Design Optimization for the Quench Protection of DTT's Superconducting Toroidal Field Magnets

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The paper is focused on the optimal design of Fast Discharge Unit for the quench protection of the Toroidal Field magnets of the Divertor Tokamak Test facility (DTT), an experimental facility under construction in ENEA Frascati Research Centre (Rome, Italy). The Fast Discharge Unit is a safety key component that protects the superconducting magnets when a quench is detected through the fast extraction of the energy stored in the magnets by adding in the Toroidal Field magnets circuit a discharge dump resistor. A comparison between a fixed dump resistor and a switched variable dump resistor has been implemented by changing resistor parameters and by using multiple control of the power electronics components (IGCTs).

The new configuration allows to reduce the maximum voltage and thermal stresses both for superconducting magnets and for FDUs (Fast Discharge Units), reducing the insulation level of all TF (Toroidal Field) coil circuits, including also the power supply, reducing the hotspot temperature on the TF coils and the specific energy through them. Another advantage of the configuration is that it reduces the sizing of all electrical devices of TF coil circuits achieving a more effective and more reliable design, also reducing the overall costs.

Keywords: FDU, Quench Protection, Superconducting Magnets, Dump Resistor, Linear Discharge, DTT.

1. Introduction to DTT

Divertor Tokamak Test facility (DTT) is a facility under construction in ENEA research center in Frascati (Rome); this facility is part of the European fusion research programme.

The DTT project was approved by EUROfusion in 2017 and the first plasma is expected in 2026; it will follow ITER during its operational phase since DTT collected data will be used as support for the European nuclear fusion research.

The main tasks of this project are:

- to test different divertor design solutions;
- to improve heat exhaust [1].

The project is tightly connected to nuclear fusion project DEMO (DEMOnstration power plant) as all the data collected in DTT project will be used and studied to improve the final performances of a commercial nuclear fusion reactor. The design of DTT has been proposed in recent years by ENEA in collaboration with the scientific world and Italian universities. Presently, the DTT project is developed in partnership among public and private research bodies joined in a cooperative entity (DTT S.C. a.r.l.) that includes ENEA, ENI and CREATE Consortium; other scientific and academic entities have expressed the interest to join the DTT S.c.a.r.l.

This paper is focused on modelling and simulation of a Fast Discharge Unit (FDU) for quench protection of the Toroidal Field Coils (TFCs) of the DTT in order to protect the machine and to deal with all the technical problems about the magnetic energy dissipation of the machine itself, which is about 2 GJ.

The FDUs are designed and projected to open the feeding circuit of the superconducting magnets of the tokamak machine and to dissipate all the magnetic energy via a Dump Resistor (DR). The classic design approach of this component foresaw a static resistor to dissipate magnetic energy stored in TF superconducting magnets through an exponential discharge. Instead in this work through switched variable dump resistors we achieve a more efficient linear discharge optimizing all parameters of the FDU described in details in the following Sections.

The FDU opening circuit signal is triggered when a quench is detected; this phenomenon occurs when a superconductor is in the superconducting stage: mechanical stress or a little defect on the conductor can cause a hotspot in the coil by producing a localized increase in temperature of some degrees which can propagate itself in the whole superconductor and forcing it to return in the normal conduction state. Since the nominal current for the TFCs is 42,5 kA, the intervention of the FDUs must be as fast as possible in order to avoid the complete destruction of the superconductor magnet.

2. DTT Superconducting Magnet System

DTT superconducting magnet system consists of three types of superconductor (cooled down by a super critical helium at 4,5 K) [2]:

- 18 Toroidal Field Coils (TFCs) in Nb_3Sn operating at 42,5 kA (blue in Fig.1);
- 6 independently fed Central Solenoid Coils (CSs) operating at 30 kA (pink in Fig.1);

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- 6 independently fed Poloidal Field Coils (PFCs) operating at 30 kA (two of which made in Nb_3Sn, other in NbTi) (white in Fig.1);

The TFCs winding packs are constituted by 5 Double-Pancakes enclosed into a stainless-steel casing 316LN as structure reinforce. The TFCs are fed in series at 42,5 kA and further are grouped in 3 sectors in order to limit the maximum voltage at coil terminals during safety discharge with FDU.

The 18 TFCs are divided in three group and each FDU is connected in series with each group of 6 TFCs so the current circulating into each FDU during normal operation is 42,5 kA as the superconducting magnets.

In the following simulations the FDUs were considered with a switched variable dump resistor implemented by changing resistor parameters and multiple control of the power electronics components (IGCTs).

The total inductance of the TFCs has an estimated value equal to 2,272 H.

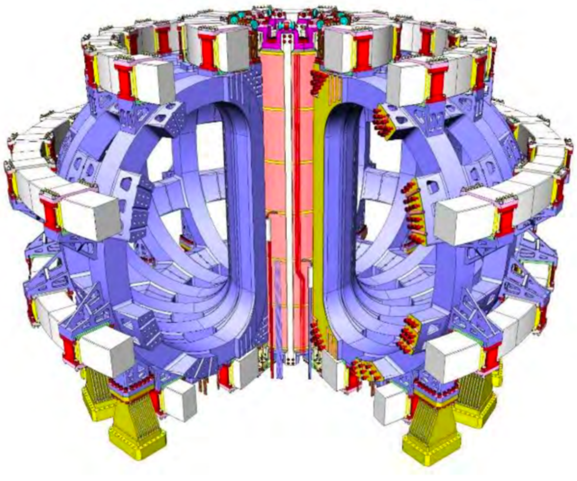

Fig. 1 Superconducting Magnet System of DTT.

3. Toroidal Field Coils' Fast Discharge Units (FDUs)

The Fast Discharge Unit is a safety key component of the Tokamak. The total magnetic energy stored in the TFCs is about 2 GJ, as mentioned before. This energy must be rapidly extracted from the superconducting magnets in case of quench or in case of fault in another system.

The reliability of the FDU is fundamental for the safety of all the superconducting magnet since a malfunction on it causes an increase in temperature of the conductors with a related high thermal stress.

The first FDU design simulated on MATLAB Simulink of the FDU is composed by 5 components, this layout is the one used for the Quench Protection Circuit of JT-60SA (Fig. 2) [3]:

- BPS: bypass switch (mechanical)
- SCB: static circuit breaker
- Backup pyrobreaker
- Dump Resistor (DR)
- Earthing resistor

During normal operation the BPS is closed and it brings 42,5 kA to the superconducting magnets. When a quench is detected, a closing signal is given to the SCB and the current flows from the BPS to the SCB with a delay time due to power electronics; once the current on the BPS reaches a zero value, an opening signal is given to the SCB and the current flows into the DR with an exponential trend and a dissipation of the energy with Joule effect with a time constant of τ due to the R-L parameters of the coils [2, 3, 4].

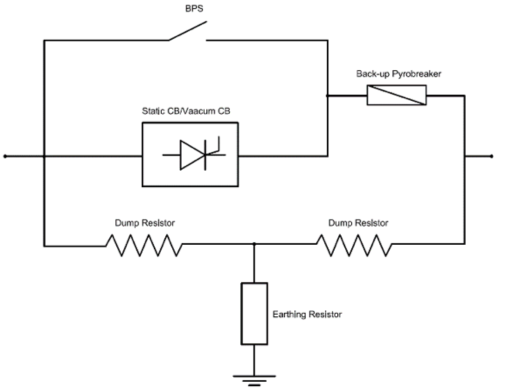

Fig. 2 Simplified scheme of FDU

4. FDU Upgrade with Linear Discharge

The exponential discharge is achieved with a fixed value on the DR which is $0{,}151\,\Omega$ and a $\tau = 5\,s$; those parameters were evaluated considering a total inductance of the TFCs of 2,272 H. This configuration involves a voltage applied to the coil sector at the discharge of 6,5 kV.

A new configuration was studied and simulated: the fixed Dump Resistor was replaced with a switched Dump Resistor (also called linear discharge) based on 15 IGCT's branches controlled on threshold currents. This new configuration, shown on Fig.3 allows better performances even with a more complex layout [5].

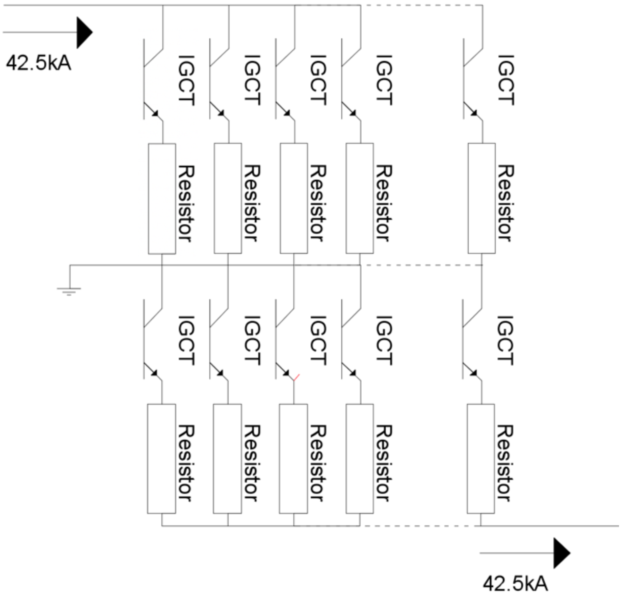

Fig. 3 New configuration of the DR for Linear Discharge [5].

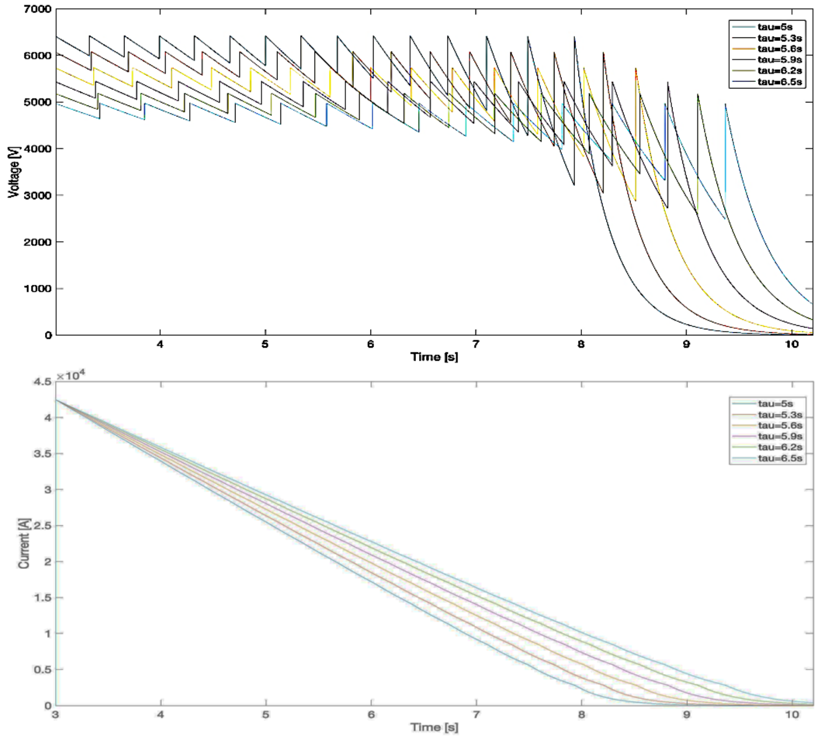

Fig. 4 Overview of the voltage related to the τ value.

With a linear discharge the time constant is different from the exponential one, in particular the starting time constant is calculated with the equivalent resistance but during the discharge the time constant keeps changing so the new time constant related to linear discharge is to be intended as the starting value with an equivalent resistance.

In Table 1 all the main values are reported of the simulation with exponential discharge and time constant of $\tau = 5\ s$.

The new simulation conducted with linear discharge considered the same value of nominal current of 42,5 kA and equivalent inductance of 2,272 H; only the starting value of the time constant was changed from 5 s to 6,5 s with an interval of 0,3 s (with different simulations), Table 2.

Table 1. Electrical and thermal simulation results with exponential discharge.

$\tau\ [s]$	**Discharge time [s]**	**Maximum Volt. [V]**	**Hotspot Temp. [K]**	**Fix.DR [Ω]**	$I^2t\ [GA^2s]$
5	23,5	6437,33	312	0,151	4,33

With the results of the previous tables, there are some evident advantages by using a switching DR discharge (also called linear discharge due to the linear trend of the TFCs current, Fig.4).

With a preliminary consideration about the hotspot temperature, the time constant value of $\tau = 6{,}5\ s$ was not considered in order to avoid to increase the temperature on the superconducting magnet above 250 K, this is justified by the following IGCT fault analysis in which more overtemperature are reached by the magnet due to different IGCTs' fault scenarios.

Table 2. Electrical and thermal simulation results with linear discharge.

$\tau\ [s]$	**Discharge time [s]**	**Maximum Volt. [V]**	**Hotspot Temp. [K]**	**Var.DR [Ω]**	$I^2t\ [GA^2s]$
5	5,9	6437,33	197	0,151	3,03
5,3	6,3	6072,96	207	0,143	3,20
5,6	6,7	5747,62	220	0,135	3,38
5,9	7,2	5455,37	232	0,128	3,57
6,2	**7,4**	**5191,40**	**245**	**0,122**	**3,74**
6,5	7,5	4951,79	258	0,117	3,90

The main considerations are reported with a $\tau = 6{,}2\ s$: with this value there is a better performance on the discharge (related to the exponential discharge), in particular:

- Discharge time reduced of 68,51%;
- Maximum voltage reduced of 19,35%;
- Hotspot temperature at the end of the discharge reduced of 21,47%;
- Specific energy through reduced of 13,52%.

5. IGCT Fault analysis

An extended fault analysis with switched Dump Resistor on IGCTs has been carried out by considering the values of $\tau = 5{,}9\ s$ and $\tau = 6{,}2\ s$ in order to reduce the maximum overvoltage on the conductors (the value of $\tau = 6{,}5$ s was excluded for the reason explained in the previous paragraph).

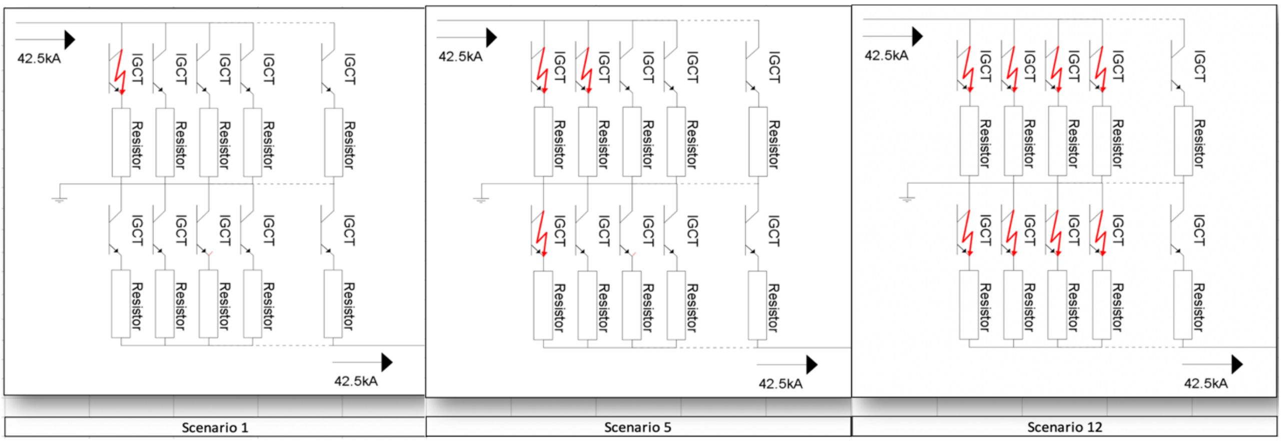

Fig. 5 Different scenarios example.

In the following simulations, different scenarios were implemented considering the worst case depending on the number of IGCTs faulted, in particular: a Scenario 1 is with only one IGCT faulted on the first branch which must open during the discharge (Fig. 5, Scenario 1); in this way the first branch remains half closed during the discharge by changing the equivalent Dump Resistor value and slowing down the discharge process (all the scenarios were considered with the worst case because the power electronic device, in this way, keeps the failure for the longest time as possible).

With a time constant of $\tau = 5{,}9\ s$ the hotspot temperature is reached with a Scenario 12 (8 faults on the first IGCTs); with a time constant of $\tau = 6{,}2\ s$ the hotspot temperature of 250 K is reached with just 3 faults (Scenario 5) but, with further investigations, with a fault on every IGCT of a single FDU the maximum temperature reached is 271 K which is otherwise acceptable.

The results reported on Table 3 are simulated with a Dump Resistor of 0,122 Ω, with a maximum related voltage of 5191,4 V and $\tau = 6{,}2\ s$.

Table 3. IGCT fault analysis with $\tau = 6{,}2\ s$.

Scenario	**Number of IGCT faulted**	**Discharge time [s]**	$I^2t\ [GA^2s]$	**Hotspot temperature [K]**
1	1	7,690	3,7920	249
2	2	7,835	3,8256	252
3	2	7,987	3,8408	253
4	3	7,931	3,8492	253
5	3	8,148	3,8756	256
12	8	8,712	3,9992	265
13	16	9,066	4,0586	270
14	**FDU 1 not working**	**9,186**	**4,0653**	**271**

6. Conclusion

In this article a different solution is described for the discharge during a quench of the DTT Toroidal Field superconducting magnets.

The linear discharge is more efficient than the exponential one allowing a better performance and a general improvement on all the thermal and electrical parameters with an important reduction on the maximum voltage which is of about 5,2 kV for $\tau = 6{,}2$ s; however, the more complex layout needs a higher volume occupied by the machine and a more general complexity of the Fast Discharge Unit. With a linear discharge a higher value of τ is admitted and, the higher is this value the lower is the overvoltage on the FDU; the results of the optimization procedure allows to find a tradeoff between the need of reducing the overvoltage and the maximum hotspot temperature limit.

Finally, a fault analysis has been carried out by simulating different IGCT's fault scenarios, concluding even one complete fault on all IGCTs of an entire FDU is accepted, during a linear discharge and in this case, the hotspot temperature on the TFCs would be lower than the exponential discharge with no faults; this is due to the other two FDUs which is supposed are working without faults and by discharging with a linear trend.

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