System Investigation of High Temperature Superconducting Self-limiting Transformer

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Abstract. A high temperature superconducting (HTS) self-limiting transformer (SLT) is a combination of a transformer and a fault current limiter in one unit. We designed and built a small-size self-limiting transformer. This device has two or more copper windings and one or more HTS ring(s) placed on a separate limb to operate when short circuit currents occur. We have investigated several constructions on the experimental device, viz. iron core with two or more limbs. The self-limiting transformer was connected to various loads: resistive, capacitive and inductive. The effects of various loads were studied, which helps fit the parameters of HTS SLT to the electric power network. A calculation about a real power network in order to realize the requirement for the SLT is presented.

1. Introduction
The high temperature superconducting self-limiting transformer with YBCO rings (HTS SLT(R)) is developed from an inductive type high temperature superconducting fault current limiter and a transformer. We designed, built and tested a small-size self-limiting transformer.

This self-limiting transformer contains a closed magnetic core with three limbs and YBCO HTS ring(s) with a diameter of 40 mm. The primary and the secondary windings are placed separately on the outer limbs [1]. In this paper the cases of devices with one and two rings are studied.

It is well-known that fault current influences the power quality, namely voltage level and causes dips. Fault current can be limited by HTS devices such as HTS SLTs and fault current limiters (FCL) due to their increased impedance in limitation operation [2]. For HTS devices to be applied in power network in future it is worth getting information about usual power level, fault current and dips. E.ON Hungary is interested to carry out such lab-experiments, measurements with HTS devices which connect with above mentioned network parameters (e.g. increasing power level of devices) and to calculate and investigate fault events and conditions providing useful information for designing and parameter adjustment of lab-measurements. [3,4]

2. Self-limiting Transformer with 2 rings
Previously the self-limiting transformer with one ring was investigated in [1,5]. In normal operational mode the HTS ring is in superconducting state and counteracts with the mmf of the transformer windings. In the limitation mode, the mmf acting in the middle limb exceeds the activation value – app. corresponding to the critical current of the HTS ring – thus the HTS rings goes into its normal state.
Two rings were placed to the center limb and the effect was studied. The construction is shown in Fig. 1, where 1A – primary voltage, 1B – primary coil, 2A – secondary voltage, 2B – secondary coil, 3ABC – iron core legs, 4 – HTS rings, 5 – self-limiting transformer, 6 – iron core.

![Fig. 1 The construction of the Self-Limiting Transformer with 2 rings](image)

2.1. Various constructional arrangements of the SLT(R)
The leakage magnetic fields of the rings interact with each other, so the effects of the placement of the rings were investigated. Three variations were studied: a) two rings as close as possible, b) two rings as far as possible and c) magnetic shield between the HTS rings.

2.1.1. SLT(R) with two rings placed closely
The construction is similar to that shown in Fig. 4, but the rings are very close. As Fig. 2a. shows, one activation was realized. It was caused by the leakage magnetic field of the rings. Due to their close placement, if any of the two undergoes S-N transition, the other will also do the same. This activation is very similar to the SLT(R) with one ring. In this case the activation current was 3.61 A, the recovery current was 1.75 A.

2.1.2. SLT(R) with two rings placed far
The two rings were placed as far as possible in order to reduce the interaction of the magnetic fields of the rings. At the maximum distance – equal to 190 mm – the effect is seen in Fig. 2b. The characteristic shows two separate activations, because when one ring quenches then its magnetic field has virtually no effect on the other ring.

The activation currents were measured as 3.45 A and 3.35 A, the recovery are 1.9 A and 1.8 A.

2.1.3. Magnetic shield placed in between the HTS rings
In the third case, a magnetic shield with iron plates was used to further reduce the interaction of the magnetic fields of the rings. In Fig. 2c. two activations are shown, but they are not so sharp as in the case of SLT(R) with two rings placed as far as possible.

The activation currents were measured 3.2 A and 2.87 A, the recovery currents were 2 A and 1.6 A.

![Fig. 2: Primary V-I characteristic for the three cases](image)
a. b. c.

We assume that the activation method of SLT(R) with two rings depends on several parameters: the geometries of the HTS rings, the distance between the rings and the number of the rings.
3. Fault calculation on a cable-line

There is a well-known method of fault current limitation, namely the application of choke coils. The usage of fault current limiting first of all serves the reduction of the damage caused by short circuit currents, but recently power quality issues are becoming more and more important as well. Among others this is one important reason why to use HTS FCLs and/or SLTs for fault current limitation and improve power quality.

In the following we provide a numerical example concerning fault current, voltage dip and dominant impedances on a part of the Hungarian network. This calculation will provide the requirements, which the HTS devices should meet in a real power network.

The calculation is carried out for (quantities are reduced to) the 11 kV level. We used grouped coils with cable lines for calculation. That is why intact cable groups „feel” a voltage dip while the voltage level at faulty group is zero.

The base of calculation was a medium voltage/low voltage (MV/LV) transformer and its LV busbar fault. If one takes a MV/LV transformer close to high voltage/medium voltage (HV/MV) substation, the impedances of the MV cables can be neglected. When a fault occurs on the LV busbar of the MV/LV transformer, a voltage dip can be experienced on MV voltage level after the choke coil.

Fig. 3 shows a part of a real network. Here the 630kVA MV/LV transformer, the choke coils and the cable lines can be identified. This transformer power level is common in downtowns and industrial areas. This is the reason why we deal with LV busbar faults which cause measurable voltage dip on the MV level.

For the calculation of the voltage dip, the impedances and the currents were calculated. The impedances are assumed to be inductive. The reactance of the source and the HV/MV transformer on the 11kV side are as follows:

\[
X_{\text{source,11kV}} = \frac{U_{\text{11kV}}^2}{S_{\text{nom}}} = 0.036 \ \Omega
\]

\[
Z_{\text{HV/MV,11kV}} = \frac{E_{\text{HV/MV}}}{100} \cdot \frac{U_{\text{11kV}}^2}{S_{\text{nom}}} = 0.344 \ \Omega
\]  

The impedance of the MV/LV transformer on the 11kV side is obtained as

\[
Z_{\text{MV/LV,11kV}} = \frac{U_{\text{11kV}}^2}{S_{\text{nom}}} = 7.93 \ \Omega
\]
where the $\varepsilon$ is the voltage drop of the transformer. The reactance of the choke coil is 0.8 $\Omega$, so the three-phase short-circuit current is calculated as

$$I_{\text{short,3ph}} = \frac{U_{\text{th1ph}}}{X_{\text{source}} + X_{\text{th/MV-MV,31AV}} + X_{\text{coil}} + Z_{\text{th/LV,31AV}}} = 696.9 \ A$$

(3)

The remaining voltage on the MV side of the MV/LV transformer is

$$U_{\text{remain}} = \frac{\Delta U_{\text{MV/LV}}}{U_{\text{nom}}} \times 100 = 87\% U_n$$

(4)

The above calculation gives an important information about the relation between voltage dips and the impedances in network. EN 50160 (and several national standards and regulators) offer a range of voltage levels which are used by public utilities, namely $U_n \pm 10\%$ (low voltage level). It is worth mentioning that regulators may determine more strictly rules, e.g. $U_n \pm 7.5\%$.

If we increase three times the impedance of MV/LV transformer, the remaining voltage level can be increased according to (5):

$$Z_{\text{MV/LV,31AV,MOD}} = 3 \cdot Z_{\text{MV/LV,31AV}} \cdot \frac{\Delta U_{\text{MV/LV,MOD}}}{U_{\text{nom}}} \cdot 100 = 95.3\% U_n.$$  

(5)

This value is in the range of the regulator’s rules.

3.1. Assessment of the application of Possibility of HTS SLTs

As we have mentioned above, HTS devices in fault current limiting area have favorable properties. HTS SLT in fault shows other features than conventional transformers. In normal operation SLT has similar impedance than that of conventional transformers, while in fault operation (e.g. fault at secondary busbar) has higher impedance than a conventional transformer. This is why an HTS SLT can be favorably used to adjust fault impedance and voltage level.

4. Self-limiting Transformer with various loads

The self-limiting transformer with one ring was studied with different passive loads, like resistive, capacitive and inductive. Since in the real network a cable line was investigated, the measurements with resistive and capacitive loads are shown below.

The primary V-I characteristics are in Fig.4. At the measurement process the primary voltage was increased until the activation, and up to 3 A. After reaching the maximum value, the current was decreased until its recovery value and then and further down to zero value of the voltage.

![Fig. 4 Primary V-I characteristic](image)

a. Resistive type load, $R=1.1\,\Omega$; b. Capacitive load, $C=10\mu F$

In the real network a transformer and a choke coil are used to limit the current. As result of the fault calculation of the network the limitation impedance must be three times higher than that in the normal operational mode to satisfy the regulator’s rules.

To estimate the potential application of our SLT(R) we have investigated the limitation effect of the experimental device in various cases. Since the power network is voltage-source type, the results were analyzed at a constant voltage level. In our experimental device this value was set to 12 V. At this voltage level the ratios between normal and limitation mode impedances of the SLT(R) were
measured as 2.85 for the resistive load and 2.98 for the capacitive load. The results have shown, that, assuming an upscaled HTS SLT(R), it may be adequate to the sample power network.

5. Conclusions

A calculation of a three-phase short circuit on the MV/LV transformer’s LV busbar was performed in order to determine the requirements of the HTS device regarding short-circuit current and impedance. In order to satisfy the requirements of the regulators’ rules regarding power quality (allowable voltage dip), the impedance of the transformer in case of limitation mode has to be increased. In our sample-network for a proper fault operation the impedance of the transformer is to be increased by approximately three times.

Small-size self-limiting transformers with YBCO rings were designed, built and tested in our lab. We carried out measurements on the self-limiting transformer with two HTS rings having different placements along the limb. The measurements of SLT(R) with two HTS rings have resulted in the following results. The activation method and operation of SLT(R) depend on the placement of the rings. In case of the rings placed closely to each other, the magnetic fields of the rings interact and, thus, the activations (S-N and N-S transitions) in the two rings take place virtually in the same moment. When the rings are placed far from each other, the rings activate independently at different time instants.

From the V-I characteristic obtained from the measurements of SLT(R) with resistive and capacitive loads, the impedance ratio between the fault and the normal operations has fallen between 2.85 and 3. These results satisfy the requirement of the investigated power network.

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