# An AC Loss Model for Bi2223 Superconductors in Partial Core Transformers

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***Abstract*—This paper presents a modelling technique for calculating the ac losses for a high temperature superconducting partial core transformer using Bi2223 superconducting tape. The model is a function of the current in the tape and the magnetic field of the transformer. A time harmonic, two dimensional, finite element analysis of the transformer was used to determine the magnetic field in the winding area. This analysis showed that there was significant radial flux in the end winding regions, resulting in an elliptical nature of the magnetic field. The major and minor axes of the ellipse were used in the ac loss model. The AC losses modelled were compared with measured data from a sample HTS partial core transformer.**

## I. Introduction

Partial core transformers (PCTX) have been designed as an alternative to full core transformers, the difference being that the outer limbs and connecting yokes are absent from the PCTX (Fig 1) [1], [2]. This means that the magnetic circuit for a PCTX consists of the core and the surrounding air, which results in a high magnetic reluctance. A significant reason why there are not PCTXs in the power system is because the copper losses and efficiency can be poor due to the high magnetising current. The machine can be large because of the larger cross-section of conductor size required due to the extra magnetising current.

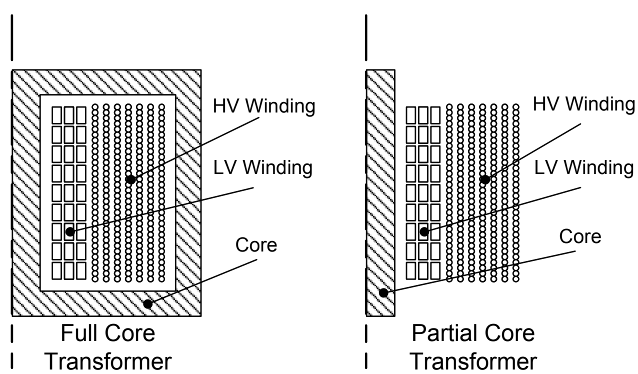


Fig. 1. A cross-sectional view of the differences between full core and partial-core transformers

However, the application of high temperature superconductor (HTS) eliminates this issue, i.e. very low conductor losses and small cross-sectional area, allowing for a very compact and light PCTX. Furthermore, what is also important is that the problematic magnetising current reduces with the square of the number of turns, (Equation 1).

$$X_m = \omega L = \omega \frac{N^2}{\Re}, \tag{1}$$

where $X_m$ is the magnetising reactance, $\omega$ is the angular frequency, $L$ is the inductance of the winding, $N^2$ is the number of turns of the winding and $\Re$ is the reluctance of the magnetic flux path. Small increases in HTS wire length and therefore number of turns, gives significant reductions in magnetising current without increases in losses.

A disadvantage of the PCTX is the cost of the HTS wire. However, as with other technologies, the price of HTS is likely to reduce significantly as the technology matures. As such, the University of Canterbury decided to build a high temperature superconducting partial-core transformer (HTSPCTX) to investigate the implication of the above mentioned advantages. To assist in the design of the transformer, knowledge of the AC losses in the HTS windings is desirable. This paper presents a model for calculating the AC losses in Bismuth based superconductors, $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223), the conductor used in the HTSPCTX.

## II. AC Loss Model

Under DC conditions, HTS tapes have essentially zero resistance provided that the current, temperature, and external magnetic field remain below critical values [3]. However, with alternating currents and magnetic fields this is not the case. The total AC loss for Bi2223 tape is dependent on both the ac current through the conductor and any external magnetic fields [4], [5], both of which are present in a superconducting transformer. Furthermore, the orientation of the magnetic field to the tape surface has a large impact on the losses with fields perpendicular to the wide surface of the transformer causing larger losses than parallel fields. For engineering purposes, it is useful to have an equation that describes the losses in the form of,

$$Q_{tot} = Q_{tot}\left(B_a, I_t, \alpha\right), \tag{2}$$

where $B_a$ is the amplitude of the applied magnetic field, $I_t$ is the amplitude of the transport current and $\alpha$ is the orientation of the magnetic field to the wide surface of the tape.

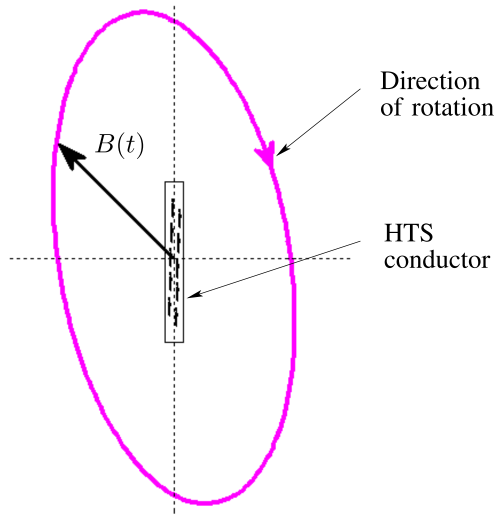


Fig. 2. Diagram of the elliptical nature of the magnetic field for a partial core transformer

An engineering formula describing the ac loss in Bi2223 tape has been proposed by Rabbers et. al. The total ac loss is the summation of the magnetisation loss, $Q_m$, which is function of magnetic field amplitude and orientation, and the transport current loss, $Q_{tr}$, which is a function of the magnetic field amplitude and orientation and the transport current. The total ac loss is therefore,

$$\begin{aligned} Q_{tot}\left(B_a, I_t, \alpha\right) &= Q_m\left(B_a, \alpha\right) + Q_{tr}\left(B_a, I_t, \alpha\right) \\ &= \frac{C_1\left(\alpha\right) B_a^P \cdot C_2\left(\alpha\right) B_a}{C_1\left(\alpha\right) B_a^P + C_2\left(\alpha\right) B_a} \\ &\quad + C_3 I_t^q + C_4\left(\alpha\right) B_a I_t^2, \end{aligned} \tag{3}$$

where $C_1\left(\alpha\right)$, $C_2\left(\alpha\right)$, $C_3$, $C_4\left(\alpha\right)$, $p$ and $q$ are parameters that have to be determined from measured data.

## III. Modelling the Magnetic Field

In order to use the model in Equation 3 it is necessary to know what the magnetic field throughout the transformer is. This was achieved by using finite element analysis (FEA) from a commercial software application. Because of the radial symmetry present in the partial core transformer design a 2D time-harmonic simulation was used to model the magnetic field of the transformer.

Each layer of the PCT windings was modelled as a block of perfect conductor that covers all turns of that winding layer. The insulation between windings was modelled as air. This model was considered sufficient as the windings were packed close together. Magnetic field screening from the Meissner effect was not modelled.

The core was modelled as a single block of isotropic linear material with a relative permeability of 3000. This model does not take into account the non-linear effects such as core saturation and radial flux not being restricted to the lamination plane. These non-linearities were assumed to have minimal effect on the global field distribution.

Results from the simulation proved interesting in that the magnetic field at a point in the winding did not have a static orientation throughout the simulation cycle. Instead the field tended to rotate in an elliptical pattern, Fig 2, with the magnitude and orientation changing over time.

The elliptical nature of the magnetic field causes a problem when trying to use the ac loss model of Equation 3, which assumes a constant angle throughout the cycle. The approach taken in this case was to find the magnitude and angle of the major and minor axes of the ellipse, calculate the losses for each case and then summed them together so that,

$$\begin{aligned} Q_{tot} &= Q_{Maj}\left(B_{aMaj}, I_t, \alpha_{Maj}\right) \\ &\quad + Q_{Min}\left(B_{aMin}, I_t, \alpha_{Min}\right). \end{aligned} \tag{4}$$

The time harmonic data from FEA software presents the magnetic field as a complex vector field. The $x$ and $y$ components of the field are complex scalars so that the magnetic field $\mathbf{B}$ is,

$$\mathbf{B} = \left(x_1 + j\,x_2\right)\mathbf{i} + \left(y_1 + j\,y_2\right)\mathbf{j} \tag{5}$$

where $\mathbf{i}$ and $\mathbf{j}$ are orthogonal unit vectors. The major and minor axes for the ellipse of $\mathbf{B}$ can be found from [6],

$$\mathbf{B}_{Major} = |\sqrt{\mathbf{B}\cdot\mathbf{B}}|\Re\left\{\frac{\mathbf{B}}{\sqrt{\mathbf{B}\cdot\mathbf{B}}}\right\}, \tag{6}$$

$$\mathbf{B}_{Minor} = |\sqrt{\mathbf{B}\cdot\mathbf{B}}|\Im\left\{\frac{\mathbf{B}}{\sqrt{\mathbf{B}\cdot\mathbf{B}}}\right\}, \tag{7}$$

The complex scalar components of the magnetic field were found for each turn the the transformer windings and the corresponding ellipse axes were used in Equation 4 to find the ac losses for each turn.

## IV. Experimental Testing

Electrical tests on a HTSPCTX were performed and compared to the results from the modelling. The transformer was constructed as part of a master thesis at the University of Canterbury [7] using Bi2223 HTS tape (Fig 3). The transformer was designed so that it could be operated in either full core or partial core configuration. The partial core configuration was used for the electrical tests. Specifications for the transformer are given in Table I.

TABLE I
Specifications for the High Temperature Superconductor Partial Core Transformer

| | | |
|---|---|---|
| Inside Winding Voltage | 230 | V |
| Inside Winding Current | 65 | A |
| Outside Winding Voltage | 230 | V |
| Outside Winding Current | 65 | A |
| kVA Rating | 15 | kVA |
| Operating Temperature | 77 | K |

Open circuit, short circuit and load tests were conducted while the transformer was submerged in liquid nitrogen ($LN_2$) (Fig 4). The $LN_2$ served to keep the windings operating below the critical temperature for the duration of the testing. A summery of the test results is presented in Table II.

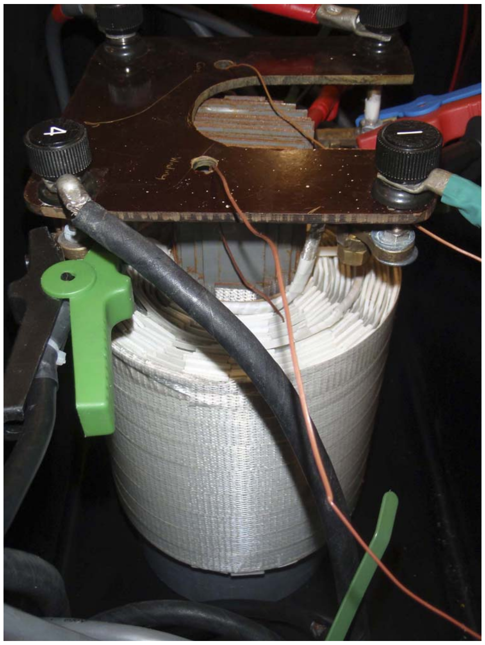

Fig. 3. Photograph of the HTSPCTX prior to testing

TABLE II
TEST RESULTS FOR THE HIGH TEMPERATURE SUPERCONDUCTOR PARTIAL CORE TRANSFORMER

| **Open Circuit Test** | |
|---|---|
| **Parameter** | **Measured** |
| Inside winding voltage (V) | 233 |
| Inside winding current (A) | 25 |
| Outside winding voltage (V) | 220 |
| Inside winding real power (W) | 184 |
| **Short Circuit Test** | |
| **Parameter** | **Measured** |
| Inside winding voltage (V) | 72 |
| Inside winding current (A) | 66 |
| Outside winding current (A) | 62 |
| Inside winding real power (W) | 176 |
| **Load Test** | |
| **Parameter** | **Measured** |
| Inside winding voltage (V) | 230 |
| Inside winding current (A) | 65 |
| Inside winding real power (kW) | 11.0 |
| Outside winding voltage (V) | 200 |
| Outside winding current (A) | 61 |
| Outside winding real power (kW) | 10.7 |
| Real power loss (kW) | 0.3 |
| Efficiency (%) | 97 |
| Voltage regulation (%) | 15 |

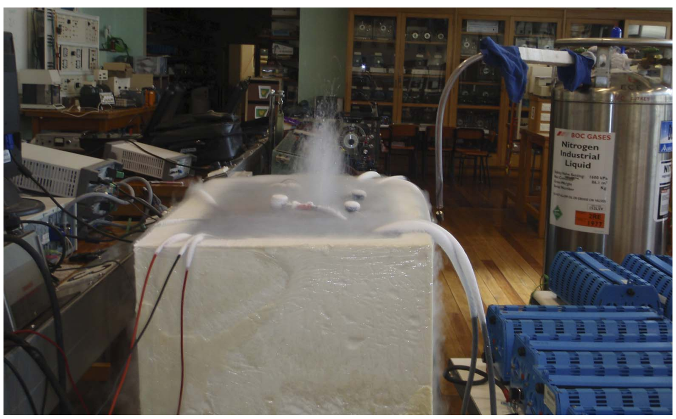


Fig. 4. Photograph of the HTSPCTX during the load testing.

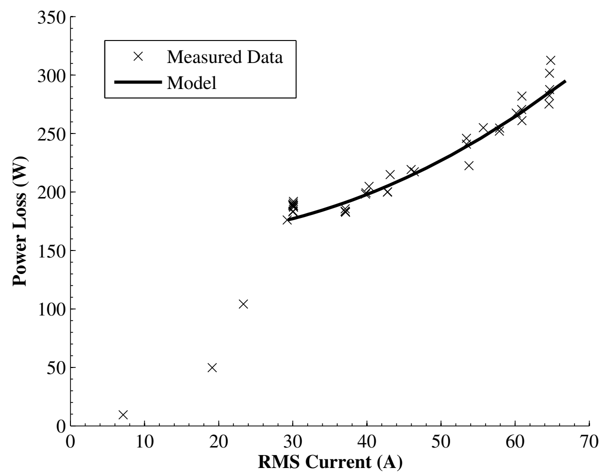


Fig. 5. Comparison between the measured results and the model data for a loaded test.

## V. RESULTS

The model of Equation 4 was used to predict the ac losses for the HTSPCTX that was tested. The magnetisation and transport current losses were calculated for each turn in the HTSPCTX then summed together along with the core losses to give the total loss of the transformer. The calculated values were then compared to measured losses from the short circuit and load tests.

### *A. Obtaining the Model Variables*

The variables from Equation 3 need to be found before the model of Equation 4 can be used to predict the ac losses of the HTS tape. These variables can be found by conducting a series of experiments on a sample tape. $C_1(\alpha)$, $C_2(\alpha)$ and $p$ can be determined from standard magnetisation loss experiments. $C_3$ and $q$ can be found from standard self field loss experiments. $C_4(\alpha)$ is the only parameter that needs an experiment with both ac magnetic field and transport current present.

Unfortunately, at the time of writing, the authors did not have access to the equipment required to carry out the above experiments and so accurate determination of the equation variables was not possible. The variables for Equation 3 were found by using the values given by Rabbers et. al. as a basis and modifying them until a good match was found with the measured losses from the experiments in Section IV. The results of the modelling are presented in Fig 5 and Fig 6 and the Equation 3 parameters used are presented in Table III.

Fig 5 demonstrates a good correlation between the measured values and the modelled data. The few outliers of measured data for low currents were taken before the transformer had reached rated voltage and were not modelled. The comparison between the measured and modelled data for the short circuit test shown in Fig 6, while not as good as the load test results, still demonstrates a good correlation.

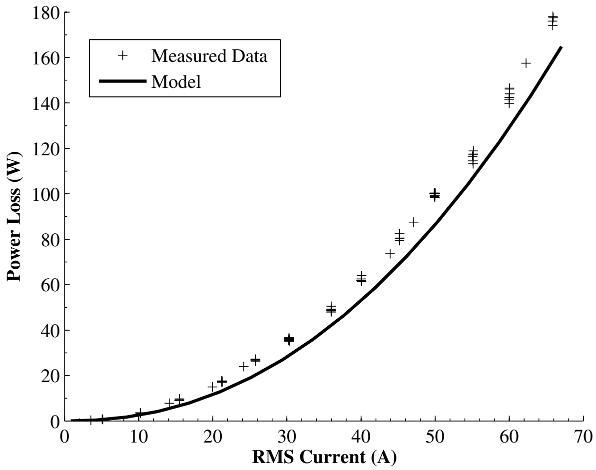


Fig. 6. Comparison between the measured results and the model data for a short circuit test.

TABLE III
VARIABLES USED IN EQUATION 3 FOUND FROM COMPARISONS TO MEASURED DATA

| | |
|---|---|
| $C_1\,(\alpha)$ | 13 |
| $C_2\,(\alpha)$ | 0.38 |
| $C_3$ | 0.6E-6 |
| $C_4\,(\alpha)$ | 1.5E-6 |
| $p$ | 3.6 |
| $q$ | 2.2 |

## VI. ADDITIONAL WORK

Standard magnetisation loss, self field loss and an experiment with both ac magnetic field and transport current present will be conducted on a sample tape. Results from these tests will be used to further verify the validity of the model used.

## VII. CONCLUSIONS

A model for the ac losses of Bi2223 HTS tape for use in partial core transformers has been presented. The model uses finite element analysis to obtain the magnetic field of a partial core transformer. The magnetic field was found to have significant radial flux resulting in an elliptical field in the winding space. Axial decomposition of the ellipse is used in the ac loss calculation. Results of the modelling have been compared to measured losses on an experimental HTS partial core transformer and found to have good correlation.

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