LOT 2: Distribution and Power Transformers

Design Report on Large Power Transformers
25 MVA, 63 MVA and 100 MVA

An assessment of the relationship between energy-efficiency and price

Prepared for:
Cesar Santos-Gil, European Commission, DG ENTR/B1

Submitted by:
Pernille Schiellerup, Director of European Programmes, CLASP

07 May 2013

DISCLAIMER
This document is provided as a contribution to and for the use of the European Commission for its work on Ecodesign Lot 2: Power and Distribution Transformers. CLASP accepts no liability of whatsoever nature for any use of this document by any other party.

ABOUT CLASP
Established in 1999, CLASP's primary objective is to identify and respond to the analytical needs of S&L practitioners in selected countries and regions while making the highest quality technical information on S&L best practice available globally. To this end, CLASP provides technical analysis and expertise to national governments and local partners; aggregates resources; assembles project teams from diverse and highly-qualified organizations; oversees projects; partners and collaborates with policy makers and members of industry alike; and disseminates information for maximum impact. CLASP has provided technical assistance on standards and labelling in over 50 countries, supporting and promoting energy-efficiency in appliances, lighting and equipment. Currently, CLASP has offices or programmes in China, the European Union, India, Latin-American and the United States. For more information about CLASP, please visit: www.clasponline.org/index.php

COMMENTS
This report presents a series of cost-efficiency curves for large power transformers, which were prepared for CLASP by Professor Antonio Bossi (University of Pavia) and Professor Angelo Baggini (University of Bergamo) with support on the write-up and presentation of the design work by Michael Scholand (N14 Energy). CLASP would welcome any comments on this report to Pernille Schiellerup, Director of European Programmes, at the following email address (change the “[at]” to “@”): PSchiellerup[at]clasponline.org

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

CLASP	Collaborative Labeling and Appliance Standards Program
EC	European Commission
EN	European Standard (Européenne Norme)
EU	European Union
kg	kilogram
kV	kilovolt (i.e., thousand volts)
kVA	kilovolt-ampere
kW	kilowatt
LCC	life-cycle cost
MVA	megavolt-ampere
MWh	megawatt-hours
ONAN	Oil Natural Air Natural
TCO	Total Cost of Ownership
W	Watts

1 Results Summary

1.1 Overview of the Designs

In support of the European Commission's assessment of ecodesign requirements for Distribution and Power Transformers, CLASP has undertaken this study investigating the relationship between the manufacturer's selling price[1] and efficiency for large power transformers. This is the third transformer design report prepared by CLASP for this regulatory proceeding (i.e., DG Enterprise Lot 2: Distribution and Power Transformers), the others being a report on three oil-immersed transformers[2] in August 2010 and a report on two cast-coil dry-type transformers[3] in March 2011.

This report presents the design results of three large power transformers:

- 25 MVA three-phase oil-immersed, 150/20 kV with on-load tap changer
- 63 MVA three-phase oil-immersed, 150/20 kV with on-load tap changer
- 100 MVA three-phase oil-immersed, 220/23.8 kV with on-load tap changer

Understanding how the price of transformers increases as the efficiency improves is important because it enables an accurate assessment of life-cycle costs and associated payback periods. Generally, a transformer becomes more expensive as efficiency improves because it is incorporating either more material and/or better quality materials.

The designs presented in this report were prepared by Professor Antonio Bossi and Professor Angelo Baggini. The megavolt-ampere (MVA) ratings, voltages and other design parameters were selected to try and be representative of models installed in Europe. Detail about these three sets of transformer designs can be found in Chapter 2 of this report.

1.2 Design Results

The design results are presented below in a series of tables and graphs that depict an estimate of the manufacturer's selling price divided by the annual electricity consumption in megawatt-hours (MWh). The manufacturer's selling price is only an estimate (± 10%), and it does not include transportation, commissioning or any special accessories. The annual electricity consumption is meant to represent the average loading that these transformers

[1] This study makes reference to the 'manufacturer's selling price' which represents what a utility pays when procuring a transformer. The selling price is needed because it is used in the life-cycle cost (LCC) calculation, where, electricity savings from more efficient transformers are off-set against higher purchase prices. Although this report provides absolute values on the manufacturer selling prices these are only estimates. However, the absolute values of the prices don't have a significant impact on the analysis because it is the difference in price between transformers that really matters. In other words, relative to the baseline, it is the additional cost of the more energy-efficient design compared to the discounted value of future electricity savings that is used to determine the LCC differences in this analysis.

2 The oil-immersed transformer report included 400 kVA three-phase units (distribution transformers), 1000 kVA three-phase units (industry transformers), and 2000 kVA three-phase units (distributed energy resources transformers).

3 The dry-type transformer report included 1250 kVA cast-coil three-phase units (industry transformers) and 2000 kVA cast-coil three-phase unit (distributed energy resources transformers.

will experience over their entire service lifetime (assumed to be 40 years). It is assumed that the average loading is 40% of the rated capacity (i.e., 10 MVA loading for the 25 MVA unit).

These data were plotted and then subjected to a curve-fit function using Microsoft Excel, to derive an equation describing the relationship between cost and efficiency for each particular MVA rating. Establishing this relationship enables a more detailed analysis of life-cycle costs (LCC) at smaller increments than the small sample of designs. This LCC analysis was designed to be consistent with the methodology followed in the draft impact assessment that the Commission shared with the Consultation Forum.

The table and figure below presents the seven 25 MVA designs that were prepared for this study. The figure contains a regression line based on the power law which has an R^2 of 0.95.[4] This regression line characterises the relationship between the approximate manufacturer's selling price and energy consumption for the 25 MVA transformers.

Table 1-1. Summary of the Designs Prepared for 25 MVA Large Power Transformers

Design Number	1	2	3	4	5	6	7
No-load loss, Po (kW)	16	13	11.2	13	11.5	11.2	9
Load loss, Pk (kW)	122	98	85.5	80	95	110	100
Core steel (type)	M1H30	M0H23	M0H23	M0H23	M0H23	M0H23	M0H23
Core steel (kg)	12,920	15,935	21,350	18,645	18,280	16,825	20,475
Copper winding (kg)	5,535	7,365	11,940	9,992	9,890	7,860	10,375
Approx. selling price (€)	348,000	390,000	469,200	438,000	433,956	405,600	448,800
Full load efficiency (%)	99.451%	99.558%	99.615%	99.629%	99.576%	99.518%	99.566%
Peak loss perf. index (%)[5]	99.650%	99.710%	99.750%	99.740%	99.740%	99.720%	99.760%
Electricity use (MWh/yr)	311.2	251.2	217.9	226.0	233.9	252.3	219.0

[4] The equation for the curve-fit to the 25 MVA designs is: $y = 7569919584.07705*x^{--0.790796341512798}$

[5] The 'peak loss performance index' has previously been called the 'maximum peak efficiency'. It represents the design point where the core losses (Po) are equal to the winding losses (Pk), which is the apex of the efficiency curve for any transformer.

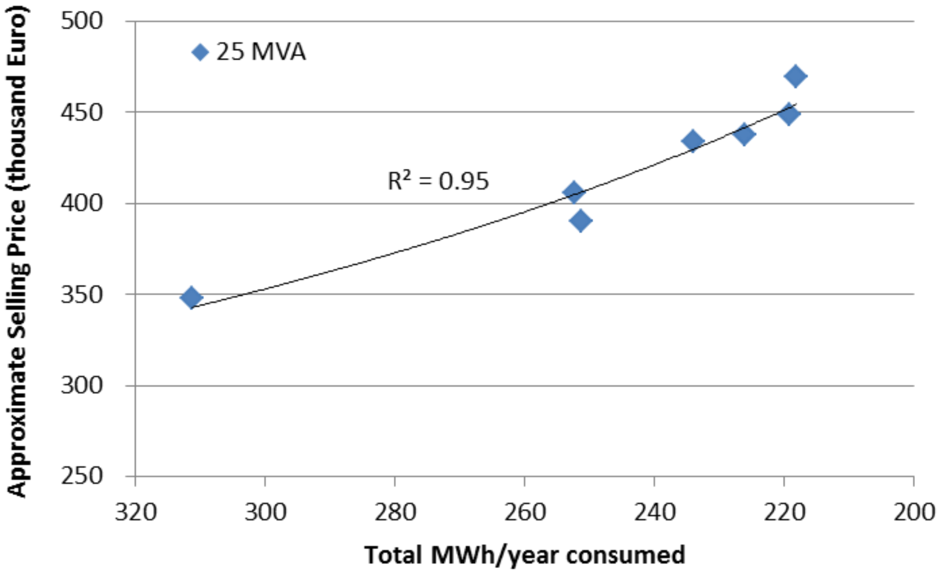

Figure 1-1. Plot of 25 MVA Transformer, Selling Price versus Energy Consumption

This same approach was followed for the 63 MVA large power transformer, for which four designs were prepared. The table and figure below present these designs. The figure contains a regression line based on the power law which has an R^2 of 0.997.[6] This regression line characterises the relationship between the approximate manufacturer's selling price and energy consumption for the 63 MVA transformers.

Table 1-2. Summary of the Designs Prepared for 63 MVA Large Power Transformers

Design Number	1	2	3	4
No-load loss, Po (kW)	32	26	22.5	20
Load loss, Pk (kW)	258	210	170	150
Core steel (type)	M1H30	M0H23	M0H23	M0H23
Core steel (kg)	25,300	31,195	38,500	42,850
Copper winding (kg)	11,200	15,170	21,200	24,050
Approx. selling price (€)	480,000	564,000	667,200	756,000
Full load efficiency (%)	99.543%	99.625%	99.695%	99.731%
Peak loss performance index (%)	99.712%	99.765%	99.804%	99.826%
Electricity use (MWh/yr)	641.9	522.1	435.4	385.4

[6] The equation for the curve-fit to the 63 MVA designs is: $y = 68970073148.6967 * x^{-0.888760163766824}$

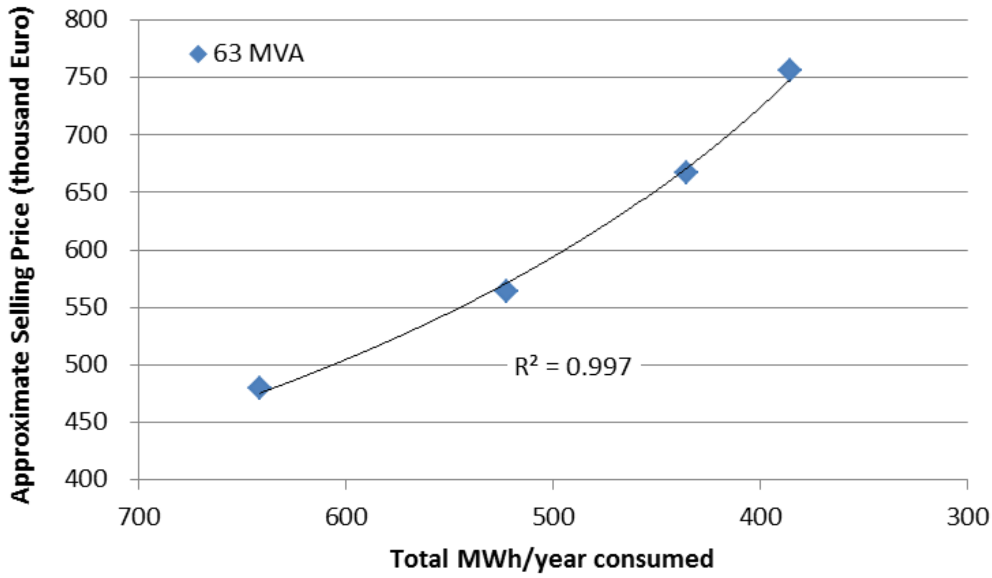

Figure 1-2. Plot of 63 MVA Transformer, Selling Price versus Energy Consumption

The same methodology was followed for the 100 MVA large power transformer, for which seven designs were prepared. The table and figure below present these designs. The figure contains a regression line based on the power law which has an R^2 of 0.88.[7] This regression line characterises the relationship between the approximate manufacturer's selling price and energy consumption for the 100 MVA transformer.

Table 1-3. Summary of the Designs Prepared for 100 MVA Large Power Transformers

Design Number	1	2	3	4	5	6	7
No-load loss, Po (kW)	53	50	45	34	50	39	37
Load loss, Pk (kW)	355	320	270	315	230	240	230
Core steel (type)	M1H30	M1H30	M1H30	M0H23	M0H23	M0H23	M0H23
Core steel (kg)	36,444	39,550	43,142	44,558	45,244	48,615	51,354
Copper winding (kg)	14,680	22,697	22,697	20,261	22,996	24,014	34,427
Approx. selling price (€)	690,061	714,482	787,586	795,062	804,306	831,889	972,312
Full load efficiency (%)	99.594%	99.631%	99.686%	99.652%	99.721%	99.722%	99.734%
Peak loss perf. index (%)	99.730%	99.750%	99.780%	99.790%	99.790%	99.810%	99.820%
Electricity use (MWh/yr)	961.8	886.5	772.6	739.3	760.4	678.0	646.5

[7] The equation for the curve-fit to the 100 MVA designs is: $y = 19026424998.1432*x^{--0.743807384435527}$

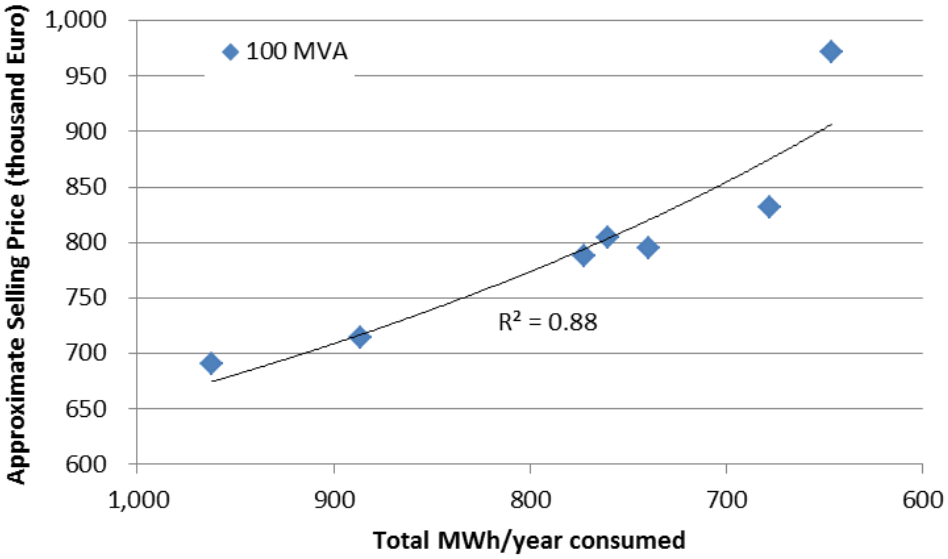

Figure 1-3. Plot of 100 MVA Transformer, Selling Price versus Energy Consumption

1.3 Life-Cycle Cost Analysis

In order to conduct a LCC analysis that is consistent with the methodology followed in the Impact Assessment, assumptions must be made with respect to the cost of electricity consumed by large power transformers and the expected service life of a large power transformer. For all three units analysed (i.e., 25 MVA, 63 MVA and 100 MVA), we used the same assumptions for the LCC analysis:

- Loading over lifetime: 40% of rated nameplate
- Value of electricity: 0.06 Euro/kWh in 2012
- Price increase of electricity: 1% per annum[8]
- Lifetime: 40 years
- Discount rate: 4%[9]

The following figure presents the projected cost of electricity at the point where it passes through the large power transformers. Starting with 6 Eurocents per kilowatt-hour in 2012, the price is assumed to increase at a rate of 1% per annum (real increase in price, excluding inflation). As per the requirements of the impact assessment methodology, a 4% real discount rate is applied to this electricity price, so in terms of 2012 Euros, the discounted future electricity price for large power transformers declines from 6 Eurocents per kilowatt-hour to 2 Eurocents (in today's terms) by 2050. The figure below illustrates this point.

[8] This is the real increase in electricity price experienced by utilities due to changes in generation mix and higher running costs such as fuel costs and overheads. This figure does not include inflation, which is currently approximately 1.7 to 2% in Europe.
[9] This discount rate is the real discount rate (excludes inflation) used by the Commission in its ecodesign analysis.

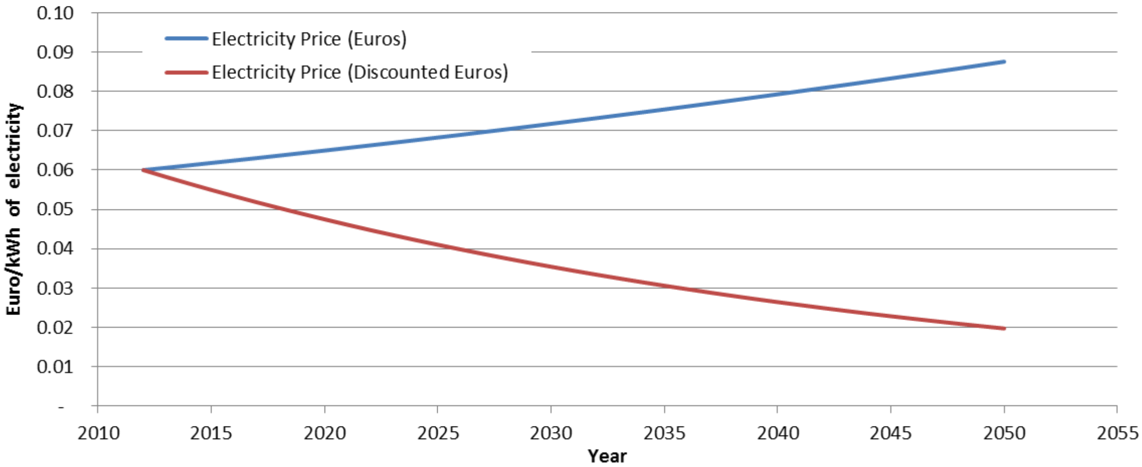

Figure 1-4. Projected Electricity Price in Nominal Euros, 2012-2050

Using the aforementioned inputs, the life-cycle cost (LCC) is calculated for each of three transformer ratings analysed.

The figure below presents the results of the LCC analysis on the 25 MVA transformer. The LCC results are given in a matrix, arranged by kilowatts (kW) of core and coil losses. The positive %LCC results in this figure represent savings relative to the baseline unit. The 25 MVA transformers that were designed and used to develop the price-efficiency relationship are the white cells scattered in the colourful LCC matrix. For the 25 MVA units, the greatest LCC savings potential is approximately 3% of the LCC for the baseline unit and is shown as a diagonal line on the diagram.

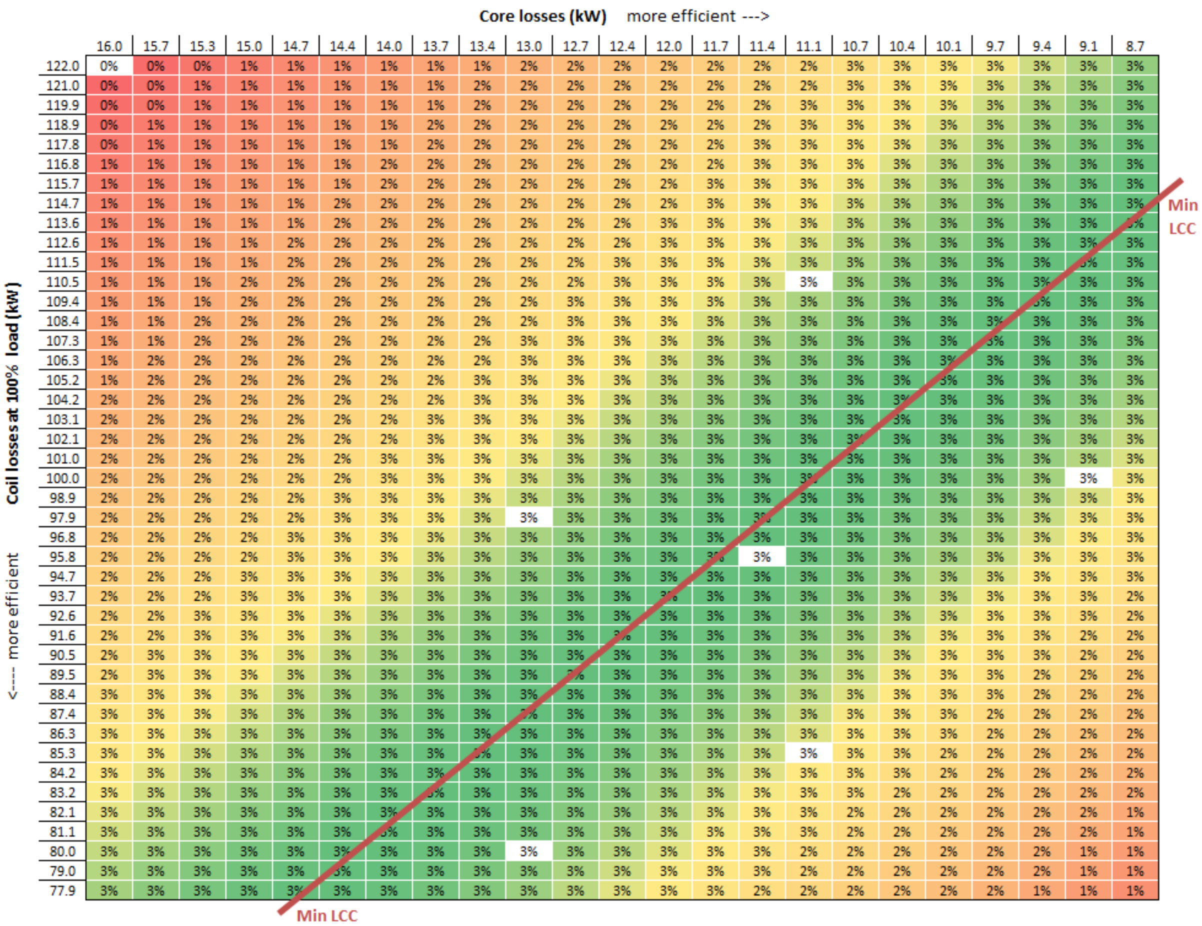

Figure 1-5. Life-Cycle Cost Savings Matrix for the 25 MVA Transformer

The above figure illustrates LCC savings across a wide range of losses, starting from the baseline unit to a level slightly higher than the most efficient design modelled for this study. The figure shows that the percentage of LCC savings can be the same for a variety of transformer designs, spanning a range of anticipated loading points. The following table illustrates this point with a few designs taken in the figure above. Designs A through C are three models with roughly equivalent LCC and peak loss performance indices, but designed with different anticipated loading points (i.e., where Po = Pk). This type of design flexibility is inherent in the peak loss performance index approach, because it enables utilities to continue to specify the loading of a particular installation while enabling the regulator to ensure that the transformer is energy-efficient.

Table 1-4. Loading Comparison of 25 MVA Large Power Transformers

Parameter	Design A	Design B	Design C
Core losses, Po (kW)	10.1	12.4	15.7
Coil losses, Pk (kW)	122.0	100.0	77.9
LCC savings over baseline	3%	3%	3%
Peak loss performance index (%)	99.720%	99.719%	99.720%
Loading point Po=Pk (%)	28.7%	35.2%	44.9%

The following figure presents the relative LCC results for the 63 MVA transformer. It provides a matrix of core and coil losses in kW and the corresponding %LCC savings relative to the baseline unit. This model had four designs, shown by the white boxes in the colourful LCC matrix. For the 63 MVA units, the greatest LCC savings potential is approximately 7% of the LCC for the baseline unit and is shown as a diagonal line on the diagram.

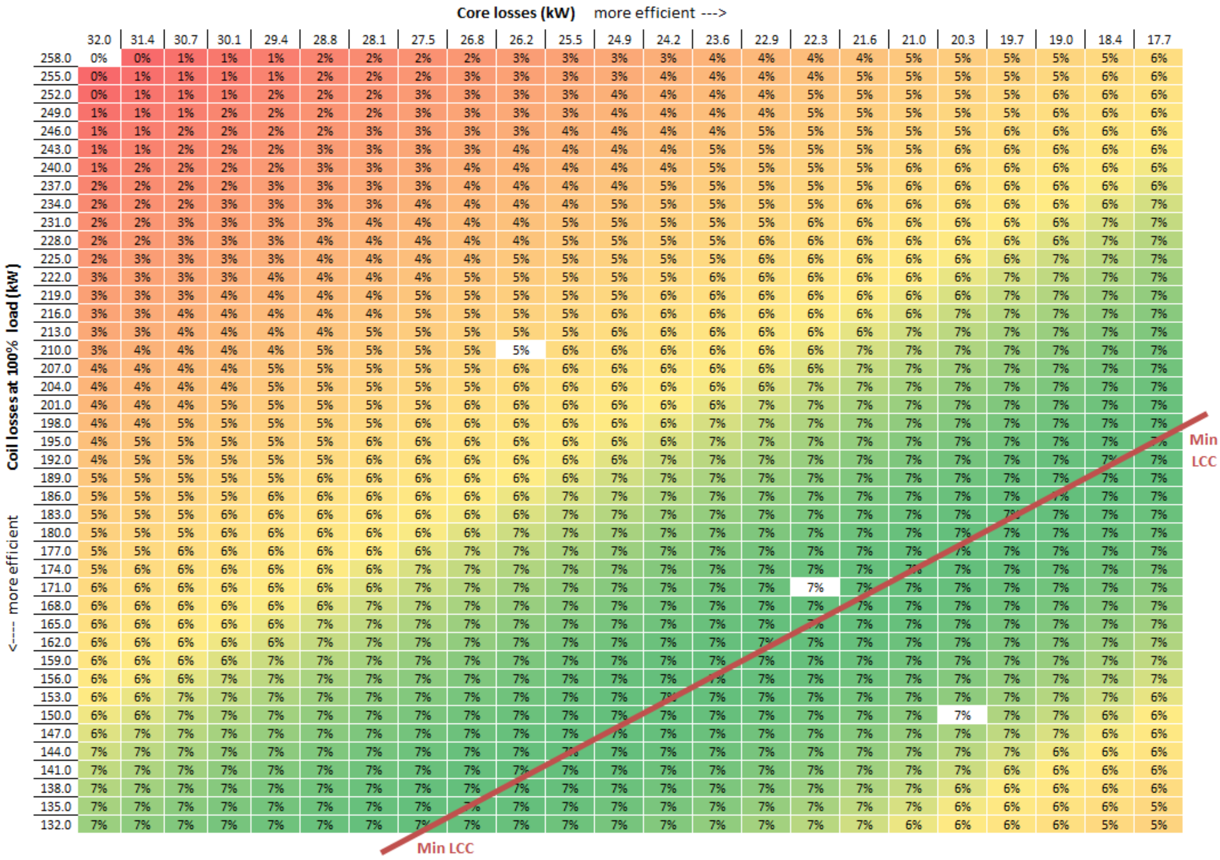

Figure 1-6. Life-Cycle Cost Savings Matrix for the 63 MVA Transformer

The following table examines three designs taken from the matrix above. Designs A through C illustrate three models with roughly equivalent LCC and peak loss performance indices, but designed with different anticipated loading points (i.e., where Po = Pk).

Table 1-5. Loading Comparison of 63 MVA Large Power Transformers

Parameter	Design A	Design B	Design C
Core losses, Po (kW)	17.7	22.3	32.0
Coil losses, Pk (kW)	237.0	189.0	132.0
LCC savings over baseline	6%	7%	7%
Peak loss performance index (%)	99.794	99.794	99.794
Loading point Po=Pk (%)	27.3%	34.3%	49.2%

Finally, the figure below presents the relative LCC savings for the 100 MVA unit, for which there are seven designs shown on the colourful LCC surface. For the 100 MVA unit, the greatest LCC savings potential occurs with the most efficient transformer modelled. The greatest LCC savings potential covered by our analysis and shown in Figure 1-7 represents approximately 12% of the LCC for the baseline unit but the least life-cycle cost would potentially happen for lower losses than what our range of designs allowed us to cover.

Core losses (kW) more efficient --->

Coil losses at 100% load (kW) <---- more efficient

Coil losses (kW) \ Core losses (kW)	53.0	52.0	51.0	50.0	49.0	48.0	47.0	46.0	45.0	44.0	43.0	42.0	41.0	40.0	39.0	38.0	37.0	36.0	35.0	34.0	33.0	32.0	31.0
355.0	0%	0%	1%	1%	2%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%
351.5	0%	1%	1%	1%	2%	2%	2%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%
348.0	0%	1%	1%	2%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%
344.5	1%	1%	1%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%
341.0	1%	1%	2%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%
337.5	1%	1%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%
334.0	1%	2%	2%	2%	3%	3%	3%	4%	4%	5%	5%	5%	6%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%
330.5	1%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%
327.0	2%	2%	2%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%
323.5	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%
320.0	2%	2%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	8%	9%	9%
316.5	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%
313.0	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%
309.5	3%	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%
306.0	3%	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	10%
302.5	3%	3%	4%	4%	5%	5%	5%	6%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%
299.0	3%	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%
295.5	4%	4%	4%	5%	5%	5%	6%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%
292.0	4%	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%
288.5	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	9%	10%	10%	10%
285.0	4%	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%
281.5	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%
278.0	4%	5%	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%
274.5	5%	5%	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%
271.0	5%	5%	6%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%
267.5	5%	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%
264.0	5%	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%
260.5	5%	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%
257.0	6%	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	9%	10%	10%	10%	10%	11%	11%	11%	11%
253.5	6%	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%
250.0	6%	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%
246.5	6%	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%
243.0	6%	7%	7%	7%	7%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%
239.5	6%	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%
236.0	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%
232.5	7%	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%
229.0	7%	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%	12%
225.5	7%	7%	8%	8%	8%	9%	9%	9%	9%	9%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%	12%	12%
222.0	7%	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%	12%	12%
218.5	7%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	12%	12%	12%	12%
215.0	8%	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%	12%	12%	12%
211.5	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%	12%	12%	12%	12%
208.0	8%	8%	8%	9%	9%	9%	9%	10%	10%	10%	10%	10%	11%	11%	11%	11%	11%	11%	11%	12%	12%	12%	12%

Min LCC

Figure 1-7. Life-Cycle Cost Savings Matrix for the 100 MVA Transformer

The following table examines three designs taken from the matrix above. Designs A through C illustrate three models with roughly equivalent LCC and peak loss performance indices, but designed with different anticipated loading points (i.e., where Po = Pk).

Table 1-6. Loading Comparison of 100 MVA Large Power Transformers

Parameter	Design A	Design B	Design C
Core losses, Po (kW)	31.0	40.0	53.0
Coil losses, Pk (kW)	355.0	274.5	208.0
LCC savings over baseline	8%	9%	8%
Peak loss performance index (%)	99.790	99.790	99.790
Loading point Po=Pk (%)	29.6%	38.2%	50.5%

1.4 Selected Designs and Efficiency Suggestion

The designs prepared and the life-cycle cost analysis have shown that for all three large power transformers analysed, positive LCC savings exist at efficiency levels above the baseline model. It would be appropriate, therefore, to establish minimum peak loss performance index requirements as a means of enabling utilities to lower operating costs in the long-term, and thereby reducing electricity supply costs across the EU-27.

For the 100 MVA transformers, the highest LCC savings point occurs for the most efficient (i.e., lowest kW of core and coil losses) of the designs analysed. This indicates that there is an LCC savings potential that exists beyond the range of energy-efficient designs created for this paper. However, due to time and resource constraints, these higher efficiency levels were not analysed. The Commission may wish to specifically annotate the importance of considering the LCC-justified savings of more efficient large power transformers rated over 100 MVA during its future review.

CLASP is suggesting a two-tiered requirement for large-power transformers that reflects a relatively modest LCC savings at Tier 1 and then more ambitious (higher LCC savings) at Tier 2. The LCC savings for Tier 1 correspond to 2% for the 25 MVA, 2% for the 63 MVA and 6% for the 100 MVA. The LCC savings associated with Tier 2 correspond to 3% for the 25 MVA, 7% for the 63 MVA and 11% for the 100 MVA.

The requirements are presented as a table of peak loss performance index requirements, to ensure that utilities still have the flexibility to specify the expected loading point of the power transformer. The values selected from the representative units were then smoothed using the 0.75 scaling rule to different MVA ratings, to ensure there were no discontinuities in the table of efficiency values.

The German national standard was converted into peak loss performance indices, assuming these requirements were applied to naturally ventilated, naturally circulated cooling (ONAN) large power transformers. This conversion makes them comparable to the level of regulatory ambition modelled in this study, which are also ONAN designs.

Finally, the draft Working Group 29 (WG29) efficiency requirements proposed at the meeting of the Technical Subgroup of the Consultation Forum on Large Power Transformers on Friday, 12 April are also included for comparative purposes. It should be noted that for the 25 MVA and 100 MVA requirements of the WG29 proposal, the requirement is essentially the same as the baseline (i.e., lowest efficiency) model prepared for this study. This can be observed, for example, by looking up the efficiency level in the surface plots shown in Annex A (99.656% for the 25 MVA and 99.729% for the 100 MVA). For the 63 MVA design, the efficiency requirement of WG29 is below the least efficient model designed for this study (i.e., baseline unit, 63 MVA). Furthermore, nearly all of the WG29 levels are lower than the existing German national standard. Should the Commission choose to adopt the requirements of the April 12th WG29 proposal, CLASP would be concerned that cost-justified energy savings would not be realised in Europe. In some cases there may be a negative impact on the purchase of new large power transformers, increasing energy consumption in this product group. Indeed, in the current climate of austerity measures and cuts, it could be hard for a utility buying transformers at LLCC level to defend its decision to buy transformers above a minimum ecodesign level recently adopted by Brussels.

Table 1-7. CLASP Suggestion for Regulatory Requirements for Large Power Transformers and Comparison

MVA	Suggestion for Tier 1	Suggestion for Tier 2	German DIN*	WG29 Draft (12 April)
	Peak Loss Performance Index	Peak Loss Performance Index	Peak Loss Performance Index	Peak Loss Performance Index
6.3	99.541%	99.642%	99.423%	
8	99.567%	99.662%	99.526%	
10	99.591%	99.681%	99.583%	99.626%
12.5	99.613%	99.698%	99.635%	
16	99.636%	99.716%	99.658%	99.639%
20	99.656%	99.731%	99.671%	99.646%
25	99.675%	99.746%	99.675%	99.656%
31.5	99.686%	99.757%	99.691%	99.666%
40	99.704%	99.771%	99.706%	99.677%
50	99.720%	99.784%	99.716%	99.689%
63	99.730%	99.793%	99.732%	99.703%
80	99.748%	99.804%	99.747%	99.716%
100	99.764%	99.813%		99.729%
120	99.775%	99.821%		
150	99.787%	99.831%		
200	99.802%	99.843%		
250	99.812%	99.851%		

*The German national standard is published as maximum no-load and maximum load losses. For the purposes of comparison, the maximum losses were assumed to be in place for a naturally ventilated, naturally air cooled (ONAN) unit.

The following figure presents these same regulatory requirements for large power transformers for the tier levels suggested by CLASP, the German national standard and the April 12th WG29 proposal. To help visualise the level of ambition relative to the market, the WG29 database of models installed since 2002 in several EU countries, including Denmark, France, Germany, Ireland, Italy, Spain, the UK and others is included in the figure.

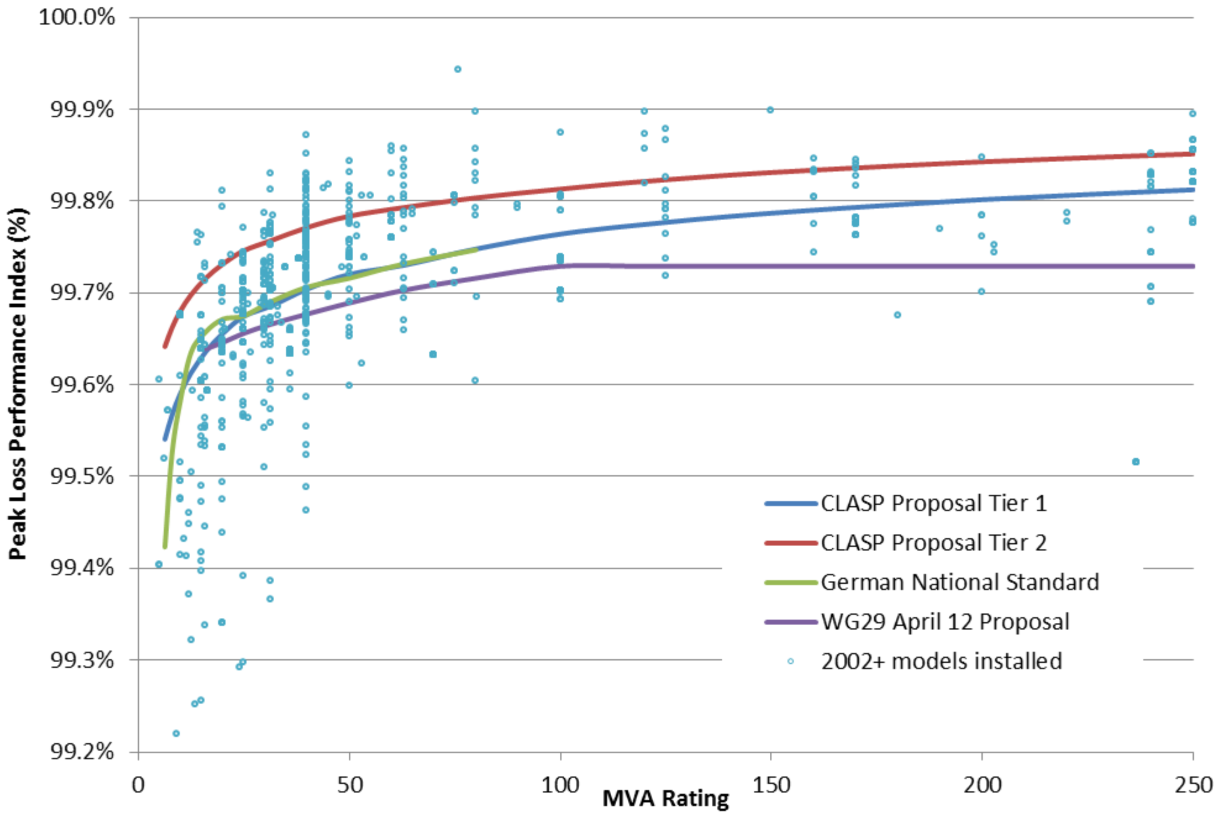

Figure 1-8. CLASP Proposed Regulatory Requirements for Large Power Transformers and Comparison to 2002-2012 Market

As a further check on the level of ambition associated with the CLASP Tier levels, the total cost of ownership (TCO) was calculated for each of the three ratings analysed.

The table below shows the seven 25 MVA designs prepared and a TCO calculation for a low level of loss evaluation in Europe, 6.25 €/W and 1.00 €/W (note: this is less than the European average, as estimated by T&D Europe). The lowest TCO for the 25 MVA occurs at design 2, at €569,750. This corresponds to a peak loss performance index of 99.714%, which falls between CLASP's proposal at 25 MVA of Tier 1 (99.675%) and Tier 2 (99.746%).

Table 1-8. Total Cost of Ownership Calculation for Seven Designs of the 25 MVA

Case	1	2	3	4	5	6	7
No-load loss, Po (kW)	16	13	11.2	13	11.5	11.2	9
No-load cost (€)	100,000	81,250	70,000	81,250	71,875	70,000	56,250
Load loss, Pk (kW)	122	98.5	85.5	80	95	110	100
Load loss cost (€)	122,000	98,500	85,500	80,000	95,000	110,000	100,000
Selling price (€)	348,000	390,000	469,200	438,000	433,956	405,600	448,800
Total cost of ownership (€)	**570,000**	**569,750**	**624,700**	**599,250**	**600,831**	**585,600**	**605,050**
Peak Loss Perform. Index	99.647%	99.714%	99.752%	99.742%	99.736%	99.719%	99.760%

The TCO was calculated for each of the four 63 MVA designs using the same level of loss evaluation: 6.25 €/W and 1.00 €/W. The lowest TCO given this level of European average loss evaluation occurs for design 2, at €936,500. This corresponds to a peak loss performance index of 99.765%, which falls between CLASP's suggested requirements for 63 MVA of Tier 1 (99.730%) and Tier 2 (99.793%).

Table 1-9. Total Cost of Ownership Calculation for Four Designs of the 63 MVA

Case	1	2	3	4
No-load loss, Po (kW)	32	26	22.5	20
No-load cost (€)	200,000	162,500	140,625	125,000
Load loss, Pk (kW)	258	210	170	150
Load loss cost (€)	258,000	210,000	170,000	150,000
Selling price (€)	480,000	564,000	667,200	756,000
Total cost of ownership (€)	938,000	936,500	977,825	1,031,000
Peak Loss Perform. Index	99.712%	99.765%	99.804%	99.826%

The TCO was calculated for each of the seven 100 MVA designs using the same loss evaluation values: 6.25 €/W and 1.00 €/W. The lowest TCO given this level of European average loss evaluation occurs for design 6, at €1,521,541. This corresponds to a peak loss performance index of 99.807%, which falls between CLASP's proposal for 100 MVA of Tier 1 (99.764%) and Tier 2 (99.813%).

Table 1-10. Total Cost of Ownership Calculation for Seven Designs of the 100 MVA

Case	1	2	3	4	5	6	7
No-load loss, Po (kW)	53	50	45	34	50	39	37
No-load cost (€)	331,250	312,500	281,250	212,500	312,500	243,750	231,250
Load loss, Pk (kW)	355	320	270	315	230	240	230
Load loss cost (€)	355,000	320,000	270,000	315,000	230,000	240,000	230,000
Selling price (€)	690,061	714,482	787,586	795,062	804,306	831,889	972,312
Total cost of ownership (€)	1,376,311	1,346,982	1,338,836	1,322,562	1,346,806	1,315,639	1,433,562
Peak Loss Perform. Index	99.726%	99.747%	99.780%	99.793%	99.786%	99.807%	99.816%

Overall, the fact that the lowest TCO design for all three of the representative units fell at an peak loss performance index between the proposed Tier 1 and Tier 2 levels suggested by CLASP indicates that these suggested requirements are reasonable. Indeed, the loss valuation used for the calculation (Po at 6.25 €/W and Pk at 1.00 €/W) reflect a low level of loss evaluation, and is below the EU-27 average as reported by T&D Europe. We therefore suggest that the Commission consider the requirements proposed and we would be happy to provide further information or analysis upon request.

2 Large Power Transformer Design Detail

The table below provides the basic transformer design parameters for the three ratings studied.

Table 2-1. Main Design Characteristics of the Three Oil-Immersed Outdoor Transformers

Type		25 MVA	63 MVA	100 MVA
Number of Phases		3	3	3
Number of Windings		2	2	2
Rated frequency		50 Hz	50 Hz	50 Hz
Cooling system		ONAN	ONAN	ONAN
High Voltage Winding	Rated voltage	150 kV	150 kV	220 kV
	Voltage regulation	± 10 x 1,5%	± 10 x 1,5%	± 10 x 1,5%
	Connection	Star with neutral	Star with neutral	Star with neutral
	Insulation level	LI 650 – AC 275	LI 650 – AC 275	LI 1050 – SI 950
Low Voltage Winding	Rated voltage	20 kV	20 kV	23.8 kV
	Connection	Star with neutral	Star with neutral	Star with neutral
	Insulation level (uniform)	LI 125 – AC 50	LI 125 – AC 50	LI 125 – AC 50
Connection symbol / phase displacement		YNyn0	YNyn0	YNyn0
Short-circuit impedance 75°C (%):		14	19	17

The individual sub-sections of this chapter provide more detail from the design reports prepared by Professor A. Bossi and Professor A. Baggini.

2.1 Results for 25 MVA Three-Phase Oil-Immersed

The purpose of these designs was to explore and estimate the industrial cost variations of oil-immersed power transformers in relation to the loss values for a three-phase, 25 MVA, 150/20 KV, with on-load tap changer. In addition to the design characteristics presented in Table 2-1, the following manufacturing characteristics were included for the 25 MVA:

- concentric windings with medium voltage (MV) winding closest to core steel;
- copper strip conductors for high voltage (HV) windings and transposed cable for MV windings;
- interleaved disk arrangement for the HV windings;
- voltage regulation windings placed on the outer HV windings;
- HV tap change by on-load tap-changer with coarse tap change-over selector;
- three column magnetic core with step-lap construction of the magnetic sheets;
- constant flux density under normal operating conditions.

The estimated manufacturer’s cost of the 25 MVA transformers is € 290,000 ± 10%. This estimate does not include the manufacturer profit, transportation, commissioning or any special accessories. To develop this reference transformer cost, the following assumptions were made, based on European experience:

- active materials of variable cost (magnetic core, windings): 40%
- other materials (bushings, tap changer, cooling system): 20%
- labour costs: 35%
- other costs: 5%

The basic costs of copper and magnetic material, mineral oil and tank steel used in the calculations are shown in the table below.

Table 2-2. Basic Costs of Materials Used in the Designs

Material	Cost (€/kg)
M1H30 Magnetic Steel	2.15
M0H23 Laser Scribed Magnetic Steel	2.50
Finished Magnetic Core (clamping included)	3.00 – 3.30
Copper (market value as of 18/3/2013)	6.95
Copper working / transformation into wire	0.70
Copper transposed cables	8.40
Mineral oil	1.20
Tank steel	2.80

The costs of oil, tank and accessories were considered fixed because variations in these costs are somewhat compensated for by the variable cost of the magnetic circuit and winding material. Costs associated with new designs, manufacturing conversion and testing of new designs were excluded from the cost estimates.

The results obtained from the design calculations for the 25 MVA transformer are reported below in Table 2-3. In that table, the second column from the left (with the number 1) represents a basic transformer used on a public transmission system with a ratio of 7.5:1 between load and no-load losses. Columns numbered 2 and 3 represent modifications to that basic design, keeping the loss ratio at 7.5 by changing the core steel from M1H30 to H085-23 (M0H23) to reduce the losses. M0H23 is a grain oriented magnetic steel that has been laser scribed, and represents the best magnetic steel on the European market. The working induction for these designs was also reduced and the volts per turn modified in order to maintain in a reasonable range for the short-circuit impedance. The insulation requirement was met and consideration was given to the thermal behaviour of the design, which is a naturally cooled oil, naturally cooled air (ONAN) design. In columns numbered 4 to 7 the transformer designs have been adjusted to have different load and no-load loss ratio, with an emphasis on reducing losses. The working induction was reduced and the volts per turn modified in order to maintain a reasonable short-circuit impedance.

Table 2-3. Results Obtained for the Three-Phase Transformer 25 MVA, 150/20 kV

Ref.	1	2	3	4	5	6	7
Loss ratio	7.6	7.5	7.6	6.2	8.3	9.8	11.1
Material	M1H30	M0H23	M0H23	M0H23	M0H23	M0H23	M0H23
Induction (T)	1.68	1.52	1.22	1.41	1.32	1.37	1.17
No-load loss (kW)	16.0	13.0	11.2	13	11.5	11.2	9
No-load loss reduction (%)	-	19	30	19	28	30	44
Magnetic circuit mass (kg)	12,920	15,935	21,350	18,645	18,280	16,825	20,475
Magnetic material cost (€)	32,295	45,415	60,820	53,135	52,095	47,950	58,385
Magnetic material cost increase (%)	-	41	88	65	61	48	81
Current density (mean) (A/mm^2)	3.00	2.30	1.66	1.41	1.92	2.4	1.97
Load loss (kW)	122	98.0	85.5	80	95	110	100
Load loss reduction (%)	-	20.0	30.0	34	22	10	18
Copper mass (kg)	5,535	7,365	11,940	9,992	9,890	7,860	10,375
Copper cost (€)	42,070	56,115	96,880	81,225	80,355	63,560	83,950
Copper cost increase (%)	-	33.0	130.0	93	91	51	100
Total active material cost increase (€)	-	27,165	83,340	59,970	58,085	37,145	67,970
Total active material cost increase (%)	-	36.5	112.1	80.7	78.1	49.9	91.4
Estimated industrial cost (€)	290,000	325,000	391,000	365,000	361,630	338,000	374,000
Industrial cost increase (%)	-	10.4	33	24.1	23.0	15	27.2
Full load conventional efficiency (%)	99.451	99.558	99.615	99.629	99.576	99.518	99.566
Peak loss performance index (%)	99.647	99.714	99.752	99.742	99.736	99.719	99.760

In the following table more details are given on the design of columns 1, 5 and 7.

Table 2-4. More Detail on the Construction of the 25 MVA, 150/20 kV

Ref.		1	5	7
Core	Diameter (mm)	558	508	578
	Number of step	15	15	15
	Height of window (mm)	1650	1315	1805
	Distance phase-phase (mm)	1215	1105	1205
	Type of Magnetic Material	M0H23	M1H30	M0H23
Low Voltage Winding	Type of winding	Barrel	Barrel	Barrel
	Inner diameter (mm)	592	542	612
	Radial thickness (mm)	79	73	77
	Type of conductor	Transposed cable	Transposed cable	Transposed cable
	Conductor	15 x (1.5 x 7.1)	15 x (1.3 x 5.5)	27 x (1.2 x 5.5)
	Number of strands per turn	2 x 15	2 x 15	2 x 27
High Voltage Winding	Type of winding	Disk	Disk	Disk
	Inner diameter (mm)	840	778	1168
	Radial thickness (mm)	99.5	72	118
	Type of conductor	Transposed cable	Twin strand	Transposed cable
	Conductor	7 x (1.6 x 5.4)	2.2 x 8.0	5 x (1.6 x 6.4)
	Number of strands per turn	7	2	5

The graph below presents a scatter-plot of the design results for the 25 MVA three-phase oil-immersed large power transformer. As the peak loss performance index improves (and the losses are reduced in the transformer), the selling price increases.

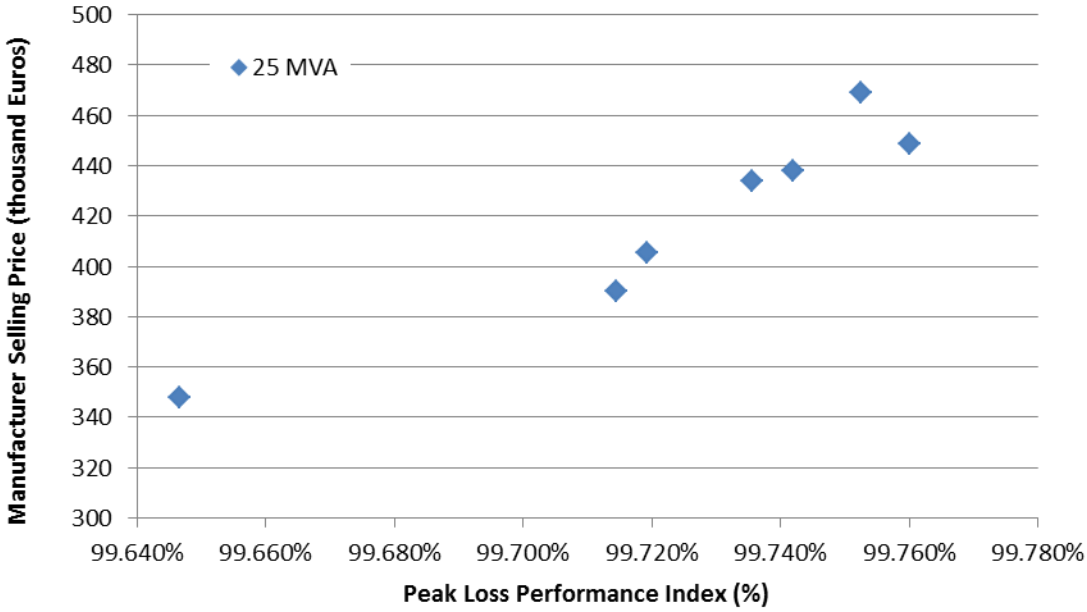

Figure 2-1. Selling Price vs. Peak Loss Performance Index for 25 MVA Transformer

2.2 Results for 63 MVA Three-Phase Oil-Immersed

The purpose of these designs was to explore and estimate the industrial cost variations of oil-immersed power transformers in relation to the loss values for a three-phase, 63 MVA, 150/20 KV, with on-load tap changer. In addition to the design characteristics presented in Table 2-1, the following manufacturing characteristics were included for the 63 MVA:

- concentric windings with medium voltage (MV) winding closest to core steel;
- copper strip conductors for high voltage (HV) windings and transposed cable for MV windings;
- voltage regulation windings placed on the outer HV windings;
- HV tap change by on-load tap-changer with coarse tap change-over selector;
- three column magnetic core with step-lap construction of the magnetic sheets;
- constant flux density under normal operating conditions;
- magnetic shield on the internal tank walls.

The estimated manufacturer's cost of the 63 MVA transformers is € 380,000 ± 10%. This estimate does not include the manufacturer profit, transportation, commissioning or any special accessories. To develop this reference transformer cost, the following assumptions were made, based on European experience:

- active materials of variable cost (magnetic core, windings): 40%

- other materials (bushings, tap changer, cooling system): 20%
- labour costs: 35%
- other costs: 5%

The basic costs of copper and magnetic material, mineral oil and tank steel used in the calculations are the same as those shown in Table 2-2. The costs of oil, tank and accessories were considered fixed because variations in these costs are somewhat compensated for by the variable cost of the magnetic circuit and winding material. Costs associated with new designs, manufacturing conversion and testing of new designs were excluded from the cost estimates.

The results obtained from the design calculations for the 63 MVA transformer are reported in the table below. In that table, the second column from the left (with the number 1) represents a basic transformer used on a public transmission system. Columns numbered 2 through 4 represent modifications to that basic design, changing the core steel from M1H30 to H085-23 (M0H23) to reduce the losses. M0H23 is a grain oriented magnetic steel that has been laser scribed, and represents the best magnetic steel on the European market. The working induction for these designs was also reduced and the volts per turn modified in order to maintain in a reasonable range for the short-circuit impedance. The insulation requirement was met and consideration was given to the thermal behaviour of the design, which is a naturally cooled oil, naturally cooled air (ONAN) design.

An effort was made to further reduce both load and no-load losses, but it did not result in practical designs. In doing the electromagnetic design of transformers, there are a lot of variables (e.g., the volts per turn, short-circuit impedance and magnetic material, insulation and thermal requirements) and the values presented in the table reflect a few alternatives. While further improvements would still be possible, it was felt that for the purpose of this study the four designs would be adequate for establishing the relationship between manufacturer's selling price and efficiency.

Table 2-5. Results Obtained for the Three-Phase Transformer 63 MVA, 150/20 kV

Ref.	1	2	3	4
Material	M1H30	M0H23	M0H23	M0H23
Induction (T)	1.68	1.49	1.37	1.30
No-load loss (kW)	32	26	22.5	20
No-load loss reduction (%)	-	19	31.2	37.5
Magnetic circuit mass (kg)	25,300	31,195	38,500	428,500
Magnetic material cost (€)	54,390	77,990	96,250	107,150
Magnetic material cost increase (%)	-	43.3	76.9	97.0
Current density (mean) (A/mm^2)	2.85	2.15	1.59	1.40
Load loss (kW)	258	210	170	150
Load loss reduction (%)	-	19.4	34.1	41.9
Copper mass (kg)	11,200	15,170	21,200	24,050
Copper cost (€)	89,350	127,430	178,100	201,850
Copper cost increase (%)	-	42.6	99.3	125.9
Total active material cost increase (€)	-	61,680	130,600	165,250
Total active material cost increase (%)	-	42.9	90.8	114.9
Estimated industrial cost (€)	400,000	470,000	556,000	630,000
Industrial cost increase (%)	-	17.5	39.0	57.5
Full load conventional efficiency (%)	99.543	99.625	99.695	99.731
Peak loss performance index (%)	99.711	99.765	99.804	99.826

In the following table more details are given on the design of columns 1,2 and 3.

Table 2-6. More Detail on the Construction of the 63 MVA, 150/20 kV

Ref.		1	2	3
Core	Diameter (mm)	667	728	758
	Number of step	15	15	15
	Height of window (mm)	1150	1185	1480
	Distance phase-phase (mm)	1140	1565	1605
	Type of Magnetic Material	M1H30	M0H23	M0H23
Low Voltage Winding	Type of winding	Barrel	Barrel	Barrel
	Inner diameter (mm)	701	762	792
	Radial thickness (mm)	121	133	143
	Type of conductor	Transposed cable	Transposed cable	Transposed cable
	Conductor	27 x (1.5 x 5.5)	31 x (1.5 x 6.3)	35 x (1.5 x 8)
	Number of strands per turn	3 x 27	3 x 31	3 x 35
High Voltage Winding	Type of winding	Disk	Disk	Disk
	Inner diameter (mm)	1033	1118	1168
	Radial thickness (mm)	105	124	118
	Type of conductor	Twin strand	Transposed cable	Transposed cable
	Conductor	2.2 x 9.9	13 x (1.6 x 5.2)	15 x (1.5 x 6.2)
	Number of strands per turn	4	13	15

The graph below presents a scatter-plot of the design results for the 63 MVA three-phase oil-immersed large power transformer. As the peak loss performance index improves (and the losses are reduced in the transformer), the selling price increases.

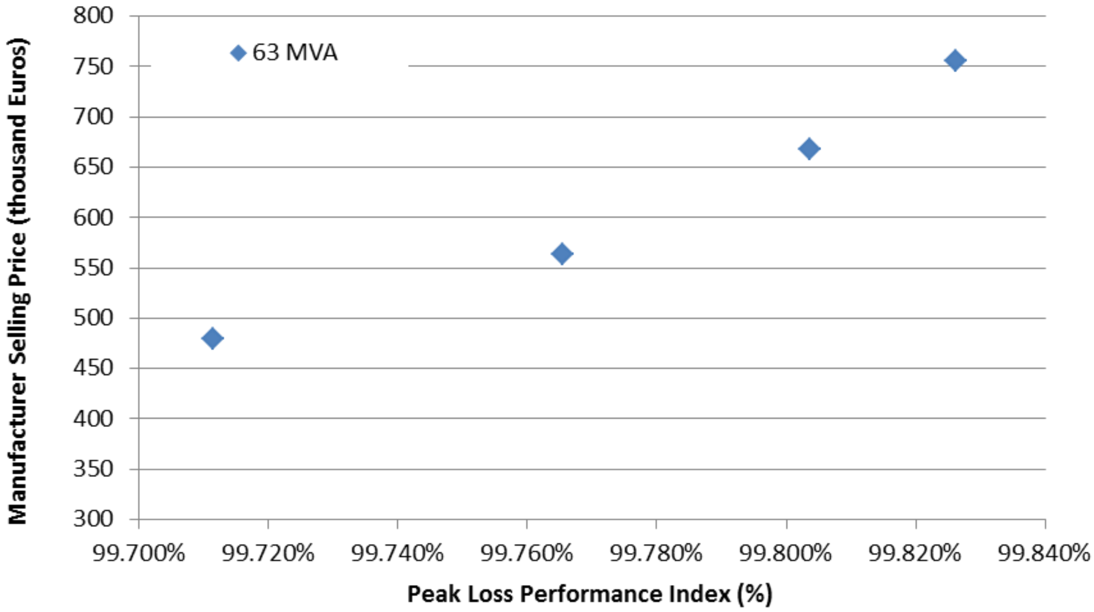

Figure 2-2. Selling Price vs. Peak Loss Performance Index for 63 MVA Transformer

2.3 Results for 100 MVA Three-Phase Oil-Immersed

The purpose of these designs was to explore and estimate the industrial cost variations of oil-immersed power transformers in relation to the loss values for a three-phase, 100 MVA, 220/23.8 KV, with on-load tap changer. In addition to the design characteristics presented in Table 2-1, the following manufacturing characteristics were included for the 100 MVA:

- concentric windings with medium voltage (MV) winding closest to core steel;
- transposed copper cables for both HV and MV windings;
- interleaved disk arrangement for the HV windings;
- voltage regulation windings placed on the outer HV windings;
- HV tap change by on-load tap-changer with coarse tap change-over selector;
- three column magnetic core with step-lap construction of the magnetic sheets;
- constant flux density under normal operating conditions;
- magnetic shield on the tank internal walls.

The estimated manufacturer's cost of the 100 MVA transformers is €575,000 ± 10%. This estimate does not include the manufacturer profit, transportation, commissioning or any special accessories. To develop this reference transformer cost, the following assumptions were made, based on European experience:

- active materials of variable cost (magnetic core, windings): 40%

- other materials (bushings, tap changer, cooling system): 20%
- labour costs: 35%
- other costs: 5%

The basic costs of copper and magnetic material, mineral oil and tank steel used in the calculations are the same as those shown in Table 2-2. The costs of oil, tank and accessories were considered fixed because variations in these costs are somewhat compensated for by the variable cost of the magnetic circuit and winding material. Costs associated with new designs, manufacturing conversion and testing of new designs were excluded from the cost estimates.

The results obtained from the design calculations for the 100 MVA transformer are reported in the table below. In that table, the second column from the left (with the number 1) represents a basic transformer used on a public transmission system. For the other columns, the losses were reduced as in the previous models by improving the core steel, increasing the quantity of core-steel (while reducing the working induction), adjusting the volts per turn modified in order to maintain in a reasonable range for the short-circuit impedance and so-on. The insulation requirement was met and consideration was given to the thermal behaviour of the design, which is a naturally cooled oil, naturally cooled air (ONAN) design.

Table 2-7. Results Obtained for the Three-Phase Transformer 100 MVA, 220/23.8 kV

Ref.	1	2	3	4	5	6	7
Loss ratio	6.7	6.4	6.0	9.3	4.6	6.2	6.2
Material	M1H30	M1H30	M1H30	M0H23	M0H23	M0H23	M0H23
Induction (T)	1.73	1.68	1.59	1.45	1.68	1.51	1.41
No-load loss (kW)	53	50	45	34	50	39	37
No-load loss reduction (%)	-	6	15	36	6	26	30
Magnetic circuit mass (kg)	36,444	39,550	43,142	44,558	45,244	48,615	51,354
Magnetic material cost (€)	91,108	98,875	107,854	126,989	128,944	138,553	146,375
Magnetic material cost increase (%)	100	109	118	139	142	152	161
Current density (mean) (A/mm^2)	3.1	2.7	2.0	2.45	1.8	1.75	1.49
Load loss (kW)	355	320	270	315	230	240	230
Load loss reduction (%)	-	10	24	11	35	32	35
Copper mass (kg)	14,680	22,697	22,697	20,261	22,996	24,014	34,427
Copper cost (€)	118,170	129,983	187,025	166,957	188,065	197,872	283,683
Copper cost increase (%)	100	110	158	141	159	167	240
Total active material cost increase (€)	-	19,580	85,601	84,668	107,731	127,147	220,780
Total active material cost increase (%)	100	109.4	140.9	140.5	151.5	160.8	205.5
Estimated industrial cost (€)	575,051	595,402	656,322	662,552	670,255	693,241	810,260
Industrial cost increase (%)	100	103.5	114.1	115.2	116.6	120.6	140.9
Full load conventional efficiency (%)	99.594	99.631	99.686	99.652	99.721	99.722	99.734
Peak loss performance index (%)	99.726	99.747	99.780	99.793	99.786	99.807	99.816

In the following table more details are given on the designs for columns 1, 3 and 6.

Table 2-8. More Detail on the Construction of the 100 MVA, 220/23.8 kV

Ref.		1	3	6
Core	Diameter (mm)	728	758	788
	Number of step	15	15	15
	Height of window (mm)	1735	1960	2045
	Distance phase-phase (mm)	1520	1610	1675
	Type of Magnetic Material	M1H30	M1H30	M0H23
Low Voltage Winding	Type of winding	Barrel	Barrel	Barrel
	Inner diameter (mm)	762	792	822
	Radial thickness (mm)	89	108	110
	Type of conductor	Transposed cable	Transposed cable	Transposed cable
	Conductor	19 x (1.3 x 7.2)	23 x(1.5 x 8.4)	25 x (1.4 x 9.0)
	Number of strands per turn	4 x 19	4 x 23	4 x 25
High Voltage Winding	Type of winding	Disk	Disk	Disk
	Inner diameter (mm)	1066	1134	1168
	Radial thickness (mm)	105	114	128
	Type of conductor	Transposed cable	Transposed cable	Transposed cable
	Conductor	15 x (1.1 x 5.9)	21 x (1.2 x 5.6)	19 x (1.3 x 7.8)
	Number of strands per turn	15	21	19

The graph below presents a scatter-plot of the design results for the 100 MVA three-phase oil-immersed large power transformer. As the peak loss performance index improves (and the losses are reduced in the transformer), the selling price increases.

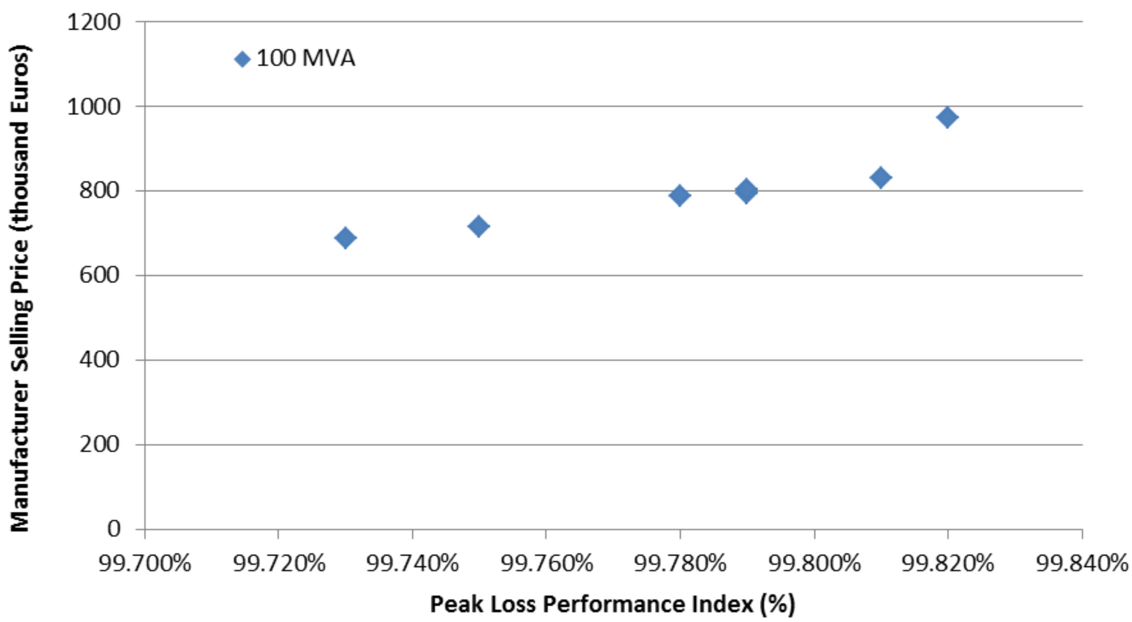

Figure 2-3. Selling Price vs. Peak Loss Performance Index for 100 MVA Transformer

3 Life-Cycle Cost Methodology Description

CLASP developed a broad range of appropriate core and coil losses for each transformer analysed. The combinations of core and coil losses combine to create 989 unique combinations of Po and Pk. For each combination, the kWh/year consumed is calculated, along with the LCC of those losses. Then, the cost of the transformer is estimated for each design based on the equation derived from the curve-fit to the large power transformer designs prepared by Professor A. Bossi and Professor A. Baggini. Finally, with first cost and operating cost known, the relative LCC is calculated for the entire matrix of designs and the results are colour-coded to facilitate interpretation of the graph.

CLASP developed this approach to be consistent with the draft results shared by the Commission in its Impact Assessment. The following text discusses the steps involved in more detail.

1. Establishing the Range of Losses – each of the transformer ratings analysed (i.e., 25 MVA, 63 MVA and 100 MVA) has a range of losses that are given in the designs prepared. The 25 MVA, for example, has a range of core losses from 16 kW to 9 kW, and coil losses from 122 kW to 80 kW. The lower losses corresponding to the more efficient designs. The spreadsheet starts with the least efficient design, which constitutes the baseline unit for analysis, and then extends out to lower maximum loss levels, slightly surpassing the most efficient design to extend the range of analysis.

2. Calculate kWh per year consumption – given the known losses for the transformer (Po, Pk), it is known that the Po losses will be occurring 8,760 hours per year. The losses occurring in the windings are calculated based on the average expected loading (i.e., 40%) applied to each of the designs in the matrix. These are added together, and the kWh consumed is calculated for each of 989 combinations of Po, Pk.

3. Calculate LCC of operating costs – starting with the total LCC and deducting the first cost, the LCC of operating the transformer is calculated. From this residual and the known kWh per year consumption, another constant is calculated, which reflects the assumed lifetime (40 years), electricity price (0.06 Euro/kWh, increasing by 1% per annum, excluding inflation) and real discount rate (4%). The constant is then applied to the kWh/year consumption to calculate the discounted operating cost in Euro.

4. Calculate purchase price of the transformer – CLASP plotted each of the large power transformer designs prepared by Professor A. Bossi and Professor A. Baggini, showing purchase price over kWh per year of energy consumption. This metric is used for the X-axis because it takes into account both Po and Pk, as well as the embedded assumptions about average loading (40%). A curve is fit to these data, using the power law, which provides a function of the kWh/year losses. The equation is then applied to the matrix of 989 combinations of Po, Pk to estimate a manufacturer's selling price for each of the designs.

5. Calculate the LCC relative to the baseline model – the LCC is then derived by summing together the purchase price and the discounted operating cost, resulting in a net present value LCC for the transformer. This is compared to the baseline model (i.e., least efficient design) and the percentage change in LCC for each of the 989 combinations of Po, Pk is calculated.

6. Transpose matrix and provide colour coding – the data is then transposed for ease of presentation and a conditional formatting rule is applied to colour-code the least cost-efficient options as red/orange and the most cost-efficient as green. Looking across the surface of Po, Pk combinations created, the large area in green represents the economic-optimum for this base case model.

4 Transformer Design Experts

In support of the European Commission's analysis of Distribution and Power Transformers, CLASP has undertaken three studies on the relationship between manufacturer's selling price and efficiency covering six of the seven base case transformers evaluated by the Commission.

In August 2010, CLASP published a design report on three oil-immersed transformers:

- 400 kVA oil-immersed three-phase unit, representing distribution transformers
- 1000 kVA oil-immersed three-phase unit, representing industry transformers
- 2000 kVA oil-immersed three-phase unit, representing distributed energy resources (DER) transformers

In March 2011, CLASP published design results on two cast-coil dry-type transformers:

- 1250 kVA cast-coil dry-type three-phase unit, representing industry transformers
- 2000 kVA cast-coil dry-type three-phase unit, representing distributed energy resources (DER) transformers

In this report, CLASP is presenting design results on three large power transformers:

- 25 MVA oil-immersed three-phase large power transformers
- 63 MVA oil-immersed three-phase large power transformers
- 100 MVA oil-immersed three-phase large power transformers

Understanding how the price of transformers increases as the efficiency improves is important because it enables an accurate assessment of LCC and quantification of benefits accruing to the electric utility and society as a whole.

CLASP commissioned the development of 18 transformer designs spanning a range of efficiency levels for these three large power transformers. The designs were based initially on a baseline unit, constructed with M1H30 core steel and a copper primary and secondary. Design parameters and materials would then be adjusted that would improve the efficiency, such as using better core steel (i.e., laser-scribed domain-refined, M0H23).

For the three base case models, this analysis explored the relationship between the manufacturer selling prices and corresponding transformer efficiencies. To prepare these designs, CLASP contracted Professor Antonio Bossi and Professor Angelo Baggini, each of whom have considerable experience studying large power transformers in Italy.

Using a range of input parameters and material prices, the design team prepared designs that explored the relationship between manufacturer's selling price and efficiency. The design files prepared for each design contain specific information about the core and coil, including physical characteristics, dimensions and material requirements, as well as a complete electrical analysis of the final design. This output is then used to generate an estimated cost of manufacturing materials and labour, which is then converted to a manufacturer's selling price by applying a 1.2 mark-up on direct costs.

4.1 Design Team Member: Professor Antonio Bossi

Professor Antonio Bossi received his engineering degree in 1948, after which he worked with Edisonvolta Company (an electric utility of the Edison Group) in Milan until 1963. He then moved to the Electrical Research Department of ENEL, the Italian National Electricity Board, where he worked until 1985. At ENEL, he began advanced studies and guided extensive research programs on power and measuring transformers, power cables and capacitors. He has been a lecturer in Construction of Electrical Machines and Electrical Measurements at the University of Pavia since 1978. He has authored many technical papers and technical books on electrical machines, testing techniques and electric installations. He is currently the chairman of CENELEC TC14.

4.2 Design Team Member: Professor Angelo Baggini

Angelo Baggini received his degree in Electrical Engineering cum laude from University of Pavia in 1993; his thesis research work in CESI Metrological Lab, was awarded with the "AEI Stefano e Flora Badoni" prize by AEI (Associazione Elettrotecnica Italiana). He received his PhD in Electrical Engineering from University of Pavia in 1997. He has been a member of CEI TC14 since 1997 and from 2007 he has been secretary of CENELEC TC14. He is currently working both as a professor of Electrical Engineering at University of Bergamo and an international consultant. He is an author of several technical books and of over 200 technical and scientific papers both on magazines and in national and international conferences either in the industry or at University.

Annex A. Surface Plots with Efficiency Values

As discussed in section 1.4, Selected Designs and Efficiency Suggestion, a series of figures are provided in this Annex which plot the peak loss performance indices that correspond to the combinations of Po, Pk in the study.

Core losses (kW) more efficient --->

Coil losses at 100% load (kW) <---- more efficient

	16.0	15.7	15.3	15.0	14.7	14.4	14.0	13.7	13.4	13.0	12.7	12.4	12.0	11.7	11.4	11.1	10.7	10.4	10.1	9.7	9.4	9.1	8.7
122.0	99.647	99.650	99.654	99.658	99.661	99.665	99.669	99.673	99.677	99.681	99.685	99.689	99.693	99.698	99.702	99.706	99.711	99.715	99.720	99.724	99.729	99.734	99.739
121.0	99.648	99.652	99.655	99.659	99.663	99.667	99.671	99.674	99.678	99.682	99.686	99.691	99.695	99.699	99.703	99.708	99.712	99.716	99.721	99.726	99.730	99.735	99.740
119.9	99.650	99.653	99.657	99.661	99.664	99.668	99.672	99.676	99.680	99.684	99.688	99.692	99.696	99.700	99.704	99.709	99.713	99.718	99.722	99.727	99.731	99.736	99.741
118.9	99.651	99.655	99.658	99.662	99.666	99.670	99.673	99.677	99.681	99.685	99.689	99.693	99.697	99.702	99.706	99.710	99.714	99.719	99.723	99.728	99.733	99.737	99.742
117.8	99.653	99.656	99.660	99.664	99.667	99.671	99.675	99.679	99.683	99.687	99.691	99.695	99.699	99.703	99.707	99.711	99.716	99.720	99.725	99.729	99.734	99.739	99.743
116.8	99.654	99.658	99.661	99.665	99.669	99.673	99.676	99.680	99.684	99.688	99.692	99.696	99.700	99.704	99.708	99.713	99.717	99.721	99.726	99.730	99.735	99.740	99.744
115.7	99.656	99.659	99.663	99.667	99.670	99.674	99.678	99.682	99.685	99.689	99.693	99.697	99.701	99.706	99.710	99.714	99.718	99.723	99.727	99.732	99.736	99.741	99.746
114.7	99.657	99.661	99.665	99.668	99.672	99.676	99.679	99.683	99.687	99.691	99.695	99.699	99.703	99.707	99.711	99.715	99.720	99.724	99.728	99.733	99.737	99.742	99.747
113.6	99.659	99.662	99.666	99.670	99.673	99.677	99.681	99.685	99.688	99.692	99.696	99.700	99.704	99.708	99.712	99.717	99.721	99.725	99.730	99.734	99.739	99.743	99.748
112.6	99.661	99.664	99.668	99.671	99.675	99.678	99.682	99.686	99.690	99.694	99.698	99.701	99.706	99.710	99.714	99.718	99.722	99.726	99.731	99.735	99.740	99.744	99.749
111.5	99.662	99.666	99.669	99.673	99.676	99.680	99.684	99.687	99.691	99.695	99.699	99.703	99.707	99.711	99.715	99.719	99.723	99.728	99.732	99.736	99.741	99.746	99.750
110.5	99.664	99.667	99.671	99.674	99.678	99.682	99.685	99.689	99.693	99.697	99.700	99.704	99.708	99.712	99.716	99.721	99.725	99.729	99.733	99.738	99.742	99.747	99.751
109.4	99.665	99.669	99.672	99.676	99.679	99.683	99.687	99.690	99.694	99.698	99.702	99.706	99.710	99.714	99.718	99.722	99.726	99.730	99.735	99.739	99.743	99.748	99.753
108.4	99.667	99.670	99.674	99.677	99.681	99.685	99.688	99.692	99.696	99.699	99.703	99.707	99.711	99.715	99.719	99.723	99.727	99.732	99.736	99.740	99.745	99.749	99.754
107.3	99.669	99.672	99.675	99.679	99.682	99.686	99.690	99.693	99.697	99.701	99.705	99.709	99.712	99.716	99.720	99.725	99.729	99.733	99.737	99.742	99.746	99.750	99.755
106.3	99.670	99.674	99.677	99.681	99.684	99.688	99.691	99.695	99.699	99.702	99.706	99.710	99.714	99.718	99.722	99.726	99.730	99.734	99.738	99.743	99.747	99.752	99.756
105.2	99.672	99.675	99.679	99.682	99.686	99.689	99.693	99.696	99.700	99.704	99.708	99.711	99.715	99.719	99.723	99.727	99.731	99.736	99.740	99.744	99.748	99.753	99.757
104.2	99.673	99.677	99.680	99.684	99.687	99.691	99.694	99.698	99.702	99.705	99.709	99.713	99.717	99.721	99.725	99.729	99.733	99.737	99.741	99.745	99.750	99.754	99.759
103.1	99.675	99.678	99.682	99.685	99.689	99.692	99.696	99.699	99.703	99.707	99.711	99.714	99.718	99.722	99.726	99.730	99.734	99.738	99.742	99.747	99.751	99.755	99.760
102.1	99.677	99.680	99.683	99.687	99.690	99.694	99.697	99.701	99.705	99.708	99.712	99.716	99.720	99.723	99.727	99.731	99.735	99.740	99.744	99.748	99.752	99.757	99.761
101.0	99.678	99.682	99.685	99.689	99.692	99.695	99.699	99.703	99.706	99.710	99.713	99.717	99.721	99.725	99.729	99.733	99.737	99.741	99.745	99.749	99.754	99.758	99.762
100.0	99.680	99.683	99.687	99.690	99.694	99.697	99.701	99.704	99.708	99.711	99.715	99.719	99.722	99.726	99.730	99.734	99.738	99.742	99.746	99.751	99.755	99.759	99.764
98.9	99.682	99.685	99.688	99.692	99.695	99.699	99.702	99.706	99.709	99.713	99.716	99.720	99.724	99.728	99.732	99.736	99.740	99.744	99.748	99.752	99.756	99.760	99.765
97.9	99.683	99.687	99.690	99.693	99.697	99.700	99.704	99.707	99.711	99.714	99.718	99.722	99.725	99.729	99.733	99.737	99.741	99.745	99.749	99.753	99.757	99.762	99.766
96.8	99.685	99.688	99.692	99.695	99.698	99.702	99.705	99.709	99.712	99.716	99.720	99.723	99.727	99.731	99.734	99.738	99.742	99.746	99.750	99.754	99.759	99.763	99.767
95.8	99.687	99.690	99.693	99.697	99.700	99.703	99.707	99.710	99.714	99.717	99.721	99.725	99.728	99.732	99.736	99.740	99.744	99.748	99.752	99.756	99.760	99.764	99.769
94.7	99.689	99.692	99.695	99.698	99.702	99.705	99.708	99.712	99.715	99.719	99.723	99.726	99.730	99.734	99.737	99.741	99.745	99.749	99.753	99.757	99.761	99.766	99.770
93.7	99.690	99.694	99.697	99.700	99.703	99.707	99.710	99.714	99.717	99.721	99.724	99.728	99.731	99.735	99.739	99.743	99.747	99.750	99.754	99.759	99.763	99.767	99.771
92.6	99.692	99.695	99.698	99.702	99.705	99.708	99.712	99.715	99.719	99.722	99.726	99.729	99.733	99.737	99.740	99.744	99.748	99.752	99.756	99.760	99.764	99.768	99.772
91.6	99.694	99.697	99.700	99.703	99.707	99.710	99.713	99.717	99.720	99.724	99.727	99.731	99.734	99.738	99.742	99.746	99.749	99.753	99.757	99.761	99.765	99.769	99.774
90.5	99.696	99.699	99.702	99.705	99.708	99.712	99.715	99.718	99.722	99.725	99.729	99.732	99.736	99.740	99.743	99.747	99.751	99.755	99.759	99.763	99.767	99.771	99.775
89.5	99.697	99.700	99.704	99.707	99.710	99.713	99.717	99.720	99.723	99.727	99.730	99.734	99.737	99.741	99.745	99.748	99.752	99.756	99.760	99.764	99.768	99.772	99.776
88.4	99.699	99.702	99.705	99.709	99.712	99.715	99.718	99.722	99.725	99.728	99.732	99.735	99.739	99.743	99.746	99.750	99.754	99.758	99.761	99.765	99.769	99.773	99.778
87.4	99.701	99.704	99.707	99.710	99.714	99.717	99.720	99.723	99.727	99.730	99.734	99.737	99.741	99.744	99.748	99.751	99.755	99.759	99.763	99.767	99.771	99.775	99.779
86.3	99.703	99.706	99.709	99.712	99.715	99.718	99.722	99.725	99.728	99.732	99.735	99.739	99.742	99.746	99.749	99.753	99.757	99.760	99.764	99.768	99.772	99.776	99.780
85.3	99.705	99.708	99.711	99.714	99.717	99.720	99.723	99.727	99.730	99.733	99.737	99.740	99.744	99.747	99.751	99.754	99.758	99.762	99.766	99.770	99.774	99.778	99.782
84.2	99.706	99.709	99.712	99.716	99.719	99.722	99.725	99.728	99.732	99.735	99.738	99.742	99.745	99.749	99.752	99.756	99.760	99.763	99.767	99.771	99.775	99.779	99.783
83.2	99.708	99.711	99.714	99.717	99.720	99.724	99.727	99.730	99.733	99.737	99.740	99.743	99.747	99.750	99.754	99.758	99.761	99.765	99.769	99.772	99.776	99.780	99.784
82.1	99.710	99.713	99.716	99.719	99.722	99.725	99.729	99.732	99.735	99.738	99.742	99.745	99.748	99.752	99.755	99.759	99.763	99.766	99.770	99.774	99.778	99.782	99.786
81.1	99.712	99.715	99.718	99.721	99.724	99.727	99.730	99.734	99.737	99.740	99.743	99.747	99.750	99.754	99.757	99.761	99.764	99.768	99.772	99.775	99.779	99.783	99.787
80.0	99.714	99.717	99.720	99.723	99.726	99.729	99.732	99.735	99.738	99.742	99.745	99.748	99.752	99.755	99.759	99.762	99.766	99.769	99.773	99.777	99.781	99.785	99.788
79.0	99.716	99.719	99.722	99.725	99.728	99.731	99.734	99.737	99.740	99.743	99.747	99.750	99.753	99.757	99.760	99.764	99.767	99.771	99.775	99.778	99.782	99.786	99.790
77.9	99.718	99.720	99.723	99.726	99.729	99.733	99.736	99.739	99.742	99.745	99.748	99.752	99.755	99.758	99.762	99.765	99.769	99.772	99.776	99.780	99.784	99.787	99.791

Figure A-1. Peak Loss Performance Indices for the 25 MVA Transformer Designs

Core losses (kW) more efficient --->

Coil losses at 100% load (kW) <---- more efficient	32.0	31.4	30.7	30.1	29.4	28.8	28.1	27.5	26.8	26.2	25.5	24.9	24.2	23.6	22.9	22.3	21.6	21.0	20.3	19.7	19.0	18.4	17.7
258.0	99.712	99.714	99.717	99.720	99.724	99.727	99.730	99.733	99.736	99.739	99.743	99.746	99.749	99.753	99.756	99.759	99.763	99.767	99.770	99.774	99.778	99.782	99.785
255.0	99.713	99.716	99.719	99.722	99.725	99.728	99.731	99.734	99.738	99.741	99.744	99.747	99.751	99.754	99.757	99.761	99.764	99.768	99.772	99.775	99.779	99.783	99.787
252.0	99.715	99.718	99.721	99.724	99.727	99.730	99.733	99.736	99.739	99.742	99.746	99.749	99.752	99.755	99.759	99.762	99.766	99.769	99.773	99.777	99.780	99.784	99.788
249.0	99.717	99.720	99.722	99.725	99.728	99.731	99.734	99.738	99.741	99.744	99.747	99.750	99.754	99.757	99.760	99.764	99.767	99.771	99.774	99.778	99.782	99.785	99.789
246.0	99.718	99.721	99.724	99.727	99.730	99.733	99.736	99.739	99.742	99.745	99.749	99.752	99.755	99.758	99.762	99.765	99.769	99.772	99.776	99.779	99.783	99.787	99.791
243.0	99.720	99.723	99.726	99.729	99.732	99.735	99.738	99.741	99.744	99.747	99.750	99.753	99.757	99.760	99.763	99.767	99.770	99.773	99.777	99.781	99.784	99.788	99.792
240.0	99.722	99.725	99.728	99.730	99.733	99.736	99.739	99.742	99.745	99.749	99.752	99.755	99.758	99.761	99.765	99.768	99.771	99.775	99.778	99.782	99.786	99.789	99.793
237.0	99.724	99.726	99.729	99.732	99.735	99.738	99.741	99.744	99.747	99.750	99.753	99.756	99.760	99.763	99.766	99.769	99.773	99.776	99.780	99.783	99.787	99.791	99.794
234.0	99.725	99.728	99.731	99.734	99.737	99.740	99.743	99.746	99.749	99.752	99.755	99.758	99.761	99.764	99.768	99.771	99.774	99.778	99.781	99.785	99.788	99.792	99.796
231.0	99.727	99.730	99.733	99.736	99.738	99.741	99.744	99.747	99.750	99.753	99.756	99.759	99.763	99.766	99.769	99.772	99.776	99.779	99.783	99.786	99.790	99.793	99.797
228.0	99.729	99.732	99.734	99.737	99.740	99.743	99.746	99.749	99.752	99.755	99.758	99.761	99.764	99.767	99.771	99.774	99.777	99.781	99.784	99.788	99.791	99.795	99.798
225.0	99.731	99.733	99.736	99.739	99.742	99.745	99.748	99.751	99.753	99.756	99.760	99.763	99.766	99.769	99.772	99.775	99.779	99.782	99.785	99.789	99.792	99.796	99.800
222.0	99.732	99.735	99.738	99.741	99.744	99.746	99.749	99.752	99.755	99.758	99.761	99.764	99.767	99.770	99.774	99.777	99.780	99.783	99.787	99.790	99.794	99.797	99.801
219.0	99.734	99.737	99.740	99.742	99.745	99.748	99.751	99.754	99.757	99.760	99.763	99.766	99.769	99.772	99.775	99.778	99.782	99.785	99.788	99.792	99.795	99.799	99.802
216.0	99.736	99.739	99.741	99.744	99.747	99.750	99.753	99.756	99.758	99.761	99.764	99.767	99.770	99.774	99.777	99.780	99.783	99.786	99.790	99.793	99.797	99.800	99.804
213.0	99.738	99.741	99.743	99.746	99.749	99.752	99.754	99.757	99.760	99.763	99.766	99.769	99.772	99.775	99.778	99.781	99.785	99.788	99.791	99.795	99.798	99.802	99.805
210.0	99.740	99.742	99.745	99.748	99.751	99.753	99.756	99.759	99.762	99.765	99.768	99.771	99.774	99.777	99.780	99.783	99.786	99.789	99.793	99.796	99.799	99.803	99.806
207.0	99.742	99.744	99.747	99.750	99.752	99.755	99.758	99.761	99.764	99.766	99.769	99.772	99.775	99.778	99.781	99.785	99.788	99.791	99.794	99.798	99.801	99.804	99.808
204.0	99.744	99.746	99.749	99.751	99.754	99.757	99.760	99.762	99.765	99.768	99.771	99.774	99.777	99.780	99.783	99.786	99.789	99.792	99.796	99.799	99.802	99.806	99.809
201.0	99.745	99.748	99.751	99.753	99.756	99.759	99.761	99.764	99.767	99.770	99.773	99.776	99.779	99.782	99.785	99.788	99.791	99.794	99.797	99.800	99.804	99.807	99.811
198.0	99.747	99.750	99.752	99.755	99.758	99.760	99.763	99.766	99.769	99.772	99.774	99.777	99.780	99.783	99.786	99.789	99.792	99.796	99.799	99.802	99.805	99.809	99.812
195.0	99.749	99.752	99.754	99.757	99.760	99.762	99.765	99.768	99.771	99.773	99.776	99.779	99.782	99.785	99.788	99.791	99.794	99.797	99.800	99.803	99.807	99.810	99.813
192.0	99.751	99.754	99.756	99.759	99.761	99.764	99.767	99.770	99.772	99.775	99.778	99.781	99.784	99.787	99.789	99.793	99.796	99.799	99.802	99.805	99.808	99.812	99.815
189.0	99.753	99.756	99.758	99.761	99.763	99.766	99.769	99.771	99.774	99.777	99.780	99.782	99.785	99.788	99.791	99.794	99.797	99.800	99.803	99.807	99.810	99.813	99.816
186.0	99.755	99.758	99.760	99.763	99.765	99.768	99.770	99.773	99.776	99.779	99.781	99.784	99.787	99.790	99.793	99.796	99.799	99.802	99.805	99.808	99.811	99.815	99.818
183.0	99.757	99.760	99.762	99.765	99.767	99.770	99.772	99.775	99.778	99.780	99.783	99.786	99.789	99.792	99.794	99.797	99.800	99.803	99.807	99.810	99.813	99.816	99.819
180.0	99.759	99.762	99.764	99.767	99.769	99.772	99.774	99.777	99.780	99.782	99.785	99.788	99.790	99.793	99.796	99.799	99.802	99.805	99.808	99.811	99.814	99.818	99.821
177.0	99.761	99.764	99.766	99.768	99.771	99.774	99.776	99.779	99.781	99.784	99.787	99.789	99.792	99.795	99.798	99.801	99.804	99.807	99.810	99.813	99.816	99.819	99.822
174.0	99.763	99.766	99.768	99.770	99.773	99.775	99.778	99.781	99.783	99.786	99.789	99.791	99.794	99.797	99.800	99.802	99.805	99.808	99.811	99.814	99.817	99.821	99.824
171.0	99.765	99.768	99.770	99.772	99.775	99.777	99.780	99.783	99.785	99.788	99.790	99.793	99.796	99.799	99.801	99.804	99.807	99.810	99.813	99.816	99.819	99.822	99.825
168.0	99.767	99.770	99.772	99.774	99.777	99.779	99.782	99.784	99.787	99.790	99.792	99.795	99.798	99.800	99.803	99.806	99.809	99.812	99.815	99.818	99.821	99.824	99.827
165.0	99.769	99.772	99.774	99.776	99.779	99.781	99.784	99.786	99.789	99.791	99.794	99.797	99.799	99.802	99.805	99.808	99.810	99.813	99.816	99.819	99.822	99.825	99.828
162.0	99.771	99.774	99.776	99.779	99.781	99.783	99.786	99.788	99.791	99.793	99.796	99.799	99.801	99.804	99.807	99.809	99.812	99.815	99.818	99.821	99.824	99.827	99.830
159.0	99.774	99.776	99.778	99.781	99.783	99.785	99.788	99.790	99.793	99.795	99.798	99.800	99.803	99.806	99.808	99.811	99.814	99.817	99.820	99.823	99.826	99.829	99.832
156.0	99.776	99.778	99.780	99.783	99.785	99.787	99.790	99.792	99.795	99.797	99.800	99.802	99.805	99.808	99.810	99.813	99.816	99.819	99.821	99.824	99.827	99.830	99.833
153.0	99.778	99.780	99.782	99.785	99.787	99.789	99.792	99.794	99.797	99.799	99.802	99.804	99.807	99.809	99.812	99.815	99.818	99.820	99.823	99.826	99.829	99.832	99.835
150.0	99.780	99.782	99.785	99.787	99.789	99.792	99.794	99.796	99.799	99.801	99.804	99.806	99.809	99.811	99.814	99.817	99.819	99.822	99.825	99.828	99.831	99.833	99.836
147.0	99.782	99.784	99.787	99.789	99.791	99.794	99.796	99.798	99.801	99.803	99.806	99.808	99.811	99.813	99.816	99.818	99.821	99.824	99.827	99.829	99.832	99.835	99.838
144.0	99.785	99.787	99.789	99.791	99.793	99.796	99.798	99.800	99.803	99.805	99.808	99.810	99.813	99.815	99.818	99.820	99.823	99.826	99.828	99.831	99.834	99.837	99.840
141.0	99.787	99.789	99.791	99.793	99.796	99.798	99.800	99.802	99.805	99.807	99.810	99.812	99.815	99.817	99.820	99.822	99.825	99.827	99.830	99.833	99.836	99.839	99.841
138.0	99.789	99.791	99.793	99.796	99.798	99.800	99.802	99.805	99.807	99.809	99.812	99.814	99.817	99.819	99.822	99.824	99.827	99.829	99.832	99.835	99.837	99.840	99.843
135.0	99.791	99.793	99.796	99.798	99.800	99.802	99.804	99.807	99.809	99.811	99.814	99.816	99.819	99.821	99.823	99.826	99.829	99.831	99.834	99.836	99.839	99.842	99.845
132.0	99.794	99.796	99.798	99.800	99.802	99.804	99.807	99.809	99.811	99.813	99.816	99.818	99.821	99.823	99.825	99.828	99.830	99.833	99.836	99.838	99.841	99.844	99.847

Figure A-2. Peak Loss Performance Indices for the 63 MVA Transformer Designs

Core losses (kW) more efficient --->

Coil losses at 100% load (kW) <---- more efficient

	53.0	52.0	51.0	50.0	49.0	48.0	47.0	46.0	45.0	44.0	43.0	42.0	41.0	40.0	39.0	38.0	37.0	36.0	35.0	34.0	33.0	32.0	31.0
355.0	99.726	99.728	99.731	99.734	99.736	99.739	99.742	99.744	99.747	99.750	99.753	99.756	99.759	99.762	99.765	99.768	99.771	99.774	99.777	99.780	99.784	99.787	99.790
351.5	99.727	99.730	99.732	99.735	99.738	99.740	99.743	99.746	99.748	99.751	99.754	99.757	99.760	99.763	99.766	99.769	99.772	99.775	99.778	99.781	99.785	99.788	99.791
348.0	99.728	99.731	99.734	99.736	99.739	99.742	99.744	99.747	99.750	99.753	99.755	99.758	99.761	99.764	99.767	99.770	99.773	99.776	99.779	99.782	99.786	99.789	99.792
344.5	99.730	99.732	99.735	99.738	99.740	99.743	99.746	99.748	99.751	99.754	99.757	99.759	99.762	99.765	99.768	99.771	99.774	99.777	99.780	99.784	99.787	99.790	99.793
341.0	99.731	99.734	99.736	99.739	99.741	99.744	99.747	99.750	99.752	99.755	99.758	99.761	99.764	99.766	99.769	99.772	99.775	99.778	99.782	99.785	99.788	99.791	99.794
337.5	99.733	99.735	99.738	99.740	99.743	99.745	99.748	99.751	99.754	99.756	99.759	99.762	99.765	99.768	99.771	99.774	99.777	99.780	99.783	99.786	99.789	99.792	99.795
334.0	99.734	99.736	99.739	99.742	99.744	99.747	99.749	99.752	99.755	99.758	99.760	99.763	99.766	99.769	99.772	99.775	99.778	99.781	99.784	99.787	99.790	99.793	99.796
330.5	99.735	99.738	99.740	99.743	99.745	99.748	99.751	99.753	99.756	99.759	99.762	99.764	99.767	99.770	99.773	99.776	99.779	99.782	99.785	99.788	99.791	99.794	99.798
327.0	99.737	99.739	99.742	99.744	99.747	99.749	99.752	99.755	99.757	99.760	99.763	99.766	99.768	99.771	99.774	99.777	99.780	99.783	99.786	99.789	99.792	99.795	99.799
323.5	99.738	99.741	99.743	99.746	99.748	99.751	99.753	99.756	99.759	99.761	99.764	99.767	99.770	99.772	99.775	99.778	99.781	99.784	99.787	99.790	99.793	99.797	99.800
320.0	99.740	99.742	99.745	99.747	99.750	99.752	99.755	99.757	99.760	99.763	99.765	99.768	99.771	99.774	99.777	99.779	99.782	99.785	99.788	99.791	99.794	99.798	99.801
316.5	99.741	99.743	99.746	99.748	99.751	99.753	99.756	99.759	99.761	99.764	99.767	99.769	99.772	99.775	99.778	99.781	99.784	99.787	99.790	99.793	99.796	99.799	99.802
313.0	99.742	99.745	99.747	99.750	99.752	99.755	99.757	99.760	99.763	99.765	99.768	99.771	99.773	99.776	99.779	99.782	99.785	99.788	99.791	99.794	99.797	99.800	99.803
309.5	99.744	99.746	99.749	99.751	99.754	99.756	99.759	99.761	99.764	99.767	99.769	99.772	99.775	99.777	99.780	99.783	99.786	99.789	99.792	99.795	99.798	99.801	99.804
306.0	99.745	99.748	99.750	99.753	99.755	99.758	99.760	99.763	99.765	99.768	99.771	99.773	99.776	99.779	99.782	99.784	99.787	99.790	99.793	99.796	99.799	99.802	99.805
302.5	99.747	99.749	99.752	99.754	99.757	99.759	99.762	99.764	99.767	99.769	99.772	99.775	99.777	99.780	99.783	99.786	99.788	99.791	99.794	99.797	99.800	99.803	99.806
299.0	99.748	99.751	99.753	99.755	99.758	99.760	99.763	99.765	99.768	99.771	99.773	99.776	99.779	99.781	99.784	99.787	99.790	99.793	99.795	99.798	99.801	99.804	99.807
295.5	99.750	99.752	99.754	99.757	99.759	99.762	99.764	99.767	99.769	99.772	99.775	99.777	99.780	99.783	99.785	99.788	99.791	99.794	99.797	99.800	99.803	99.806	99.809
292.0	99.751	99.754	99.756	99.758	99.761	99.763	99.766	99.768	99.771	99.773	99.776	99.779	99.781	99.784	99.787	99.789	99.792	99.795	99.798	99.801	99.804	99.807	99.810
288.5	99.753	99.755	99.757	99.760	99.762	99.765	99.767	99.770	99.772	99.775	99.777	99.780	99.782	99.785	99.788	99.791	99.793	99.796	99.799	99.802	99.805	99.808	99.811
285.0	99.754	99.757	99.759	99.761	99.764	99.766	99.769	99.771	99.774	99.776	99.779	99.781	99.784	99.786	99.789	99.792	99.795	99.797	99.800	99.803	99.806	99.809	99.812
281.5	99.756	99.758	99.760	99.763	99.765	99.768	99.770	99.772	99.775	99.777	99.780	99.783	99.785	99.788	99.790	99.793	99.796	99.799	99.801	99.804	99.807	99.810	99.813
278.0	99.757	99.760	99.762	99.764	99.767	99.769	99.771	99.774	99.776	99.779	99.781	99.784	99.786	99.789	99.792	99.794	99.797	99.800	99.803	99.806	99.808	99.811	99.814
274.5	99.759	99.761	99.763	99.766	99.768	99.770	99.773	99.775	99.778	99.780	99.783	99.785	99.788	99.790	99.793	99.796	99.798	99.801	99.804	99.807	99.810	99.813	99.816
271.0	99.760	99.763	99.765	99.767	99.770	99.772	99.774	99.777	99.779	99.782	99.784	99.787	99.789	99.792	99.794	99.797	99.800	99.802	99.805	99.808	99.811	99.814	99.817
267.5	99.762	99.764	99.766	99.769	99.771	99.773	99.776	99.778	99.781	99.783	99.786	99.788	99.791	99.793	99.796	99.798	99.801	99.804	99.806	99.809	99.812	99.815	99.818
264.0	99.763	99.766	99.768	99.770	99.773	99.775	99.777	99.780	99.782	99.784	99.787	99.789	99.792	99.794	99.797	99.800	99.802	99.805	99.808	99.811	99.813	99.816	99.819
260.5	99.765	99.767	99.769	99.772	99.774	99.776	99.779	99.781	99.783	99.786	99.788	99.791	99.793	99.796	99.798	99.801	99.804	99.806	99.809	99.812	99.815	99.817	99.820
257.0	99.767	99.769	99.771	99.773	99.776	99.778	99.780	99.783	99.785	99.787	99.790	99.792	99.795	99.797	99.800	99.802	99.805	99.808	99.810	99.813	99.816	99.819	99.821
253.5	99.768	99.770	99.773	99.775	99.777	99.779	99.782	99.784	99.786	99.789	99.791	99.794	99.796	99.799	99.801	99.804	99.806	99.809	99.812	99.814	99.817	99.820	99.823
250.0	99.770	99.772	99.774	99.776	99.779	99.781	99.783	99.786	99.788	99.790	99.793	99.795	99.798	99.800	99.803	99.805	99.808	99.810	99.813	99.816	99.818	99.821	99.824
246.5	99.771	99.774	99.776	99.778	99.780	99.782	99.785	99.787	99.789	99.792	99.794	99.797	99.799	99.801	99.804	99.806	99.809	99.812	99.814	99.817	99.820	99.822	99.825
243.0	99.773	99.775	99.777	99.780	99.782	99.784	99.786	99.789	99.791	99.793	99.796	99.798	99.800	99.803	99.805	99.808	99.810	99.813	99.816	99.818	99.821	99.824	99.826
239.5	99.775	99.777	99.779	99.781	99.783	99.786	99.788	99.790	99.792	99.795	99.797	99.799	99.802	99.804	99.807	99.809	99.812	99.814	99.817	99.820	99.822	99.825	99.828
236.0	99.776	99.778	99.781	99.783	99.785	99.787	99.789	99.792	99.794	99.796	99.799	99.801	99.803	99.806	99.808	99.811	99.813	99.816	99.818	99.821	99.824	99.826	99.829
232.5	99.778	99.780	99.782	99.784	99.787	99.789	99.791	99.793	99.795	99.798	99.800	99.802	99.805	99.807	99.810	99.812	99.815	99.817	99.820	99.822	99.825	99.827	99.830
229.0	99.780	99.782	99.784	99.786	99.788	99.790	99.793	99.795	99.797	99.799	99.802	99.804	99.806	99.809	99.811	99.813	99.816	99.818	99.821	99.824	99.826	99.829	99.831
225.5	99.781	99.783	99.786	99.788	99.790	99.792	99.794	99.796	99.799	99.801	99.803	99.805	99.808	99.810	99.812	99.815	99.817	99.820	99.822	99.825	99.827	99.830	99.833
222.0	99.783	99.785	99.787	99.789	99.791	99.794	99.796	99.798	99.800	99.802	99.805	99.807	99.809	99.812	99.814	99.816	99.819	99.821	99.824	99.826	99.829	99.831	99.834
218.5	99.785	99.787	99.789	99.791	99.793	99.795	99.797	99.799	99.802	99.804	99.806	99.808	99.811	99.813	99.815	99.818	99.820	99.823	99.825	99.828	99.830	99.833	99.835
215.0	99.787	99.789	99.791	99.793	99.795	99.797	99.799	99.801	99.803	99.805	99.808	99.810	99.812	99.815	99.817	99.819	99.822	99.824	99.827	99.829	99.832	99.834	99.837
211.5	99.788	99.790	99.792	99.794	99.796	99.798	99.801	99.803	99.805	99.807	99.809	99.812	99.814	99.816	99.818	99.821	99.823	99.825	99.828	99.830	99.833	99.835	99.838
208.0	99.790	99.792	99.794	99.796	99.798	99.800	99.802	99.804	99.807	99.809	99.811	99.813	99.815	99.818	99.820	99.822	99.825	99.827	99.829	99.832	99.834	99.837	99.839

Figure A-3. Peak Loss Performance Indices for the 100 MVA Transformer Designs