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

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***Abstract*— Transfer of high power flow over long distances will be the one of the major task for energetics in this century. Liquid hydrogen's attraction is clear -- it has the highest energy content of any known fuel and when it's burned, the "waste" is water. It could be transferred via cryogenic tubes like other cryogen liquids. Moreover, with the use of "gratis" cold to cool a superconducting cable an extra electrical power can be delivered with the same line. One of solutions is to use of MgB_2 based DC power cables with single phase liquid hydrogen as a cooler and energy carrier. The team of Russian researchers developed and tested the first experimental prototype of the future hydrogen and superconducting energy transport system. In the paper presented the analysis of superconducting materials to work at temperatures ~20K are considered and choice of MgB_2 is justified. Experimental MgB_2 cable design and test facility are described. Test results of the first proof of concept of hybrid energy systems are presented. Future prospective of hybrid energy transfer systems is discussed.**

***Index Terms*—liquid hydrogen, superconducting cables, MgB_2, energy transfer.**

I. INTRODUCTION

ENERGY transfer from its production site to the place of its consuming is as much important task as just energy production itself. Very often energy production facilities are located far away from densely populated areas. It can apply to both nuclear and future thermonuclear energy production. It may apply to hydropower stations as well. Speaking on green energy, the world-wide deployment of new forms of electricity likes 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 generate energy to the areas that have demands for power. Different energy carriers could be used: oil, gas, and of course electricity.

The problem of energy transfer on the level of few GWs and more is being discussing for many years. One of the first discussions is back as far as to 1967 considering low-T_c superconductors [1]. Few low-T_c Nb_3Sn based high power superconducting cables has been developed [2] - [4] and tested in the end of 70-ties and mid 80-ties. Anyway, AC cables are feasible up to 35-40 km delivery distance only due to reactive power rising.

Superconductivity is the choice for electricity transfer by DC cables. Absence of any losses but for cooling only makes DC superconductivity very effective. It was discussed also long time back starting from [1] and later for example in [5].

High temperature discovery inspired for new developments for energy transfer by superconducting cables. It is generally acknowledged that superconducting power cables are most advanced HTS applications and they are most close to commercialization. The biggest HTS AC power cable up to now has 600 m in length and up to ~570 MWA rated power [6].

Nevertheless, future energy transfer demands should be more than tenths of GW. The discussions about such power grids started again with HTS discovery, see for example [7]. Similar issues were discussed during symposium [8]. And one of idea that was in the air for a long time is to use liquid hydrogen as a cryogen and as an extra fuel to deliver very high flow of 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 other purposes becomes more and more common point of view.

Considering as the burning fuel the hydrogen could be a best solution. It has highest fuel efficiency among others – 120 MJ/kg. It could be transferred as a liquid fuel by a long cryogenic transferring line to place of demands.

On the other hand, the liquid hydrogen is the best cryogen as well, with 446 kJ/kg cooling capacity against 20.3 kJ/kg for LHe and 199 kJ/kg for LN2. Thus, the idea to place into the liquid hydrogen transfer line some superconducting cable to transfer electricity in parallel is quite natural. This idea has been discussed in [10]-[12].

The question is: what kind of superconductor to use for the

Manuscript received October 9, 2012. This study was performed in the framework of the program "Basic Principles of Development of Power Systems and Technologies, Including High Temperature Superconductors" supported by the Presidium of the Russian Academy of Sciences.

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cable in an energy transfer line. The decision was that optimal should be rather recently discovered MgB_2 with its critical temperature ~39 K [10].

So, there are a lot of theoretical and simulation works about possible hybrid energy transfer lines using liquid hydrogen as fuel and cryogen and superconducting power cable to deliver more extra electrical energy [10]-[13]. Nevertheless, no any experimental works have been performed to proof of this concept. We got this task to complete the experimental study of hybrid energy transfer.

The major goals of our work were:

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

To complete these goals we had:

- To choose the proper superconductor, that is of course MgB_2;
- To check what is MgB_2, its manufacturability and how to work with it?
- To design and make superconducting cable with it;
- To develop and produce liquid hydrogen cryogenic line;
- To insert a cable inside cryogenic line and connect to cryogenics and electricity
- Bring to test facility with liquid hydrogen;
- Make tests.

Here we are presenting the details of superconducting wire and cable used and test results of this prototype of hybrid energy transfer system. The cryogenic system details have been presented earlier in [14].

II. SUPERCONDUCTOR'S CHOICE

The most common superconductors that are used in application and are available at the market are shown in the Table I. The liquid hydrogen at atmospheric pressure has temperature ~20 K. Thus, there are no talks about usual LTS superconductors. The choice should be done between superconductors that can work at LH_2 that are either HTS or MgB_2. HTS both of 1G and 2G are freely available at the market. But considering the price (see the Table I) and good superconducting properties including high stability at 20 K [15], the MgB_2 is of course the superconductor of choice for liquid hydrogen cooled systems.

Only two companies are offering MgB_2 wires right now: Hyper Tech Research Inc. in Columbus, Ohio, USA [16] and Columbus Superconductor SpA in Genoa, Italy [17].

The first company offers MgB_2 wires that should be heat treated after the winding that are of course good for any winding and magnets, but definitely are not suitable for 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 Columbus Superconductor offers long length wires that can be used without heat treatments. The shape of the wires is varying from round and quadratic wires to different flat tapes [16].

Previously, we developed the technology of HTS power cables made of flat HTS tapes [17]. For this project we decided to use flat tape as well to use same cabling and insulation technology as before.

The tape selected and its critical current dependence on field and temperature obtained from [16] are shown in Fig.1. Wire cross section is: 3.64 mm x 0.65 mm; MgB_2 cross section: 12% of total area; copper cross section: 15% of total area. Minimum bending diameter at no degradation: 110 mm.

As there was no specific data about critical currents at ~20 K in self field for the wire selected we used extrapolation data shown in Fig.1, that provided expected $I_c(20\text{ K})$ ~ 520 - 540 A. This value was used for the preliminary design of the cable.

TABLE I.
PROPERTIES OF MOST COMMON SUPERCONDUCTORS

Type - Superconducting technology	Basic material, T_c	Cryogen and its temperature	Approximate prices US$ per 1kA·m (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 $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ (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

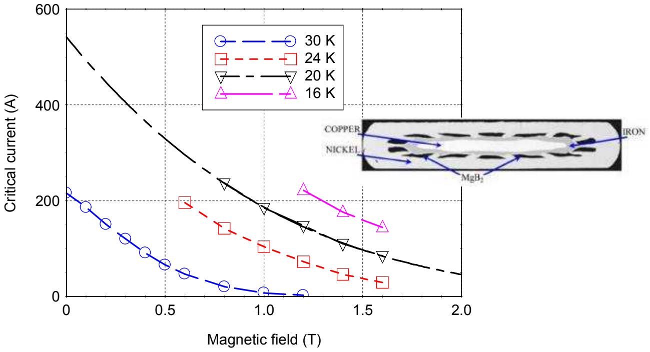

Fig. 1. Dependence of critical current on magnetic field and temperature for the flat MgB2 wire we used in our experiment [16]. Cross-section of the wire used is shown.

Later we performed measuring of *Ic(T)* for this wire and found that there is some scattering of *Ic* along a sample and evaluated the influence of scattering on the current of a cable [20]. Anyway the preliminary estimation returned fair result for the cable current evaluation.

III. CABLE DESIGN AND PRODUCTION

The design of a prototype superconducting MgB_2 cable consists of three elements: 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;
- a twisted bunch of copper wires with a total cross section sufficient to ensure reliable protection of the main current carrying layer in cases of short circuit fault;
- a bunch of copper tapes providing a smooth outer surface of the former for assembling the superconducting MgB_2 tapes of the main current carrying layer.

The main current carrying layer consists of two serially connected layers, each consist of five MgB_2 tapes helically wound on the former. Number of tapes has been selected to ensure the maximum current not more than 3 kA as we had currents limited by our DC power supplies. The insulation consists of 20 layers of 50 µm thick polyimide (Kapton™) film. The total insulation thickness of ~1 mm allowed the cable to operate in principle at voltages more than 20 kV. Fig. 2a shows the design of a cable with all sizes, artistic view of a cable (Fig.2 b); cross-section (Fig.2 c) and general view (Fig.2 d) of the MgB_2 cable. The cable had a length of 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. The cable has expected that critical current could be ~2.5–3 kA at a temperature of ~20 K.

The cable has been produced by use of standard cable equipment in JSC "VNIIKP" by use of technology developed for HTS power cable production [19]. The process of the cable production is shown in Fig.3.

After production the cable has been delivered to Moscow Aviation Institute (Technical University – MAI) to be installed into a cryostat,

IV. HYBRID ENERGY TRANSFER LINE

The Hybrid Energy Transfer Line (HETL) has been described in details in [14], [15]. It consists of long hydrogen cryostat with ~12 m length and systems for liquid hydrogen supplying and experiment control (Fig. 4). These systems provide liquid hydrogen with controlled pressure, flow and temperature.

The cryostat for liquid hydrogen transfer at 20–30 K simultaneously ensured cryostating of the MgB_2 cable for the electric energy transfer and LH_2 flow to deliver it as a fuel.

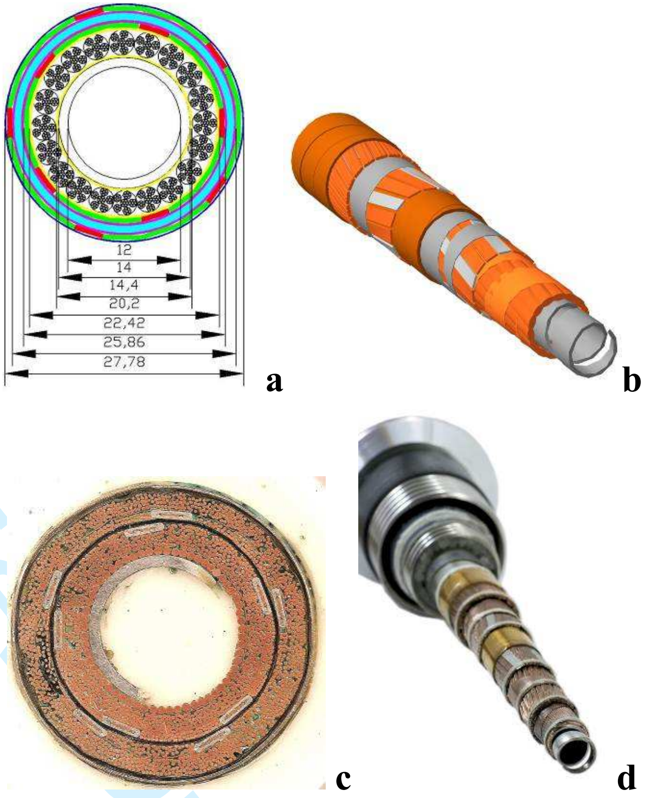

Fig.2 MgB_2 cable design: a – cables sizes; b – artistic view of a cable design; c – cable's cross-section; d – photo of the cable's maket

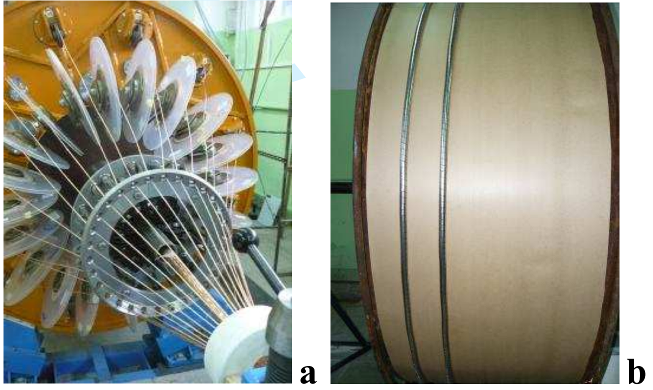

Fig.3 Cable's production: a – wires output from a a cabling machine; cable on a take in drum.

Others parts are: power sources, measuring systems and test facility control systems.

The cryostat (Fig.4) consist of outer shell (3) with diameter D4 = 80 mm, vacuum thermal insulation (7) and inner cryostat shell (5) with diameter D3 = 40 mm. There were 4 sections of

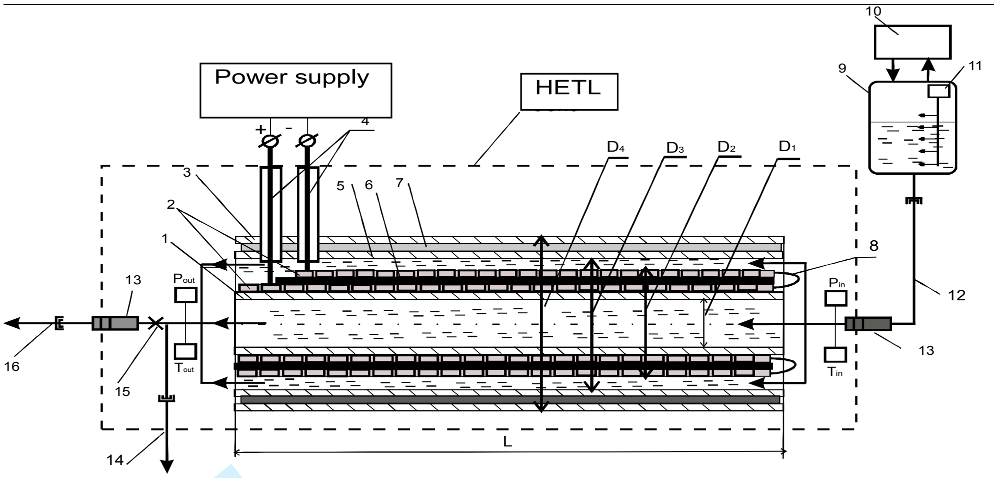

Fig. 4. The scheme of the experimental test facility HETL: 1- former; 2 – current carrying superconductors; 3 – outer tube of cryostat; 4 – current leads; 5 – inner tube of the cryostat; 6 – polyimide; 7 – layered super-insulation; 8 – current jumpers; 9 – liquid hydrogen storage tank; 10 – filling,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

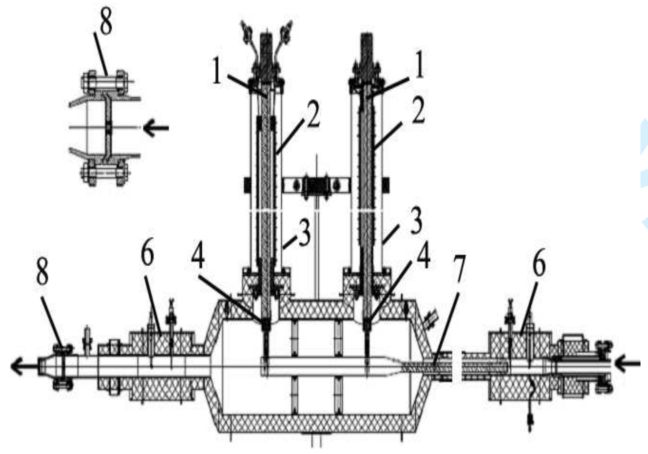

Fig. 5. Current leads for the superconducting cable of the HETL: 1 – current pathway; 2 – insulating polyimide tube with outer bandages; 3 – load bearing support; 4 – connection of the joint with a cable; 5 – getter; 6 – measuring probes; 7 – connections of flexible copper bunches and superconductors;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

the cryostat to provide safe work in case of vacuum loss in one section.

The current leads (terminations) are shown in Fig.5. Current leads consist of:

- The 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 (Kapton™) insulating tubes with outer bandaging and welded edges from stainless steel flanges (2);
- Load bearing support to provide the rigidity of the insulating tube (3);
- Joints of current pathways (4) with flexible copper bunches and superconductors (7);
- Joints for power cables from power supplies.

At the inlet and outlet of the HETL two measuring gauges 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 HETL installed at the test facility is shown in Fig.6

V. TEST RESULTS

The experiments with the prototype of hybrid power transmission line with forced flow of liquid hydrogen were carried out in November 2011 on a special facility intended for testing oxygen–hydrogen liquid propellant rocket engines and employed a hydrogen production plant of the KB "Khimavtomatika" (Voronezh City). Detailed cryogenic test results are presented in [14].

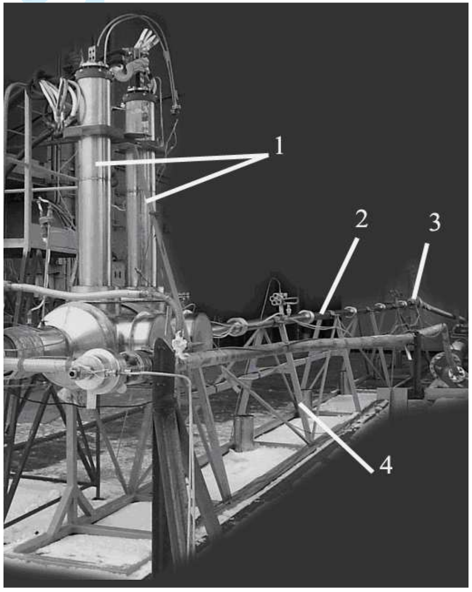

Fig. 6. General view of the HETL installed at the test facility 1 – current leads; 2 - cryostat; 3 – inlet part; 4 – mounting frame

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

For electrical measurements the three parallel power supplies Agilent 6680A were used. Current has been measured by a standard 7500A - 75 mV shunt. The output signal from the shunt and the values of 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 liquid hydrogen temperatures within 20–26 K, with pressures (as it was said above) in the interval from 0.12 to 0.5 MPa, and 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 view from the main control monitor during experiments is shown in Fig.7.

Fig. 7. The general view of the control monitor during tests

The variation of a temperature along a cable was from 0.2 to 0.8 K depending on hydrogen flow rate. These cooling conditions mean the liquid phase of subcooled LH_2 under pressure without bubbles.

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, pressure, and flow rate of liquid hydrogen in the line were monitored simultaneously with the measurement of voltages on the internal and external current layers of the cable.

Fig. 8 shows the typical experimental plot of voltage V on the current carrying layers versus current I (voltage – current characteristic). Current measurements 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 presents the corresponding temperature dependence of the critical current.

In Fig.9 we are presenting the sum of five wires' currents in from extrapolation to zero field data in Fig.1. The evaluation of critical current by averaged its non – uniformity along a wire from [20] for five wires is presented also. One can see the good coincidence of all data that confirm good state of a cable after industrial manufacturing process.

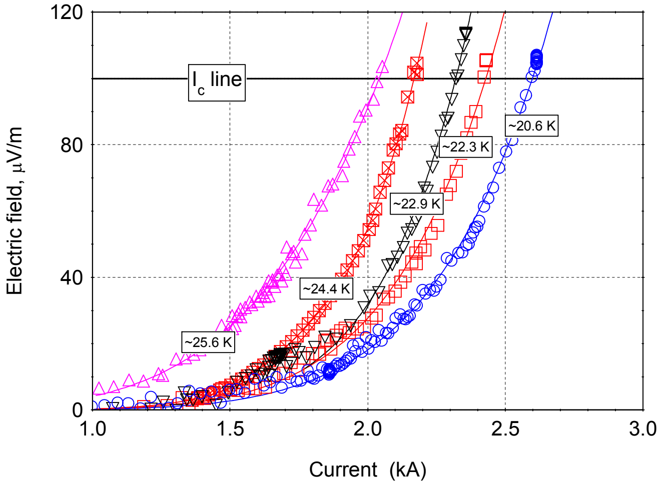

Fig.8 Typical V-I characteristics of MgB2 cable at different temperatures

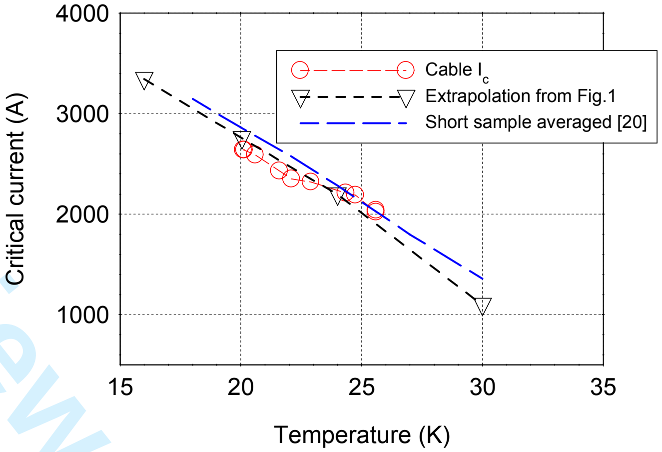

Fig.9. Measured dependence of critical current on temperature of MgB2 cable

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 a thermal 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 that will increase electrical power to 150 MW and total power to ~180 MW. Cross section of energy line is about 50 cm^2. Therefore, the prototype of the hybrid energy transfer line tested is able to deliver energy flow more than 100-150 MW with power flow density more than p~$3{\cdot}10^6$ W/cm^2.

The first thread of the "North Stream" gas pipeline from Russia to Europe has to deliver $27.5{\cdot}10^9$ m^3/year of natural gas. This means ~870 m^3/s and with ~ 40 MJ/m^3 of fuel efficiency [21] this lead to ~$3.5{\cdot}10^{10}$ W of power. Typical diameters of gas pipeline tubes are ~150 cm that means cross section s~18000 cm^2 and power density flow p~$2{\cdot}10^6$ W/cm^2. Thus, our rather modest in a size hybrid line has potential to provide power flow similar to the biggest gas pipelines.

With the tests done, the concept of hybrid energy transfer system for high energy flows should be considered experimentally proved.

During these our experiments we have 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 future. Right now we are developing longer and flexible cryogenic line (~ 30 m). Of course the cable will be longer as well. The test plan is considering high voltage test and current test separately during LH$_2$ cooling. We also plan to use another cable design made of round MgB$_2$ wires with two cable cores in one cryostat (bipolar DC cable). New coaxial cable design is considered as well (monopolar DC cable with returning wire). Cryostat and new cable should be ready by the end of this year. The hydrogen test of a new system is planning for the next year.

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.

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 ~220 A/mm^2 of overall critical current density at 20 K.

Liquid hydrogen cryogenic line with special current leads has been developed and tested. Maximum liquid hydrogen flow achieved 250 g/s. First hydrodynamic and superconducting data of the hybrid energy transport system has been obtained [14], [15].

The MgB$_2$ based superconducting power cable prototype with 10 m length has been developed produced and tested. Currents achieved were ~ 2000-2600 A.

These developments and experiments demonstrated high potential and perspectives of hybrid energy transfer lines which are able to deliver a high power with modest sizes of a line. The concept of hybrid energy transfer lines has been proved.

ACKNOWLEDGMENT

The authors are grateful to personnel of “Ekotekhnologiya” company and “KB Khimavtomatika” (Voronezh) for their help in preparation and conducting tests on the prototype power transmission line with liquid hydrogen and superconducting cable.

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