Theoretical Calculation of Inductance of Flat Type Fault Current Limiter with High $T_c$ Superconducting Plate

Toshiro Matsumura$^1$, Keita Mutsuura$^1$, Yasunobu Yokomizu$^1$, Daisuke Iioka$^1$, Hirotaka Shimizu$^2$, Masatoyo Shibuya$^3$, Hiroyuki Kado$^3$, Michiharu Ichikawa$^3$

$^1$ Department of Electrical Engineering and Computer Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
$^2$ Department of Electrical System Engineering, Polytechnic University, 4-1-1 Hasimotodai, Sagamihara, Kanagawa 229-1196, Japan
$^3$ Central Research Institute of Electric Power Industry (CRIEPI), 2-6-1 Nagasaka, Yokosuka, Kanagawa 240-0196, Japan

E-mail: k.mutuur@echo.nuee.nagoya-u.ac.jp

Abstract. A flat type fault current limiter (FCL) proposed by us consists of a spiral primary winding and high $T_c$ superconducting (HTS) plate. In order to clarify the static current-limiting performance of the flat type FCL, the magnetic field analyses were carried out for small modules of the FCL. The inductance of the FCL was calculated by analyzing the magnetic field. The magnetic field analysis suggested that a high inductance ratio might be realized by radically enlarging both the primary winding and the HTS plate, installing the high permeability material such as an iron on the FCL and stacking the FCL modules vertically in layers. It is also pointed out that the volume of the flat type FCL is smaller than that of the cylinder type FCL with same magnitude of the limiting inductance.

1. Introduction
Fault current limiter (FCL) is expected to be installed in power system as a means to control large short-circuit currents. Several types of FCLs have been researched and developed [1]–[5]. We have proposed a flat type of superconducting fault current limiter, which is a modified version of a magnetic shielding type FCL [6][7]. The flat type FCL has a simple construction and basically consists of a doughnut-like form high $T_c$ superconductor (HTS) plate and a spiral coil, each of which works as a secondary one-turn winding and a primary winding, respectively. This type of FCL modules can be easily built up to make a large scale FCL for a practical use. Also, since it is easy to make the HTS plates, the FCL may enable us to reduce the manufacturing costs.

This paper describes how to improve the ratio of the limiting inductance to the normal one of the flat type FCL, which were calculated by analyzing the magnetic field in the FCL under the normal-conducting and superconducting conditions of the HTS plate. Furthermore, we also compared the flat type FCL with the conventional cylinder type FCL.
2. Flat Type Fault Current Limiter with HTS Plate [6][7]
Fig. 1 illustrates a basic configuration of the flat type FCL which consists of a spiral winding (primary winding) and a HTS plate in doughnut shape. The spacer is inserted between the primary winding and the HTS plate for an electrical and thermal insulation. The spiral winding is connected to an electrical power system in series and the current $I_1$ (load current or fault current) in the power system flows in it. The shielding current $I_2$ is induced in the HTS plate by the time variation in the magnetic flux $\phi_1$ due to $I_1$. The principle of this type of FCL is essentially same as that of a magnetic shielding type FCL.

3. Estimation of inductance ratio of flat type FCL
3.1. Magnetic field analysis model
In order to clarify the static current-limiting performance of the flat type FCL, the magnetic field analyses were carried out for the small modules of the FCL by using the finite element code. An air core type module illustrated in Fig. 1 has the primary winding of 14 turns, which is referred to as a basic module in this paper. In our magnetic field analyses, the relative permeability $\mu_r$ of air, primary winding and HTS plate was assumed to be 1.0. The electrical conductivity $\sigma$ of the HTS plate was assumed to be $10^{20}$ S/m at the superconducting condition and $10^6$ S/m at the normal-conducting condition[8]. We calculated the magnetic flux due to ac current of 10 A and 60 Hz in the primary winding and the shielding current (eddy current) induced in the HTS plate for the superconducting and normal-conducting states.

3.2. Inductance of basic module
The inductances of the basic module in Fig. 1 were estimated by calculating the magnetic energy. In the top column of Table 1, the derived magnitudes of the inductance for superconducting and normal-conducting condition of the HTS plate, $L_0$ and $L_{\text{limit}}$, are shown together with their ratio $L_{\text{limit}}/L_0$, the outside radius and height of the FCL $r$ and $h$, the total length of the primary winding $l_1$ and the volume of the FCL $V_{\text{FCL}}$.

In case of the basic module having 14-turns primary winding, the inductance $L_0$ at the superconducting condition of the HTS plate was calculated to be 1.71 $\mu$H. This very small inductance is brought about by canceling out the magnetic flux due to the current in the primary winding by the inverse flux due to the shielding current in the HTS plate. Even if the HTS plate becomes the normal-conducting condition, the basic module has relative low inductance $L_{\text{limit}} = 9.39$ $\mu$H and therefore has an inductance ratio of $L_{\text{limit}}/L_0 = 5.49$.

3.3. Improvement of inductance ratio
In order to investigate the effects of the number of turns and the configuration of the primary winding on the inductance ratio, the magnetic field analyses were carried out for the double and single layer modules of 28-turns primary winding. In the former type a pair of 14-turns windings is vertically built up, while the primary winding and the HTS plate are radically enlarged in the latter type. Table 1 also shows the derived magnitudes of inductance of the single and double layer type modules.

![Figure 1. Configuration of basic module of flat type fault current limiter using HTS plate.](image)
Table 1. Inductance of flat type modules estimated by magnetic field analyses.

| Module         | Winding | $r$  | $h$  | $l_1$ | $V_{FCL}$ | $L_0$  | $L_{limit}$ | $L_{limit}/L_0$ |
|----------------|---------|------|------|-------|-----------|--------|-------------|-----------------|
| Basic          | 14 turns| 38.1 | 3.0  | 2.23  | $1.37 \times 10^{-4}$ | 1.71  | 9.39        | 5.49            |
| Double layer   | 28 turns| 38.1 | 4.5  | 4.47  | $2.05 \times 10^{-4}$ | 8.87  | 37.0        | 4.17            |
| Single layer   | 28 turns| 63.5 | 3.0  | 6.69  | $3.80 \times 10^{-4}$ | 5.58  | 46.5        | 8.33            |

In case of the double layer type module, the inductance $L_{limit}$ is 37.0 μH, which is about four times as high as that of the basic module. This is because the inductance of the coil increases almost in proportion to the square of the winding turn ratio ($28/14 = 2$). The inductance $L_0$ under the superconducting condition is 8.87 μH. This relatively large magnitude of $L_0$ is brought about due to the less coupling between the upper winding and the HTS plate, and thus results in the smaller inductance ratio of 4.17 in comparison with the basic module.

On the other hand, in the single layer type module, $L_{limit}$ is 46.5 μH, which is about five times as large as that of the basic module. This is interpreted to be brought about not only by the increase of the winding turn number but also by the radical enlargement of the primary winding. Since both of the winding and the HTS plate is radically enlarged, the inductance at the superconducting condition is not increased much and then becomes 5.58 μH. As a result, the inductance ratio is increased to be 8.33, which is 1.5 times as high as that of the basic module.

Consequently, it is pointed out that a higher inductance ratio of the flat type FCL can be obtained by radically enlarging both the primary winding and the HTS plate.

4. Discussion

4.1. Comparison between flat type FCL and cylinder type one

A magnetic shielding type FCL has been conventionally researched and developed by using an HTS cylinder. Then, in this section, the inductance and dimensions of the flat type FCL are compared with those of the cylinder type FCL to clarify the advantage of the flat type FCL. The basic cylinder module with 14-turns winding, double layer cylinder module with 28-turns winding and single layer cylinder module were designed to have almost the same limiting inductance $L_{limit}$ as corresponding modules of the flat type FCL. It was supposed to produce both HTS plate and cylinder so that ab-plane of the crystals were aligned together in the conducting direction. In Table 2, the calculated magnitudes of $L_0$, $L_{limit}$ and their ratio $L_{limit}/L_0$ are summarized together with the dimensions of the FCL.

It is found from comparison between Tables 1 and 2 that each cylinder module has almost same $L_0$, $L_{limit}/L_0$ and $l_1$ as the corresponding flat type module while only volume of the FCL is different from each other. The volume of the cylinder type FCL becomes bigger than that of the corresponding flat type FCL. As an example, in case of the single layer module with 28-turns primary winding, the volume of the cylinder type FCL is about five times as large as that of the corresponding flat type FCL. It is concluded that the flat type FCL needs less volume than the cylinder type one to produce the same limiting performance.

Table 2. Inductance of the cylinder type modules estimated by magnetic field analyses.

| Module          | Winding | $r$    | $h$    | $l_1$  | $V_{FCL}$ | $L_0$  | $L_{limit}$ | $L_{limit}/L_0$ |
|-----------------|---------|--------|--------|--------|-----------|--------|-------------|-----------------|
| Basic cylinder  | 14 turns| 26.5   | 25.4   | 2.27   | $5.6 \times 10^{-4}$ | 1.81  | 9.94        | 5.49            |
| Double layer    | 28 turns| 26.5   | 25.4   | 4.40   | $5.6 \times 10^{-4}$ | 9.11  | 37.0        | 4.06            |
| Single layer    | 28 turns| 37.5   | 50.8   | 6.47   | $2.24 \times 10^{-4}$ | 5.45  | 45.9        | 8.42            |
4.2. Effect of iron core on inductance ratio

From the electromagnetic theory, the insertion of an iron core is expected to increase the inductance of the coil. We estimated the inductance ratio of a semi-iron-core type module, where only an iron bar is inserted in the center hole of the basic module of the flat type FCL with 14-turns winding. The iron bar is 63.5 mm in height and 12.7 mm in radius and is assumed to have a relative permeability $\mu_r$ of 1000.

As shown in upper column of Table 3, although $L_0$ does not increase so much, the limiting inductance $L_{\text{limit}}$ increases from 9.39 $\mu$H to 21.4 $\mu$H by the insertion of the iron bar. Then, the inductance ratio is improved from 5.49 to 11.5. Therefore, it is pointed out that the insertion of the high permeable material enables us to improve the inductance ratio.

4.3. Built-up effect of basic module for improving inductance ratio

The flat type FCL has an advantage that it can be easily built up to make a large scale FCL. Two basic modules with 14-turns winding are vertically stacked through a spacer of 1 mm in thickness to make a built-up structure. The inductances evaluated for the built-up structure are summarized in the lower column of Table 3. In spite of the series connection of two modules, $L_0$ becomes only 1.46 (=2.49/1.71) times because of the cancellation effect of the HTS plate for the linkage magnetic field. On the other hand, at the normal-conducting condition of the HTS plate, two primary windings are connected each other with a magnetic mutual linkage. Thus, the limiting inductance of the build-up FCL increases to be 34.6 $\mu$H. This magnitude is nearly four times as large as that of the single basic module. As a result, the inductance ratio is improved to be 13.9. Consequently, the built-up structure enable us not only to make a large scale FCL but also to effectively improve the inductance ratio, that is, the performance of the FCL.

5. Conclusion

The inductance of the FCL under the normal and limiting condition was calculated by analyzing the magnetic field of the FCL. We investigated the ratio of the limiting inductance to the normal one of the flat type fault current limiter. It is confirmed that a higher ratio of the limiting inductance to the normal inductance of the FCL may be realized by radically enlarging both the primary winding and HTS plate, using a high permeability material and building up the FCL vertically in layers. We also compared the flat type FCL with the cylinder type FCL. It is found that the volume of the flat type FCL is smaller than that of the cylinder type FCL with same magnitude of the limiting inductance. Therefore, the flat type FCL has an advantage that it can be easily built up to make a large scale FCL and to realize a higher inductance ratio.

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