PULSED D.C. POWER SUPPLY 16 KA, 60 V

SCHNEIDER-WESTINGHOUSE

by

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Summary

The power supply for the septum magnets employed for the slow and fast ejection from the CPS straight-sections 58 and 62 is described. The power supply feeds the ejection magnets with D.C. current pulses of high stability and small ripple. The results of the tests made on the power supply are given.

The power supply was built, according to CERN specifications, as a joint effort of Schneider-Westinghouse\(^*\), one of its subsidiaries, SFME, (both of Paris), and the "Laboratoire de Génie Electrique", of Toulouse University.

Résumé

On décrit l'alimentation pour les aimants à septum des éjections lente et rapide à partir des sections droites 58 et 62 du synchrotron à protons du CERN. Les aimants sont alimentés par des impulsions de courant continu de haute stabilité et de faible ronflement. On donne les résultats des essais sur l'alimentation.

L'alimentation a été construite d'après des spécifications CERN. Sa réalisation est le résultat d'un effort commun de Schneider-Westinghouse\(^+\) d'une de ses filiales, la SFME (toutes les deux à Paris) ainsi que du Laboratoire de Génie Electrique de l'Université de Toulouse.

\(^*\) The firm has since changed its name and is now called Jeumont-Schneider.

\(^+\) Le firme a changé de nom entretemps et s'appelle maintenant Jeumont-Schneider.
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1. Specifications

1.1 General remarks

The specifications of the power supply were dictated by the requirements of the East Ejection System. Slow and fast ejection was to be possible from straight-sections 58 and 62.

For each type of ejection the deviation angle is 19 mrad, a value which does not change with energy. In order to reach this angle, two septum magnets are connected in cascade. The first has one winding, its effective length is 72 cms, and at maximum current (16 kA) the induction arrives at 1 T. The second which is 54 cm long and has two windings reaches 2 T. Therefore the maximum current is fixed at 16 kA and a variation of 10:1 is judged necessary.

For reasons of space and maintenance the power supply is housed in a special building outside the ring tunnel. The result of this is the considerable length of the bus-bars between power supply and magnets. As we want to operate each of the two ejection systems alone or both together, the two pairs of septum magnets are connected to the power supply either singly or both pairs in series. The resulting load variation is about 1:2.

The requirements of the current ripple and the stability of $\pm 1 \cdot 10^{-3}$ were determined by the beam optics. In the specification this value was doubled in order not to discourage the manufacturer too much.

The pulsed operation was necessary because the septum magnets cannot be operated continuously owing to the risk of overheating the septum. The pulse lengths as well as the repetition rate were imposed by the present performance of the power supply for the CPS main magnet.
1.2 Load

The load conditions are given by the impedances of the septum magnets, the connecting bus-bars, flexible cables and the three possible operating modes:

- ejection 58 alone,
- ejection 62 alone,
- ejection 58 and 62 (electrical series connection).

Bearing in mind the possibility of connecting a quadrupole in series with the ejection magnets, the extreme values of the useful load range are fixed:

Maximum load: 3.5 mohms in series with 40 μH.
Minimum load: 1.8 mohms in series with 12 μH.

As, during the current pulse, the septa heat up from 20°C to 100°C, a resistance variation of 17% during the pulse was specified.

The magnets are built of 0.5 mm laminated iron resulting in a practically constant inductance up to 100 kHz. For reasons of flexibility any point of the load can be connected to earth.

1.3 Current

The maximum current, the current range of the continuously variable current, the ripple and the stability are given by the requirements of the ejection.

The current waveform is fixed so as to obtain the rise and fall times of the load current with reasonable over-voltages. Rise and fall times are limited to 30 ms, nearly three times the time constant of the maximum load. The rise time is defined as the period from the start of the current rise to the moment when the current reaches the precision band of ±2 0/60 (see Fig. 1.1).
The current precision of ±2 °/oo is defined for the whole load range and includes the current ripple, the reference stability, the influence of the heating-up of the load as well as the mains perturbations. These comprise slow amplitude variations of ± 5%, fast amplitude variations of ± 2%, amplitude asymmetries of ±1% and phase instability of ±1°.

The maximum voltage is 60V, resulting in a maximum peak power of 1 MW on the load.

Maximum current 16000 A
Minimum current 1500 A
Current precision ±2 °/oo
Rise-time 30 ms
Overshoot during rise ≤10%
Fall-time 30 ms

Pulse length, duty cycle:

<table>
<thead>
<tr>
<th>Current I</th>
<th>Max. Pulse Interval T</th>
<th>Max. Pulse Length τ</th>
<th>Max. Duty Cycle τ/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-16 kA</td>
<td>5 s</td>
<td>200 ms</td>
<td>1:25</td>
</tr>
<tr>
<td>12-14 kA</td>
<td>5 s</td>
<td>300 ms</td>
<td>1:16</td>
</tr>
<tr>
<td>9-12 kA</td>
<td>4 s</td>
<td>400 ms</td>
<td>1:10</td>
</tr>
<tr>
<td>16-9 kA</td>
<td>2 s</td>
<td>400 ms</td>
<td>1:5</td>
</tr>
</tbody>
</table>

PS/5544
2. **Description of the Power Supply**

2.1 **General remarks**

Initially the power supply was projected and built as a 48-phase, silicon-controlled rectifier with a single servo loop controlling the load current. The 48-phase rectifier was to have an inherent current ripple of about one quarter of the specified current tolerance and, in addition, it was to have a cut-off frequency of about 250 Hz for the servo loop. This band-width was considered sufficient to compensate for the load variations and the mains perturbations.

The first measurements on the terminated power supply showed an excessive current ripple (mainly of 300 Hz) which was much higher than expected. This was mostly due to, on the one hand, the unavoidable manufacturing tolerances of the 48-phase rectifier and, on the other hand, to the imperfections of the 3-phase mains voltage somewhat amplified by the double induction regulator (asymmetries in amplitude and phase, 5th and 7th harmonic). Since the ripple could not be reduced at its origin and there was no sufficient margin in the output voltage to permit an efficient passive filtering, the decision was taken that an electronic filter should be added to meet the specification.

The general circuit diagram of the rectifier and the electronic filter is given in Fig. 2.1. The rectifier produced an output voltage with two components: the desired D.C. component: \( U_m \), the unwanted A.C. component: \( U^R \). An inductor is placed in series with the load; from a separate current source a current is injected into the inductor so that at any given moment the voltage \( U^F \) is equal, but opposite in sign, to \( U^R \). The two voltages cancel each other out, and on the load only the desired voltage \( U_m \) appears.

Figs. 2.4 to 2.6 show the 48-phase rectifier, its control racks, the induction regulator "Matabon" and the power stage of the electronic filter.
2.2 Block diagram

The power supply and its load is considered as one unit, its block diagram is given in Fig. 2.2. The whole arrangement consists of the main switch, the induction regulator, the controlled 48-phase rectifier set, the electronic filter, the shunt, the load and the servo loop for the current regulation.

To start with the shunt: its signal is compared with the reference signal. When we want to eject the protons, the reference signal is switched on and off by external timing pulses from the CPS timing system. The error signal is amplified in G1, from where it is separated into the slow and the fast chain of the servo loop. In the slow channel the isolation amplifier is followed by the operational amplifier, the power amplifier, the pulse generators and the pulse distributors. They feed the firing pulse to the thyristors of the 48-phase rectifier which delivers the D.C. current pulse and compensates for the slow variation of the output current. The fast changes are compensated by the fast chain, formed by amplifier G2, the driver and the transistor power stage having an inductor as a load.

The filter as well as the rectifier are protected by an interlock system. A remote control and a remote measuring and indicating system permits operating the power supply from the CPS Main Control Room.

2.3 Current Servo Loop

The output current is controlled by a single servo loop having two branches. The total current is measured by the shunt and the shunt signal compared with the reference. Special attention was given to the fact that the inter-connections between shunt, reference source and error amplifier were as short as possible; the reference points of these different circuits were chosen with great
care. That is why the reference and the two error signal amplifiers G1 and G2 were built onto a special chassis installed as near the shunt as possible.

The reference element is a temperature-compensated zener diode. It serves as a reference for a variable power supply (0 to ±8 V). Its output voltage can be varied by the ten-turn reference potentiometer. Through a 1:10 voltage divider the 0 to ±8 V signal is added to the negative shunt signal and the error signal amplified by the wide-band differential amplifier G1. For pulsing the load current the reference voltage (0 to ±8 V) is switched on and off by means of two chopper transistors. They get their driving current from a general logic system where the necessary rectangular pulses are derived from the external start and stop pulses.

The output signal of G1 is fed on the one hand to G2, on the other to the differential amplifier A16 (Electro Instruments) the main purpose of which is to separate the floating shunt circuit from the slow chain, where one side is on earth potential.

After the separation amplifier A16 the error signal is fed to the operational amplifier 0A1 - A12 N where the correcting networks of the slow chain are installed. Its transfer function can be seen in Fig. 2.3. A potentiometer geared to the reference potentiometer changes the gain of the operational amplifier so as to render the loop gain constant. This gain adaptation is necessary because the gain of the power stage varies with the output current. The output signal of the operational amplifier passes through a power amplifier LP4 of a voltage gain one, before feeding the 24 Giesco (pulse generators). These circuits produce the ignition pulses for the thyristors by combining the D.C. voltage of the LP4 and the carefully filtered 50 Hz reference voltage. Each ignition pulse is multiplied by five by the pulse distributors called GDI. As a
result, the ignition pulses for the controlled rectifiers are independent of each other and so avoid trouble when thyristors connected in parallel do not fire at exactly the same moment.

Amplifier G 2 contains the correcting networks of the fast chain (see Fig. 2.3 for transfer function). In addition, the gain of the filter can be set to three different values adapting the filter operation to the load conditions. A D.C. current added to the output of G 2 permits choosing the working point of the power stage of the filter, in accordance with the reference. The output of G 2 feeds the seven parallel driver stages, one for each "turbine". They are built of 2 HF silicon power transistors connected (TI 1136) in parallel.

2.4 Matabon, controlled rectifier, shunt

Matabon: Mainly because of the strict ripple requirements the rectifier has to work with a more or less constant ignition angle. The result is a variable input voltage to the rectifier. In our case a double induction regulator called "Matabon" was chosen permitting a voltage variation from about 20 V to 1550 V. After the Matabon a small step-up transformer was added which permits an increase of the output voltage to 1720 V. The variation needed to cover the current range as well as the load range is 1:20. At low voltages the output waveform is considerably distorted, which leads to an increase of ripple of the D.C. current.

The output voltage of the Matabon is varied by turning the two stators. A separate servo loop with an on-off control ensures the correct value of the Matabon output voltage. The reference potentiometer for this servo loop is geared to the potentiometer for the main reference. To avoid adjustments of the stator position during pulsing, the servo loop is not in operation during the current pulse.
The phase shift between input and output voltages of the
Matador as a function of output voltage is only a few degrees at
very low voltages, it is negligible at higher voltages.

**Controlled rectifier**: The 48-phase rectifier is composed of
eight 6-phase rectifiers. Each of them consists of a polygonal
phase shifter, a rectifier transformer with a triangle-double star
connection, a 150 Hz iron core interphase transformer and 30 thy-
ristors TSW 70 40 C.

The phase shifts of the eight units have been chosen as
follows:

\[0^\circ, -30^\circ, +15^\circ, -15^\circ, +7.5^\circ, -22.5^\circ, +22.5^\circ, -7.5^\circ.\]

This choice allows connecting each two adjacent 6-phase
systems to a 12-phase system (with an air core 300 Hz interphase
transformer). The two pairs form two 24-phase systems, which thus
make up the 48-phase rectifier. The inductance of the connecting
rectifier bars was chosen so that the higher order interphase trans-
formers could be dispensed with.

The whole arrangement of phase shifting transformers is
duplicated - at much lower power, of course - to give the
reference voltages for the ignition circuits of the controlled
rectifiers.

The thyristors are of the 70 A type (TSW 70 40 C). At
the time of ordering they were the largest: within the Schneider-
Westinghouse production. For reasons of mean current and of
junction temperature rise during the current pulse five of them per
phase had to be connected in parallel. Each thyristor is protected by
by a fast fuse and a RC network whereas the five thyristors in
parallel are protected by a voltage-limiting device. Five trans-
formers connected in a ring circuit equilibrate the current through
the five thyristors in parallel which are fired from independent sources; thus, all possible precautions are taken to obtain faultless operation. The thyristors are mounted on black copper bars and natural convection cooling is sufficient.

**Shunt**: The shunt manufactured by Otto Wolff of Berlin is a D.C. current shunt. Its active part is composed of a large number of thin manganin plates arranged parallel to each other. A considerable effort was necessary to improve the shunt transfer function at higher frequencies. The transfer characteristic could be made flat up to about 20 kHz by changing the location of the measuring leads inside the shunt.

The shunt resistance is 50 μohms resulting in a shunt signal of 800 mV at 16 kA. The active part of the shunt is immersed in oil which is water-cooled.

2.5 **Electronic filter**

The power stage of the electronic filter is composed of the D.C. power supply, the transistor series regulator and the load (6 μH inductor in parallel with 33 mohm resistor).

The power supply of 22 V, 1500 A, is a conventional 6-phase diode rectifier with considerable capacitive filtering (~0.6 F). Care was taken that, owing to an oscillation between the power supply inductance and the filter condenser, the voltage did not drop too much at the beginning of the filter current rise.

The series regulator is a class A amplifier in which the D.C. current is switched on and off along with the pulse sequence. The maximum dissipation is 40 kW divided among 280 germanium power transistors (2N1100) connected in parallel. The transistors need...
forced air-cooling and for this purpose are mounted on seven turbines. Each of them is electrically divided into four identical sectors. The ten power transistors per sector have a common driver \((2N\ 1100)\) and the four drivers per turbine have, as already mentioned, a common HF driver stage.

Special care was taken to ensure that the power transistors, \(2N\ 1100\), did not at any moment exceed the rated values of current, voltage or power. An emitter resistor of 0.4 ohms for each transistor guarantees a current distribution within \(\pm 10\%\). To limit the power dissipation still further, a 20 ohm resistor is connected in series with each turbine. A special thyatron protection circuit to short-circuit the 6 \(\mu\)H inductor permits the protection of the power transistors against momentary over-voltage and over-power. By limiting the input signal to each turbine, the current per transistor does not exceed 10 A.

2.6 Measurement of output current

The load current or, to be more precise, the shunt signal, can be observed by an oscilloscope. A variable D.C. opposition voltage serves to observe the flat top of the pulse and to measure the ripple accurately. Since neither of the shunt terminals is at ground potential, the shunt signal passes through an isolation amplifier A 16.

The shunt signal as well as the reference signal can be measured by a digital voltmeter DM with a precision of \(10^{-4}\). Its measuring time is 10 ms. It can be triggered by an external pulse, which helps to determine the current value at any moment during the flat-top. The digital voltmeter indication is transmitted to the Main Control Room.
2.7 Interlocks, remote control

Interlocks: The interlock system protects rectifier, filter and load by stopping the power supply.

For the rectifier two cases of overload are considered. In the first the rectifier stops operating if the output current exceeds by 1500 A the value given by the reference. In the second case the operation stops if the time integral of the load-current exceeds a pre-determined value. This case becomes important mainly when the stop pulse fails to arrive. The oil temperature and the cooling-water flow (both for the shunt), the reference voltage to the Giccos, the thyristor fuses, and the doors on the high-voltage side of the rectifier are all interlocked.

The filter is protected against overload by limiting the time integral of the mean filter current. In addition, the temperature of the transistors belonging to the power stage as well as their blocking voltage form part of the interlock chain to which also the protection circuits of the load are connected.

Remote control: A switch on the control racks permits the choice between local and remote operation. The power supply can be switched on and off and operated from the CPS Main Control Room. In addition to the controls for the operation, also the interlock indications and the digital voltmeter readings are duplicated in the Main Control Room. The resetting of the interlocks as well as the operation of the local-remote switch can only be done locally.
3. Tests

3.1 Output current, ripple, stability, output voltage

The rise and fall times, the ripple and the stability during the flat top of the output current were measured for the whole current range, the maximum and the minimum load.

The rise time (as defined in 1.3) as well as the fall time were within the specified limit of 30 ms. The method of measuring the rise time can be seen in Figs. 3.2 and 3.3.

The ripple is always within the specified peak-to-peak value of 4°/oo. The ripple as a function of load current is plotted in Fig. 3.22 for both maximum and minimum load. Owing to distortions of the 50 Hz voltage by the induction regulators, the ripple increases for currents below about 6 kA. For the minimum load the ripple remains constant in the range of about 6 to 16 kA (≤ 1.4°/oo), whereas for the maximum load the ripple, after a more or less flat plateau from 3 to 12 kA (≤1.3°/oo), rises and reaches 5°/oo at 16 kA. Fig. 3.3 proves that this increase is due to small spikes, whereas the "normal" ripple is again 1.5°/oo. Figs. 3.4 to 3.11 show ripples for different load currents and loads; an exception is Fig. 3.7 with the whole current pulse for 16'000 A and the maximum load; the overshoot is smaller than 5%. In Figs. 3.1 and 3.2 we can observe two smaller pulses preceding the real current pulse (time runs from left to right). They are due to a first 5% step of the reference before the final 100% step. This 5% jump was thought necessary in order not to saturate the interphase transformers. In Fig. 3.6 we observe a net current decrease due to the heating-up of the load. The zero line lies outside, i.e. above, the photo.

The stability from pulse to pulse, measured with the oscilloscope and the digital voltmeter, is better than 3·10^{-4} for all currents and loads.
The voltage on the load during a 16'000 A current pulse can be seen in Fig. 3.12. At the beginning the full voltage appears on the load. During the current rise the voltage drops owing to the internal impedance of the rectifier. When the current has reached the flat top, the voltage is reduced to its steady-state value. Since the load increases its resistance the output voltage increases proportionally (in the case of the dummy load by 24%).

3.2 Rectifier, filter, servo loop

The voltage across one of the thyristors was measured (Fig. 3.13). It can clearly be observed how after one full ignition cycle the ignition angle is changed to reduce the output voltage. Fig. 3.14 gives the wave-form across two end-points of one star of a rectifier transformer. The distorted form of the 50Hz is mainly due to the high series inductance of the Matabon. The output voltage and the voltage across its 150 Hz interphase transformer are oscillographed in Fig. 3.16 and Fig. 3.15, respectively.

The steering voltage to the ignition circuits (Gimcos) can be seen from Fig. 3.17. Before the arrival of the start pulse the Gimcos are completely blocked (positive voltage on Fig. 3.17), after arrival of the start pulse they are wide open; then, after about 15 ms, they work in regulated operation (~ -2.5V). At the end of the pulse there is a linear rise towards the blocked state.

The input voltage to the driver of the filter (Fig. 3.20), the current of the power stage (Fig. 3.18) and the voltage across the 6/μH inductor (Fig. 3.21) give a picture of the operation of the filter. In Fig. 3.19 one can observe the voltage drop and the ripple of the 22 V, 1500 A power supply for the power stage of the filter.
3.3 Earthing of load, mains asymmetry

With the maximum current of 16'000 A and the maximum load, various points of the latter were connected to earth. No change was observed in the ripple.

With a maximum load and a number of varying current values we produced a 380 V mains asymmetry of either 1° in phase or 1% in amplitude. Here again no change in ripple could be detected. The mains asymmetry was produced with two transformers, which made it possible to add the necessary small voltages to the mains voltage.

3.4 Life test

The performance, especially the ripple, was observed before and after the 24-hour test at maximum load, 16'000 A, 5 secs repetition time and 200 msecs flat top. The ripple did not change during the whole life test. Only one of the power transistors (2N1100) of the filter had its current gain reduced to unity, the rest did not change their current gain. Later it was discovered that the 380 V mains power switch had suffered. The relays for the short-circuit protection were worn out owing to the pulsed operation; they were replaced. No other defect could be detected.

During the life test (1 MW D.C. pulsed power) we measured the input power to the rectifier: 2,3 MVA during the pulse, 0,2 MVA during the pulse interval.

The temperature rise in the various parts of the equipment were not alarming, the induction regulator was the warmest component we could find, its hottest point showed a 45°C rise above ambient temperature.
FORM OF CURRENT PULSE

FIG. 1.1
FIG. 2.1  RECTIFIER AND FILTER
Fig. 2.5
Rack for Remote Control
3 Control Racks for Rectifier
Induction regulator "Matabon"
Fig. 2.6

Power Stage of Filter
with power supply 22 V, 1500 A
and 5 of the 7 turbines installed
**Fig. 3.1**

Output current: 1600 A  
Max. load: 3.5 mohms, 40/μH  
400 A/cm  
20 ms/cm

**Fig. 3.2**

Output current: 1600 A  
Maximum load  
400 A/cm  
10 ms/cm

**Fig. 3.3**

Output current: 1600 A  
Maximum load  
5 A/cm  
10 ms/cm  
Same time origin as Fig. 3.2  
Rise time: <30 ms
Fig. 3.4
Output current: 1600 A
Maximum load
5 A/cm
50 ms/cm
4°/oo ≈ 6.4 A ≈ 1.3 cm
Ripple: 1.3°/oo

Fig. 3.5
Output current: 6000 A
Maximum load
10 A/cm
50 ms/cm
4°/oo ≈ 24 A ≈ 2.4 cm
Ripple: 1.0°/oo

Fig. 3.6
Output current: 12000 A
Maximum load
20 A/cm
50 ms/cm
4°/oo ≈ 48 A ≈ 2.4 cm
Ripple: 1.3°/oo
Fig. 3.7
Output current: 16000 A
Maximum load
4000 A/cm
20 ms/cm

Fig. 3.8
Output current: 16000 A
Maximum load
40 A/cm
20 ms/cm
4 °/oo ≤ 64 A ≤ 1.6 cm
Ripple: 3.0 °/oo

Fig. 3.9
Output current: 1600 A
Minimum load: 1.8 mohms, 12 μH
5 A/cm
50 ms/cm
4 °/oo ≤ 6.4 A ≤ 1.3 cm
Ripple: 2.8 °/oo
Fig. 3.10
Output current: 9000 A
Minimum load
20 A/cm
50 ms/cm
4 \(\%\) \(\pm\) 36 A \(\pm\) 1.8 cm
Ripple: 1.3 \(\%\)

Fig. 3.11
Output current: 16000 A
Minimum load
40 A/cm
50 ms/cm
4 \(\%\) \(\pm\) 64 A \(\pm\) 1.6 cm
Ripple: 1.2 \(\%\)

Fig. 3.12
Voltage on the load
Output current: 16000 A
Maximum load
20 V/cm
50 ms/cm
Fig. 3.13
Voltage across one thyristor
Output current: 16000 A
Maximum load
Beginning of pulse
100 V/cm
20 ms/cm

Fig. 3.14
Output voltage of 1 rectifier transformer
Output current 16000 A
Maximum load
Beginning of pulse
100 V/cm
20 ms/cm

Fig. 3.15
Voltage on one 150 Hz inter-phase transformer
Output current: 16000 A
Maximum load
Beginning of pulse
100 V/cm
10 ms/cm
Fig. 3.16
Output voltage of one six-phase rectifier
Output current: 16000 A
Maximum load
50 V/cm
50 ms/cm

Fig. 3.17
Output voltage of power amplifier LP4 of slow chain of servo loop
Output current: 16000 A
Maximum load
5 V/cm
20 ms/cm

Fig. 3.18
Filter current
Output current: 16000 A
Maximum load
700 A/cm
20 ms/cm
Fig. 3.19
Output voltage of rectifier: 22 V, 1500 A
Output current: 16000 A
Maximum load
5 V/cm
20 ms/cm
(zero: bottom of picture)

Fig. 3.20
Input voltage to driver of filter
Output current: 16000 A
Maximum load
2 V/cm
20 ms/cm
(zero: at bottom of picture)

Fig. 3.21
Voltage across 6 μH filter inductor:
Output current: 16000 A
Maximum load
5 V/cm
20 ms/cm
(zero: middle of picture)
RIPPLE AS FUNCTION OF LOAD CURRENT

FIG. 3.22