FIELD MODELLING AND OPTIMISATION OF A HIGH TEMPERATURE SUPERCONDUCTING SYNCHRONOUS GENERATOR WITH A CORELESS ROTOR

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INTRODUCTION

The discovery of high temperature superconductivity (HTS) opened up a door of opportunity for development of new generation of power devices, including smaller and more efficient rotating electrical machines. In the case of synchronous generators, the replacement of copper field winding with a superconducting tape promises to deliver superior performance, more compact design, higher reliability, and easier operation [1]. The HTS coils are inherently more stable than low temperature superconducting coils (which require liquid helium cooling), especially when operated in a liquid nitrogen environment. The recent advancements in the refrigeration systems have helped significantly in reducing the overall costs, thus making the technology more attractive.

Building on the success of our previous design and construction of a 100kVA HTS demonstrator synchronous generator with a magnetic iron core [2], which has proved the feasibility of HTS generation and established a number of key design principles, it is possible now to consider a HTS synchronous generator with a coreless rotor. However, in order to achieve a successful design, it is imperative to first conduct computational and simulation studies to predict the performance and identify critical issues. In particular, the severe non-linearity and anisotropy of the BSCCO tapes necessitates very careful shaping of local distribution of magnetic field in the area of the HTS winding so that the undesirable field components are reduced and maintained at an acceptable level; this is a crucial requirement which may decide about the success or failure of the whole design as HTS tapes will simply not work if the normal component of field is too high. Thus the geometry and placement of the necessary flux diverters is of paramount importance. This paper reports on the 2D studies undertaken to arrive at an optimal magnetic design for further perusal.

PRELIMINARY DESIGN

The machine will utilise an existing stator, which has 48 slots and a balanced 2-pole, 3-phase star-connected winding. The use of an existing stator lowers the costs but restricts our flexibility to control the voltage waveform; thus careful positioning and shaping of the flux diverters and HTS field winding become very important. These requirements are very different from the usual design criteria for a conventional generator. The target air-gap density of the coreless rotor design is around 0.6T, while the flux density normal to the broad face of the tape must be kept as low as possible. The machine will probably operate using sub cooled liquid nitrogen at 64K (rather than 77K); at this temperature – and by using the currently best available material properties – it is possible for the HTS tape to transport 130A provided that the normal field is below 0.1 T. The amount of iron used for the flux diverters must be kept to minimum so that the total weight reduction compared with the existing cored design will be significant.

A preliminary model of the machine was based on our previous experience and the following constraints:

- The distance from the HTS tape to the flux diverters is 0.5mm and 1.5mm respectively (top and bottom).
- The flux diverters are longer than the coils by 4mm on both sides.
- The assembly of the HTS coils and flux diverters has to fit within the 140mm radius.

The 0.5mm and 1.5mm gaps are to avoid short circuit contact and at the same time provide space (larger gap) for connecting conductors from one HTS coil to another. The need to reduce the magnetic field component normal to the broad face of the tape, especially in the corner region, has already been explained. Finally, the large air-gap was needed to accommodate the supporting structure and thermal insulation. Moreover, for ease of manufacture, it was decided later that the inner diameters of some HTS coils (and flux diverters) should be the same; thus the bottom five sets of coils and diverters were aligned to each other. Figure 1 shows the preliminary model with details of the applied constraints, as well as the distribution of the normal field in the HTS coils. This shape was obtained by fitting as many HTS coils as possible within the 140 mm radius. Each coil consisted of 70 turns with each turn being of 0.5mm width.

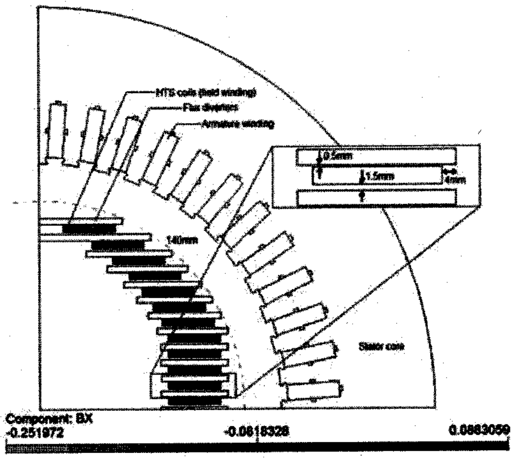

Fig. 1. Design details and normal field distribution in the superconducting coils.

A non-linear analysis was performed throughout since saturation of the magnetic flux diverters was thought to be important. The symmetry of the machine is exploited by considering a quarter the area. The magnitudes of the sine components of odd harmonic order were extracted using Fourier series. This data can be used to construct the voltage waveforms and the resultant root-mean-square (*rms*) value.

In the preliminary model, it was found that the total *rms* harmonic voltage content was 1.59% and the air-gap flux density estimated at 0.676T. The component of the magnetic field normal to the broad face tape was unfortunately found to peak at 0.252T (as shown in Fig. 1). This undesirable high normal field would significantly reduce the critical current and could cause the coils to loose superconducting properties.

FIELD OPTIMISATION

The preliminary investigation revealed that the main problem in the design is due to the normal component of magnetic field in the HTS coils. Through careful examination it was found that the high normal field was caused by the saturation of flux diverters. In order to minimise this effect, the amount of iron could be increased in the identified areas. Therefore, one HTS coil was removed leaving 11 coils as shown in Fig. 3(a). Figure 3(a) also shows harmonic content of the voltage waveform and the distribution of the normal field after the thickness of the four upper most flux diverters was increased. The graph shows the gap field up to 19th harmonic, while the higher order components will be reduced by the distribution of the phase conductors throughout each phase belt. The reduction of the normal field was very welcome but the total *rms* harmonic voltage content became worse and increased to 3.898%.

Since the air-gap flux density obtained in the preliminary design was above the target value, the number of turns in the coils was reduced initially. However, reducing the number of turns in the three upper most coils to 60 gave only a slight improvement to the normal field and caused significant deterioration of the voltage waveform. Hence, to deal with the problem, two particular regions of the waveform were identified. First, at the angle between 70° and 90°, to keep the overall weight to the minimum a block of iron with width and height of 10mm was placed on top of the upper flux diverter and the results shown in Fig. 3(b) are very encouraging. Finally, in order to gain some idea on the effect of changing the local flux density on the total harmonic content of the voltage waveform, a simple formula of partial derivative was used,

$$\frac{\partial}{\partial \mathbf{B}_r(\theta)}\left(\frac{\sum\limits_{i>1} V_i^2}{V_1^2}\right)=\left(\frac{2}{V_1^2}\right)\left[\sum_{i>1}\left(V_i\frac{\partial V_i}{\partial \mathbf{B}_r(\theta)}\right)-\left(\frac{\sum\limits_{i>1} V_i^2}{V_1^2}\right)\left(V_1\frac{\partial V_1}{\partial \mathbf{B}_r(\theta)}\right)\right] \qquad (1)$$

where V_i is the i^{th} harmonic of the voltage, B_r is the radial flux density, and other symbols have the usual meaning. This expression provides a useful guide to target the specific area for optimisation. Hence, the flux diverters and coils were moved further away from the stator at the angle between 31° to 62° (see Fig. 2) and – when possible – the number of turns in selected coils was further reduced without compromising the earlier constraints. The results, after the final modifications, are shown in Fig. 3 (c) together with the flux lines. The normal field in the coils was reduced from 0.133T to 0.086T and the total *rms* harmonic voltage content improved from 3.39% to 1.394%, thus the modifications proved extremely successful.

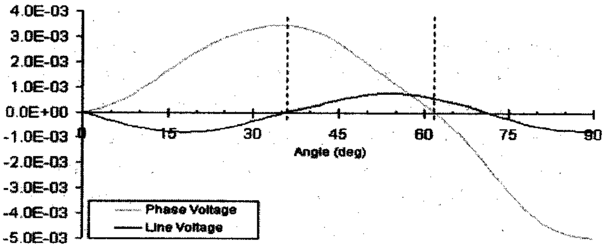

Fig. 2. Weighted errors in the air gap flux density.

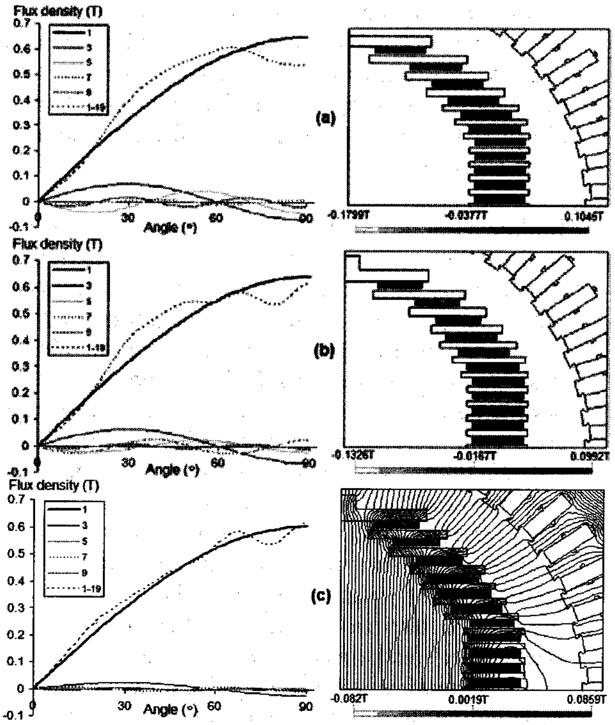

Fig. 3. The air-gap field and the distribution of the normal field in the HTS coils.

CONCLUSIONS

The 2D finite element investigations reported here demonstrate the unique requirements of the superconducting generator compared with a conventional design. Such modelling studies have been shown to be essential before the actual design could commence. Some 3D investigations have also been conducted but are not reported due to lack of space.

REFERENCES

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2. Al-Mosawi M. K., Beduz C., Goddard K., Sykulski J.K., Yang Y., Xu B., Ship K.S., Stoll R. and Stephen N.G., 2002, Physica C, 372-376, 1539-1542