Design, manufacturing and tests of first cryogen-free MgB_2 prototype coils for offshore wind generators

G Sarmiento[1], S Sanz[1], A Pujana[1], J M Merino[1], R Iturbe[2], S Apiñaniz[1], D Nardelli[3], I Marino[1]

[1]TECNALIA. Parque Tecnológico, Edificio 700. 48160 Derio. Spain
[2]ANTEC S.A. Ramón y Cajal, 74 48920 Portugalete. Spain
[3]COLUMBUS SUPERCONDUCTORS SpA, Via delle Terre Rosse, 30 16133 Genova. Italy

E-mail: gustavo.sarmiento@tecnalia.com

Abstract. Although renewable sector has started to take advantage of the offshore wind energy recently, the development is very intense. Turbines reliability, size, and cost are key aspects for the wind industry, especially in marine locations. A superconducting generator will allow a significant reduction in terms of weight and size, but cost and reliability are two aspects to deal with. MgB_2 wire is presented as one promising option to be used in superconducting coils for wind generators. This work shows the experimental results in first cryogen-free MgB_2 prototype coils, designed according to specific requirements of TECNALIA's wind generator concept.

1. Introduction

Offshore wind sector is being developed in recent times, choosing direct drive machines as one of the possible generator configuration to exploit the renewable resource. Such machines present larger size as generator power is increased, which impact directly in the turbines economy. Superconductivity has the potential to allow drastic reductions in terms of size and weight [1, 2], but cost and reliability are two key aspects required by industry in marine locations. So, intense efforts developing new concepts of superconducting (SC) wind generator are being done [3-6]; mostly based on high temperature superconductors (HTS). Among them, MgB_2 has an interesting position because it accomplishes a good compromise between performance and price, and additionally, it is available in km lengths. SC coils main parameters and cooling system have been selected according to TECNALIA's concept [7]. MgB_2 wire will be used for the field coils but its reliability must be validated. In the following sections, some results of testing first cryogen free cooled prototype coils are presented.

2. Experimental

Commercial MgB_2 wire from Columbus SpA has been selected for the field coils in the wind generator. Chosen wire is a sandwich class with 19 MgB_2 filaments and a Ni external sheath. SC filling factor is 24.1% and its size is 3 x 0.5 mm^2. An additional 0.2 mm thickness Cu strip soldered to one side of the Ni sheath provides stabilization. Maximum bending diameter is 150 mm. Critical temperature (T_c) at self-field is around 35.5 K. Important industrial issues are the length in a batch, more than 1.5 km and the performance vs. cost, with a reasonable price of 30 €/(kA m) at 1.8 T and 20 K. According manufacturer, the cost is foreseen to be reduced due to both performance improvement and cost reduction by a factor of 5 in a short-medium time. Figure 1(a) presents some wire pictures and its general performance under magnetic field. Generator field coils will be constituted of a stack of several racetrack shape MgB_2 double pancakes, with an overall size of about 914 mm x 662 mm x 90 mm. Before building such as field coils, it is compulsory to validate the wire and the coil manufacturing in order to demonstrate the coil performance under cryogen-free cooling and to obtain experimental results for the simulations models. After having tested straight samples, some small-scale coils have been built: a three-turn solenoid with one layer called SC1 and a solenoid of 7 turns with one layer called SC2.1. Similar coil architecture has been used by others [8]. The procedure for the SC2.2 is presented in this paper. It follows the same SC2.1 parameters. Seven turns of MgB_2 wire were wounded in one layer over a copper disk (110 mm radius, 10 mm thick). Coil cross section is around 3.13 x 6.39 mm^2 and external radius is 116.4 mm. About 5 wire meters were used. Inside coil terminal was soldered to the plate with SnPb in the Ni side. Outside one was soldered to a copper sector (Cu strip side). Disk and sector purpose is twofold: to energize the coil and to refrigerate the terminals. Soldering length is around 165 mm (outside) and 177 mm (inside) to ensure complete current transfer and refrigeration. Sector, coil and disk were vacuum impregnated using Araldit F. Winding, moulding, impregnation, curing and mould releasing were carried out by Antec S.A. Figure 1 ((b) to (e)) shows the manufacturing process.

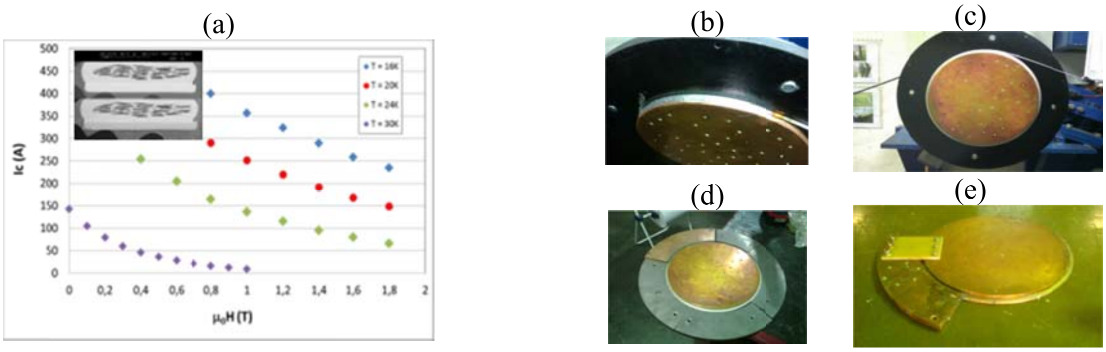

Figure 1. (a) MgB_2 sandwich class wire and current vs. magnetic field characteristics. Manufacturing process: soldering internal terminal (b), winding (c), impregnation tooling (d) and end coil (e)

Figure 2 shows the coil sketched; copper plate and sector are refrigerated by oxygen free copper braids, electrically insulated and connected to the cryocooler 2^{nd} stage. Electric feeding is done through six DI-BSCCO tapes (manufactured by Sumitomo), put in contact by pressure using In interface to the plate and sector. Cooling is allowed by extracting heat through the Cu plate and sector. The most relevant voltage taps and thermometers are also defined in figure 2. Wiring is thermally anchored to the disk, to minimize heat entrances. Hot spot heater is also located at point (3), though induced quench results are not showed.

3. Results and discussion

Coil was tested under three thermal ranges: ~11 K, ~25 K, ~30 K. Cooling configuration was designed to have temperature gradients between disk and sector and, therefore, inside the coil. In figure 3, a current ramp in the ~11 K test is shown; similar trends were followed in higher temperature tests. As the coil aim is to work under DC conditions, current steps were kept more than one minute.

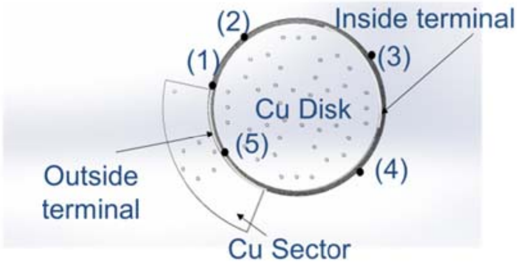

Figure 2. Coil SC2.2 sketched, showing voltage taps and thermometers distribution (1) to (5)

In order to extract current transfer effects, the inner and outer terminal performances are also presented. Inside one presents a mix between resistance and superconductivity behavior. For the 11 and 25 K tests, the electric field vs. temperature follows the same trend; with a resistance of about 10^{-8} Ω. It could be due to the solder SnPb and the Ni length that the current crosses during the current transfer process. For the 30 K test, the SC behavior is denoted with an I_c of 100 A and "n" value around 6. Outside terminal presents a thermal dependence and a resistance of ~1 μΩ, in which SC part has almost disappeared, probably because of manipulation during soldering. Estimated values for the SC2.2 load line present critical currents (I_c) higher than 500 A, 400 A and 80 A for temperatures of 15 K, 20 K, and 30 K respectively. Inside terminal I_c fits well with the expected critical current.

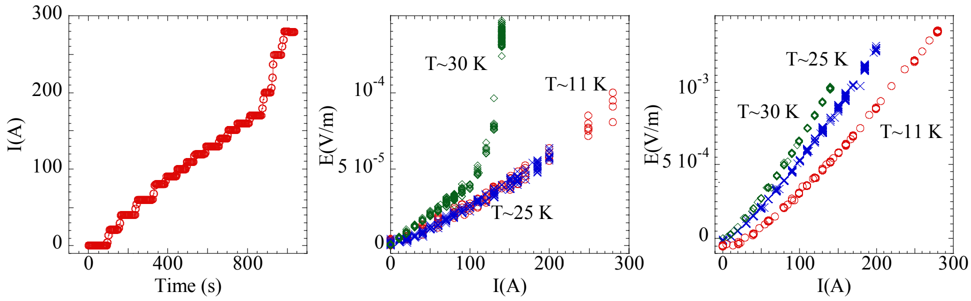

Figure 3. Current ramp for the test at ~11K (left). Electric field for the terminals, inside one (middle) and outside one (left), at different test temperatures.

Coil performance under current injection is presented in figure 4. A set of voltage taps and thermometers is distributed in the coil according to the sketch in figure 2, located in the most external turn. Temperature behavior is presented for the 11 K, 25 K and 30 K range, showing a thermal gradient through the wire in the coil. However, even with zero current, temperatures are not in the gap between disk and sector. That is explained as a heat entrance through wiring. In the lower part of figure 4, voltage drops in the whole coil (V_{coil}) and in selected voltage taps are presented. They are located at the end of wire length, close to the outside terminal (V2-V1) and in the last turn (V5-V4). Degradation due to the manipulation could be the reason of (V2-V1) voltage drop. An artificial defect generated in the wire during winding by accidental bending is probably the responsible of the (V5-V4) voltage drop. Subtraction of voltage drops (V2-V1) and (V5-V4) to the total V_{coil} (named "$V_{residual}$") shows the current injection evolution in the non-degraded part of the coil. Degraded points are the responsible of the thermal increase detected in all range tests, due to internal heat generation. Special interest has the 30 K range test, in which, above 100 A, $V_{residual}$ is increased. That fact is explained taking into account that inside terminal has quenched, and it is propagating outwards. Despite the heat generation, coil is rather stable below DC current of 100 A. In the 11 K range test applied current reaches 280A, the maximum allowed with the used current leads. Note that sector temperature is fairly constant and that the disk follows the same trend that temperature in selected voltage taps. That may be explained as the heat extraction is more effective through thin insulation to the disk than longitudinal through Cu strip to the sector.

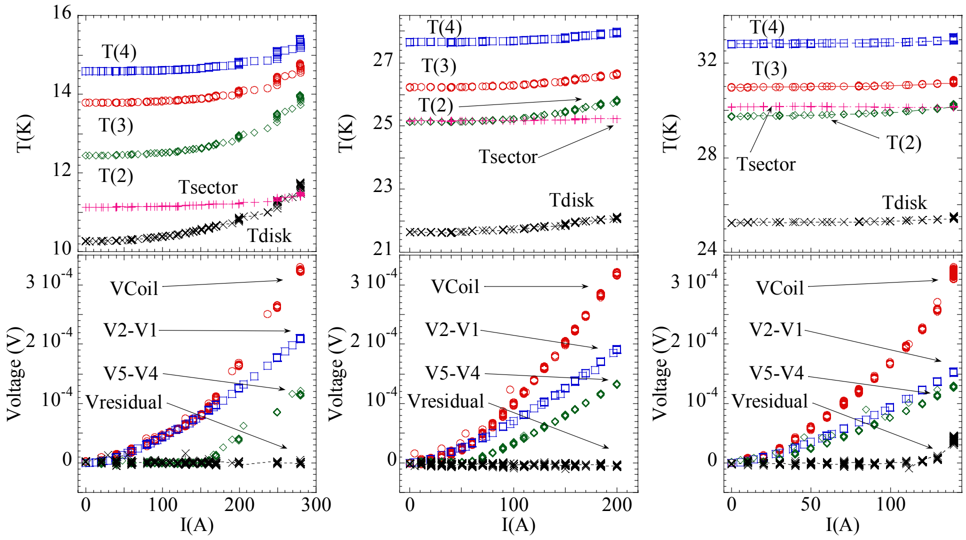

Figure 4. Temperature evolution in selected voltage taps and voltage drops, corresponding to 11 K (left), 25 K (middle) and 30 K (right) range tests.

4. Conclusions

Prototype MgB_2 coils have been designed, manufactured and tested, according TECNALIA's requirements for wind generators SC field coils. SC2.2 coil has been found superconductor and thermally stable for DC current up to 100 A in three temperature ranges of 11 K, 25 K and 30 K. Higher currents developed heating in the coil, though at 11 K up to DC 280 A were applied without quench. Degradation is found in outside terminal end wire part and in an internal defect. Two last ones are responsible of internal heat generation. Quench started in the inside terminal at its expected I_c. Further works are necessary to analyse the thermal process, quench propagation and the overall coil I_c.

Acknowledgment

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References

[1] Kalsi S, 2011 Applications of High Temperature Superconductors to Electric Power Equipment (Wiley-IEEE Press).
[2] Nick W, Frank M, Klaus G, Frauenhofer J. and Neumuller H 2007 IEEE Trans. Appl. Supercond. 17 2030–2033
[3] Abrahamsen A B, Jensen B B, Seiler E, Mijatovic N, Manuel R C V, Andersen N H and Østergaard J 2011 Physica C 471 1464–1469
[4] Lewis C 2010 Direct drive superconducting wind generators. Wind Power Generation and Wind Turbine Design (Southampton, UK: Witpress)
[5] Snitchler G, Gamble B, King C and Winn P, 2011 IEEE Trans.Appl. Supercond. 21 1089–1092
[6] Fair R, 2012 Superconductivity for large scale wind turbines Final Scientific Report - DE-EE0005143, General Electric –Global Research, Niskayuna/DUNS 08618840
[7] Scuotto M, Sarmiento G, Merino Azcárraga J M, García-Tejedor J, Ibañez P, Apiñániz S 2009 Patent Application WO2011080357 A1, PCT/ES2009/070639
[8] Pelegrín J, Romano G, Martínez E, Angurel L A, Navarro R, Ferdeghini C, Brisigotti S, Grasso G and Nardelli D 2013 Supercond. Sci. Technol 26 045002