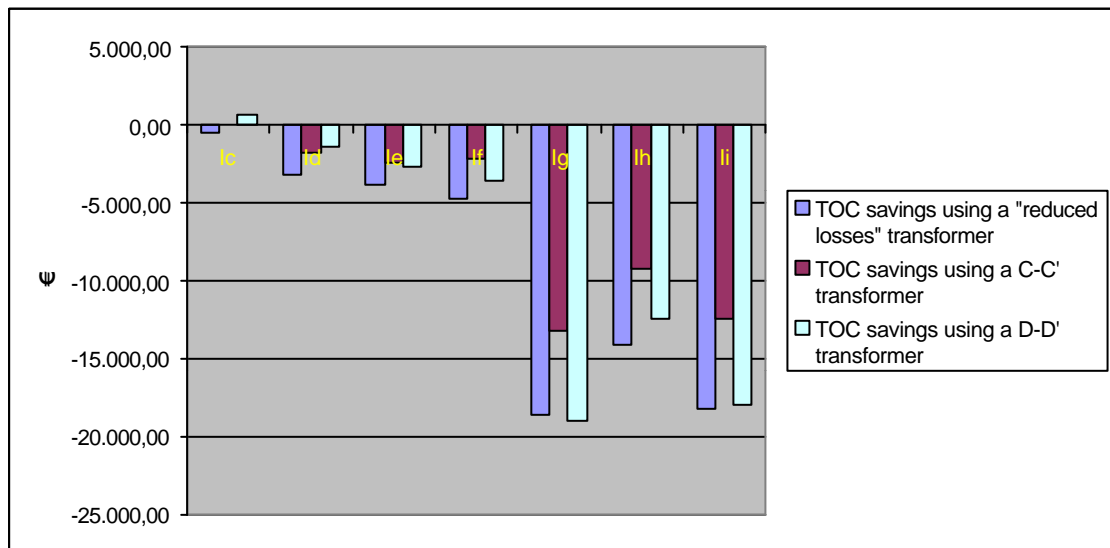


Figure 3 - TOC of a oversized transformer instead of a "normal losses" (€)

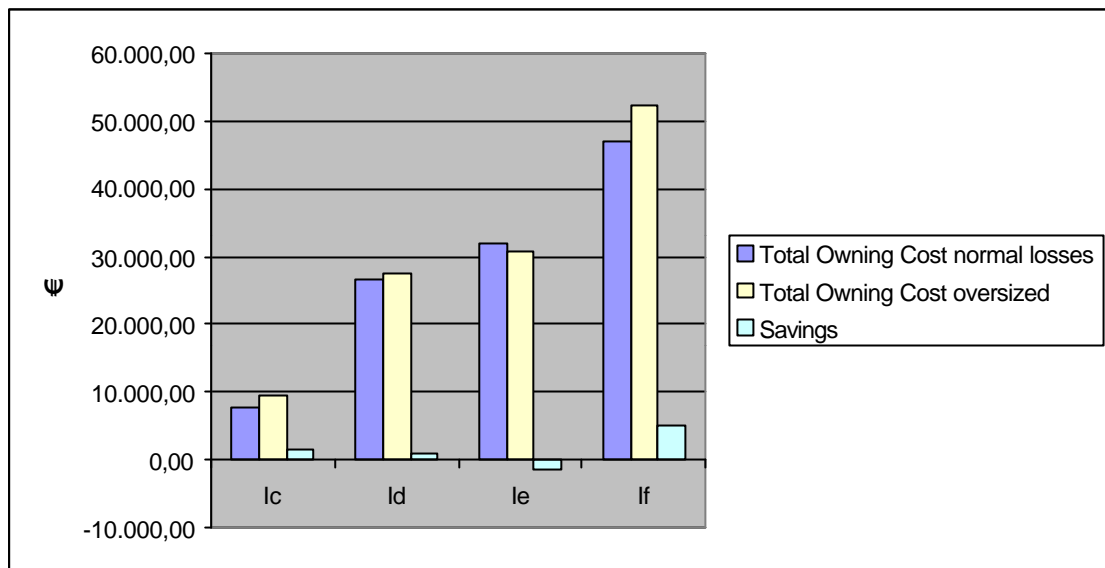
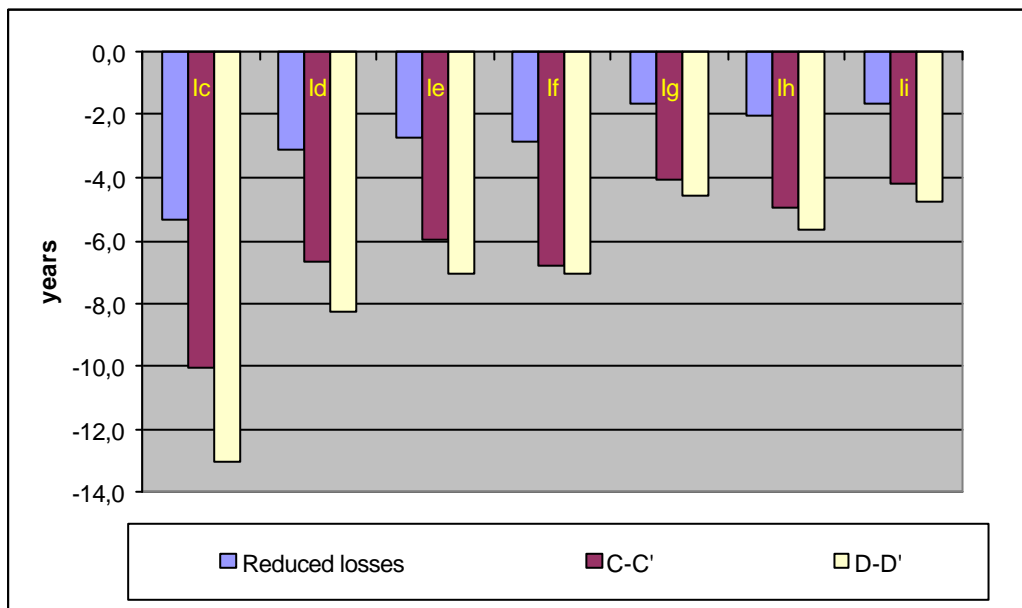


Figure 5 - Simple payback time of the increase in the purchase cost for a "reduced losses", C-C' and D-D' transformer with respect to a "normal losses"



6. CONCLUSIONS

The findings suggest that the choice of "reduced losses" transformers can be attractive for an industrial purchaser provided that he has the need of buying a new transformer or substituting an old one (end of life).

Purchase cost plays an important role in the composition of TOC for energy efficient transformers (C-C', D-D') especially for smaller transformers.

It seems that a further improvement of the energy efficiency of transformers (D-D') does not provide a sufficiently consistent marginal economical improvement in an industrial purchaser perspective, unless some kind of incentives exist.

7. REFERENCES

- [1] CEI EN 60076-1: *Power transformers. Part 1: General*. III Edition.
- [2] HD 428.1 S1:1992: *Three phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2500 kVA, with highest voltage for equipment not exceeding 36 kV. Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV.*
- [3] HD 538.1 S1:1992: *Three-phase dry-type distribution transformers 50 Hz, from 100 kVA to 2500 kVA, with highest voltage for equipment not exceeding 36 kV Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV.*
- [4] Norma CEI 14-13: 1998: *Trasformatori trifase per distribuzione a raffreddamento naturale in olio, di potenza 50-2500 kVA, 50 Hz, con tensione massima U_m per il componente non superiore a 36 kV. Parte 1: Prescrizioni generali e prescrizioni per trasformatori con tensione massima U_m per il componente non superiore a 24 kV.*

8. LIST OF FIGURES

Figure 6 - Capitalised cost of losses and TOC for a "normal losses" transformer.

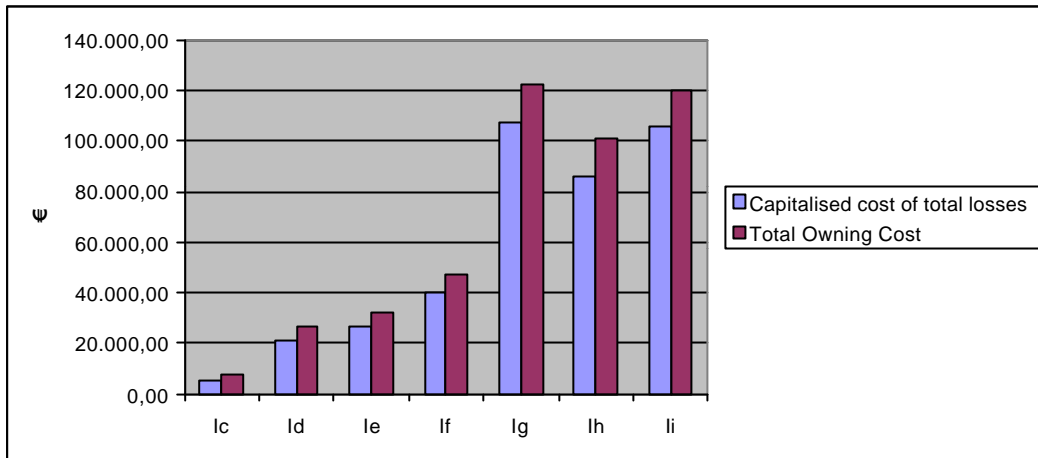


Figure 7 - Composition of TOC for a "normal losses" transformer.

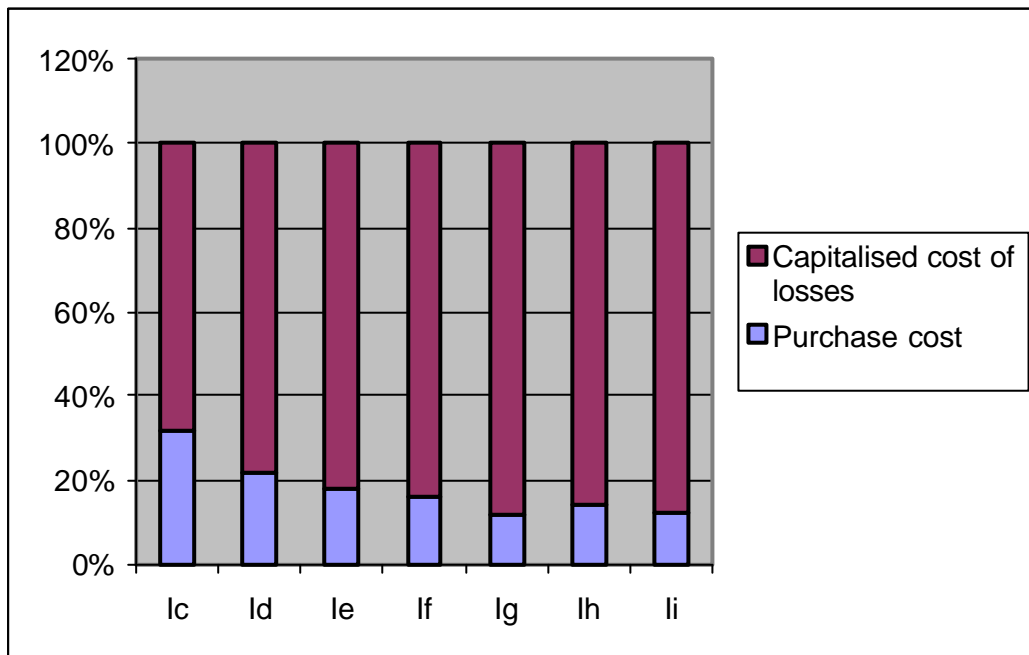


Figure 8 - Composition of TOC savings for a "reduced losses" transformer versus a "normal losses" one (absolute values).

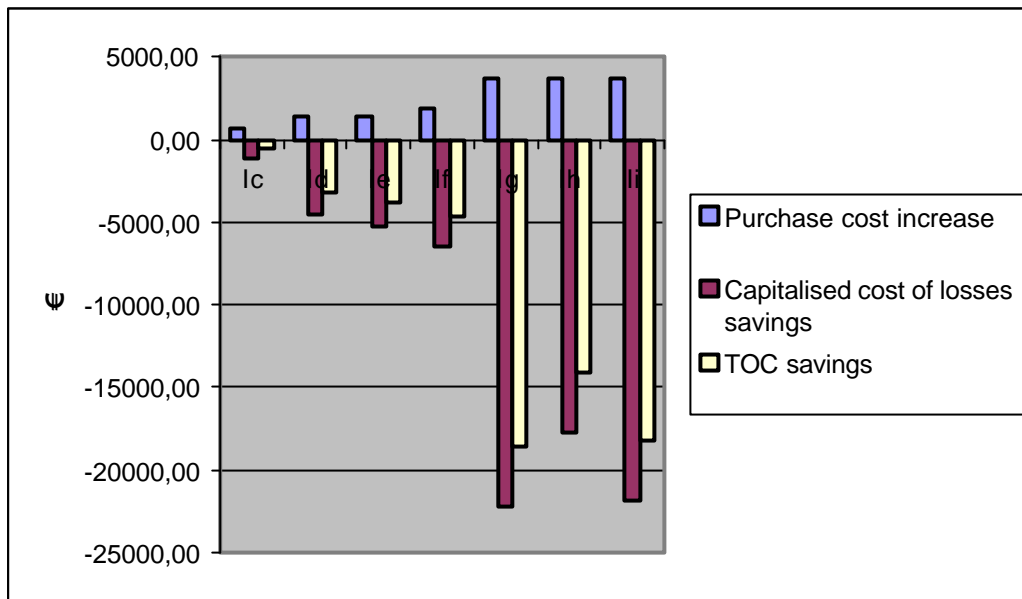


Figure 9 - Capitalised cost of losses and TOC savings for a "reduced losses" transformer versus a "normal losses" one (relative values).

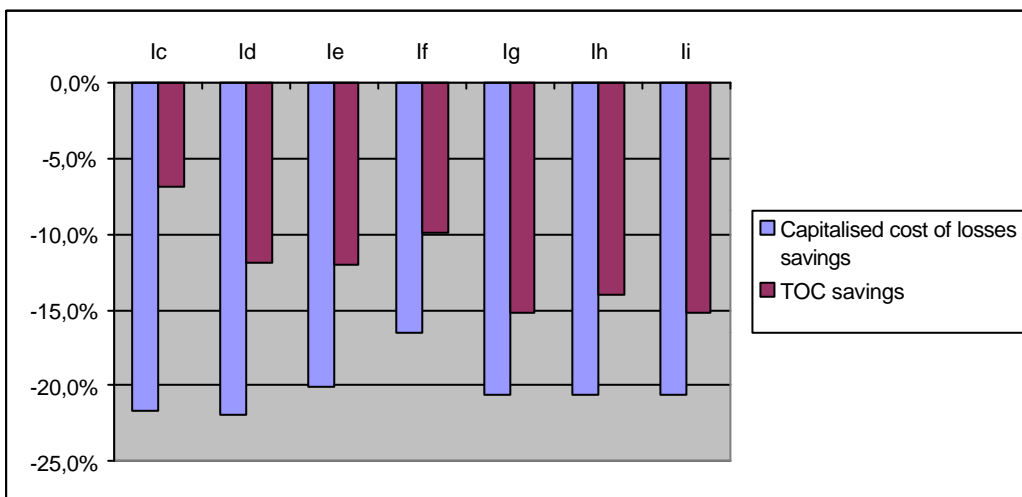


Figure 10 - Composition of TOC for a "reduced losses" transformer.

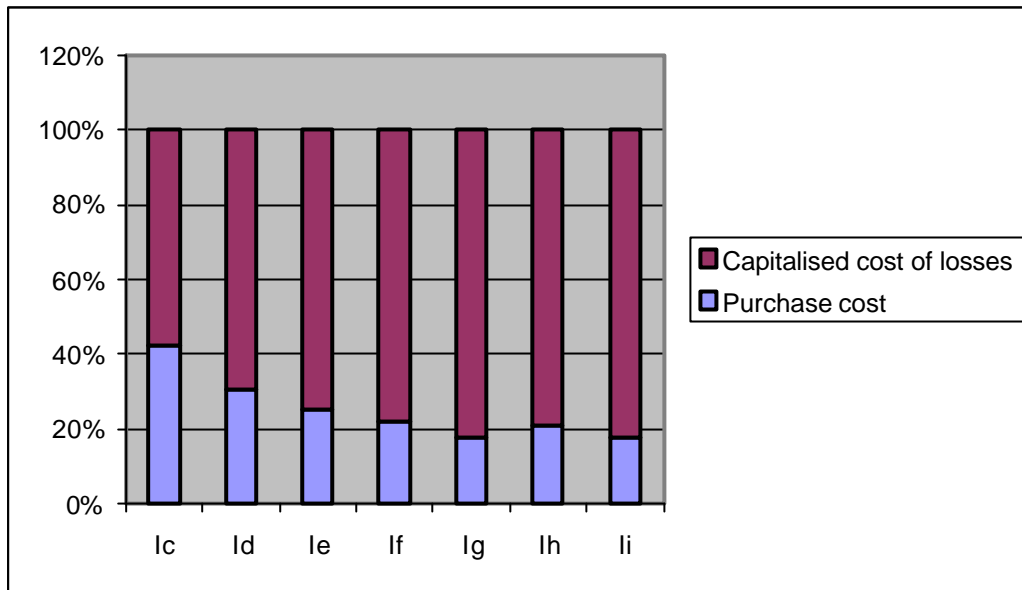


Figure 11 - Composition of TOC savings for a "reduced losses + oversizing" transformer versus a "normal losses" one (absolute values).

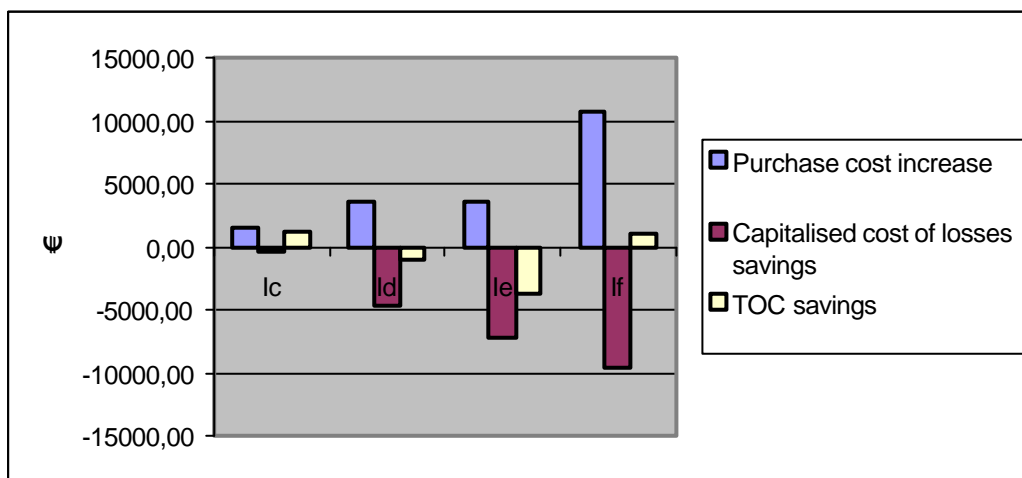


Figure 12 - Composition of TOC savings for a C-C' transformer versus a "normal losses" one (absolute values).

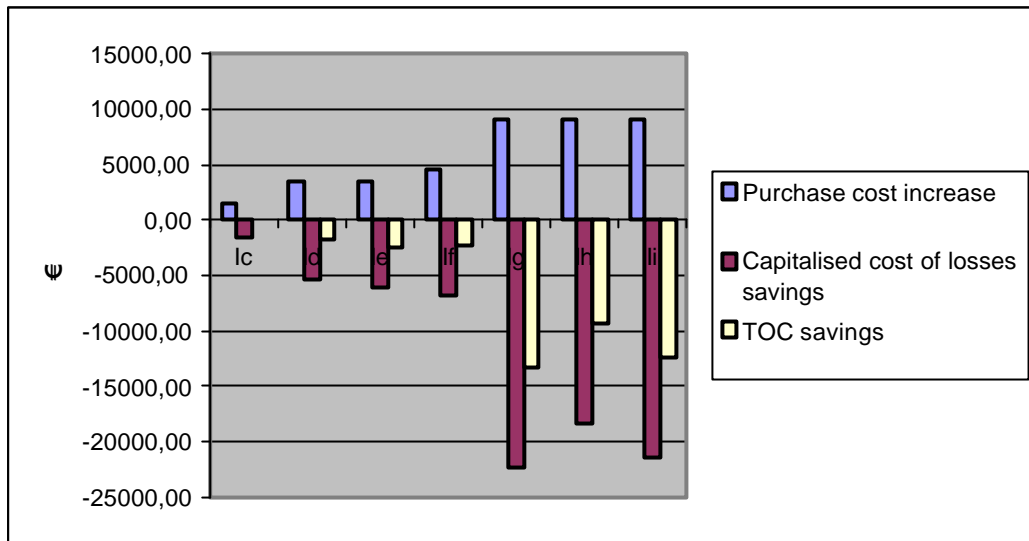


Figure 13 - Capitalised cost of losses and TOC savings for a C-C' transformer versus a "normal losses" one (relative values).

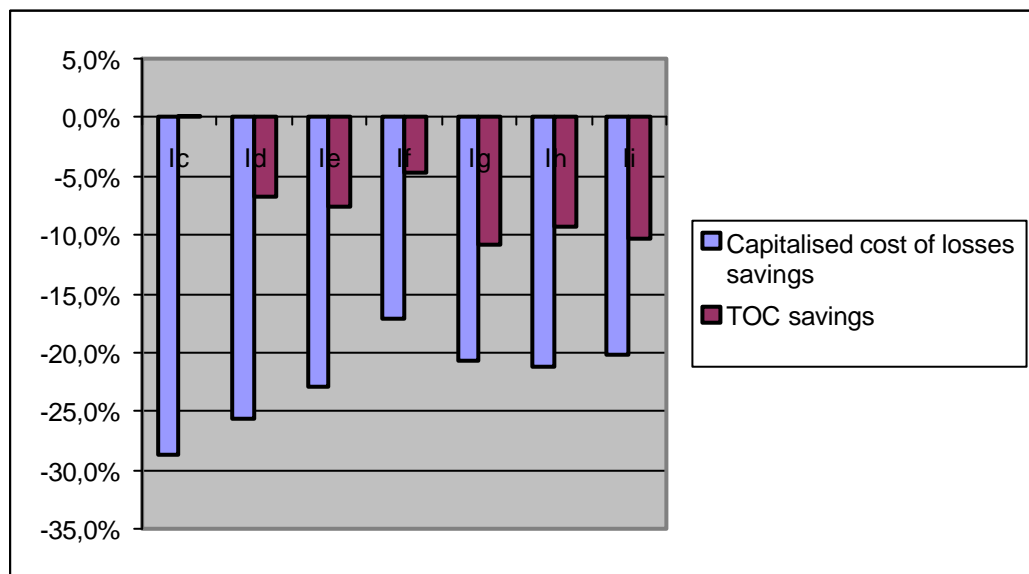


Figure 14 - Composition of TOC for a C-C' transformer.

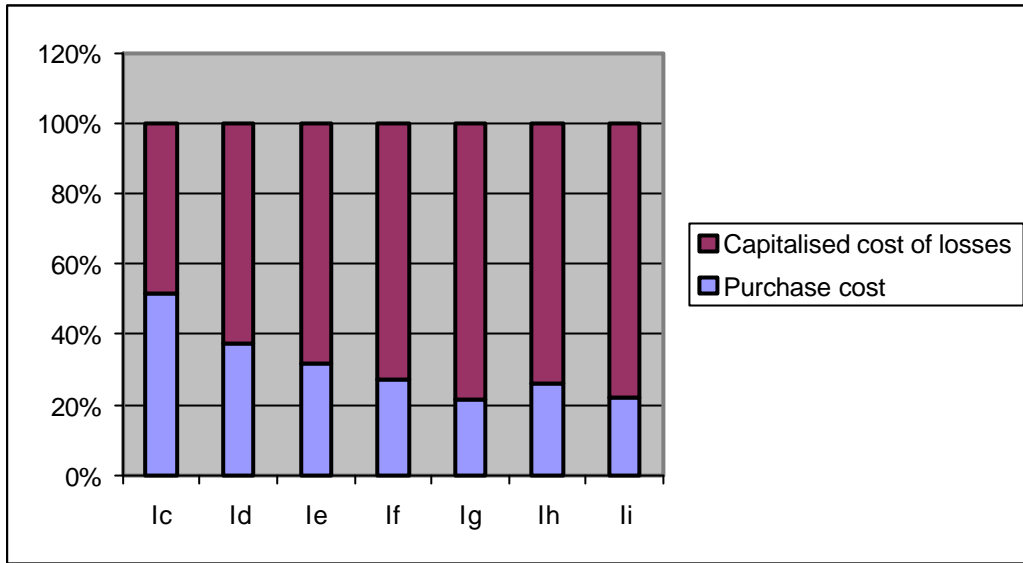


Figure 15 - Composition of TOC savings for a D-D' transformer versus a "normal losses" one (absolute values).

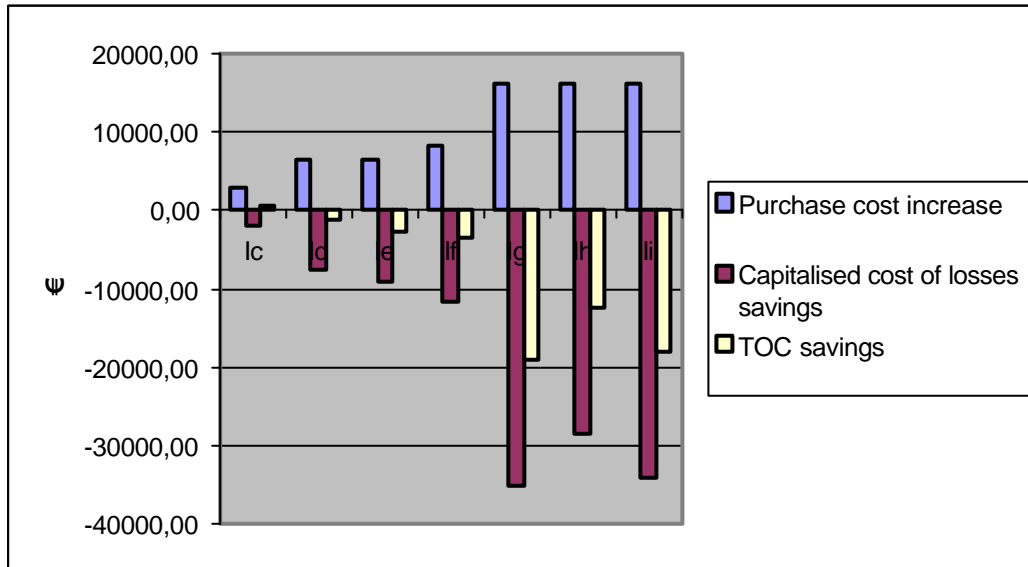


Figure 16 - Capitalised cost of losses and TOC savings for a D-D' transformer versus a "normal losses" one (relative values).

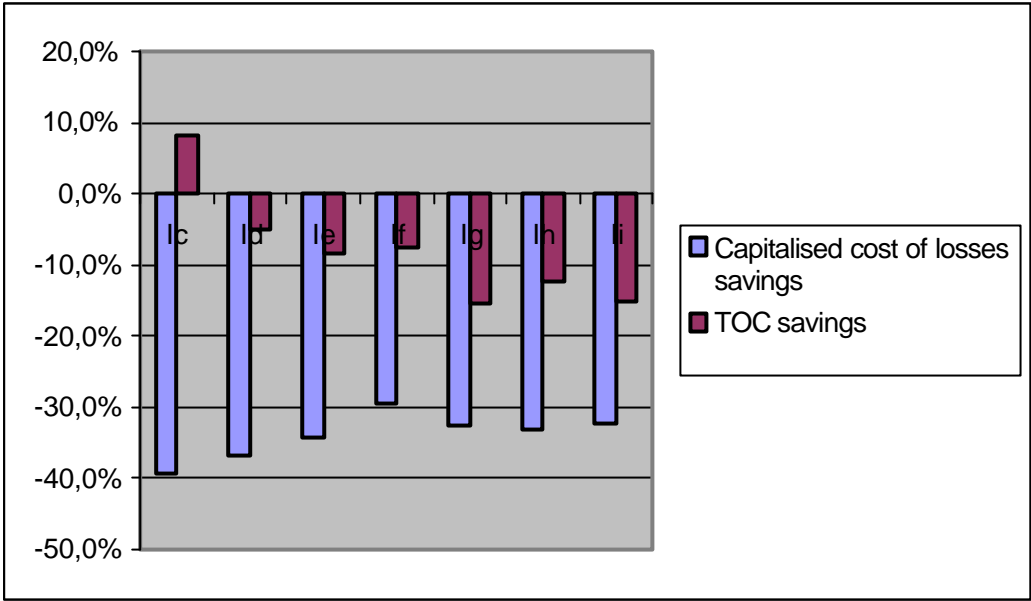


Figure 17 - Composition of TOC for a D-D' transformer.

