6.6kV-200A급 DC 리액터형 고온초전도한류기의 최적설계

Optimal Design of 6.6kV-200A DC Reactor Type High-Tc Superconducting Fault Current Limter

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Abstract: This study deals with the optimal design of a DC reactor type high-Tc superconducting fault current limiter(SFCL). The condition in which the cost function is minimized under given constraints is one of the things to be first considered in developing SFCLs. This condition is a group of the values corresponding to the variables the cost function depends on. In this paper, the length of tape was taken as a dependent variable, the inductance of DC reactor and the turns ratio of magnetic core reactors as independent variables. For the SFCL available at the level of 6.6kV-200A, we examined 4 cases: at the fault times of 80msec, 50msec, 30msec and 10msec. Since thyristors would be utilized instead of diodes, we chose the result at 10msec as the basic data. Considering safety factor 30%, our optimal design was decided to be the inductance 570mH, the critical current over 620A, the turns ratio 0.89 and the fault time within 20msec.

Key Words: optimal design, Newton method, DC reactor type high-Tc SFCL, cost function

1. Introduction

An SFCL is a device for protecting the expensive electric machines installed in power systems by holding down the fault current below the upper limit when a fault occurs. DC reactor type SFCLs, which we deal with here, have high-Tc superconducting coil as a reactor. Compared with low-Tc SFCLs, high-Tc SFCLs are more advantageous because they require less cost for cooling system and operate more effectively.

But in the commercial aspect, it is a serious weakpoint that the price of high-Tc superconducting tape is surprisingly high. SFCLs play their role from the point of time that fault state begins to the point of time that circuit breakers operate. Thus, if this fault time that SFCLs are expected to experience is determined, the cost can be lower according to how well we harmonize the inductance of superconducting coil, the turns ratio of magnetic core reactors, normal voltage, normal current and critical current, etc.

Our laboratory has made and tested three-phase DC reactor type SFCLs as well as single-phase for the first time in South Korea. This paper suggests Newton method as a way of designing optimally a 6.6kV-200A level SFCL. We first set up the cost function and then found the values of each variable so that this function has the lowest value under the given conditions by simulation.

2. Three-phase DC reactor type SFCL

2.1. Structure

A three-phase DC reactor type SFCL consists of three magnetic core reactors for connecting the SFCL to a power system, a superconducting coil for restraining the increase of fault current as a reactor at fault state, six rectifiers for changing the AC current that will flow through the coil into the DC and a cryostat for keeping the coil in superconducting state. Fig.1 shows its schematic.

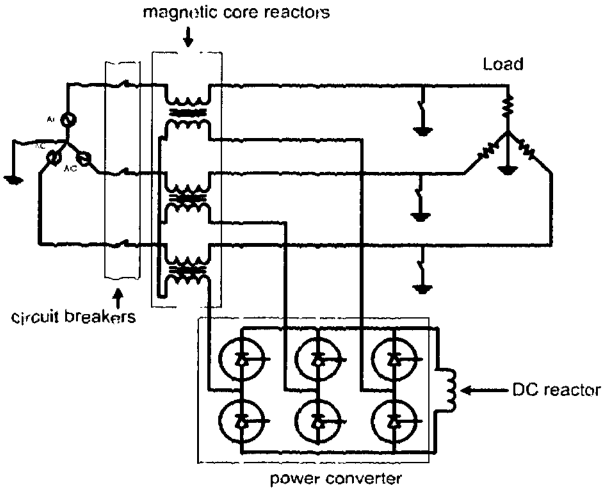

Fig. 1. Schematic drawing of three-phase DC reactor type high-Tc SFCL

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2.2. Operational Characteristics

The basic operational characteristics of three-phase DC reactor type SFCLs are the same as that of the general bridge rectifier. In the case that power is transmitted to a given system in normal condition, the three-phase AC current that enters the bridge circuit is fully rectified and sent to the superconducting coil. Because of its inductance, the rectified current has ripples.

As it turns out, the larger the inductance is, the smaller the ripples are. The inductance of our superconducting coil is so large that almost constant DC current goes through the reactor, from which the voltage drop between the two terminals of the DC reactor is close to zero. So, we can say the power loss inside the circuit is caused by the resistance of the tape used for the coil and by the forward bias voltage drop of the rectifiers.

But the tape is made of superconducting material and the loss in the former case is negligible. The loss in the latter case is also very little and can be ignored. That is, it can be said that the SFCL doesn't give rise to loss at normal state. If the system is short-circuited, the voltages of each rectifier become much larger than in the normal condition and so does the current passing through the coil. However, before that fault current goes up to the upper limit, the circuit breakers work such that the circuit is isolated from the power sources for protecting the system.

3. Optimal Design

3.1. Concept

Optimal design is to find the values of the variables that minimize a given function. This function usually relies on dependent variables and independent variables which are the variables of the dependent variables.

$$C = C(w_1 x_1, \cdots, w_n x_n) \qquad (1)$$
$$x_1 = x_1(s_1, s_2, \cdots, s_m)$$
$$x_2 = x_2(s_1, s_2, \cdots, s_m)$$
$$\cdots$$
$$x_n = x_n(s_1, s_2, \cdots, s_m) \qquad (a_l \le s_l \le b_l)$$

where C is a function, $x_1, \cdots, x_n$ are dependent variables, $s_1, \cdots, s_m$ independent variables and $w_1, \cdots, w_n$ constants. For optimal design, Euler-Lagrange method and Newton method are generally used. We employed Newton method because calculations in its process are more stable and easier than in that of Euler-Lagrange method. The process to seek for the minimum value of a function by Newton method is this:

1. Pick up some point on the function at random.
2. Find the gradient of the function at that point.
3. Move in the opposite direction of the gradient.
4. Find the gradient of the function there. This point must be closer than the previous one to the position where the function has its minimum value.
5. Move in the opposite direction of the gradient again.

Repeat this process until we reach the point where the gradient is zero. The value of the function at that point is minimum.

$$\nabla C = \sum_{k=1}^{m} \overset{\rho}{a}_k \frac{\partial C}{\partial s_k}\bigg|_{s_1, s_2, \cdots, s_m} \quad \left(\frac{\partial C}{\partial s_l} = \sum_{k=1}^{n} \frac{\partial C}{\partial x_k}\frac{\partial x_k}{\partial s_l}\right) \qquad (2)$$

It is the values of the variables at this point that we have to obtain as a result. Formula (2) shows the gradient of a scalar function C and the chain rule formed in differentiating a function having both dependent variables and independent variables. Fig.2 displays the process to find the minimum point in two dimensions.

But this method performs parallel processing, so we can't help simply finding each value. In other words, the inductance, the turns ratio, the current and the capacity of the power converter are decided but the size and shape of the coil, the structure of the power converter, etc. are not. Visualization is also impossible in more than three dimensions. Furthermore, it is also a serious defect that zero gradient can say the extremum values as well as the minimum values as illustrated in Fig.2. In order to solve this problem, we repeated the process with a lot of randomly chosen initial points. Of the values we'd found, the lowest one was taken as the minimum. For example, considering this way in Fig.2, we get to find two extremum values. The right point is lower than the left one, and hence our conclusion would be the values of the right one.

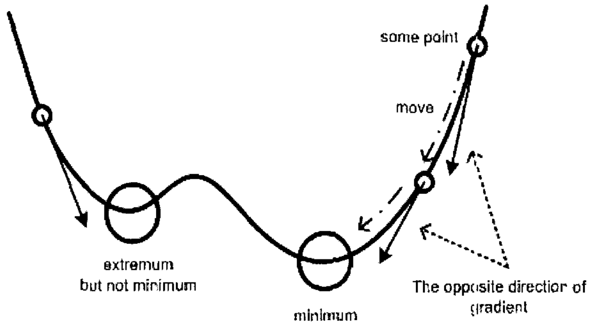

Fig. 2. Process to find minimum values by Newton Method

3.2. Design & Algorithm

Assuredly, the cost function for our SFCL has several dependent variables but this study selected only one for convenience: the length of tape. Of the actually controllable dependent variables, this is of the most importance to decide the cost. And the inductance of a superconducting coil and the turns ratio of the magnetic core reactors are chosen as the independent variables, say, the variables of the length of tape. In general, the inductance and the length of a coil are

$$L=\mu_0\pi\frac{a^2}{b}N^2K \tag{3}$$

$$l=2\pi aN \tag{4}$$

respectively. So, the length of tape is expressed as

$$l=\gamma\sqrt{L}\quad(\gamma:\text{constant}) \tag{5}$$

Ultimately, the actual cost function is

$$C=\zeta\gamma\sqrt{L}\frac{I_f}{I_c} \tag{6}$$

where ζ is the price of tape per unit length and I_c the critical current, I_f the fault current. I_f depends on the inductance and the turns ratio. But optimal design requires a function should be linear combination. So, expressing the cost function actually used,

$$C_{\text{cost}}=\alpha\sqrt{L}+\beta\frac{I_f}{I_c} \tag{7}$$

where α and β are constants. These were decided considering the relationship between (6) and (7). The minimum C_{cost} was our target.

Table 1 is the conditions for design and

Table 1. Conditions

parameters		values
input voltage	line to line	6.6 kV(rms)
	line	3.8 kV(rms)
resistance	load	19.05 Ω
	line + power converter	0.5~1.5 Ω
maximum power		over 2.3 MVA
current		200 A(rms)
inductance		0.01~2 H
turns ratio (s/p)		0.01~2

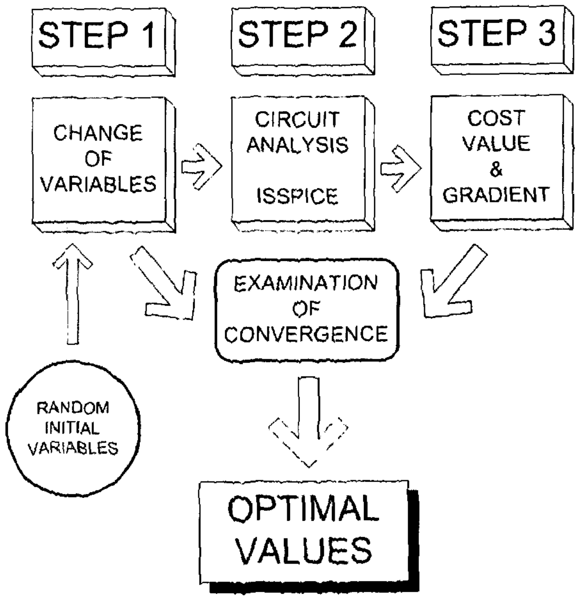

Fig. 3. Algorithm for simulation

Fig.3 is the algorithm of simulation, which shows the process to find the minimum point in the form of diagram. STEP 2 tells us SPICE worked linked with simulation to get and apply I_f at once. The fault in this analysis was balanced three-phase fault that is the worst case.

4. Simulation Results & onsideration

4.1. Simulation Results

As mentioned before, finding the values of the variables at the position where the function became minimized was our goal. Here, the whole distributions of the cost function are also displayed together with the results in order to help understand the process more easily in three dimensions just as Fig.2 does in two dimensions. Fig.4~Fig.11 are the distributions and the results at each fault time.

4.2. Consideration

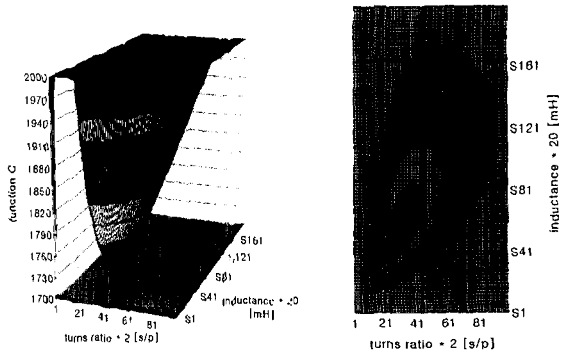

Fig. 4. Cost distribution at fault time 80msec

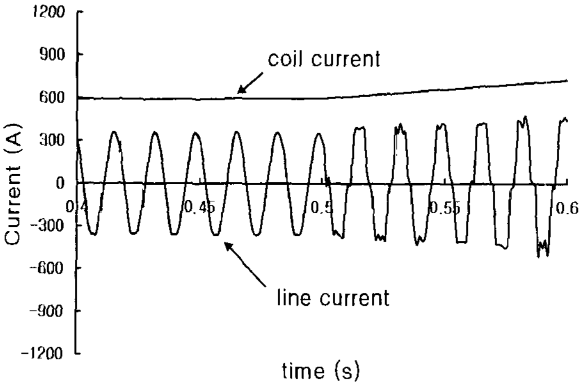

Fig. 5. Coil current & line current at fault time 80msec

Table 2. Result at fault time 80msec

parameters	values
turns ratio (s/p)	0.61
inductance	1.09 H
critical current (after 30ms)	884 A

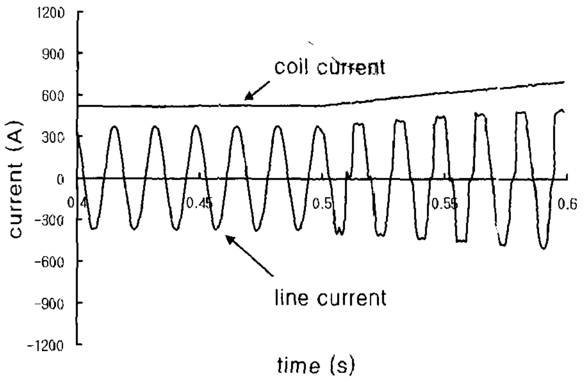

Fig. 7. Coil current & line current at fault time 50msec

Table 3. Result at fault time 50msec

parameters	values
turns ratio (s/p)	0.71
inductance	0.38 H
critical current (after 30ms)	783 A

Fig.4, 6, 8, 10 show the distributions of the cost function with respect both to the inductance and to the turns ratio in the left, and its projections to the inductance-turns ratio plane in the right. The peak point in the left indicates the minimum position, which is illustrated as the innermost area in the right. The inductance and the turns ratio at any point inside this area are available. As fault time is longer, the value of the cost function is lower and the area is smaller. This means we have more options in shorter fault times. Also with our intuition, we naturally get to think this is feasible. Because the damage during the shorter fault is less serious, we would have more choices for the same minimum values.

Fig.5, 7, 9, 11 show the currents flowing through the DC reactor and along the lines connected to the loads. The DC reactor current may be below or above the peak value of the line current according to the turns ratio; in secondary winding, the number of turns is inversely proportional to the current. As fault time is longer, the inductance is lower, which causes the increase rate(the slope) of fault current to be higher.

Fig.12 shows our results synthetically. In case of fault current, even though its increase rate is reduced by the inductance, it still keeps increasing. So, It′s resonable for the peak current to be proportional to fault time. The inductance is proportional to fault time, too. As mentioned in Introduction, SFCLs start to operate when fault state begins and their operation goes on with the fault current increasing until circuit breakers operate. Reflecting on the fact that the fault current has to be below the upper current limit of the superconducting tape at the point of time that circuit breakers cut the system off the power sources, the proportionality of the inductance

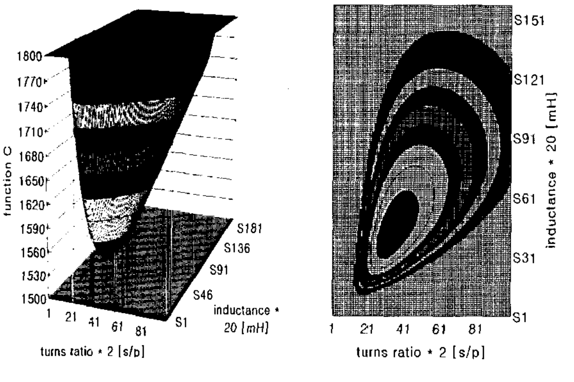

Fig. 6. Cost distribution at fault time 50msec

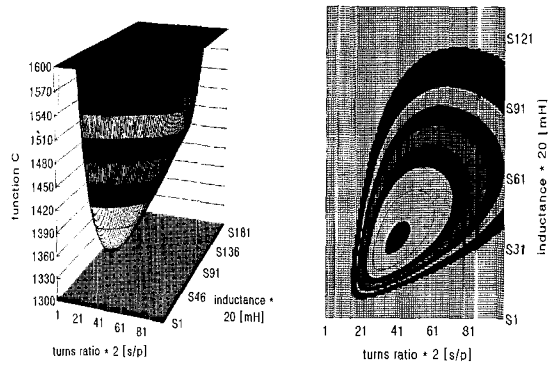

Fig. 8. Cost distribution at fault time 30msec

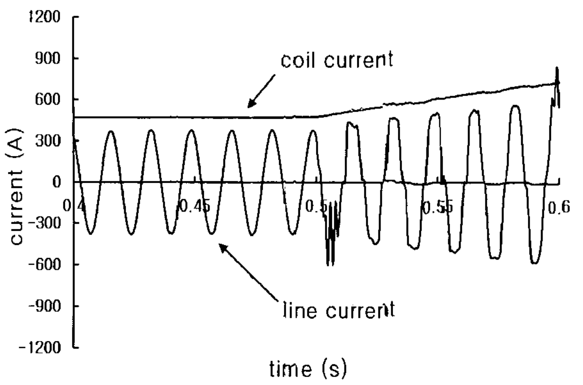

Fig. 9. Coil current & line current at fault time 30msec

Table 4. Result in fault time 30msec

parameters	values
turns ratio (s/p)	0.80
inductance	0.69 H
critical current (after 30ms)	688 A

to fault time makes sense. In addition, the inductance is in proportion to the square of the number of winding. Therefore the length of tape is increased. If the turns ratio goes up, both the increase rate of the fault current and the voltage drop at the two terminals of the DC reactor get higher. The longer fault state lasts, the lower the turns ratio should be.

For our 6.6kV-200A SFCL thyristors are going to be used as rectifiers. Thus, the fault current will be cut off within half a cycle after a fault occurs and we regarded the result at fault time of 10msec as the basic data for our optimal design. If we would use diodes, we would adopt the result at fault time of 80msec.

At last, we concluded Table 6 is the optimal design for the 6.6kV-200A level SFCL with safety factor of 30%. The reason why this factor was 30% is that it would operate within, at least, the next one cycle even if the thyristors couldn't break the flow of fault current at the time it must do.

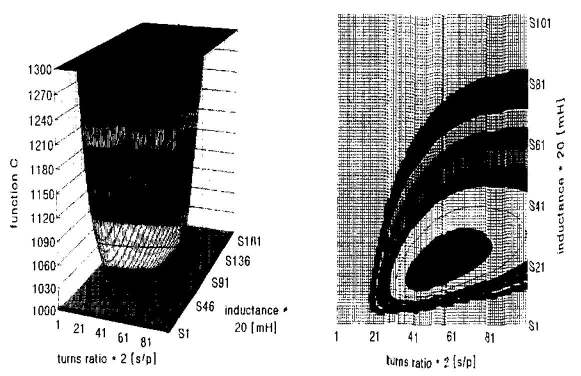

Fig. 10. Cost distribution at fault time 10msec

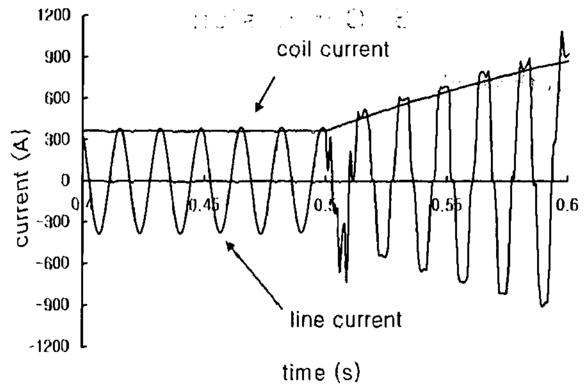

Fig. 11. Coil current & line current at fault time 10msec

Table 5. Result at fault time 10msec

parameters	values
turns ratio (s/p)	1.06
inductance	0.40 H
critical current (after 30ms)	520 A

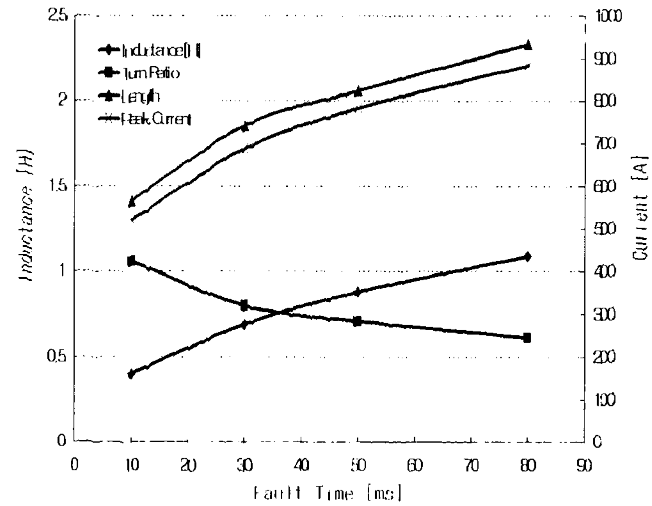

Fig. 12. Optimized values with respect to fault time

Table 6. Optimal design

parameters	values
inductance	570 mH
critical current	over 620 A
fault time	within 20 msec
turns ratio (s/p)	0.89

5. Conclusion

A three-phase DC reactor type SFCL plays the role of protecting systems from the damage caused by the excessive fault current when a fault happens. But superconducting tape itself is very expensive, which will cause a SFCL to cost a lot. So, the optimal design is inevitable for its commercialization. This paper introduced the optimal design using Newton method for 6.6kV-200A DC reactor type High-Tc SFCL and showed the results of 4 cases(fault time: 80msec, 50msec, 30msec, 10msec) by analyzing and simulating the distributions of the cost function from that method. Since we will utilize thyristors instead of diodes at the level of 6.6kV-200A, the result at the shortest fault time case(10msec) was selected as the data for the optimal design. In this study, the length of tape only, which is of the most influence, was the dependent variable of the cost function. If all of the dependent and independent variables are included in analysis, more accurate results will come out.

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References

[1] M. Yamaguchi, "Performance of DC Reactor Type Fault Current Limiter Using High Temperature Superconducting Coil", IEEE Transactions on Applied Superconductivity, Vol. 9, No. 2, June 1999, pp.940~943

[2] Eung Ro Lee, "Simulation of the Three-phase DC Reactor Type Fault Current Limiter for the Short-circuit Test", 2001 KIEE 하계학술대회 논문집, 18~20 July, 2001, pp.717~719

[3] Erwin Kreyszig, "Advenced Engineering Mathematics", 7th ed., 1993, pp.925~934

[4] Frederick W. Grover, "Inductance Calculations", pp.142~147

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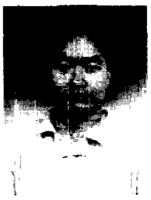

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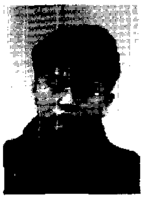

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