Electric and magnetic properties measurement and analysis of a conventional and a superconducting power transformer

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Abstract. Power transformers based on High Temperature Superconductors (HTS) technology have revealed potential for several practical applications, offering economic, environmental and operational benefits. In this work, two 650 VA single-phase transformers prototypes were developed, tested and characterized: a conventional one, using copper windings, and another with the same primary copper winding, but with a secondary winding made of HTS BSCCO tape. The two prototypes were compared regarding magnetic properties, losses, electric parameters and efficiency, and the results are presented and interpreted. Also, several measures to determine AC critical current of the HTS tape were made. The results are compared with DC critical current for the same tape.

1. Introduction

High temperature superconductors (HTS) power transformers technology have revealed potential for energy applications offering economic, environmental and operational benefits. Among them, perhaps volume and weight reduction, comparing with similar conventional power transformers, is one of the most interesting aspects associated with this technology. Nevertheless, electric and magnetic losses minimization is also very important for transformers' efficiency and HTS transformers could also contribute to it improvement, especially through electric losses reduction related to the use of superconducting materials.

This work presents two 650 VA single phase transformer prototypes, a conventional one using copper windings and another one with the same primary copper winding but with an HTS BSCCO tape on secondary. Several tests were made to measure electric and magnetic properties of constitutive transformer materials, namely to determine AC critical current of BSCCO tape, and to characterize and compare operation performance of both transformer prototypes.

The final objective is to contribute to the analysis of superconducting power transformer potentialities in energy systems.

2. Characterization of the superconducting tape

Before the assemblage of the HTS transformer prototype, the tape was tested in order to measure its AC critical current. In practice, it does not exist a detailed regulation for AC critical criterion, whereas DC critical current measurement is regulated by IEC 61788-3 international standard. Table 1
summarizes the characteristics of the superconducting Bi-2223 tape. Data is provided by the manufacturer and concerns to DC.

**Table 1.** Innost Bi-2223 technical characteristics

| Characteristic                  | Value                  |
|---------------------------------|------------------------|
| Critical current                | 90 A                   |
| Engineering critical current density | 93 A/mm²              |
| Width                           | 4,2 (±0,2) mm          |
| Thickness                       | 0,23 (±0,02) mm        |
| Minimum curvature radius        | 30 mm (5% I_c degradation) |

To determine AC critical current of the tape, two configurations were analyzed: one, where the sample is straight and another where the tape is wound in a coil (30 turns). Measurement procedure followed reference [1]. This method is applied to determine critical current on both configurations (tape and winding) and the results are indicated in figure 1.

![Figure 1. AC critical current approximation. (a) Tape (b) Coil](image)

Following [1], the critical current is defined by the intersection point of the two tangents represented in figure 1. It is 97.3 A for the straight tape, and 95.7 A for the coil. The difference observed is due to the magnetic induction field normal to coil winding, which partially destroys superconductivity and therefore reduces critical current. These values are slightly higher than the manufacturer’s indication (90 A in DC).

### 3. Comparison between conventional and HTS transformer

This section presents the development and comparison between the two built prototypes, one conventional transformer (CT) using copper windings and working at room temperature (298 K) and another with the same primary copper winding, but with secondary one made of HTS BSCCO tape immersed in liquid nitrogen (77 K). For simplicity, the last is called superconducting transformer (SCT) despite it does not have both HTS windings.

#### 3.1. Design characteristics

Main design characteristics of iron core, HTS and copper windings and cryostat, of both transformers are presented in this section. Table 2 and 3 resume the main geometric characteristics and specification of the C T e SCT prototypes.

**Table 2.** Main geometries of the designed transformers

| Iron core      | Diameter     | Filling factor | Laminated factor | Cross-section area |
|----------------|--------------|----------------|------------------|--------------------|
|                | 62,8 mm      | 86,6%          | 95%              | 2550 mm²           |

**Table 3.** Specifications of the designed transformers

| Characteristic      | Value                  |
|---------------------|------------------------|
| Capacity            | 650 VA                 |
| Frequency           | 50 Hz                  |
| Voltage ratio       | 208,2 V / 18,0 V       |
| Current             | 3,1 A / 36 A           |
3.2. Core characterization
Due to the fact that SCT has its secondary winding at 77 K, it was decided to characterize the iron core in two different conditions: one, with the core at room temperature and another with the core cooled in a non-uniform way due to the proximity of HTS winding cryostat (in figure 2, 3 and 4 referred as (CT) and (SCT), respectively). The achieved results obtained for magnetic characteristics are represented in figures 2, 3 and 4.

![Figure 2. First magnetization curves for ferromagnetic core material in CT and SCT](image)
![Figure 3. Relative magnetic permeability for CT and SCT](image)
![Figure 4. Total magnetic losses for CT and SCT](image)

It can be concluded that:
- The ferromagnetic core exhibits higher saturation flux density on SCT.
- Higher magnetic permeability is observed for SCT core for all range of $B_m$. These results are justified by the temperature decrease in the cryostat column [2]. According to [3,4], this decrease causes a reduction in thermal agitation of the atomic structure which contributes to decrease the electrical resistivity and to increase magnetic permeability of the ferromagnetic material.
- According to figure 4, total magnetic losses could be considered similar in both transformers.

3.3. Steinmetz equivalent circuit parameters
Open and short circuit tests were performed, in order to characterize and compare both transformers and to establish Steinmetz equivalent circuit parameters. Figure 5 shows the equivalent circuits obtained for CT and SCT.

![Figure 5. Steinmetz equivalent circuit (a) for CT (b) for SCT (values in ohm)](image)

Comparing the obtained equivalent circuits, it can be concluded:
- Primary electrical resistance and leakage reactance, are similar for both prototypes (2% variation).
- In SCT the tape exhibits a decrease of 14% in electric resistance when compared with CT cooper winding. It was expected even a lower value but the resistive tape terminal contacts and the electrical conductor used in the short circuit test have a strong influence on secondary resistance.
- The leakage reactance increases 7% in SCT due to the distance between the HTS coil and the leg of the core, created by the cryostat.
- SCT equivalent magnetizing reactance (232.07 $\Omega$) and core losses equivalent resistance (29.05 $\Omega$) increase 9% and 13%, respectively, compared with CT parameters. It means that, ferromagnetic core has higher permeability and lower resistivity when cooled, which is according with [3,4]. Lower temperatures reduce thermal agitation and, consequently, reduce electrical resistivity. This increases eddy currents leading to higher core losses [3]. Another possible justification for this increasing is, LN$_2$ evaporation and subsequent water condensation along magnetic flux path, causing short-circuits and increasing eddy currents.
3.4. Transformer load tests
In order to evaluate transformer’s behavior, both transformers were tested for different loads. Figure 6 shows real power \(P_1\), primary voltage \(U_1\), apparent power \(S_1\) and efficiency versus current per unit, i.e. \(I_2 / I_{2n}\), for both prototypes. Analyzing the graphics it can be concluded:

- For equal load, real power \(P_1\) is the same for CT and SCT transformers (figure 6a).
- The superconducting transformer shows better voltage regulation (figure 6b). Nevertheless, in both transformers voltage regulation values are higher than desirable: 45% to SCT and 50% to CT.
- SCT requires a lower primary apparent power (figure 6c), to supply the same load current.
- SCT has slightly lower efficiency when compared to CT, a difference of 0.47% (figure 6d).

![Figure 6](image)

**Figure 6.** Transformers load tests (a) Real power supplied (b) Transformers primary voltage (c) Transformers primary apparent power (d) Transformers efficiency

4. Conclusions
The use of HTS tape in transformers’ secondary winding reduces electrical resistance although less than expected. This is due to electrical contacts made to solder the HTS tape to copper wires outside the cryostat. Superconducting windings impose the existence of a cooling system which increase the distance between transformer leg and the winding, leading to increase leakage reactance, and to decrease the working temperature of the core. This last aspect contribute to increase magnetic losses probably caused by condensation along magnetic flux path which forms short-circuits, increasing eddy currents. Superconducting transformer shows better voltage regulation, lower apparent power but also lower efficiency. For a deeper study of the real impact and potential of using HTS tape on power transformers, it would be relevant to have both windings made of superconducting material.

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