3.4 Pulsed and Steady-State Power Supplies

The pulsed and steady-state power supplies consist of the following four major systems:

pulsed power distribution system;
coil power supplies;
heating and current drive (H&CD) power supplies (PS);
steady state electric power network (SSEPN).

The pulsed power distribution system will supply ac power to the coil PS and H&CD PS, while the SSEPN will provide ac power to different loads (mainly motors) within the plant systems, such as the cooling water system, cryoplant etc. The coil PS and H&CD PS will supply their corresponding loads, the magnet coils and H&CD systems, in general with dc power.

The main general functions of the pulsed power distribution system PS systems are:

- to supply the ITER machine and ITER plant systems with electric power;
- to protect them in case of electric faults;
- to provide proper grounding of the machine and power supply components.

3.4.1 Pulsed Power Distribution System

The ITER pulsed power distribution system will be connected to a powerful high-voltage (HV) grid capable of providing the large pulsed power needed to supply the superconducting coils and the H&CD systems.

Ac power is assumed to be received from the HV grid at 400 kV voltage and is transformed to an intermediate level (69 kV) via 3 step-down transformers, each rated at 300 MVA continuous power (see the simplified one-line diagram in Figure 3.4.1-1). All loads (ac/dc converters for the TF coils, CS, PF coils and CCs, and H&CD systems) are shared among the three 69 kV busbars as equally as possible. Most of these loads are directly supplied from the 69 kV busbars. The loads with relatively lower power per unit (normally less than 20 MVA) are connected to the medium, 22 kV, busbars, which are powered from the 69 kV busbars through 3 step-down transformers, 50 MVA power each.

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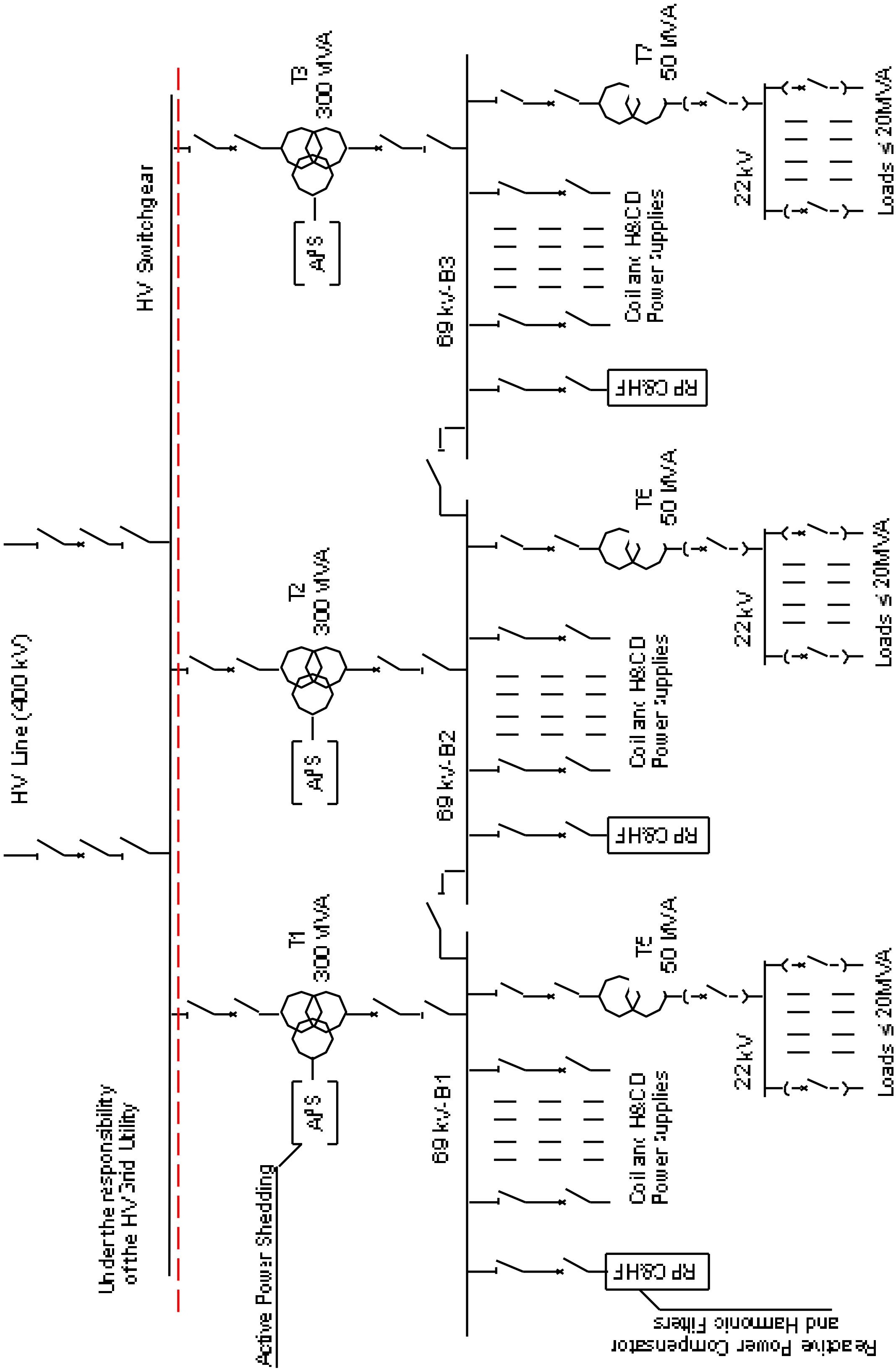

Figure 3.4.1-1 Pulsed Power HV Substation and Distribution System – Simplified Diagram

The total peak pulsed power demand will be limited to 500 MW active power and 400 Mvar reactive power. This includes power required for the pre-programmed PF scenarios, power needed for the plasma current, position and shape control, including the vertical stabilisation, and power to supply the H&CD systems. The active power demand will be limited in derivative to 200 MW/s, with maximum step changes of 60 MW in normal operation. (The power steps are defined as the variation of the total power during the time when the absolute value of the power derivative is higher than 250 MW/s.)

A 180 Mvar reactive power compensation unit, including harmonic reactive power and high frequency filters, is connected to each 69 kV busbar to compensate for the ac/dc converters. Each unit consists of one thyristor-controlled reactor and 6 LC filters.

In addition, a system for active power shedding is foreseen. It consists of 3 identical units supplied by the tertiary (33 kV) winding of the 400/69 kV step-down transformers. Each unit consists of 3 three-phase resistor banks connected to the transformer via 3 vacuum circuit breakers. Altogether the three units, if switched on, may absorb up to 350 MW, thus preventing large negative power steps in the HV grid. Such steps are expected in case of plasma disruption, when all H&CD systems have to be simultaneously switched off. Later the resistors are progressively switched off in about 3 s, providing the smooth variation of the active power (about 40 MW per step). This system, however, cannot be used for the correction of steps caused by fast plasma control, which in some cases are very high (up to 90 MW). If measures to improve plasma control are unsuccessful in reducing the power step to less than that presently specified (60 MW), an increase in the power step should be considered as part of the work on the power supplies for site adaptation.

An alternative design has been developed of a power supply system fed from a HV grid with a more limited capability (e.g. 400 MW, 300 Mvar). In this design, a local energy storage will supply power required for fast control to stabilise plasma disturbances. Several options were considered, but the preference is for ac-excited flywheel motor-generators with controlled output voltage frequency, that allows them to be synchronised with the HV grid. Therefore, the common 69 kV busbars for ac power distribution can be used, and no changes are needed for the ac/dc conversion system.

3.4.2 Coil Power Supplies

The coil power supplies include the following 9 systems supplying controlled dc current to the TF and PF coils and the CS modules:

- one common power supply system for the 18 TF coils;
- 5 PS systems for the CS modules: 4 individual PS systems for CS2 and CS3 upper and lower modules, and one common PS system for the CS1 upper and lower modules connected in series;
- 2 PS systems for individual supply of the PF1 and PF6 coils;
- one common system for the 4 outer PF coils, PF2 - PF5, used for plasma vertical stabilisation.

In addition, 9 relatively small PS systems with identical configuration will supply the 9 correction coils (CCs).

3.4.2.1 TF Coil Power Supply System

The TF coils are combined in nine groups, each containing 2 coils which are connected in series inside the cryostat. These groups are connected in series and supplied with power by one 12-pulse, 2-quadrant thyristor-converter rated for 68 kA current, 900 V no-load voltage (see Figure 3.4.2-1). When the TF system has been charged and the current has reached the requested constant value, the primary winding of the rectifier transformer is switched from the 69 kV ac supply to the 22 kV supply. This results in a corresponding reduction of the output converter voltage and, therefore, of reactive power, for the long (a few weeks/months) period of operation with constant current. To discharge the coils, the ac power supply from the 69 kV busbar has to be restored. The minimum charge/discharge time is about half an hour. The energy stored in the TF coils at the maximum (68 kA) current is about 40 GJ.

In case of quench or a failure in the power supply system requiring immediate extraction of the coil energy, 9 fast discharge units interleaved in series with each coil pair are activated to rapidly discharge the stored energy. These units consist of circuit breakers and discharge resistors, which are rated to absorb 35 GJ and provide the discharge with an equivalent time constant of 11 s. About 5 GJ will be dissipated in the vacuum vessel, TF coil radial plates and cases, and other passive components. The maximum voltage on the discharge resistors will not exceed 8 kV.

Two circuit breakers are included and connected in series in each of the fast discharge units. The first, called the current commutation unit, is designed for multiple operation and will open when a quench is detected. In case of failure in one current commutation unit, the second circuit breaker (pyrobreaker), not suitable for repetitive operation but very reliable, will interrupt the current.

The circuit breakers for fast discharge are located in the tokamak building gallery, near the coil terminal boxes. A fast make switch also located in the gallery is switched on simultaneously with the initiation of the fast discharge. Therefore, the whole discharge circuit will be closed within the gallery and detached from the ac/dc converters and the busbars between the converters and the fast discharge units. The discharge resistors, and the counterpulse capacitor banks used to create the current zero in the current commutation unit, are located in the diagnostic building adjacent to the tokamak building, and are connected with the switches by coaxial cables.

Other provisions aimed at increasing the coil protection reliability include, in particular, the use of capacitors and reservoirs for compressed gas to provide autonomous operation of electromagnetic and pneumatic drives, redundancy, and uninterruptible supply for instrumentation and control devices and others. Moreover, two or more “lines of defence” are foreseen for the detection of, and protection against, over-current in the coils, as well as excessive or deficient values of parameters within the power supplies, e.g. over-temperature of busbars, low flow rate of cooling water etc.

3.4.2.2 Power Supplies for the CS Modules and for the Coils PF1 & PF6

These power supplies drive one CS module or PF coil, as shown in Figure 3.4.2-2 for the PF1 system (as an example), or drive two modules in series, as shown in Figure 3.4.2-3 for the CS1.

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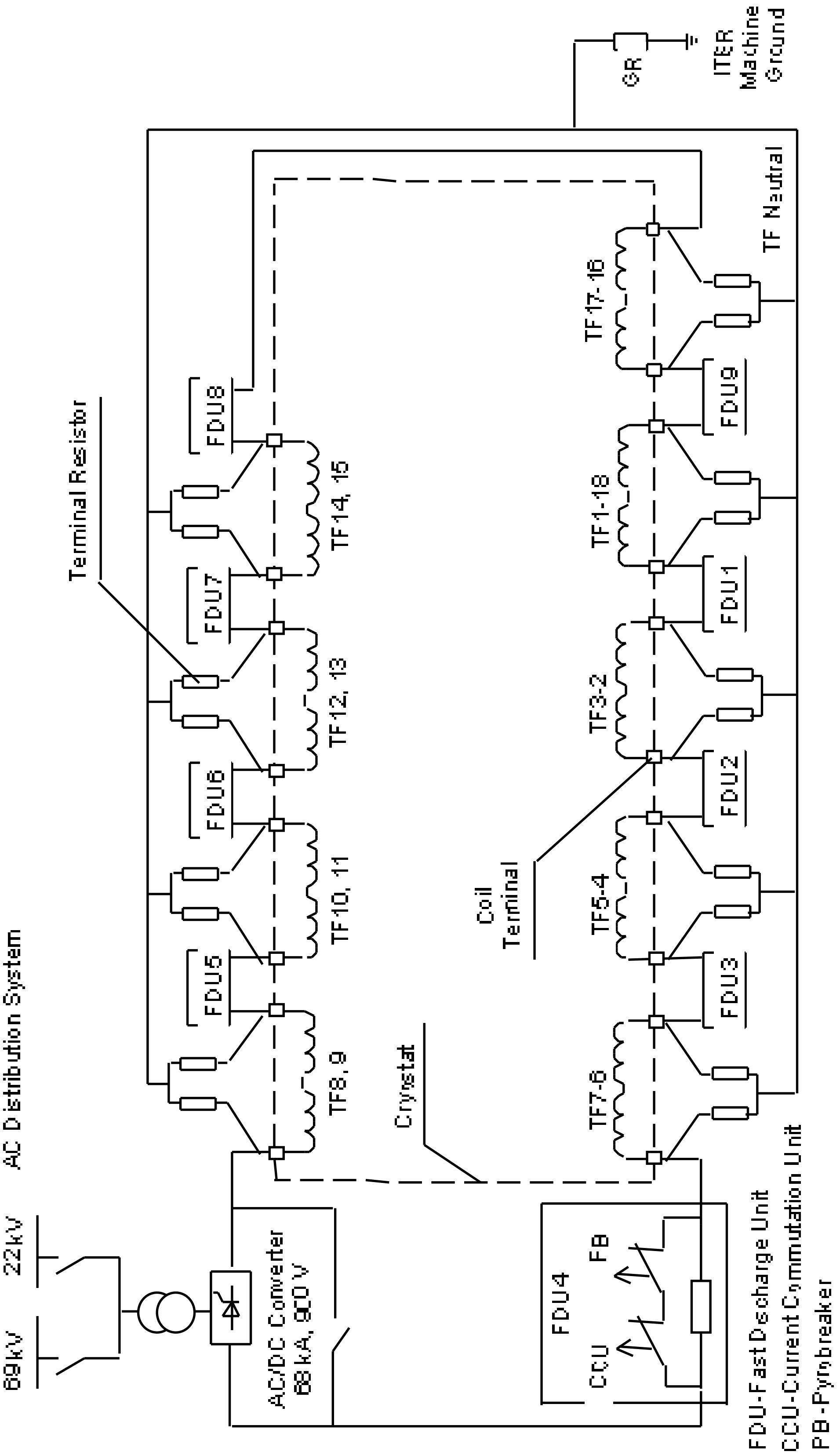

Figure 3.4.2-1 TF Coil Power Supply – Simplified Diagram

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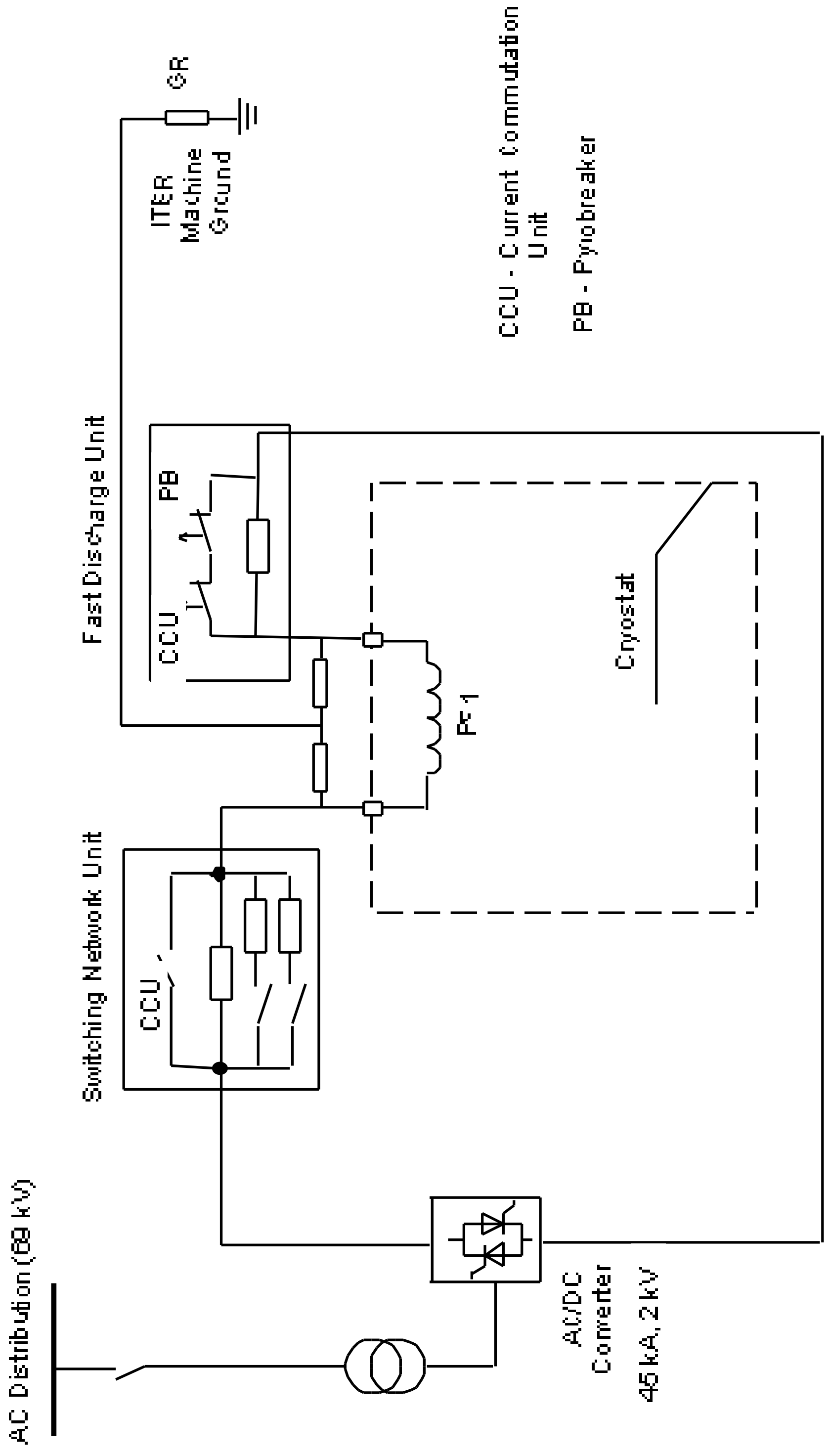

Figure 3.4.2-2 Coil PF1 Power Supply – Simplified Diagram

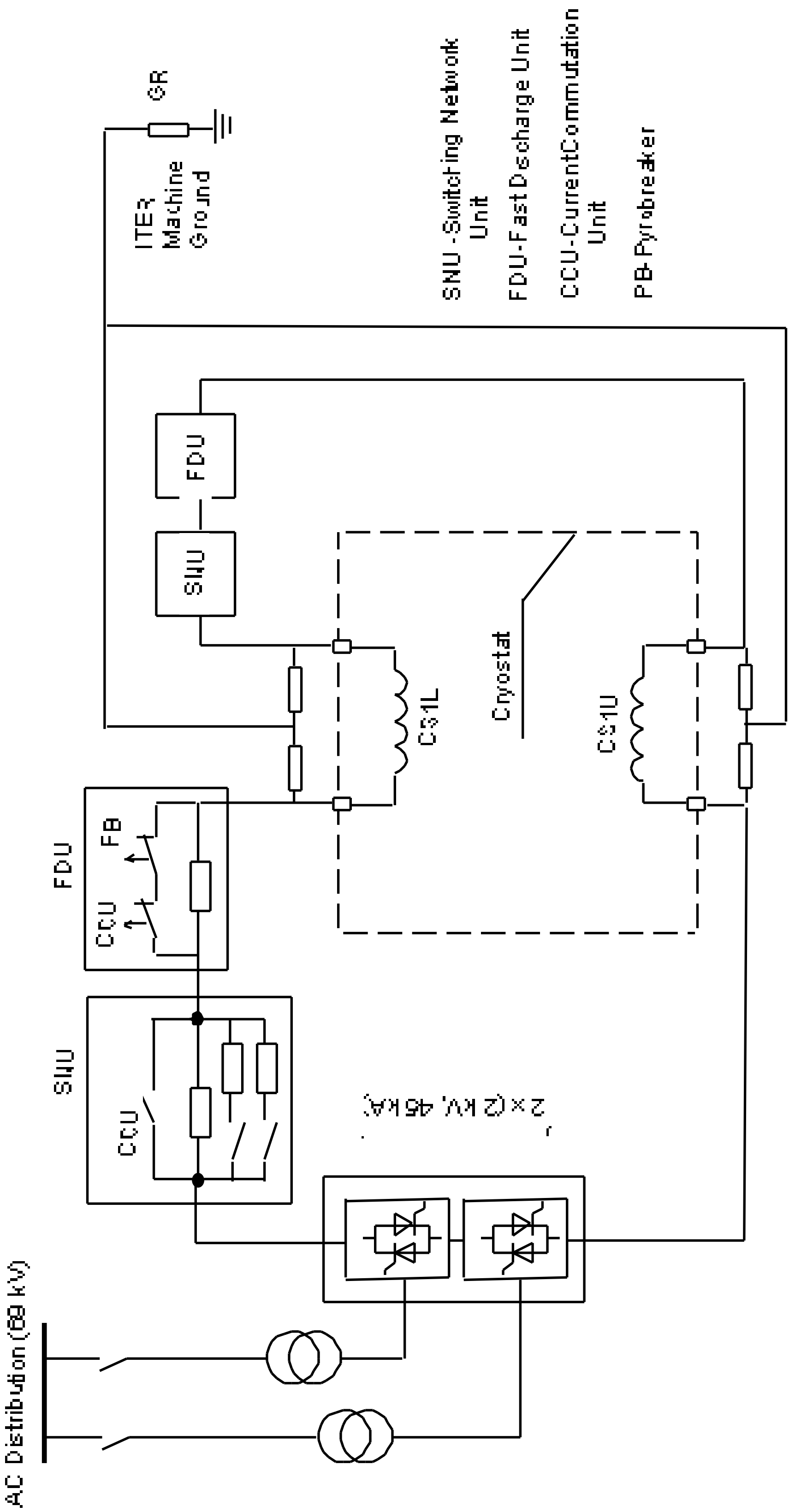

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Figure 3.4.2-3 CS1 Power Supply – Simplified Diagram

The loop voltage required for breakdown and plasma initiation is obtained by connecting resistors in series with the CS modules, PF1 and PF6 coils, causing a very large amount of power (about 2 GW) to be extracted. These circuits, called switching networks, are made up of circuit breakers, make switches and resistors. A switching network unit contains 3 resistors banks connected in parallel to the current commutation unit: one resistor bank directly and the other two through make switches. When the current commutation unit is open, the first resistor is inserted simultaneously in series with the coils. Then, at predetermined time steps, the other 2 resistors are progressively included in parallel with their own make switches.

After plasma initiation, the power required for plasma current, shape, and position control is provided by one 12-pulse, 4-quadrant thyristor converter, rated for 45 kA continuous current, 2 kV no-load voltage.

The fast discharge units for coil energy discharge are identical with those used for TF coil protection. A fast discharge with the equivalent time constant of 7.5 s for the CS and 14 s for the PF coils is provided with a voltage not exceeding 7 kV. The maximum energy dissipated in the discharge resistors is in the range of 1-2 GJ per system.

3.4.2.3 Power Supply System for the Coils PF2-PF5

The quasi-symmetrical distribution of currents in these coils make it possible to use one fast-response thyristor converter, dedicated to plasma vertical stabilisation, in an integrated power supply system, as shown schematically in Figure 3.4.2-4. The two pairs of quasi-symmetrical coils (PF2-PF5 and PF3-PF4) are connected in parallel to the vertical stabilisation converter. Within each pair, the two coils are connected in anti-parallel.

Three types of thyristor-converters are utilised in this scheme. The main converter, rated for 45 kA, 1.5 kV (on-load), provides relatively slow variation of coil current needed for the plasma current and shape control. The design is the same as that of the CS/PF converter. The “booster” converter generates a relatively high voltage (up to 4.2 kV at the maximum current 10 kA) that, together with the voltage of the main converter, creates the conditions required for breakdown at plasma initiation. When this phase is over, the booster converter is switched into freewheeling mode and then bypassed by the make switch. Finally, the 22 kA fast response vertical stabilisation converter generates a voltage up to 6 kV (on-load) when requested by the plasma feedback control system.

The fast discharge units are identical with those described previously. When a fast discharge is initiated, the vertical stabilisation converter is bypassed by the protective make switch. The fast discharge is characterised by an equivalent time constant of 14 s, a maximum voltage up to 7 kV and a maximum energy per coil of 1.8 GJ.

3.4.2.4 Power Supply System for the Correction Coils

Three groups of correction coils (CCs), top, side and bottom, are included in the design of the magnet system. Each group consists of 6 identical modules shifted toroidally with respect to each other by 60°. The opposite modules are connected in anti-series, forming together 3 top CCs (CCT1, 2 and 3), 3 side CCs (CCS1, 2 and 3) and 3 bottom CCs (CCB1, 2 and 3). Each CC set has its own power supply system, as shown schematically in Figure 3.4.2-5.

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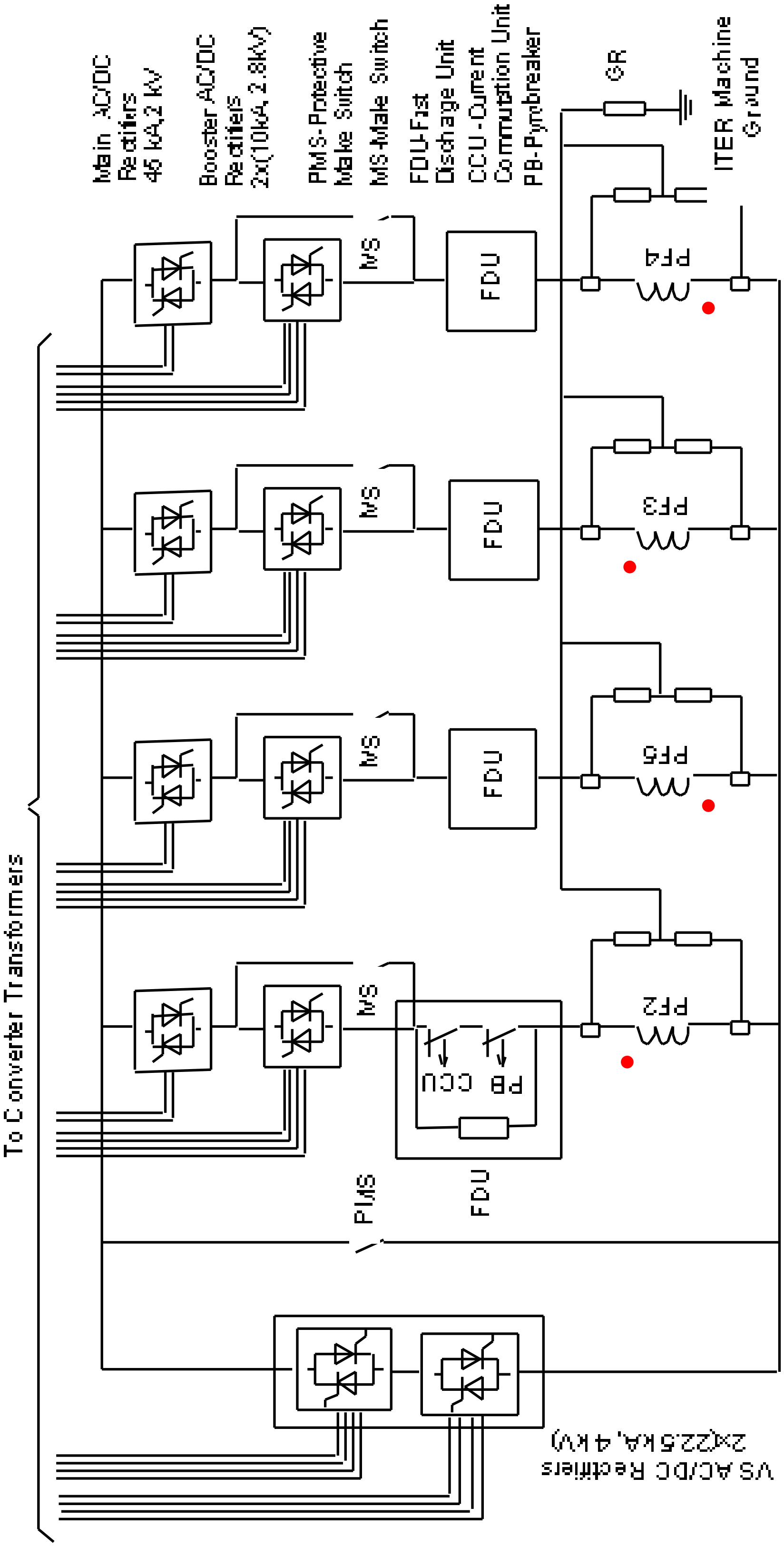

Figure 3.4.2-4 Coils PF2-PF5 Power Supply – Simplified Diagram

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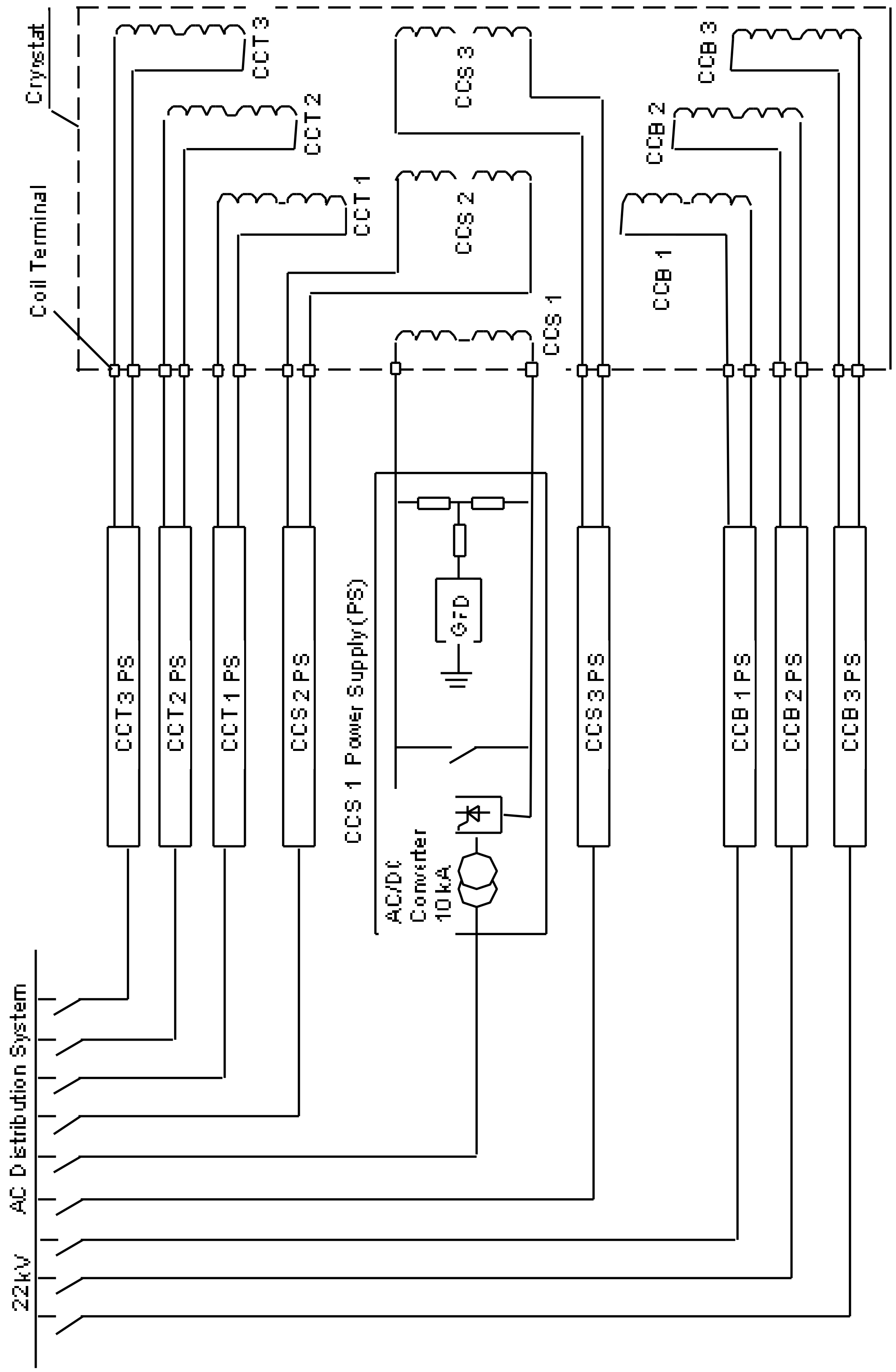

Figure 3.4.2-5 Correction Coils Power Supply – Simplified Diagram

All 9 power supplies have the same, simple, configuration: an ac/dc converter supplies dc power to the coil. Acting in inversion mode it also provides fast discharge of the coil energy in case of quench. If the converter fails to perform this action, it will be bridged by a parallel-connected make switch, and the coil energy will be dissipated in the busbars with a time constant less than 20 s (backup protection). All converters are rated for 10 kA current, but have different output voltages in the range 100 - 800 V, depending on the coil contribution to the stabilisation of resistive wall modes.

3.4.2.5 Coil Grounding

A soft grounding via high impedance (1-2 kΩ) resistors is provided for all the coils. This approach is illustrated by the grounding scheme of the TF coils shown in Figure 3.4.2-1. The TF system is grounded through a set of identical resistors connected in parallel to each coil pair. Their midpoint is connected to the TF neutral, which is a common busbar connected to the ITER machine ground, through one resistor (GR). Its resistance is about 1 kΩ to limit the fault current to ground and the related arc energy in the case of a single failure in the ground insulation of the TF system. The leakage current to ground will be measured and used for ground fault detection. A similar concept is used for the CS, PF coils and CCs (see Figures 3.4.2-2 to 5).

3.4.3 H&CD Power Supplies

The H&CD power supply (PS) systems will supply dc or ac controlled voltages and/or currents to the H&CD equipment, which are radio frequency (RF) generators or neutral beam (NB) injectors. In particular the PS systems will be connected to:

- the anodes and driver stages of the IC H&CD tetrodes;
- the cathodes, anodes and bodies of the EC H&CD gyrotrons;
- the collectors of the LH H&CD klystrons;
- the acceleration grids and auxiliaries of the NB H&CD and DNB injectors.

The different components are ac/dc converters, dc/ac inverters, etc., based mainly on solid-state devices (diode, thyristor, gate-turn-off thyristor, insulated gate bipolar transistor, etc.). The ac power will be supplied from the pulsed power distribution system at the 69 kV or 22 kV busbars, according to the level of power required for their operation.

The basic combination of heating systems (for initial operation) will deliver 73 MW to the plasma (20 MW IC, 20 MW EC and 33 MW NB). The power delivered to the plasma can be upgraded to 110 MW, by increasing the number of IC, EC or NB units and/or by adding the LH system. The total peak power demand on the pulsed power system will be around 210 MW (330 MW with upgrade). Differing requirements have led to the use of different power supply technologies for each of the H&CD systems. These PS systems are briefly described below.

3.4.3.1 IC H&CD Power Supplies

One IC H&CD PS unit feeds one tetrode with controlled dc voltages between anode and cathode and between driver stage and cathode. A simplified scheme of this unit is shown in Figure 3.4.3-1. The parameters of the PS units are given in Table 3.4.3-1.

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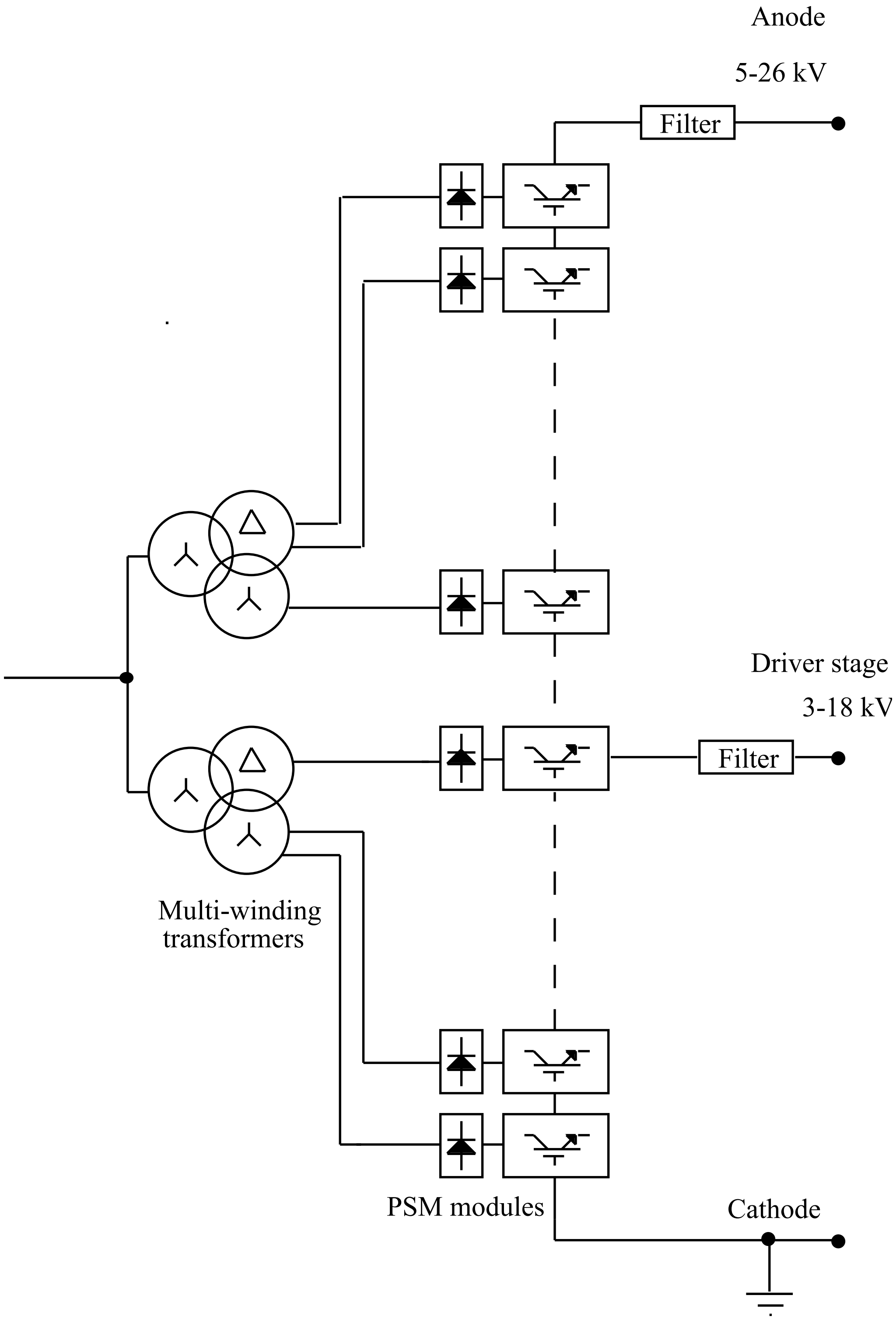

Figure 3.4.3-1 IC H&CD PS Unit – Block Diagram

Table 3.4.3-1 Parameters of the IC H&CD PS Units

Parameters	Unit	Value
Number of IC H&CD PS units		8
Anode maximum power per unit (150 A)	MW	3.9
Driver stage maximum power per unit (25 A)	kW	450
Maximum current per unit	A	175
Anode voltage range	kV	5 - 26
Anode voltage modulation frequency	Hz	200
Driver stage voltage range	kV	3 - 18

The use of individual PS units for the tetrodes of the IC H&CD, based on "pulse step modulator" (PSM) technology, has been adopted to control with high accuracy the voltage applied to the tetrodes. This technology uses 36 separate voltage steps, 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. Moreover, pulse width modulation, with an overall effective frequency per PS unit of 90 kHz, is employed to regulate the voltage with more accuracy, to smooth the 12-pulse rectification ripple, and to provide required 200 Hz modulation of the anode voltage.

Load protection is accomplished by the insulated gate bipolar transistor, which is part of the switched PS module; all modules are switched off in less than 10 μs, limiting the energy dissipated in a fault to 10 J.

3.4.3.2 EC H&CD Power Supplies

The gyrotrons require two types of HV dc power sources to supply its cathode, anode and body as shown in Figure 3.4.3-2. The main, cathode, PS consists of 2 units each feeding six pairs of gyrotrons with a controlled dc voltage between cathode and collector. A simplified scheme of this unit is shown in Figure 3.4.3-3. Another PS (one for each gyrotron) supplies a controlled and modulated (1 kHz) voltage between body and cathode (see Figure 3.4.3-2). Part of this voltage is derived between anode and cathode, through a resistive voltage divider. The parameters of the PS units are given in Table 3.4.3-2.

The use of one main PS unit for twelve gyrotrons, based on a conventional ac/dc thyristor converter, has been adopted for its limited cost, and its capability to control the cathode voltage with the requested accuracy. Connection, protection and commutation, between the H&CD gyrotrons and those used to assist the plasma start-up, are performed by insulated gate bipolar transistor switches for every pair of gyrotrons. Voltage overshoots and undershoots, which can appear in the case of an intervention of the protective switch of a pair of gyrotrons on the cathode voltage of other gyrotrons connected to the same power supply, remain within ± 1% of the maximum voltage. The high dynamic accuracy in the control of body-to-cathode voltage (± 0.5%) is obtained with an individual generator for every gyrotron.

Load protection is accomplished by the insulated gate bipolar transistor switch, which is in series with the faulty gyrotron. This acts in less than 10 μs, limiting the energy dissipated in a fault to 10 J.

N 42 GR 30 00-12-20 F 2

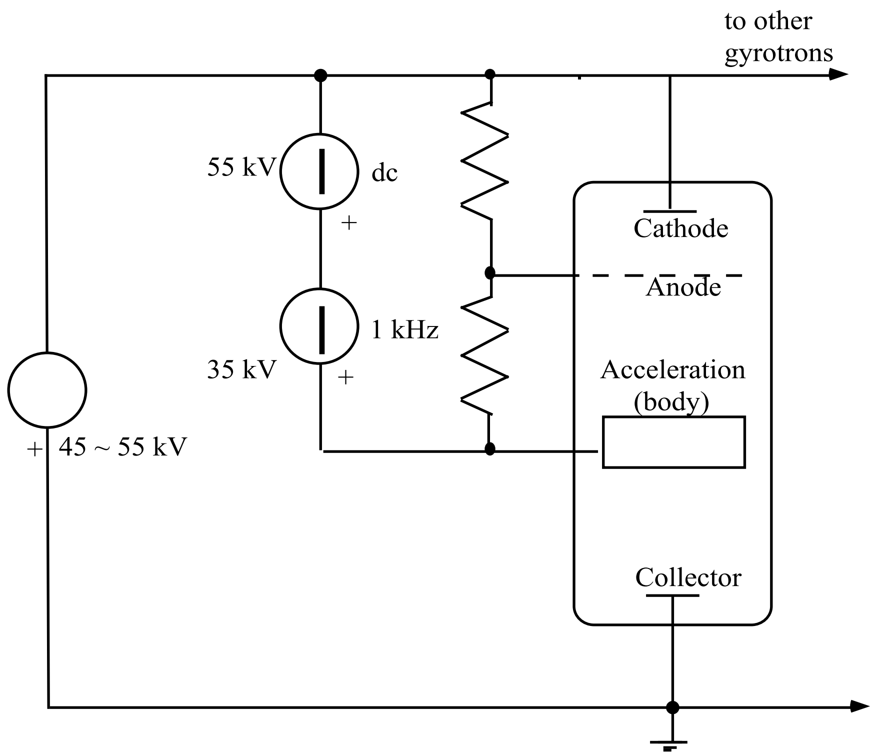

Figure 3.4.3-2 Connection of the EC H&CD PS to Gyrotron Electrodes

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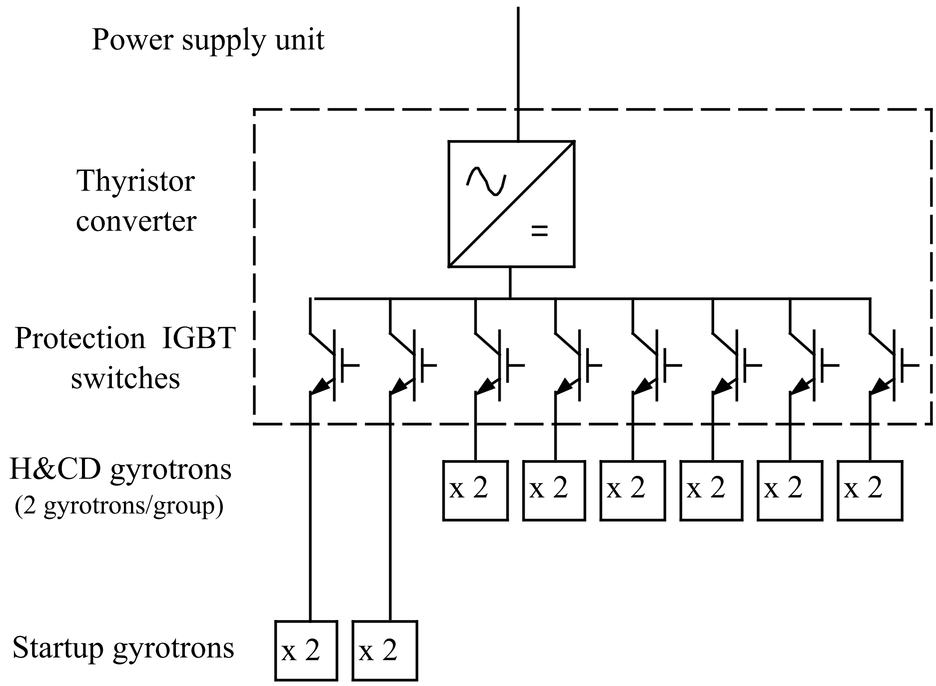

Figure 3.4.3-3 EC H&CD PS Unit - Block Diagram

Table 3.4.3-2 Parameters of the EC H&CD PS Units

Parameters	Unit	Value
Number of main (cathode) PS units		2
Cathode-to-collector voltage range	kV	- 45 to - 55
Nominal cathode current per unit	A	540
Maximum power per unit	MW	30
Number of body/anode PS units		24
Body-to-cathode voltage range	kV	+ 45 to + 90
Maximum body current	A	0.1
Anode-to-cathode voltage range	kV	0 to + 50
Anode and body voltage modulation range	kV	35
Anode and body voltage modulation frequency	kHz	1
Maximum anode current	A	0.1

3.4.3.3 LH H&CD Power Supplies

One PS unit feeds six pairs of klystrons with a controlled dc voltage between collector and anode, with a scheme similar to that for EC H&CD, shown in Figure 3.4.3-3. The parameters of the PS units are given in Table 3.4.3-3.

Table 3.4.3-3 Parameters of the LH H&CD PS units

Parameters	Unit	Value
Number of LH H&CD PS units		2
Collector voltage	kV	80
Nominal collector current per unit	A	300
Maximum power per unit	MW	24

The use of one PS unit for twelve klystrons, based on the "star point controller" technique[1], has been adopted due to its limited cost even with high values of dc voltage (80 kV load voltage), capability to control the collector voltage with the requested accuracy, and the limited amount of energy released in case of a fault. (This solution was not adopted for the EC H&CD PS because it is more expensive than the thyristor converter solution at the 55 kV voltage level). Connection and protection are performed by insulated gate bipolar transistor switches for every pair of klystrons.

Load protection is accomplished by an insulated gate bipolar transistor switch, which is in series to the faulty klystron. This acts in less than 10 μs, limiting the energy dissipated in the fault to 10 J.

[1] R. Claesen and PL Mondino, "Neutral Beam Injection and Radio-Frequency Power Supplies", in Fusion Technology, Vol.11, Jan.1987, Pages 141-162.

3.4.3.4 NB H&CD Power Supplies

The NB H&CD PS provides:

- frequency and voltage conversion for voltage control and fast power interruption at low voltage level;
- voltage transformation rectification and filtering, to provide high voltage power to the beam sources, with different levels for the different source grids;
- dc power transmission to the beam sources;
- auxiliary power (both ac and dc) to produce and extract the negative ion beam; the power supplies are floating at a high voltage level (- 1 MV) and are contained in a HV deck, located in the machine gallery;
- power to the active correction/compensation coils and the residual ion dump at ground reference level.

One PS system feeds one NB injector. The PS system is split into three parts. An acceleration PS provides a negative voltage (up to 1 MV to ground) to the beam source, together with intermediate voltages to the acceleration grids. An ion source PS provides different voltages and current to several items of equipment in the HV deck (SF_6-insulated). A third group of power supplies provides individual dc voltages to seven active correction/compensation coils and to the residual ion dump. A simplified scheme of the acceleration PS is shown in Figure 3.4.3-4, where frequency and voltage conversion is provided by gate-turn-off thyristor inverters and voltage transformation is provided by five transformers, connected in series, with 1 MV insulation between primary and secondary windings. The parameters of the PS system are given in Table 3.4.3-4.

The connection between power supply and beam source is done by a multi-axial, SF_6-insulated, HV transmission line (see 3.4.5.3). The line is split in two parts by the HV deck, where the ion source power supply is located.

The load protection is obtained by fast switch-off of the gate-turn-off thyristor inverters. These act in less than 200 μs, limiting the energy dissipated in a fault to 50 J.

Table 3.4.3-4 Parameters of the NB H&CD PS System Unit

Parameters	Unit	Value
Number of units		2
Acceleration supply voltage/current	kV/A	- 1000 / 59
Grid 1 voltage/current	kV/A	- 800 / 7
Grid 2 voltage/current	kV/A	- 600 / 6
Grid 3 voltage/current	kV/A	- 400 / 3
Grid 4 voltage/current	kV/A	- 200 / 3
Current at ground level	A	40
Rated power per acceleration unit	MW	48
Rated power of ion source PS per unit	MW	6
Rated power of active correction/compensation coils and residual ion dump PS per unit	MW	6

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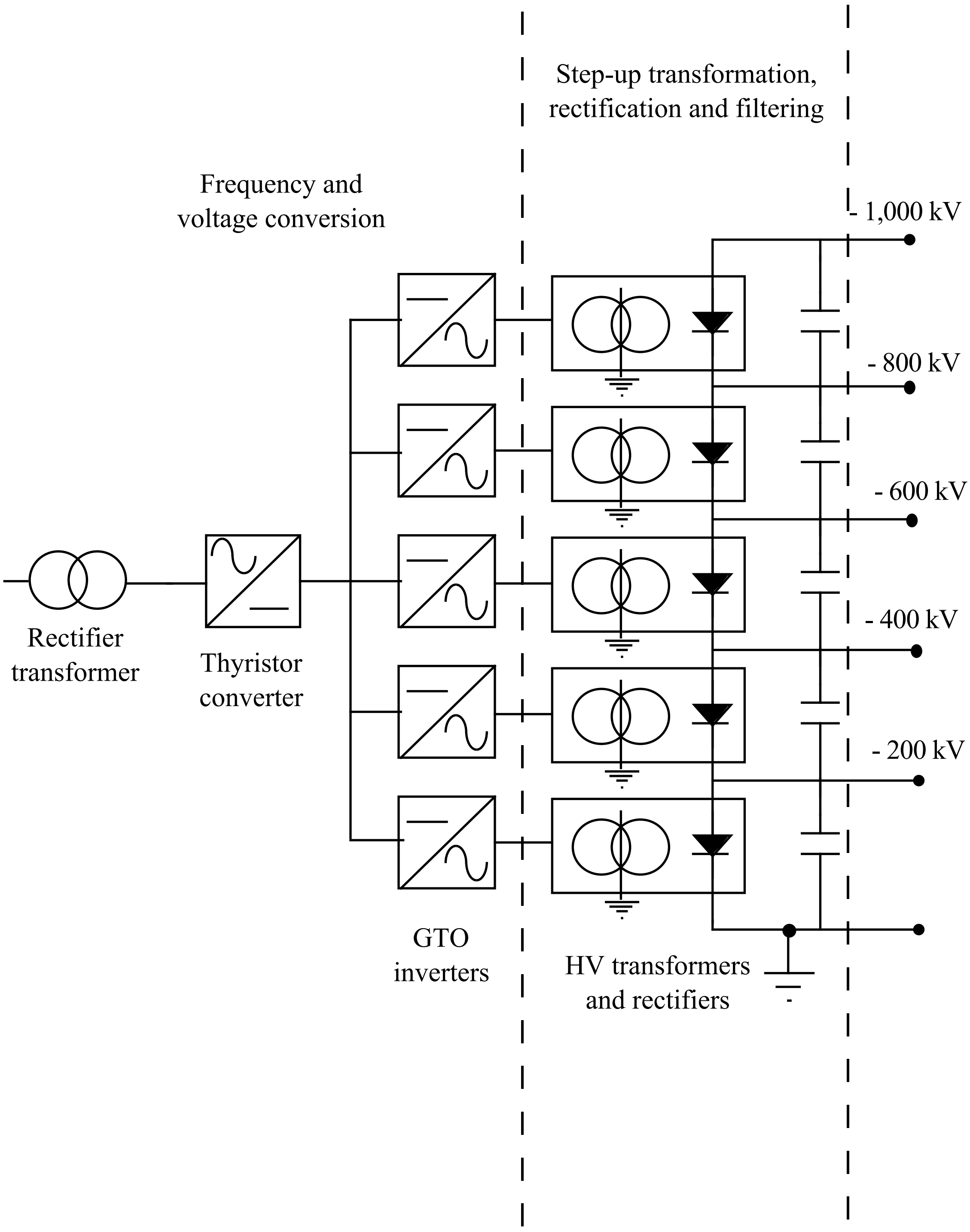

Figure 3.4.3-4 NB H&CD PS - Simplified Diagram

3.4.3.5 DNB Power Supplies

The DNB injector will provide a hydrogen beam for pulsed operation (1 to 3 s) with trains of pulses at 5 Hz (100 ms beam on/100 ms beam off) and 20 s between pulse trains. The PS system is split into three parts, with a structure very similar to the NB H&CD one. The main differences are that only one voltage (- 100 kV) is provided to the beam source and only five active correction/compensation coils are used. The parameters of the DNB power supply units are given in Table 3.4.3 5.

Table 3.4.3-5 Parameters of the DNB PS unit

Parameters	Unit	Value
Acceleration supply voltage/current	kV/A	- 100 / 71
Rated acceleration power	MW	7.1
Rated power of ion source PS	MW	1.5
Rated power of active correction/compensation coils and residual ion dump PS	MW	1.8

3.4.4 Steady-State Electric Power Network

The SSEPN will provide ac power to all plant electric loads, except those supplied by the pulsed power distribution system. These are listed in Table 3.4.4-1. The major consumers are the cooling water and cryogenic systems requiring together about 80% of the total demand of 112 MW. About 6 MW (or 5.5% of the total amount) must be provided even in case of a loss of off-site power. Backup, autonomous power generators will be used in such a case. Loads that would not tolerate the 30 s interruption needed to start up the backup generators, will get power from ac or dc uninterruptible power supplies. This service will not be centralised: the uninterruptible supplies will be part of those individual systems requiring them.

The SSEPN will receive up to 120 MW continuous power from a HV grid through two independent transmission lines, each capable of supplying the entire plant maximum load. The nominal voltage of the grid power source is assumed to be 220 kV. The grid power is then transformed to the 11 kV level by four, 3-winding, step-down transformers, each rated at 40 MVA, and is distributed among 8 Class IV (i.e. infinitely interruptible AC) power busbars, as shown in Figure 3.4.4-1. Three 1.8 Mvar capacitor banks for the reactive power compensation are connected to each busbar. Having a 43.2 Mvar total capacity, they will improve the power factor in nominal operating conditions to 0.95.

Emergency backup power will be generated by two diesel generators, each rated for 6.3 MW. These generators are connected to 2 separate 11 kV busbars for supplying Class III (i.e. temporarily interruptible AC) power to the loads, most of which are safety classified. The two redundant channels for the supply of the safety-related loads, starting from the diesel generators and including switchgear components, transformers and cables, are entirely segregated from each other.

The most powerful loads (larger than 400 kW) are directly supplied from the 11 kV busbars. The loads with power in the range of 100-400 kW are supplied at the 3.3 kV level, through additional, 11 kV/3.3 kV, step-down transformers and 3.3 kV, class IV and class III, busbars.

The remaining, less powerful, loads will be connected to the 400/230 V network created with the help of 12 transformer load-centre substations, or load centres (LC).

Table 3.4.4-1 Steady-state Power Supply and Emergency Loads

System	Connected loads (MW)	Class IV Power in POS (MW)	Class IV Power in LTM (MW)	Class III Power (MW)
Cooling Water	60.4	46.1	21.1	2.1
Cryoplant & Cryodistribution	33.9	26.7	8.5	(3)
Buildings and Layout	12.3	5.5	6.8	0.9
Heating &Current Drive (total)	2.9	2.6	0.3	(3)
-IC H&CD (for 20MW)	2.3	2.2	0.3	(3)
-EC H&CD(for 20MW)	0.6	0.4	(3)	(3)
-NB H&CD(for 33MW)	(3)	(3)	(3)	(3)
Remote Handling Equipment	3.0	0.0	1.0	0.0
Liquid and Gas Distribution	2.8	1.8	1.8	0.5
Tritium Plant & Detritiation	1.6	0.5	0.5	0.6
Diagnostic	2.0	2.0	0.2	0.1
Power Supplies	1.9	1.4	0.3	0.3
Vacuum Pumping & Fuelling	1.1	0.5	0.7	0.2
Hot Cell and Waste Processing	1.1	0.4	0.5	0.0
Radiological and Environmental Monitoring	0.4	0.2	0.2	0.1
Supervisory Control, Interlock and General Alarm System	0.2	0.2	0.2	0.2
Magnet	0.1	0.1	0.1	0.1
Others	0.3	0.2	0.1	0.1
Total	124.0	88.2	42.3	5.2
Total, including uncertainty factor (1)		101.5		5.7
Total, including future growth factor (2)		112.0		6.2

Note:
(1)15% for class IV, 10% for class III
(2)25% for class IV, 15% for class III, with exception of the Cooling Water system, the requirements of which correspond to the extended capability.
(3)Less than 100 kW. Accounted in Others.

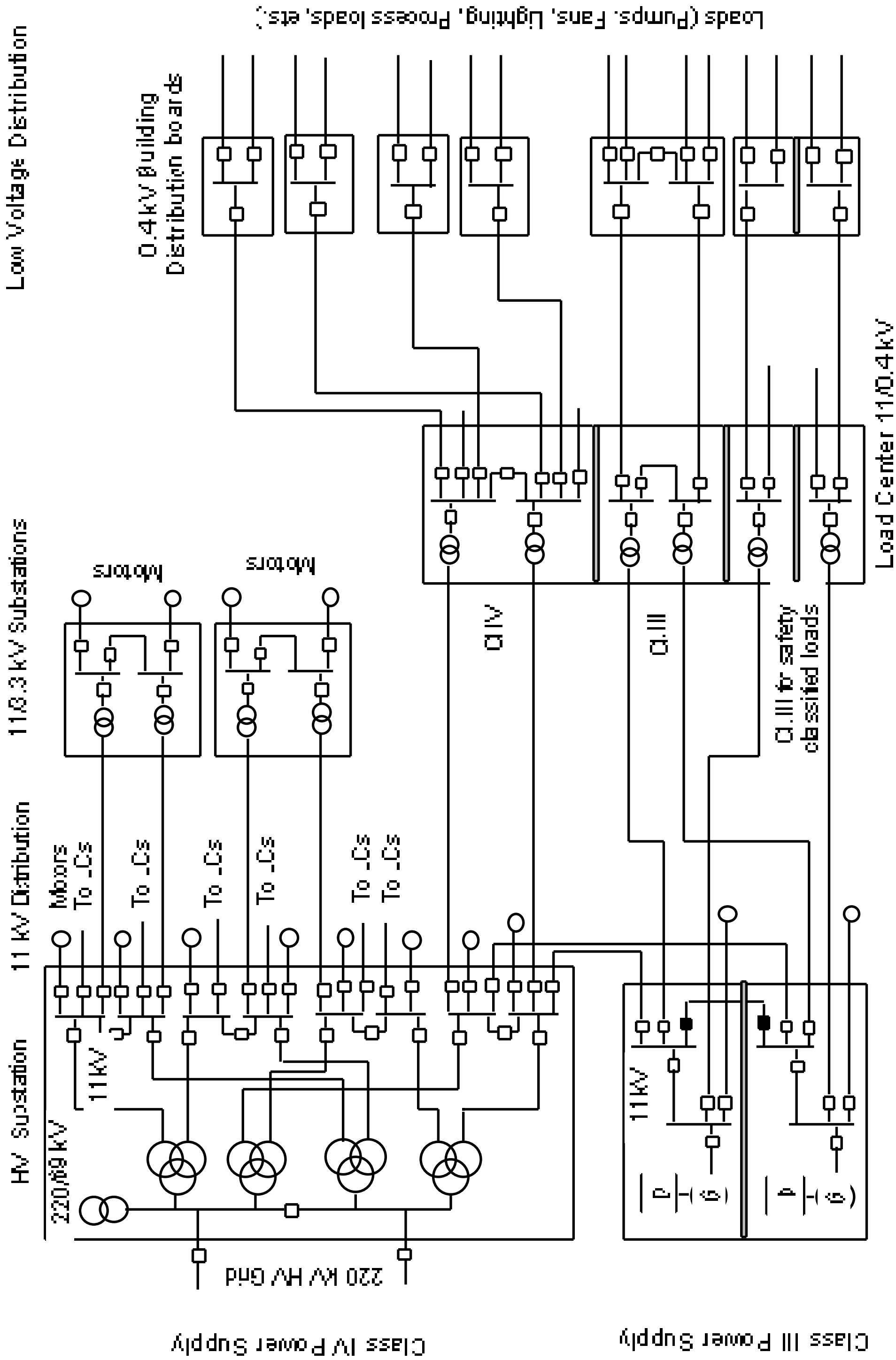

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Figure 3.4.4-1 Simplified Diagram of the SSEPN

3.4.5 Components

The reference designs described above are mainly based on existing technology and products available in the world market, or on progress that is expected to be achieved in the near future. However, design issues existed, mainly relating to the dc current switches for the extraction of energy stored in the coils, and to the super-high voltage (1 MV) equipment for the NB H&CD power supplies. Therefore, R&D was undertaken during the EDA with the overall aim of demonstrating the feasibility of those components. In addition, limited R&D was necessary to verify the design of the 90 MVA basic module for the thyristor converters of about 1500 MVA total power, which will supply controlled dc power to the magnet coils.

3.4.5.1 AC/DC Converters

Different types of converter units have to be used in the TF and PF circuits due to the various operating requirements: the current and voltage ratings vary from 10 kA to 68 kA and from 0.9 kV up to 5.6 kV correspondingly. Nevertheless, some common criteria have been used in the design.

In particular, the converters are designed both for fault suppression and for operation in internal bypass (internal no-cycled freewheeling) mode. The former implies the capability to clear the over-current due to the most frequent internal faults by gate pulse suppression without melting the internal fuses, thus improving the availability. It is normally used in converters without fuses with one thyristor per arm, but its extension to cases with many thyristors in parallel had to be proved by R&D.

A 4-quadrant 6-pulse bridge was designed, built and tested[1]:

- to verify the feasibility of design solutions able to reduce the maximum current imbalance among 10 thyristors in parallel below 1.4, both in normal operations and fault conditions;
- to demonstrate that fault suppression can be achieved in ac/dc converters with several thyristors in parallel;
- to demonstrate the converter capability to repeatedly withstand the severe electromechanical stresses due to the high value of the current to be cleared by fault suppression.

The framework built could integrate a 12-pulse 4-quadrant 2 kV, 45 kA continuous operation converter with a power density of more than 3 MVA/m^3. The results of the tests were completely successful and confirm the viability of the design.

3.4.5.2 DC Switches for Current Commutation

The key components in the coil energy discharge systems are the current commutation units used in both the switching networks and discharge circuits. DC circuit breakers rated at 45-68 kA steady state and 10-15 kV are required to transfer current from the coil to discharge resistors. A scheme consisting of two parallel-connected devices, a mechanical bypass switch and a pulsed circuit breaker, equipped with a counterpulse system to create an artificial current zero, is foreseen.

[1] E. Gaio et al., "Main technological aspects of the ITER ac/dc converter system". Proceedings 20th SOFT, Marseille, 1998, pp 861-864.

The program established to develop and test these switches has been implemented by the EU and RF Home Teams. The EU HT concentrated on the development of a conventional current commutation units with a vacuum circuit breaker[1] for the fast discharge units, starting from industrial components with lower current and/or voltage ratings. The RF HT has developed a novel scheme[2] in which a mechanical bypass switch with arcless commutation is to be used in a current commutation unit together with a thyristor circuit breaker. This design is more challenging but may assure the very long lifetime (10^4 cycles or more) necessary for the switching network units. In addition, the RF HT developed a fast make switch intended for long term repetitive operation within the switching network units, and two explosively actuated switches for backup protection: a circuit breaker and a make switch. All these switches have been successfully tested at continuous current up to 60 kA and at switching currents up to 66 kA. Additional R&D activities are now in progress with the aim of assessing the margins and of demonstrating the capability of operating at a current of up to 70-75 kA for the TF coil system.

3.4.5.3 Transmission Line and HV Bushing for NB H&CD PS

One of the crucial elements in the neutral beam power supply system is a dc HV transmission line, which connects the NB injector to the remotely located power supply. The transmission line has multiple conductors at intermediate potentials. A high voltage (1 MV dc) bushing, called the "transmission line bushing", which can support and insulate these conductors, is essential for a practical power supply system.

An R&D program was established to design this bushing, to develop the required manufacturing techniques, and to test the prototype. The program has been implemented by the JA Home Team and the bushing has been realised with alumina-ceramic powder mixed with epoxy resin, hardened twice under vacuum in an electric oven and then finished up. First electrostatic field analyses have been performed, in order to outline the electrical design of the bushing. Then a computer simulation using a 3D code was performed to investigate the mechanical strength of the bushing. Finally, the fabrication technology developed for making UHV bushings for ac lines was adopted for fabricating the transmission line bushing.

Due to limitations of the manufacturing facilities, the prototype was built with a reduction to 90% of the final dimensions and the test voltages were chosen accordingly. The prototype withstood all the tests performed.

3.4.6 Performance Analysis

Computer simulation studies of the entire ac/dc conversion plant, including pulsed ac power supply, have been performed. The results show that, with the selected parameters of the reactive power compensation and harmonic filter system, the level of reactive power, and the content of harmonics in the reference HV grid, do not exceed specified limits.

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[1] T. Bonicelli et al., "The Development and Testing of a 66 kA Bypass Switch with Arc Commutation Capability for the ITER Coil Power Supply System". Proceedings 17th SOFE, San Diego, 1997, pp 1129-1132. F. Bellina et al., "Design, Construction and Operation of the 66 kA Life Tests Facility for the ITER Magnet Protection Vacuum Circuit Breakers", Proceedings 17th SOFE, San Diego, 1997, pp 1137-1140.

[2] S.D. Avanesov et al., "The High DC Current Commutating Devices for the ITER Power Supply System developed in Russia". Presented at the EPTR-6 conference, May 1997, St. Petersburg, RF.

The typical active (P) and reactive (Q) power pulse, corresponding to the 15 MA plasma inductive scenario with 73 MW heating power starting in the current ramp-up phase, is shown in Figure 3.4.6-1. The dashed line shows that the compensation systems in the design are effective in reducing the reactive power taken from the grid (Q_{grid}) to the 400 Mvar generic site assumptions indicated in the PDS, section 4.II.C.2. The variations of reactive power "Q" and "Q_{grid}" during the fast (≤ 10 s duration) plasma control actions, which are not shown in Figure 3.4.6-1, are insignificant.

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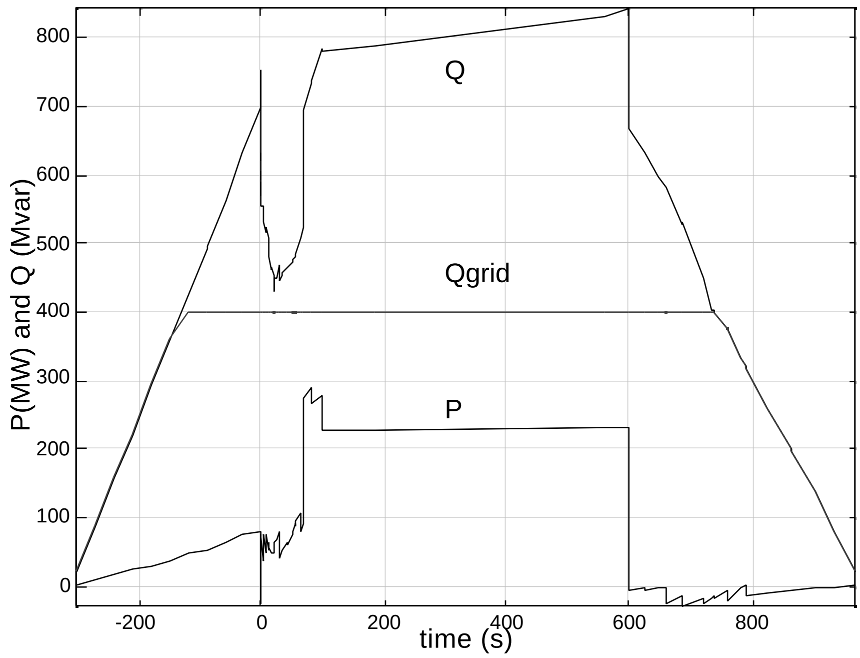

Figure 3.4.6-1 Active (P) and Reactive (Q) Power Plot for 15MA/73MW Additional Heating

Intensive studies have been carried out to define extreme conditions in case of faults. For the magnet coils, one of the most important parameters is overvoltage on the coil terminals that can cause an insulation breakdown and trigger a chain of other fault events. The results of fault analysis have shown that the highest voltage to ground in case of a single fault or malfunction within the coil PS system, aggravated by a coil terminal short circuit to ground, may reach 12.4 kV in the TF system and 15.6 kV in the CS/PF systems. With regard to the H&CD systems, it has, in particular, been verified that the reference PS designs meet the most critical restriction related to the energy dissipated in the load (50 J for the NB source and 10 J for the RF generators) in case of its breakdown.

Among several trade-off studies aimed at the optimisation of the PS schemes and parameters of components, the most important was the comparison of two technical solutions for the EC H&CD power supply. The first is based on the pulsed step modulator technology and is similar to that used for the individual supply of the IC H&CD generators; the second includes a powerful thyristor converter supplying 12 gyrotrons in parallel. The latter solution has been selected as the reference, because of its lower price.