Transient electrical behaviour of the ITER TF coils during fast discharge and two fault cases

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***Abstract*-- Improvements of high voltage design criteria and quality assurance for ITER coils are indispensable taking into account the problems occurred during high voltage tests of the ITER TF model coil. One important aspect to consider is the transient electrical behaviour because fast changes of voltages may cause local overloading and destruction of the insulation system. This paper will present the calculation of the terminal voltages within the ITER TF coil system and the voltage stress of the insulation within an individual ITER TF coil for the fast discharge and two fault cases. Proposals for the high voltage tests are discussed based on the calculated voltage stress of the two fault cases and the experiences gained during the ITER TF Model Coil test to ensure appropriate dielectric quality of the ITER TF coils.**

Keywords: electrical insulation, high voltage, ITER, superconducting coil.

1. Introduction

The toroidal field of the present ITER design is generated by 18 TF coils. In case of a quench under rated current operation the stored energy of 40 GJ is dissipated mainly in 9 Fast Discharge Units (FDU) which causes a transient excitation of the coils. It is well known from conventional large energy devices (e. g. transformers) that transient voltage excitations can lead to much higher electrical stress than at DC and AC operation. Therefore detailed calculations are necessary to calculate the maximum electrical stress for the insulation during fast discharge. In addition fault cases may increase the voltage stress above the values of a normal sequence of a fast discharge. Hence two examples of fault cases were examined considering malfunction of FDUs and an additional earth fault.

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2. Establishment of network models

The design concept of the ITER TF coils [1] is based on the electrically insulated embedding of a conductor with a circular cross section into seven radial plates made of stainless steel. Every radial plate comprises a double pancake and is surrounded with its own insulation. After stacking the seven radial plates and connecting the conductor of each double pancake with the adjacent one, the ground insulation is inserted between the pack and the stainless steel coil case.

Thus, the insulation system of the coil consists of three different types (Fig. 1): the conductor insulation between the conductor and the surrounding radial plates, the radial plate insulation between two neighboured radial plates and the ground insulation between the radial plates and the grounded coil case.

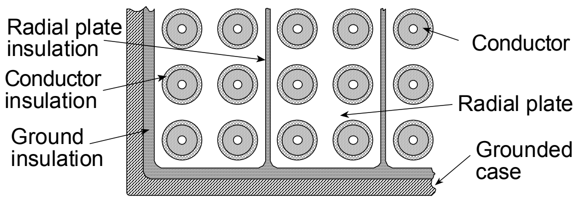

Fig. 1.: Part of the cross section of an ITER TF coil showing the three different types of the electrical insulation.

Hence it is necessary to determine the maximum voltage for each type of insulation. The calculation of the maximum voltages for all 3 types of insulation during a fast discharge was performed step by step. In fact, it was not possible to integrate all conditions and solve all problems in a frequency dependent network model directly because in every coil the transient current is superposed to the transport current with the much longer equivalent discharge time constant of 15 s.

For the first step the detailed network model of a single TF coil was established by determination of one capacitance, one resistance and one inductance per turn. The turn capacitances were calculated as cylinder capacitors. Radial plate and case capacitances were calculated as plate capacitors; additional capacitances were assumed for the instrumentation cables. The resistances, inductances and mutual inductances were calculated for several frequencies with the FEM program Maxwell [2].

The established network model was treated by the code PSpice [3], which does not allow the use of frequency dependent lumped elements. So several network models were established for different frequencies. The natural frequency (i.e. first resonance frequency) was calculated to be at 50 kHz, which is considerable lower as the value of 300 kHz which was calculated and measured for the TF Model Coil [4].

For the second step a network model with 18 simplified coils and 9 models of a FDU was built up (the simplified analogue circuit is shown in fig. 2) for the determination of the coil terminal voltages. The coils act in this step as coupled superconducting DC coils and were excited with the rated current of I_0 = 68 kA.

The simulation of the fast discharge starts with the commutation from the short circuit path (that bridges the resistor path during DC current operation) to the discharge resistor path in the FDUs. This commutation produces a maximum voltage of about $U = R \bullet I_0$ at the resistor R of the FDUs. For a perfect symmetrical ITER system, this causes a voltage to ground of +U / 2 or –U / 2 at every FDU terminal because the FDUs are symmetrically grounded over resistors with 500 Ω [5]. For such a "soft grounded" symmetrical ITER system, every coil has one terminal with a maximum voltage of +U / 2 or –U / 2 (the one which is connected to the FDU) and one terminal with ground potential (the one which is connected to the neighboured coil). Hence all coils have the same terminal to terminal voltage and the same voltage to ground (neglecting polarity) during the fast discharge. It is therefore sufficient to collect the data of one coil terminal that is connected with the FDU.

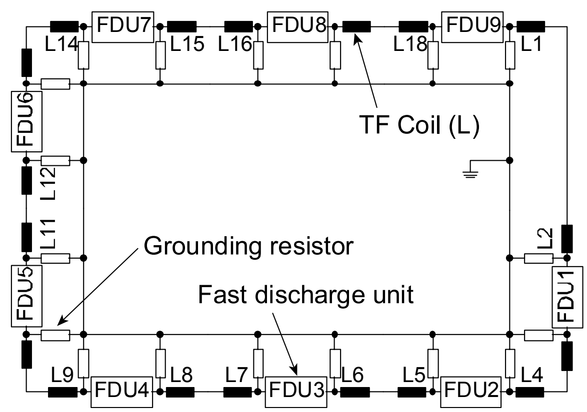

Fig. 2: Simplified analogue circuit of the ITER coil system during a fast discharge (power supply already disconnected). The network model itself is more comprehensive e. g. it includes instrumentation cables and internal elements of the FDUs.

The system is not symmetrical in case of a malfunction of a FDU or an earth fault. Hence for the fault cases, the maximum terminal to terminal voltages and the maximum terminal to earth voltages (which do no occur at the same coils) were identified.

In the last step, these terminal voltages from the system network are used for the excitation of the detailed single coil model. For this purpose the models with the natural frequency (50 kHz) and with a rise time in the ms range (chosen: 1 kHz, which corresponds roughly to a rise time of 0.25 ms) are used. For the fast discharge, one terminal was earthed and the other one was excited with the calculated terminal voltages. In the fault cases it was necessary to excite both terminals.

3. Results of the calculation

The single coil models (1 kHz and 50 kHz) were examined for fast discharge and the two fault cases for determination of the maximum voltages on every type of insulation. The results are presented in Tab 1.

Tab. 1: Overview of the calculated maximum voltage at ground, radial plate and conductor insulation for the 1 kHz and 50 kHz model.

Insulation type	f / kHz	Maximum calculated voltage / kV		
		fast discharge	fault case 1	fault case 2
Ground	1	3.5	8.1	16.4
	50	3.5	8.1	16.4
Radial plate	1	0.7	0.7	4.8
	50	0.6	0.7	4.3
Conductor	1	0.6	0.8	4.3
	50	0.5	0.8	3.7

For fault case 1, a fast discharge with the simultaneous failure of 2 neighbouring FDUs was assumed, i.e. that for these units the current remains in the short circuit path and the energy of all coils dissipates in only 7 discharge resistors instead of 9. The voltage values for this case and the fast discharge without a fault are preferably chosen from the 1 kHz model because the rise times are 1.5 ms or longer.

For the second fault case it was assumed that the voltage imbalance in the system, caused by fault 1, with the increase of terminal to earth voltages, leads to an earth fault at the time and location of the maximum voltage to earth. For this second fault case, the rise times are in the range of few µs for the maximum radial plate and conductor insulation voltage and in the range of some ms for the ground insulation voltage. The reason for such a difference between the rise times is that the maximum values were not found at the same coil.

It should be stressed that critical voltage values were often found at locations which will be not accessible for measurement because these locations have no high frequency suitable connection to the high voltage instrumentation in the present ITER design.

4. Test voltages and arrangements

The test voltages are chosen in relation to the maximum values and the waveforms of the calculated voltages. The DC tests can be considered as representative for the "slow" fall of the voltages and the AC and impulse tests are selected in relation to the calculated rise times. In this context it is obvious that a calculated maximum voltage in the ms range determines the AC peak value (and not directly the rms value).

The proposed DC and AC test voltage values (Tab. 2) derive from the following considerations:

The standard rule for voltage tests related to the fault events is proposed to be $2*U_{fault} + 1$ kV. The value is rounded up to integer values (e. g. 2*8.1 kV + 1 kV = 17.2 kV => 18 kV).

The test voltage for values lower than 5 kV is taken as 5 kV.

For radial plate and conductor insulation the higher value is taken for both.

Tab. 2: DC and AC (peak value) test voltages for ground, radial plate and conductor insulation based on the calculated voltages for the two different fault cases.

Insulation	Test voltage / kV	
	Based on fault case 1	Based on fault case 2
Ground	18	34
Radial plate	5	11
Conductor	5	11

With the DC and AC tests it is possible to examine a specific insulation type of one coil, e. g. the conductor insulation by grounding all radial plates and applying the high voltage potential to a coil terminal. Additional AC insulation diagnostic tools like partial discharge measurement and the determination of the dissipation factor by a Schering bridge are recommended.

During the impulse test all insulation types are stressed, but it is not possible to establish an arrangement that fits for all test voltage values simultaneously. Hence the impulse test voltages should be limited with respect to internal overvoltages and the used circuit elements to avoid local overstressing. For an impulse test circuit with a capacitor bank of 150 µF and a damping resistor of 0.77 Ω, the terminal voltage of 29.6 kV was calculated with the 50 kHz model to ensure at a double pancake joint a maximum voltage stress of 34 kV to earth. This double pancake joint (and not the high voltage terminal!) was found in the 50 kHz model to be the location with the highest voltage to ground, if the coil is excited with impulses in the relevant time range.

At least one criterion must be defined for every test to be successful. The criterion of the absence of a breakdown is indispensable. A minimum value of 1 GΩ is proposed for the insulation resistance measured during DC tests. If additional conductivities (e. g. water for cooling purposes of bus bars) are unavoidable this criterion can be skipped after installation of the coil at the reactor site. During AC tests the charging current must be constant. A slightly lower charging current is expected under cryogenic conditions due to a lower permittivity as at room temperature. The dissipation factor and partial discharge behaviour (e. g. inception voltage) cannot be defined in advance, but the experience with testing of high voltage components for the ITER TF Model Coil shows that especially the partial discharge measurement can be a valuable diagnostic tool if routine tests of components have to be performed. In this sense the comparison of the partial discharge behaviour of complete coils can lead to a further improvement. It will also be a suitable method for monitoring the dielectric properties of the magnet over the lifetime. The experience of the partial discharge measurement on the ITER TF Model Coil shows that, under cryogenic conditions, an increased noise level caused by the cold operation infrastructure may drastically decrease the sensitivity of the method.

The different tests should be performed in a sequence that delivers a maximum amount of information, minimises additional damage in case of an insulation fault and minimises the assembly work. The sequence for a complete acceptance test including all measurements is given in [6]. Such a full acceptance test is recommended at least after completion of fabrication under ambient conditions, for a cold test and again under ambient conditions.

To identify clearly that the dielectric coil insulation is Paschen tight it is necessary to make a DC test with the coil in the Paschen minimum at room temperature. A good method would be to apply permanently the full DC voltage while increasing the pressure around the coil continuously and slowly from vacuum up to about 100 mbar.

5. Conclusions

The calculation of the transient behaviour of the ITER TF coils during fast discharge and two fault cases shows significant increasing of the radial plate and conductor insulation stress as a consequence of a malfunction of two adjacent FDUs followed by an additional earth fault. The design and test voltages must be chosen depending on the realistic fault scenarios identified by the ITER community. As an example, two sets of tests voltages based on the two fault scenarios considered in this analysis were proposed. Insulation tests on samples must show that the ITER design is compatible with the credible worst case scenario otherwise the design must be improved or the risk of coil destruction by not covered fault scenarios must be taken.

Further activities aimed at improving and updating the TF network models are recommended. In addition the transient electrical behaviour of the Poloidal Field coils and the Central Solenoid should be examined.

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