The Optimal Design of HTS Devices

Rajeev Das[1], Fernando B Oliveira[2], Frederico G Guimaraes[2], and David A. Lowther[1],
[1]Department of Electrical and Computer Engineering, McGill University 3480 University Street, Montreal, H3A 2A7, Canada.
[2]Department of Electrical Engineering, Federal University of Minas Gerais, UFMG, Belo Horizonte - MG, Brazil.

Abstract — **In the design of High Temperature Superconductor (HTS) based electromagnetic devices, some of the major challenges include AC loss reduction, minimization of heat leakage, and reduction of the amount of HTS material used in order to decrease cost. This paper considers a computer model of HTS based leads involving a multiphysics scenario that takes into account the electromagnetic and thermal behavior of the system. The work provides an optimum solution by applying an approach based on Multi Objective Optimization (MOO). The proposed framework provides a technique to optimize effectively HTS leads, which not only deals with the non-linear aspect of HTS materials but also includes a multiphysics environment.**

Index Terms **– Superconducting materials, optimization, numerical analysis, electromagnetic fields.**

I. INTRODUCTION

In an effort to design electric machines that are more efficient, have a high power density and low noise; the property of superconductivity has aroused great interest in the engineering community for decades. The superconducting state ensures the passage of a high current density that helps in constructing machines, which have smaller volumes, and higher efficiencies compared to conventional machines with similar specifications. Superconductivity was discovered by Heike Kamerlingh Onnes in the year 1911, and until the 1980's, the known materials that showed this property were usually metals such as Mercury, or compounds of metals kept at cryogenic temperatures. They require extremely low temperatures, usually close to absolute zero to sustain superconductivity, which in turn results in a high cost and was the main reason behind the limited success of this technology. The discovery of High Temperature Superconductors (HTS) [1] two decades ago that could provide superconductivity at relatively high temperatures led to a renewed interest in this field.

This work considers a simple device; a HTS current lead [2], to model the thermal and electromagnetic behavior of a HTS based system. Current leads are used to make the electrical connection between two components at different temperatures. HTS materials have no Joule heating and very low thermal conductivity compared to metals, and these help in reducing heat transfers to the cold regions, which provides substantial benefit, as they reduce refrigeration requirements. When compared to low-temperature superconductors (LTS), HTS have a much wider transition region between superconducting and normal states; hence they provide more flexibility in terms of operation. HTS based leads are usually made of tape, or in the shape of rods or tubes, Fig 1, A manufacturing technique known as the Melt Casting Process (MCP) has proved to be a very effective approach to fabricate structures of latter type, and this work restricts itself to such geometries. The challenges involved in the design of HTS leads are the reduction of heat leakage and A.C losses [3], [4], and a reduced amount of superconducting material to reduce the cost. This paper attempts to achieve these objectives and provide an optimum design for such leads by applying concepts used in Multi Objective Optimization (MOO).

In the field of electromagnetics there exist scenarios where the requirements involved for an optimum design of a device are numerous, and at times competing. To solve such problems, under a given set of constraints, the MOO approach has been a very effective instrument. There are several computational tools to achieve such tasks, for instance Genetic and Evolutionary techniques; this paper uses an approach of the latter kind, known as Differential Evolution (D.E) [5]. The D.E method is a non-derivative or a direct search approach, and it can handle nonlinear, non-differentiable functions effectively. Apart from this it is easily parallelizable and simple to use. In order to solve an optimization problem, a single or a set of cost functions are defined depending on the problem and its requirements, in addition to a set of constraint relations to implement the MOO algorithm are needed. This paper discusses the possible objective functions and constraints applicable to the problems associated with the design of HTS leads. The computation cost for a multiphysics problem in a 3D environment, as in the present scenario, is considerable, this condition is further aggravated by the presence of nonlinearity due to the HTS material. This work also investigates the possible way D.E could be applied for MOO in such an environment.

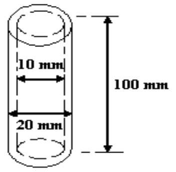

Fig 1 A typical HTS lead having a tube structure.

II. THE COUPLED SIMULATION

To design and numerically optimize a HTS based lead, the approach involved modelling the magnetic field behavior in 2D, and the thermal behavior in 3D.The iteration algorithm is shown in Fig 2, a Matlab program was developed to solve the magnetic problem, and the thermal solution was obtained using the ThermNet package from Infolytica.

A simple scenario was considered for both the problems, involving a HTS cylinder to represent a lead. The problem considered here was that of eddy currents in the magnetic field simulation, and defined in terms of the magnetic vector potential $\vec{A}$ and the electric scalar potential V [6]. The conductivity σ_z , which introduces the non-linearity, was described using the E-J relation shown in (2). The Galerkin Method along with time discretization was used to organize equations (1) and (2) in matrix form. The Finite Element Method (FEM) was utilized to solve the problem.

$$\frac{1}{\mu_0}\nabla \times \nabla \times \vec{A} + \sigma_z \frac{\partial \vec{A}}{\partial t} - \sigma_z dV/dz = 0 \tag{1}$$

$$\sigma_z = \frac{J_c}{E_c}\left(\frac{E}{E_c}\right)^{\frac{1}{N}-1} \tag{2}$$

where E_c and J_c are the critical electric field and the critical current density respectively, μ_0 is the permeability of free space and N is the exponent term which was set to 11.

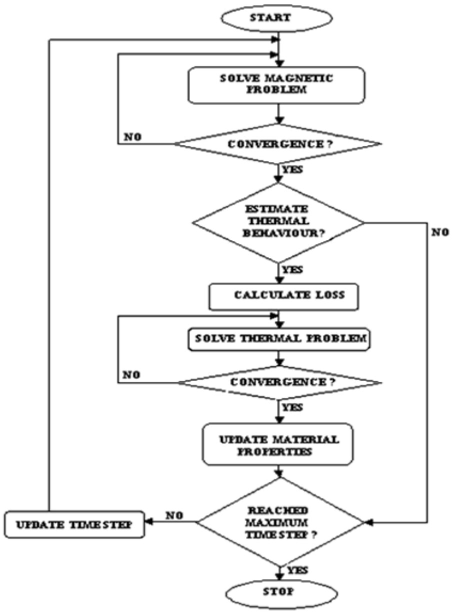

Fig 2 Flow diagram for the coupled problem.

Subsequently the thermal analysis was performed as shown above, using the following equation to estimate the temperature distribution

$$\nabla.\left(K\nabla(T)\right) - \rho C\frac{\partial T}{\partial t} = -q \qquad (3)$$

the term T is the unknown temperature, K represents the thermal conductivity, ρ stands for the mass density, C is the specific heat, and q denotes the heat loss. The properties of HTS materials are affected by the variation in temperature, current density and magnetic field. Once the system described above was implemented to determine the behavior of a HTS lead, the next step involved optimizing the lead for better performance and cost saving.

III. OPTIMIZATION AND DIFFERENTIAL EVOLUTION

The requisites for the optimum design of a HTS lead were highlighted in Section I. To lessen heat leakage, one feasible approach is to reduce the cross section since thermal leakage is proportional to the area. To achieve this, a variable cross section was considered, in which the area of the lead is smaller at the cold end compared to the warm end, and a linear variation was considered here for simplicity. An objective function (4) was used to produce the change across the length; it also achieves the task of defining a shape in which the material used is reduced, thereby reducing cost. The passage of AC current contributes to the losses as heat dissipation, which affects the efficiency of superconducting devices. The other cost function (5) was used to model the loss reduction.

$$A(x) = \left(1 + \left(\frac{A_H}{A_C} - 1\right)\frac{x}{L}\right)A_c \qquad (4)$$

where A(x) is the cross-section at a distance x from the reference point, A_H represents the cross-section at the warm end, A_C denotes the cross-section at the cold end, and L is the total length of the lead.

$$Q = \frac{\mu_0 I_c^2}{\pi\delta^2}\left[(1-\delta\beta)\ln(1-\delta\beta) + \delta\beta\ln\left(1-\frac{\delta\beta}{2}\right)\right] \qquad (5)$$

where $\delta = \left(1 - \left(\frac{R_i}{R_o}\right)^2\right)$, and $\beta = I_p/I_c$, the term R_i is the internal radius, the external radius is given by R_o, I_p represents the peak value of operating current, and I_c denotes the critical current. The constraints were applied on the operating current density so that that it always remains less than the critical value under varying temperature and field. The parameters were represented by a vector consisting of a set of radii distributed along the length.

The D.E method is chosen to provide an optimizer, which is robust, simple, and efficient since the HTS nonlinear multiphysics set up was already a complex system. D.E encodes solutions as vectors, which it tries to manipulate and exploit using mutation and crossover, and it incorporates elitism in its approach. The following diagram shows the interaction between the solver and the optimizer.

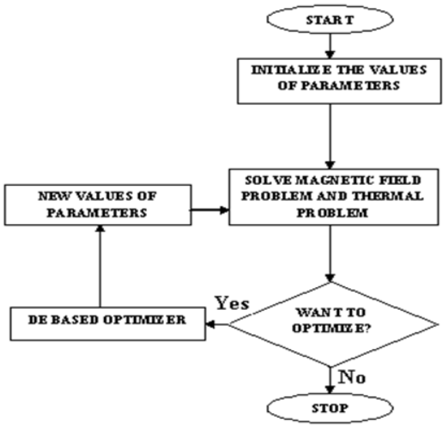

Fig 3 The flow diagram showing the interaction between the optimizer and the solvers.

IV. RESULTS

The experimental samples were initially generated at regular intervals in the search space using the solvers described above, as there was no prior knowledge of the space. An interpolation was performed on the generated specimens to produce more data and then the optimizer was used on them. The final paper will present the approach that could best be used for the D.Es under such environment and will include full results for the optimum design of HTS based leads that would address all the requirements.

V. REFERENCES

[1]Thomas P. Sheahen, “Introduction to High-Temperature Superconductivity,” *Kluwer Academic Publishers* 2002.

[2] Jian Li, Mingzhe Rong, Yi Wu, and Jianyong Lou, “Electromagnetic-Thermal Characteristics of MCP BSCCO-2212 Tube during Quenching Process in Self-Field,” IEEE Transactions on Magnetics, Vol. 42, No. 4, 2006.

[3] W. J Carr, “AC loss and macroscopic theory of superconductors,” CRC Press 2001.

[4] S. Y. Seol, J. R. Hull, and M.C. Chyu, “Optimization Of High-Temperature Superconductor Current Leads,” IEEE Transactions on Magnetics, Vol. 5, No. 2, 1995.

[5] Kenneth V. Price, Rainer M. Storn, and Jouni A. Lampinen, “Differential Evolution A Practical Approach to Global Optimization,” Springer, 2005.

[6] Rajeev Das and David A. Lowther, “ Acceleration of Field Computation involving HTS,” Proceedings at the 15th Biennial IEEE Conference on Electromagnetic Field Computation (CEFC), Oita, Japan 2012.