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Fault analysis and overvoltage estimation in the DEMO Toroidal Field circuit

Alberto Maistrello[a], Mattia Dan[a], Valentina Corato[b], Kamil Sedlak[c] and Elena Gaio[a]

[a]Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete S.p.A.), 35127 Padova (Italy)
[b]ENEA C.R. Frascati, 00044 Frascati (Italy)
[c]EPFL-SPC, 5232 Villigen PSI (Switzerland)

In the present configuration of the European demonstration nuclear fusion power plant (DEMO), the toroidal magnetic field is produced by 16 superconducting toroidal field (TF) coils. The total stored energy of 146 GJ, more than 3 times the energy stored in ITER TF coils, has to be quickly dissipated in case of quench by suitable Fast Discharge Units (FDU).

The energy, the current and the discharge time constant define the voltage to be applied to the coils; however, the peak value at the coil terminals during the fast transient phase at the beginning of the discharge or in case of faults can be much higher.

This paper deals with first studies addressed to estimate maximum voltage stresses on the coils in various operating and fault conditions and to evaluate the relative merit of different TF circuit topologies to support the design work, aimed at finding the best compromise between requirements for the coil insulation and cost and size of FDUs, busbars and current leads.

Analyses and numerical simulations have been carried out, for both the cases of TF circuit composed of 16 and 8 sectors. The results are reported and discussed.

Keywords: DEMO, superconducting coils, quench protection, fast discharge, overvoltages

1 Introduction

The European demonstration nuclear fusion power plant (DEMO) is under pre-conceptual design phase within the EUROfusion consortium. One of the design options, called DEMO1, is the most conservative in terms of science and technological developments with respect to ITER: it is characterized by pulses 2 hours long and production of a net electricity power of 500 MW [1].

In the previous DEMO1 reference design (2015), the toroidal magnetic field was produced by 18 superconducting toroidal field (TF) coils [2], while in the new one (2017) the TF coil number is reduced to 16. The coils are supplied by a steady state current on the order of 90 kA to produce a magnetic field at the plasma centre of 4.89 T, giving a total stored energy of 146 GJ [3]. This large amount of energy, more than three times the energy stored in ITER TF coils, has to be quickly dissipated in case of quench by the intervention of Fast Discharge Units (FDU) generally based on a dc Circuit Breaker (CB), a suitable Discharge Resistor (DR) and a backup CB. The time constant for the discharge considered for DEMO TF coils is about 23 s, which is more than twice the equivalent discharge time constant for ITER.

The basic calculation of the coil voltage at the discharge are derived from the energy, the current and the discharge time constant; however, the peak value at the coil terminals during the fast transient phase at the beginning of the discharge can be much higher. In fact, the peak voltage value depends on the CB technology and on the stray impedances of the connections between the CB and the DR, as explained in [4] and [5] for the JT-60SA case.

In addition, the highest overvoltages can occur in fault conditions, like for example a ground fault at one coil terminal exactly at the time of the FDU intervention. Studies were done for ITER to analyze different cases and to identify relevant overvoltage values at the superconducting coil terminals; they are reported in [6] and [7]. Moreover, besides the identification of the peak values of the coils terminal potential versus ground, another important issue is related to the voltage distribution among the turns inside each coil. This distribution is not linear during fast transients, thus the internal peak voltage value can be higher than the peak value at the coil terminals; this fact was also confirmed by tests made on the ITER TF coil mock-up [8]. Similar studies were done for JT-60SA too, where a suitable model of the coils was worked out, capable to reproduce these phenomena [9], [10].

The matter is not trivial; the estimation of maximum voltage stresses is very important to support the design work, aimed at finding the best compromise between requirements for the coil insulation and cost and size of FDUs, busbars and current leads. First studies on this topic for DEMO are the subject of this paper: the TF circuit in particular is analyzed with main reference to the number of coil groups, earthing system, and to the evaluation of relative merit of different topologies in limiting the voltage across the coil terminals and versus ground in normal and fault conditions.

2 DEMO Toroidal field circuit

In fusion experiments, the TF circuit is generally composed of a base converter supplying all the TF coils connected in series, with interleaved Fast Discharge Units (FDU) to balance the voltage to ground (Fig. 1). To reduce the voltage at their intervention, the number of FDU can be increased up to the number of TF coils. In ITER, the TF circuit is arranged in 9 groups of two coils and a FDU in between them, while in JT-60SA the 18 TF coils are grouped in sector of 6 coils, protected by 3 discharge units.

Presently, for DEMO, the solution with the lowest voltage

author's email: alberto.maistrello@igi.cnr.it

across the coils and to ground has been assumed, which means to have 16 sectors, with one FDU for each TF coil. The study of a TF circuit composed of 8 sectors (groups of 2 coils) is explored as well in this paper.

The main data of DEMO TF magnets used in the following analyses are summarized in Table 1.

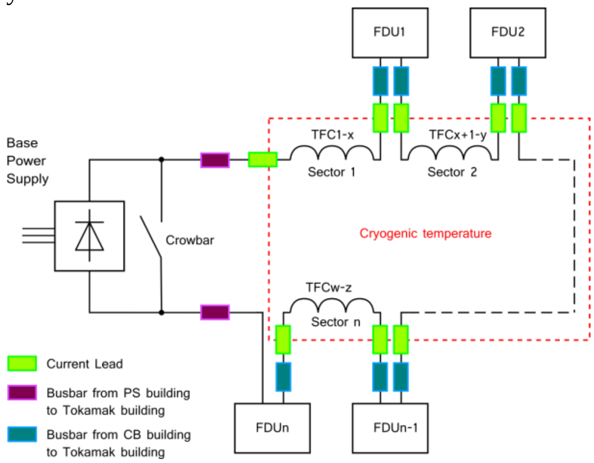

Fig. 1 – Generic TF circuit

Table 1 - Main data of DEMO1 TF coils [3]

Symbol	Description	Value	Unit
Ec	Stored energy per TF coil	9.12	GJ
Nt	Number of turns per coils	163	-
Iop	Operating coil current	90	kA
Lc	Inductance per TF coil	2.25	H
τ	Time constant for discharge	23.17	s
DR	Discharge resistance value (Dump Resistor)	97.1	mΩ
Vd	Voltage applied to the coils at the discharge	8.7	kV
t_f	FDU reaction time	1	s
i^2t_f	Joule integral during the discharge, including t_f	102	GA^2s

2.1 TF circuit topologies analysed for DEMO

Four different topologies have been identified as possible candidate for the DEMO TF circuit, differing for the earthing system and for the connection of the discharge resistors (DR), see Fig. 2.

The earthing systems derive from those adopted in ITER and JT-60SA: the first consisting in a couple of terminal resistors (TR) connected on one side to the terminals of each coil and in the central point to a common earthing resistor (ER) grounded on the other terminal (Fig. 2 - A). The JT-60SA earthing system is realized connecting the central point of each DR to ground through a grounded earthing resistor (Fig. 2 - B).

Both the earthing systems make the circuit symmetric in terms of voltage versus ground in normal operating conditions; in fact, the ground reference is fixed so that the voltage applied to the two terminals versus ground is half the total voltage across the coil, as sketched in Fig. 3.

As far as the connection point of the DR is concerned, both in ITER and JT-60SA the DR is connected in parallel to the CB of each FDU. Other possibilities, which were investigated for DEMO, are the connection of the DR to the coil terminals (Fig. 2 C and D).

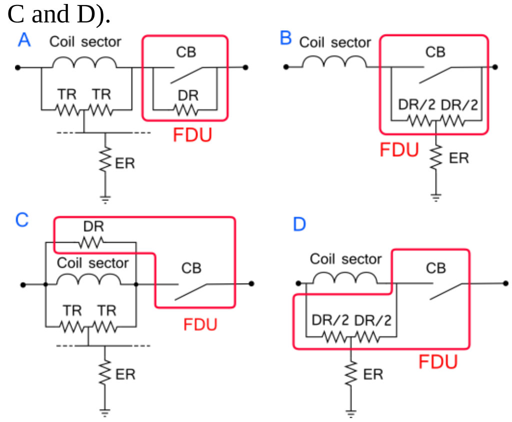

Fig. 2 - Circuit topologies: A is ITER-like, B is JT-60SA like, C and D differ from A and B respectively for having the discharge resistor connected in parallel to the relevant coil sector.

The study of these further topological arrangements seemed interesting because the connection of the DR in parallel to the coil implies that it is not short circuited by the CB even in case of its interruption failure; thus the time constant for the discharge and the related i^2t is not affected by this kind of fault. This means that, in principle, a backup CB is not required.

However, a first drawback of both C and D topologies is that also during the slow charge/discharge of the TF coils the DRs dissipate energy.

A second major drawback is that in case of untimely opening of the CB of one FDU only, the transient voltage across the CB raises up to the total circuit voltage at the discharge, and the voltage at the terminals of the close coils up to half of this value. Thus, a backup strategy would be anyway required, but it could not avoid the first transient peak. This leads discarding topologies C and D, therefore the paper reports the results of the analysis carried out for topologies A and B only.

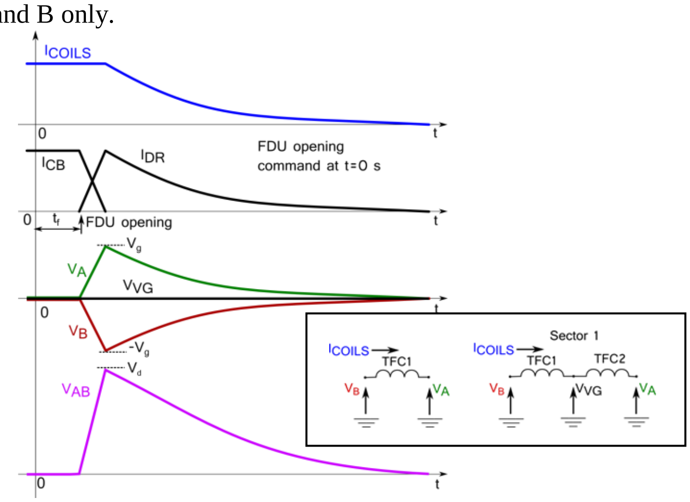

Fig. 3 - Conceptual waveforms of main currents and voltages in the TF circuit

3 Analysis of different Operating conditions

The analyses described in the following are addressed to estimate the waveforms of the voltage applied at the coil terminals with respect to ground, the voltage across each coil and the i^2t after the intervention of FDUs, assuming the topologies A and B above described, and considering the operating conditions:

1. Intervention of all the FDUs;
2. Intervention of all the FDUs and a ground fault at one FDU terminal;
3. Intervention of all the FDUs, except one (FDU opening failure);
4. Intervention of all the FDUs except one opening with a delay of 10 ms;
5. Intervention of all the FDUs except one, and a ground fault on the opposite side of the circuit with respect to the faulted FDU;
6. Intervention of all the FDUs except one, and a ground fault on the sector terminal next to the faulted FDU;

The following simplifications are assumed for the analyses, which are acceptable for the scope of the present work:

- the PS is assumed short-circuited at the moment of the FDU intervention;
- the busbars stray parameters are neglected;
- the FDU CB is modelled as an ideal switch;
- each TF coil is modelled as a pure inductor;
- coil mutual couplings are neglected;
- the resistance of the fault branch is zero;
- the presence of a backup circuit breaker is neglected;

For each operating condition, the desired quantities have been estimated by means of numerical simulations of electrical models of the TF circuit for each of the A, B topologies under evaluation.

3.1 TF circuit with 16 sectors

An example of the analysis is given in the following for the case of the TF circuit with 16 sectors and topology A (ITER like – Fig. 4) and the results of numerical simulations are shown in Fig. 5 for the operating condition #6: worst case for topology A in terms of maximum peak voltage values.

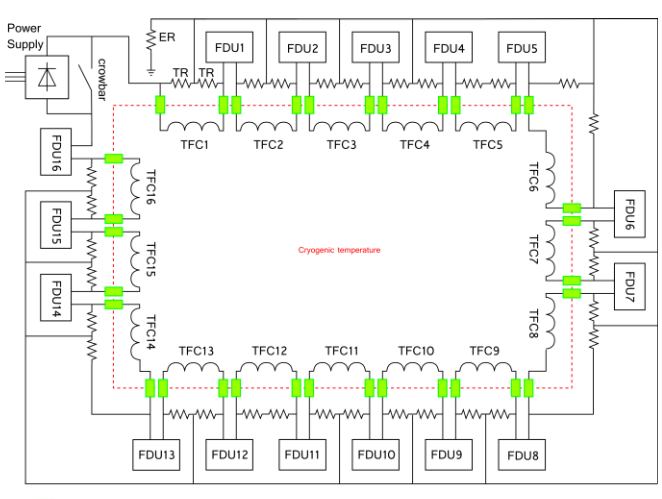

Fig. 4 - DEMO TF circuit with 16 sectors, topology A

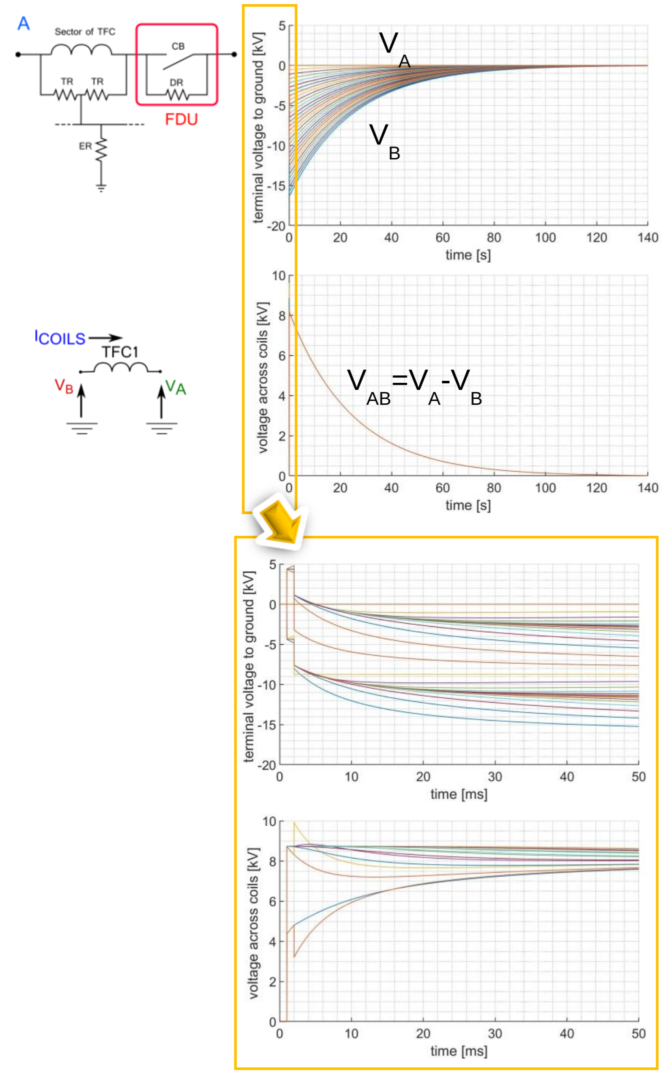

Fig. 5 - 16 sectors, topology A, operating condition #6: Coils terminal voltage to ground (V_A,V_B) and voltage applied across each coil (V_{AB})

The opening of all the FDUs Circuit Breaker (CB) except FDU1 occurs at 1 ms and at 2 ms there is also a ground fault at the FDU2 terminal, corresponding to A terminal of the second coil (TFC2 in Fig.4). The first plot of Fig. 5 shows the voltage waveforms of the coil terminals (V_A and V_B) versus ground, the second plot shows the voltage across the coils, the third and fourth plots are the zoomed view of the previous ones around the FDUs intervention and ground fault times.

The symmetry of the circuit is lost already at 1 ms and the voltages to ground are different for each coil terminals.

A summary of the results of all the cases analyzed is given in Table 2, where the same quantities (peak absolute value of the coil terminal voltage to ground (V_A, V_B), of the voltage applied to the coil (V_{AB}) and the i^2t value) for each TF circuit topology and operating condition are reported. For both topologies there is one operating condition, the sixth, which causes a peak absolute voltage to ground around 16 kV: about 3.5 times higher than that one in case of regular FDU intervention. The maximum value of 13.2 kV for the peak differential voltage V_{AB} is obtained for the operating condition #6 and topology B, while for topology A the peak differential voltage remains below 11 kV for all the operating conditions.

The i^2t value, as expected, increases for the operating conditions foreseeing the FDU opening failure; a delayed opening of 10 ms (operating condition #4) does not significantly influence this parameter.

Table 2 - 16 sectors: peak absolute coil terminal voltage to ground (V_A, V_B), peak absolute voltage applied to the coil (V_{AB}) and i^2t

id	Topology A			Topology B		
	$V_{A,B}$ [kV]	V_{AB} [kV]	i^2t [GA²s]	$V_{A,B}$ [kV]	V_{AB} [kV]	i^2t [GA²s]
1	4.4	8.7	102.0	4.4	8.7	102.0
2	8.5	10.2	102.0	8.7	13.1	102.1
3	8.1	8.7	108.3	8.1	8.7	108.3
4	6.5	10.9	102.0	7.6	11.5	102.0
5	12.4	10.2	108.3	12.2	13.1	108.3
6	16.2	9.9	108.3	16.0	13.2	108.6

3.2 TF circuit with 8 sectors

The numerical simulations have been repeated for the case of TF circuit with 8 sectors (**Error! Reference source not found.**). **Error! Reference source not found.** summarizes all the results; as expected, the voltage values are almost doubled with respect to the 16 sector cases.

Table 3 - 8 sectors: peak absolute coil terminal voltage to ground (V_A, V_B), peak absolute voltage applied to the coil (V_{AB}) and i^2t

id	Topology A			Topology B		
	$V_{A,B}$ kV	V_{AB} kV	i^2t GA²s	$V_{A,B}$ kV	V_{AB} kV	i^2t GA²s
1	8.7	17.5	102.0	8.7	17.5	102.0
2	17.5	20.4	102.0	17.5	26.2	102.1
3	15.2	17.5	115.5	15.2	17.5	115.4
4	11.8	20.5	102.0	13.1	21.8	102.0
5	23.8	20.4	115.5	23.7	26.2	115.5
6	30.3	20.1	115.5	30.2	26.3	115.5

4 Conclusion and future work

Four different topologies (called A, B, C and D) have been identified as possible candidate for the DEMO TF circuit, differing for the earthing system (ITER-like or JT-60SA like) and for the connection of the discharge resistors: in parallel to the FDU circuit breaker or to the coil.

The analysis of fault conditions led to discard C and D topologies since in case of untimely intervention of one FDU only, the transient voltage peak applied to the coil could raise to very high values before the intervention of a backup circuit breaker. However, their relative merits could be keeped in further mixed topologies, that could be studied in the future.

The results of numerical simulations of the TF circuit operation for both the cases with 16 and 8 coil sectors and for A and B topologies have shown minor merits of one topology versus the other in terms of maximum values of voltage at the coil terminals, across the coils and i^2t in the coils during the discharge. Both of them could be adopted for DEMO: deeper analyses will be possible after having defined the technology of the FDU CB and at least a tentative layout to evaluate the stray impedances of the TF circuit connections so as to better estimate the transient voltage waveforms at the coil discharge and gain more arguments for the topology selection.

As for the reduction of the number of TF coil sectors to eight, the analyses suggest to maintain the present reference TF circuit topology with 16 sectors.

However, it has to be underlined that all these analyses have been carried out assuming resistors with constant resistance. If resistors with temperature dependent resistance were adopted, as for ITER and JT-60SA, the peak voltage value could be significantly reduced.

Acknowldgement

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