Power converters for ITER

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Abstract

The International Thermonuclear Experimental Reactor (ITER) is a thermonuclear fusion experiment designed to provide long deuterium–tritium burning plasma operation. After a short description of ITER objectives, the main design parameters and the construction schedule, the paper describes the electrical characteristics of the French 400 kV grid at Cadarache: the European site proposed for ITER. Moreover, the paper describes the main requirements and features of the power converters designed for the ITER coil and additional heating power supplies, characterized by a total installed power of about 1.8 GVA, modular design with basic units up to 90 MVA continuous duty, dc currents up to 68 kA, and voltages from 1 kV to 1 MV dc.

1 Introduction

New large energy sources will have to be developed before the middle of this century to prevent an environmental crisis. With a successful demonstration of controlled fusion and key technologies, and further optimization, fusion power plants could contribute to the world's electricity needs for the second half of this century.

The ITER project aims at establishing nuclear fusion as an energy source. In particular, ITER will demonstrate the scientific and technological feasibility of fusion energy and thus bridge the gap between the present Tokamak experiments and a first demonstration fusion power-plant.

After conceptual design activities, carried out between 1988 and 1990, the Engineering Design Activities (EDA)[1] started in 1992 and were carried out as a collaborative project between the European Union, Japan, the Russian Federation, and the U.S.A. The design work was carried out by an international Joint Central Team (JCT) and the Home Teams of the four ITER Parties. During the EDA phase a design capable of ignition $Q = \infty$ (Q is the ratio of fusion power to additional heating power injected into the plasma) was developed. In 1998, the Parties (EU, JA, RF and US) endorsed the design, but could not afford to build it. In 1999, the US withdrew from the project and the remaining Parties searched for a less ambitious goal: moderate plasma power amplification at about half the cost. A new design with $Q \geq 10$ was completed in 2001. After that, negotiations on construction and operation were carried out. Site offers were presented by Canada, Europe (two sites) and Japan. The US re-joined, and China and South Korea have been accepted as full partners. The *ad hoc* group for the ITER Joint Assessment of Specific Site offers concluded that all sites meet the ITER site requirements. At the end of 2003, the EU Research Ministers chose Cadarache (France) as the EU site offer for ITER and Canada withdrew its site offer, therefore at present there are two potential sites: Cadarache (France), and Rokkasho (Japan).

The design of the ITER power converters was carried out by the ITER JCT between 1994 and 1998, with the collaboration of the Home Teams (industries and national laboratories). The 1998 design was characterized by a modular approach and a total installed power of about 3.7 GVA. After

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[1] A table with the main acronyms is available in Appendix B.

1998, as a consequence of the new reduced cost design of ITER, the power supply system was revised in accordance with the new power requirements of the loads. This design revision was implemented mainly by changing the quantity of the basic modular components and by minor modifications to the concepts and design features of the individual basic components. Optimizations, aimed to reduce the cost/MVA were also introduced, mainly in the power supplies of the heating and current drive systems. After this design revision, the total installed power was reduced to the present value of about 1.8 GVA.

2 ITER objectives and the main design parameters

The overall programme objective of ITER, as defined in the ITER Engineering Design Activities agreement, is “To demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes” [1].

ITER is a burning plasma experiment, designed to confine a deuterium–tritium plasma in which α-particle heating dominates all other forms of plasma heating. Experiments will be carried out to study, in an integrated way, the following aspects of the burning plasma: alpha-particle physics, controllability of fusion reaction, advanced scenarios aiming at steady-state operation and the divertor operation (impurity control). Moreover, with an average 14 MeV neutron wall load ≥ 0.5 MW/m^2 and average lifetime fluence of ≥ 0.3 MW/m^2, ITER aims to demonstrate the technologies essential to a fusion reactor.

The ITER main plasma parameters and dimensions are reported in Table 1. ITER is a Tokamak with elongated plasma designed to produce deuterium–tritium fusion power of 500 MW for a burn length of at least 300 s, with 73 MW additional heating power injected to the plasma. An extended phase, with increased additional heating power up to 110–130 MW, is also planned to carry out experiments up to 700 MW fusion power.

Table 1: ITER major plasma parameters and dimensions

Total fusion power	500 MW (*700 MW)
Q = fusion power/auxiliary heating power	≥10
Average neutron wall loading	0.57 MW/m^2 (*0.8 MW/m^2)
Plasma inductive burn time	≥ 300 s
Plasma current	15 MA
Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Vertical elongation	1.70
Toroidal field @ 6.2 m radius (plasma axis)	5.3 T
Max. field in the conductor (toroidal coils)	12 T
Plasma volume and surface	837 m^3, 3678 m^2
Installed auxiliary heating/current drive power	73 MW (*110–130 MW)

(*) During the extended phase.

The major components of the Tokamak (Fig. 1) are the superconductive magnet system and the vacuum vessel. The magnet system comprises 18 Toroidal Field (TF) coils, a Central Solenoid (CS), 6 external Poloidal Field (PF) coils, and Correction Coils (CCs). The TF coil system produces the magnetic field for the plasma confinement. The CS induces the current in the plasma. The PF coils create the magnetic field for shaping and position control of the plasma inside the vacuum vessel. Finally, the CCs correct the error field resulting from manufacturing and assembly inaccuracies; moreover they also contribute to plasma stabilization. The vacuum vessel is a double-walled steel structure, which contains blanket shielding modules, divertor cassettes, and access ports. The ports allow access for limiter radio-frequency heating antennae, neutral beam injectors, test blanket modules, remote handling and diagnostics modules. Detailed technical information on ITER and the design description of the main components is available in Refs. [2,3].

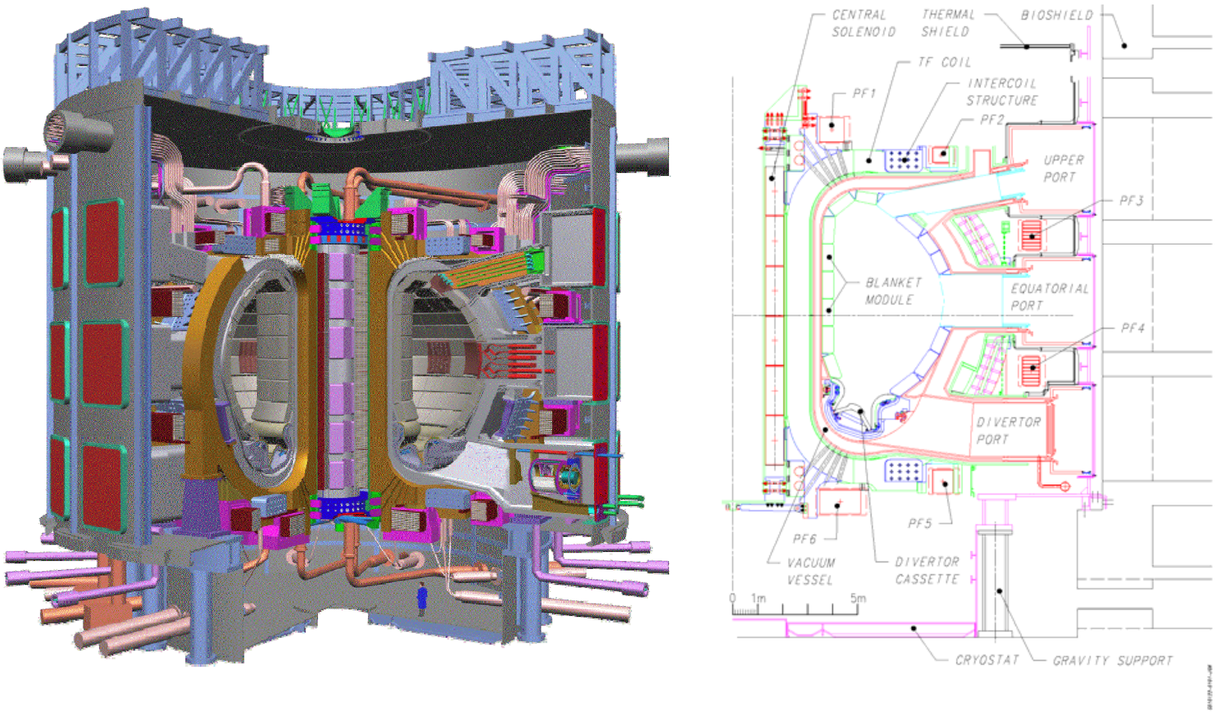

Fig. 1: Cross-section and elevation view of the ITER Tokamak

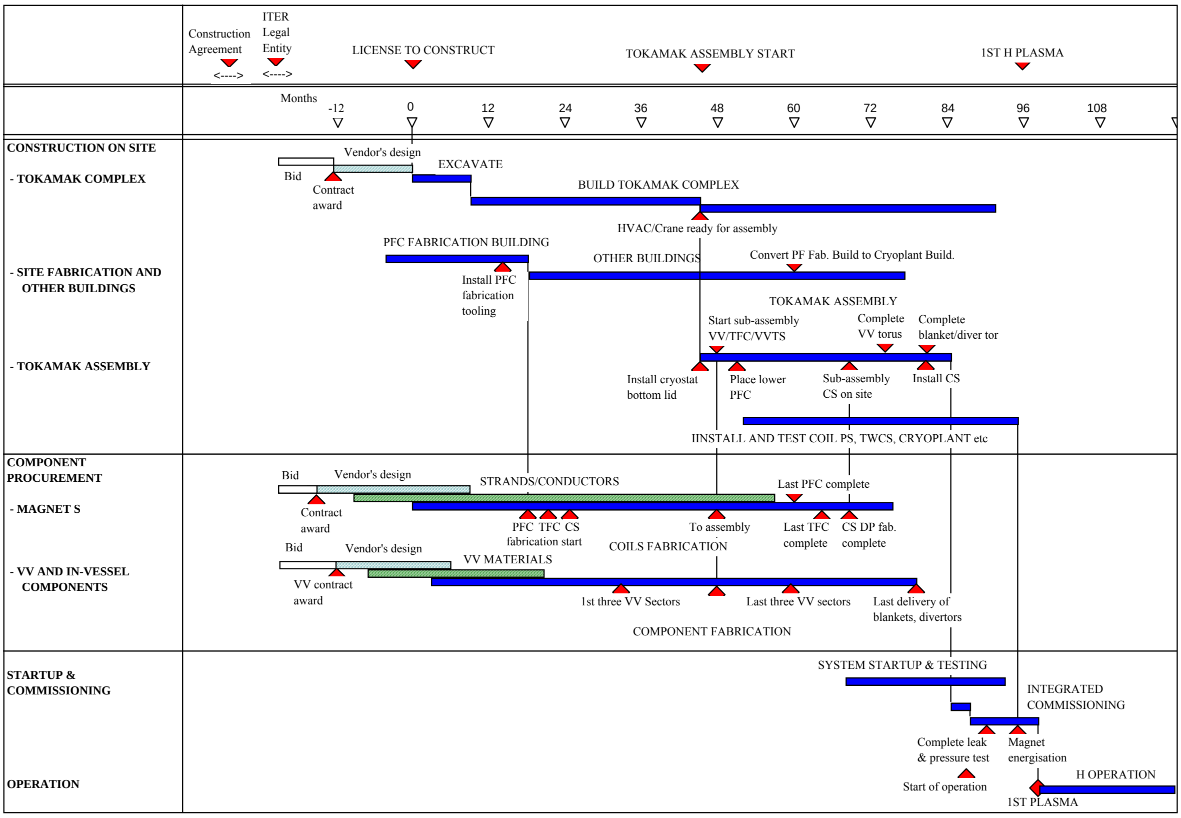

Fig. 2: Overall licensing and construction schedule

3 Schedule and costs

The overall schedule up to the first plasma is shown in Fig. 2. Starting from the establishment of the ITER legal entity, the licensing and construction will take about nine years. After that, another year of integrated commissioning is necessary before the first plasma experiment. The total direct construction cost is estimated to be 4.6 billion euros. The expected operational lifetime is 20 years with a running cost of about 250 million euros/year. At the ITER site there will be an international organization of 600 staff plus visiting scientists. Infrastructures for remote participation in the ITER operation will also be implemented. Therefore scientists will participate remotely in experiments (e.g., operating diagnostics, analysing data, making proposals for the experimental programme) from many locations in the world.

4 The electrical characteristics of the ITER European site

The European site offered for ITER is located in France, 35 km from Aix-en-Provence, in the Cadarache centre of the Commissariat à l'Energie Atomique (CEA). Inside the centre there is already a Tokamak experiment (Tore Supra) fed by a 400 kV line. Cadarache is in a region well supplied with electric power (Fig. 3). The Cadarache centre is located at a distance of about 5 km from the Boutre 400 kV node, which is interconnected by a double circuit line (about 100 km in length) to the Tavel node, in the Rhône valley, where the short circuit power is one of the highest in Europe, thanks to a number of existing nuclear power plants. Detailed information on the Cadarache site is available in Ref. [4].

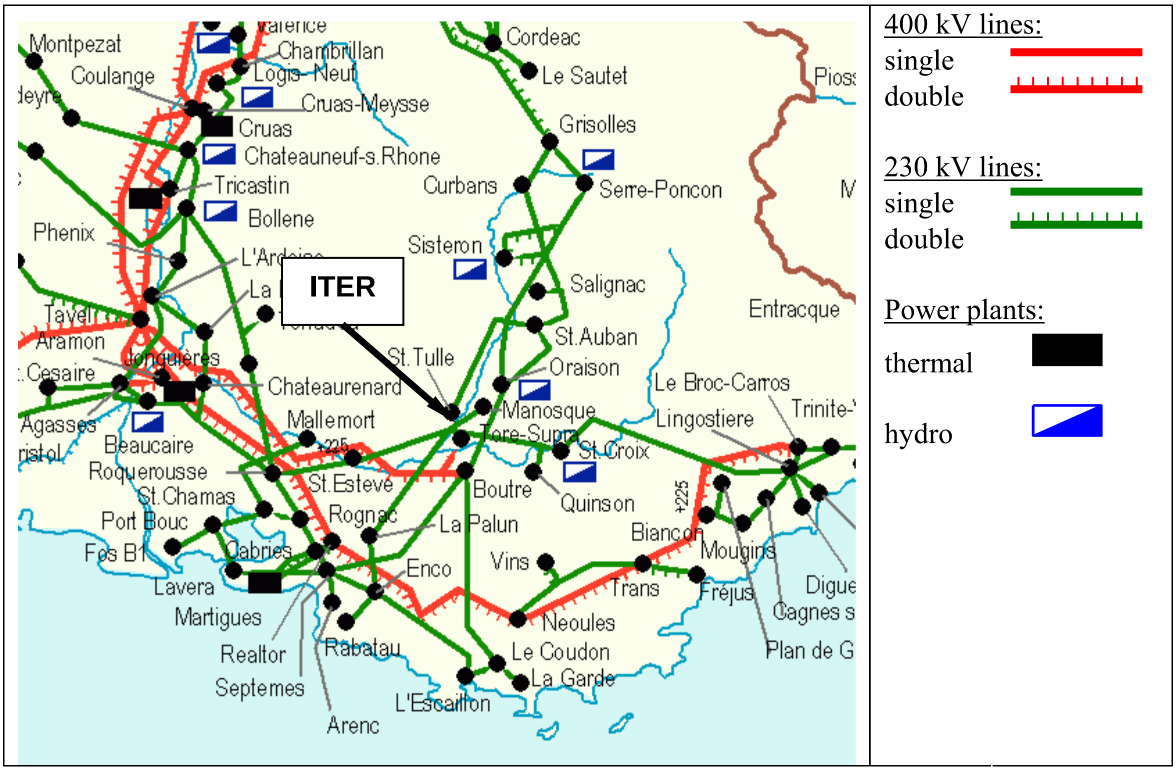

Fig. 3: Map of the HV transmission grid surrounding Cadarache, Ref. [5]

Table 2 shows the reference design requirements and assumptions for ITER pulsed power demand. Figure 4 shows the active and reactive power waveforms assumed for the assessment of the ITER site characteristics. The waveforms do not include the power consumption (about 120 MW, 40 Mvar) required by the plant auxiliary systems (cryoplant, cooling water system, heating and ventilation system, offices, etc.). To simulate a kind of worst-case scenario, the pulses of active power required for fast plasma control (pulses up to 100 MW of a few seconds duration) have been assumed at the beginning (2 pulses) and at the end (8 pulses) of the flat-top phase. In the actual operational scenarios, these pulses are randomly distributed on the flat-top phase, with at least 10 s between two consecutive pulses. These pulses are characterized by very high power derivative, therefore such a variation should be considered as a power step. The reactive power waveform includes the compensation already foreseen in the ITER reference design. This system compensates 450 Mvar and has been assumed to be operated under feedback control of the reactive power absorbed from the 400 kV grid. Therefore the maximum reactive power absorbed from the grid is 400 Mvar with a power rate of ±2 Mvar/s. After the selection of the site, the assumption on the control criterion of the reactive power compensator will be reviewed with the Transmission Grid Operator. In principle, other control criteria are possible, for example, feedback control of the voltage at the ITER 400 kV node.

Table 2: Reference design requirements and assumptions for the ITER pulsed power demand

Voltage	400 kV
Max. active power, to be added to the steady-state active power	± 500 MW
Max. reactive power, to be added to the steady reactive power	400 Mvar
Max. active power step	± 60 MW
Max. active power rate	± 200 MW/sec
Short circuit power	10 – 25 GVA
Pulse length	1000 s
Pulse repetition rate	1800 s
Number of pulses per day at nominal duty cycle	20
Number of pulses per month at nominal duty cycle	300

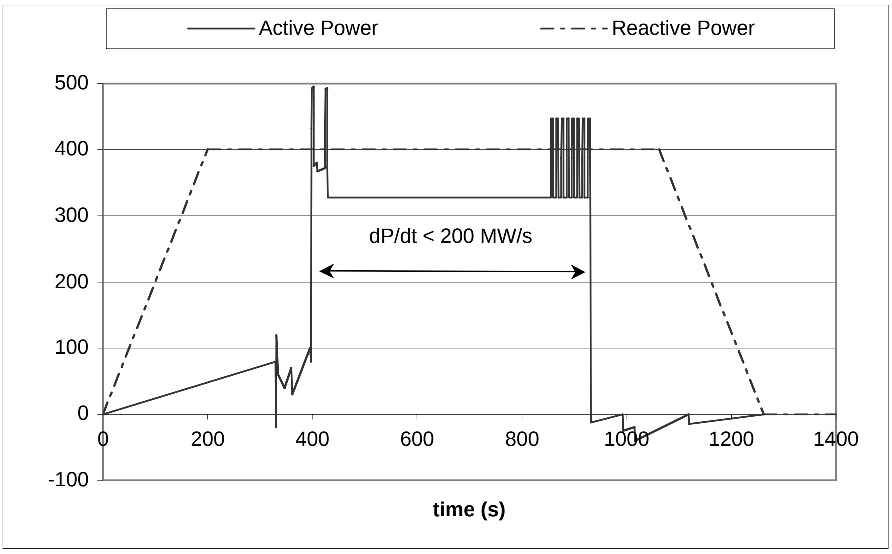

Fig. 4: Active and reactive power waveforms of the ITER pulsed-power demand, assumed for the assessment of the European ITER site characteristics. The power consumption of the plant auxiliary systems (about 120 MW, 40 Mvar) is not included.

During the European ITER Site Study performed in 2001–02, the French Grid Operator RTE (Gestionnaire du Réseau de Transport d'Electricité) investigated the effects of the ITER active and reactive power demand on the 400 kV and 230 kV transmission grid. The study included also the transient analysis of the perturbations produced by the ITER pulsed load on the transmission network, the power stations, and the automatic tap changers of the substation transformers. This study concluded that the ITER power requirements are compatible with the French transmission grid provided that the ITER reactive power demand is limited below 180 Mvar. This condition implies a 30% increase in the reactive power compensation system quoted in the ITER reference design. Tables 3 and 4 summarize the main results of the study performed by RTE.

Table 3: 400 kV grid capability at the European site proposed for ITER

Max. active power ($P_{\max}$)	± 510 MW (*)
Max. reactive power	180 Mvar (*)
Max. active power step	± 510 MW
Max. active power rate	step variation is acceptable up to $P_{\max}$
Max. reactive power rate	3.8 Mvar/s
Short circuit power	10–12 GVA
Power-frequency characteristic 'stiffness'	18 GW/Hz
Max. permissible frequency variation	50 mHz
Max. expected frequency variation	28 mHz

(*) Added to the steady-state power (120 MW, 40 Mvar) absorbed by the plant auxiliary systems.

Table 4: Permissible harmonic voltage distortion at the European site proposed for ITER (mean values computed on a time window of 10 min)

Odd harmonics				**Even harmonics**	
Not multiples of 3		**Multiples of 3**			
Order	(%)	Order	(%)	Order	(%)
5, 7	2	3	2	2	1.5
11, 13	1.5	9	1	4	1
17, 19	1	15, 21	0.5	6–24	0.5
23, 25	0.7				

Total harmonic voltage distortion: $\tau_g < 3\%$ $\tau_g = \sqrt{\sum_{h=2}^{40} \tau_h^2}$.

5 ITER power supplies[2]

The ITER power supplies consist of two independent systems: the Steady-State Electrical Power Network and the Pulsed-Power Supply System.

The Steady-State Electrical Power Network (SSEPN) provides 6.6 kV and 400V ac power to loads of the ITER plant auxiliary systems. The loads are mainly motors and the maximum power demand is about 120 MW, including a certain margin for uncertainty and future growth. The major consumers are the water-cooling and cryogenic systems requiring together about 80% of the total demand. The SSEPN includes also two emergency Diesel generators with a rated power of 7.5 MVA each for the supply of safety relevant and investment protection loads. Although the SSEPN is a

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[2] The design values quoted in the rest of this paper are related to the design of the reduced-cost ITER.

standard industrial electrical distribution system, the requirement to start powerful motors (up to 3.7 MW) without causing excessive disturbances (voltage flicker) on the low-voltage distribution system has imposed a design with relatively high short-circuit power and the consequent choice of components with short-circuit capacity at the top of the commercially available range. Moreover, inside the Tokamak building, the low-voltage distribution boards have to be located in areas with constant, or slowly variable, stray magnetic field up to about 25 mT; this requires specific experimental campaigns aimed to asses the magnetic compatibility of the commercially available components for low-voltage distribution boards.

The Pulsed-Power Supply System (PPSS) provides controlled dc power to the superconductive magnets and the Heating and Current Drive (H&CD) systems. These are powerful loads, requiring a total active power up to 500 MW. The load voltages are in the range from about 1 kV (supeconductive magnets) to 1 MV (Neutral Beam H&CD system). The rated currents are up to 68 kA (Toroidal Field Coil power supplies). The PPSS includes also dedicated components for the fast discharge of the superconductive magnets in case of a quench. The protection of the H&CD systems is included in the design features of the H&CD power converters and obtained by fast switch-off (10–200 µs) of the dc power source and limitation of the energy delivered to the faulty load (10–50 J).

6 The pulsed-power supply system

6.1 The ac distribution and the reactive power compensators and harmonic filters

The ac power is received from the 400 kV grid and transformed to an intermediate voltage level (69 kV) via three step-down transformers of 300 MVA/each continuous power [3]. Each step-down transformer feeds one distribution busbar. Most of the loads are directly fed from the 69 kV busbars. The loads with relatively lower power (normally less than 20 MVA/unit) are fed from the 22 kV busbars, which are powered from the 69 kV busbars through three step-down transformers of 50 MVA/each continuous power.

The PPSS [3, 6] includes several ac/dc converters producing reactive power and harmonic currents much higher than the level accepted by the Transmission Grid Operator. Therefore, a Reactive Power Compensator and Harmonic Filtering (RPC&HF) system has been foreseen to reduce reactive power consumption and the voltage distortion below the levels indicated in Tables 3 and 4. The RPC&HF units are connected to the 69 kV busbars (one unit for each busbar) and based on the Static Var Compensation (SVC) technology. In comparison with conventional SVCs, the ITER RPC&HF does not have Thyristor Switched Capacitor (TSC), because the generation of ‘inductive’ reactive power is not required; this reduces costs. On the other hand, harmonic filters are required and imply capacitor banks permanently connected to the distribution system. Finally, taking into account the expected development of Thyristor Controlled Reactor (TCR) technology, the construction of TCRs that can be directly connected to the 69 kV voltage level should be feasible by the time of ITER construction. Therefore, a design without TCR step-down transformer has been proposed for ITER. The disadvantage of this concept is the six-pulse operation of the TCRs that produces fifth, seventh harmonic currents and requires the corresponding harmonic filters. Nevertheless, the solution without TCR step-down transformer is the most convenient one.

6.2 The ITER power converters

6.2.1 *Power converters supplying the superconductive magnets*

The ITER magnets are supplied by a large ac/dc conversion plant, which has a total installed power of about 1.6 GVA [3, 7]. The quantity and main ratings of the magnet power converters are given in Table 5. One converter supplies continuous controlled dc current to the TF coils. Twelve converters supply the CS and PF coils with controlled voltage and/or current for plasma current and shape control. Four booster PF converters provide relatively high voltage during the plasma initiation (breakdown) and initial plasma current ramp-up. Two converters, with a 7.5 ms voltage response time, provide controlled voltage for the plasma vertical position control. Finally, nine converters supply the CC for error field correction and plasma stabilization.

Table 5: Quantity and main ratings of the ac/dc thyristor converter basic units

Converter	**Quantity**	**dc current (kA)**	**No-load output voltage (kV)**	**Rated unit power (*) (MVA)**	**Operational quadrants**	**Voltage response time (ms)**
TF	1	68	0.9	61	2	15
Main PF	12	45	2.0	90	4	15
Booster PF	4	10	5.6	56	4	15
Vertical stabilization	2	22.5	4.0	90	4	7.5
Correction coil	9	7.5	0.8	6	4	15

(*) All converters are for continuous duty, except the Booster PF converters that are for a duty cycle of 30/1800 s/s.

6.2.2 Power converters supplying the heating and current drive systems

The H&CD systems consist of Radio Frequency (RF) generators and Neutral Beam (NB) injectors. The RF generators are based on tetrode tubes, depressed collector gyrotrons, and klystrons operating, respectively, at the Ion Cyclotron (45–55 MHz), Electron Cyclotron (170 GHz), and Lower Hybrid (5 GHz) frequencies. The Neutral Beam injector basically consists of a negative ion source, 1 MV beam accelerator, neutralizer, and residual ion dump.

The main functions of the H&CD power supplies are to provide regulated and controlled dc voltage to the individual RF generators and NB injectors, and to switch off the output power in a very short time (< 10 μs for the RF generators, < 200 μs for the NB system), limiting the fault energy below the specified value (< 10 J for the RF generators, < 50 J for the NB system). The quantity and main ratings of the H&CD basic power supply units are given in Table 6.

Table 6: Quantity and main rating of the H&CD power supply basic units

System	**Quantity**		**Rated on load output voltage (kV)**	**Rated active power/unit (MW/unit)**	**Switch-off time (μs)**	**Max. fault energy (J)**
	Initial configuration	**Possible later upgrade**				
NB	2	+ 1	1000	55	200	50
IC	8	+8 (*)	26	3.9	10	10
EC	2	+2 (*)	50	30	10	10
LH	0	4	80	24	10	10

(*) One system only, between IC and EC, will be upgraded.

6.2.3 The design strategy and the technologies of the ITER power supplies

The main design work on individual power converters was carried out by the ITER JCT between 1994 and 1998, with the collaboration of the Home Teams, in particular EU and JA (industries and national laboratories). Several different converter technologies were adopted to meet the design requirements of the ITER magnets, RF generator, and NB injectors. The design strategy adopted for the ITER power converters was to demonstrate the feasibility of the basic components, adopting the cheapest solutions and limiting, as much as possible, the development of new components/technologies. As a consequence of this strategy, special technologies, quite different from standard industrial solutions, were adopted only for the H&CD power supplies with rated output voltage above 50 kV. Moreover, the use of fast devices such as GTO, IGCT or IGBT was limited to the power converters of loads requiring fast switch-off protection. Finally, a modular approach was adopted to simplify the component design and to reduce the cost for construction, testing, commissioning, and maintenance.

High-current thyristor converters, derived form the power converters of electrochemical plants, were adopted as the basis for the design of the coil power converters. In comparison with conventional industrial applications, the main design improvements have been the four-quadrant operation, fault suppression capability (normally adopted in low-current, high-voltage converters designed without thyristor in parallel), the internal freewheeling in all arms, and the use of bridges in series to achieve output voltages up to 5.6 kV.

The 'Pulse Step Modulator' is the technology adopted for the power supplies of the IC RF generators (tetrode tubes). In comparison with the conventional industrial application (power supplies for broadcasting transmitters), there are no substantial differences. In principle this technology could also be used to supply EC and LH RF generators.

Diode and thyristor rectifiers, up to 200 kV and 80 kV, respectively, are used in the power converters of the H&CD systems requiring dc voltage above 50 kV (EC, LH and NB). These are special power converters which require a specific design and, in some cases, development.

IGBT switches, rated up to 80 kV dc, are used in the power supplies of the EC and LH RF generators for the fast protection of the load. This is a special component developed in 1995, by the Japanese Home Team, for the EC H&CD generators [8]. EFDA is going to place a contract for the development and construction of a similar switch that can also perform the function of modulator.

GTO, IGCT and IGBT dc/ac inverters are used at ground potential level in the 1 MV dc power supplies of the NB injectors. These dc/ac inverters are based on technologies adopted in standard industrial drives. Therefore, no special development is necessary.

6.2.4 *The high-current power converters for the ITER magnets*

The reference design concept adopted for the 90 MVA Main PF converter (Fig. 5) is a 12-pulse, 4-quadrant converter made with back-to-back thyristors assembled on a common heat sink. It contains two 6-pulse thyristor bridges connected in parallel through interphase reactors, and a rectifier transformer with two phase-shifter secondary windings to provide the 12-pulse operation.

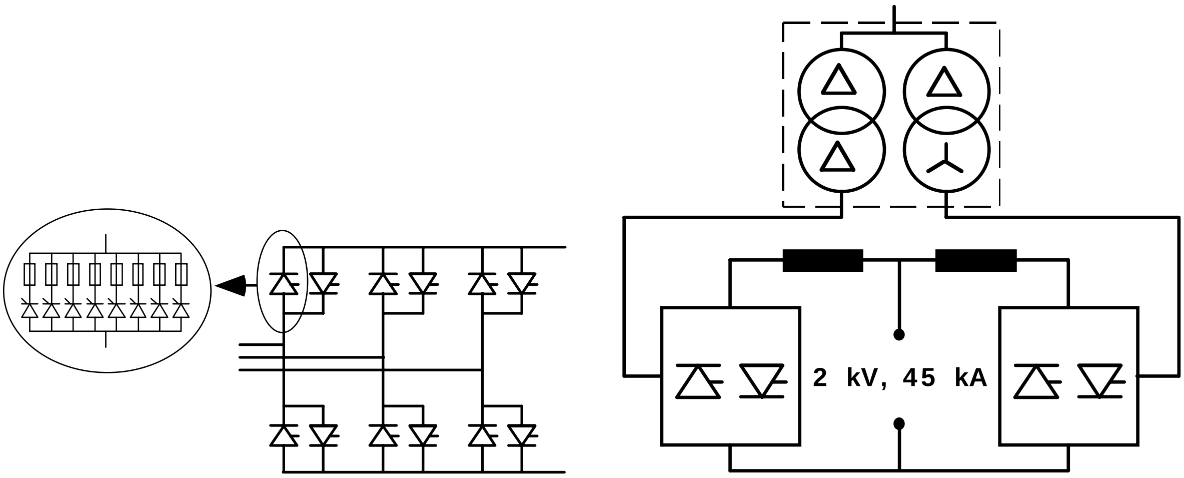

Fig. 5: Electrical schematic of the 90 MVA Main PF converter

In order to increase the reliability and availability of the conversion plant, the following design criteria have been assumed: 12-pulse operation, Fault Suppression Capability (FSC), one redundant thyristor per arm [3, 7 and 9]. The FSC is the capability of the converter to clear the overcurrents due to the most frequent faults (for example, circulating current between the back-to-back connected bridges or short circuit at the dc side), by gate pulse suppression without melting of the fuses. A fuse is connected in series with each thyristor (Fig. 5), but the pre-arcing I^2t of the fuse is coordinated with the thyristor I^2t so that the fuse operates only in the case of one thyristor failure. After the fault suppression, the remaining thyristors are capable of withstanding the nominal direct voltage, thus allowing the operation to be restarted immediately after the fault. The ac circuit breaker is used as back-up protection. Therefore it opens only in case of failure of the FSC procedure. A more detailed description of this design criterion is reported in Table 7.

Table 7: ‘Fault Suppression Capability’ design criterion

Fault type	Protective actions
Short circuit on the dc side (downstream of the dc reactor)	Electronic protection shutdown and back-up ac breaker opening (3 cycles)
Short circuit on the converter dc terminal	Electronic protection shutdown and back-up ac breaker opening (3 cycles)
Thyristor failure (short circuit)	Faulted thyristor fuse melting; back-up electronic protection shutdown and ac breaker opening (3 cycles). Note: there is one fuse in series to each thyristor (arm fuse)
Circulation current	Electronic protection shutdown and back-up ac breaker opening (3 cycles)

The FSC concept had already been used in fuseless, one thyristor per arm converters (like those installed in the HVDC plants), but this design requirement had to be demonstrated for cases with many thyristors in parallel. For this reason, in 1995, the European Home Team, in agreement with the ITER JCT, carried out an R&D programme aimed at identifying design solutions suitable to reduce the maximum current imbalance, thus reducing the cost and dimension of the basic unit and demonstrating that FSC can be achieved in ac/dc converters with several thyristors in parallel.

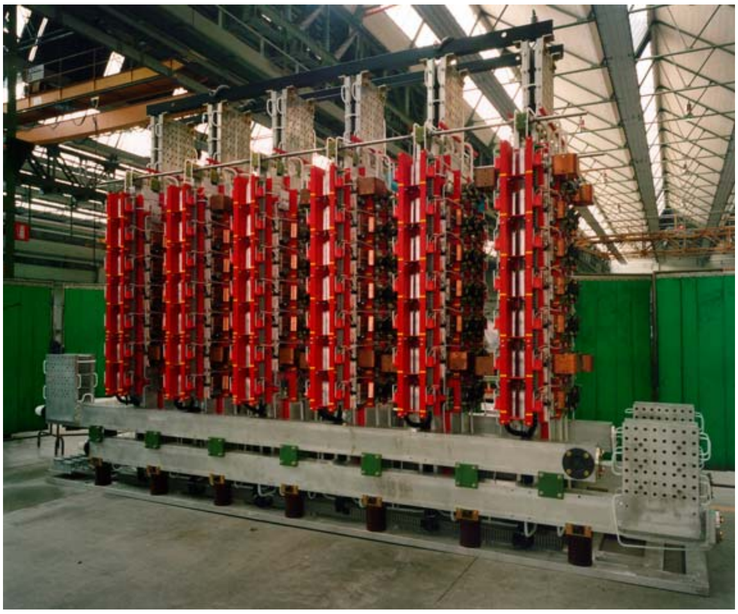

Fig. 6: 90 MVA main converter prototype built and tested in 1998

The converter prototype (Fig. 6) was successfully tested in 1998 [9]. The FSC was demonstrated with ten, 100 mm, thyristors in parallel (eight, 125 mm in the 1998 ITER design). A current imbalance factor < 1.4 was achieved, without ‘selected’ thyristors, not only in the case of normal operation, but also under fault conditions. After 1998, the manufacturer of the converter prototype continued the development and optimization of this technology achieving current imbalance factors better than 1.25.

The ITER Main PF converter has a voltage response time of 15 ms. To achieve the voltage response time required by the vertical stabilization converter (i.e., 7.5 ms) using the topology of the Main PF converter (Fig. 5), large interphase reactors would be required because of the parallel connection between phase-shifted six-pulse sub-units. In fact, in case of fast output voltage variation, the two parallel connected sub-units do not react in the same way (because they are phase shifted), producing a current imbalance which is limited by the interphase reactors. To limit the inductance of the interface inductors, a rate limiter has to be included in the control chain of the voltage control system. Therefore in the vertical stabilization converter, to achieve the 7.5 ms response time, without increasing the inductance of the interphase reactors, the 12-pulse operation is obtained via the series connection (instead of parallel) of six-pulse sub-units (Fig. 7). This topology and its control system have been optimized in a specific design study performed by the EU Home Team [10].

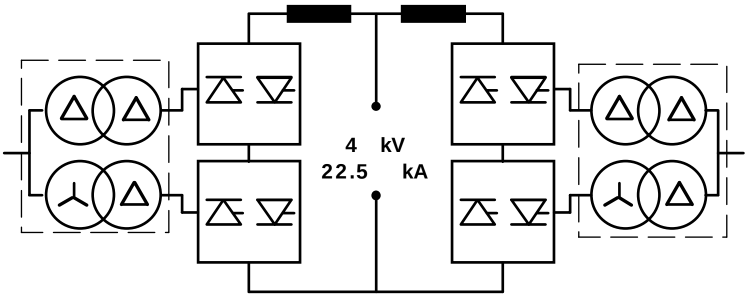

Fig. 7: Electrical schematic of the vertical stabilization converter

6.2.5 The Pulse Step Modulator (PSM)

The Pulse Step Modulator (PSM) technology is the reference design concept adopted for the power supplies of the IC RF generators (tetrode tubes) [3]. The PSM was developed during the 1980s for broadcasting transmitters. It uses several separate voltage steps (see Fig. 8), which can be electronically switched in and out of the circuit. In this way the output voltage can be rapidly varied to meet the voltage requirements of the tetrode. An intermediate tap supplies the anode of the pre-stage amplifier (low power tetrodes). Load protection is accomplished by rapidly (< 10 µs) switching off all voltage steps. Table 8 lists the salient features of this power converter [11].

Table 8: Main parameters of the IC H&CD power supplies

Total installed power	47 MVA
Number of power supply units	8
Number of tetrodes per power supply unit	1
Rated output power (each unit)	3.9 MW
Output voltage/current of main supply	5–26 kV/ 0–150 A
Output voltage/current of driver stage	3–18 kV/0–11 A
Number of steps/voltage per step	52/700 V
Voltage regulation	±1%
Protection time	< 10 µs

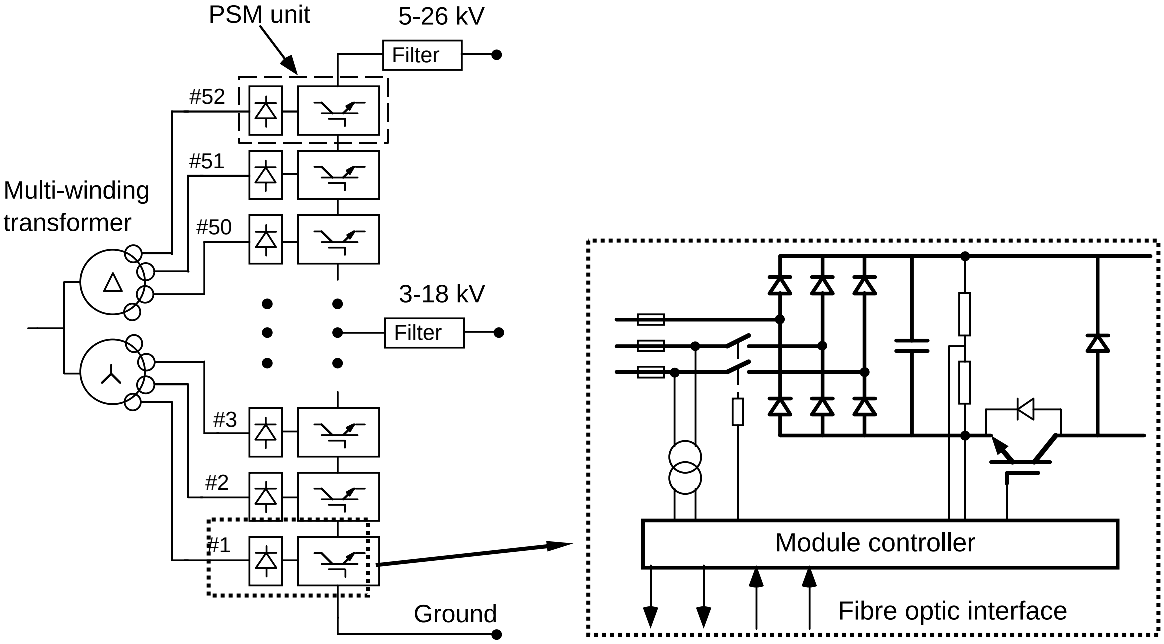

Fig.8: Pulse step modulator circuit diagram (left) and one-line diagram of the 'step module' (right)

6.2.6 *Thyristor converter with series IGBT modulator/switch*

The combination of a diode/thyristor converter with a high voltage IGBT switch/modulator valve (see Fig. 9) is the reference design concept of the EC and LH H&CD power supplies [3]. The requirements of these power supplies (see Tables 9 and 10) would be compatible with the performances of the PSM technology. However, in comparison with the PSM, the diode/thyristor converter with series IGBT switch/modulator is expected to be competitive (lower cost/MVA) when, as in the ITER design, the required RF power implies the use of several EC and/or LH RF generators. The main difference between the EC and LC power supply is the output voltage: 50 kV for the EC gyrotrons and 80 kV for the LH klystrons.

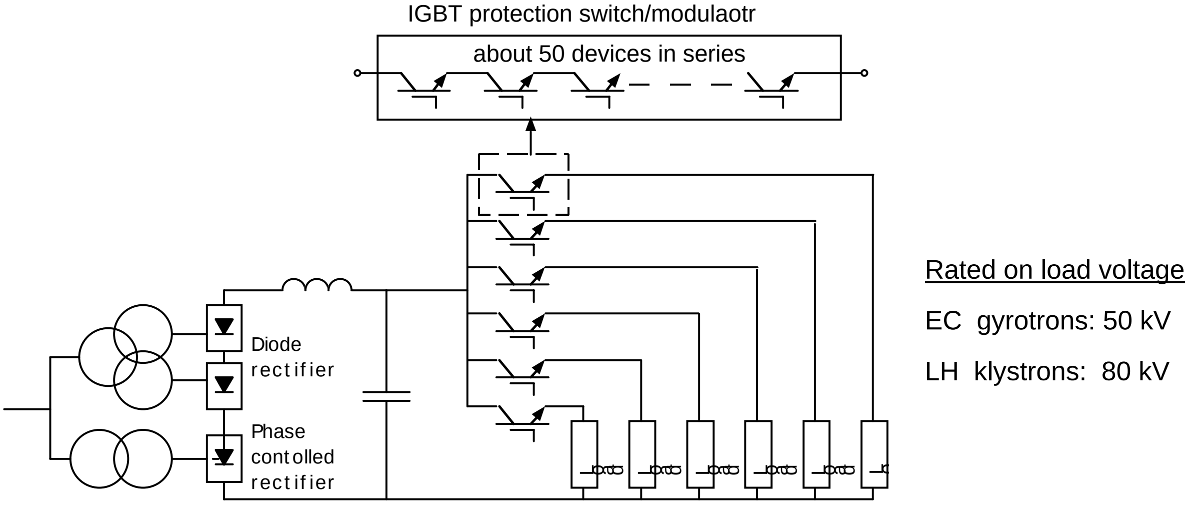

Fig. 9: One-line diagram of the power supply unit for the EC and LH H&CD systems

Table 9: EC H&CD power supply parameters. Initial configuration.

Total installed power	62 MVA
Number of power supply units	2
Number of gyrotrons per power supply unit	2 × 6
Rated output power (each unit)	22.5 MW
Rated output voltage / current	50 kV / 0–450 A
Voltage regulation of output voltage	± 5 %
Protection time	< 10 μs

Table 10: LH H&CD power supply parameters. Installed during the later upgrade of the ITER plasma heating systems.

Total installed power	120 MVA
Number of power supply units	4
Number of klystrons per power supply unit	2 × 6
Rated output power (each power supply unit)	24 MW
Rated output voltage/current	80 kV / 0–300 A
Voltage regulation of output voltage	±2%
No load output voltage/current of main supply	94 kV/ 0–300 A
Protection time	< 10 μs

6.2.7 The 1 MV dc power supplies for the NB H&CD

The NB H&CD injector consists of a negative-ion beam source, beam acceleration grids, neutralizer, residual ion dump and a few other auxiliary components [3]. The acceleration power supply is the most powerful component and is designed to provide a negative voltage up to 1 MV to ground, together with four intermediate voltages for the supply of the acceleration grids. The main design parameters of this power supply are reported in Table 11. The topology of the 1 MV acceleration power supply (Fig. 10) is based on ac/dc/ac frequency and voltage conversion, oil insulated step-up transformers, and an SF_6 gas-insulated dc rectification system. The dc/ac converters are based on GTO (or IGCT) inverters derived from industrial drives. The frequency is converted to about 300–400 Hz to reduce the size (and stored energy) of the HV output filters. To obtain the –1 MV voltage, five stages of 200 kV/each are connected in series. This splitting is required, not only to provide the intermediate voltages of the intermediate acceleration grids, but also because of feasibility problems of the step-up transformers. In fact, a single, 1 MV stage design would require a step-up transformer with 1 MV insulation between the two terminals of the HV winding. The design and manufacture of such a 1 MV winding is an extremely difficult task. The design and manufacture of the 1 MV insulation between LV and HV windings is also a difficult task, but not quite so difficult as the inter-turn and terminal-to-terminal insulation of the 1 MV winding. Therefore, even if intermediate supply voltages were not required, a multistage approach is required to overcome the feasibility limits of the HV step-up transformer.

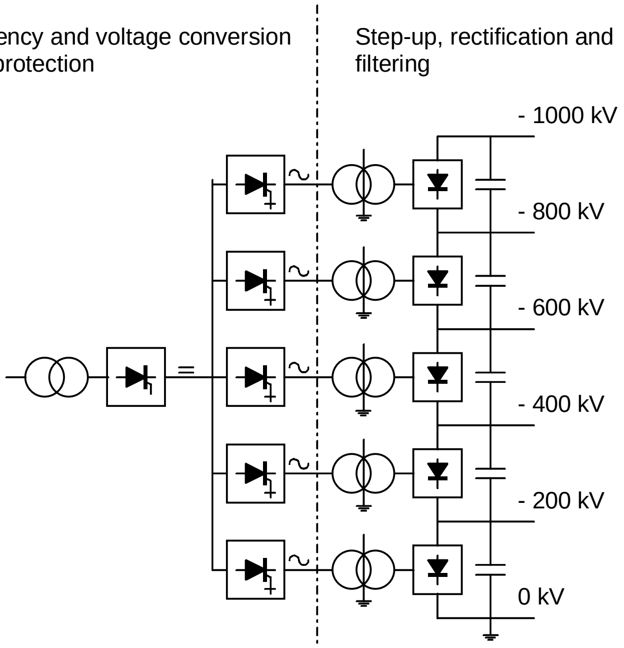

Fig. 10: One-line diagram of the 1 MV acceleration power supply for the NB injectors

Table 11: Design parameters of the main NB H&CD power supply: ‘acceleration beam power supply’

Total installed power	130 MVA
Number of power supply units	2
Rated power (each unit)	46 MW
Output voltage/current of main supply	1000 kV / 59 A
Output voltage/current of grid 1 supply	800 kV / 12A
Output voltage/current of grid 2 supply	600 kV / 4 A
Output voltage/current of grid 3 supply	400 kV / 2 A
Output voltage/current of grid 4 supply	200 kV / 1 A
Voltage regulation	+5%
Protection time	< 200 µs

The 1 MV power supply components are without precedent. In 1996, the JA Home Team tested a 500 kV prototype in the JT 60-U Tokamak facility [12]. The results obtained from this prototype have been used for the design study of the ITER 1 MV NB system, which has been carried out by the JA Home Team together with a parallel R&D activity dedicated to the development of a 1 MV bushing for the 1 MV, gas insulated, transmission line. The EU Home Team also contributed to the design of the ITER 1 MV power supplies, proposing a concept based on cascade transformers [13]. The JA proposal was adopted as reference design for ITER because it allows the individual control of each intermediate grid supply voltage. In any case, R&D activities are required for design validation of all the 1 MV components and expected to be carried out in collaboration between the EU and JA Home Teams.

7 Conclusion

ITER is the essential step needed in fusion research towards an energy source. After the completion of the engineering design activities, technical preparations are well advanced to turn the design of ITER into technical reality. The ITER project offers a wide variety of fusion development activities for the worldwide scientific community. During operation, scientists will participate remotely in experiments (e.g., operating diagnostics, analysing data, making proposals for the experimental programme) from many locations in the world.

At present there are two potential sites: Cadarache (France) and Rokkasho (Japan); the *ad hoc* group for the ITER Joint Assessment of Specific Site offers concluded that all sites meet the ITER site requirements. Concerning the European site, the study of the perturbations produced by the ITER power demand on the transmission network concluded that the ITER electric power requirements are compatible with the French transmission grid provided that the ITER reactive power demand is less than 180 Mvar.

The design work carried out by the ITER Joint Central Team, with contributions from the European and Japanese Home Teams (national laboratories and industry), has demonstrated the feasibility of all power converters. The use of GTO, IGCT, or IGBT was limited to the power supplies of loads requiring fast switch-off protection (H&CD power supplies).

High-current, thyristor converters, derived form the power converters of electrochemical plants, have been adopted as a basis for the design of the coil power converters. In comparison with conventional industrial applications, one of the main design improvements has been the Fault Suppression Capability, which was successfully demonstrated in a prototype built and tested in 1998. In this prototype a current imbalance factor < 1.4 was achieved, without ‘selected’ thyristors, not only in case of normal operation, but also under fault conditions. After 1998, the manufacturer of the converter prototype improved this technology achieving current imbalance factors better than 1.25.

The ‘Pulse Step Modulator’ technology of power supplies for broadcasting transmitters is the technology adopted for the power supplies of the IC RF generators (tetrode tubes). The combination of a diode/thyristor converter with a high-voltage IGBT switch/modulator valve is the reference design concept of the EC and LH H&CD power supplies.

Finally, ac/dc/ac frequency and voltage conversion (made with GTO or IGCT converters), oil insulated step-up transformers, and an SF_6 gas-insulated dc rectification system is the design topology adopted for the 1 MV dc acceleration power supply of the NB injectors. This is a component without precedent, which still requires challenging R&D activities for design validation (see Appendix A).

Appendix A: Challenges of power supply developments

The most challenging task is the development of the following 1 MV dc components for the NB H&CD system:

- step-up transformers;
- gas-insulated transmission lines;
- bushings: air/pressurized gas, oil/air, oil/pressurized gas.

Other challenging tasks are the fabrication and testing of an IGBT valve, which combines the function of protective switch and modulator for the EC and LH H&CD systems, and the revision of the component design, taking into account emerging new technologies (for example, HVDC light®–HVDC plus®).

HVDC light® (ABB)–HVDC plus® (Siemens) is a recently developed technology for advanced transmission systems. This technology uses ac/dc converters up to 150 kV dc based on IGBT bridges with IGBT valves made of several IGBT is series. Detailed information is available on the WWW sites of ABB and Siemens. This technology could be attractive for the ITER H&CD power supplies (IC, EC, LH and NB), if the price is competitive. The circuit diagram shown in Fig. A.1 describes an idea presently under evaluation by EFDA (still preliminary and not yet discussed with industry) concerning the application of high-voltage IGBT converters, developed for the HVDC light®/plus® technology, to the −1 MV dc acceleration power supply of the ITER NB injectors. The cascade transformer concept, shown in Fig. A.1, is derived from the design proposed by Siemens for the same application [13]. In Fig. A.1, this design concept is improved by moving to the HV side the converter for voltage regulation and load protection; this allows the regulation and control of each individual grid voltage, as in the ITER reference design (Fig. A.2).

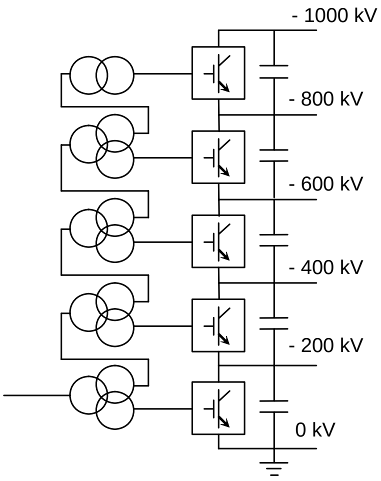

Fig. A.1: Alternative design of the −1 MV acceleration power supply, based on IGBT converters derived from HVDC light®/plus® technology.

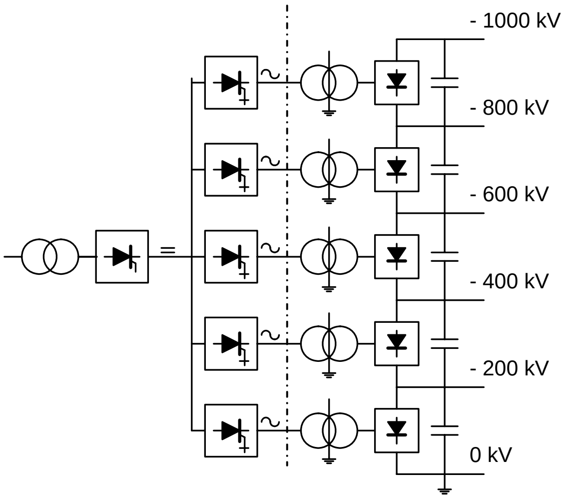

Fig. A.2: ITER reference design of the −1 MV acceleration power supply

Appendix B: Main acronyms

BC	Booster Converters
CC	Correction Coils
CPS	Coil Power Supplies
CS	Central Solenoid
EC H&CD	Electron Cyclotron Heating and Current Drive
EDA	Engineering Design Activities
FSC	Fault Suppression Capability
H&CD	Heating and Current Drive
IC H&CD	Ion Cyclotron Heating and Current Drive
JCT	Joint Central Team (International ITER Joint Central Team)
LH H&CD	Lower Hybrid Heating and Current Drive
NB	Neutral Beam
NB H&CD	Neutral Beam Heating and Current Drive
PF	Poloidal Field
PPSS	Pulsed-Power Supply System
PS	Power Supply
PSM	Pulse Step Modulator

RF	Radio Frequency
RPC&HF	Reactive Power Compensation and Harmonic Filtering
RTE	(Operator of the French Transmission Grid)
SSEPN	Steady-State Electrical Power Network
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
TF	Toroidal Field
TSC	Thyristor Switched Capacitor
VS	Vertical Stabilization

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