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NSGA-II Based Multi Objective Design Optimization of Resistive Superconducting Fault Current Limiters

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Abstract: Superconducting fault current limiters (SFCLs) are the devices that uses the superconducting properties of the materials to limit the fault current. In comparison to the conventional fault current limiters (FCLs), the SFCL has advantage that its current limiting property is inherent and no external controls are required. However, to achieve the exact current limiting ratings with other characteristics like quench time, recovery time, peak current etc. a design optimization is required. Since the whole characteristics of SFCL depends upon the superconducting material adopted, and the parameters of cooling systems. The parameters defining the behavior of these two entities are selected as optimization variables. Because in this work second-generation high temperature superconducting (HTS) material known as YBCO (Yttrium Barium Copper Oxide $YBa_2Cu_3O_7$) is considered. Hence, in this paper non-dominated Sorting GA (NSGA-II) optimization algorithm is adopted that exploits the 2G YBCO mathematical model relating its electrical and thermal characteristics and cooling system specifications to find the optimal parameters according to the requirements (or objectives) of resistive-SFCL. The simulation results show that the presented algorithm is able to achieve multiple design objectives (required for SFCL) simultaneously within the range of 5%.

Keywords : Superconducting fault current limiter (SFCL), high temperature superconductors (HTS), Non-dominated Sorting GA (NSGA-II).

I. INTRODUCTION

With the development of second-generation high temperature superconducting materials, the SFCLs are looking more promising than ever. Although there exists many types of SFCL such as resistive [1], inductive [2], flux-lock [3] etc.

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However, this paper is focused on resistive type SFCL which uses the superconductor material which during normal operating conditions has zero resistance and increases very quickly as the current through it crosses the specific limit. The response time of SFCL can go as low as 1 ms, which is much faster than the conventional FCLs [4]. The SFCL also possess the automatic recovery properties, hence it returns to its normal state automatically when current comes down to limits. The other advantage of SFCL includes low losses, reliable, and low maintenance [5].

Since the working principle of the SFCL is different from the conventional FCL, its designing process are also different. Unlike the conventional FCLs where characteristics depends upon simple resistive, inductive, electromagnetic properties or solid state device controlling algorithms, the SFCLs characteristics mostly depends upon the complex electro-thermal characteristics of superconducting materials. These thermos-electric properties of superconducting materials are far more complex and depends upon the current density, electric field, magnetic field and temperature [6], [7].

Although the primary design objective of SFCL remains the quenching current but involving other objectives like quench time, recovery time, peak current etc. could improve overall performance of SFCL as well as the power system. To achieve this non-dominated Sorting GA (NSGA-II, [10]) optimization algorithm is adopted.

Multi-objective optimization is one of the most useful method adopted for solving complex optimization problems in engineering, which required to simultaneously satisfying multiple objectives or requirements. Because of their vast applicability a number of such algorithms are developed such as multi-objective genetic algorithm (MOGA), strength pareto evolutionary algorithm (SPEA), pareto archived evolutionary strategy (PAES), niched pareto GA (NPGA), vector evaluated genetic algorithm (VEGA), Non-dominated Sorting GA (NSGA-II), and multi-objective differential evolution (MODE). However, in this work NSGA-II algorithm is adopted because of its well-known convergence behavior [8].

II. RESISTIVE TYPE SUPERCONDUCTING FAULT CURRENT LIMITERS (SFCL)

The resistive type SFCL (R-SFCL), is one of the most common type of SFCL, because of its relative simple operating principle and smaller size. The R-SFCL functionality depends upon the resistive properties of superconductor materials, which sharply changes when current (I) flowing through it, crosses the critical limit (I_c).

However, the current is not the only parameter which affects its resistance but it is also affected by magnetic field (H) and temperature (T) [15]. Since this work is focused on the optimal designing of R-SFCL, we selected the equations, which relates the resistive properties with different parameters. During the SFCL operation the superconducting material operates in three states, (1) superconducting state, (2) flux flow state, and (3) normal resistive state, the equations related to these three states are givens as [9], [14]:

A. Superconducting State

In this state, the material behaves like superconductor with near zero resistance, also the electric field remains below the critical value and given as:

$$E(J,T) = E_c \left(\frac{J}{J_c(T)}\right), \quad (1)$$

Where, E_c is the critical electric field taken as $1\mu V/cm$, $J_c(T)$ is the critical current density as a function of temperature T in degree kelvin (K). The $J_c(T)$ shows that linearly dependency on $J_c(T_0)$ and given as:

$$J_c(T) = J_c(T_0)\left(\frac{T_c - T}{T_c - T_0}\right), \quad (2)$$

Where, T_0 is temperature of coolant of initial temperature, T_c is critical temperature, and T is the temperature at which the critical current density is calculated.

B. Flux Flow State

This states occurs when the current density (J) increases beyond the critical current density (J_c). Since the current density crosses the critical limit the material loses its superconducting property, this results in increase in resistance, also due to dissipation of power the temperature starts increasing which decreases the critical current density ($J_c(T)$). During this state, the electric field is given as:

$$E(J,T) = E_0 \left(\frac{E_c}{E_0}\right)^{\frac{\beta}{\alpha}} \left(\frac{J_c(T_0)}{J_c(T)}\right)\left(\frac{J}{J_c(T_0)}\right)^{\beta}, \quad (3)$$

Where E_0, the electric field during his transition from previous state and taken as $0.1\ V/m$, and β is kept between 2 to 4.

C. Normal Resistive State

The is state occurs when the rising temperature due to flux flow state crosses the critical temperature (T_c) value, in this state the material behaves like normal resistance. In addition, the electric field during this state is given as:

$$E(J,T) = \rho(T_c)(J)\left(\frac{T}{T_c}\right), \quad (4)$$

Where, $\rho(T_c)$ is the resistivity of the material during this state, it is generally remains around $1\mu\,\Omega\,m$. Using this the resistance of the material can be calculated as:

$$R = \frac{\rho l}{A}, \quad (5)$$

Where l is the length of superconducting material and A is the area of the superconducting material.

Finally, the heat balance equation during this state can be written as:

$$A \times l \times C_p \times \Delta T = P_d \times \Delta t_f - P_{cool} \times \Delta t_f, \quad (6)$$

$$\Delta T = T - T_0$$

Where, C_p is the specific volume heat of the superconducting material, Δt_f is the fault duration, P_d is the power dissipation in superconducting material, P_{cool} is the cooling system power.

After the fault when the current is reduces to zero the equation, (6) can be rewritten as:

$$A \times l \times C_p \times \Delta T + P_{cool} \times \Delta t_R = 0, \quad (7)$$

Where Δt_R is recovery time during which the cooling system removes the heat from superconducting material and brings the SFCL to normal functioning.

III. NON-DOMINATED SORTING GA (NSGA-II)

GA is inspired by the natural evolution system explaining the origin of species. In the survival of the fittest rule is followed or in other words, the species unfit to their environment are eliminated by natural selection procedure. According to natural selection procedure, the stronger species have greater possibility to pass their genes to next generations via reproduction.

In lots of real-life problems, objectives involved conflict with each other, and optimizing a specific solution regarding an individual objective can lead to unacceptable results with regards to the other objectives. A practical solution to a multi-objective problem is to find a set of solutions, each of which fulfills the objectives at a satisfactory level without being dominated by any other solution [11].

A. Terminology used with GA [12]

Chromosome: is a n-dimensional decision variable vector $x = \{x_1, \ldots, x_n\}$ in the solution space X, or a chromosome corresponds to a unique solution x in the solution space. Chromosomes are formed by discrete units known as genes. Each gene regulates one or more characteristics of the chromosome. In the initial implementation, genes are considered as binary numbers. However, with the time different gene types have also been introduced.

Population: is the collection of chromosomes used to find the solution by evolution. The population is randomly initialized and as the algorithm progress the population evolves, towards the fitter solutions and ultimately it converges, i.e. it is led by the best solution.

Crossover: The crossover is the most crucial operator of GA. In crossover, two chromosomes called parents, are merged together to create new chromosomes, called offspring. The parents are chosen from the population in the order of their fitness to ensure that offspring is likely to inherit better genes which will make the offspring much fitter. Through the use of the crossover operator iteratively, genes of better chromosomes are expected to appear more often in the population, ultimately resulting in convergence to an overall better solution.

Mutation: The mutation operator performs random variation into characteristics of chromosomes. Mutation is normally performed at the gene level. In contrast to crossover, which leads the population to converge by making the chromosomes in the population similar, the Mutation introduces genetic diversity into the population and diversify the search to escape from local optima.

The step-by-step procedure of a GA can be written as [13]:

1. Initialization: Set $t = 1$. Initialize the population (of size N) by assigning random values to form the first generation of population (P_1).

Evaluate the fitness of each chromosomes in the population P_1 using given objective function.

2. Crossover: Arrange the chromosomes in the population in descending order list based on their fitness value. Generate an offspring population O_t by performing crossover operation on the two successive chromosomes of the ordered list formed before.
3. Mutation: Mutate each solution $x \in Q_t$ with a predefined mutation rate.
4. Fitness Evaluation: Evaluate each $x \in Q_t$ against the provided objective function.
5. Selection: Select N solutions from Q_t and P_t based on their fitness value and assigned them new generation of population P_{t+1}.
6. If the stopping conditions meet, terminate the search and return the current population as optimal solution, otherwise, set $t = t + 1$ go to Step 2.

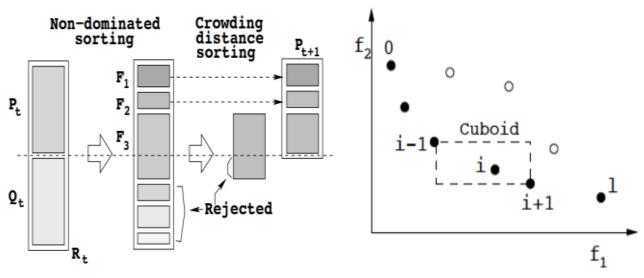
B. NSGA-II

The NSGA-II procedure is one of the commonly used Evolutionary Multi-objective Optimization (EMO) technique, which try to find the solution of multi-objective problem by searching the multiple Pareto-optimal solutions [10].

The NSGA-II comprises the following three features:

1. It uses an elitist principle,
2. It uses an explicit diversity preserving mechanism, and
3. It emphasizes non-dominated solutions.

In the NSGA-II the offspring population at t^{th} iteration (Q_t) is calculated by performing generic operations (crossover and mutation) on parent population (P_t). After getting Q_t from the P_t the two population are collectively forms a new population denoted as R_t, which has the size twice of the initial population (N).



(a) (b)

Fig. 1: Schematic of the NSGA-II procedure (a), the crowding distance calculation (b) as presented in [16].

The population in R_t is then grouped into non-dominating population and sorted according to an ascending level of non-domination. Where non-domination population group $R_t{}'$ among the whole population R_t is defined as the populations those are not dominated by any population in R_t. While domination of a population over other is considered only if solution provided by it for objectives are either better or equal to other, and it has better solution for at least one objective. Now the new population of N solutions is created by collecting the population from non-dominated population groups formed earlier, the priorities are given to higher non-dominating group populations.

When the lower order non-dominating group population is being considered, there may exist more population in the group than the remaining slots in the new population. This condition is illustrated in Fig. 1(a).

In such cases instead of randomly avoiding some population from the lower order groups, the populations which will make the diversity of the selected points the highest are chosen.

The crowded-sorting of the populations of the lower order non-dominating group which could not be selected fully is achieved in the descending order of their crowding distance values and points from the top of the ordered list are chosen. The crowding distance d_i of point i is a measure of the objective space around i which is not occupied by any other solution in the population. The d_i is calculated by estimating the perimeter of the cuboid (Fig. 1(b)) formed by using the nearest neighbors in the objective space as the vertices (we call this the crowding distance).

IV. EVALUATION MODAL

To test the proposed multi-objective optimization approaches in design of superconducting fault current limiter, a model in which a SFCL is situated at in a 1 kV DC system with very limited components as shown in Fig. 2 is considered. The proposed R-SFCL model is developed in MATLAB environment by using the equations (1) to (6).

The fault is simulated by changing the value of load to zero at time $t = 0$ seconds. The system is simulated for total 0.1 seconds which is sufficient to capture the quenching event with a time resolution of 0.0001 seconds to get the significant details and accuracy.

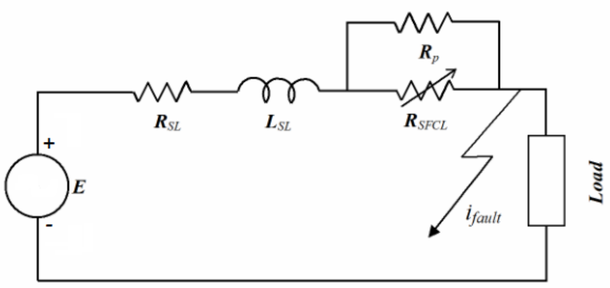


Fig. 2: The single-phase equivalent circuit for 20kV system.

The initial simulation is performed for the different values of superconductor length and width to validate the performance of the model and the results are shown in Fig. (3) and (4).

V. OPTIMIZATION ALGORITHM CONFIGURATION

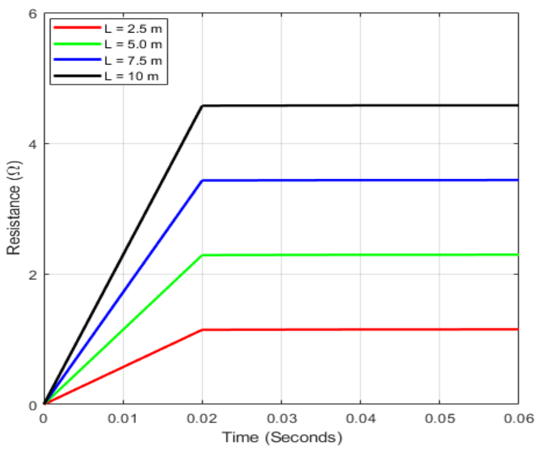
Since in this work the MATLAB environment is used for the simulation of the proposed model, the NSGA-II is comes integrated with MATLAB optimization toolbox, code development for this is not required. However the proper setting of parameters value are required to achieve the better results and quicker convergence. In this work the following configuration parameters values are used.

Table I: Configuration Parameters values for NSGA-II Optimization algorithm.

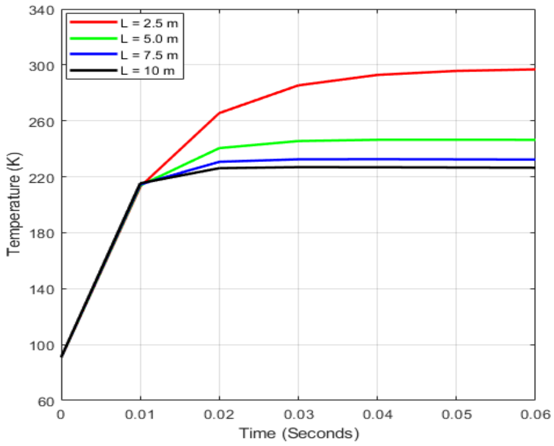
Configuration Parameter Name	Value
Population Size	50
Maximum Generations	100
Mutation Probability	0.05
Initialization Method	Random
Bounds for Length ($[L_{min}, L_{max}]$)	$[1.0\ m, 20\ m]$
Bounds for Width ($[W_{min}, W_{max}]$)	$[0.001\ m, 0.1\ m]$
Cooling Power ($[P_{min}, P_{max}]$)	$[100\ kW, 1000\ kW]$

VI. SIMULATION RESULTS AND ANALYSIS

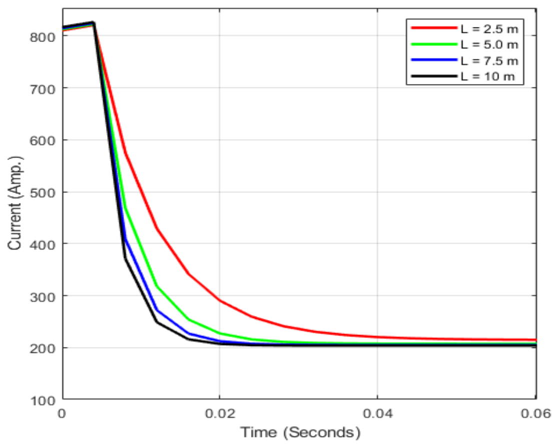
The Fig. (3) Shows the variation of resistance, temperature and current with respect to superconductor length. It can be seen that resistance variation is proportionate to length, which validates the authenticity of the developed model. Looking at the temperature variation graph it shows that the initial response remains the almost same for all length of conductor however after 10 ms of time the temperature of highest length conductor settles however the settling time and temperature value both increases as the length decreases and seems to follow power law. Observing the fault current plot reveals that it decreases quickly for the higher length of conductor and takes much longer time for shorter conductors.



(a) Impact on limiting resistance.



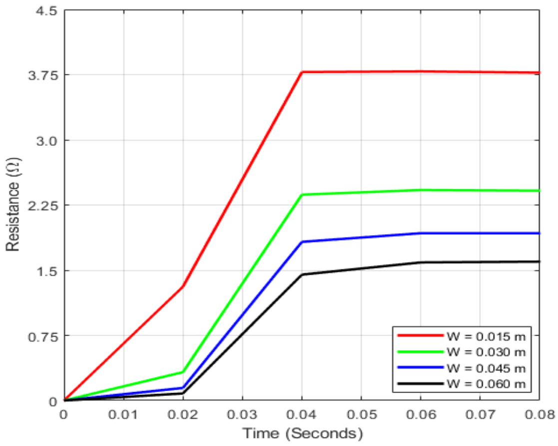
(b) Impact on limiting temperature.



(c) Impact on limiting current.

Fig. 3: Simulating impact of changing length on performance of SFCL.

The Fig. (4) Shows the impact of width on limiting resistance and current. The figure depicts that for smaller width the resistance rises to much higher values than the larger width and similar effect can also be observed for limiting current although in opposite fashion.



(a) Impact on limiting resistance.

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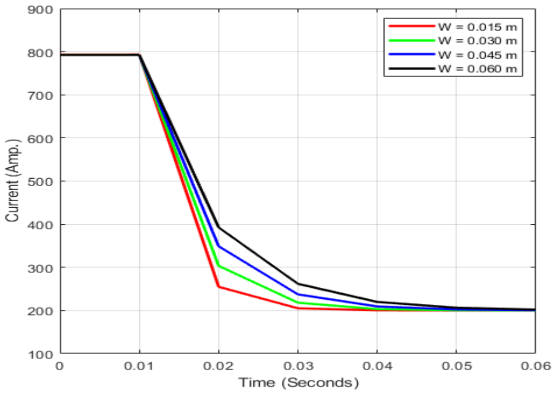

(b) Impact on limiting current.

Fig. 4: Simulating impact of changing thickness on performance of SFCL.

To optimize the SFCL design some parameters are used as the design variables and some kept constant while the specific value of characteristics are decided as objectives. In this work, the variable parameters are: cooling power related to cryogenic system, cross area and length of HTS material. The upper and lower limits of these variables are given in table 1. The objectives of the systems are maximum temperature (T_{max}), quenching time (t_q), and restore time (t_r).

Case 1

The objectives for this case is to achieve the quench time (t_q) of 1 ms and recovery time (t_r) of 50 ms.

Table II: Optimization Results for Case 1.

Parameters	Run 1	Run 2	Run 3
Cross Section (m^2)	3.16×10^{-4}	3.24×10^{-4}	3.19×10^{-4}
Length (m)	4.56	4.67	4.52
Cooling Power (kW)	383.53	381.76	386.27
Maximum Temperature (K)	252.3	257.5	258.6
Quench Time (ms)	0.966	0.932	0.945
Restore Time (ms)	52.32	50.66	49.28

Case 2

The objectives for this case is similar to case 1 but the cooling power is fixed to 200 kW.

Table III: The objectives for this case is similar to case 1 but the cooling power is fixed to 200 kW.

Parameters	Run 1	Run 2	Run 3
Cross Section (m^2)	2.41×10^{-4}	2.44×10^{-4}	2.38×10^{-4}
Length (m)	4.82	4.73	4.76
Cooling Power (kW)	200	200	200
Maximum Temperature (K)	271.44	277.82	273.73
Quench Time (ms)	0.983	1.143	1.054
Restore Time (ms)	48.56	49.37	51.68

The results for both cases shows that the configuration parameters with sufficient upper and lower limits can be tuned to obtain specific characteristics. The results also show that similar characteristics can be achieved even if some variable are kept constant because the SFCL model involves intercalated variables.

VII. CONCLUSION

In this work a multi-objective optimization approach is presented for the design of superconducting fault current limiters. The presented model is based on the thermos-electric equations used to define the SFCL characteristics. The proposed model is firstly verified by analyzing its output and then the optimization is performed. For the optimization NSGA-II algorithm is chosen because of its well-known performance, which is again verified by this work as the algorithm converges to similar values in multiple runs. The results shows that design variables have significant impact on output characteristics of the SFCL also because of complex interrelation among the variable the impact of one variable can also be achieved by other variables. This provides the great flexibility in designing of SFCL.

REFERENCES

1. Xiang, Bin, Zhiyuan Liu, Yingsan Geng, and Satoru Yanabu. "DC circuit breaker using superconductor for current limiting." IEEE transactions on applied superconductivity 25, no. 2 (2014): 1-7.
2. Usoskin, Alexander, Frank Mumford, Reinhard Dietrich, Abdeljabbar Handaze, Burkhard Prause, Alexander Rutt, and Klaus Schlenga. "Inductive fault current limiters: Kinetics of quenching and recovery." IEEE transactions on applied superconductivity 19, no. 3 (2009): 1859-1862.
3. Choi, H-S., H-M. Park, Y-S. Cho, S-H. Lim, and B-S. Han. "Quench characteristics of current limiting elements in a flux-lock type superconducting fault current limiter." IEEE transactions on applied superconductivity 16, no. 2 (2006): 670-673.
4. Noe, Mathias, K-P. Juengst, Frank Werfel, Lisa Cowey, André Wolf, and Steffen Elschner. "Investigation of high-Tc bulk material for its use in resistive superconducting fault current limiters." IEEE transactions on applied superconductivity 11, no. 1 (2001): 1960-1963.
5. Alam, Md Shafiul, Mohammad Ali Yousef Abido, and Ibrahim El-Amin. "Fault current limiters in power systems: A Comprehensive Review." Energies 11, no. 5 (2018): 1025.
6. Kim, Heesun, Ji-Young Lee, Hye-Rim Kim, Seong-Eun Yang, Seung-Duck Yu, Woo-Seok Kim, Ok-Bae Hyun, Junseok Ko, and Hankil Yeom. "An effect of HTS wire configuration on quench recovery time in a resistive SFCL." IEEE transactions on applied superconductivity 23, no. 3 (2013): 5604104-5604104.
7. Kim, Hye-Rim, Hyo-Sang Choi, Hae-Ryong Lim, In-Seon Kim, and Ok-Bae Hyun. "Resistance of superconducting fault current limiters based on YBa2Cu3O7 thin films after quench completion." Physica C: Superconductivity 372 (2002): 1606-1609.
8. Awad M., Khanna R. (2015) Multiobjective Optimization. In: Efficient Learning Machines. Apress, Berkeley, CA, Online ISBN 978-1-4302-5990-9, April 2015.
9. Meerovich, Victor, and Vladimir Sokolovsky. "Thermal regimes of HTS cylinders operating in devices for fault current limitation." Superconductor Science and Technology 20, no. 5 (2007): 457.
10. Deb, Kalyanmoy, Samir Agrawal, Amrit Pratap, and Tanaka Meyarivan. "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II." In International conference on parallel problem solving from nature, pp. 849-858. Springer, Berlin, Heidelberg, 2000.
11. Marler, R. Timothy, and Jasbir S. Arora. "Survey of multi-objective optimization methods for engineering." Structural and multidisciplinary optimization 26, no. 6 (2004): 369-395.
12. Davis, Lawrence. "*Handbook of genetic algorithms*", Van Nostrand Reinhold, New York, (1991).
13. Houck, Christopher R., Jeff Joines, and Michael G. Kay. "A genetic algorithm for function optimization: a Matlab implementation." Ncsu-ie tr 95, no. 09 (1995): 1-10.
14. Sharifi, Reza, and Hossein Heydari. "Electro-thermal modeling and optimization algorithm of resistive superconducting fault current limiters." In 2010 IEEE International Energy Conference, pp. 814-819. IEEE, 2010.

15. Kim, Heesun, Ji-Young Lee, Hye-Rim Kim, Seong-Eun Yang, Seung-Duck Yu, oo-Seok Kim, Ok-Bae Hyun, Junseok Ko, and Hankil Yeom. "An effect of HTS wire configuration on quench recovery time in a resistive SFCL." IEEE transactions on applied superconductivity 23, no. 3 (2013): 5604104-5604104.
16. Deb, Kalyanmoy. "Multi-objective optimisation using evolutionary algorithms an introduction." In Multi-objective evolutionary optimisation for product design and manufacturing, pp. 3-34. Springer, London, 2011.

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