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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. Tacking 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 mageneto-motive 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

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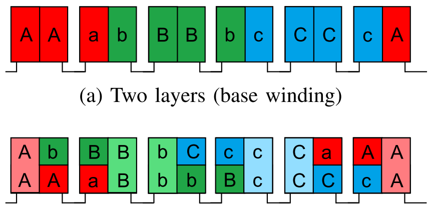
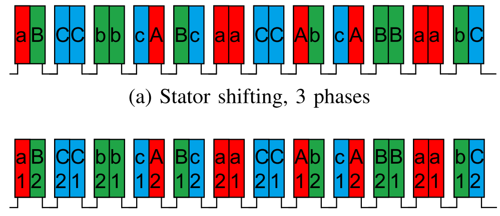


(a) Two layers (base winding)

(b) Four layers

Fig. 1. Distribution of a multi-layer FSCW for 12-slot 10-pole configuration.



(a) Stator shifting, 3 phases

(b) Stator shifting, 6 phases (two sets of three phases)

Fig. 2. Distribution of a stator-shifting FSCW for 12-slot 10-pole windings.

wind turbine generator. The effects of these winding schemes on normal operational performance and short circuit torques are evaluated. In the end, the most feasible option for applying FSCWs to HTS generators is identified.

II. Concept of Multi-Layer and Stator-Shifting FSCWs

A. Multi-Layer Winding

This concept is to split the coils into two sets and shift one set by one or more slots. The same number of slots for a given number of pole pairs remains the same. A multi-layer FSCW configuration is proposed for conventional 12-slot, 10-pole windings as illustrated in Fig. 1(b). This configuration has two forms. The base form is the 4-layer winding that keeps the same number of turns per layer for all the three phases. The modified form manipulates the number of turns in such a way that two layers that belong to the same phase in one slot have $\sqrt{3}$ time the number of turns of the other single layer. As depicted in Fig. 1(b), specifically, if the coil A or b in the first slot has 1 turn, the coil AA (two As are combined) in the same slot has $\sqrt{3}$ turn [18]. This rule also applies to the other phases. The total number of turns per phase of the four-layer windings (both the base and modified forms) should be adapted to be equal to that of the two-layer base winding. Series currents flow in the same phase.

B. Stator-Shifting Winding

This concept is to use two sets of three-phase windings, arrange them with a specific mechanical phase shift. The mechanical phase shift between the two sets of windings is determined by which order of the MMF harmonics needs to be eliminated. To keep identical tooth width, this phase shift may not be optimal so that the targeted harmonics may not be fully eliminated but minimized. For example, for the 12-slot 10-pole winding configuration, two sets of windings double the number of slots (from 12 to 24). Then the optimal phase shift is 77.14° (electrical angle) but the phase shift should be set to 75° to obtain an equal tooth width [17].

Balanced three phase currents flow in either of the sets of windings. There is a phase shift in the current of the same phase between these two sets. If the phase shift is zero, then the two sets are connected in series and the 1st order MMF harmonic may not be eliminated. This winding still has three phases and is thus called a 3-phase stator shifting winding (SS 3 phase). If this phase shift is manipulated properly, the 1st order MMF harmonic can be completely eliminated. For a 12-slot 10-pole winding, this phase shift is 30° for a zero 1st order harmonic. This winding actually has six phases (two sets of three phases) and is thus called a 6-phase stator shifting winding (SS 6phase) [19]. The six phases with a phase shift in the current requires two sets of three-phase power electronic converters in a wind power conversion system.

C. Harmonics Analysis

Based on 12-slot 10-pole configuration, the original 2-layer winding (2 L Base), 4-layer base winding (4 L Base), 4-layer modified winding (4 L Mod.), 3-phase stator-shifting winding and 6-phase stator-shifting winding are compared regarding their MMF harmonics. The spectra of the MMF are shown in Fig. 3. All the amplitudes are normalized to the 2-layer base winding. The torque-producing harmonic for 12-slot 10-pole windings is the 5th order. Orders lower than the 5th are subharmonics and orders higher than the 5th are super-harmonics.

These studied windings have similar amplitudes at the 5th order with small differences. Among the multi-layer windings, the 4-layer base winding already reduces the 1st order while the 4-layer modified winding fully eliminates this order. However, these two multi-layers do not effectively reduce the 7th order which will induce considerably eddy current losses in the rotor. The 11th and 13th orders are almost zero while the 17th and 19th orders are not negligible.

Differently, the two stator-shifting windings effectively reduce the 7th order. The 3-phase winding still has some 1st, 11th and 13th orders while eliminates the 17th and 19th orders. The 6-phase winding with a 30° phase shift in the current fully eliminates the 1st, 11th and 13th harmonics.

Due to the fact that the 1st and 7th orders contribute most to the space harmonics that induce eddy current losses in the rotor, the 6-phase stator-shifting winding should be the most effective winding. This expectation can also be supported by the flux density spectra at the HTS field winding as shown in Fig. 4. Both the 6th and 12th harmonics contribute most to the loss induction in the rotor. The 6th harmonic is almost eliminated by the 4-layer modified winding and fully eliminated by the 6-phase stator-shifting winding. The 12th harmonic is significantly reduced by the two stator-shifting windings but cannot be completely zero.

III. HTS Generator Design

The multi-layer windings and the stator-shifting windings are compared under a same HTS generator. This HTS generator is designed for a 10-MW 9.6-rpm reference DD wind turbine [20]. The generator design has been optimized for the minimum levelized capital cost of energy for this wind turbine [21], [22]. This HTS generator is partially superconducting. The superconducting field winding is made with 2 G HTS wires (GdBCO) operating at 30 K. The armature winding is not superconducting

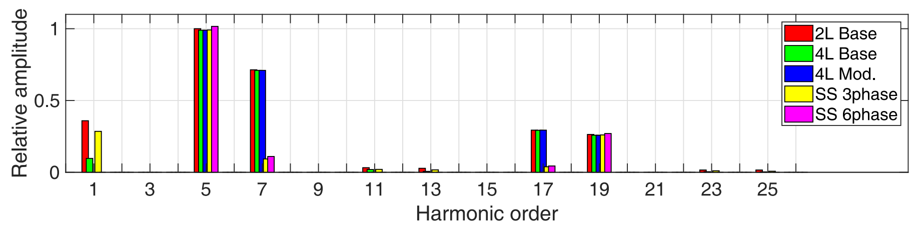


Fig. 3. MMF spectrum of two multi-layer windings and two stator shifting windings. The amplitude is normalized to the two-layer base winding.

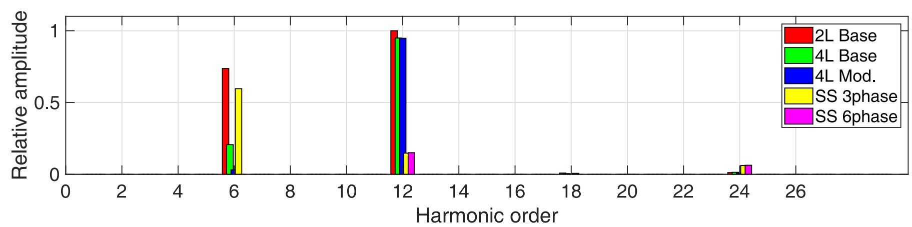


Fig. 4. Spectra of radial flux density at one point of the HTS field winding. The amplitude is normalized to the two-layer base winding.

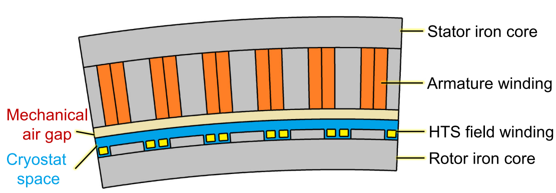


Fig. 5. Sketch of the HTS generator. Five poles are shown which form a half symmetry for finite element analysis.

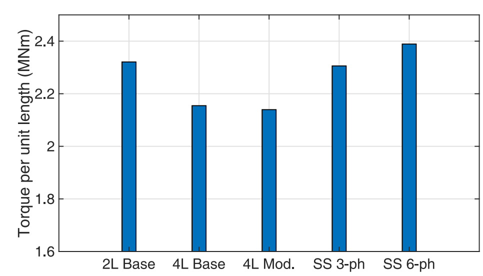


Fig. 6. Comparison of produced electromagnetic torque per unit length.

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/mm^2 to keep affordable copper losses. The engineering current density in the HTS field winding is 122 A/mm^2, 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].

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

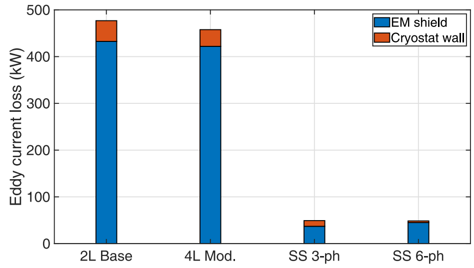


Fig. 7. Comparison of eddy current losses in the EM shield and the cryostat wall.

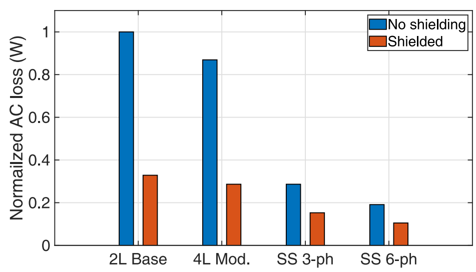


Fig. 8. Comparison of AC losses in the HTS field winding with and without the EM shield.

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 reduces 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.

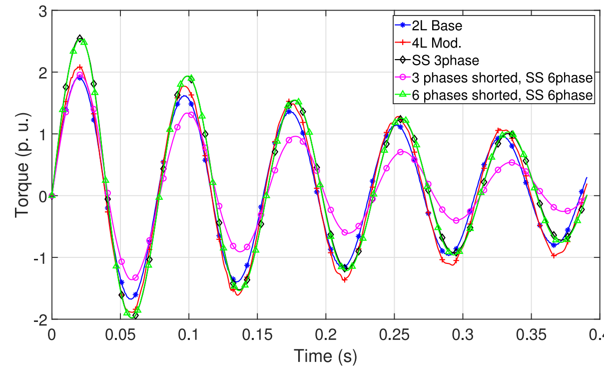


Fig. 9. EM torque waveforms of the studied winding schemes during a three-phase no-load short circuit.

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.

REFERENCES

[1] K. S. Haran *et al.*, "High power density superconducting rotating machines–development status and technology roadmap," *Supercond. Sci. Technol.*, vol. 30, 2017, Art. no. 123002.

[2] B. Maples, M. M. Hand, and W. D. Musial, *Comparative Assessment of Direct Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines*. Golden, CO, USA: National Renewable Energy Laboratory, 2010.

[3] A. B. Abrahamsen *et al.*, "Superconducting wind turbine generators," *Supercond. Sci. Technol.*, vol. 23, 2010, Art. no. 034019.

[4] B. B. Jensen, N. Mijatovic, and A. B. Abrahamsen, "Development of superconducting wind turbine generators," *J. Renewable Sustain. Energy*, vol. 5, 2013, Art. no. 023137.

[5] H. Polinder, J. A. Ferreira, B. B. Jensen, A. B. Abrahamsen, K. Atallah, and R. A. McMahon, "Trends in wind turbine generator systems," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 1, pp. 174–185, Sep. 2013.

[6] X. Li, S. Yu and Y. Wang, "A novel HTS Claw-Pole vernier machine using single excitation unit with stationary seal," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019, Art. no. 5201505.

[7] S. S. Kalsi, *Applications of High Temperature Superconductors to Electric Power Equipment*, 1st ed. Wiley-IEEE Press, Apr. 2011, ch. 4, pp. 83–85.

[8] Y. Liu, R. Qu, Z. Zhu, J. Wang, and H. Fang, "Analysis on the performances of a rotor screen for a 12 MW superconducting direct-drive wind generator," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 5, Oct. 2014, Art. no. 5202505.

[9] Y. Liu, R. Qu, J. Wang, H. Fang, X. Zhang, and H. Chen, "Influence of generator parameters on fault current and torque in a large-scale superconducting wind generator," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 4, Dec. 2015, Art. no. 5204309.

[10] D. Liu, H. Polinder, A. B. Abrahamsen and J. A. Ferreira, " Effects of armature winding segmentation with multiple converters on the short circuit torque of 10-MW superconducting wind turbine generators," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 5200305.

[11] J. Pyrhonen, T. Jokinen, and V. Hrabovcova, *Design of Rotating Electrical Machines*. New York, NY, USA: Wiley, 2009.

[12] H. Vu Xuan, "Modeling of exterior rotor permanent magnet machines with concentrated windings," Dissertation, Faculty Elect. Eng., Math. Comput. Sci., Delft Univ. Technol., 2012.

[13] A. Jassal, H. Polinder and J. A. Ferreira, "Literature survey of eddy-current loss analysis in rotating electrical machines," *IET Electric Power Appl.*, vol. 6, no. 9, pp. 743–752, Nov. 2012.

[14] X. Chen and J. Wang, "Magnetomotive force harmonic reduction techniques for fractional-slot non-overlapping winding configurations in permanent-magnet synchronous machines," *Chin. J. Elect. Eng.*, vol. 3, no. 2, pp. 102–113, Sep. 2017.

[15] M. V. Cistelecan, F. J. T. E. Ferreira, and M. Popescu, "Three phase tooth-concentrated multiple-layer fractional windings with low space harmonic content," in *Proc. IEEE Energy Convers. Congr. Expo.*, Atlanta, GA, USA, 2010, pp. 1399–1405.

[16] L. Alberti and N. Bianchi, "Theory and design of fractional-slot multilayer windings," *IEEE Trans. Ind. Appl.*, vol. 49, no. 2, pp. 841–849, Mar./Apr. 2013.

[17] P. B. Reddy, K. Huh, and A. M. EL-Refaie, "Generalized approach of stator shifting in interior permanent-magnet machines equipped with fractional-slot concentrated windings," *IEEE Ind. Electron.*, vol. 61, no. 9, pp. 5035–5046, Sep. 2014.

[18] A. Sun, J. Li, R. Qu, and D. Li, "Effect of multilayer windings on rotor losses of interior permanent magnet generator with fractional-slot concentrated-windings," *IEEE Trans. Magn.*, vol. 50, no. 11, Nov. 2014, Art. no. 8105404.

[19] A. S. Abdel-Khalik, S. Ahmed, and A. M. Massoud, "A six-phase 24-slot/10-pole permanent-magnet machine with low space harmonics for electric vehicle applications," *IEEE Trans. Magn.*, vol. 52, no. 6, Jun. 2016, Art. no. 8700110.

[20] P. Chaviaropoulos and A. Natarajan, "Deliverable D1.2.2: Definition of performance indicators (PIs) and target values," Oct. 2018. [Online]. Available: http://www.innwind.eu/publications/deliverable-reports/

[21] D. Liu *et al.*, "Comparison of superconducting generator topologies for a 10 MW wind turbine applications," *Int. J. Appl. Electromag. Mech.*, vol. 53, no. S2, pp. S191–S202, 2017.

[22] D. Liu, H. Polinder, A. B. Abrahamsen, and J. A. Ferreira, " Topology comparison of superconducting generators for 10-MW direct-drive wind turbines: Cost of energy based," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 5202007.

[23] X. Song *et al.*, "Designing and basic experimental validation of the world's first MW-class direct-drive superconducting wind turbine generator," *IEEE Trans. Energy Convers.*, vol. 34, no. 4, pp. 2218–2225, Dec. 2019.

[24] X. Song *et al.*, "Experimental validation of a full-size pole pair set-up of an MW-class direct drive superconducting wind turbine generator," *IEEE Trans. Energy Convers.*, early access, Dec. 2019, doi: 10.1109/TEC.2019.2958613.

[25] X. Song, N. Mijatovic, S. Zou, B. B. Jensen, and J. Holbll, "AC losses and their thermal effect in high-temperature superconducting machines," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 5900105.

[26] V. M. Zermeno, A. B. Abrahamsen, N. Mijatovic, B. B. Jensen, and M. P. Sørensen, "Calculation of alternating current losses in stacks and coils made of second generation high temperature superconducting tapes for large scale applications," *J. Appl. Phys.*, vol. 114, no. 17, 2013.

[27] X. Song, D. Liu, H. Polinder, N. Mijatovic, J. Holbll, and B. B. Jensen, "Short circuit of a 10-MW high-temperature superconducting wind turbine generator," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 5201505.