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# Armature reaction effects on a high temperature superconducting field winding of an synchronous machine: Experimental results

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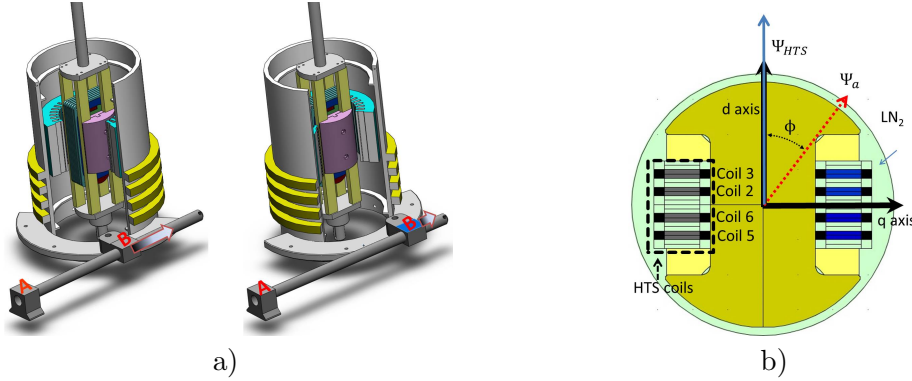
**Abstract.** This paper presents experimental results from the Superwind laboratory setup. Particular focus in the paper has been placed on describing and quantifying the influence of armature reaction on performance of the HTS field winding. Presented experimental results have confirmed the HTS field winding sensitivity to both armature reaction intensity and angular position with respect to the HTS coils. Furthermore, the characterization of the HTS field winding has been correlated to the electromagnetic torque of the machine where the maximal  $I_c$  reduction of 21% has been observed for the maximum torque.

## 1. Introduction

Superconducting (SC) machines have been proposed as direct drive generators for large wind turbines due to their high torque density and very limited, if any, dependence on rare earth elements [1, 2, 3]. Dating from 1950's, the number of large scale application which have tried to exploit potential benefits of SC machines have risen, a few of which are utility generators, ship propulsion drives and industrial motors. For each of the mentioned application a particular SC machine topology has been mostly cited and regarded as an optimal [4]. It seems that multi-pole wound field synchronous machine with SC field winding and conventional copper armature has been the most consistent topology proposed for wind turbine direct drive generators [5]. Since SC field winding is in its essence an electromagnet, rules and guidelines used for SC magnet design have often been the starting point of SC machine design process. Design would involve following steps: required MMF for a given magnetic flux density in air (a load line) is plotted against  $I_c(B, T)$  for specific SC after which magnet designer would determine operating current and temperature of SC winding based on the thermal stability and other constrains of the design. If this approach is likewise followed in the SC machine design, magnetic field coming from the AC winding (also known as armature reaction) could compromise stability of the SC field winding which often is not emphasize strongly enough.

The choice of operating current presents a tradeoff between thermal stability of SC and the cost optimization of the system. On the other hand, thermal stability of the SC field winding, or how much SC coils are prone to a quench among other parameters can be correlated to  $I/I_c$  ratio and to an appropriate critical current evaluation of SC coils [6]. 30-60% value of  $I_c$  is usually regarded as a safe operating current with sufficient current margin for SC coils [7], depending on which criteria  $I_c$  has been derived from. Thus, proper  $I_c$  evaluation of SC coils in the context of

the application is of great importance. Having that in mind we have used the Superwind setup [8, 9], to evaluate the impact of armature reaction on  $I_c$  of a HTS field winding derived from voltage measurements, both quantitatively and qualitatively.



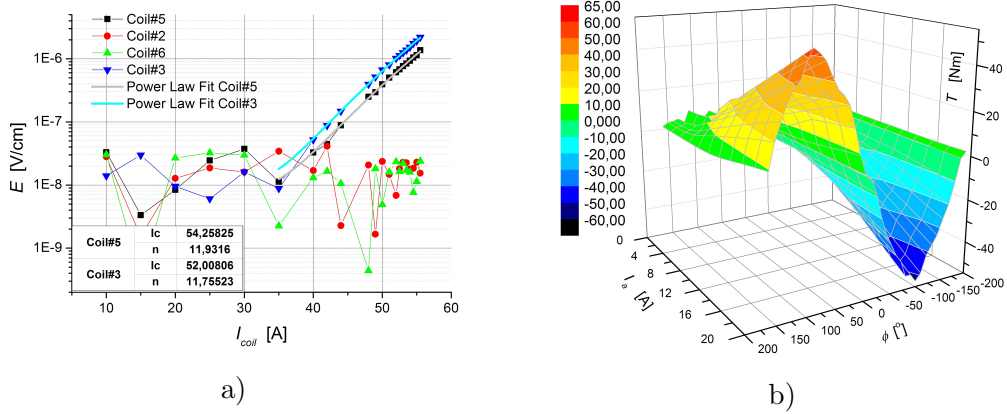
**Figure 1.** (a) 3D CAD illustration of rotor locking add-in in Superwind setup. ;(b) Illustration of the 2D cross section of the HTS field winding assembly with field flux axis colored in blue and armature flux axis in red. Coil ID numbers are identified.

## 2. Materials and Methods - Superwind setup

Superwind setup [9], has been constructed with the intention to test and characterize verity of HTS coils in field winding of synchronous machine under various conditions. Six epoxy impregnated HTS coils have been constructed and tested at liquid nitrogen ( $LN_2$ ) boiling temperature (77K). Three coils have been wound with BSCCO HTS and other three coils with YBCO HTS tape [3]. However, due to availability, in the experiment described here only four coils have been used, three BSCOO and one YBCO. Focus of the experimental investigation was to determine the influence of armature reaction on operating condition of HTS winding. Hence, a static locked rotor experiment has been performed. In the experiment, magnetic field of the armature winding is controlled with phase currents. A DC current flows through two phases, phase A and B, connected in series with third phase disconnected. In this way, armature reaction is aligned with disconnected phase while the value of it can be correlated with three phase operation making it fully defined. If the DC current in experiments is  $I_{DC} = \sqrt{2} \cdot I_{RMS} \cdot \sin(\frac{\pi}{3})$ , where  $I_{RMS}$  is a RMS value of three phase operation, the armature reaction will have the same value. Field flux has been controlled by the field current control of 4 serial connected HTS coils. The condition monitoring of the HTS field winding was performed by measuring the voltages of individual coils and coil segments. In addition to HTS diagnostics, the armature winding was equipped with an absolute position sensing and torque measurement at the cryostat. Hence, the state of HTS field winding could be correlated to the mechanical output of electrical machine, i.e. electromagnetic torque. The illustration of Locked rotor experimental setup is shown in 1(a) and 1(b) where armature position is controlled by linear adjustment of a threaded rod. Point A is the point of rest while point B can move along the rod resulting in a controlled angular displacement of the armature. The 1(a) illustrates an angular shift of  $\approx 45^\circ$ .

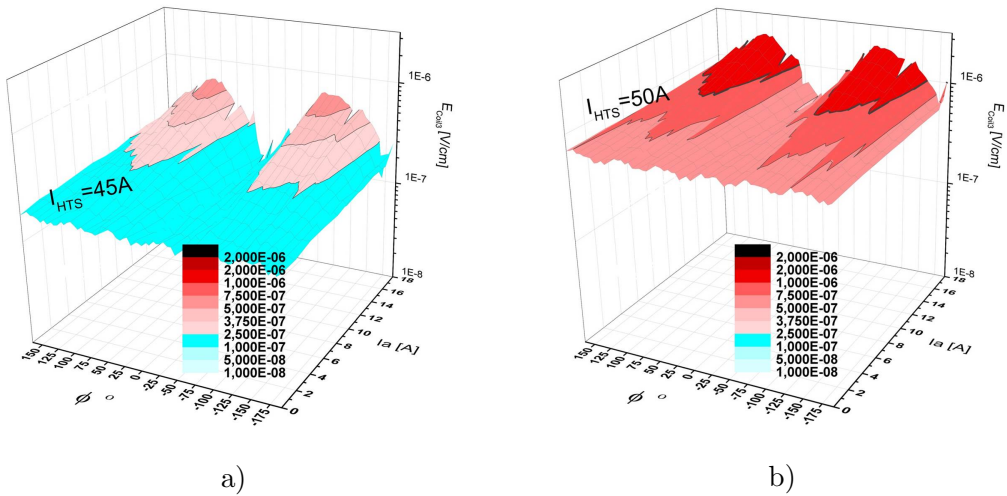
## 3. Experimental results

In the set of HTS coils, two BSCCO coils, Coil 3 and Coil 5, placed as shown in 1(b), have exhibited the lowest critical current from the stack of HTS coils, as presented in 2(a). The critical current of the field winding was determined by comparing the average electrical field of



**Figure 2.** (a) IV curves of 4 HTS coils with no armature current. The critical current of the field winding is 52A and is set by Coil 3; (b) 3D plot of a measured electromagnetic torque as a function of armature current and angle between field and armature fields while current of HTS field winding is 50A.

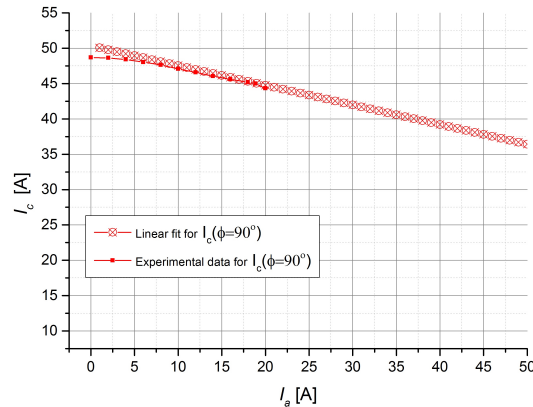
coils to  $E_0 = 1\mu V/cm$ . Hence, the critical current of the field winding in the No load (absence of the armature reaction) is 52A and is set by Coil 3.



**Figure 3.** Average electric field of the Coil 3 as a function of armature current  $I_a$  and angle between field and armature flux axes,  $\phi$  while current of HTS field winding is (a)  $I_{HTS} = 45A$ ; (b)  $I_{HTS} = 50A$

With the increase of armature reaction, the field condition of the HTS field winding will change which is expected to result in the change of operating current. Indeed, experimental results shown in 3, where the average electric field of HTS coil is shown as a function of both armature reaction intensity (value of the DC current) and the angle between the armature reaction flux and field flux for a constant current of field winding, validate the expectations. Average electrical field of the coils is not necessarily increasing with the increase of armature reaction but has two maximums at dedicated angles  $\phi \approx \pm 90^\circ$ , where the electromagnetic torque has its extremes likewise, as seen in 2(b). Having this in mind, we can conclude that the largest

reduction of critical current occurs when machine develops maximal electromagnetic torque per Amp of armature current. The  $I_c$  for loaded machine (for maximal torque, i.e.  $\phi = 90^\circ$ ) is presented at 4. For rated armature reaction, which corresponds to  $I_{DC}=35$  A, the critical current for the maximal developed torque is 40 A, which is 20% lower value compared to a No Load.



**Figure 4.** The critical current of the field winding as a function of armature current  $I_a$  for  $\phi = 90^\circ$

#### 4. Conclusion

Armature influence on operating performance of SC field winding stems from magnetic field sensitivity of the HTS tape. Based on experiments shown in this paper, magnetic anisotropy was dominant source of armature reaction impact to the HTS field winding since the value of  $I_c$  was not affected by the armature reaction at  $\phi = 0^\circ$ , as seen at 3. The reduction of critical current without and with the armature reaction can be significant, and in the case of the Superwind setup was found to be as much as 20%. It should be noted that the performed experiments were static, which implies absence of AC loss in HTS winding from slot harmonics or other sources, all of which would additionally decrease the  $I_c$ . Thus, the impact of armature reaction on SC field winding can be very significant and should be taken into account in design phase of SC machine.

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