AC-loss considerations of a pulse SMES for an accelerator

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Abstract. In particle accelerators quasi-DC superconducting magnets are used to keep particles in desired tracks. The needed rapid field variations of these high energy magnets require large energy bursts. If these bursts are taken from and fed back to the utility grid, its voltage is distorted and the quality of the electricity degrades. In addition, these bursts may decrease operation life time of generators and extra arrangements may be required by the electricity producers. Thus, an energy storage is an essential component for a cost-effective particle accelerator. Flywheels, capacitors and superconducting magnetic energy storage (SMES) are possible options for these relatively large and high power energy storages. Here we concentrate on AC-loss of a pulse SMES aiming to demonstrate the feasibility of NbTi SMES in a particle accelerator. The designing of a SMES requires highly reliable AC-loss simulations. In this paper, calorimetric AC-loss measurements of a NbTi magnet have been carried out to consider conductor’s suitability in a pulse SMES. In addition, the measured results are compared with AC-loss simulations.

1. Introduction
When a high power for a short time is needed relatively often, the superconducting magnetic energy storage (SMES) can be considered for the power source. In applications such as particle accelerators and in fault situations in the utility grid, high power pulses are needed with a duration of 100 ms to seconds to compensate fast alterations in the load [1, ch H7.1].

In particle accelerators, SMES systems might be competitive when compared to flywheels according to [2]. In this application, a major advantage of a SMES is a ready cryogenic support provided by the cooling system of superconducting magnets of the accelerator ring [3]. In the past, several SMES projects have been started aiming to improve the power quality [4, 5, 6]. In these projects both the low and the high temperature superconductors have been used. However, high temperature superconductors are not yet technically feasible for large AC-applications. Higher critical current density and better mechanical performance are needed [7, 8].

We are developing a liquid helium (LHe) cooled NbTi SMES that can provide continuous 1 MJ pulses at peak power of 1 MW. Main objectives of the project are to test the feasibility of the SMES in a pulse use at frequency between 0.1 to 1 Hz and try to find a method to estimate its feasibility at powers up to 30 MW in a particle accelerator system. Tests are planned to be carried out in a shipping container crane.

In filamentary composite superconductors AC-losses are composed of hysteresis and self field losses ($Q_h$) and the sum of eddy current and coupling loss ($Q_e$) [10, ch 8]. AC-loss of the wire is...
a very important factor in designing a SMES. In this paper AC-test results of the test coil are presented.

2. Experiment and computational model
The first step in our project was to build a test coil to estimate the AC-losses of the OK3900 NbTi conductor [9]. Important parameters of the conductor and the test solenoid are shown in table 1.

Table 1. Wire data and dimensions of test coil.

| OK3900 Conductor:     |             |
|-----------------------|-------------|
| Material (SC / Matrix) | NbTi / (Cu/Mn) |
| Number of filaments   | 3858        |
| Filament diameter [µm] | 7.10        |
| Diameter [mm]         | 0.76        |
| Diameter (insulated) [mm] | 0.81    |
| Twist pitch [mm]      | 15.10       |
| Cu/Mn:NbTi            | 2           |
| Test coil:            |             |
| Height [mm]           | 40.00       |
| Inner radius [mm]     | 70.00       |
| Outer radius [mm]     | 84.60       |
| Conductor length [m]  | 432.80      |
| Inductance [H]        | 0.15        |

The coil was wound using wet layer technique with prestress of 2 kg. To impregnate the winding Stygast epoxy was used because of its similar thermal contraction compared to the coil bobbin made of fibreglass. Several holes were made on the coil bobbin to get coil flanges in contact with helium. The coil is shown in figure 1.

We used a gas flow rate meter and LHe level meter to measure helium boil off during AC-operation. To calibrate the gas flow rate meter, one heater was installed on the coil bobbin. Temperature sensors were installed on the upper flange of the coil and on current leads. Voltage sensors were also installed to measure voltage over coil terminals and current leads. For the AC-loss measurements, we ramped the coil with triangular current pulses.

2.1. Empirical method to define AC-losses
AC-loss measurements were based on the calorimetric method. This means that AC-loss is determined from the volume of helium gas flow from the cryostat or liquid helium boil off during pulse operation.

When measuring helium gas flow, 1 W of losses at 4.2 K corresponds to 16.08 l/min flow at n.t.p. Liquid helium boil off of 1.378 l/hour corresponds to 1 W losses at 4.2 K. [10, ch 10] In addition to AC-loss, conduction and radiation losses are also directed to the cryostat. Thus, to solve AC-losses, static losses need to be removed from the measurement results. Guidelines for compensating static losses are presented in [1, ch B4.2]. Here we used the gas flow to determine the AC-loss, since we found variation in gas flow that depended on the surface height of LHe between repeated measurements.
2.2. Analytic method to calculate AC-losses

To compare the measured results, analytic calculations have been made according to formulas presented in [10, ch 8]. These are based on Kim’s model for current distribution. For hysteresis and self field loss it states

\[
Q_h = \frac{8}{3\pi} a J_{co} B_0 \left( \frac{B_m + B_o}{B_m} \ln \left( \frac{B_m + B_o}{B_o} \right) - 1 \right) \left( 1 + \left( \frac{I_t}{I_c} \right)^2 \right) \lambda_1 \lambda_2 V_{coil},
\]

where \( a \) is the filament radius, \( J_{co} \) and \( B_0 \) are constants in Kim’s model to be defined from \( I_c \)-curve of the conductor, \( B_m \) is the amplitude of the magnetic flux density, \( \lambda_1 \) and \( \lambda_2 \) are the fill factor of the coil and NbTi proportion of the conductor, respectively, and \( V_{coil} \) is the volume of the coil. The term

\[
\left( 1 + \left( \frac{I_t}{I_c} \right)^2 \right),
\]

where \( I_t \) is the transport current and \( I_c \) the critical current, stands for the effect of transport current.

For coupling and eddy current loss it states

\[
Q_e = \frac{B_m^2}{2\mu_0} \frac{8\tau}{3T_m} \lambda_1 V_{coil},
\]

where \( T_m \) is the rise time of the current ramp. The time constant can be determined from

\[
\tau = \frac{\rho_{ef}}{2\mu_0 p} \left( \frac{p}{2\pi} \right)^2,
\]

where \( \rho_{ef} \) and \( p \) are effective transverse resistivity and twist pitch, respectively. Equations (1) and (3) give losses as joules per cycle.

3. Results

In figure 2 the training curve for the coil is presented. The training effect appears quite strong here and is most likely due to the small prestress during winding. Besides the small prestress another reason for the long training period might also be the compound of the matrix. To
reduce coupling losses manganese has been added to the matrix. This increases the resistivity of the conductor but also decrease stability and the conductor becomes more sensitive to different perturbations [12]. Finally, the coil reached 310 A, 83 % of its calculated critical current 373 A.

A temperature increase of 0.03-0.44 K was measured with the heater, shown in figure 1, during AC-loss measurements. Thus for (1) and (3) \( I_c \) should be lowered from the measured 310 A. However, since we did not know the real temperature distribution in the winding we used constant \( I_c \), 310 A, in computations.

![Figure 2. Training curve.](image)

Figure 3 shows the maximum ramping amplitude for continuous (\( > 20 \) min) AC exposure without a quench. As seen at 0.08 Hz \( I_c \) reduction was about 10 % from DC case whereas at 1 Hz it was already more than 70 %.

Figure 4 shows the measured and computed AC-loss. For the measurements the losses of current leads could not be separated. In analytic calculations the effective transverse resistivity plays a very important role. Different ways to estimate \( \rho_{ef} \) are presented in [1, ch B4.3]. These methods require detailed information of the conductor geometry and constituents. At this phase of our project, further study, including measurements of \( \rho_{ef} \), have not been performed. Thus, we varied \( \rho_{ef} \) as 0.5 nΩm, 1 nΩm and 5 nΩm based on results presented in [12],[13] and [14]. In reality, \( \rho_{ef} \) is an increasing function of \( B \).

From (3) one can see that \( \rho_{ef} \) has an effect on \( Q_e \). When the effective transverse resistivity is high enough, \( Q_e \) becomes very small compared to \( Q_h \). This is the case with the test coil according to the measurements. The amplitude of the current is higher at frequency 0.2 Hz than 0.4 Hz and so are the losses. If the transverse resistivity is small (0.5 nΩm), amount of \( Q_e \) increases especially at higher frequencies and the loss behaviour changes. Another reason for the measured behaviour might be the inaccuracy of the gas-flow rate meter. When we calibrated it via heater, there was +/- 0.3 W error detected. This can change the behavior into such as calculated with \( \rho_{ef} = 1 \) nΩm.

In figure 5, AC-loss of the coil and current leads as a function of amplitude at frequency of 0.4 Hz is presented. Analytic computations show constantly increasing loss dependence on amplitude, which is in balance with the measured behaviour within the inaccuracy of the gas flow meter. However, the calculated AC-loss can only be a crude estimate taking into account
the different effects related to e.g. the local heating at the conductor, the different magnetic fields at different coil locations or the geometrical uncertainties of the conductor.

At this point of the work it is difficult to estimate the feasibility of the conductor. The final dimensions of the target coil are not yet fully optimized. The volume of the coil will be bigger and most probably the field maximum will be lower than 5.56 T which was calculated for our test coil at $I_c$. These will have an effect on AC-losses. It seems that the test coil could not be driven with sufficient current amplitudes at frequencies above 0.4 Hz. However, adequate usability might be achieved with better cooling also at frequencies above 0.4 Hz.

Figure 3. Critical current dependence on ramp frequency.

Figure 4. Measured and computed AC-loss as function of frequency. Different frequencies correspond amplitudes $I(0.08 \text{ Hz}) = 187 \text{ A}$, $I(0.2 \text{ Hz}) = 195 \text{ A}$, $I(0.4 \text{ Hz}) = 169 \text{ A}$, $I(0.5 \text{ Hz}) = 141 \text{ A}$, $I(1 \text{ Hz}) = 70.5 \text{ A}$.
Figure 5. AC-loss as function of current amplitude at frequency of 0.4 Hz.

4. Error sources
During measurements background boil off depended on the LHe level. When defining the AC-losses, we used constant static boil off. In addition, static boil off depended on the heating power. When the boiling due to AC-losses becomes larger the cooling improves inside the cryostat and the static loss decreases. This effect could not be quantitatively estimated, but it seems apparent since in figure 5 AC-loss increases only a little compared to the theory when amplitude increases from 146 A to 169 A.

Variation in repeated measurements was greater when AC-loss was determined from LHe-level meter instead of gas flow rate meter. The boiling of LHe might have disturbed the level meter especially at higher heat loads. Also, to defining boil off via LHe-level the volume of instrumentation needed to be considered. Due to this, the AC-losses were defined from the readings of gas flow rate meter.

5. Conclusions
The AC-losses of the test coil have been measured. The AC-loss of the test coil and the current leads stays under 8 J/cycle under frequency of 0.4 Hz with usable current amplitudes. The coil can not be driven with very high amplitudes at frequencies above 0.4 Hz. One reason is that there is no cooling channels. Despite of holes on coil flanges, cooling is not very effective and the temperature rises in the coil when increasing pulse frequency.

Better $I_c$ performance in AC use could be attained with a coil including cooling channels. This will be considered in our next step. Another step is to optimize the final coil geometry and consider its stability and quench.

5.1. Acknowledgments
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6. References
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