

LIQHYSMES - spectral power distributions of imbalances and implications for the SMES

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Abstract. LIQHYSMES, the recently proposed hybrid energy storage concept for variable renewable energies, combines the storage of LIQuid HYdrogen (LH2) with Superconducting Magnetic Energy Storage (SMES). LH2 as the bulk energy carrier is used for the large scale stationary longer-term energy storage, and the SMES cooled by the LH2 bath, provides highest power over shorter periods and at superior efficiencies. Both together contribute to the balancing of electric load or supply fluctuations from seconds to several hours, days or even weeks. Here different spectral power distributions of such imbalances between electricity supply and load reflecting different sources of fluctuations in the range between 1 sec and 15 minutes are considered. Some related implications for MgB2-based 100 MW-SMES operated at maximum fields of 2 T and 4 T, are considered for these buffering scenarios. Requirements as regards the storage capacity and correspondingly the minimum size of the LH2 storage tank are derived. The related loss contributions with a particular focus on the ramping losses are analysed.

1. Introduction

Energy storage systems providing tens to hundreds of MW and GWh and storing large amounts of excess energy from renewable energy sources could contribute to balancing electricity supply and demand from seconds to several days or weeks. For this purpose recently the LIQHYSMES approach has been proposed [1-4]. The imbalance (or difference) between (e.g. wind power) supply and (consumers') demand can vary significantly. The required power level and storage capacity of the SMES for buffering the momentary imbalance will then directly depend on the characteristics of this difference. In the following it will be assumed that the electrochemical energy (re-) conversion of H2 fully compensates the variations of the imbalance on a time scale above 15 minutes which is typical for the (primary) control and trading of electric power. In the following different remaining imbalances on time scales below 15 minutes will then be used to investigate the corresponding requirements for the SMES.

2. Simulation of Balancing Cases #1 to #3

Three different spectral power distributions are used to simulate the remaining imbalances between supply and load on time scales below 15 minutes. The power spectrum contains a geometric sequence made of 100 discrete frequencies f between $1/(15 \text{ min})$ and $1/(1 \text{ sec})$, and the relative phases have been created by generating random numbers. The relative peak intensities are chosen so that white, $1/f$ and



1/f² spectral power densities are approximated. Widely Gaussian distributions are obtained for all three cases when averaging over periods of 1 sec, 10 sec, 1 minute and 5 minutes. All distributions are adapted so that the standard deviation for the power averaged over 1 second is in all three cases 25 MW (values for longer periods differ due to their specific spectral power distribution). Therefore also the mean absolute power is with 20 MW identical in all cases. Whereas the “white” case #1 has strong fluctuations on a second time scale, the “1/f²” case #3 shows only slow variations over several minutes, and the “1/f” case #1 lies in between. The maximum SMES power is then assumed to be four standard deviations or ± 100 MW, but the requirements as regards the stored SMES energy differ for the three distributions. For all SMES systems toroidal configurations having 20 identical solenoidal coils of Magnesium Diboride (MgB₂) round wires with a diameter of 100 μ m and maximum magnetic fields of 4 T and 2 T have been assumed. The data are summarized in Table 1.

Table 1: Characteristics of Test Cases #1 to #3 and 100MW-10kA-SMES for 4T & 2T

Spectral Variation of Power Density of Imbalance	“white”	“1/f”	“1/f ² ”
Standard Deviation in MW for Averaging over @	25 /	25 /	25 /
1sec / 10 sec / 1 min / 5 min (20MW Mean Power)	~ 4.7 / 0.56 / 0.15	18 / 13 / 6.0	25 / 25 / 16
Test Case / Rated SMES Energy in GJ (discharged @ 50 % of max. Coil Current 10kA)	#1A / #1B /	#2 /	#3 /
	0.25 2.5	10.0	22.5
Maximum Magnetic Field at Coil in T	4 (top data in each line below) / 2 (bottom data in each line below)		
Outer Coil Radius R in m (Height = R / 5; Total SMES System: Radius / Height ~ 2.75 R / 2 R)	1.92 / 3.04	4.13 / 6.55	6.55 / 10.4
Required Conductor in GAm (on the Basis of the Critical Current I _c @4T,20K)	0.71 / 0.16	3.29 / 0.76	8.29 / 1.91
Max. Mean Operating Current Density in Coil	1.85 / 0.58	0.86 / 0.27	0.54 / 0.17
Winding in kA/cm ²	0.58 / 0.05	0.27 / 0.21	0.17 / 0.53
Full-Cycle Ramping Loss of SMES (round MgB ₂ wire, diameter 100 μ m) in MJ	0.18 / 0.05	0.83 / 0.21	2.09 / 0.53
Electric Power for Removing Thermal Losses of Cryostat & Current Leads in MW (~ 93 W/W)	0.104 / 0.136	0.178 / 0.306	0.306 / 0.607
Mean Electric Power for Removing the SMES Ramping Loss in MW (~ 93 W/W)	0.964 / 0.225	0.426 / 0.101	0.247 / 0.060
Total Mean Loss of SMES in MW (w/o ~ 1.6 MW Mean PCC Loss)	1.07 / 0.36	0.60 / 0.41	0.56 / 0.67
			1.00

For case #1 with the predominantly higher frequency components a discharge duration of 2.5 seconds at the maximum power of 100 MW would be sufficient (case #1A) for providing a reliable primary control. Due to the buffering requirements coming from the H₂ components of a LIQHYSMES plant a ten-fold oversized SMES for 25 seconds of discharge duration is also included (case #1B). For cases #2 and #3 the much stronger low frequency contributions require higher storable energies for the SMES. To reduce the losses and to have sufficient safety margins as regards a quench, the maximum operating current is set to be only 50 % of the critical current. The assumed I_c(B) characteristic has been shown in [2]. Full-cycle ramping losses are calculated for the SMES systems when ramped between 50 % and 100 % of the operating current or magnetic field. The calculation method has already been described in [1]. In brief, for sufficiently slow ramping processes and high fields, the hysteretic magnetization losses strongly dominate and can be well approximated by the critical state model. Under these assumptions the ramping losses become independent of the ramping rate. The introduction of a differential ramping loss giving the loss per field change allows calculating the local conductor losses for any local magnetic field B in the coil winding and taking into account the I_c(B) characteristic. For the fields and the discharge times under consideration the ramping rates

are in the range of about 4 mT/s (case #3 @ 2 T) to 800 mT/s (case #1A @ 4 T). Thus for discharge times of only 2.5 seconds the assumption for the calculation method may not be fully valid and loss data provide only a crude estimate for the lower bounds.

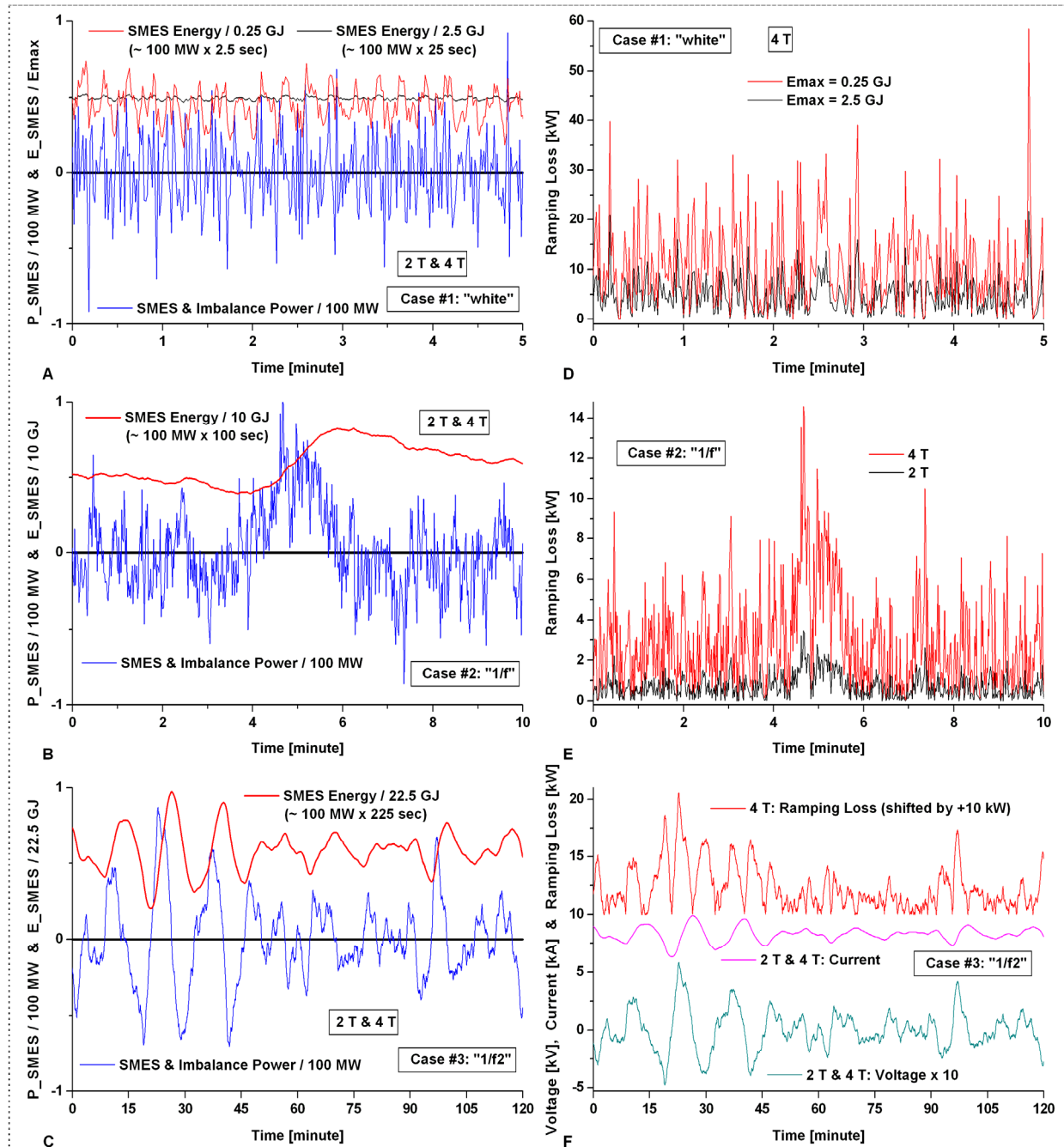


Figure 1. A-C) Momentary power level for the cases #1 to #3 and charging status for both magnet designs of 2 T and 4 T (in case #1 also for the two different storage capacities E_{max}); D) Raming loss of one coil for both storage capacities and the 4 T magnet design (case #1); E) Raming loss of one coil for both magnet designs (case #2); F) Raming loss for the 4 T magnet design and momentary current & voltage levels (identical for both magnetic field designs) of one coil.

3. Simulation Results for Balancing Cases #1 to #3

The balancing processes for cases #1 to #3 have been calculated for a total period of four days which was found to give a sufficient statistics. These averaged data were then used to calculate the mean loss components which are included in Table 1. The heat created by the ramping losses has to be removed by a cooling system and the related electric power varies from 0.05 MW for the 2 T design of case #3 to almost 1 MW for the 4 T design of case #1A. The thermal load on the cryostat necessarily increases with its size, and, therefore, also the electric cooling power for cryostat and current leads goes up with the SMES size. For all cases the estimated losses of about 1.6 MW for the power conversion and control are the strongest individual loss contribution reflecting the assumed operational and standby losses.

Typical examples for the simulated balancing processes are given in Figure 1. The momentary power levels and the charging status of the SMES systems used in the cases #1 to #3 are given in the graphs A-C. For case #1 the two different storage capacities E_{\max} corresponding to 2.5 and to 25 seconds are shown in Figure 1A. The corresponding ramping losses occurring in one coil of the SMES are provided for the magnetic field design for 4 T in Figure 1D. For a discharge duration of 2.5 seconds the strongly fluctuating power level of the imbalance results in quite significant changes of the charging status and, consequently, also in significant ramping losses. The tenfold larger storage capacity of 25 seconds reduces the fluctuations of the charging status and, in particular, the losses by roughly a factor of 2. For case #2 the ramping losses of one coil for both magnetic field designs are provided in Figure 1E. The lower field of 2 T shows only roughly a fourth of the losses of the 4 T design, and this is actually observed for all cases which reflects the general trend for field dependencies of ramping losses [2]. The storage capacity of 10 GJ is four times the one for case #1B, and the losses decrease almost by a factor of 2 when comparing the 4 T designs. Going to case #3 with 225 seconds of specified discharge duration gives only a modest additional reduction of losses (Figure 1F). Figure 1F also shows an example for the relations between the momentary power and charging status of the whole SMES system and the current and voltage levels seen by a single solenoidal coil. The latter applies to both magnetic field designs. The rated power of the SMES and the operating currents were assumed to be same for all cases (changing between 5 kA and 10 kA). Consequently also the voltage levels are about the same for case #1 to case #3 and stay well below 1 kV.

4. Conclusion

A simple calculation method is used to simulate imbalances between supply and load for different spectral power distributions and for a time scale below 15 minutes which is typical for the (primary) control and trading of electric power. In LIQHYSMES plants these contributions mainly have to be buffered by a SMES of adequate storage capacity. SMES operated at smaller magnetic field require more space, but show lower losses, and may be particularly attractive when very large amounts of excess energy i.e. tens to hundreds of GWh from variable renewable energy sources have to be stored as LH2 anyway.

5. References

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