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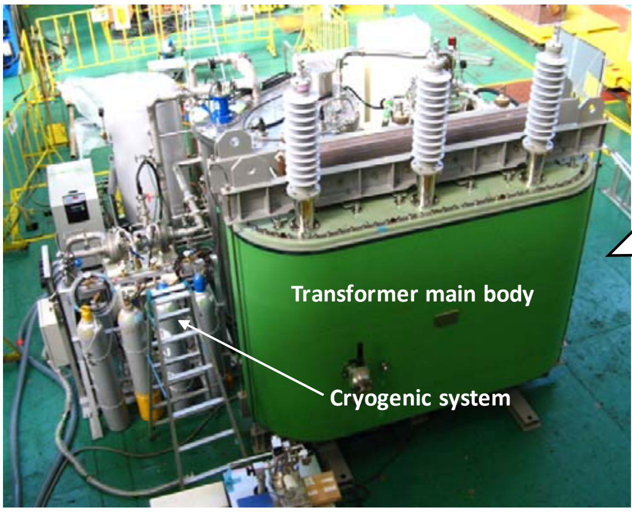
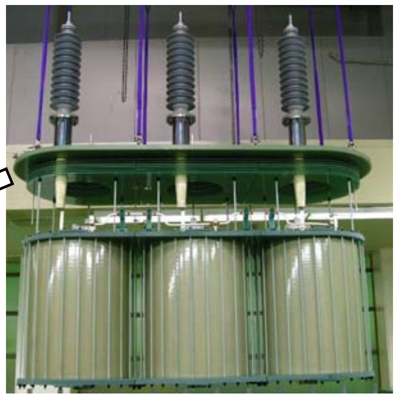
Feature Article: Development of Superconducting Power Equipment Technology
- Technology Development of A Superconducting Transformer

Hidemi Hayashi, Sub-leader
Superconducting Transformer Group
R&D of Yttrium-based superconducting Power Development

A transformer can be made highly efficient and compact by employing a superconducting wire exhibiting low ac-loss characteristics. In particular, Yttrium-based (hitherto Y-based) superconducting wires have large critical current properties even at high temperatures. Additionally, the filament process applied to superconducting wires further reduces ac losses and is expected to reduce wire costs in the future. Therefore, the earlier realization of a Y-based superconducting transformer intended for practical use is anticipated.

Under the “Technology Development of Y-based Superconducting Power Equipment,” a superconductivity technology development project led by NEDO, the author and his group have developed and demonstrated a 66kV/6kV-2MVA high-temperature superconducting transformer. The transformer is the world’s largest class Y-based superconducting transformer, fabricated to determine the performance attributes and to investigate the fabrication methodologies required for the ultimate realization of a 20 MVA-class superconducting transformer for practical use. Additionally, the current limiting functionality afforded by superconducting wires has been verified by employing a several-hundred kVA-class prototype transformer. Kyushu Electric Power Co., Inc. has led the consortium with collaborations between Fuji Electric Co., Ltd, Taiyo Nippon Sanso Corporation, International Superconductivity Technology Center (ISTEC), Fujikura, Showa Cable Systems Co., Ltd, Kyushu University, Iwate University, and Japan Fine Ceramics Center (JFCC), for the periods between 2008-2012.Figure 1 shows a 2 MVA-class superconducting prototype transformer used for demonstrations in this study.





Wire winding of superconducting transformer

Fig.1 Outline of a 2 MVA-class high-temperature superconducting transformer (Main body of transformer; length 1.6 m, width 3.2 m, height 3.7 m)

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The developmental status of component technology and the transformer system technology was introduced in the November 2011, December 2012 and June 2013 issues of Superconductivity Web21. This article summarizes the attributes of a superconducting transformer equipped with fault current limiting (FCL) function, with the research findings determining the feasibility of such a system.

1. Investigations of a superconducting transformer equipped with FCL function

The wire windings of a transformer equipped with FCL were cooled using sub-cooled liquid nitrogen in order to maintain the insulating characteristics. A non-magnetic GFRP vessel was employed and in addition, the iron core was set to room temperature to prevent thermal loads affecting the cooling system due to core loss. The % impedance of transformers with and without current limiting functionality was set at 10 % and 15 %, respectively.

To take advantage of the attributes afforded by a superconducting transformer, it was necessary to reduce the iron core volume by increasing the superconducting wire winding volume. This, however, increases the impedance, which has to be adjusted by increasing the number of magnetic paths between the wire-windings. Figure 2 shows the resulting weight of the iron core, wire length and wire-winding height utilizing voltage between turns as a comparison parameter. An optimized design voltage was 41.5 V/turn when considering each of these factors.

A cable comprised of a Y-based superconducting wire and CuNi wire allowed the transformer to have current limiting functionality. Figure 3 shows the analysis results of resistance required for current limiting functionality, categorized by the thickness of the CuNi-layer and thickness of the silver layer in

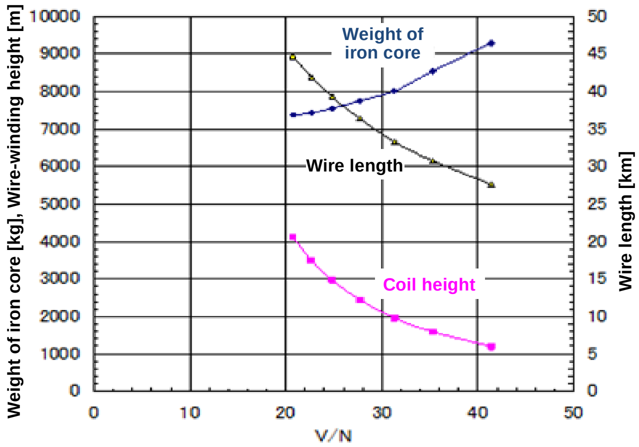

Fig.2 V/N dependency of voltage between turns of transformer

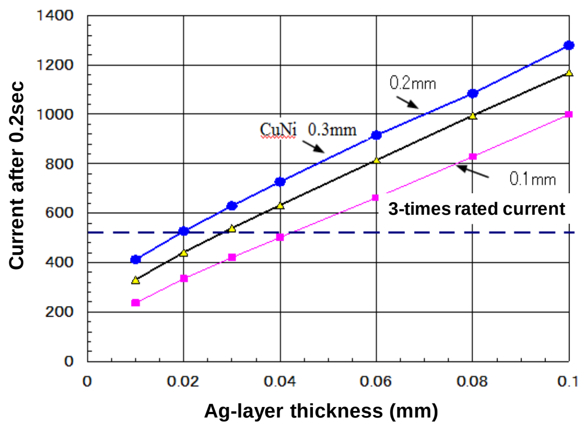

Fig.3 The variation in short-circuit after 0.2 sec and the Ag-layer thickness

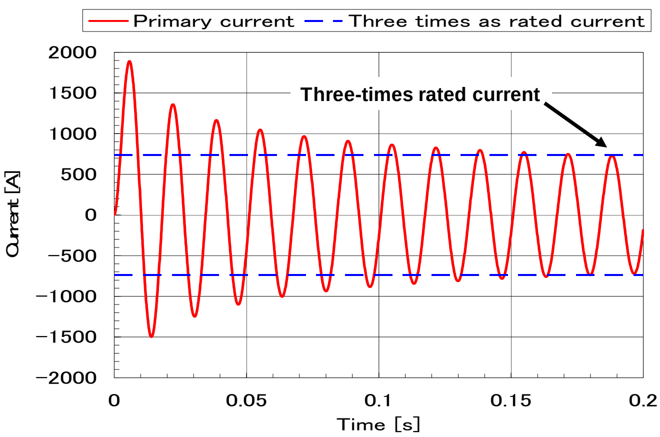

Fig.4 Short circuit current analysis of transformer equipped with current limiting functionality

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Y-based superconducting wires. Current-limiting requirements that offer protective coordination of the transmission system necessitate the short circuit current to be set to less than three-times the rated current for 0.2-sec short circuit durations. Figure 4 shows the transient analysis results of short circuit current measurements for a transformer employing an 18μm silver layer and 0.3mm-CuNi layer in superconducting wire. The findings reveal that the favorable operational characteristics of the wire have short circuit currents of less than three-times the rated current.

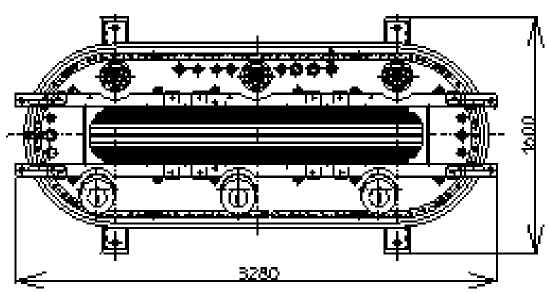
Table 1 shows comparison transformer specifications without current limiting functionality and a 66kV/6.9kV three-phase 20 MVA-class superconducting transformer equipped with current limiting functionality, and based upon the research outcomes detailed in this article. Wire-length was reduced by about 7 %. Table 2 shows a comparison with a conventional oil-immersed transformer. The measured loss was 46 % of an oil-immersed transformer, even taking into account the cooling drive having a COP of 0.06, as well as its weight and its footprint reduced by half. This confirmed greater efficiency and compact characteristics compared to existing transformers. Figure 5 shows an outline of a transformer equipped with current limiting functionality.

Table 1 Comparisons of superconducting transformers with or without current limiting functionality

	With current limiting functionality	Without current limiting functionality
Number of phases, wire connection type	3Φ, Y−Y	
Rated voltage	66 kV/6.9 kV	
Rated current	175 A/1,674 A	
% Impedance	10%	15%
Number of turns	918/96	1033/108
V/N	41.5	36.9
Cable structure	3/24 parallel	3/24 parallel
Wire length	33.1 km (8.0/15.0 km)	35.6 km (19.3/16.3 km)

Table 2 Comparisons of superconducting transformers and oil-immersed transformers

Type	Superconducting transformer	Oil-immersed transformer
Loss	46%	100%
AC Loss/ohmic loss	31 % (AC Loss)	91 % (ohmic loss)
Core loss	7%	9%
Thermal leakage	8%	
Efficiency	99.7 %	99.4 %
Weight (including cryocooling)	50%	100%
Footprint (ditto)	51%	100%



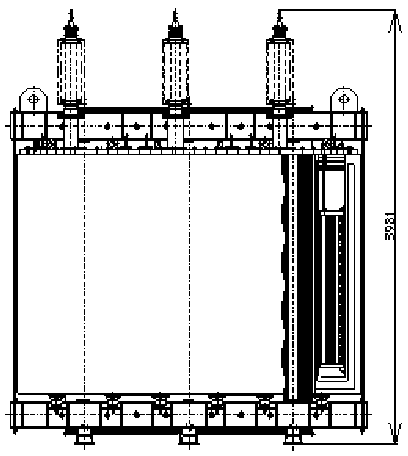


Fig. 5 Outline of a 66kV/6.9kV three-phase 20 MVA-class transformer equipped with current limiting functionality

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2. Feasibility of superconducting transformer applications

Figure 6 shows a potential transformer with current limiting functionality applied to power transmission systems. The figure aims to denote the effectiveness in loop operations and the protection offered by increased short circuit capacity utilizing a dispersed power source, in addition to potential current limiting effects observed in conventional power transmission lines. Figure 7 shows the system comprising of the superconducting cable and superconducting transformer. The effectiveness of a transformer equipped with current limiting functionality is highly anticipated to offer protection from increased risk of short circuit capacity due to a large-current superconducting cable.

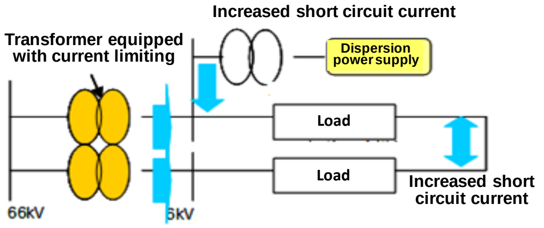

Fig. 6 An example application of a transformer equipped with current limiting functionality applied to power transmission system

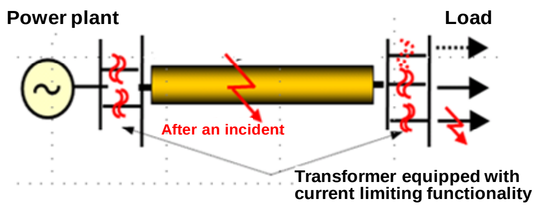

Fig. 7 An example application of a superconducting cable and transformer equipped with current limiting functionality

Figure 8 shows examples of superconducting transformer applications employed in the entire grid system. Arrays of applications include transformer, power supply, grid system, transmission, industrial and transportation use, etc. When superconductivity is applied to transformer applications and current limiting functionality is added, expectations such as compactness, higher efficiency, and effectiveness in short-circuit protection will be realized.

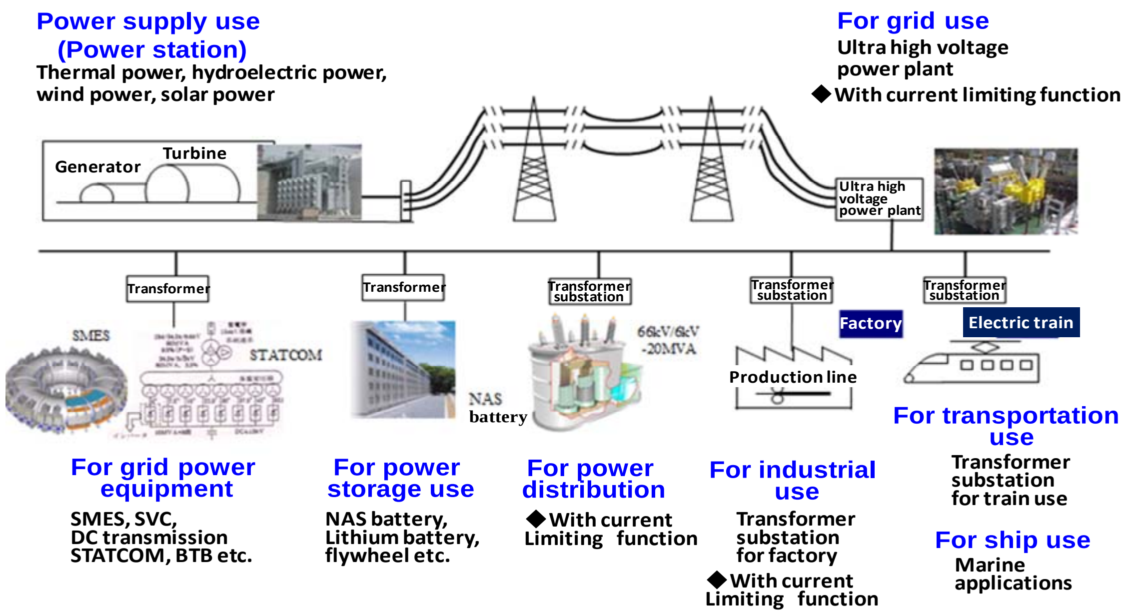

Fig. 8 An example of a superconducting transformer application

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3. Conclusions

R&D investigations into a superconducting transformer equipped with current limiting functionality confirmed a % reduction in impedance and additional cost reduction due to a reduction of wire length. An example of a transformer equipped with current limiting functionality applied to the grid system as well as feasibilities of superconducting transformers applied to the entire grid system were also explained. The author anticipates that based upon the research outcomes, superconducting transformers will be realized for practical use in industry and power utilities in the future.

The technology development was undertaken as part of the Y-based superconducting power equipment technology development project, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

Top of Superconductivity Web21