Construction and Test of MgB_2 Mock-Up Coils for LIQHYSMES

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***Abstract*—One of the major challenges that come with an increasing contribution of renewable energies is the storage of the produced energy to balance the temporal fluctuations of power generation and consumption. Therefore, a novel multifunctional hybrid energy storage concept, i.e., LIQHYSMES, has recently been proposed. LIQHYSMES combines the advantages of the energy carrier LIQHYSMES (LH_2) and the Superconducting Magnetic Energy Storage (SMES). With its critical temperature of 39 K, magnesium diboride (MgB_2) is a promising superconductor for this application. In this paper, we report on the construction and test of the first demonstrator LIQHYSMES solenoid mock-up coils made of MgB_2 wires with lengths up to 1000 m. The results of cycling (charging and discharging) of the coils with different load curves and ramp rates up to 50 A/s are presented.**

***Index Terms*—Energy storage, liquid hydrogen, renewable energy sources, superconducting coils, superconducting magnetic energy storage, superconducting magnets.**

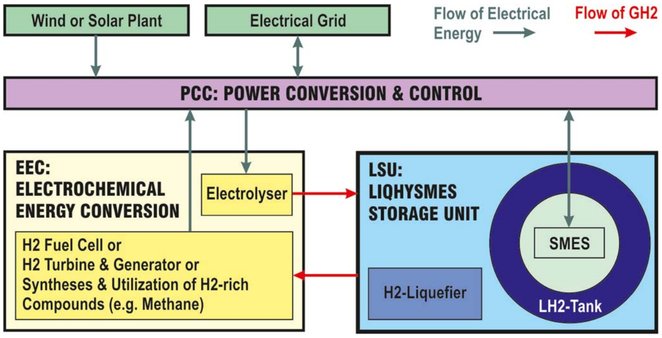

Fig. 1. Block diagram of a LIQHYSMES plant showing the main components: LIQHYSMES Storage Unit (LSU), Electrochemical Energy Conversation unit (EEC), and Power Conversion & Control unit (PCC) [3]. The flows of electricity and gaseous H_2 (GH_2) are indicated.

I. INTRODUCTION TO LIQHYSMES

WITH the aim of a substantial future contribution of photovoltaics and wind power to the total energy supply, their temporal variations in output become a major problem: minutes-to-hour changes of up to 100 % in solar and wind power are possible; further diurnal and seasonal variations—in both supply and load—exist. To balance these fluctuations and variations that come along with green electricity, an appropriate energy store is indispensable. The recently proposed LIQHYSMES storage concept addresses these challenges.

Energy storage in chemical form using hydrogen is a much discussed option. LIQHYSMES is the synergy of LIQuid HYdrogen (LH_2) as a safe high-density energy carrier and Superconducting Magnetic Energy Storage (SMES) as a fast and efficient energy buffer. The concept of LIQHYSMES has been recently proposed in several papers [1]–[6]. As this concept is a novel approach, the main features are summarized here.

In principle, LIQHYSMES consists of three subsystems (see Fig. 1):

1) The LIQHYSMES Storage Unit (LSU) is the core element. The LSU encompasses the LH_2 tank, the liquefaction plant, and the SMES. As a main feature, the SMES is placed and cooled in a connected chamber within the LH_2 storage tank, so that the cryogenic infrastructure including the H_2-liquefier can be shared as synergy.
2) The Electrochemical Energy Conversation unit (EEC) is responsible for the conversion of electrical energy into chemical energy and vice versa. In the charging phase—i.e., in the case of an excess of green electricity—water is dissociated into H_2 and O_2 by electrolysers. Subsequently, the gaseous H_2 is liquefied and stored in the tank. Conversely,—i.e., in the case of power shortage—the stored H_2 is converted to electricity using e.g., fuel cells or gas turbines with generators. The LH_2 produced can also be used for other purposes e.g., for mobility or to synthesize other H_2-rich compounds like methane.
3) The Power Conversion & Control unit (PCC) manages the flow of electricity between the wind and/or solar power plant, the SMES, the ECC, and the electrical grid.

Considering the basic operation of LIQHYSMES, short-term (seconds-to-minutes) and medium-term (about 15 min. time scale) imbalances between supply of green electricity and consumer load have to be distinguished. Medium-term changes in supply and load can be predicted quite well using ongoing updated weather and load forecasts. With this knowledge together with the current charging status of the SMES, the relatively slow-acting EEC can be adjusted. For an excess of green energy the electrolyser blocks produce H_2; on the contrary for the load case, LH_2 from the storage tank is converted to electricity e.g., by fuel cell blocks. After each update of the imbalance forecast additional blocks have to be switched on or off, if required. This leads to a larger response time, so that single LH_2 storage tanks cannot react on short-term imbalances. Massive fluctuations

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This work was supported in part by the "Energie- und Wasserstoff-Initiative" of the Helmholtz Association.

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of the output power in the short-term time scale can occur, especially for large solar power plants. These imbalances in the seconds-to-minutes range—which cannot be forecasted—can be covered by the SMES. Complementary to the more steadily and energy balancing operated LH_2 storage, the fast responding and highly efficient SMES buffer provides directly electricity, improving power quality and frequency control.

As a worst case scenario, the rated LIQHYSMES output power has to be provided solely by the SMES for a few minutes (in [4] 240 s are assumed) until the EEC has adjusted to the imbalance. Further, to maintain the feed-in ability of the SMES and to support the H_2-liquefaction by conversion of H_2 from the ortho to para spin state by magnetic field [7], the SMES should be discharged to approximately maximal 1/4 of the nominal energy (i.e., run with at least half nominal coil current).

The core element of LIQHYSMES is its superconducting magnet system. In the past, several small SMES facilities up to a few MW and a few MJ have been built using low temperature superconductors (LTS) cooled with liquid helium at 1.8 K–4.5 K, but the high cooling costs prevent further application and scaling of SMES [8]–[11]. Raising the operation temperature to 20 K, using e.g., LH_2 as coolant, lowers the costs for cooling considerably making SMES more attractive. As a drawback, LTS cannot be used any more at that temperature. With a T_c of 39 K MgB_2 is a promising superconductor for SMES with LH_2 cooling for fields up to approximately 4 T. MgB_2 is already commercially available in long lengths and at acceptable prices. Other materials like the high temperature superconductors (HTS), e.g., YBCO coated conductors, might become attractive for SMES in future with increased long length availability and reduced costs.

The aforementioned LIQHYSMES feasibility studies [1]–[6] follow a top-down approach based on the requirements and specifications for large scale green electricity storage. In the subsequent sections a bottom-up approach is followed starting with basics like in-field characterization of MgB_2 wires as well as the construction and test of first MgB_2 coils with regard to the application for SMES.

II. CONSTRUCTION OF THE MgB_2 MOCK-UP COILS

For the construction of two MgB_2 solenoid coils two batches of MgB_2 wires of 150 m and 1000 m length have been acquired from Columbus Superconductors. Both wires are tape-shaped with dimensions of 3.10 mm × 1.30 mm (insulated) and were produced by a powder in tube ex-situ process with 19 MgB_2 filaments embedded in a nickel matrix. For thermal and electrical stabilization, OFHC copper tape is laminated one-sided by PbSn solder.

The two wires were characterized in the facility JUMBO [12], [13] at 4.2 K (LHe bath) in external magnetic fields up to 8 T. Part of these results were submitted for publication recently [14]. Furthermore, the compatibility of the MgB_2 wires with gaseous H_2 (GH_2) has been tested. Several samples were stored in GH_2 atmosphere for more than 10 hours and measured afterwards in JUMBO. Neither corrosion nor degradation of the superconducting properties due to the storage in GH_2 was observed.

Using the 150 m batch, a first single-layer coil was made consisting of 42.4 m wire wound in 90 turns on a bobbin with 15 cm diameter and a length of 30 cm. For quench detection a center voltage tap was attached to the winding and a compensation coil made of enameled copper wire was placed around the MgB_2 layer. After winding, the coil was impregnated and bandaged. The main objective of this coil was to test the experimental setup and to perform initial measurements.

The second coil was made from the 1000 m length of MgB_2 tape. It consists of 6 layers each with 133 turns, i.e., 798 turns in total. The inner winding diameter is 36.5 cm, the outer 38.1 cm and the total coil length 49.0 cm. Overall, the coil consists of 935 m of MgB_2 wire. The coil inductance was calculated to be 142 mH and at room temperature a value of 160 mH was measured. The calculated coil constant is 1.75×10^{-3} T/A. As for the single-layer coil, a compensation winding made of enameled copper wire was wound around the outermost MgB_2 layer for quench detection. Finally, the coil was impregnated and bandaged. After a successful test in LHe, this major coil will be tested within the framework of the "Energie- und Wasserstoff-Initiative (EWI)" of the Helmholtz Association.

III. TEST OF THE SINGLE-LAYER MgB_2 COIL

The main objective of the testing of the MgB_2 coils is to evaluate their electro-dynamic behavior and stability with regard to the requirements of the SMES application i.e., fast charging, holding the current constant and fast discharging. The coil is operated by two power supplies that are connected in parallel: A 500 A power supply which is driven by a ramp generator is used to provide an offset current; the charging/discharging of the coil is executed by a 50 A 4-quadrant power supply in combination with a function generator. The individual and total currents are controlled by shunt resistors. This setup simulates the above described situation in a LIQHYSMES where the coil should not be discharged completely (see Section I). In case of a quench—i.e., exceeding of a minimum quench voltage for a minimum time duration—the quench detection system switches the power supplies off by means of a relay control. Simultaneously the protective circuit is opened to discharge the coil via a dump resistor. All relevant measurands are logged by a transient recorder which is controlled by a PC.

The test of the single layer MgB_2 coil was performed in the superconducting high field facility HOMER I in He-bath using the 15 T configuration with a free bore of 160 mm [12], [13]. To reduce the critical current of the coil to the I_c-level at LH_2 temperature, the testing was done in background fields of up to 6.5 T. Within the scope of the test, to simulate the SMES application, offset currents of up to 50 A were applied and in addition different periodic currents $I(t)$ with frequencies from 0.1 Hz to 3 Hz and magnitudes of up to 50 A were added resulting in total currents of up to 100 A maximum. Considering a charging-holding-discharging cycle of the coil with linear current changes, one gets a trapezoidal $I(t)$ as a basic shape form. When reducing the holding time periods to zero, a triangle $I(t)$ profile results as limiting case. Thinking in terms of "energy," a linear current variation is linked to a quadratic change of the stored energy of the coil. Therefore, to simulate

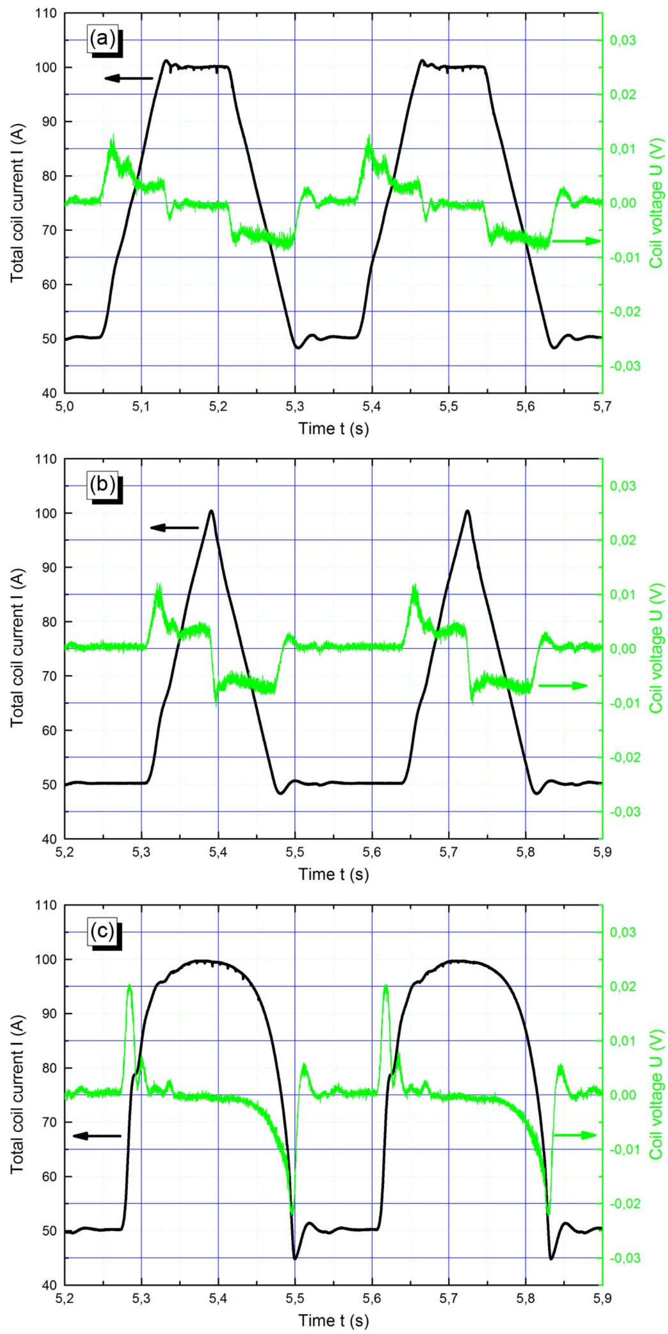

Fig. 2. Testing of the one-layer MgB_2 coil with different current profiles (black curves) at 3 Hz, self-field, and 50 A offset current: (a) trapezoidal, (b) triangle, and (c) root-like shape. The polarity of the measured coil voltage (green curves) was chosen arbitrary.

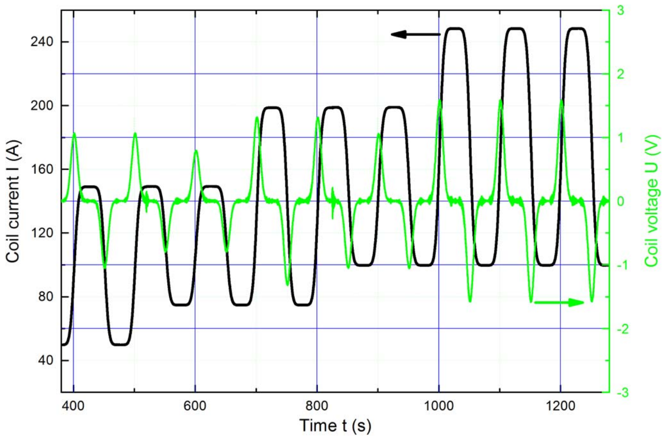

Fig. 3. Testing of the EWI multi-layer MgB_2 coil with a tanh-like current profile (black curve) with increasing offset and maximum up to approximately 250 A (partial graph for clarity). The polarity of the measured coil voltage (green curve) was chosen arbitrary.

a linear change in energy, a root shape $I(t)$ has to be applied. Fig. 2(a)–(c) shows the results obtained for these three current profiles for the highest applied frequency of 3 Hz. In the graphs the coil current and the voltage across the coil is shown. The curve of the trapezoidal $I(t)$ profile [see Fig. 2(a)] shows according to Faraday's law constant inductive coil voltages when the current is increased/decreased linearly and zero coil voltage for periods with constant current. At the kinks of the $I(t)$ profile overshoots in the coil voltage occur that may be of concern for larger magnets and should therefore be avoided. When reducing the plateau of the trapezoid the regions with coil voltage $\neq 0$ approach each other. Finally, for the triangle profile a sharp change in the coil voltage with change of sign occurs at the maximum current [see Fig. 2(b)]. Fig. 2(c) shows the results obtained for a root-like shape $I(t)$ profile which runs exponentially into a maximum. This profile combines two extremes: a steep current rise (drop) at the start (end) of charging (discharging) as well as a smooth transition at maximum current. Correspondingly, high coil voltages occur at the start/end of current change whereas no voltage arises at maximum current. Using the root-like shape $I(t)$ profile it was possible to operate the coil near I_c: At a background field of 5.1 T and therefore a coil I_c of approximately 110 A a maximum coil current of 100 A was reached periodically without quench or other problems.

For quench detection both methods — center tap and compensation winding — have been tested. By means of a bridge circuit, inductive voltage contributions ideally cancel out in both set-ups. The disadvantage of the center tap method is that only the difference in the resistive behavior of the two halves of the coil is detected. Therefore, a symmetric quench can be missed. When using a compensation winding, as a benefit, the resistivity of the complete coil is monitored. The quench detection system has been tested using both set-ups by raising the coil current wilfully above I_c. The resistivity of the coil was detected, subsequently the power supply was switched off and the protective circuit opened.

To summarize, the single layer test coil passed all the testing successfully without (spontaneous) quench or any degradation.

IV. TEST OF THE EWI MULTI-LAYER MgB_2 COIL

In view of the successful operation of the single-layer coil, the EWI multi-layer solenoid was tested using an analog experimental setup. However, due to the increased dimensions of the EWI coil, the testing was carried out in the magnet test facility MTA I which provides He-bath cooling without background field as a testbed for larger coils. For quench detection, the balanced signal of the MgB_2 coil and compensation winding was monitored.

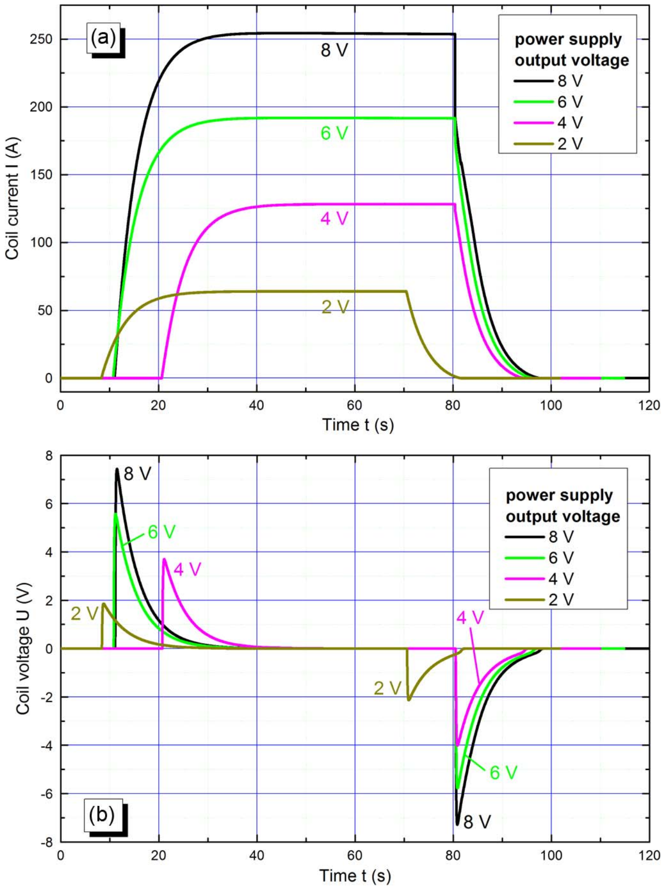

Fig. 4. Testing of the EWI multi-layer MgB_2 coil with a rectangular voltage profile sequence from 1 V up to 8 V: (a) coil current, (b) coil voltage. For clarity, only every 2nd curve is shown.

The testing of the single-layer coil using different $I(t)$ profiles like “trapezoidal”, “triangle”, and “root-like shape” showed that to limit the coil voltage the applied current profile should show no kinks and no steep alterations. Accordingly, hyperbolic tangent-like current profiles are advantageous. Fig. 3 shows the voltage measured for the EWI coil when applying such a tanh-like current profile. $I(t)$ was changed periodically with stepwise increased offsets of up to 100 A and maximum currents of up to approximately 250 A. With respect to the time scale for charging/discharging in the LIQHYSMES application in the order of some minutes (see above) a period of 100 s was chosen. For the latter case — i.e., oscillations between 100 A and 250 A—a maximum coil voltage of ±1.6 V was measured. With a maximum ramp rate of approximately ±11.1 A/s a coil inductance of 144 mH results which is in good agreement with the calculated value. As a result, the EWI-coil passed the complete current testing using several $I(t)$ profiles with currents up to approximately 250 A and ramp rates appropriate to the LIQHYSMES application problem-free without any quench or evidence for degradation.

For the evaluation of the stability of the EWI-coil against fast load changes and disturbances, the response of the coil to voltage steps and voltage peaks according to the linear response theory was investigated. Fig. 4 shows the response of the coil to a voltage step sequence starting from 1 V up to 8 V with 1 V increment and the subsequent shutdown of the power supply for each voltage step after dwell times of 25 s–50 s. After switching on the power supply, the current increases exponentially with initial slopes of up to 52 A/s and relaxation time constants of approximately 4.7 s. For the highest power supply output voltage of 8 V a coil current of 255 A is obtained [see Fig. 4(a)]. Therefore, the total resistance of the circuit adds up to approximately 31.4 mΩ including a series resistor of 20 mΩ. This data lead to a coil inductance of approximately 148 mH which is in between the calculated inductance (142 mH) and the measured value (160 mH). In the setup used for the voltage experiments, the coil is discharged via the power supply after switching off the power. As expected, the coil voltage shows a relaxation behavior correlating to the current [see Fig. 4(b)]. In conclusion, the EWI-coil passed the voltage step testing with slopes up to 50 A/s problem-free without any quench or evidence for degradation.

Finally, to investigate the impulse response of the EWI-coil, a sequence of short voltage peaks from 7 V up to 10 V with 1 V increment was applied. Immediately after the power supply reached the target output voltage it was switched off. As before, the coil was discharged via the power supply. As a result, the EWI-coil also passed the voltage peak testing problem-free without any quench or evidence for degradation.

V. CONCLUSION

The recently proposed LIQHYSMES energy storage concept addresses the major challenge that comes with an increasing contribution of fluctuating green electricity. It merges the benefits of LH_2 as a high density energy carrier to cover middle- and long-term imbalances in energy supply and demand as well as the benefits of SMES as a fast and efficient buffer to cover short-term imbalances. With this background two MgB_2 demonstration coils were manufactured and tested with regard to the SMES application; a single layer winding and a multi-layer coil consisting of almost 1000 m MgB_2 wire. Both solenoids have been successfully tested by applying different current and voltage profiles simulating the charging/discharging up to 250 A and 50 A/s. Trapezoidal, triangle, root-like shape, and tanh-like profiles as well as step and peak form disturbances have been investigated in detail. In conclusion, the coils passed the demanding testing problem-free without any quench or degradation. Up to now, the investigations were performed in LHe bath. Currently a LH_2 cryostat and the required LH_2 cryogenic infrastructure are under construction to confirm the results in LH_2 bath.

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