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To cite this article: Jiuce Sun *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012067

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Development of a rotary union for Gifford-McMahon cryocoolers utilized in a 10 MW offshore superconducting wind turbine

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Abstract. Superconducting generators (SCG) show the potential to reduce the head mass of large offshore wind turbines. By evaluating the availability and required cooling capacity in the temperatures range around 20 K, a Gifford-McMahon (GM) cryocooler among all the candidates was selected. The cold head of GM cryocooler is supposed to rotate together with the rotating superconducting coil. However, the scroll compressor of the GM cryocooler must stay stationary due to lubricating oil. As a consequence, a rotary helium union (RHU) utilizing Ferrofluidic® sealing technology was successfully developed to transfer helium gas between the rotating cold head and stationary helium compressor at ambient temperatures. It contains a high-pressure and low-pressure helium path with multiple ports, respectively. Besides the helium line, slip rings with optical fiber channels are also integrated into this RHU to transfer current and measurement signals. With promising preliminary test results, the RHU will be installed in a demonstrator of SCG and further performance investigation will be performed.

1. Introduction

Offshore superconducting wind turbines show the potential to reduce weight and size due to the high magnetic field and low current loss of using high temperature superconductors (HTS). Unlike the conventional conductor, HTS applied in the wind turbine work at cryogenic temperatures. For instance, the MgB₂ tapes used in SURPAPOWER project have been characterized to operate around 20 K [1]. To reach and maintain such a desired low temperature in the scenario of offshore wind farm, we need to develop a cryogenic cooling system with a simple structure and high reliability [2]. Considering structure and reliability, a cryogen-free method was proposed to use conduction to deliver cooling power from close-cycle regenerative cryocoolers. Among all regenerative cryocoolers in the market [3], taking into account of both cooling capacity and working temperature, we chose the Gifford-McMahon (G-M) type. G-M cryocoolers are commercialized and readily available from many manufacturers at relatively low cost. To reduce the cost, G-M cryocoolers normally utilize cost-competitive scroll compressors that are extensively used in the refrigeration industry. These scroll compressors use oil to lubricate, and thus are unable to be rotated. However, as shown in figure 1, the cold head of the G-M cryocooler will rotate together with the HTS winding integrated into the rotor. Therefore, a rotary helium union (RHU) acting like a feed through is indispensable to transfer helium gas between the stationary compressor and rotating cold head.



Many experimental methods have been proposed to seal the rotating fluid in HTS applications. Those prototype rotating feed throughs are based on either polytetrafluoroethylene (PTFE) seals [4] or ferrofluid seals [5]. However, they are often developed to seal the cryogenics like Liquid Nitrogen (LN_2) or Liquid Neon (LNe) [6]. Those fluids work at cryogenic temperatures and low pressures, which are different from the RHU required by the G-M cryocooler. There is no commercial product in the market to achieve such rotating sealing for G-M cryocooler. Recently some prototype RHU has been applied to rotating HTS demonstrators on wind generators that also adopts G-M cryocoolers to cool down the superconducting coil [7][8]. These prototypes developed to seal the helium gas for the G-M cryocooler shows the feasibility of transferring high-pressure gaseous fluid to the rotating cold head. Nevertheless, they are not shown in details and the reliability needs to be further investigated. Moreover, they are highly integrated into the whole system and thus difficult to be separately applied to other HTS applications that have the similar needs.

In this paper, we propose a prototype RHU for Gifford-McMahon cryocoolers utilized on a large scale offshore superconducting wind turbine. The aim of this prototype RHU is to achieve a compact and reliable solution to the applications of using rotating G-M cryocoolers. The prototype uses ferrofluid to seal the rotating working fluid (i.e. high pressure helium gas). Multi-stage sealings are performed to manage a pressure difference as high as 3 MPa. The RHU provides two independent helium channels, as shown in figure 1, and each channel has multiple standard hydraulic interfaces to connect with the cold head and compressor, respectively. Besides the helium circulating path, there is also essential needs for transferring electricity into the rotating cold head in which a rotary valve is located to distinguish high-pressure and low-pressure helium flow. Therefore, to realize a compact design, we have also integrated a slip ring system into the RHU to transfer current. Additional optical fibers are also equipped to transfer signals from instrumentation installed in the rotating applications. The specification, design, manufacturing, preliminary test, and installation of this prototype RHU will be presented.

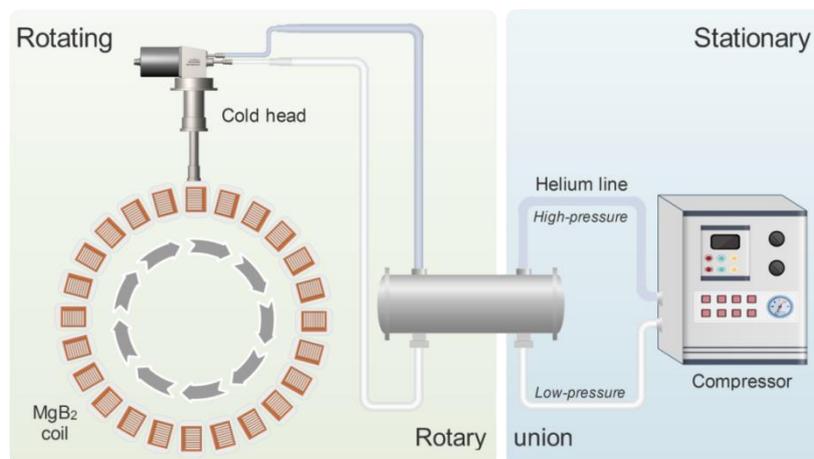


Figure 1. Schematic illustration of the rotary union between the stationary compressor and rotating cold head.

2. Technical specification

The RHU is developed based on a specified G-M cryocooler. In the SUPRAPOWER project, a two-stage G-M cryocooler (model COOLPOWER 10 MD) from Leybold is selected as the cooling source. The 2nd stage of this cryocooler could provide 20 W cooling power at 20 K while achieving around 100 W at 80 K in the 1st stage. This cryocooler is equipped with a compressor model of COOLPAK 6200 MD also from Leybold to compress the returning helium flow. The cold head and compressor model mentioned above will define most of the technical specifications of the RHU, as listed in the table 1.

The RHU will work at ambient temperature and in horizontal orientation. Helium gas at a pressure of 16-18 bar will be charged into the RHU before operation. The nominal working pressure of the helium gas inside the RHU will be 25 bar and 18 bar in the high-pressure and low-pressure channel, respectively. However, the RHU is specified to be leak tight at 33 bar in the high-pressure side and 25 bar in the low-pressure side to provide certain safety margin. The maximum allowable helium leak rate is in the magnitude of 10^{-9} mbar·l/s.

The RHU is specified to operate at a rotation speed less than 150 rpm. A slip ring system with 30 electrical circuits and 2 optical fibers will be implemented to transfer current and measuring signal. The resistance of the circuits should be less than 5 ohm, and the transmission loss of the optical fiber is supposed to be no larger than 3 dB and 6 dB for the 1st and 2nd channel, respectively.

Table 1. Technical specification of the prototype RHU.

General data						
Temperature range	<i>ambient</i>	Mounting orientation	<i>horizontal</i>		Process gas	<i>helium</i>
Rotation speed	<i>< 150 rpm</i>	Charging pressure	<i>16-18 bar</i>		Leak rate	<i><10⁻⁹ mbar·l/s</i>
	Helium line			Slip ring		
Channel	Working pressure	Maximum pressure	Electrical Circuits		Optical fiber	
High-pressure side	<i>25 bar</i>	<i>33 bar</i>	Number	<i>30*5A</i>	Number	<i>2</i>
Low-pressure side	<i>18 bar</i>	<i>25 bar</i>	Loss	<i><5 Ω</i>	Loss	<i>< 3dB @ <6dB</i>

3. Design and manufacturing

Figure 2 shows the outer view of a preliminary RHU design. The dotted line in figure 2 indicates the helium circulation path. The shorter channel represents the low-pressure side and the longer one is the high pressure side. On the flange located in the right side of the RHU, each helium channel contains a hydraulic port to connect the helium compressor. Six helium ports are installed on the main body of the RHU to connect with the cold head. Among them, three ports are distributed in the left end of the low-pressure line. The other three ports are reserved for the high-pressure helium line. Those hydraulic interfaces adopt self-sealing adaptors and thus will stay closed until being connected. For the cooling system in the SUPRAPOWER project, we need only one hydraulic port for each helium transfer line (high and low pressure), respectively. However, we still keep three ports for each line in order to retain the scalability of using one compressor to drive multiple cold heads.

Figure 3 illustrates the cutaway view of the RHU engineering design. The sealing between the stationary and rotating part inside the RHU is realized by means of ferrofluid. The ferrofluid is a colloidal liquid that responds to a strong magnetic field; it is made of nanoscale magnetic particles that are covered with a surfactant agent and suspended in a carrier fluid such as water and oil. As shown in figure 3, a ferrofluid rotary shaft seal consists of a permanent magnet, pole pieces, and ferrofluid. The pole pieces and the shaft concentrate magnetic flux from the magnet into a narrow gap region surrounding the shaft. The ferrofluid is attracted to the region known as “stage” forming rings that generate a hermetic seal. Each ferrofluid ring or stage has a pressure capacity of a 70-340 mbar typically.

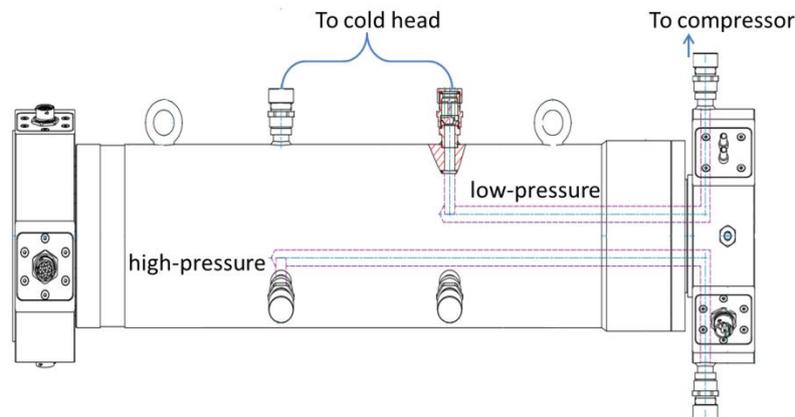


Figure 2. Illustration of the helium transfer channels inside the RHU (high and low pressure are both included).

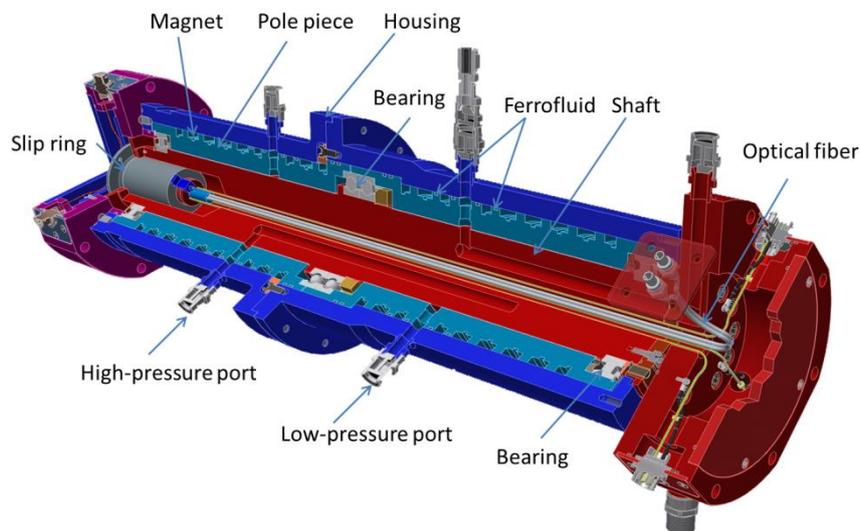


Figure 3. Cutaway view of the RHU engineering design.

At the beginning of the RHU design the main challenge was to create a seal design that would meet the high pressure requirement of 33 bar. As each stage of the ferrofluid seal has a limited pressure capacity, we need to add stages in order to reach higher pressure. Consequently, a multi-stage seal unit was accomplished by putting 132 stages together to achieve higher pressure capacity. Those stages lay on 12 pole pieces driven by 6 magnetic circuits since one pole piece could support many stages depending on the magnetic circuit. This multi-stage seal unit has a length of 18.5 cm. The final gas union consists of 3 such seal units, flanges, spacers, and bearings. By implementing multi-stage ferrofluid sealing, the final RHU reaches a length of 93.61 cm.

The length gave rise to our next challenge as the shaft is 77.4 cm long and the gap between shaft and pole piece is relatively small (few hundredths of a millimeter). Tight control of the seals' radial gap is needed as eccentricity will degrade the seal by weakening the magnetic flux as the gap gets bigger. It indicates that we needed a stiff shaft and bearing system to minimize the deflection. Deflection originates from the magnetic attraction between the pole pieces and shaft. If the gap is completely concentric, this force will be almost zero, but this is not practical as fits, tolerance, and manufacturing limitations play a roll. The gap must have some eccentricity and the greater it is the greater the force and deflection.

A preliminary RHU as shown in figure 2 uses only two bearings in the end to support the shaft. With this approach, the distance between bearings would have been 62.2 cm, and the deflection would have been in the same order of magnitude as the seal's radial gap. This large deflection will lead to appreciable reduction in pressure capacity. An improved approach was then proposed where a set of angular contact bearings will be added in the middle (as shown in figure 3) of the shaft to provide extra support besides two end support of roller bearings. With this optimized design, the unsupported length of the shaft was reduced in half and deflection was reduced by an order of magnitude.

figure 4 shows the picture of the manufactured and assembled RHU following the improved design of using angular contact bearings in the middle. The housing of this RHU combines two parts instead of one single housing as shown in figure 2. The two parts housing allow clamping of the middle angular bearings and corresponding poles and thus stabilize the assembly. The hydraulic ports shown in figure 4 are made of Aeroquip couplings. Each coupling will be covered with a dust cap as protection. Additionally, a purge port is connected to the region within the shaft where the slip rings, wires, optical fibers, and associated fittings reside. The purpose of this purge port is to allow that space to be slightly pressurized with dry air. In service at offshore, it would protect the contents from the corrosive effect of salt.

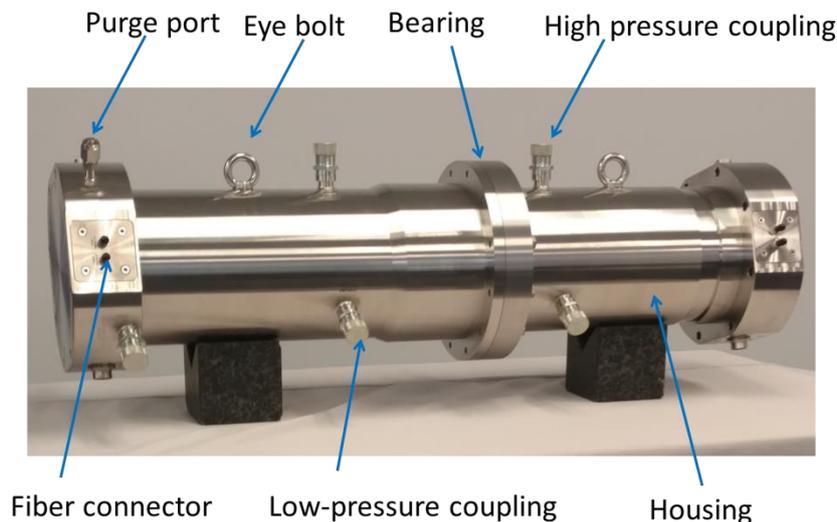


Figure 4. Picture of the manufactured and assembled rotary helium union.

4. Test setup and results

After manufacturing and assembling the prototype RHU, a series of tests were performed to examine the performance according to the specifications listed in table 1. Figure 5 shows the picture of the test bench used to check the behaviour of the RHU. In the actual applications, the right-end flange connecting with the compressor keeps stationary, and the housing of the RHU rotates driven by the shaft. However, noticing that the rotation is a relative movement, it is possible to perform the rotation in a reverse but simpler way on the test bench shown in figure 5. Since the compressor would not be connected during the test, we will rotate the right-end flange instead of the whole housing of RHU. A drive plate was developed to attach the flange and connect with a driving motor. A gear box is used in between to adjust the rotation speed. Moreover, a torque sensor is inserted to measure the starting and operating torque of the RHU under rotation.

The first test step is to check the sealing performance of this novel RHU. We started from the high-pressure line. To test the pressure capacity of the helium transfer line, we capped off three of the four ports and left one open to connect to the gas source through an assembly regulator. In the pressure test of the high pressure line, the pressure circuit in the low-pressure line remained open. Then we proceeded to pressurize the circuit to 33 bar and monitored the pressure for an hour. The same set up and test procedure was conducted on the low-pressure line to a pressure of 25 bar. The measured

pressures as function of time is presented in figure 6, in which both high-pressure and low-pressure line are included. As can be seen in figure 6, no noticeable pressure drop was overserved in both helium lines. We had also tested the leak rate of this RHU under stationary conditions using a leak detector. The measured leak rate of both helium lines at specified pressure was smaller than the sensor limit of the detector, which is 1.0×10^{-9} mbar·l/s.

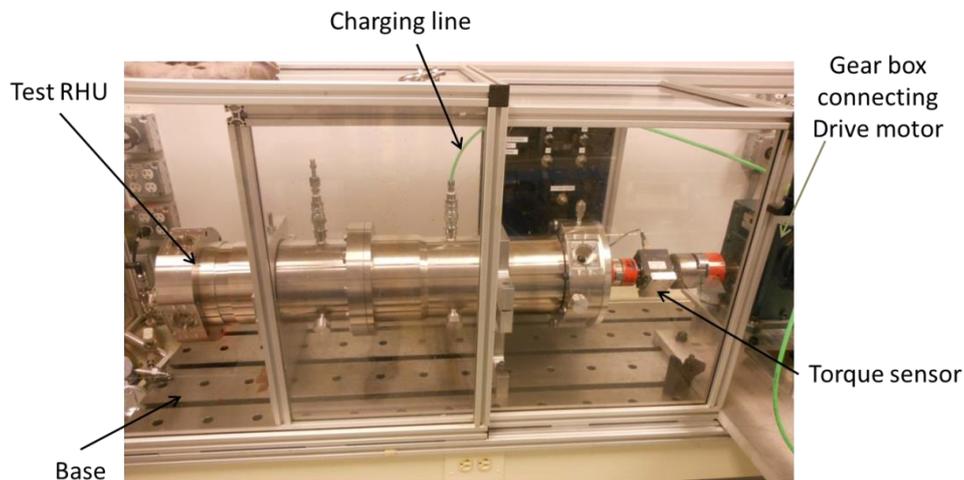


Figure 5. Picture of the test bench used to examine the assembled RHU.

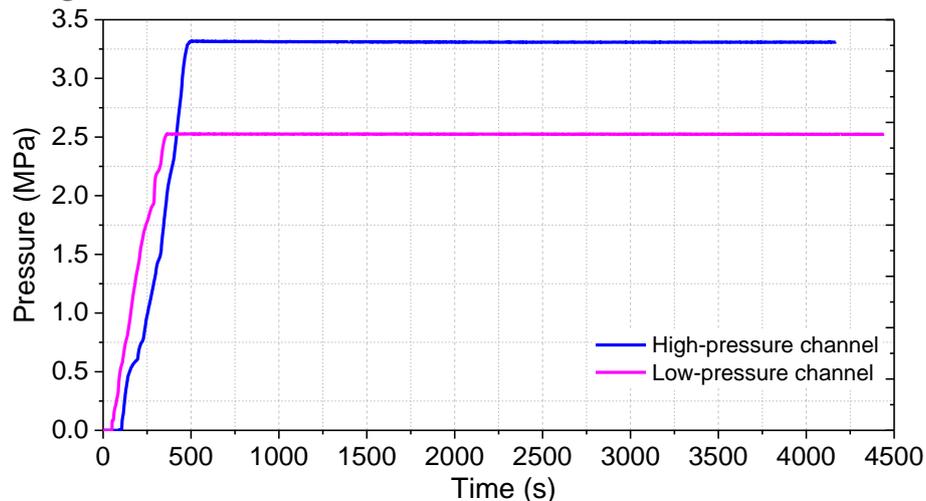


Figure 6. Measured pressure as function of time

Figure 7 presents the measured running torque of the RHU at a rotation speed of 150 rpm. The results were recorded after 24 hours and 48 hours, respectively. After starting the unit, the running torque first rapidly increases to a peak value and then gradually reduces to a stable state. Since the torque transducer has a measurement range up to 50 N·m, the torque above the limit is replaced with the value of 50 N·m as indicated by the straight line on the torque curve, and thus the actual peak torque was not illustrated in figure 7. However, using curve fitting we estimated the maximum starting torque is 57 N·m and 62.5 N·m after a time period of 24 hours and 48 hours, respectively. The normal running torque of the RHU was around 23 N·m. These torque characteristics of the RHU is necessary for the end user who will need to select the appropriate AC motor to drive the RHU.

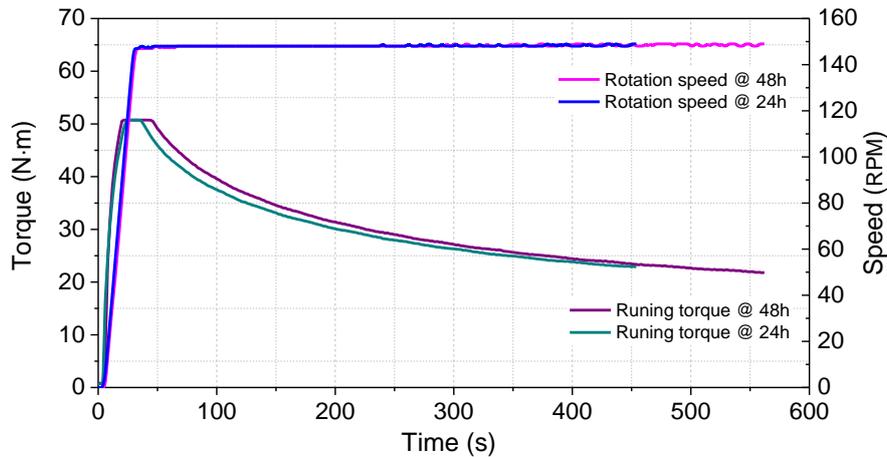


Figure 7. Measured running torque and rotation speed of the RHU after 24 hours and 48 hours.

5. On site installation

Figure 8 shows the picture of the RHU mounted in position in the SCG demonstrator. Mechanically, the RHU rotating flange linking to the cold head is fixed to the non-drive end of the shaft. The shaft adopts hollow shape in order to permit passing the helium transfer lines, cables and optical fiber through the bearing. To avoid problems regarding thermal expansion, the opposite stationary flange has been mounted over linear guides. In between the rotating flange and the end of shaft, there is a cylindrical part with window saved to allow the access to the shaft central hole.

The on-board electronic system installed in the rotor is used to acquire the experiment results of measured voltages, temperatures and also the magnetic field through hall sensors and flux measuring coils. The optical fiber in the RHU has been designed to work together with a pair of Ethernet media converter to convert and transfer measurement signals from rotating side to the stationary side. In this way, as shown in figure 9, the on-board electronic system and the PC running the supervisory control and data acquisition (SCADA) can be connected through a common LAN, taking advantage of the TCP / IP flexibility for the data transmission and reception. The optical link is able to provide couplings for two multimode fibers and externally behaves as a passive and bidirectional component.

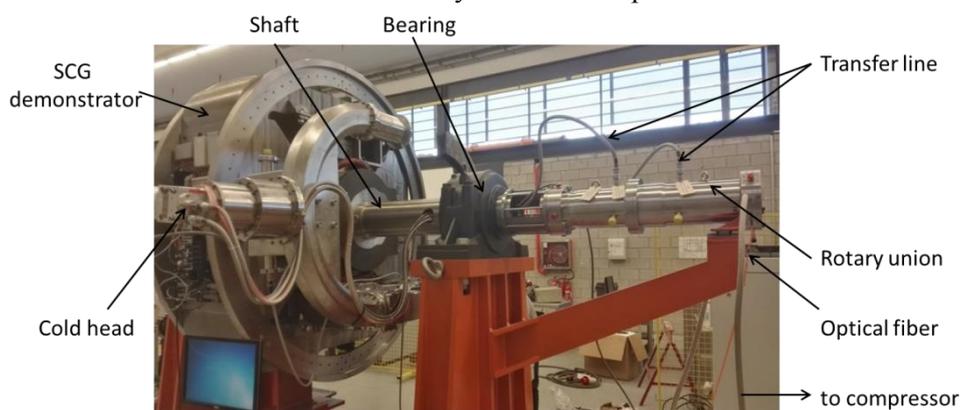


Figure 8. Picture of the rotary union installed in the Rotating Magnetic Validator (RMV).

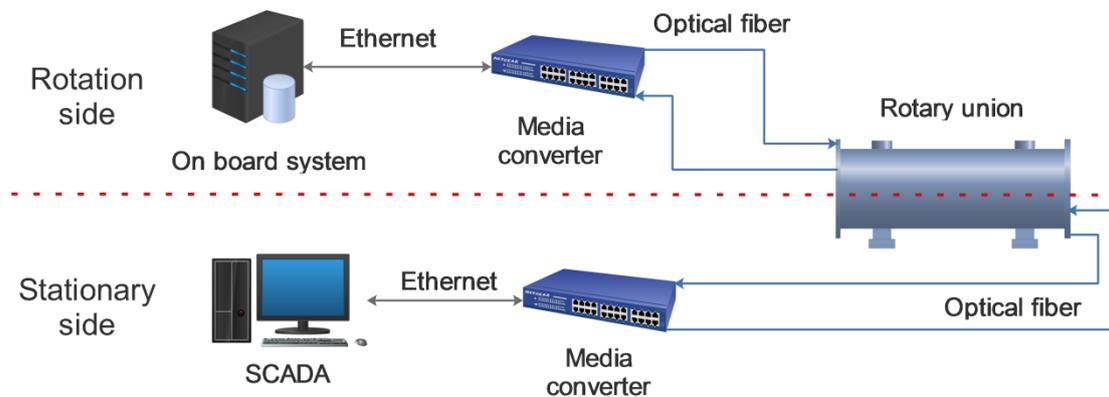


Figure 9. Signal transfer in the SCG demonstrator from the rotation side to the stationary side.

6. Conclusion

A compact and fully functional rotary union using ferrofluid sealing was successfully developed for the G-M cryocooler applied in the HTS rotating wind generators. The preliminary test results prove the performance and availability of the assembled union. The use of standard hydraulic, electrical and optical couplings makes it feasible to be applied in other similar applications. This novel RHU has already been installed on site and more experiments will be performed in order to further investigate the reliability.

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Acknowledgement

This research is primarily supported by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement 308793. Thanks for the technical support from Tom Black and Mark Granoff at Ferrotec.