Electromagnetic Performance of 10-MW HTS Double-Stator Flux Modulation Generators Considering Distributed/Concentrated Armature Winding

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Abstract. For HTS conventional synchronous generator, the superconducting (SC) field windings or armature windings are rotating, which could complicate their industrial feasibility for the off-shore wind generation. In order to overcome this drawback, a kind of HTS double-stator flux modulation generator (HTS-DSFMG) with stationary seal is proposed. Meanwhile, the electromagnetic performances of 10-MW HTS double-stator flux modulation generators with two different armature winding structure, i.e., distributed and concentrated armature windings are compared in this paper. In detail, the magnetomotive force (MMF) harmonic and the saturation effect of each armature winding structure have been studied. The objective is to intensive study the advantages and disadvantages of HTS-DSFMG with different armature windings, and to find the suitable configuration of the armature winding for large scale HTS double-stator flux modulation generators.

1. Introduction
Offshore wind power, as a clean and renewable energy, has become the main growth point of wind power development. It is a trend, for offshore wind power, that large power even above 10 MW direct-drive wind generators are preferred to reduce the cost per MW. However, traditional permanent machines and induction machines with extremely high weight and volume for large scale power are not very suitable for offshore wind generator. Superconducting electrical machines have the advantages of smaller volume, low weight, and higher efficiency compared with conventional electrical machine due to the advantage of much higher magnetic loading excited by high temperature superconducting (HTS) coils. Therefore, HTS wind generator becomes a potential candidate with higher torque density and efficiency for offshore wind direct drive generator in the future.

Various topologies of SC machines have been proposed and studied since the 1960s. Some cases of direct-drive SC generators are listed in Table 1. The common topology in these cases is conventional synchronous machine structure. This topology simply changes the copper field windings of traditional DC current excitation synchronous generator to superconducting field coils. Nevertheless, the SC field windings or armature windings are rotating in this machine, which could complicate their industrial feasibility for the offshore wind generation. In order to overcome this drawback, a kind of HTS double-stator flux modulation generator (HTS-DSFMG) with stationary seal is proposed. The field and armature coils are fixed on the two stator respectively. The rotor consists of the modulation ring and its supporting structure. Besides, modular cryostat concept is adopted for this machine.

In this paper, the principle and detailed structure of double-stator flux modulation generator HTS wind generator are introduced in Part 2. Then, this paper compares the electromagnetic performance...
Table 1. Cases of direct-drive SC generators

| Country | Affiliation/project                  | Power (MW) | SC material | Machine Topology       | Ref  |
|---------|-------------------------------------|------------|-------------|------------------------|------|
| USA     | GE                                 | 10         | NbTi        | Synchronous Machine    | [1]  |
| USA     | Kalsi Green Power Systems           | 10         | MgB$_2$     | Synchronous Machine    | [2]  |
| Europe  | Converteam                          | 8          | YBCO        | Synchronous Machine    | [3]  |
| Europe  | SupraPower                          | 10         | MgB$_2$     | Synchronous Machine    | [4]  |
| Europe  | INNWIND                             | 10         | MgB$_2$     | Synchronous Machine    | [5]  |
| Japan   | Univ.of Tokyo                       | 10         | MgB$_2$     | Synchronous Machine    | [6]  |
| Japan   | Niigata Univ.                       | 10         | YBCO        | Synchronous Machine    | [7]  |
| Korea   | Univ.Changwon National              | 10         | YBCO        | Synchronous Machine    | [8]  |
| China   | HUST                                | 12         | NbTi        | Synchronous Machine    | [9]  |

of 10-MW HTS double-stator flux modulation generators with two different copper armature winding structure, i.e., distributed and concentrated armature windings. In detail, the magnetomotive force harmonic and the saturation effect of each armature winding structure have been studied. The objective is to intensive study the advantages and disadvantages of HTS-DSFMG with different armature windings, and to find the suitable configuration of the armature winding for large scale HTS double-stator flux modulation generators.

2. Design of proposed generator

2.1. Topology

The structure of the double-stator flux modulation topology is shown as Figure 1. The dc HTS field and ac copper armature coils are fixed on the two ironed-stators respectively while the modulation ring between the two stators is rotating. Due to the stationary armature and field windings, no brush, slip ring and rotating excitation equipment are required which can obviously improve the reliability of the topology. Besides, instead of conventional integrated cryostat which will lead to transportation, installation and maintenance challenge, modulation cryostat concept is adopted in the study. The assembly of the proposed machine is illustrated in Figure 1. Each HTS field coil is enclosed by a multilayer damper tube, which consists of a vacuum chamber and a thermal shield to reduce the heat transfer from the ambient to the cold SC windings. The modulation ring is designed as disc structure with cavity where the inner stator with SC coils is amounted.
2.2. Operating principle

The HTS-DSFMG operates on the flux modulation effect between the excited field produced by HTS windings and the rotating modulation blocks [10]-[11]. The inner slot $Z_i$ where the DC HTS field coils are wound is 36, so the pole pair $P_f$ of magnetomotive force (MMF) excited by HTS coils is 18. The rotor is composed of 30 iron modulation blocks. Therefore the pole pair $P_r$ of the permeance of the rotor is 30. The flux density in the outer air-gap can be achieved by multiplying the HTS MMF with the permeance based on the flux modulation theory demonstrated in equation 1.

$$B_g(\theta_s,t) = F_c(\theta_s)\Lambda_g(\theta_s,t)$$

$$\approx \sum_{i=1,3,5,\ldots} F_i A_{g_i} \sin\left(\frac{Z_{in}}{2} i \theta_s\right)$$

$$- \sum_{i=1,3,5,\ldots} F_i A_{g_i} \sin\left[(\frac{Z_{in}}{2} i \pm Z_{in}) \theta_s\right]$$

$$+ \sum_{i=1,3,5,\ldots} \frac{F_i A_{g_{N+2}}}{2} \sin\left[(\frac{Z_{in}}{2} i \pm (N_i + Z_{in}) \theta_s \mp N_i \omega t\right]$$

$$- \sum_{i=1,3,5,\ldots} \frac{F_i A_{g_{-N+2}}}{2} \sin\left[(\frac{Z_{in}}{2} i \pm (Z_{in} - N_i) \theta_s \pm N_i \omega t]\right]$$

where $F_c$ is the MMF produced by HTS coils, $\theta_s$ the air-gap position, $i$ the harmonic order, $\Lambda_{g_i}$ the permeance of the inner air-gap, $\Lambda_0$ and $\Lambda_v$ are the coefficients of the air gap permeance function for the average component and $v$th harmonics, respectively.

There are some magnetic field harmonics including the stationary and rotating fields in the outer air-gap and the rotating components listed in Table 2 will induce back EMFs in the armature windings for energy exchange. The pole pair of armature windings $P_s$ should meet the requirement that $P_s=|P_f - P_r|=12$ [12]. Through the modulation effect of the rotor, the static magnetic field generated by HTS coils can generate a rotating magnetic field in the air-gap and that is why the HTS filed and copper armature coils can be both installed on the stators.

2.3. Superconducting Tapes and Cryostat for HTS Field Winding

The type of the superconducting tapes is YBCO and the dimension is 4 mm \times 0.165 mm. The operating temperature of the HTS coils is 30 K and the I$_c$-B characterization of the SC tape at 30 K is underlined in the Fig. 2. In order to keep the stable operation of SC tapes, 40% safety margin is
imposed in the critical current. The SC current load line is illustrated in the figure due to the peak flux density in the SC coils region is about 1.2 T. According to the load line, the operating current of SC coils is set as 150 A.

Modular cryostat concept has been taken to minimize the cold mass inside the cryostat as well as modularize the superconducting winding [13]. Meanwhile, without cryostat wall in the direction of radial flux path, the electrical air gap can be much smaller than topologies with integer cryostat, which can reduce the cost of SC material to achieve the optional magnetic loading. As illustrated in Figure 3, the thickness of cryostat wall is assumed 10 mm to satisfy the mechanical requirement. The cooling channel thickness is assumed 20 mm. The multi-layer insulation (MLI) & vacuum of thickness of 20 mm is accommodated between cooling channel and cryostat wall [14].

3. Comparison Result
In this section, the electromagnetic performances of 10-MW HTS double-stator flux modulation generators with two different armature winding structure, i.e., distributed and concentrated armature windings are compared. The rated revolution of offshore wind generator is set as 10 rpm which is determined by the turbine, and the rated output voltage is set as 3.3 kV, since the corresponding DC link voltage of the full power converter is 5.5 kV. For topology with distributed windings, the outer

| Spatial Order | Working harmonics |
|--------------|-------------------|
| $\frac{Z_{n-i}}{2} \pm N_i$ | 12, 48 |
| $\frac{Z_{n-i}}{2} \pm (N_i + Z_n)$ | 48, 84 |
| $\frac{Z_{n-i}}{2} \pm (Z_n - N_i)$ | 12, 24 |

Figure 2. Load line for HTS tapes.

Figure 3. Rotor pole with modular cryostat.
Table 3. Basic specification of the generators

| Parameter                              | Value         | Parameter                              | Value         |
|----------------------------------------|---------------|----------------------------------------|---------------|
| Number of phases                       | 3             | Outer stator outer diameter [mm]       | 7000          |
| Output power [MW]                      | 10            | Outer & Inner air gap [mm]             | 10            |
| Number of inner slots                  | 36            | Armature current density [A/mm²]       | 3.5           |
| Number of rotating module units       | 30            | Superconducting tape type              | YBCO          |
| Outer stator pole pair                 | 12            | Dimension of SC tape [mm×mm]           | 4×0.165       |
| Rated speed [rpm]                      | 10            | HTS coil operating current [A]         | 150           |
| Active stack length [mm]               | 1200          | Turns per HTS coil                     | 250           |

stator slot number and pole pairs are 384 and 12 respectively. For the other, the outer stator slot number and pole pairs are 36 and 12. To ensure the fairness and validity of the comparison, the two topologies have the same inner stator and rotor ring structure parameter. Besides, total number of turns per phase, the stator yoke width, total teeth width and slot area are kept the same for the two topologies. More specifications of this machine are listed in Table 3.

3.1. No-load condition

The change of EMF with SC turn number per coil ($N_{HTS}$) are illustrated in Figure 4. According to Figure 3, for both topologies, when $N_{HTS} < 250$ the no-load back EMF gradually increases with the increasing of SC MMF, while EMF approaches saturation when $N_{HTS} = 250$. In order to make full use of the HTS coils and reduce the cost of the superconducting material, the turn number is determined as 250 at rated condition. The slight difference in back EMF of two topologies is due to the slot opening and the flux density distribution of these two topologies are shown in Figure 5.

![Fig. 4. Line-line EMF versus current curve](image1)

![Fig. 5. Flux density distribution under no-load conditions](image2)

Fig. 4. Line-line EMF versus current curve  
Fig. 5. Flux density distribution under no-load conditions

3.2. Load condition

With the increase of phase current, outer stator is gradually saturated and the structure with concentrated winding is more sensitive to the outer stator saturation, which is shown in Figure 6. Besides, the out stator flux density distribution with rated armature current is illustrated in Figure 7. The concentrated winding structure is characterized by harmonic contents in the armature MMF distribution higher than that of the corresponding distributed winding structure. The MMF harmonic contents of two structures are shown in Figure 8 and Figure 9 respectively. For concentrated winding structure, the amplitude of 24th and 60th harmonics are comparable with the amplitude of the operating harmonic, of order 12. Besides, the winding factor of these useless harmonic is same with the operating harmonic. These harmonics contribute to the outer stator saturation with the increasing of phase current. However, the distributed winding structure has less harmonic content due to small or
zero winding factor. The winding factor comparison of these two structures is clarified in Table 4. With the same rated current and active stack length, the torque of distributed winding structure is 1.18 time that of concentrated one. Therefore, with the same volume and weight, the distributed one can produce 1.5 MW electric energy more than concentrated one. Due to the strong saturation effect of concentrated winding structure, to up to the rated power, the volume, weight of the generator and cost of SC should be increased.

| HO | Concentrated | Distributed |
|----|--------------|-------------|
| 12 | 0.866        | 0.957       |
| 24 | 0.866        | 0           |
| 48 | 0.866        | 0           |
| 60 | 0.866        | 0.200       |
| 84 | 0.866        | 0.149       |
| 96 | 0.866        | 0           |

HO: MMF harmonic order
4. Conclusion
In this study, a kind of HTS double-stator flux modulation generator (HTS-DSFMG) with stationary seal is proposed and the electromagnetic performance of 10-MW HTS-DSFMG with two different armature winding structure, i.e., distributed and concentrated armature windings are compared. According to the results, the generator with concentrated winding structure has strong saturation effect due to the abundant the harmonic contents in the armature MMF while the distributed winding one has less harmonic contents due to small or zero winding factor for harmonics. Under the same volume and weight, the generator with distributed winding can produce 1.5 MW more power than concentrated winding one. Therefore, the distributed winding is more suitable for the double-stator flux modulation generator.

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