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DOI

[10.1109/TASC.2020.2971436](https://doi.org/10.1109/TASC.2020.2971436)

Publication date

2020

Document Version

Final published version

Published in

IEEE Transactions on Applied Superconductivity

Citation (APA)

Liu, D., Song, X., & Dong, J. (2020). Performance of Multi-Layer and Stator-Shifting Fractional-Slot Concentrated Windings for Superconducting Wind Turbine Generators under Normal and Short-Circuit Operation Conditions. *IEEE Transactions on Applied Superconductivity*, 30(4), 1-5. Article 8981885. <https://doi.org/10.1109/TASC.2020.2971436>

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Performance of Multi-Layer and Stator-Shifting Fractional-Slot Concentrated Windings for Superconducting Wind Turbine Generators Under Normal and Short-Circuit Operation Conditions

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Abstract—High temperature superconducting (HTS) generators are being considered for large offshore direct-drive (DD) wind turbines as they are expected to be lightweight and compact. However, short circuit torques of an HTS generator with integral-slot distributed windings (ISDWs) are too high for wind turbine constructions, mainly due to the large magnetic air gap. Fractional-slot concentrated windings (FSCWs) can be considered to address this issue since their high leakage inductance can limit short circuit currents and torques. Unlike ISDWs, FSCWs produce great contents of space harmonics that induce excessive losses in rotor components. Multi-layer and stator-shifting windings have been proposed to effectively reduce such losses. Based on a conventional 12-slot 10-pole configuration, this paper evaluates the effects of multi-layer and stator-shifting FSCWs on torque production and loss reduction in a 10 MW DD HTS generator. The examined losses include eddy current losses in the rotor shields and AC losses in the HTS field winding. This paper also checks if these FSCW schemes maintain the advantage of achieving a low short circuit torque. The results show that a 6-phase stator-shifting winding is the best choice for applying FSCWs to HTS generators.

Index Terms—AC loss, eddy current loss, fractional-slot winding, multi-layer, stator shifting, superconducting generator, torque, wind turbine.

I. INTRODUCTION

SUPERCONDUCTING synchronous generators can be more lightweight and compact compared with conventional synchronous generators. High temperature superconducting (HTS) generators are more interesting because of a relatively high operating temperature of superconductors. Thus, HTS generators are being considered in large offshore direct-drive (DD) wind turbines in 10 MW and above [1]–[6]. HTS generators

usually have a cold superconducting rotor and a conventional warm stator, thus having larger magnetic air gaps compared to their conventional counterparts. The space for a cryostat also increases the magnetic air gap. As a result, the inductance becomes lower, and then short circuit torques can become much higher than the rated torque and could be as high as ten times [7], [8]. Wind turbines cannot withstand such high torques and usually the upper limit is about three times the rated torque. Tackling the challenge of high short circuit torques is decisive for commercializing HTS generators.

Some approaches have been proposed to reduce short circuit torques, e.g., using more ferromagnetic core or multiple armature windings [9]. The effects of more ferromagnetic core and segmented armature windings with multiple converters have been evaluated in [9], [10]. These methods are all based on integral-slot distributed windings (ISDWs). Nevertheless, fractional-slot concentrated windings (FSCWs) have many advantages over ISDWs, such as higher manufacturability using automation, much shorter end-windings [11]. High leakage inductances associated with FSCWs can also be beneficial for limiting short circuit currents and torques [12].

However, traditional three-phase FSCWs have significant harmonics contents in their magnetomotive force (MMF) [13]. These MMF harmonics produce space harmonics in the flux density which then induce excessive eddy current losses in electrically conductive materials in the rotor. Such a drawback is hindering application of this winding type. Multi-layer and stator-shifting winding concepts have been proposed to reduce MMF harmonics of FSCWs by re-distributing the windings in a manipulated way [14]–[17]. These two methods for FSCWs are easy to be implemented in a wind turbine generator, and thus, they have high potentials among the methods dealing with this issue.

Multi-layer and stator-shifting windings have been studied for permanent-magnet machines. Their effects on MMF harmonics and then rotor losses have been evaluated and the results are encouraging [18], [19]. To date, their application to HTS generators have not been studied yet since HTS generators have some unique features and special considerations, for instance, using an electromagnetic shield (EM) and a cryostat wall between the HTS field winding and the stator, as well as limiting AC losses in the HTS field winding.

This paper analyzes one modified 4-layer FSCW and two stator-shifting FSCWs in addition to an original 2-layer FSCW. These windings are designed for a 10-MW, 9.6-rpm DD HTS

Manuscript received September 25, 2019; accepted January 28, 2020. Date of publication February 4, 2020; date of current version March 9, 2020. This work was supported in part by the Natural Science Foundation of Jiangsu Province of China under Grant BK20190486 and in part by the Fundamental Research Funds for the Central Universities under Grant 2018B02114. (Corresponding author: Xiaowei Song.)

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Digital Object Identifier 10.1109/TASC.2020.2971436

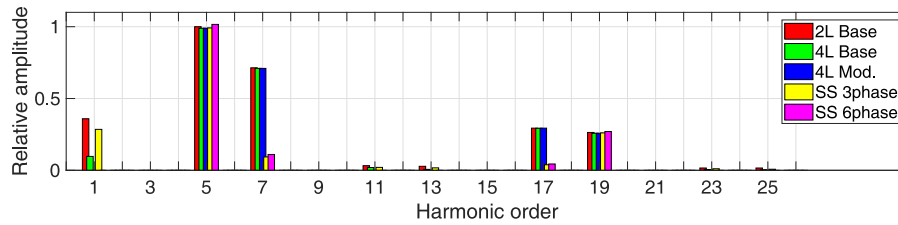


Fig. 3. MMF spectrum of two multi-layer windings and two stator shifting windings. The amplitude is normalized to the two-layer base winding.

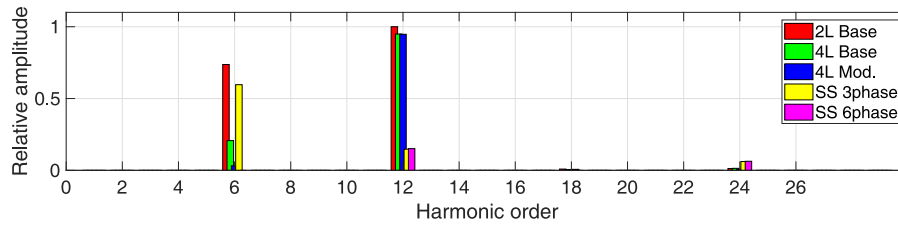


Fig. 4. Spectra of radial flux density at one point of the HTS field winding. The amplitude is normalized to the two-layer base winding.

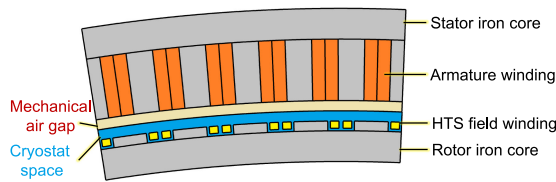


Fig. 5. Sketch of the HTS generator. Five poles are shown which form a half symmetry for finite element analysis.

but working at ambient temperature with conventional copper wires. Iron is used in both the rotor and stator and the rotor poles are salient. The cryostat is cylindrical and placed around the rotor so the distance from the rotor poles to the stator is still large, as depicted in Fig. 5.

The air gap diameter of this HTS generator is 6112 mm. The generator has as many as 80 poles pairs to limit the short circuit torque below three times the rated torque. A lower number of poles will increase the pole pitch and then reduce the flux leakage. A low flux leakage may lead to excessive short circuit currents and torques. The number of slots is 192 for the 2-layer base winding and the 4-layer windings, or 384 for the two stator-shifting windings. The slot height and width are 120 mm and 51 mm, respectively. The cross-sectional dimension of the HTS field coils is 17.1 mm by 14 mm, including a fill factor of 0.7, accommodating 70 turns per pole. The armature current density (RMS) is 2.6 A/mm² to keep affordable copper losses. The engineering current density in the HTS field winding is 122 A/mm², which is about 30% below the critical current density.

An EM shield (copper) is placed next to the cryostat wall (stainless steel). They work together to mitigate the effects of magnetic field harmonics from the stator to the HTS field winding. In other words, they work as a shield to limit the AC loss production in the HTS field winding. Multi-layer insulation is placed next to the HTS field winding as a thermal barrier but this part does not have induced losses [23], [24].

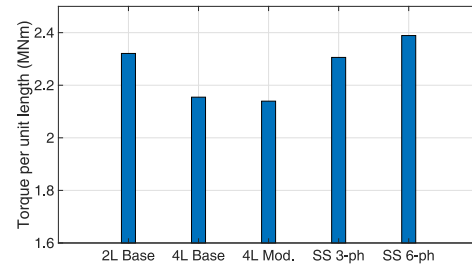


Fig. 6. Comparison of produced electromagnetic torque per unit length.

IV. EFFECTS ON NORMAL OPERATION

The normal operation performance and short circuit torque due to the studied winding schemes are analyzed in this and the next sections. This work is done by calculation and simulation with finite element methods (FEM).

A. Torque Production

Compared with the original 2-layer base winding, the studied multi-layer windings and stator-shifting windings should produce similar EM torque, otherwise their benefits on other performance will not make sense. As shown in Fig. 6, the torque produced per unit length is compared. The 4-layer windings produce lower torques while the 6-phase stator-shifting winding increases the torque production. This result complies with the trend of the 5th harmonic (i.e. the torque-producing harmonic) in Fig. 3. The 6-phase stator-shifting winding produces the highest amplitude of the 5th harmonic.

B. Eddy Current Losses

Since the motivation of this paper is to reduce the induced losses originating from applying FSCWs, it is of utmost importance to check eddy current losses and AC losses in the rotor. The eddy current losses are compared in Fig. 7. The total eddy current loss due to the 4-layer modified winding is almost the same as the 2-layer base winding. This order of losses is

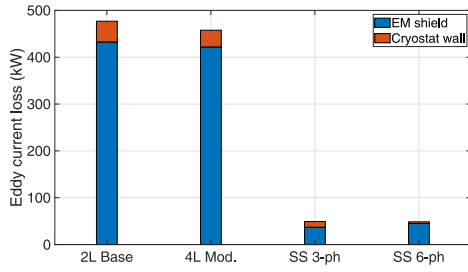


Fig. 7. Comparison of eddy current losses in the EM shield and the cryostat wall.

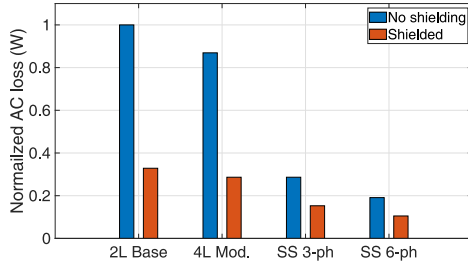


Fig. 8. Comparison of AC losses in the HTS field winding with and without the EM shield.

definitely not accepted in this 10-MW power generation application since the loss considerably lowers the efficiency. Interestingly, both the 3-phase and 6-phase stator-shifting windings reduce the eddy current loss to around 1/10. Then the loss level is only 0.5% of the rated power. Looking back at Fig. 3, this result indicates that reducing the 7th order MMF harmonic is much more effective than reducing the 1st order.

C. AC Losses

The AC loss produced in the HTS winding is calculated with FEM using H-formulation [25], [26]. The value of the calculated AC loss is compared in Fig. 8 with and without the shielding effect by the EM shield and the cryostat wall. All the values have been normalized to the 2-layer base winding without shielding. The shielding effect is stronger with the 2-layer base winding and the 4-layer winding. Seeing from the rotor, the stator-shifting windings effectively reduce the 12th space harmonics while the 4-layer winding affects the 6th, as shown in Fig. 4. The shielding works better at higher frequencies since the shield is not thick enough for mitigating all frequencies of the space harmonics.

With the shielding, compared with the original 2-layer base winding, the AC loss with the 6-phase stator-shifting winding is effectively reduced by 68.0%. This number rises to 80.9% when the shielding is removed. The 3-phase stator shifting winding has a similar result but is not as good as the 6-phase one. The 4-layer modified winding does not significantly reduce the AC loss. The shielding effect works best with the 2-layer base winding but the penalty is the unaccepted eddy current loss in the EM shield and cryostat wall as pointed out in Fig. 7. Adding the AC loss to the eddy current loss shows that the effect of stator-shifting windings on reducing the total induced rotor loss is remarkable.

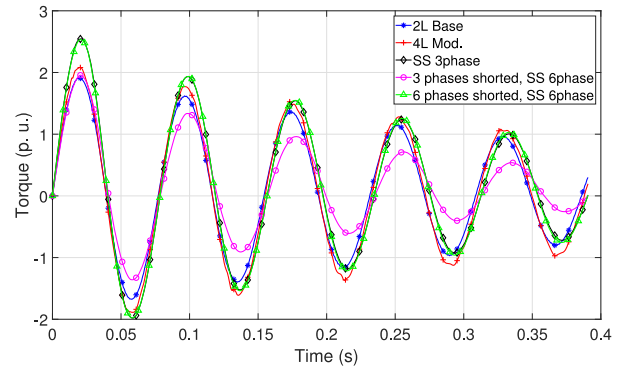


Fig. 9. EM torque waveforms of the studied winding schemes during a three-phase no-load short circuit.

V. EVALUATION OF SHORT CIRCUIT TORQUE

As pointed out in the introduction, FSCWs have the potential to effectively suppress the peak torque when a short circuit occurs at the armature winding terminal. It is important to evaluate the winding schemes studied in this paper to check if they keep this advantage. Three-phase no-load short circuits are modeled and simulated with FEM [27], and the result of torque is plotted in Fig. 9. The original 2-layer base winding gives a torque peak of almost two times the rated torque (2 p.u.), during the short circuit. The 4-layer modified winding slightly increases the peak torque but the torque is still far from 3 p.u. which can still be withstood by a wind turbine. The 3-phase stator shifting winding increases the peak torque to 2.5 times (2.5 p.u.) which is still sufficiently low.

The 6-phase stator-shifting winding has two types of "three-phase" short circuits. One is that both sets of the three balanced phases are shorted. This short circuit is identical to a three-phase short circuit on the 3-phase stator-shifting winding. The other is that only one set of the three balanced phases is shorted. This short circuit produces a peak torque of 2 p.u. and the amplitude of torque decays more than the other studied winding schemes. In general, all the studied windings maintain the same short-circuit torque level under the allowed limit.

VI. CONCLUSION

This paper is motivated by the employment of FSCWs in HTS generators for limiting short circuit torques. For suppressing high space harmonics that accompany FSCWs, two mitigation measures, i.e. multi-layer windings and stator-shifting windings, are investigated.

The findings show that using multi-layer windings slightly reduces torque production, and the effects on reducing induced losses in the rotor are limited. Using stator shifting windings does not reduce torque production, but the effects on reducing induced losses in the rotor are remarkable, especially the 6-phase winding being capable of reducing 90% eddy current losses and 68% AC losses. The evaluated FSCWs produce a short-circuit torque below 3 p.u. that is accepted by mechanical structures in the wind turbine. Such a low short-circuit torque complies with the feature that FSCWs have higher leakage inductances. Moreover, the results show that among the options studied in this paper, the stator-shifting winding with 6 phases is the best choice for applying FSCWs to HTS generators.

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