NEW PRINCIPLE FOR POWER SUPPLIES FOR SYNCHROTRON MAGNETS WITHOUT TRACKING ERRORS

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The Power Supply of the Ring Magnet System of SIS

The power supply of the ring magnet system of the heavy ion synchrotron SIS at GSI consists of the following six units:

- one power supply composed of four subunits feeding the chain of the 24 dipole magnets with a maximum output current of 3.5 kA, a maximum output power of 26 MW and a maximum current rise of ± 19 kA/s,
- four separate power supplies each of them feeding a chain of 6 quadrupole magnets with a maximum output current of 1.76 kA, a maximum output power of 1.6 MW and a maximum current rise of ± 10 kA/s,
- one power supply feeding the chain of the 12 quadrupole magnets for triplett-focussing with a maximum output current of 820 A, a maximum output power of 510 kW and a maximum current rise of ± 6 kA/s.

These power supplies and also the 11 main power supplies for the experimental storage ring (ESR) have been developped, installed and successfully put into operation by the manufacturer AEG.

The most difficult design problems arose from the following specifications for the power supplies of SIS:

- rise time of current from minimum to its rated value: 117 ms,
- rise time of load voltage from zero to its maximum value: 10 ... 20 ms,
- maximum load voltage of 11.2 kV and a rated current of 2.3 kA for the dipole power supply with the four subunits connected in series,
- maximum load voltage of 5.5 kV and a rated current of 3.5 kA for the dipole power supply with two groups connected in series each consisting of two subunits connected in parallel,
- accuracy and ripple of the current with respect to the instantaneous current value better than ± 2.5 • 10^{-4} at every instant of time during the cycle while the current varies from 2.2 % to 100 % of its rated value,
- no time-lag between the set value of the current and the actual value of the current tolerance band, i.e. no tracking error.

The last condition is of great importance for simplifying the operation of the synchrotron as it allows to supply the RF-acceleration system with set values tabulated in the computer memory thus avoiding the necessity of an additional control of the RF-system by the B-train. Furthermore, considering the focussing system of SIS which consists of five separate magnet systems each of them individually controllable it is a great advantage to set precalculated current values without having to take into account individual time-lags of the five power supplies thus making an individual Q-train control unnessary.

As a result of this it is now possible to generate super-cycles for the synchrotron operation thus verifying the concept of several virtual accelerators serving different experiments in time-sharing. For every virtual accelerator the kind of beam, its energy, its extraction time etc. can be chosen separately.

Selection of the Power Converter Concept

Hitherto existing "classical" designs of magnet power converters with passive filter and serial active filter (see Fig. 1) cannot avoid the tracking error mentioned before.

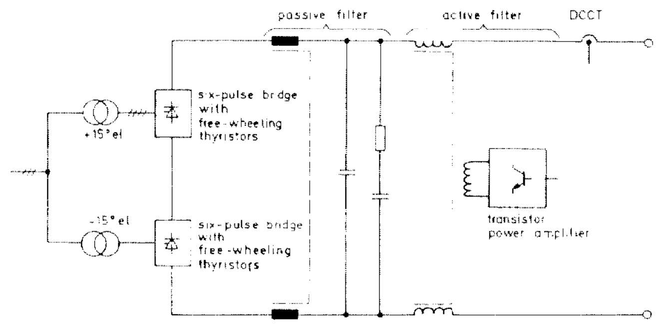

Fig.1 Power converter with "classical" passive and active filter

This tracking error is caused by the integrating controller (PI-controller) which is absolutely necessary for this power supply concept and on principle generates a time-lag t_L between dynamically varying set values and actual values of currents (see Fig. 3a). The tracking error is even not constant in time but varies depending on external disturbances as there are changes in load parameters resulting from temperature fluctuations, inductance saturation etc..

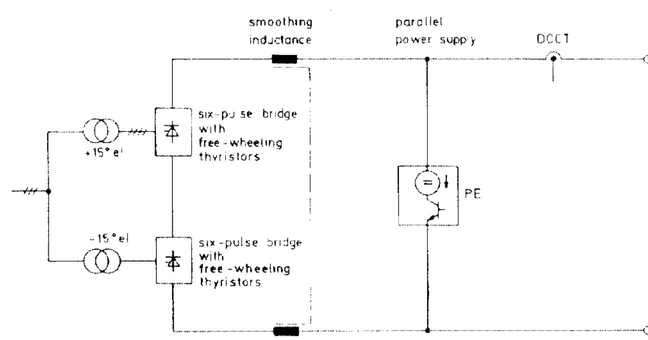

Fig.2 Power converter with the new concept of active filter (parallel-power-supply)

The new magnet power converters with "Paralleleinspeisung" (PE) as proposed in Fig. 2 do not have any tracking error. The time-lag t_L between the set value and the actual value of the current is equal to zero in every instant of time as shown in Fig. 3b. The actual current value is always within the permitted tolerance band of the width Δx_i surrounding the set value of current.

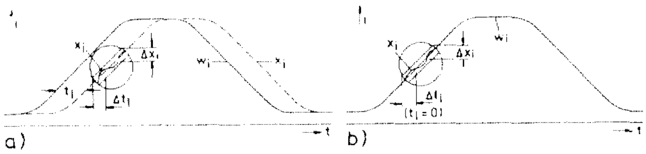

Fig.3 Set value w_i and actual current x_i for
a) power converter with classical filters
b) power converter with PE

This ideal performance is obtained by the good dynamical characteristics of the Paralleleinspeisung (PE) on the one hand and by the use of entirely proportional controllers (P-controller) for the load current on the other hand. They can only be used as the PE enables simple presetting of all control elements just by knowledge of the load voltage which can be calculated easily in advance. For this power converter concept the time behaviour of the main power unit (SCR) does not enter into the calculation of the preset values. The original combined system of load and main power unit as represented by the classical design concept is a third order system with three independent energy storage elements whereas the new concept results in a first order system with the load inductance as the only independent energy storage element.

Electrical Circuit Diagram of the PE

As indicated in Fig. 2 the PE mainly consists of a d.c. voltage source and a linear transistor bank connected in series to it. The magnitude of the voltage of the d.c. voltage source is determined by the maximum load voltage. In the case of the dipole magnet power supply of SIS it is 3 kV for one of the four subunits. The magnitude of the PE-current depends on two parameters:

- the speed of changig the set value of the current,
- the size of the smoothing inductance of the main power unit.

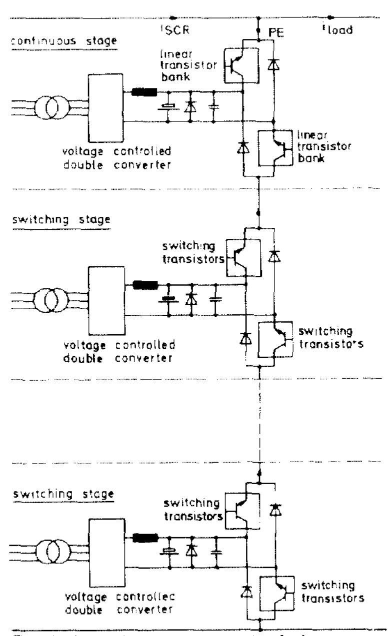

Fig. 4 Circuit arrangement of the parallel-power-supply (PE)

The PE-voltage source and the PE-current determine the maximum power dissipation in the transistor bank. To reduce this power dissipation the PE of the SIS/ESR power supplies is not conceived as one single stage but as a series connection of several stages with fixed voltage (switching stages) and one stage with continuously controllable voltage (continuous stage). The number of stages being used is dependent on the required load voltage.

In the case of the SIS dipole magnet power supply the PE of one subunit consists of eight switching stages and one continuous stage each having a voltage of ± 300 V while carrying a current of 100 A.

In Fig. 4 the basic circuit diagram of the PE is shown. Each of the stages is fed by a voltage controlled double converter and the switching stages are connected to the load circuit as positive or negative or zero voltage sources via transistor switches.

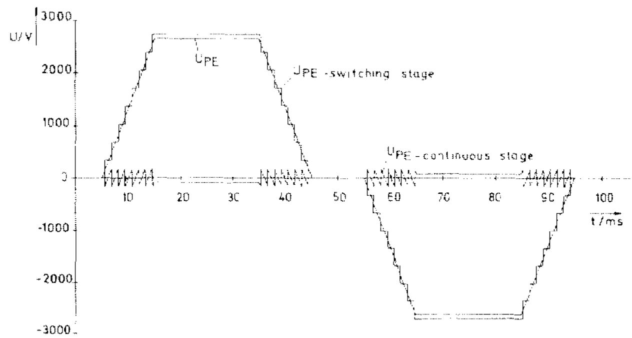

Fig.5 Voltage shapes of the parallel power supply (PE)

Fig. 5 shows the voltage shapes in the PE and at the load. The sum of the voltages of the switching stages gives a staircase-like wave shape while the continuous stage always has to give the difference voltage between the required total voltage U_{PE} (load voltage) and the voltage sum of the switching stages thus forming a sawtooth-like wave shape. A fast internal voltage control guarantees that the voltage U_{PE} is free of glitches even during the instance of changing over from a switching stage to the continuous stage and vice versa.

Control Concept

Fig. 6 shows the control system of the power converter with PE. The system consists mainly of the following three subsystems:

- Master Control Circuit

  It controls the load current with the PE, whereby the PE has to compensate all performance insufficiencies of the main power unit. The PE-controller is a mere proportional controller.

- Slave Control Circuit

  This circuit controls the main power unit (SCR) in such a way that the PE-current is kept nearly constant to a preset value. By that the SCR carries approximately 99 % of the load current while the PE carries at most 3 % of the load current in the most unfavorable dynamical case (SIS dipole magnet power supply).
  The SCR-controller is a PI-controller with only small integral portion. The integrating element is necessary to compensate errors which are beyond the preset control mentioned below as there are fluctuations of the main voltage.

Preset Control

The preset control of the PE-circuit is realized exclusively by an additional set value for the load voltage which acts directly on the stage control of the PE. Only by this the requirements with respect to the accuracy of the load current can be fulfilled even with a gain of the proportional controller which is limited by reasons of stability. The set value of the load voltage has to be calculated and given into the system with an accuracy of 1 %. This is easy to accomplish for all conceivable synchrotron cycles after a sufficiently exact model of the magnet system has been formulated.
Even the SCR has a preset control with the aim to keep the PE-current within the given tolerance band while the gain of the SCR-controller is small because of the structure of the power converter system.

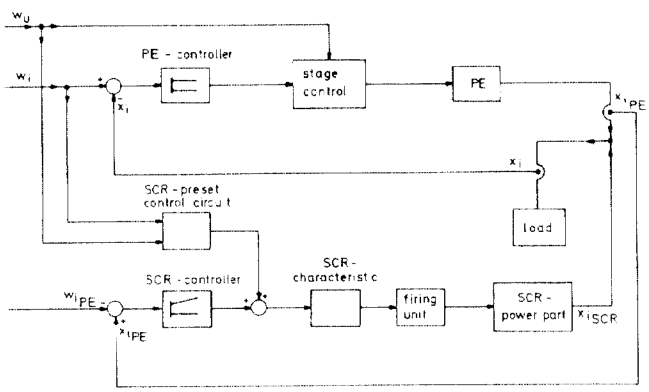

Fig. 6 Control system of the power supply with PE

Concluding remarks

The concept of the Paralleleinspeisung allows to design magnet power supplies the actual values of which follow given set values of almost any wave shape without time-lag. Through that a flexible and simple operation of separated function accelerators is rendered possible. However, these advantages have to be paid for by the elaborate construction and complex operating hardware of the PE.