A proposal of the hybrid energy transfer pipe

Yury V Ivanov, Hirofumi Watanabe, Noriko Chikumoto, Noriyuki Inoue, Hirohisa Takano, Masae Kanda and Satarou Yamaguchi
Chubu University, Kasugai, Aichi 487-8501, Japan

E-mail: ivanov@isc.chubu.ac.jp

Abstract. Among the many modifications of superconducting power transmission lines, hybrid lines stand out for their originality. Their design implies the joint transmission of cold liquid fuel through the pipe and electricity through the high-temperature superconducting (HTS) cable cooled by this fuel directly or indirectly. Currently, the critical temperatures of HTS materials are low and that means that only liquid hydrogen can be the "cooling fuel". It is known that natural gas is a viable alternative to hydrogen as a chemical fuel for many reasons. Since its boiling temperature is too high, the use of liquefied natural gas (LNG) in hybrid lines is considered only in the future when suitable HTS materials will be discovered. Assuming that LNG cannot be used to cool HTS cable over the coming years, we propose to combine the LNG pipeline and the cable pipelines cold by liquid nitrogen in the common heat-insulating pipe. In addition to the considerable economic effect due to the common thermal insulation, the LNG cold will be utilized to cool the radiation shield that prevents the penetration of heat to the cable pipes.

1. Introduction
The steady increase in electricity consumption since Edison requires the permanent improvement of the transmission and distribution systems. It is expected that in the first half of the 21st century there will be a qualitative leap when introducing technical solutions based on high-temperature superconductors (HTS) into the power grid complex. The advantages of HTS DC technologies will be fully manifested when creating power transmission lines of hundreds of kilometers long [1]. Currently, there are several dozens of experimental HTS AC and DC lines in the world, some of which are incorporated in the commercial grids [2]. However, the maximum length is only 1 km, and the laying of a 2.5 km line in Russia will be completed in about 1-2 years [3, 4]. This is very short in comparison with the target length. The main problem is the need to keep superconducting cable at low temperature by maintaining the circulation of coolant along the entire length of the cable route. The heat penetrating through the thermal insulation invariably heats coolant. It means that it is necessary to build cooling stations along the route of the long cable.

There are several designs of the cryostats for HTS cable which is usually cooled by liquid nitrogen (LN2). In the simplest case, cable is installed inside one pipe and the second pipe closes the LN2 circulation loop (see figure 1). Pipes can be placed in individual vacuum jackets (outer pipes) or the single one as shown in figures 2(a) and 2(b), correspondingly. The interval between the stations depends on the quality of the thermal insulation taking into account the additional restriction imposed by the hydraulic resistance of the cryogenic channels. If the heat inflow is significant, the construction and operation costs will be too high.
Figure 1. Sketch of the simplest HTS power transmission line.

The pumping length can be increased by redistributing the incoming heat between the parallel cable and return pipes in such a way that most of the heat flux will be absorbed by the return flow of LN2. The increase in the temperature difference across the return pipe is not a crucial factor, while a decrease in the temperature gradient along the cable pipe will provide the preferred operating conditions for the HTS cable. Technically, that can be done by protecting the cable pipe with a radiation shield cooled by the return flow of LN2 (see figures 2(c), 2(d)). A similar design was tested with HTS DC cable in Ishikari, Japan [5, 6]. As a result, a record-low heat leak of about 0.034 W/m into cable pipe was achieved [7]. It is pertinent to note that the conventional value of the reported heat leaks is 1-2 W/m.

Figure 2. Schematic drawings of the cryogenic pipes that can be used in superconducting power transmission lines of different types. Similar structural elements are specified ones. HTS cable cooled by LN2: (a) with individual vacuum jackets; (b) with single vacuum jacket; (c), (d) with radiation shield. Hybrid systems: (e) MgB2 cable cooled by LH2; (f), (g) MgB2 cable cooled by LH2 with radiation shield cooled by LN2.
There is also an expanded approach to energy transfer, which involves the joint transportation of electricity by HTS cable and chemical energy in the form of liquefied fuel gas through the pipeline. Typically, a combination of the cryogenic pipeline with superconducting MgB₂ cable directly cooled by transported liquid hydrogen (LH2) is considered [8, 9]. Some of the suitable design solutions can be seen in figures 2(c)-2(g).

2. Hybrid energy transfer lines

Hybrid lines attract attention with their apparent simplicity and naturalness of the design. Indeed, it seems very tempting from the energetic point of view to abandon the closed-loop pumping of ballast LN2 in favor of the unidirectional pumping of fuel or chemical raw material (compare figures 2(b) and 2(e), respectively). Unfortunately, the critical temperatures of the existing HTS materials remain quite low that means that only LH2 can be the "cooling fuel". The thermophysical properties of LN2 and LH2 vary significantly. The advantages of LH2 as a coolant are its high heat capacity and low viscosity. On the other hand, its disadvantage is low density, which requires an increased flow rate. Besides, the temperature range in which hydrogen is in the liquid state is about 2.3 times narrower than that of the nitrogen. It is easy to compare the flow parameters for LN2 and LH2 using conventional hydraulic calculations [10]. The pressure drop \( \Delta p \) is determined by the equation (1)

\[
\Delta p = f \frac{L}{D_h} \frac{\rho v^2}{2},
\]

where \( f \) is the friction factor, \( L \) is the length and \( D_h \) is the hydraulic diameter of the pipeline, \( \rho \) is the density, and \( v \) is the flow velocity which depends on the total heat load and flow area. Taking into account that the specific heat inflow through multilayer thermal insulation (MLI) for identical LN2 and LH2 pipelines differs insignificantly and assuming that the same temperature difference is maintained, one can find that on average the pressure drop of LN2 flow will be approximately two times higher than that of LH2. In the evaluation, we assume that the average temperature of LN2 is 76 K, while the average temperature of LH2 is 20 K. The power consumption of the pump can be obtained by multiplying the pressure drop by the volumetric flow rate. A very large difference in the densities of LN2 and LH2 leads to the fact that the energy consumption of LN2 cryogenic pump is slightly lower than that of LH2 pump. Hereinafter, without loss of generality, we assume that the efficiency of the pumps is 100%.

The main difference between systems with LN2 and LH2 is the critical difference in coefficients of performance (COP) of refrigerators. Therefore, at the equal heat load, the energy consumption of the LH2 refrigerator will be approximately 5 times higher. This situation leads to the need to significantly complicate the design of the cryogenic pipeline by introducing the radiation shield as shown in figures 2(f) and 2(g). Although the idea of the hybrid line is quite obvious and has long been discussed, it was experimentally tested only in the early 2010s, when the first 10 m long line was created in Russia [11]. Later, the line was extended to 30 m, while the authors tested three types of thermal insulation, including the mentioned LN2-cooled radiation shield [12]. As can be seen, the development of hybrid lines is in its infancy, two generations behind the traditional HTS power transmission lines.

3. LNG as an alternative to LH2

Although hydrogen is an ideal chemical fuel, issues of its cheap mass and environmentally friendly production have not yet been fully resolved. It is known that natural gas is a viable alternative to hydrogen as a fuel for many reasons. Since its boiling temperature is too high, the use of liquefied natural gas (LNG) as a coolant in hybrid lines is considered only in the future when suitable HTS materials will be discovered and commercialized [13]. However, it is optimistically overlooked that tens of years can pass from the discovery of a new HTS to the manufacturing of wires suitable for the production of a long power cable. The use of pseudo-LNG (CH₄:C₂H₆:C₃H₈:N₂ = 13:7:10:6), as
described in [14], allows to reduce the operating temperature to 90-107 K, but, in our opinion, significantly complicates the entire system. However, it seems to us that the combination of HTS cable and LNG pipeline should be economically justified taking into account the significant costs of production, liquefying and subsequent regasification of hydrogen. Our main postulate is that LNG cannot be directly used to cool the HTS cable. Instead, it is proposed to cool the radiation shield enveloping the cable pipe [15]. It is easy to estimate that the heat transfer to the cable pipe that is still cooled by LN2 will decrease by at least 10 times as compared to the pipe without radiation shield [16]. A sketch of the suitable design of the two-cable power transfer system is presented in figure 3(a). For comparison, figure 3(b) shows a sketch of the cryogenic pipe of the Ishikari project that should be considered as a prototype of the proposed system [5-7]. Because of the high cost of the systems under discussion, it will be beneficial to build hybrid transmission lines for the delivery of electricity and LNG to the large consumers. Since LNG is used not only to generate energy but also as a chemical feedstock, its mass flow is expected to be large. Consequently, the penetrating heat that can be removed will also be large, which will allow the cooling stations to be spaced wide apart.

4. LNG transfer vs. high-pressure gas transfer

Let us compare the conditions of pipeline transportation of LNG and compressed natural gas (CNG) assuming that the length of the pipeline is 100 km which is the characteristic distance between the gas pumping stations. The correlations tabulated in [10] were used to calculate the coefficient of hydraulic friction and pressure drop of LNG. The pressure drop of CNG was determined by the standard formula given in [17]. The CNG pump power \( P \) was estimated by

\[
P = \dot{m} \left[ (H_2 - H_1) + \frac{v_2^2 - v_1^2}{2} \right],
\]

where \( \dot{m} \) is the mass flow rate, \( H \) is the enthalpy, \( v \) is the flow velocity, and indices 1 and 2 denote inlet and outlet, respectively. It was assumed that the gas temperature was constant and equal to 288 K, and the inlet and outlet pressures were 7 and 5 MPa, respectively. Heat leak of LNG pipe was estimated by the experimental data of the Ishikari project and the laboratory experiments.

The main results of the calculations are presented in table 1. As can be seen, for a wide range of pipe diameters, the power required to pump the same amount of natural gas is reduced by about 50-100 times if the gas is liquefied. In this case, the temperature difference of the LNG remains within reasonable limits, not exceeding 5.4 K. The pressure loss will be about 0.25 MPa. Therefore, despite the significant cost of stainless steel used in cryogenics, the cost of the pipeline can be reduced by reducing the wall thickness of pipes that are not exposed to high pressure. For illustration purposes, it
can be noted that the 200 mm cryogenic pipe from table 1 provides an annual supply of 0.24 billion standard cubic meters of gas that correspond to the export from Russia to Bosnia and Herzegovina in 2018. If the pump power will increase to 290 kW / 100 km, the 800 mm cryogenic pipe will deliver 12.9 billion standard cubic meters per year that correspond to the export from Russia to France [18].

As for the cable pipes, an example of the similar calculations with a step-by-step description can be found in [19]. With a cable diameter of 40 mm and an internal pipe diameter of 100 mm, the LN2 flow of 60 L/min will provide a temperature difference of 6 K with a pressure loss of 0.37 MPa. In this case, the power of the LN2 pump will be only 370 W per one pipe.

Table 1. Parameters of the 100 km long CNG pipelines and LNG pipelines at the same flow rates.

| Pipe I.D. (mm) | Heat leak (W/m) | Flow rate (t/hr) | CNG pump power (MW) | LNG pump power (MW) | ΔT (K) | Δp (MPa) | LNG/LNG pump power ratio (MW/MW) |
|---------------|-----------------|-----------------|---------------------|---------------------|--------|---------|---------------------------------|
| 200           | 1               | 18.2            | 0.140               | 0.00294             | 5.4    | 0.25    | 47.6                            |
| 400           | 2               | 112             | 1.08                | 0.0171              | 1.8    | 0.24    | 63.2                            |
| 600           | 3               | 326             | 3.85                | 0.0481              | 1.0    | 0.23    | 79.9                            |
| 800           | 4               | 694             | 9.84                | 0.101               | 0.70   | 0.23    | 97.8                            |

Heat losses of the pipeline should be compensated by the operation of refrigeration equipment. For large-scale refrigerators, Carnot efficiency is close to 35% [20]. Assuming an LNG temperature of 100 K, the actual COP can be estimated as 0.18. Therefore, the energy consumption for cooling the considered 100 km pipeline will be approximately 0.56 MW at the heat leak of 1 W/m. Compared to the energy consumption of pumps, this seems like a large amount, but we should not forget that this consumption should not be attributed to LNG transportation, but to the transmission of electricity. This clearly shows the advantage of the unified system. If only HTS cable is cooled by LN2, then due to the lower COP the energy consumption is 0.94 MW at the same heat leak. In our opinion, the technology of thermal insulation of cryogenic pipes can be significantly improved, which will lead to the lower energy consumption of refrigerators. Besides, since consumer product is the natural gas, LNG regasification for intermediate consumers can be used to decrease the temperature of the main flow. This approach will also provide significant energy savings.

5. HTS DC vs. HVDC power transmission

Power transmission systems based on superconductors have attracted the attention of researchers for a long time, however, the development of appropriate technologies is restrained by the high cost of superconducting tapes and cryogenic equipment. The design of hybrid lines allows us to reduce the cost of the cryogenic component of the system. It is known that HTS DC cables are the most effective for long-distance power transmission. In addition to zero resistance, superconductors exhibit a high critical current density reaching 200 A/mm² for HTS based on bismuth that allows constructing compact low voltage transmission lines. For example, a 10 kA cable installed at an aluminum electrolysis plant in China has a diameter of 45 mm, and the total diameter along with thermal and electrical insulations is 151 mm [21]. The pipe with a diameter of 318.5 mm in Ishikari in Japan contains HTS cable with the radiation shield, as shown in figure 3(b) [5-7]. Being laid in a trench or tunnel, the HTS line will require a right-of-way width of only a few meters, while conventional overhead high-voltage DC (HVDC) power transmission line with the same transmitting capacitance and rated voltage of 250 or 500 kV will require right-of-way of several tens of meters wide.

The bipolar hybrid system proposed in figure 3(a) has two 39 mm HTS cables with an operating current of 10 kA. It can transmit 500 MW at a voltage of ±25 kV. This configuration will have a high inductance that is useful to suppress short circuit current. A technical discussion of the right-of-way requirements is necessary in the case of the hybrid line. When transmitting high power at a relatively low (generator) voltage, no intermediate substations are required, which gives significant savings in capital costs and land resources. An additional advantage of the HTS lines is their ecological
cleanliness, including the absence of oils, minimal electromagnetic, and thermal impacts on the environment.

6. Conclusion
As is well known, the main methods of transportation of natural gas are high-pressure pipelines and LNG carriers. Transportation can also be carried out through cryogenic pipelines; however, this method does not find wide application due to the high cost of cryogenic equipment. The capital investment can be reduced by creating a hybrid line for joint transmission of electricity and LNG. The significant economic effect will be achieved by using common thermal insulation and utilizing LNG cold to cool the radiation shield that protects the HTS cable from penetrating heat. This approach provides clear guidance on how to use high-boiling cryogenic fuels in the hybrid energy transmission line. Estimates made using the results of the Ishikari project show that by combining the LNG pipeline with the HTS cable line, it is possible to reduce metal consumption and capital construction costs, significantly (by 50-100 times) reduce the energy consumption of LNG pumps compared to CNG pumps and save on power of the HTS cable refrigeration units. On the consumer side, the cold of regasified LNG can be used to cool freezing storage warehouses and other large-scale facilities. In any case, the hybrid line should be carefully designed taking into account all material and energy flows.

Acknowledgments
The authors would like to thank Dr. A. Iiyoshi, Chair of the Board of Trustees and the Chancellor of Chubu University, for his encouragement during the course of this work.

References
[1] Romashov M A, Sytnikov V E, Shakarian Y G and Ivanov Y V 2014 Prospects of long-distance HTS DC power transmission systems J. Phys. Conf. Ser. 507 032037
[2] Thomas H, Marian A, Chervyakov A, Stückrad S, Salmieri D and Rubbia C 2016 Superconducting transmission lines - Sustainable electric energy transfer with higher public acceptance? Renew. Sustain. Energy Rev. 55 59-72
[3] Sytnikov V E, Bemert S E, Kopylov S I, Romashov M A, Ryabin T V, Shakaryan Y G and Lobynstev V V 2015 Status of HTS cable link project for St. Petersburg grid IEEE Trans. Appl. Supercond. 25 5400904
[4] Sytnikov V E, Bemert S E, Krivetsky I V, Karpov V N, Romashov M A, Shakarian Y G, Nosov A A and Fetisov S S 2016 The test results of AC and DC HTS cables in Russia IEEE Trans. Appl. Supercond. 26 5401304
[5] Yamaguchi S, Koshizuka H, Hayashi K and Sawamura T 2015 Concept and design of 500 meter and 1000 meter DC superconducting power cables in Ishikari, Japan IEEE Trans. Appl. Supercond. 25 5402504
[6] Chikumoto N, Watanabe H, Ivanov Y V, Takano H, Yamaguchi S, Koshizuka H, Hayashi K and Sawamura T 2016 Construction and the circulation test of the 500-m and 1000-m DC superconducting power cables in Ishikari IEEE Trans. Appl. Supercond. 26 5402204
[7] Watanabe H et al. 2017 Cooling and liquid nitrogen circulation of the 1000 m class superconducting DC power transmission system in Ishikari IEEE Trans. Appl. Supercond. 27 5400205
[8] Grant P M 2005 The SuperCable: dual delivery of chemical and electric power IEEE Trans. Appl. Supercond. 15 1810-3
[9] Morandi A 2015 HTS dc transmission and distribution: concepts, applications and benefits Supercond. Sci. Technol. 28 123001
[10] Idelchik I E 1989 Flow resistance: a design guide for engineers ed E Fried (New York, NY, USA: Hemisphere Publ. Corp.) pp 5-42
[11] Vysotsky V S et al. 2013 Hybrid energy transfer line with liquid hydrogen and superconducting MgB2 cable - first experimental proof of concept IEEE Trans. Appl. Supercond. 23 5400906
[12] Kostyuk V V et al. 2015 Cryogenic design and test results of 30-m flexible hybrid energy transfer line with liquid hydrogen and superconducting MgB$_2$ cable Cryogenics 66 34-42
[13] Zhang Y, Tan H, Li Y, Zheng J and Wang C 2014 Feasibility analysis and application design of a novel long-distance natural gas and electricity combined transmission system Energy 77 710-9
[14] Wang L, Bai G, Zhang R and Liang J 2019 Concept design of 1 GW LH$_2$-LNG-superconducting energy pipeline IEEE Trans. Appl. Supercond. 29 5401002
[15] Iiyoshi A 2017 Panel session "The Asian Energy Ring. Are Politicians and Energy Companies Ready?" Eastern Economic Forum (Vladivostok, Russia) Sept. 6-7
[16] Kaganer M G 1969 Thermal insulation in cryogenic engineering (Jerusalem: IPST Press) 220 p
[17] Menon E S 2005 Gas pipeline hydraulics (Boca Raton, FL: CRC Press) pp 33-5
[18] Gazprom Export: Delivery statistics 2018 http://www.gazpromexport.ru/en/statistics/
[19] Ivanov Y V, Romashov M A, Bemert S E and Sytnikov V E 2014 Choice of flexible cryostat for 2.5 km DC HTS cable to be laid in St. Petersburg AIP Conf. Proc. 1573 887-92
[20] Strobridge T R 1974 Cryogenic refrigerators - an updated survey NBS Tech. Note 655 1-12
[21] Dai S et al. 2014 Testing and demonstration of a 10-kA HTS DC power cable IEEE Trans. Appl. Supercond. 24 5400104