ITER Power Supply Innovations and Advances*

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***Abstract*— The ITER Power Supply it will be the largest ever built in terms of power, pulse length, and energy capacity. It will also be responsible for fast discharge of the ITER superconducting magnets whose energy storage will be at an unprecedented scale. Nearly all of the components that comprise the system will be unique, custom designed items that will exceed the prior state of the art. This paper describes the ITER power supply system and its components with an emphasis on the extrapolation in scale and technology compared to the TFTR/JET/JT-60/T-15 era of large tokamaks with normal (copper) magnets as well as the present fleet of superconducting tokamaks (EAST, KSTAR). The main design issues, the chosen design solutions, and the collaborative design process will be described. The present state of development of the components by the Domestic Agencies is summarized, and areas of technological advancement are highlighted.**

Keywords—AC/DC Converter, Reactive Power Compensation, Superconducting Coil Protection

I. INTRODUCTION

In the midst of the 1970's "energy crisis" the world's "four large tokamaks" TFTR, JET, JT-60, and T-15 were born, and began operation in the 1980's. At the time, these machines, their supporting systems, and their power supplies represented an order-of-magnitude advance in performance and state-of-the-art by most measures. Many innovations occurred and a new generation of engineers carried forward these developments to future machines, bridging the gap to ITER. Now ITER is on the horizon and will represent an advance of similar proportions, building on prior developments, but with a fresh set of innovations and a new generation of engineers to carry the program forward. This paper puts the ITER Power Supply System in perspective with respect to the prior generation of machines (mainly copper) including TFTR/JET/JT-60/T-15 and the present fleet of superconducting machines (EAST/KSTAR). Highlights of innovation and advancement are cited. The scope is limited to the magnet power supplies, although the auxiliary heating power supply systems (neutral beam and RF) have a similar story to tell.

II. BACKGROUND

A. Typical Tokamak Power Supply Subsystems

Typical tokamak power supply subsystems and key components are shown in Fig. 1 and Fig. 2 and described in subsequent paragraphs.

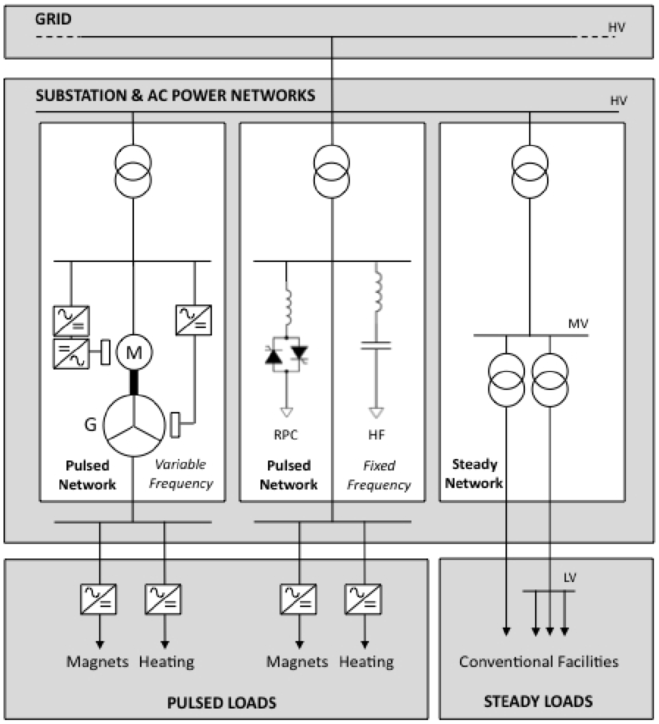

Fig. 1 Typical AC subsystems

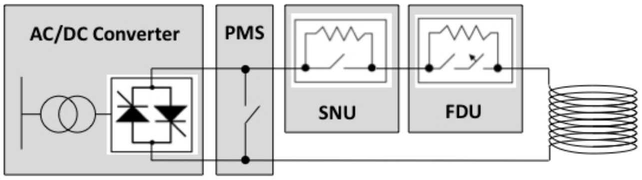

Fig. 2 Typical DC subsystem

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*This work supported by the US DOE Contract No. DE-AC02-09CH11466

Grid –AC transmission grid provides the input power source.

Pulsed Network/Variable Frequency –receives low level of power from the grid, stores energy between pulses, and delivers a high level of active (P) and reactive power (Q) during pulses, typically using a motor – generator (MG) system with variable frequency output.

Pulsed Network/Fixed Frequency – delivers a high level of P and Q during pulses, directly from the grid. Reactive Power Compensation (RPC) controls net Q and Harmonic Filtering (HF) filters harmonic currents.

Steady Network/Fixed Frequency –receives power from grid and delivers to medium voltage (MV) and low voltage (LV) conventional steady-state facility loads.

AC/DC Converter – phase controlled thyristors rectifiers provide adjustable DC voltage to drive current in the magnets. Arrays of 6-pulse bridges are connected in series, parallel, and anti-parallel to provide the rated total voltage and current.

Switching Network Unit (SNU) – provides a transient high voltage for plasma initiation by opening a switch via a DC circuit breaker (DCCB) and inserting a resistor in the circuit. DCCB technology may be mechanical, solid state, or a combination.

Fast Discharge Unit (FDU) – required for superconducting magnet quench protection, provides a transient high voltage for discharge of stored magnetic energy by opening a switch via a DCCB and back-up Piro-breaker (PB), and inserting a resistor in the circuit that absorbs the coil magnetic energy.

Protective Make Switch (PMS) – provides a bypass to maintain circuit continuity in case of a faulty component

DC Cable/Bus Bar – provides electrical connection between the various power supply components and the load.

B. Comparison of ITER Parameters to Prior State-of-the-Art

Table I presents ITER power supply parameters (for full rated ITER operation) along with those of the predecessor machines. The "ITER Scale Factor" is the ratio of the ITER parameter to the prior state of art taken from the largest value amongst the predecessors (cells highlighted in blue). Interestingly, prior parameters were similar or even larger in some cases. Similarity in power ratings is consistent with the fact that some of the predecessor machines, while smaller in scale, utilized copper magnets. The largest extrapolations are in the SNU and FDU energy capacities owing to the much larger stored magnetic energy.

TABLE I – COMPARISON BETWEEN ITER AND PRIOR FACILITIES' POWER SUPPLY SUBSYSTEMS (n.a.= not applicable, d.n.a. = data not available)

Parameter	ITER Scale Factor	ITER	TFTR [1]	JET [2]	JT-60 [3]	T-15 [4]	KSTAR [5]	EAST [6]
Grid Voltage	n.a.	400 kV	138 kV	400 kV	275 kV	110 kV	154 kV	110 kV
Grid Fault Power	0.4	10 GVA	3.5 GVA	25 GVA	d.n.a.	10 GVA	0.7 GVA	4 GVA
Grid Q Limit	0.7	250 Mvar	35 Mvar	375 Mvar	85 Mvar	160 Mvar	35 Mvar	d.n.a.
Pulse length	3.3	1000 sec	10 sec	60 sec	10 sec	5 – 10 sec	300 sec	d.n.a.
Pulsed Network/Variable Frequency (MG)	n.a.	n.a.	2 @ 475 MVA/2.25 GJ	2 @ 400 MW/2.6 GJ	215 MVA/9 GJ 400 MVA/2.6 GJ 500 MVA/1.3 GJ	n.a.	200 MVA/1.6 GJ	n.a.
Pulsed Network/Fixed Freq	1.5	1000 MVA	n.a.	687 MVA	162 MVA	170 MVA	70 MVA	200 MVA
RPC & HF	3.8	750 Mvar	n.a.	200 Mvar	n.a.	n.a.	118 Mvar	50 Mvar
Steady Network/Fixed Freq	6.0	180 MVA	30 MVA	20 MVA	30 MVA		30 MVA	20 MVA
AC/DC Converters	n.a.	12@1.4kV/45kA 16@1.4kV/55kA 6@1.4kV/23kA 1@900V/68kA 3@500V/10kA 6@100V/10kA	74@1kV/24kA	2@1.7kV/67kA 1@2.3kV/25kA 2@4.6kV/25kA	16@0.7kV/13kA 8@ 0.9kV/27kA 2@2.5kV/100kA 2@2.5kV/58kA 1@5kV/40kA 2@2.5kV/15kA 1@1kV/28kA 1@0.5kV/25kA 1@0.85kV/120kA	1@100V/52kA 8@825V/20kA	1@50V/36kA 3@1kV/20kA 4@0.5kV/25kA 4@1kV/25kA	1@30V/16kA 10@350V/15kA 2@200V15kA 2@700V/15kA
Total No. of Thyristor	1.5	11006	7104	960	d.n.a.	864	528	d.n.a.
Thyristor Wafer	1.3	125 mm	47 mm	63 mm	100 mm	63 mm	100 mm	d.n.a.
Thyristor V*I	1.7	27 MW	2 MW	5.4 MW	12 MW	2.2 MW	16 MW	
∑AC/DC Converter Installed Power	1.2	2.2 GVA	1.8 GVA	0.5 GVA	1.0 GVA	0.2 GVA	0.2 GVA	0.080 GVA
SNU DC Circuit Breaker	0.8	5 @ 45kA/8.5kV	6 @ 24kA/25kV	2 @ 80kA/20kV	92kA/25kV	10kA/3kV	6 @ 25kA/3kV 2 @ 25kA/5kV 2 @ 20kA/5kV	15kA/2.4kV
∑SNU Energy	22.4	8.5 GJ	55 MJ	320 MJ	35 MJ	d.n.a.	3 MJ	d.n.a.
FDU DC Circuit Breaker	-	9@68kA/10kV 12@55kA/10kV	n.a.	n.a.	n.a.	6 @ 6kA/0.5kV	8 @ 25kA/3kV 3 @ 20kA/3kV	2 @ 14.3kA/2kV
∑FDU Energy	70.0	56 GJ	n.a.	n.a.	n.a.	0.79 GJ	0.25 GJ	0.3 GJ
TF Stored Energy	7.5	41 GJ	1.4 GJ	5.5 GJ	2.6 GJ	0.4 GJ	0.5 GJ	0.4 GJ

C. *ITER Features Derived from Prior Machines*

Table II highlights features of prior machines that have influenced the solutions adopted by ITER.

TABLE II – FEATURES ADOPTED BY ITER

TFTR	Modular power supplies; multi-series sequential control; interleaved coils; high resistance earthing
JET	Direct pulsing from grid with RPC; large Al bus bars
JT-60	Direct digital control; large 100 mm thyristor
T-15	Multi-action mechanical/thyristor DCCB; galvanically coupled PF circuit to minimize circulating power
KSTAR	TF and PF coils all superconducting
EAST	4-quadrant parallel/anti-parallel converter

III. THE ITER AC POWER SYSTEMS

ITER AC power system [7,8] consists of independent subsystems: the Pulsed Power Electrical Network (PPEN) that supplies the pulsed loads and the Steady State Electrical Network (SSEN) feeding the steady loads. Input power for both networks will be provided directly from a new 400 kV substation named “Prionnet” that has been installed by the French transmission system (grid) operator “Réseau de Transport d'Electricité” (RTE) and energized in 2012.

RTE has performed dynamic studies and confirmed that the ITER load is within an acceptable range in terms of voltage drop (maximum 3%) and electromechanical effects on nearby power generation units, as long as the net reactive power (Q) consumption of ITER is limited to 200 Mvar (not including the additional static Q load from SSEN). Fast voltage variations induced by the ITER load (“flicker”) has been studied and confirmed to be within RTE limits [9].

A. *Pulsed Power Electrical Network (PPEN)*

The PPEN (Fig. 3) will supply AC power to the AC/DC converters that supply the superconducting magnet and in-vessel coils, along with the Heating & Current Drive (H & CD) power supply systems. The grid voltage is transformed to 66kV and 22kV distribution voltage levels in three power trains that will normally operate uncoupled from each other. The main step-down transformers are 3-winding, 400/66/22 kV rated 300/250/150MVA with impedance of 11% 400kV to 66kV, 14% 66kV to 22kV and 25% 400kV to 22kV.

The loads connected to the PPEN are comprised of large thyristor converters ranging from 5 to 90 MVA. The largest and most dynamic loads (magnet and Neutral Beam converters) are fed from the 66 kV busbars and the loads with relatively lower power (normally less than 20 MVA/unit) are fed from the 22 kV busbars.

RPC & HF based on Static Var Compensation (SVC) technology are applied on the 66 kV busbars.

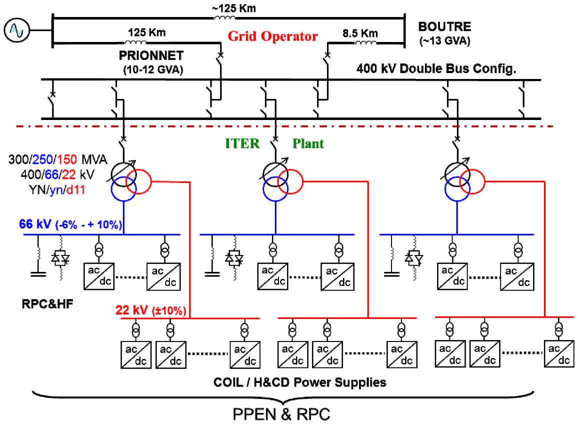

Fig. 3 PPEN Configuration

A simulation of the PPEN power profile (Fig. 4) for full rated ITER operation indicates P < 400 MW and net Q ~ 200 Mvar. The periodic spikes arise from plasma control response to simulated instabilities.

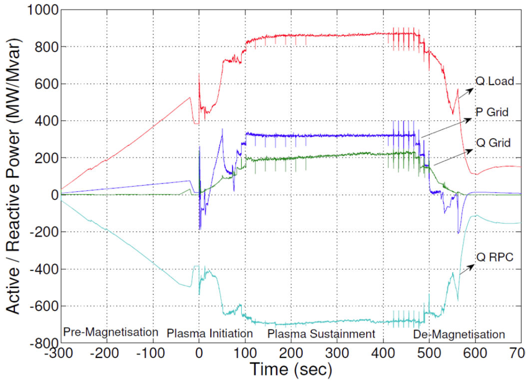

Fig. 4 PPEN Power Profile

B. *Steady State Electrical Network (SSEN)*

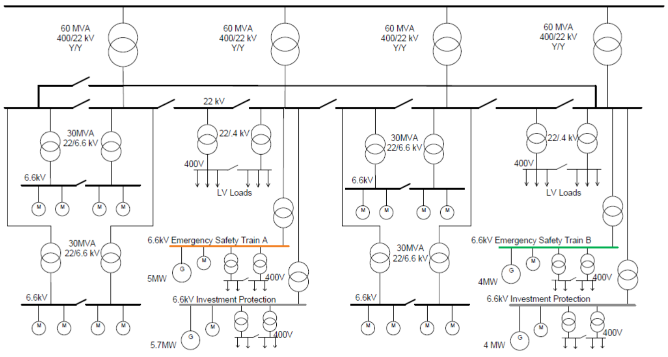

Fig. 5 SSEN Configuration

The SSEN (Fig. 5) will receive ~ 120 MW continuous power to supply all auxiliary systems of the ITER facility. The largest loads (~ 75% of total) are taken by the Tokamak Cooling Water System (TCWS) and the Cryoplant.

Incoming power will be transformed to 22 kV by four step-down transformers, each rated at 60/75 MVA ONAN/ONAF, 17% impedance. Power is distributed through eight main busbars that can be interconnected to form a ring bus. Rated load can be delivered with any one of the four step-down transformers out of service (N-1 capability). Power will be distributed at 22kV to delivery points around the 180 hectare ITER site. Loads > 200kW are supplied from six MV Power Centres at 6.6 kV. Remaining loads are supplied from fourteen LV Load Centres.

Emergency power up to 14 MW will be supplied by four 6.6kV diesel generators (DG), two supplying Safety Important Components (SIC) and two for Investment Protection (IP) loads. Two 15kV connections to an independent distribution network are available to supply SIC loads in case a DG is unavailable.

A total of sixteen (16) RPC units rated 3.5 Mvar, based on mechanically switched capacitor technology, will be connected at different points in the 6.6kV network to provide up to 56 Mvar to maintain net SSEN power factor above 0.95.

C. Reactive Power Compensation and Harmonic Filtering

A 750 Mvar RPC & HF system [9,10] will be deployed at the 66kV level of the PPEN to compensate for the large reactive power consumption and harmonic currents of the AC/DC converters. The RPC & HF will serve to:

- Limit net Q from the grid to ≤ 200 Mvar;
- Limit flicker and voltage drop at Prionnet to ±3 %;
- Limit the voltage variation on 66 kV busbars to -6% to +10% and on 22 kV busbars to ± 10%;
- Limit the harmonics and total harmonic distortion (THD) to levels defined in IEC 61000-3-6;
- Provide dynamic Q control during the plasma scenario as the AC/DC converter phase control angles respond to the plasma control system commands;
- Limit the voltage rise on the busbars and grid in the event of fast switch off of inductive load, e.g. during plasma disruption, magnet quench, etc.

The ITER RPC & HF solution is based on SVC technology consisting of TCR (Thyristor Controlled Reactor) + FC (Fixed Capacitor). Each of the three FC consists of six fixed harmonic filters tuned to the 3rd, 5th, 7th, 11th, 13th and 23rd harmonics of 50 Hz, resulting in Q = 250 x 3 = 750 Mvar. Innovations and advances include:

- Large scale-up (~ 4x) from prior experience (e.g. JET, EAST, KSTAR) with tokamak power supply;
- Multivariable controller including feed-forward signals from the AC/DC converter system to prevent transient overcompensation and overvoltages;
- High voltage (66kV) SVC using 26 series connected light triggered thyristors per valve;
- 750Mvar capacitive Q amongst largest worldwide.

IV. THE ITER DC POWER SUPPLY SYSTEMS

A complex system [11] is needed to supply power to the ITER superconducting magnets, consisting of the Toroidal Field (TF) coils, the Poloidal Field (PF) coils, the Central Solenoid (CS) coils, and the Correction Coils (CC). During each ITER pulse the system has to supply controllable DC power over a wide range of conditions during pre-magnetization, plasma initiation, plasma ramp up, plasma flat top, and plasma ramp down. In addition, in case of magnet quench, the stored magnetic energy has to be withdrawn from the coils at a very high power level and discharged in external resistors. An optimization process led to the selection of circuit topology, and the deployment of SNUs and AC/DC converters of modular unit ratings in each circuit, along with the FDUs. The circuit arrangement and the distribution of SNU, FDU, PMS, and AC/DC converters that are supplied by the China (CN), Korean (KO), and Russian (RF) Domestic Agencies of ITER is depicted in Fig. 6.

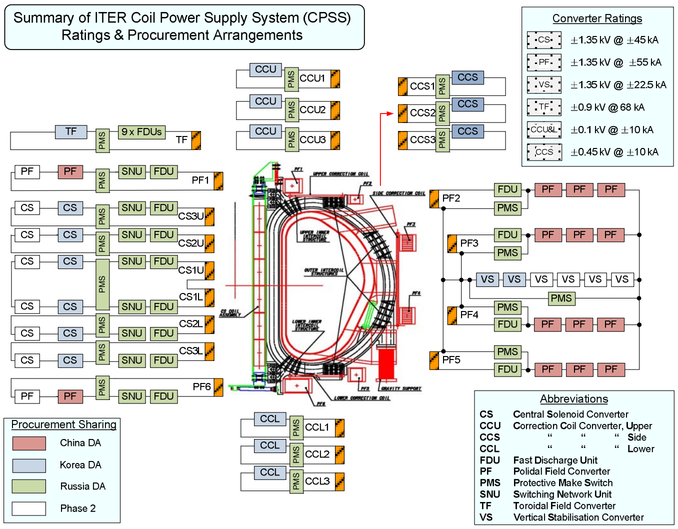

Fig. 6 ITER AC/DC Converters

A. AC/DC Converters

A variety of converter types are required to satisfy the unique requirements of each coil set as indicated in Table III.

TABLE III – ITER CONVERTER TYPES

Coil	Requirement	Design Solution
TF	High current, unipolar, dual voltage (charge/discharge and flat top), continuous rated bypass	2-quadrant, 12-pulse with tap changer on converter transformer
PF/ CS	High current, bipolar, high voltage for plasma ramping, low voltage for plasma flat top, pulse rated bypass	Multi-series 4-quadrant, 12-pulse with sequential control
VS	Medium current, bipolar, high voltage, fast response, pulse rated bypass	Multi-series 4-quadrant, 6-pulse with sequential control
CC	Low current, bipolar, low voltage, pulse rated bypass	4-quadrant, 12-pulse

All of the ITER converters are designed with “Fault Suppression Capability” (FSC) which means that faults on the 12-pulse converter terminals (~ 175 kA) shall be cleared by gate suppression, faults on the 6-pulse bridge (~ 350 kA) terminals shall be cleared by circuit breaker opening, and fuses should only blow in case of thyristor short circuits or misfires.

One of the main challenges was the design of the PF and CS converters. The optimization processes was guided by several expert-group committees and considered the following.

- Number of series units and unit voltage rating based on scenario requirements (initial and upgrade phases), SNU voltage contribution, sequential control methods and reactive power consumption;
- Bypass topology and conduction duty based on fault scenarios and reactive power control considerations;
- Number of parallel thyristors considering normal operation plus FSC requirements, based on state-of-the-art thyristor (5.2kV, 5kA) and fuse voltage and current ratings;
- DC reactor inductance based on transient current sharing between 6-pulse bridges during normal and fault modes and rate of rise of fault currents.

The resultant PF and CS converter design represents a significant advance in the state of the art of continuous rated 4-quadrant converters, with the power level up to 1.35kV x 55kA = 74 MVA. The topology is shown in Fig. 7.

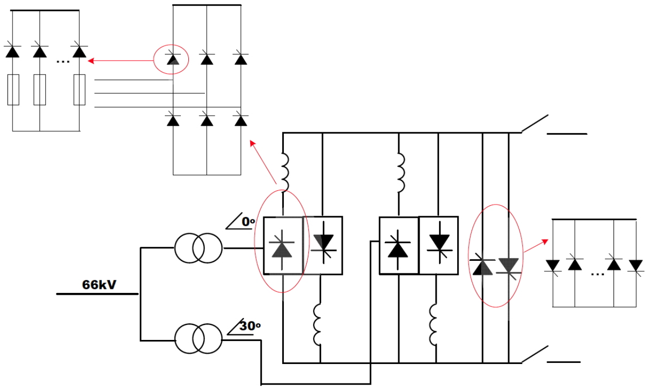

Fig. 7 PF and CS Converter Topology

The forward (F) and reverse (R) bridges connected to each transformer secondary are operated with anti-parallel mode achieved in a band around zero current and parallel operation invoked outside that zone. This scheme allows the 12-pulse, 4-quadrant operation to be achieved using only two transformers.

Operation of multi-series converters will use sequential control as shown in Fig. 8 for the case of two series units. At low load a Q reduction of 0.5 p.u. is theoretically achieved but at full load the reduction is less due to commutation effects. Full bypassing of series converters is not an option because the bypasses are not continuous rated. Although this would provide greater Q reduction, cost optimization favors the inclusion of more RPC.

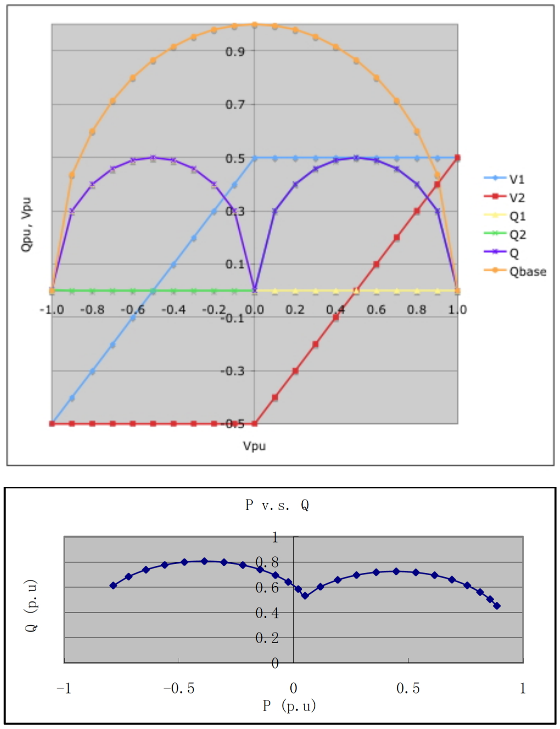

Fig. 8 Sequential Control of Multi-Series Converters
(Upper plot = low load, lower plot = full load)

The physical layout of the converters to be supplied by KO [12] (Fig. 9) and CN (Fig. 10) are similar for the larger units. The forward and reverse 6-pulse bridges are integrated with common AC bus bars supported by the insulators mounted on a bottom frame.

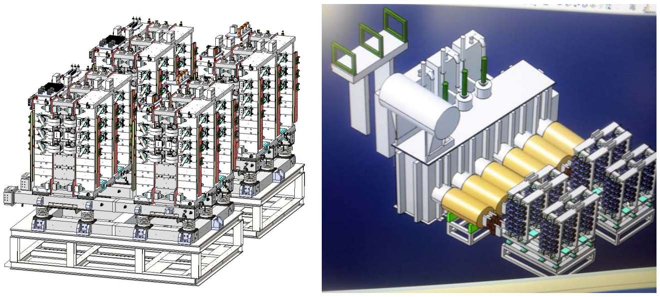

Fig. 9 KO Converter Design for CS and VS

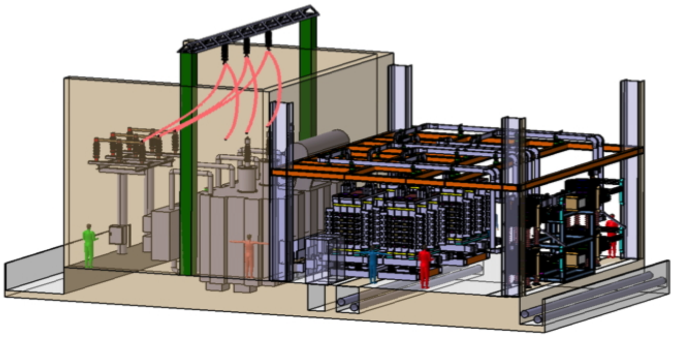

Fig. 10 CN PF Converter (width 12m x length 20m x height 7.5m)

The KO team has constructed and tested a 6-pulse prototype (Fig. 11) [13], and construction of a full scale CN prototype is underway. The purpose of testing is to ensure proper operation under normal and fault conditions, including current sharing, temperature rise, and mechanical strength.

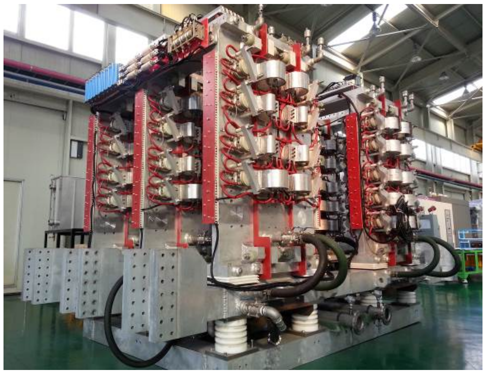

Fig. 11 KO 6-pulse prototype

KO prototype DC Reactors are shown in Fig. 12.

Fig. 12 Prototype DC reactors: TF (left), CS/ VS (right)

The KO bypass switch (Fig. 13) uses the same type of thyristor as the converters. Current sharing within 20% among parallel thyristors is controlled by flexible balancing resistor (0.4 mΩ) made of 304 SS, and has been verified by the prototype test under short circuit condition as shown in Fig. 4.

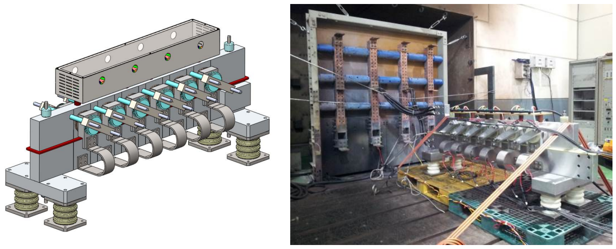

Fig. 13 Bypass switch for VS (left) and prototype test (right)

B. Switching Network and Fast Discharge Units

The Switching Network Units (SNU) and Fast Discharge Units (FDU) are based on the use of powerful non-conventional DC-current switching devices supplied by Siemens and the Efremov Institute of the RF DA. These devices are unique, innovative, and represent a large advance in the state-of-the-art.

The SNU are included in each of the CS, PF1 and PF6 circuits and provide the loop voltage needed for plasma initiation. Circuit breakers in series with the coils open the circuits and divert the coil current into energy dissipating resistors. Rated coil current and voltage are 45 kA and 8.5 kV (6 kV for CS1 circuits), respectively; the total energy dissipated in the resistors can reach 8.5 GJ.

Each SNU (Fig. 14) consists of a Current Commutation Unit (CCU) and a discharge resistor (SNR) made of two resistor banks (R1 and R2). Details of the SNU working principles are given in [14]. To operate reliably for 30,000 pulses over 20 years a new concept was developed for the CCU, providing three consecutive current commutation steps [14,15]. The scheme relies on the use of unique mechanical switches that combine a high continuous current rating with very fast operation. Characteristics of the three types of switches are given in Table IV. One of these switches, i.e. FOS, is shown in Fig. 16.

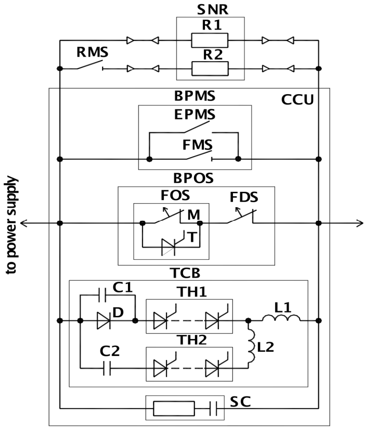

Fig. 14 SNU circuit diagram (SNR = SN Resistor; CCU = Current Commutation Unit; BPMS = By-Pass Make Switch; FMS = Fast Make Switch; EPMS = Extra Protective Make Switch; BPOS = By-Pass Open Switch; FOS = Fast Open Switch; FDS = Fast Disconnect Switch; TCB = Thyristor Circuit Breaker; RMS = Resistor Make Switch)

Table IV – RATINGS AND CHARACTERISTICS OF SNU SWITCHES

Parameter	Unit	FOS	FDS	FMS
Rated current	kA	50	50	60
Rated voltage	kV DC	1	10	10
Insulation rating	kV AC	3.6	12	12
Operating time	ms	< 5	< 5	< 3
Contact resistance	µΩ	< 3	< 3	< 3
Rated current endurance*	shots	>1500	n/a	>1500
Mechanical endurance*	shots	>5000	>5000	>5000

* Without major maintenance.

Fig. 15 Fast Open Switch (FOS)

The design of the SNR is based on a modular approach: each resistor consists of 64 identical sections (grouped in 32 modules, Fig. 17), made from stainless steel tape in a tight serpentine pattern, to minimize the inductance. Each module can be connected to any of the two resistor banks (R1 or R2 in Fig. 14) or remain disconnected. Forced ventilation provides cooldown between pulses.

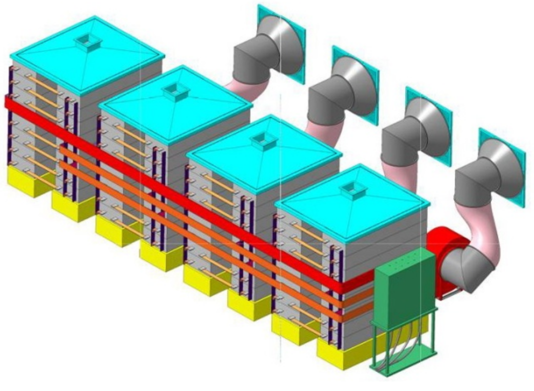

Fig. 16 Isometric view of Switching Network Resistor (SNR)

The FDUs are a key system for machine protection, providing extraction of more than 55 GJ from the superconducting coils in case of quench. A simplified circuit diagram of the TF FDU is shown in Fig. 19.

Like the SNU, each FDU is composed of a Current Commutation Unit (CCU) and a Discharge Resistor (FDR, or DR in Fig. 19), connected by coaxial power cables. The CCU is composed of a By-Pass Switch (BPS) connected in parallel to a Vacuum Circuit Breaker (VCB). An explosively actuated current interrupter, called Piro-Breaker (PB), is included in series with BPS and VCB to assure a back-up protection in case of their failure.

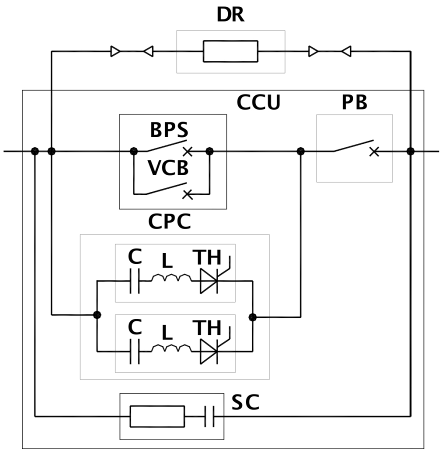

Fig. 17 FDU circuit diagram (DR = Discharge Resistor; CCU = Current Commutation Unit; BPS = By-Pass Switch; VCB = Vacuum Circuit Breaker; PB = Piro-Breaker; CPC = Counter-Pulse Circuit)

When a fast discharge is needed, the BPS (able to carry the steady state current but with limited interruption capability) is opened and the current is fully transferred to the closely located VCB; subsequently, a Counter-Pulse Circuit (CPC) is discharged onto the VCB to create an artificial zero of the current in the arc chamber and the total current is finally commutated into the FDR [15, 16].

The PB [17] is a "single action" switch that is actuated by the detonation of an explosive, resulting in a reliable and compact fast-operating (200±25 μs) switch.

Rated parameters of the switches are given in Table V.

Table V RATINGS AND CHARACTERISTICS OF FDU SWITCHES

Parameter	Unit	BPS	VCB	PB
Rated current	kA	70	70	60
Rated voltage	kV DC	10	10	20
Insulation rating	kV AC	12	12	12
Operating time	ms	260	30	1
Contact resistance	μΩ	< 1	< 60	<10
Rated current endurance *	shots	>100* >1000	1000	>1500
Mechanical endurance*	shots	>2000	>5000	>20

* Arc contacts.

The FDRs will be built by using identical resistor sections similar to those designed for SNU except using carbon steel with high resistance temperature coefficient, allowing for reduction of peak voltage at fast discharge by about 20 %.

The FDRs are composed of vertical modules built with 2 to 4 resistor sections connected in parallel. The number of the module in the resistors varies from 5 in PF1 system to 18 in TF system (Fig. 20).

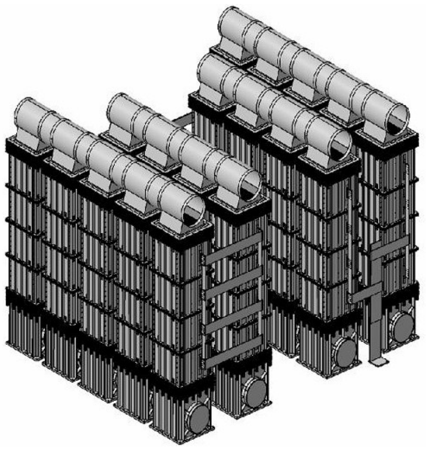

Fig. 18 TF Fast Discharge Resistor (total of 9 required)

C. R&D

Two intensive R&D campaigns on the switches for SNU and FDU were realized. The first one took place in 1995-2001 with the purpose to demonstrate performance and confirm reliability [18]. The second campaign implemented in Russia after 2007 focused on optimization of the basic designs and adaptation to the latest specifications.

Type testing of the SNU basic components, FOS, FDS and EPMS, has started at the Efremov Institute test laboratory and will be completed in July 2013. The type tests of FMS and PB are scheduled for November 2013. Type tests of the integrated components, BPOS and BPMS, will be carried out in 2014.

V. DC BUSBARS

The DC busbars will connect the coils, FDU, SNU, and converters, all located in different buildings at the ITER site. The total length of the busbars will exceed 4 km.

The busbars will be water-cooled aluminum consisting of two-pole straight or bent pieces up to 12 m with interconnecting links to provide compensation for cyclic thermal expansion. Two types of rectangular conductor bars, 24000 mm^2 and 5000 mm^2 in cross-section, will be used for PF/CS/TF and CC coils respectively. Current density ranges between 1.45 A/mm^2 (TF) up to 2.3 A/mm^2 (PF); in the flexible copper links, it reaches 4.6 A/mm^2.

Each bus is insulated for 40 kV. Two single busbars are put together and enclosed in a common shroud and a thin steel casing. A grounded separator is inserted between busbars of different polarities to prevent pole-to-pole short circuits and provide indication of single insulation breakdowns.

In 2009, a 40 m full-scale busbar prototype was successfully tested (Fig. 21). New prototypes are being manufactured for the type tests scheduled for the end of 2013-beginning of 2014. The tests will include HV insulation tests, temperature rise tests and peak current withstand tests with (350 kA, 0.1 s).

Fig. 19. PF busbar prototype

CONCLUSIONS

The ITER Power Supply System has been developed from a foundation of experience and technology accumulated in the past. It will represent a major advance in the state-of-the-art in numerous areas including:

- Major scale-up of parameters from prior machines;
- RPC at 66kV with capacitive Q amongst world's largest;
- Advanced 12-pulse, 4 quadrant, continuous rated converters at unprecedented power levels;
- Unique and sophisticated DC circuit breakers;
- Massive SNU and FDU energy dissipation resistors.

In addition the close collaboration of tokamak power supply engineers worldwide, and the in-kind contribution from the various international DAs is a unique and noteworthy development.

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