Journal of Optoelectronics and Advanced Materials Vol. 4, No. 2, June 2002, p. 231 - 236

IRON-BASED AMORPHOUS RIBBON – CHALLENGES AND OPPORTUNITY FOR POWER APPLICATIONS

A. J. Moses

Wolfson Centre for Magnetics Technology, School of Engineering Cardiff University, Wales, UK

Iron-based amorphous ribbon has been considered as a high efficiency option for distribution transformer core material but only a small penetration into the market has occurred. There is a trend towards a greener approach to energy conservation in several parts of the world with for instance energy taxes proposed in several countries with long term goals of major reductions of Co_2 emission. This together with the awareness of the possible effect of increased harmonic distortion on electrical distribution systems on transformer no-load loss makes it worth reconsidering the performance of amorphous ribbons under such conditions. This paper reviews the present status of amorphous material in distribution transformers and shows that in many situations it is the best option where true energy losses operating conditions are considered fully. It is shown that amorphous material performs well under the type of voltage distortion which is becoming more widespread in power systems. The paper also refers to progress and problems in measurement and assessment of the material properties under magnetisation conditions which prevail in distribution transformers.

(Received February 21, 2002; accepted May 15, 2002)

Keywords: Amorphous Material, Magnetic Losses, Energy Efficiency, Distribution Transformers

1. Introduction

Iron-based amorphous material with composition around $Fe_{78}B_{13}Si_9$ has at various times been recommended as a contender to replace traditional electrical steels in a range of power devices because of its well documented excellent soft magnetic characteristics. A few years ago it was being referred to as “the material of the century” in USA and “a dream material” in Japan, but up until now it has not penetrated its potential market around the world. The object of this paper is to report the present status of the material with respect to its technical and economic suitability for use in the distribution transformer market which is at present dominated by grain-oriented 3% silicon steel.

The history of amorphous materials started in 1960’s and in the early 1970’s the potential of magnetic alloys was identified. The main attraction at the time was the realisation that the iron loss of the material at power frequencies was of the order of three to four times lower than the best commercially available electrical steel. In the following 30 years commercial production of iron-based amorphous material has risen to a capacity of 60,000 tons/year. During that time there has been continued debate about its advantages and disadvantages but although it is reported to have penetrated around 10% at the distribution transformer market in the USA, its application throughout the rest of the world is still insignificant.

It will be shown in this paper that although there has been practically no technical advance in developing magnetic properties of commercial iron-based amorphous material during the past 5 yeas, the time may have come to carefully review its potential. This is timely because of a rising acceptance of the importance of taking real cost of ownership of transformers into account and a better knowledge of actual magnetisation conditions in cores when transformers are operated on industrial power systems, both of which might make amorphous cores attractive in many situations.

It is claimed that amorphous magnetic material is finding increasing applications in distribution transformers, power electronic and conditioning equipment, automotive components and sensor systems [1]. The driving forces are increased energy efficiency or improved technical performance and sometimes both. However, put in perspective, at present amorphous material comprises about 0.3 % of the volume production of soft magnetic materials throughout the world or around 1.5% by value. The main opportunity for major growth by capturing a greater market share is still in the field of distribution transformers. Energy losses in distribution transformers are estimated to account for some 3-5 % of all electrical power generated and if the add-on losses in cables, network substations and other equipment are included, this accounts for large additional amounts of fossil fuel consumption with the corresponding increase in emission of pollutant gases and solid waste. In the UK alone it is estimated that distribution transformer losses of 4×10^9 kWh can account for 12×10^6 tonnes of coal, which in turn produces around 500×10^3 tons of carbon dioxide and 50×10^3 tons of sulphur dioxide each year. Reducing this significantly can help towards the UK target of reducing ‘greenhouse’ gas emissions by 20 % in 2020 as specified in the Kyoto Summit meeting on global warming.

Distribution transformer cores, in the approximate range 15 kVA – 1000 kVA, are either assembled in layers of stacked lamination or in the form of continuous windings. In the USA, where single phase transformers predominate, wound cores are almost always used, whereas in countries such as the UK, the cores are normally assembled as stacks of laminations because of the requirements for greater numbers of three phase transformers on the power systems. It is difficult to assemble amorphous ribbon in stacked form or in 3 phase assemblies will be referred to later because of its thinness and the harmful effect of building stress on the materials magnetic properties. The amorphous ribbon cannot normally be made greater than around 0.03 mm thick because of the need to cool strip at around 10^6 K/s to avoid crystallisation.

The most important magnetic properties of materials being considered for medium power transformer cores are low iron loss, high permeability, low stress sensitivity, low susceptivity to the presence of harmonic components of flux correct texture and low rotational losses. The texture and rotational loss characteristics are not important in wound cores but the other parameters are important in both types. Table 1 summarises differences between these and other important characteristics in typical commercial materials.

Table 1. Comparison between important transformer characteristics of amorphous material and grain oriented electrical steel.

	3% SiFe	**Fe-based ribbon**	**Powercore**
Thickness (mm)	0.3	0.03	0.13
Max. operating temp (^{o}C)	650	150	125
Space factor (%)	95.98	85	90
Loss at 1.3T, 50 Hz	0.64	0.11	0.12
Saturation (T)	2.03	1.56	1.56
Resistivity (μΩm)	45	135	135

One of the largest difficulties in assembling amorphous cores is the high stress sensitivity of many of its magnetic properties. Fig. 1 shows the high sensitivity of losses compared to those in silicon steel under longitudinal tensile and compressive stress.

2. Powercore

In the 1970's an attempt was made by Allied Corporation (now Honeywell) to market amorphous ribbon in a form more suitable for stacked core assemblies. This was done by forming thick laminations by bonding around 8 ribbons together. Some properties of POWERCORE are shown in Table 1. The material was still stress sensitive and difficult to cut because of its brittleness but several prototype transformers were built with stacked POWERCORE laminations forming the three-phase magnetic circuits.

However it still proved difficulty to assemble economically and although low losses could be achieved, manufacturing costs appeared prohibitive and the product was withdrawn from the market.

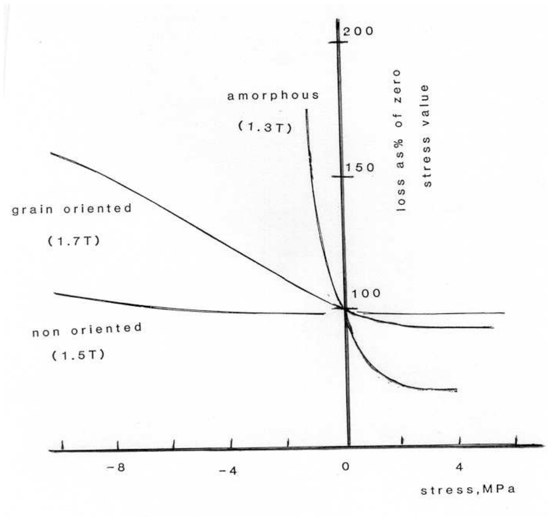

Fig. 1. Percentage increase of loss due to longitudinal stress in typical electrical steel and iron-based amorphous material.

3. Loss evaluation

Transformer users consider the cost of ownership of a unit by estimating the total cost of purchase, maintenance, and the capitalised cost of the no-load iron and load copper losses over the transformers lifetime, or some specified time such as 30 years. Table 2 shows some data estimating the cost of ownership of equivalent transformers assembled from stacked laminations of grain-oriented 3 % silicon-iron in standard and low-loss transformers, and of a three phase wound amorphous core with the same 315 kVA rating.

Table 2. Comparison of true lifetime losses of conventional and amorphous cores, 3 phase, 315 kVA transformers [based on ref. [2]].

	Standard		Low Loss		Amorphous	
	Loss	Cost (£)	Loss	Cost (£)	Loss	Cost (£)
No Load Loss (kW)	0.735	7754	0.38	4009	0.145	1530
Load Loss (kW)	4.8	10330	4.1	8780	4.8	10265
Manufacturing Price (£)	-	5000	-	6690	-	7315
Total Loss (£)	-	23084	-	19479	-	19110

The iron loss was capitalised at £10550/kW and the copper loss at £2152/kW in this case. The values used for capitalisation vary widely in practice and are supposedly based on actual and predicted electricity costs but in many cases they are down-valued by the user who does not pay due attention to the real energy costs. In this particular example the amorphous cored transformer, although almost 50% more expensive to purchase, has marginally lower total cost of ownership.

There has been a steady trend over the past 20 years for the cost of amorphous material to drop relative to traditional grain oriented electrical steel but the magnetic performance of electrical steel has steadily improved as will be shown later. A method of estimating the economics of amorphous material in a distribution core is shown in Fig. 2. Even at low capitalised loss values, amorphous transformers can compete with best traditional cores as shown in Table 3 for a range of transformer sizes [4].

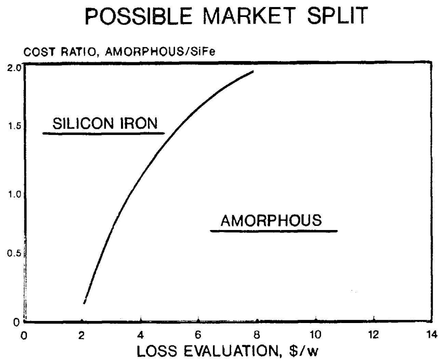

Fig. 2. Estimation of economic advantage of materials dependent on loss evaluation.

Table 3. Breakdown of total cost of ownership of amorphous and other distribution transformers of different sizes.

Transformer kVA (15 kV / 480-277 V)	Price		Loss Value: $5.50 Core Loss $1.50 Load Loss					
	AMDT	**Other DT**	**AMDT**	**Other DT**	**AMDT**	**Other DT**	**AMDT**	**Other DT**
60 Hz			No Load	No Load	Load	Load	TOC	TOC
750 kVA	$14.950	$13.000	$1.727	$4.934	$6.599	$6.582	$23.276	$24.516
1000 kVA	$17.250	$15.000	$2.200	$5.682	$8.226	$8.765	$27.676	$29.446
1500 kVA	$24.725	$21.500	$3.124	$7.750	$10.820	$13.401	$38.669	$42.651

4. Thermie project

An attempt was made in the UK several years ago to evaluate the performance of amorphous material in a range of single and three phase transformers [3]. The main objective was to demonstrate in a range of cores from 25 kVA to 630 kVA that transformers could be assembled with losses less than 30 % of comparable conventional transformers and their manufacturing/material costs would only be slightly higher than normal. When the project was specified it was intended to assemble the cores with POWERCORE laminations. The material became unavailable when the project was about to start but the partners decided to go ahead and make transformers using wound amorphous cores instead. In the majority of cases the manufacturers were not used to large scale production of such cores but they all managed prototype/development cores without difficulty. Some of these were installed on power systems and are still operating satisfactory.

The transformers met their technical specification without any difficulty with loss reductions of 60-85 % compared with traditional designs. Table 4 show the performances of two of the larger transformers.

Table 4. Performance of 315 kVA and 630 kVA 3 phase, demonstration transformers with wound amorphous cores.

kVA	No load loss (kW)		Saving (kW)	Saving per year at 5p/unit	Payback (years)
	Amorphous	Conventional			
315	0.140	0.725	0.585	£256	6
630	0.240	1.225	0.985	£431	5

At that time the Thermie work was carried out, the 6 year payback period was considered excessive. More recent results on even larger transformers indicate that this period can now be halved and in many instances become quite viable even when not taking the real cost of energy into account. For example, a recent 1.6 MVA, 3 phase transformer was reported with an iron loss of 384 W (less than 25 % of a comparable silicon iron-cored transformer) with a payback period of 3 years [1]. This particular transformer is claimed to be designed specifically for the European market using construction techniques which could be applied to transformers up to 2.5 MVA.

5. Greater incentives for implementation?

The previous sections confirm the economic viability of amorphous cored transformers in some power systems. In the UK there is now a new incentive for industry to reduce energy consumption by the introduction of the Climate Change Levy tax. This effectively puts a premium on energy consumption in an attempt to encourage users to reduce their electricity consumption and hence help the UK achieve the target reductions in carbon emissions as specified at the Kyoto Summit. Iron loss is a very small part of total industrial consumption so the introduction of energy efficient cores would not produce any significant savings in the tax payment but the levy should make users more conscious of the possibility of saving energy in distribution transformers.

Of more significance might be the increasing awareness of the presence voltage harmonics on power systems and the affect on iron losses. Levels of harmonic pollution are increasing on supply networks and in the UK the level of 5^{th} harmonic distortion in Low Voltage (LV) supplies has risen to the stage where they are penetrating the High Voltage (HV) network [5]. It is reported that the level of 5^{th} harmonic on LV networks in the UK is as high as 6 %, the maximum allowable under EMC compliance. The main source of this harmonic distortion is from TVs and SMPSs in PCs [5].

Such supply voltage harmonics will lead to increased iron losses approximately proportional to the square of the harmonic number and the magnitude of the harmonic component. Laboratory studies confirm that losses under such conditions in amorphous material are not as great as in conventional electrical steel because of its lower thickness and greater resistivity. Until now very little quantitative measurement of the effect of flux harmonic distortion on the losses and permeability of amorphous material has been reported because of the difficulty of the measurements. However new systems such as reported in [6] are capable of such measurements although the user should be very careful to interpret measurements in the right way. For example, there is considerable ambiguity in the literature referring to effects of harmonics on loss in conventional electrical steels because some findings are presented at fixed peak value of the fundamental component of a flux density waveform, others refer to either the effective value or even the total harmonic distortion; usually it is not specified which is used. When sinusoidal flux density is present no problems arise but under other reconditions major interpretation might arise [7].

The other problem with basic measurement of losses in amorphous material is that there is no internationally agreed Standard method. Although attempts are being made to obtain an agreed measurement method, or methods, as in the case of electrical steels this is still far off even for measurement under sine wave flux density conditions because of magnetising and signal data capture difficulties which must be overcome by introducing agreed new measuring systems.

However another recent set of results appear to show that the benefit of using amorphous cores in distribution transformers is even greater than anticipated because the presence of harmonics on supply systems is not so harmful as indicated in Fig. 3 [1]. This shows that the actual iron losses in transformers on a power system are far higher than calculated expected particularly in units with conventional silicon iron cores. The building factors estimated from the results in Fig. 3 are around 2 for the amorphous cores but over 5 for the silicon steel cores. This remarkable finding has been attributed to the presence of high harmonic voltage levels on the supply systems. Recent comparisons between the materials under distorted flux waveforms under laboratory conditions show building factors of around 1.7 for silicon iron and 1.1 for amorphous material under the same waveform [8]. Other field data indicates that for Total Harmonic Distortion level of 75 % the increase in no load loss in amorphous cores is around 60 % whereas it is 300 % in transformers with silicon-iron cores [1]. These reports suggest that the benefits of using amorphous material are even greater under distorted waveforms hence if this is properly taken account of in cost of ownership evaluations then the advantage of using amorphous material might be far greater than previous estimates. This is not unexpected because of the greater resistivity and lower thickness of the material which will make it less lossy better at higher frequency or in the presence of harmonic flux.

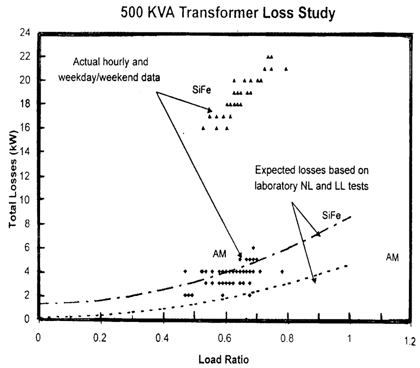

Fig. 3. Actual and nominal performance of conventional and amorphous material based 500KVA transformers [1].

6. The future

The extent to which the use of amorphous material in distribution transformers increases depends mainly on attitudes to energy saving in general. In the UK at present it is felt that the energy suppliers have no real interest in improving energy efficiency, they just wish to maximise sales [9]. The industry will not of its own accord protect the environment unless forced by legislation or taxation. The continued need for a one or two year payback is the other major barrier to the growth of use of amorphous transforms.

However as was shown earlier payback times are approaching 2 years and although the iron loss of the commercial material has not dropped over the past few years its physical features have steadily improved so it is easier to handle without inducing additions losses due to stressing. Harmonics on supply systems are likely to increase more in the future and will only be restricted to limit potential damage such as overheating of transmission cables and malfunction of instrumentation so the effect on transformer losses will increase and if the recent report showing a much smaller effect on losses in amorphous material are proven to be general then substantial energy saving will be recognised by its use.

However it is widely recognised that by use of purer steel, better process control and reduction in thickness the magnetic properties of grain oriented steel can be improved substantially and even compete with amorphous material [9].

References

[1] R. Hasegawa, J. Magn. Magn. Mater. **215-6**, 240 (2000).
[2] Electrical Energy Efficiency, Copper Development Ass. p. 116, 1997.
[3] EU Thermie report E1 393/91/UK “Demonstration of energy saving in distribution transformers with amorphous cores”.
[4] C. Pruess, IEEE Power Eng. Review, July, 13 (1998).
[5] R. Critchely, Design Products and Applications, Drives Supplement, Feb, (1998).
[6] P. Anderson, J. Leicht, A. J. Moses, UK Magnetics Society Seminar Proceedings, Warwick, 2000.
[7] A. J. Moses, J. Leicht, IEEE Trans. Magn. **37**, 2737 (2001).
[8] S. Hori, Y. Ishihara, K. Harada & T. Todaka, SMM 15 Conference, Bilbao, Spain 2001.
[9] I. Fells, Power Eng. J. April 2000.