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The reactive power demand in DEMO: estimations and study of mitigation via a novel design approach for base converters

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In the present pre-conceptual design, the base converters for the main DEMO magnets are rated for 45 kA and about 10 kV. If the traditional design approach, based on thyristor bridges, would be adopted, this would result in very large reactive power consumption when low voltage values are required by the load. To satisfy the limitations imposed by the National Grid Operator, this reactive power has to be compensated internally by the DEMO Plant Electrical System. In ITER, this is realized with a huge Reactive Power Compensation and Harmonic Filtering system, rated for 750 MVAR in total. This system represents an additional cost, occupies a large area of the plant and does not guarantee a perfect compensation during power transients due to its slow dynamic response. These problems would be much amplified in DEMO, where the power ratings of the base converters are much higher. This paper demonstrates that the reactive power demand, estimated with an analytical model starting from the current/voltage waveforms foreseen in DEMO magnets, is very huge. Therefore, an innovative approach, based on Active Front End converters, is proposed and compared with the traditional solution.

Keywords: power supply, reactive power, DEMO, Active Front End, thyristor converter

1. Introduction

The European DEMO, which will follow ITER according to the Roadmap of the European fusion program, is presently under Pre-Conceptual Design [1]. The DEMO Plant Electrical System (PES) will include the Power Supply (PS) and the Electrical Power Generation systems. In all the present tokamaks, the main magnets, which constitute the major loads, are powered by thyristor rectifiers; in DEMO they should be rated for several tens of kA and around ten kV. One of the main drawback of this technology is the large reactive power exchanged with the grid when high current and low voltage are required by the load, as occurs during a large part of the plasma pulse. To satisfy the limitations imposed by the National Grid Operators and to reduce the currents flowing in the Medium Voltage Distribution System, the reactive power has to be compensated. In ITER, this is realized with a huge Reactive Power Compensation and Harmonic Filtering system (RPC&HF), rated for 750 MVAR in total and based on Thyristor Controlled Reactors (TCR) and tuned filters [2]. Besides its additional cost and area occupancy, the dynamics required to satisfy the reactive power limit in transient conditions represents a further challenge [3]. These problems would be much amplified in DEMO, where the power ratings of the base converters are about five times higher. Therefore, it is worth considering more recent technologies, until now never adopted in the major tokamaks, which intrinsically do not exchange significant reactive power with the grid.

This paper presents the analytical model developed to estimate the reactive power demand of DEMO and the results achieved, assuming the traditional design solution based on thyristor converters and the typical reactive power mitigation strategies. Then, a different approach, based on Active Front End converters (AFE, [4]), is considered. A possible topology is studied; the achievable performance is derived by means of numerical simulations, and the pros and cons of the two options are discussed.

2. DEMO magnet power supply system

The main DEMO magnets are composed of Central Solenoid (CS), Poloidal Field Coils (PF) and Toroidal Field Coils (TF), all superconductive. The magnets will be fed by the Medium Voltage (MV) distribution network, which in turn will be fed by the HV grid. In the first study, the voltage to feed the magnets is assumed to be generated by base converters and Switching Network Units (SNUs), like in ITER [5]. The base converters are two-quadrants (for TF) or four-quadrants (for CS and PF). The SNUs are, basically, resistors with making switches in parallel, aimed at producing the additional voltage required across some poloidal coils at plasma breakdown and ramp-up. In case of quench, the coils are discharged on damping resistors by Fast Discharge Units (FDU).

Since the voltage necessary to keep constant the toroidal current is very low with respect to that required for charge/discharge, the reactive power demand of the TF base converter can be reduced with a tap-changer on the step-down transformer, as foreseen in ITER [5]. Therefore, in this paper only the circuits feeding the poloidal magnets are considered, since they give the major contribution to the reactive power. The first tentative ITER-like scheme for DEMO PF base converters is shown in Fig. 1.

The CS magnet is divided in 6 coils (CS1U, CS1L, CS2U, CS2L, CS3U, CS3L). The current on CS1U and CS1L is assumed to be identical, thus they can be

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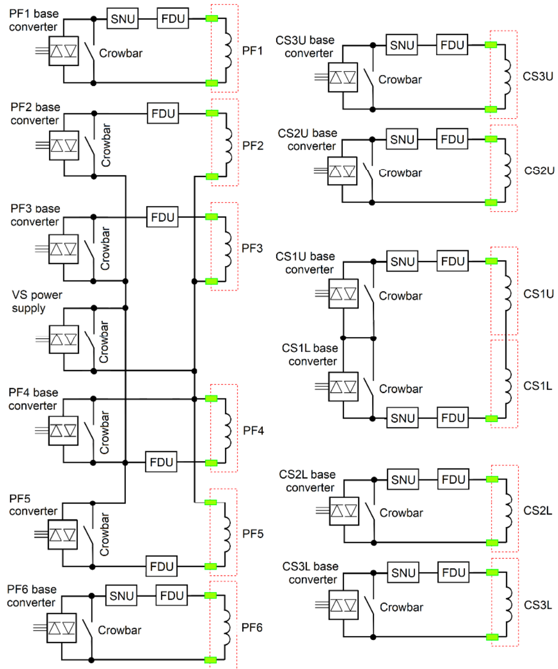

Fig. 1. Tentative circuits for main DEMO poloidal magnets.

connected in series together with their base converters, SNUs and FDUs, as in ITER [5]. The other CS and the PF coils are independently fed by the respective power supply, in series with their SNU (for CS, PF1 and PF6 only) and FDU. In the following analysis, SNUs and FDUs will not be considered, since they do not exchange power with the grid. An additional power supply (VS) is connected to PF2, PF3, PF4 and PF5 coils for vertical stabilization, as foreseen in the ITER design [5]. The voltage/current ratings for the main poloidal base converters (Table 1) have been tentatively derived from the output of physics studies performed by CREATE Consortium, keeping some margin to account also for the voltage drops in the feeders and during transients. As can be seen, the current ratings are similar to the ITER ones, while the voltage ratings are about 4 times higher.

Table 1. Tentative ratings for DEMO poloidal base converters and comparison with ITER

Load	Voltage rating*	Current rating	ITER voltage rating*	ITER current rating
CS1U, CS1L, CS2U, CS2L, CS3U, CS3U	±8 kV	±45 kA	±2.1 kV	±45 kA
PF1, PF6				±55 kA
PF2, PF3, PF4, PF5	±10 kV		±3.15 kV	

* on load, at coil terminals

The DEMO base converters can be designed following the same modular approach adopted for ITER, where 2 or 3 basic units are connected in series to produce the required voltage [2]. In ITER, each basic unit is a 12-pulse 4-quadrant thyristor converter with 4 basic bridges, rated for ±1.05 kV at full current and fed by a 2-secondaries step-down transformer. For PF coils, in ITER each leg of the bridges is realized with 12 thyristors with V_{DRM} = 5.2 kV, $I_{T(AV)M}$ = 5 kA [6]. However, considering a less stringent voltage safety factor (2.4, common for industrial products), the voltage rating of each basic bridge could be increased to 1.6 kV. Supposing to adopt the same technology for DEMO, the number of units in series would be 5 for CS, PF1 and PF6 and 7 for PF2..5 base converters. The number of thyristors in parallel can be obtained scaling those of ITER with the rated current of the converter, obtaining 10 thyristors per branch, 1200 in total for each CS, PF1 and PF6 base converter, 1680 for PF2..5 converters.

3. Reactive power estimation in case of thyristor base converters

In order to compute the active and reactive power demand of DEMO PF and CS loads assuming the thyristor technology, two Simulink® models have been developed. The first model implements the same sequential control of series-connected units adopted in ITER [2]. There, just one unit regulates the required voltage and the others produce maximum positive or negative values. However, being the maximum/minimum voltage limited by the operational range of the firing angle of the thyristor bridges (assumed [15÷135°], as in ITER), an important amount of reactive power is exchanged with the grid also by these units. In the second model, the zero voltage is provided by introducing a bypass switch at the output of each unit; in this way, the reactive power demand of the unused units is nullified [7]. Both models receive as inputs the voltage and current profiles of the base converters for the breakdown, ramp-up and ramp-down phases of the DEMO pulse (in one of the reference scenarios). The output voltage of each converter unit is derived from the reference voltage considering the control logic described above, while a specific current control logic has been implemented to calculate the current on each basic bridge. As already reported in literature [8], this current control avoids discontinuities around the zero-crossing of the current. In detail, each unit can operate either as a 12-pulse rectifier, a 6-pulse rectifier, or in circulating-current mode. The thresholds between the three configurations are set at 30% and 15% of the nominal current. In the models, the firing angle of each basic bridge is calculated from its output voltage and current, accounting also for the voltage drop on the step-down transformer. From the angle and the voltage/current at secondary side of the transformer, the reactive power is calculated. The active power, instead, is assumed equal to the output power of the bridge, neglecting the power losses.

Fig. 2 reports the current and voltage profiles at base converter outputs during breakdown phase, and Fig. 3 shows the corresponding active and reactive power profiles obtained with the two models. In the scenario considered, the active power peaks reaches about ±1.6 GW, with a fast transition from negative to positive in about 0.5 s. The reactive power is in the order of 2.6 GVAR with sequential control and 2 GVAR with bypass logic control. Similar numbers result with sequential control at plasma ramp-up and ramp-

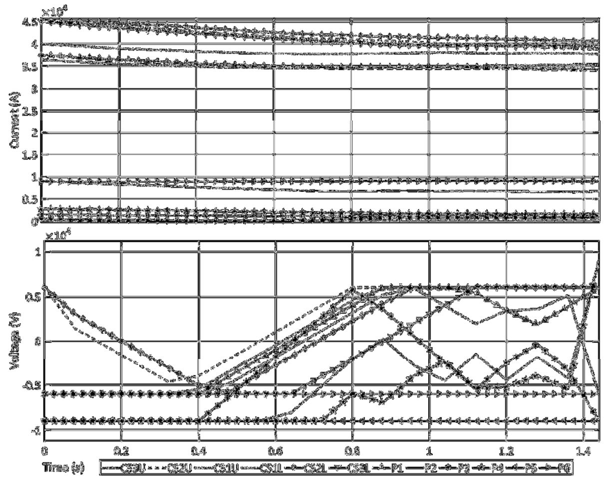

Fig. 2. Current (top) and voltage (bottom) profiles during the DEMO plasma breakdown phase (courtesy of CREATE)

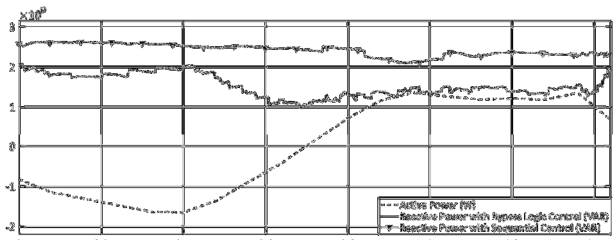

Fig. 3. Active and reactive power profiles obtained for the DEMO plasma breakdown phase

down phases, while in those cases the bypass solution gives much lower values (500÷700 MVAR); this because the voltages required are lower than those of breakdown phase, so the bypasses can give a greater advantage. It is pointed out that the reactive power resulting at breakdown is more than 2.9 times that of ITER (~700 MVAR for magnet power supplies [9]); in addition, this could not represent the worst case, which in fact is expected at plasma flat-top. Unfortunately, the worst case for DEMO cannot be identified at the time of writing due to the lack of a voltage/current profiles for the full plasma discharge at this stage of the DEMO design; nevertheless, the reactive power issue is evident. Therefore, a more advanced solution for the poloidal base converter design, which intrinsically does not exchange any reactive power at the input, is proposed in the following.

4. Alternative solution based on Active-Front-End converters

The AFE topology studied for the 8 kV DEMO base converter is shown in Fig. 4. It is based on 2 cells in series, each composed of a line-side ac/dc converter, a dc-link capacitor bank and a load-side inverter. Both the ac/dc converter and the inverter are based on fully controlled active switches, such as IGCTs (Integrated Gate-Commutated Thyristors). The two inverters in series at the output constitute a 5-Level Cascaded H-Bridge (5L-CHB) [10]. The AFE solution conceived for

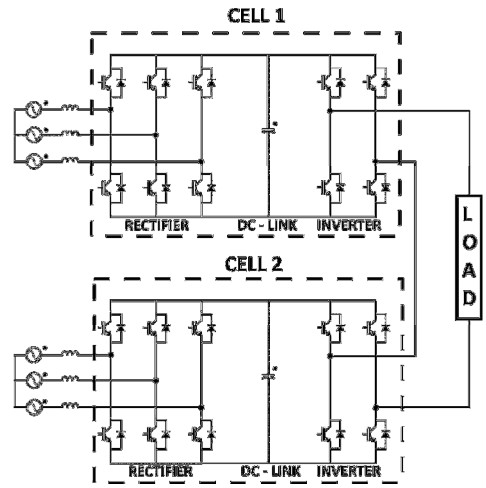

Fig. 4. Possible scheme of a 8 kV DEMO base converter based on AFE solution

the 10 kV base converter is similar, but with 3 cells in series, the coil-side inverters being controlled as a single 7-Level Cascaded H-bridge (7L-CHB). With respect to other topologies, such as the Neutral Point Clamped (NPC) converter, this solution has been preferred since it is modular and requires less power switches.

Each cell is fed by the secondary winding of a step-down transformer through a L-filter, the primary being connected to the MV grid. The ac/dc converter can operate both as a rectifier and as an inverter, depending on the direction of the power flow. For this converter, the Sinusoidal Pulse Width Modulation (SPWM) can be adopted; a reasonable switching frequency could be 750 Hz, as a compromise between dynamic performance, ac current ripple for a given filter and commutation losses. The converter control is based on two nested closed loops: dc-link voltage control as outer loop and ac current control as inner loop. The latter shapes the ac input currents as sinusoidal, in phase with the line voltage, to nullify the reactive power exchanged with the grid. For the load-side inverter, the Phase Disposition Pulse Width Modulation [11] is envisaged, the modulation index being generated by a load current control loop. A suitable switching frequency is 300 Hz.

A tentative design has been carried out to estimate the converter size with today's components. For the 8 kV base converters, a suitable dc-link nominal voltage of each cell is 4 kV, such to adopt Asymmetric IGCTs with the highest V_{DRM} in the market (6.5 kV, e.g. ABB 5SHY42L6500) and reasonable voltage safety factor (1.6). For the repetitive peak reverse voltage (V_{RRM}) of the diodes, a safety factor of 2 gives $V_{RRM} \geq 8$ kV. Two Infineon D4600U45X172 (V_{RRM} = 4.5 kV) in series are considered, The dc-link capacitance of each cell is estimated such to limit the dc-link voltage fluctuation below ±15% in case of full power step variations, giving $C \geq 190$ mF. The filter inductor (21 μH) can be selected such to limit the ac current ripple below 15 kA peak-to-peak (~20% of the nominal ac current).

A detailed model of the AFE converter has been realized in Simulink®, to quantify the main electrical quantities necessary for the thermal design and verify the dynamic performance. The ac line voltage and current are shown in Fig. 5. As desired, excluding the ripple, the input current is sinusoidal and in phase with the voltage.

From the thermal analysis, the number of IGCTs and diodes in parallel per equivalent branch has been derived, considering a current sharing mismatch of 20%: the result is 74 IGCTs and 15+15 diodes for the ac/dc converter branches, and 68 IGCTs and 19+19 diodes for the load-side inverter branches, to be divided on a proper number of units in parallel. In total, 1432 IGCTs and 664 diodes are required for a 8 kV, 45 kA base converter.

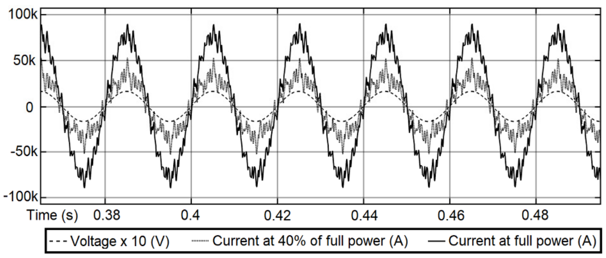

Fig. 5. Input voltage and current of a 4 kV cell of the AFE base converter, at 100% and 40% of rated power.

5. Size estimation of a DEMO base converter

In this section, a comparison of the area occupancy of a DEMO base converter based on the traditional and AFE solutions is given. For the first option, the areas of the converter and of the corresponding portion of RPC&HF system have been estimated from those of ITER by scaling with the converter power ratings. For the AFE solution, the footprint has been estimated from the size of existing applications based on IGCTs, by scaling with the number of components and the dc-link and input inductor stored energies; then, the building area has been derived multiplying by the same filling factor found in ITER. The results are shown in Table 2.

Table 2.Estimated sizes of a DEMO base converter with thyristor and AFE solutions (based on today's components)

	BASE CONVERTER				RPC&HF SYSTEM			TOT.
	Ratings	Indoor area	Transf. pits	Total area	Indoor area	Outdoor area	Total area	Area
ITER	2.1 kV x 55 kA	413 m^2	260 m^2	673 m^2	64 m^2	656 m^2	720 m^2	**1393 m^2**
DEMO THYR.	8 kV x 45 kA	1032 m^2	814 m^2	1846 m^2	199 m^2	2045 m^2	2244 m^2	**4090 m^2**
DEMO AFE	8 kV x 45 kA	859 m^2	803 m^2	1662 m^2	0 m^2	0	0	**1662 m^2**

6. Conclusions

In this paper it is demonstrated that the reactive power demand of DEMO ac/dc converters for poloidal magnets based on the traditional thyristor technology would be enormous, also when mitigated with the typical control strategies. Thus, a RPC&HF system occupying an area in the order of 30000 m^2 in total would be necessary. Therefore, an alternative solution based on AFE technology has been studied. As demonstrated by numerical simulations, the proposed scheme is capable to almost nullify the reactive power demand in every load condition and also during power transients.

Since the highest rated power of an AFE converter is presently in the order of 10 MVA, the actual industrial feasibility of AFE converters with the required ratings is to be demonstrated. Moreover, since this technology has never been used in tokamaks, further studies are in progress to verify the feasibility of its integration in the DEMO poloidal magnet circuits, considering also fault and anomalous conditions. If its suitability is confirmed, the AFE solution would be very promising considering the good dynamic performance and the potential space saving given by the elimination of the RPC&HF system. The overall balance of cost and reliability of the whole system will be object of future considerations.

Acknowledgments

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