Design challenges of direct-drive permanent magnet superconducting wind turbine generators

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Design Challenges of Direct-Drive Permanent Magnet Superconducting Wind Turbine Generators

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***Abstract*—In recent years, permanent magnet superconducting (PMSC) generators have become a candidate for applying superconducting (SC) generators in large direct-drive wind turbines. This configuration keeps the SC armature winding and its cooling system stationary and eliminates rotational cooling couplings. However, the low excitation by permanent magnets may lead to poor power factors if the armature current is high. Furthermore, the permanent magnets are prone to demagnetization when the armature reaction is strong. This paper investigates the design challenges regarding the power factor, demagnetization and short circuit characteristics by analyzing two PMSC generator designs. The results show that the power factor cannot be as high as 0.9 and a low power factor such as 0.6 can take advantage of the high current carrying capability of the SC armature winding. However, this low power factor will cause demagnetization. The armature current may cause quenching of the SC wires during a three-phase short circuit. Demagnetization of the permanent magnets during the short circuit is strong and could be an intrinsic weakness of a PMSC generator.**

***Index Terms*—Demagnetization, permanent magnet, MgB_2, short circuit, superconducting generator, wind turbine**

I. Introduction

Superconducting (SC) generators have been proposed for large direct-drive offshore wind turbines for years. They can be much more compact and lighter than conventional permanent magnet (PM) counterparts [1]–[4]. At present, partially SC generators (P-SCGs) are more feasible than fully SC generators (F-SCGs) due to critical AC loss problems with implementing armature SC winding [5]. As synchronous machines, conventionally, P-SCGs have a rotating SC field winding and a stationary copper armature winding. The SC field winding is enclosed in a cryostat working at a low temperature. The rotation of the SC winding and its cryostat requires rotation coupling for the cryogenic cooling system. Such rotation coupling is complicated and reduces reliability of the cooling system due to cooling leakage. One way to avoid the rotating cooling system is to rotate the copper armature winding at an ambient temperature while keeping the cold field winding stationary. This reversal requires the brushes and slip rings of the armature winding to withstand full power of the generator, bringing a new reliability challenge to these rotating coupling elements.

In recent years, a new concept, namely permanent magnet superconducting (PMSC) generators, has been presented to avoid the rotational cooling coupling [6]–[8]. This concept uses PMs on the rotor as the field excitation while uses an SC winding on the stator as the armature winding. This concept keeps the SC winding and its cooling system stationary and lets the PMs rotate as used in a conventional PM machine. High currents can flow in the SC armature winding and boost the electrical loading of the generator. As shown in the research [8]. therefore, a 10 MW wind turbine generator could be made relatively small with a diameter of 5 m and an axial stack length of 2 m.. However, the same research in [8] also showed the generator had very low power factors (PFs), about 0.6, resulted from the achieved high electrical loading. Such low power factors will significantly increase the capacity of the back-to-back full power electronic converter. The resulted increasing cost can cancel the benefit of apply SC armature winding to reduce the size and weight of the generator. In addition, the PMs were prone to demagnetization due to the high armature reaction.

It is obvious that this concept has a few critical design challenges. Certainly, the AC loss problem still remains with this concept since the SC winding works in an alternating-current and -field environment. This paper ignores the AC loss problem and mainly analyzes the design challenges with the power factor and demagnetization. The AC loss problem will be worth studying after the power factor is sufficiently high and the demagnetization of PMs is avoided.

This paper studies both the normal operation and short-circuit characteristic. The normal operation study looks at the operating current of the SC winding, the shear stress of the generator and the demagnetization with respect to the power factor. The short-circuit study looks at the torque, current and demagnetization.

II. Concept of PMSC Generators

PMSC generators have the PMs (excitation) on the rotor work at ambient temperature and the SC winding (armature) on the stator works at a cryogenic temperature. For a low AC loss, multi-filamentary MgB_2 wires are used for the SC winding. The more the filaments, the lower the AC loss. The

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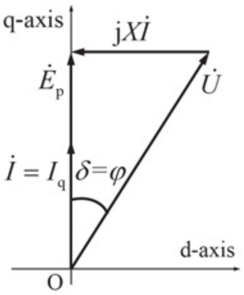


Fig. 1: Phasor diagram of zero direct-axis current control. The phase resistance is zero. E_p is the EMF, U is the phase voltage, I is the phase current, X is the synchronous reactance, δ is the power angle and ϕ is the power factor angle.

cryogenic temperature should be set to 10-30 K since the critical temperature of MgB_2 is only 39 K. Round wires are preferred to tape wires due to isotropy and the capacity of a large number of filaments.

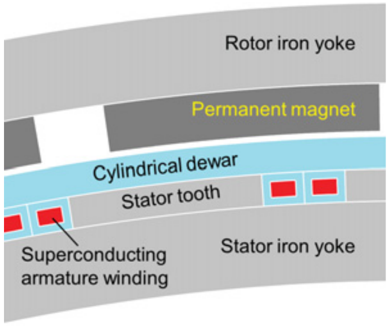
The stator with the SC armature winding can be interior or exterior to the permanent-magnet rotor. An interior stator is preferred since the cryostat can be a simple cylindrical dewar enclosing the whole stator. If multiple modular cryostats are used instead of one cylindrical dewar, the difference between interior and exterior layouts will be negligible except that the exterior rotor has a slightly larger diameter and thus a higher torque production.

The cooling system for the SC armature winding is stationary both inside and outside of the cryostat. A rotation coupling is thus eliminated. However, the cryostat wall enlarges the magnetic air gap if a cylindrical dewar is used. The large magnetic air gap increases flux leakage from the PMs to the armature, reduces the synchronous inductance, increases the short-circuit torque but reduces the risk of demagnetization of the PMs and reduces the field harmonics from the stator to the rotor.

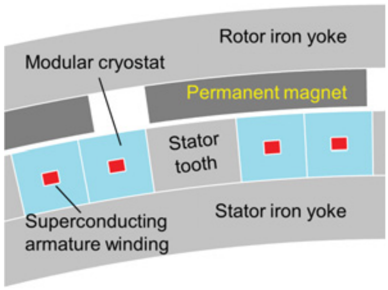
The permanent-magnet rotor has no saliency because surface-mounted PMs are used. Thus, a simple zero direct-axis current control can be applied, i.e. $I_d = 0$, as shown in Fig. 1. The angle between the electro-motive force (MMF) and the phase voltage is not only the power angle but also the power factor angle. A higher current will increase the phase voltage as well as the power factor angle. For a reasonable power factor, thus, the current cannot be increased as much as the SC winding allows.

SC wires have minimum bending diameters. Bending or twisting the end winding as seen in a double-layer distributed winding can damage the SC wire. Thus, the SC armature winding must be a fractional-slot concentrated winding, i.e. a tooth-coil winding, in which the bending of the end wire is simple and much safer for the SC wire.

Fractional-slot windings produce high field harmonics and cause eddy current losses in the PMs. A cylindrical dewar, which increases the magnetic air gap, can reduce the eddy current loss in the PMs. In addition, the PM can be segmented to cut off the path of eddy currents so that the eddy current loss can be significantly reduced.



(a) Design A



(b) Design B

Fig. 2: Sketch of the PMSC generator designs.

III. Base Design of a 10 MW PMSC Generator

According to the concept of PMSC generators, a 10 MW PMSC generator can preliminarily be designed for the study purpose of this paper. This generator is designed for a 10 MW direct-drive wind turbine. The rated speed is 9.6 rpm and the rated voltage (line to line) is 3300 V. Two generators are designed. One is with a cylindrical dewar (Design A) and the other is with modular cryostats (Design B) for the SC armature winding [9], as illustrated in Fig. 2. The cryogenic temperature has been set to 20 K to leave sufficient margin to the critical temperature while the balance between the wire cost and the cooling cost is well achieved.

A. Topology Selection

The generator has an iron stator and rotor cores. Since the remanence of the PMs is about 1.25 T, iron cores are still applied to keep a high excited air gap field [10]. The higher the excitation field, the smaller the power factor angle.

The stator is interior to allow both a cylindrical dewar and modular cryostats. The inner radius of the generator, i.e. the bore radius of the rotor, is set to 2.5 m for accommodating support structures for the stator.

B. Permanent magnets

The PMs are NdFeB magnets and the grade is N38H. Its remanence flux density is 1.25 T. The flux density at which irreversible demagnetization occurs is 0.25 T. This grade is a good balance between performance and price. The PMs are mounted on the surface of the rotor iron core. The height of the magnets is 60 mm and the pole embrace is 0.8.

C. Superconducting wires

The SC winding is made from MgB_2 wires. The used HyperTech wires are round wires with many filaments. The wire with 36 filaments is chosen for low AC losses. The wire diameter is 0.83 mm [11]. The minimum bending diameter is estimated as 100 mm.

D. Armature winding arrangement

The armature winding is a fractional-slot concentrated winding. The number of slots per pole per phase is chosen as $q = 0.4$. This slot-pole combination is most used in concentrated winding designs and results in low torque ripples [12], [13]. Further investigation may compare different slot-pole combinations in future.

E. Dimensioning

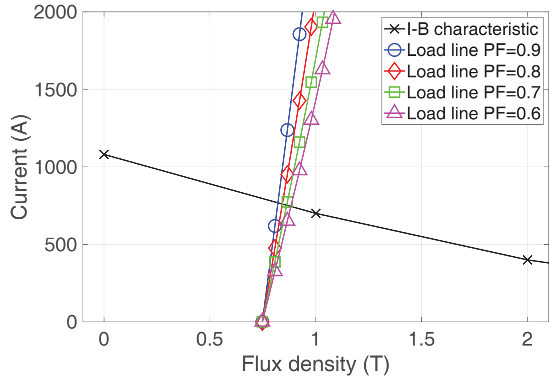
1) With a cylindrical dewar (Design A): The magnetic air gap between the PMs and the armature winding contains two parts. The mechanical air gap length is 6 mm which about 1/1000 of the diameter. The cryostat wall, vacuum layer and multi-layer thermal insulation constitute the other part, which is about 40 mm thick. In total, the magnetic air gap is as large as 46 mm, which is far larger than that of a conventional PM machine. The pole pitch should thus be sufficiently large to minimize the flux leakage from the PMs to the armature winding. It is assumed that a pole pitch larger than about 10 times the magnetic air gap is sufficient. This requirement together with the number of q results in a number of pole pairs to be 40 and the resulted pole pitch is 426 mm.

Due to the small cross-sectional area of one MgB_2 wire, the slot of the stator can be made small too, and the slot height does not have to be large. A sweeping shows that the ratio of slot to slot pitch is 0.3 for the highest torque production and the slot height is 40 mm for a balance between the stator iron mass and the torque production. The tooth width is sufficiently large for the minimum bending radius of the MgB_2 wire.

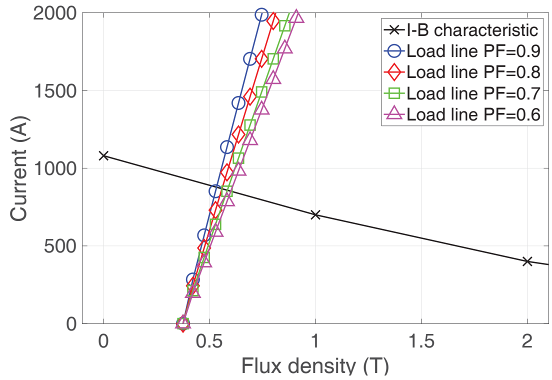
2) With modular cryostats (Design B): In this case, the magnetic air gap is merely the mechanical air gap, which is 6 mm large. However, the slot size must be sufficiently large to accommodate the modular cryostat. This requirement together with the number of q results in a number of pole pairs to be 20. The ratio of slot to slot pitch should be increased to 0.6 for placing modular cryostats while keeping a reasonably wide stator tooth. The tooth width is sufficiently large for the minimum bending radius of the MgB_2 wire.

IV. Determination of the Armature Current

According to the zero direct-axis current control, the phase current is in phase with the EMF. The change of the phase current varies the angle between the phase current and phase voltage and thus the power factor. Since the rated line-to-line voltage is fixed to 3300 V, varying the phase current will change the power factor or the required power determines the phase current.



(a) Design A



(b) Design B

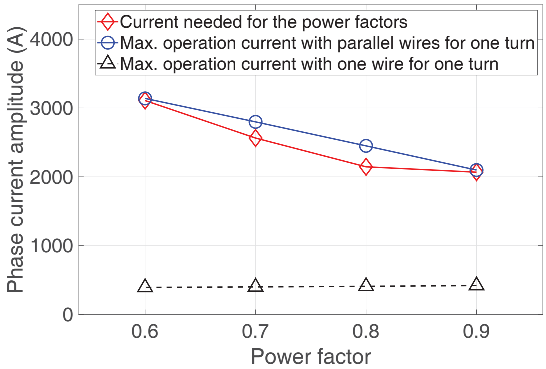
Fig. 3: Critical characteristic and load lines of the MgB_2 wire and determination of the critical currents.

Four power factors, i.e. 0.6, 0.7, 0.8, 0.9, are selected to determine the armature current. Meanwhile, higher armature currents may demagnetize the PMs and therefore demagnetization must be examined. Most importantly, however, the current must not exceed the critical current of the used MgB_2 wire.

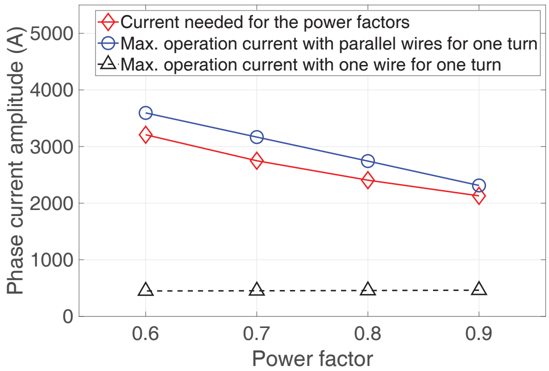
A. Based on I-B characteristics

The selected HyperTech MgB_2 wire has a critical characteristics shown by the black curve with crosses in Fig. 3. The critical characteristic is the relationship between the maximum magnetic flux density in a wire and the maximum allowed current flowing in the wire to remain superconducting.

The load lines of the MgB_2 wires at the four power factors are also plotted in Fig. 3. The currents of the intersections are critical currents. Practically, a safety margin of 0.25 is set for the current and thus the maximum operation currents are 75% of the corresponding critical currents. Different power factors do not significantly change the critical currents and

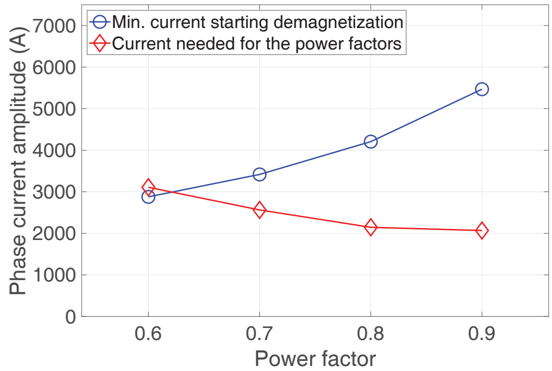


(a) Design A

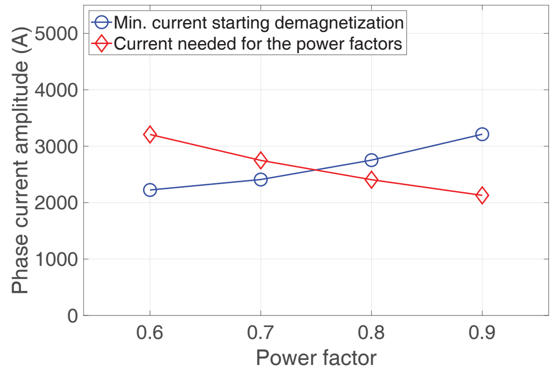


(b) Design B

Fig. 4: Currents needed for the four power factors and the maximum operation currents in the MgB_2 wires.



(a) Design A



(b) Design B

Fig. 5: Currents needed for the four power factors and minimum currents that start demagnetizatio of the permanent magnets.

the operation currents. The higher power factor increases the operation current a little bit. Besides, the operation currents for Design B are a slightly higher than those for Design A.

B. *Based on power factors*

The phase current must be right to achieve the power factors while maintaining the rated line-to-line voltage of 3300 V. The red curve with diamonds in Fig. 4 shows the phase currents needed to lead to the four power factors. As expected, higher power factors need lower currents.

The maximum operation currents (RMS) in the MgB_2 wire are also shown on the black dashed lines with triangles. It is apparent that the needed phase currents are much higher than the maximum operation currents. One solution is to use multiple MgB_2 wires in parallel to form one turn so that the phase currents do not exceed the maximum operation currents. It is assumed here that the critical current of the MgB_2 wire does not change by stranding multiple MgB_2 wires in parallel.

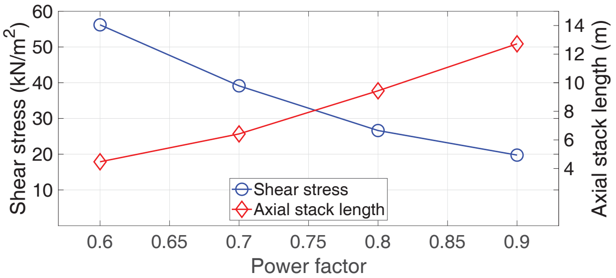
As a result, the numbers of parallel MgB_2 wires for one turn are 5, 6, 7 and 8, respectively for $PF = 0.9$, 0.8, 0.7 and 0.6, for Design A. These numbers do not change for Design B. More wires in one turn will make the winding manufacturing much more difficult but the AC loss can be reduced if these parallel wires are appropriately arranged.

C. *Based on avoiding demagnetization*

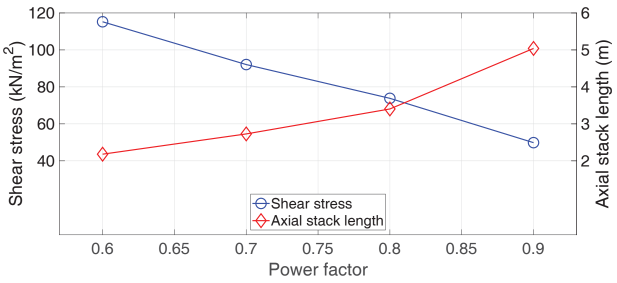
A high current causes strong armature reaction which may irreversibly demagnetize the PMs on the rotor surface. The minimum currents that cause demagnetization with the four power factors are shown in Fig. 5 for Design A and Design B. The higher power factors leave larger margins between the phase current and the minimum demagnetizing current. For Design A, only the current with $PF = 0.6$ causes a bit demagnetization. For Design B, both the currents with $PF = 0.6$ and $PF = 0.7$ cause demagnetization. The current with $PF = 0.75$ is roughly the divide.

V. Shear Stresses

As implied above, a higher power factor requires a lower current and makes the PM farther from demagnetization. However, the lower current for the high power factor takes no advantage of the SC winding which is supposed to carry high currents. In Fig. 6, thus, the shear stresses of the generator designs are compared with the four power factors, equivalently, the four phase currents. The power factor of 0.9 leads to a shear stress of 20 kN/m^2 for the generator design with a cylindrical dewar and a shear stress of 48 kN/m^2 for the generator design with modular cryostats. The former shear stress is much lower than that of a conventional PM



(a) Design A



(b) Design B

Fig. 6: Shear stresses and resulting axial stack lengths at the four power factors.

generator (about 60 kN/^{2} with forced air cooling). The latter shear stress is closer to that of a conventional PM generator but still a bit lower. The advantage of applying SC windings does not appear.

For Design A, even reducing the power factor to 0.6 cannot reach a high shear stress (still lower than 60 kN/m^2). For Design B, reducing the power factor to 0.7 will reach a shear stress higher than 90 kN/m^2. However, this shear stress can also be obtained in a conventional PM generator when water or oil cooling is used for the copper armature winding. Paying much more for the SC winding and its cooling system will not benefit. The power factor can further be reduced to 0.6 for Design B and a shear stress close to 120 kN/m^2 can be obtained. Now the SC winding show its benefit since the needed current for $PF = 0.6$ has already been very high (over 3000 A). Such a low power factor will need a power electronic converter of which the capacity (i.e. apparent power) is 50% larger than the converter for $PF = 0.9$. The cost of the converter will partly cancel the benefit of small size and low weight of the generator.

The reason for this low shear stress with a high power factor is that the main field excited by the PMs is low. A high armature current can increase the shear stress but meanwhile enlarges the angle between the EMF and the phase voltage. The power factor will thus become low. The resulted axial stack lengths of the generator designs are also shown in Fig. 6. In line with the shear stress, the stack lengths of Design A are all larger than 4 m with the four power factors. The stack length is even as large as 12 m with $PF = 0.9$. The stack lengths of Design B become lower. The power factor of 0.6 can achieve almost 2 m which the power factor of 0.9 leads to over 5 m. Note that $PF = 0.6$ causes demagnetization for Design B so it may not be a correct choice even if the capacity of the converter is not a problem.

VI. Challenges from Short Circuits

Short circuits at the generator terminal lead to high currents and torques. The high currents may cause demagnetization of the PMs. A high current in SC wires that exceed the critical current will cause quench which means the SC wires leaves its SC state. Both no-load and full-load three-phase short circuits at the generator terminal are modeled with finite element methods and field-circuit coupling methods as used in [14]. The results examine the characteristics of the current, torque and demagnetization.

The resistance of the SC armature winding is assumed to be 0.02 Ω considering the joint parts which are not superconducting. The rotational speed of the generator is assumed to be constant during the short circuit. The short circuit occurs when the voltage of phase A reaches to zero.

A. *Short-Circuit Current*

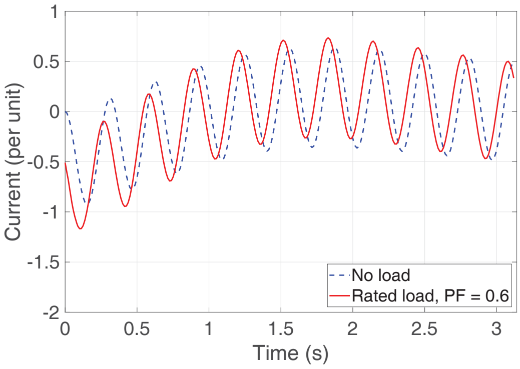
The currents of phase A are plotted in Fig. 7 for the no-load and full-load short circuits. The power factor is selected to be 0.6 for Design A and 0.8 for Design B, considering the effects of power factor on demagnetization discussed in Section IV-C. The base current for the per unit value is the amplitude of the rated phase current. The peak current is slightly over 1 p.u. for Design A and almost 2 p.u. for Design B. The SC armature winding of Design B is more prone to quenching. The current for the rated load short circuit is slightly larger than that for the no load short circuit at the beginning of the short circuit. When the steady state is reached, the difference is quite small.

B. *Short-Circuit Torque*

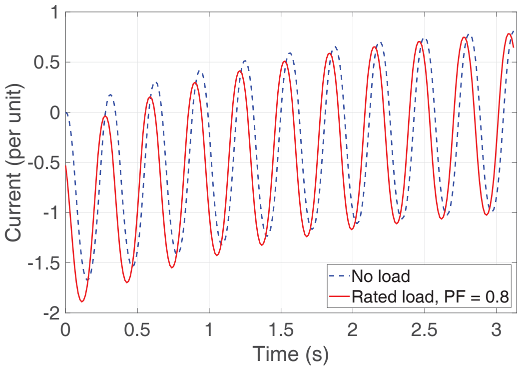
Design A has a large magnetic air gap which may cause high torque during a short circuit. However, the fractional-slot concentrated winding has large leakage inductances which limit the current and then the torque. As a combine result, the peak torque is slightly higher than the rated torque when a full-load short circuit occurs, as shown in Fig. 8. Therefore, Design A and Design B do not challenge the mechanical constructions of the wind turbine during a short circuit.

C. *Demagnetization*

As shown in Section VI-A, the current may exceed the amplitude of the rated current. Such high currents may cause demagnetization of the PMs. The radial flux density of the PMs is examined to check if it becomes lower than 0.25 T when the current of phase A reaches its peak. The results are plotted in Figs. 9 and 10 for Design A and Design B, respectively. Demagnetization in two magnets can be observed. The demagnetization in the full-load short circuit is more severe than that in the no-load case. Design B suffers more demagnetization than Design A. To avoid demagnetization,

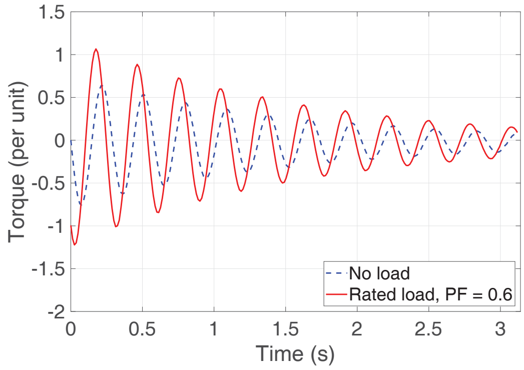


(a) Design A

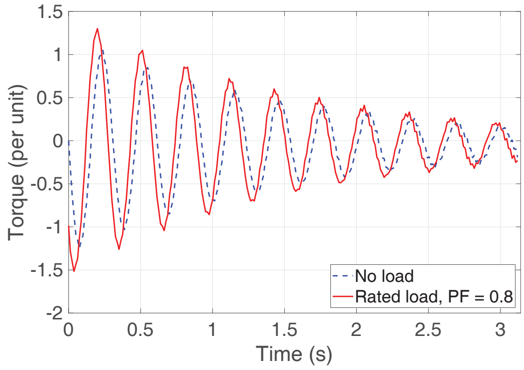


(b) Design B

Fig. 7: Currents of phase A during the three-phase short circuits.



(a) Design A



(b) Design B

Fig. 8: Torques of phase A during the three-phase short circuits.

the PMs can be made higher in the magnetizing direction. However, the PMs in Design A and Design B are already 60 mm high. Increasing the height will increase both the cost and the manufacturing difficulty of the PMs. Combining the results of Fig. 5, the PMSC generators are prone to demagnetization when the armature current becomes high.

VII. Conclusions

This paper uses two PMSC generator designs to analyze the design challenges of PMSC generator regarding the power factor issue, shear stress, demagnetization and short circuit characteristics. The conclusions are listed as follows:

- The power factor cannot be as high as 0.8 or 0.9 due to low shear stresses and demagnetization of PMs. The power factor of 0.6 takes advantage of applying the SC armature winding to obtain a high current. However, this low power factor requires a large capacity of the power electronic converter (50% larger than the converter for $PF = 0.9$) and causes demagnetization.

- The PMSC generator with a cylindrical dewar is not feasible due to its poor shear stress. The PMSC generator with modular cryostats can reach a high shear stress only with the low power factor of 0.6.

- The short circuit current is higher than the rated current and may cause quench of the SC wires. The short circuit torque is not problematic since the fractional-slot winding has a large leakage inductance and limits the current and torque. The demagnetization during the short circuit is strong and could be an intrinsic weakness of a PMSC generator.

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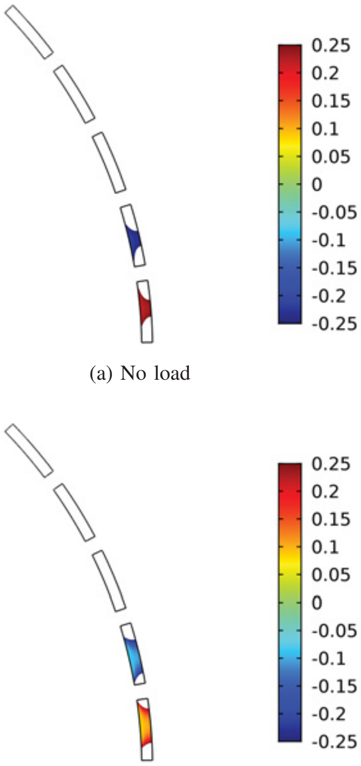
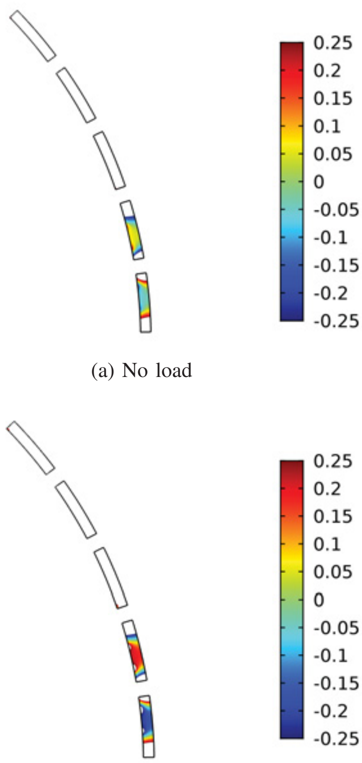


(a) No load

(b) Full load with $PF = 0.6$

Fig. 9: Demagnetization indicated by flux densities lower than 0.25 T when the current in phase A is maximum, Design A, $PF = 0.6$.



(a) No load

(b) Full load with $PF = 0.8$

Fig. 10: Demagnetization indicated by flux densities lower than 0.25 T when the current in phase A is maximum, Design B, $PF = 0.8$.

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VIII. Biographies

Dong Liu received his bachelor degree from Harbin Institute of Technology, Harbin, China, in 2007. He received his MSc. degree and Ph.D degree from Delft University of Technology, Delft, the Netherlands, in 2012 and 2017, respectively. From 2017 to 2018, he was an electrical machine& power conversion engineer at XEMC Darwind BV, Hilversum, the Netherlands. Since 2018, he has been an associate professor at Hohai University, Nanjing, China. His research interests are design of novel electrical machines for renewable energy and superconducting machines.

Xiaowei Song received the BSc. degree from Jilin University, Changchun, China, in 2007, and the MSc. degree from the Institute of Electrical Engineering (IEE), Chinese Academy of Sciences (CAS), Beijing, China, in 2010. He got his Ph.D. degree in electrical engineering from the Technical University of Denmark in Jun. 2017. From 2010 to 2013, he was an Electrical Engineer with the R&D Center of Dongfang Electric Corporation Ltd., Chengdu, China. From 2017 to 2019, he was a specialist on superconducting machines with Envision Energy Global Innovation Centre in Silkeborg, Denmark. Since Aug. 2019, he has been a Lead Engineer of wind turbine generators in Vestas Wind Systems A/S, Aarhus, Denmark. His research centers on superconducting and permanent magnet electric machines for wind power applications.

Xuezhou Wang Xuezhou Wang received the B.Sc. and M.Sc. degree in Electrical Engineering from Northwestern Polytechnical University, Xi’an, China, in 2010 and 2013, respectively, and the Ph.D. degree also in Electrical Engineering from Delft University of Technology, Delft, The Netherlands, in 2017. Afterwards, he worked as a senior electromagnetic engineer at Envision Energy in Shanghai until 2020. He is now working as a postdoc researcher in the field of hybrid drivetrain systems for ship applications in TU Delft. His current research interests include modeling and design of electrical machines, novel generators for wind turbines and transportation electrification.