Mariusz NAJGEBAUER, Krzysztof CHWASTEK, Jan SZCZYGŁOWSKI

Institute of Power Engineering, Częstochowa University of Technology

Energy efficient distribution transformers

***Abstract**. The paper presented the possibilities of improvement in properties of electric distribution transformers through the use of new soft magnetic materials, mainly amorphous alloys, as transformer cores. The properties of amorphous were compared to conventional electrical steel sheets. Economic and pro-ecological advantages resulting from application of amorphous distribution transformers in electric power systems were considered.*

***Streszczenie.** W pracy przedstawiono możliwości poprawy właściwości transformatorów rozdzielczych poprzez zastosowanie w nich rdzeni z nowych materiałów magnetycznych, głównie stopów amorficznych. Właściwości stopów amorficznych zostały porównane z właściwościami blach elektrotechnicznych. Przeanalizowano ekonomiczne i proekologiczne korzyści wynikające z wykorzystania transformatorów rozdzielczych z rdzeniami amorficznych w systemach elektroenergetycznych. (**Możliwości poprawy właściwości transformatorów rozdzielczych**)*

Keywords: distribution transformers, energy savings, investment profitability, environment protection.
Słowa kluczowe: transformatory rozdzielcze, oszczędność energii, opłacalność inwestycji, ochrona środowiska.

Introduction

Distribution transformers are units of electric power systems, in which electricity is transformed form the voltage level 1 - 50 kV to the voltage level 120 V + 1 kV, in dependence on consumers' needs. Energy efficiency of distribution transformers is very high, typically ranging between 96% and 99%. However, due to a large number of distribution transformers in electric power system and their long lifetime (30 - 40 years), even small improvement in the efficiency of these units could result in significant energy savings [1]. These issues are important both from economic and ecological viewpoints.

Increase of energy efficiency of distribution transformers could be obtained reducing three types of transformer losses:

- no-load loss (iron or core loss) can be reduced by improvement in design and assembling processes or in magnetic properties of material core,
- load loss (copper loss) can be reduced increasing the cross-section of the windings,
- cooling loss can be reduced by decrease of other types of transformer losses [1].

Further increase in transformer efficiency is possible to reach by replacement silicon steel cores with new types of magnetic core materials, e.g. amorphous ribbons.

Amorphous materials were developed in the seventies of the last century. These materials are produced by rapid solidification of a liquid alloy, what gives specific magnetic properties, especially very low energy loss. However, these materials have quite low saturation induction and they are thermal unstable. Production technology and properties of amorphous materials were described in detail in earlier authors' papers [2-8]. The properties of amorphous alloy and commonly used silicon steel are compared in Table 1.

Table 1. Chosen properties of transformer core materials [9]

Material	B_S	ρ	$W_{1,3/50}$	d
	[T]	[μΩ·cm]	[W/kg]	[mm]
Silicon steel	2,03	50	0,440	0,23
Fe-based amorphous alloy	1,56	130	0,070	0,025

Construction of amorphous transformers

Amorphous cores are usually produced as wounded, one-side cutting ones, due to mechanical properties of amorphous ribbons. This solution ensures the correct location of air gaps inside a core and simplifies electric windings assembling as well [2,7,11]. Amorphous transformers are produced as 1-phase or 3-phase units, with 3-limbs or 5-limbs core construction [2,7,9]. The capacity of currently produced amorphous transformers is limited up to 10 MVA [1]. The construction of an oil immersed type amorphous transformer produced by Hitachi Corporation, which is representative for this kind of transformers, is presented in Figure 1.

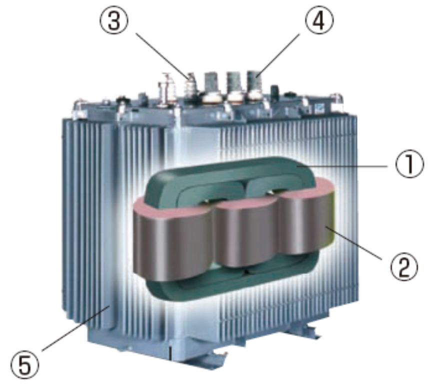

Fig.1. 3-phase amorphous transformer (1000 kVA, 6 kV/210 V, 60 Hz): 1 – 3-limbs core, 2 – coil, 3/4 – primary/secondary bushing, 5 – tank [9]

The cross-section of amorphous cores is larger in comparision to silicon steel ones, due to lower saturation induction of amorphous ribbons. It results in the increase of transformer dimensions and weight. Dimensions and weight of silicon steel core and amorphous core transformers are compared in Table 2.

Table 2. Transformer dimensions and weight [9]

Item		SiT	AMT
Dimension [mm]	width	1 395	1 430 (103%)*
	depth	700	800 (114%)*
	height	1 490	1 605 (108%)*
Weight [kg]		2 400	3 050 (120%)*

SiT – 3-phase silicon steel core transformer, 1000 kVA, AMT – 3-phase amorphous core transformer, 1000 kVA
* with relation to SiT

Energy savings and economic profits of amorphous transformers

No-load loss of amorphous core transformers is very low comparing to conventional transformers with silicon steel core. It results from very low energy loss of amorphous ribbons and also its small thickness, what significant reduces eddy currents flow. The reduction of no-load loss in amorphous transformers is estimated at 70% - 80% [2-14]. The following Tables 3-6 present the reduction of energy loss in amorphous transformers, produced by different companies.

Table 3. Energy loss in silicon steel and amorphous transformers, 6,6 kV/210 V, 60 Hz, produced by Hitachi Co. [9]

Capacity [kVA]	Silicon steel transformer		Amorphous transformer	
	No-load loss [W]	Load loss [W]	No-load loss [W]	Load loss [W]
100	300	1 875	95 (68%)*	1 800
500	939	4 522	240 (74%)*	5 450
1000	1 670	7 880	440 (74%)*	9 170

* reduction of no-load loss

Table 4. Energy loss in silicon steel and amorphous transformers, produced by ABB Group [15]

Capacity [kVA]	Silicon steel transformer		Amorphous transformer	
	No-load loss [W]	Load loss [W]	No-load loss [W]	Load loss [W]
250	650	3 250	160 (75%)*	2 300
400	930	4 600	210 (77%)*	3 650
630	1 300	6 500	300 (77%)*	4 930

* reduction of no-load loss

Table 5. Energy loss in silicon steel and amorphous transformers, produced by Transformateurs Ferranti-Packard Ltée [16]

Capacity [kVA]	Silicon steel transformer		Amorphous transformer	
	No-load loss [W]	Load loss [W]	No-load loss [W]	Load loss [W]
50	126	327	40 (68%)*	340
100	206	523	50 (76%)*	826

* reduction of no-load loss

Table 6. Comparison of no-load loss in silicon steel (SiT) and amorphous transformers (AMT) [17]

Capacity [kVA]	No-load loss [W]		
	SiT (in-service) [W]	SiT (best) [W]	AMT [W]
50 (1-phase)	210	105	35 (83%)* (67%)**
300 (3-phase)	1000	500	165 (83%)* (67%)**

* reduction of no-load loss with relation to SiT (in-service)
** reduction of no-load loss with relation to SiT (best)

It is estimated, that currently over 83 million distribution transformers operate in six biggest economies in the world, including 3,6 million units in UE-25 countries [18,19]. Thus, a worldwide potential of energy savings, through the use of amorphous transformers instead of the conventional ones, seems to be significant. There are a lot of estimations of energy savings, worked out by transformer producers, government and non-government institutions, as European Commission [20], US Department of Energy [21], European Copper Institute [18,19], with Leonardo ENERGY and ProPHET (Promotion Partnership for High Efficiency Transformers). The estimations of annual transformer loss and potential energy savings for six biggest economies are given in Table 7.

Table 7. Annual transformer loss and potential energy saving through the use of amorphous transformers [21]

Country	Annual transformer loss [TWh]	Annual potential savings [TWh]
USA	141	84 (60%)
EU-25	55	22 (40%)
Japan	44	31 (70%)
China	33	18 (54%)
India	6	3 (50%)
Australia	6	3 (50%)
Total	285	161 (56%)

It is obvious that energy savings in transformers give economic profits. The Cost Saving Effect (CSE) could be calculated from a simple relation

$$\text{CSE} = \text{CP}_{\text{SiT}} - \text{CP}_{\text{AMT}}, \tag{1}$$

where: $\text{CP}_{\text{SiT/AMT}}$ – cost of annual loss in silicon steel or amorphous transformer in [USD/year], given by

$$\text{CP} = \frac{\left(\text{NLL} + \text{LL} \times \text{LF}^2\right) \times 8760 \times \text{ECh}}{1000}, \tag{2}$$

where: NLL – no-load loss [W], LL – load loss [W], LF – load factor, ECh – electric charge in [USD/kWh] [9].

For a typical 3-phase 100 kVA transformer, e.g. listed in Table 3, under the assumption ECh = 0,01 USD/kWh and LF = 0,5 [9], it was obtained from calculations that CP_{SiT} = 1 144,81 USD/year and CP_{AMT} = 811,81 USD/year. Thus, CSE in case of a single amorphous transformer is equal to 333,20 USD/year (own calculation, based on [9]). Considering a large number of distribution transformers, the potential Cost Saving Effect through the use of amorphous units is estimated at billions of US dollars each year.

The economic analysis of the investment in amorphous transformer technology could be based at Total Owning Cost (TOC). The TOC coefficient encompasses the initial cost of the transformer and the future cost of the no-load and load losses over its lifetime [10]. Amorphous transformers are 30 - 50% more expensive than silicon steel ones [10,22]. Nevertheless, the significant reduction of no-load loss in amorphous transformers provides TOC benefit over transformer lifetime, what is presented in Figure 2. It indicates the amorphous transformers as better solution.

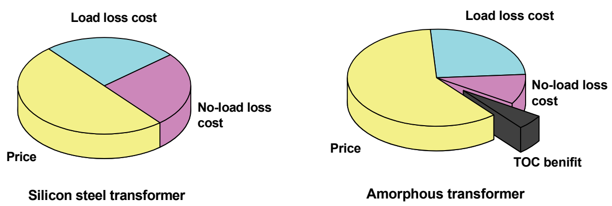

Fig.2. Diagram of Total Owning Cost [10]

The calculation of the TOC factor for the typical 500 kVA and 1000 kVA silicon steel and amorphous distribution transformers are presented in Table 8.

Table 8. The calculation of the TOC factor for silicon steel and amorphous transformers [own calculation, basing on 11]

Distribution transformer 500 kVA, 60 Hz, 15 kV/480 V	Silicon steel transformer	Amorphous transformer
No-load loss [W]	610	230
No-load loss factor [USD/W]	5,50	5,50
Load loss [W]	3153	3192
Load loss factor [USD/W]	1,50	1,50
Efficiency [%]	99,4	99,6
Purchase price [USD]	10 000	11 500
No-load loss value [USD]	3 355	1 265
Load loss value [USD]	4 730	4 788
Total Owning Cost [USD]	18 085	17 558

Distribution transformer 1000 kVA, 60 Hz, 15 kV/480 V	Silicon steel transformer	Amorphous transformer
No-load loss [W]	1 033	400
No-load loss factor [USD/W]	5,50	5,50
Load loss [W]	5 843	5 484
Load loss factor [USD/W]	1,50	1,50
Efficiency [%]	99,3	99,5
Purchase price [USD]	15 000	17 250
No-load loss value [USD]	5 682	2 200
Load loss value [USD]	8 765	8 226
Total Owning Cost [USD]	29 446	27 676

Ecological profits of amorphous transformers

Wider application of amorphous transformers in electric power systems gives not only energy savings and economic profits. This process has also ecological aspects. Significant energy savings result in decrease of fuel consumption in power plants, what reduces the emission of greenhouse gases. This issue is important form social considerations and for economic policy, because it simplifies the fulfilment of the international agreements of environment protection.

The Reduction Effect of CO_2 emissions (RE_{CO2}) could be calculated form the following relation

$$RE_{CO2} = E_{CO2\_SiT} - E_{CO2\_AMT} \, , \tag{3}$$

where: $E_{CO2\_SiT/AMT}$ – annual CO_2 emissions of silicon steel or amorphous transformer in [t/year], given by

$$E_{CO2} = \frac{\left(NLL + LL \times LF^2\right) \times 8760 \times EC_{CO2}}{1000} \, , \tag{4}$$

where: EC_{CO2} – CO_2 emission coefficient [kg/kWh] [9].

In case of 100 kVA transformer and for the emission coefficient EC_{CO2} = 0,555 kg/kWh, the reduction of CO_2 emissions is equal to RE_{CO2} = 8,9 t/year [9]. The potential reduction of greenhouse gas emissions through the use of high efficiency amorphous transformers is given in Table 9.

Table 9. Environmental impact of amorphous transformers [11,18]

Country	CO_2*,**	NO_x**	SO_2**
	[million tons]	[thousand tons]	[thousand tons]
USA	60* (35)**	110	260
EU-25* / Europe**	9* (20)**	70	160
Japan	12* (10)**	30	75
China	13* (12)**	90	210
India	3* (3)**	22	52
Australia	3* (---)**	---	---
Total	100* (80)**	322	757

* estimation of Leonardo ENERGY (European Copper Institute)
** estimation of US Environmental Protection Agency

Conclusions

High efficiency distribution transformers with amorphous core become more and more popular. At present, there are more than 1,5 million amorphous transformers operating worldwide. Each year, 10% - 15% of new transformer sales in USA and Japan are amorphous ones [22]. The increasing number of amorphous transformers results both from energy savings and reduction of greenhouse gas emission. Only in the countries of European Union, annual energy savings are estimated at 18,5 TWh, corresponding to 1€ billion saving in operating cost. The energy savings are equivalent to the annual production of three nuclear power stations (1 000 MW) or eleven fossil fuel power units (350 MW) [1].

The energy savings from amorphous transformers have a great influence on the scope of electricity production and consumption. Thereby, this issue should be considered in forecasting models applied in electric power engineering.

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Autors*: dr inż. Mariusz Najgebauer, dr inż. Krzysztof Chwastek, dr hab. inż. Jan Szczygłowski, prof. PCz., Institute of Power Engineering, Częstochowa University of Technology, al. Armii Krajowej 17, 42-200 Częstochowa, Poland*
e-mail: najgebauer@el.pcz.czest.pl, krzych@el.pcz.czest.pl, jszczyg@el.pcz.czest.pl