Simulation of Voltage and Current Development in the Wendelstein 7-X Coil System Taking into Account Fault Conditions

M. Köppen *, J. Kißlinger

Max-Planck-Institut für Plasmaphysik, Euratom Association, Teilinstitut Greifswald, Wendelsteinstr. 1, 17491 Greifswald, Germany

* Corresponding author: Tel.: +49 3834 88 1825; fax: +49 3834 88 2439.

E-mail address: matthias.koeppen@ipp.mpg.de (M. Köppen)

Abstract

At present the Wendelstein 7-X stellarator experiment is under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik. During operation the plasma will be confined by the magnetic field of superconducting coils which will store a magnetic energy of about 620 MJ at 3T average field strength at the magnetic axis. In a fast shut down this energy will be mainly absorbed by discharge resistors which heat up in the process and change their resistances to about 4 times the initial value. These changing resistances not only decrease the time constants of the discharge process but also determine the voltages applied to the coils. The paper describes the simulation of the currents and voltages during shut down and gives an example for increased coil currents due to a shut down failure which would lead to higher magnetic forces acting on the coils.

Keywords: Stellarator; Superconducting Coils; Simulation; Currents; Voltages; Forces

1. Introduction

Wendelstein 7-X (W7-X) [1] is an advanced stellarator where the optimized magnetic field of up to 3T is generated by 70 superconducting coils of seven different types. The five non-planar coil types generate the field for plasma confinement, and the two planar coil types provide additional experimental flexibility. During normal operation the current in the coils reaches a maximum value of 18.3 kA. Coils of the same type are electrically connected in series, the seven groups of ten coils each can be operated independently. During fast shut down the energy of each coil group is discharged via a dump resistor [2]. When absorbing the maximum energy the dump resistors of the non planar coils (NPC) heat up to 570°C, increasing their resistances from 148mΩ to 680mΩ. The dump resistors of the planar coils (PLC) reach temperatures of about 580°C, changing their resistance from 54mΩ to about 250mΩ. Some of the energy is also dissipated in the coil casings which act as shorted secondary windings for the coils. Using the simulation software SIMPLORER [4], a circuit model of the W7-X coil system has been developed. This model takes into account the self inductances and the mutual inductances of the different coil types, and the non-linear temperature dependencies of the component resistances. The self- and mutual inductances for all coils and casings have been calculated using the EFFI code [3]. Aim of the simulations is to investigate the voltage and current developments in the coils, coil casings and discharge resistors under normal and fault conditions. Additional results are the energy transfer between different components as well as asymmetries and peak currents in fault scenarios which lead to highly increased forces acting on the coils. The paper presents the model and results of the simulation.

2. Simulation Model

2.1. Overview

The simulation of the W7-X coil system was done using SIMPLORER. Each group of ten superconducting coils was modelled as one inductance and one resistance. The same approach was used for modelling the groups of coil casings. In this way it was possible to keep the simulation at a manageable size, i.e. 7 coil groups, 7 groups of casings, 91 mutual inductances and one discharge resistor per coil group. Fig. 1 shows one coil group with its dump resistor and casing. Due to the strong inductive coupling between coils and casings SIMPLORER requires the complete inductance matrix to be used, even though only mutual inductances between different winding packs and between winding packs and their own casings are relevant.

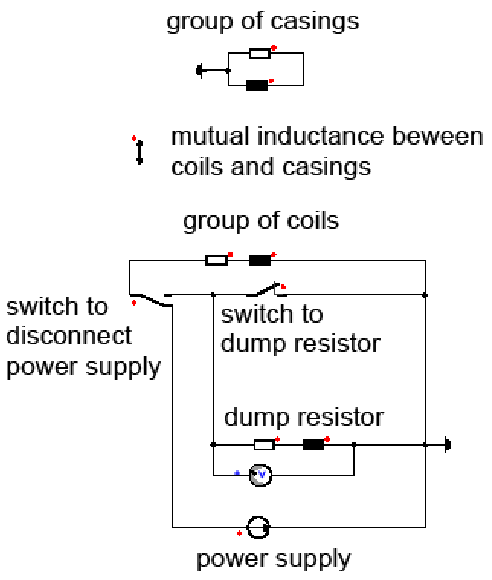

Fig. 1. Schematic of one coil group with casings and discharge resistor

2.2. Discharge Resistors

Every non planar coil group is discharged via a resistor of 750 kg of almost pure nickel. For each planar coil group a 270 kg resistor of the same material is used. The specific heat and temperature coefficient of the material depend heavily on the temperature (Fig. 2) and in addition, these dependences are slightly different for different batches of the material. Depending on the chosen characteristics, the results of the voltage simulations will differ by about 5%. For keeping the calculations conservative, the worst cases were assumed for all 7 dump resistors.

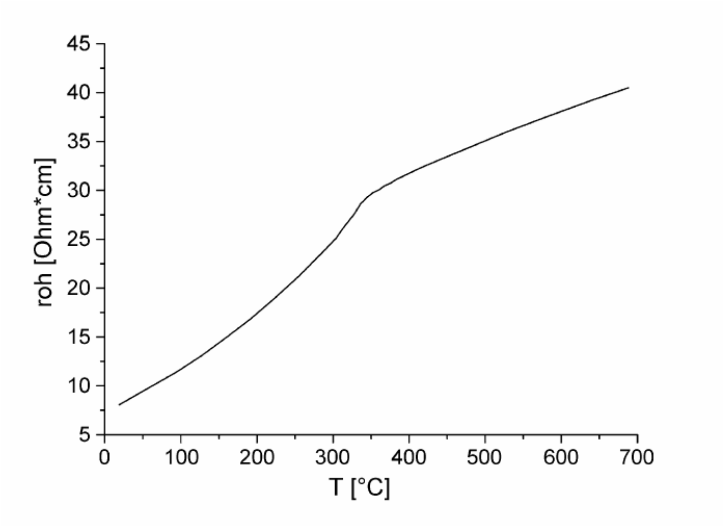

Fig. 2. Specific resistance of one Ni 99.6 batch

These characteristics were then used to determine the temperature development of the discharge resistors. Fig. 3 shows how – in every time step of the simulation – voltage and current at the discharge resistor are used for calculating the new temperature of the resistor which also leads to new values for specific heat (c), temperature coefficient (a), and resistance. This resistance influences the time constant of the discharge process and also the voltage at the discharge resistor. Since every discharge resistor is connected in series to a coil group, the voltages at the coils are proportional to this value.

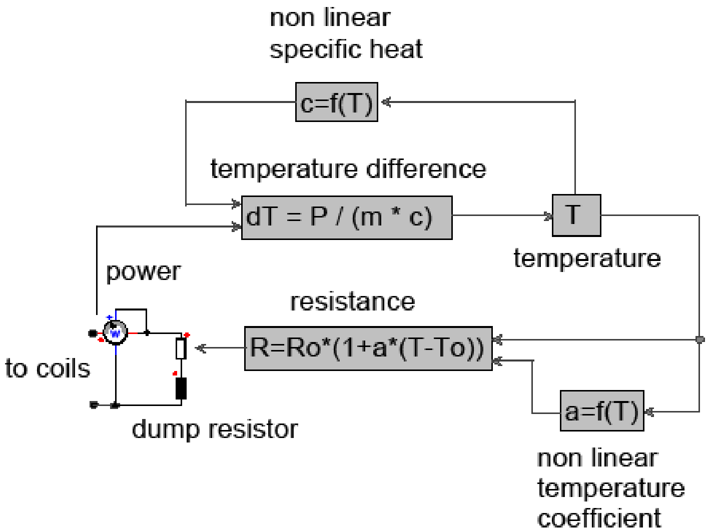

Fig. 3. Schematic of dump resistor

2.3. Initial Coil Currents

The simulations were started with different initial values of the coil currents. For experimental flexibility all seven coil groups can have individual currents, while the current direction in the groups of non-planar coils is fixed, the current direction in the groups of planar coils can be changed. As design limit 20 kA in all coils are assumed. For the W7-X experiment nine different load cases have been specified which investigate different approaches for plasma confinement. Out of these nine cases the “Low Shear” case features the highest current values and also involves different current directions in the planar coils. During operation the superconducting coils will be deformed due to magnetic forces acting on them. These deformations change the magnetic field structure and a correction of the current distribution in the coil groups is necessary in some cases.

Simulations were done for all nine load cases, the worst case with 20kA in all coils and also for the “Low Shear” case with corrected coil currents. All simulations were run twice, with and without considering the coil casings, so the influence of the casing can be investigated.

3. Currents and Voltages during Discharge

Maximum values for currents and voltages during discharge can be expected for the highest currents in the coils. Therefore, the following three cases will be presented here: The design limit (DL) of the coils, the Low Shear case (LS) and the Low Shear case with current correction to compensate coil deformation (LSc). In addition, to see the full effect of the magnetic coupling and to investigate the behaviour of the system in cases in which the PLC have no initial currents, the standard configuration (ST) of the W7-X is given. Tab. 1 contains the coil currents for the five groups of non planar coils (NPC1 – NPC5) and the two groups of planar coils (PLC A and PLC B) in these configurations. In all load cases, with exception of DL, the average field strength on the magnetic axis is 3T.

case	NPC 1	NPC 2	NPC 3	NPC 4	NPC 5	PLC A	PLC B
DL	20 kA	20 kA	20 kA	20 kA	20 kA	20 kA	20 kA
LS	18.2 kA	17.9 kA	16.9 kA	13.7 kA	13.5 kA	-11.6 kA	12.1 kA
LSc	18.3 kA	18.1 kA	17.3 kA	14.1 kA	13.9 kA	-11.7 kA	8.2 kA
ST	16.1 kA	16.1 kA	16.1 kA	16.1 kA	16.1 kA	-	-

Tab. 1. Coil currents for different load cases

These currents were used as starting vales for the simulation (see Fig. 1). After 1s the power supply is disconnected and the coil groups are discharged via their individual dump resistors (see Fig. 3).

Fig. 4 gives an example for the voltages at the 7 dump resistors. Here all coil casings were considered and the currents of the corrected Low Shear configuration were used as initial values. The initial voltage peak is due to the inductive properties of the dump resistor itself (see Fig 3). Since its inductance is small (80μH) compared to the inductances of the coil groups (approx. 0.6H), the voltage development thereafter is mainly determined by the time constant resulting from the coil inductances and the changing resistances of the dump resistors.

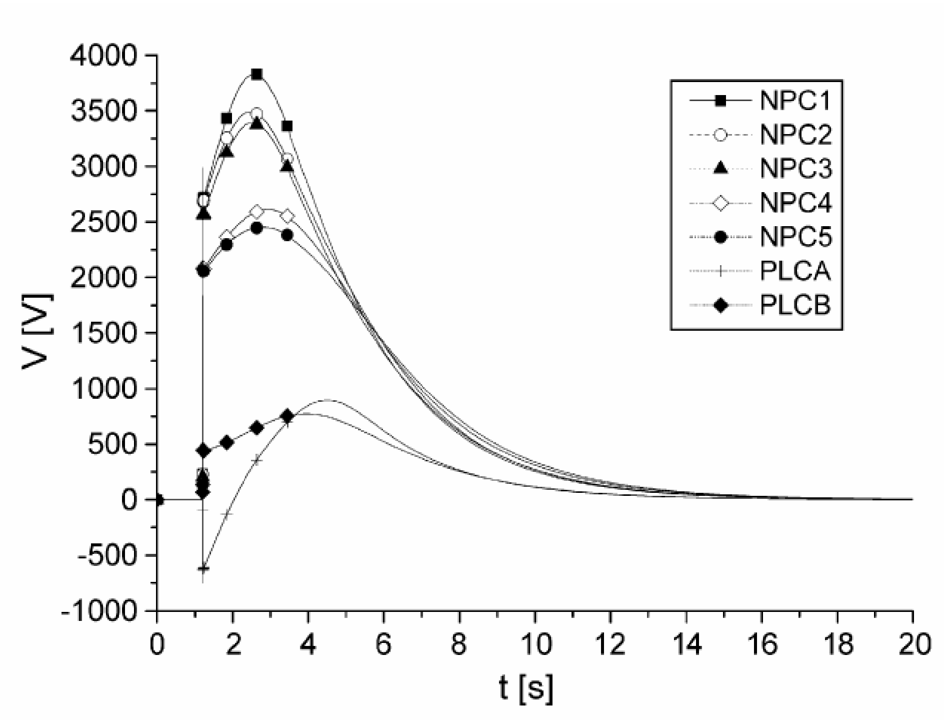

Fig. 4. Voltages [V] for discharge from corrected Low Shear case

For a better comparison of the results, the maximum voltage values [kV] of the simulation are given in Tab. 2.

case	NPC 1	NPC 2	NPC 3	NPC 4	NPC 5	PLC A	PLC B
DL (no casing)	6.987	7.002	6.752	6.733	6.827	2.582	2.355
DL (casing)	6.592	6.589	6.365	6.331	6.434	2.439	2.207
LS (no casing)	3.892	3.491	3.357	2.659	2.520	0.918	0.845
LS (casing)	3.771	3.390	3.266	2.577	2.448	0.879	0.816
LSc (no casing)	3.955	3.593	3.486	2.697	2.519	0.934	0.802
LSc (casing)	3.830	3.487	3.390	2.615	2.451	0.894	0.773
ST (no casing)	3.223	3.080	3.164	3.103	3.036	0.951	0.807
ST (casing)	3.133	2.993	3.077	3.014	2.954	0.911	0.774

Tab. 2. Maximum voltages [kV] at the coils

This comparison clearly shows lower maximum voltages when the coil casings are taken into account. The difference of about 3-5% is due to the fact that the energy of the coils is not only transferred to the discharge resistors but is also dissipated in the coil casings which act as shorted secondary windings for the coils. Just like in a transformer, the energy transferred to the secondary winding also depends on the current change in the primary windings. Larger currents in the coils and thus larger change rates will transfer more energy to the casings leading to a relatively lower voltage at the dump resistors.

However, overall this effect is relatively small since the time constants of the casings and the coils are quite different. Lower resistances of the casings would lead to time constants closer to those of the coils and the energy transfer to the casings would be increased. This would lead to lower voltages at the discharge resistors and coils – an effect that would be welcome – but it would also quickly heat up the coil casings – an effect that has to be avoided.

The standard configuration shows the effect of the large mutual inductances between the coils. Even though there are no initial currents in the planar coils PLC A and PLC B, the voltages induced in these coils during shut down lead to quite high voltages at their discharge resistors, i.e. during discharge a relatively large amount of energy is transferred from the non planar coils to the planar coils. Tab. 3 shows the energy distribution for all dump resistors in this case.

The current in coil group A reaches almost 11kA and the discharge resistor of this coil group actually heats up to about 240°C in the process.

	NPC 1	NPC 2	NPC 3	NPC 4	NPC 5	PLC A	PLC B
ST: Initial current [kA]	16.1	16.1	16.1	16.1	16.1	-	-
Energy dumped [MJ]	115.0	111.4	110.8	108.4	106.9	29.7	24.6

Tab. 3. Energy taken up by the dump resistors

4. Currents and Forces under Fault Conditions

The power supply and protection system of the W7-X coils is designed in such a way that the time difference between the shut down of different coil groups is not greater than 50ms. Such a small time difference would lead only to a small peak in the currents of the coil groups with later shutdown. This difference would have no significant influence on the system.

However, if – e.g. due to a fault in the power supply and protection system or an electric arc at the connections – the shutdown of one coil group would occur a few seconds later than the shutdown of the rest of the system, the energy coupled into this one coil group would lead to much larger currents. Together with the developing asymmetry extreme forces would act on these coils. The strongest forces due to larger currents would occur in either coil group NPC 1 or NPC 5. All coils of the same type carry the same current but coils of type NPC 2 – 4 are distributed more evenly over the torus. Coils of type NPC 1 and NPC 5 are always positioned next to each other (see Fig. 5) and thus a larger current in one of these two groups will lead to stronger forces acting on the two neighbouring coils.

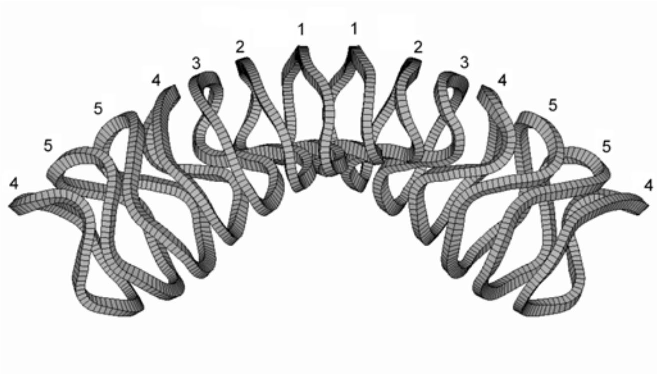

Fig. 5. Partial view of the W7-X coil system (only 14 NPC shown)

In normal operation the highest currents will occur in coil group NPC 1 during the Low Shear case. Fig. 6 shows the current development for a shutdown from the Low Shear case when coil group NPC 1 is disconnected from the power supply (like all other groups) and shorted via a permanent arc. The changing currents in the 6 coil groups during shutdown induce additional voltages in coil group NPC 1 which adds to its current.

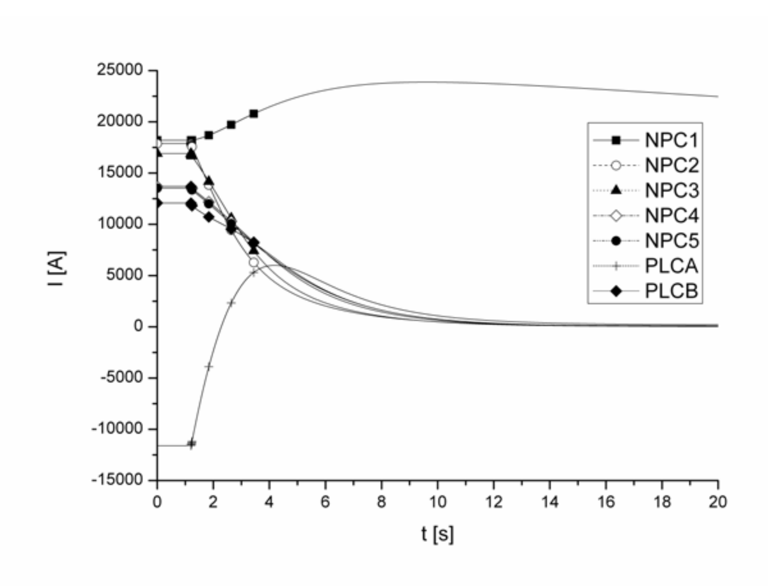

Fig. 6. Coil currents [A] for shutdown failure

Using these current curves EFFI can be applied to calculate the total forces [kN] acting on a shorted non planar coil of type NPC 1. Tab. 4 shows the results:

	0s	**1.5s**	**2s**	**4s**	**6s**	**9.62s**	**20s**
Fx [kN]	-2454	-2531	-2632	-2176	-1292	-438	-136
Fy [kN]	-783	-1393	-2520	-7162	-9964	-11623	-10544
Fz [kN]	-852	-887	-1008	-1866	-2581	-3070	-2801
|F| [kN]	**2713**	**3022**	**3781**	**7714**	**10374**	**12030**	**10911**

Tab. 4. Total forces [kN] on coil NPC 1 due to shutdown failure

After 9.62s the total forces acting on a coil of this type have increased to about four times the initial value (e.g. at t=0s), the lateral forces are even multiplied by a factor of ten. Extreme care has to be taken to avoid such a situation. The electric insulation is designed accordingly and the coils are tested for voltages higher than the ones that can be expected during discharge.

5. Summary of the Results

Using SIMPLORER a circuit simulation of the W7-X magnet system including coils, casings, and dump resistors was developed. Simulations of discharge processes show the maximum voltages at the dump resistors and coil groups. The maximum voltage of 7kV is reached for currents according to the design limit of 20kA. During shut down from load cases without initial currents in the planar coils, strong inductive coupling supports the fast discharge of the system. In these cases part of the energy of the non-planar coils is actually dissipated by the discharge resistors of the planar coils. Also the coil casings dissipate part of the energy stored in the magnetic field, however, this effect is relatively small.

The discharge switches are designed for time differences smaller than 50ms between the coil groups, which will have no significant influence on the system. However fault conditions are able to introduce delays for single coil groups. Considering the forces acting on the coils, a late shutdown of coil group NPC 1 from the Low Shear configuration would be the worst case. The total forces acting on a coil of type NPC 1 would be multiplied by a factor of four within 10 seconds.

6. Conclusions

Using the strong temperature dependence of the pure nickel based dump resistor has helped to minimize the discharge time while keeping voltages at a moderate level.

Utmost care has to be taken to avoid an asynchronous shutdown of the magnet system, since this would lead to intolerable high lateral forces acting on the coils. Fault conditions that could lead to an asynchrony are short circuits and arcs at the coil system. Therefore the coils and the busbar system, including the current leads, are designed and have to be constructed to withstand the conceivable discharge voltages with a high margin.

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