MODELLING THE TRANSIENT BEHAVIOUR OF A LARGE SUPERCONDUCTING COIL SUBJECTED TO HIGH VOLTAGE PULSES

A. M. Miri*, C. Sihler**, M. Droll*, A. Ulbricht**

* Universität Karlsruhe, Institut für Elektroenergiesysteme und Hochspannungstechnik (IEH), Kaiserstraße 12,
D-76128 Karlsruhe, e-mail: miri@ieh.etec.uni-karlsruhe.de

** Forschungszentrum Karlsruhe (FZK), Institut für Technische Physik, Postfach 3640, D-76021 Karlsruhe
e-mail: sihler@itpsih.kfk.de

Germany

ABSTRACT — Magnet coils can be excited into internal voltage oscillations by transient voltages. Magnetic confinement in fusion experiments necessitates the use of large superconducting magnet coils. Transient high voltages are produced by the switching processes used for the safety discharge of a superconducting magnet. The surges caused by counteracting current switches, which are used if a magnet shall be discharged at high current level and a discharge voltage above 5 kV, may electrically stress the magnet's dielectric components to many times its normal stress due to internal high voltage oscillations. In order to ensure that no dielectric failure can occur, it is important to know the natural frequencies of oscillations of a magnet during the design stage, and to determine whether the expected switching transient voltages can excite the magnet into internal high voltage oscillations. After a short introduction about superconducting magnets in fusion experiments the paper will present the applied method for calculating the transient behaviour of superconducting coils and the transient reaction of two prototype coils, one for generating the poloidal field and one for generating the toroidal field in a tokamak experimental reactor.

1. INTRODUCTION

Superconducting magnets are stringent for fusion reactors with magnetic confinement to provide an economic energy balance [1]. Presently the engineering design of the next fusion technology experiment ITER (International Thermonuclear Experimental Reactor) is planned in a worldwide cooperation [2]. The toroidal magnetic field of the ITER tokamak will be generated by 24 superconducting magnet coils (TF coils in Fig. 1). Each coil has a size of 12 m x 17 m and a weight of 400 t [3]. The magnet system represents roughly ¼ of the total plant investments and must be designed as a reliable, semipermanent component with sufficient inherent safety, even under fault conditions.

The knowledge and experience of experiments with superconducting prototype coils serves as an indispensable background for a safe operation of the magnet system of a fusion reactor. Such experiments are performed in the TOSKA facility of Forschungszentrum Karlsruhe [4].

From March 1994 until March 1995 the superconducting prototype poloidal field (PF) coil POLO was tested at FZK. The POLO project was the most demanding step of development towards superconducting high-power magnets. The goal of that project was to demonstrate that the POLO coil fulfills the requirements derived from the specifications of the tokamak operation [5]. The coil has a diameter of 3 m, 56 turns, a rated current of 15 kA and was designed and constructed to withstand high magnetic field transients occuring at fast ramp up, plasma control, and disruption requiring a rated voltage of 23 kV. The insulation material has to withstand the voltage in the presence of the coolant helium with varying density, and the thermal stresses at temperatures between 300 K and 4 K [6]. In some applications the insulation material has to be vacuum leak tight up to pressure levels of 2.5 MPa.

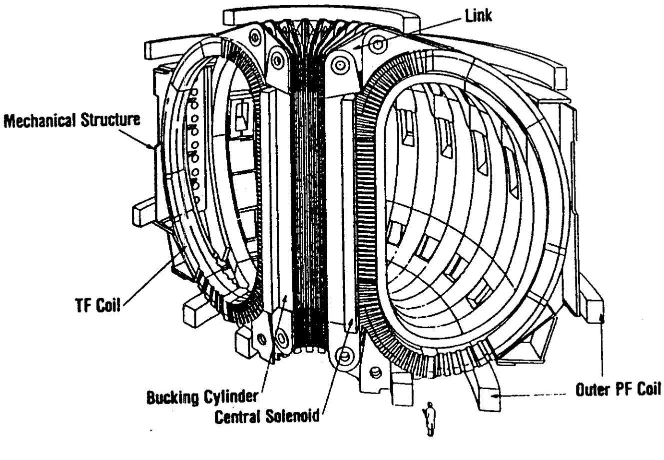


Fig. 1. Cutaway view of the ITER coil system.

The electrical insulation system designed for large superconducting coils also requires mechanical integrity against high stresses resulting from bending and torsional loads due to the electromagnetic forces. Insulation materials and special components, like e. g. high voltage and high current leads, instrumentation feedthroughs, insulation breaks, and instrumentation cables have been developed to meet these requirements [7]-[8].

As part of the high voltage test program pulse voltage tests were performed with the POLO coil being in the normal conducting and superconducting state. Voltage taps were installed at the double pancake (DP) joints to measure the transient voltage distribution across them. At excitation of the coil with a pulse voltage rising in 5 µs to a peak value of 24 kV the voltage level across the four double pancakes of the winding reached values up to 8.5 kV (Fig. 2) [9]. The measurement results from the coil being in the superconduting state hardly differed from the measurement results at room temperature. Since high voltage pulses with short rise times may also occur in the magnet system of a tokamak in case of switching or ground faults, the measured transient phenomena inside the coil were further investigated by numerical simulations.

The calculations were performed by means of a detailed network model for the POLO coil which also included the terminals, the instrumentation cabling, and the switching circuit [9]. Due to the high magnetic coupling inside the winding a numerical solution of the linear differential equations could only be achieved in the frequency domain by means of the Fast Fourier Transformation (FFT). Comparing the calculated and measured DP voltages shown in Fig. 2 the mathematical and computational expense involved with the simulation seems to be justified.

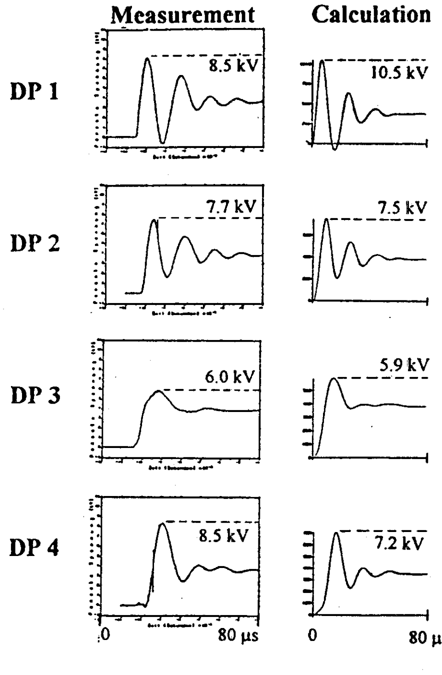


Fig. 2. Calculated and measured double pancake voltages inside the POLO winding at h.v. pulse excitation

As a consequence of the experience with the POLO coil a simulation model for the TF model coil of ITER was developed in order to clarify the transient electrical behaviour of that coil at different grounding conditions of the steel plates the conductor is inserted in (Fig. 4).

2. DESIGN OF THE ITER TF MODEL COIL

The ITER TF Model Coil (ITER TF MC) is designed to test the manufacturing feasibility of the TF magnet concepts and the mechanical and electrical margins of the winding pack under ITER relevant mechanical loads. For that purpose the 4 m long racetrack shaped coil which has a nominal current of 80 kA and a nominal voltage of 10 kV will be tested in the TOSKA facility of FZK under in-plane and out-of-plane loads with the use of the superconducting EURATOM LCT Coil [10]. Fig. 3 shows one possible arrangement for that test. This year the test arrangement and the design of the ITER TF MC (Fig. 3, Fig. 4) has been subject to some technical changes. In this paper the old design of the ITER TF MC [12] is presented, since only for that design a detailed network model was developed. But seen from the electrical point of view the new coil design [13] hardly differs from the old one [12].

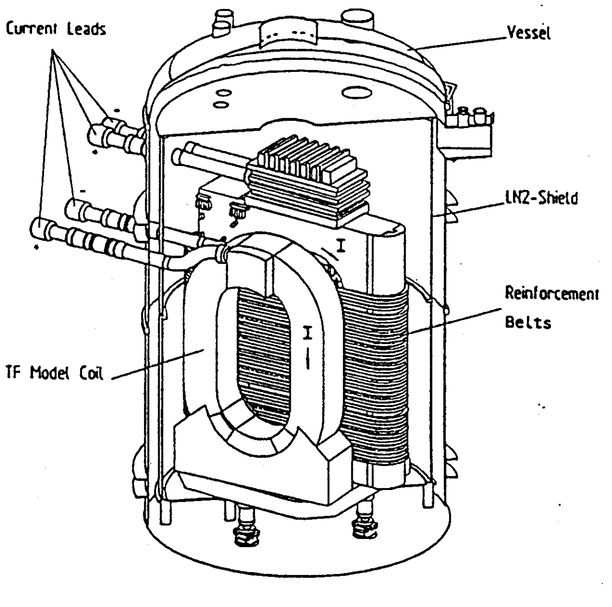


Fig. 3. ITER TF model coil adjacent to LCT coil (with reinforcement belts) in the TOSKA cryostat vessel

The ITER TF MC has 101 turns and the conductor is layer wound inside stainless steel plates, with equally spaced turns, except for the inner layer, in which there are three groups of joining turns [12]. Each layer is inserted between an inner and an outer plate which have flat surfaces on the side opposite to the conductor (Fig. 4). Between these shear plates a layer insulation with 2.0 mm thickness is foreseen, the turn insulation having a thickness of 2.5 mm. A steel strap is installed around the coil, the ground insulation between the shear plates and that outer surface has a thickness of 10 mm. Proceeding from these data a simulation model for the transient electrical behaviour of the coil at different grounding conditions of the shear plates was developed.

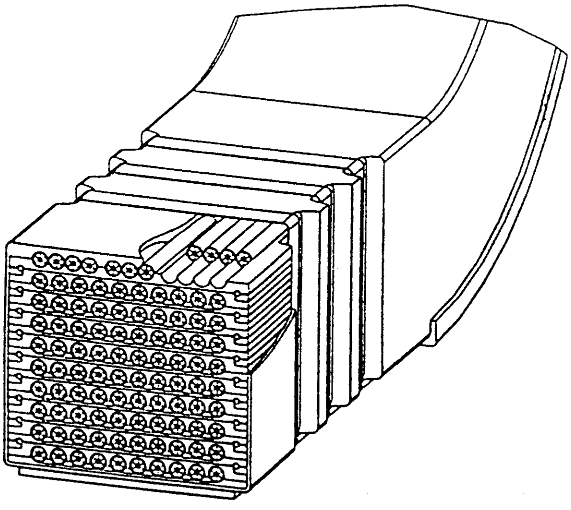


Fig. 4. ITER TF model coil cross section [11]

Naturally the optimum insulation thicknesses depend on the grounding condition for the shear plates chosen for the final design of the ITER TF MC which is still under discussion.

3. DERIVATION OF THE COIL PARAMETERS FOR THE SIMULATION MODEL

3.1 Self and mutual inductances

DC values of self and mutual inductances have been used. When the diameter of the coil is large compared to the thickness of the conductor, the change in the inductances due to skin effect is bound to be small [14]. The inductance matrix has been computed with EFFI [15] which is based on Biot-Savart's Law:

$$\mathbf{A}(\mathbf{r}) = \frac{\mu}{4\pi}\iiint \frac{\mathbf{J}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\,dv' \quad , \qquad (1)$$

where **A** is the magnetic vector potential, **J** is the current density vector, μ is the permeability in free space, **r'** is the position vector of the source point, **r** is the position vector of the fieldpoint, and dv' is the differential volume element of the conductor.

To calculate the inductance matrix of a system of windings, EFFI uses the following formula:

$$M_{ab} = (J_b S_a S_b)^{-1} \oint_{l_a} \int_{S_a} \mathbf{A}_b \cdot d\mathbf{l}_a \, dS_a \quad , \qquad (2)$$

where M_{ab} is the mutual inductance between winding a and winding b, J_b is the current density in winding b, S_a and S_b are the respective winding cross-sectional areas, $d\mathbf{l}_a$ is the vector differential element in direction of the current flow in winding a, and $\mathbf{A}_b$ is the vector potential due to winding b.

The calculated values for the self inductance of single windings of the ITER TF MC vary from 6.37 μH to 10.19 μH, the corresponding magnetic coupling factors have values between 0.19 and 0.71.

3.2 Effective resistances (skin and proximity effect)

In the high voltage pulse tests performed with the POLO coil the superconducting filaments in the cable did not show an influence on the internal overvoltage oscillations at the beginning of the high voltage pulse [9]. Therefore it is assumed that the damping of the overvoltage oscillations is not influenced by the superconducting filaments in the cable.

Since the conductor design is similar to that of the POLO cable the determination of the effective resistance of the ITER TF Model Coil conductor (ITER TF2 conductor) is based on the electromagnetic Finite Element Method (FEM) calculations performed for investigating the skin effect in the POLO conductor.

To evaluate the skin effect in the time domain a single frequency value is used for the FE analysis. According with other authors [14] this frequency is such that a quarter wave corresponds to the rise time of the applied voltage pulse. Consequently a frequency of 10 kHz is used for the skin effect evaluation in case of the pulse voltage caused by counteracting current switching (see section IV).

The value of the corresponding ohmic resistance of the POLO conductor was 353 times higher than the DC value at 4 K [9]. Simulating the transient behaviour of the ITER TF MC it is assumed that the ITER TF2 conductor has a twenty times higher resistance rise factor due to skin effect than the POLO conductor. That assumption is made for the following two reasons:

1. The conductor has a non-twisted Cu cross-section of 400 mm ^{2} which is 8 times more than the whole Cu cross-section of the POLO conductor
2. The ohmic damping caused by skin and proximity effect does not influence the calculated transient voltage oscillations inside a winding as long as only the order of magnitude of the damping is correct. In order to make sure that the amplitude and duration of the calculated internal oscillations are not itensified by too low damping values, the simulations were performed with effective resistances which secure sufficient damping.

In addition to the skin effect a mean proximity factor of 8 [14] is used for the serial resistances in the network model of the coil. Considering the skin and proximity effect, the transient overvoltages at the beginning of the pulse were calculated using a high frequency value for the resistance of the ITER TF2 conductor of 56500 times the DC value at cryogenic temperature. This corresponds to effective resistances of about 300 mΩ per winding at 10 kHz and 4 K.

3.3 Capacitances

The turn-to-plate, plate-to-plate and plate-to-ground capacitances were calculated analytically from the construction drawings using the formulas for a cylindrical (3) and a plate (4) capacitor:

$$C_{cyl} = \frac{2\pi\varepsilon_0\varepsilon_r l}{\ln\frac{r_a}{r_b}} \qquad (3)$$

$$C_{pl} = \frac{\varepsilon_0\varepsilon_r A}{d} \qquad (4)$$

Values ranging from 9.66 nF to 13.95 nF were calculated for the turn-to-plate capacitances. Accordingly the plate-to-plate capacitances have values between 59.4 nF and 88.9 nF and the plate-to-ground capacitances of the first and last layer have a capacity of about 25 nF, whereas all other plate to ground capacities have only about 3 nF.

3.4 The equivalent circuit for the ITER TF MC

In the coil equivalent circuit shown in Figure 5 all shear plates are floating.

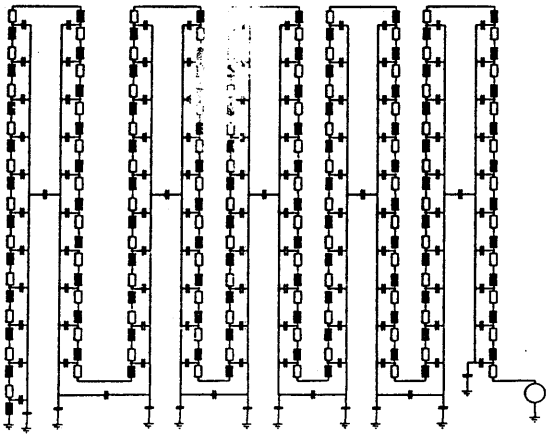


Fig. 5. Detailed network model of the ITER TF Model Coil

In order to investigate the transient behaviour of the coil at different grounding conditions of the shear plates simulations were performed for the grounding conditions shown in Fig. 6 and also for the case that the shearplates are tied to the potential at the conductor joints by a transition resistance R. If a transition resistance of e.g. 20 Ω is used, the simulation results do not differ from the results of Case 2. Therefore only Cases 1, 2, and 3 are presented.

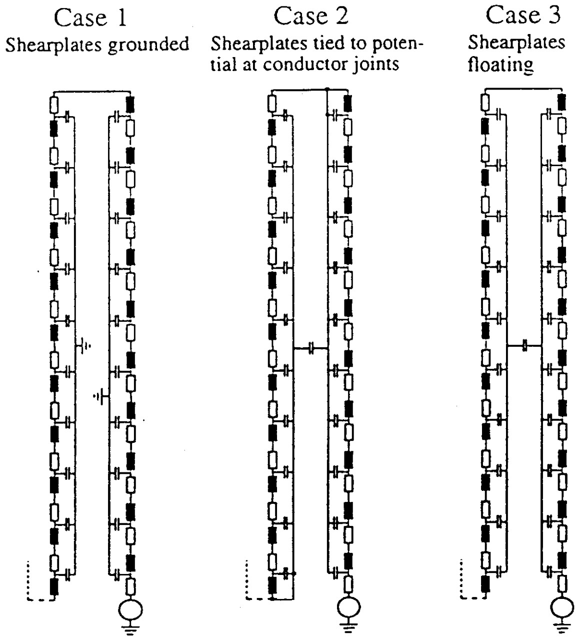
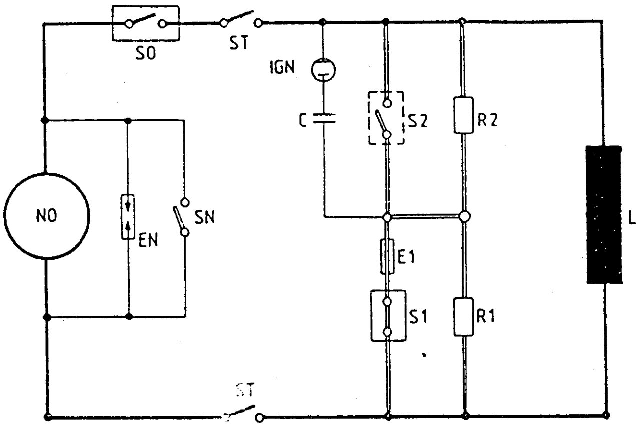


Fig. 6. Shear plate grounding conditions investigated in the simulations

4. TRANSIENT HIGH VOLTAGES RESULTING FROM COUNTERACTING CURRENT SWITCHES

If the superconductor should go normal during a high current experiment, the magnetic energy stored in the coil (2 GJ in case of the ITER TF full size coils) must quickly be discharged into an ohmic resistance. Working with high DC currents and discharge voltages above 5 kV this can only be achieved by using counteracting current switches. Fig. 7 shows the counteracting current switching circuit used for the high voltage discharge of the POLO model coil [5].



N0: power supply; EN, SN: overvoltage protection; S0: breaker; ST: isolation switch; IGN: ignitron switch; C: capacitor bank; S2: AC vacuum breaker; R2: high voltage discharge resistance; E1: pyrobreaker; S1: DC breaker; R1: discharge resistance for slow discharges (U_{coil} < 1 kV); L: superconducting coil

Fig. 7. POLO high power switching circuit (I_N = 30 kA, U_N = 23 kV)

High voltage discharges are initiated by closing S2 and commutating the coil current into the busbar S2-S1. Then the isolation switches ST are opened and the ignitron switch is fired. The counteracting current generated by discharging the capacitor bank C causes a zero current in the AC vakuum breaker S2. This enables the vacuum breaker to commutate the current into the discharge resistance R2. During the POLO experiment switched powers up to 350 MW were safely mastered that way.

Because of the high inductance of superconducting coils (16.7 mH in case of the POLO coil and 32.0 mH in case of the ITER TF MC) only a small counteracting current pulse is caused in the circuit C-IGN-L-S1-E1-C when the capacitor bank is discharged. Discharging the POLO coil at a current level of 15 kA the current pulse in the circuit C-IGN-L-S1-E1-C reached only 100 A which represents less than 0.7 % of the whole counteracting current. However: The rise time of that current was 200 μs causing a voltage peak of 16.7mH x (100 A / 200 μs) = 8.35 kV at the coil before the actual coil discharge. The higher the discharge current level is, the higher is the voltage peak to be expected from counteracting current switching.

A valid simulation model of the high power switching circuit in the TOSKA facility was developed during the POLO experiment. Assuming that the high voltage discharge of the ITER TF MC will be performed with that switching circuit at a current level of 25 kA, the simulation result for the voltage peak to be expected from counteracting current switching is shown in Fig. 8. The actual discharge of the coil starts about 350 μs after firing the ignitron switch. The discharge voltage level is 8.3 kV whereas the voltage peak caused by the counteracting current rises to a peak value of 13 kV within 40 μs.

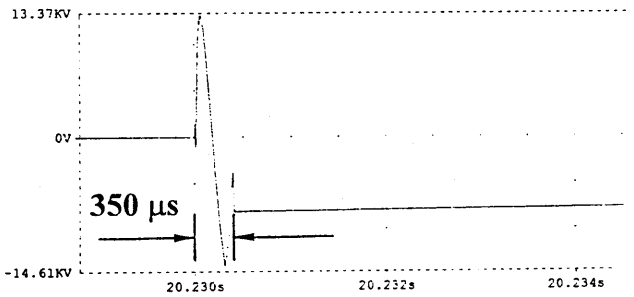


Fig. 8. Transient high voltage used as excitation for the ITER TF MC

Although the transient behaviour of the high power switching circuit could be improved the simulations were performed with that transient voltage in order to investigate the transient reaction of the coil. The transient reaction of the coil at different surges was also investigated, but this type of excitation seems to be the most typical.

5. NUMERICAL CALCULATION METHOD

A prerequisite for modelling the transient behaviour of coreless magnets is the exact knowledge of the inductance matrix of the coil. 101 self and 5050 mutual inductances had to be calculated for the circuit shown in Figure 5 employing the computer code described in section III and taking advantage of the regularities in the inductance matrix. Due to the fully occupied inductance matrix, the calculations performed in the time domain had to be interrupted because of convergence problems. However the linear differential equations could be solved in the frequency domain with the help of the Fast Fourier Transformation (FFT).

6. RESULTS OF COMPUTATION

As a measure for the initial voltage distribution inside the winding, the maximum transient voltages between adjacent layers of the winding will be presented for all the three cases shown in Fig. 6. Since in all three cases the overvoltages between layers 7-8 and 9-10 are smaller than the ones between the layers 1-2, 3-4, and 5-6, only these transient voltages are compared to each other.

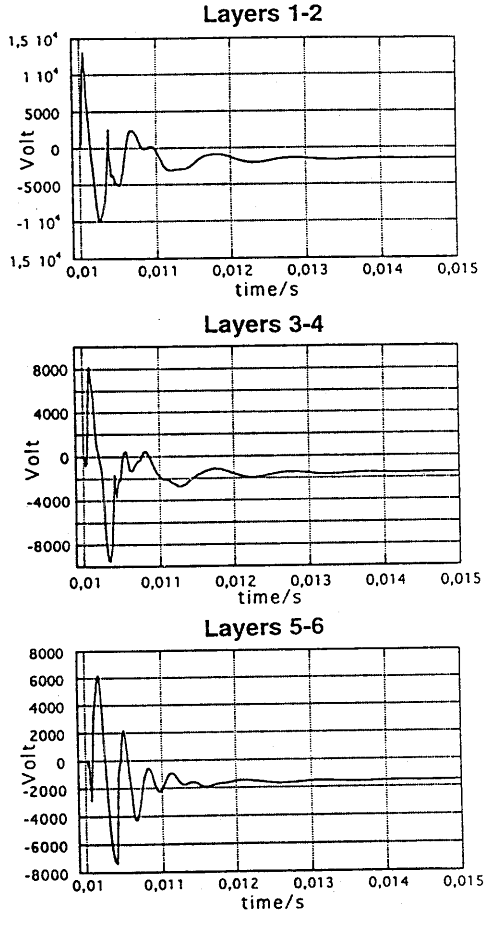


Fig. 9. Case I - grounded shear plates: Transient interlayer voltages during the first 5 ms

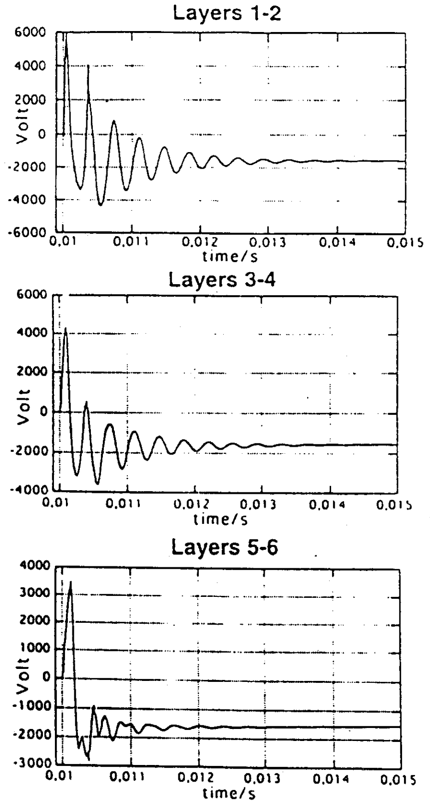


Fig. 10. Case II-shear plates tied to potential at conductor joints: Transient inter-layer voltages during the first 5 ms

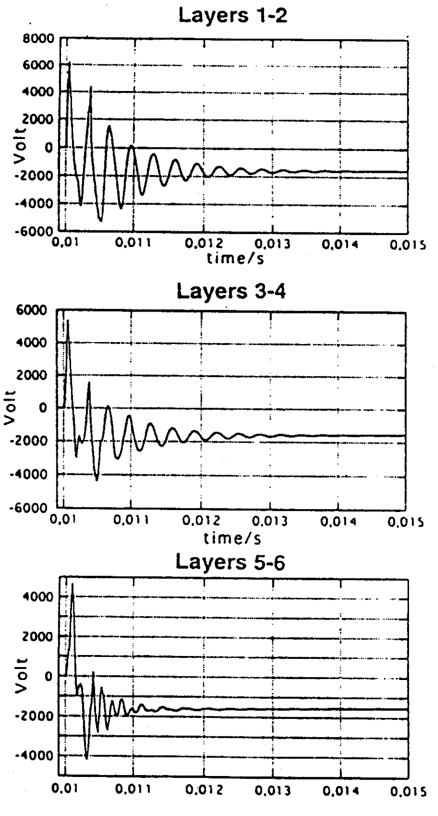


Fig. 11. Case III - shear plates floating: Transient inter-layer voltages during the first 5 ms

7. CONCLUSION

Coils with grounded shear plates have an extremely high ratio of the turn-to-ground to turn-to-turn capacity. Therefore such coils can easily be excited into internal voltage oscillations, even by surges caused by regular switching breaking processes.

These internal oscillations can be reduced by about half tying the potential of shear plates to that of the winding-either directly or across a resistance of e.g. 20 Ω.

The rated inter-layer voltage is 2 kV. Depending on the grounding scheme of the shear plates transient voltages which are seven times higher than that can occur between two layers. The insulation system of the coil has to be designed according to this requirement.

ACKNOWLEDGEMENTS

The authors thank Prof. Dr. P. Komarek and Prof. Dr.-Ing. A. Schwab for their substantial support in performing this work. This work has been performed in the framework of the Nuclear Fusion Project of Forschungszentrum Karlsruhe and is supported by the European Union within the European Fusion Technology Programme.

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