Using Amorphous Iron Cores in 50 Hz Net Transformers – A Technique to Save Cost and Energy

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Abstract

In this paper we show the construction and properties of net transformers based on amorphous iron cores and compare them to laminated steel transformers. Material properties of the amorphous iron ribbon and their influence to the core losses of a low frequency transformer are explained. We present the measured losses of three different amorphous materials at a typical net transformer operation point and compare them to each other. At the end we show the design of a 50 Hz, 110 VA, 1:1 insulation transformer based on an amorphous core. On this concrete example we compare the size and iron losses of an amorphous transformer to the one of a conventional transformer based on iron steel.

1 Introduction

Although there exist many alternatives, 50/60 Hz transformers are still omnipresent in the power distribution net as well as in industrial or residential buildings. In the most cases these transformers use traditional iron steel laminated cores, which is a relatively cheap, but lossy material compared to amorphous iron ribbon cores. With the background of increasing energy prices, increasing energy consumption and shrinking of traditional (fossil) energy sources this technology can help saving cost and energy waste, with all its effects. Also for external ACAC power supplies, powering standalone devices, the 2016 released LEVEL V efficiency requirements are hardly to fulfill with traditional laminated steel transformers, but with amorphous iron based transformers (and of course switched mode power supplies).

2 State of the art

Amorphous cores are - due to their lower losses - often used in applications (transformers or inductors) with frequencies up to approx. 25 kHz. Their advantages were already also used in the application of higher power net transformers, as presented in [1] and [2]. Both publications show that the transformer manufacturer were able to decrease core losses by 70 %.

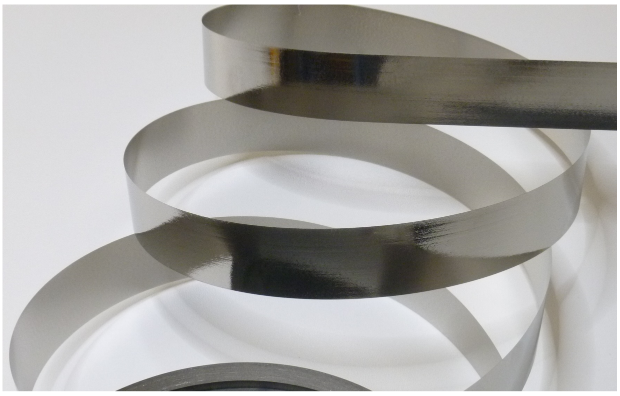

Fig. 1: Amorphous iron ribbon

3 Amorphous iron material

Manufacturing

Amorphous iron cores consist of a thin, tape like metal band with a thickness of 17...27 µm, see Figure 1. This ribbon is wound to get the final core, which is often cut to be able to mount the winding on it, as shown in Figure 2.

The tape is manufactured in a technologically challenging rapid solidification process. In this process the liquid iron alloy is cooled down with a rate of 1,000,000 K/s, by casting a thin film of

Fig. 2: Cut core made from amorphous ribbon

Tab. 1: Amorphous Iron Cut Core Properties

Initial relative permeability	1,500 ... 17,000
Saturation flux density	1560 mT (at room temperature)
Curie temperature	395...415 °C
Tape thickness	17...27 µm
Filling factor	78...91 %
Main chemical composition	$Fe_{80}Si_7B_{13}$

it on a fast rotating copper wheel. This fast cool-down does not allow the metal atoms to get into their normal metallic structure, but forces them to stay in a random amorphous state. Also the Silicon and Boron elements of the ally (composition see Table 1) prohibit the alloy to go into a crystalline structure. After the fabrication of the ribbon different temperature and magnetic treatments are applied to set the final properties of the material. [3] [4]

Properties

Among technically used soft magnetic materials, there exist a bunch of different amorphous iron based alloys from different manufacturers, with slightly different properties. The main properties and their typical range among the different suppliers are shown in Table 1. [5][6][7]

While the filling factor (stating the relative metal proportion of the total volume), the tape thickness and Curie Temperature of different amorphous materials vary a bit depending on the manufacturer, the saturation flux density at room temperature is identical for all of them. The relative permeability is usually not mentioned in the datasheets, as it depends on size and quality of the cores cut. For the losses of the material also slightly different values are shown in the datasheets. At a frequency of 50/60 Hz and a max. flux density of 1.3 T all of the given values are below 1.8 W/kg. Amorphous iron has combines both, relatively low hysteresis and eddy current losses due to its composition of very thin metal layers.

4 Design hints

Amorphous cores allow - due to their manufacturing process (see section 3) - a wide range of different shapes and sizes [5]. All diameters (core width, heith, length, windows size) of a core as shown in Figure 2 can be easily changed by modifying the winding body of the core and the tape width. Transformers may be wound on two opposed legs of a double U-core or with both windings above each other on the middle leg of an E-core, composed of two cut cores, what is the method also used in the design example in this paper, see section 6 (Figure 5). Other possible shapes are e.g. toroidal and oval cores or blocks.

To calculate the primary number of turns N_1 we use the common equation 1, where the integral is the voltage-time area of halve a sine wave, $Bmax$ the maximum flux density in and A_{Fe} the cross surface of the magnetic core .

$$N_1 > \frac{\int U(t)dt}{2 \cdot Bmax \cdot A_{Fe}} \tag{1}$$

When using equation 1 for the design of a transformer with an amorphous iron core the following should be considered:

- The saturation flux density is around 1.5 T, according to Table 1. To stay safe 1.4 T is recommended to use as maximum flux density.
- The magnetically active cross section of the iron core is just 78...91% of the geometrical core surface, as described by the fill factor, see Table 1. In the A_{Fe}-values stated in datasheets, usually the magnetically usable surface is given.

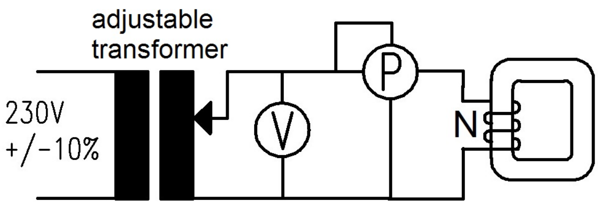

Fig. 3: Cut core power loss setup

Tab. 2: Losses of Three Different Amorphous Material at 50 Hz, 1.3 T

Amorphous Iron Material	Iron Power Losses [W/kg]
Manufacturer 1	1.6
Manufacturer 2	0.93
Manufacturer 3	1.4

- The voltage in the European electrical distribution network has a tolerance of 10 % according to EN50160. So the maximum rms-voltage has to be set to $230V + 23V = 253V$.[8]

Taking this into account, equation 1 a can be rewritten to Equation 2.

$$N_1 > \frac{230V \cdot 1.1}{\sqrt{2} \cdot \pi \cdot 50Hz \cdot 1.4T \cdot A_{Fe}} = \frac{0.82}{A_{Fe}/m^2} \quad (2)$$

After the calculation of the primary number of turns, the secondary number of turns has to be calculated using the desired turns ratio or voltage level. In the final step wire diameter has to be chosen and it has to be tested, whether it fits into the winding window.

5 Test of different amorphous iron materials

Three different materials were tested at 50 Hz frequency and 1.3 T peak excitation. The complete measurement setup is shown in Figure 3. The voltage is set to exactly 230 V using an adjustable transformer. The number of turns and the core surface are in a relation, which leads to a flux density of 1.3 T, according to equation 1.

The losses measured for the amorphous cores of three different suppliers are shown in Table 2.

It can be seen that depending on the manufacturer the losses at a frequency of 50 Hz are quite different.

Fig. 4: Laminated steal transformer 230V, 50Hz, 110VA, 1:1

One of the three analyzed tapes has much lower losses than the other two.

6 Amorphous iron versus steel transformer – design example

In this section we compare to transformers - one based on laminated steal to on using an amorphous iron core.

The laminated steel transformer shown in Figure 4 (110 W, 50 Hz, 1:1, lamination thickness 0.35 mm) works as reference. In Figure 5 the designed amorphous transformer is shown. The amorphous material used for the new design is the material of manufacturer 2, which was found to be the most efficient according Table 2.

6.1 Size and weight comparison

The Figures 4 and 5 show the transformer based on the amorphous cut core (Figure 5) to be slightly bigger than the one based on laminated steal (Figure 4). It is also around 10 % heavier (2.21 kg

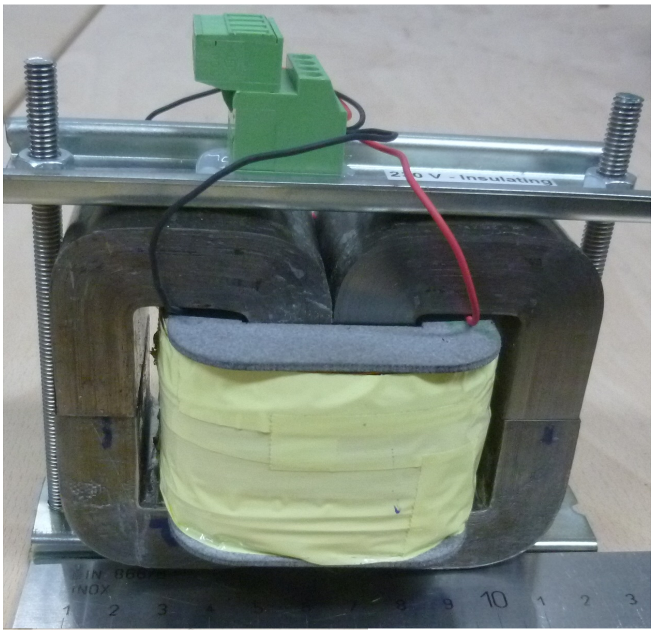

Fig. 5: Amorphous transformer 230V, 50Hz,110VA, 1:1

compared to 1.97 kg). The two main reasons for this are:

- The saturation flux density of transformer steal is slightly higher (1.6 ... 1.7 T) [9] compared to amorphous iron (1.56 T).
- The fill factor of the steal lamination is higher than the one of the amorphous cut core. So the volume of the amorphous iron core with an equivalent core cross-section is larger.

6.2 Electrical properties and efficiency comparison

Both transformers have almost the same turns ratio of approximately 1:1.04, what leads to a voltage ratio of U_{in}/U_{out} =1 in the case of operation at nominal load, what can be seen also in Figure 6.

The drop of the transformers output voltage over load is also almost identical, what means that the winding resistances of both, input and output winding of both transformers are in the same range. Indeed the winding resistance of the designed amorphous transformer is a bit lower, as voltage drop over load is a bit slower (Figure 6).

Iron losses

The iron losses of both transformers are calculated based on the no load (secondary open circuit) measurements of both transformers using Formula 3.

$$P_{Fe} = P_{in} - R_{pri} \cdot I_{pri}^2 \Big|_{secondary\ open\ circui} \quad (3)$$

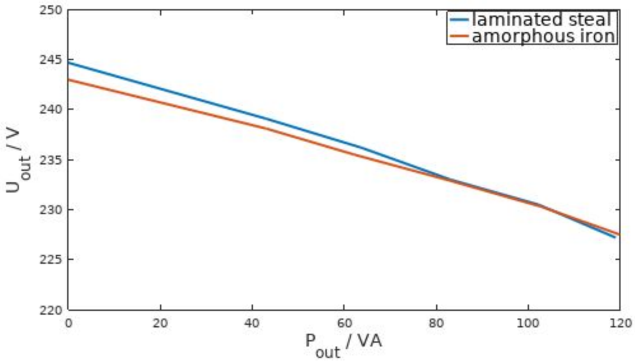

Fig. 6: Transformers output voltage over load ($U_{in} = 230V$)

Tab. 3: Weight and Iron Losses of an Amorphous and a Laminated Steel Core Transformer

Transformer core	Total weight	Core losses
Amorphous Iron Cut Core	2.21 kg	0.59 W
Laminated Steal Core (lamination thickness 0.35 mm)	1.97 kg	4.7 W

Comparing just the iron losses of both transformers, measured in the open circuit test, we find that the transformer with the amorphous core has significantly lower iron losses in total 0.59 W, compared to a similar transformer using laminated steel sheets, as can be seen in Table 3.

This means that the most efficient amorphous iron material is (in our example) able to save more than 87 % of the losses in the magnetic core.

Copper losses

As copper resistances of both transformers are in the same range the copper losses are quite similar over the whole power range form zero to nominal load.

Overall losses

Iron losses are constant, independent of the load of the transformers, while the iron losses increase

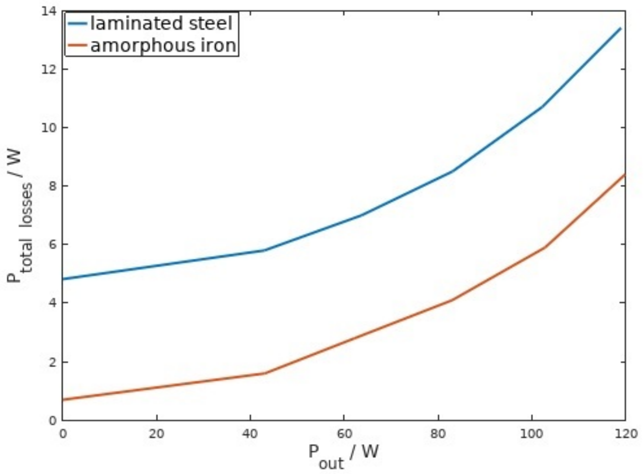

Fig. 7: Transformers losses versus output power ($U_{in} = 230V$)

Tab. 4: Nominal Operation Point ($P_{out} = 110W$) Measurements

Transformer	Power consumption	Efficiency
Amorphous Iron Cut Core	117 W	94.0 %
Laminated Steal Core (lamination thickness 0.35 mm)	123 W	89.4 %

quadratic with the output power. This can be seen on the two curves in Figure 7. Both lines are almost in parallel, but the blue curve - showing the losses of the steal based transformer - has an offset, which is the difference in iron losses.

At the nominal operation point at an output power of 110 W the amorphous iron based transformer has an efficiency of around 94 %, the laminated steal transformer has an efficiency of 89 %.

6.3 Cost and amortization

The manufacturing cost of amorphous ribbon and so of the cut-cores is more labor intensive and so more expensive compared to laminated steal cores. The buy price for a the designed transformer with amorphous iron core is around 25 Euro, while the price for the shown transformer with the laminated steal core is around 10 Euros. Nevertheless, due to its lower losses, the amorphous transformer will pay back after some time. Considering an

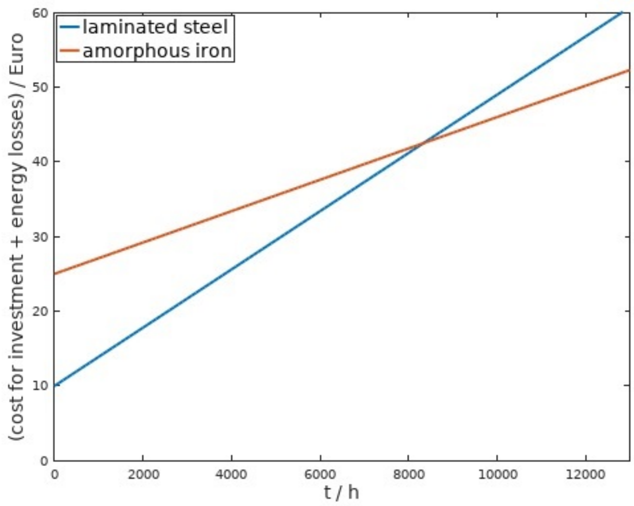

Fig. 8: Transformers losses versus output power ($U_{in} = 230V$)

energy-price of 0.3 Euro the amortization time will be around 8300 hours. This means approximately one year of operation, which is a much smaller than the transformers life time. As the lower power consumption of the amorphous transformer is based on lower core losses, the energy difference is independent of the operation point (Figure 7) and so the amortization time is.

7 Conclusion and Outline

In this paper we showed the measurement procedure to get the iron losses of amorphous materials at 50 Hz. We used this procedure to identify the most efficient of three different amorphous materials. This material was chosen to design a transformer equivalent to a laminated steel one. The electric behavior of both transformers was shown and found to be quit similar. The big advantage of the amorphous based transformer are the significant lowered iron losses, which were decreased to a level of 12.6 % compared the value of the reference transformer with a laminated steal core. The weight of the amorphous transformer was found to be around 10 % bigger.The reason for this is the lower saturation flux density and the fill factor of the material.

Based on the technical advantage - its lower power losses - the amorphous transformer is also the more economic of both parts assuming a normal transformer lifetime, as we showed in a rough amortization time calculation.

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