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# LIQHYSMES – a 48 GJ Toroidal MgB2-SMES for Buffering Minute and Second Fluctuations

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***Abstract*—Recently, a new hybrid energy storage concept, LIQHYSMES, has been proposed which combines the use of liquid hydrogen (LH2) as the bulk energy carrier with much faster and efficient superconducting magnetic energy storage (SMES). Here, an example for a large scale plant potentially addressing the electricity transmission system, is discussed: stored energies are about 125 GWh for the H2 part and 48 GJ for the SMES at power levels of 200 MW to 1 GW. Imbalances between the varying supply of renewable energies and the customers' demand are simulated. The response of the storage plant is analyzed concerning its capability of buffering variations on time scales from hours down to seconds. Losses of the whole hybrid storage plant are provided with a specific focus on the LIQHYSMES Storage Unit (LSU) which integrates the H2 liquefier, the LH2 storage tank and the MgB2 SMES. Some implications of the operating conditions for the SMES as regards field, ramping losses, currents and voltages are addressed. Cost estimates indicate that the LSU could become an economically viable component in future H2 supply networks for utilizing excess renewable energy.**

***Index Terms*— AC Loss, Energy Storage, High-Temperature Superconductors, Hydrogen, Superconducting Magnets .**

## I. Introduction

A substantial increase of the contribution of renewable energy sources will increase the need for balancing supplies and demands in the electrical grid which eventually will require energy storage systems providing tens to hundreds of MW and GWh. The recently proposed LIQHYSMES approach [1]-[6] combines liquefied hydrogen (LH2) as the primary, high-density energy carrier with Superconducting Magnetic Energy Storage (SMES) for a fast and efficient buffering so that the H2 parts can be operated more steadily, and reduced lifetimes can be avoided. A LIQHYSMES plant consists of three major units: the Power Conversion & Control Unit (PCC), the Electrochemical Energy Conversion (EEC) and the LIQHYSMES Storage Unit (LSU) which integrates the three cryogenic parts: the H2 liquefaction, its intermediate storage in liquefied form and the SMES. The basic synergy is thus the joint utilization of the cryogenic infrastructure. The overall concept with a specific focus on the LSU has been described in [6].

Here the contribution of the SMES to the buffering of imbalances on time scales from minutes down to seconds is investigated by simulation. The related losses are compared with the other plant losses, and some implications for the design and the operation of the SMES are addressed.

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## II. Simulation of a Buffering Process

TABLE I
PARAMETERS USED FOR THE SIMULATION

| | |
|---|---|
| **Electrochemical Energy Conversion - EEC:** | |
| Rated Power for Electrolyser | 25 x 40 MW |
| Rated Power for Gas Turbines & Generator | 4 x 55 MW |
| Efficiency of Electrolyser / Gas Turbines & Generator | ~ 85 / 55 % |
| **Power Conversion & Control Unit - PCC:** | |
| Operational Loss per Momentary EEC or SMES Power | 3 % |
| Standby Loss per Rated EEC or SMES Power | 1 % |
| **LIQHYSMES Storage Unit - LSU:** | |
| Outer Radius / Inner Radius / Width of Individual Solenoidal Coil of SMES (Total: 20 Coils in a Toroidal Configuration) | 11.1 / 9.79 / 2.21 m |
| Total Radius / Height of SMES System & LH2 Cryostat | 30.4 m / 22.1 m |
| Radial / Vertical Distance for Heart Pacemaker Limit (0.5 mT) | ~ 42 / 19 m |
| Rated Power x Supply Period of SMES = Rated Energy of SMES (discharged @ 50 % Coil Current) / Total Stored Energy | 200 MW x 240s = 48 GJ / 64 GJ |
| Mean Operating Current Density in Winding | ~ 320 A/cm2 |
| Total Conductor Length x Operating Current (=Ic/2) | ~ 11.8 GAm |
| Max Operating Current / Operating Magnetic Field of SMES / Max. Operating Voltage over a single Coil | 10 kA / 4 T / 5 kV |
| Cable Length per Coil / Number of normalconducting Joints per Coil / Number of Windings per Coil | ~ 30 x 2 km / 29 / ~ 30 x 30 |
| Self Inductance of a single Coil / Mutual Inductance of the other 19 Coils | ~ 28 H / ~ 35 H |
| Full-Cycle Ramping Loss of SMES (round MgB2 wire, diameter 100 µm) / Electric Loss in % of Rated Energy | 5.94 MJ / 1.16 % |
| Chemical Energy of LH2 (max. 70% of cryostat filled with LH2) / Deliverable Electrical Energy of LH2 / max. Electric Output Power of EEC x Supply Period | ~ 125 GWh / ~ 69 GWhe / 220 MWe x 13d |
| H2 Liquefaction Loss per Stored Chemical Energy | 10 % |
| Standby Losses of Cryostat / Current Leads (cryocooler) | 595 / 75 kW |

Table I gives the major plant parameters like power, energy and the loss assumptions which have been used to crudely simulate the buffering behavior of a simplified LIQHYSMES model plant. Widely modular concepts have been assumed for all plant parts. For the EEC part a solution based on 25 modules of 40 MW electrolyser blocks and 4 gas turbines and generators each providing 55 MW for the re-conversion of H2 into electricity has been chosen. The electrical energy stored as LH2 and deliverable by the gas turbines is about 69 GWhe which translates into LH2 reservoirs with linear dimensions of tens of meters, large enough to house also a large scale SMES. For the SMES a toroidal configuration based on 20 solenoidal coils ("T20", [5]) is used. It is here assumed that for the energy balancing of strong, variable renewable energy sources the SMES should bridge a supply period of about 4 minutes, and with a rated power of about 200 MW this translates into a storage capacity of about 48 GJ. An adequate PCC given, the SMES can also take up or deliver higher power over a few seconds which then contributes to power quality and frequency control. Full-cycle ramping losses of the SMES that can be expected when the magnet system is ramped between 50 % and 100 % of the operating current or field, have been calculated on the basis of the method described in [3]. The spatial distribution of these losses over the coil volume has been shown in [5]. The assumed losses related to the liquefaction of the H2 crudely follow the estimates given in [6]. For consistency reasons the stored energy of the H2 (and consequently also the electrical energy needed/available for the electrolysis/re-conversion of H2) is here calculated on the basis of the total enthalpy change of about 286 kJ/mol for the water splitting/formation under standard conditions (298 K, 1.013 bar). The large electrically usable energy of the LH2 and the large size of the LSU lead to only very modest self discharge rates per day.

## III. Discussion of the Results

The imbalance (or difference) between (e.g. wind power) supply and (consumers') demand can vary significantly. It is assumed that (with the help of permanently updated weather and load forecasts) the mean imbalance over time scales of about 15 minutes can be predicted reasonably well. But momentary fluctuations of the imbalance occurring on a timescale of minutes and below can still be significant, e.g. for strong contributions of solar power. Fig. 1 shows the operational principle of the LIQHYSMES hybrid energy storage and the simulation of the buffering process applied to an arbitrary 24-hour period of fluctuating imbalance between supply and load. For demonstration purposes definitely extreme fluctuations of up to 284 MW/s (Table II) have been assumed, although it may be noted that comparable power changes of about 100 MW/s are targeted by the European Network of Transmission System Operators for Electricity when the primary control reserve has to compensate strong incidents like the sudden loss of generation or load [7]. Fig. 1A shows data with a time resolution of 1 minute. Here the assumed strong 1-second-fluctuations are indicated by only providing the upper and lower limits of the imbalance over each minute period (upper and lower green line). The complete fluctuating imbalance is presented in Fig. 1B with a time resolution of 1 second over a particularly busy 0.7-hour period. The power levels for H2 and SMES shown in Fig. 1, represent the effective power levels including all losses (PCC, EEC, liquefaction, ramping losses) occurring between the grid connection and the storage medium (LH2 and magnetic field).

The forecasted mean imbalance is used to define the operating conditions for the "slow" electrolyser modules and the gas turbines of the EEC. For a positive imbalance the electrolyser blocks produce H2 whereas for a negative one H2 is used-up in the gas turbines. If the EEC system is operated "too far" away from this mean imbalance, then the H2 system can be adapted by switching an additional block on or off. The very simple "control algorithm" also takes into account the current charging status of the SMES i.e. whether the currently stored energy is below or above certain thresholds (10 % and 90 % of the storage capacity). The difference between the actual momentary imbalance and the operational level of the H2 part is then compensated by the SMES. In practice, one may seek an even smoother adaptation of the EEC to the mean imbalance e.g. by adequately varying operating voltages / currents of the electrolyser modules.

TABLE II
Buffering Capability, Energies & Losses for the Simulated 24-Hour Period

| | |
|---|---|
| **Buffering Capability** | |
| Max. Positive / Negative. Imbalance over the 24-Hour Period | +1,316 MW / -238 MW |
| Max. Buffered 1-min- / 1-sec-Fluctuation of the Imbalance | ~ 147 MW/ 284 MW |
| Max. 1-sec Peak Power of SMES / Mean Power of SMES (averaged over the 24-Hour Period) | ~ 421 MW / ~ 36 MW |
| **Energy Shifting & Balances** | |
| Electrical Energy Uptake | 4.990 GWh |
| Electrical Energy Delivery | 1.614 GWh |
| Chem. Energy Balance of LH2 | + 0.460 GWh |
| Mag. Energy Balance of SMES | + 0.001 GWh |
| **Losses** | |
| PCC Loss of H2 | 0.338 GWh |
| EEC Loss (Electrolyser and Gas Turbines & Generator) | 2.109 GWh |
| LSU Loss of H2 (Cryostat, H2 Liquefaction & Compression) | 0.384 GWh |
| Total Loss of H2 | 2.831 GWh |
| PCC Loss of SMES | 0.075 GWh |
| LSU Loss of SMES (n.c. Joints of ~1nΩ ~ 0.08 MWh, Current Leads ~ 1.8 MWh & Ramping Loss ~ 7.3 MWh) | 0.009 GWh |
| Total Loss of SMES | 0.084 GWh |
| Total Loss | 2.914 GWh |

The imbalance is assumed to vary between +1,316 MW and -238 MW over the 24 hours. 1-minute and 1-second fluctuations are assumed to be as high as ~ 147 MW and 284 MW, respectively. These exceptionally large fluctuations sometimes require a SMES power (up to 421 MW) that well exceeds the rated power of 200 MW. Overall, the hybrid energy storage plant seems to be fully capable of handling even extreme short-term fluctuations. Fig. 1E shows the corresponding energy and loss analysis over the 24-hour period. The shifting of the electrical input energy from times of strong e.g. wind power supply to times where the demand strongly exceeds the weak supply, is clearly demonstrated and corresponds directly to the increase and decrease of the stored LH2. The energy stored in the magnetic field of the SMES necessarily fluctuates on a much shorter time scale (inset in Fig. 1A). The total plant losses are strongly dominated by the EEC, and the losses of PCC and LSU are comparable. In terms of H2 versus SMES, the losses almost all come from H2. The data concerning the buffering capability, the energies and the losses are summarized in Table II.

## IV. Some Implications for the SMES

As a starting point for the discussion of potential implications for the SMES, some assumptions have already been included in Table I: A toroidal magnet system consists of 20 solenoidal coil modules each being individually connected to the PCC and using an MgB2 cable with a maximum operating current

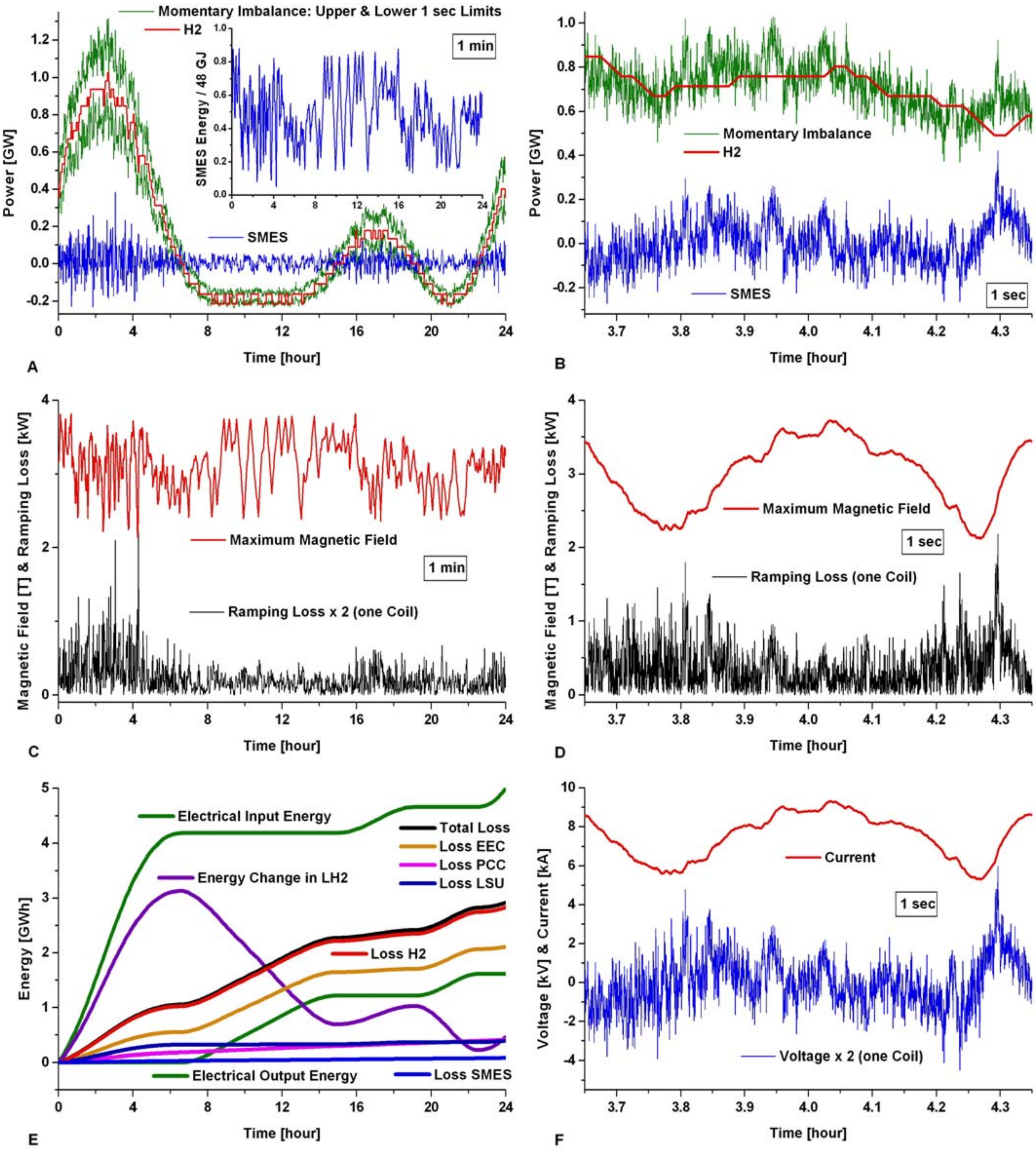


Fig. 1. A: Simulated 24-hour buffering process showing the power of the momentary imbalance between supply and load, of the H2-based energy storage and of the SMES; the inset presents the corresponding charging state of the SMES; for a positive imbalance the electrolyser blocks produce H2 whereas for a negative one H2 is used-up in the gas turbines; the difference between the momentary imbalance and the operational level of the H2 part is compensated by the SMES (time resolution: 1 minute); B: part of A showing a particularly busy 0.7-hour period: the stepwise adaptation of the H2 part and the fast compensation by the SMES are demonstrated with a 1-sec time resolution; C & D: variation of the maximum magnetic field and the related momentary ramping loss occurring in a single coil of the SMES, again with 1-minute and 1-second time resolution; E: energy and loss analysis showing the summed-up electrical input/output energy taken up from the grid and delivered back at a later time, the variation of the energy stored in the LH2 and the SMES as well as the accumulated losses of the three major plant parts PCC, EEC and LSU; the up-take / delivery of energy from / to the grid corresponds directly to an increase / decrease of stored LH2; the LSU losses which cover the electric losses related to liquefaction, LH2 cryostat and SMES, are comparable with the PCC losses and substantially lower than the EEC losses; for comparison, also the H2-related and the SMES-related overall contributions are given separately; F: momentary current of the SMES and voltage over a single coil shown with 1-second time resolution.

of 10 kA. Piece lengths of about 2 km and a total cable length of about 60 km require 29 normalconducting joints and in total about 30 x 30 windings per coil. Contact resistances on the order of 1 nΩ per joint would result in refrigeration losses well below those related to the current leads or the ramping of the coils (Table II). The latter which are here based on the hysteretic magnetization losses only (eddy current and coupling losses are believed to be significantly lower because of the slow ramping processes, [3]), require some attention. The minute-averaged losses are shown for the whole 24 hours in Fig. 1C, whereas Fig. 1D gives the peak values of up to about 2.2 kW on a second time scale. Taking into account that the ramping losses occur not homogenously over the coil volume [5], this gives a maximum local heat load well below 100 μW/cm3 or heat transfer rates at the coil surface on the order of a few W/m2 which is well below the film boiling limit for LH2. Together with the higher heat capacities at 20 K (compared with 4 K) these ramping losses should be well manageable. This should also increase the available reaction time in the case of a quench risk. In this respect the moderate mean operating current density in the coil helps taking care of various questions related to the electrical, thermal and mechanical stabilization of the magnet system. This also includes measures to avoid H2-related aging and embrittlement. Fig. 1F shows the coil current and voltage with 1-second time resolution. The maximum operating current of 10 kA allows keeping the voltages over each coil well below 5 kV (peak value of 3 kV). The self inductance of a single coil and its mutual inductance with the other 19 coils are comparable (Table I), and the fabrication- & assembling-related tolerances may result in slight deviations e.g. of the individual coil voltages which due to the used current feeding scheme then have to be managed individually by the PCC.

## V. Cost Considerations for the LSU

TABLE III
Cost Estimate for LSU

| | |
|---|---|
| Rated Power /<br>Peak Power of SMES | 200 MW /<br>421 MW |
| Rated Energy of SMES (@ 4 T (Rated Power x 240 s) | 48 GJ |
| Chemical Energy /<br>Deliverable Electrical Energy of LH2 | ~ 125 GWh /<br>~ 69 GWhe |
| Total Cost of LSU | ~ 200 M€ |
| Cost of LSU per Usable Stored Energy of SMES | ~ 15,000 €/kWhe |
| Cost of LSU per Rated Power of SMES /<br>Cost of LSU per Peak Power of SMES | ~ 1,000 €/kWe /<br>~ 475 €/kWe |
| Cost of LSU per Chemical Energy of LH2 /<br>Cost of LSU per Deliverable Electrical Energy of LH2 | ~1.6 €/kWh /<br>~ 2.9 €/kWhe |

For the cryogenic parts of the LSU integrating liquefaction stage, LH2 tank and SMES, significant reductions for investment costs and operational losses are foreseen for larger sizes. Consequently, smallest economical LSU (and LIQHYSMES plant) sizes are expected. The major cost factor for the LSU is the SMES. In general, toroidal SMES designs offer not only low stray fields but also the most versatile application-specific scaling based on standardized and easy-to-manufacture solenoidal coil modules. With MgB2 the currently lowest cost superconductor that can be operated at LH2 temperature, has been selected. For the MgB2-SMES specific costs of 5 €/kAm@4T,20K were assumed, a number which seems to be well within reach [8], [9]. The other costs are related to the cryogenic infrastructure (cryostat, liquefaction part, cooling, current leads). A preliminary cost estimate for the complete LSU as the core element of different types of LIQHYSMES plants is given in Table III. Both the (peak-) power-specific costs for the SMES (w/o PCC) and the energy-specific costs for the LH2 (w/o EEC & PCC) represent attractive parameters when compared with existing or projected large scale electrical energy storage systems [10].

## VI. Conclusion

The proposed LIQHYSMES Storage Unit, LSU, represents the core element of a novel hybrid energy storage concept which combines LH2 with a SMES, and which could well contribute to the large-scale grid integration of variable renewable energy sources in terms of both longer-term energy balancing and short-term power quality and frequency control. It doesn't require any precious raw materials or specific geological formations, has minimum space requirements and allows flexible positioning. It increases the efficiency and operational safety of the electrochemical energy conversion due to a widely steady operation resulting from the SMES-based short-term buffering, and it is applicable to any combination of electrolysers, fuel cells, gas turbines etc..

The key design parameters incl. power, energy and losses for PCC, EEC and LSU have been estimated for a 100-MW- to 1-GW-class LIQHYSMES model plant providing energy storage capacities of about 125 GWh in the LH2 and about 48 GJ in the SMES. The buffering behavior of this model plant has been simulated using an arbitrary 24-hour period of fluctuating imbalance between supply and load, and the hybrid energy storage plant seems to be capable of handling even very strong variations. The total plant losses are strongly dominated by the EEC, and the losses of PCC and LSU are comparable. A first estimate for the investment cost of the LSU only gave about 200 M€. The corresponding (peak-) power-specific costs of about 500 €/kW for the SMES as well as the energy-specific costs of about 2.0 €/kWh for the LH2 represent promising parameters. In summary, the presented simulations and estimations indicate that the combination of LH2 and SMES simultaneously provides attractive synergies in terms of operational safety, efficiency and cost, and thus a strong motivation for further work.

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