

Article

Preliminary Design of the Electrical Power Systems for DTT Nuclear Fusion Plant

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Abstract: The realization of the Divertor Tokamak Test (DTT) facility is one of the key milestones of the European Roadmap, aiming to explore alternative power exhaust solutions for DEMO, the first nuclear-fusion power plant that will be connected to the European grid. For the actual implementation of the DTT and DEMO plants, it is necessary to define the structure of the internal electric power distribution system, able to supply unconventional loads with a sufficient level of reliability. The present paper reports the preliminary studies for the feasibility and realization of the electrical power systems of DTT, describing the methodology adopted to obtain a first distribution configuration and providing some simulation results. In particular, the first stage of the study deals with the survey and characterization of the electrical loads, which allows defining a general layout of the facility and size the main electrical components. To verify the correctness of the assumptions, simulation models of the grid were implemented in the DiGSILENT PowerFactory software in order to carry out power flow and fault analyses.

Keywords: nuclear fusion; balance of plant; electrical grid; fusion reactor; tokamak; power system; power flow



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1. Introduction

The Divertor Tokamak Test (DTT) facility is one of the main projects within the framework of the European Roadmap to the realization of fusion energy [1] whose final goal is the development of DEMO [2,3], the first demonstrative power plant able to deliver to an external grid a net electrical energy produced by nuclear-fusion processes. DEMO is presently under design and is expected to be connected to the European grid by 2050 [1].

Among the eight missions towards fusion electricity defined in the European Roadmap, DTT is a key facility in the framework of Mission 2 (“Heat-exhaust system”), aiming to identify the optimal solution for the problem of disposing the heat load through the “divertor” [4,5], which is one of the main components of the future commercial reactors. Even though some conventional approaches for the divertor systems will be tested in the international experiment ITER, under construction in France [6], it could be difficult to extrapolate them to the operating conditions expected in DEMO or in a commercial power plant. For this reason, the DTT facility is a high-performance superconducting tokamak [4] addressed to explore alternative solutions for the power exhaust problem by testing different divertor geometries and materials suitable for DEMO [7].

The construction of the DTT facility started in the ENEA Research Center in Frascati, Italy, with several scientific collaborations and financial supports including the European Agency EUROfusion. The number of DTT partners (universities, research bodies and companies) is continuously growing [8].

The design of the electrical power systems of a nuclear-fusion plant is a crucial issue, especially to investigate the possibility to adopt it as an energy source. Unlike DEMO, which is designed to deliver the net electrical energy to the grid [3,9], DTT is an experimental plant, which means that its electrical power systems will be “simpler” than those expected for DEMO [10] and the nuclear requirements are less stringent [11]. Nevertheless, the power systems are not trivial in terms of size and complexity, especially in terms of power density [12–14]. In fact, all the main types of loads present in ITER (and maybe in DEMO) will be implemented in DTT [12,15,16]: Converter for superconducting and copper coils [14], electron cyclotron resonance heating (ECRH) [17], ion cyclotron resonance heating (ICRH) [18], negative neutral beam injector (NBI) [19], cryogenic and water cooling systems and so on [10,16]. Therefore, DTT may also be a good reduced-scale experiment for the study and the optimization of the power systems for possible ITER upgrades and for DEMO.

As a part of the process to define the electrical supply system of DTT, the identification of the electrical loads is the first necessary step [16]. Since the loads have been characterized from a quantitative and a qualitative point of view, it is possible to proceed to the preliminary design and sizing of the internal distribution network.

The present paper describes the preliminary studies to verify the design of the electrical distribution and protection systems of the DTT plant. The scheme obtained for the electrical system was implemented in the DigSILENT PowerFactory software environment [20] in order to analyze the trends of power flows and to verify the design of the main electrical components.

The paper is divided in five sections. Section 2 presents the main DTT features and shows how the electrical loads were characterized and classified. Section 3 describes the organization of the distribution system and provides a first estimation of the required power. Section 4 presents the results of the model implemented for the preliminary design of the power systems (power flow and fault analyses). Section 5 reports the conclusions.

2. DTT Power Plant

2.1. Main Features

Figure 1 summarizes the power demand estimated for the DTT facility. As a tokamak, DTT has an intrinsically pulsed behavior, strictly related to the physics of plasma, which implies that the grid will supply the power in a discontinuous way [3,10,13]. In particular, as shown in Figure 1, the DTT nominal operations are characterized by a baseline with a power absorption lower than 100 MVA and by pulses reaching about 300 MVA for a duration in the range 100–200 s. These periodic pulses are repeated every 3600 s (duty cycle $\approx 200\text{ s}/3600\text{ s}$) and are due to the actual experimental phases, in which a high power is required to control the fusion plasma.

The power profile reported in Figure 1 derives from the superimposition of some high-power pulsed loads on a constant baseline produced by loads characterized by small variations. This difference will be exploited for a first load classification and for the selection of the distribution structure. As DTT is an experiment with successive upgrades and possible improvements, the power demand estimation also takes into account some theoretical considerations and experiences in the design of other tokamaks (such as ITER, JT-60SA and FTU [10]). The estimated power demand is compared in Figure 1 with the load profile requested for the connection to the Italian Transmission System Operator (TSO).

Since the electrical grid present in the zone of the DTT facility is not adequate to support such high and variable power, the grid infrastructures will be significantly developed. Two new 150-kV lines will be installed (for about 15 km) to connect a new TSO substation to the closest 380-kV line. The new TSO substation will be placed in proximity to the ENEA Research Center. Then, the DTT facility will be supplied by the National High Voltage Grid (NHVG) through a single (not redundant) underground 150-kV cable (with a length of about 1 km) connecting the new TSO substation with a new substation, called SS0, located inside the ENEA Research Center.

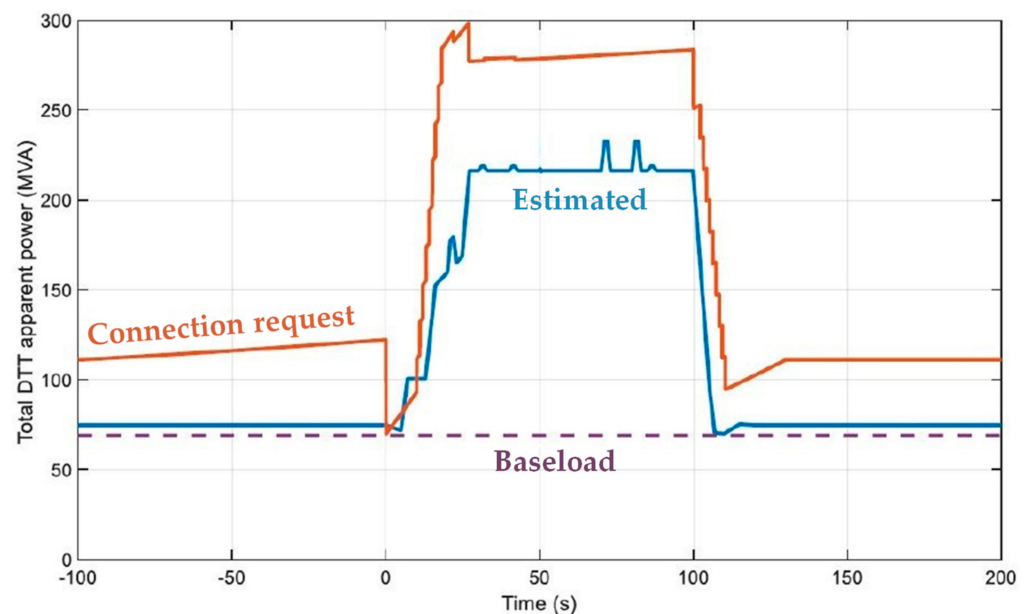


Figure 1. DTT estimated load profile compared with the connection request to the national grid. The dashed line shows the contribution of the baseload that is practically constant during the entire operation cycle.

2.2. Load Classification

An adequate survey of the electrical loads is necessary to preliminarily define the electrical distribution configuration, cable characteristics and other equipment design.

Electrical loads can be classified mainly according to the following criteria:

1. Power profiles, leading to two possible types of load:
 - a. Steady-state loads: Characterized by a continuous load profile (i.e., constant or quasi-constant load with slow variations).
 - b. Pulsed loads: Characterized by an intermittent load profile, a very high value of load (comparable to the rating of the equipment) and very sharp variations; this kind of load could imply severe effects on the whole electrical network, such as very deep voltage sags and load disconnections.
2. Power supply reliability, classified according to the following categories:
 - a. Ordinary loads (OLs): Loads related to the normal operations of the processes and utilities; the lack of their power supply does not impair the safety of the personnel and does not cause damages to the plant. The national grid constitutes the normal (or main) power supply.
 - b. Investment Protection (IP) loads: Essential loads related to keeping alive the essential services of the plant (e.g., air conditioning, fire-fighting, cooling water, etc.) and to avoiding extensive damages to the plant in the case of sudden loss of the main power supply. These loads may accept an interruption in the power supply of at least 90 s; in the case of sudden loss of the main power supply, they will be fed by the emergency power generation.
 - c. Safety Important Class (SIC) loads: Vital loads related to the safety of the personnel, to the protection and continuous monitoring of the plant and to the safe shut down of the equipment in order to avoid potential incidents in the case of sudden loss of power supply. These loads will be uninterruptedly fed by the AC UPSs and DC UPSs.

To allow a smooth design process of the electrical distribution system, all electrical loads are characterized according to the above-mentioned criteria and categories and

collected in an Electrical Load List (ELL), a database clustering the loads as functional macro-areas, in a Plant Breakdown Structures (PBS) [16].

For each load, the following relevant information is indicated:

- Location: The building where the load is located.
- Load profile: Steady state or pulsed.
- Voltage at the terminals.
- Load Class: OL, IP or SIC.
- Type of power supply, depending on whether the load is powered only by the national grid (normal load) or also by the Emergency Diesel Generator (EDG) or by the Uninterruptible Power Supply system (UPS).
- Power factor.
- Power absorption in terms of active and apparent power, measured in MW and MVA, respectively (only peak values are reported).
- Load center: The distribution substation to which the load is connected.

The number of PBS currently identified for DTT is ten; they are listed in Table 1, which also provides a short description for each of them.

Table 1. PBS organization and description.

PBS	Name	Description
1	Physics	This PBS concerns the study of plasma physics, so no loads are foreseen No (or negligible) loads are expected in this PBS No (or negligible) loads are expected in this PBS
2	Magnets	
3	Mechanical Structures	
4	Heating and Current Drive (H&CD)	This PBS concerns the additional heating system and consists of three subsections, corresponding to the three heating systems (ECRH, ICRH, NBI) [10,17–19]
5	Auxiliary Plant Systems	This PBS includes the main components of the auxiliary systems of DTT (Cryogenic System, Water Cooling System, Vacuum Pumping System, Fueling Control Systems, Baking and Cleaning Systems)
6	Coil Power Supply Systems	This PBS collects all the components belonging to the subsystems (power converters) to feeding the coils [10,14,21,22]
7	Building Layout and Services	This PBS includes the service loads such as light panel, FM panel and Heating, Ventilation and Air Conditioning (HVAC) system
8	Diagnostics and Control System	This PBS contains information about diagnostics, instrumentation and control system, telecommunication and security system
9	System Level Engineering	No (or negligible) loads are expected in this PBS
10	Remote Handling	This PBS is about remote handling systems (to handle components inside the vessel or in harsh environments)

3. Distribution System of DTT Facility

3.1. Electrical Distribution Network

Because of the different nature of the steady-state and pulsed-power loads, the design choice was to split the DTT distribution network in two sections:

- Steady-State Electrical Distribution (SSED) designated to supply only the steady-state loads.
- Pulsed-Power Electrical Distribution (PPED) designated to supply only the pulsed loads.

This means that the SSED and the PPED sections are electrically coupled only at the HV level, while their downstream distributions are kept separated.

As a general design choice, the MV level for the internal electrical distribution is fixed at 20 kV. To be precise, the power flow analyses identified 21 kV as the optimal value for the no-load secondary voltage at the central tap of the HV/MV transformers. However, such voltage will be simply denoted as 20 kV in the following.

Based on this design approach, as shown in Figure 2, the HV/MV substation SS0 includes six 150/20 kV transformers in order to balance the load requirements and to guarantee an adequate level of reliability and redundancy in the event of a failure of one of the transformers.

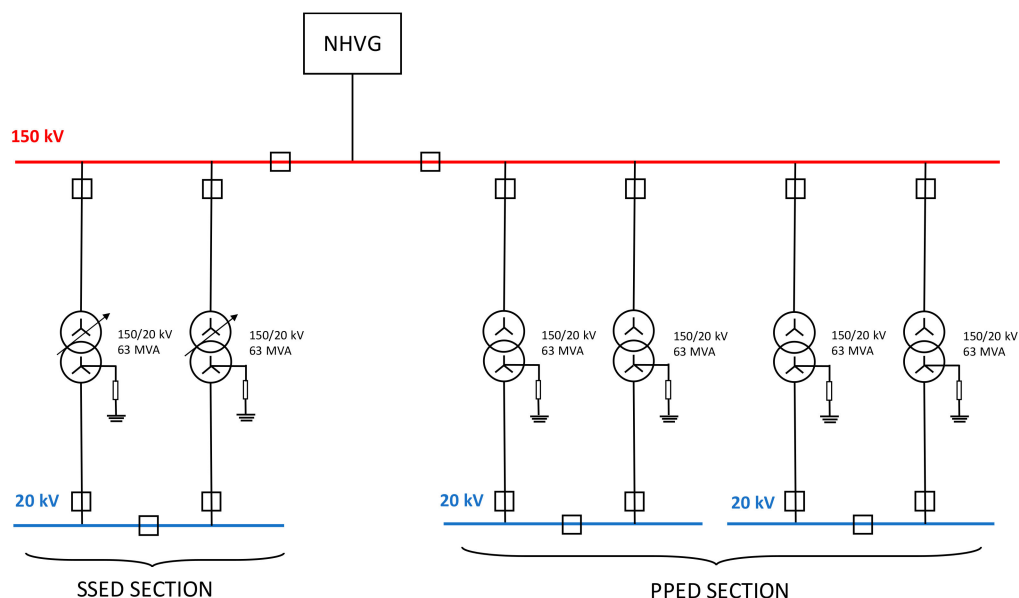


Figure 2. Scheme of the DTT HV/MV substation (SS0).

In particular, there will be:

- Four three-phase two-winding power transformers with a rated power of 63 MVA (and an overload capacity up to 100 MVA for 100 s) to supply PPED loads.
- Two three-phase two-winding power transformers with a rated power of 63 MVA to supply SSED loads, in a double redundant configuration.

As shown in Figure 2, the two SSED transformers are equipped with on-load tap changers (OLTCs). Such a solution was not adopted for the PPED section because, since the OLTCs cannot follow the fast load variations of the PPED loads, the limited advantage does not compensate the risk of instabilities and the possible reduction in the transformers' reliability.

The distribution system, downstream from the SS0, is arranged in different voltage levels that are: 20 kV, 6 kV and 400 V (230 V single phase).

3.2. Preliminary Layout and Configuration of the Electrical Distribution Network

The power profile, the classification of the facility loads and the selection of the voltage levels allowed to draw up a preliminary layout of the DTT site and to identify the locations of five electrical load centers (LCs), denoted as LC1, LC2, LC3, LC4 and LC5, respectively, where the distribution equipment will be installed. The allocation of each LC, shown in Figure 3, has been chosen to be as barycentric with possible respect to the supplied loads in order to contain the cross section of power cables within acceptable limits. In this way, the maximum distance of each low-voltage load result is to be within 200–300 m from its LC.

Each LC can supply all the different categories of loads (SSED, PPED, OL, EDG, UPS) and voltage level. However, a specific category or voltage level could be unnecessary in some cases.

The MV distribution network of SSED (20 kV and 6 kV) will be arranged in double radial configuration, while the LV distribution network of SSED is arranged in single radial configuration. The MV distribution network of PPED (20 kV) is arranged in single radial configuration. Considering that the SSED LV distribution network is integrated by the

EDG and UPS systems, the redundancy of the electrical system is ensured leading to a good level of reliability.

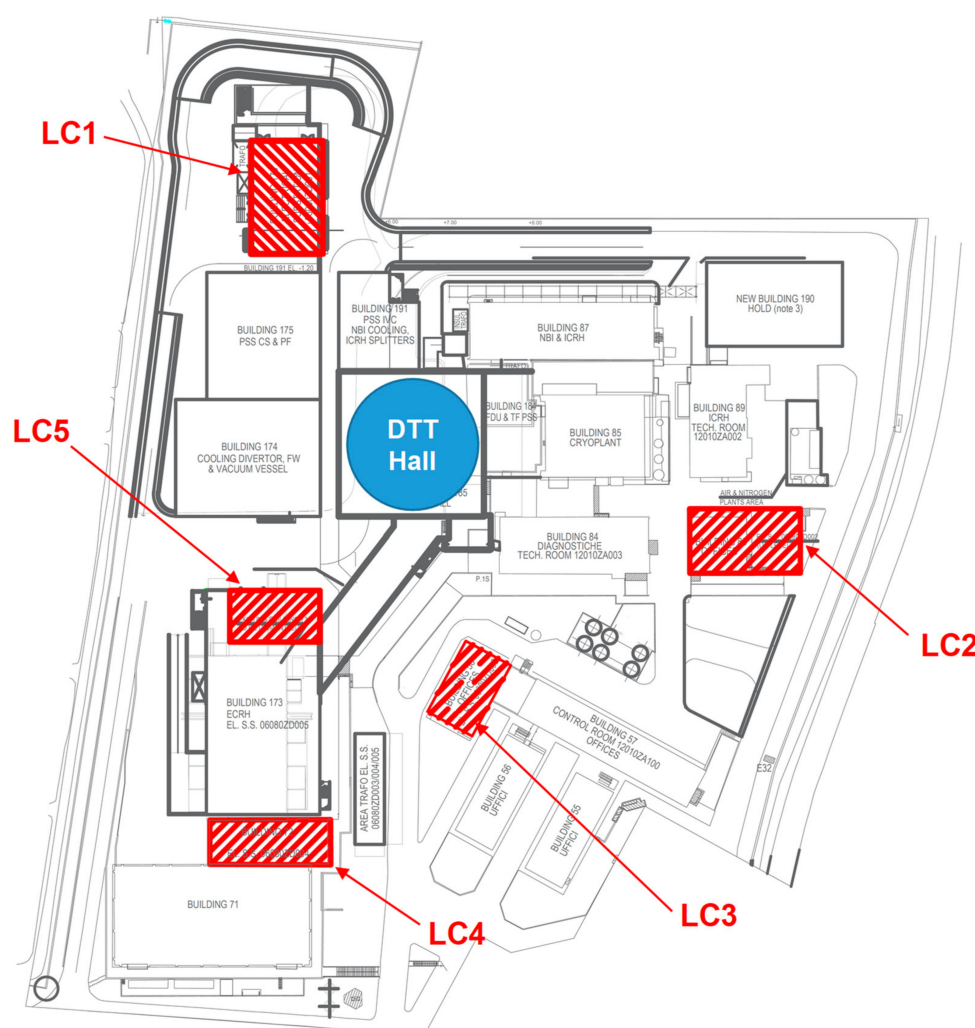


Figure 3. Layout of DTT facility, with a focus on the 5 LCs. All the services are used for the operation of the tokamak located inside the DTT Hall.

The five distribution LCs are supplied by the 20-kV system of the HV/MV substation, directly or indirectly.

The electrical configuration of each LC is defined according to the following rules:

1. For the 20-kV SSED section, the main power supply will be derived from the HV/MV substation and brought through two redundant 20-kV cable lines to each LC, where foreseen (like for LC1, LC2 and LC5, while LC3 and LC4 are powered at 400 V by LC5). Each couple of feeders will be connected to a SF₆-gas insulated type (GIS) switchgear in double radial configuration. From each 20-kV SSED switchgear it will also be possible to directly feed loads classified as steady state.
2. In LCs where pulsed loads are also foreseen, power supply will be derived from the 20-kV PPED section of the HV/MV substation and brought to each concerned LC through non-redundant 20-kV feeders, each one made by a cable line. Each feeder will be connected to the switchgear in single radial configuration. The PPED distribution system will be at 20 kV only; pulsed loads which cannot be directly supplied at 20 kV shall be fed by the SSED distribution system.
3. Downstream from the 20-kV SSED switchgears, the distribution system may be composed of:

- Double radial 6-kV distribution level obtained through redundant 20/6.3 kV power transformers connected to air-insulated type switchgears in double radial configuration.
- (a) Single radial 400–230 V distribution level obtained through 20/0.42–0.24 kV power transformers connected to air-insulated type switchgears in single radial configuration with an additional incomer from the spare 20/0.42–0.24 kV power transformer installed in each LC.
- One or more EDG for each LC will be installed and connected to a dedicated LV distribution switchgear, depending on how the electrical network of the LC is configured. It distributes the emergency power to the switchgears where essential loads are connected or, in the case that all essential loads are connected to only one switchgear, the EDG will be directly connected to this latter.
- LV auxiliary service panels are foreseen to feed the minor static loads (such as lighting, power sockets, auxiliary loads, etc.) not directly related to the main processes and utilities. Each panel will be in single radial configuration, fed by a dedicated 0.4/0.42–0.24 kV isolation transformer with a spare incomer to connect an external service diesel generator, if necessary.

3.3. Preliminary Evaluation of the Power

According to the load classification and to the information listed in the ELL, a load analysis with the aim of achieving an electrical load balance was drawn up. The load analysis constitutes the basis to evaluate the power required by the entire system and to select the number of pieces of equipment (i.e., transformers, switchgears, etc.) and their preliminary size; the amount of equipment and rating is then confirmed or updated during the network calculations and studies.

Tables 2–5 summarize the power required by the entire system and the estimated powers for each distribution LC.

Table 2. Active, reactive and apparent power required by DTT distribution LCs, SSED section.

SSED Section					
LC	Load Demand			Power Factor without Correction System	Notes
	MW	MVA _r	MVA		
1	9.07	8.48	12.4	0.73	–
2	7.93	5.60	9.71	0.82	–
3	1.86	1.43	2.35	0.79	Only LV loads
4	5.60	3.92	6.83	0.82	Only LV loads
5	20.5	13.4	24.5	0.84	–

Table 3. Total active, reactive and apparent power required by SSED distribution subsystem of DTT. The total steady-state 20-kV load does not include the load of LC3 and LC4 (LV loads only) indicated above because they are accounted for in the total load of LC5 from which they are supplied.

Total Steady State Load			
MW	MVA _r	MVA	Power Factor
37.5	27.5	46.5	0.81

It is important to stress that most of loads in nuclear fusion facilities are normally characterized by low power factors, requiring relevant systems for their corrections [15,23]. As shown in Tables 2–5, the DTT loads still feature low power factors, but some solutions were adopted at load level to increase them [13,14,17].

Table 4. Active, reactive and apparent power required by DTT distribution LCs, PPED section.

PPED Section				
LC	Load Demand			Power Factor without Correction System
	MW	MVA _r	MVA	
1	21.7	22.9	31.6	0.69
2	72.9	38.9	82.6	0.88
3	0.0	0.0	0.0	–
4	0.0	0.0	0.0	–
5	106	34.9	112	0.95

Table 5. Total active, reactive and apparent power required by PPED distribution subsystem of DTT.

Total Pulsed Load			
MW	MVA _r	MVA	PF
201	96.8	223	0.90

4. Operating Scenarios: Grid Calculations and Studies

The outcomes of the electrical load analysis were used as the basis to obtain a preliminary design of the distribution system. Then, the electrical configuration was implemented in the DigSILENT PowerFactory software environment to be validated. PowerFactory is a power system software for the analyses and simulations of generation, transmission, distribution and industrial electrical power systems, covering the full range of models and functionalities [24,25], from the traditional algorithms to real-time simulations. The same software was adopted for the preliminary design of the DEMO electrical power system [9,16]. In the present paper PowerFactory was used to implement the power flow method [26] and the fault analysis to verify the correct design of the main electrical components.

The assumptions used for the simulations are the following:

- The steady state loads were accounted for at 100% (duty factor).
- The pulsed loads were accounted for at 100% in the normal operating scenario.
- The loads marked as intermittent were accounted for at 50%.
- The loads marked as stand-by were accounted for at 10%.
- Load power factors were assumed to be equal to those identified in the electrical load list.
- Nodal voltage variations were accepted within $\pm 5\%$ during operation and $\pm 10\%$ in case of violation of the constraint.
- The OLTCs were considered only for the 150/20 kV transformers supplying the SSED section.
- The taps for the PPED transformers were kept fixed at a value that was identified as optimal. Such value may be adapted in no-load conditions in case of variations in the voltage from the external grid. A different strategy including OLTCs would make sense only for operations of some minutes [27].
- The earth resistance R_e was assumed to be equal to 230 Ω for the 150/20 kV transformers, while R_e was equal to 100 Ω for the 20/6.3 kV transformers. At the LV level, the transformers were directly connected to the ground (i.e., $R_e = 0$).

Various operating scenarios were analyzed in order to cover the most significant operating conditions. In particular, the simulations were carried out by varying the configuration of the distribution system (the MV network in single or double radial configuration), connecting and disconnecting the power factor correction systems, under different load conditions. The two extreme instances that were studied are the maximum load scenario in a single radial network configuration and the no-load scenario in a double radial network configuration.

To properly design and size the electrical distribution system, suitable network calculations and studies were performed:

1. Power flow analysis, to verify the correctness of the sizing of each equipment and power line and to define some operating parameters, such as the optimum position of the taps of power transformers. Moreover, the power flow calculations allow to define and size the needs for power factor compensation systems.
2. Fault analysis, to determine both the maximum and the minimum short-circuit levels in each node of the power distribution system. The maximum short-circuit calculations are used to size the switchgears and, in general, any equipment of the electrical distribution system. They are also used to determine the current at breaking time I_b and the relevant DC component i_{DC} to allow the correct selection of the circuit breakers. The maximum short-circuit level was determined considering the maximum short-circuit power at the connection point with the NHVG and the contribution from the electric motors. The minimum short-circuit levels will be used in protection settings and to verify the protection coordination and in the harmonics study. This was performed with the minimum short-circuit power at the connection point with the NHVG and without any additional contribution such as motors or other active equipment during the time of fault.

4.1. Power Flow Analysis for DTT Power System Design

The power flow calculations were performed in the most significant scenarios and electrical network configurations to pinpoint whether the electrical equipment was correctly sized (e.g., not overloaded, voltage drops within the limits, etc.) and to verify that, with the regulation systems provided (transformer tap changers and capacitor banks), it is possible to maintain the voltage profiles within appropriate intervals.

From the simulations, the equipment and, in general, the electrical distribution network were correctly sized. The main data of the transformers are reported in Tables 6–9, where S_n is the rated power in MVA, P_0 is the no-load power in kW, P_k is the short-circuit power in kW and V_k is the short-circuit voltage in percentage. It is important to stress that the data and size of the HV/MV and MV/LV transformers were provided by existing catalogs, while for the remaining transformers the specifications were estimated on the basis of catalogs of transformers, similar in terms of voltage and power.

Table 6. Electrical data of the HV/MV transformers.

Transformation Ratio 150 ± 10%/20 kV			
S_n [MVA]	P_0 [kW]	P_k [kW]	V_k [%]
63	32	300	12.5

Table 7. Electrical data of the MV/MV transformers.

Transformation Ratio 20 ± 5%/6.3 kV			
S_n [MVA]	P_0 [kW]	P_k [kW]	V_k [%]
15	16	37.5	8

Table 8. Electrical data of the MV/LV transformers.

Transformation Ratio 20 ± 5%/0.42–0.24 kV			
S_n [MVA]	P_0 [kW]	P_k [kW]	V_k [%]
2.5	3.1	19	6
3.15	3.8	22	8

Table 9. Electrical data of the LV/LV transformers.

Transformation Ratio $0.4 \pm 5\%/0.42\text{--}0.24\text{ kV}$			
S_n [kVA]	P_0 [kW]	P_k [kW]	V_k [%]
500	0.9	3.9	4

As regards the cable sizing, the technical characteristics and the electrical data of the selected cables are summarized in Tables 10–12, reporting for the single conductor and for each voltage level the values assumed for the cross section (area), the number of cores and laying method, the current carrying capacity, the resistance R' (both at the reference temperature and at the maximum operating temperature) and the reactance X' per unit length. Copper is considered as material for conductors and EPR for insulation.

Table 10. Electrical data and technical characteristics assumed for 20-kV cables.

Section [mm ²]	Cores and Laying Method	Rated Current [A]	R' (20 °C) [Ω/km]	Max R' (90 °C) [Ω/km]	X' [Ω/km]
120	Single core—direct in the ground	156	0.155	0.198	0.12
150	Single core—direct in the ground	175	0.126	0.161	0.11
185	Single core—direct in the ground	197	0.102	0.13	0.11
300	Single core—in air	602	0.0633	0.081	0.11
400	Single core—direct in the ground	313	0.0508	0.065	0.099
	Single core—in air	692	0.0508	0.065	0.099

Table 11. Electrical data and technical characteristics assumed for 6-kV cables.

Section [mm ²]	Cores and Laying Method	Rated Current [A]	R' (20 °C) [Ω/km]	Max R' (90 °C) [Ω/km]	X' [Ω/km]
150	Multi cores—in air	325	0.125	0.16	0.086
300	Single core—in air	602	0.0633	0.081	0.092

4.2. Fault Analysis for DTT Power System Design

The short-circuit calculations were performed, in accordance with the standard IEC 60909-0, for all types of faults (three-phase, line-to-line, line-to-line with earth connection and line-to-earth) and for each node of the grid. The analysis was carried out for the most severe scenario: Distribution network operating in single radial configuration without power factor correction. For each simulation, the goal is to identify/verify the rated short-circuit withstand values and the breaking capacity of switchboards, transformers, cables and circuit breakers.

The most important outcomes of the analysis are:

- I_{kss} initial symmetrical short-circuit current.
- i_p peak short-circuit current.

As a further design criterion related to the short-circuit withstand, the equipment is selected assuming a 15% margin for both the peak and the symmetrical current and for all the types of fault.

At this stage, because of the level of the data reliability and the design choices, which are not yet final, it was not possible to proceed with the preliminary sizing and choice of the protection system. However, the short-circuit currents were evaluated to verify the correct design of the switchboards.

Tables 13–16 report the withstand values, grouped by categories, that shall be compared with the outcomes of the simulations to verify the correctness of the selected fault withstand ratings: rms value I_k of the permanent short-circuit current for the duration t_k of the event, its maximum allowable value I_{kmax} and the peak short-circuit current. In

particular, a maximum temperature of 250 °C was considered for the calculation of I_{kmax} for the cables (insulated in EPR).

Table 12. Electrical data and technical characteristics assumed for 0.4 kV cables.

Section [mm ²]	Cores and Laying Method	Rated Current [A]	R' (20 °C) [Ω/km]	Max R' (90 °C) [Ω/km]	X' [Ω/km]
25	Multi cores—direct in the ground	87	0.773	0.99	0.076
35	Multi cores—direct in the ground	66	0.555	0.71	0.074
	Multi cores—in free air	92	0.555	0.71	0.074
	Multi cores—in free air	108	0.555	0.71	0.074
	Multi cores—in free air	246	0.555	0.71	0.074
50	Multi cores—direct in the ground	78	0.391	0.5	0.073
	Multi cores—in free air	112	0.391	0.5	0.073
70	Multi cores—in free air	143	0.273	0.35	0.072
150	Single core—in free air	363	0.133	0.17	0.07
300	Single core—direct in the ground	282	0.0664	0.085	0.079
	Single core—direct in the ground	322	0.0664	0.085	0.079
	Single core—in free air	601	0.0664	0.085	0.079
	Single core—in free air	640	0.0664	0.085	0.079
	Single core—in free air	713	0.0633	0.081	0.079
400	Single core—in free air	697	0.0508	0.065	0.079
	Single core—in free air	711	0.0508	0.065	0.079
630	Single core—in free air	921	0.0336	0.043	0.076

Table 13. Sizing values of busbars and switchboards.

Busbar/Switchboard	Rated Voltage [kV]	I_{kmax} [kA rms]	i_p [kA]	t_k [s]
HV Busbars—SS0	150	31.5	80	1
MV Busbars—SS0	20	31.5	80	1
MV Busbars—LCs	20	31.5	78.75	3
LV Switchboards	0.4	70	164.5	1
LV Auxiliary Switchboards	0.4–0.23	20	41	1

Table 14. Electrical data assumed for the 20-kV cables.

Section [mm ²]	Rated Current [A]	I_k [kA rms]	t_k [s]	I_{kmax} [kA rms]
120	156	15.40	1	17.16
150	175	19.80	1	21.45
185	197	15.40	1	17.16
300	602	19.80	1	21.45
400	313	19.80	1	21.45
	692	15.40	1	17.16

Table 15. Electrical data assumed for 6 kV cables.

Section [mm ²]	Rated Current [A]	I_k [kA rms]	t_k [s]	I_{kmax} [kA rms]
150	325	19.39	1	21.45
300	602	19.39	1	21.45

Table 16. Electrical data assumed for 0.4 kV cables.

Section [mm ²]	Rated Current [A]	I_k [kA rms]	t_k [s]	I_{kmax} [kA rms]
25	87	10	0.1	11.31
35	66	12.1	0.1	15.83
	92	12.1	0.1	15.83
	108	12.1	0.1	15.83
	246	10	0.1	11.31
50	78	10	0.3	13.05
	112	12.1	0.3	13.05
70	143	12.1	0.3	13.05
150	363	67.1	0.1	67.83
300	282	67.1	0.3	78.32
	322	67.1	0.3	78.32
	601	67.1	0.3	78.32
	640	67.1	0.1	67.83
	713	19.3	0.1	22.61
400	697	67.1	0.5	80.89
	711	67.8	0.5	80.89
630	921	67.8	0.5	80.89

5. Conclusions

Several large experiments are under development around the world to demonstrate the feasibility of nuclear fusion as a sound energy source. The goals of these experiments include the design of power systems able to supply the unconventional loads required by the physical process, to ensure a good level of reliability and power quality and to allow the possibility to deliver net energy when the fusion technology will be sufficiently mature to be exploited for power generation plants.

DTT is one of the largest and most recent tokamaks under construction, with the main scope of producing and disposing a large power density.

This paper illustrates the studies for the realization of the electrical power systems of DTT, moving from the analysis of the electrical loads to the definition of a preliminary configuration of the internal distribution grid, including the sizing of the main electrical components.

Simulation models, implemented in the DiGSILENT PowerFactory software, were used to verify the choices of the most suitable design options and optimize them. The simulations regarded the power flow analysis and fault analysis and were carried out in several scenarios, corresponding to different operating conditions of the overall system. The achieved results, although preliminary, have provided indications for the load allocation, the size and characteristics of transformers and switchboards, the characteristics and number of cables and the minimum and maximum voltage drops.

However, even if the project requirements seem to be satisfied so far, a further electrical design optimization is still possible, also considering possible future updates. This means that the results shall be continuously refined in the next years, following the DTT updates and progress and also the development of other related projects, such as ITER or its satellite experiments. In particular, the following aspects are the objects of study and research in progress:

- Detailed survey of the critical loads in order to size the UPSs and the EDGs with the proper redundancy.
- Assessment of the most appropriate reactive power correction and filtering systems and concurrent location and sizing.

Moreover, it would be interesting to carry out a transient analysis considering the sudden changes in power (and therefore in voltage and current) which occur during the

energization of the PPED loads and study how they can affect the performance of the entire system.

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