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Detailed review and application of the 3-Phase self-limiting transformer with magnetic flux applied

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Abstract

The paper describes in detail the 3-phase self-limiting transformer with magnetic flux applied and contains measured results. The solution includes two independent iron cores. I applied two pieces of iron cores with 3 limbs on each. One of the iron cores contains the 3 primary coils on the limbs respectively and the other iron core also contains 3 secondary coils. As I use two iron cores the loss, the size, the weight and the cost are higher compared to the conventional transformers but this solution has several advantages. For example, the fault power is less, switching is fast. In the case, when there is no load on the secondary side and primary voltage increases, the arrangement is able to break coupling between the primary and secondary sides. The work has been carried out by me as a novel possibility of application of the principle of magnetic flux constancy in the closed loop.

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Keywords: Perfect closed YBCO wire loop; self-limiting superconducting transformer; three-phase transformer.

1. Introduction

The possibility of this application is based on the principle of magnetic flux constancy in the closed loop. The solution includes two independent iron cores. The solution is the flux transformer with one loop [1, 2, 3, 4]. I have created a new type three-phase self-limiting transformer (400 VA). I prepared the primary and secondary windings of the three-phase transformer for this experiment with copper wires. Naturally, my final target is a full HTS transformer. Earlier I used YBCO superconductor rings from bulk for other experiments. These superconducting bulks were produced at IPHT in Jena, Germany. The applied YBCO rings were drilled in just some minutes with a new technology I had elaborated [5], [6].

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2. Experimental Arrangement

Fig. 1 shows the cutaway view of the experimental device and its photo.

Fig. 1. (a) Cutaway view of the three-phase self-limiting transformer; (b) Photo of the device

For the experiment I put extra secondary coils on all the phases on the primary sides. Thus I could measure the secondary voltage on both sides. We can see the scheme in Fig. 2 in one phase.

Fig. 2. The scheme of the one phase (e.g. L1 phase)

Table 1 shows the parameters of the three-phase self-limiting transformer.

Table 1. Parameters of the transformer

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{rated}$</td>
<td>400 VA / one iron core</td>
</tr>
<tr>
<td>$U_{primary}$</td>
<td>3 x 400 V</td>
</tr>
<tr>
<td>$U_{secondary}$</td>
<td>3 x 24 V + 3 x 24 V</td>
</tr>
<tr>
<td>$R_{load}$</td>
<td>2 x (3 x 4.5 Ω)</td>
</tr>
</tbody>
</table>
3. Measuring Results

I measured the voltage and current with load and without load.

3.1. With load in $L_1$ phase on both secondary coils ($R_{load} = 4.5 \, \Omega$, this is maximum load) (Fig. 3)

3.2. Load ($R_{load} = 3 \times 4.5 \, \Omega$) on the secondary side (2) and single-phase short circuit in $L_1$ phase (Fig. 4)

The advantage of the equipment is that in the case of single-phase short circuit the current will decrease in all the three phases. This can be an appropriate solution for high power machines. In the case of high-power electric motor if there is a single-phase breaking or a single phase short circuit, we can decrease the current in the three phases with this solution.
3.3. The non-load voltage of the self-limiting transformer

We can see the non-load secondary voltage in Fig. 5, if there is single-phase short circuit in phase L₁.

Fig. 5. Fault in non-load state

Fig. 6 shows the recovery voltage after fault.

I used SF 12050 superconducting wire. It was produced by SuperPower, Inc., New York, USA. I used an industrial blade to slit the tape. We have to cut the wire on plane, even plastic. It is very important as in this case there should be no extra mechanical stress. The YBCO layer is about 1 micrometer.
4. Theoretical Examination in the Case of the Single-Phase Self-Limiting Transformer

I describe the current of the superconductor in details. I used the scheme that we can see in Fig. 7.

**Fig. 7. The scheme for the solution**

**Nomenclature**

- \( N_1; N_2 \): number of primary and secondary turns
- \( i_{\text{SUP}}(t) \): current of the superconducting loop
- \( R_1^m; R_2^m \): reluctance (magnetic resistance) of the primary and secondary iron cores
- \( \phi_G \): flux of the primary iron core without superconducting loop
- \( \phi_{\text{SUP}_1}; \phi_{\text{SUP}_2} \): flux of the superconducting loop in the primary and secondary iron cores
- \( \phi_{\text{air}} \): flux in air inside the closed superconducting loop

\[
\phi_G(t) + \phi_2(t) = \phi_{\text{SUP}_1}(t) + \phi_{\text{SUP}_2}(t) + \phi_{\text{air}}(t)
\]  

\[
\frac{N_1i_1(t)}{R_1^m} + \frac{N_2i_2(t)}{R_2^m} = i_{\text{SUP}}(t) + \frac{i_{\text{SUP}}(t)}{R_1^m} + \frac{i_{\text{SUP}}(t)}{R_2^m} + \frac{i_{\text{SUP}}(t)}{R_{\text{air}}} = (i_{\text{SUP}}(t)\left(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{\text{air}}}ight))
\]  

\[
i_{\text{SUP}}(t) = \frac{N_1i_1(t)}{R_1^m \left(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{\text{air}}}\right)} + \frac{N_2i_2(t)}{R_2^m \left(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{\text{air}}}\right)} = \frac{N_1i_1(t)}{1 + \frac{R_1^m}{R_2^m} + \frac{R_1^m}{R_{\text{air}}} + \frac{R_2^m}{R_{\text{air}}}} + \frac{N_2i_2(t)}{1 + \frac{R_2^m}{R_1^m} + \frac{R_2^m}{R_{\text{air}}} + \frac{R_1^m}{R_{\text{air}}}}
\]  

\[
i_{\text{SUP}}(t) = \frac{N_1i_1(t)}{1 + \frac{R_1^m}{R_2^m} + \frac{R_1^m}{R_{\text{air}}} + \frac{R_2^m}{R_{\text{air}}}} + \frac{N_2i_2(t)}{1 + \frac{R_2^m}{R_1^m} + \frac{R_2^m}{R_{\text{air}}} + \frac{R_1^m}{R_{\text{air}}}} = \frac{N_1i_1(t)}{R_2^m R_{\text{air}} + R_1^m R_{\text{air}} + R_1^m R_2^m} + \frac{N_2i_2(t)}{R_2^m R_{\text{air}} + R_1^m R_{\text{air}} + R_1^m R_2^m}
\]
\[ i_{SUP}(t) = \frac{N_1i_1(t) \cdot R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} + \frac{N_2i_2(t) \cdot R_{air}^m}{R_2^m R_{air}^m + R_1^m R_{air}^m + R_1^m R_2^m} \]  

If \( R_{air}^m \to \infty \), then

\[ i_{SUP}(t) = \frac{N_1i_1(t) \cdot R_{air}^m}{R_2^m + R_1^m} + \frac{N_2i_2(t) \cdot R_{air}^m}{R_2^m + R_1^m} \]

5. Conclusion

The limiting current has considerably lower value than the fault current of a conventional 3-phase transformer at the same power. The short circuit current is less than the operational current within some periods.

With this solution we can create two selective secondary coils.

The described method can be an appropriate solution for high power machines. For example, in the case of high-power electric motor if there is a single-phase breaking or a single phase short circuit, the current decreases in the three phases.

The applied superconducting wire (SF 12050) is suitable for self-limiting transformer in this method. When the fault time is long, more than 3.5 s, the device can operate without damage.

Acknowledgements

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References


