MULTIPOLE SUPERCONDUCTING SYNCHRONOUS GENERATOR

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Abstract - This paper shows the preliminary studies for a superconducting synchronous wind generator. The HTS superconductors are used both on the armature winding and on the stator coils. The flux plots and the electromagnetic torque are used to make a comparison between this HTS prototype and a conventional wind generator and also with a superconducting wind generator in which superconductors are used only in the rotor to generate the armature field. The three machines considered have the same geometric dimensions. The flux plots and the electromagnetic torque are obtained performing a two-dimensional finite element tool.

Index Terms **—** HTS pre-magnetized, Superconducting Synchronous generator, wind generator.

1. Introduction

The superconductivity state is characterized by extremely low values of the resistivity; because of this it is possible to carry currents bigger (about an order of magnitude or more) than the currents in the conventional copper wires. Another important feature of the superconducting state is the flux trapping or pinning at higher field. This property allows having persistent circulating currents inside the material.

HTS materials were discovery in 1986 by Bednorz and Muller[1] and since then a great manufacture's improvement have been done. Superconductors in practical industrial applications in power devices are now being used mainly on electrical machines. Research groups in the world are deeply investigating superconducting machines [2,3] in order to get a better design.

The introduction of superconductors in electrical machines would provide an advance in terms of efficiency and annual savings, weight, volume and performance characteristics. However, some care must be taken when using HTS materials due to its brittle nature.

HTS superconductor motors find applications in situations where size and weight is critical. With the advent of hydrogen-fuelled vehicles, HTS motors can be used in automobile and aerospace industry.

2. Machine Design

For any electrical machine, the power output can be expressed as

$$P_{out} = k A_s B_m D^2 \ell N \qquad (1)$$

where

- A_s is the armature electric loading [A/m];
- B_m is the magnetic loading [T];
- D is the armature diameter [m];
- ℓ is the machine active length [m];
- N is the rotor speed [rad/s];
- k is a constructive constant.

In conventional machines, both the armature electric loading A_s and the magnetic loading B_m cannot be increased above a certain limit. In the conventional machines, B_m is limited by iron core saturation and core loss and in particular in a synchronous machine, the air gap presents a very high reluctance and consequently the maximum field is limited to about 0,5 T. On the other hand, electrical loading As is limited by the ability to cool the machine coils and by the space available for the embedded conductors.

Using HTS superconductors in electrical machines construction, it is possible to increase As and Bm and consequently it is possible to increase the power output per unit volume of the machine.

In this paper a new prototype of a superconducting synchronous generator (SSG), used for wind generation, is considered and the attention is focused only on the electrical behavior of the machine. A preliminary study is presented. This superconducting machine is under development in the Supermachines Project No RTN1-1999-00282 involving six European Universities. The particularity of this SSG is the use of pre-magnetized HTS pieces to create the armature field and the employment of HTS coils on the stator.

Until now, all synchronous superconducting generators prototype are built using superconductors only on the rotor

to create the rotating field in the air gap (it is used a multiturn magnet out of superconducting wire). In this case at the superconductor coils are applied only a DC current and there are no problems concerning the hysteresis losses associated with the superconductor wires.
In fact when a superconductor is subjected to a time varying magnetic field, it is possible to identify hysteresis losses in the superconductor. The losses in a type II superconductor, below 200 Hz, can be expressed as

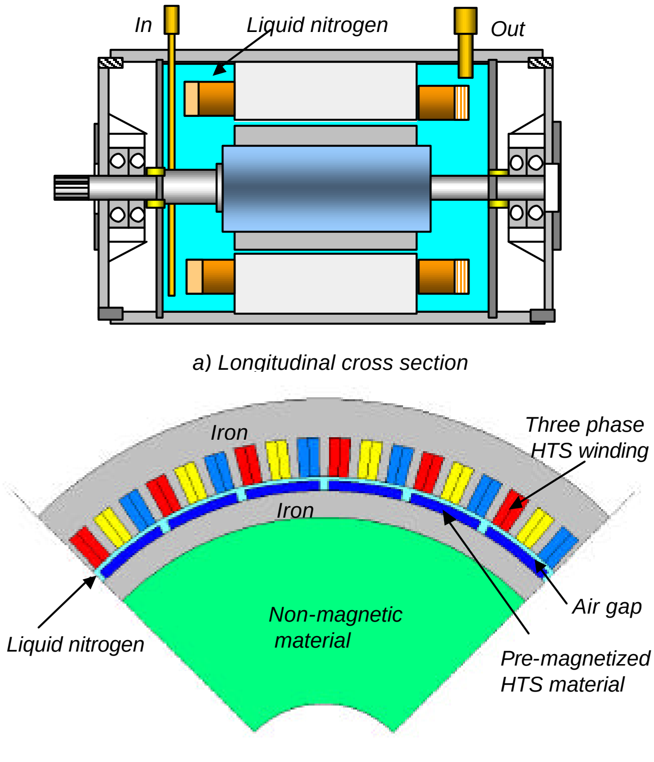
$$P_{losses} = K_h f + K_e f^2 \qquad (2)$$

where the first term represents the hysteresis losses, the second represents the losses due to eddy currents induced.
Using the HTS on the rotor it is possible to increase only the magnetic loading of the machine.
Because of the recent improvements in the HTS manufacture (only recently superconductors with high matrix resistivity are produced, and this allows reducing the losses associated with the eddy currents) it is possible to use of HTS materials also on the stator coils and the use of pre magnetized HTS to create the armature field. The creation of bulk superconducting magnets raises the possibility of producing magnetic fields of 1-5 T at low cost, better than any good permanent magnet [4].
The HTS materials can be used as mmf sources because of their flux trapping ability. Using HTS permanent magnets as mmf sources on the rotor, it is possible to develop powerful synchronous machines without electrical connections. In fact, currently, the trappable field in a 25 mm diameter bulk YBCO material at 77K is approaching the field trapped in the best permanent magnets; for lower temperatures it is possible to obtain significantly larger fields.
Using stator HTS coils it is possible to increase, also, the electrical loading of the machine and consequently increase the power output for the same dimensions of the machine.
The technical data and the machine layout are presented in section 3. In the next section a brief introduction on the principles behind the HTS pre-magnetized is treated. The flux plot and the electromagnetic torque, obtained with a 2-D FEM model, are presented in section 4.

3. Machine Layout

The considered machine is a three-phase synchronous wind generator with 24 poles, as illustrated in figure 1. Superconductors are present both on the rotor and on the stator.
The rotor excitation instead using the conventional rare earth permanent magnets is obtained by pre-magnetized HTS pieces. HTS conductors make the armature windings.
The technical data for the considered machine is shown below:

- Rated power: 10 kW;
- Rated voltage: 400 V;
- Power factor: cosφ = 0.85;
- Number of poles 24;
- Frequency 50 Hz;
- Synchronous reactance 0.35 p.u.
- Rotor radius: 190 mm;
- Air gap 1.5 mm



a) Longitudinal cross section

b) Transversal cross section

Figure 1 - Layout of the machine

In this design the rotor and stator winding are bathed in liquid nitrogen (LN_2). Because liquid nitrogen is evaporating due to the machine losses a flow of about 9 mg/hour/kW is necessary [5]

4. Pre-magnetised HTS rotor

A conventional wind generator generally uses permanent magnets for its rotor excitation. In this design, however, pre-magnetized HTS materials are used [6,7]. The power from wind generation is variable according to the wind speed. Therefore all the electric power produced should be delivered into the grid and so the power should cover the lower part of the daily load curve as shown in figure 2.
Bulk pre-magnetized HTS materials are used for the machine excitation and not large single domain crystals. One way for pre-fluxing the HTS bulk is using a large current pulse through the superconductor, which was cooled below its critical temperature. During the pulse, the field enters and

leaves the superconductor resulting in a field trapped inside the superconductor. When the external field is removed, there is a current circulating persistently inside the bulk, so the HTS behaviour is equal to the one of the best conventional permanent magnet [8].

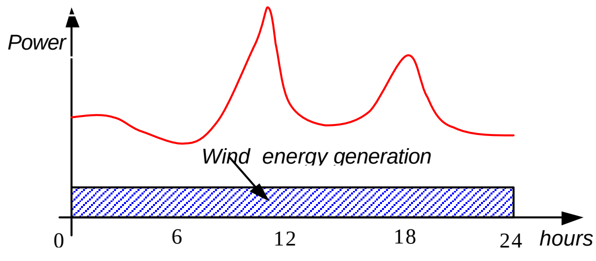


Figure 2 - Daily load curve

The field decay $B(t)$ in the HTS permanent magnets follows a logarithmic law according to the equation

$$\frac{B(t)}{B(0)} = 1 - c \times log(t) \tag{3}$$

where t is the time and c is a constant depending on the material considered. In any case, the magnetic relaxation of the trapped field can be suppressed by further cooling the superconductor after the field has been trapped. Small additional cooling (~3 K) has been shown to be sufficient for the required goals [9,10].
A little care has to be taken when the HTS is pre-magnetized because during the normal operation, the magnetic field created by the armature current penetrates the pre-magnetized HTS pieces. Thus, it is important that the pre-magnetizing field penetrates further than the armature field, otherwise, in the normal working condition of the machine, the magnetization current distribution will be overwritten and the trapped-field is lost. Most of the times it is sufficient to apply a magnetization current twice the amplitude of the current during normal operation. With the assumption of linearity, this means that the pre-fluxing applied field should have twice the amplitude of the rotating field.

5. Numerical Results

For this study only four poles are considered and everything is expressed in terms of electrical degrees. The considered section has been linearized, so in this case a linear three phase, four poles machine is considered.
The HTS machine is compared with a conventional one, with the same number of poles and the same geometric dimensions. This prototype is also compared with the superconducting synchronous generator, in which the HTS are used only on the rotor to create the armature field. Comparison of these three machines is made in terms of tangential force.

Power density of all this three machines can be derived from the tangential force density.
The force is calculated for different phase angles θ (angle between magnetic stator axis and magnetic rotor axis), as shown in figure 3.

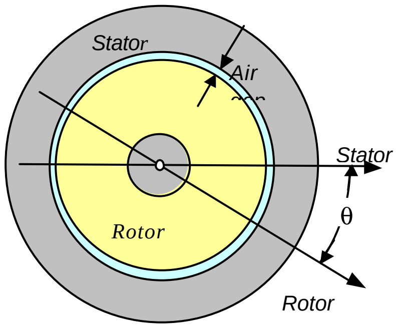
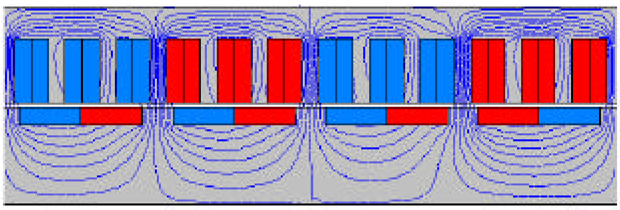
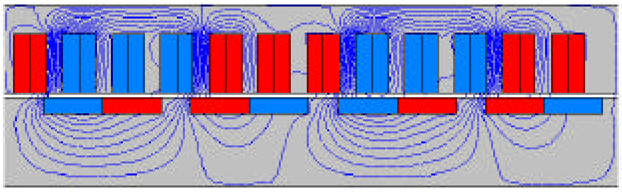


Figure 3 - Simplified two-pole machine

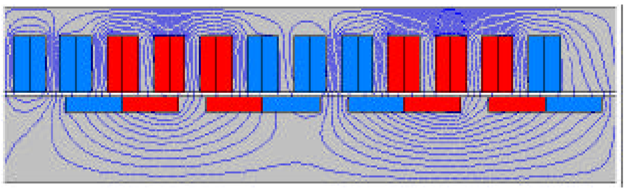
The conventional machine has the same geometric dimensions of the HTS generator, but the armature field is generated by conventional permanent magnets and copper wires for the stator coils [11]. So the maximum current density to carry on the stator wires is $5x10^6$ A/m^2.
For the conventional superconducting synchronous generator, copper wires are used for the stator coils and the excitation system is obtained by HTS permanent magnets.
The program that has been used to run the simulations is 2D FEM tool. This program does not allow introducing new materials in its material library and superconducting materials are not included. However, the superconductors have been simulated by using current sources. Assuming that the HTS permanent magnets and the HTS stator coils are both current sources, the HTS microscopic structure is completely ignored. It is a reasonable assumption because the HTS is used as coils in the stator and as current sources in the rotor and not as flux barriers. Considering the HTS as current sources it is not possible to evaluate the penetration depth in the HTS material. However, it is possible to take into consideration the losses according to the maximum current density admissible in the coils. Moreover this is a preliminary study and it is important to focus the attention on the advantages that rise from this new design.
To run the simulations and to observe the behaviour of the three machines the stator and the rotor are assumed to be infinite long slabs with a uniform air gap. Thus, when the rotor is moved from its initial position by an angle θ the air gap reluctance is almost constant.
Figure 4 shows the flux plots for the torque angles θ = 0, 30, 60 and 90 electrical degrees. The flux lines for the three machines considered are equal in the shape, but the values of the magnetic field are different because current sources were assumed.
Comparison of tangential force per unit air gap area versus rotor angle for conventional wind synchronous generator and for the superconducting synchronous generator with HTS elements on the rotor only is displayed in figure5.



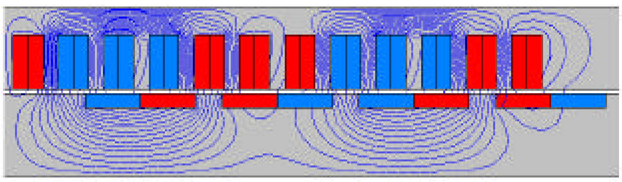
θ = 0 electrical degrees



θ = 30 electrical degrees



θ = 60 electrical degrees



θ = 90 electrical degrees

Figure 4 - Flux plots for different torque angles

The HTS machine produces a force density, obviously, bigger than the conventional wind generator, and also the output power is bigger for the HTS machine than for the conventional one.

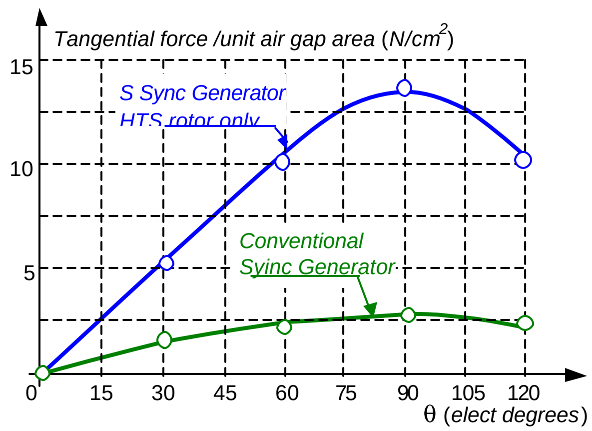


Figure 5 - Comparison between conventional and HTS machine

The diagram shows also that the force produced by the HTS synchronous generator compared with the conventional is very convenient to improve the synchronous generator behaviour.

Using HTS coils in the stator armature the electric loading A_S can be improved and consequently efficiency of the machine will be better. Figure 6 shows the comparison between the three types of synchronous generator under investigation.

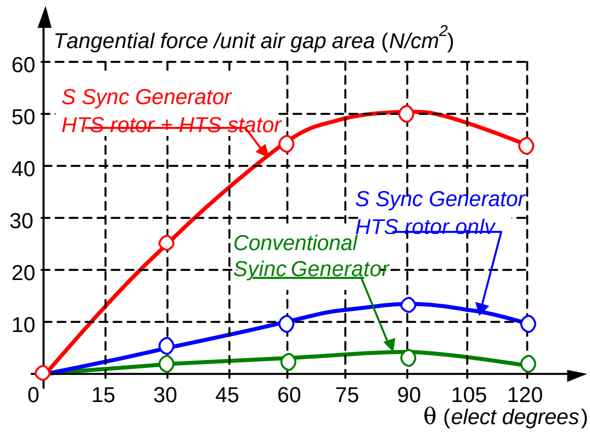


Figure 6 - Comparison between the three machines considered

Again the tangential force per unit air gap area for the completely HTS generator (superconductors on the rotor and stator) is about five times bigger than of the superconducting synchronous generator with HTS elements on the rotor only and twenty five times bigger than the conventional synchronous machine.

6. Conclusion

The flux plots and the tangential force on the stator of a completely HTS superconducting wind generator were presented. According to the force diagrams the completely HTS generator presents the higher tangential force compared with the other ones for the same geometric dimensions. Therefore the completely HTS machine presents a higher power density output. However this comparison should be taken into account the energy requested by the liquid nitrogen to cool the machine.

The environment where the machine is going to be installed must be taken into consideration. In some applications, where liquid nitrogen or liquid hydrogen are available, as for example in cryoplane and in automobile industry, the completely HTS machine could be useful.

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