Amorphous Transformer Contributing to Global Environmental Protection

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OVERVIEW: The electricity grid is essential to the infrastructure of our way of life and, with protection of the global environment having become a matter of urgency, there is a strong need for environmental measures based on achieving greater efficiency in the equipment and systems used in the grid. Hitachi was among the first companies to research and subsequently commercialize amorphous transformers that achieve ultra-high efficiency characteristics by significantly reducing no-load losses (the power consumed by transformers when idle). Development has been ongoing, with objectives such as larger capacity and higher quality, and total shipments to date have reached about 150,000 units. In response to a worldwide demand for environmental protection that is likely to keep growing in future, Hitachi intends to encourage greater use of amorphous transformers in Japan and elsewhere through ongoing strategic technical development and business expansion in which amorphous materials will also play a role. Through these business activities, Hitachi will play its part in bequeathing a rich global environment to the future by reducing transformer losses in the electricity grid.

INTRODUCTION

THE electricity grid is an essential part of our social infrastructure, and with moves to protect the global environment gaining momentum internationally there is a strong need for environmental measures based on efficiency gains and other initiatives that make effective use of the materials and equipment that comprise the grid. The efficiency characteristics of amorphous transformers are dramatically better than those of conventional transformers and Hitachi is helping protect the global environment by working on a comprehensive program extending from materials development to the technologies used in these transformers.

This article describes the background to the development of amorphous transformers and the benefits achieved by their use in Japan.

TRENDS IN EFFICIENCY REGULATIONS FOR DISTRIBUTION TRANSFORMERS

Transformer efficiency is a subject of global attention in the electricity distribution industry and the formulation of efficiency standards is ongoing in Japan and elsewhere.

Trends in Japanese Efficiency Regulations

Japan has led the world in improving the efficiency of distribution transformers with power companies having taken the lead in improving the efficiency of pole-mounted transformer since the 1980s while

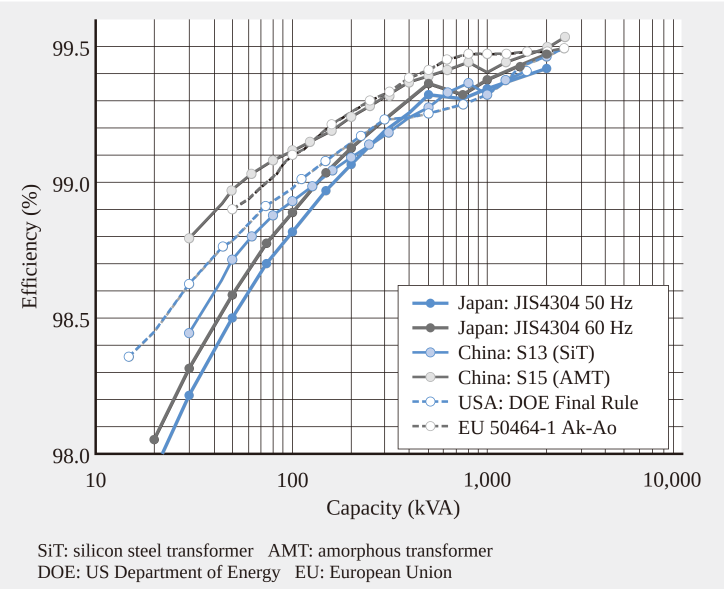


Fig. 1—Comparison of Efficiency Standards for Distribution Transformers (Three-phase Transformers).
While Japan led the world in the introduction of efficiency standards with its Top Runner Program, other countries are now enacting even higher efficiency standards.

for general industrial transformers, oil-immersed transformers were added to the Top Runner Program in 2006 and molded transformers in 2007. Inclusion in the Top Runner Program has seen total transformer losses fall by about 30% producing savings of roughly 16,500 GW·h annually. In terms of CO_2 (carbon dioxide), this corresponds to a reduction in emissions of about 6.2 million t (based on figures published by The Japan Electrical Manufacturers' Association).

To achieve further environmental benefits, work by government agencies, industry bodies, and others on introducing the second stage of the Top Runner Program is already underway with a target date of 2014.

Trends in Overseas Efficiency Regulations

Efficiency standards set by the U.S. Department of Energy (DOE) came into force in January 2010. Work is also in progress on formulating more stringent efficiency standards with a target for implementation in 2016 (see Fig. 1).

In Europe, the latest-introduced EN50464-1 standard stipulates lower losses than the previous standard. Also, transformers were added to the Directive on Eco-Design of Energy Using Products (EuP), an eco-design framework issued in August 2005 with the aim of increasing the efficiency of industrial products. A project reviewing this system is currently underway with the aim of publishing a standard in 2012 that will come into force in 2013.

In China, meanwhile, which is experiencing rapid economic growth, the standards for distribution transformers are being updated to require higher efficiency with the aim of encouraging greater use of higher-performance transformers so that the provision of electricity infrastructure will take greater account of the environment.

As these developments indicate, countries are vying with each other to find ways of boosting the efficiency of distribution transformers meaning that accelerating development of technologies for amorphous and other types of efficient transformer and introducing a regulatory regime that encourages their wider adoption are matters of urgency for Japan if it is to be a world leader in environment measures.

DEVELOPMENT BACKGROUND AND FEATURES OF AMORPHOUS TRANSFORMERS

Hitachi, Ltd. produced a 2-kVA transformer in 1911. This makes the transformer a product with a long history at the company, dating back to the same era as the company's very first product that was an electric motor. Since then, Hitachi has been working to make transformers smaller and reduce their losses while also undertaking developments such as greater capacity and higher voltage. In particular, it is anticipated that amorphous transformers will enter wide use because of their dramatically lower losses compared to previous types of transformer.

Amorphous Ribbon and Amorphous Transformers

Amorphous ribbon is produced by melting its main elements (iron, boron, and silicon) followed by rapid quenching. "Amorphous" means non-crystalline and

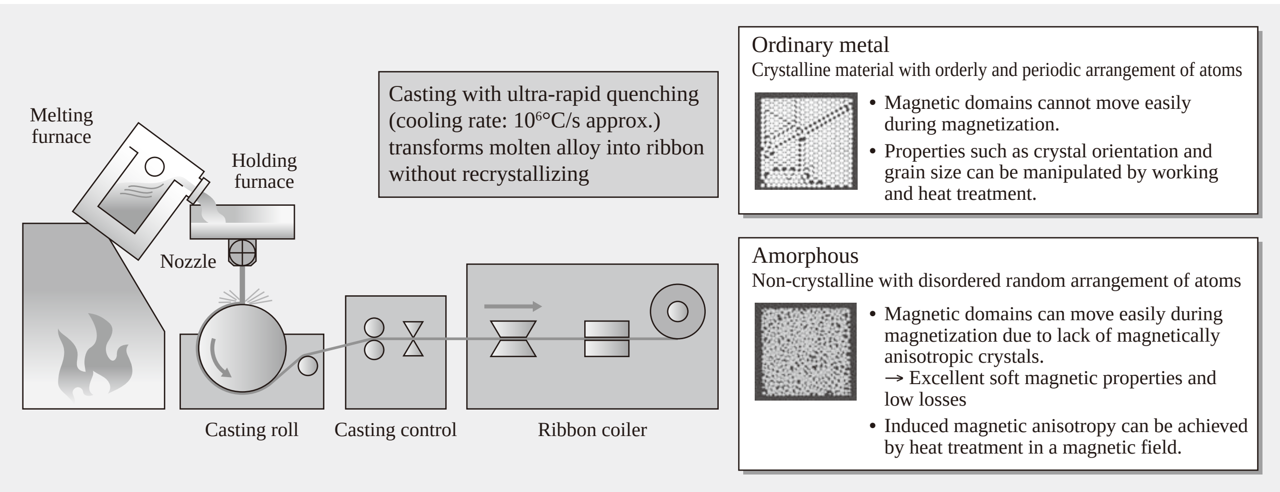


Fig. 2—Features of Amorphous Ribbon and its Production Process.
A casting process with ultra-rapid quenching is used to transform molten alloy into ribbon without recrystallizing. The non-crystalline structure and ultra-thin material characteristics provide superior soft magnetic properties and low losses.

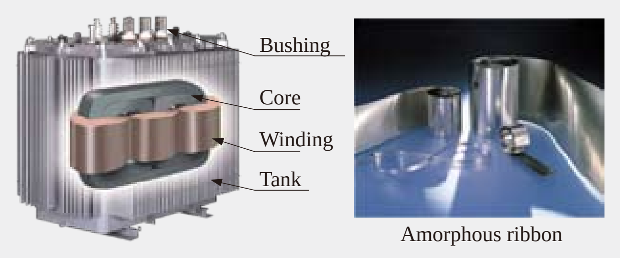


Fig. 3—Amorphous Transformer Structure and Amorphous Ribbon.
Dramatically lower losses can be achieved by using amorphous ribbon (approximately 25 µm thick) for the core.

alloy ribbon can be produced by rapid quenching whereby the material solidifies with the metal atoms in random arrangements rather than forming a periodic crystalline structure (see Fig. 2).

Conventionally, silicon steel has been used as the transformer core material and while steel makers have made great advances in its properties, Hitachi was the first to turn its attention to amorphous transformers that use amorphous ribbon as their core material and engage in active development of the product in order to reduce losses further (see Fig. 3).

Background to Development of Amorphous Transformers

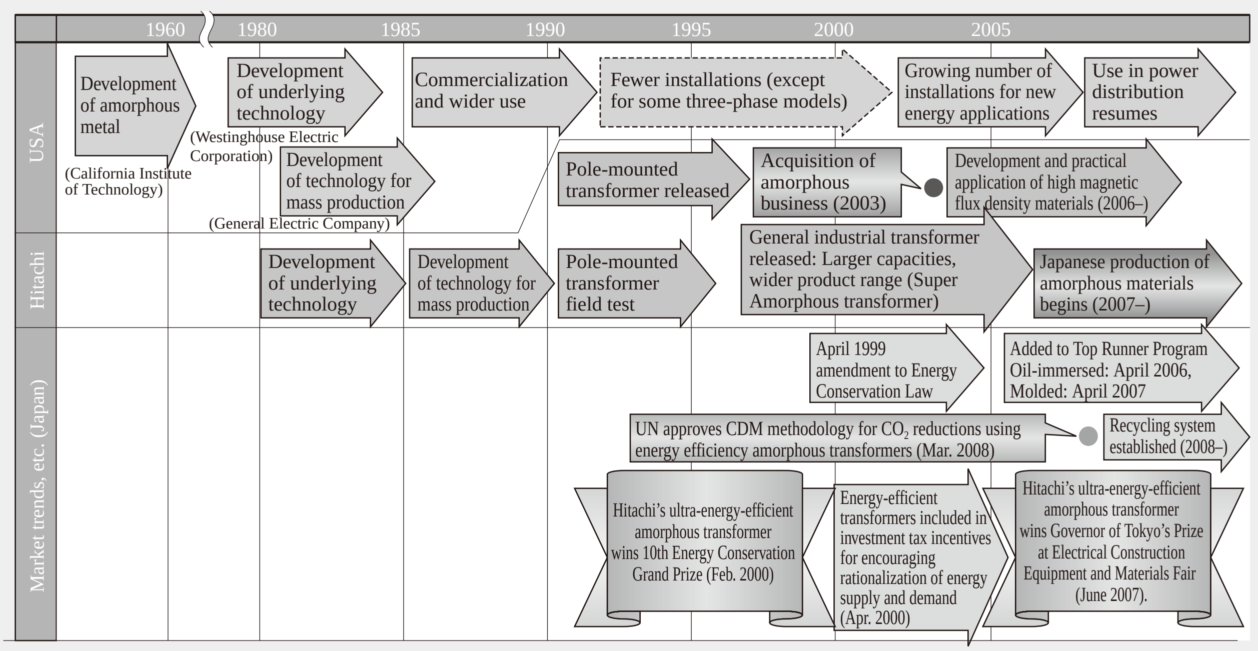
Fig. 4 shows the history of amorphous transformer development and application by Hitachi.

Development of the underlying technology started in the early 1980s. Pole-mounted transformers for power companies were released in 1991 followed by a general industrial transformer in 1997. Since then, Hitachi has been filling out its product range and has been improving further performance with the result that over 150,000 units have been shipped in 20 years since entering the market. With the aim of making its transformers truly environmentally conscious, Hitachi established a recycling system of amorphous alloy that has been adopted by some of power companies since 2008.

Regarding Hitachi's materials business, Hitachi Metals, Ltd. acquired the amorphous products business of Honeywell International Inc. (USA) in 2003 and established a new production facility at its Yasugi Works in Shimane Prefecture, Japan in 2007 in addition to its US plant. Together, these provide an annual capacity of 100,000 t to meet the growing demand for amorphous ribbon from around the world.

Features of Amorphous Transformers

Transformer losses can be broadly divided into the no-load loss that occurs continuously regardless of the load and the load loss that is proportional to the square of the load current. Amorphous transformers have very low no-load losses giving them much lower



UN: United Nations CDM: clean development mechanism CO_2: carbon dioxide

Fig. 4—History of Amorphous Transformer Development and Application.
Hitachi started development at an early stage and undertook comprehensive technical and business development covering everything from materials to the transformer itself to satisfy society's need for environmental protection.

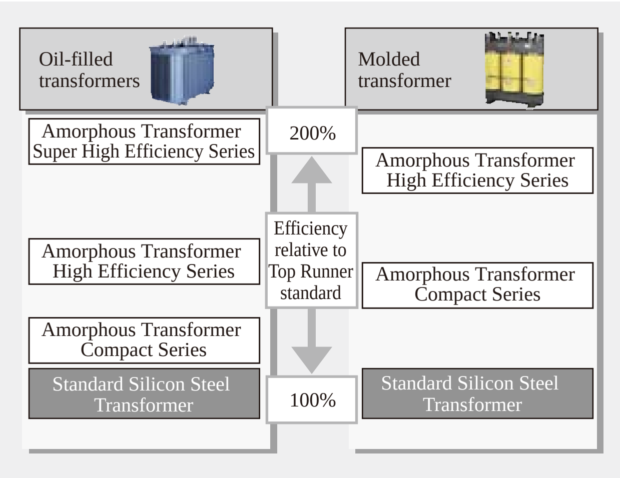


Fig. 5—Amorphous Transformer Product Range.
When choosing a transformer, it is important to consider the actual load factor and choose the best possible model based on its efficiency characteristics. Hitachi has a number of different series of amorphous transformers to suit different customer needs.

losses than conventional transformers. They have particularly good efficiency when used as distribution transformers commonly at mean load factor of around 20 to 30%(1), (2). Hitachi has an extensive range of transformers including silicon steel models so that customers can select the transformer that best suits their load factor (see Fig. 5 and Fig. 6).

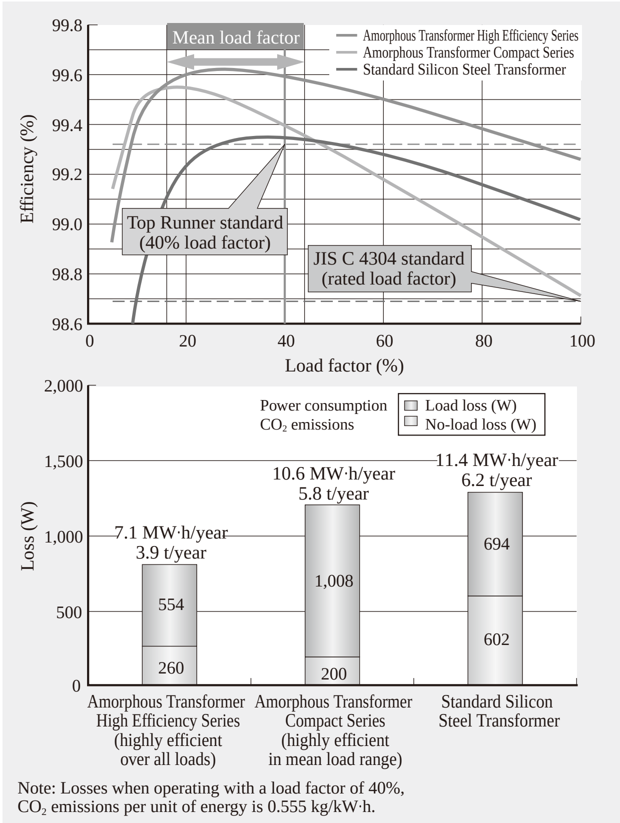
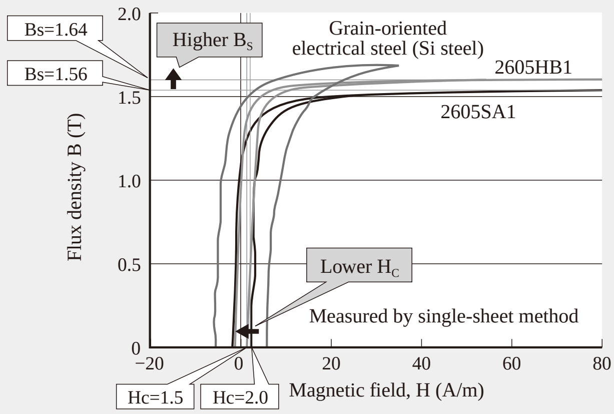


Fig. 6—Features of Amorphous Transformers (3 Phase, 500 kVA, 50 Hz).
Amorphous transformers have a very low no-load loss and a good efficiency particularly in the low load range where generally transformers are operated.

Material	Saturation flux density B_S (T)	Coercive force H_C (A/m)	Electric resistivity ρ (μΩ · m)	Iron loss $P_{13/50}$ (W/kg)	Magneto-striction λs (ppm)	Sheet thickness t (mm)	Lamination factor SF (%)
Grain-oriented electrical steel (Si steel) (highest grade)	2.03	45.0	0.5	0.440	−1	0.23	>95
Amorphous material (2605SA1)	1.56	2.0	1.3	0.070	27	0.025	>84
New amorphous material (2605HB1)	1.64	1.5	1.3	0.063	27	0.025	>84
Remarks	Higher values allow smaller size.	Lower values produce lower losses.	Higher values produce lower losses.	Smaller is better.	Lower values mean quieter operation.	Thicker is easier to work.	Higher values allow smaller size.



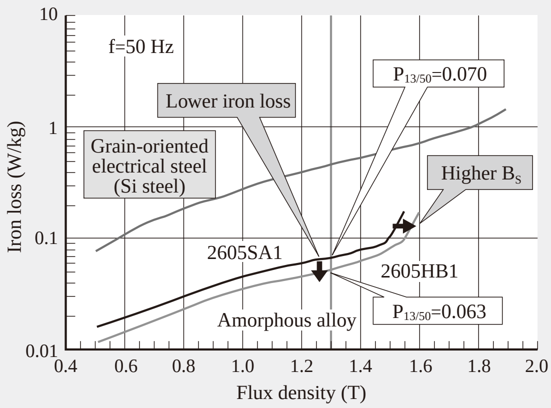


Fig. 7—Characteristics of 2605HB1 Amorphous Material with High Magnetic Flux Density.
To improve transformer performance and specifications, Hitachi is working on comprehensive developments extending from materials to techniques for their application in transformers. The benefits of using 2605HB1 include lighter transformers with lower losses.

Item		Single-phase power transformer 6 k/210 V 20 kVA 60 Hz		
		SiT	AMT(SA1)	AMT(HB1)
External diameter (mm)		364 (100)	385 (104)	355 (98)
Height (mm)		713 (100)	740 (104)	707 (99)
Weight (kg)		138 (100)	170 (128)	148 (107)
No-load loss (W)		61 (100)	22 (36)	17 (27)
Load loss (W)		281 (100)	285 (102)	280 (100)
Total loss (W)	Rated load	342 (100)	307 (90)	297 (87)
	40% load	106 (100)	68 (64)	62 (58)

Fig. 8—Comparison of Specifications for Transformers Using 2605HB1.
Use of 2605HB1 allows amorphous transformers to be produced with similar dimensions and weight to existing silicon steel transformers.

Trends in Technology Development for Amorphous Transformers

Due to its lower saturation flux density than that of silicon steel, amorphous transformer has some disadvantages such as in size and weight. Amorphous transformers are larger and heavier than silicon steel transformers. To resolve this problem, Hitachi Metals, Ltd. embarked in 2003 on development aimed at increasing the saturation flux density based on iron base amorphous alloy: 2605SA1. This led to the 2605HB1 high-flux-density material entering full-scale production in 2005. Fig. 7 shows the characteristics of this new material with its superior flux density.

Because it was anticipated that use of 2605HB1 would have many benefits including making the amorphous transformers smaller, lighter, and quieter, work on incorporating the new material into the transformer was undertaken in parallel with material development[3]. It was first used by a power company in 2006 and is increasingly being adopted in general industrial transformers (see Fig. 8).

The product is also attracting attention overseas where it is expected that amorphous transformers will become more widely used in future and Hitachi is working to further improve its performance and reduce costs.

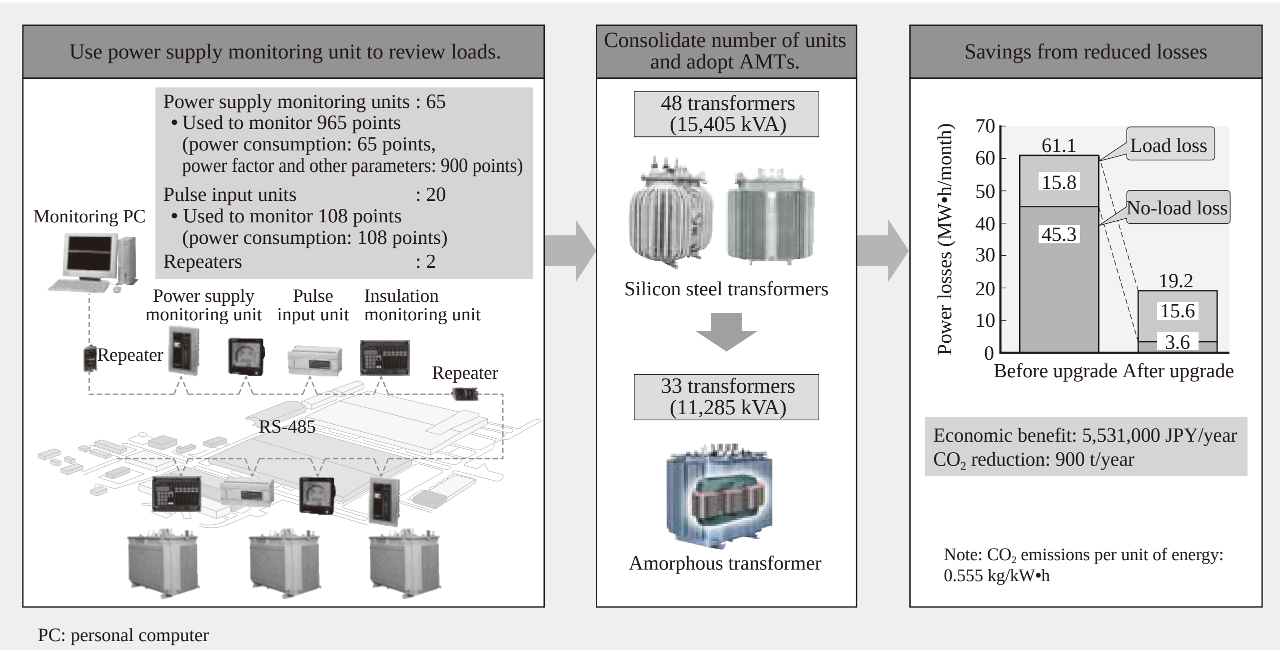


Fig. 9—Case Study of Benefits of Amorphous Transformer Installation.
Hitachi Industrial Equipment Systems succeeded in reducing power losses to one-third of their previous level at its Nakajo Division by consolidating transformer numbers and adopting amorphous transformers, thereby achieving significant economic benefits while reducing the burden on the environment.

BENEFITS OF INSTALLING AMORPHOUS TRANSFORMERS

As explained above, the low loss characteristics of amorphous transformers provide significant benefits for energy conservation and reducing the burden on the environment.

Case Study of Installation at Hitachi Industrial Equipment Systems' Nakajo Division

Nakajo Division, Hitachi Industrial Equipment Systems Co., Ltd. is fed by a 66-kV line that is stepped-down to 6 kV for distribution around the site. The 6-kV supply is further stepped-down at each production facility to provide the low-voltage supply to the various equipment. To conserve energy and reduce unit emissions of CO_2, electricity distribution monitoring systems were installed at each production facility in 1997 to make visible the electricity usage of each production line. When aging transformers were subsequently upgraded, the results from these systems were used to determine the number and capacity of new transformers based on the operating conditions at each production line and a significant reduction in electric losses was achieved by using amorphous transformers throughout (see Fig. 9).

Estimate of Benefits from Installing Amorphous Transformers in Japan

Amorphous transformers are making a major contribution to reducing CO_2 emissions with a total of approximately 400,000 currently in use made up of about 390,000 pole-mounted transformers for power companies (including those from other suppliers) and about 12,000 general industrial transformers (including both oil-immersed and molded).

TABLE 1. Benefits of Installing Amorphous Transformers (Across Entire Grid in Japan)

Although the benefit per transformer is small, the large number of distribution transformers in use means the total benefit is large.

User	No. in use (×10,000)	Average capacity (kVA)	Loss reduction (kW/transformer)	CO_2 emissions per unit of energy (kg·CO_2/kW·h)	CO_2 reduction (t/year)
Power companies	39.0	20	0.04	0.453*1	61,900
General industry	1.2	500	0.95	0.555*2	55,500
Total	40.2	–	–	–	117,400

*1: Mean actual value for power use in Japan in 2007 published by The Federation of Electric Power Companies of Japan
*2: Default value stipulated in the directive on estimating greenhouse gas emissions resulting from the business activities of certain emitters (Ministry of Economy, Trade and Industry/Ministry of the Environment Directive No. 3, 2006)

This achieves a big reduction in the burden on the environment, corresponding to a reduction of roughly 120,000 t/year in CO_2 emissions, and it is anticipated that use of these transformers will continue to grow in Japan and elsewhere (see Table 1).

CONCLUSIONS

This article has described the background to the development of amorphous transformers and the benefits achieved by their use in Japan.

Amorphous transformers are also attracting attention in other countries. Installation of amorphous transformers is currently growing rapidly in Asia, particularly in China and India where environmental measures are being adopted in parallel with the provision of infrastructure. It is also expected in future in America and Europe that measures aimed at protecting the environment lead to the prevalence of high performance transformers[4] and it is predicted that use of amorphous transformers will expand all around the world.

To respond to the social requirement, Hitachi contributes to keeping a rich global environment for the next generation by supplying products and service protecting with environmental measures in the power distribution field.

REFERENCES

(1) M. Takagi et al., "An Evaluation of Amorphous Transformer Using Load Curve Pattern Model for Pole Transformer," IEEJ Transactions on Power and Energy **128**, pp. 885−892 (2008).
(2) "Potential for Global Energy Savings from High Efficiency Distribution Transformers," Leonardo Energy Transformers (Feb. 2005).
(3) A. Sato et al., "Development of Distribution Transformer Based on New Amorphous Metals," CIRED2009 Session 4 Paper No. 0474 (2009).
(4) "Amorphous Metal Transformer: Next Steps," EPRI White Paper, Electric Power Research Institute (Jul. 2009).

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