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STATUS REPORT OF THE THREE PHASE 25 kA, 1.5 kW THERMALLY SWITCHED SUPERCONDUCTING RECTIFIER. TRANSFORMER AND SWITCHES.

H.H.J. ten Kate, A.H.M. Holtslag, J. Knoben, H.A. Steffens and L.J.M. van de Klundert

Twente University of Technology
Dept. of Applied Physics
P.O.B. 217, 7500 AE ENSCHEDE
THE NETHERLANDS

Abstract

A 25 kA, 1.5 kW superconducting rectifier system has been developed. This rectifier system working like an a.c.-d.c. converter with a primary current of 35 A at 0.1 Hz, will energize a 25 kA coil with an average power of 5.4 MJ/hr and a proposed energy efficiency of at least 96%. Such a highly efficient device might work instead of a 'normal' rectifier and a pair of 25 kA current leads with its energy loss of at least 2 W/kA. The 25 kA current step-up transformer has been tested succesfully concerning its maximum current (26.4 kA) and a.c. losses (2 W at 25 kA and 0.1 Hz). A conductor for the 25 kA switches has been manufactured and processed into the switching system. Their construction is described.

Introduction

The aim of this research project is to investigate the feasibility of high current superconducting rectifiers as a highly efficient cryogenic current supply for s.c. coils. In the frame work of these activities since 1979 a review[1] about the subject has been made and three earlier 1 and 9 kA rectifiers[2,3] have been built and tested. The present step is to prove the successful operation of a 25 kA, 1.5 kW s.c. rectifier system being a series connection of three full wave rectifiers (see Fig. 1.). Each rectifier (25 kA, 0.5 kW) consists of a current step up transformer and two rectifier switches. In case of failure modes a protection switch decouples the rectifiers and the load (s.c. magnet). In this way damage to the low impedance rectifier, caused by the coil energy, is prevented. For a detailed description of the operation and principles reference is made to earlier work[1]. The design data being the inductances, resistances, power, currents and efficiency of the 25 kA rectifier have been published previously[4]. This paper describes the construction and test results of the 25 kA s.c. transformer T_1 and the construction of both rectifier switches S_1, S_2 and protection switch S_{pr} (see Fig. 1). The design and construction of the s.c. load coil L is published separately[5].

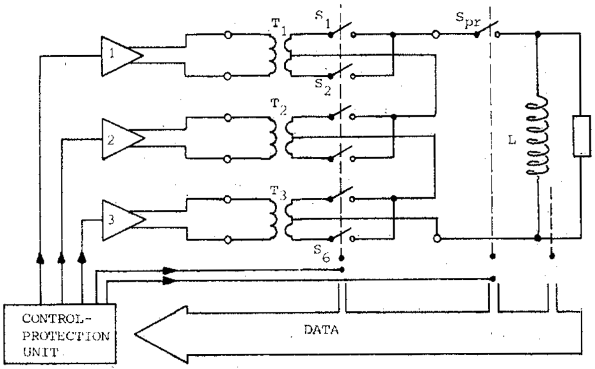

Fig. 1. Scheme of the 25 kA, 1.5 kW s.c. rectifing system being a series connection of three full wave rectifiers with its transformers T_{1-3}, switches S_{1-6}, protection switch S_{pr}, dump resistor R_d and load coil L.

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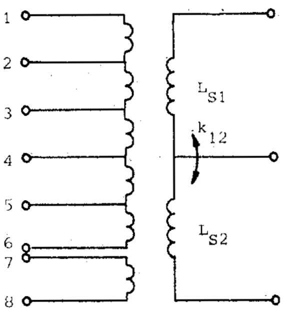
The transformer

The design of the s.c. centre tap transformer is determined by many conditions[4]. The desired average power (500 W), the current (25 kA) and the maximum frequency of operation due to the thermal switching (0.1 Hz) fix the inductance of the secondary of the transformer to $L_{sec} = 20$ μH.

As a consequence the primary inductance L_p and current $\hat{I}_p$ can be fitted to the available power supply and the available conductor obeying $\hat{I}_p \cdot L_p = 6464$[4]. A many-sided design has been obtained by choosing more inductance and current combinations in order to achieve always the desired power if the allowable cycle frequency would be less then 0.1 Hz[4]. Fig. 2 shows the scheme of connection terminals and some relevant data about the transformer.



$L_{P18} = 10.5$ H

$L_{P48} = 5.5$ H

$M \doteq k\sqrt{L_P L_S} = 10.2 - 14.1$ mH

$L_{sec} \doteq L_{S1} + L_{S2} + 2m = 20.2$ μH

$m \doteq k_{12}\sqrt{L_{S1} L_{S2}} = 2{,}6$ μH

$L_{S1} = L_{S2} = 7{,}38$ μH

$k_{12} = 0.358$

$k = 0.965 - 0.970$

Fig. 2. Scheme of connection terminals and data of the 25 kA air core transformer. The primary inductance and the mutual inductance are adjustable.

Conductors. The maximum magnetic field in the air core transformer is about 2.5 T. The amplitude of the primary current will be between 30 and 40 A. The conductor choosen for this purpose is a 0.28 mm diameter wire with 367 filaments of 9.7 μm diameter and a Cu/NbTi ratio of 1.25 (77 A/3T). For the secondary winding a 24 strand MCA Rutherford cable (12.5x2.05 mm^2; 26 kA/3T) is used. The strand is a 1.05 mm diameter Cu/NbTi wire with 367 filaments of 30 μm.

Coupling coefficient. In the case of an air core transformer it is very important to maximize the coupling-coefficient k ($\doteq M/\sqrt{L_p L_s}$) of the transformer to obtain the maximum transmitted power between the primary and secondary circuits. The relation between the average

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output power $\bar{P}_L$ of the rectifier and the input power P_p is given by[4]: $\bar{P}_L = \delta_p k^2 i^2 / 2\ln(1-i)$; in which i is the current ratio I_L/I_{max}, δ_p the fraction of the period time of the primary current effectively used for energizing. The coupling coefficient k of the transformer can be optimized by choosing the best geometry for the primary and secondary windings. Preconditions, for example, are set by conductor sizes, available space, maximum fields at the conductor because of the $J_c(B)$ curve, the desired primary and secondary inductances and the possibility of technical realization. The ultimate cross section of the transformer is shown in Figure 3.

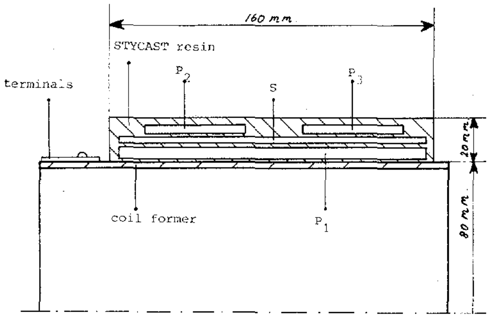

Fig. 3. Longitudinal section of the transformer. P_{1-3} are the primary coils, S is the secondary coil.

The three primary coils P_{1-3} and the secondary windings S form a system of concentric solenoids. The primary terminals 1-6 are in P_1, the terminals 7 and 8 connects P_2 and P_3 to P_1 (see Figure 2). The coupling coefficient k is maximal if the secondary windings lie at the plane where the axial component of the magnetic field of the primary coils are zero. This cannot be done perfectly as mentioned before. Computer calculations have given the maximal obtainable coefficient k in relation to realistic coil sizes. Figure 4 shows the coefficient k in dependence of the ratio h/H being the quotient of the thicknesses h and H of the primary coils $P_{2,3}$ and P_1 respectively. A maximum of 0.970 exists for a primary inductance L_{48} = 5.5 H (h/H = 1).

In case of L_{18} = 10.5 H (h/H = 0.57) the k reduces to 0.965. Thus the reduction of the transmitted power in this air core transformer by imperfect coupling is maximal 7% ($\sim k^2$).

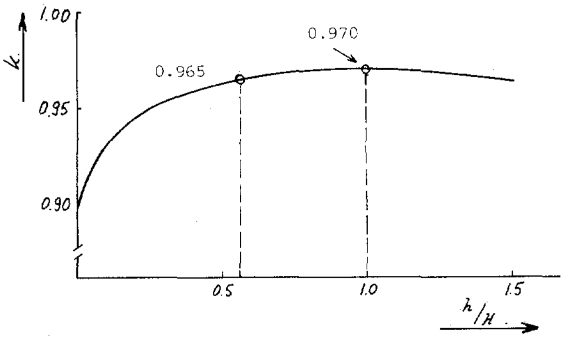

Fig. 4. The realized coupling coefficient k of the 25 kA air-core transformer. This coefficient is 0.965 for L_p = 10.5 H and 0.970 for L_p = 5.5 H.

Construction and cooling. The coils are wound on a glassfibre-epoxy tube (dia = 160 mm) (see Fig. 3): at first 6668 primary windings divided in six sections and fourteen layers, then twelve secondary windings in two sections and one layer and after that again 2804 primary windings in two sections each of 8 layers. While the windings are vacuum impregnated with STYCAST 2850 FT resin special attention has to be paid to the cooling aspects. Between the primary layers thin copper wires (ø = 0.2 mm) act as spacers and cooling channels at the same time. Between the primary and secondary windings 1 mm copper wires do the same. The wires lie in axial direction and are in contact with the liquid helium on both sides of the coils. These copper wires will hardly increase the a.c. losses of the transformer because their cross sectional areas are small, they lie in the direction of the magnetic field and they are mutually insulated in the azimuthal directions of the coils. We have successfully applied this cooling technique of s.c. coils before[3]. The a.c. losses in the copper wires was calculated to be maximal 40 mW which is negligible compared to the a.c. losses in the superconductors as discussed below. The finished transformer is shown in Fig. 5.

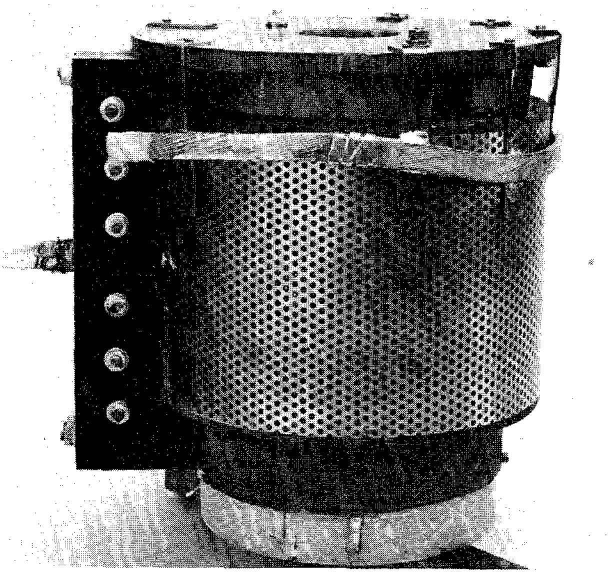

Fig. 5. Photograph of the finished 25 kA transformer.

Stresses. The spatial distribution of the stresses in the transformer is very complex and will not be discussed here. Suffice it to say that for the most pessimistically assumed load the stresses in the conductors are limited to the acceptable values of 80 MPa and 25 MPa in azimuthal and axial direction respectively.

Test results. The maximum secondary current and the a.c. losses of the current step-up transformer have been measured. The current amplification of the transformer is determined to be 660 ± 15. All measurements are done with a repetition frequency of the primary current of 0.1 Hz because this is also the final cycle frequency of the rectifier. The maximum induced current I_S at 0.1 Hz is 26.4 ± 0.6 kA if the secondary circuit is closed (centre tap not connected). At this current the secondary conductor quenches, the primary not.

Figure 6 shows the primary and secondary currents. The a.c. losses of the transformer with the secondary closed have been measured in two cases and at different current rates. In case one the secondary current is swept between $-\hat{I}_S$ and $+\hat{I}_S$ ($\hat{I}_S$ = 5; 10; 15 kA). The measured energy loss per period is shown in Fig. 7. The hysteretic losses are given for $\dot{I}_S = 0$. The perfectly straight lines for $\dot{I}_S \neq 0$ include that the additional matrix losses are proportional to I_S^2 as might be expected. In the second case the secondary current is swept between 0 and $+\hat{I}_S$ whereas the primary current is still alternating. The losses at comparable currents (± 12.5 kA equals 0-25 kA) are somewhat lower (10 to 20%) because of the smaller area of the magnetization loop. More results, the measuring method and a comparison between measured and calculated losses will be published elsewhere[6].

In real operation the current and field rates in the

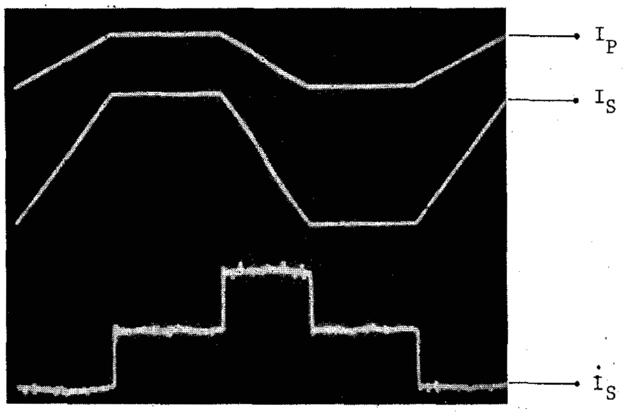

Fig. 6. Primary current, secondary current and secondary current rate during transformer tests.

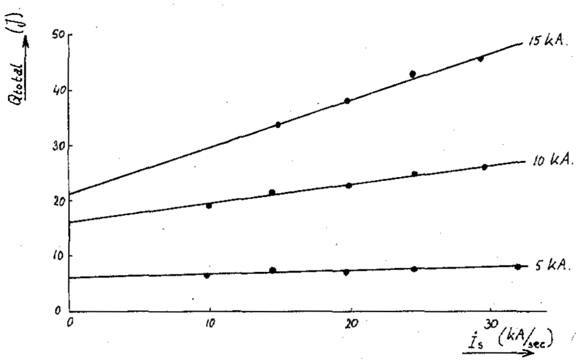

Fig. 7. Total energy loss of the transformer with the secondary closed. The dots are the measurements.

rectifier are maximal 15 kA/s and 1.5 T/s if I_S is swept between 0 and 25 kA. Thus the maximum contribution of the losses in the rectifier due to the transformer will be 20 J per cycle at 25 kA.

Rectifier and protection switches

The resistances of the opened rectifier switches $S_{1,2}$, of the protection switch S_{pr} and of the dump resistor R_d (Fig. 1) determine the energy loss and the dump efficiency of the rectifier. Their mutual ratios have to be well-balanced[4]. These resistances are obtained by heating the superconductor in a highly resistive matrix (Cu30Ni) above its critical temperature.

25 kA NbTi-CuNi-cable. A 720 strand combined twisted and braided rectangular cable (6 x 35 mm^2) has been manufactured. The strand is a 0.295 mm diameter MCA Cu30Ni/NbTi = 1.1 wire with 574 filaments of 8.5 μm diameter. The width of this cable is adjustable between 35 and 50 mm in order to manupulate the average current density. The strands are insulated. The critical current of a single strand is measured to be 80 A at 2 T. In the switch geometry the cable experiences a maximum field of 2 T due to selffield and stray fields. Thus the current-safely factor is at least 720.80/25000 = 2.3 in order to prevent unknown effects such as current degradation and to allow for a somewhat higher temperature in the conductor. The rectangular shape with a small thickness of the cable is essential. Otherwise the cooling of the conductor and thus also the recovery time of the switches become problematic. In the case of a rectangular shape and if the surface has the bath temperature, the description of the cooling process can be simplified to a one dimensional problem of thermal conduction. The recovery time constant is then proportional to the inverse of the square of the thickness.

Geometry of the switches. The conductor lengths in the switches $S_{1,2}$ and S_{pr} are 0.6 and 12 meter respectively in order to achieve the proposed resistance of 5.0 and 100 mΩ. These lengths have to be packed bifilarly into a minimum volume. Fig. 8 shows our solution just before the package with the three switches is impregnated. At first a tap-joint was made to connect S_2 to S_1 and S_{pr} (Fig. 1). Then the conductor is doubled up and bifilarly wound from the centre. Three ends put out for the connections with the transformer and one terminal of the load coil (Fig. 1). The three switches take a volume of 7.3 litre. The section XY on Fig. 8 is shown in Fig. 9. One sees from the inside out the

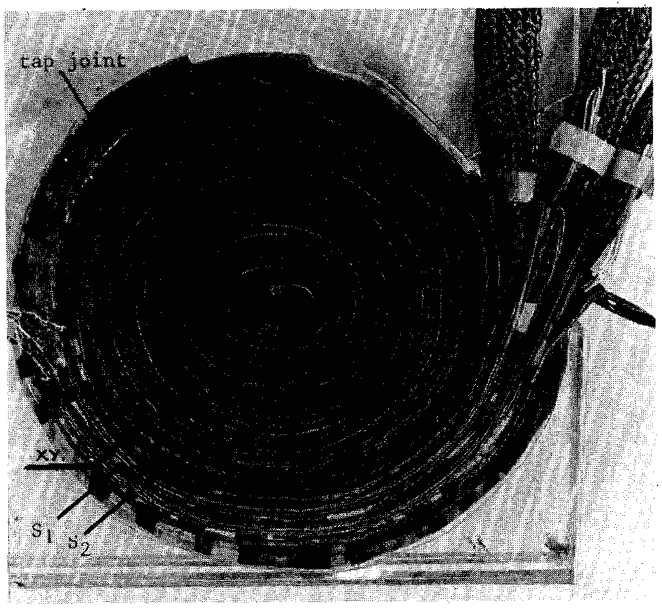

Fig. 8. Top view of the geometry of the switches $S_{1,2}$ and S_{pr}.

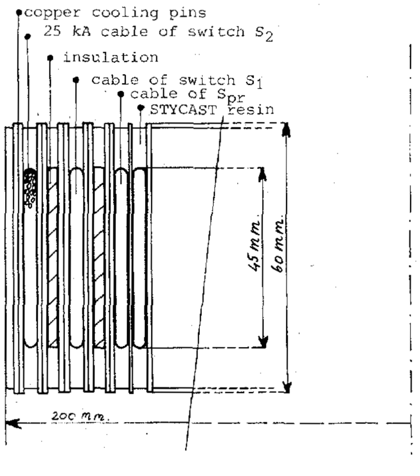

Fig. 9. Section XY' (Fig. 8) of the rectifier switches.

bifilarly turns of the protection switch and then the conductors of the switches S_1 and S_2. Between the turns of the protection switch lie insulated copper pins (ø 1 mm) along the total length and stick into the helium bath after impregnation of the switches. These pins conduct the a.c. loss in the conductor during normal operation and conduct in case of a quench (open switch) the dissipated heat to the bath. The conductors in S_1 and S_2 are insulated to prevent any thermal coupling. The number of copper pins are doubled here to let out the periodically (0.1 Hz) dissipated heat if the rectifier switches $S_{1,2}$ recover to the superconducting state. The design of this cooling concept assumes the switch recovery time constant to be about 600 ms.

Heating elements. The heating elements have to trigger the switches. For the protection switch this means that within the shortest time and at many places normal zones have to be created in the 25 kA cable. The ohmic dissipation in these zones due to the current through the switch will open the switch fast and completely. A safe operation of the rectifier, i.e., the quench protection, is achieved by applying sufficiently redundancy of heater elements. Therefore nine separate heating systems have been combined into one heating strip (Fig. 10) which has been inserted in the centre of the conductor. The heating elements I, II and III are repeated every 75 cm; their mutual distance is 25 cm. The heating elements A, B and C are at the same place. Comparable arguments are valid for the switches S_1 and S_2. In both several independently operating heaters are present.

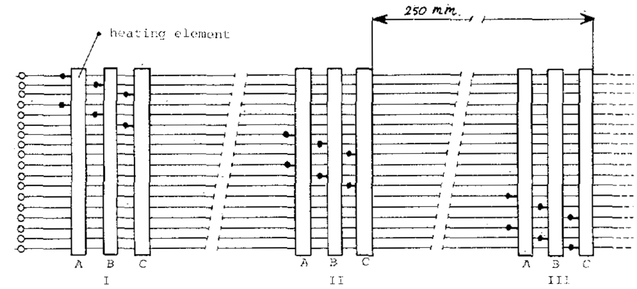

Fig. 10. Twelve meter heating strip of the protection switch, consisting of 144 heating elements divided in 3 separate sections (I, II, III). In every section a threefold redundance is present (A, B, C).

The behaviour of the rectifier switches will be demonstrated with measurements done on our 9 kA rectifier[3]. The photograph in Fig. 11 shows the relation between the temperature in the open rectifier switch dependent on the primary current which effects a current increase in the closed switch. It is observed that during a loading cycle the pumping step in the primary current decreases caused by the method of inductive commutation[1]. This decreasing step and thus decreasing current rate lowers the secondary voltage. The ohmic heat in the open switch which is proportional to the square of the secondary voltage decreases now and therefore also the temperature in the switch.

If the trigger heat pulse is too small the conductor in the switch will return to the superconducting state. The rectifier does not work then anymore. This example demonstrates the conditions concerning heating and cooling aspects and the switch heater control.

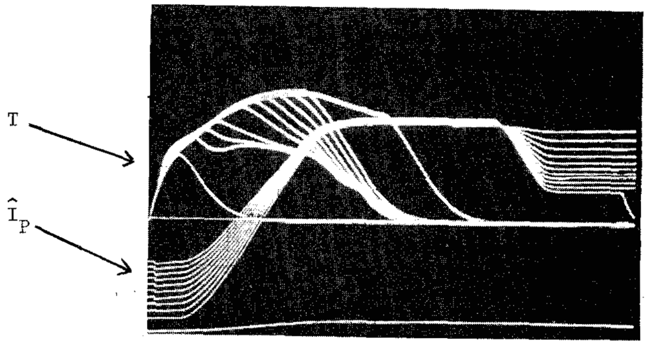

Fig. 11. Temperature in the open rectifier switch and the primary current during a loading cycle. At zero time the primary current sweep has its maximum and the temperature too.

Finishing up. The switches are vacuum impregnated with Stycast 2850 FT resin to achieve a solid apparatus. One rectifier is complete if the connection between switches, transformer and load coil have been made.

Final remarks

The assembled 25 kA rectifier will be tested soon. There have been some delay concerning the conductor processing. The tests of the transformer showed no faults. The maximum current and a.c. losses at 0.1 Hz of 26,4 kA and 2 W respectively were expected. Therefore there is full confidence that the rectifier will operate successfully.

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