Design Study of High-Temperature Superconducting Generators for Wind Power Systems

N Maki
Technova Inc. 13th Fl. Imperial Hotel Tower, 1-chome, Chiyoda-ku, Tokyo 100-0011 Japan

E-mail: naokmaki@technova.co.jp

Abstract. Design study on high-temperature superconducting machines (HTSM) for wind power systems was carried out using specially developed design program. Outline of the design program was shown and the influence of machine parameters such as pole number, rotor outer diameter and synchronous reactance on the machine performance was clarified. Three kinds of generator structure are considered for wind power systems and the HTSM operated under highly magnetic saturated conditions with conventional rotor and stator has better performance than the other types of HTSM. Furthermore, conceptual structure of 8 MW, 20 pole HTSM adopting salient-pole rotor as in the case of water turbine generators and race-truck shaped HTS field windings like Japanese Maglev was shown.

1. Introduction
Wind power generation systems are one of the most promising types of renewable energy sources and their commercial deployment is progressing. Since generators for the systems are operated under the very low revolution speed and large torque conditions, induction generators and step-up gears are adopted for on-shore small-scale machines, and synchronous generators and electric power converters are adopted for off-shore large-scale machines considering the power system stability. In the latter case, nacelles are getting bigger, and their transportation and installation are more difficult as the capacity of the generators becomes larger. The application of high-temperature superconducting synchronous machines (HTSM) to their systems looks hopeful from the standpoint of compactness [1]. The HTSM apply high-temperature superconductors (HTS) to the field windings and can have the merits of a reduction in size and weight (about 1/3 to 2/3), improvement in rating and partial load efficiency (more than approximately 1% and 10 %) and increase in overload capacity up to several times during short periods of several seconds. Therefore, HTSM for electric propulsion ships have been developing all over the world including USA [2] and Germany [3]. Meanwhile, HTSM for wind power systems remain in the study stage [4].

2. Outline of fundamental design program
Figure 1 shows the flowchart of the fundamental design program of HTSM developed using the electrical equations taking into consideration the size of machine components and excitation characteristics of the superconducting windings [5]. As HTS conductors for the field windings, DI-BSCCO conductors are selected from the standpoint of easy manufacturing of km class unit length with considerable high critical current [6]. The features of the design program are as follows.
For a given HTSM specification, a rational fundamental design is conducted using repeated adjusting computations for the armature and field winding thickness.

The influences of various parameters such as synchronous reactance, diameter of field winding, maximum magnetic flux density on superconductors and operating load factors, which affect the machine parameters and performance, can be obtained easily.

Designs of HTSM with magnetic or non-magnetic rotors and also with air-gap armature windings or conventional stators can be conducted.

Designs of fully HTSM with HTS field and armature windings can be conducted.

**Figure 1.** Flowchart of the fundamental design program

### 3. Influence of machine parameters on the basic performances of HTSM

Influence of machine parameters such as number of poles, rotor outer diameter and synchronous reactance on the basic performance of HTSM is studied from the fundamental electric design results. Figure 2 shows influence of number of poles on basic performances of 2 [MW], 21.5 [1/min] HTSM and the following become obvious.

- Generator efficiency increases from 92 to 96 [%] as number of poles varies 6 to 16 and tends to be saturated at more than 20 poles.
- Generator weight decreases considerably as number of poles varies 6 to 16 and is almost the same at 18-28 poles.
- The required length of HTS field windings is minimized at 16-20 poles and somewhat increases as number of poles is far from those poles.

From the above results, it is found that a 20 pole machine is desirable.
Figure 2. Influence of number of poles on basic performances of HTSM

Figure 3 shows influence of rotor outer diameter on basic performances of 2 [MW], 21.5 [1/min] HTSM and the following become obvious.

- Generator efficiency decreases gradually from 96.6 to 95.3 [%] as rotor outer diameter varies 3.48 to 6.89 [m], which is because that the influence of end windings become bigger.
- Generator weight increases slightly as rotor outer diameter varies 3.48 to 4.45 [m] and increases significantly at more than 4.45 [m].
- The required length of HTS field windings increases gradually with the rotor outer diameter.

From the above results, it is found that a smaller rotor outer diameter is desirable, and the rotor outer diameter of 3.48 [m] is selected considering easiness of manufacture.

Figure 3. Influence of rotor outer diameter on basic performances of HTSM

Figure 4 shows influence of synchronous reactance on basic performances of 2 [MW], 21.5 [1/min] HTSM and the following become obvious.

- Generator efficiency increases from 94.2 to 97.2 [%] as synchronous reactance varies from 0.35 to 0.75 [pu], which tend to increases gradually and be saturated slightly.
Generator weight increases gradually from 38 to 58 [ton] as synchronous reactance varies from 0.35 to 0.75 [pu].

The required length of HTS field windings is almost the same regardless of synchronous reactance.

From the above results, it is found that the influence of synchronous reactance $x_d$ on both generator efficiency and weight is in the trade-off relation and then $x_d$ of 0.65 [pu] is desirable.

4. Fundamental design of various HTSM

The following three kinds of generator structure are considered for wind power systems.

(A) HTSM utilizing nonmagnetic rotor and air gap armature winding

(B) HTSM utilizing weakly magnetic rotor made from Ni alloy and conventional stator

(C) HTSM operated under highly magnetic saturated conditions with conventional rotor and stator

Figure 5 shows basic performances of the above three kinds of 8 [MW], 12 [1/min] HTSM and the following can be clearly observed.

- Compared basic performance of (B) type to (A) type HTSM, the required HTS length is about 1/2 which shows a significant economic effect, while generator weight increases slightly.
- Compared basic performance of (C) type to (B) type HTSM, the required HTS length is about 1/3, generator weight decreases to about 2/3 and generator efficiency increases by 0.1 [%], which shows that (C) type HTSM has a very excellent performance.

From the above results, it is found that (C) type has better performance than the other types of HTSM.
Figure 6 shows basic performances of 2, 5 and 8 [MW] HTSM adopting (C) type and the following can be clearly observed.

- Generator efficiency decreases slightly by 0.9 and 0.6 [%], respectively, as machine capacity varies 2 $\rightarrow$ 5 $\rightarrow$ 8 [MW], which is because that the rated machine revolution speed drops 21.5 $\rightarrow$ 14.8 $\rightarrow$ 12 [1/min]. Since induced voltage decreases as the machine revolution speed drops, armature current increases to maintain the same generator capacity, which causes larger armature copper loss.

- Generator weight at 2 $\rightarrow$ 5 $\rightarrow$ 8 [MW] are 54, 108 and 154 [ton], respectively. Generator weight is in proportiona to generator capacity and in inverse proportiona to revolution speed theoretically, and therefore, (generator weight [ton] × revolution speed [1/min] / generator capacity [MW]) is estimated to be 34×21.5/2 = 366, 108×14.8/5 = 320 and 154×12/8 = 231, respectively. That is, the scale merit effect, which relative weight decreases as generator capacity becomes bigger, is occurred remarkably.

- The required length of HTS field windings increases as machine capacity varies 2 $\rightarrow$ 5 $\rightarrow$ 8 [MW].

![Figure 6. Basic performances of 2, 5, 8 [MW] HTSM adopting (C) type](image)

5. Conceptual structure of 8 MW HTSM
An example of conceptual structure of 8 MW, 20 pole HTSM for wind power systems is shown in Fig. 7. Inner diameter of stator yoke is 4.0 [m], and outer diameter of the rotor is 4.45 [m]. Outer diameter and length of the stator are 5.0 [m] and 2.8 [m], respectively. For HTS field windings, race truck shaped coils, which is like Japanese Maglev, are adopted. A warm rotor bore, in which rotor iron is not necessary to be cooled in the cryogenic condition, is adopted because the cooling structure is simpler and the cooling load is smaller than a cold rotor bore. Salient-pole shape rotor, which is the same as one for water-turbine generators, is adopted because race-track shaped coils may be used for easier winding work. The required magnetomotive force of the salient-pole shape rotor is 42 [kA/pole], which is 0.3 times that of cylindrical shape rotor with Ni alloy core. This is results from that relative permeability of Ni alloy is less than 5. With the magnetic steel sheet having very high permeability for the rotor bore, the required magnetomotive force of field windings is reduced significantly.
6. Conclusion
Design study on HTSM for wind power systems was carried out using specially developed design program and the followings become clear. First the influence of machine parameters such as pole number, rotor outer diameter and synchronous reactance on the machine performance were clarified on the basis of various fundamental design results for 2 MW HTSM. Next, the three kinds of generator structure are considered for wind power systems and it is found that HTSM operated under highly magnetic saturated conditions with conventional rotor and stator has better performance than the other type HTSM. Furthermore, from the design results of 2, 5 and 8 [MW] HTSM, the influence of machine sizes and basic performances on machine capacity was clarified. Last, conceptual structure of 8 MW, 20 pole HTSM adopting salient-pole rotor as in the case of water turbine generators and race-truck shaped HTS field windings like Japanese Maglev was shown.
In the near future, we are going to proceed the design study toward more compact and efficient HTSM. This work was carried out as a part of strategic R&D for new energy development, being consigned by NEDO.

7. References
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