20. ELECTRICAL CIRCUIT AND POWER SUPPLY

20.1 INTRODUCTION

This chapter describes the electrical system which provides the power for the solenoid and ensures its safety in the event of a quench or in case a fault has been detected.

The electrical circuit of the CMS solenoid is shown in Fig. 20.1.

20.1.1 General description

The power supply has a +16 V, 20000 A output with two circuit breakers CP1 and CP2 connected between the dc outputs and the two main electrical supply lines to the magnet. The dump resistor RD is composed of 5 x 10 mΩ resistor elements linked in series and mounted in parallel to the two breakers CR1 and CR2 which are doubled for safety. Depending of the position of the CR breakers the dump resistor can either be in the fast discharge configuration or in the slow discharge configuration. In the first case the CR breakers are keeping open the 5 elements in series hence a dump resistor of 50 mΩ while in the second case the CR breakers are maintaining closed the 5 elements in parallel hence a dump resistor of 2 mΩ.

The middle of the solenoid is indirectly grounded by means of a resistor tapped into the central point of the bridge. This grounding line is protected against over-current by a breaker. By grounding the magnet in the middle the “dump voltage to ground” is divided by a factor of two and also allows the leakage current to be monitored thus making it possible to detect a short with respect to ground.

For safety reasons two breakers are used which open both polarities and also:

- quickly separate the magnet from the power supply for easy checking of the insulation,
- protect the power supply against the high voltage developed during the energy dump.

20.1.2 Protection concept

The protection of the solenoid is based on the classical concept of the extraction of the stored energy into an external resistor. It also benefits from of the presence of the outer cylinder which produces eddy currents during the current decay and creates heat, initiating quenches in all solenoid layers. Therefore the maximal temperature and the temperature gradient in the winding is moderate. Quench analysis is treated in Chapt. 16.

The value of the dump resistor limits the maximum voltage across the solenoid terminals to 1000 volts, that is normally ± 500 V with respect to ground.

20.2 ELECTRICAL COMPONENTS

20.2.1 DC Power Supply

The power supply is a thyristor D.C. generator. It delivers up to 20000 A, at 16 V maximum, and is operated in voltage control mode during ramping up of the current, and in current control mode during steady state operations. It is provided with free wheel diode system and needs demineralised water cooling. Its main parameters are given in Table 20.1.

The power supply has a size of about 3 m x 4 m with a height of 2.5 m and a weight of about 7 tonnes. It is located inside the cryogenic cavern USC5, see Fig. 26.8, p. C-58.

Table 20.1
DC Power Supply Parameters.

Current rating	20000	A
Voltage	16	V
Ramp up time	5	h
Stability	$\leq 1.10^{-4}$	
AC power,	800	kVA
Ripple, 10 Hz-10 MHz	0.8	V rms

20.2.2 Breakers CP

The two 20 kA breakers are air cooled and must support an opening voltage of 1000 V. They are of the "normally open" type.

They are housed in a cabinet attached to the power supply in the cryogenic cavern USC5 of about 3 m x 4 m, height 2 m and weight about 5 tonnes, see Fig. 26.8, p. C-58.

20.2.3 Dump resistor and breakers CR

In all operation phases, except the slow discharge one, the CR breakers are open. This is the fast dump configuration with the 5 resistors in series providing a total resistance of 50 mΩ.

For the slow discharge phase the CR breakers are closed. The 5 resistors are coupled in parallel providing the slow dump configuration of 2 mΩ resistance. In case of a quench during the slow dump, the CR breakers are opened commuting to the fast dump configuration.

The stainless steel dump resistor is air-cooled through convection cooling. It is designed to absorb the total solenoid magnetic energy with a temperature increase of 300 °C at its hottest point.

The associated CR breakers are four pole air-breakers for 8000 A and must support an opening voltage of 1000 V. They are of the "normally open" type.

The estimated volume of the dump resistor housing and its electrical lines is about 100 m^3. The resistor is fixed to the wall of the shaft above the platform covering the experimental cavern, see Fig 26.8, p. C-58. The CR breakers are located beneath the five elements of the dump resistor on the platform itself [20-1].

20.2.4 Grounding circuit

As shown in Fig. 20.1, the grounding circuit is composed of a resistor bridge in series with a ground resistor and the over current protection breaker CM. These 3 resistors have the same value of 40 Ω. Normally the electrical circuit is grounded at the electrical middle point. Monitoring the leak current through the grounding resistor allows to follow the insulation evolution.

20.2.5 Electrical lines

The 20 kA electrical buses between the power supply, the solenoid and the dump resistor are made of water-cooled copper cables [20-2]. The copper cross-section limits the voltage drop to less than 2 V. Table 20.2 indicates the main parameters of the cable buses. No break in the cables between the solenoid and the dump resistor can be allowed at any time, therefore, in the event of a lack of coolant at full current, the integrity of the cables must be ensured. Temperature of the junctions will be permanently monitored. All the bus sections will be fully protected to detect and prevent any accidental short circuits.

The space occupied in section by each cable bus is of 450 x 450 or 900 x 200 mm^2, depending whether the cables are disposed in a flat or square arrangement.

Table 20.2
Electrical Cable Bus Parameters.

	Solenoid - Power Supply		Solenoid - Dump Resistor	
Length per polarity	50	m	40	m
Cable number per polarity	4		4	
Section of copper per polarity	23800	mm^2	23800	mm^2
Resistance of bus feed and return	0.075	mΩ	0.060	mΩ
Total voltage drop	1.5	V	1.2	V
Water flow per cable	8		l/mn	
Temperature increase	<10		°C	
Holding time without flow	13		h	
Holding time without water	4.5		h	

20.2.6 Current leads

Cryogenic current leads are sensitive parts of superconducting magnet circuitry because they have to conduct the nominal current between room temperature and liquid helium temperature while not consuming too much helium for cooling. The continuity of lines between the magnet and its dump resistor is of major importance. The main considerations for the current leads is their robustness and their holding time without helium cooling.

The leads must be able to carry the nominal current in case of coolant flow loss for a duration of several minutes (say between 5 and 10) without suffering any thermal damage. This time provides a safety margin for the safe discharge of the solenoid.

The projected structure of the current leads is a copper cable in a stainless steel conduit, identical to the one at ALEPH.

20.3 DISCHARGE MODES

Three modes for discharging the solenoid are available.

- Slow discharge through the slow-dump-configured resistor.

This is the regular mode of decreasing the solenoid current to zero, along with the safety mode of discharging the solenoid in the event of a minor fault described in paragraph 20.2.

The time constant of the slow discharge is 6750 s. To quickly lower the solenoid current, a fast discharge is commanded by opening the CR breakers when the current goes below 2000 A.

A slow discharge can be interrupted when the fault is cancelled: the operator can recover the process and reset the current to its initial value.

- Fast discharge through the fast-dump-configured resistor.

This is the emergency mode of discharging the solenoid in the event of a major fault, described in paragraph 20.2.

The time constant is 210 s due to the winding resistance developed during the quench of the solenoid (280 s if there were no quench).

- Free wheel discharge through the diodes of the power supply.

This is not considered a regular mode for operation; nevertheless it is available and its duration which is related to the resistance's of the diodes and the electrical buses is estimated to about 18 h.

20.4 SAFETY VS FAULTS

20.4.1 Fault interlocks

The diagram of the safety interlocks is shown in Fig. 20.2. Two levels of faults are shown.

- First the major faults which imply the fast discharge of the stored energy through the 50 mΩ dump resistor. As the fast dumps cause large perturbations on the physics experiments and need several days to re-cool, their number must be reduced to the minimum. The fast dump faults are the following:
  - quench of the superconductor,
  - excessive temperature of current lead heat exchangers,
  - other emergency cases still to be defined.

  The fast dump operation is initiated by:
  - opening the CR contactors,
  - opening the CP breakers,
  - opening the main power supply breaker.
- Secondly, the minor faults which only imply the slow discharge of the stored energy through the 2 mΩ dump resistor. These faults are the following:
  - excessive current lead voltage drop,
  - low helium flow in current leads,
  - low vacuum pressure,
  - water cooling failure of the bus,
  - overheating the bus junctions,
  - other faults still to be defined.

  The slow dump operation is initiated by:
  - closing the CR breakers,
  - opening the CP breakers,
  - opening the main power supply breaker.
- Furthermore, a safety interlock checks the connection of the dump resistor every time the solenoid is excited in current, by monitoring the dump resistor voltage. Lack of voltage commands the ramping back of the power supply current to zero.

20.4.2 Fault repertory

Ground insulation failure

All the components of the solenoid electrical circuit - power supply, breakers, dump resistor, winding - are entirely insulated from earth, but as already mentioned in paragraph 20.2.4 the middle of the solenoid is indirectly grounded. A degradation of the solenoid insulation to earth will allow leakage current through the grounding resistor whenever the solenoid voltage is not zero, *i.e.* whenever the field is changing.

Monitoring the leakage current allows the evolution of the insulation to be controlled and to detect a short-circuit. The level of the leakage current which triggers the opening of the breaker must be set low enough to prevent the generation of an arc which could cause damage to the conductor in the event of a single coil short.

Most critical situations arise if multiple shorts to ground exist at the same time, creating a shorted winding section. Whenever the field is changing, circulating currents are induced into the shorted section. The faster the field change, the higher the current in the shorted section. Consequently these currents will be maximum during a fast dump commanded by a conductor quench. The difference between the currents of the normal and shorted sections results in a redistribution of the forces inside the solenoid and also in an unbalance of the axial forces between the solenoid and the iron caps.

An analysis of the shorting effects is to be carried out.

Protection system failure

In case of a total failure of the protection system in presence of quench, the current will only begin to decay when the resistive voltage across the coil reaches the power supply voltage capability

If only the CR breakers fail to open, a slow dump into 2 mΩ is performed in place of a fast dump into 50 mΩ, which is fairly similar to the above total failure case. In both cases, Chapt. 16 shows that the solenoid does not suffer damage from overheating or over-voltage.

Electrical buses failure

The continuity of the electrical lines between the solenoid and the dump resistor ensures the safety of the solenoid. In particular the lines and the junctions must be permanently monitored to avoid overheating.

Disconnection of the dump resistor

Disconnecting the dump resistor would be fatal to the solenoid. This could occur if the dump resistor is not reconnected after maintenance. To check the actual connection of the dump resistor across the solenoid terminals, the voltage of the resistor central element is monitored every time the solenoid is switched on: the absence of the dump resistor voltage commands the ramping back of the current to zero.

20.5 SURFACE MAGNET TESTS

It is planned to test the complete CMS solenoid, with its yoke closed, in the surface building around October 2003, before its transfer and final installation in the experimental cavern. The electrical circuit for these tests will make use of the final components, which will be later installed in the cavern, except the electrical buses (which may be simple copper cables) because the respective positions of the elements will be quite different in the cavern.

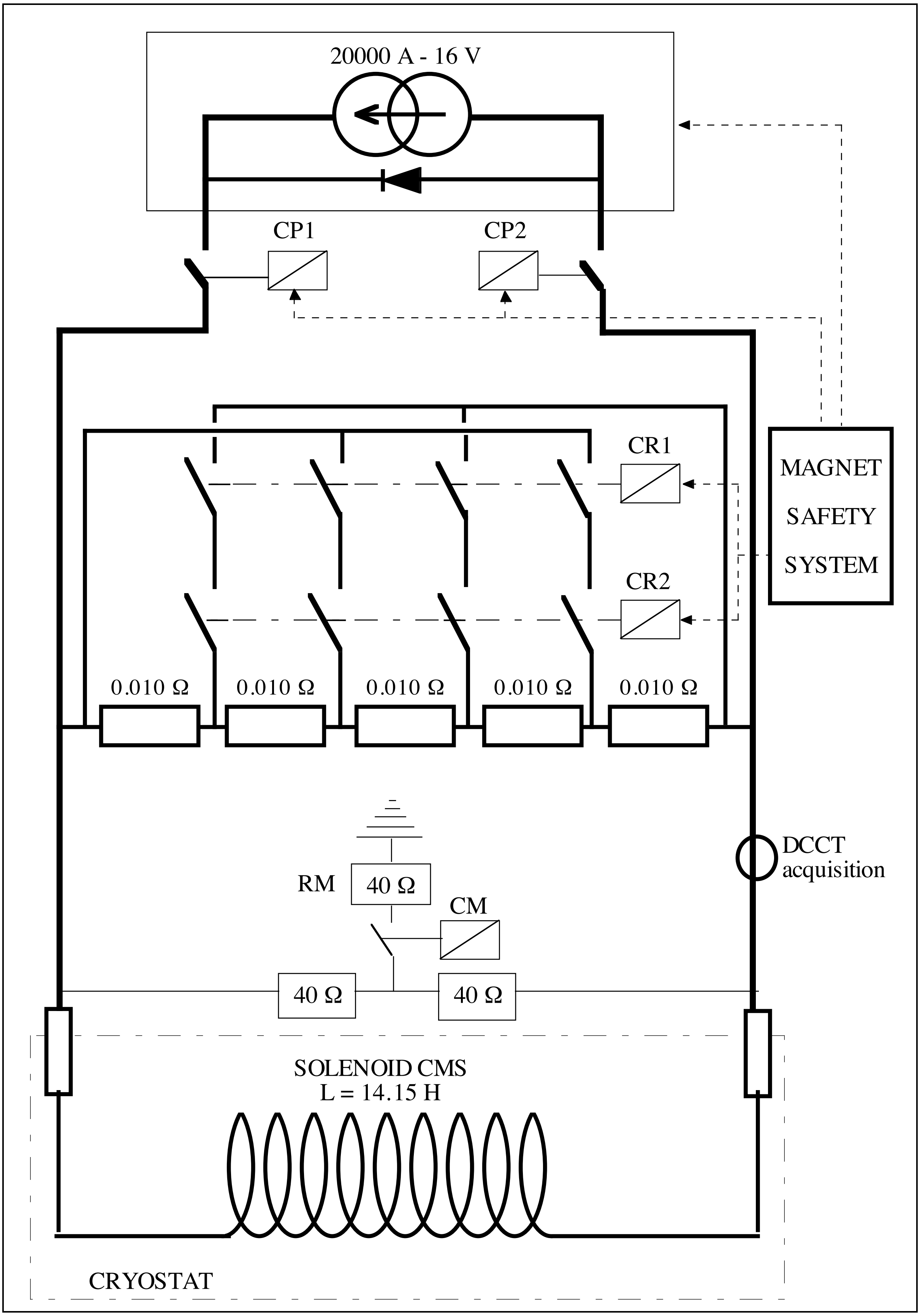

Fig. 20.1: Electrical circuit for the CMS solenoid.

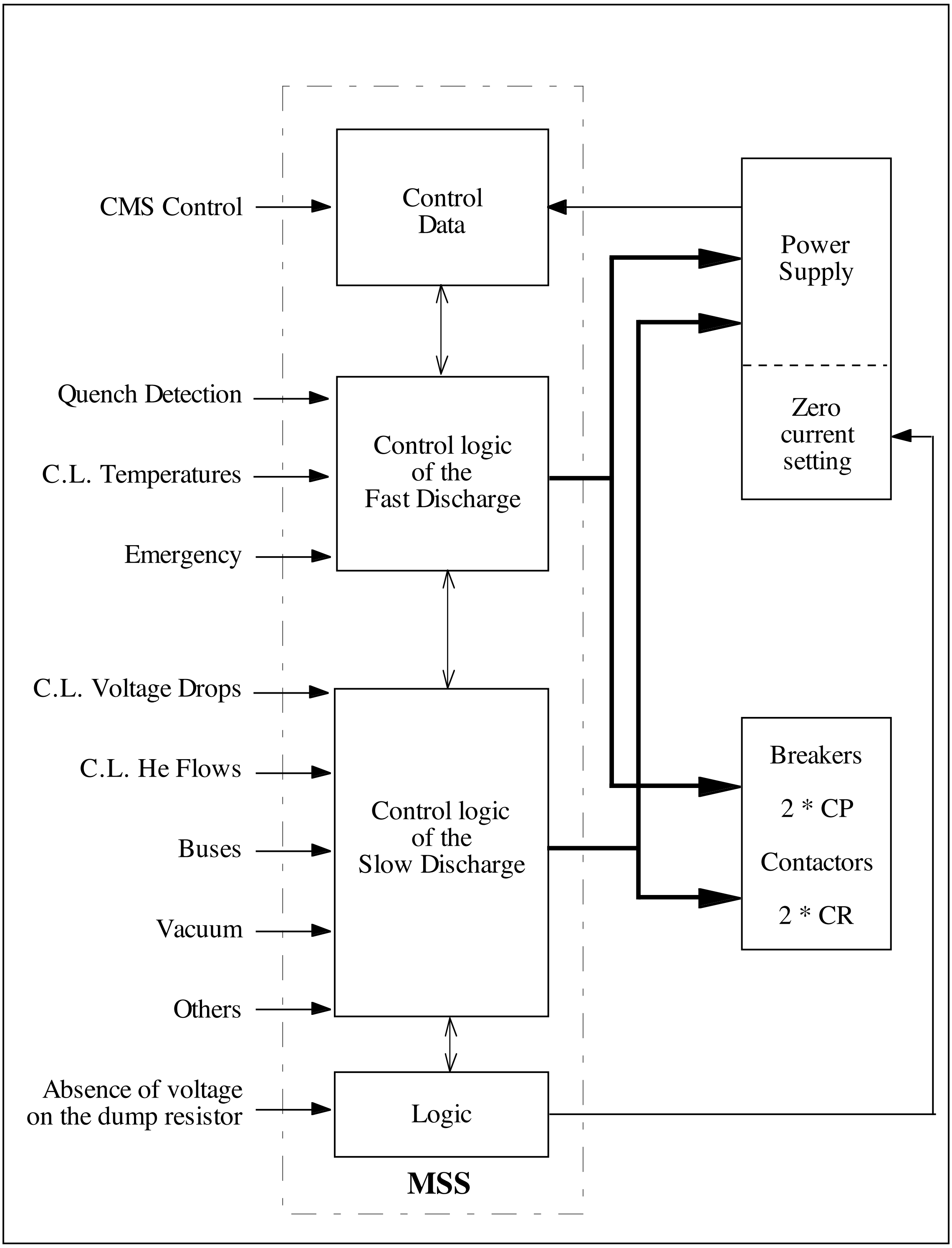

Fig 20.2: Diagram of the Safety Interlocks.