ISEF 2009 - XIV International Symposium on Electromagnetic Fields
in Mechatronics, Electrical and Electronic Engineering
Arras, France, September 10-12, 2009

DESIGN STUDY OF A HIGH TEMPERATURE SUPERCONDUCTING GENERATOR WITH YBCO WINDINGS

K. F. Goddard, B. Lukasik*, M. Rotaru, J. K. Sykulski

kfg@ecs.soton.ac.uk, bartosz.lukasik@areva-td.com, mr@ecs.soton.ac.uk, jks@soton.ac.uk
School of Electronics and Computer Science, University of Southampton, SO17 1BJ, United Kingdom
*Areva T&D Technology Centre – St Leonard’s Ave, ST17 4LX Stafford, United Kingdom

Abstract ***– This paper considers the potential merits of using a HTS rotor winding in a low-speed high-torque synchronous generator and the possibility of building a small-scale demonstrator to investigate the practicality of building such a full-size machine. Pareto optimization results are presented for a full size machine with a high temperature superconducting rotor winding made from a new generation YBCO material and for three configurations of demonstrator. Because evaluation of FEM models is usually computationally expensive, a variation of Kriging method has been used for this optimization. A number of design issues and some other configurations of demonstrator are discussed. Some sensitivity analysis was performed to determine the importance of: the temperature of the HTS winding, the size of the demonstrator, and the clearance between the HTS coils and the warm parts of the machine.***

Introduction

Continuing advances in cryocoolers and superconducting materials motivate the interest in constructing superconducting generators. Improving performance and increasing available lengths of YBCO superconducting tapes make this material a preferred choice compared to the earlier BiSCCO materials. Although the nominal current rating of YBCO superconducting tape is lower than that of BiSCCO tapes, the tapes are thinner and more tolerant to the normal component of magnetic field – a property with significant implications for the design of electromechanical devices. Moreover, their performance is improving at a faster rate. The superior properties of YBCO allow a high current density to be obtained in the presence of the associated magnetic field, without the need to control the orientation of the field relative to the superconductor, a requirement which was identified in the previous designs of generators using BiSCCO and which led to the use of flux diverters [1, 2] For the multi-pole rotor configurations considered here, it would be difficult to make the maximum value of the magnetic field component normal to the HTS tape significantly less than that of the parallel field component. Usually, the field component normal to the plane of the superconductor has a much larger effect on the critical current; hence the effect of this component would be dominant and the use of BiSCCO material might be considered impractical. However, recent developments using various doped YBCO materials [3] allow considerable control over the relative sensitivity to normal and parallel field components.

Our previous experience of designing, building and testing both cored and coreless BiSCCO based superconducting machines [1, 2, 4] suggested that multi-pole machines in low-frequency high-torque applications (such as wind farms) were more likely to benefit from the use of HTS rotor windings. These applications typically require a rating of 2-10 MW. While this may appear to be a modest requirement, it should be noted that obtaining this power at the low speeds required (a large wind turbine may reach full power at speeds as low as 12 rev/min) requires a very large torque.

In this study, we consider the potential merits of using a HTS rotor winding in such a high-torque application and the possibility of building a small-scale demonstrator to investigate the practicality of building such a full-size machine. Ideally, we should optimize the design of the full-size machine for performance, and then optimize the design of the demonstrator to make it as representative as possible within the resource constraints. However, representativeness is difficult to quantify; there are a number of parameters that we would like to match, and their relative importance depends which design issues are most in need of testing. The paper is our first attempt to analyse alternative designs and compare their relative strengths and weaknesses, with the purpose to provide guidance for future research in this area.

Possible Configurations of HTS Rotor and Stator

In this study several possible rotor configurations have been chosen for evaluation (Fig. 1). In all cases, it was assumed that the demonstrator would be a 6-pole machine, thought to be the minimum number that could represent the real situation of a much larger number of poles in a full-size machine.

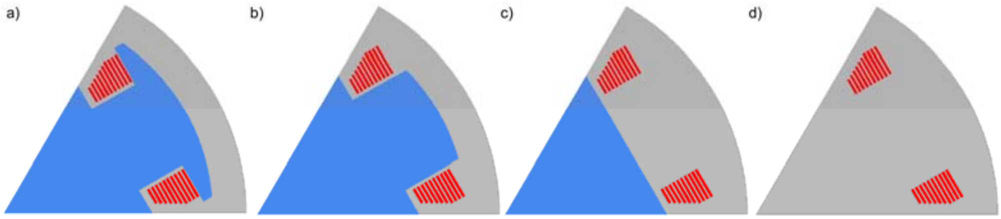

Fig. 1 Rotor configurations chosen for the design study:
a) fully cored, b) inner core and coil core, c) inner core, d) fully coreless

The first of these is based on a classical configuration (as used in a conventional rotor with a copper winding) with the winding enclosed inside the pole (Fig. 1a). In the second configuration (Fig. 1b), the pole tips are non-magnetic; this reduces leakage flux, but leaves us little control over the field in the superconducting winding. The last two configurations (Fig. 1c with an inner core, and Fig. 1d completely coreless) aim to represent a full-size machine with a coreless rotor, which offers the greatest prospect of lower mass as well as simpler cryostat construction than the former two.

If a magnetic rotor core is used, the working temperature of this core is an important consideration. Use of a warm core gives the widest choice of magnetic materials and avoids the need for thermal insulation in the structure that supports the core, but requires the coils and their cooling pipes to be supported by a low-thermal-conductivity structure and thermally insulated from the core. At the other extreme, a cold core could be used to support the coils; however, if the HTS required a working temperature below 73K, the choice of magnetic structural materials would be reduced to Invar. This is not ideal, since the low thermal contraction of Invar tends to cause problems with differential contraction (all the other materials considered have much higher contraction coefficients than Invar) while its lower saturation flux density reduces the benefit of using a magnetic rotor core. A third possibility would be to make the core slightly warmer than the HTS winding (above 73K to benefit from the higher saturation flux density of 9% Ni steel). This would require low-thermal-conductivity structures to support both the core and the winding assembly, but would require minimal thermal insulation between the core and the HTS winding.

Two possible arrangements for the stator were considered for each rotor configuration. The first is classical with the winding placed in slots, and the second has a slotless stator with an air-gap winding. The use of teeth to carry flux through the stator winding allows more flux to be driven by a small rotor MMF. However, once the teeth saturate, their presence reduces the stator flux linkage produced by additional rotor MMF. This is because they increase the depth of the stator winding, thus reducing the benefit of the stator back iron and increasing leakage flux. Hence, the additional flux linkage due to the teeth reaches a maximum as they become saturated and then declines to become negative for high values of rotor MMF; saturation of the teeth by itself is not sufficient to indicate that they are no longer useful. Another effect of having stator slots is to modulate the main air-gap field. This produces high-spatial-frequency field components, which appear on the rotor at stator-slot-passing frequency.

In the course of our most recent study [4], in which a high-speed machine was considered, it was found that a slotted stator could induce substantial eddy-current losses in the wall of the vacuum vessel. In a low-speed machine, these losses would be smaller – but, if it was necessary to reduce them further, the cryostat wall and the cold parts of the rotor would have to be moved further away from the teeth, which would reduce the benefits of having magnetic teeth.

Optimization using surrogate modelling

The principal measure of performance that must be predicted using an electromagnetic finite-element model is the mutual flux linking the stator winding. Since varying the current in a superconducting winding alters the magnetic field in the coils and with it the critical current density of the superconductor, the finite-element model must first be used to find the maximum current that the HTS winding can carry. This requirement significantly increases the computational cost of modelling, since the maximum field current must be found iteratively by solving the model with a number of different values of field current. Using such an objective function directly in a standard optimization algorithm would make the optimization very computationally expensive, especially if the search space were large. To overcome this problem, we use a response surface method that allows a search for the optimum to be undertaken using a relatively small number of finite-element models. After calculating the value of the objective function for each of the initial set of design vectors, such methods fit an approximating or interpolating function to this data; the global minimum of the objective function can then be estimated by finding the minimum of this response surface. The response surface is used to guide the selection of a new design vector for full evaluation, and is then re-fitted to take advantage of the new data point.

We have employed the Kriging interpolation method, since this provides an estimate of its uncertainty as well as an estimate of the objective function. The algorithm uses these two values and seeks to maximize the expected improvement obtained by adding each new point. A similar method and the underlying theory are described in [5].

Two versions of the optimizer were used to produce the results presented in this paper. The initial set of points is chosen using the Latin Hypercube Sampling [6]. This technique aims to give uniform coverage of the search space. With a sufficient number of well distributed data points, it is possible [5] to use statistical analysis to test the validity of the uniform noisiness assumption that underlies the Kriging method, and to consider various data shaping functions to improve this validity. However, we do not consider the use of such shaping functions, and so use a smaller number of initial points to reduce the computational cost. We therefore depend more heavily on the optimizer to explore the search space. Exploration is encouraged by the fact that neither version of the optimizer seeks a single optimum design; instead they both seek to expand the Pareto front, maximizing the objective function in relation to one or more cost functions.

The simpler version, which has been used for various possible configurations of demonstrator, requires the search space to be restricted. By fixing the stator dimensions and quantising the remaining design parameters, the number of values that the design vector can take is reduced to less than 40000. This relatively small search space allows an exhaustive search to be made for the design vector for which the expected improvement is greatest. It is not entirely clear what quantity should be maximized to find the optimum design for a small demonstrator, but it was considered necessary to obtain a reasonably high air-gap flux density. It was assumed that the principal constraint on the size and performance of any small demonstrator would be set by the quantity of HTS tape that could be used. This version of the optimizer therefore considers only this cost component, and seeks to maximize the air-gap flux density in relation to the quantity of HTS tape used. Satisfactory results were obtained usually after evaluating approximately 70 points.

The other version of the optimizer, which was used to produce the results in the next section, is allowed to vary a larger number of parameters. The number of possible design vectors therefore becomes very large, and it is not practical to use an exhaustive search. Since the expected improvement function is not amenable to gradient search methods, we can either use a simulated annealing algorithm, or simply evaluate a large number of random points. In either case, we must accept a sub-optimal solution in order to reduce the computational cost of the search.
For the reasons described in the next section, this version of the optimizer considers the required quantities of HTS tape and stator iron per unit air-gap surface area as cost components, and seeks to maximize the air-gap flux density in relation to these quantities. Since we expect increased use of either HTS tape or stator iron to yield diminishing returns, the surface defining the achievable value of air-gap flux density as a function of these costs (the Pareto front) should be convex. The optimizer can therefore be made to search for a point on this surface with a specified normal vector by applying suitable penalty factors for the use of iron and HTS tape. It would clearly be very inefficient to run separate optimizations for each of these directions. The computational cost is reduced greatly by combining them so that each can benefit from knowledge obtained by the others. For each of these directions the expected improvement is evaluated for a number of different design vectors; the optimizer is allowed to use each new finite-element model to explore the Pareto front in whichever direction seems most profitable.

Achievable performance of a full-size machine

To justify the use of a HTS rotor winding, a full-size machine needs to offer a significant advantage either in reduced losses or reduced mass. For the wind turbine application, the reduction of losses may not be enough if accompanied by an increase in mass (unless the increase in mass was very slight).

True optimization of a full-size machine would require the achievable torque to be maximized as a function of the three main cost components: capital cost – related to use of materials; cost of losses – mainly stator copper loss and refrigeration loss; and installation costs related to total mass and overall diameter. However, these three aspects of the cost are difficult to estimate and depend on variables that change over time; hence a design that is optimal now may not be optimal in the future. Moreover, to use the results to judge whether the use of a HTS rotor winding offered a significant benefit, would appear to require a separate optimization to be done for a conventional machine. In this preliminary study, we take a much simpler approach, which avoids these problems as follows. We avoid changes in prices making the results out of date by plotting a Pareto front rather than seeking a single optimum design. Furthermore, to enable this surface to be visualized, it is helpful to eliminate one of the three cost components. The variations in the stator copper loss and the refrigeration loss are largely eliminated by fixing: the depth of the stator winding, the rotor diameter, and the length of the stator core; hence these losses can be regarded as constant and do not need to be considered within the optimization process. Prescribing these dimensions also fixes the ratio between the achievable torque and the air-gap flux density; since it is well known that the air-gap flux density of a conventional machine is limited to about 1 T, this enables us to compare the performance with that of a conventional machine without having to design one. Instead of capital cost and installation cost, we consider only use of HTS tape and volume of stator iron. To make these parameters more widely applicable, they are divided by the area of the cylindrical surface at which the air-gap flux density is evaluated.

Figure 2 shows the air-gap flux density obtained by the optimizer as a function of the two principal cost components. These results were obtained for a machine with a slotless stator and a coreless rotor with a winding temperature of 40K. It can be seen that the flux density is usually limited by the amount of HTS tape used. With about 50 km of tape for each square metre of air-gap surface area, an air-gap flux density of 2 T can be obtained. This is achieved with as little as 0.16 m^3 of stator iron per square metre of air-gap surface. Increasing the flux density to 2.7 T requires about 60% more HTS tape, and a similar increase in the volume of the stator core.

By identifying a number of *Pareto optimal* solutions and using them to define the limits of what is possible (the *Pareto front*), the type of optimization used offers more flexibility in interpreting the results. The design of any system that uses such a machine is therefore better informed.

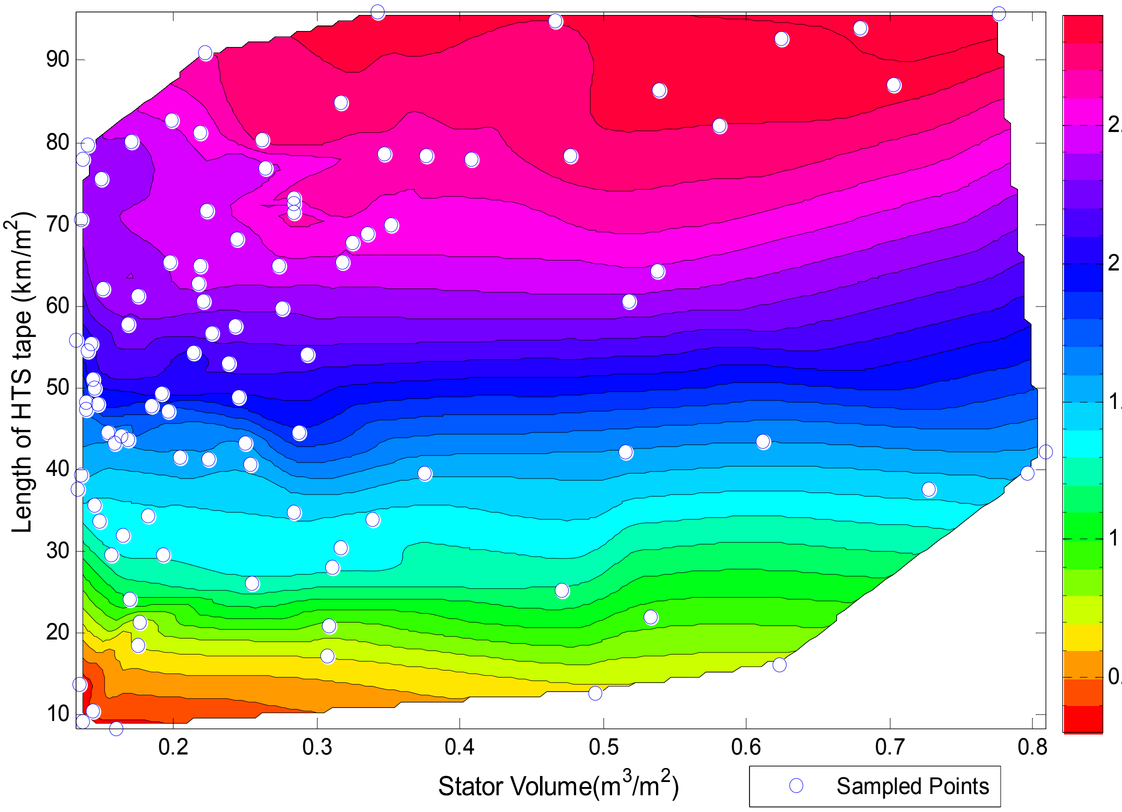

Fig. 2 Achievable air-gap flux density in a full size machine as a function of the quantities of stator iron and HTS tape used. These quantities are expressed per unit air-gap surface area.

Evaluation of various demonstrator configurations

For the purpose of this study, we assume that the demonstrator should represent a machine with a coreless rotor and a slotless stator, which would be appropriate if mass reduction were the primary motivation for the use of a HTS winding. However, if loss reduction were the main objective, it is not clear that this would be the preferred configuration.

The most obvious way to represent such a full-size machine is to build the demonstrator in the same configuration. However, using the minimum amount of iron increases the amount of HTS tape required to drive the flux. Since we wish to consider building a demonstrator without waiting for the price of HTS tape to fall to a level that might make a full-size machine economic, the cost of HTS tape is probably the principal constraint on the design of the demonstrator. The results presented in Fig. 3 suggest that representative values of air-gap flux density can be obtained with this configuration without the need for an excessively large demonstrator; the results presented are for a maximum rotor diameter of 660 mm. However, to obtain an air-gap flux density of 1.5 T would require around 10 km of HTS tape in the rotor winding, and this would need to be cooled to around 40K. With the winding at 60 K, which would make cooling much easier, the flux density would be limited to around 1.1 T, which would not justify the use of a slotless stator. Reducing the winding temperature to 40 K yields a considerable improvement in the tolerance to the perpendicular field, which improves the machine performance. Lower temperatures were not considered because the cost of cooling was expected to be too high.

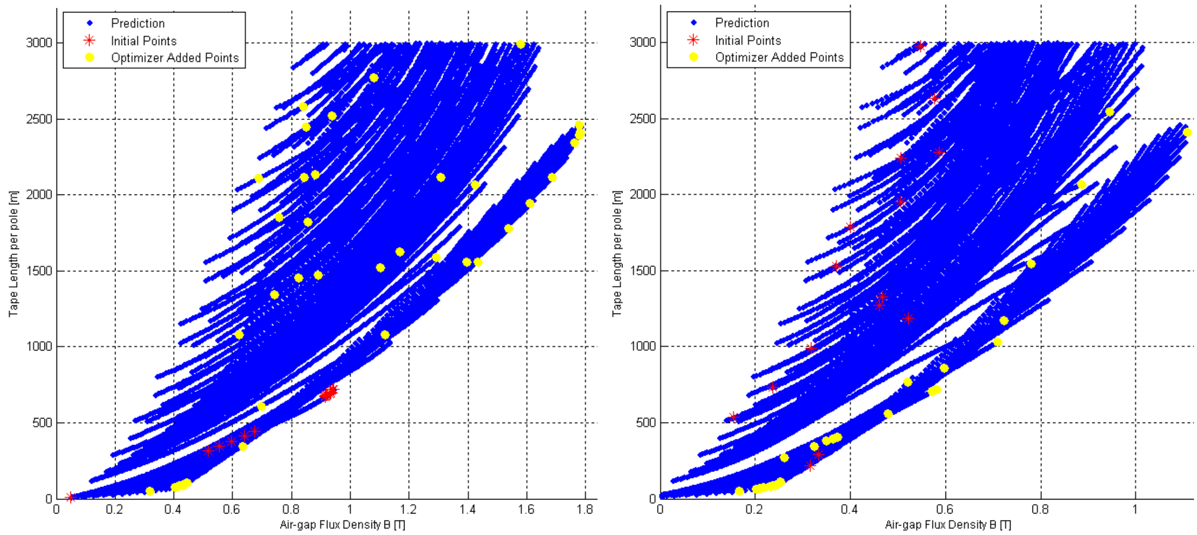

Fig. 3. HTS tape requirements and achievable air-gap flux densities for various coreless rotor designs with a slotless stator, with the winding at 40K (left) and at 60K (right).

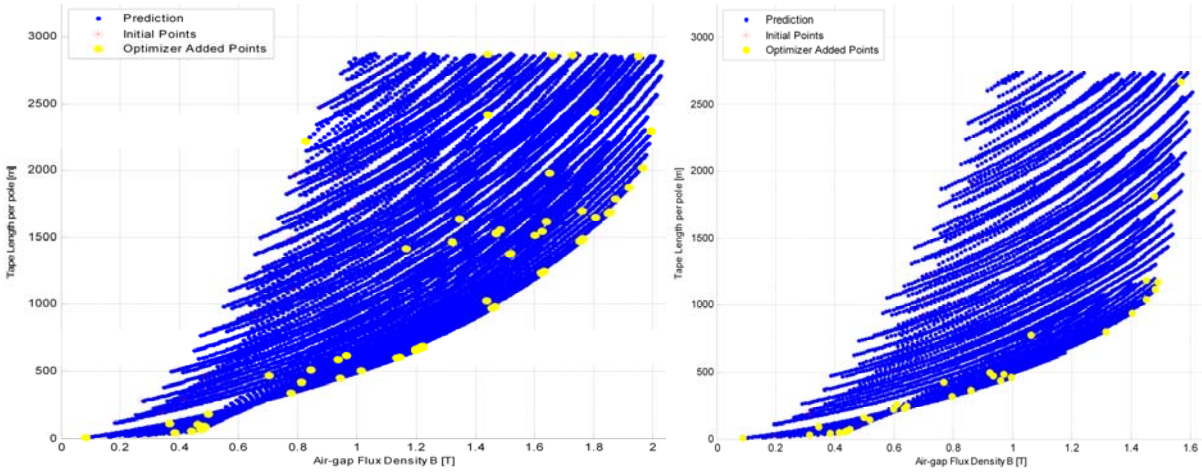

Fig. 4. Achievable air-gap flux density with an inner rotor core and HTS winding at 40 K, as a function of the quantity of HTS tape used. The results on the right are for the smaller rotor radius.

An appealing option is the use of an inner rotor core (Fig. 1c). The effect of this core on the field in the stator and in the rotor winding is similar to that of additional rotor coils within the space that is, in reality, occupied by the iron. Use of a cylindrical inner rotor core makes it relatively easy to insulate the core from the cryogenic cooling fluid, and so allows the core to work at a significantly higher temperature than the HTS winding. Using a warm core reduces the difficulty of supporting the cold parts of the rotor with adequate stiffness and minimal heat leak. Replacing the inner coils of the rotor winding by iron saves HTS tape and allows a higher air-gap flux density to be achieved, but makes the field in the rotor winding less representative. In particular, it should be noted that removing the innermost coils prevents them from limiting the current in the winding as they would in a coreless rotor. Figure 4 shows the optimization results for this configuration. They show that flux densities approaching 2 T can be obtained with a winding temperature of 40 K, and that obtaining 1.5 T requires around 6 km of HTS tape. Since the size of the rotor first considered clearly allowed excessive quantities of HTS tape to be used, the possibility of building a smaller rotor was investigated. In Fig. 4, the outer radius has been reduced by 40 mm (left), and 80 mm (right). The first 40 mm reduction has no noticeable effect on the Pareto front except at flux densities above 1.8 T, where there is a marginal reduction in the achievable flux density. The larger reduction in radius greatly reduces the maximum air-gap flux density, but does not significantly increase the amount of HTS tape required to obtain flux densities up to 1.4 T.

Adding iron poles as in Fig. 1b allows the air-gap flux density to be increased further, but makes the field in the HTS coils completely unrepresentative of that in a coreless rotor. The presence of such poles also complicates the design of the cryostat, especially if we wish to operate the core at a higher temperature than the HTS winding. Whereas an annular fluid vessel containing the whole rotor winding could be slid over an inner core, this would not be possible if the core had poles sticking into the spaces within the rotor coils. To cool the winding, it would be helpful for the cryogenic fluid to surround the coils, but the fluid would need to be separated from the core by a vacuum gap. If a fully warm core is used, the vacuum gap would need to be subdivided to suppress heat transfer by radiation. This thermal insulation and the wall of the fluid vessel, would occupy space that might otherwise be used for iron or superconducting coils. Since we have not reached any firm conclusion as to how such a rotor should be constructed, it is difficult to judge how much space should be allowed between the coils and the core. Figure 5 shows the effect of changing these allowances. The results on the left were obtained with a tight 10 mm allowance, while those on the right are for a generous 24 mm allowance. The spaces between the coils of adjacent poles and between the coils and the outer surface of the rotor were also increased in the latter case.

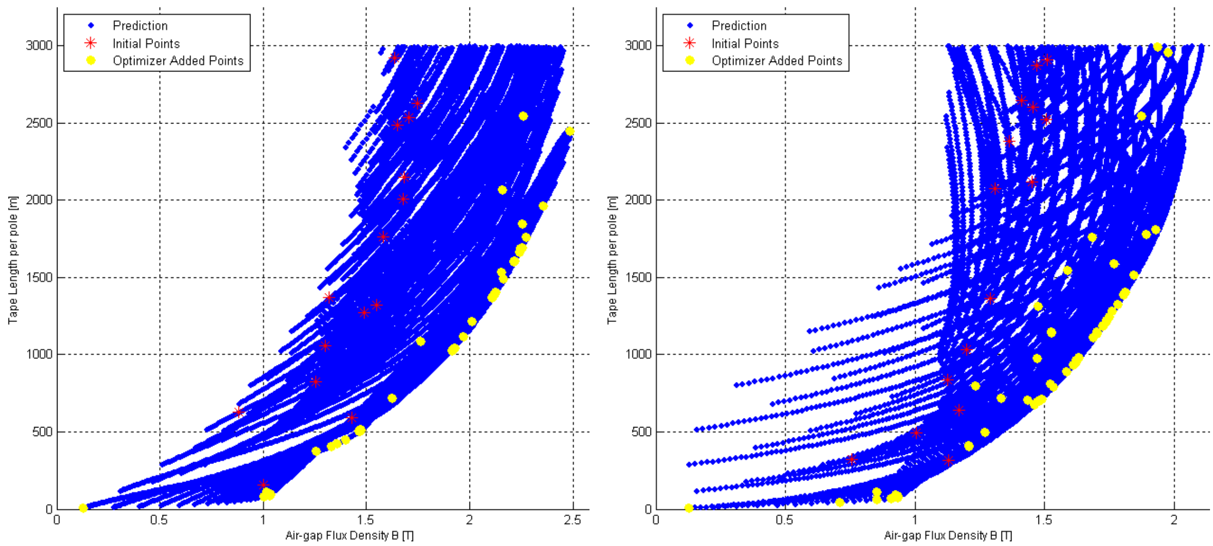

Fig. 5. Achievable air-gap flux density with iron poles on the rotor core and HTS winding at 40 K, as a function of the quantity of HTS tape used. The results on the right were obtained with larger allowances around the coils.

All the results presented above are for a slotless stator. While the techniques described could be applied to the case of a slotted stator, some additional calculations would be required to confirm that eddy-current losses due to ripple fields produced by the stator slots would not greatly increase the cost of cooling the HTS winding.

All the results presented above were produced on the assumption that 4 mm wide YBCO coated conductors could be wound at 0.25mm pitch, and that the tape would have a 200A nominal current with the same field dependence as the 100A tape that was available when we started work on this study. This is believed to be a fair allowance for the rate of improvement in this conductor technology. However it is possible that, in the near future, the best choice of HTS tape may use some kind of doping of the YBCO material, to substantially alter the field dependence of the critical current.

Conclusions

The paper is an attempt to demonstrate the way forward how to build a small demonstrator to assess and explore the design of a full-scale superconducting generator made of YBCO tapes for wind farm applications. It is argued that the choice of the best machine configuration for a full size machine is likely to be dictated by a compromise between performance and cost, while the demonstrator should be designed with the view of best representing the features and properties of the machine it is supposed to represent rather than being optimized for performance in its own right. It is also emphasised that comparisons with a conventional machine would require optimizing such a machine as well, although the criteria for such comparisons are by no means obvious. In order to provide more flexibility for interpreting the results, Pareto optimization has been used throughout. Finite element electromagnetic simulation has been employed to predict the magnetic field in the air gap and in the HTS winding, where it is used to estimate the critical current.

References

[1] K. S. Ship, K. F. Goddard, and J. K. Sykulski, "Field optimisation in a synchronous generator with high temperature superconducting field winding and magnetic core," *IEE Proceedings (Science, Measurement and Technology)*, 149 (5), pp. 194–198, 2002.

[2] K. S. Ship, and J. K. Sykulski, "Field simulation studies for a high temperature superconducting synchronous generator with a coreless rotor," *IEE Proceedings (Science, Measurement and Technology)*, 151 (6), pp. 414–418, 2004.

[3] American Superconductor, "Second Generation HTS Wire: An Assessment," *http://www.amsc.com/products/htswire/documents/2GWhitePaper-July04_000.pdf*, White Paper, July 2004.

[4] B. Lukasik, K. F. Goddard, and J. K. Sykulski, "Finite Element Assisted Method of Estimating Equivalent Circuit Parameters for a Superconducting Synchronous Generator With a Coreless Rotor," *IEEE Transactions on Magnetics,* vol. 45, pp. 1226–1229, 2009.

[5] D. R. Jones, M. Schonlau, and W. J. Welch, "Efficient global optimization of expensive black-box functions," *Journal of Global Optimization,* vol. 13, pp. 455–492, Dec 1998.

[6] M. D. McKay, “Latin Hypercube Sampling as a Tool in Uncertainty Analysis of Computer Models,” *Proceedings of the 24th Conference in Winter Simulation*, pp. 557–564, 1992.