Simulation, Design of an Innovative Superconducting Transformer by Using Flux Transfer for Next-Generation Grid

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HTS 2018 MODELLING

6th International Workshop on Numerical Modelling of High Temperature Superconductors

26 - 29 June 2018

Caparica - Portugal

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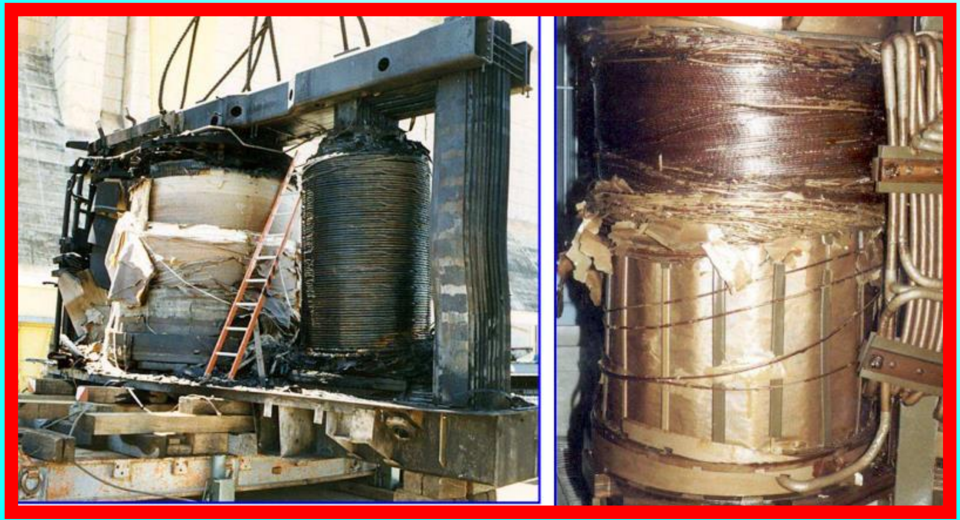
Goal of this work

Examination with MATLAB software for SFCL in the case of flux transfer.

What is the triggering thought?

- In the future the grids, power systems may reach their short-circuit limit.
- The devices should bear the short-circuit current until the operation time of the protection.



High power transformer damage

Nowadays Requirements of the Conventional Protection are the followings:

Faults interrupted within:

less

100 msec (< 100 kV system)

60 msec (> 100 kV system)

We go to the limit.

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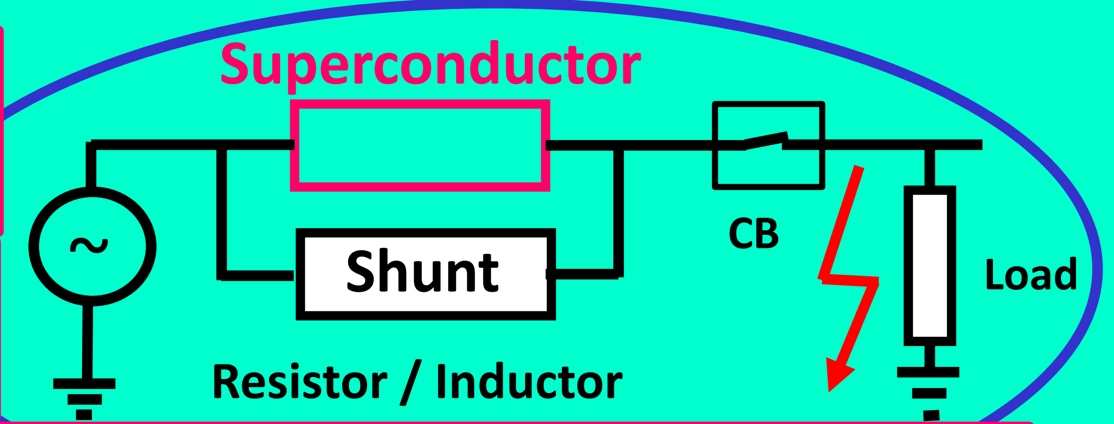
Conventional solutions

- Resistive
- Inductive

The applied superconducting wire can damage easly.



The energy source **GIVES** directly energy to the fault location only through superconducting wire and the short circuit power loss will be totally on superconducting wire. The superconducting wire will damage.

OFFER instead of these conventional solutions

↓

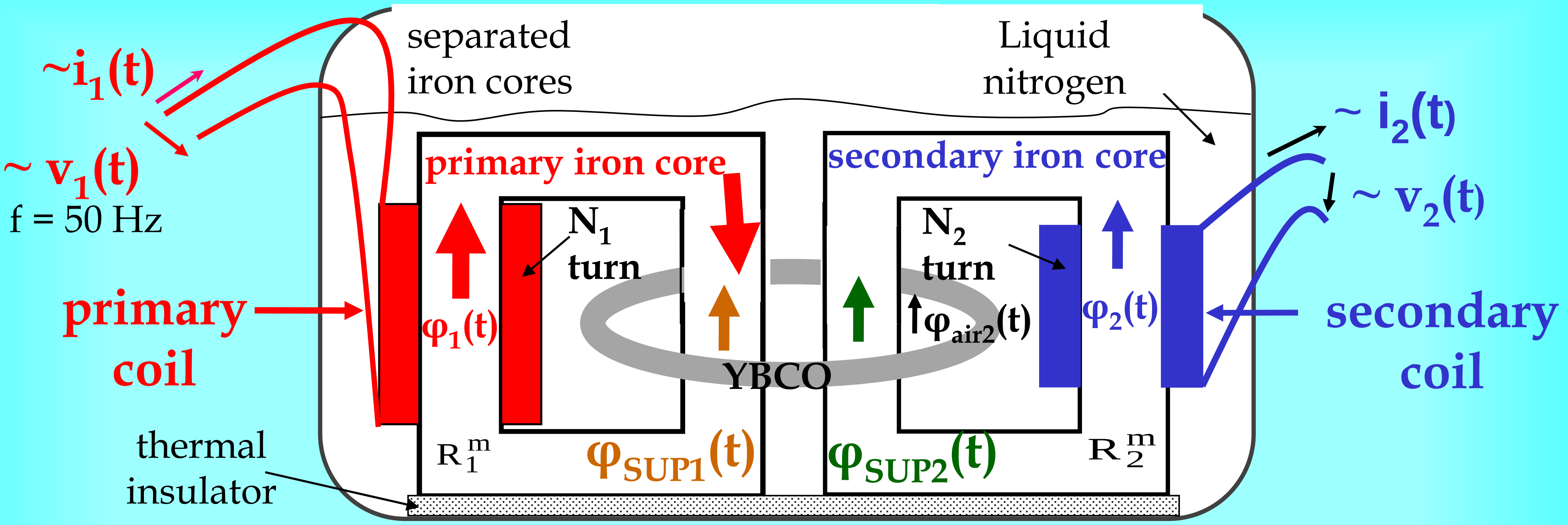
By using flux transfer

Why?

The energy source **DOES NOT GIVE** electrical energy directly to the fault place through superconducting wire.

Analysing by MATLAB software

Scheme of the arrangement



$$\boxed{\varphi_1(t) + \varphi_2(t) = \varphi_{SUP1}(t) + \varphi_{SUP2}(t) + \varphi_{air}(t)}$$

$$\boxed{\frac{N_1 i_1(t)}{R_1^m} + \frac{N_2 i_2(t)}{R_2^m} = \frac{i_{SUP}(t)}{R_1^m} + \frac{i_{SUP}(t)}{R_2^m} + \frac{i_{SUP}(t)}{R_{air}} = (i_{SUP}(t))\left(\frac{1}{R_1^m} + \frac{1}{R_2^m} + \frac{1}{R_{air}}\right)}$$

If $R_{air}^m \longrightarrow \infty$, **then**

$$\boxed{i_{SUP}(t) = \frac{N_1 i_1(t) \quad R_2^m}{R_2^m + R_1^m} + \frac{N_2 i_2(t) \quad R_1^m}{R_2^m + R_1^m}}$$

Equations for MATLAB

$$\boxed{v_1 = L_1 \cdot \frac{di_1}{dt} + M_{13} \cdot \frac{di_3}{dt} + M_{12}\frac{di_2}{dt} + R_1 \cdot i_1}$$

$$\boxed{v_2 = L_2 \cdot \frac{di_2}{dt} + M_{23} \cdot \frac{di_3}{dt} + M_{21}\frac{di_1}{dt} + R_2 \cdot i_2}$$

$$\boxed{0 = L_3 \cdot \frac{di_3}{dt} + M_{31} \cdot \frac{di_1}{dt} + M_{32}\frac{di_2}{dt} + R_3 \cdot i_3}$$

i_1 = primary current
i_2 = secondary current
i_3 = current of superconductor

Object of our examination:

1. What is the connection between the resistance of superconducting loop and the current of superconducting loop? Because the superconducting current creates the magnetic flux for secondary coil. Secondary voltage depends on magnetic flux in secondary iron core.

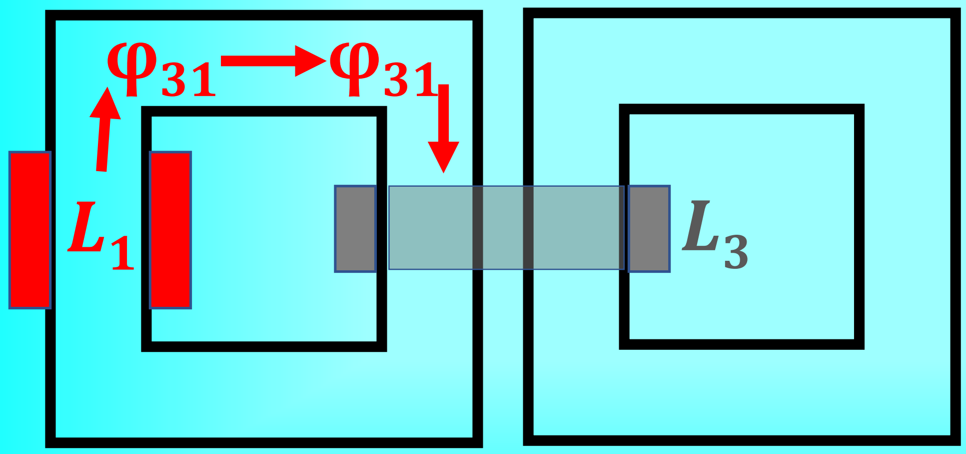
2. What is the connection between the resistance of superconducting loop and primary current.

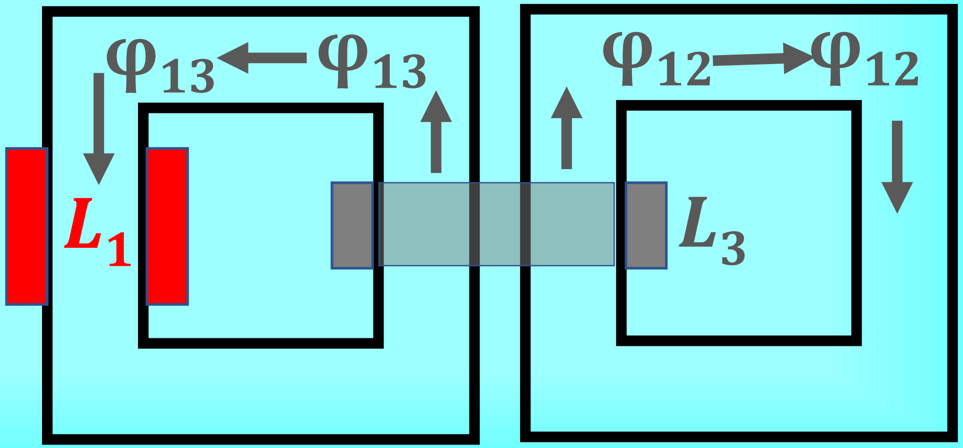
M_{13} and M_{31} are not the same!!!

$$M_{13} \neq M_{31} \qquad M_{13} = k_1 \cdot L_{13} \qquad M_{31} = k_2 \cdot L_{31}$$

The proportion of L_{13} and L_{31} depend on reluctance (magnetic resistance) of primary and secondary iron cores. $R_{reluctance} = \frac{l}{\mu \cdot A}$ k = coupling factor

$$\varphi_{31} = \varphi_{13} + \varphi_{12}$$





Conditions and solution

Conditions:

i_2 = 0 (there is not load)
$M_{12} = M_{21} = 0$

Result:

Primary current →

$$\frac{di_1}{dt} = \frac{v_1 - M_{13}\frac{M_{31}\cdot v_1 + R_3\cdot i_3\cdot L_1}{M_{31}\cdot M_{13} - L_1\cdot L_3}}{L_1}$$

Current of superconducting loop →

$$\frac{di_3}{dt} = M_{13}\frac{M_{31}\cdot v_1 + R_3\cdot i_3\cdot L_1}{M_{31}\cdot M_{13} - L_1\cdot L_3}$$

These equations give a command what are the input parameters.

For solution we have to give the v_1 and the inductance of L_1, L_3, M_{13}, M_{31}.

Our calculation

Constant input parameters in MATLAB program:

$$v_1(t) = V_0 \cdot sin(\omega \cdot t)$$

V_0= 35 000 V

f = 50 Hz

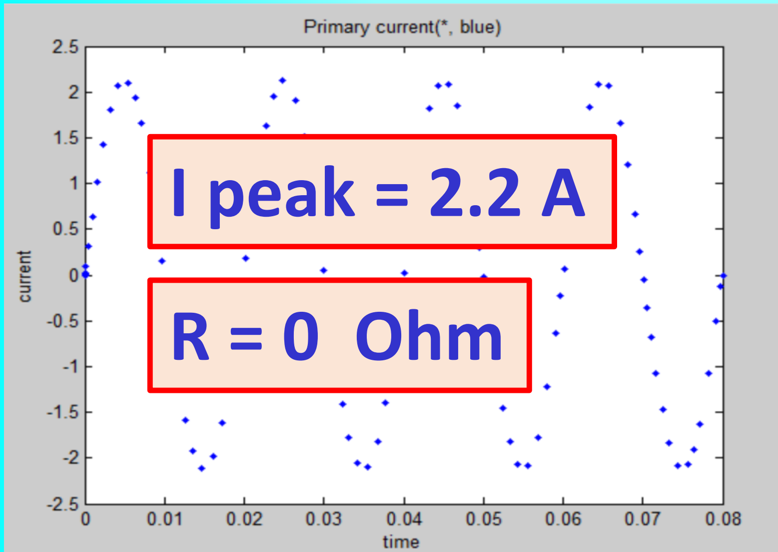
$$\left.\begin{array}{l} L_1 \\ L_{3(superconductor)} \\ M_{13} \text{ and } M_{31} \end{array}\right\} \text{(depend on geometry and turns).}$$

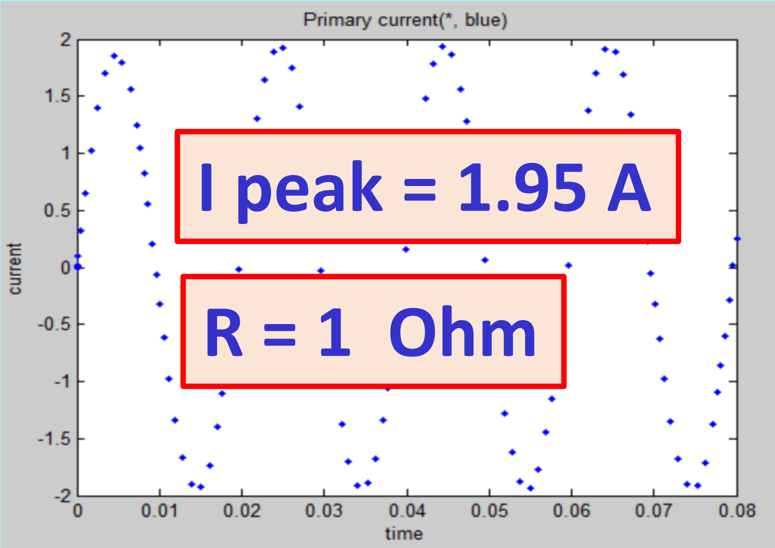
Changed parameters: $R_{3(superconductor)}$

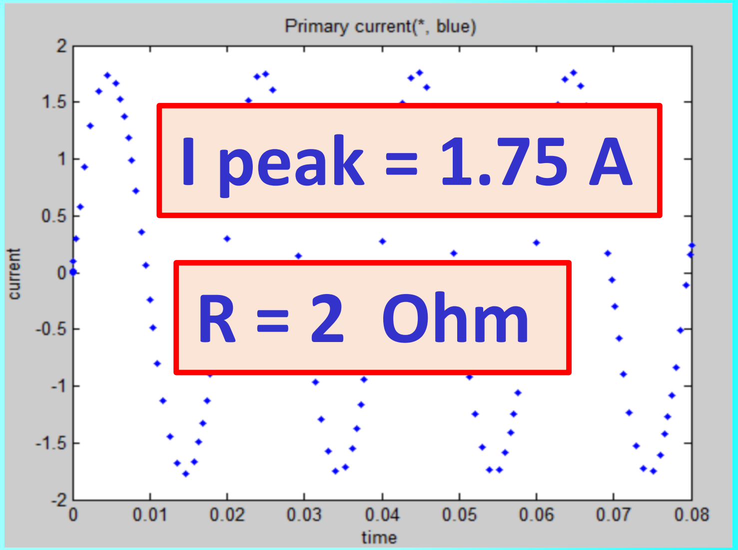
Hereinafter you can see some results of calculations.

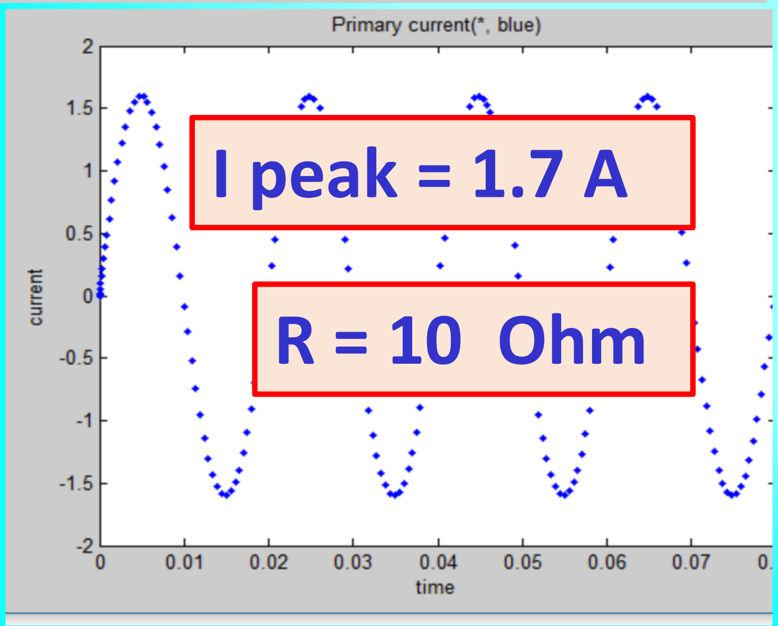
Calculation results

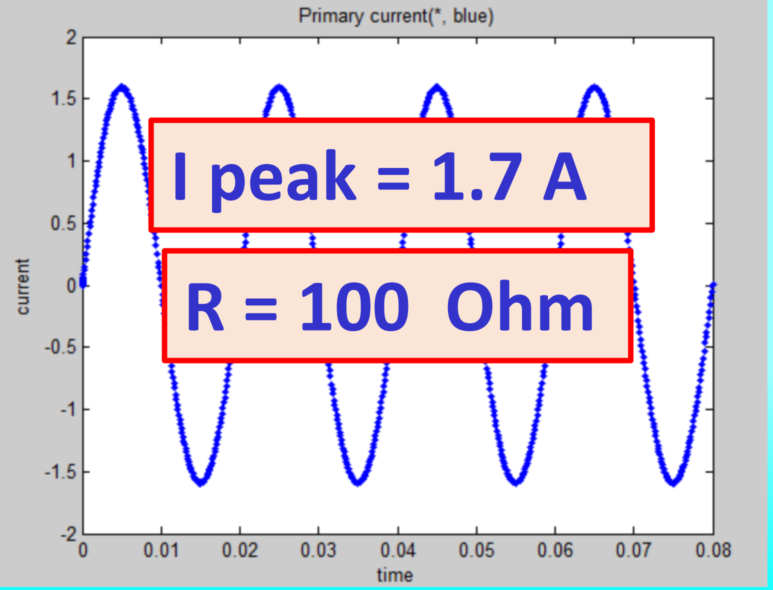
Given parameters: L_1, M_{13}, M_{31}, L_3, V_0, f for 400 kVA single phase transformer. **They are depend on geometry and turns.**







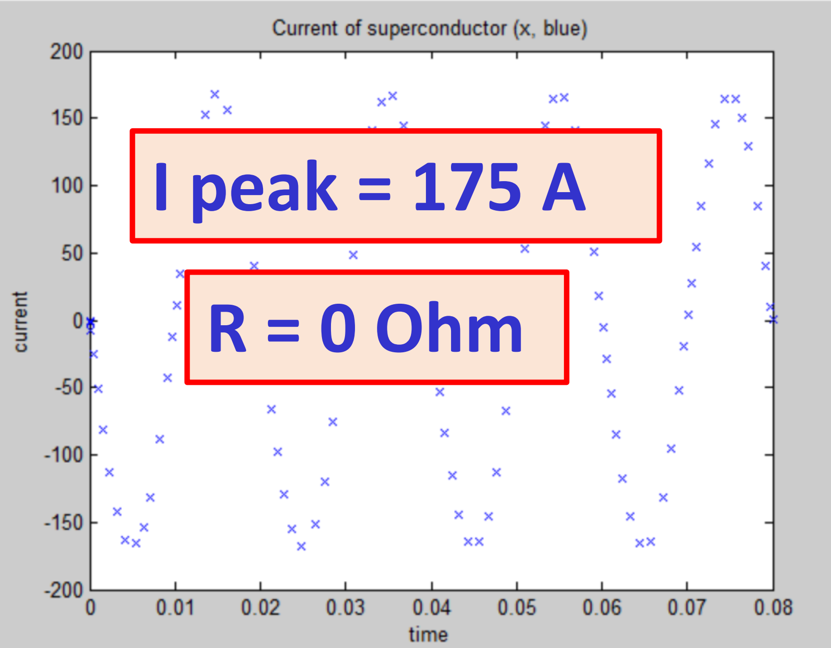


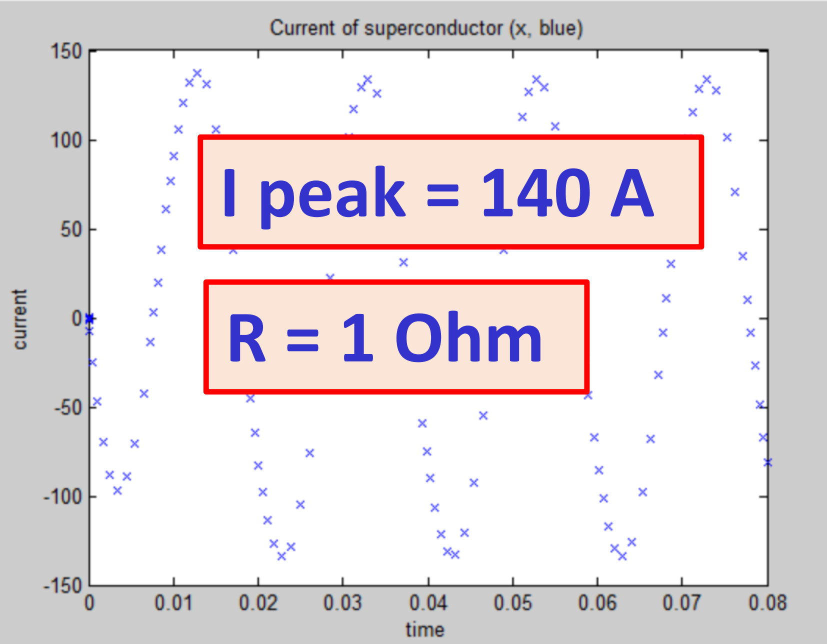


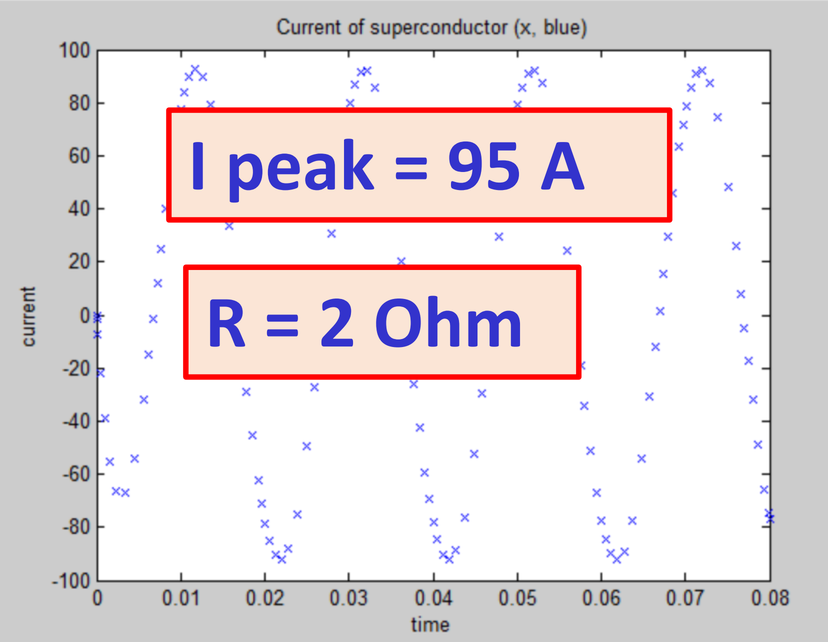
Primary current is decreasing.

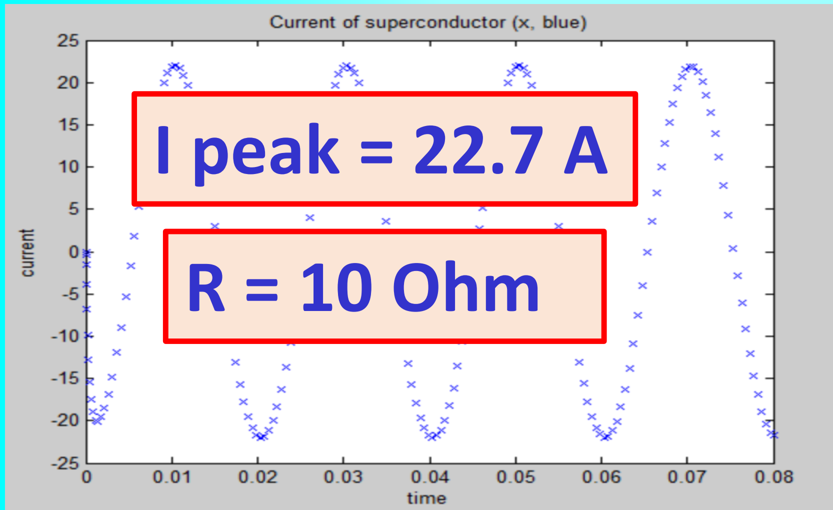
Calculation results

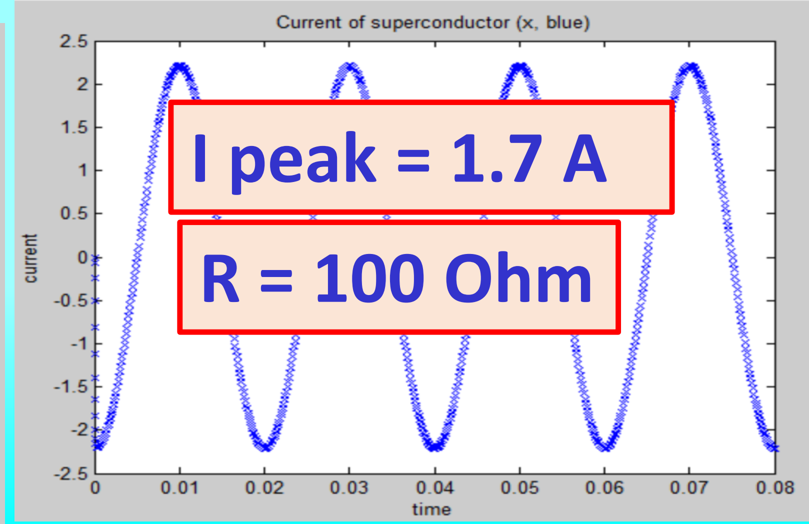
Given parameters: L_1, M_{13}, M_{31}, L_3, V_0, f for 400 kVA single phase transformer. **They are depend on geometry and turns.**







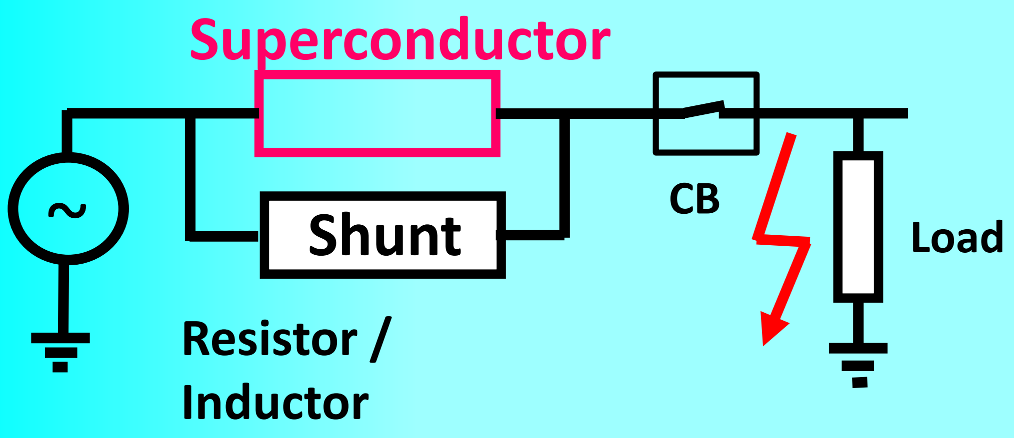




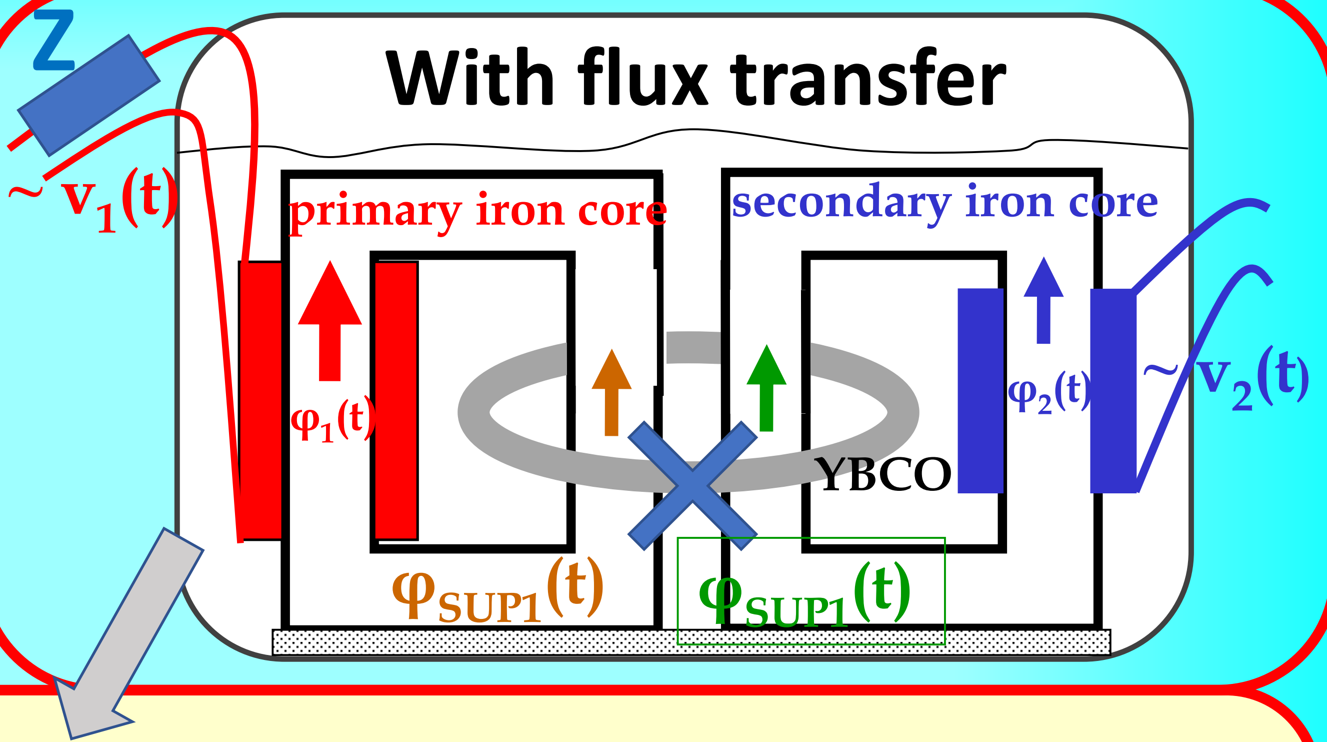
Current of superconductor is decreasing.

What is the advantage of flux transfer solution contrary to conventional resistiv solution?

Conventional



With flux transfer



- Coupling will be less between primary and secondary iron cores, thus V_2 will decrease, hence less voltage will give energy to the fault location.

- Primary current is decreasing because primary impedance is increasing because of reducing of $\varphi_{SUP1}(t)$. We have higher magnetic flux ($\varphi_1(t)$ - $\varphi_{SUP1}(t)$) in primary iron core hence primary impedance is growing.

Some previous measurement results, 1 video.

Applied material

2G HTS wire SF 12050
was produced at
SuperPower, Inc. in New York, USA

Original 12 mm wide tape

I_c= 320 A DC

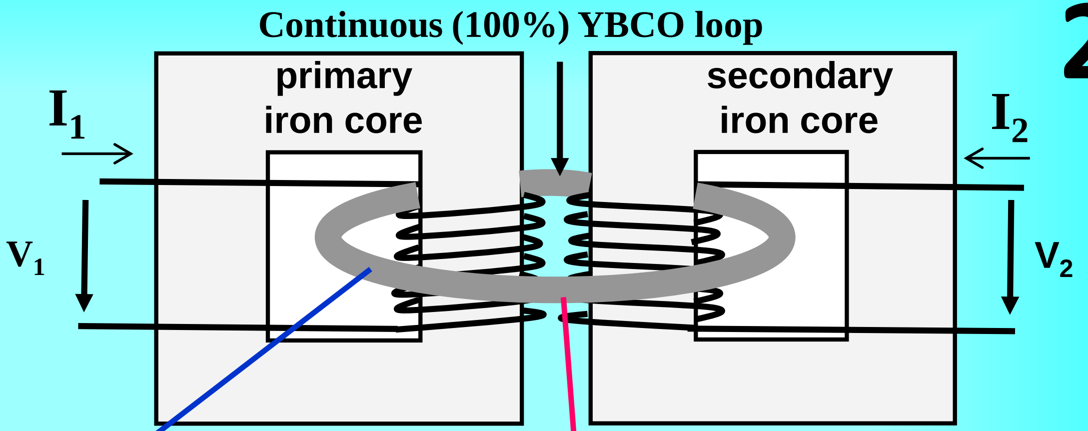
1 closed turn

6 mm wide tape

$I_{quench\ eff}$ ~100 - 105 A at 50 Hz

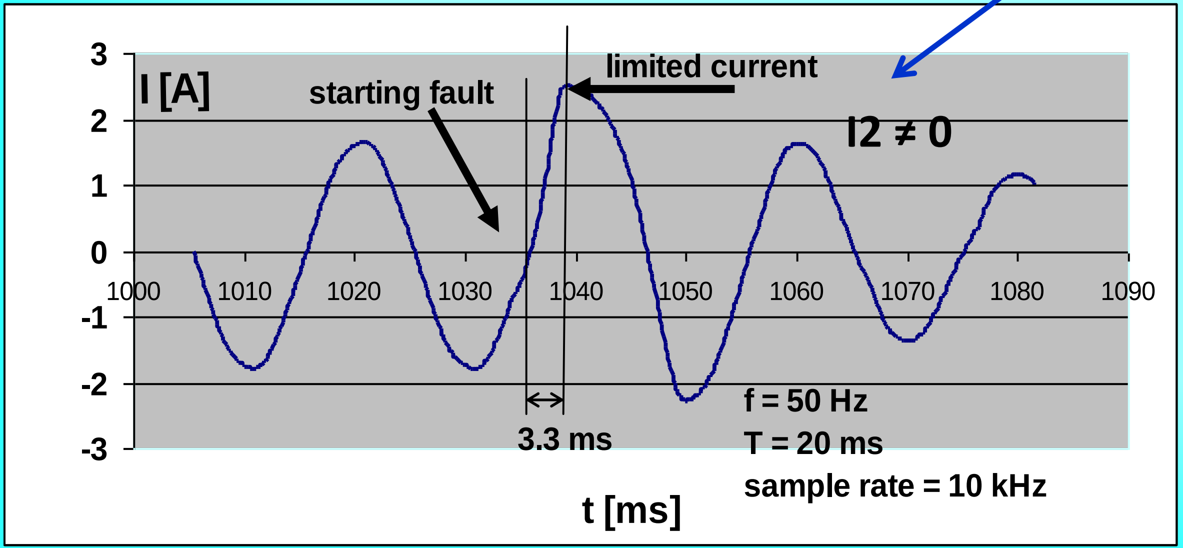
Self-limiting transformer

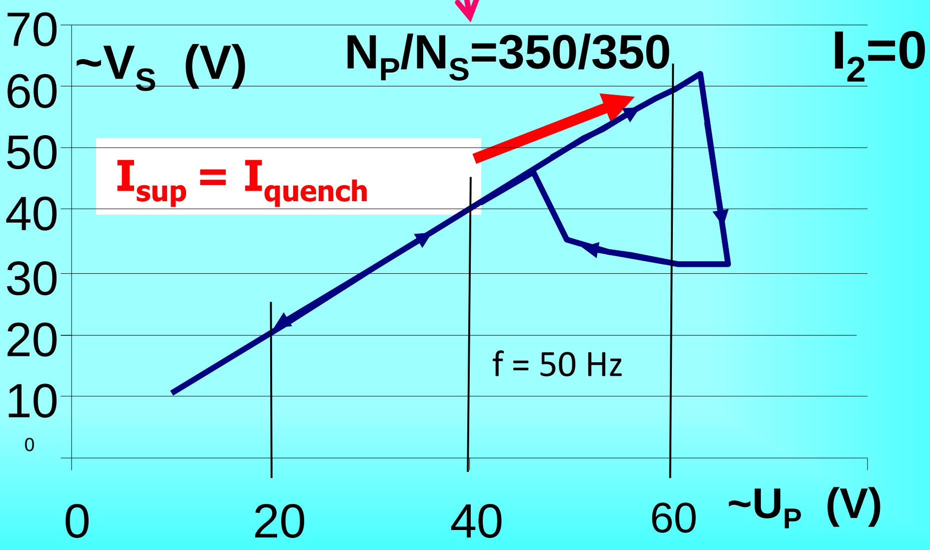
2009



5 turns I2 ≠ 0

1 turn I_2 = 0





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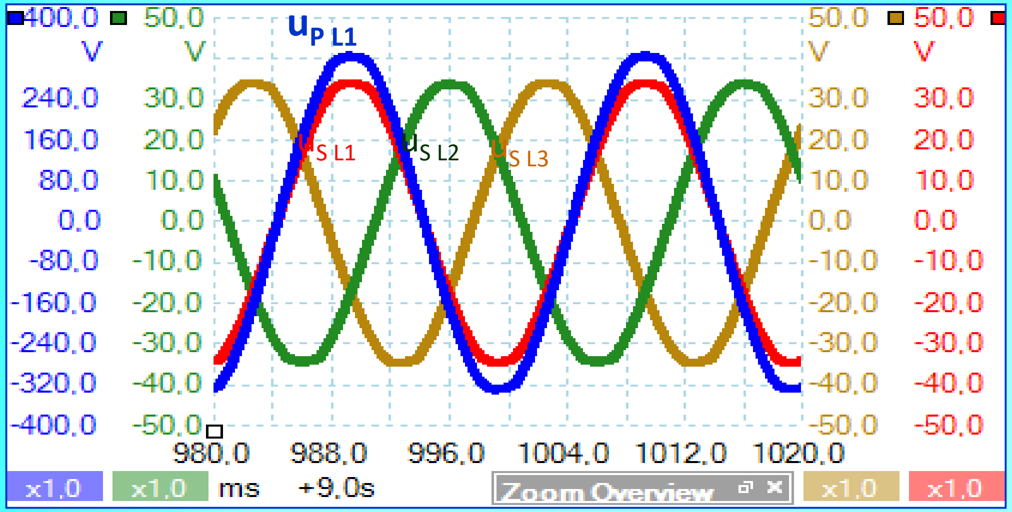
Measurement Results (1-phase short circuit in a three phase system)

2010

A conventional $Y_0y_0 0$ transformer (400 VA)

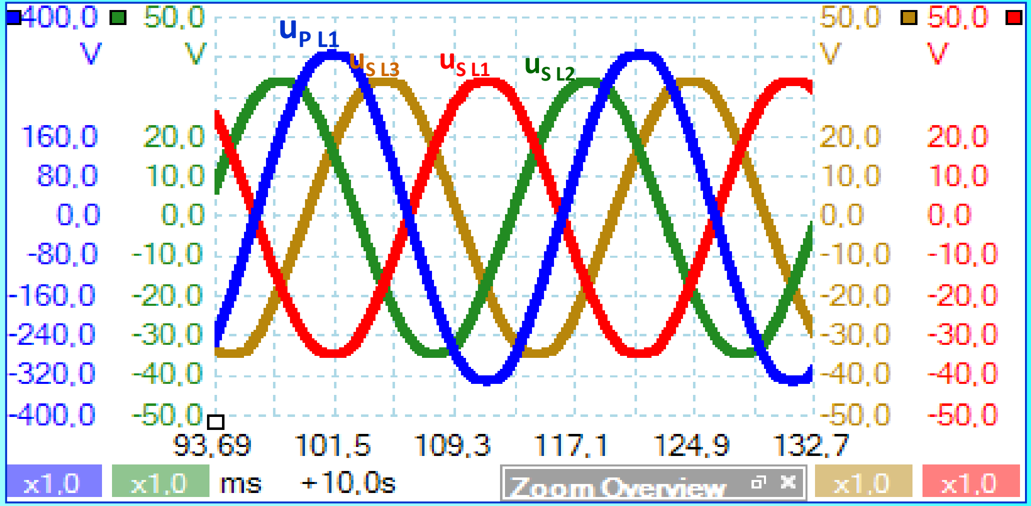


The non-load voltage of a conventional $Y_0y_0 0$ transformer.

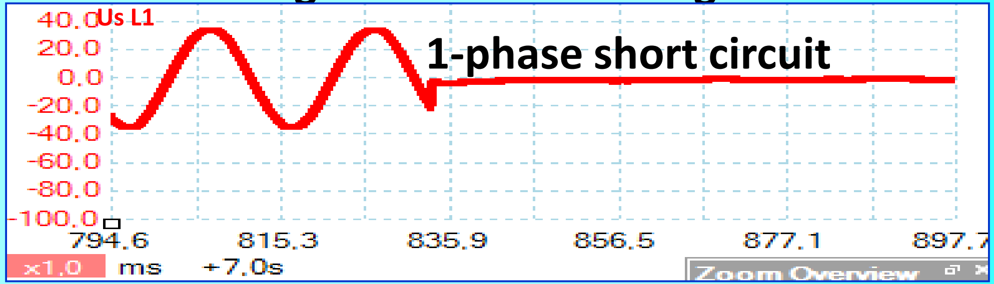
The **1-phase short circuit** of a conventional $Y_0y_0 0$ transformer equals: $\mathbf{I_{short\ circuit\ RMS} = 98\ A}$.

After effect

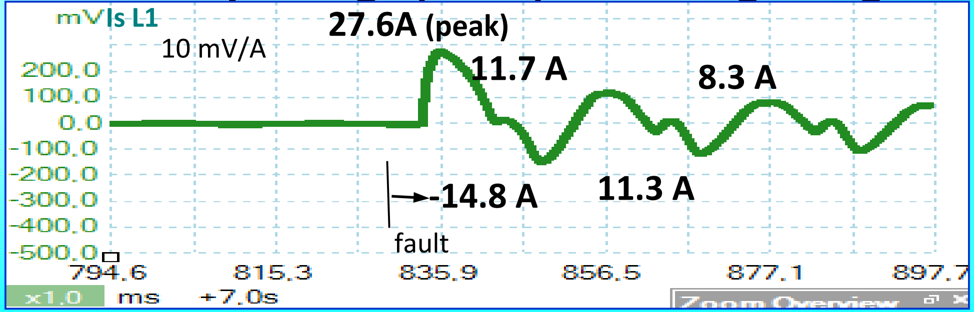
The self-limiting transformer (400 VA)



The non-load voltage of the self-limiting transformer.



Secondary voltage (Us L1) at the beginning of fault.



Secondary transient (Is L1) curernt

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A video about a short circuit

2015

Power 2 x 2.5 kW on the secondary side.

You should see the electric spark, arc. I created a short circuit between 210 V. And you can see that short circuit time is longer. Superconductor wire did not damage.

We can use this theory in a totally integrated system.

And we can realise the selectivity also.

I developed it at Ankara University in 2015 as a visiting scientist.

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Advantages

- The energy source gives lower power to the fault location during the short circuit current. Thus, the conventional protection (for example a circuit breaker) has to break lower short circuit current.

- Impedance of transformer by using flux transfer is higher. This requirement is for high power transformer in conventional system also.

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My passion and humility to science help me to reach the aims.

That is my aspect and motto.

Thank you for your attention!

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