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Hybrid Energy Transfer Line With Liquid Hydrogen and Superconducting MgB_2 Cable First Experimental Proof of Concept

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(Invited Paper)

Abstract The transfer of massive amounts of both electrical and chemical power over long distances will present a major challenge for the global energy enterprise in the future. Attraction of hydrogen is apparent as a chemical energy agent, possessing among the highest energy density content of various common fuels, whose combustive waste is simply water. It could be transferred via cryogenic tubes being liquid at temperatures 18 26 K. The usage of gratis cold to cool a superconducting cable made of a proper superconductor permits to deliver extra electrical power with the same line. In this paper, we describe the experimental modeling of this concept via a combined MgB_2-cryogenic dc superconducting cable refrigerated by singlet phase liquid hydrogen. We present the design, construction details, and test results of a 10-m prototype, focusing on choice of MgB_2 cable and cryostat technologies. We also discuss the opportunities and possibilities for future practical deployment of such hybrid energy delivery systems.

Index Terms Energy transmission, liquid hydrogen, MgB_2, superconducting cables.

I. Introduction

THE ENERGY transmission from a production site to the place of its consuming is as much important task as just energy production itself. Very often the energy production facilities are located faraway from densely populated areas. It can apply to both nuclear and future thermonuclear energy production. It may be applied to hydropower stations as well. Speaking on green energy, the world-wide deployment of new forms of the electricity generation such as wind, geothermal or solar cannot occur without a renewed investment in the energy transmission infrastructures. New connections should be built to link areas with vast potential to deliver the energy to the areas that have demands for power. Different energy carriers could be used: oil, gas, and certainly electricity.

The problem of the power transfer in the amounts of few GWs and more is discussing for many years. One of the initial discussions returns us back far to 1967 and consider low-T_c superconductors (LTS) [1]. A few LTS high power superconducting cables based on Nb3Sn has been developed [2] [4] and tested in the end of 70-ties early 80-ties. Anyway the AC cables put into effect a delivery only for distance up to 35 40 km from over rising of the reactive power.

Superconductivity is the choice for the electricity transmission by DC cables. Absence of any losses except for cooling makes DC superconductivity very effective. It was also discussed for a long time starting from [1] and later, for example in [5]. One of the most extensive reviews of the previous projects of the AC and DC cable may be found in [6].

The discovery of high temperature superconducting (HTS) materials has inspired new developments for energy transmission by means of superconducting cables. It is generally acknowledged that superconducting power cables are the most advanced HTS applications and they are practically near the commercialization. Up to now the biggest HTS AC power cable is 600 m in length and has rated power about 570 MWA [7].

Nevertheless, in the future power transmission demands could be more than tenths of GW. The discussions about such power grids renewed again with HTS discovery, see for example [6]. The similar issues were discussed during symposium [8]. One of ideas that were in the wind for a long time is to use the liquid hydrogen both as a cryogen and as an extra fuel to provide a very high ow of the energy. This led to the idea of a super-grid [9] that is more attractive as the necessity to use of hydrogen in the power energetics and for other purposes becomes a rather popular point of view.

We have to acknowledge that the concept of the dual delivery of chemical and electrical power employing just MgB_2 wire

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TABLE I
PROPERTIES OF MOST COMMON SUPERCONDUCTORS

Type - Wire technology	Basic material, T_c	Cryogen and typical temperature	Approximate prices US$ per 1кA·м (as of mid-2012)
LTS – metallurgy	NbTi - alloy ~ 10 K	Liquid helium at 4.2 K and below	Up to 3-5$ @ 4.2 K
LTS – metallurgy	Nb_3Sn – compound ~ 18 K	Helium up to 8-10 K and below	Up to 15$ @ 4.2K
HTS 1 Generation (Powder in tube – metallurgy)	Ceramic $Bi_2Sr_2Ca_{n-1}Cu_nO2_{n-4}$ (Bi-2223,Bi-2212) ~90-110 K	Liquid nitrogen at 77 K and below (with other cryogens)	About 120-150$ @ 77 K About 40-50$ @ 20 K
HTS 2 Generation (Long coated conductors - electronics)	Ceramic $YBa_2Cu_3O_{7-d}$ ~90 K	Liquid nitrogen at 77 K and below (with other cryogens)	About 300-500$ @ 77 K About 80-150$ @ 20 K
Magnesium diboride - (Powder in tube – metallurgy)	MgB_2 – compound ~39 K	Liquid hydrogen and below (with other cryogens)	About 5$ @ 20 K

cooled by liquid hydrogen through a single cable corridor was first mentioned by P.M. Grant as early as 2001–2002 [10], [11], very shortly after MgB_2 has been discovered in January 2001. This concept has been termed as hydricity after hydrogen + electricity. Later in a lot of papers, both popular and peer-reviewed, the problems of the hybrid energy delivery were discussed using a hydricity concept [12]–[19].

Combusting hydrogen as a fuel would be the optimal choice. It has highest fuel efficiency among others 120 MJ/kg. It could be transferred in a liquid state through a long cryogenic transferring line to place of consuming. We have to note that liquid hydrogen is the best cryogen having the cooling capacity 446 kJ/kg against 20.3 kJ/kg for LHe and 199 kJ/kg for LN_2. Thus, the idea to place into a transfer line with liquid hydrogen a superconducting cable to transmit the electricity in parallel is quite natural. Besides references mentioned, this idea has been discussed in [20]–[22] as well.

The question is what kind of superconductor should be used for the cable in a hydrogen energy transfer line. It was shown that an optimal choice could be recently discovered MgB_2 with a critical temperature of ~39 K [20].

To conclude, there are a lot of theoretical and simulation works discussing possible hybrid energy transfer lines using liquid hydrogen both as a fuel and cryogen, and a superconducting power cable to deliver extra electrical energy [8]–[23]. Nevertheless no any experimental works have been performed so far to proof this concept. In our work we took the challenge to perform the experimental study of hybrid energy transmission.

The major goals of our work were:

- To learn how to work with LH_2;
- To get the first experimental data about hybrid energy transport systems with LH_2 and superconductivity.

To succeed in these goals we had to:

- choose the proper superconductor: that is surely MgB_2;
- check characteristics of MgB2, its manufacturability and how to work with it;
- design and make a superconducting cable with it;
- develop and manufacture a liquid hydrogen cryogenic line;
- insert a cable inside a cryogenic line and connect to cryogenic system and electric grid;
- deliver it to a test facility equipped with a liquid hydrogen supply;
- make tests.

Here we are presenting the detailed data on the superconducting wire and cable which were used, and the test results of the prototype of a hybrid energy transfer line. The details of the cryogenic system were presented earlier in [24]; the earliest test results presented in [25].

II. CHOICE OF SUPERCONDUCTOR

The most common superconductors that are used in applications and are available at the market are listed in the Table I. The liquid hydrogen has temperature ~20 K at atmospheric pressure. Thus it is out of the question to use common LTS superconductors. The choice should be done between superconductors that can work at LH_2. They are either HTS or MgB_2. HTS of both generations (1G and 2G) are freely available at the market. But considering the price (see the Table I) and the good superconducting properties including the high stability at 20 K [26], the MgB_2 is the preferable choice for a system with liquid hydrogen.

Only two companies are selling MgB_2 wires right now: Hyper Tech Research Inc. in Columbus, Ohio, USA [27] and Columbus Superconductor (CS) SpA in Genoa, Italy [28].

The first company offers MgB_2 wires that should be heat treated after the making a device. Assuredly they are good for any winding and magnets, but definitely are not suitable for the long cables. It is difficult to imagine heat treatment of long cable with ~100–200 m length that could be bending and unbending after heat treatment. On the other hand, the CS offers long length wires that can be used without heat treatment. The shape of the wires is varying from round and quadratic wires to different flat tapes [28].

Recently we developed the technology for HTS power cables made of flat HTS tapes [29]. That is why for this project we also decided to use flat tape to employ the same cabling and insulation technology as for HTS power cables.

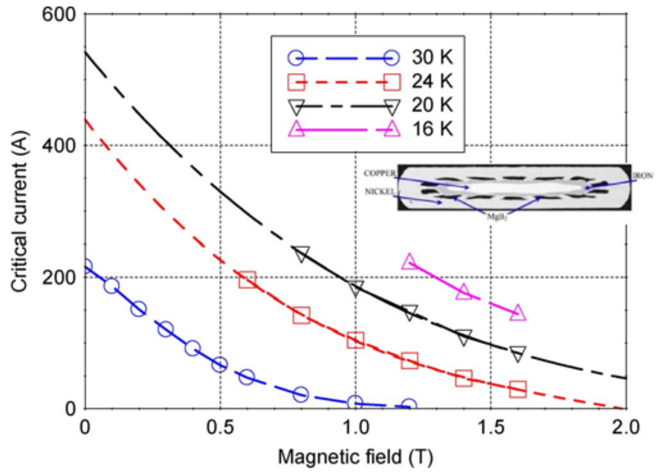

Fig. 1. Dependence of critical current on magnetic field at different temperatures for the flat MgB_2 wire used in our experiment [28]. Cross-section of the wire is shown.

The selected tape and its critical current dependence on field and temperature obtained from [28] are shown in Fig. 1. The cross section of the wire is: 3.64 mm × 0.65 mm; MgB_2 cross section ≈ 12% of total area; cross section of copper ≈ 15% of total area. The minimum diameter of bending with no degradation of critical current specified by CS is 110 mm.

As there were no specific data about critical currents at ~20 K in self field for the wire selected we used some extrapolation of data from CS shown in Fig. 1, that returned expected I_c (20 K) ≈520–540 A. This value was used for the preliminary design of the cable. Later we performed measuring of $I_c(T)$ for this wire and found that there is some scattering of I_c along wires and evaluated the influence of scattering on the current of a cable [29]. Anyway the preliminary estimation returned fair result for the cable current evaluation.

III. Cable Design and Production

The design of a prototype of a superconducting MgB_2 cable consists of three elements: a former, current carrying layers and insulation (Fig. 2(a)). The former is a central element that performed the supporting function. It consists of:

- the main supporting stainless steel spiral that formed a ~12 mm diameter internal channel for the flow of liquid hydrogen;
- twisted winding of copper wires with a total cross section sufficient to ensure reliable protection of the superconducting current carrying layer in case of short circuit fault;
- copper tapes winding providing a smooth outer surface of the former for assembling the superconducting MgB_2 tapes which are the main current carrying layer.

The superconducting current carrying path consists of two serially connected layers; each of them consists of five MgB_2 tapes helically wound on the former. The number of tapes has been selected to ensure the maximum current not more than 3 kA inasmuch as DC power supplies limited us by this current.

The insulation consists of 20 layers of a polyimide (Kapton) tape with the thickness of 50 μm. The total insulation thickness of ~1 mm allowed the cable to operate in principle at voltages more than 20 kV. In Fig. 2 are shown: the sketch of cross-section of the cable with all sizes (Fig. 2(a)), 3D view of the cable (Fig. 2(b)); cross-section (Fig. 2(c)) and photo of the MgB_2 cable model (Fig. 2(d)). The cable had a length about 10 m. At one end both current layers were connected by jumpers to provide the returning current. Thus, the total length of the current carrying element considering the two layers assembly was ~20 m. We expected that the critical current of the cable could be ~2.5–3 kA at temperature ~20 K.

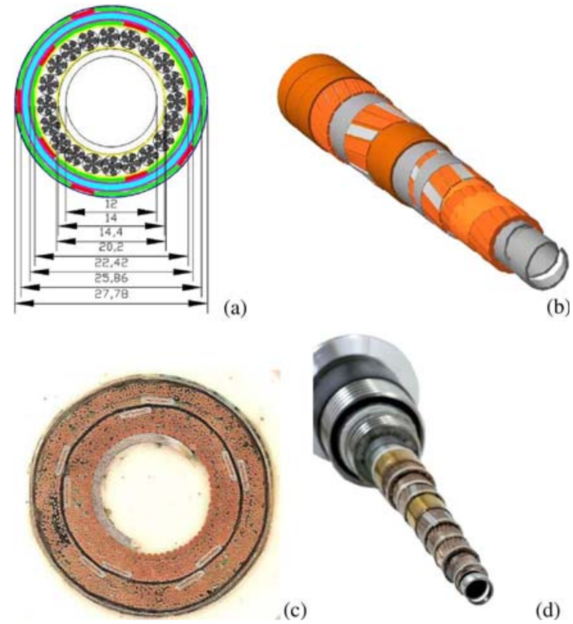

Fig. 2. MgB_2 cable design: (a) sketch of cross-section with sizes shown; (b) 3D view of cable; (c) cross-section of a cable; and (d) photo of the cable model.

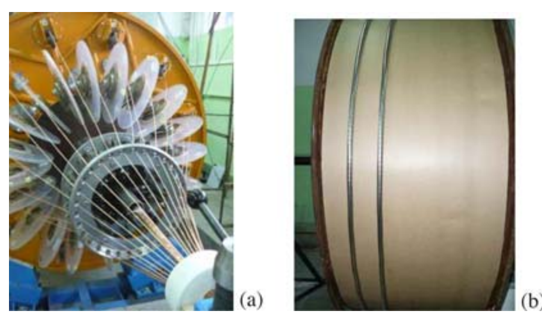

Fig. 3. Cable production illustrations: (a) pay off wires from a cabling machine and (b) cable on a take up drum.

The cable has been manufactured with the standard cabling equipment in JSC "VNIIKP" and with the technology developed for HTS power cable production [29]. Some illustrations from the cable manufacturing process are shown in Fig. 3.

After production the cable has been delivered to the Moscow Aviation Institute to be installed into a cryostat.

IV. Hybrid Energy Transmission Line

The Hybrid Energy Transmission Line (HETL) has been described in details in [24], [25]. It consists of a long hydrogen cryostat with ~12 m length, a system for liquid hydrogen

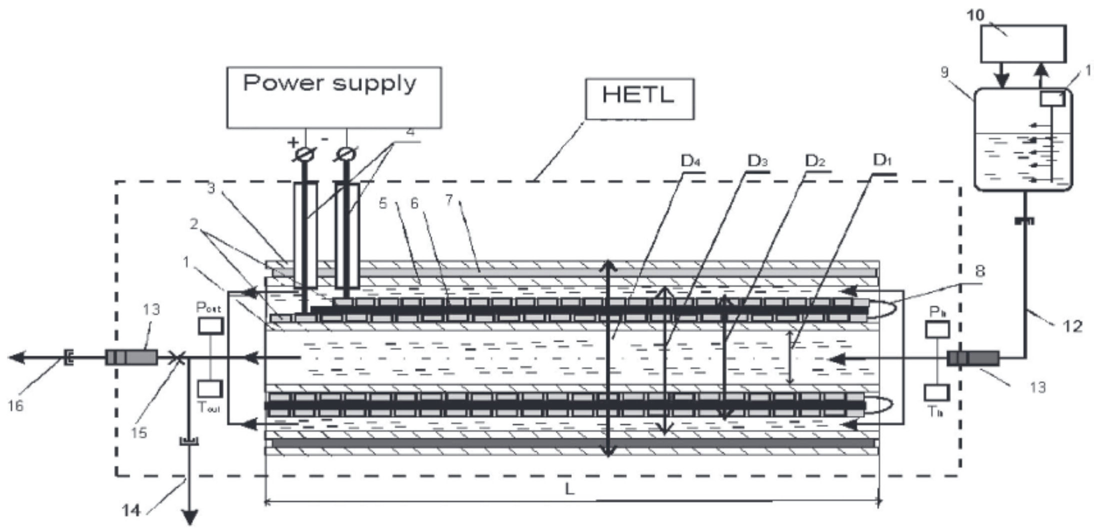

Fig. 4. Sketch of the HETL experimental test facility: (1) former; (2) current carrying superconductors; (3) outer tube of cryostat; (4) current leads; (5) inner tube of the cryostat; (6) polyimide insulation; (7) layered super-insulation; (8) current jumpers; (9) liquid hydrogen storage tank; (10) filling, pressure busting and drainage systems; (11) level meter and temperature sensors; (12) liquid hydrogen 12 m transfer line; (13) bayonet connectors ? = 32 mm; (14) drainage 4 m flexible line ? = 32 mm; (15) jet nozzle ? = 4 mm; (16) drainage flexible line ? = 32 mm; L □ 12 m, is the total length of the cryostat with current leads, the length of the cable is 10 m.

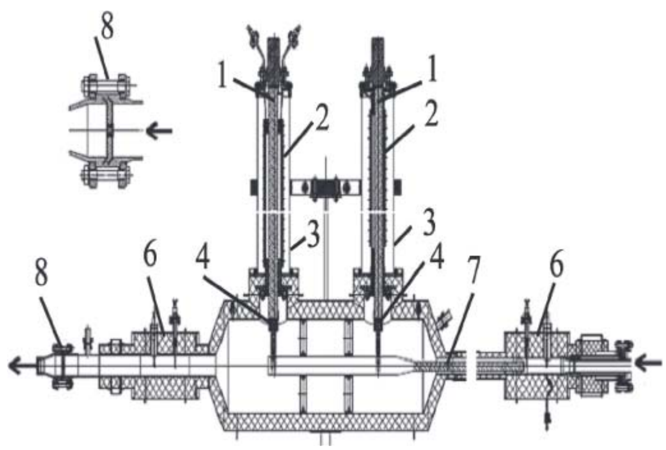

Fig. 5. Current leads for the superconducting cable of the HETL: (1) current pathway; (2) insulating polyimide tube with outer bandages; (3) load bearing support; (4) connectors to join cable; (5) getter; (6) measuring probes; (7) connections of flexible copper bunches and superconductors; (8) mounting part.

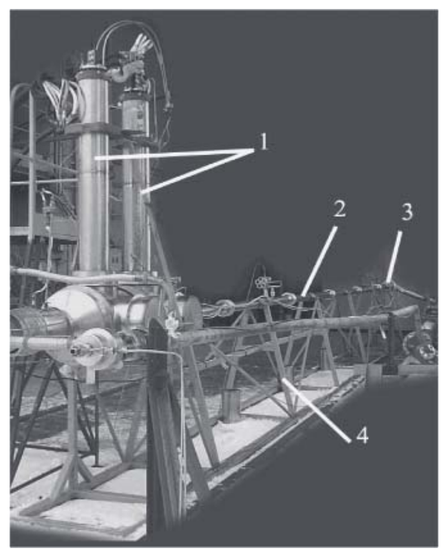

Fig. 6. General view of the HETL installed at the test facility: (1) current leads; (2) cryostat; (3) inlet part; and (4) mounting frame.

supplying and an experiment control unit to control parameters of pressure, flow and temperature.

The cryostat for the liquid hydrogen transfer at 20–30 K simultaneously ensures cryostating of the MgB_2 cable for the transfer of the electricity and the flow of LH_2 as a fuel.

The cryostat (Fig. 4) consist of an outer shell (3) with diameter $D4 = 80$ mm, a vacuum thermal insulation (7) and an inner cryostat shell (5) with diameter $D3 = 40$ mm. There were 6 sections of the cryostat to provide the safe work in case of vacuum loss in one of sections.

The current leads (terminations) are shown in Fig. 5. The current lead consists of:

- a vessel formed by inner and outer shells with diameters 270 mm and 370 mm correspondingly;
- flexible copper current pathways with 600 mm^2 cross-section (1);
- polyimide insulating tubes with an outer banding and welded edges made from stainless steel flanges (2);
- a load bearing support to provide the rigidity of the insulating tube (3);
- connectors of current pathways (4) with flexible copper bunches and superconductors (7);
- joints to the cable from power supplies.

At the inlet and outlet of the HETL two sets of measuring probes have been installed to measure pressure and temperature of the liquid hydrogen flow.

The HETL was mounted on the rigid frame with 10.2 m length and 0.8 m width. The cantilevers of the frame provided vertical stability of current leads that have 1.26 m height. The total height of the HETL was 2.48 m. General view of the HETL installed at the test facility is shown in Fig. 6.

Fig. 7. General view of the control monitor during tests.

V. Test Results

The experiments with the prototype of the hybrid power transmission line with forced flow of liquid hydrogen were carried out in November 2011. They were performed at the special facility intended for testing oxygen-hydrogen liquid propellant rocket engines with liquid hydrogen production plant of the KB “Khimavtomatika” (Voronezh City). The detailed results of the cryogenic tests are presented in [24].

The total cooling time was ≈380 s. To cool the system ≈2.3 kg of LH_2 was used. The evaluated heat losses were below 10 ± 2 W/m, the current lead losses at 2600 A were ≈300 W. The variations of temperature during measurements were from 20 K to 26 K, pressure was from 0.12 MPa to 0.5 MPa.

For electrical measurements the three parallel power supplies Agilent 6680 A were used. Current has been measured by a standard 7500 A/75 mV shunt. The output signal from the shunt and voltages from the voltage taps of the cable were measured by a multichannel digital analyzing oscilloscope Yokogawa DL 850. The operation of current sources and oscilloscope was remotely controlled via special communication lines.

The current carrying characteristics of the MgB_2 cable were recorded at the liquid hydrogen temperatures within 20–26 K, with the pressure (as mentioned above) in the interval from 0.12 to 0.5 MPa, and the mass flow rates in the range from 18 g/s to 250 g/s. The pressure drop at 250 g/s did not exceed 28 kPa. The variation of a temperature along a cable was from 0.2 to 0.8 K depending on the hydrogen flow rate. The conditions of cooling mean that the liquid phase of subcooled LH_2 under pressure was without bubbles. The view of the main control monitor during experiments is shown in Fig. 7.

The critical current $I_c(T)$ at a given temperature T was defined as the current for which the electric field between the voltage taps amounted to 1 μV/cm. The temperature, the pressure, and the flow rate of liquid hydrogen in the line were monitored simultaneously with the measurement of voltage on the internal and external current layers of the cable.

Fig. 8 shows typical experimental plots of voltages V on the current carrying layers against current I (voltage-current characteristic). The measurements of critical current were performed at low voltages up to ≈3 V. The values of critical currents determined from these plots amounted to ≈2640 A at $T = 20.4$ K and ≈2020 A at $T = 25.7$ K. Fig. 9 shows the corresponding dependence of the critical current on temperature.

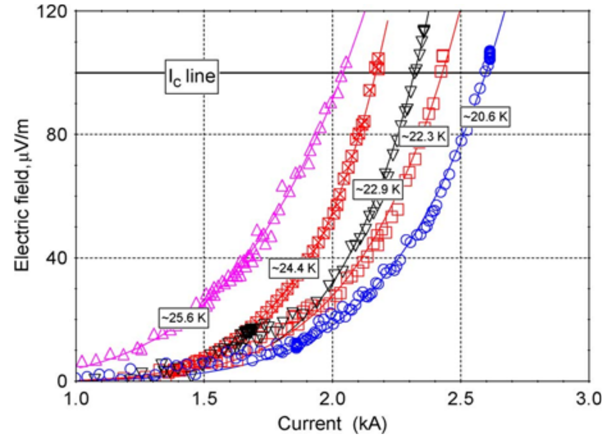

Fig. 8. Typical V–I characteristics of MgB_2 cable at different temperatures.

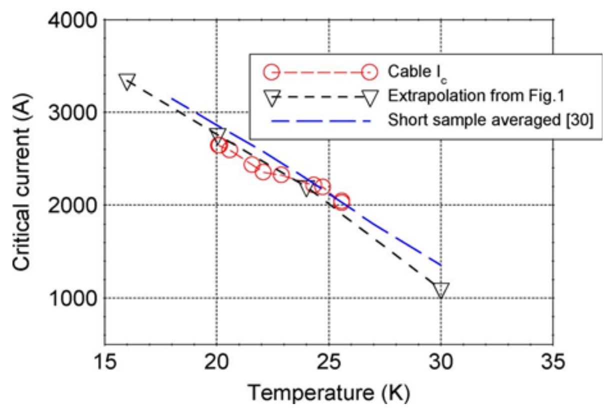

Fig. 9. Measured dependence of critical current on temperature of MgB_2 cable.

In Fig. 9 is shown the sum of currents of five wires from extrapolation to zero field data in Fig. 1. The evaluation of critical current by averaging its non-uniformity along a wire from [30] for five wires is presented also. One can see the good coincidence of all data that confirm good state of the cable after the industrial manufacturing process.

VI. Discussion and Future Plans

With LH_2 flow 250 g/s achieved in our cryostat, the energy transfer line would deliver ≈31 MW of chemical power. Superconducting cable at 2.5 kA and 20 kV prospective voltages would be able to deliver extra 50 MW, so ≈80 MW in total with only 5 MgB_2 tapes.

As it is seen in Fig. 2 it is easy to add at least ten tapes more to our current carrying layers that will increase the transport current threefold and corresponding electrical power to 150 MW and the total power to ≈180 MW. The cross section of our energy line is about 50 cm^2 only. Therefore the prototype of the tested hybrid energy transfer line has potential to deliver a power more than 100–150 MW with power flow density more than $p \approx 3 \times 10^6$ W/cm^2.

The first thread of the “North Stream” (gas pipeline from Russia to Europe via Baltic sea) has to deliver 27.5×10^9 m^3/year of natural gas. This means ≈870 m^3/s and deeming of the fuel efficiency $\sim$ 40 MJ/m^3 [31] this amounts to $\sim 3{:}5 \times 10^{10}$ W of power. The typical diameters of gas pipeline tubes are $\sim$150 cm that means that the cross section is $s \sim 18\,000$ cm^2 and power density flow $p \sim 2 \times 10^6$ W/cm^2. Thus our hybrid line being rather modest in size has potential to provide power flow equal to the biggest gas pipelines.

Acknowledging the result of tests performed the concept of a hybrid energy transmission system with high energy flows, first mentioned in [10], [11] should be considered experimentally proved.

During our experiments we had no opportunity to perform high voltage tests, so we only estimated the high voltage prospective. Therefore the high voltage test is our first priority in the future. Right now we are developing a longer and flexible cryogenic line ($\sim$30 m). The cable will be longer also. The test plan will include the separate high voltage test and the current test with LH_2 cooling. Cryostat and new cable should be ready by the end of this year. The hydrogen test of a new system is planning for the 2013.

VII. Conclusion

The first in the world prototype of hybrid energy transfer line consisting of liquid hydrogen cryogenic line and MgB_2 based superconducting cable has been developed and successfully tested.

The flat MgB_2 wire from Columbus Superconductor has a good manufacturability and could be used for industrial cable production. Its superconducting parameters are good with more than $\sim$ 220 A/mm^2 of overall critical current density at 20 K.

The liquid hydrogen cryogenic line with special current leads has been developed and tested. The maximum of a liquid hydrogen flow achieved 250 g/s. The first hydrodynamic and superconducting data of the hybrid energy transport system have been obtained [24]–[26].

The MgB_2 based superconducting power cable prototype with 10 m length has been developed produced and tested. Currents achieved were $\sim$2000–2600 A.

These developments and experiments demonstrated high potential of hybrid energy transfer lines which are able to deliver a high power flow within modest sizes of a line. The concept of hybrid energy transfer lines [10], [11] has been proved experimentally.

Acknowledgment

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