Analysis for the Integration of the Toroidal Field Power Supply in the DTT Nuclear Fusion Facility

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***Abstract*—The Divertor Tokamak Test (DTT) is an innovative effort aligned with the European Fusion Road Map. Backed by Enea and EUROfusion, it will be conducted at the Frascati Research Centre. The goal is to glean insights into diverse magnetic setups and components, all of which are based on liquid metals. These findings are crucial for finalizing the design of DEMO (DEMOnstration Power Plant), a pioneering nuclear fusion reactor prototype set to generate electricity for the grid. The study focuses on TFC (Toroidal Field Coils) power supply and introduces a Simulink model for performance simulation, aiding design, and sizing. These coils play a pivotal role in confining the plasma within the vacuum vessel, and thus, their power supply is of utmost importance. The model also assesses power requirements during TFC charging, offering valuable insights into power factor control methods.**

Keywords—Divertor Tokamak Test (DTT), nuclear fusion, toroidal field coils, power system, reactive power compensation

I. Introduction

The limited availability of fossil fuels and the growing environmental concerns pose new challenges in the research for alternative energy sources. While renewables alone cannot meet the current global energy demand, nuclear fusion emerges as a potential solution to facilitate the necessary transition to combat climate change. Fusion can provide clean energy and satisfy a large part of energy needs. Moreover, it can contribute to low-carbon development as prescribed in the Paris Agreement [15]. Despite its high potential, it still faces technical limitations and challenges that need to be overcome.

Significant progress has been achieved within the European Research Roadmap to the Realization of Fusion Energy [1], especially with the deployment of the ITER experimental facility [2]. A key challenge in this program is the disposal of the plasma heat loads on the divertor [1]. This led to the development of an experimental reactor, the Divertor Tokamak Test (DTT) facility [3-4]. The aim of this project is to explore technological alternatives for the divertor used in DEMO [5-7]. DEMO is a demonstrative nuclear fusion plant expected to be connected to the European High-Voltage grid by 2050, becoming the first nuclear reactor capable of bidirectional power exchange with the grid [16].

Specific tests will therefore be carried out in DTT on different magnetic configurations to address thermal load deployment issues on the divertor. DTT will share many similarities with DEMO in terms of size, complexity, and load requirements [8-12]. Consequently, the correct sizing of the power systems is crucial.

This paper presents simulation results for the DTT power system, with a particular focus on the Toroidal Field Coils (TFC) and their power supply. These magnets generate a magnetic field along the vessel's symmetry axis that forces plasma particles to follow along that precise direction. Additionally, the poloidal field coils (PFC) and the central solenoid (CS) contribute to plasma confinement. Furthermore, TFC also supports the tokamak frame with their unique D-shape [14].

The Simulink model for the TFC power supply ensured the calculation of current profiles and so of active and reactive power requirements from the grid. In addition, the model of the thyristor rectifier control system allowed the simulation of the real behaviour of this load in its three operating phases: charge (ramp up), hold, and discharge (ramp down). These new and more detailed results are necessary to correctly size and design the TFC power supply and its reactive power compensation system. Three solutions were evaluated for this purpose, including capacitor banks and a STATCOM with harmonic filters.

The paper is organized into IV Sections. Section II deals with the reactor power system, its connection to the national HV grid, and TFC power supply. Section III explains the software, the simulation models for the TFC power supply, and the reactive power compensation options. Section IV summarises the conclusions drawn from the simulation results, focusing on the choice of the reactive power compensation method.

II. DTT Power Systems

A. Connection to the National HV grid

The DTT power plant is located at the ENEA Research Centre in Frascati, where many research facilities already exist, including the FTU tokamak. Therefore, the location grants access to existing electrical systems and allows for potential upgrades. However, it presents spatial and layout constraints within the pre-existing buildings.

The ENEA Research Centre is currently connected to a 150 kV transmission line that can supply less than 10 MVA and cannot be upgraded due to the presence of other electrical loads on the same line [13]. Therefore, it is necessary to build a new HV line to supply the DTT, which is planned for the upcoming years. Two new 150 kV lines will connect the nearest 400 kV station, located approximately 15 km from Frascati, to a new electrical substation located near the ENEA Centre. Subsequently, the DTT plant will be fed by the National High Voltage Grid (NHVG) through a single 150 kV underground cable connecting the new Terna substation with another one, referred to as SS0, located directly inside the centre. The existing HV line will be kept for emergency backup in the event of a failure in the new system [16].

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B. *Power Supply of the Electrical Loads*

The DTT has an intrinsically pulsed behaviour linked to the physics of plasma, typical of a tokamak-type nuclear reactor, resulting in intermitted power demand from the grid.

During nominal operations, power consumption remains below 100 MVA, which is the baseline, with intermittent pulses peaking at 300 MVA for a duration of 100-200 s. These pulses occur periodically every 3600 s and are due to the experimental phases requiring high power for plasma control. The estimated power demand of the DTT is shown in Fig. 1. [13].

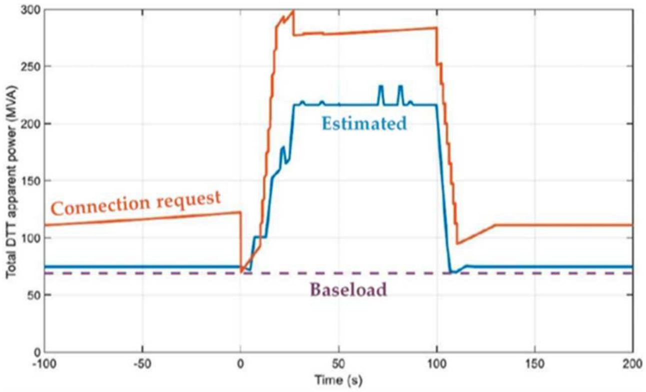

Fig. 1. DTT estimated load profile compared to the connection request to the national grid [13].

All the electrical loads of the DTT power plant are classified based on two main criteria: power profiles and power supply reliability. Power profiles distinguish between steady-state and pulsed loads. The former type is characterised by a continuous load profile while the latter by an intermitted profile, high peaks, and sharp variations. The loads are further classified into three primary groups: ordinary loads (OLs), investment protection (IP) loads and safety important class (SIC) loads. OLs are used for the normal operations of the processes and utilities. IP loads play a critical role in protecting essential reactor services when a sudden loss of the main power supply occurs. The latter are the most important type of loads due to their role in keeping the personnel and the reactor safe [13].

Given the unique characteristics of typical loads in a fusion reactor, DTT power is distributed through two separate substations: one to supply steady-state loads only (Steady-State Electrical Distribution, SSED) and one for the pulsed loads only (Pulsed-Power Electrical Distribution, PPED) [13-16]. In particular, the TFC are classified as pulsed electrical loads, therefore are powered by the PPED.

C. *TFC Power Supply*

The TFC system consists of 18 Niobium-Tin (Nb3Sn) coils, operating with a peak field of 11.8 T and a current of approx. 44 kA [3]. All 18 coils are fed in series to minimise the ripple of the toroidal magnetic field and are divided into 3 groups to limit the maximum voltage across a single coil. The main requirements and constraints for the design of the TFC electrical system are summarised in Table I [3].

TABLE I. ELECTRICAL FEATURES OF TFC POWER SYSTEM

Feature	Value
Number of Coils	18
Number of loops per coil	80
Total inductance	2.272 H
Self-infuctance of a single coil	41.4 mH
Total stored energy	2.1 GJ
Nominal current	44 kA

The power supply circuit consists of:

1. The basic supply to the coils.
2. A DC busbar system.
3. A crowbar unit for circuit protection.
4. 3 Fast Discharge Units (FDU).
5. 6 power supplies.
6. 18 superconducting coils grouped into 3 sectors.

The energy stored in TFC coils can exceed 2 GJ. This energy is dangerous for the safety of the tokamak and must be extracted quickly in the event of a quench in superconductors or a failure in other systems such as the cryogenic system. FDUs are protection systems for the safe and fast dissipation of this energy [17, 18].

The crowbar system is crucial for safeguarding both the power supply and the superconducting magnets. It allows the current to flow freely through the magnets in the event of a fault or quench, preventing induced overvoltage. It incorporates a hybrid switch consisting of a static switch, a mechanical switch, and a varistor. The static switch is implemented by several thyristors in parallel and it is designed to operate safely, even if a thyristor or the mechanical switch is not operating.

The basic supply of the coils relies on a 24-pulse AC/DC converter. This configuration is obtained using a total of eight 6-pulse thyristor rectifier bridges arranged in parallel two by two. Each parallel is fed by a 20 kV/75 V power transformer connected to the grid. The phase shift is realised by using phase-shifting transformers with phase shifting angles of 0°, +15°, +30°, and -15° respectively. This solution reduces harmonic input to the gid, increases power quality and consequently improves the power factor [3].

III. MODELS AND SIMULATIONS RESULTS

A model of TFC power supply was implemented in Simulink. The software was chosen because it enables time-step selection and acceleration of simulation times while maintaining high data quality.

The model was simplified in terms of control and protection components, with the main goal of calculating current, active power, and reactive power. Based on these values, reactive power compensation solutions were analysed and implemented.

A. *Details on models and simulations*

The simulation model is shown in Fig. 2. Downstream of the 20 kV power supply, there are four 20 kV/75 V phase-shifting transformers. To simplify the model without

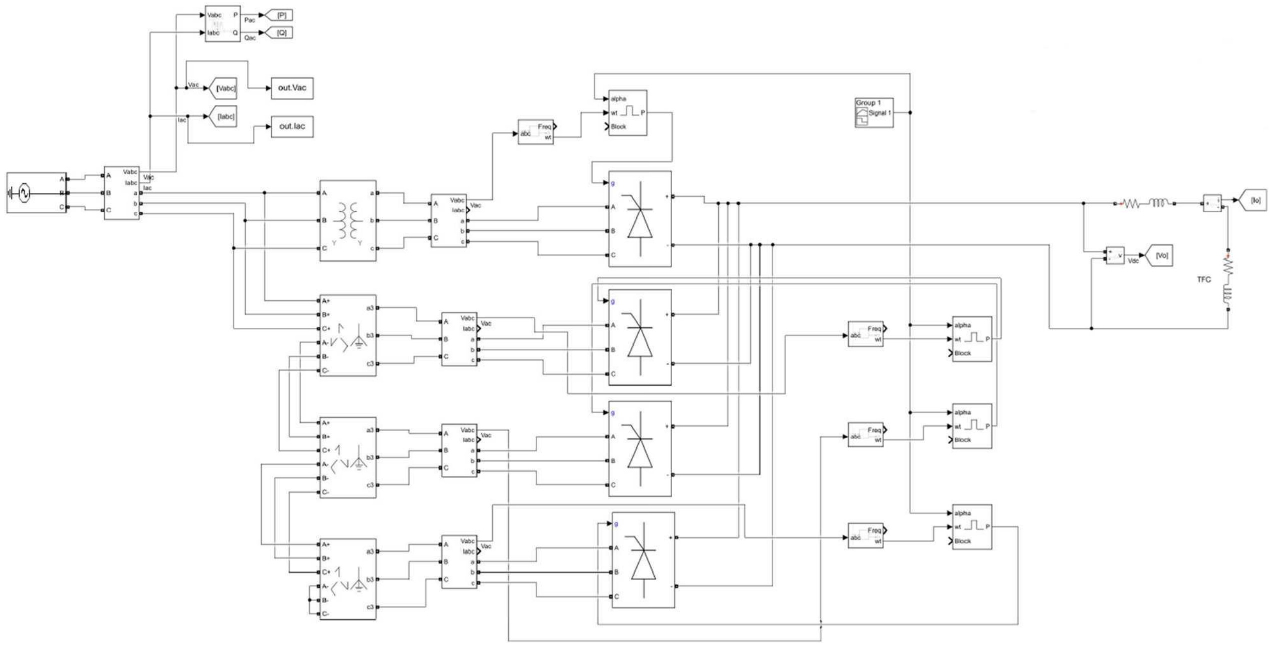

Fig. 2. TFC Power Supply model.

compromising the results, the number of rectifiers has been reduced from eight to four, with one downstream of each transformer. The output supplies the series of the TFC and an R-L branch representing some LV-side connections. In particular, the branch resistance is 250 μΩ and the inductance is 490 μH. Smaller MV-side connections haven't been implemented as they were considered negligible.

The turn-on angle of the controlled rectifiers takes into consideration the output voltage of the respective transformers and was varied during the simulations, starting from 35° provided by the regulation system and increasing progressively. This allows for the adjustment of the output current until the desired value is reached.

All the protection systems, including FDUs and crowbar, have been neglected in the simulations.

B. Reactive Power Compensation Systems

Once the required current trend was determined, starting from zero and increasing up to 42 kA, the normal operating point, the active and reactive power trends required by the load were also obtained.

Two power reduction controls were analysed in detail and then implemented on Simulink. These two solutions are based on the insertion of capacitor banks on the MV side of the power supply with the aim of fully compensating the reactive power at the current flat top:

- Flat top only compensation: the capacitor bank is star-connected to the three-phase power supply and sized for the peak value of reactive power. This is simulated by means of capacitors connected via power-controlled switches. Once the reactive power required by the load reaches the peak value, the switch turns the bank on. This Simulink model is shown in Fig.3.
- Compensation with controlled insertion: the bank is split into three partial banks, star-connected to the power supply as well. The insertion is controlled by switches once again. The control system switches on one of the partial banks as soon as one third of the reactive power reached at the flat top is exceeded.

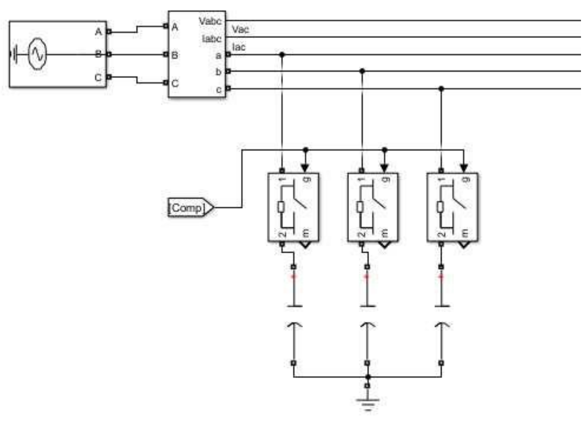

Fig. 3. Flat top only compensation model.

The blocks used in the Simulink model consist of three capacitors, three switches controlled by an external signal, and a "compare to constant" block. The latter instantly compares the reactive power obtained from a power meter with the steady-state value. As long as the measured reactive power is lower than the nominal value, the output signal from the block is 0. When they are equal, the output signal becomes 1, triggering the switches that turn on the bank, thereby compensating the reactive power. After the bank is turned on, the reactive power is below the set value, therefore the output of the compare to constant block returns to 0. To ensure that the bank remains on, there is a logical OR operator that takes input from the comparison aforementioned and from another "compare to constant" block. This block outputs 1 if the capacitor is still supplying reactive power. Consequently, even if the reactive power falls below the set value, the bank remains on because it is actively providing power.

When the insertion is controlled, the blocks remain the same as described above, but there are three of these modules. The input signals originate from the control blocks as described above, but they are time delayed. Through a previous study of the TFC charge, it was possible to approximate the timing required to delay the insertion of the capacitors. Consequently, one capacitor block has zero delay and is the first to activate, initiating the compensation of reactive power. The other two capacitor blocks are intentionally delayed, so they activate sequentially with staggered timing.

The second solution was considered because of the variable nature of the load. Toroidal field coils have three different operating regimes: charge, discharge, and a constant regime (flat-top). Therefore, this solution was implemented to try to adjust the power factor correction according to the variability of the load itself. Since the power supply is three-phase, a capacitor must be shunted to each phase. Although in the delta configuration the capacitors are sized for a smaller capacitance, the voltage to which they are subjected is the line voltage and not the phase voltage, which is smaller. Therefore, this type of capacitor requires insulation for a higher voltage value. Consequently, as the power factor correction is carried out at medium voltage, the star configuration is preferred.

The use of a STATCOM with the addition of harmonic filters is another solution that has been considered for reactive power compensation. However, this option has not been implemented in the software and the results are based on solutions provided by two companies in the industry.

C. Results

Following the initial simulations using the complete Simulink model, the behaviour of the coils was studied analytically. This was represented as a series circuit with an inductance value of 2.272 H and a resistance value of 490 nΩ in MATLAB. In the ideal case of a single-mesh resistive-inductive circuit, the presence of the inductance causes a gradual increase in current.

This ideal trend was compared with the realistic one obtained by imposing a constant firing angle of 35°. In the real case, the current shows a slower increasing trend compared to the ideal case due to non-ideal elements in the circuit that introduce losses. Moreover, the current output of a converter differs from the output of a battery, causing a slower increase. As a result, the exponential trend, typical of a R-L circuit, is hardly visible.

This preliminary study, with a constant firing angle of 35°, showed that the current exceeds the nominal current of 42 kA and continues to rise. This condition is typical of the transient phase and therefore cannot be used to load the magnets. In order to reach and maintain 42 kA, it is necessary to vary the firing angle at which the bridges are switched on to slow down the rise in current until the desired value is achieved.

Once the angle at which the current remains constant at 42 kA was defined, an increasing continuous signal was implemented. This signal designed to slow down the rise of the current without causing a sudden step change as the angle changes. Under this condition, the trends of current, active power, and reactive power were subsequently determined.

Once the reactive power values were determined, the capacitor banks for power factor correction were sized accordingly.

All simulations ran for 1800 s, although the output current reaches the desired value after just over 1500 s. This time margin was included to verify the correct functioning of the control and compensation systems.

The current trend in the TFC and reactive power consumption are shown in Fig. 4 and Fig. 5.

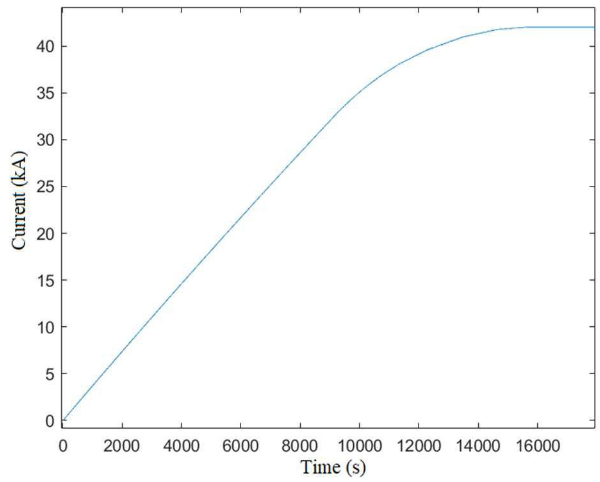

Fig. 4. TFC's current trend.

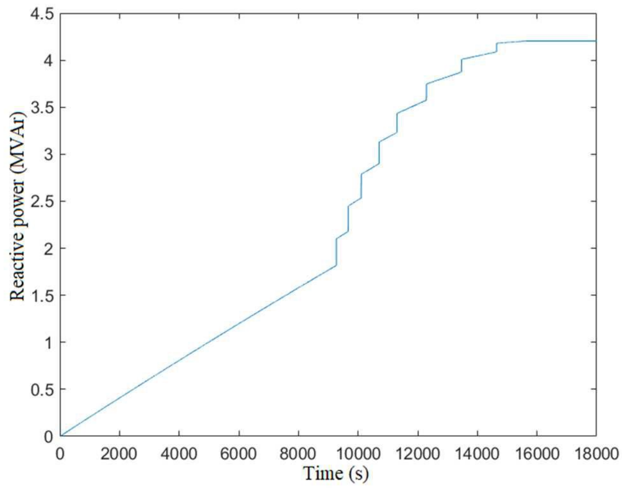

Fig. 5. Reactive power absorbed by the load.

The current trend is typical for an R-L load. It increases with a positive derivative, and it slows down as the alpha angle increases until it remains constant at 42 kA. As the alpha angle increases, the output voltage at the converter gradually decreases in steps and settles at a value of 12.5 V.

As long as the alpha angle is constant, the reactive power grows linearly. As the angle increases, the reactive power grows in steps until it reaches the constant value of 4.203 MVAr at the current flat top.

Although the firing angle varies continuously, the reactive power has a stepped pattern.

The same stepwise trend was found for the active power, which increases as long as the firing angle is constant and decreases in steps as it varies.

Reactive power trends with the two compensation systems are shown in Fig. 6 and Fig. 7.

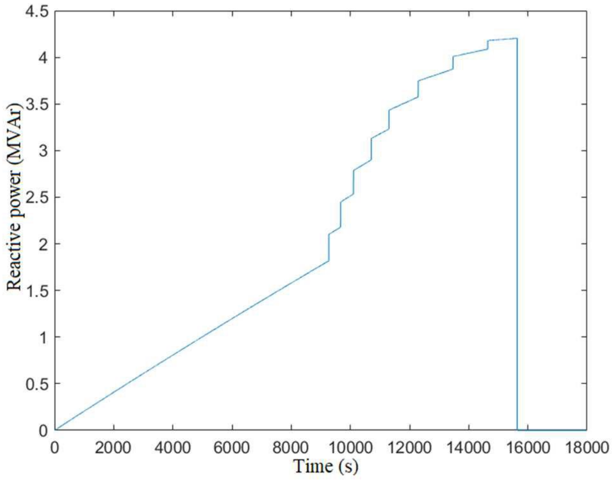

Fig. 6. Flat top only compensation.

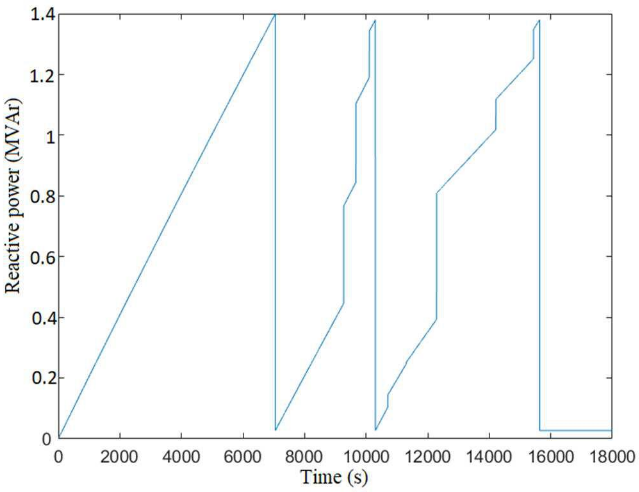

Fig. 7. Compensation with controlled insertion.

Reactive power compensation only at the current flat top was implemented first. Accordingly, the capacitor banks were sized for the reactive power peak of 4.203 MVAr. Considering a star-connected bank, the capacitance value per phase is calculated as:

$$C = \frac{Q}{\omega V_{LL}^2} = 33.44\ \mu F$$

By dividing the required capacity into four banks, one per each transformer, the capacity per phase is reduced to 8.36 µF. The dimensions for a bank of this capacity value are approximately 2500 x 900 x 1300 mm.

With the controlled insertion of three capacitor banks, the sizing is reduced to one-third of the reactive power at the flat top. This results in a capacitance per phase of 11.14 µF for each of the three banks that are gradually inserted.

In both cases, the reactive power drops to zero instantaneously once the bank is switched on. When a partial bank is switched on, the reactive power rapidly grows back because the TFCs are still charging, and the current hasn't reached its peak yet.

It is evident from both the formulas and the graph that with controlled switching of the banks, the reactive power has a value of 1/3 of the maximum reactive power.

Since the partial banks are dimensioned for a lower capacity, the size of a single bank is correspondingly smaller. However, it must be taken into account that as many as 3 partial banks per phase will be required, and no longer just 1 per phase as in the case of full flat-top compensation.

In this specific case of TFCs power supply, the STATCOM is formed by the connection of a fixed number of inverter Power Modules in parallel, with a maximum of 6 modules per compensation unit. Each inverter section or module must be equipped with its own dedicated power electronics, LC filter, and output switch to ensure a completely independent operation from the other converter modules.

Since the reactive power required by the load exceeds 4 MVAr, the solution involves the connection on the MV side of two STATCOMs of 2.5 MVAr each for a total of 5 MVAr. Each STATCOM is installed on an 8-10 m long floor suitable for outdoor conditions, resulting in a total length of approximately 20 m and a width of 4 m. Another solution involves the use of a single 2.7 MVAr STATCOM with the addition of three 0.9 MVAr filters, for a total of 5.4 MVAr. The dimensions of this STATCOM are 4m in length and 1.3 m in width, while the harmonic filters require 12 m in length and 4 m in width. From the point of view of size and reactive power output, the two solutions are almost equivalent.

IV. Conclusions

Previous works provided an overview of the DTT electrical power systems and categorized the primary electrical loads. Preliminary studies were also carried out to establish an initial design for the magnets' power supplies. The design presented in this paper serves as basis for the construction of the DTT facility.

The simulation results offer valuable insights for the sizing of the DTT TFCs power supply network. The three solutions analysed for reactive power compensation require different sizing of the power equipment, depending on the type of compensation used. The analysis of power factor correction solutions for the final design of the DTT Hall suggests that a capacitor bank is likely the best option because:

- It is a robust solution with a long history of use in various sectors such as railway traction and electric arc furnaces.
- The original power system topology would remain unchanged.

- The connection of the bank via switches and their monitoring could be integrated into the power supply control system with relative ease.
- The physical dimensions of the bank would be relatively small, making it suitable for outdoor installations.
- The cost is low compared to other solution.

Once this solution is chosen, the power system can be sized for the power peak value that is reached at a current of 42 kA, and the decision on the type of insertion can be made later. This flexibility arises because adding capacitor banks does not change the original structure of the power supply.

Considering that the DTT power grid must be built from scratch, it is feasible to implement a compensation system that only compensates reactive power when the flat top is reached. While the peak value of power required from the network is certainly higher, the control is simplified. Importantly, the capacitor banks used for both solutions can be reused in the future.

Future works will focus on perfecting the model and refining the accuracy of the simulations that can be conducted during the construction of DTT. Additionally, FDU and crowbar implementation in the model will also be considered. These components contribute to creating a comprehensive model suitable for various future studies and can lead to even more accurate results.

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