Simulation and experiment of a YBCO SMES prototype in voltage sag compensation

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\textbf{A B S T R A C T}

This paper gives a introduction of a SMES unit using 2G HTS wires. A complete SMES system including both superconducting coils and control circuit has been designed to operate at 77 K. Three single-phase H-bridge converters have been used in the control circuit. A loop control signal is sent out by using 32 fixed point Digital Signal Processor (DSP). The complete circuit has been both modelled in simulation and built experimentally. The results validate that this SMES successfully compensates a voltage sag in a power system.

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1. Introduction

A voltage sag in a power system will damage the sensitive electrical loads and equipments. Connected to a power system through a power electronics control circuit, a Superconducting Magnetic Energy Storage (SMES) system can release its energy within several milli-seconds with a high cyclic efficiency to recover the voltage. Therefore SMES is a good candidate to compensate a voltage sag in a power system [1–4].

Since long length of second generation high-temperature superconducting (2G HTS) wires became commercially available, it is possible to use 2G HTS wires to wind the SMES coils. 2G HTS – YBCO conductors are more promising than BSCCO conductors in SMES systems since the current density of YBCO is much higher than BSCCO and also YBCO has better performance in external magnetic field. The design of the SMES coils are aimed for the operation at 77 K as the first step to build a 2G HTS system. This design will be adapted for the operation at lower temperatures in future. Fourteen SMES coils have been built and tested.

To control our SMES unit, we build three single-phase H-bridge converters in our SMES control circuit. This converter is superior to the traditional voltage-source converter since it uses a DC voltage more efficiently and control the voltage more flexibly [5–7].

2. The SMES design and control circuit

2.1. The SMES coil design

Second-generation high-temperature tapes produced by Superpower. Inc. are used to wind the SMES coil, thus the coil consists of a stack of pancake coils. Both 4 mm and 12 mm width tapes are used in this SMES coil. The 12 mm width tape can carry three times the current that the 4 mm width tape can carry, but is also more expensive. Since the perpendicular magnetic field around the top and bottom of the coil is at maximum, and the critical currents of 2G tapes depend more on the perpendicular rather than parallel magnetic field, the 12 mm width tape is used in the top and bottom of the SMES coil to increase the operation current, while the 4 mm width tape is used in the middle of the coil to save cost. Table 1 gives the configuration of the hybrid SMES coil. Fig. 1 gives the cross section view of the SMES coil.

A 3D Finite Element Method (FEM) model is used for calculating the optimal current of the hybrid SMES coil. According to the distribution of the magnetic field and Stoke’s Law, the self inductance and mutual inductance of each coil can be obtained after calculation. The maximum operation current of the SMES coil is determined by the intersection point of the $I_{c}\sim B_{h}$ curve of the superconducting tapes and the $I\sim B_{h}$ curve of the coil. We should notice that this design is for 77 K thus the $I_{c}\sim B_{h}$ curve is based on experimental data at 77 K. Fig. 2 gives the $I\sim B_{h}$ curve of the superconducting tapes. These curves are measured by experiments. From Fig. 2 we can find that the tape is most vulnerable to the magnetic field which is 40–50 ° from the parallel direction of the tape surface. The $I\sim B_{h}$ curve is uniquely determined by

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the configuration of the magnet. By finding intersection point of the \( I_c - B - \theta \) curve and the \( I - B - \theta \) curve, we can calculate the maximum operation current of the SMES coil. The whole FEM calculation process is shown in Fig. 3. After optimization, the inductance of the SMES coil is 2.39 H, the operation current is 20 A, and the total stored energy is 0.478 kJ. Fig. 4 gives the 3D figure of the stack of coils and Fig. 5 gives the cross section view of the magnetic field in the stack of the coils. Fig. 6 gives the photograph of the SMES coils.

2.2. The SMES cooling system

The first stage is to test the SMES at 77 K. All the design, simulation and experiment introduced in this paper is aimed for operation at 77 K. However, future research will include the operation at lower temperatures to achieve more stored energy. Therefore the cooling system is designed in such a way that it can operate at 77 K as well as 65 K or even 30 K.

Fig. 7 presents the photograph of the cooling system. The SMES coil is put into a dewar which is filled with LN\(_2\). Normally the coil is operating at 77 K. In addition, A 600 W GM refrigerator is connected to the dewar. When the refrigerator is working, the LN\(_2\) will be sub-cooled and the temperature can reach 65 K. This SMES coil can also possibly be cooled down using conducting cooling method. We can see the copper strains and copper plates in the SMES coil for heat transfer in Fig. 6.

2.3. The SMES control circuit

2.3.1. The control strategy

The connection of the SMES system with the power system is shown in Fig. 8, it includes a SMES unit, a chopper, a voltage-source converter and a low-pass filter. The SMES system is connected through the power system with an isolation transformer. During the operation, if a voltage sag at Bus1 is detected, the SMES system will release its energy to compensate the voltage sag and maintain the Bus2 voltage at a constant amplitude value, therefore the important sensitive load is protected.

Fig. 9 shows the compensation process. In the normal condition the sensitive load requires a voltage \( V_{Bus2} \). During a voltage sag, the voltage at Bus1 will drop to \( V_{Bus1} \). The voltage value decreases and the phase shifts compared to the normal condition. The control circuit will release the SMES energy to produce a compensation voltage \( V_{conv} \) and this \( V_{conv} \) will keep the load voltage \( V_{Bus2} \) the same as the normal condition.

Fig. 10 shows the algorithm to calculate the compensation voltage. Firstly, the three-phase voltages are transformed to \( d, q \)-axis voltage by the phase-locked loop. Since \( U_\phi \) is a constantly 0 for a symmetric three-phase voltage, we only need to compensate the

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape length (m)</td>
<td>2800</td>
</tr>
<tr>
<td>Pancake number (12 mm tape)</td>
<td>4</td>
</tr>
<tr>
<td>Pancake number (4 mm tape)</td>
<td>10</td>
</tr>
<tr>
<td>Inner diameter (mm)</td>
<td>70</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>280</td>
</tr>
<tr>
<td>Turns per pancake</td>
<td>360</td>
</tr>
<tr>
<td>Coil height (mm)</td>
<td>219</td>
</tr>
</tbody>
</table>

Table 1

Design of the hybrid SMES magnet.

Fig. 1. The cross section view of the hybrid SMES coil.

Fig. 2. The relationship between the tape critical current \( I_c \) and the magnetic field \( B \) with an angel \( \theta \).
Fig. 3. The solution process of the optimal operation current of the SMES coil.

Fig. 4. The 3D dimension of the SMES coil.

Fig. 5. The magnetic field distribution of the SMES coil.

Fig. 6. The photograph of the SMES coil.

Fig. 7. The cooling system for the SMES unit.
Then we compare the monitored \( U_d \) with the reference voltage \( U' \). Finally, we can calculate the compensation voltage needed. After Proportional Integral (PI) control and transferring the \( d, q \)-axis voltage back to normal three-phase voltage system, we can send it as SPWM (Sinusoidal Pulse Width Modulation) signal to the converter, which will produce the compensation voltage needed in power system.

### 2.3.2. The system circuit

**Fig. 11** shows the whole system circuit. It includes the SMES unit, a voltage-source converter, a low-pass filter, an isolation transformer, a power source, a fault circuit and a sensitive load.

The Bus1 voltage is monitored and sent into a digital-signal processor DSP2812 by the sampling circuit at 5 K sampling rate. The processor compares the sampling voltage with the reference normal voltage. If a voltage sag happens, the processor will calculate...
the difference, send the driving PWM signal to the converter and produce the compensation voltage needed. Then the voltage is filtered by the filter circuit and sent to the power system through the transformer. By the process above, the load voltage is maintained at a normal value during a voltage sag.

The filter circuit consists of a capacitor and an inductance. The output voltage of the converter includes the normal 50 Hz component and high-frequency harmonics. The filter circuit will filter the harmonics and let the normal 50 Hz component go through.

There are three transformers $U_{\text{ain}}$, $U_{\text{bin}}$ and $U_{\text{cin}}$ in three phases to transform the converter output voltage to the power system voltage.

In the main system circuit, $U_a$, $U_b$ and $U_c$ are a three-phase power source. $X_S$ is the impedance of the transmission lines. $R_L$ and $X_L$ are the important sensitive load which requires a constant voltage. Fault circuit consists of $X_b$, $X_L$, $R_L$ and a fault controller. This fault circuit is able to produce a voltage sag on Bus1.

We can also see the components of the SMES unit in Fig. 11. It includes three single-phase H-bridge converters and a chopper. Each H-bridge converter consists of four power electronics transistors (Insulated-gate bipolar transistor, IGBT). These converters are able to convert DC voltage from the SMES coil to AC voltage in the power system. The chopper consists of a capacitor $C_d$, two IGBTs $S_1$ and $S_2$, and two diodes $V_{D1}$ and $V_{D2}$. The chopper manages the conversion between the SMES coil current and the H-bridge converter voltage. It increases operation safety by isolating the SMES magnet from the power system. It also controls the current flow of the SMES by switching $S_1$ and $S_2$. During the charging process the current will go through $S_1$, the coil and $S_2$, and during the discharging process the current will go through $V_{D1}$, the coil and $V_{D2}$.

3. Simulation and experiment results

3.1. Simulation results

To demonstrate the performance of the SMES in a voltage sag, we first built the whole system in Matlab/Simulink. The whole system was modelled according to Fig. 11. Since the three-phase voltages are symmetrical, we just take phase A for example. The Phase A voltage will be dropped for about 300 ms. Fig. 12 gives
the simulation result. We used a 50 Hz voltage. The peak value of the normal voltage before compensation was 75 V. A voltage sag happened at \( t = 75 \) ms. Immediately after the voltage sag happened, the converter released the SMES energy and produced a compensation voltage. The total voltage after compensation is maintained at 75 V. The simulation result validates the control strategy of the SMES system.

3.2. Experiment results

An experiment rig was set up to test the SMES system as well. This experiment system was built up according to Fig. 11 as well. Fig. 13 shows the components of the experimental set-up. Again, we are using a 50 Hz 75 V (peak value) voltage. At \( t = 75 \) ms a voltage sag happened, the converter produced a compensation voltage. We can find that there are little spikes in the compensation voltage since the high-frequency harmonics cannot be completely filtered by the filter in the real experimental set-up. However, the SMES system still compensated the voltage sag. The voltage after compensation is nearly at the same value as shown in Fig. 14.

4. Conclusions

We have built up a complete SMES system consisted of superconducting coils using 2G HTS wires and a control circuit. The control circuits consists of a voltage-source converter, a three-phase filter and a three-phase transformer. We have designed a control strategy to control the SMES unit to compensate a voltage sag in a power system. A simulation circuit was built in Matlab/Simulink to validate the control strategy. Finally we built up the whole system experimentally and successfully controlled the SMES unit to compensate a voltage sag in a power system.

References