An Optimal Design Approach for Resistive and Inductive Superconducting Fault Current Limiters via MCDM Techniques

R. Sharifi* and H. Heydari*

Abstract: The design process of a superconducting fault current limiter (SFCL) requires simulation and definition of its electrical, magnetic and thermal properties in form of equivalent circuits and mathematical models. However, any change in SFCL parameters: dimension, resistance, and operating temperature can affect the limiting mode, quench time, and restore time. In this paper, following the simulation of electrical and thermal behavior of resistive and inductive SFCLs and investigation on their performance variation responded to change parameters, the best design cases will be selected by using multiple criteria decision making (MCDM) techniques. As a case study, to evaluate proposed MCDM approaches in design of superconducting fault current limiter, a model in which a SFCL is located at an outgoing feeder in a 20 kV distribution substation will be considered and best designs will be presented for both resistive and inductive type.

Keywords: Superconducting Fault Current Limiter, Multiple Criteria Decision Making, Analytic Hierarchy Process.

1 Introduction

High fault currents can cause severe mechanical and thermal stresses in generators, transformers, and other equipment that reduce security and reliability in the system. As a result, upgrading and replacement of equipments is necessary. The reduction and or limiting the fault current would lead to a great saving from technical and economical point of view [1]. The superconducting fault current limiter (SFCL) has many advantageous functions such as automatic excessive current detecting, automatic recovering and faster excessive current limiting operations [2]. In the past two decades, several types of SFCL presented including normal resistive [3], flux flow resistive [4], inductive [5], flux-lock [6], and saturated core [7].

Multi-criteria decision making (MCDM) is one of the most widely used decision methodologies in the business and engineering worlds. Some applications of MCDM in engineering include the use on flexible manufacturing systems, layout design, integrated manufacturing systems, and the evaluation of technology investment decisions [8].

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The analytic hierarchy process (AHP), is a simple and convenient MCDM technique that can provide a positive approach to the complex decision-making problems with multiple objectives/criteria and no architectural characteristic [9]. In the recent years, the use of AHP as a flexible tool effectively compatible with the other techniques has unexpectedly grown [10]. This technique is used in various intentions to solve issues related to power systems [11]-[14]. Although, in the prior publications some of the optimization algorithms such as direct search, genetic algorithm (GA), simulated annealing (SA) and particle swarm optimization (PSO) provide the global optimum in design process of superconducting magnets, generators, motors, cables, fault current limiters, and microwave filters, there are some demerits mainly addressing single objective optimization [15]-[21]. However, optimization algorithms via multi-criteria optimization techniques are rarely reported in the literature [22]-[25].

The principle object of this paper is to achieve a feasible and full penetrative approach in optimal design of both resistive and inductive SFCL by means of MCDM techniques using analytical hierarchy process. Hence comes the need for advanced numerical model defining electrical and thermal behavior of a LSFCL in a sample distribution system, within PSCAD/EMTDC environment.

2 Electro-Thermal Modeling of Superconducting Fault Current Limiters

High temperature superconducting fault current limiters have been generally categorized into resistive type (RSFCL), inductive type (LSFCL), and hybrid type (HSFCL). The resistive type SFCL consists of a lengthy superconductor wire inserted in series with the transmission lines or distribution feeders and can limit fault current instantly by the abruptly increasing resistance. In this type the limitation performance is a multisided interaction between the fault current, temperature and current dependent resistance, the variable resistance of HTS substrate and other specifications in the external power system [26]. A parallel resistance to the superconductor is necessary to protect the superconductor from destructive hot spots during the quench while it adjusts the limited current to avoid overvoltages probably occur when the resistance of the superconductor rises too rapidly [27].

In several SFCL designs it was considered that the necessary HTS volume to limit the fault current by the resistance introduced in the electrical circuit is independent of conductor resistance. It can be calculated as [28]:

$$\text{Volume} = \frac{I_{Lim}.V_{rms}.\Delta t}{C_p.\Delta T} \tag{1}$$

where I_{Lim}, V_{rms}, Δt, C_p, ΔT are limited current, RMS voltage, fault duration time, specific heat of HTS and stabilizer, and temperature rise in HTS tape. On the other hand, superconductivity states are estimated by a non-linear voltage–current characteristic including three portions corresponding to the flux creep, flux flow and normal state [29]. In the second zone (flux flow), the critical current and flux flow resistance depend on the HTS temperature (T) and instantaneous value of flowing current (i_s). Such temperature and flux density dependencies must be taken into account for the limiting performance of the SFCL. Detailed formulation can be found in [24].

The inductive SFCLs are divided into quench and non-quench types. The quench types are magnetic shielding type, transformer type, and ring type while; saturation reactor type and dc reactor type are non-quench types. Except minor difference in normal condition, the inductive type limiters have common characteristics in fault condition. In that sense, a common model can be considered for the current limiting regime. A magnetic shield type LSFCL is a passive device that consists mainly of a closed (open) iron core inside a superconductor tube, around the outside of which is wound a copper coil. Under normal conditions the shielding capability of a superconductor tube keeps the inductance low thus, no flux penetration into iron core occurs. Under fault conditions, the high current in the copper coil exceeds the shielding capability of the superconductor tube and a jump in impedance occurs because the flux profile in the superconducting screen penetrates to the iron core. The transformer type is another version of LSFCL, in which both the primary and secondary windings are made of cooper coils. The primary coil is wholly similar to the magnetic shield type but the secondary winding is shorted via a superconducting element. As a result, the impedance seen from primary side is almost zero except the resistance and stray inductance of the coils. Contrary to the magnetic shielded type, in transformer type there is an effective magnetic coupling, leading to more core loss and secondary copper loss [25]. Occasionally, the secondary winding of the magnetic shield and transformer types, can be made of a single/few HTS ring. The working principle of this limiter is based on the field screening effect of the HTS which drives the magnetic core to a zero flux condition while it is on the superconducting state [30]. This type of LSFCL is similar to the transformer in which the secondary copper winding is omitted. Based on the aforementioned behavior of the three types LSFCLs, a common model can be considered as a transformer with a variable load accompanied with the corresponding electrical equivalent circuit, as shown in Fig. 1 [31].

In this equivalent circuit, R_1, R_2, L_1, L_2, M, L_s and L_m are the resistance of primary and secondary winding (for transformer type R_2=0), the self inductance of primary and secondary winding, the mutual inductance between primary and secondary winding, the stray inductance of primary winding and the magnetizing inductance of transformer respectively. Moreover, the turn ratio of transformer is simplified as n= (N_1/N_2). By considering the core radius, primary winding and secondary coil/cylinder, the inductances can be calculated as mentioned in [31].

3 Multi Objective Decision Making and Analytical Hierarchy Process

MCDM problems are generally divided in two main categories: multiple attribute decision making (MADM) and multiple objective decision making (MODM). A typical problem in MADM is concerned with the task of ranking a finite number of decision alternatives, each of which is explicitly described in terms of different attributes as well as MODM optimize several objective functions simultaneously [24], [32]. In the other words, a MADM method can find the best alternative or group the alternatives into well-defined classes in a discrete environment while a MODM approach searches the best point satisfied some different goals in a continuous area. All methods of MCDM require information regarding the relative or absolute importance of each criterion. The main challenge of a MCDM problem is that, mathematically speaking, it is not well defined. A central problem is how to quantify all relevant data. Even in the very special case of which one can know precisely the values of the different alternatives in terms of the decision criteria, it is not clear how to process the

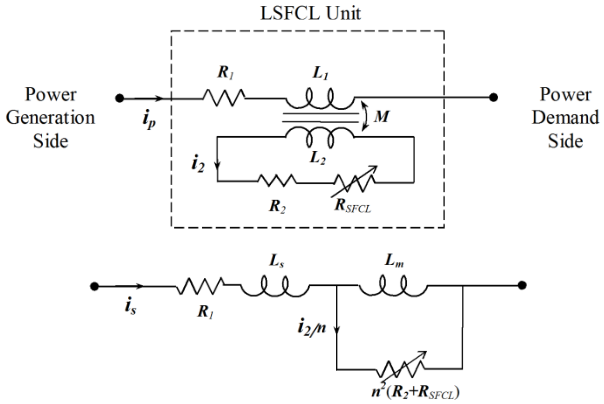

Fig. 1 The transformer model (up) and equivalent circuit of LSFCL (down).

data. For such cases, the main methodological problem is how to process data which may be expressed in different units [8]. After defining the mutual relation between criteria, a major problem occurs in order to compare of decision criteria which are grouped into two opposite categories, usually called the benefit (reward) and the cost (regret or loss) criteria. A benefit criterion means that the higher an alternative score in terms of it, the better the alternative is. The opposite is considered true for the cost criteria. To merge the benefit and cost criteria, there are five important methods including: weighted sum model (WSM), analytic hierarchy process (AHP), revised analytic hierarchy process (RAHP), weighted product model (WPM), and multiplicative AHP [8].

The simplest and most commonly used method in above techniques is WSM which is based on the additive utility assumption of alternatives. As the parameters in optimization of fault current limiter have different units, WSM is not a suitable method for our purpose. AHP, another most prevalent MCDM technique, created by Professor Saaty is a decision analysis method of bringing quantitative and qualitative analysis together for handling human judgment numerically in decision-making processes. The principle of the analytic hierarchy process is that first a structural model of the analytic hierarchy is established through analysis of the complex system. Then the complex problem is transformed into the problem of ranking calculation within the hierarchical structure. In the ranking calculation, the ranking in each hierarchy can also be converted into the judgment and comparison of a series of pairs of factors. Thus, a vector of priority is computed from the eigenvector of each matrix. The sum of all vectors of priorities forms a matrix of alternative evaluation and the final vector of priorities is calculated by multiplying the criteria weighted vector by the matrix of alternative evaluation. Obviously, the best alternative has the highest priority value [11]. In this method, values with units of measurement can be transformed into dimensionless ones. For m alternatives and n criteria, the best alternative can be defined as:

$$P^*_{AHP} = \max_i \sum_{j=1}^{n} a_{ij} w_j \quad \text{for } i = 1,2,3,...,m \tag{2}$$

where a_{ij} and w_j are the evaluation of alternative i respect to criterion j and the weight of criterion j respectively. If the a_{ij} values of the decision matrix are normalized by dividing the elements of each column in the decision matrix by the largest value in that column, revised analytic hierarchy process or ideal mode AHP can be obtained.

Another technique, WPM, is a method that uses multiplication to rank alternatives instead of addition. Each alternative is compared with others in terms of a number of ratios, one for each criterion. Each ratio is raised to the power of the relative weight of the corresponding criterion. Comparison between two alternatives A_K and A_L can be written as:

$$R\left(\frac{A_K}{A_L}\right) = \prod_{j=1}^{n} \left(\frac{a_{Kj}}{a_{Lj}}\right)^{w_j} \tag{3}$$

$R(A_K/A_L)>1$ means that A_K in better than A_L. As the structure of the WPM eliminates any units of measure, it is also called dimensionless analysis. Therefore, this method can be used for single and multidimensional decision problems. In multiplicative version of the AHP, equation (4) is used to calculate priority value instead of (3). So it can be written as:

$$P^*_{RAHP} = \max_i \prod_{j=1}^{n} \left(a_{ij}\right)^{w_j} \quad \text{for } i = 1,2,3,...,m \tag{4}$$

For WSM, AHP and RAHP methods, if the optimization problem has n_1 benefit criteria and $n-n_1$ cost criteria, there are two main approaches for aggregating criteria i.e. ratio performance and difference performance. They can be representing as (5) and (6).

$$P_{i,Ratio} = \sum_{j=1}^{n_1} a_{ij} w_j \times \left(\sum_{j=n_1+1}^{n} a_{ij} w_j\right)^{-1} \tag{5}$$

$$P_{i,Dif} = \sum_{j=1}^{n_1} a_{ij} w_j - \sum_{j=n_1+1}^{n} a_{ij} w_j \tag{6}$$

4 Case Study and Simulation Results for Resistive SFCL

To evaluate proposed MCDM approaches in design of superconducting fault current limiter, a model in which a SFCL is located at an outgoing feeder in a 20 kV distribution substation (single phase 11.5 kV) is considered. Suppose a three-phase short-circuit fault occurs close to the substation, as shown in a single-phase equivalent circuit of Fig. 2.

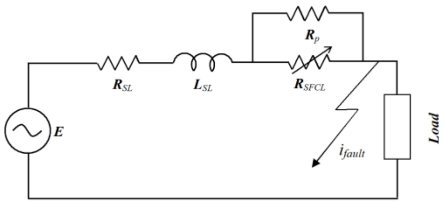

Fig. 2 The single-phase equivalent circuit for 20kV system with RSFCL.

In order to combination electrical and thermal model, the SFCL was defined as a component in PSCAD/EMTDC environment. Simulations were carried out with a fault occurring at t=300ms and cleared after 200ms. To overcome the transient faults, the total simulation time was 1 seconds being enough for quenching and restoration of the superconductor in the cooling system. The simulation time interval of 10μs was sufficient to see the transient pattern. In order to evaluate the operating characteristic and limiting behaviors of the resistive SFCL, case simulations based on the sample parameters were carried out for without and with the limiter. The peak of feeder current in pre-fault state is 150A and exceeds 6.5kA without fault current limiter. It can be reduced to 4kA in flux flow and 500A after inserting the SFCL. Other considered parameters and system characteristics for simulation study are according to [13]. The feasibility of the model for limiting the fault current and variation of temperature and resistance are shown in Fig. 3.

To optimize the RSFCL design some parameters are varied and their effects on system behavior are observed. In this study, variable parameters are: critical temperature, specific heat, flux flow resistivity and

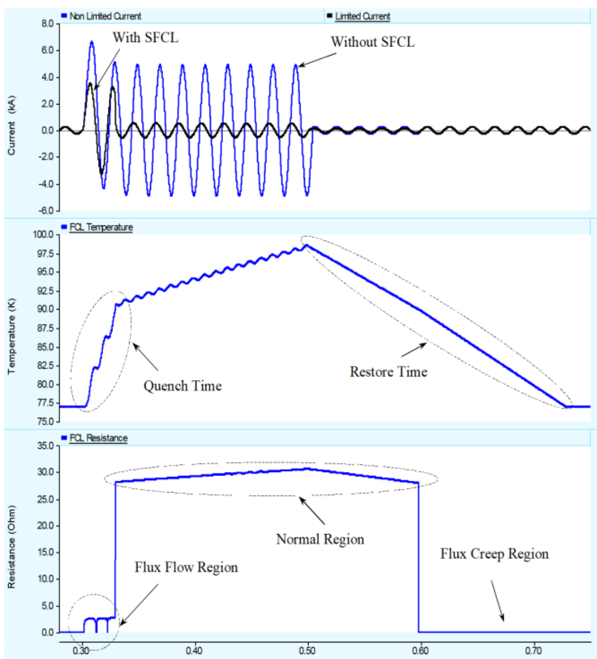

Fig. 3 Fault current limiting performance.

normal resistivity related to HTS material, cooling temperature and cooling power related to cryogenic system, and finally, cross section and volume of HTS related to manufacturing process and system needs. Alternatives can be obtained by varying these parameters in a predefined area; and then some criteria including: maximum resistance (R_{max}), maximum temperature (T_{max}), 1^{st} peak in fault current (I_1), quenching time (t_q), and restore time (t_r) can be assessed for each alternative. Before making the alternatives, it is important to understand which parameters affect criteria positively or negatively. Hence, in the next step several simulations were carried out by increasing and decreasing variables i.e. critical temperature (T_c), cooling temperature (T_0), cross section (A_{sc}), volume or length (V_{sc}), flux flow resistivity (ρ_f), normal resistivity (ρ_n), specific heat (C_p), and cooling power (P_c). The results of these variations and related changes in all criteria are shown in Table 1.

Among assumed criteria, the maximum resistance is a benefit that its raising can be considered as a desirable affair. All other criteria are costs because fewer amounts of them are more yearned. As it is shown, changing the critical temperature affects all criteria positively. Consequently, any reduction in critical temperature improves all criteria. It is obvious that using superconductors having lower critical temperature, leads to improve SFCL behavior except economical cost for lower temperatures. On the other hand, cooling temperature for liquid nitrogen and hydrogen are 77K and 23K respectively.

Since using liquid nitrogen is cheaper and safer, it is selected as the cooling fluid and therefore, MgB_2 superconductor (Tc=39K) is departed from alternatives. Considering above analysis, among remained possible alternatives: YBCO (Tc=90K) and BSCCO (Tc=107K);

Table 1 Output criteria of the resistive SFCL.

Variables \ Criteria		R_{max}	T_{max}	I_1	t_q	t_r
T_c	+	-	+	×	+	+
	-	+	-	×	-	-
T_0	+	+	+	-	-	+
	-	-	-	+	+	-
A_{sc}	+	-	+	+	+	-
	-	+	-	-	-	-
V_{sc}	+	+	-	-	+	-
	-	-	+	+	×	+
ρ_f	+	+	+	-	-	+
	-	-	-	+	+	-
ρ_n	+	+	-	×	×	-
	-	-	+	×	×	+
C_p	+	-	-	×	+	+
	-	+	+	×	-	-
P_c	+	-	-	×	+	-
	-	+	+	×	-	+

choosing YBCO in more technically and moreover commercially because recent improvement of Coated Conductor wires. Thus YBCO is constantly selected and the related parameters i.e. critical temperature, cooling temperature, flux flow resistivity, and normal resistivity are emitted from variables. Another variable, the equivalent specific heat, can be determined as a function of temperature taking into account the material configuration. As the stabilizer becomes thicker, the equivalent resistivity and specific heat of superconductor wire becomes closer to the resistivity and specific heat of the stabilizer. The specific heat of YBCO core was assumed to be 0.7 of Ag and equivalent specific heat can be presumed as a variable of shape and dimensions of RSFCL. This and all other parameters are changed several steps between a minimum and maximum limit and RSFCL behavior is evaluated regarding variation of criteria. If each variable is changed in 10 steps, four variables create 10^4 alternatives for applying to electrical simulation model. It is noticeable that cases exceed predefined constraints must be deleted from possible choices. In this simulation, constraints are: maximum and minimum fault current for accurate operation of relays ($2I_n$<If<5In); maximum permitted temperature (<423K) and maximum restore time for transient faults (<200ms). So, about 2658 cases remain from 10^4 possible alternatives. After carrying simulations out, firstly, each criterion is considered as a unit objective (highest priority). Consequently, five best results can be written as is shown in first five column of Table 2.

The weight matrix for criteria (w_j) can be obtained by summing each relative importance. For three levels criteria comparison (high, medium and low) and five considered criteria, this matrix must be calculated 241 times (3^5-2) by varying the relative importance. Because, the cases; high-high-high-high-high and low-low-low-low-low develop similar matrix as the case of medium-medium-medium-medium-medium, they are therefore omitted. In this study, to simplify the design procedure only the optimized case considering equal priority of criteria is obtained.

Table 2 Output results according optimization of RSFCL.

Obtained Quantities \ Highest Priority Criteria		Unit Objectives: R_{max}	T_{max}	I_l	t_q	t_r	MCDM: Ratio RAHP	Differential RAHP
Variables	A_{sc} (m^2)	5e-7	5e-7	5e-7	6e-7	4e-7	4e-7	4e-7
	V_{sc} (m^3)	1e-3	1e-3	1e-3	5e-4	7e-4	7e-4	7e-4
	C_p (MJ/m^3K)	1.6	2	1.1	1.1	1.7	1.7	1.7
	P_c (kW)	300	900	900	100	900	900	900
Criteria	R_{max} (Ω)	47.7	39.9	47.1	43.7	46.6	46.6	46.6
	T_{max} (K)	145	124	151	385	132	132	132
	I_l (kA)	2.7	2.7	2.4	3	2.47	2.47	2.47
	t_q (ms)	0.93	1.4	0.39	0.17	0.47	0.47	0.47
	t_r (ms)	99	61	44	171	37	37	37

To identify the best alternative from calculated cases, each of two methods for aggregating criteria i.e. ratio performance and difference performance are used in RAHP approach. The quantities of variables and criteria for best alternative are shown in two last column of Table 2. As the best alternative in two approaches is one of the cases had been selected for unit objective, it can be finally chosen to design RSFCL. Although, another AHP approach, multiplicative AHP, because high number of mutual compare indexes for alternatives is really impossible in this case, but only for comparing five alternatives obtained by considering each lonely criterion, multiplicative AHP was applied and confirm previous results.

5 Case Study and Simulation Results for Inductive SFCL

As the optimization approach LSFCL is another object of this paper thus, a magnetic shield type one was located at an outgoing feeder in a single phase 11.5 kV distribution substation instead of RSFCL in previous study. The LSFCL model was defined as a component in PSCAD/EMTDC environment to combine its electrical and thermal properties. Simulations were carried out with a fault occurring at t=300ms and cleared after Δt=200 ms. To overcome the transient faults, the total simulation time was 2 seconds which is enough for quenching and restoration of the HTS. The simulation time interval of 10 µs was sufficient to observe the transient pattern. The characteristics of the system and the selected LSFCL parameters are shown in Table 3.

In order to evaluate the operating characteristic and limiting behaviors of the LSFCL, case simulations based on the sample parameters were carried out in the presence and absence of the limiter. The feeder peak current in pre-fault state is 260A and exceeds 5kA with no SFCL.

By locating the LSFCL in the system, the fault current is reduced to 3.5kA in the flux flow mode and 950A in normal mode of HTS. The feasibility of the model for limiting the fault current in the case study system is shown in Fig. 4.

The estimated stray reactance and calculated magnetizing reactance of the LSFCL parameters are about 0.127Ω and 15.6Ω respectively. As it can be seen from Fig. 4, the current limiting impedance (Z_{SFCL}) of LSFCL consists of a pure resistance of the HTS (R_{SFCL}) and a magnetizing reactance (X_m).

When a fault occurs, R_{SFCL} becomes 1.2mΩ and 16.2mΩ in flux flow and normal mode and the corresponding values on the primary side are 3Ω and

40.5Ω, respectively. The maximum limiting impedance appears to be about 10.76Ω, before removal of fault from the feeder. The variation of the HTS resistance of the LSFCL is shown in Fig. 5.

As be shown in Fig. 5, when a fault occurs at t=300ms, HTS element transition (S/N) takes place initially by going to flux-flow state for 20ms and then to normal state at temperature rise of 117 K. However, this temperature rise requires 700ms (35 cycles) for the HTS to reverse to its superconducting regime. This is a critical issue which must not be overlooked particularly for transient fault prompt; the HTS N/S time constant - characterizing the appearance of Z_{SFCL} ($X_m \parallel R_{SFCL}$), - is rather long after fault clearance. However, from technical point of view, there are two alternatives to overcome this issue (keeping the HTS in the flux flow-state): either decrease of the HTS length or increase its cooling ability, accounting for its specific heat capacity. On the other hand, from economical point of view, for the normal mode performance can obviously reduce the cost of HTS and cooling system.

Table 3 Characteristics of the system and LSFCL.

Symbol	Quantity	Value
E	Phase voltage	11.5 kV
R_{SL}	Resistance of the system and the line	2 Ω
L_{SL}	Inductance of the system and the line	10 mH
f	System frequency	50 Hz
Load	Distributed power of the system	2 MW
T_c	Critical temperature for HTS	90 K
T_0	Temperature of LN_2	77 K
I_{c0}	Critical current in $T=T_c$	520 A
R_{sh}	Shunt resistance to HTS	0.1 Ω
C_p	Specific heat of HTS	1 MJ/m^{3}K
P_c	Cooling power	200 kW
V_{SC}	Volume of HTS	0.004m^3
A_{SC}	Cross section of HTS	1.5e-4m^2
h	Height of iron core	0.5 m
μ_r	Relative permeability of iron core	250
r_c	Radius of iron core	0.1 m
r_s	Radius of HTS cylinder	0.14 m
r_p	Radius of cooper coil	0.2 m
N	Turn ratio of transformer(N_1/N_2)	50

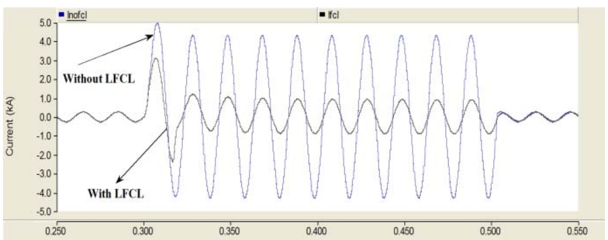

Fig. 4 The fault current with and without LSFCL.

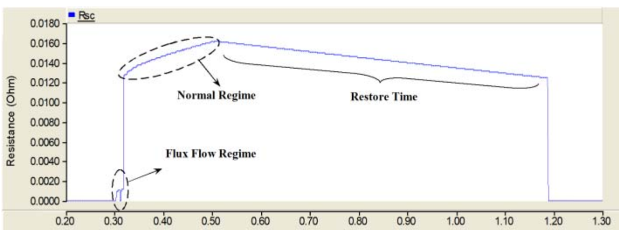

Fig. 5 The variation of superconducting resistance.

As the optimization algorithm for resistive superconducting parameters proposed in previous section, other variable parameters relating to inductive part structure are considered. These variables are: transformer turn ratio (turn of primary copper coil in this study), permeability factor and dimension of iron core (r_c and h). To identify optimal design, alternatives can be obtained by several running the combined electrical and thermal model while varying parameters in a predefined area. After that, considering some criteria such as: maximum current limiting factor, minimum quenching time and minimum ac loss the priority for each alternative should be assessed regard to constraints. In order to identify to what extent these objective functions are varied, numerical analysis is implemented, as shown in Table 4.

Table 4 Output criteria of the inductive SFCL.

Variables (Parameters) \ Criteria (Objectives)		Current Limiting Factor	Quenching Time	AC Loss
Turn Ratio	+	+	-	+
	-	-	+	-
Permeability Factor	+	+	-	+
	-	-	+	-
Radius of Iron Core	+	-	-	+
	-	+	+	-
Height of Iron Core	+	-	+	-
	-	+	-	+

Similar to resistive SFCL, cases exceed predefined constraints must be deleted from possible choices. So considered constraints are: the limiting ratio i.e. the ratio of the peak limited current to peak nominal current must be greater than 2 for allowing the relays and fault detection systems to prompt and minimum sag less than 10% during post-fault clearance, for the power quality enhancement. Referring to Table 4, by changing any one of the parameters creates a new solution and the best alternative can be achieved when all parameters are changed. Consequently, four best results and MCDM combination of results can be written as is shown in Table 5.

6 Conclusion

It was shown that resistive and inductive SFCLs can reduce the short circuit level of the system, if its parameters are appropriately designed. To optimize parameters of SFCLs, several multiple criteria decision making approach based on the analytical hierarchical process was described. The viability of the method was verified by applying it to a simple five variable three objective optimization case for resistive SFCL and four variable three objective optimization case for inductive SFCL. Electrical and mathematical simulation results indicated that proposed discrete approach is a useful method for SFCL design, though if heuristic methods are used in a continues range, can provide improvement in faster convergence and enhanced results.

Table 5 Output results according optimization of LSFCL.

Highest Priority Criteria / Obtained Quantities		Unit Objectives: Current Limiting Factor	Unit Objectives: Quench Time (ms)	Unit Objectives: AC Loss (W)	MCDM: Ratio RAHP	MCDM: Differential RAHP
Variables	Turn Ratio	105	85	65	105	105
	Permeability Factor	100	300	200	100	100
	Radius of Iron Core (m)	0.6	0.65	0.75	0.6	0.6
	Height of Iron Core (m)	0.12	0.08	0.08	0.12	0.12
Criteria	Current Limiting Factor	9.60	7.91	3.50	9.61	9.61
	Quenching Time (ms)	33.55	25.63	2.93	33.55	33.55
	AC Loss (W)	1.64	27.4	0.72	1.64	1.64

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