How Amorphous Transformers Enhance Efficiency and Reduce CO_2 Emissions Levels

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Executive summary

Annual transformer losses in the European Union amounted to 93 TWh in 2008, representing €5 billion in annual waste. New regulations are mandating that consumers of transformer equipment install units with higher energy efficiency. Amorphous technology transformers are now available that cut efficiency losses by half. This paper reviews purchasing cost, efficiency loss, and CO_2 emissions considerations when evaluating suitable distribution transformers.

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Introduction

While CO_2 emissions emerge as a rapidly growing global concern, electrical efficiency is becoming a more important performance factor in the specification and selection of distribution transformers.

Two issues are now conspiring to move efficiency to the forefront in transformer evaluation: (1) a focus on total cost of ownership (TCO) over the lifetime of the system, and (2) public and private environmental initiatives, as exemplified by European Union's enforcement of its Ecodesign Directive.

On the TCO side, three subtle but significant factors can affect an organization's cost of operating a distribution transformer: purchasing cost, efficiency loss, and CO_2 emissions. Those who specify these systems need to recognize these three factors. If not, an owner will experience increased costs because operational efficiencies are not correctly considered.

On the government regulation side, as a result of recently announced government mandates, owners / users of transformers need to fulfill ecodesign requirements as of the 1st of July 2015. Specifically they need to place into service more efficient power transformers to support their electricity transmission and distribution networks and their industrial applications.

Total European Union (EU27) transformer loss in 2008 amounted to 93 terawatt hours (TWh). That figure represents an annual energy waste of 5 billion Euros. These types of figures can no longer be ignored.

Fortunately, today it is possible to install low loss transformers in distribution networks and within industrial applications. New generations of amorphous transformers with significant improvements in efficiency increase the options available for consumers of distribution transformer technologies. Amorphous technology makes it possible to halve efficiency losses. In addition to reducing CO_2 emissions, these new technologies reduce operational costs.

This paper reviews how to select the proper transformers for electrical utility distribution networks, photovoltaic and wind applications, and industrial applications for rated power not exceeding 3150 kVA and highest voltage not exceeding 36 kV. The selection procedure takes into account purchasing cost, losses, the cost of CO_2 emissions, and the amorphous technology. Ramifications of the European Union's Ecodesign Directive are also discussed.

Amorphous transformer efficiency benefit

Issue: Inefficient transformer installed base

The benefit resulting from more efficient transformer designs has been estimated to be about 16 TWh per year by 2025.[1] This corresponds to 8 $MtCO_2$ /year emissions. The installed base of European distribution and power transformers is estimated to be around 5 million units. Distribution transformers have the second highest potential for energy efficiency improvement.

Strategy: Reduction of costs and losses via technology upgrades

When comparing both transformers and overhead lines and cables, transformers are easier and less costly to replace. Modern transformer technology will significantly reduce existing transformer losses.

[1] COMMISSION REGULATION (EU) No 548/2014 of 21 May 2014 on implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers.

Within the realm of transformers, two types of losses exist: iron and copper losses. Iron losses are independent of the load and are referred to as “no load losses” or “fixed losses”. Copper losses are dependent of the load and are referred to as “load losses”. “No load” or “fixed” losses are present as soon as the transformer is energized. “Load losses” vary according to the load on the transformer.

Table 1 compares conventional transformers to new generation transformers (which are equipped with amorphous technology). The data concludes that loss reduction can be realized through upgrades to the newer technology. For example, new conventional Grain-Oriented Electrical Steel (GOES) transformers (which are listed in the second row of **Table 1**) have 30% less “no load loss” compared to conventional GOES transformers. A 37% loss reduction can be achieved with the future GOES technology, and a 64% loss reduction can be achieved with amorphous technology.

The amorphous technology is a breakthrough technology that divides efficiency losses by two compared to the new conventional GOES technology.

Table 1
Loss comparison of conventional, new conventional, new future GOES, and amorphous transformers

Rated power	Technology	No load losses level	Load losses level	No load losses reduction
400kVA/Oil immersed	Conventional GOES	C_0: 610 W	Ck: 4600 W	0%
400kVA/Oil immersed	New conventional GOES	A_0: 430 W	Ck: 4600 W	29.5%
400kVA/Oil immersed	New future GOES	AA_0: 387 W	Ck: 4600 W	36.6%
400kVA/Oil immersed	Amorphous	AAA_0: 220 W	Ck: 4600 W	63.9%

EU Ecodesign Directive

As a result of the Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009[2], owners / users of transformers need to fulfill ecodesign requirements as of the 1st of July 2015. In addition, in regard to small, medium and large power transformers, a Commission Regulation (EU) No 548/2014 of 21 May 2014 has been issued.[3]

Specifically, this means owners / users of transformers need to begin putting into service higher efficiency power transformers for use in electricity transmission and distribution networks and / or for industrial applications. This applies to transformers with minimum power rating of 1 kVA used in 50 Hz environments. The regulation is only applicable to transformers purchased after the entry into force of the regulation.

Note that according to regulation 2014/548/EU loss rates must be harmonized with ecodesign requirements and new transformers installed from July 1, 2015 onward must satisfy higher efficiency requirements. Category C_0 (610 W) is no longer allowed for new transformers from 1st of July 2015 on. A transition phase has been defined between 2015 and 2021. In 2021, a second step consisting of requirements for even higher energy efficiencies will be enforced.

Consider the example of a 400 kVA, 20/0.4 kV transformers. If we refer to **Table 2**, we see that the no load losses category A_0 (430 W) applies from 1 July 2015 on Tier 1. From 1 July

[2] DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products

[3] Op. cit., COMMISSION REGULATION (EU) No 548/2014 of 21 May 2014.

2021 and onwards it applies to a Tier 2 category with 10% higher efficiency [A_0 (387 W)] (see **Table 2**, the circled areas).

Table 2

Extract from the COMMISSION REGULATION (EU) No 548/2014 [1] shows maximum load and no-load losses (in W) for three-phase liquid-immersed medium power transformers with one winding with Um ≤ 24 kV and the other one with Um ≤ 1,1 kV

	Tier 1 (from 1 July 2015)		Tier 2 (from 1 July 2021)	
Rated Power (kVA)	Maximum load losses P_k (W) (*)	Maximum no-load losses P_o (W) (*)	Maximum load losses P_k (W) (*)	Maximum no-load losses P_o (W) (*)
≤ 25	C_k (900)	A_o (70)	A_k (600)	A_o − 10 % (63)
50	C_k (1 100)	A_o (90)	A_k (750)	A_o − 10 % (81)
100	C_k (1 750)	A_o (145)	A_k (1 250)	A_o − 10 % (130)
160	C_k (2 350)	A_o (210)	A_k (1 750)	A_o − 10 % (189)
250	C_k (3 250)	A_o (300)	A_k (2 350)	A_o − 10 % (270)
315	C_k (3 900)	A_o (360)	A_k (2 800)	A_o − 10 % (324)
400	C_k (4 600)	A_o (430)	A_k (3 250)	A_o − 10 % (387)
500	C_k (5 500)	A_o (510)	A_k (3 900)	A_o − 10 % (459)
630	C_k (6 500)	A_o (600)	A_k (4 600)	A_o − 10 % (540)
800	C_k (8 400)	A_o (650)	A_k (6 000)	A_o − 10 % (585)
1 000	C_k (10 500)	A_o (770)	A_k (7 600)	A_o − 10 % (693)
1 250	B_k (11 000)	A_o (950)	A_k (9 500)	A_o − 10 % (855)
1 600	B_k (14 000)	A_o (1 200)	A_k (12 000)	A_o − 10 % (1080)
2 000	B_k (18 000)	A_o (1 450)	A_k (15 000)	A_o − 10 % (1 305)
2 500	B_k (22 000)	A_o (1 750)	A_k (18 500)	A_o − 10 % (1 575)
3 150	B_k (27 500)	A_o (2 200)	A_k (23 000)	A_o − 10 % (1 980)

(*) Maximum losses for kVA ratings that fall in between the ratings given in Table I.1 shall be obtained by linear interpolation.

Efficiency as a selection criteria

When electrical utility transmission and distribution sector stakeholders procure transformers they specify maximum dimensions and weight. The transformers are designed accordingly. When engaged in such a procedure, it may happen that losses are not factored in with respect to energy efficiency. If the evaluation criterion is energy efficiency, as required by the new regulation, the weight and the dimensions of the transformer for the same application at the same rating may sometimes increase slightly. A physical size comparison example of a high efficiency transformer versus a conventional transformer is provided in **Table 3**.

Table 3
Conventional vs. amorphous transformer physical size comparison

Rated power	Technology	No load losses level	Load losses level	Weight (kg)	Dimensions (mm)
400kVA/Oil immersed	Conventional GOES	610W	4600W	1400	1310 (W) 890 (D) 1400 (H)
400kVA/Oil immersed	Amorphous	220W	4600W	2000	1480 (W) 950 (D) 1425 (H)

Amorphous technology availability

This technology was developed in 1970's[4] and amorphous transformers were beginning to be used in the 1980's. They became popular in the mid 2000's because of the rise of energy conservation and because of CO_2 emissions concerns. They have been deployed in many countries including Japan (410,000 units installed), USA (420,000 units installed), China (385,000 units installed) and India (800,000 units installed).

Several amorphous transformers have been installed in France for over 5 years, and in Germany and Belgium for over 3 years with positive results.

The effects of short circuit currents greatly impact transformer performance, the stability of the network, and the environment. Transformers which do not withstand a short circuit can explode. Therefore, since short circuits occur quite often, short circuit withstand capability is recognized as a key characteristic for transformers installed in a European distribution network.

Short circuit tests performed on amorphous core transformers show that cores and coils can be totally destroyed, or that they significantly affect the no load losses due to the partial damage to the core. This is because of the fragility of the amorphous material. It is more critical for amorphous core transformers to withstand the short circuit dynamic effects, and the withstand capability must be proven through short circuit testing.

Therefore, from a transformer reliability perspective, the equipment must pass a short circuit test. Unfortunately, only very few manufacturers have successfully carried out these types of specialized tests worldwide.

Cost calculations

In order to assess the efficiency of a transformer it is suitable to capitalize the losses. The financial value of losses generated during the lifetime represents an important part of the investment. Transformers run 24 hours a day, therefore their energy efficiency can be impacted by reductions in both “no load losses” and “load losses”.

For utilities, it may be more advantageous to reduce iron losses than copper losses, since the transformers are energized 8,760 hours a year. These transformers typically do not supply load during this entire period and when they do supply load, it is never at the maximum load capacity.

On the other hand, for industrial applications, it may be advantageous to reduce the “load losses”, as these transformers are operated mainly at high load factor.

The following sub-sections provide guidance for selecting the most suitable distribution transformer regarding purchasing cost, losses, and cost of CO_2 emissions for different applications.

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[4] http://www.unido.or.jp/en/technology_db/414/

Electric utilities

Utilities in the European Union add the value of losses generated during the lifetime of the equipment to the purchasing cost. The financial value of losses is calculated by multiplying the amount of losses in watts (W) declared by the manufacturer, by the value indicated by the purchaser (expressed in €/W). The calculation in **Table 4** shows that the total investment cost of an amorphous transformer is lower than that of the conventional transformer, despite the fact that the purchasing cost for the amorphous transformer is higher.

Table 4
Conventional vs. amorphous transformer cost comparison

Rated power (kVA)	No load losses level & value (W)	Load losses level & value (W)	Purchasing cost (€)	No load losses cost (€/W)	Load losses cost [€/W)	Total investment [€]
400kVA/Oil immersed GOES	430W	4600W	8810	8	1	16850
400kVA/Oil immersed Amorphous	200W	4600W	10240	8	1	16440

Industrial consumers

Within the industry sector, the financial value of losses is calculated from the cost of the annual energy losses. The annual energy losses of a transformer can be estimated from the following formula:

W [kWh]=(P0 + Pk * L ^{2}) * 8760 [h]
P0= no-load loss in kW.
PK= load loss in kW.
L= average per-unit load of the transformer.

This formula is valid for industrial consumers' applications, as well as for photovoltaic / wind applications and for the replacement of old transformers. The only variables are L (average per unit load of the transformer) and the energy cost. **Table 5** illustrates the cost comparison.

Table 5
Cost comparison for industrial sector stakeholders

Rated power (kVA)	P0 [kW]	Pk [kW]	L	Energy cost [€/kWh]	Cost of energy per year[€]	Purchasing cost [€]
400kVA/Oil immersed GOES	0.43	4.6	0.5	0.08	1107.26	8810
400kVA/Oil immersed Amorphous	0.2	4.6	0.5	0.08	946.08	10240
Cost difference					161.18	1430

From **Table 5** we can derive a pay-back after 8.87 years for industry. In the case of electric utilities the total investment is calculated for the entire life of the transformer (typical value from utilities is 30 years).

Photovoltaic (PV) applications

The difference in total investment cost between amorphous and conventional transformers is much larger in the case of transformers for photovoltaic parks (see **Table 6**). This is despite the fact that PV energy prices of electricity sold to utilities have decreased dramatically and have been divided by a factor of three in six years in most markets. In most EU member states, electric utilities now buy electricity generated from photovoltaic parks in a price range varying from 0.1 €/kWh to 0.35 €/kWh. If an average value of 0.22€/kWh is considered, a payback can be calculated (illustrated in **Table 6)**. In this case (PV park), the pay-back occurs after 3.2 years.

Table 6
Cost comparison for PV applications

Rated power (kVA)	P0 [kW]	Pk [kW]	L	Energy cost [€/kWh]	Cost of energy per year[€]	Purchasing cost [€]
400kVA/Oil immersed GOES	0.43	4.6	0.3	0.22	1626.55	8810
400kVA/Oil immersed Amorphous	0.2	4.6	0.3	0.22	1183.3	10240
Cost difference					443.2	1430

Wind applications

For wind applications, transformers are similar in load factor and cost to industrial applications. Load factor is close to 0.5 and the selling price is approximately 0.08 €/kWh. The data presented in **Table 7** illustrates a calculated pay-back of 8.87 years.

Table 7
Cost comparison for wind applications

Rated power (kVA)	P0 [kW]	Pk [kW]	L	Energy cost [€/kWh]	Cost of energy per year[€]	Purchasing cost [€]
400kVA/Oil immersed GOES	0.43	4.6	0.5	0.08	1107.26	8810
400kVA/Oil immersed Amorphous	0.2	4.6	0.5	0.08	946.08	10240
Cost difference	*Lower amorphous energy cost (-161.18 €/year)* *Higher amorphous purchasing cost (+1430 €)*				161.18	1430

Old transformer replacement

Conventional transformers with high losses can also be replaced at the end of their useful life (typically 20 to 25 years) by amorphous transformers. Most older transformers have been built based on the popular DIN 42511 standard. This implies, for a 400kVA transformer, no load losses of 850 W and load losses of 6450 W. **Table 8** illustrates cost savings that occur when an old transformer is replaced with a new amorphous transformer. In this case, a payback of 13 years is calculated.

Table 8
Payback scenario for replacement of old transformers

Rated power (kVA)	P0 [kW]	Pk [kW]	L	Energy cost [€/kWh]	Cost of energy per year[€]	Purchasing cost [€]
400kVA/Oil immersed GOES	0.85	6.45	0.5	0.08	1725.72	We consider the worst case with old transformers having a value of 0 €.
400kVA/Oil immersed Amorphous	0.2	4.6	0.5	0.08	946.08	10240
Cost difference					779.64	10240

Cost of CO_2 emissions

Mandating a price on carbon emissions is essential to the success of any serious, comprehensive climate plan. When pricing is applied to CO_2 emissions, greater savings and shorter pay-back scenarios result when amorphous transformers are deployed. The specifics of the cost comparison depend on the quantity of CO_2 emissions and the price of CO_2 per ton. Electricity produced through different sources, such as coal, diesel, or natural gas, present different values of CO_2 emissions. These can vary between 0.5 kg CO_2 / kWh and 0.75 kg CO_2/kWh. Let's assume a mean value of 0.625 kg CO_2/kWh.

Based on the Spring CO_2 price report[5] and a middle of the road 2020-2040 scenario, a price of 33.54 $ per ton of CO_2 can be estimated, which corresponds to 29.42 € per ton CO_2 (1€ =1.14 $). This price per ton can be converted into a price per kWh, and, as a result, we perform the following calculation: 29.42 €/ton CO_2 * 0.625 kg CO_2/kWh = 0.018 €/kWh (see **Appendix A** for specifics for how these calculations are derived).

This calculation allows us to assign a value to CO_2 emissions. From there we analyzed three different cases (old transformers, industrial consumers, and electric utilities). **Tables 9 and 10** illustrate the results.

Table 9
Amorphous technology payback scenarios for industrial sector and for old transformer replacement that factor in CO_2 emissions cost

Application	Pay-back period in years investing in amorphous instead of traditional technology	
	CO2 cost not considered	CO2 cost considered
Replacing old transformers	13 years	10.7 years
Industrial customers	8.9 years	7.2 years

Table 10
CO_2 cost difference between GOES and amorphous for electric utilities sector (Ownership cost difference over the lifetime)

Application	Difference in total investment cost in favour of amorphous technology compared to GOES	
	CO2 cost not considered	CO2 cost considered
New investment in electric utilities	410 €	1307€

[5] Synapse Energy Economics. Inc. "CO2 Price Report, Spring 2014"

Conclusion

Many transformers that are under operation today are inefficient. According to European Union energy efficiency requirements, higher efficiency transformers need to be installed in Europre starting from July 1, 2015.

A number of factors need to be considered when purchasing new, more efficient transformers that conform to European Union targets.

- New amorphous technology transformers, when compared to new conventional GOES transformers will divide efficiency losses by a factor of 2.
- When considering replacement of old transformers or when buying new transformers, calculate the cost of transformer's energy loss and compare the conventional and amorphous transformers. Determine the pay-back and CO_2 emissions levels produced.
- In PV applications choose transformers with low "no-load losses" as they work with low load factor and are subject to long-term no-load operation conditions, at least at night.
- In wind applications, choose transformers with low load and low "no-load losses".
- In industrial applications, choose transformers with low "no-load losses" and low "load-losses" (because of the large load factor between 50 and 60%).
- Make decisions based upon the calculation of energy losses and consider the cost of CO_2 emissions.

About the authors

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Appendix A

Forecast of CO_2 prices (Dollars per ton CO_2):

Source: Synapse Energy Economics. Inc. “CO_2 Price Report, Spring 2014”

Year	Low case	Mid case	High case
2020	$10.00	$15.00	$25.00
2021	$11.50	$17.25	$28.25
2022	$13.00	$19.50	$31.50
2023	$14.50	$21.75	$34.75
2024	$16.00	$24.00	$38.00
2025	$17.50	$26.25	$41.25
2026	$19.00	$28.50	$44.50
2027	$20.50	$30.75	$47.75
2028	$22.00	$33.00	$51.00
2029	$23.50	$35.25	$54.25
2030	$25.00	$37.50	$57.50
2031	$26.50	$39.75	$60.75
2032	$28.00	$42.00	$64.00
2033	$29.50	$44.25	$67.25
2034	$31.00	$46.50	$70.50
2035	$32.50	$48.75	$73.75
2036	$34.00	$51.00	$77.00
2037	$35.50	$53.25	$80.25
2038	$37.00	$55.50	$83.50
2039	$38.50	$57.75	$86.75
2040	$40.00	$60.00	$90.00
Levelized 2020-2040	$22.36	$33.54	$51.79

Details of cost calculation for CO_2 emissions

Replacing of old transformers including CO_2 cost
When adding the cost of CO_2 (0.018 €/kWh) to the energy cost (0.08 €/kWh), the total cost will be 0.098 €/kWh. Assuming we have the same parameters as in **Table 8**, the difference in cost of energy then becomes 955 €. So there is a pay-back of 10.7 years instead of 13 years.

Industrial consumers including CO_2 cost
We use the same procedure as above
Total energy cost = 0.018+0.08=0.098 €/kwh
Assuming the same parameters as in **Table 5**, the difference in cost of energy then becomes 197.5 €. So there is a pay-back of 7.2 years instead of 8.87 years.

Electric utilities including CO_2 cost
In case of Electric utilities there is a different approach of calculation, as the cost of losses is expressed in [€/w]. So we have to convert the CO_2 cost from [€/kwh] to [€/w].
Supposing a load factor of 0.45 we calculate as following:
For every kW of Load loss saved there is an associated kWh saving per annum of 0.45*0.45*8760hrs*1kW = 1773.9 kWh pa. For No load loss there is 1*8760hrs*1kW = 8760 kWh pa

At a cost of 0.018 €/kwh the annual savings from a kW of load losses and no load Losses are:
1kW Load Loss: 1773.9 kWh pa * 0.018 €/kWh = 31.93 €pa
1kW No load Loss: 8760 kWh pa x 0.018 €/kWh =157.68 €pa

For 25 years each kW of Load loss saved is worth 798.25 € (0.798 €/w), and each kW of No load loss saved is 3942 € (3.942 €/w).

If we add these values to the previous cost we had in **Table 4**, (8 €/w for no load losses, and 1 €/w for load losses), we have the new cost of losses including CO_2 emission.
8 €/w+3.9 €/w =11.9 €/w for no load losses,
1 €/w+0.8 €/w =1.8 €/w for load losses.

Calculating using the same parameters as in **Table 4** with the new cost of losses, the total investment will be 22207 € for transformer with GOES, and 20900 € for transformer with amorphous core.
Compared to the calculation w/o CO_2, we have now a difference of 1307 € instead of 410 €, it is more convenient to chose amorphous transformers instead of GOES.

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