Energy Efficient Transformers and Reactors
Some incentive models and case studies to show the long term profitability of such designs

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SUMMARY
During the coming decades energy efficiency will be a critical factor in reducing carbon emissions and fighting global warming. The power generation industry and transmission and distribution industries (T&D) contribute to a large part of energy losses in the society. The losses in T&D systems alone are total 10 % of a global average of the T&D energy transferred. One-third of these T&D losses have their origin in transformers and shunt reactors.

This report emphasizes the need to bring in appropriate financial incentives and directives to utilities, in order to encourage investment in energy efficient electrical power systems. A critical financial parameter is the internal interest rate. In some countries there are directives from the authorities that internal interest rates shall be 5 %. If this is to be applied together with the current prevailing electricity prices in Europe, capitalized cost of total transformer losses should increase by 2-3 times of the average value used in the European market today.

It is shown that the capitalized cost of losses may vary from 8,000 to 17,000 €/kW today or even higher in the future.

This paper highlights cases where low and high capitalized costs of losses are used and the implications for cost related factors of transformer and shunt reactor are analyzed. It is shown that the transformer losses and total ownership cost (TOC) can be substantially reduced with an increase in price (first cost) of the transformers or shunt reactors. With increased value of losses, accuracy of loss measurement will play a much more important business role and require action to improve International Standards.

New energy efficient solutions to combat network losses will require further research and development. Different focus and strategies regarding interest rates and electricity prices in transmission companies lead to very different investment decisions. Without clear regulations promoting reductions in power loss, there might not be enough incentive for more aggressive innovation in the field of transformer and electrical system technology and efficiency.

KEYWORDS
Energy-efficient, low-loss transformers and reactors, total ownership cost, loss evaluations, T&D investment incentive model, loss measurement accuracy, T&D market regulation.

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1. Introduction

Over the past decades, communities all over the world have made concerted efforts to reduce the risk of global warming. However, there are many mega trends which will increase carbon emissions, such as rapid industrialization in developing countries and urbanization, taking place all over the world. Unfortunately, there is no single unique solution to the problem. Thousands of sensible actions are required. Among the more important global actions are investments in efficient use of energy, in the energy efficiency of electric power infrastructures and in renewable resources. The International Energy Agency (IEA), describes a scenario and actions in this endeavor to stabilize CO\textsubscript{2} levels to 450 ppm by 2050 [1], (see Figure 1).

![Figure 1. World energy-related CO\textsubscript{2} savings potential by policy measure under “450 Policy” scenario relative to current scenario. Source: IEA, World Energy Outlook 2010.](image)

Energy is lost in all three stages of the electric power system viz. generation, transmission & distribution and utilization. However, energy efficiency action is mostly focused around the utilization of energy by the end consumers. If total loss in the power station from auxiliary equipment and losses in T&D network are considered, the transmission industry is the single largest consumer of electricity. A study conducted in 2003 [2] shows that the extent of T&D loss varies all over the world with a global average of 10% of the generated power in electric power network (see Figure 2).

![Figure 2. T&D losses as percentage of total electricity production, 2000. Source: IEA 2003 [2]](image)

Contributing to one-third of total T&D losses, transformers and shunt reactors are the most expensive components in the power system and hence this report mostly concentrates on the efficient design of these power devices. One of the reasons behind the decisions not to focus more on reducing losses in T&D is the weakness in incentives and also the fact that the costs of losses are paid by the end customers through tariff structures. In the two following
paragraphs two financial and technical parameters central to the purchase decisions of these products are further explained.

Firstly, it is important to understand how much, in a given situation, a utility would like to pay for every kW of saved loss, known as “loss evaluation”. Accumulated present values of the cost of losses during the long service life of T&D devices are calculated based on the given internal interest rate, inflation rate, expected service time and electricity prices. A brief treatment on loss evaluation is provided in section 4.

Secondly, there should be a rational approach to evaluate different technologies to balance losses in T&D devices and investments. The total life cycle cost (LCC) is a tool that can be used in this context. The LCC includes the cost of raw materials, production cost, operational cost due to losses and also the cost of recycling all the components in the product while giving consideration to consequential impact on the environment. Often, calculation of LCC for all possible options of designs is difficult and impractical. However, components of these devices are made of recyclable materials (low environmental impact). Given that loss in these devices has the largest consequence to the environment, cost of losses and price are the most important components contributing to LCC. For the sake of convenience, a reduced LCC model called total ownership cost (TOC) will be used throughout this paper. This simple TOC is defined as the sum total of capitalized cost of losses and the selling price of the device. It will be shown that a large benefit in terms of TOC can be achieved with incremental increases in price, when the loss evaluations are getting more accurate at higher values. These aspects will be demonstrated with actual transformer and shunt reactors delivered by ABB to a Danish customer.

The use of loss evaluation is an industry practice in most power transformer procurement processes. On the other hand, in the distribution transformer business the concept of fixed losses is more commonly used. International standards prescribe possible magnitude of losses for each kVA rating. In order to achieve the full potential of energy efficiency in the T&D network, it is recommended to propose a range of losses for a given kVA rating in upcoming revisions of the standards based on updated higher loss evaluations as shown in this report. This is expected to further decrease TOC for distribution transformers.

For the sake of convenience, the paper is organized into different sections. Section 2 describes economic perspectives on power losses and trends in the electricity price. The economic investment strategy in T&D infrastructure is presented in section 3. Simple formulations of loss evaluations are provided in section 4. Detailed case studies of energy efficient transformer and shunt reactors are made in section 5. The need for innovation in transformer and reactor technology to create energy efficient solutions is outlined in section 6. The importance of loss measurement in transformer and reactor during the factory acceptance test is explained in 7. Finally, section 8 deals with the authors’ conclusions and recommendation.

2. Trends in network losses and electricity prices

The magnitude of network losses in the future will be influenced by social, regulatory and technical factors. The power utilities have gone from a situation focusing on long-term capacity planning aimed at avoiding power shortages, to a deregulated situation in which the market was seen as a driver for matching supply with demand. The deregulation of the electricity market has resulted in a trend to focus on the asset management of the power system with a much shorter time horizon. Many utilities are under competitive pressure to
make money by financially optimizing their assets. Therefore they need to prove their business case, in relation to the corporate demands of return-on-capital investment. For network companies, more often than not, this must be balanced by National regulators who address the profitability of utilities and, more importantly, try to protect the interest of consumers and industrial customers from ‘unfair’ tariffs in a monopolistic situation.

Power losses in the network may well have a tendency to increase in the future due to changes in the pattern of power flow in the modern grid. In the recent years, power flow from supply to demand has started to change to rather complex networks where the energy production can be remote as well as distributed. Renewable energy production such as wind parks and solar panels are variable sources of power in the production. Due to these developments, certain sections of the network will be heavily loaded, leading to higher network losses [3], [4].

In the last 10 years the prices for important materials in the power industry, e.g., copper and electrical steel have increased by factors of 4 and 2.5, respectively. At the same time, the loss evaluation seems to have remained the same for the last 20 years, when the electricity prices were 2-3 times lower than today. These shifts in relations are assumed to have led to optimized power equipment with lower energy efficiency than used to be the case, a few decades earlier. This is further impaired due to global competition where equipment is designed at the critical limits, where losses are generally high. It is also worth mentioning that these trends might lead to unforeseen consequences in terms of sacrificing the reliability of the equipment and the system as a whole.

Electrical energy prices vary from country to country and depend on several primary factors, such as the international prices of fossil fuels and different mixtures of energy sources that would give a stable price path in the long term. However, prices will deviate, widely at times, from these predicted trends in response to short-term fluctuations in demand and supply, taxes and geopolitical events [5]. Market surveys in many countries shows that the spot price of electric energy has tended to increase over the last 10 years [6].

It is difficult to predict the future price of electricity, but price forecasts under many scenario predictions show examples of 2-3% annual increases in crude oil price [5]. Furthermore markets where generation involves substantial amounts of fossil fuels might see an average annual 2 % hike in spot prices if CO₂ control is exercised fully [7]. US energy administration information predicts an annual increase in electricity price of about 1.6% until 2035 in nominal dollars [8]. These forecasts are of course sensitive to the actual inflation.

3. Regulation and investment in T&D industry

The way in which regulatory bodies regulate grid markets has a marked impact on companies’ mode of operation. In the current regulations, investments made to reduce energy losses in the system are not treated explicitly and the development of electricity prices in the long-term is completely neglected. Instead, the calculation of costs related to energy losses is solved by reimbursing energy losses at spot market prices. When a grid has lower power losses the resulting allowed tariff is proportionally reduced, and vice versa. This means that losses are always reimbursed and incentives for investment in energy savings systems are de-facto non-existent.

Furthermore, to use net present value (NPV) models for very long-term investments might misguide grid companies in the absence of clear strategies and ambitions to increase power
efficiency. NPV calculations can be regarded as comparison models between alternatives, but normally for a more limited time frame (e.g. 10 years):

- For infrastructure investments over a long time horizon NPV calculations are burdened by large uncertainties about future cash flows (inflation, price and technical development).
- Discounting from a distant future with a high internal interest rate results in a very low net present value.

In order to ensure more investment in energy efficiency, an individual company will need to use a comparatively low interest rate of 5% or lower to promote more investments that are beneficial in the long-term. Some countries where the cost of capital is bigger may use a bit higher interest rate. Therefore, if governments and their regulatory bodies want to achieve power efficiency in the grid infrastructure, their incentive models need to promote this. One way to achieve this is by reallocating resources from old grid-systems with high power losses. Another scenario is that CO₂ taxes will be further increased in the future, which consequently, will lead to high network loss cost for the grid companies.

4. Formulae for calculation of loss evaluations

Only a very brief review of the calculation of loss evaluation is presented in this paper. Detailed treatment of the subject is available elsewhere in the literature [9], [10]. Investment in network infrastructure involves installation of additional or replacement equipment having a time span of 40 to 50 years. Before going to the details of how economic value of loss are calculated, it is important to note that in power transformers there are different components of losses, i.e., no-load losses (NLL) and load losses (LL).

- No-load losses in transformers as generated in magnetic cores are relatively constant, independent of load and take place whenever the transformer is energized.
- Load losses occur in windings and structural parts and depend on the load on the transformer and vary with the square of the load current and also a function of temperature.

The total ownership cost (TOC) of a power transformer can conveniently be expressed as

\[
TOC = \text{Price} + \text{NLLE} \times \text{NLL} + \text{LLE} \times \text{LL} \tag{1}
\]

where NLLE (no-load loss evaluation) is the capitalized present value of 1 kW of loss considering transformer operation throughout its service life and is a function of price of electricity, interest rate and inflation rate [10]. Similarly LLE (load loss evaluation) is the capitalized value of load loss that depends on all above parameters and additionally has a strong relationship with the average loading of the transformer, called load factor. Accurate calculation of the annual cost of losses should be calculated by considering the actual price of electricity and interest rate for each individual year. The sum of present values of all the yearly costs gives the loss evaluations. However it requires information about future electricity price and also internal interest rates. It is possible to calculate the NLLE, with an acceptable degree of accuracy, as in (2), assuming a constant energy price and internal interest rate.

\[
\text{NLLE} = 8760 \times E_{\text{cost}} \times PV \tag{2}
\]

In a realistic situation \(E_{\text{cost}}\) can be taken as the arithmetic average price of electricity in €/kWh in the life time of the equipment or even present price of electricity. The term, PV is the present value of the sum total of cost of electricity in different years from the losses, giving
appropriate treatment to real interest rate. Let us consider the price of electricity, $E_{\text{cost}}$, as 0.05 €/kWh and 0.06 €/kWh, as prevailing today in some countries in EU. Three different internal interest rates can also be considered e.g. 3%, 4% and 5%, they shall be understood as real internal interest rates, after giving adjustment for the inflation. Furthermore, four different scenarios of rate of increase in electricity prices are taken 0.5%, 1%, 1.5% and 2%. The number of years of investment is taken as 40 years, the expected transformer life time. Assuming that the transformer is 100% in service, NLLE values are calculated for twelve different scenarios and are presented in Table 1, using the NPV function in MS Excel. Results show that reasonable NLLEs of distribution and power transformers today (2012) is in the range of 8,000 to 17,000 €/kW.

Table 1. Possible no-load loss evaluation (NLLE) €/kW, to be used for distribution and power transformer

<table>
<thead>
<tr>
<th>Electricity price</th>
<th>Interest rate (%)</th>
<th>Rate of increase in electricity price (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 €/kWh</td>
<td>3</td>
<td>10,963</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9,332</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8,045</td>
</tr>
<tr>
<td>0.06 €/kWh</td>
<td>3</td>
<td>13,156</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11,199</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9,655</td>
</tr>
</tbody>
</table>

In order to provide an impression of the loss evaluation values used today in different countries within Europe, a snapshot of NLLE in several recent tenders is shown in Figure 3. This reflects that there are large variation of views and opinions on capitalized cost of losses in different market. Notable, utilities in some countries have already increased the value of loss evaluation considering above investment strategy.

Figure 3. The no-load loss evaluation (€/kW) specified in tenders from an EU power transformer plant during 2011. The values shown in this figures are “snap-shots” of several design specifications submitted to ABB.

A particular case of a grid company N1 A/S in the Jutland region of Denmark can be reviewed here. The network is operated in close co-operation with the other regional companies and Energinet.dk (the Danish TSO, Transmission System Operator). N1 have a mission to be efficient, robust and reliable in order to serve their customers and the society. N1’s philosophy of calculation of cost of losses is therefore motivated by TOC, not price. The

2 An average price of electricity is considered irrespective of location in the grid.
3 Similarly, load loss evaluation can be calculated assuming a load profile and annual rate of increase in loading. Calculation of loss evaluation of a shunt reactor is similar to NLLE in power transformer, except that in case of shunt reactor no-load and load loss considered of the same values.
assumptions taken in N1’s calculation are that energy efficient T&D equipment has high operational security, high reliability, low maintenance cost, low environmental and high retirement value. Hence a lower interest of about 3% is considered profitable, although the Danish authority allows interest rates up to 5%. The electricity prices used by N1 is about 0.056 €/kWh over a ten year period. Considering a service life between 40 and 50 years, the NLLE becomes 15000-18000 €/kW and fit well with the calculated results shown in Table 1.

5. Technical analysis - typical vs. energy efficient power transformer and reactor designs

Transformer and reactor designs are optimized to obtain minimum TOC by finding a trade-off between the amount of materials used and the operational losses. In principle, losses can be reduced to quite low values by using more materials in the active part resulting in a higher purchase price of the transformer and shunt reactor. This simple argument is valid in a situation where the cost of labor, overhead, transportation, commission and margins are all proportional to masses. However in engineering practice, most of these costs are fairly constant or at least a step function of the weight of active parts. Albeit the price of a low loss transformer will be higher, it can be argued that it is always beneficial from an investment perspective. Another important factor is that the huge amount of copper and iron used in low loss equipment has substantial appreciation in the future.

5.1 Power transformer

It is well known that energy efficient transformers can be designed when it is required by high loss evaluations. In the following, two different designs are made to demonstrate the impact of loss evaluation on the price, total ownership cost (TOC), weights and dimensions of transformer.

• Typical transformer design (TTD): Optimized with loss evaluation, as it is often used today, i.e. 4200 and 2000 €/kW for no load loss and load loss capitalization, respectively. This is taken as a reference in all the discussion throughout the paper.

• Energy efficient transformer design (EET): The original order by N1, Denmark, optimized with high loss evaluation, 18700 €/kW for no-load loss and 8000 €/kW for load loss.

It can be seen from Figure 4a that the TOC of EET is 10% less than the TOC of the typical transformer design, if evaluated at NLLE value of 18700 €/kW and LLE as 8000 €/kW. The cost of losses is reduced by 29% in the N1 transformer compared to a typical design of today. However, these reductions will be much more valuable, if the carbon tax is more severe in the future. As expected, due to use of a large amount of engineering materials, EET is 26% more expensive than the typical design (TTD).

5.2 Shunt reactors

The impact of cost of losses in shunt reactors can be demonstrated in a similar manner to that in transformers. In case of shunt reactors both no-load loss and load loss values are treated as equally important and one loss evaluation value are used.

• Typical shunt reactor design (TSD): Optimized with lower loss evaluation, as often used today, 2157 €/kW.

• Energy efficient shunt reactor (EES): Optimized with high loss evaluation 17260 €/kW, exactly the same reactor delivered to N1, Denmark.
The most important distinctions between the above two designs are that the TOC of the EES is 23% better than the TSD, if calculated at loss evaluation of 17260 €/kW (see Figure 4b). The price of EES design was 35% higher and cost of losses was reduced 45% compared to TSD.

Figure 4. (a) Comparison of price, cost of losses and TOC of transformers optimized with different loss evaluations. The TOC and cost losses are calculated at NLLE value of 18700 €/kW and LLE as 8000 €/kW. (b) Comparison of price, cost of losses and TOC of shunt reactors evaluated at loss evaluation of 17260€/kW.

As expected, energy efficient transformers and reactors delivered to N1 are heavier than typical designs commonly made today. The EET was 14% heavier than the TTD and the EES has 73% larger masses than the TSD. The energy efficient designs, EET and EES, have lower flux density and hence very low noise (about 12dB less) and about 20% lower current density compared to typical designs. Another advantage with energy efficient designs is that they use less cooling equipment and can often be managed by natural cooling. The reliability of energy efficient designs can be improved due to lower current and flux densities.

6. Technology and material development for future

One of the crucial observations made in the design calculations of orders from N1 was the relative importance of price and cost of losses to the TOC. It is seen from Figure 5a, at low loss evaluation the cost of losses contributes 30% to the ownership cost of transformer, whereas at high loss evaluation (i.e. EET) the cost of losses is 50% of the TOC. Similarly, the cost of losses for TSD is about 25% of TOC, whereas for EES the cost of losses is 52% of TOC (see Figure 5b). From power transformer R&D point of view this can be described as ‘paradigm shifts’.

Figure 5. Relative contribution of price and cost of losses to the TOC of transformer (a) and shunt reactor (b) optimized with different loss evaluations.
With present state of art technology for transformer and reactors there are several opportunities to reduce losses. The most important of them are listed in the following:

- Addition of materials, i.e., the conventional approach by using increasing amounts of core steel and conductor materials
- Materials improvements such as highly anisotropic and/or domain refined steel and/or thinner steel sheets. Amorphous core materials in distribution transformers are considered to be more energy efficient [11]. Thin multi strand continuously transposed conductors (CTC) can be highly beneficial to reduce eddy loss.
- Advanced control of core flux by adjusting core joints, anisotropy of the core material as well as core dimensions has great potential to reduce the core loss
- Leakage flux control methods to reduce losses in windings, structural materials and tank are crucial
- Improved cooling methods are a possibility

The above loss control methods are not adequate measures for facing the challenge of a situation with a loss evaluations value four/five times higher than used today. More aggressive R&D will be needed to reduce the losses in transformers and reactors further.

7. Measurement of losses - accuracy and uncertainty analysis

It has been shown section 6 that at high values of loss evaluation, the total cost of losses is larger than the price of the product. Consequently, accuracy in loss measurement is very important in the future procurement process. To explain the impact of loss measurement accuracy, two simple examples can be considered. A case where, the transformers optimized with low loss evaluation and the price is 75% of TOC and cost of losses is other 25%. Another case where the transformer is optimized with high loss evaluations, the price is 25% of TOC and cost of losses is 75% of TOC. If the accuracy of measurement of losses is in the order of ±3%, as allowed by standards [12], [13] then the accuracy of TOC is only ±0.75% for case 1. However, if the same uncertainty is considered for the case 2, TOC has rather unfavorable accuracy of ±2.25 %.

The most advanced technologies available for measurement of losses are integrated voltmeter-ammeter methods and bridge methods. Although in principle the bridge method can be more accurate compared to voltmeter-ammeter method, the accuracy is strongly influenced by calibration schemes and power factor of the load. Often manufacturers use single component calibration methods and consequently have lower accuracy. The system can be improved by system level calibration. To promote a transparent business process, the transformer test laboratory should be certified by an internationally accredited standards organization, which is not common today. Customers in the procurement process should also consider asking for an uncertainty analysis report of loss measurements. Another way to deal with the situation is to form working groups in CIGRE, or in IEEE and IEC to address the problem and to propose revised industry Standards.

8. Conclusions and recommendations

Concerns for climate change will be greater than ever due to increasing global CO2 emissions. However, the investigation shows that there is a major potential for energy savings in the T&D industry. Investing in energy efficiency pays off and is indeed a strong driver for innovation in Transformer technology as well as in other electrical system related
technologies. If utilities use a correct loss evaluation and specify accordingly, the losses in the T&D equipment can be substantially lowered. It will be even more important in the future since the cost of energy is likely to increase. The following recommendations are made to motivate different parties involved in the T&D business to contribute towards energy efficiency:

- Regulatory authorities have the responsibility to provide the appropriate energy efficient directives for the T&D industry.
- One crucial parameter is the choice of internal interest rate. Internal interest rate of 5% or lower seems to be the optimal rate for this type of industry with long term perspectives and the limited size of risk involved.
- Utilities need to revise the correct value of each saved kilowatt of loss. This report gives reasons that capitalized costs of losses may be in the range of 8,000 - 17,000 €/kW today and may be higher in the future.
- Using fixed value of losses in making purchase decision for distribution transformers requires that correct loss evaluation to be included in international standards.
- It is shown that a 10% - 20% reduction in TOC can be achieved already now and most likely more in the future. Therefore the TOC should be the procurement factor to evaluate the tenders.
- Accurate test methods and instrumentation need to be reviewed by international standards organizations.

The T&D business must consider large-scale energy efficiency in its own backyard due to following reasons:

- Prevailing uncertainties surrounding the availability of conventional and relatively inexpensive energy supplies
- A slowing rate of energy supply and therefore economic productivity
- A variety of pending climate bills might create unforeseen economic impacts

REFERENCES