The development of the flywheel energy storage system applying the high temperature superconducting magnetic bearing (second report) - The development and the performance evaluation examination of the SMB for the FESS demonstration machine -

Motohiko SUGINO**, Yoshiki MIYAZAKI*, Ken NAGASHIMA*, Masafumi OGATA*, Tomohisa YAMASHITA*, Hitoshi MATSUE*, Taro MATSUOKA**, Kengo NAKAO**

*Maglev Division, Railway Technical Research Institute

2-8-38 Hikari-cho, Kokubunji-shi,Tokyo 185-8540, Japan

E-mail: sugino.motohiko.79@rtri.or.jp

**Furukawa Electric Co.,Ltd,

6 Yawata-kaigandori, Ichihara-shi, Chiba Pref. 290-8555, Japan

Abstract

The flywheel energy storage systems (FESS) that can stabilize the fluctuation of the output of the solar photovoltaic power generation system have been developed as a joint project of five enterprises. A high temperature superconducting magnetic bearing (SMB) with high temperature conducers for its coils of stator and high temperature bulks for its rotor was developed in the project. Because it can support the large load of the rotor without contact was developed. This machine is characterized by the complete high temperature superconducting of SMB. In July, 2013, the production of the SMB for the FESS demonstration machine was started. In December, the superconducting rotor was installed to the shaft that was set on the superconducting magnetic bearing, and the SMB for the FESS demonstration machine was completed. After the production of the SMB, it was installed in the FESS demonstration machine. The FESS demonstration machine was reinstalled in the power plant, and the examination of the charge/discharge with solar photovoltaic power by the FESS demonstration machine was conducted. The long time levitation examination in the no rotating state was conducted to confirm the performance of the long time operation. After the examination, the examination of the charge/discharge with solar photovoltaic power was conducted. The SMB showed the stable ability of levitation as the main device of the FESS demonstration machine. With respect to the development project of the FESS proof machine, the planned process was completed, and also all the examinations were completed in February, 2016. During all the period, the SMB operated automatically without abnormality and showed high reliability.

Keywords : Flywheel energy storage systems, High temperature superconducting magnetic bearing, Stabilization, Solar photovoltaic power, Charge/discharge, Development project.

1. Introduction

The flywheel energy storage systems (FESS) that can stabilize the fluctuation of the output of the solar photovoltaic power generation system have been developed as a joint project of five enterprises subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

The FESS converts electricity into the kinetic energy of rotation and stores it. The following performance was required: an increase in mass and the improvement of the rotating speed for the sake of an increase in the storage capacity of the FESS, the reduction of the energy loss of rotation for the sake of an increase in the efficiency of operation, the stability for long-term use.To satisfy these requirements, a high temperature superconducting magnetic bearing (SMB) with high temperature conducers for its coils of stator and high temperature bulks for its rotor was developed in this project.

In this report, the development of SMB during the past 4 years is summarized and the following results are reported: the design process, performance evaluation examination of a unit device, the performance evaluation examination of a device of the FESS demonstration machine in the operation state.

2. Development framework of the SMB for the FESS demonstration machine

Railway Technical Research Institute and Furukawa Electric Co., Ltd. took charge of the development of the SMB in this project. At first, Railway Technical Research Institute designed the specifications of the SMB such as levitation force, magnetomotive force, and analyzed its characteristics such as the magnetic field, and eddy current heat generation caused by the magnetic field fluctuation. (1) ~(3)

The specifications required for the SMB and decided by the results are shown in Table 1.

Table 1 The specifications of the SMB for the FESS demonstration machine

Levitation force	40,000 N
the stator coil	REBCO conductor Five double pancakes that are arranged concentrically
the rotor bulks	Three GDBCO bulks that are arranged concentrically
The temperature in operation	Under 50K
Cooling method	The stator coils : Conduction cooling The rotor bulks : Gas cooling by low pressure helium gas

Baced on the specifications above and the analysis results, Railway Technical Research Institute and Furukawa Electric Co., Ltd. decided the specifications of SMB which met the specifications of the FESS demonstration machine jointly in this project. (4) Then, Furukawa Electric Co., Ltd. designed the constitution of the devise such as the structure of the stator coils and the cooling method of stator and rotor, and produced it. (5) ~(7)

The development of SMB has been conducted for four years starting from 2012 when the project started.

3. Summary of the SMB for the FESS demonstration machine

In this FESS demonstration machine, the magnetic bearings comprised two kinds of magnetic bearing as shown in Fig. 1; the active control magnetic bearing(AMB) that supports the inertial force in the radial direction of the rotor and controls whirling, the superconducting magnetic bearing that produces a magnetic field and levitates the rotor in a stable state. The production cost of SMB is dozens of times in comparison with the ordinary bearing. However, the superconducting magnet can support the large load of the rotor without contact. The service life of the FESS can be extended by removing the parts that are worn by the friction. The SMB can generate high magnetic field in compared with a passive magnetic bearing. Therefore the SMB can support large mass and its component can be composed with light weight and small size. The superconducting magnet bearing was adopted by these reasons.

To improve the stability of the SMB for long-term operation, superconducting stator coils made by REBCO conductors and a superconducting rotor made by GdBCO bulks were combined. This machine is characterized by the complete high temperature superconducting of SMB.

In addition, the active controlled magnetic bearing (AMB) that is superior in a control response during the high speed rotation and is able to support the rotor without contact was adopted as a bearing in the radial directions. The protection bearing for urgent landings is installed as a protect device for the SMB trouble.

4. The design process of the SMB for the FESS demonstration machine

The specifications of the materials which require long time for their production such as the material of the vacuum vessel for SMB or the high temperature superconductive conductor were decided prior to the decision of the whole specifications of the SMB. In November, 2013 when all the design examinations were completed, the whole design specifications of SMB were decided as shown in Table 2.

Table 2 The specifications of the SMB for the FESS demonstration machine

The temperature in operation			50 K or less
The exciting current			77 A over
The stator coils	REBCO conductor manufacturer		Super Power .Inc
	Width		6 mm
	Dimension	Inner diameter	120 mm
		Outer diameter	260 mm
The rotor bulks	Manufacturer		Sumitomo Electric Industries, Ltd.
	Arrangement of bulks		Inverse convex
	One HTS bulk for upper part	Diameter	140 mm
		Height	20mm
	Two HTS bulks for retainer part	Diameter	90 mm
		Height	20mm
Cooling method	The stator coils		Conduction cooling
	The rotor bulks		Gas cooling by low pressure helium gas

Figure 2 shows the internal configuration of the SMB. The layer between the inner vessel and the outer vessel was kept in a vacuum for thermal insulation, the layer inside the inner vessel was filled with thin helium gas to cool the superconducting rotor by gas conduction cooling.

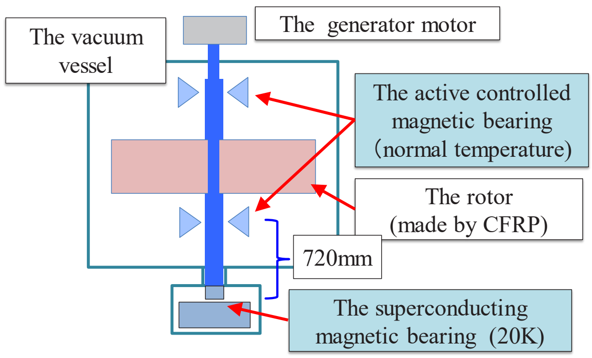


Fig .1 Magnetic bearing constitution in the FESS demonstration machine

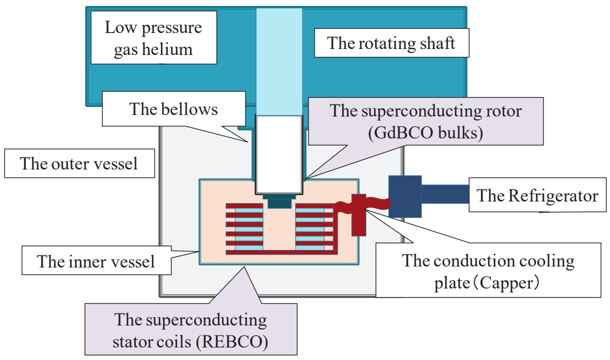


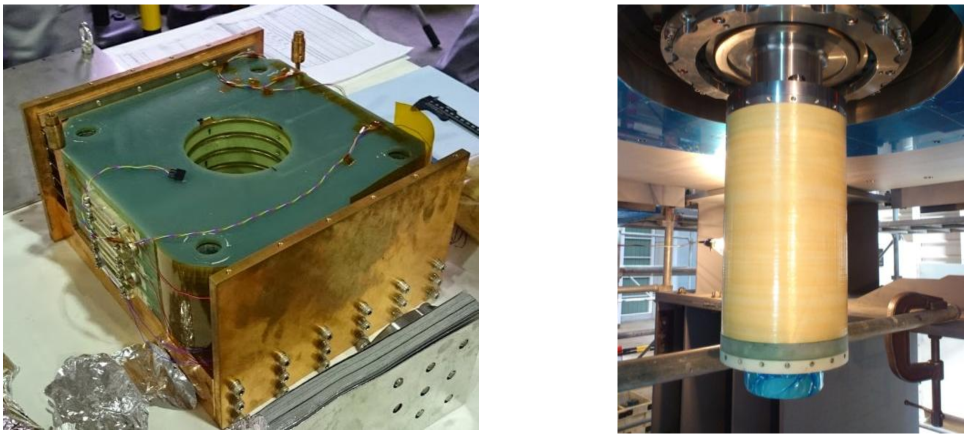
Fig.2 Internal configuration of the superconducting

5. The production of the SMB for the FESS demonstration machine

In July, 2013, the production of the SMB for the FESS demonstration machine was started.

At the design stage, the rotating shaft of the FESS demonstration machine was divided into three parts so as to make it easy to be assembled: the shaft at the vacuum seal part, the shaft at the center of the rotor, and the shaft that was set on the superconducting magnetic bearing. In the course of assemblage, these shafts were connected to be completed as a rotating shaft. In December, 2014 when the parts of the rotating shaft were being produced, the superconducting rotor was installed to the shaft that was set on the superconducting magnetic bearing, and the SMB for the FESS demonstration machine was completed.

The rotor and the stator of the produced SMB for the FESS demonstration machine are shown in Fig.3.



(a) The stator (b) The rotor (installed to the shaft)

Fig .3 The produced SMB for the FESS demonstration machine

6. The performance evaluation examination of the SMB

6.1 The performance evaluation examination of the SMB as a superconducting device

In the development of the SMB, both the performance as the superconductor and that as the bearing were evaluated in parallel. After completion of production of the SMB, the performance evaluation examination as the superconductor was conducted, and the performance that was necessary for operation was confirmed.

At first, the evaluation examination of the cooling performance necessary for keeping the superconducting state of SMB was conducted. [8] Figure 4 and Fig.5 show the results of the examination. The SMB was cooled and the equilibrium state of the temperature was established at 18 K. It was confirmed that the stator and rotor were cooled to the superconductivity transition temperature by the conduction cooling with the refrigerator.

Then, the temperature rise after the refrigerator was stopped in the cooling state was measured, and the cold reserving ability of the SMB in case the refrigerator is not able to cool was confirmed. 60 minutes after from the refrigerator stopped, the SMB kept cold less than 35K, then it was confirmed that the SMB kept the superconducting state. 60 minutes become the maximum allowable duration for emergency stop in operation. It was confirmed that the SMB maintained the levitating state of the rotor of the FESS demonstration machine up to the time when the FESS stopped in case abnormality of the refrigerator occurred.

After the cooling performance was confirmed, the SMB was excited at 50K and 30K, and the levitating force of the rotor was measured. [9] The results of the measurement are shown in Fig.6. It was confirmed that the levitating force was generated at 50K and 30K according to the results. The results accorded almost with the analytical results. It was confirmed that the levitating force of 40 kN was generated in accordance with the design.

Figure 7 shows the measurement results of the magnetic field at the center of the excited coils. The results accorded almost with the analytical results that predicted at the design process that it was more than 1.5T. It was also confirmed that the magnetic field was generated in accordance with the design.

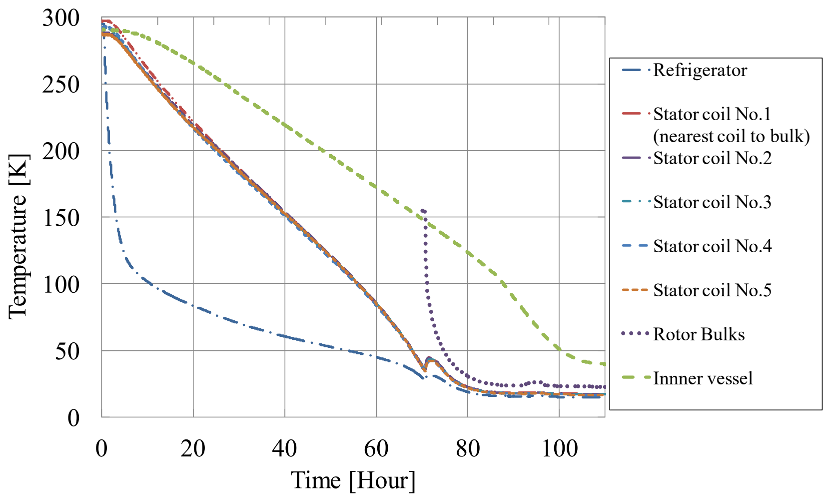


Fig.4 The cooling experiment of the SMB

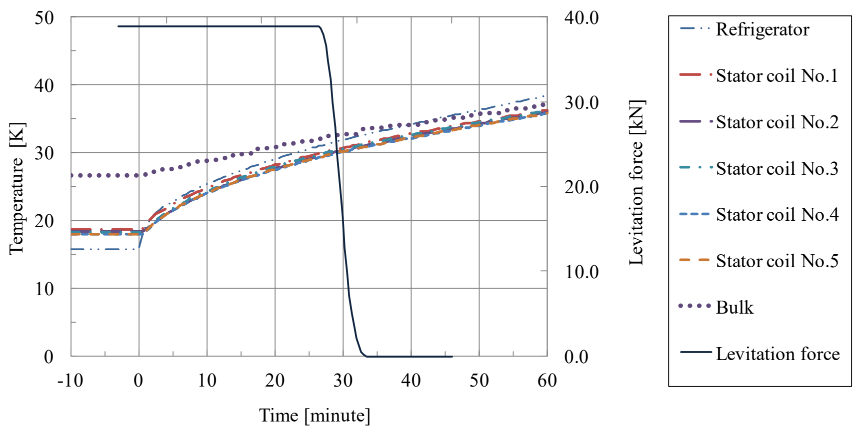


Fig.5 The cold reserving ability measuring experiment

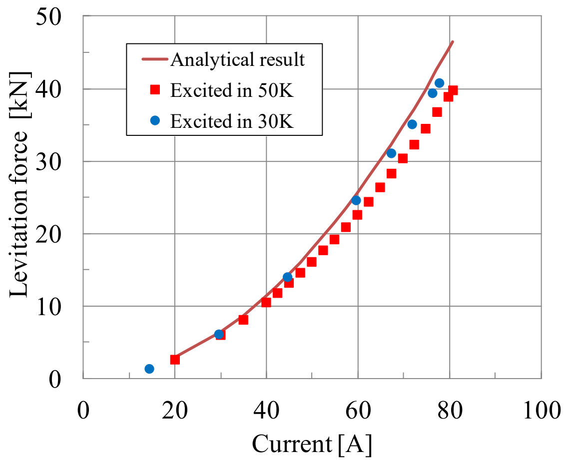


Fig.6 The levitation force exciting experiment

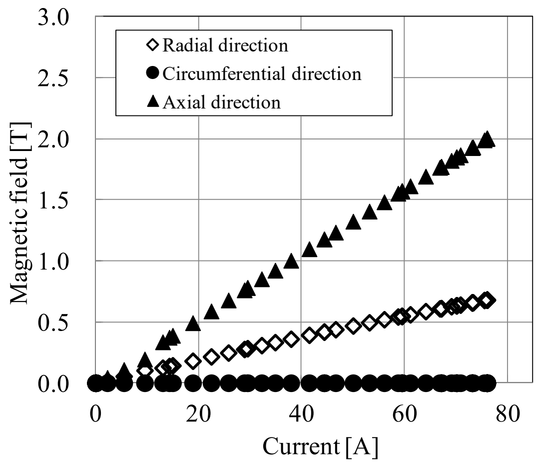


Fig.7 The measuring result of magnetic field

6.2 The evaluation examination of the performance as a magnetic bearing

Generally, the bigger electromagnetic force can be generated when the levitation gap is smaller in the case of the device that uses electromagnetic force. On the other hand, there is a demerit that the contact and damage become easy to occur when the gap is small and the displacement becomes large.

The dimension of the parts that are rotated at high speed and the dimension of the part that is not rotated are examined in consideration of both the problems. Then, the levitation gap dimension of SMB was decided. The minimum gap is decided to be 2.0 mm at the bellows which are installed to the part through which the shaft is penetrated to the SMB. To verify no occurrence of the contact of the rotating parts of the SMB with the bellows which they are rotating at high speed, the examination in which the separated shaft before installing and the rotor of the SMB were rotated at high speed was conducted. [10] The produced SMB rotor was installed to the shaft that was set on the superconducting magnetic bearing. The shaft was hung under the motor and was rotated up to 120 Hz or more in the air. The displacements of the two ends of the rotating shaft were measured by two laser displacement gages.

The results of the examination are shown in Fig.8. The surface displacements of the rotating shaft are within 0.2mm that is one-tenth of the minimum gap. It was confirmed that the abnormality such as the deformation that occurs due to whirling or high speed rotation did not occur.

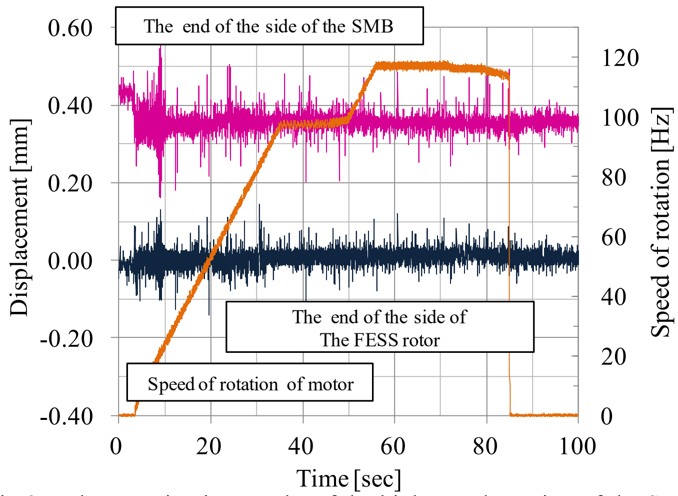


Fig.8 The examination results of the high speed rotation of the SMB rotor

Then, the shaft to which the rotor of the SMB was installed was installed to the SMB and was cooled up to 40 K. The shaft in the SMB was rotated up to 67 Hz in the state that the thermal contraction occurred. According to the visual confirmation after the examination, there was no contact of the rotating parts of the SMB with the bellows due to the high speed rotation at the operation temperature.

The confirmations of the function as a unit were completed by having obtained these results of the examinations.

8. The operation result as the main device of the FESS demonstration machine

8.1 The installing to the FESS demonstration machine

After the production and the examinations of the developed SMB, it was installed in the FESS demonstration machine in February, 2015. The adjustment examination of the FESS demonstration machine after assembling was conducted until May in the factory. The exciting examination and the operation check of the devices were conducted during the assembling period, and it was confirmed that the SMB maintained the same performance as that before installing. A solar power plant with a grade of 1MW is operating at Mt. Komekurayama that is located in Kofu City, Yamanashi Pref. The examination plant of the FESS demonstration machine was constructed in the solar power plant. The machine was reinstalled in the power plant in July 2015, and the examination of the charge/discharge with solar photovoltaic power by the FESS demonstration machine was conducted.

8.2 Operation examination

8.2.1 The long time levitation examination in the no rotating state

When the long time operation was conducted, the decrease of the levitation force that was caused by the invasion of the magnetic flux to the GdBCO bukls of rotor was apprehended. The long time levitation examination in the no rotating state was conducted to confirm the performance of the long time operation. To prevent the sudden landing, the exciting current was increased to 80A before the examination, and the levitation gap was adjusted to be 20 mm that was 5 mm higher than the gap in the operation state.

The results of the examination are shown in Fig.9. The apprehended decrease of the levitation force that is caused by the invasion of the magnetic flux occurred, and it converged after about 100 hours. Thereafter, the levitation gap and the exciting current became stable. The no occurrence of the landing due to the decrease of the levitation force and the stability of the levitation force in the long time levitation were confirmed by the examination results. In addition to these results, the following protection functions were incorporated to the control unit for safety in operation: the function to maintain the levitation gap by detecting the decrease of the gap and increasing the exciting current within the range that the conductor can maintain the superconducting state, the function to order the emergency stop of the FESS demonstration machine in case where the SMB is not able to maintain the levitation gap even if the exciting current is increase.

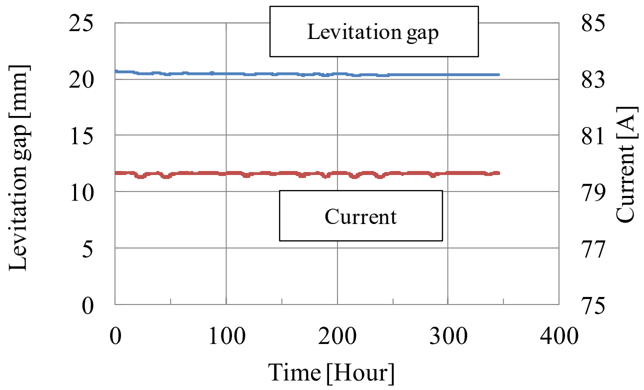


Fig.9 The results of the long time levitation examination in the stable state

8.2.2 The long time levitation examination as a part of the examination of the charge/discharge with solar photovoltaic power

After confirmation of the operation performance of the main devices including SMB, the examination of the charge/discharge with solar photovoltaic power was conducted in December, 2015. The speed of rotation was greatly changed for several hours in the examination. Figure 10 shows the results. The SMB maintained the levitating state even if the speed of rotation was greatly changed. The fluctuation of the levitation gap was within 0.5 mm as confirmed by the examinations. The SMB showed the stable ability of levitation as the main device of the FESS demonstration machine. The power that the superconducting bearing require to keep the superconducting state was 2.9kW. The power loss at rotation such as helium gas friction and friction of vacuum seal was very smaller than the output of the FESS, and it could not be measured.

8.2.3 The operation results through the examination of the FESS demonstration machine

With respect to the development project of the FESS proof machine, the planned process was completed, and also all the examinations were completed in February, 2016. The conclusive operation results of the SMB as of March 1, 2016 were as follows: consecutive levitation time is 2,000 hours (24 days) of, total levitation time is 545 hours.

During all the period, the SMB operated automatically without abnormality and showed high reliability.

9. Conclusion

With the completion of all the examinations in February 2016, the development project of the FESS demonstration machine was completed. And the high temperature superconducting magnetic bearing (SMB) with high temperature conducers for its coils of stator and high temperature bulks for its rotor was developed in this project.

After the production and the examinations, the SMB was installed in the FESS demonstration machine. The long time levitation examination in the no rotating state and in the rotating state was conducted to confirm the performance of the long time operation. After the examination, the long time levitation examination as a part of the examination of the charge/discharge with solar photovoltaic power was conducted. The SMB showed the stable ability of levitation as a main device of the FESS demonstration machine in all examinations.

After this, we will push forward studies with a focus on the higher performance of the SMB.

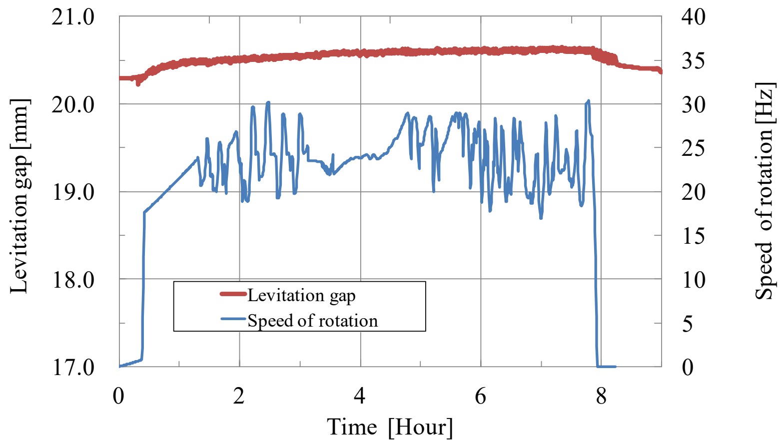


Fig.10 The long time levitation examination during the examination of the charge/discharge with solar photovoltaic power

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