THE REACTIVE POWER COMPENSATION OF THE CERN PS-BOOSTER POWER SUPPLY

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Abstract

The CERN Synchrotron Injector (PS-Booster) started operation in the spring of 1972. The pulsed power supplies for the bending magnets and quadrupole lenses are provided by static rectifiers connected directly to the network[1]. Compensation of cyclic variations in reactive power was effected with particular care to ensure that perturbance of the supply network voltage was kept to a minimum[2].

After a brief description of the circuit, produced by the German firm Siemens AG in collaboration with CERN. The characteristics of the cycle obtained on the magnets are given, followed by a more detailed description of the system of reactive power compensation. The measurement of the reactive power and the regulation loop are described and discussed. Several oscillograms show the operation of the PS-Booster with, and without, reactive power compensation. The results obtained demonstrate the usefulness of this device, which enables the residual variations in voltage, on the 18 kV busbar, to be kept within an overall range of 0.5% peak to peak. Consequently, this variation is small enough not to interfere with other users connected to the same network.

I. Introduction

The short-circuit power of the 18 kV internal grid of CERN Lab. I is between 314 and 470 MVA (with 2 or 3 transformers at the power input). The equivalent impedance is essentially inductive. Consequently a reactive current produces a voltage drop which is virtually in phase with the voltage of the source, whereas a purely resistive current causes a voltage drop in quadrature with the voltage of the source resulting in a very small variation in the supply voltage. As far as the CERN Lab. I's network is concerned (with only two supply transformers) the consumption of a reactive power of 1 MVAr results in a 0.3% voltage drop, whereas that of an active power of 1 MW results in a voltage drop of only about 0.03%.

In any supply system containing controlled rectifiers which are fed directly from the network, the active and reactive power required of the network depend on the output dc voltage and current. Consequently the phase of the alternating current depends on the output dc voltage (controlled by the thyristor firing moment) whereas the amplitude of the alternating current (without freewheeling diodes) is a function of the dc output current.

The supply of pulsed power to the magnets of the PS-BOOSTER by a power supply system composed of static controlled rectifiers causes, therefore, a cyclic variation in the active and reactive power. The active power must come from the network (and return to it during disexcitation, except for the losses); on the other hand the reactive power, which causes the troublesome voltage drop, may be compensated locally by a suitable device. The circuit produced and the performance obtained will now be examined more closely.

II. Description of the Power Supply

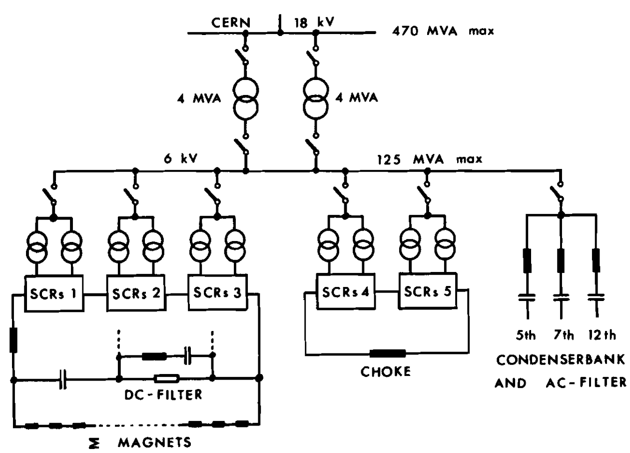

Fig. 1. PS-BOOSTER BASIC DIAGRAM

Figure 1 is the basic diagram of the overall power supply system. It consists of identical units "transformers-12-phase thyristor bridges" (2 three-phase bridges connected in-series, 30° out of phase in relation to each other). Each unit is able to supply a peak current of 3000 A at about 1000 V (rms = 2000 A). Three units are series-connected to provide energy to the magnet circuit, the two others supply power, at almost zero voltage, to a small choke. As the 5 units are located in the same room, it is possible in case of need to power the choke with a single unit and use the fifth as a stand-by set which can easily be switched over to the magnet circuit, the defective unit then being isolated from the circuit by isolating switches. This provides a simple and quick way of intervening in the event of a fault.

The operating principle is as follows, for example, during the rise phase : the three units of the magnet circuit are increased in succession from zero voltage to full voltage, supplying the magnets with the active excitation power (free-wheeling thyristors by-pass the current of the units operating at zero voltage). This way of controlling the rectifier units enables the variation of reactive power consumption to be reduced to a minimum, without, however, reducing it sufficiently. The rectifier units of the choke circuit will help to improve this situation by acting as additional modulator of reactive power. These two rectifiers units are virtually short-circuited; the active power is zero, except for losses, and the choke serves only to smooth the dc current of this circuit. Thus this set of five units will operate in such a manner as to consume a constant reactive power owing to the presence of a suitable regulation loop. Finally, the reactive power consumed is reduced almost to zero by a bank of capacitors having a power of 3.2 MVAr. These capacitors are, in fact, combined with a harmonic filter tuned to the harmonics of order 5 (0.8 MVAr) 7 (0.4 MVAr) and 12 (2 MVAr) serving to reduce the voltage distortion on the intermediate 6 kV network. This 6 kV network was produced specifically for this supply so that the voltage could be adjusted locally to within ± 10%, to optimize the capacitors and obtain some decoupling from the 18 kV network.

III. Magnet excitation cycle

The main characteristics of the magnet circuit and of the cycle are as follows[3] :

Resistance of magnets and connections	:	0.496 Ω
Inductance of magnets and connections	:	0.185 H
Stand-by current	:	300 A
Injection current (49.24 MeV)	:	583.3 A
Transfer current (800 MeV)	:	2761.7 A
Flat top voltage (transfer) RI_T	:	1369.8 V
Acceleration voltage $L\frac{dI}{dt}$	:	775.0 V
Peak voltage U_{max}	:	2144.8 V
Rise time	:	560 ms
Minimum repetition time	:	1.15 s

Figure 2 shows the current cycle, which is composed basically of three plateaux connected by the rises and drops in the current : first the stand-by plateau, then the plateau prior to injection followed by the injection and acceleration of the protons until the transfer plateau is reached; then transfer occurs, followed by return to the initial conditions, the stand-by time at present being dependent on the cycle of the other machines.

Figure 3 shows the total voltage applied to the magnet circuit after passive filtering of the voltage ripple.

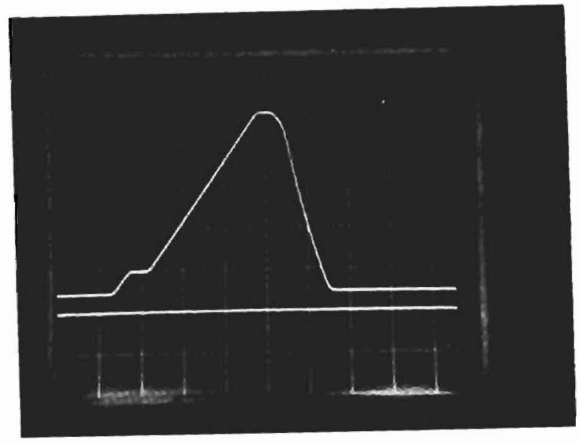

Fig. 2. CURRENT CYCLE
vert : I = 600 A/div
horiz: t = 0.2 s/div

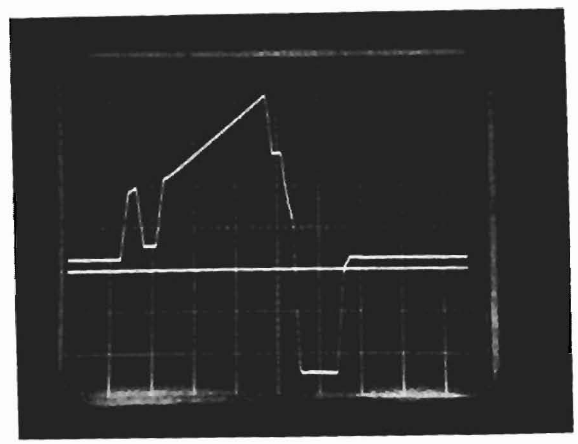

Fig. 3. VOLTAGE CYCLE
vert : U = 500 V/div
horiz : t = 0.2 s/div

Figure 4 shows, finally, the unfiltered individual voltages of the three rectifier units feeding the magnet circuit. The successive operation of the three units is clearly visible.

The cycle is controlled by an analog function generator which provides the total voltage-reference, in conjunction with the CERN PS-timing system. This reference is then fed to the three rectifier units which each have their own voltage regulation, with a high-speed loop. In this way, the total voltage is obtained. At the rounded portions of the current curve a correction is introduced, which takes into account the energy stored in the passive filter in order to minimize the current overshort on arrival at the plateau.

The exact triggering of the plateaux is based on current measurement. Finally, a slow correction is introduced, which takes account of the variation in the magnet resistance, in order to keep the plateaux essentially horizontal. In this way, the plateaux can easily be kept constant for several tenths of a second, if necessary.

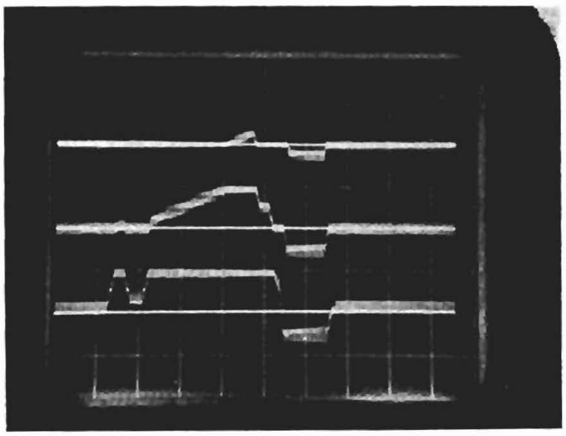

Fig. 4. THYRISTOR UNIT VOLTAGE CYCLE

vert : U = 1 kV/div

horiz : t = 0.2 s/div

This method of regulating the supply voltage without direct regulation of the current, but solely with triggering by the current provides an easy way of obtaining the performance required for the moment, even within a very short time after each start-up (several cycles). This avoids energy losses in stabilizing the machine.

The performance at present achieved is as follows:

The current accuracy at the transfer plateau, measured over several hours, is within a range of $\pm 10^{-4}$, peak to peak, including ripple. This performance is already twice as good as the design figure. The residual current ripple at 600 Hz is 30 mA max, peak to peak (value approximately constant throughout the cycle). Sometimes, however, when the network is strongly distorted by other users, a current ripple may occur at frequencies of between 50 and 600 Hz, attaining maximum resultant values of 60 mA, peak to peak. This still only represents 2×10^{-5} of maximum current[4] .

Furthermore, it should be noted that the absolute measurements are always made with two different devices: a high-accuracy coaxial shunt and a four-core transducer. The residual ripple voltage can easily be measured with a coil measuring $\dot{B}$ in the reference magnet.

IV. Measurement after reactive power

In order to obtain efficient regulation of the reactive power, it is, of course, first necessary to make a rapid and accurate measurement of this value. The principle used is the conventional one: the reactive power of each phase is measured and the sum obtained. This is shown by Figure 5, together with the phase diagram of the current and voltage vectors. To measure the reactive power of one phase it is necessary to multiply two values which represent the line current and the voltage in quadrature with a resistive line current.

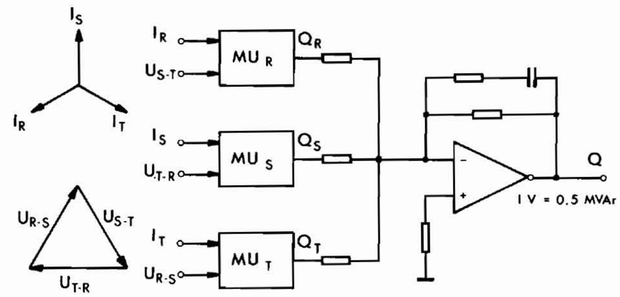

Fig. 5. REACTIVE POWER MEASUREMENT

Among the existing devices, CERN has opted for the solution with analog electronic multipliers. Considerable care should be taken when selecting these multipliers. They must be accurate, rapid, free from any temperature effects or drift, and symmetrical in the four quadrants. These requirements are stringent. Among the many types considered and tested, the best results were obtained with the Philbrick Nexus model 4450, mainly on account of its high band-pass. Its comparative lack of accuracy has been overcome by selecting three multipliers having very similar characteristics. In this way, it is possible to avoid frequency components between 50 Hz and 250 Hz in the sum of the powers of the three phases. It should be noted that some multipliers, which on paper seem to be excellent, give very disappointing results, mainly because of their restricted band-pass; it should not be forgotten that the waves to be measured are not perfectly sinusoidal! The time constant introduced to smooth the measurements is 2 ms, and this enables good performance to be obtained.

V. Reactive power regulation loop

Figure 6 shows the device for controlling the reactive power which is, in fact, composed of two loops arranged in cascade: one internal current-regulation loop, and one external reactive power regulation loop, providing the current reference. The reason for this choice is mainly due to the fact that the power stage is practically short-circuited to the choke with a high over-regulation coefficient, and this could easily result in unacceptable overcurrents. Thus, the regulation loop simplifies problems of starting, limitation of maximum current, and also the maintenance of a minimum current to avoid the opening of the control loop. Finally, a parallel limitation in rms current was also introduced into this loop to avoid excessive heating of the choke and power supply. The characteristic gain = f(ω) of the current loop shows mainly the choke time-constant (50 ms); the characteristic is horizontal again beyond 20 ms because of the proportional term of the regulator.

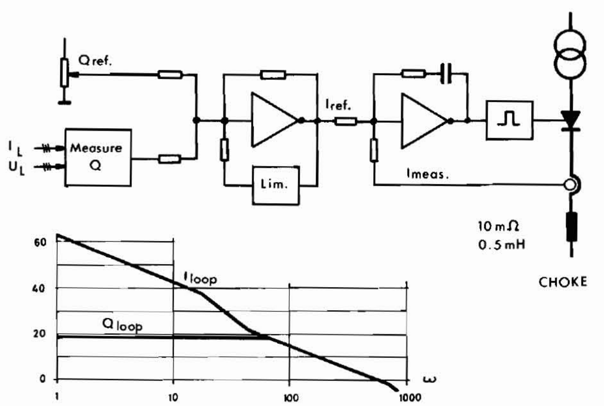

Fig. 6. REACTIVE POWER CONTROL LOOP

The gains of the current and the machine power loop are given in dB versus pulsation ω in 1/s.

The reactive power regulation loop then becomes very simple, since the power measurement has been filtered with a fairly low time constant (2 ms). In this way, the measurement is compared with the fixed reference value, with a gain of about 20 dB, to provide directly the current reference.

The oscillogram of Figure 7 represents the step response of the reactive current loop for a reference jump of 1.4 MVAr. The reactive power changes rapidly with practically no overshoot. The different speeds of response in one direction and the other result from an asymmetric adjustment of the over-regulation coefficients which have no practical consequences in normal operation, since the jumps are never so sharp.

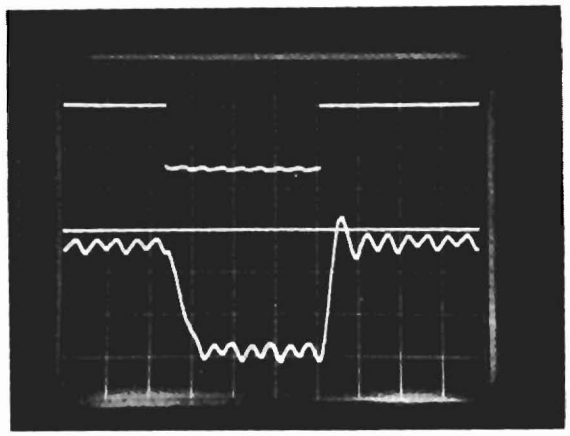

Fig. 7. STEP RESPONSE OF THE REACTIVE POWER CONTROL LOOP

Above: reference Q = 1 MVAr/div
Below: measure Q = 0.5 MVAr/div

Horiz: t = 20 ms/div

VI. Residual perturbations

The following few oscillograms enable comparison of the operation with and without reactive power compensation. With regard to all the cycle photography, synchronization and scanning rate are always identical, to ensure correlation between photographs.

Figure 8 shows the cyclic variation in reactive power, when compensation has deliberately not been provided, the units feeding the choke being inoperative. The total variation in reactive power, peak to peak, is 3.8 MVAr. Figure 9 shows, on the same scale, the residual variation in reactive power when compensation of the reactive power is operative. The fixed reference of the reactive power is about 0.8 MVAr inductive, and there remains a variation of about 0.6 MVAr which the capacitor banks can no longer compensate. Maximum value is obtained when the groups change over to inverter operation, just at the end of the transfer period.

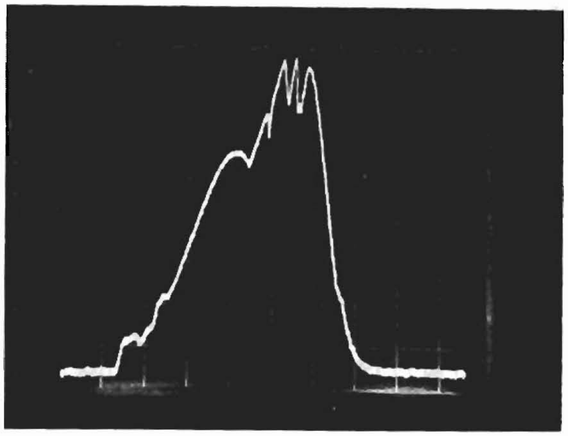

Fig. 8. REACTIVE POWER CYCLE WITHOUT COMPENSATION

vert : Q = 0.5 MVAr/div
horiz : t = 0.2 s/div

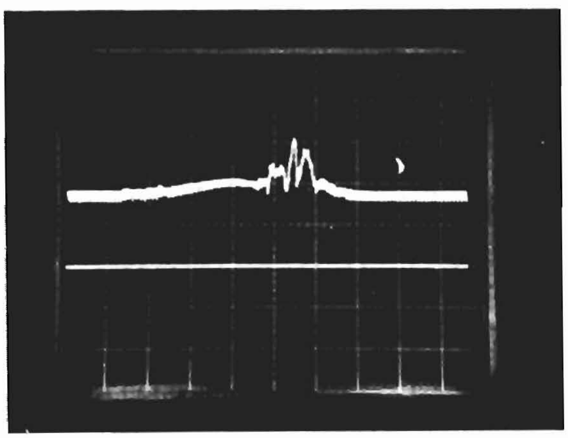

Fig. 9. REACTIVE POWER FLUCTUATION WITH COMPENSATION

vert : Q = 0.5 MVAr/div
horiz : t = 0.2 s/div

By comparing Figures 8 and 9 it will be seen that the gain of the reactive current loop is indeed about 10 (20 dB). Figure 10 shows the cyclic variation in the current in the two compensation units and the choke. It will clearly be seen that the compensation is limited at minimum current at the end of the transfer plateau. Figures 11 and 12 show the total 6 kV current with one sweep per period during the cycle. It is interesting to note the change in phase and amplitude of the current when the compensation is not operative, and to observe that only the current amplitude varies during operation with compensation; this clearly shows that only the active pulsed power is being taken from the network.

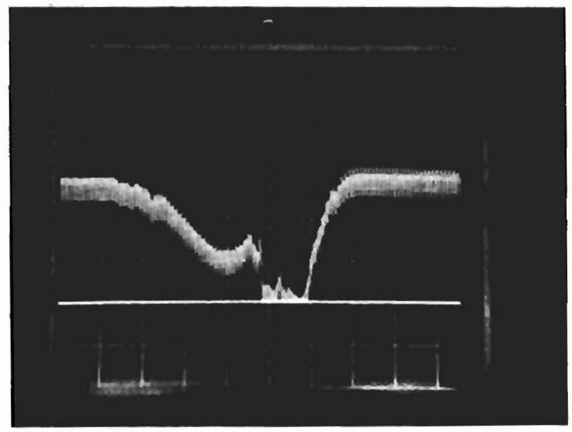

Fig. 10. COMPENSATION CHOKE CURRENT CYCLE

vert : I_{dc} = 600 A/div
horiz : t = 0.2 s/div

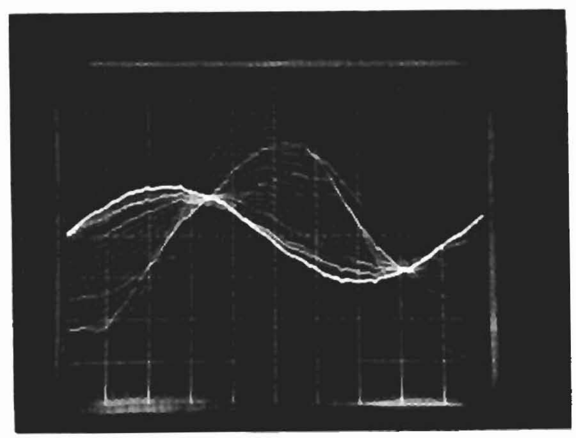

Fig. 11. 6 kV, 50 Hz CURRENT WAVEFORM WITHOUT REACTIVE POWER COMPENSATION

vert : I_{ac} = 200 A/div
horiz : t = 2 ms/div

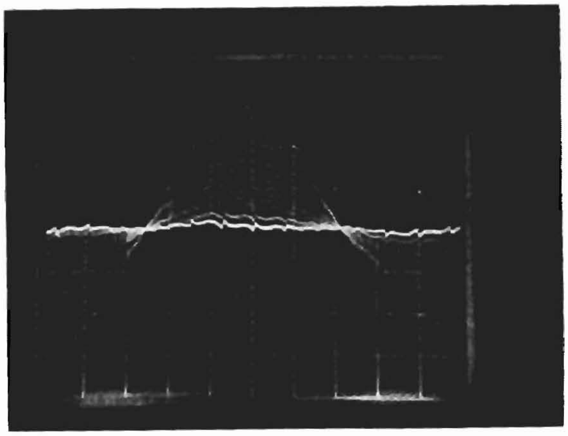

Fig. 12. 6 kV, 50 Hz, CURRENT WAVEFORM WITH REACTIVE POWER COMPENSATION

vert : I_{ac} = 200 A/div
horiz : t = 2 ms/div

The final result which interests us, in fact, is to limit the variations in the effective voltage of the network. To see the results obtained, it is necessary to measure this rms value. To this end, a photoelectric system has been used, composed of a filament lamp connected to the voltage to be measured, and of a photodiode picking up the light emitted. This measurement device is easy to calibrate, it is very stable and sufficiently rapid (inherent time constant: 20 ms); it is necessary to filter it further (here with 50 ms) to attenuate the modulation of light which occurs twice a period. Figure 13 thus shows the variation in rms voltage, during one cycle, of the 6 kV intermediate network, with and without reactive power compensation.

The total variation is 4.2% without compensation and 1.2% with compensation.

Figure 14 shows, finally, at a smaller scale, the variation in rms voltage on the 18 kV network, with and without reactive power compensation.

The residual variations are 1.25% without and 0.45% with compensation. The latter figure certainly contains other variations in the network, as it was impossible to make these measurements with an ideally stable network.

This is indeed the order of magnitude which it was hoped to achieve, so as not to perturb the other users.

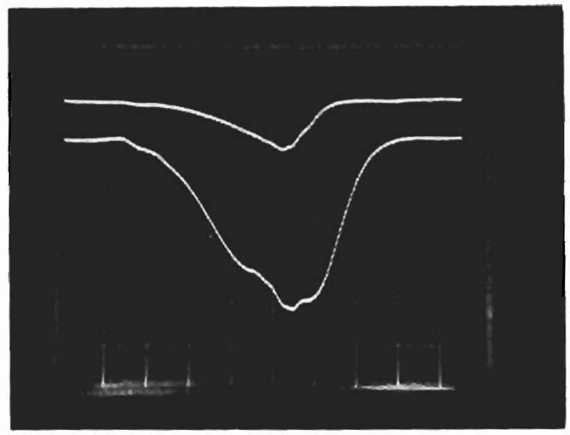

Fig. 13. 6 kV rms VOLTAGE FLUCTUATION WITH AND WITHOUT REACTIVE POWER COMPENSATION

Above: with compensation
Below: without compensation } $\frac{\Delta u}{u}$ = 1%/div
Horiz: t = 0.2 s/div

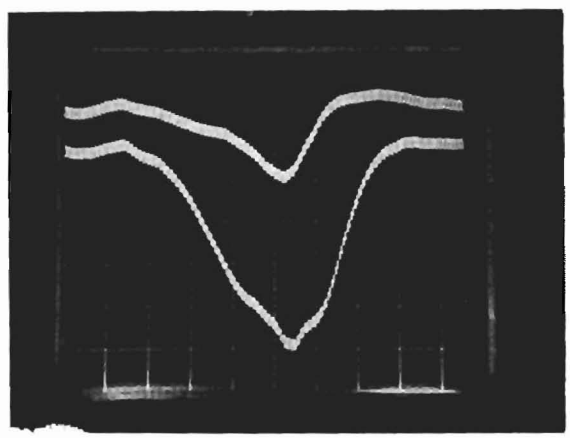

Fig. 14. 18 kV rms VOLTAGE FLUCTUATION WITH AND WITHOUT REACTIVE POWER COMPENSATION

Above: with compensation
Below: without " } $\frac{\Delta u}{u}$ = 0.25%/div
Horiz: t = 0.2 s/div

VII. Conclusions

The results described above are those obtained during the early operational stages of the PS BOOSTER. If necessary, certain points could easily be improved, for example, the measurement of the choke current, which at present introduces a 100 Hz component. The cycles used are the fastest (1.15 s) for which the machine has been designed. It is clear that in the majority of cases, such as that of the oscillograms, the repetition rate is slower, with the result that without making a large increase in the cycle duration, it is easy to eliminate the reactive power peaks which occur at the beginning of the descent, by starting the current decay with zero voltage and starting inversion after a slight delay. At present, however, there is no reason for such refinements, on account of the quality of the results already achieved.

Acknowledgements

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*) Siemens' engineers.

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