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Design aspects on winding of an MgB_2 superconducting generator coil

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Abstract

Generators based on superconducting rotor coils are considered for future large off-shore wind turbines for their low weight and compact design, and for their possibility to reduce costs. In the 10-20 K temperature range, MgB_2 superconductors carry current densities 100 times higher than standard copper conductors at room temperature at one tenth of the wire cost per unit carried current. In the framework of the European project INNWIND.EU, an MgB_2 superconducting generator pole will be designed, built and tested. Some of the design aspects of this work with emphasis on the winding process and associated coil insulation are discussed. An overall high current density in the coil is of crucial importance to obtain clear benefits compared to conventional solutions. The wire itself may be the most important parameter in that respect. However, the overall current density of the coil is also influenced by the thickness of the turn-to-turn electrical insulation. Here we discuss the impact of the insulation and suggest the use of a one-step winding process, employing wet-winding, where the applied epoxy also constitutes the insulation layer between turns. In this way the coil is densified by approximately 10% compared to the use of an additional, dedicated, electrical insulation like Kapton for wet-winding or glass-fibre for dry-winding followed by vacuum impregnation. We show the results of a trial winding of 500 m of MgB_2 superconducting wire into a double pancake coil using the wet-winding technique. The coil is tested for contacts between the turns to evaluate the suggested one-step wet-winding process.

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Superconductor generator; coil winding; electrical insulation

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1. Introduction

To reduce the foundation and installation costs per unit generated energy, off-shore wind turbines with power ratings of 10 MW and beyond are considered. New and innovative solutions are sought for every part of the construction of this next generation of wind turbines to reduce weight, volume and particularly cost.

For the generator, converting kinetic energy to electric energy, novel design features may be viable [1]. One of the new solutions considered for direct drive generators is the use of superconducting material in the generator field winding [2,3]. Under dc operation, superconductors carry current loss-free when cooled down to low temperatures, typically 4 - 40 K depending on the choice of superconductor. One main advantage is that the magnetic field can be considerably higher, a factor of two or more, than in copper coil or permanent magnet based generators. In this way the necessary torque can be realized within a much smaller volume in the superconducting generator than in its conventional counterparts. The volume and weight reductions achieved in this way may have a significant economical value, particularly for wind turbines at depths requiring floating platforms.

There are several superconductors considered for wind power generator windings, operating at various temperatures and magnetic fields, and available at different cost [4]. Operating at 4 K, the low-temperature superconductor, NbTi, extensively used in MRI machines, constitutes a proven magnet technology. One path may be to transfer this technology into the wind turbine [5]. Another path may be to employ the high-temperature superconductor YBCO at temperatures of 40 -50 K [6]. A third option is the superconductor MgB₂ operating at the intermediate temperatures of 15 - 20 K [7,8]. In this temperature interval, the current density of the wire at a magnetic field of 2 T is presently 100 - 200 A/mm² (25 – 50 times higher than in copper conductors) for commercially available wires [8]. The present wire cost is approximately 20 €/kAm, which is one fifth to one third of the cost for copper conductors. The MgB₂ conductor is still under development and an enhanced performance together with gains from up-scaling of production are expected to lead to a further cost reduction. Among the negative aspects on superconductor technology is the cost for cooling and cryogenic equipment, which also needs to be included in the economical assessment.

In the European project INNWIND.EU [9] generators based on two of these superconductors, YBCO and MgB₂, are investigated. In the present work we focus on the fabrication of superconducting windings based on MgB₂ superconductors. The principles of the winding technique are outlined and special attention is paid to the turn-to-turn electrical insulation.

Superconducting windings are normally impregnated with epoxy and can either be dry-wound or wet-wound. In the dry-winding method the conductor is insulated typically with a glass-fibre fabric, then wound into the coil and afterwards vacuum impregnated with an epoxy [10]. In the wet-winding method the conductor is typically insulated with a polymer foil (e.g. Kapton) and then wound while applying a thin layer of epoxy to the conductor sides [11].

In recent years, non-insulated coils (i.e. without turn-to-turn insulation) have gained significant interest for high-temperature superconducting coils [12,13,14,15]. There are several benefits with non-insulated coils, such as increased compactness and thereby increased overall current density, enhanced thermal stability at quench situations, overall high thermal conductivity of the coil, and avoidance of the so called spongy effect [16] due to differences in Young's modulus between the polymeric insulation and the conductor.

One disadvantage with non-insulated coils is the prolonged ramping time due to the presence of induced currents between turns at high ramping rates. The problem may be reduced or eliminated by the use of a partial insulation between the turns (using a poor conductor between turns or insulating only parts of the windings), thereby increasing the turn-to-turn resistance and allowing for an increased ramping rate [17,18]. Another disadvantage, for coils such as generator rotors which are operated in the presence of a low ac magnetic field, is that such fields, similarly to the situation during ramping, may induce unwanted ac currents in the coil through turn-to-turn contacts.

In this work we investigate the possibility to use the wet-winding technique without any dedicated electrical insulation except for the epoxy applied to the conductor during winding. In principle, the epoxy gives a sufficiently thick layer for electrical insulation [19], however the method needs to be proven and the resistance of possible contact spots needs to be determined and their effect on the coil operation to be evaluated.

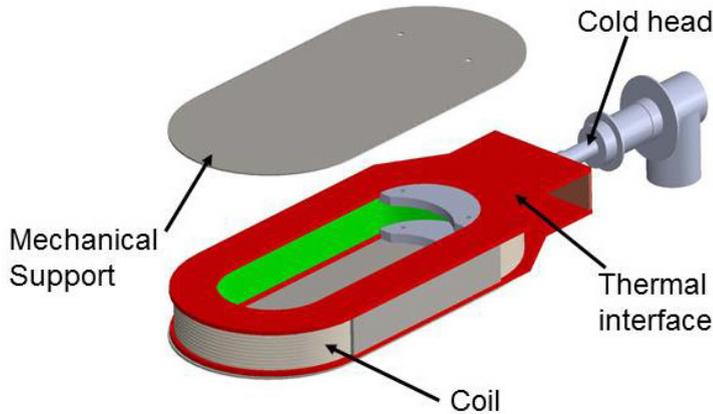


Fig. 1. Sketch of the MgB₂ demonstrator coil with thermal interface and mechanical support (to be mounted on the thermal interface).

2. The INNWIND.EU MgB₂ pole demonstrator

To evaluate the feasibility of superconducting MgB₂ generators a 10 MW generator is being designed [8]. The generator has 32 poles, and a key element is the superconducting coil itself. In the 10 MW design the race-track shaped coil has a straight section of 2.8 m and two end sections with inner radii of 0.15 m. The cross-section of the coil is 84 mm x 80 mm (width x height), the number of turns 200, and the current 235 A. The maximum magnetic field is 3 T, appearing at the inner part of the end sections.

The INNWIND.EU MgB₂ pole demonstrator has the same features except for that the straight section is made considerably shorter (0.5 m) to fit the coil into an existing test facility and to reduce the wire cost. The main objective for the coil demonstration is to evaluate the feasibility of a one-step wet-winding technique and the ability of such a coil to handle the thermal contraction and the large Lorentz forces appearing under operation. Figure 1 shows the coil with thermal interface, mechanical support and the cold head of the cryocooler.

3. Winding race-track coils

MgB₂ superconductors are currently produced in lengths of one to a few kilometres. This is less than what is required for the coil in the 10 MW design. A commonly used method to allow for well controlled splices is to wind so called double pancake coils. The winding procedure starts with the mid part of a wire length, which crosses between a lower and an upper pancake. Half of the wire length is then wound into a lower layer pancake and afterwards the remaining half is wound into an upper layer pancake. In this way the wire ends appear at the outside of the coil and are easily spliced to neighbouring double pancake coils in a low magnetic field and easily cooled region.

The wet-winding technique is previously successfully used to wind round double pancake MgB₂ coils [11]. Figure 2 shows the winding table adjusted for winding of race-track coils. To the left the lower layer of the double pancake is wound while the wire for the second half is placed in the spool at the top of the rotating table. In the right hand figure, the second layer is wound. Spacers about 0.5 mm thick (not seen because of the black epoxy) are placed at a few locations around the winding to ensure a space filled with epoxy constituting the electrical insulation between the layers. The epoxy used is the alumina filled Stycast 2850.



Fig. 2. Winding table during winding of the first layer (left) and second layer (right) of a double pan-cake MgB_2 coil.

4 Turn-to-turn insulation

4.1 Need for turn-to-turn insulation

In principal, during pure dc operation of a superconducting coil, no turn-to-turn insulation would be necessary. The current is carried loss-free and consequently no voltages would appear between turns, and the current flows only in the superconducting filaments of the wire. However, this is not the case for a coil under real operation. First, the flux flow losses appearing below (but close to) the critical current of the conductor give rise to a small dc voltage over a coil turn. Second, during ramping of the coil, the enclosed flux within the coil changes and consequently a turn-to-turn voltage is induced. If the ramping rate is constant, this voltage is a dc voltage. Thirdly, in a practical wind turbine generator rotor, ac magnetic fields are present leading to induced ac voltages in the rotor winding.

Figure 3 shows a cross-section of a test winding. The epoxy layer applied in the wet-winding process constitutes an effective electrical insulation as long as there are no spots incidentally left dry during the wetting process or that the pressure during winding has squeezed the epoxy away at certain points. The uneven top layer is due to long winding time at this first trial winding leading to problems finishing within the pot life of the epoxy. Nevertheless, the test winding can be used to estimate the quality of the epoxy as electrical insulation in the coil.

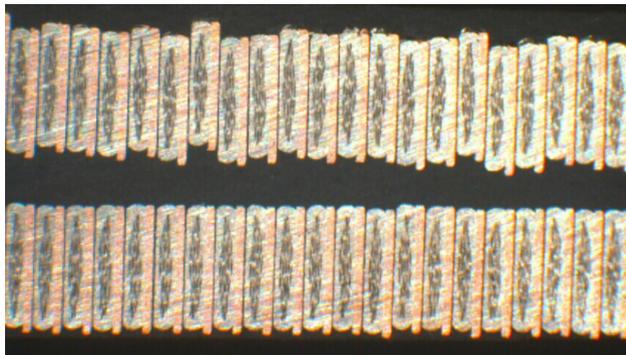


Fig. 3. Cross-section of a part of the MgB_2 double pancake test coil. In this cross-section, the microscope picture shows that a sufficiently thick layer of epoxy has been applied. The width of the MgB_2 wire is 3 mm.

4.2 Turn-to-turn voltages appearing under operation

Under steady operation, the dc electric field, E_{dc} , along a superconductor operated in the flux-flow region, i.e. relatively close to its critical current, normally follows a power-law dependence according to:

$$E_{dc} = E_0 \left(\frac{I}{I_c} \right)^n, \quad (1)$$

Where E_0 is 1×10^{-4} V/m, I is the current in the superconductor, I_c is its in-field critical current, and n is an empirically determined exponent. For an MgB₂ wire operated at a safety margin of 25% and with a typical n -value of 20, E becomes $0.3 \mu\text{V/m}$. For one turn in the 10 MW generator rotor coil the voltage then becomes $2 \mu\text{V}$ since the length of the turn is 6.6 m.

During current ramping, the voltage over the entire coil, U_{coil} , is determined by:

$$U_{coil} = L \frac{dI}{dt}, \quad (2)$$

where L is the coil inductance. The inductance of the field winding for the 10 MW generator rotor coil is around 10 H and a typical ramping rate is 0.1 A/s, energizing the coil in 40 minutes. The total coil voltage then becomes 1 V and with 200 turns in the coil, the average voltage for one turn becomes 5 mV. Although varying with position in the coil (somewhat higher at the inner turns and lower at the outer turns) this is the order of magnitude of the turn-to-turn voltage during current ramping.

The space distribution of the magnetic field in the air-gap of the machine contains a fundamental component (sinusoidal distribution) and several harmonics. The harmonics spectrum depends on the design of the rotor and stator. For a stator winding comprising slots and teeth, the harmonic spectrum depends on the number of slots per pole and per phase (q), and if the teeth are magnetic or not. The amplitude of the harmonics becomes larger with magnetic teeth.

When the number of slots per pole and phase q is an integer number, only over-harmonic components are present in the air gap field. They may cause losses in the superconducting field winding if the winding is insufficiently shielded. However, the net flux change and hence the induced voltage in the field winding is small due to the short wavelength of the over-harmonics.

In case of a fractional winding in the stator (e.g. $q=1.5$), there are sub-harmonic components in the magnetic field spanning several poles. They can create a net flux in field winding leading to an ac voltage in the winding. The sub-harmonics can however be reduced by a proper selection of the number of slots in the machine. In addition the frequency is low such that the induced voltage is usually no problem.

To get one estimation of the turn-to-turn voltage we may use the magnetic field distribution in [21] calculated for a superconducting generator with non-magnetic teeth. The dominating harmonic frequency in that design is 10 Hz and the (rms) magnetic flux density approximately 3 mT. Now, as this field varies spatially several times over the enclosed area of the field coil, the net flux is maybe one fifth of the area times the magnetic field. The voltage for one turn can then be estimated by,

$$U_{turn} = \frac{d\phi}{dt}, \quad (3)$$

where Φ is the enclosed magnetic flux (equal to the magnetic field times the area). With a total area of the field winding in the 10 MW design of 1 m^2 , the turn voltage becomes approximately 40 mV. It should be noted that this

is a very rough estimate only used to get the order of magnitude of the turn-to-turn voltage that could be appearing in the field winding.

Summarizing the turn-to-turn voltages they are of the order 2 μV , 5 mV and 40 mV for the dc operation, ramping and ac harmonics, respectively.

4.3 Turn-to-turn resistance in the double pancake test coil

The double pancake test coil was fed by a dc current of 1 A in room temperature and voltages were measured over approximately one quarter, half, three quarters and the full coil to 1.12, 2.47, 3.58 and 5.04 V, respectively. These numbers reveal no large differences between the quarters of the coil and correspond to the anticipated voltage drops in the wire without large currents passing between turns (and certainly not between the lower and upper layers). It should be noted, though, that the resistance along one turn of the test coil is only about 25 m Ω and for differences in voltages to be detected in these initial measurements, the turn-to-turn resistance needs to approach this level.

To obtain more accurate values on the possible turn-to-turn contact resistance, the coil was cut into four parts and the ends of these parts were sanded (figure 3). The resistances between turns were measured directly (under microscope) using an ohm-meter for values above and a four point method for values below 1 Ω . Several contact points were then detected without any visible contacts at the ends even in the microscope. However, a contact point of the order 1 Ω can be very small and is generally determined by:

$$d = \frac{\rho}{R}, \quad (4)$$

where d is the diameter of the contact point, ρ the resistivity of the contact materials (in this case a mixture of copper and nickel) and R the contact resistance. With ρ of the order 2×10^{-8} Ωm and the resistance of the order 1 Ω , the diameter of the contact spot becomes approximately 0.02 μm which is less than what can be seen in a microscope. To eliminate possible contacts at the sanded surfaces, 10 V was applied between turns to burn out any conducting material constituting the contact. For all resistances below 1 Ω the method was effective and sparks could be seen from one of the ends on all samples, showing that the contacts were located at the surfaces (and most likely created during cutting or sanding) and not within the actual coil. For contact resistances above a few Ω the applied voltage had no effect.

In contrast to the low resistance values which were somewhat fluctuating, there were a number of high and stable turn-to-turn resistances. It is likely to believe that these values, which were of the order tens of Ω to several k Ω , are in fact contacts between turns. Their cause may be small particles within the epoxy, imperfections in or metal rest from the wire, or simply that a too thin layer of epoxy was applied, particularly in the second layer of the double pancake test coil where the layers tended to position in an uncontrolled manner.

4.4 Influence of currents possibly passing the contact points

Taking the maximum turn-to-turn voltage from section 4.2 (40 mV) and the minimum resistance from section 4.3 (10 Ω) the current passing the worst contacts can be estimated at 4 mA. This current is far less than the 0.1% of the dc current acceptable from the ac loss point of view [20]. Another question is the power dissipated locally, in this case 0.2 mW, at the contact spot. However, the heat is not generated directly in the superconducting filaments but at the metal surface. The thermal conductivity of the materials will ensure that the heat is conducted both along the wire and through the thin epoxy layer towards the inside of the coil where it is cooled. In fact, if one considers that the heat is conducted in 1 square centimetre from the outermost turn to the inside of the coil, the 0.2 mW corresponds to a temperature increase of only approximately 2 mK.

4. Conclusion

Using the epoxy itself as electrical insulation in the wet-winding technique may be a viable and attractive method when winding superconducting coils. A test wound coil showed no low resistive contacts, and it is likely that an all through well controlled winding process would increase any contact resistances further. By avoiding a dedicated electrical insulation, like Kapton, the cost is reduced (the insulation cost is about 10% of the cost of the MgB₂ wire), one step in the coil manufacturing process is removed, and maybe most importantly, the radial thermal conductivity of the coil increases dramatically.

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