New Perspectives in HTS Transformer Design

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Abstract. Power transformers based on High Temperature Superconductors (HTS) technology are an appealing promise for several practical applications. The present designs still leave wide margins of possible improvement in terms of both layout optimisation and introduction of new technologies. In the framework of a technical-scientific cooperation among scientific and industrial subjects, a 10 kVA single-phase transformer was designed and manufactured, using copper for primary windings and BSCCO-2223 HTS tape for secondary windings. The design has been optimized taking into account the particular characteristics of BSCCO tapes, in particular their AC losses, and the usual figures (stray flux, Joule and iron losses, weight and overall footprint) considered in transformers design. The prototype has then been realized and characterized, using general as well as specific tests. The performance of the device has been evaluated and compared with numerical calculation. In the paper, an overview of the device design and manufacturing will be presented, together with a critical comparison between computed and measured performance.

1. Introduction

A 10 kVA, single-phase, high temperature superconducting (HTS) transformer based on BSCCO-2223 technology has been designed and manufactured. The rated voltages of each side of the transformer are 1kV and 230V respectively.

HTS tape has been used for the secondary winding and a copper wire has been used for the primary winding. The design has been performed by taking into account technical, technological and operative requirements. In particular the specific AC losses of BSCCO and the strong impact of the orthogonal flux density component on its critical current have been considered. The cooling to cryogenic temperature has been guaranteed by plunging the whole transformer including windings and laminated ferromagnetic core in liquid nitrogen. The prototype has been characterized both numerically and
experimentally with the aim to gain a reliable circuit model. In particular, in order to measure the AC losses of the HTS windings, we have developed a simple but effective system to collect and measure the amount of evaporating nitrogen gas generated only by these losses in stationary conditions. Using a calorimetric model AC losses have been evaluated. By means of electrical measurements an estimation of the same quantity has been obtained independently and the results have been compared. Standard short circuit and open circuit tests have been performed.

2. Design and Optimisation

The ratings of the transformer are in Table 1, while in Table 2 are listed the main figures of the HTS tape as provided by manufacturer (American Superconductor).

| Table 1 – Transformer’s electrical data |
|----------------------------------------|
| Rated power                            | 10 kVA |
| Primary rated voltage                  | 1 kV   |
| Secondary rated voltage                | 230 V  |
| Winding current HV/LV                  | 10/43 A|
| Frequency                              | 50 Hz  |

| Table 2 – BSCCO-2223 HTS tape characteristics |
|-----------------------------------------------|
| Thickness                                      | 0.305 ± 0.02mm |
| Width                                         | 4.1 ±0.2mm |
| Minimum critical current                      | 115 A @77 K self-field |

Owing to the small size of the transformer, a configuration with cold iron core has been considered cost effective. As is well known, the voltage induced in transformer windings is a function of the flux density $B$, the number of turns $N$, the frequency $f$ and the cross-section area of the iron core $A_{Fe}$ (1):

$$E = \pi \sqrt{2} B N f A_{Fe}$$  \hspace{1cm} (1)

In order to optimize the design of an HTS transformer, total losses must be minimized. While core losses increase with the core length, losses in superconductors strongly depend on the orthogonal (transverse) component of the flux density [1]. This component depends on the iron core shape and dimensions because is due to the leakage flux. In any case, some combinations of core length and cross-section areas have been investigated with the help of Finite Element simulations.

Fig.1 shows the transverse flux density obtained from 3 configurations studied with different heights of the windings $h$ on the external radius of each configuration.

Figure 1 Transverse component of the flux density for transformers with different winding heights.
The chosen configuration (h= 240 mm) seems to be a good compromise between the demand to have low transverse component and acceptable core losses. In Table 3 are shown the final dimension.

| Table 3 – Transformer’s geometrical data |
|-----------------------------------------|
| HV-turns                                | 424 |
| HV-internal radius                      | 67.5 mm |
| HV-external radius                      | 75.5 mm |
| HV –height                              | 220 mm |
| LV-turns                                | 98 |
| LV-internal radius                      | 82.0 mm |
| LV-external radius                      | 83.3 mm |
| LV –height                              | 220 mm |

3. Tests and Measurements

After the design stage, the prototype has been realized by the industrial partner GETRA. The prototype has been submitted to usual tests for transformers performance evaluation plus a set of specific tests to assess HTS tape performance.

In AC condition the thermal losses have been measured by means of a calorimetric method [2]. In short circuit test, when secondary current is maximum, at nominal value of design parameters, we have measured the amount of produced vapor obtaining an estimation of AC losses, about 3.0 Watt.

All voltages and currents are measured in open and short circuit conditions (primary winding supplied) and in open circuit condition (secondary winding supplied). (Ref. Figure 2)

![Graphs showing electrical measurements in various conditions.](image)

**Figure 2.** Electrical Measurements – Various Conditions
In order to evaluate the loss in short circuit condition with primary coil supplied, we have measured the voltage \( V_1 \), current \( I_1 \) and power dissipation \( P_{cc} \) on the primary, the secondary voltage \( V_2 \). From knowledge of the value of transformation ratio \( a \) and the resistance of copper winding \( R \) we can calculate the following (2):

\[
I_2 = I_1 a \\
P_2 = I_2 V_2 \\
P_{cc} = I_1 a \frac{1}{T} \int_0^T I_1(t)V_1(t)dt \\
P_{j1} = R I_{I_{rms}}^2 \\
P_{HTS} = P_{cc} - P_{j1} - P_2
\]

where \( P_{HTS} \) is the dissipation due to AC losses on SC coil, \( P_{j1} \) is resistive power dissipation on primary and \( P_2 \) is the residual dissipation due to non perfect zero value of short. In Table 4 the measured value with calorimetric and electric method compared with theoretical value calculated following the procedure indicated in [3].

| Table 4- AC losses in sc coil at secondary short circuit condition | \( P_{HTS} \) [W] |
|-----------------------|----------------|
| Calculated Value      | 1.5            |
| Calorimetric Measurements | 3.0        |
| Electrical Measurements | 2.7            |

4. Conclusion

A study to determine the optimal configuration for a superconductive transformer has been made and a 10 kVA prototype has been manufactured and tested. Two methods to measure AC losses of HTS winding have been developed, founding good agreement between them. HTS winding AC losses, measured at 77 K, have been normalized to room temperature (considering 20 as penalty factor for cryogenics) and compared to resistive losses of a copper winding with the same current and number of turns. It results that, by using HTS windings, losses are reduced to 1/3 and according to our preliminary estimations, this reduction factor for winding losses could be achieved also for very large size transformers (transformers for distribution network). Our vision about perspectives for practical application of HTS transformer is consequently optimistic because energy saving during operation seems sufficient to reduce the ownership cost over transformer lifetime. For example, the windings resistive losses in a 100 MVA distribution transformer are approximately 300 kW; loss reduction of 200 kW allowed by HTS windings can be considered equivalent to a saving of 175 kEuro/year and this amount appear more than sufficient to compensate, over the lifetime of 30 years, the greater investment costs. These considerations encourage more detailed analysis and efforts toward the development of HTS transformers as advanced components able to meet the issue of energy efficiency that a key aspect for a sustainable development.

References

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