Comparative analysis of electromagnetic performance of PM and HTS excited flux switching machines

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***Abstract*— The ongoing expansion of offshore wind energy generation demands significant advancements in wind turbine generator technologies, especially in the development of ultra-high-power systems beyond 10 MW. Traditional doubly-fed induction generators (DFIGs) have shown inherent limitations in offshore applications, primarily due to gearbox reliability issues under harsh marine conditions. However, scaling up low-speed direct-drive permanent magnet (PM) machines necessitates large quantities of rare earth (RE) materials. For RE materials the supply is limited and geopolitically sensitive. High temperature superconducting (HTS) machines present an alternative pathway, offering extremely high-power density and reduced material dependency. Nonetheless, classical HTS machines with rotor-mounted superconducting excitation suffer from technical and economic challenges related to the cryogenic cooling and insulation of rotating parts. A promising solution for the required technology jump in the field of offshore wind energy generation is the development of flux-switching machines (FSM) employing stator-based superconducting excitation. This paper addresses preliminary assessment of electromagnetic performance of HTS excited FSM by comparison to a reference PMFSM.**

Keywords — HTS, offshore wind energy generation, flux switching machine, high-power.

I. Introduction

The global demand for renewable energy has led to accelerated deployment of offshore wind farms, where wind conditions are more favourable for large-scale power generation. As wind turbines grow in size and capacity, conventional drivetrain systems - particularly those based on DFIGs - face increasing technical and operational challenges. The DFIG architecture, reliant on gearboxes for speed conversion, suffers from reliability issues in offshore environments due to high mechanical stress and limited accessibility for maintenance. As documented by [1], [2] gearbox failures contribute substantially to turbine downtime and operation costs, motivating a shift towards direct-drive generator systems that remove the gearbox entirely [1], [2].

Direct-drive wind turbines operate at low rotational speeds and require generators with large torque capabilities. Permanent magnet synchronous generators (PMSGs) are often favoured for their high efficiency and compactness; however, their reliance on RE materials such as neodymium and dysprosium pose a significant sustainability challenge. The limited availability, fluctuating market prices, and geopolitical concentration of RE sources raise concerns about long-term supply security and cost stability [3], [4]. Consequently, there is growing research interest in alternative excitation technologies that can mitigate these risks.

High temperature superconducting materials, such as YBCO tapes, have emerged as a transformative solution, enabling generators with high torque density and compact size. What is even more important to highlight is that the annual global Yttrium production capacity allows to build wind power generators of up to three orders of magnitude higher installed power than for PMSGs exploiting annual global Neodymium resources. This value is derived from statistical data and typical material consumption analysis.

Traditional HTS machine architectures utilize superconducting windings in the rotor to provide DC excitation. While promising, these machines face critical barriers to commercialization, including the complexity of cooling and thermal insulation for rotating cryogenic components, mechanical reliability, and high cost of cryocoolers and HTS materials [5], [6].

To overcome these limitations, researchers have proposed flux-switching machines with stator-mounted superconducting excitation. This topology places the cryogenic system on the stationary part of the machine, simplifying thermal management and enhancing system reliability, thus reducing technological risks. Moreover, conducted research on electromechanical behaviour of the HTS tapes under cyclic stress [7] allow to predict long term behaviour of HTS coils under real operation conductions.

Such innovations represent a promising direction for the development of ultra-high-power direct-drive wind turbine generators.

II. PM And HTS Excited Reference FS Machines

A. PM FSM

The reference design of a 3MW low speed PMFSM has been adopted from [8]. In order to study the electromagnetic performance of the discussed machine, a finite element analysis (FEA) are performed assuming planar symmetry of the machine. The nonlinearity of the core has been considered. The geometry of the machine is shown in Fig. 1, due to symmetry of the magnetic circuit geometry is reduced to 1/8 of the machine circumference. Main parameters of the machine are summarized in Table 1.

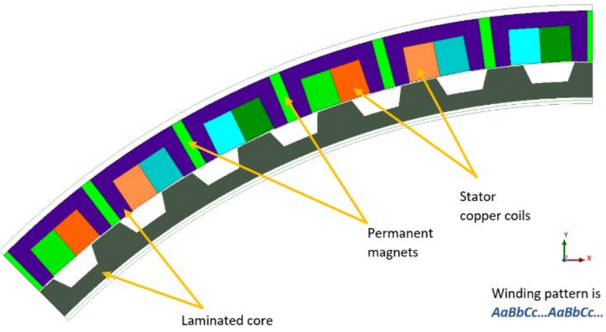

Fig. 1. Geometry of the PMFSM (reduced to 1/8 due to symmetry)

TABLE I. MAJOR PARAMETERS OF THE REFERENCE PMFSM [8]

Parameter	Unit	Value
Rated power	MW	3.0
Rated speed	rpm	15
Outer diameter	mm	5320
Inner diameter	mm	4770
Air-gap	mm	5.0
Number of stator slots	[-]	48
Number of rotor teeth	[-]	56
Permanent magnet size	mm/mm	35/160
Length of active part l_{fe}	mm	1900

B. *HTS FSM*

The geometry of the HTS excited flux switching machine is shown in Fig. 2. The overall dimensions – inner, outer diameters, core as well as airgap lengths number of slots and teeth are the same as for reference PMFSM. The HTS coils are assumed to have double pancake topology.

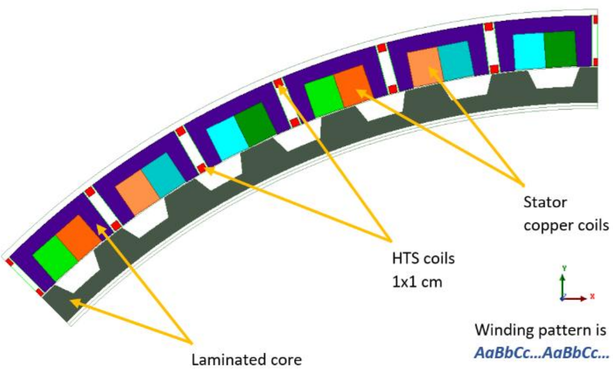

Fig. 2. Geometry of the HTSFSM (reduced to 1/8 due to symmetry)

III. RESULTS

The transient FEA has been performed in order to compare flux linkage, cogging torque as well as electromagnetic torque vs. current angle performance. The current density in the stator standard main AC winding has been the same for PM and HTS excited FSM. The HTS coil current I_{HTS} has been determined in order to obtain comparable flux density distribution in the air-gap of the machine. Presented results are determined for I_{HTS} = 50 kA.

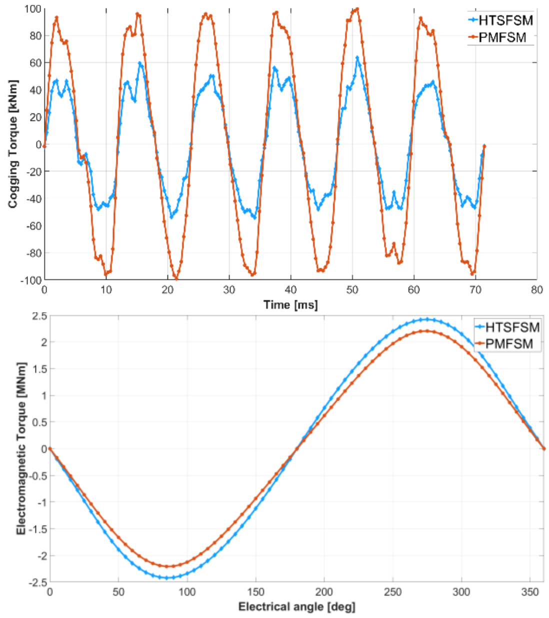

Fig. 3. Cogging torque (a) and electromagnetic torque (b) comparisons

IV. CONCLUSION

The investigation demonstrates that high-temperature superconducting (HTS) excitation is a viable alternative to permanent magnets in electric machines, maintaining high efficiency and low torque ripple. Additionally, HTS excitation offers a notable increase in torque and power density, even without in-depth optimization. However, for practical implementation, further research is needed to address challenges related to effective cooling strategies and the management of radial and electromagnetic forces, which could impact the machine's mechanical integrity and operational stability. More detail research will be discussed during conference and included in full paper.

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