Final tests of the power supply system for the W 7-X superconducting magnet system

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Abstract

Wendelstein 7-X, a superconducting fusion experiment, is presently under construction at the Max-Planck-Institut für Plasmaphysik in Greifswald. The 50 non planar and 20 planar coils are combined in seven electrical circuits with ten coils of the same type each. After the test of the seven individual power supply modules have been done in the past, now tests were made to show the proper co-ordination of the seven modules. In W7-X all seven electrical circuits are magnetically coupled. Therefore a special test load was designed and built up in order to simulate the magnetic coupling as realistic as possible. In the experimental program of W7-X eight magnetic configurations are defined, requesting different currents in the seven coil groups. During the tests all configurations were successfully tested, including the proportional energizing and slow discharging of the coils. Each power supply is combined with a protection system for the respective superconducting coil group. In case of a fast discharge all seven circuits have to discharged simultaneously to avoid an over current in the delayed circuit, caused by the inductive coupling of the coil groups. Another part of the final tests was the check of the proper reaction of the system after simulated failures. Also this kind of tests were executed successfully.

Key words: Wendelstein 7-X, superconducting coils, power supply, protection system

1. Introduction

Wendelstein 7-X (W7-X) is the next step device in the stellarator line of IPP and is being built at the IPP in Greifswald. To allow steady-state operation, W7-X has a superconducting magnet system. The standard magnetic configuration of W7-X is formed by 50 non-planar superconducting coils. 20 additional planar superconducting coils allow to modify the magnetic configuration. The coils are combined in seven electrical circuits with ten coils of the same type each. The five circuits containing non planer coils have an inductance of 1 H each and the two circuits containing the planar coils have an inductance of 0.4 H each. For the experimental program it is necessary to energize the seven groups individually, therefore seven equal power supplies and associated protection systems were ordered.

2. Power supplies

To energise the coils, a current of up to 18.2 kA has to be provided. To have a sufficient margin the power supplies are designed for a max. steady state current of 20 kA and are adjustable in a range from 0 ...20 kA. Each power supply is supplied by the 20 kV-grid and consists of two transformers, one of the delta and one of the star type on the primary side (see Fig. 1). The secondary windings are all made of the star type with a phase shift between the four secondary systems of 30°(el.) to each other. The connection of the transformer branches at the secondary side is made of midpoint connections with interphase transformers, leading to a twelve pulse converter. The output voltage of the power supplies of 30 V is a compromise between the 3 V which are necessary for steady state operation and the inductances of the coils which requires higher voltages for a sufficient ramp rate. A more detailed description can be found in [1].

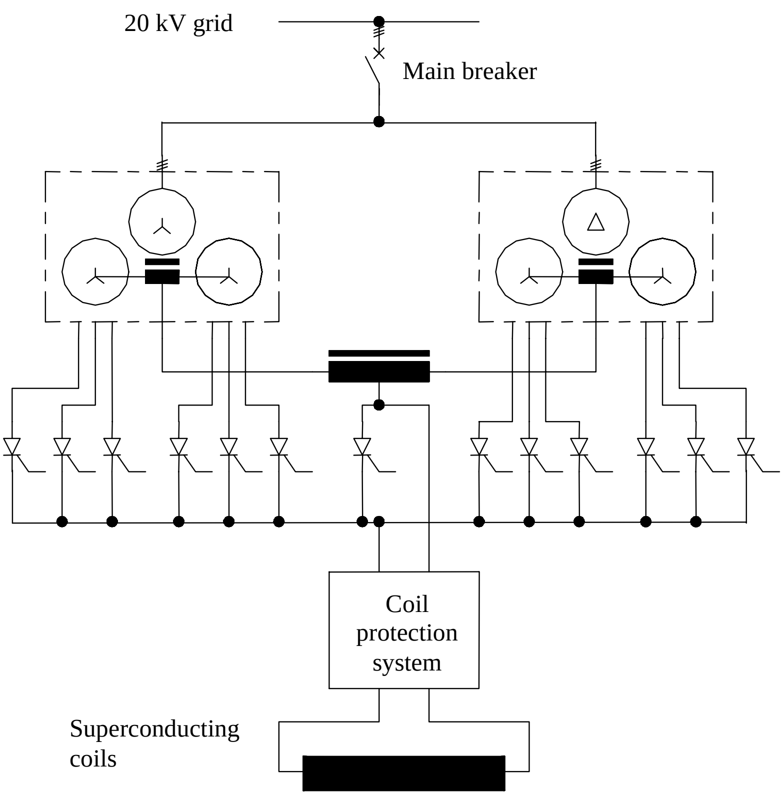

Fig 1: Electrical scheme of the power supply

3. Protection systems

The aim of the protection system is to de-energize the magnet system within a few seconds in case of emergency. The circuit shown in Fig. 2 was selected [2].

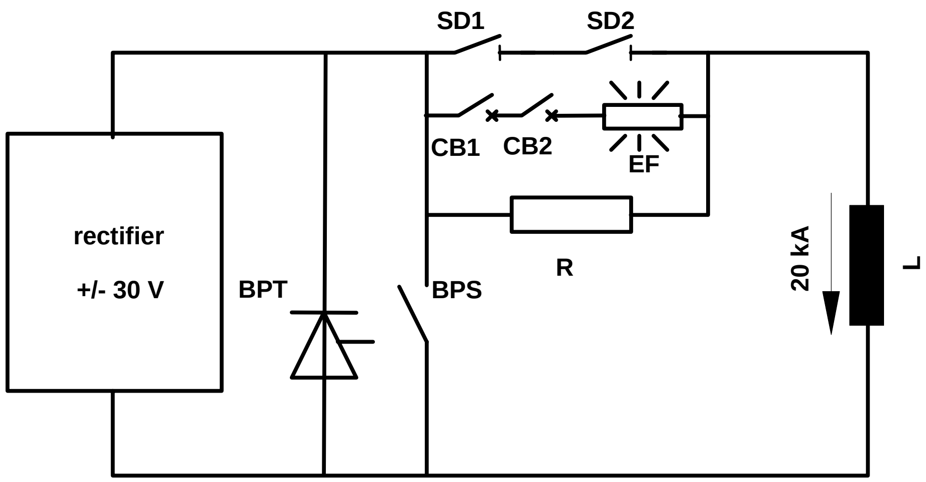

Fig 2: Design of the protection system, consisting of by-pass thyristor (BPT), mechanical by-pass switch (BPS), load switch (SD), DC-circuit-breaker (CB), explosion fuse or pyrobreaker (EF) and discharge resistor (R)

During normal operation, the switches have the following initial positions [2]: BPT and BPS open, SD1 and SD2 closed, CB1 and CB2 closed.

For a fast discharge, the following sequence is triggered: BPT and BPS will be closed to separate the rectifier from the protection system. Then the main current path will be interrupted by opening of SD1 and SD2, and the current commutates into the second path formed by the switches CB1, CB2 and the explosion fuse (EF). When the current commutation is finished the breakers CB1 and CB2 will be opened and the current is transferred into the discharge resistor. In case of a malfunction of the breakers CD 1 and CB2 the pyrobreaker is fired [2].

4. Magnetically coupled test load

A test load system consisting of seven water cooled copper coils (one per power supply module) was designed. The coils are taken from the former Wendelstein 7-A experiment. This test load provides a factor of 100 higher inductance than a simple short at the output of the power supply but at the same time a factor of 1000 less inductance compared to the original load later in W7-X. Also the resistance of 1 mOhm is a factor of 10 higher than at the original load. Nevertheless this test load creates a certain inductive load which is an important prerequisite to check the controllers behavior. The more important issue of the test load system is the simulation of the magnetic coupling between the seven circuits which should be comparable to the situation in W7-X. Calculations were made to reach an acceptable configuration. The following strategy was used: The magnetic coupling between the two test coils next to each other should be as similar as possible compared to the W7-X. This was achieved for the coils, simulating the non planar coil groups. The coupling factor in W7-X is between 0.27 and 0.32, in the tests arrangement a factor of 0.31 was used. The compromise is on the other hand that the coupling to the other coils is different to the W7-X conditions. This is obvious, because in W7-X the coils forming a toroidal arrangement compared to the straight cylindrical configuration of the test load system (see Fig. 3).

Fig.3: Test loads for the final tests

The coupling factors were created by the distance between the individual coils. For proper adjustment thin layers of pressed wooden plates were used. So the coupling factor could be adjusted properly, at the same time a good mechanical support between the coil bodies was reached.

5. Final tests of the power supply modules

5.1. Final tests of the power supplies

The so-called power supply module consists of two main parts, the thyristor converter and the protection system.

The final test of the seven thyristor converters should comprise more the co-ordination between the seven systems than the functions of a single converters. Tests of the individual converters were already made during the tests after installation on site [3]. Therefore such parameters like maximum current, accuracy of the controller, load line are already successfully tested. Now special attention was given to the accuracy of the current under the condition that all seven power supplies are working at the same time to a magnetically coupled load. There are eight predefined magnetic field configurations for W7-X. Taking into account that W7-X can work at 3 T, 2.5 T and 1.25 T on the axis, there are in total 24 magnetic configurations to check in the final acceptance test program. Table 1 shows as one example the reference values of the coils for the configuration “3T low shear”.

Table 1: Reference values of the coil currents I for the configuration “3 T low shear”.

B_0 [T]	I_1 [kA]	I_2 [kA]	I_3 [kA]	I_4 [kA]	I_5 [kA]	I_A [kA]	I_B [kA]
3.0	18.2	17.9	16.9	13.7	13.5	-11.6	12.1

B_0 is the average value of B along the magnetic axis. I is the current in the coil groups, the five non planar coil groups are named with 1..5, and the two planar coil groups with A and B.

It is in all cases requested that the accuracy of the current has to be within +- 40 A compared to the reference value. Figure 4 shows as an example the currents during the test of the configuration “3T low shear”.

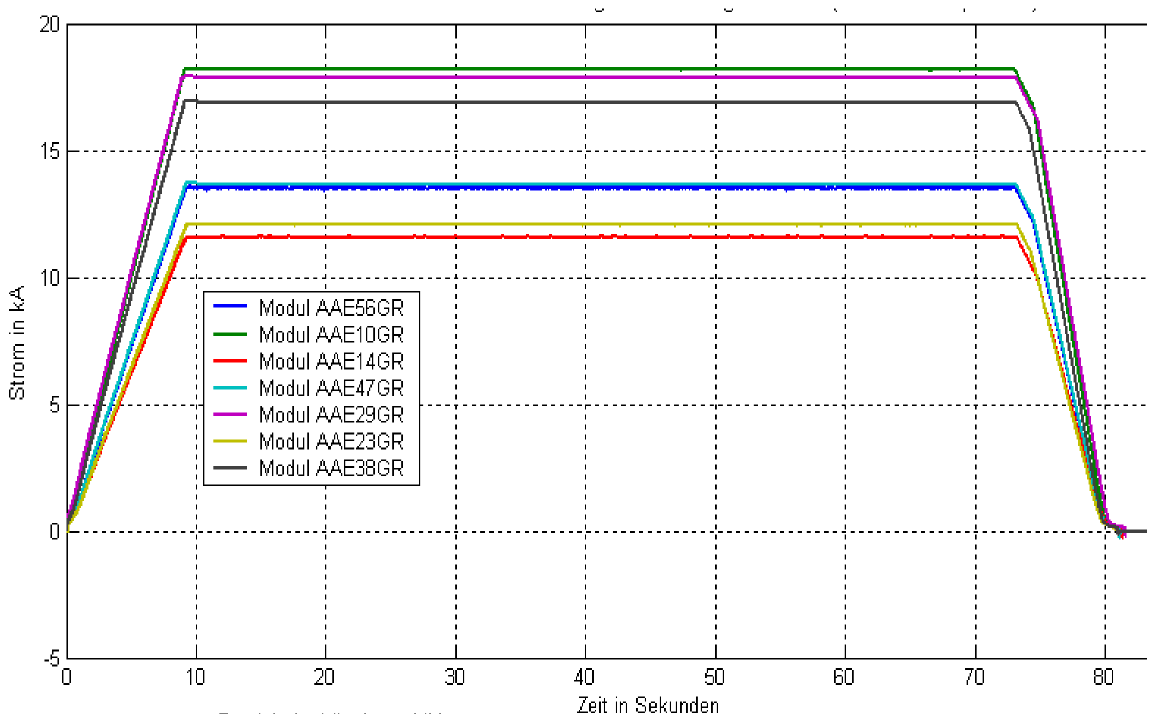

Fig. 4. Coil currents (in kA) vs. time (in seconds) in the seven circuits during the test

The following points were evaluated: During ramp up the relation between the seven currents has to be in the same relation than in the steady state-phase. As an example the factor between the currents in group one and five is 1.35. The requirement is now to have also during ramp up (and down) the same factor, but a tolerance of 10 % is allowed. This requirement is important to have a similar mechanical load distribution between the coil groups in W7-X.

During the steady-state-phase it is required that the current must not deviate more than 40 A from the reference value. The tests have shown a much better accuracy. The maximum deviation was measured to 16 A. In order to evaluate the result it is important to note that there is always a second current measurement system in the load circuit which checks permanently the function of the current measurement system for the controller.

Another point of the test program was the check of the long term stability. For that the following procedure was used: at the beginning, in the middle and at the end of an one hour flat-top phase, the mean value of the current of an interval of 10 seconds was calculated. The three mean values were compared, the deviation had to be within a range of 40 A. Also this requirement was fulfilled.

5.2. Final tests of the protection systems

The protection system will de-energize the coils in case of a mal function , e.g. in case of a quench. A detailed description of the protection system can be found in [2]. The tests of the

components as well as the test of the protection system a the first power supply module were carried out successfully in the past [3], [4].
During the final acceptance test of the seven modules the main points are the synchronism of the seven protection systems. Here the requirement is that all seven protection systems act as synchronously as possible. A maximum synchronization delay of 50 ms between the fastest and the slowest system is allowed. The synchronization delay is defined as the time difference of the last action of the switching sequence (feedback message “dc breaker off”). The background of this requirement is also the magnetic coupling of the seven coil circuits in W7-X. During a fast discharge normally all seven circuits have to be de-energized simultaneously. In case of a delay of one of the protection systems the current in the late system will be increased instead of decreased as expected. The reason is the fact that the magnetic flux tends to be constant and if one part of a coupled system decreases the flux (that means the current) the other part tries to recover the original sum of flux by increasing the individual flux. Simulation of a fast discharge with an synchronization delay of 500 ms and 1 second shows an increase of the current in the late system. The current goes up from the nominal current of 18.2 kA to 18.7 kA and 19.4 kA respectively and will reduce the margin to a quench. At the same time the mechanical balance of the W7-X coil and support structure will be reduced significantly [5].

The tests turned out that this requirement was not fulfilled, the synchronization delay was up to 80 ms. The delay was always originated in the same module and it turned out that this module starts the fast discharge to fast, compared to the other six modules. The control signals arrive more or less simultaneously the seven modules (delay in between max. 10 ms), the start of the first switching action (load switch off) is still simultaneously in all seven modules, but the switching action itself is executed in one module about 40 ms faster than in the other modules. As a countermeasures a reducer in the nozzle was developed which decreases the compressed air pressure in the load switch and consequently the switching speed. This measures is inherently safer than an artificial delay of the signal processing by an electronic device. A repetition of the fast discharge test showed that the load switch is now not faster than the other ones and the delay between the fastest and the slowest protection system is now below 50 ms.

5.3. Final tests of the control system

The proper function of the power supply modules is an important issue for the later operation in W7-X. Therefore test were made by producing or simulating failures and check the reaction with respect to a predefined reaction matrix. In general two main kinds of reactions are defined, the slow discharge or the fast discharge. Slow discharge means a discharge with the thyristor converter. The ramp rate is limited to 30 A/s which leads to a discharge duration of about 12 minutes from full current to zero. Fast discharge means discharge via the protection systems which leads to a discharge duration of about 12 seconds from full current to zero.

Internal and external failures are defined. Internal failures are events which have their origin in the power supply modules itself. This can be failures in the converters (e.g. loss of cooling water, failure in the ignition of the thyristor, ground faults, temperature alarms), in the protection system (failure message from a switch or breaker, failure message from the discharge resistor) or the control system (e.g. blackout of one or more PLC, missing or “impossible” signals, loss of communication).

External failures means sudden events coming from the environment of the power supply modules. It comprises not only failures like a black-out in the supply lines for electricity, pressured air or cooling water. It means also mainly such events like quenches in the coils or the superconducting busbar system or the superconducting part of the current leads, failures in the helium power plant or, in general, emergency switch off signals from the W7-X main control system. The tests did not bring up any problems.

The next step in the tests campaign was the simulation of a sequence of failures. As an example the water cooling pump was stopped, leading to a slow discharge of the system. During the slow discharge a quench was simulated by an artificial quench signal. The proper reaction is a switch over from the slow to the fast discharge. This kind of failure sequences was also successfully tested for a selection of failures.

6. Conclusions

Tests have been performed to show the proper co-ordination of the seven power supply modules. In W7-X all seven electrical circuits are magnetically coupled by the superconducting coil system. Therefore a special test load was designed and built up in order to simulate the magnetic coupling as realistic as possible.

During the tests all magnetic configurations of W7-X were successfully tested, including the proportional energizing and slow discharging of the coils.

Each power supply is combined with a protection system for the respective superconducting coil group. In case of a fast discharge all seven circuits have to discharged simultaneously. Therefore tests were carried out to check the simultaneous reaction of the seven protection systems. The tests were successfully performed, after small modifications in one load switch.

Another part of the final tests was the check of the proper reaction of the system after simulated failures. Depending on the origin and the importance of failures the seven power supply modules have to react in a different way, according to a reference table. The proper reaction of the system was demonstrated.

It can be summarized that the power supplies and the protection system for the superconducting magnet system of Wendelstein 7-X is ready for operation.

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