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Multi-Energy Transmission – An option for system development?

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SUMMARY

In this paper the combined transmission of electricity and hydrogen is proposed and assessed. The main reasons for considering hydrogen are its ability to serve as a storage medium in future power systems as well its potential to replace fossil fuels, e.g. in CHP or transportation applications. A modelling framework for energy systems including several energy carriers is introduced and the method for modelling the combined transmission of electricity and hydrogen at a "generic" level is explained. The simple representation permits to characterise the combined transmission device, the so-called interconnector by its inner radius, conductor cross-sectional area and required transmission voltage. The required values for these parameters have been determined for a set of potential applications ranging from distribution to high-power transmission. The results of these calculations show that the proposed concept is impractical for distribution, but might be applicable to the sub-transmission power range.

KEYWORDS

Multi-energy system – System development

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INTRODUCTION

Low carbon energy systems will likely imply the use of various energy carriers: electricity, heating/cooling (local systems or district heating/cooling) and possibly hydrogen. Establishing a hydrogen energy system implies a careful study of the integration and interaction with other currently used systems, such as the electrical energy system. Presently, the interaction level between the coexisting energy networks (e.g. electricity, hydrocarbons, district heating) is rather low: planning of each of these networks has been carried out almost independently. Current trends towards decentralized energy conversion and generation offer new options for synergies among different energy systems. The integrated planning of future energy systems using multiple energy carriers represents a promising tool for the optimization and expansion of networks. Integrated planning means modelling conversion, storage and transmission processes for several energy carriers, thus enabling the development of overall optimized solutions.

Modelling frameworks for multi-energy networks have been discussed in [1] and [2], e.g.. Previously investigated aspects include the placement and scheduling of gas or oil plants and the investigation of the upstream supply chain of primary energy to power plants. A further driver for multi-energy networks is the trend towards decentralized generation units producing several energy forms, e.g. co- or tri-generation units. A review of this evolution can be found in [3].

The work presented in this paper is based on the framework of “Energy Hubs”, introduced in [4], [5] and [6]. Energy hubs represent flexible interfaces between producers, consumers and networks for different energy carriers. They convert, store and condition energy e.g. by means of fuel cells, micro-turbines or storage equipment. This framework is used to investigate new topologies for energy T&D systems.

The most promising combination of energy carriers is electricity and hydrogen: electricity is already widespread and versatile in its uses, and hydrogen has especially the potential to be used in transportation and storage applications. Besides the aspects related to conversion and interfacing between these carriers, the question of energy transmission must also be addressed. Two options are available: separate networks for each carrier (as currently practised) or (partly) combined transmission links. The latter solution would represent quite a radical change in the T&D infrastructure and is worth a more detailed analysis. Two proposals for combined electrical and hydrogen transmission are found in [7] (liquid hydrogen and superconductive electricity transmission) and [8] (liquid hydrogen and cryogenic electricity transmission).

This work presents an approach based on the use of gaseous hydrogen and metallic electrical conductors at ambient temperature. The motivation for this study includes potential simplifications in laying and operation (e.g. common metering and control) as well as inline energy storage. Based on the review of potential “generic application scenarios”, the proposed interconnector principle appears to be feasible within a determined power and distance range corresponding to the current electrical sub-transmission network level. This concept may support the establishment of “multi-energy” or “multi-product” networks.

LAYOUT OF A COMBINED TRANSMISSION SYSTEM

The Interconnector principle

The generic idea of the Energy Interconnector is presented in [9]: an electrical conductor is integrated into the wall of a hydrogen "pipeline". A thermal insulation allows for an operation of the conductor at temperatures above the soil temperature and the hydrogen is used to evacuate a share of the ohmic conduction losses occurring in the electrical conductor. Thus the heat transfer to the surrounding soil is reduced and there is an opportunity for waste heat reuse at the interconnector outlet.

Figure 1 illustrates this principle: $P_{el1/2}$ is the electrical power at the inlet respectively outlet, P_V the electrical losses, P_{ch} the transmitted chemical power, P_U the thermal power transmitted to the surrounding soil and P_Q the total thermal power absorbed by the hydrogen (this is the sum of P_{CM}, transmitted from the conductor and the internal viscous friction heat P_R).

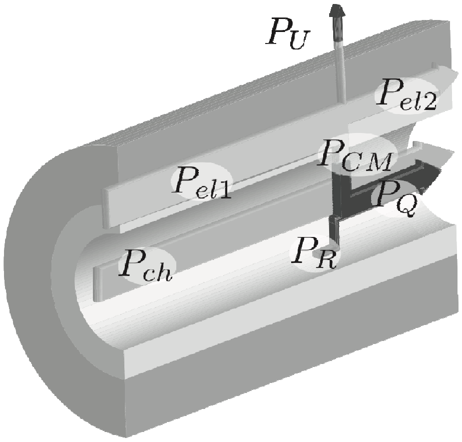

Figure 1: Illustration of the Energy Interconnector with electrical and chemical power transmission as well as waste heat reuse.

The representation of this principle requires a model for the compressible and non-isothermal hydrogen flow including the heat transfer from the conductor to the hydrogen and the surrounding soil. Viscous friction in the flowing hydrogen (as well as the resulting temperature rise) is also modelled. As a result, the coupling between the electrical and chemical power can be described. By varying the inlet and outlet pressures as well as the transmission voltage, this coupling still permits for a wide variation range of the electrical and chemical powers.

The first use of the modelling framework will be to assess the idea of combined transmission and to determine the power "range" to which it might be applicable. Therefore all models are very generic and do not rely on detailed technological layouts. This is useful in order to derive a general description of the combined transmission process (which obviously needs to be refined at a later stage).

Layout methodology

In the developed modelling framework, the layout parameters of an interconnector are its inner radius R_i, the cross-sectional area of its electrical conductor A_{cTot} (representing the sum of the cross-sectional areas of the two poles needed for d.c. transmission) and the maximum transmission voltage U_{in}. Other parameters such as material parameters (for the conductor, the insulators, etc.), temperature and pressure limitations, etc. are kept invariant since their possible variation range is constrained.

The first modelling step yields partial differential equations for the gas flow along the interconnector which cannot be solved analytically for a given maximum power. To achieve this, approximated equations were derived which permitted the identification of approximated scaling laws. An adequate layout strategy based on scaling laws applied on a set of previously computed layouts has been developed and is described in more details in [10].

POTENTIAL APPLICATION RANGE FOR COMBINED TRANSMISSION

Constraints and limitations

Besides the previously mentioned layout parameters, the model includes a number of further parameters including material properties, temperature and pressure limitations. In the first stage of the feasibility study, the following quantities will be considered as invariant for all layouts:

- The inlet temperature is limited by the ambient temperature, which will in general constitute the cold source for the gas leaving the inlet compressor. 20°C was assumed in all further calculations.
- The outlet temperature is limited by the withstand capability of the electrical insulation material. Withstand temperatures can reach 250°C for polytetrafluoroethylene (PTFE) or more 130°C for cross-linked polyethylene (XLPE). 120°C was assumed in this work.
- The maximum pressure is limited by constructive aspects (which are unknown at this stage). Considering current developments some tens of bars seem feasible. A value of 30 bar was assumed.
- Copper was selected as the material of the electrical conductor. For other materials the required cross-sectional area could easily be computed by keeping the ratio ρ/A_{cTot} constant (which correspond to equivalent losses).
- The viscous friction factor is also unknown at this stage. Where necessary, assumptions based on literature studies have been made.

The coupling among the chemical and electrical powers (due to the heat transfer between the electrical conductor and the flowing hydrogen) implies additional operational constraints: for each value of the chemical power, the electrical power is limited by the maximum value of the removed thermal power corresponding the hydrogen mass flow rate. Similarly, the assumption that the hydrogen reaches the interconnector outlet at a given temperature implies that a minimum for the electrical loss power exists. Between these maximum and minimum values, the electrical power can be varied and the heat absorption of the hydrogen can be adapted by varying its inlet pressure.

This means that some combinations of the electrical and chemical powers are not feasible. Figure 2 shows a representative example for the operational area of an interconnector. By varying the transmission voltage, every combination of electrical and chemical powers within the limitation curves is possible. This aspect has been discussed in more details in [9].

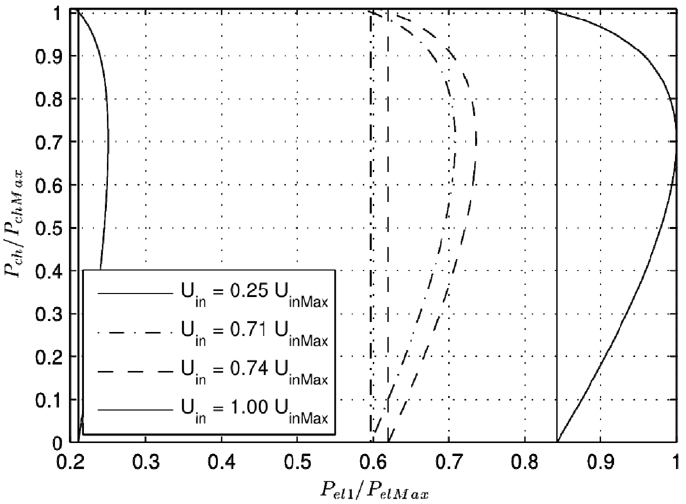

Figure 2: Example for the operational area of an interconnector.

Initial selection of variants

In order to establish a set of models, some fundamental choices on the investigated variants for the interconnector had to be made ahead of the review of potential applications.

- A first choice is to focus on an open hydrogen cycle, i.e. the hydrogen flows only in one direction. The net chemical power flow thus corresponds to the energy content of the hydrogen mass flow.
- As known from present electric cables and gas insulated lines, several parallel single pole cables might be used for the different phases or poles. This preliminary study will focus on single pipe systems, in which both poles of a d.c. transmission are within the same encapsulation.
- Lastly, the hydrogen flow might be used to cool down the electrical conductor (below ambient temperature) or to transmit thermal power. This work will focus on the transmission of gaseous hydrogen starting at ambient temperature.

Review of potential applications

An application is defined by the maximum transmitted electrical power P_{elAMax} and the maximum transmitted chemical power P_{chAMax} as well as the total interconnector length L_{tot}. Table 1 shows the specifications for some generic applications used in this work. These applications represent different ranges of transmitted powers and line lengths. The electrical power roughly corresponds to lines in the different voltage levels of current power systems. The chemical power has been selected arbitrarily, based on the assumption that the establishment of hydrogen as a transportation fuel will result in the need to distribute hydrogen energy in quantities equivalent to or higher than the present electricity consumption.

	P_{elMax}	P_{chMax}	L_{tot}
MVDC	200 MW	240 MW	50 km
HVDC	2 GW	2.4 GW	600 km
LV (a.c)	475 kW	265 kW	15 km
MV (a.c.)	250 MW	300 MW	50 km
HV (a.c.)	1 GW	1.2 GW	300 km

Table 1: Specifications of the investigated generic applications.

The previously described layout methodology has been applied to each of these to determine the order of magnitude of the required dimensions and voltages. This information can be used to discuss the feasibility of the interconnector in various contexts: Figures 3, 4 and 5 show the resulting inner radius R_i, transmission voltage U_{in} and total conductor cross-sectional area A_{cTot} for each application. The error bars show the effect of a 25% variation of either combination of the application specification P_{elMax}, P_{chMax} and L_{tot} from Table 1.

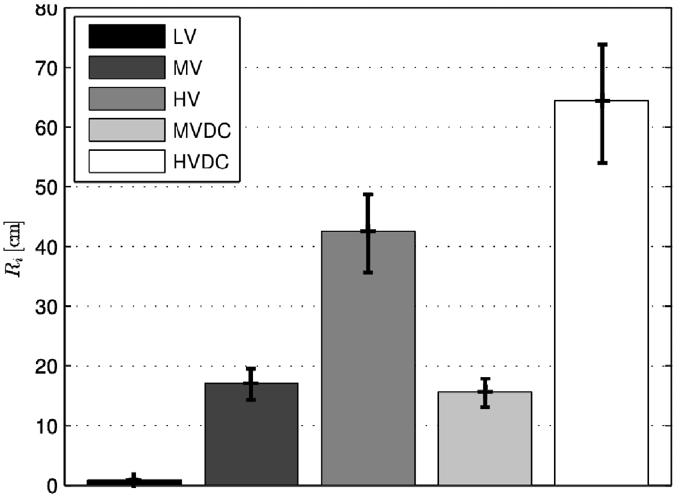

Figure 3: Required inner radius Ri of an interconnector for various generic applications (the error bars indicate the effect of a 25% variation of all specifications for an application).

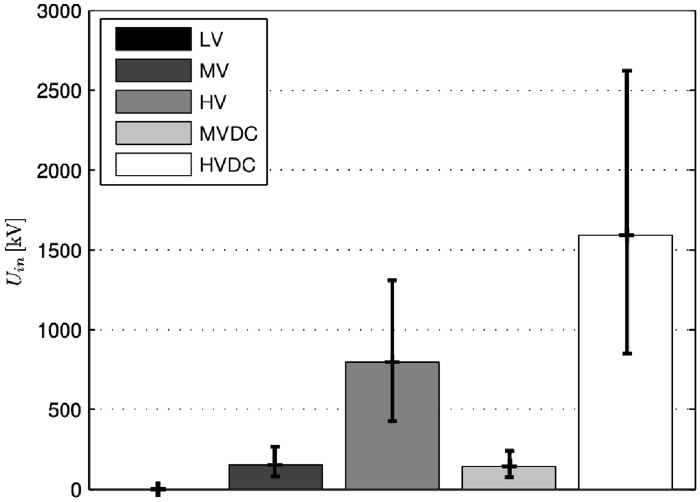

Figure 4: Required maximum transmission voltage U_{in} of an interconnector for various generic applications (the error bars indicate the effect of a 25% variation of all specifications for an application).

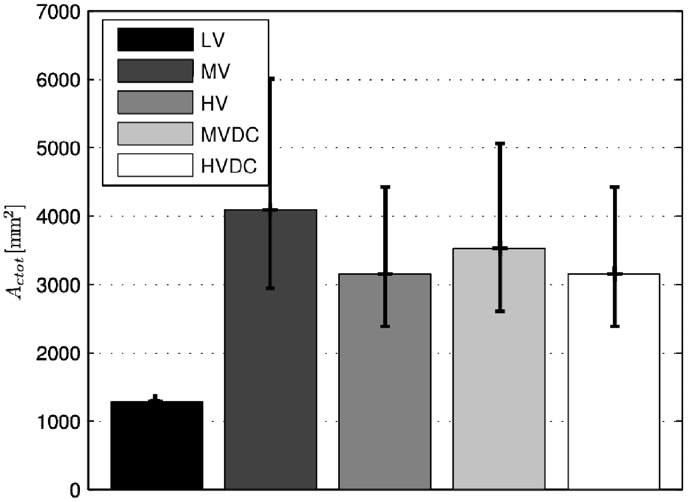

Figure 5: Required total cross-sectional area AcTot of an interconnector for various generic applications (the error bars indicate the effect of a 25% variation of all specifications for an application).

The total efficiency (including potential waste heat recovery) for the LV application is approximately 60% while it is close to 99% in all other cases. The reason is that according to the described interconnector concept, the high outlet temperature of the hydrogen must be reached over a very short distance, which means that the specific losses are comparatively high. Thus the interconnector principle (using a high hydrogen outlet temperature) is not adapted to the context of distribution to final consumers.

For all applications it appears that the required inner radius R_i and transmission voltage increase with the transmitted power, which corresponds to present practice (and thus confirms the soundness of the layout procedure). The variation in the cross-sectional area A_{cTot} is less pronounced, because in conjunction with the invariant maximum current density used in the layout procedure, the net thermal power per length unit that can be absorbed by the surrounding soil is identical for each application. The total cross-sectional areas of around 4000 mm^2, which correspond to 2000 mm^2 per pole for a d.c. transmission are within the feasible range.

The required transmission voltage for the HV and HVDC applications reaches 1000 kV and more. This exceeds currently used voltages for cables and encapsulated systems and represents a serious obstacle to the application of the interconnector principle in this power and distance range. Based on these considerations the best-suited applications are MV and MVDC, i.e. the transmission of around 200 MW of chemical and electrical power over a distance below 50 km.

CONCLUSIONS

The proposed interconnector principle appears to be feasible within a determined power and distance range corresponding to the current electrical sub-transmission network level. This concept may support the establishment of “multi-energy” or “multi-product” networks. Therefore the next step in the investigation will be the inclusion of the interconnector into energy infrastructure scenarios. This step is planned in the “Vision of Future Energy Networks” project [11]. Lastly, the constructive details for the variants assessed in these system studies shall be investigated in more details.

The selection of MV as a preferred application at this stage does not imply that other power ranges will remain inaccessible to the interconnector. Parallel systems and intermediary cooling stations may be introduced and combined, thus permitting more flexibility in the layout of an overall interconnector system.

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