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Abstract. A promising solution of the fault current problem in power systems is the application of fast-operating nonlinear superconducting fault current limiters (SFCLs) with the capability of rapidly increasing their impedance, and thus limiting high fault currents. We report the results of experiments with models of inductive (transformer type) SFCLs based on the ring-shaped bulk MgB$_2$ prepared under high quasihydrostatic pressure (2 GPa) and by hot pressing technique (30 MPa). It was shown that the SFCLs meet the main requirements to fault current limiters: they possess low impedance in the nominal regime of the protected circuit and can fast increase their impedance limiting both the transient and the steady-state fault currents. The study of quenching currents of MgB$_2$ rings (SFCL activation current) and AC losses in the rings shows that the quenching current density and critical current density determined from AC losses can be 10-20 times less than the critical current determined from the magnetization experiments.

1. Introduction

One of the promising solutions of the fault current problem in power systems is the application of fast-operating nonlinear current limiters (FCLs) with the capability of rapidly increasing their impedance, and thus limiting high fault currents. Superconducting fault current limiters (SFCLs) based on two properties of superconducting materials: an ideal conductivity and a quick phase transition to the normal conducting state under the influence of the current, magnetic field and temperature. An SFCL is one of the most attractive applications of superconductors in power systems, which has no classical equivalent.

The utility requirements to an FCL have been discussed in many publications [1-4, and see references therein]. The main of them following are:
- limitation of the first peak of a fault current (transient current);
- limitation of the steady-state fault current;
- low impedance under nominal operation conditions of the protected circuit: the voltage drop across an FCL should be usually less than 5% of the rated circuit voltage;
- low power loss under the nominal conditions: the total losses in an FCL must be much less than the transformer loss: in the range of 0.01%–0.1% of the nominal power of the protected circuit. In a

SFCL, the total losses are a sum of AC loss in the superconducting elements, losses in the normal conducting elements of the construction, and the energy consumption needed for cooling.

- quick and automatically return to the low impedance (initial) state after a fault is interrupted by other devices;

- high reliability and long lifetime similar to a conventional power transformer.

Experiments with prototypes and power models of various SFCL types based on different superconductors have demonstrated that these devices met to the requirements [see e.g. 2-4]. Devices based on the superconductor magnesium diboride MgB_2 with critical temperature T_c = 39 K can operate at temperatures of liquid helium, hydrogen or even neon. This compound can thus be envisaged for many applications, as fault current limiters, MRI magnets, cables, electromotors, magnetic bearings, etc [2,5-7]. Note that hydrogen is already used for cooling conventional generators in electrical power stations. Magnesium diboride is cheaper than the high temperature Y- and Bi-based superconductors (the technological process is cheaper); superconductivity can be realized within a wide range of Mg-B stoichiometries and some impurities do not impede to achieve high critical currents; the compounds do not contain toxic elements (such as As and F in iron-based superconductors). A high critical current densities j_c and good mechanical properties can be achieved in bulk MgB_2 samples synthesized under high quasihydrostatic pressure (at 2 GPa), spark plasma sintering (at 50 MPa) or by hot pressing (at 30 MPa) [6, 8].

In the present paper we estimate applicability of the ring-shaped bulk MgB_2 prepared under high quasihydrostatic pressure (2 GPa) and by hot pressing technique (30 MPa) in inductive (transformer type) SFCLs. Using an inductive SFCL model AC losses and the current causing transition into the resistive state (the quenching current I_q) were measured.

2. Experimental set-up

An inductive SFCL named also "shielded-core" or "transformer type" is based on magnetic coupling between a superconducting element and a protected circuit that allows the cryogenic environment to remain mechanically isolated from the rest of the circuit. Basically, the device resembles a transformer with the short-circuited secondary coil which can be performed completely from a superconducting material in the form of a hollow cylinder or ring or as a coil containing a superconducting switching element (Figure 1) [2, 3, 7]. The primary coil of this transformer is in series connected to the protected circuit. Under normal conditions in the circuit, the secondary coil is in the superconducting state. The magnetic flux produced by the primary coil is compensated by the flux originated from induced screen currents in the short-circuited superconducting coil. The device impedance is determined only by the leakage flux in an air gap between the primary and secondary coils. Under short-circuit conditions in the circuit, the increased current in the secondary coil exceeds the critical value and the coil or its part made from a superconductor pass into the resistive state. If the resistance due to the dissipation becomes much higher than the inductive reactance of the coil, the induced current in the secondary coil is sharply reduced and the magnetic flux of the primary coil is compensated no more. Thus, the FCL impedance increases and limits the fault current.

The experimental device and principal scheme for measurement of AC losses and the quenching current are presented in Figure 1. The used contactless method suitable for samples in the form of a closed loop (hollow cylinder, ring, or short-circuited coil) is based on using the transformer configuration (Figure 1) [7]. A superconducting closed loop forms the secondary coil of a transformer in which the primary coil is connected with an AC source. To increase the coupling between the coils, they are centred on a ferromagnetic core in the form of a laminated rod (open core design). The procedure of the AC loss determination in samples with induced current relies on measuring, with the help of the Hall-probe technique (Figure 1), the magnetic flux density as a function of the instantaneous current in the primary coil. An electronic switch allows one to measure AC losses during short time for ~0.1 s to prevent ring heating due to the losses and also to simulate a fault event. The main advantages of this method are: i) the high currents up to several tens of thousands amperes can be achieved in a superconductor using usual laboratory equipment; ii) no current terminals and

measuring contacts are required; iii) measurement results are not influenced by heating due to losses in contacts. More detailed description is presented in [7].
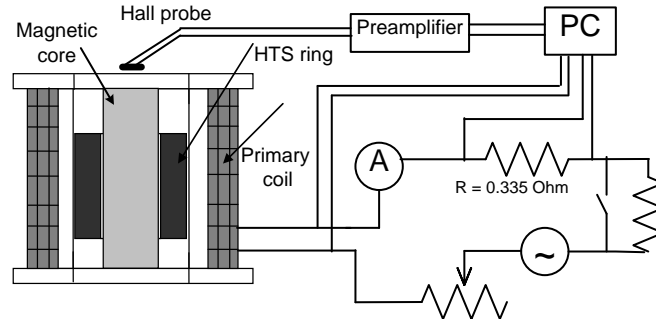
Figure 1. The experimental device and principal scheme for measurement of AC losses and simulation of a fault event.

3. Experimental samples

The measurements in temperature range from 4.2 K till 40 K were performed for MgB_2 rings with outer diameters from 21 to 112 mm, wall thicknesses of 3 - 6 mm and a height of 7 - 14 mm, manufactured under high pressure (2 GPa) and hot pressure (30 MPa) conditions (Table 1). Photos of some rings cut out from bulks are presented in Figure 2. The high-pressed (quasihydrostatically) and hot pressed (uniaxially) samples were typically synthesized or sintered during 1 hour at 2 GPa, 800 and 1050 ^{o}C or at 30 MPa, 1050 ^{o}C, respectively, from the mixture of Mg chips and amorphous B powders taken into Mg:2B stoichiometry (mixed and milled in high speed planetary activator) or from MgB_2 (Alfa Aesar powder) without and with additions of 10-12 wt. % SiC or Ti. Two types of amorphous boron B(I) and B(II) were used: B(I) - 4 μm grain size, 0.5 wt. Mg, 0.4 wt % N, 1.5 wt.%, O; 0.3 wt. % C, 0.37 % H, 0.2 wt.% H_2O, 0.1 wt.% $B-H_2O$, 0.5 wt.% $B-H_2O_2$ and B(II) -1.4 μm grain size, 0.43 wt % N, 1.9 wt.%, O; 0.27 wt. % C, 0.11 % H (other impurities did not determined). MgB_2 powder contained 44.1 wt.% B, 51.6 wt % Mg, 1.9 wt.% O and 0.9 wt.% C (other impurities did not determined). Then 200-800 nm SiC or 30 μm Ti 95% purity have been added. The technology was described in details in [9]. From the magnetization experiments, the critical temperature of the MgB_2 samples was estimated to be about 37 K.

4. Measurement results

4.1. Quenching currents

The experimental results for every ring are qualitatively similar and here we present typical results. A low long-continued current in the protected circuit, a low current in the primary coil, does not cause transition of the superconducting ring into the resistive state with a finite resistance. At higher currents to decrease losses in the normal-metal primary coil of a model we applied current pulses for ~0.1 s. At relatively low amplitudes of the pulses the primary current and voltage drop across the primary coil are also sinusoidal. An increase of the primary current causes the sharp increase of the voltage with the simultaneous decrease of the current at the end of the current pulse, at first (Figure 3a). Appearance of the trace changes, associated with the superconducting-normal state transition, at the pulse end can be explained by the heating of a superconductor due to AC losses or/and heating of a weak place and nucleation and propagation the normal zone from the place. The point of the transition moves to the pulse beginning with a primary current increase and at a higher current the deviations in the voltage and current curves appear before the first current maximum (Figure 3b). The behavior of the inductive current limiter has been observed in many experiments early. We estimate the quenching current of the

Figure 2. Some tested MgB$_2$ rings of various sizes

ring as a ring current which corresponds to the instantaneous primary current, SFCL activation current, when quench happens before the first current maximum. From Figure 3 the activation current of the FCL model with ring 5 at 4.2 K is about 16.7 A corresponding to the quenching current of 9,880 A (turn number in primary winding is 700; quenching current density is about 16,460 A/cm^2). The quenching currents of the tested rings at about 4.2 K are presented in Table 1. After quench in the model with ring 5 the primary coil inductance increases from 0.028 H up to 0.09 H achieving practically the inductance of the model without ring. This leads to limitation of a fault current about twice. A low ratio of the primary coil inductances in the current limitation regime and nominal one, 0.09/0.28≈3.2, is explained by peculiarities of the design of the magnetic system for the big ring: ratio of the height of the magnetic core to its diameter was about only 0.39. For more realistic SFLC model with other rings the inductance ration increases up to 5-7. In liquid helium all tested models returned into an initial state for 1-2 s.

a)   b)
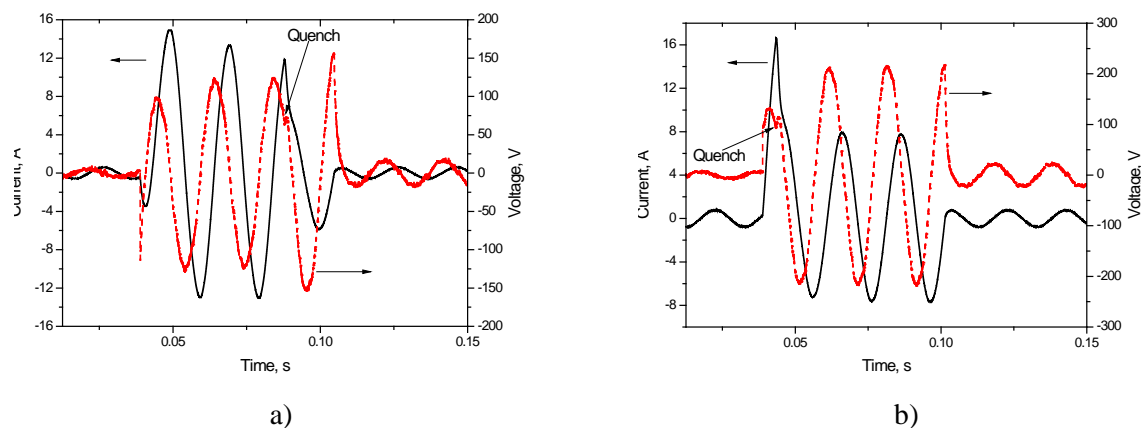
Figure 3. Quench, activation of the model with ring 5, under the current pulse at 50 Hz a) – at the pulse end and b) - before the first current maximum: black solid curve – primary current; dashed curve – voltage drop across the primary coil.

A quenching current in rings, I_q, changes in the range of 4,500 ÷ 24,000 A, corresponding to the quenching current density J_q= 19,000÷63,200 A/cm^2. The quenching current density estimated by the transformer method usually is 10-20 times lower than the critical current density J_c estimated by the magnetization method using the Bean model [11] from 2.24·10^5 up to 5.1·10^5 A/cm^2 at 10 K in zero magnetic field. For example, for ring 1 J_q = 22,700 A/cm^2 at 4.2 K and J_c = 224,000 A/cm^2 at 10 K. This difference can be explained by existence of cracks appearing during machining, normal-metal inclusions, granular structure of the material, the material inhomogeneity and thermal instability of a bulk sample caused by varying current or magnetic field. The normal zones can nucleate near the cracks and normal-metal inclusions and, then, propagate through a superconductor causing its

transition into the normal state. The observed dependence of the trapped magnetic field on a rate of the applied field variation [11] witnesses the instability. Stability of the superconducting state can be increased by decrease of the superconductor thickness, shunting a superconductor by a normal-metal layer, an increase of the heat transfer from a superconductor to coolant e.g. replacing helium gas by liquid helium or hydrogen.

4.2 Quenching current vs. temperature

The dependence of the quenching current on temperature was determined by two ways. First, temperature was increased up to a defined value, then we kept this temperature and waited about 15 min to provide uniform temperature distribution inside the ring wall. As example the results for ring 1 (Table 1) are presented here; for other rings results are qualitatively the same. The measurement results are presented by circle points (red) in Figure 4. Second, temperature was increased up to a defined value, and then the cylinder was cooled till an equilibrium temperature. We waited about for 30 min to provide uniform temperature distribution inside the wall. The measurement results are presented by squared black points in Figure 4. In the both cases at every temperature several measurements were carried out with 10 min breaks. The both ways give very close values of the quenching current at temperature higher than 15 K. At lower temperatures the second method gives higher values than the first one. Difference between values obtained by these methods is about 10%. The quenching current very slowly decreases with a temperature increase up to 20 K and sharply decreases in the temperature range from 20 K till 34 K.

Table 1. Quenching currents of the tested MgB_2 rings at about 4.2 K

	Conditions of synthesis	Outer diameter, mm	Height, mm	Wall thickness, mm	Quenching current, A
Ring 1	B(II), with 10%SiC, 2 GPa, 1050 ^{o}C, 1 h	24.3	7	3.2	4500
Ring 2	B(I), with 10% SiC, 2 GPa, 1050 ^{o}C, 1 h	24.3	7.7	3.2	5500
Ring 3	B(II), 30 MPa, 800 ^{o}C, 2 h	45	11.6	3.3	24000
Ring 4	B(II), 2 GPa, 800 ^{o}C, 1 h	21.3	14.1	3.5	9350
Ring 5	MgB_2, 30 MPa, 1050 ^{o}C, 1 h	112	10	6	9880
Ring 6	B(II) with 12% Ti, 30 MPa, 1050 ^{o}C, 1 h	45	12	5	14800

4.3. AC losses

AC losses were measured by a contactless transformer method [7] allows us to study the characteristics of a superconductor with an induced transport current. In experiment the AC source voltage was increased step by step until appearance of characteristic blips in the voltage traces, which correspond to quenching (transition of the ring into the normal state). At a low current (typically <0.2 A_{rms}) AC losses in the rings are unmeasured small. The current and frequency dependences of AC losses per the period in ring 2 are shown in Figure 5. The losses in ring 1 are about 10% lower and have the same dependences on the current and frequency.
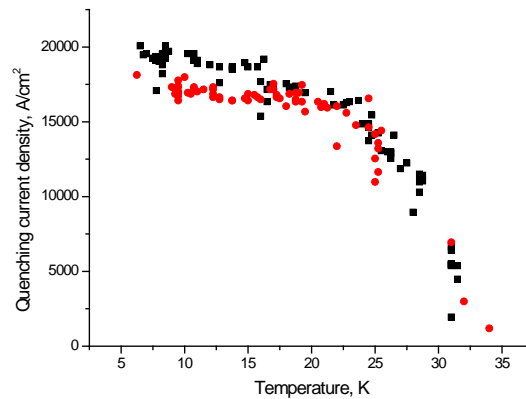
Figure 4. Temperature dependence of the quenching current density of ring 1 (Table 1). Circles – quenching current was estimated with temperature increase, squares - quenching current was estimated with temperature decrease.

The measurement results show that the AC losses in MgB_2 rings 1 and 2 have the following features: (i) the loss value per cycle depends strongly on the frequency ($\sim 1/f^{0.4}$ at an rms current of 5 A), (ii) the dependences of the losses on the primary current i are well fitted by a power law $P \sim i^m$ with an exponent m of about 2.1 (Figure 5c).

The Bean model predicts AC losses independent of frequency and fitted by a power law with an exponent of about 3 [12,13]. The widely used model based on the power law E–J characteristics, $E \sim J^n$, gives deviations from the Bean model results, but, even at a relatively low index of $n = 7$, these deviations are not very pronounced. For comparison, we measured AC losses in a BSCCO cylinder using the same experimental technique and Hall sensor (the experimental details are given in [7]). The dependence of the AC losses in BSCCO on the primary current is fitted by a power law with an exponent m of about 2.8 (Figure 5c, curves for BSCCO). These results are in full accordance with the theoretical and experimental investigations presented in [13,14]. Experiments with ring 5 gives also a power law dependence of losses with an exponent of about 3: $m = 3.2$ at 50 Hz and temperature of 4.2 K.

To clarify the reasons for this behavior of the AC losses in MgB_2 rings 1 and 2, we measured the E–J characteristics of the samples applying pulses of direct current to the primary coil. In our experimental setup (Figure 1), the AC source was replaced by a DC one. The detailed description is presented in [7]. The current in the ring and the voltage drop across it were determined from oscilloscope traces of the primary current and the Hall probe signal. The voltage–current characteristic of ring 2 (Table 1) obtained in this experiment is shown in Figure 5d and demonstrate almost linear increase after the critical value. For comparison, the calculated power law E–J dependence with the index n = 100 and the same critical current determined by the criterion 1 μV/cm is also presented on the plot (the triangles with top turned up or blue dotted line). Assuming that the superconductor is homogeneous and the current density is uniform over the superconductor cross-section, we obtain that the E–J characteristics are well described in the framework of the extended critical state model [15]

$$E = \begin{cases} \rho_f \left[J - sign(J_c) J_c \right], & |J| > J_c \\ 0, & |J| < J_c \end{cases} \tag{1}$$

where ρ_f estimated from the curve of Figure 5d equals about 1.8×10^{-9} Ω·m, the critical current $I_c \cong 5500$ A for ring 2. For ring 1 these values are $\rho_f = 1.8 \times 10^{-9}$ Ω·m and $I_c \cong 4500$ A.

The simulation with equation (1) using COMSOL within the axial-symmetric 1D approximation where the primary coil, superconductor and ferromagnetic core are infinitely long gives close to the experimental AC losses dependences on the frequency and primary current [7]. The obtained differences in dependences of AC losses on the frequency and primary current in various rings can be explained by different pinning mechanisms. The differences in the pinning can be the result of usage of various preparation technologies and additions (see Table 1). This question is needed in an additional investigation.
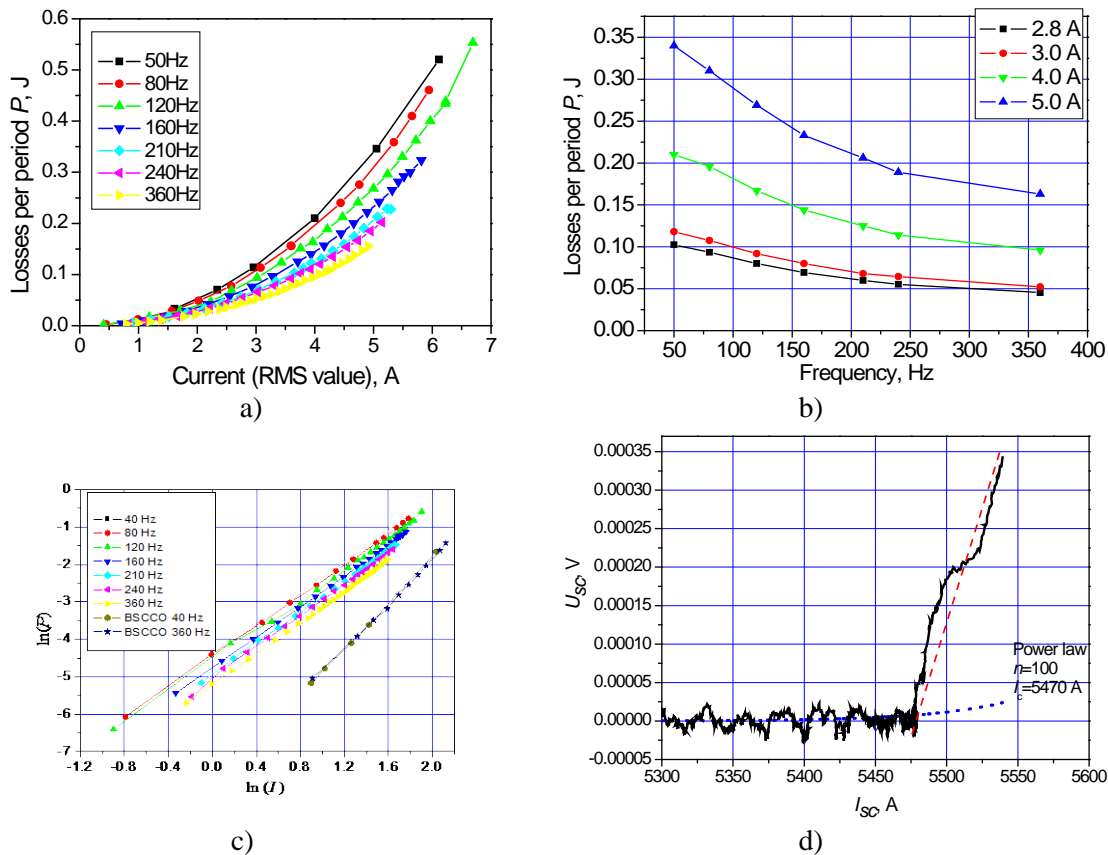
Figure 5. The dependence of the AC losses in MgB$_2$ ring (ring 2) at a temperature of 4.2 K on: a) the primary current at different frequencies; b) frequency at different rms currents in the primary coil; c) – the logarithm of the AC losses in the MgB$_2$ ring and BSCCO cylinder as a function of the logarithm of the primary current (here P_{norm} =1 J and I_{norm} = 1 A$_{rms}$); d) – the voltage-current characteristic of ring 2.

5. Conclusion

Our experiments with models of inductive (transformer type) SFCLs based on the ring-shaped bulk MgB$_2$ prepared under high quasihydrostatic pressure (2 GPa) and by hot pressing technique (30 MPa) demonstrate possibility of application of these devices in power systems. The SFCLs meet the main requirements to fault current limiters: they possess low impedance in the nominal regime of the protected circuit and can fast increase their impedance limiting both the transient and the steady-state fault currents.

The study of quenching currents of MgB$_2$ rings (SFCL activation current) and AC losses in the rings shows that the quenching current density and critical current density determined from AC losses can be 10-20 times less than the critical current determined from the magnetization experiments. This should be taken into account at SFCL design.

Acknowledgement

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