Detailed Review of a Novel Model SFCL for Grid

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Abstract. Our paper shows an RL-Indirect SFCL model (RL-I-SFCL). The applied superconducting tape is SF 12100 (Furukawa Electric Group). In the case of the operational current of a grid, the superconducting wire is in a serial connection with the grid as in a resistive SFCL. If we have a short circuit current on the grid, the RL-I-SFCL protection includes an extra inductance. This inductance is in a serial connection with the short circuit current. The change of the resistance of the superconducting wire creates an extra impedance in the main circuit without delay. It is an advantage. We have measured our SFCL and developed a simulation program by using MATLAB program. Hence, we could test our real measured results using a simulation program. We examined only the steady state in fault. Our checking was successful. We can protect the grid, switchgears and the superconducting wire effectively with this solution. We would like to contribute with this novel model solution to the development of an SFCL in industry because this technology is very simple and it can work safely.

Keywords: 2G tape, Superconducting Fault Current Limiter, Resistive SFCL, Inductive SFCL, Simulation, Mutual Inductivity.

1. Introduction

The ‘Resistive and Inductive Indirect’ superconducting fault current limiter (RL-I-SFCL) offered by us contains a resistive part and an inductive part in the case of short circuit current. This SFCL has a near zero impedance at the superconducting state of the superconducting wire. The short circuit current activates an inductance in the main circuit without delay by increasing of the resistance of the superconducting tape. This inductivity can influence the voltage and current on the superconductor. It is an advantage of this solution.

Currently we have several types of SFCL-s [1, 2, 3, 4] in the world. We can also use a 100 % closed superconducting loop for SFCL [5, 6]. Pancake coils are popular regarding SFCL [6]. Nowadays the electrical power is increasing. We have a limit of the current in the case of conventional resistive SFCL-s because the dissipation loss can be high on a very expensive superconducting tape. The short circuit current can damage it easily. We would like to avoid this incident. This is a criterion. For this reason, we tried to look for another solution for the superconducting fault current limiter. So, our purpose was to develop a novel type (RL-I-SFCL).

Our paper presents real measured results and MATLAB simulations of an RL-I-SFCL for comparison.
2. Theoretical background of an RL-I-SFCL
The construction is very simple. Its theoretical scheme can be seen in figure 1. We have a coil and partition into two parts \((L_1, L_2)\). Two parts have to have a mutual inductance. The superconducting wire is between \(B\) and \(C\) points.

If \(R_{sup} = 0 \, \Omega\), then \(X_{L1} = 0 \, \Omega\). Thus, \(Z_{AC} = 0 \, \Omega\).
If \(R_{sup} > 0 \, \Omega\), then \(X_{L1} > 0 \, \Omega\). Thus, \(Z_{AC} > 0 \, \Omega\).

Our comment in advance: If the superconducting tape has about zero resistance, \(i_1\) and \(i_2\) have opposite direction. If the superconducting wire breaks (the case of infinite resistance), \(i_1\) and \(i_2\) have the same direction. The change of direction of \(i_2\) can change by the phase shift of the \(i_2\) at normal state. The degree of the phase change of \(i_2\) depends on the resistance of the superconducting tape and applied inductivity.

![Figure 1. Theoretical scheme.](image1)

2.1 The operation of the RL-I-SFCL when the superconducting tape is in the superconducting state
First, we suppose an ideal case. It means that the coupling factor \((k)\) between \(L_1\) and \(L_2\) is \(k = 1\), and coils have not got resistance. The coated superconductor is in the superconducting state and \(L_1 = L_2\). We can see it in figure 2. \(L_2\) and the superconducting wire give a totally closed loop. This loop has zero resistance, and it gives the opposite magnetic field against the magnetic field of the \(L_1\) coil. Hence, \(L_1\) coil has a zero resultant magnetic field. For this reason, \(L_1\) has not got reactance. It means zero impedance between \(A\) and \(C\) points. In our model, number of turns of \(L_1\) and \(L_2\) are the same \((N_1 = N_2)\).

![Figure 2. Magnetic flux of the L2 in superconducting state, \(\varphi_2 = -\varphi_1\), \(Z_{AC} = 0\).](image2)
Using the positive reference direction, we can see, that

\[ i_1 = i_{SUP} + i_2 \]  
(1)

\[ N_1 \cdot i_1 + N_2 \cdot i_2 = 0 \]  
(2)

As \( N_1 = N_2 \) thus,

\[ i_1 = -i_2 \]  
(3)

\[ i_{SUP} = i_1 - i_2 = 2 \cdot i_1 \]  
(4)

\[ V_{AC} = V_{AB} + V_{BC} = 0 \]  
(5)

\[ Z_{SFCL} = \frac{V_{AC}}{i_1} = \frac{0}{i_1} = 0 \]  
(6)

If \( N_1 \neq N_2 \), then the proportion of \( i_{sup} \) and \( i_1 \) changes but \( Z_{SFCL} = 0 \).

Figure 3 shows the phasor diagram at the superconducting state.

![Figure 3. Phasor diagram at the superconducting state.](image)

2.1.1 Real measured results in the case of the superconducting state

We wanted to measure the result. We created a very simple circuit. It can be seen in figure 4. We have tested the theoretical and measured results at 77 K. A MATLAB program was developed by us to check the measured results.

![Figure 4. The created model for the measurement and MATLAB calculation.](image)
Table 1 shows parameters of the circuit.

Table 1. The measured parameters before measurement.

| Parameters for Figure 4. | Value          |
|--------------------------|----------------|
| $V_0$ peak value of the voltage | 163.7 V         |
| $L_{TR}$ inductivity of the transformer | 3.1 mH         |
| $R_{TR}$ resistance of the transformer | 0.1 Ω          |
| $R_G$ resistance of the grid | 2.7 Ω          |
| $R_1$ resistance of the $L_1$ | 6.5 mΩ         |
| $R_2$ resistance of the $L_2$ | 6.5 mΩ         |
| $R_3$ resistance of the connection | 0.35 mΩ        |
| $R_4$ resistance of the connection | 0.35 mΩ        |
| $L_1$ inductivity 1       | 7.5 mH          |
| $L_2$ inductivity 2       | 7.5 mH          |
| $k$ coupling factor       | 0.98            |
| $f$ frequency             | 50 Hz           |
| $R_{sup}$ presumed        | 0.00000001 Ω    |

Figure 5 shows $V_{AC}(t)$, $i_1(t)$, $i_2(t)$, $i_{sup}(t)$.

Figure 5. Real measured results in the superconducting state at 77 K, the applied wire is SF 12100.
2.1.2 The results of the simulation in the superconducting state using MATLAB program

Figure 6 shows the simulation results.

![Figure 6. Currents: $i_1(t)$, $i_2(t)$, $i_{sup}(t)$ using MATLAB Program.](image)

We can see $i_1(t)$ and $V_{AC}(t)$ in figure 7. The impedance of RL-I-SFCL can be calculated from measuring results.

![Figure 7. Currents: $i_1(t)$ and $V_{AC}(t)$, $k=0.98$ using MATLAB Program.](image)

$Z_{SFCL}$ is between A and C points. The calculated $Z_{SFCL}$: $Z_{SFCL} = \frac{V_{AC \text{ peak}}}{i_1 \text{ peak}} = 0.09427 \ \Omega$ at $k=0.98$ (coupling factor). Naturally, if coupling factor changes, $Z_{SFCL}$ changes as well.

For example: $Z_{SFCL} = \frac{V_{AC \text{ peak}}}{i_1 \text{ peak}} = 0.0488 \ \Omega$ at $k=0.99$, or $Z_{SFCL} = \frac{V_{AC \text{ peak}}}{i_1 \text{ peak}} = 0.2302 \ \Omega$ at $k=0.95$. 
2.2 The case of the infinite resistance of the superconducting tape

In this case the impedance is the following:

As \( M = M_{12} = M_{21} \)

\[
\bar{Z}_{SFCL} = j\omega L = j\omega (L_1 + L_2 + 2 \cdot M) = j\omega (L_1 + L_2 + 2 \cdot \sqrt{L_1 \cdot L_2})
\]

(7)

\[
i_1 = i_2
\]

(8)

If \( L_1 = L_2 \), then \( V_{AB} = V_{BC} \)

(9)

Figure 8 shows the magnetic flux and current relationships.

![RL-I-SFCL unit diagram](image)

**Figure 8.** Break of continuity of the superconducting wire.

Figure 9 shows the phasor diagram in the case of the infinite resistance of the superconducting tape

![Phasor diagram](image)

**Figure 9.** Phasor diagram in the case of the infinite resistance of the superconductor.

2.3 Examination in the normal state of the superconducting tape

We examine how the SFCL impedance depends on the resistance of the superconducting wire.

In the normal state, the superconducting tape was substituted with some resistances.

These are the following: \( 0.05 \, \Omega, 0.1 \, \Omega, 0.15 \, \Omega, 0.26 \, \Omega, 0.315 \, \Omega, 0.37 \, \Omega, 0.43 \, \Omega \).

All currents \( (i_1(t), i_2(t), i_3(t), \text{and } V_{AC}(t)) \) were measured with all the mentioned resistances but we show only one measurement of them in this paper.

The applied resistance: \( 0.37 \, \Omega \). You can see the measured result in figure 10.
The real measured result if the superconducting wire would be 0.37 Ω.

The calculated $Z_{SFCL}$ from figure 10 is the following: $Z_{SFCL} = \frac{V_{AC\,\text{peak}}}{I_{1\,\text{peak}}} = 1.3926 \, \Omega$.

Figure 11 shows the MATLAB simulation result, $k=0.98$.

Figure 10. The real measured result if the superconducting wire would be 0.37 Ω.

Figure 11. Simulation results using 0.37 Ω instead of superconductor, $k=0.98$ using MATLAB Program.
We calculated the $Z_{SFCL}$ using simulation. It gave $1.455 \, \Omega$. $V_{AC}(t)$ and $i_1(t)$ can be seen in figure 12.

![Figure 12. The simulation result using 0.37 Ω instead of the superconductor, $V_{AC}(t)$, $i_1(t)$ using MATLAB Program.](image)

The calculated $Z_{SFCL}$ from figure 12 is the following: $Z_{SFCL} = \frac{V_{AC, peak}}{i_1, peak} = 1.4554 \, \Omega$. Table 2 shows the dependence of $Z_{SFCL}$ on the resistance of the superconductor using simulation.

| Resistance of superconductor [Ω] | $Z_{SFCL}$ [Ω] | $Z_{SFCL}/R_{sup}$ |
|----------------------------------|----------------|-------------------|
| 0.05                             | 0.2287         | 4.574             |
| 0.1                              | 0.4152         | 4.152             |
| 0.15                             | 0.6137         | 4.091             |
| 0.26                             | 1.0441         | 4.015             |
| 0.315                            | 1.2501         | 3.968             |
| 0.37                             | 1.4554         | 3.933             |
| 0.43                             | 1.6903         | 3.931             |

Naturally, these values depend on other parameters of the grid too. One of the biggest advantages of the developed RL-I-SFCL is that

\[
\frac{SFCL \text{ impedance}}{Resistance \text{ of superconductor}} > 1
\]

(10)

It can be seen in figure 13.
Figure 13. The dependence of this developed RL-I-SFCL on the resistance of the superconductor in the case of $L_1=L_2$.

3. An example for replacing current limiting reactive coil using RL-I-SFCL

Figure 14 shows a given grid with a reactive coil (hereafter: air coil). We would like to compare the operation of the air coil and RL-I-SFCL. We do a calculation using a conventional air coil, and after this we give the MATLAB calculation of an RL-I-SFCL. Parameters can be seen in table 3.

The requirement for this electrical problem is the following: We have to decrease the $S_{\text{short circuit}}$ at point $B$. We would like to reach only 120 MVA $S_{\text{short circuit}}$ at point $B$. Thus, in the conventional solution we can apply a circuit breaker only with 120 MVA breaking capacity. It is cheaper than 400 MVA type circuit breaker. In a conventional solution we use an air coil to decrease the short circuit current.

**Figure 14.** Decrease of the short circuit current with air coil.
3.1 Sizing of the air coil in the conventional solution
We can see the scheme for calculation of the X_{air coil} in figure 15.

\begin{table}
\centering
\begin{tabular}{|l|c|c|}
\hline
Given parameters & Values & Unit \\
\hline
V_{rated} line of the grid (hereafter: V_{rated}) & 22 & kV \\
S_{short circuit on the bus, at A point (hereafter: S_A), short circuit is between 3 phases} & 400 & MVA \\
S_{short circuit at B point (hereafter: S_B) short circuit is between 3 phases (requirement)} & 120 & MVA \\
I_{rated} & 280 & A \\
\hline
\end{tabular}
\end{table}

\begin{equation}
X_{grid} = \frac{V_{rated}^2}{S_A} (11)
\end{equation}

\begin{equation}
S_B = \frac{V_{rated}^2}{X_{grid} + X_{air coil}} (12)
\end{equation}

\begin{equation}
S_B = \frac{V_{rated}^2}{S_A} (13)
\end{equation}

\begin{equation}
X_{air coil} = \frac{V_{rated}^2}{S_B} - \frac{V_{rated}^2}{S_A} (14)
\end{equation}

\begin{equation}
X_{air coil} = \frac{(22 \text{ kV})^2}{120 \text{ MVA}} - \frac{(22 \text{ kV})^2}{400 \text{ MVA}} = 2.83 \Omega/\text{phase} (15)
\end{equation}

The short circuit current is at B point in a steady state:
\begin{equation}
I_{short circuit B} = \frac{S_B}{\sqrt{3} V_{rated}} = \frac{120 \text{ MVA}}{\sqrt{3} \times 22 \text{ kV}} = 3150 A (16)
\end{equation}

Voltage drop is on the air coil at rated current:
\begin{equation}
V_{air coil} = I_{rated} \cdot X_{air coil} = 280 A \cdot 2.83 \Omega = 792.4 V (17)
\end{equation}

Voltage drop in percent:
\begin{equation}
\varepsilon = \frac{\sqrt{3} V_{air coil}}{V_{rated}} = \frac{\sqrt{3} \times 792.4}{22000} = 6.24 \% (18)
\end{equation}

Reactive power:
\begin{equation}
Q = I_{rated}^2 \cdot X_{air coil} = (280 A)^2 \cdot 2.83 \Omega = 221.9 \text{ kvar/phase} (19)
\end{equation}
3.2 The calculation of the RL-I-SFCL using MATLAB simulation

Earlier we could see that measuring results and simulation gave about the same solutions. The given parameters of our software can be seen in table 4.

**Table 4.** Input parameters for calculation.

| Given parameters | Values | Units |
|------------------|--------|-------|
| \( V_{\text{rated}} \) | 22 | kV |
| \( S_{\text{rated}} \) | 10.67 | MVA |
| cos\( \phi \) | 1 (ideal) | |
| \( I_{\text{rated}} \) | 280 | A |
| \( k \) (coupling factor) | 0.9 | |
| \( L_1 \) | 0.0075 | H |
| \( L_2 \) | 0.0075 | H |

3.2.1 Simulation in the case of the rated current in the superconducting state, \( k=0.9 \) using MATLAB program

Figure 16 shows the operational currents and we can see the reactive power of the SFCL in table 5.

![Figure 16. Rated currents in the superconducting state, \( k=0.9 \), and \( S_{\text{rated}}=10.67 \) MVA using MATLAB program.](image)

**Table 5.** Reactive power of the SFCL in the superconducting state.

| \( k \) | Q (reactive power/phase) | Unit |
|--------|--------------------------|------|
| 0.98   | 7.312                    | kvar |
| 0.95   | 18                       | kvar |
| 0.9    | 35.08                    | kvar |
| 0.85   | 51.24                    | kvar |
| 0.8    | 66.468                   | kvar |
3.2.2  Simulation in the case of the changed resistance of the superconducting wire

In our simulation we changed the resistance of the superconductor. The results can be seen in table 6.

Table 6. Results in the normal state of the superconductor.

| Resistance of the superconductor [Ω] | Z_{SFCL} k=0.98 [Ω] | I_{short circuit peak} k=0.98 [kA] | Z_{SFCL} k=0.95 [Ω] | I_{short circuit peak} k=0.95 [kA] | Z_{SFCL} k=0.9 [Ω] | I_{short circuit peak} k=0.9 [kA] |
|--------------------------------------|---------------------|-----------------------------------|---------------------|-----------------------------------|---------------------|-----------------------------------|
| 0.00000001                          | 0.0964              | 13.431                            | 0.2363              | 12.126                            | 0.4576              | 10.576                            |
| 0.05                                | 0.2298              | 13.374                            | 0.3087              | 12.32                             | 0.4952              | 10.557                            |
| 0.1                                 | 0.4216              | 12.809                            | 0.4601              | 11.860                            | 0.5902              | 10.421                            |
| 0.5                                 | 1.92                | 7.0705                            | 1.9144              | 6.9437                            | 1.9147              | 6.713                             |
| 1                                   | 3.6485              | 4.1759                            | 3.5687              | 4.1998                            | 3.5                 | 4.217                             |
| 1.5                                 | 5                   | 3.1081                            | 4.9175              | 3.1431                            | 4.8242              | 3.179                             |
| 2                                   | 6.033               | 2.6044                            | 5.9452              | 2.6311                            | 5.7768              | 2.681                             |

4. Conclusion

The advantage of this solution (RL-I-SFCL) is an extra serial impedance in the case of the short circuit current in the grid. Thus, SFCL impedance > Resistance of the superconductor.

The presented device can effectively reduce the short circuit current and it is suitable to protect the applied superconducting wire as well. We can operate a more stable application. RL-I-SFCL has lower reactive power in the superconducting state than an air coil at the operational current.

Based on the calculated parameters, we can scale the length of the superconductor and the number of parallel tapes.

The disadvantage of this solution is a higher current on the superconducting wire than the operational current but we can apply more superconducting tapes in parallel connection.

5. References

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