Kriging assisted design of a synchronous superconducting generator with YBCO windings

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***Abstract* — This paper describes the applicability of a kriging assisted method to the design of a synchronous generator with a high temperature superconducting (HTS) rotor winding. The derived algorithm provides pareto optimal fronts maximising the air-gap flux density while minimising the length of YBCO tapes.**

I. INTRODUCTION

The prospect of reducing the size and weight of a machine through using HTS windings is very appealing, especially for applications such as offshore wind power generation. Until recently the performance of such machines was somewhat hampered by the limited capabilities of the available BiSCCO tapes. Now that the second generation (2G) HTS tapes have become commercially available [1], with improved tolerance to the perpendicular component of the magnetic field, the possibility of building much smaller and lighter electrical machines is becoming a reality. The design of such devices requires substantial simulation effort; structural and thermal as well as electromagnetic requirements may require modelling. The cost is greatly increased if optimisation is required.

II. THE SPECIFIC OPTIMISATION PROBLEM

As an example, we consider a 6-pole arrangement with a 2G HTS rotor winding which may be used to demonstrate the principle of a high torque slow rotating multi-pole machine working in applications such as wind power generation. The objective is to maximise the air-gap flux density using the shortest possible length of the HTS tape

There are a number of possibilities regarding the rotor configuration (Fig.1). Although a coreless rotor is clearly the best choice to achieve the substantial mass reduction required to justify the use of a HTS winding in a full size machine, use of some iron may be warranted in a demonstrator. The choice of rotor configuration is a compromise between obtaining a high air-gap flux density and making the small demonstrator as similar as possible to the full-size machine. Similarity to the full size machine is not easily quantified; each configuration was therefore optimised separately, allowing the final choice to be informed by the results of these optimisations.

Each of the arrangements of Fig. 1 has two possible stator configurations: ‘slotted’ and ‘slotless’. In a conventional machine, the stator teeth are required to help raise the air-gap flux density by providing a low-reluctance flux path through the stator winding. The high current densities available in a HTS field winding may allow a high air-gap flux density to be obtained without the aid of teeth, suggesting that they are not required; hence they could be removed to save weight.

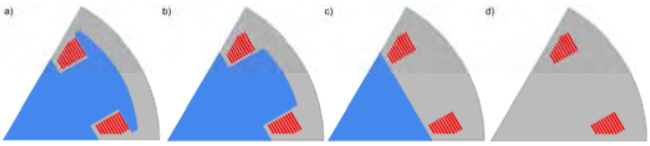

Fig. 1. Rotor configurations chosen for the design study: a) fully cored, b) inner core and coil core, c) inner core, d) fully coreless.

Moreover, the high flux density may saturate the teeth, reducing their effectiveness. It has also been found that modulation of the air-gap field by the stator teeth can induce quite substantial tooth ripple losses in the rotor. While these considerations favour the removal of the teeth, it should be noted that the teeth provide mechanical support for the winding and a radial thermal conduction path to help cool the winding. If they are removed, alternative arrangements must be sought to ensure support and cooling of the winding.

Optimising the design of an electrical machine is a computationally expensive process requiring repetitive use of finite element models. An added complication arises from the use of HTS windings. Since the critical current density of the HTS tape depends on the magnetic field that impinges on it, the critical current is a function of the current in the winding. This implies that for any configuration to be analysed the critical current density needs to be found iteratively, further increasing the computational cost. An efficient algorithm is therefore required, which should minimise the number of evaluations for which finite-element modelling is required. In this work we propose a methodology based on surrogate modelling using kriging [2, 3] to improve the efficiency of the optimization process.

III. SURROGATE MODELLING

The response surface methodology fits an approximation function to data obtained from the computationally expensive objective function at a small number of points. This response surface can then be used to predict the value of the objective function at intermediate positions in the search space. After constructing the response surface from an initial set of data points (off-line learning), it is used to guide the optimiser in selecting a new design vector for evaluation. As each new point is added, the surface fitting is repeated to take advantage of the new data point (on-line learning).

Kriging is a form of response surface modelling based on the principle of maximum likelihood and, in addition to providing a response surface that passes through all the data points, provides a meaningful estimate of the uncertainty of its predictions. Using these two values it is possible to estimate the expected improvement that may be obtained by adding a new data point to the existing set. Using this measure to determine where the next point should be added greatly reduces the risk of the optimiser getting trapped in a local minimum. However, this technique is not foolproof; the algorithm may still fail to find the global minimum if the kriging function significantly underestimates the uncertainty in this region of the search space.

The goal of this study is to find a design which will give the highest possible air-gap flux density while using the least amount of superconducting tape. Due to the anisotropy of the tape both magnitude and direction of the magnetic flux density need to be considered. The manufacturer's data for the dependence of the critical current of the YBCO tape on the field, in both the perpendicular and parallel directions, has been incorporated into the command script executing in the finite element package. The critical current is taken to be the lower of the value estimated from the maximum normal component of *B* and that estimated from the maximum parallel component of *B*. The critical current is found by repeatedly solving the model and changing the assumed current in the superconductor towards the minimum value given by the graphs of $I_C(B)$ until satisfactory convergence is obtained. The fundamental D-axis component of the air-gap flux density predicted by the model is then returned to the optimisation algorithm written in MATLAB.

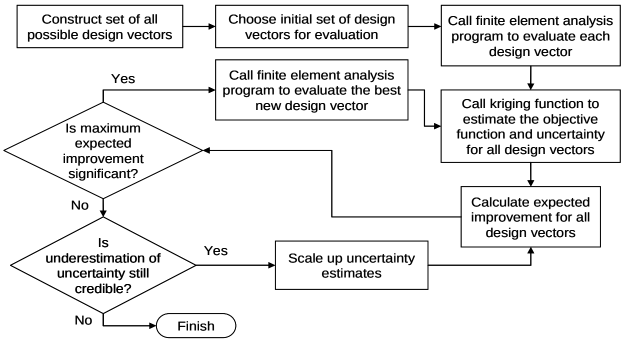

Fig. 2. Optimization algorithm.

A simplified illustration of the algorithm is presented in Fig. 2. The optimizer varies the following parameters: the number of turns in the largest coils, the number of coils and the number of coils that have reduced number of turns to leave space between adjacent poles. A constraint was imposed on the minimum bend radius at the ends of the HTS coils.

A set of 16 points is first chosen using the Latin sampling cube [4]. After evaluating these points and fitting a surface the algorithm finds the maximum of the expected improvement

$$E[I(x)] = (f_{\min} - y)\Phi(\frac{f_{\min} - y}{s}) + s\phi(\frac{f_{\min} - y}{s}) \qquad (1)$$

and evaluates the objective function at the new point. In (1) $f_{\min}$ is the minimum value of the objective function at the sampled points, y is the predicted value at point x, s is the square root of the expected square error at point x predicted by the surrogate model, ϕ is the standard normal distribution function and Φ is its integral. This equation is easily obtained by integrating the product of the improvement and the estimated (assumed normal) probability density function.

Use of the expected improvement to drive the algorithm seams reasonable, but it has its limitations. First, as noted previously, it is likely that the values of expected square error predicted by the kriging function are under-estimated; hence the algorithm could stop after finding a good local minimum but fail to find the global minimum. Secondly, maximising the expected improvement for each new point is a short-term objective and places no value on the knowledge gained by adding new data points. Scaling up the uncertainty estimates as proposed in Fig. 2 should overcome the first problem, although the method of deciding whether under-estimation of uncertainty is still credible needs further consideration. While the optimiser can be encouraged to explore more widely by deliberately over-estimating the uncertainty, the expected value of the information obtained from a new data point is difficult to estimate. More discussion about exploration versus exploitation and enhanced formulations will be provided in the extended paper. Figure 3 shows the pareto optimal front obtained for a coreless rotor at 40K in a slotless stator.

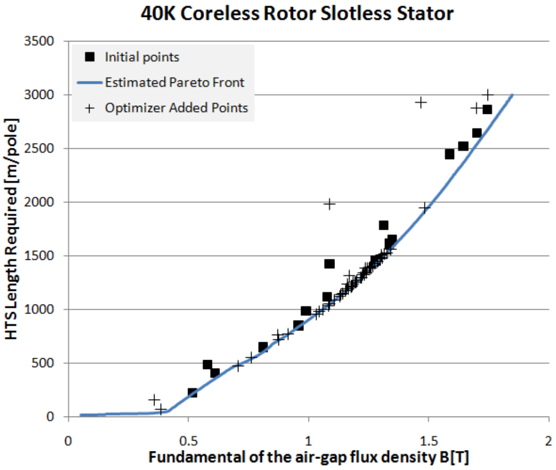

Fig. 3. Pareto optimal front for one of the considered configurations.

IV. CONCLUSIONS

The paper demonstrates the use of surrogate modelling and kriging assisted optimisation in the context of the design of a synchronous generator having a superconducting rotor winding made of YBCO tapes. The necessary repetitive use of finite element models makes the design process computationally expensive but is helped by efficient use of the response surface methodology. The criterion of expected improvement is applied but the balance between exploitation and exploration needs to be carefully controlled.

V. REFERENCES

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