Simulation Studies of the Power Supply and the Protection System for the Helias Reactor Coils

A. Wieczorek*, E. Harmeyer**, G. Linhofer***
*FACHHOCHSCHULE REGENSBURG (UNIVERSITY OF APPLIED SCIENCES)
Seybothstrasse 2, D-93025 Regensburg, Germany
Tel. (+49941)9431111, Fax. (+49941)9431424
Email: andreas.wieczorek@e-technik.fh-regensburg.de
**MAX-PLANCK-INSTITUTE FÜR PLASMAPHYSIK (IPP)
Wendelsteinstrasse 1, D-17491 Greifswald, Germany
Tel. (+493834)882386, Fax. (+493834)882009
Email: ebh@ipp.mpg.de
***ABB SWITZERLAND LTD, DEPT. ATPF (ADVANCED POWER ELECTRONICS)
Austrasse 1, CH-5300 Turgi, Switzerland
Tel. (+4158)5892476, Fax. (+4158)5892090
Email: gerhard.o.linhofer@ch.abb.com

1. Introduction

The Stellarator System Studies group at Max-Planck-Institut für Plasmaphysik (IPP) in Garching, Greifswald and Berlin is concerned with investigating the physical and technological issues underlying a nuclear fusion power plant based on the stellarator concept. For this reason the HELIAS (HELIcal Advanced Stellarator) configurations have been developed. HELIAS configurations offer an optimized magnetic confinement concept for the Helias reactor (HSR) [1]-[2].

The main advantage of the Helias reactor concept is the inherent potential of steady state operation. This is due to the absence of net toroidal plasma current. The magnetic field is produced by a single set of modular coils. Plasma disruptions like in tokamaks are not possible.

TABLE I: Main parameters of HSR4/18 and HSR5/22

	HSR4/18	HSR5/22
Major radius [m]	18	22
Plasma volume [m^3]	1567	1407
Av.magnetic field on axis [T]	5.0	4.75
Max.magnetic field on coils [T]	10.3	10.0
Number of coils	40	50
Stored magnetic energy [GJ]	98	100

Two reactor versions have been investigated, a five periodic arrangement HSR5/22 with 22m and a four periodic system HSR4/18 with 18m major radius. The fusion output is in the range of 3GW. The magnetic field on axis is chosen to be 4.75T in the first version, and to be 5T in the second one, resp., resulting in a total stored magnetic energy in the coil system of about 100GJ in both cases.

2. Coil system of the Helias Reactor

The main technical component of the HELIAS reactor is the coil system [3]. The studies on HELIAS reactor were made on the premise of using NbTi superconductors at a temperature of 1.8 K which limits the magnetic field on the coils to 11 T. The operational current will be 40 kA to achieve a magnetic field on axis of 5 T, resulting in a total stored magnetic energy of less than 100 GJ.

This magnetic confinement system of the HSR4/18 consists of 40 nonplanar coils, modularely arranged in 4 toroidal periods with 10 coils per period (Fig. 1.). The magnetic energy of the coil system is a rough figure of merit for the costs of the coil system.

In order to withstand the large magnetic forces in the modular nonplanar coils, the winding pack will be surrounded by a coil housing of stainless steel, as shown in Fig.2. The coil winding pack is split into 8 double-pancakes, using a trapezoidally shaped cross-section and containing a total number of 18×2×8=288 turns per coil.

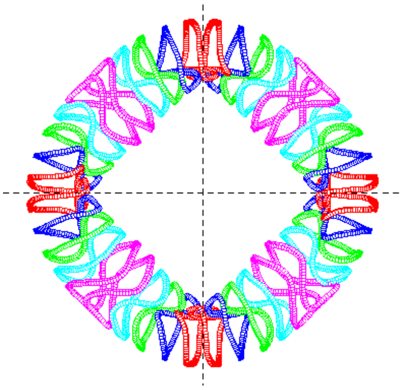

Figure 1. The magnetic confinement system of the HSR4/18

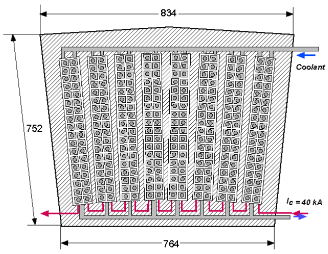

Figure 2. Cross section of a coil surrounded by a housing

3. Power supply system

The electrical circuit of the coil system comprises 5 superconducting coil groups, each consisting of 8 equally-shaped coils which are electrically connected in series and fed by one power supply (Fig. 3). These coil groups are magnetically coupled, described by the symmetrical inductance matrix [3].

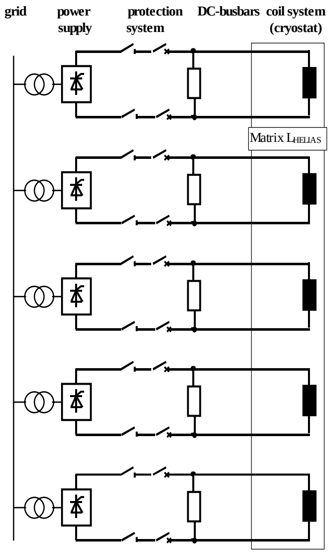

Figure 3. Electrical scheme of HELIAS magnet system

These five coil systems will be powered individually by five power supplies of the thyristor type. The power supply units must generate currents of up to 40 kA to achieve a magnetic field on axis of 5 T. The function of the power supplies is to provide the necessary time variations of the HELIAS magnetic field:

1. to charge the coils with a ramp rate of $\leq$ 10 A/s – rectifier mode,
2. to discharge them after the operation with a ramp rate of $\leq$ -10 A/s – inverter mode,

3. to stabilize currents at a specified level during the energy production (steady-state operation). All five coil systems will be powered direct from the medium voltage utility interface for auxiliary system [4]. The grid is loaded by the operation of the line commutated converters with reactive power and harmonics. These harmonic currents flowing through the internal impedance of the utility source result in distorted voltage waveform at the point of common coupling. The voltage distortion at this point depends on the internal impedance of the ac source and the amplitudes of the injected harmonic currents. The reactive power consumption results in a very poor power factor of operation.

The power-related parameters (power factor, displacement factor, harmonic content, harmonic spectrum) are dependent upon loading, control and configuration of the converter and short-circuit levels of the grid. Both the reactive power and the harmonics of the converter can be compensated by harmonic filters and power factor correction capacitors.

In addition to these problems, the phase-controlled converters cause notches in the voltage waveform of the utility system. If several converters are connected to the same supply mains, they will affect one another through the commutation notches. Operation directly in parallel is not possible, they must therefore be decoupled by transformer inductances.

4. Protection system

A safety system, inserted between each power supply unit and the coil group (Fig. 3), protects the superconducting coils in case of faults in the coils or in the power supply units [4], [5].

If the coil becomes resistive, a safety discharge, triggered by a quench detection system, has to be initiated. The magnet is disconnected by means of fast-acting switches from the power supply. The current flows through an external resistor and the field decay is dictated by the time constant $\tau = L/R$. This system transfers in this case the stored magnetic energy in the coil system of HSR4/18 (about 100 GJ with the operational current of 40 kA) to a set of dump resistors, which absorb the magnetic energy stored in the magnets, thus heating up.

Since the HELIAS coil systems are magnetically strongly coupled to each other, the dumping of current in only one magnetic group induces overcurrents in the other groups, so that simultaneous dumping of currents in all systems is necessary.

5. Simulation results

5.1 Power supply units

The goal of the investigation is to optimize the magnet power supplies with respect to losses in components and interaction with the utility grid . Investigation of the behavior of the equivalent electric schemes with complete models of the thyristor power supplies for the machine circuits were conducted with the SIMPLORER code [6].

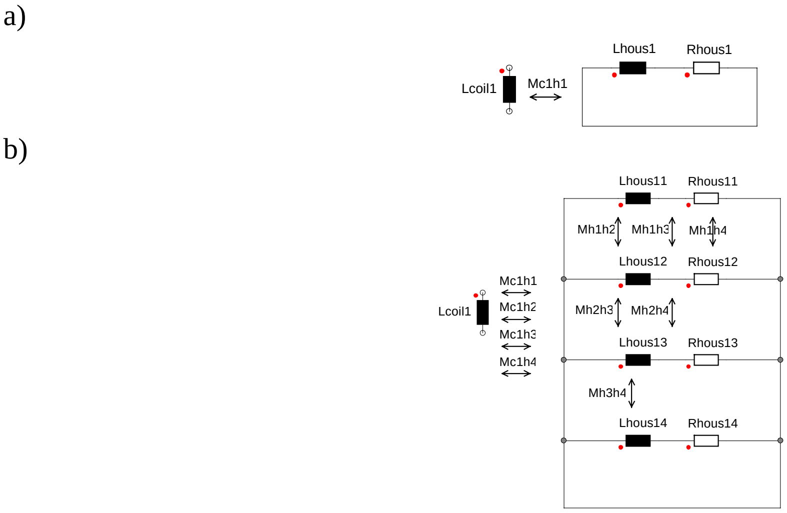

Figure 4. FEN-model of one coil with housing
a)First approximation, b) Second approximation

One of the problems arising when designing cryogenic devices is the investigation of the magnetic field diffusion through the walls of the structural elements, i.e. in the casings of the coils, cryostats walls, vacuum vessel, radiation shields, etc. The accurate calculations of the losses of eddy currents, induced in the walls, are required for dimensioning of the cooling system. The influence of the casing on the operation of the power supply system was investigated. Other passive elements like vacuum vessel, shields, etc, were not taken into account. By means of the Finite Element Network (FEN) Method the computation of diffusing magnetic fields and of the eddy currents induced during the transient process in the walls of the coil housing is converted to analysis of transient processes in electric networks [7]-[11].

The basic principle of the method is to represent a conducting surface, as a network comprised of a number of branches. The branches are properly interconnected and magnetically coupled to all external and internal circuit elements. Each branch has a resistance and a self-inductance as well as mutuals to all other branches. The matrix of the inductances was computed by an EFFI-code [12]. Eddy currents are then found by using a standard method for solving differential equations.

The SIMPLORER-model of one coil with a housing is shown in Fig. 4

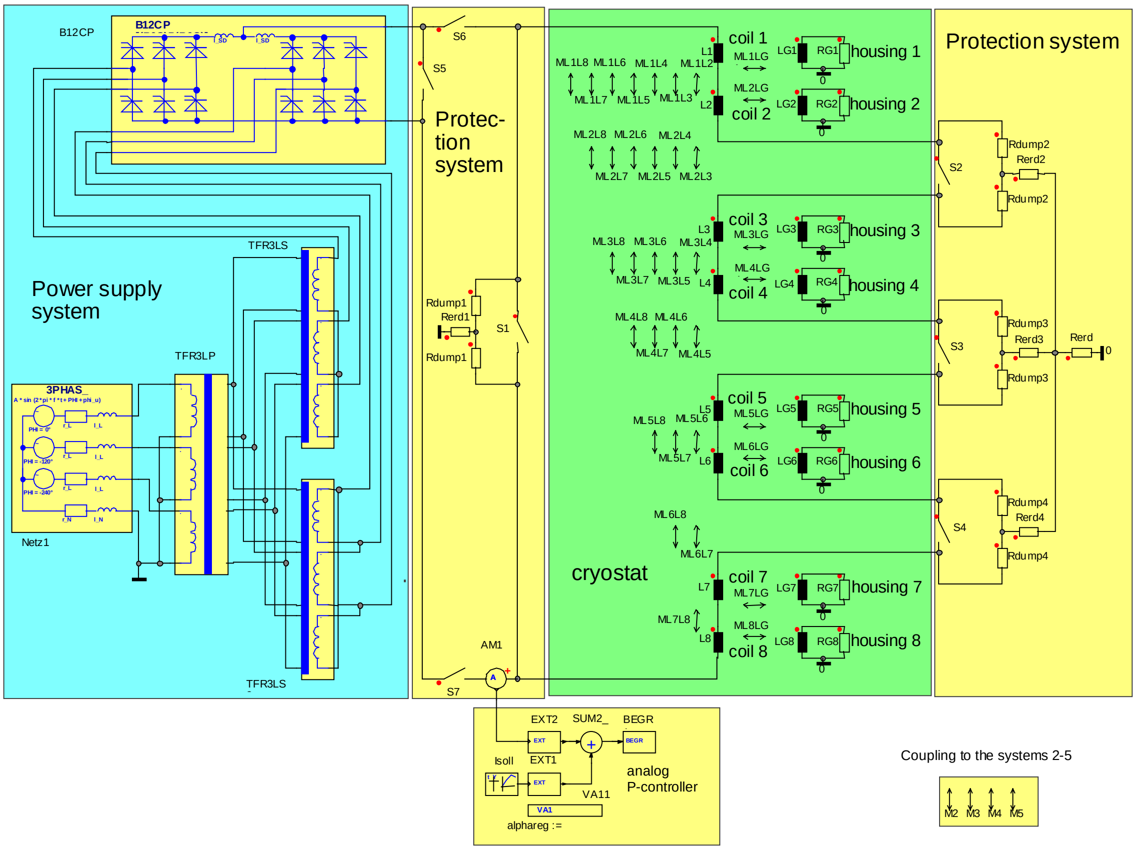

Figure 5. SIMPLORER model of power supply and protection system for one coil system of HELIAS

Many different classes of confinement configurations were studied. A complete model of the thyristor power supply (Fig. 5) was used to carry out the simulation of the dynamic behaviour of the system described by the L_{HELIAS}-Matrix.

Figure 6 shows some exemplary results in one system during the operation. It illustrates the feasibility of stable coil-current control with 2-quadrant phase-controlled thyristor converters in HELIAS reactor in spite of magnetically coupling of the system.

To evaluate the extent of the distortions, the interaction of the harmonic currents with the AC grid was investigated by numerical network analysis with five modules connected to the bus. The FFT-Analysis of these signals can be found in [17].

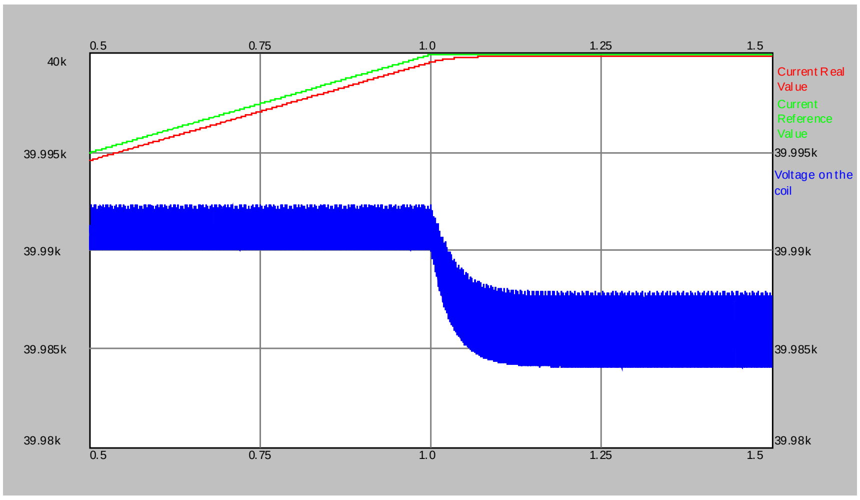

Figure 6. Currents and voltages on the dc side in the power supply with a complete model of the converter

For the five twelve-pulse rectifiers system the power factor during the steady state operation must be improved by capacitor banks, which are switched in and out by means of vacuum contactors to compensate for the changes in the reactive power of the load in order to keep the overall load power factor as close to unity as possible [16].
Other methods to reduce the reactive power demand are:

1) The asymmetrical control of groups of six-pulse rectifiers [14]-[15]
2) changing the voltage under load with OLTCs (On Load Tape Changer) at the primary of the transformer

5.2 Protection system

The decay time constant τ of the whole system determinates the construction and the parameter of the superconducting cable for the coil [4], [5]. The proposed 40 kA superconductor achieves a dump time constant of about 12s (“hot-spot” integral). The computer simulations show, that to fulfill this requirements, a discharge voltage of about 80 kV with one current leads per coil group and one dump resistor is necessary (Fig.3). On the other hand, the maximum voltage between windings and ground must not exceed 20 kV.

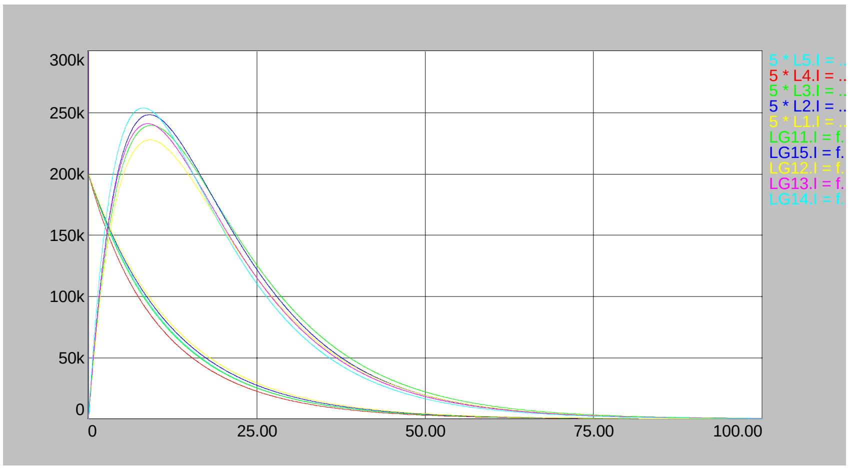

Figure 7. Currents in the coil systems and in the casings during discharge

For these reasons, the dump resistor of each coil group has to be subdivided into 4 units, connected to the 8 coils of this group (Fig. 5). Consequently, 8 current leads per coil group, in total 20 pairs, have to be installed to ensure the connections through the cryostat.

It was possible to simulate the different kinds of faults that may occur in the confinement system and power supply units. Particularly, the behavior of the coil in case of quench must be studded carefully and the energy dissipated inside that coil has to be limited to an acceptable level.
The protection system shown in Fig.5 assures a decay time constant of less than 12 s for the confinement system (Fig. 7).

6. Conclusions

The goal of investigation was an optimized magnet protection system and to achieve low losses in the components and little negative impact of the multiconverter supply system to the power grid. The design of the system has been studied by means of computer simulations, using the SIMPLORER code. The computation of induced eddy currents in the structure during transient processes was transformed into electric network analysis by means of the Finite Element Network (FEN) method. It was possible to study the design of the whole coil system including power supplies, the safety system and the passive structure and to simulate different kinds of faults that may occur in the reactor coil system and in the power supply units.
To calculate exactly the eddy-current losses in structural elements of the cryogenic devices during the magnetic field diffusion process, the approach based on coupled solution of the electromagnetic and thermal problems must be applied, taking into account the strong dependence of resistivity, heat capacity and heat-transfer coefficient on temperature. These losses, calculated with consideration of the thermal processes, can differ widely from those obtained by calculations considering constant temperature [13].

7. References

[1]. Wobig H. et al, Concept of a Helias Ignition Experiment, Nuclear Fusion, Vol.43,No.9, (2003), 889-898.
[2]. Beidler C.D.et al, The Helias Reactor 4/18, Nuclear Fusion, Vol.41, No.12, (2001), 1759-1766.
[3]. Harmeyer E., Kißlinger J., Wieczorek A., Wobig H., Superconducting Coil System for a Stellarator Fusion Reactor, IEEE Transactions on Applied Superconductivity, Vol.12,No.1, (2002), 558-561.
[4]. Wieczorek A., Zacharias L., Computer Simulation of the Power Supply and the Protection System for the Superconducting Coils of a Fusion Reactor, Proc. 5th Eur. Power Quality Conf., Nürnberg, BRD, 1998, 141-150.
[5]. Harmeyer E., Wieczorek A., Computer Simulations of the Protection System for the Stellarator Fusion Reactor Superconducting Coils, Proc. ANSOFT Workshop, Chemnitz, Germany, June 12-14, 2002, 27-38.
[6]. Simulation System SIMPLORER – user manual, Copyright 1996-2003 Ansoft Corporation
[7]. Weissenburger D.W., Christensen U.R., Transient eddy current on finite plane and toroidal conducting surfaces, Plasma Physics Laboratory, Princeton University, Princeton, New Jersey, April 1979.
[8]. Christensen U.R., Time varying eddy currents on a conducting surface in 3-D using a network mesh method, Plasma Physics Laboratory, Princeton University, Princeton, New Jersey, April 1979.
[9]. Preis H., Die Finite-Element-Netzwerksmethode für dreidimensionale Wirbelstromberechnungen in Experimenten zur kontrollierten Kernfusion, Archiv für Elektrotechnik 65 (1982) 233-239.
[10]. Preis H., Die Berechnung von Wirbelströmen und magnetischen Kräften in Kernfusion-Experimenten, Archiv für Elektrotechnik 69 (1986) 359-365.
[11]. Farschtschi A., Dreidimensionale Wirbelstromberechnung nach der Netzwerkmethode, etzArchiv, Bd.8 (1986) H.5, 165-169.
[12]. Sackett S.J, EFFI - A Code for Calculating the Electromagnetic Field, Force and Inductance in Coil Systems of Arbitrary Geometry, LLNL Report UCRL-52402, 1978.
[13]. Sokolowsky V., Meerovich V., Slonim M., Eddy current losses at cryogenic temperatures, IEEE Transations on Magnetics, Vol. 29, No. 3, May 1993, 2095-2098
[14]. Weiß V., Simultane Ventilsteuerung als Verfahren zur Reduzierung der Grundschwingungsblindleistung, etzArchiv Bd.10 (1988) H.2, 33-40
[15]. Richardeau F., Cheron Y., du Parc J., Constant Reactive Power Strategies for High Power Phase-Controlled Rectifiers, EP^2 Forum`95, 2 and 3 March, CERN, Geneva, 55- 61.
[16]. Mondino P.L. et al, Reactive Power Compensation for the JET Pulsed Loads Supply, Fusion Technology 1992 (SOFT Rom), 902-906
[17]. Gorski R., Analysis of the multiconverters systems for Fusion Reactor Superconducting Coils, Diploma Work for M.Sc., Silesian University of Technology, Gliwice and FH (University of Applied Sciences) Regensburg, Regensburg, 2002.