

Development and Application of Amorphous Core-Distribution Transformers in Québec

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This paper describes research and development activities at Hydro-Québec over the last ten years for improving the efficiency of distribution transformers in Québec. A shell-type (wound-core) design making optimum use of the properties of amorphous metals (Metglas TCA formerly known as Metglas 2605s-2, Allied Signal Inc., Morristown, NJ) was adopted. Dry and oil-cooled, amorphous-core transformer prototypes were built. The joint research and development project was initiated with Transformateurs Ferranti-Packard Ltée, a company of Rolls-Royce Industries Canada Inc., to build and test a few units of high performance transformers on the Hydro-Québec power system.

Keywords
transformer, amorphous metals, magnetic, iron-silicon, losses

1. Introduction

1995 MARKS the twentieth anniversary of the Allied Chemical (today Allied Signal Inc.) announcement of the availability of amorphous iron-silicon-boron alloys, such as Metglas 2605S-2 (Ref 1). The new alloys, made in the form of thin ribbons, have much lower core losses (hysteresis and eddy current) at 60 Hz than those of conventional grain-oriented silicon steels, but there were more than two orders of magnitude difference in price. The price of Metglas, when purchased in large quantities, dropped from about $300 kg in 1978 to below $3/kg in 1995.

Consumption of amorphous steel is expected to grow 25% annually, whereas low-carbon steels (cold-rolled lamination steels) and silicon steels (electrical steels) are expected to grow about 6% annually through 1997 (Ref 2). Cold-rolled lamination steels are primarily used for motors and generators while silicon steels and amorphous alloys are used for transformers. Those three applications represent 86% of the total U.S. market for soft magnetic materials; the balance is composed of soft ferrite (11%) and special metallic soft magnetic alloys, such as iron-nickel, iron-cobalt, and stainless steels (Ref 3). The total U.S. market for soft magnetic materials is approximately $2 billion annually.

2. Results and Discussion

The introduction of amorphous alloys on electrical networks has been in competition with a constant improvement in the properties of grain-oriented electrical steel. Similar to the strong effort devoted to reduce core losses in conventional silicon steels, new materials with losses even lower than those of amorphous alloys were discovered. Table 1 summarizes the properties of some important soft magnetic materials.

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Table 1 shows that the core loss can be reduced by more than a factor of three if the best grain-oriented electrical steel is replaced by amorphous alloys. The recent discovery of nanocrystalline soft magnetic alloys suggests that it will be possible to reduce core losses further in the near future (Ref 6). Indeed, the core losses of nanocrystalline Fe-Zr-Cu-B alloys are half those of amorphous Metglas alloys at 1.3 T and 50 Hz (Ref 5). The microstructure of these new alloys consists of very small alpha-iron crystallites embedded in an amorphous matrix (Ref 5). Since the crystallites are much smaller than the magnetic domains, the effective magneto-crystalline anisotropy is an average over several grains and, thus, is reduced in magnitude (Ref 7). Moreover, the induction limit for Fe-Zr-B nanocrystalline alloys is greater than that of amorphous metals (Ref 6). At this time, however, these new alloys are quite brittle and, therefore, still far from commercialization (Ref 5) (see Table 1, Minimum bending radius after annealing).

Substantial energy savings can be attained by introducing amorphous alloys on distribution networks. Table 2 estimates the total core losses in transformers in the United States (Ref 8). The core losses in distribution transformers in the United States

Table 1 Properties of some important soft magnetic materials

Material	Core loss, W/kg	Operating point	Price, U.S.$/kg	Minimum bending radius after annealing
Electrical steels in 1953 (Ref 4)	4.4	1.7 T, 60 Hz	<1	...
Orientcore HI-B 23ZH90, 0.23 mm	1.12	1.7 T, 60 Hz	~2.5	...
	0.62	1.3 T, 60 Hz		
	0.47	1.3 T, 50 Hz		
Metglas TCA, 0.025 mm	0.18	1.3 T, 60 Hz	<3.0	0.5 mm
	0.14	1.3 T, 50 Hz		
Nanocrystalline Fe-Zr-Cu-B, 0.025 mm (Ref 5)	0.07	1.3 T, 50 Hz	Not available commercially	3 mm

Note: Orientcore is a registered tradename of Nippon Steel Corp., Sumitomo Canada Limited, Quebec.

are about a quarter of the total annual production of Hydro-Québec and, therefore, are quite substantial. There are about 40 million distribution transformers in the United States, and the annual replacement rate is approximately 1 million. Of those new ones, 7 to 10% are amorphous core distribution transformers. In Québec, there are more than 500,000 distribution transformers with about 30,000 new ones added each year. Amorphous core transformers have not been introduced yet, except for experimental purposes.

Ten years ago a program was initiated at the Hydro- Québec Research Institute, IREQ, to develop a transformer based on amorphous alloys. In view of the need for large-scale production and the properties of amorphous alloys, a wound-core, shell-type design was chosen. The IREQ design is shown in Fig. 1 (section III-A).

Compared to others, the IREQ design has several advantages. First, uncut ribbons of very large widths can be used. The core has no sharp corners or parts with small radius of curvature

Table 2 Annual core loss in transformers in United States

Transformers	Core losses, Wh × 10^{12}
Distribution	31
Other	17
Total	48

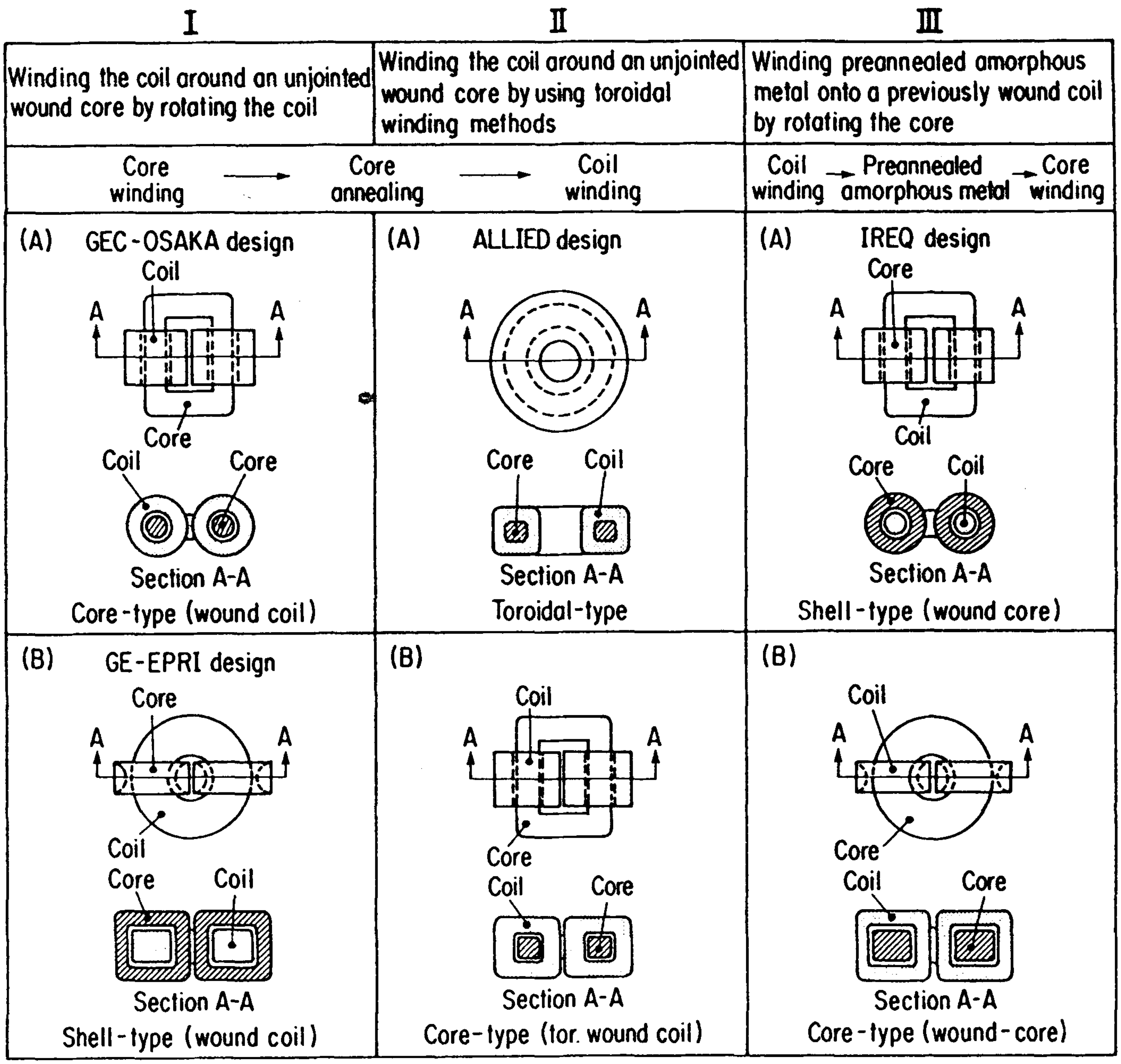
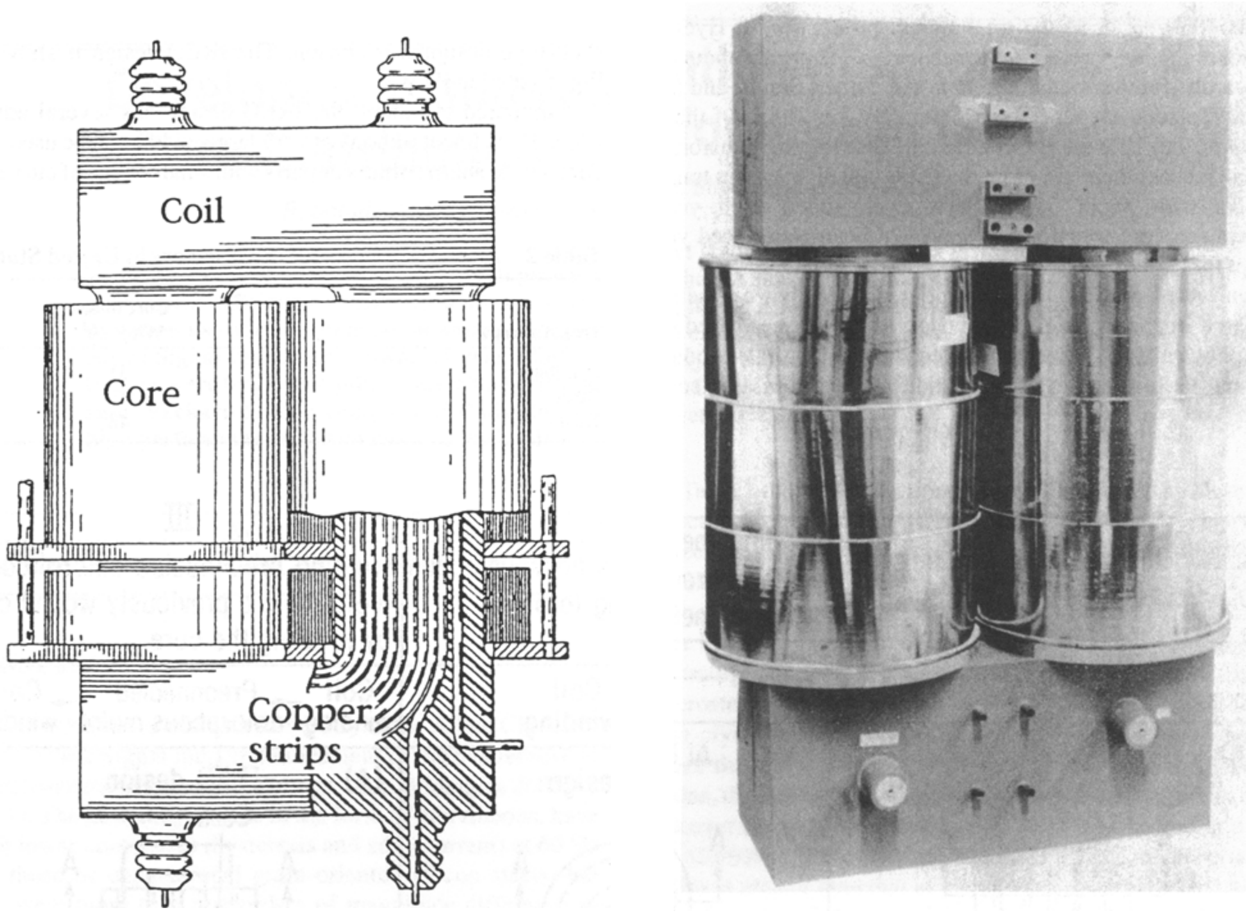


Fig. 1 Various possible core-coil configurations and assembly options for distribution transformers



(a) (b)

Fig. 2 IREQ dry-type transformer. (a) Schematic diagram. (b) Photograph of a 25 kVA prototype, dimension 27 in. by 18 in. by 8 in.

Table 3 Characteristics of a 25 kVA amorphous-core dry-type transformer

Power rating with no internal cooling	25 kVA
Power rating with 4 4 cm^3/s of water	50 kVA
Voltage rating	6.56 kV/115 V
Number of primary turns	1084
Number of secondary turns	19
Total weight	200 kg
Weight of amorphous metal	76.2 kg
Core loss at 1.3 T and 22 °C	18.5 W
Copper loss at 25 kVA	300 W
Copper loss at 50 kVA	1230 W
High voltage winding resistance	25 Ω

where magnetostriction can give rise to higher losses. The design is such that, instead of the usual batch annealing of toroids, continuous on-line thermal treatment of the amorphous ribbons can easily be implemented. We are presently working on the development of this technology. Last, very simple core support can be used because it does not have to hold up the whole assembly as in core-type configurations. The coil assembly is made first by using copper strips of different cross section. After heat treatment (2 h at 360 °C), the annealed ribbon is wound around each leg of the electrical circuit. More information on the manufacturing steps is found in Ref 9 and 10. Figure 2 presents (a) a schematic diagram of an IREQ dry-type transformer and (b) a photo of a 25 kVA prototype built at IREQ.

Table 3 gives general characteristics of the prototype in Fig. 2(b). The measurements were made at the Hydro-Québec Research Institute in Varennes.

Internal cooling was achieved using a cooling coil soldered on the secondary winding. This made it easy to double, if not triple, the nominal power capacity of this type of transformer. For instance, this prototype could handle 100% overcharge with only 4 cm^3/s of cooling flow.

Oil-cooled, amorphous-core transformers also were built in collaboration with Transformateurs Ferranti-Packard Ltée, a company of Rolls-Royce Industries Canada Inc. Five of these transformers with a nominal power rating of 100 kVA and one of 50 kVA were installed on the Hydro- Québec power system and tested over a period of one year. Their properties remained unchanged throughout the year except for a small increase in losses in one of the transformers. Usually a decrease in losses is observed during the first year as the amorphous ribbon is further annealed. The noise levels are comparable to those of conventional transformers and far below Canadian regulations. Four of them are kept on the system for a five-year test.

Table 4 Characteristics of four 100 kVA amorphous-core distribution transformers and a standard transformer of the same power rating

Characteristic	Standard M-4	Amorphous core 1	2	3	4
Core loss(a), W/kg	0.82 (0.30 mm)	0.185	0.18	0.151	0.130
Induction, T	1.38	1.3	1.3	1.35	1.35
No-load losses, W/kg	0.777	0.255	0.187	0.215	0.170
No-load losses, W	206	96	70	63	50
Load losses, W	523	624	582	827	826
Impedance (IZ), %	1.62	2.23	1.90	2.25	2.29
Weight of Metglas, kg	265(b)	375	375	300	300
Total weight(c), kg	550	970	970	675	675
Stacking factor	...	0.72	0.72	0.78	0,78
Core	2 ribbons, 24 cm	6 ribbons, 12.8 cm	4 ribbons, 17 cm	4 ribbons, 21.3 cm	4 ribbons, 21.3 cm

(a) Measured on annealed specimens at 1.3 T and 60 Hz. (b) Weight of the grain-oriented silicon steel (grade M4). (c) Including oil and container.

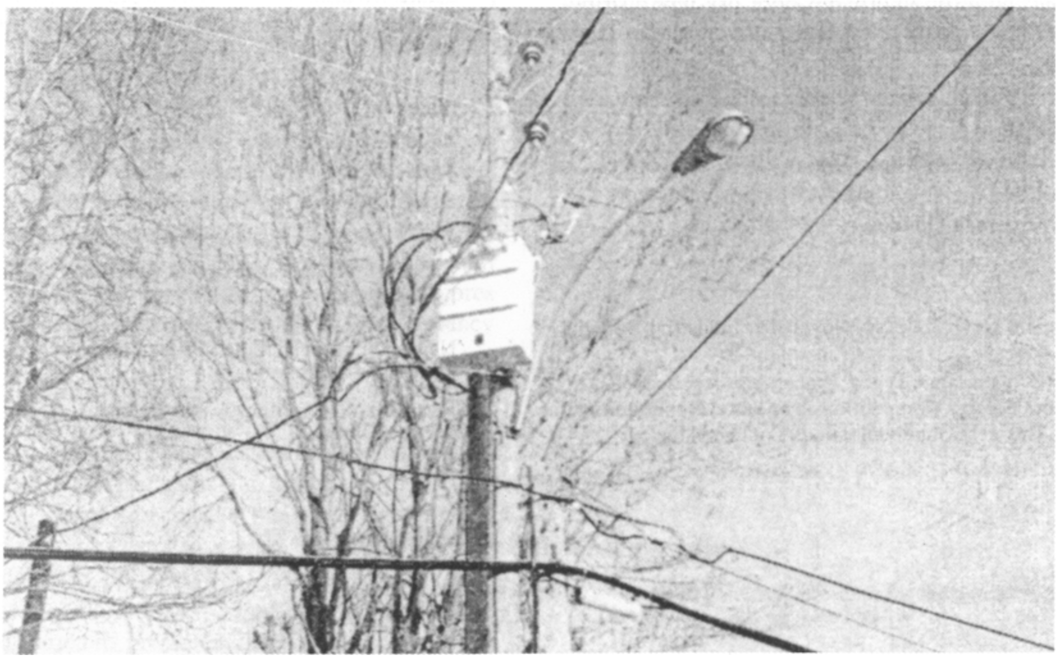


Fig. 3 Pole-type amorphous-core distribution transformer on Hydro-Québec power system

Table 4 compares the general characteristics of four 100 kVA oil-cooled, amorphous-core distribution transformer prototypes built sequentially over a period of about two years with a conventional transformer of the same power rating.

The equipment for heat treating amorphous alloys has improved over the years and is reflected by the decrease in core losses observed from prototypes 1 to 4. Today the heat treatment and winding process for amorphous ribbons is fully automated. Transformers 1 and 2 were designed at 1.3 T induction. The stacking factor was low (0.72), and the total weight of the transformer was higher than that of conventional transformers (970 kg instead of 550 kg, see Table 4). To reduce the weight, a second series of prototypes (transformers 3 and 4 in Table 4) were designed at an induction of 1.35 T and a stacking factor of 0.78. The total weight is 675 kg. About 300 kg of Metglas is used, and the no-load losses were as low as 50 W. The tests were conducted at the Hydro-Québec Research Institute in Varennes. Figure 3 shows a transformer on the Hydro-Québec network.

Table 5 compares amorphous-core and conventional distribution transformers for 50 and 100 kVA power ratings. The advantage of using amorphous alloys to reduce the cost of no-load losses is obvious from Table 5 although, at the present time, this gain is offset by the higher price of the materials. In areas where the cost of the no-load losses exceeds U.S. $5.20/W (current price in Québec), it would be advantageous to use amorphous alloys.

3. Conclusions

Oil-cooled, amorphous-core distribution transformer prototypes were built and tested on the Hydro-Québec power system. The properties of the transformers remained practically

Table 5 Comparative study of amorphous and standard 50 and 100 kVA distribution transformers

	50 kVA		100 kVA	
Characteristic	Standard	Amorphous	Standard	Amorphous
No-load losses, W	126	40	206	50
Load losses, W	327	340	523	826
Impedance (IZ), %	1.58	1.77	1.62	2.29
Weight, kg	335	540	550	675
No-load losses cost, U.S. $5.20/W	655	208	1071	260
Load-losses cost, U.S. $2.80/W	915	952	1464	2313
Total	1570	1160	2535	2573

(a) Transformer No. 4 in Table 4.

unchanged throughout the 12 months of operation. The introduction of amorphous metals on the electrical power system was slow because of the relatively low cost of electricity in this province. Future research and development projects at Hydro-Québec will concentrate on amorphous-core, dry-type distribution transformers making use of the latest materials and of heat pipe for cooling.

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