First tests of a Bi/Y transformer

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Abstract. High Temperature Superconducting (HTS) materials bring to transformers benefits such as weight reduction and improve the efficiency as well as the electrical behaviour in the network. In the frame of an European project called READY we designed a 41 kVA 2050 V / 410 V single phase transformer. The primary winding uses a PIT-Bi-2223 tape. A first secondary is wound with two lengths of YBCO coated conductors. We designed the transformer as a whole device with an integrated cooling. The cooler is a large cooling capacity (100 W at 80 K) single stage coaxial pulse tube cooler (PTC) developed by Air Liquide. We chose a cold magnetic circuit with low iron loss FeSi sheets. The cryostat is then very simple with metallic vessels and only one interface with the cooling system. The cooling fluid is helium in order to investigate a large temperature range (40 - 80 K). About 30 hours are required to reach 70 K from ambiant temperature using only the PTC. The thermal losses are around 20 W at 35 K. The article presents also electrical transformer test (no load and short circuit tests) with an half primary and a reduced secondary (75 V - 50 A @ 77 K). The A.C. losses are high in the PIT coil. In the YBCO coil the A.C. losses are in good agreement with the Norris formula.

1. Introduction

Transformer are key devices in power grids. Since their discovery in 1882, a lot of improvements have been brought but now only the use of superconductor makes possible to significantly enhance their performances in term of weight in particular. The superconductors due to their very current densities increase the ampere turns and reduce the magnetic circuit section, then the transformer weight. Nevertheless the losses must very low to keep a very high efficiency. The transformer is an A.C. device and the windings show A.C. losses. Fortunately the magnetic induction level is low on the windings which is favourable for low A.C. losses. The idea of superconducting (SC) transformer is old [1] but only the emergence of low ac loss NbTi wire in the eighties made possible and successful the construction of SC transformer with a high efficiency. The very high cost of 4 K cryogenics makes nevertheless the economical viability of NbTi transformers very difficult. The cryogenic cost decreases rapidly when the temperature increases, so the revived interest of SC transformers with high temperature superconductors [2]. But to open the large distribution transformer market to the SC solution, cryogenics and SC wires should meet some requirements in terms of performance and cost.

2. READY project

The READY project funded by the European Community aims to produce about 60 meter YBCO tape for a single-phase 41 kVA power transformer. This project has nine partners (academia and companies) ranging from material supplier to system integrators and end users. One objective was to promote the SC transformer by integrating its cryogenics. Since the YBCO tape is limited in length, only the secondary winding uses a coated conductor. The primary is wound with a more conventional PIT Bi-2223 tape.

3. Transformer general structure

A transformer has a rather simple structure. It basically consists of a magnetic circuit and windings. The use of superconductors require their cooling. But when both the magnetic circuit and the windings are cooled, the cryogenic structure is also simple, the whole transformer is in a simple cryogenic vessel at the convenient temperature. Since the flux is confined in the transformer, the vessels can be metallic so a well known and mastered technique. The cooling of only the SC windings makes the cryogenic design more difficult. A three phase transformer requires three cryogenic vessels with a complex toroidal shape. They should use composite materials to avoid eddy current losses. These materials are more difficult to use in cryogenics compared to stainless steel. The porosity of the fibre materials sets some difficulties for long-term operation without pumping.

Nevertheless the iron losses of a cooled magnetic circuit must be multiplied by the refrigeration penalty ratio which depends on the temperature and the refrigeration system rating. For an operating temperature of 70 K the multiplying factor is about 15 to 30. This is the important penalty for the cold iron option. Low loss magnetic materials must be used in this case. Amorphous materials could be appropriate.

The choice of the magnetic circuit operating temperature will depend on the transformer purpose (optimization criteria, operating conditions, load factor, ...). To cut a long story short, the distribution transformers will preferably use a warm iron and the railway transformers a cold iron.

The READY experimental transformer was designed with a cold magnetic circuit for an easy interface with the cryocooler and a good cryogenic integration, one of the scope of the project. The iron losses are high all the more we should chose conventional iron sheet for availability reasons. The magnetic circuit uses low loss scratched (surface laser treatment) high induction grain oriented HiB FeSi 23/100 sheets.

4. READY transformer design

The 41 kVA transformer was designed with the READY specifications that is 60 m coated conductor with an operating current of 100 $A_{r.m.s.}$ (141 A_{max}). This length is low taking into account the rating and the current. Since we chose a cold iron, we optimized the transformer to get the lowest cold losses (iron and A.C. winding losses). The primary and secondary are interlaced in order to reduce the magnetic field on the conductors for low A.C. losses. If the primary, instead of being between two half secondaries, is beside the primary the magnetic field is multiplied by two. The specific iron losses of the FeSi HiB laminations were measured at 77 K to get the accurate value for the design. The iron losses increase only slightly at 77 K compare to room temperature.

The main parameter are in table 1. This table gathers also two other designs without the 60 m specification, but optimized one for minimum losses and the other for minimum weight. These two designs led to the same superconductor length and A.C. losses. The absence of length constraint reduces the losses by a factor 5 or the iron weight by a factor 2.5 in function of the design criterion.

Table 1 shows the advantage in terms of A.C. losses of coated conductors compared to PIT tapes all the more the Ni substrate iron losses contribute to 60 % of the conductor losses. The low A.C. losses are linked to the small thickness of the YBaCuO layer (1 μm). The major losses of the READY transformer are the iron losses.

Table 1. Parameters of 41 kVA single phase transformers.

Quantity	Fixed SC length	Minimum losses	Minimum weight
Capacity / Operating temperature	41 kVA - 50 Hz / 77 K		
Primary / Secondary	2050 V - 20 A / 410 V - 100 A		
Core	HiB scratched FeSi lamination		
Flux density	1.46 T	0.72 T	1.5 T
Weight / Losses	72 kg / 50 W	75 kg / 10 W	29 kg / 20 W
A.C. losses : primary/secondary	3 W / 0.18 W	8 W / 0.51 W	8 W / 0.51 W
Secondary length	59 m	160 m	160 m
Short-circuit reactance	0.75 %	2 %	2 %

5. Cryogenic design and test

Figure 1 shows the cryogenic design. The cold source is a single stage coaxial Pulsed Tube Cryocooler (PTC) specialy developed by Air Liquide and CEA/SBT [3] for easy integration. Figure 2 gives its cold power in function of the cold head with a 6.5 kW helium 50 Hz compressor. Its cold head is screwed on a copper flange where the upper part of the magnetic circuit is glued. The iron and the windings are in a vessel, filled with helium or nitrogen. A larger temperature range can be investigated with helium which is easier to manage too. This vessel is inside a vacuum vessel. The copper flange is supported by a composite material tube. The PTC is so freely fixed on the external flange to avoid any stress on it. A thermal shield surrounds the windings inside the vessel. It reduces the temperature rise on the conductors at the coil extremities when the cooling is performed by helium gas. The thermal shield consists in isolated copper wires thermally connected to the copper flange. This configuration reduces the eddy currents in copper since it is very close to the windings. With a copper shield thickness of 2 mm the SC conductor temperature is reduced nearly by 4 K. A higher thickness does not bring further temperature reduction. The electrical (current leads, voltage taps), instrumentation (platinum sensors) and fluid connections are made through two exits (tubes). The temperature sensors are connected to a data acquisition unit linked to a micro-computer. This processes the data, regularly stores them and displays them on a screen.

The operating temperature is given by the balance between the PTC power and the total losses. Higher temperatures can be regulated thank to a heating resistance on the copper flange. Using the design data, the operating temperature should be about 65 K on the coils (59 K on the PTC cold head). Lower temperatures can be reached by decreasing the voltage. The iron losses are nearly proportional to the square of the voltage and they are a major contribution to the total losses. Temperatures lower than 50 K should be reached by operating at half of the rated voltage.

On the outside, the transformer is a cylinder. It has to be connected to a helium compressor for the cooling. Its cryogenic use is very easy, just plug and start the compressor as well the valve on the PTC. The cryogenic integration and transparency for the user were two scopes of the project.

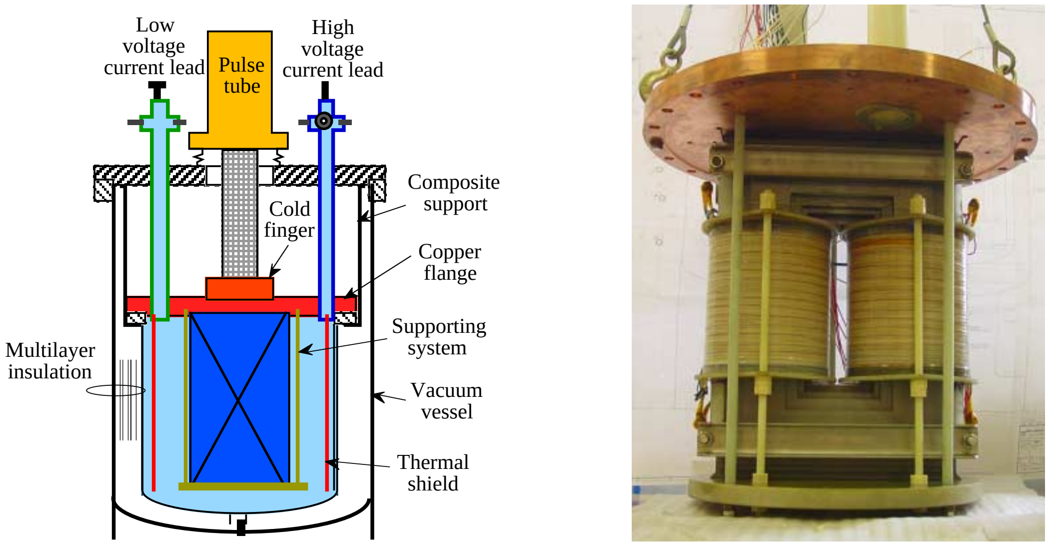


Figure 1. General transformer skeleton diagram and transformer picture.

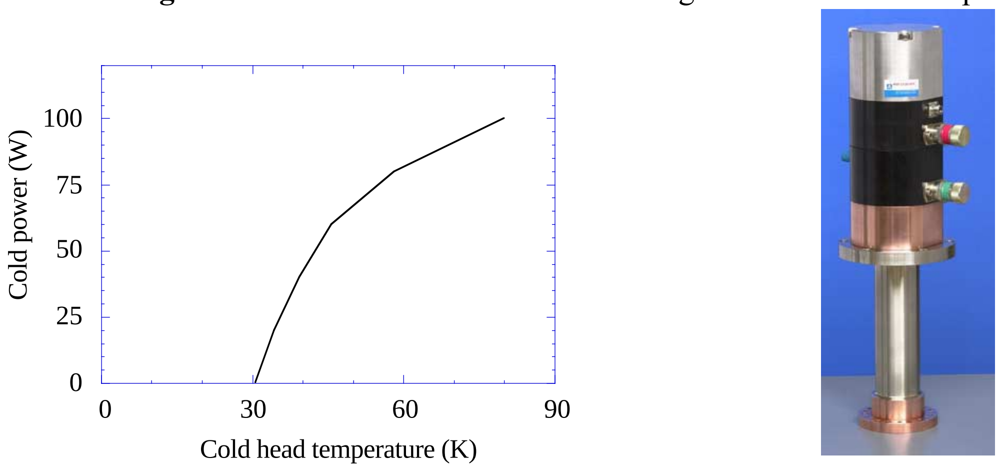


Figure 2. Cold power versus temperature of the Air Liquide TGP.

Figure 3 shows the cooling down of the transformer after the PTC starting. One and an half day is necessary to reach the minimum temperatures.

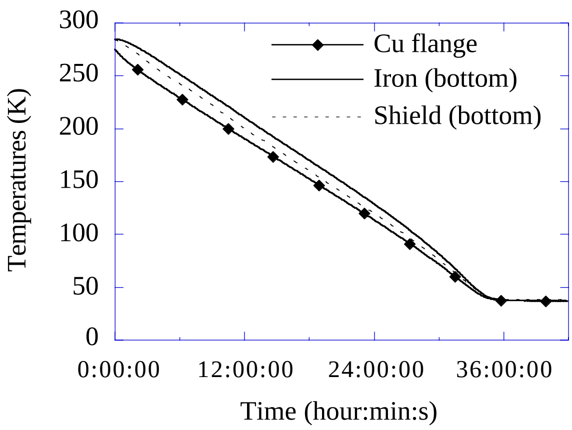


Figure 3. Different temperatures during the cooling down.

From the minimum temperature and the PTC characteristics the total thermal losses are about 20 W. It is rather high but for this experimental transformer there are more current leads than strictly necessary and there bring losses. The two exits could be better optimized in term of losses too.

6. Superconducting windings

The two primary coils are wound with each about 160 meters of Bi PIT non isolated tape (3.6 x 0.22 mm^2) from Vacuumschmelze GmbH. An isolating wire wound simultaneously isolates the turns between them and a Kapton® foil isolates the layers between them. The coils have 9 layers and the total number of series turns is 333, a little higher than designed. The critical performances of the tape are also lower than the hypothesis taken for the design. The critical currents for the coils 1 and 2 are 19.3 A and 18.5 A in self field condition at 77 K (100 µV/m criterion). The 50 Hz A.C. losses of both coils alone were also measured. They are rather high due to the transverse field component at the extremities of the solenoids. The losses increase about as the square of the current. For coil 2 the 50 Hz A.C. losses are 10 W for a current of 16 $A_{r.m.s.}$. One coil does not operate properly after the first tests, it shows an abnormal heating at one extremity. The reasons are not clear, short circuit turns, PIT tape damage, ...

The production of high performance long length coated conductors is very difficult and it takes a long time to perfecting the elaboration process. READY partner succeed to elaborate reduced length samples with high critical current density [4, 5] but it was not possible in the project time scale to get long length conductors. So it was decided to obtain coated conductors from C&C Technologies [6] which produce high quality coated conductors with lengths of ten or so meters. Due to the conductor high cost in the present development stage, two lengths of around 7.5 m have been used for the secondary. Table 2 gives some characteristics of the used coated conductors. Two single layer coils have been built on the same composite material cylinder (see fig. 5 after).

Figure 4 shows the ac losses of a coated conductor secondary coil at 77 K. Since it is a single layer coil with a space between the turns, the operation is close to self field conditions. These measurements are indeed in good agreement with the Norris formula [7] (elliptic assumption).

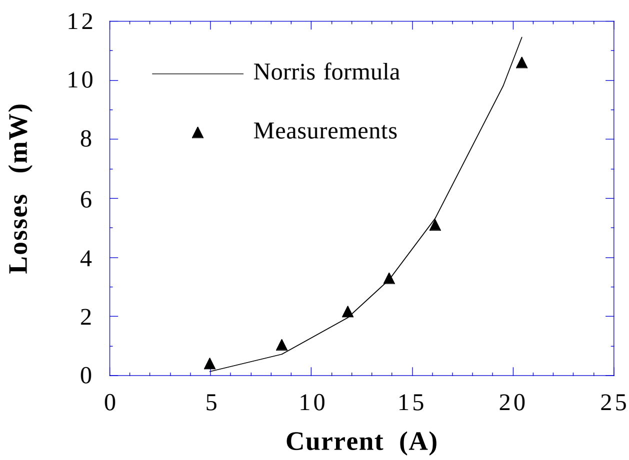


Figure 4. A.C. losses versus transport current for a secondary coil at 77 K.

Table 2. Characteristics of the YBCO Coated Conductor (C&C Technologies).

Width		4 mm
Thichnesses:	- Substrate	100 µm
	- YBaCuO	1.6 µm
	- Shunt (Au)	0.3 µm
Ic (100 µV/m ; 77 K, 0 T)		> 70 A

7. First electrical tests

The first electrical test on the READY transformer were performed in very special conditions. We used only the safe primary winding and the rated voltage for the primary is then 1025 V, instead of the planned 2050V. The secondary are the two YBCO coils connected in series.

Due to the lack of time in the final READY phase, the two available YBCO secondary coils were not placed around the BSCCO primary on the same magnetic column but on the other magnetic column as shown in figure 5. In this configuration, the magnetic coupling between the primary and secondary is not good so that the short-circuit inductance is very high. Furthermore the Ampere turn compensation is not performed on the windings and the leakage magnetic fields are high, leading to eddy current losses in any conducting part.

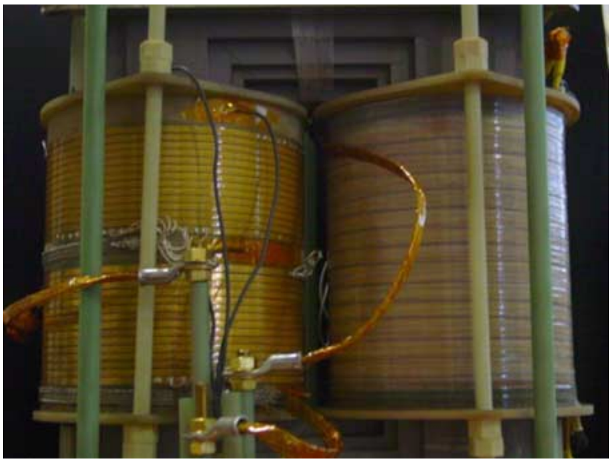


Figure 5. View of the transformer with the C-C windings (on the left) and the PIT tape winding (on the right).

The transformer has suffered the two classical transformer tests : open and short-circuit tests. All the tests have been carried out at the grid frequency, that is 50 Hz. The voltages and currents are given in rms value, not in maximum value (1.414 times higher).

7.1 Open circuit test

In this test the secondary windings are not loaded. This test makes it possible to measure the magnetic circuit losses, the no-load (magnetizing) current and the voltage ratio. This test has been carried out at only one temperature (45 K).

Figure 6 gives the losses and the current as a function of the voltage. This curve shows a good agreement between the measurements and the theoretical iron loss calculations from the short sample data. At the rated operation the no-load losses are 48 W.

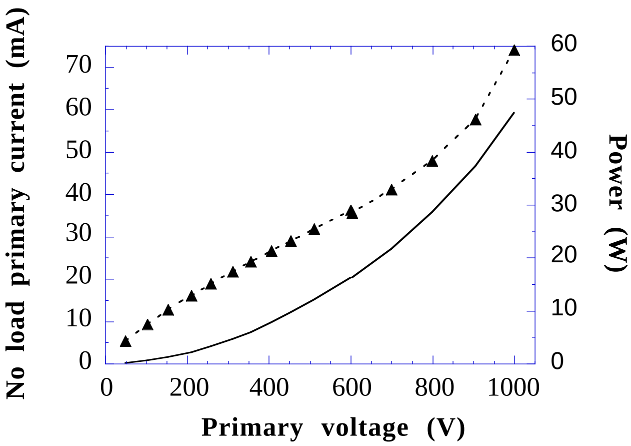


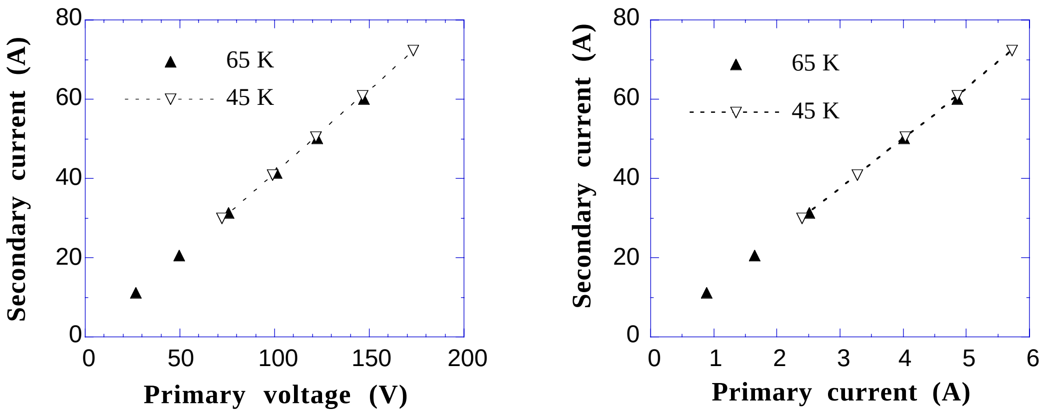
Figure 6. No-load losses and current versus primary voltage.

The no load current nearly increases linearly since the operating magnetic induction is low, under 1.5 T at rated voltage. The saturation bend can be nevertheless observed for the last points. The no-load current at the rated voltage is less than 0.4 % of the rated current. In the normal configuration, with the two primary coils, the no-load current would be half (ie. 0.2 %). This very low value is due to the low operating field and the magnetic circuit quality, in particular the lamination joints.

7.2 Short-circuit test

In this test the two secondary coils are connected in series and short-circuited at room temperature. The short circuit tests have been carried out for two temperatures : 45 K and 65 K.

Figure 7a shows the short-circuit secondary current as a function of the primary voltage for the two temperatures. Figure 7b gives the secondary current as a function of the primary current for both temperatures. The slope (12.41) is the inverse of the transformation ratio ($m_1 + m_2$) (12.35) since the no load current is negligible.



a **b**

Figure 7. Short-circuit test for two temperatures.
7a. Short-circuit secondary current versus primary voltage.
7b. Short-circuit secondary current versus primary current.

At 45 K and 65 K, the coated conductor coils have carried respectively 99 A and 85 A (maximum values).

From these data it is possible to calculate the short circuit impedance which is huge since it amounts to 57 % in relative value (rated voltage over rated current). This figure is very far from the calculated one for the READY transformer (0.75 %). This difference is due to the primary and secondary configuration. In the theoretical calculations the two primary coils were inside the two half secondaries in order to reduce the field on the wire. In the configuration used during these tests the primary and secondary are only coupled by the magnetic circuit.

8. Perspectives and Conclusion

The transformer will be dismantled in order to place the coated conductor coils around the primary winding to improve the magnetic coupling.

A 41 kVA single phase transformer has been designed and built. Using a cold magnetic core, its cryogenic integration with a pulse tube is simple. Its operation is very easy and does not require any cryogenic skill. Due to the limited superconductor quantity, the iron losses are high but in good agreement with the calculations. The Bi PIT tape primary coils show relatively high A.C. losses. YBCO coils show lower losses and they are in good agreement with the Norris formula in the tested configuration.

YBCO coated conductor have high promises for future devices, not only transformers.

Acknowledgement

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