The EcoSwing Project

T Winkler on behalf of the EcoSwing Consortium
Applied Physics, Energy, Materials and Systems, Carre 2.041, Drienerlolaan 5, 7522 NB
Enschede, The Netherlands
E-mail: t.winkler@utwente.nl

Abstract. The goal of the EcoSwing project is to build the world’s first MW-scale superconducting generator for wind turbines. We report on the main features of the machine’s design; on the assembly of its superconducting rotor, including the cryostat and the rotating GM-based cooling system; and on the preliminary results of the ground-based test campaign that was executed prior to the upcoming field test.

1. Introduction
The EcoSwing project is a project funded in part by the Horizon 2020 framework. It aims to design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator. This superconducting drive train will be operated on an existing modern wind turbine in Thyborøn, Denmark. One of the main goals of the project is to prove that superconducting technology has matured enough so that it can be used in industrial applications.

Nine European partners form the EcoSwing consortium. Envision Energy (Denmark) Aps from Denmark is one of the world’s leading manufacturers of wind turbines and operates the wind turbine prototype on which the generator will be installed. ECO 5 GmbH, a German engineering office, designed the superconducting rotor. Jeumont Electric SAS, a French manufacturer of electric generators and motors, developed and manufactured the conventional stator. Delta Energy Systems GmbH from Germany designed and built the power converter, the data acquisition as well as the quench detection system for the superconductive rotor. THEVA Dünnschichttechnik GmbH, a German HTS tape manufacturer, designed and built the superconducting rotor poles. Sumitomo Cryogenics of Europe, Ltd provided the cooling system necessary to maintain the rotor at operating temperature. Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) provided the ground-based test bench upon which the generator was operated for the first time. The University of Twente was responsible for the qualification of the superconducting poles, extensive materials testing, and the construction of the rotor. DNV GL Renewables Certification is provides guidance on future certification processes of superconductive generators and develops guidelines for the construction of superconducting wind generators.

1 EcoSwing has received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement No 656024. Herein we reflect only the author’s view. The Commission is not responsible for any use that may be made of the information it contains.
2. The EcoSwing Generator
The EcoSwing generator uses a conventional stator and a superconducting rotor. It is designed to have a mechanical input power of 3.6 MW; the maximum rotation speed is 15 rpm and its outer dimensions are below 4 m in order to have all roads capabilities.

3. The superconducting Rotor
The rotor of the EcoSwing generator is made using superconducting poles. In the following subsection the main components of the rotor are explained in detail. First the thermal design and its components are shown, then the cold electric components are presented. Finally the instrumentation of the rotor is discussed.

3.1. Thermal Design
The rotor is cooled by GM-cryocoolers mounted in the rotating part of the rotor. In order to reach the desired temperature it was decided to use SRDK-500B cold heads that can deliver up to 40 W of cooling power at 20 K. The cold heads can be exchanged without breaking the main insulation vacuum of the cold mass. This facilitates the maintenance of the cold heads.

The compressors on the other hand are mounted on service platforms behind the generator and are thus not rotating. To supply the cold heads with high pressure gas a rotating joint assembly is used. It also passes out control signals and provides an emergency shutdown signal in case of unexpected events.

The cold heads are connected to the cold mass by flexible copper bridges effectively compensating for differences in thermal shrinkage. The copper bridges connect to the main thermal bus, mounted on the rotor yoke. This bus is used to cool the rotor yoke and the poles. Heat intercepts are used to cool the mechanical supports of the cold mass.

During the first tests of the generator it was found that a small spread in the temperatures of the rotor exists. Figure 1 shows this phenomenon, where at first the rotor is at standstill and then starts to turn. Before rotation the temperature spread is about 4 K, which during rotation with 15 rpm decreases to 2 K. The difference during stand still can be explained with the small orientation dependency of the cold head performance. Six minutes after the beginning of the rotation the temperature difference is decreasing and the cold head temperatures have settled at a new lower temperature level.

The cold mass is housed in a single large vacuum container, which has to be evacuated before cool-down. For this reason a turbomolecular pump (TMP) was installed on the rotor. An additional external roughing pump provides the rough vacuum before the TMP can be started. The TMP is only needed to provide a pressure low enough such that the cryo coolers can be started. After the cool-down the TMP is deactivated and the roughing pump demounted. A further improvement of the rotor vacuum is the result of trapping the residual gas on the cold mass. This also guarantees the vacuum pressure during operation. The ultimate pressure in the rotor is below 1E-9 mbar.

To decrease the radiative heat transfer the cold mass is covered in 30 layers of multi-layer insulation (MLI). It is wrapped closely around the cold mass and the cold heads. To account for the varying forces due to the rotation the MLI is attached to the rotor at different positions around the rotor. These attachment points are designed to minimize the additional heat load.

3.2. Superconducting Poles
The rotor has a grand total of 40 identical poles. Each pole contains about 500 m of superconducting tape and has more than 200 turns in two layers. After winding the tape on a former the winding pack is potted with a glass fiber reinforced commercial resin. Figure 2 shows a winding pack after potting. The potted winding pack is mounted on a pole piece and enclosed by a stainless steel cassette. A copper cooling sheet is placed between the stainless
steel cassette and the winding pack. The majority of the heat is transported through this copper sheet. Figure 3 shows an assembled pole, ready for testing.

To insure the electric performance of the superconducting poles two tests setups were developed. One test rig was built at the University of Twente to test fully assembled poles in an environment similar to the situation in the rotor. This includes the cooling of the poles with conduction cooling and a magnetic environment simulating the forces expected in the rotor. Figure 4 shows the test rig at the University of Twente, where 4 poles can be qualified simultaneously. In order for a pole to pass the acceptance test it needs to reach nominal operating current and also pass a thermal test in which the current is kept stable and the temperatures of the poles are monitored.

The critical current was measured as a function of temperature for the first pole. The result of this measurement are shown in Figure 5. It plots the critical current as a function of the temperature, where the critical current is given as a ratio with the nominal operating current. The critical current at 71 K is 190 A and it increases to 470 A at a temperature of 50 K. This current level will also be used in the final wind generator, but at a temperature below 30 K. This provides enough safety margin for safe operation.

A different qualification method was used to qualify the potted winding packs. In this setup the field environment was different and also the forces were not similar to the forces in the rotor. To account for this fact a lift factor was determined, which could then be used to calculate the required $I_c$ of a winding pack at 77K in self field. The winding packs were immersed in liquid nitrogen and an I-V curve was measured. For a winding pack to be accepted it had to have an $I_c$ higher than 120 A with a quench criterion of 10 mV over the whole winding pack. Figure 6 shows results of the 77 K tests. All tested poles show the characteristic shape of an I-V-curve and were accepted for the pole assembly. The red lines indicate the quench criterion and the lowest acceptable critical current on the ordinate and the abscissa respectively.

**Current Leads** The current leads of the EcoSwing generator are of a hybrid design. From the vacuum feed to an intermediate heat exchanger the current lead is made from solid copper. Its cross section is designed such that the heat inleak is minimized, while only generating minimal

![Figure 1. Plot of the cold head temperature spread during stand-still and rotation. During stand-still the cold head performance is a function of the cold head orientation, leading to a temperature difference of 4 K between cold heads. During rotation the cold head performance is no longer affected with a single orientation and the difference between the warmest and the coldest cold head decreases to 2 K.](image)
Figure 2. Picture of the winding pack after potting. The terminals can be seen at the bottom of the assembly. The holes in the winding pack that are visible close to the current terminals are needed for mechanical stability.

Figure 3. Picture of an assembled pole. Clearly visible is the pole piece in the center of the pole and the terminals at the pole at the bottom of the picture. This is also where the cooling connection from the main thermal bus to the cooling sheets in the pole is made.

Figure 4. Picture of the test rig at the University of Twente. It allows to test up to four poles at the same time. It provides a magnetic field environment similar to the rotor and cooling is achieved via thermal conduction.

losses. The last part of the current lead from the heat exchanger to the first pole is made using a flexible HTS bridge to further minimize the heat inleak to the cold mass. As a last step the current lead is thermalized at the main thermal bus (MTB) before connecting to a pole.
Figure 5. The critical current in unit percent of operating current of a superconducting pole as a function of the temperature. It can clearly be seen, that the test pole exceeds the requirements for the rotor. The design of the superconducting poles provides enough safety margin to enable safe rotor operation.

Figure 6. Plot of the I-V curves of a series of poles measured in 77 K and self-field. The red lines mark the quench criterion and the required minimum critical current. As can clearly be seen, all poles in this series passed the test.

Splices One EcoSwing pole contains more than 500 m of HTS conductor. At the same time the requirements for the conductor are not equal at any position of the pole. To increase the yield of the HTS tape it was decided to allow superconducting splices within one layer of a pole. The resistance of these joints was measured and the influence of temperature and magnetic field was determined. A special soldering machine was developed to guarantee a high quality solder joints of superconducting HTS tapes. In this investigation it was found that a mean joint resistance of 36 nΩ cm$^{-2}$ could be achieved, independent of temperature and applied magnetic field in the relevant range.

Current Bridges During the design of the superconducting poles care was taken to minimize the number of components. This effort resulted in a pole design that doesn’t distinguish between poles of opposite field direction in the rotor. To achieve this reversal of the field direction between neighboring poles it is sufficient to connect the terminals in an alternating fashion. Figure 7 shows the alternating connections to have a NSNS orientation of the field.

The current bridges are made from OFHC copper. The current bridges are made semi rigid to account for thermal shrinkage. An average resistance of 33 nΩ was measured in liquid nitrogen.
Figure 7. Photograph of the connections between poles. Connecting the poles like this has the added advantage of creating alternating field directions between neighboring poles, whilst having only one pole design. Note the coil to coil connections on the left and right are connecting to two different layers of the pole and therefore the current direction between neighboring poles is changed.

All electric connections inside the rotor are made with indium. These connections have to be tightened over a series of days to account for the indium creep and to insure a good thermal contact. The resistance of the cold welds was measured during the rotor assembly to be $10 \, \mu\Omega$ per indium cold weld at room temperature.

4. Vacuum System
The rotor has one big vacuum chamber, containing the cold mass. The chamber is welded shut and all access ports are on the inner wall of the chamber. To create the vacuum in the chamber a turbomolecular pump (TMP) is mounted at a particular rotor position. A removable rough pump is used to provide the rough vacuum in the rotor and it is also used as a backing pump for the TMP. The TMP can only be operated when the rotor is at standstill but it is not necessary for the TMP to be operating continuously, since the cold heads are cryopumping the residual gases in the rotor. The cryopumping is effective enough to maintain a rotor vacuum pressure below $1E^{-8}$ mbar.

The pressure in the rotor is measured with three separate pressure gauges. Two identical Pirani type sensors are mounted to measure the rough vacuum pressure during pump down. The third sensor is a cold cathode type sensor. This gauge is used to measure the vacuum pressure during cool-down, to determine the pressure at which the TMP and the backing pump can be switched off.

For safety reasons the Pirani sensors are used to create an interlock on the rotor pressure. The exciter will be shut down should the pressure exceed a threshold value. For mechanical safety a burst disk is mounted on the rotor as a protection against overpressure in case of a vacuum loss.

5. Quench Detection
The EcoSwing rotor is equipped with a quench detection system to detect a faulty behavior of the rotor and to shut down the exciter in such an event. The quench detection system is based on a voltage measurement, which is made on multiple independent circuit boards. The rotor is split in multiple identical sections, each containing several poles. Each quench detection board is connected to two neighboring sections. It measures the absolute voltage across each section separately and also measures the analog differential voltage between the two sections. To achieve redundancy of the quench detection each sector is measured twice by two different quench detection boards.

6. Test Bench Results
The generator was tested at the DyNaLab test bench at Fraunhofer IWES in Bremerhaven. For the tests the generator was cooled down for the first time. After the cool-down first excitation
tests were made in stand-still to test the functionality of all systems. First rotation was also achieved on the test bench and first experiences with exciting the rotor during rotation were gained.

A whole series of tests were made and in the following a selection of the test results are shown.

During the short circuit test the stator temperatures were monitored to validate the stator design. Figure 8 shows the different temperatures that were measured in the stator. None of the stator temperatures exceeded a critical limit and the thermal design of the stator was thus confirmed.

In Figure 9 the results of the no load tests are shown. It can clearly be seen by the non-linear behavior at elevated rotor currents that the stator is fully saturated.

Additionally, it was found that the harmonics of the generator are very low over the whole operating range. The reason for this could be the large air gap found in this type of machines. Figure 10 shows the measured harmonics the nominal voltage of the stator.

**Quench** During one of the excitation tests an anomalous behavior was detected in one the poles and the exciter was shut-down. A Quench was detected during the ramping of the current, where
Figure 10. Analysis of the higher order harmonics of the stator operating at 690 V. It can be seen the major contribution is the 11th order harmonic, which only reaches 1.6% of the total induced voltage. The reason for this very low amplitude could be found in the large air gap possible by superconducting machines.

The voltages are heavily affected by the inductive voltages. Figure 11 shows the temperature change rates as well as the current on the day of the quench. The heating rate shows large excursions during current ramping and during the rotation of the generator. This is due to the AC loss in the conductor on one side and due to the performance dependency of the cryo coolers as discussed above. During the current ramp in the afternoon it can be seen that most poles return to a heating rate of zero after some time. Only one pole shows a different behavior and a clear deviation from the others poles can be seen in the same time slot. This plot was created in a post-mortem analysis and it can be seen that the affected pole already showed a slightly different behavior shortly before the quench. As a consequence, it was decided that in future operations of the EcoSwing generator the heating rate will be measured as an additional signal.

Figure 11. Overview of the rotor current and the heating rates of the poles on the day of the quench event. The red line shows the rotor current; the flat plateau in the morning is the no-load test, the current ramp in the afternoon is cut short by the quench. The black lines, including the turquoise line, are the heating rates of the 40 poles.

A further investigation of the affected pole shows that the defect spot is close to the location of the temperature sensor. This also explains why in Figure 12 the temperature of the affected pole showed such a clear increase after the quench. In this plot the green and purple lines are the voltage traces of the two quench detection cards which measure the affected sector. The blue trace is the temperature trace of the quench pole.
Figure 12. A detailed plot of the differential voltages of the quench detection cards and the temperature trace of the quenched pole. The green and purple lines are the differential voltages of the two quench detection cards that measured the quenched pole. The temperature of the pole temperature is plotted in blue. The maximum temperature of the pole is measured 20 min after the quench occurred.

The delay between the exciter shut down and the temperature maximum of the pole can be explained with the position of the temperature sensor. The sensor is not measuring the conductor temperature directly but is mounted on the far end of the pole on the cooling plate. Thus the thermal time constants in a pole are in the order of several minutes.

7. Conclusions
The EcoSwing consortium successfully designed and built a wind turbine generator with a superconducting rotor, for a rated power of 3.6 MW. This generator was successfully tested at Fraunhofer IWES, where the characteristics of the machine were confirmed and the generator successfully produced 1 MW electric power despite a defective pole.

In the coming months the generator will prove its capabilities in the field, where it has been installed on the GC-1 turbine prototype by Envision Energy (Denmark) Aps.