Experimental study on using a high-temperature superconducting inductor for power loss reduction in an active power filter

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Abstract. An active power filter improves the electric power quality through the compensation of harmonics in the power network. A current-source active power filter using a conventional copper inductor for its energy storage has a significant power loss. The loss in the copper inductor can be substantially reduced by using a high-temperature superconducting (HTS) inductor instead. Experiments have been conducted on a prototype current-source active power filter for studying the power loss reduction effect and harmonics compensation performance of the active power filter using a HTS inductor. Experimental results are analysed and discussed in this paper.

1. Introduction
Nonlinear loads such as rectifiers, switched-mode power supplies and variable-speed drive systems generate harmonics in electric power distribution systems. Today, a large number of nonlinear loads have increased the harmonics in power systems in many areas to problematic levels that will inevitably disrupt the other loads on the network by causing overheating of motors, drives, cables, thermal tripping of protective devices and logic faults of digital devices. In addition the life span of many devices may be reduced by overheating.

A nonlinear load generates harmonics in the power distribution system because it draws non-sinusoidal currents from the system. A shunt active power filter connected close to the non-linear load can eliminate the current harmonics on the supply side of the power distribution system by injecting a harmonic current equal-but-opposite to the one produced by the non-linear load (Figure 1). Based on its converter circuit topology, active filters can be broadly classified into: (1) current-source active power filter (CS-APF) which uses a dc inductor for energy storage, and (2) voltage-source active power filter (VS-APF) which uses a dc capacitor for energy storage. The CS-APF has a better current-control capability, faster response, easier protection and higher reliability, but is less power-efficient [1] than the VS-APF. Since the power loss in the APF dc-link inductor contributes a significant part to the total power loss in a CS-APF, replacing the conventional copper inductor with a superconducting inductor will reduce this power loss and hence improve the CS-APF efficiency. Using a CS-APF system which has been built at the UNSW, the APF performance of harmonics compensation and loss reduction effect when replacing a conventional copper inductor with a HTS inductor were tested in the laboratory.
2. Experimental setup

Figure 2 shows the experimental setup of the prototype CS-APF system built at the UNSW. The APF was controlled by a DSP (digital signal processor)-based controller, and the nonlinear load was a three-phase controlled rectifier. The main data acquisition instrument was a Yokogawa PZ4000 Power Analyser, which can acquire and analyse with a sufficient accuracy the electrical quantities containing high level of harmonics such as voltage and/or current waveforms of a PWM converter [3].

The converter losses and the dc-inductor losses were derived from the power measured at the ac- and dc-side of the APF converter. As the APF does not generate active power to the lines, the power measured at the ac-side of the APF, $P_{ac}$, is the power consumed by the APF due to losses in its converter and its dc-link inductor. The power measured at the dc-side of the APF, $P_{dc}$, is the power loss in the dc-link inductor. Thus, two main components of the power loss in the APF can be obtained as follows:

- Inductor loss: $P_{inductor} = P_{dc}$  
- Converter loss: $P_{converter} = P_{ac} - P_{dc}$

3. Harmonics compensation performance

For comparative study, a conventional copper inductor and a HTS inductor are used in the experiments. The conventional copper inductor is an iron-cored choke of 500mH whilst the HTS inductor, built with BSCCO-2223/Ag tape operating at 77K in liquid nitrogen, is an iron-cored thin solenoid of 410mH [2].
In Figure 3, the harmonics compensation performance of the CS-APF with the conventional copper inductor is compared to that with the HTS inductor. It can be seen that the performances of the APF in these two cases have little, if any, difference while the nonlinear load currents are the same in both cases. In other words, the replacement of the conventional copper inductor in the dc-link with a HTS inductor of similar inductance will not change the harmonics compensation performance of the APF. This is because the inductance of the dc-link inductor has more influence on the APF performance while the resistance of the inductor has little influence on the APF performance. In general, the compensation for the harmonic and reactive currents from the load does not require very large inductance in the dc-link. However, very low inductance in the dc-link will generate a high level of ripple in the dc-link current, which will affect the compensation current generated by the APF and degrade the compensation performance for harmonic and reactive currents.

4. Power loss reduction effect
The power loss reduction effect of replacing the conventional copper inductor in the dc-link with the liquid-nitrogen-cooled HTS inductor has also been investigated experimentally using the CS-APF. In both cases, the power loss or the real power consumed in the coils was measured at different dc current levels and the results are shown in Figure 4. It is found that the power loss in the HTS inductor was less than 15% of that in its copper equivalent when operating below the critical current of the HTS inductor. The results are summarized in Figure 5.
However, this does not mean that the replacement of a copper inductor with a HTS magnet will reduce the power loss by more than 85 % for the energy storage in the dc-link of a CS-APF. The power consumption for cooling the HTS magnet has to be taken into account when calculating the efficiency of a CS-APF using a HTS magnet for its dc-link energy storage. A preliminary study based on the boiling-off rate of the liquid nitrogen during the experiments indicates that a good thermally-designed HTS magnet can still reduce the power loss by at least 50 % when the cooling power consumption is included.

5. Power loss in converter
The power loss in the converter contributes a considerable portion to the total power loss in the APF and this can be calculated from the experimental results using (2). The APF power loss in the converter consists of two types of losses in the power semiconductor devices: the switching loss and the conduction loss. Figure 6 shows the variation of converter loss with different switching frequencies for the APF converter under test. It can be seen that a significant reduction in switching frequency from 8097Hz to 3096Hz results in only a small decrease in converter loss. This means that the switching loss contributes only a small portion of the converter loss in the CS-APF under test.

Figure 7 shows the variation of converter loss with the dc-link current. Tests with the CS-APF in different operation modes (stand-by and compensation) show that the converter loss depends mainly on the dc-link current level and remains almost unchanged when the APF operation mode changes. This implies that the converter loss depends only on the dc-current level in the dc-link inductor. Therefore the replacement of a conventional copper inductor with a HTS inductor will not affect the converter loss as long as the dc-current level in the dc-link inductor is kept unchanged.

6. Conclusions
A shunt current-source active power filter was tested with a conventional copper inductor and with a HTS inductor in the dc link. The replacement of the conventional copper inductor with a HTS inductor in the dc link can reduce the dc-link power loss by at least 50% even with the cooling power consumption included. This replacement will not affect the harmonics compensation performance of the active power filter and the power losses in the CS-APF converter.

References
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