Modelling short-circuit current of a 21 MVA HTS superconducting transformer

P Surdacki, L Jaroszyński and Ł Woźniak
Lublin University of Technology, Lublin, Poland
E-mail: p.surdacki@pollub.pl

Abstract. The paper presents a computer model of an HTS 21 MVA 70/10.5 kV two-winding superconducting transformer. The model takes into account the influence of temperature and current intensity on electrical and thermal properties of windings made of two types of second generation superconducting tape differing in the presence of copper stabilizer. Rhyner's power law was used to describe the transition to the resistive state of the YBCO superconductor layer. A model of the non-linear magnetic core of the transformer was developed by using modified Jiles-Atherton equations. The proposed model allows numerical determination of current, resistance and winding temperature waveforms during an operating short circuit of a 21 MVA superconducting transformer.

1. Introduction
A transient state occurs at each sudden change of one or more parameters defining the transformer's operating conditions. Transient states are relatively short-lived, yet they can lead to failure or destruction of the transformer due to large electrodynamic forces acting on the windings and an increase in their temperature.

The currently used second generation high temperature superconducting tapes (2G HTS) in the resistive state have parameters that allow the design and manufacture of HTS transformer windings, limiting the current in transient states, such as short circuits. During the faults, the resistance of the windings increases after the critical current of the superconductor is exceeded, limiting the effects of a short-circuit [1-6] and supporting the operation of electric power equipment [2, 3].

Performing an operating short circuit test on the physical model of the HTS transformer poses a risk of its serious damage. Therefore, it is necessary to run a simulation on a computer model. As a result, at the design stage, the best design solutions can be selected [4-12].

The authors previously carried out computer simulations of a 10 kVA HTS superconducting transformer model, the physical model of which was built at the Laboratory of Superconducting Technologies in Lublin and the Institute of Electrical Engineering in Warsaw [13,14]. The obtained simulation results, both for steady and transient states, coincided with high accuracy with the laboratory measurements. The results of the work were presented in previous papers [14-18]. The next step was to extend the model and use it for simulation and numerical testing of a 21 MVA HTS transformer. The results of this work are presented below.
2. Limiting short-circuit current by a superconducting transformer
It is assumed that the percentage short-circuit voltage can be described by the area of the trapezoid formed by a distribution of the radial component of magnetic flux density $B_r$ along radial coordinate $r$ [9], shown in Figure 1.

![Figure 1](Image)

**Figure 1.** Cross-section of a superconducting transformer with geometric dimensions, and the relation of $B_r(r)$ showing the trapezoid area proportional to short-circuit voltage for very thin HTS windings [9, 13], illustration drawing without scale, dimensions in mm, where $a_{HTS1}$ and $a_{HTS1}$ are thicknesses of the primary and secondary winding, respectively, and $\delta$ is width of the air gap, HV and LV are primary and secondary windings, respectively.

![Figure 2](Image)

**Figure 2.** The process of limiting the short-circuit current by an HTS transformer.
The smaller the area of the trapezoid, the lower the percentage short-circuit voltage. With the same width of the air gap $\delta$ for HTS and copper transformers, the thickness of the windings varies significantly. In the case of a superconducting transformer, the thickness of the windings is much smaller than in the case of copper transformers ($a_{\text{HTS}} \ll a_{\text{Cu}}$). It can be assumed that in the case of superconducting transformers the percentage short-circuit voltage depends mainly on the width of the air gap [2, 9, 13].

The process of short-circuit current limitation in transformers with superconducting windings is shown in Figure 2. The dashed line shows the short-circuit current of a conventional transformer, and the continuous line relates to a superconducting transformer. In the superconducting state, the current can reach the rated value $I_n$, but is less than the critical current $I_C$. After a short-circuit occurs, the winding current begins to increase and exceeds the critical current $I_C$. A transient state begins and continues until the superconducting winding is completely resistive. After the $\Delta t$ time, the short-circuit current reaches the set value resulting from the transformer's short-circuit voltage [2, 9, 10].

3. Computer model of a 21 MVA superconducting transformer

PSpice is a well-known simulator of electrical and electronic circuits. Circuit modelling with this package gives good results and for a class of non-linear problems is many times faster than FEM analysis [9, 14, 15]. The ABM behavioral modelling blocks allow any mathematical description of the problem analyzed.

![Figure 3. PSpice model of 21 MVA HTS transformer](image)

An extended computer model of a two-winding HTS 21 MVA 69.86/10.5 kV transformer (Figure 3) was developed on the basis of the previously verified HTS 10 kVA transformer model [14, 15].

For the construction of windings two types of layered superconducting tapes YBCO were proposed: SCS12050 and SF12050. The magnetic circuit of the transformer made of PN ET114-27 sheet metal is maintained at the ambient temperature. The core is therefore thermally isolated from the windings, which are cooled in an LN$_2$ nitrogen bath to 77 K. To develop a model of a non-linear magnetic core of the transformer, a modified model of Jiles-Atherton level 2 was used [11, 12]. Modelling of magnetic circuit was presented in more detail in previous articles of the authors [13-16].

Layers of the tape substrate (Hastelloy) and lamination (silver and copper) are modelled with ABM blocks 1 and 6, superconductor layers YBCO – with blocks 2 and 5. ABM blocks 3 and 4 model the electrical parameters of full windings. A sketch of the construction and dimensions of the windings of a single-phase superconducting transformer (HTS) is shown in Figure 1. Table 1 presents basic data of the modelled transformer.
Table 1. 21 MVA superconducting transformer data

| Description                                                                 | Data                        |
|-----------------------------------------------------------------------------|----------------------------|
| HTS HV and LV windings made of tape                                         | SF 12050                   |
|                                                                             | SCS 12050                  |
| The critical current of the tape                                           | 280 A                      |
| Core type sheet                                                             | ET 114-27                  |
| The dimensions of the tape (width/thickness)                                | 12 mm / 0.055 mm           |
|                                                                             | 12 mm / 0.1 mm             |
| Magnetic core cross-section                                                 | 0.2844 m²                  |
| Working flux density B                                                      | 1.63 T                     |
| Rated HV winding current                                                    | 301 A                      |
| Rated LV winding current                                                    | 2000 A                     |
| HV side (primary) voltage                                                  | 69.86 kV                   |
| LV side (secondary) voltage                                                | 10.5 kV                    |
| Tape length HV/LV, m                                                       | 3791 m / 2360 m            |
| No. of layers HV/LV                                                        | 9 / 7                      |
| Number of turns/layer                                                      | 88                         |

Layers of tape base (Hastelloy) and lamination (silver and copper) are modelled with ABM 1 and 6 blocks, superconducting layers YBCO – with blocks 2 and 5. ABM 3 and 4 blocks model electrical parameters of full windings. A sketch of the construction and dimensions of the windings of a single-phase superconducting transformer (HTS) is shown in Figure 1. Table 1 presents the basic data of the transformer modelled.

The windings of a 21 MVA HTS transformer have a much more complex structure than their low power counterparts. The primary winding consists of 2, and the secondary one of 10 parallel HTS tapes. The 21 MVA windings are split equally for two core columns (legs). The primary winding has 8 layers \(N_{wp} = 8\) and the secondary one has 7 layers \(N_{ws} = 7\). The cooling conditions of inner winding layers need careful consideration. Therefore, an extended thermal model of the multilayer winding was prepared. In addition to heat exchange with LN\(_2\) on external surfaces and heat accumulation in the winding structure, it takes into account heat conduction in HTS tapes and insulating foil in radial direction.

4. Results and comparison of short-circuit faults
The proposed model of a superconducting transformer is idealized: it does not take into account the influence of magnetic field on the critical parameters of the tape, assuming that the layers of HTS tape heat up evenly and that electrical and thermal parameters of layered 2G HTS tape does not depend on its length.

The waveforms of the short-circuit current of the superconducting transformer with windings made of copper laminated SCS12050 tape and those made of SF12050 tape (no copper lamination) are shown in Figure 4.
The inrush current in HTS primary winding laminated with copper (SCS) reaches 4 965 A, while in the case of windings made of tape without lamination (SF), the impact current reaches a lower value 1 523 A.

The waveforms of short-circuit current in secondary windings of the transformers being compared are shown in Figure 5. For secondary windings made of SCS tape, the impact current is 32 998 A and is more than three times higher than for SF12050 (10 121 A). The subsequent inrush current pulses for SF12050 are limited and are below the critical current for both the primary and secondary winding. Such an effect cannot be observed with SCS tape – subsequent inrush current pulses exceed the critical current of the tape.

The changes of resistance of windings made of SF12050 tape during transition from superconductive to resistive state are shown in Figure 6.
Resistance of primary winding at the moment of a short circuit increases to 42.32 Ω and then drops rapidly. This may indicate that the primary winding made of SF12050 tape returns to the superconductive state faster due to its lower thermal capacity. In the case of a secondary winding, the resistance reaches 83.07 Ω after a time of 0.1 s after a short circuit.

The waveforms of temperature in windings made of tape without copper lamination are shown in Figure 7. During an operating short circuit the temperature increase for the primary winding is 6.33 K, while for the secondary winding it is 275.66 K.

Figures 8 and 9 respectively show the resistances and temperature changes of the windings made of SCS12050 tap during the short-circuit process.

When a short circuit occurs, the resistance of the primary winding increases to 39 Ω, while that of the secondary winding reaches 13.41 Ω. For SCS tape with copper lamination the temperature increase is 175.19 K for the primary winding and 545.49 K for the secondary winding after 0.1 s after the occurrence of the short-circuit. Such a significant temperature rise can be destructive – the tape undergoes thermal degradation and the winding parameters will not recover its previous values. In order to effectively protect the superconducting transformer against thermal damage, appropriately fast switches should be used. Achieving transformer robustness to short circuits lasting several seconds is problematic. The circuit breaker automatics should detect and switch off the HTS transformer’s short circuit in less than 0.1 s.

The results obtained for a computer model of a transformer with windings made of SF tape without a copper stabilizer are promising. However, it should again be noted that the proposed model is idealized. In practice, making transformer windings with the use of tape without copper stabilizer will be very difficult due to the possibility of creating local resistive zones.

5. Conclusions

A properly designed superconductor transformer, in addition to its basic role, can act in the power network as a short-circuit current limiter with a very short activation time. However, superconducting windings are characterized by relatively low weight and low thermal capacity. In order to protect superconducting windings from thermal degradation, it is necessary to use automation and circuit breakers capable of detecting and disconnecting a short-circuit in a shorter time than that typical of the protection of oil transformers with copper windings.
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