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Power Electronics Systems at JET: Objectives and Operational Experience

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ABSTRACT

Twelve years of operation with the Joint European Torus (JET), the major experiment of the European Union fusion research programme, have allowed studies of tokamak plasmas up to reactor relevant performance and to resolve key physics and engineering issues for the design of the International Tokamak Experimental Reactor (ITER). A key role in the success of JET has been the development of the power conversion system, which supplies the main electrical loads of a tokamak. The JET machine recently underwent a major upgrade with the installation of a pumped divertor for the control of the impurity influx into the plasma. The objective of this paper is to describe the new power supplies required to supply the divertor coils and to control the plasma.

1. INTRODUCTION

Fusion reactions between nuclei of hydrogen isotopes require low densities ($\sim 10^{20} \text{m}^{-3}$) and high temperatures ($> 10 \text{keV}$). At these temperatures the fuel is in the plasma state (i.e. a mixture of positively charged nuclei and negatively charged electrons). Charged particles may be trapped in magnetic fields and free electrons can carry an electric current. Magnetic confinement fusion is based on the exploitation of these properties. The most effective concept for containing plasmas has proven to be the tokamak, developed originally by Russian scientists and was made known in the 1960's (Fig.1). Since then, the major facilities in fusion research worldwide are tokamaks. A tokamak is essentially supplied by DC electrical power. Therefore, wide use is made of AC/DC conversion systems. The magnetic field for confinement and for keeping the hot plasma away from the vacuum vessel walls is provided by a combination of the high magnetic field (typically $\geq 3 \text{T}$) produced by the toroidal coils with the more modest magnetic field (typically $\leq 1 \text{T}$) associated with the current flowing in the plasma ring.

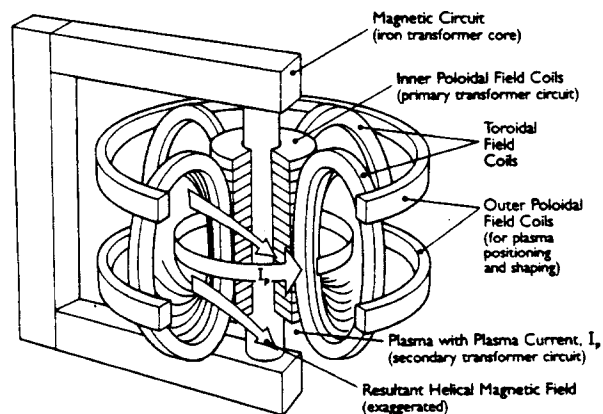


Fig.1: Schematic of the Tokamak magnetic confinement system.

The major electrical loads of a tokamak are therefore:

- (a) *the toroidal coils*, to create the main magnetic field;
- (b) *the ohmic heating circuit*, for the control of the DC current flowing in the central solenoid, thus inducing and maintaining the plasma current in the plasma ring;

- (c) *the additional heating system*, due to bridge the gap between the plasma temperature reached by joule dissipation and the required thermonuclear temperatures;
- (d) *the poloidal coil system* for plasma shape and position control, required because the plasma, a mixture of ions and electrons at low density and high temperature carrying an electric current of several mega-amperes, is unstable and has to be kept in position with the required shape, with fast changing and well controlled magnetic fields.

Since the DC plasma current is induced by an externally supplied winding, a tokamak is an inherently non-continuous machine. Being an experimental device, JET has been designed to operate in pulses of 20s every 600s. Therefore, the power supplies are designed to supply pulsed loads^[1].

2. THE JET POWER SYSTEM

A large amount of DC pulsed power and energy is required to operate JET, with a peak above 1000MW and an energy content per pulse that can reach 10,000MJ. More than 50% of this power and energy is taken directly by the British 400kV Grid (575MW and up to 10GJ), via the JET 400/36kV substation. The rest of the power is provided by two local flywheel generators with diode converter (designed for 400MW, 2.6GJ each). The toroidal coils and the ohmic heating circuit are each supplied by one of the generators and directly by the UK Grid system. The other loads, additional heating system and poloidal coils are supplied only from the Grid^[2]. A reactive power compensation system, consisting of 4×50MVAR banks of vacuum breaker switched capacitors, allows the voltage drop at 400kV to be less than 2.5% .

3. THE DIVERTOR DEVELOPMENT

Impurities (i.e. elements other than hydrogen isotopes), generated by the interaction of the plasma with the vessel walls, adversely effect plasma performance in the thermonuclear regime. An active control of impurity influx into the plasma is therefore essential for efficient operation of a fusion reactor. JET has therefore been recently modified, with the installation of a pumped divertor^[3]. Main components of the divertor are the four divertor coils, to create the required magnetic configuration, the target plates to collect the energy released from the plasma and the cryogenic pump to control the plasma density in the divertor region. The divertor magnetic configuration is achieved by a magnetic null (X-point) created by circulating a DC current in the four divertor coils (Fig.2). To reduce the localised heat loading into the target plates, the X-point must be swept across the plates at low frequency (4Hz) by controlling the distribution of the DC current in the four coils. This is achieved by supplying each of the four coils with a *Poloidal Divertor Field Amplifier (PDFA)*.

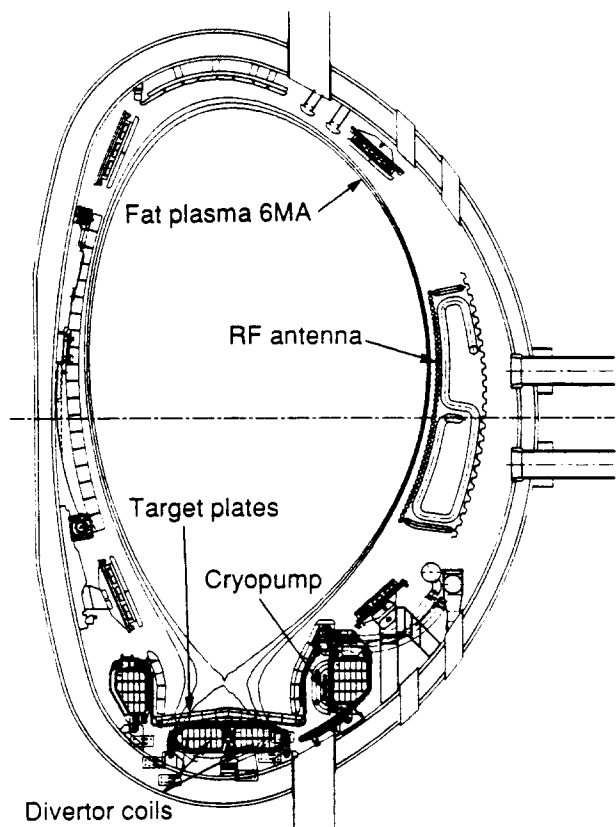


Fig.2: Cross-section of the JET Tokamak with divertor.

The vertical position of the JET plasma is unstable and active stabilization by means of feedback technique is necessary. The degree of instability for the divertor plasma configurations was calculated to be beyond the stabilizing capability of the existing power supplies (the Poloidal Radial Field Amplifiers) based on a 12-pulse line-frequency phase controlled thyristor converters.

Therefore, faster power supplies with higher peak power capability were provided, (the *Fast Radial Field Amplifiers, FRFA*).

In tokamaks, when operating beyond certain operational limits, sudden disappearance of the plasma current (plasma disruptions) may occur, leading to the loss of magnetic confinement and to the generation of high electromechanical stresses in the machine structural components. In attempts to

convert disruptions into softer discharge terminations, stabilizing the main disruption precursor by magnetic feedback a new system has been installed. It consists of the *Disruption Feedback Amplifier System (DFAS)* feeding four pairs of saddle coils, installed inside the vessel, four at the top and four at the bottom.

4. NEW POWER SUPPLIES

The three new power supply systems, based on line-frequency phase controlled thyristor converter (PDFA), on Gate Turn Off thyristors (FRFA) and on Isolated Gate Bipolar Transistors (DFAS) are briefly described.

4.1. Poloidal Divertor Field Amplifiers (PDFA)

4.1.1. System description (Fig.3)

Each one of the four PDFA's is a 12-pulse thyristor rectifier consisting of two identical modules, which can be connected either in parallel or in series configuration. The two modules

are supplied from the 36kV intermediate voltage by two independent transformers fitted in the same tank and operated into two quadrants (output voltage function of the positive output current). The connection between the 2 transformers and the 2 rectifier modules of each PDFA is by cables, while on the DC side the modules are interconnected with copper busbars via air cooled chokes ($45\mu\text{H}$). This limits the ripple current in the parallel configuration and the current rise time in the event of an output short circuit in both configurations.

Each module consists of 2 water cooled aluminium stacks, each stack bearing 3 bridges of six thyristors (type DCR 1475SY-ITav 2220A) protected by individual snubbers. Each module is individually protected against overvoltage, which may be generated by plasma disruptions, by a bipolar thyristor crowbar consisting of a $40\text{m}\Omega$ dump resistor in series with two pairs of thyristor. One of the pairs is used to provide a freewheeling path to the bridge current (“negative” crowbar) and the other to provide a current path to induced currents opposite to the normal direction of the bridge current (“positive” crowbar). Each crowbar thyristor is triggered by means of a break-over diode and is also intertriggered with the other thyristor crowbar. Each PDFA is connected to the JET earth via a mid-point resistor ($1\text{k}\Omega$ between each pole of PDFA and ground) and a neutral connection cable fitted with an earth leakage detection system^[4].

4.1.2. Rating and performance

The ratings of the power supplies are shown in Table I for parallel configuration. In series configuration, the voltage is doubled and the current is halved. The dual voltage rating of PDFA1,2 is achieved by off-load transformer tap changers. The PDFAs have been designed to withstand a short-circuit current of 172kA , in parallel configuration and to block the voltage induced by the load up to 1.5kV (PDFA1,4) and up to 1.8kV (PDFA2,3).

The PDFAs are required to operate in three modes, according to the status of the JET machine:

- (a) the *freewheeling mode*, made through one of the 3 branches of each thyristor bridge, is the status in between JET pulses, thus providing zero voltage to the load;

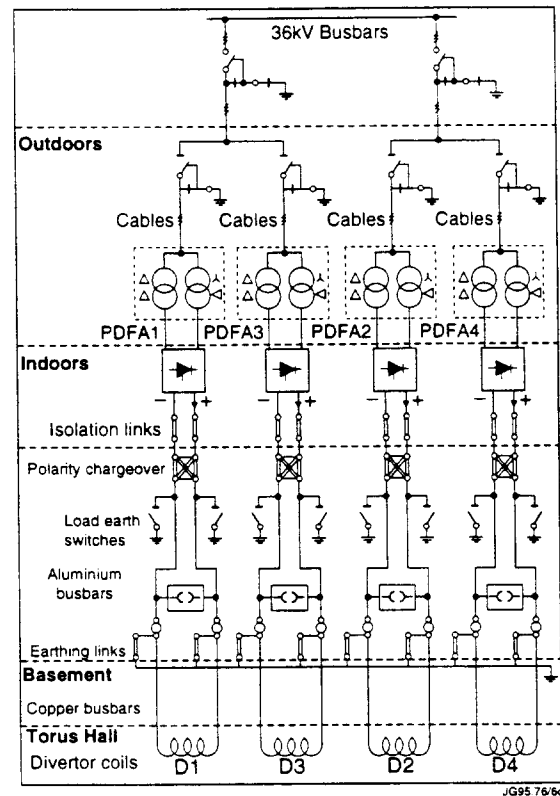


Fig.3: Configuration of the Poloidal Divertor Field Amplifier system (PDFA).

Table I: Main parameters of the PDFA

Parameter (parallel configuration)	PDFA 1	PDFA 2	PDFA 3	PDFA 4
Nominal Duty Cycle	20s/580s	20s/580s	20s/580s	20s/580s
Nominal AC Supply Voltage U_n	36kV	36kV	36kV	36kV
Nominal Output Current I_n	40kA	40kA	40kA	40kA
Continuous Current Rating	8kA	8kA	8kA	8kA
2 Tap Transformer	no	yes	yes	no
No Load Voltage at U_n (Tap 1)	910V	1180V	1180V	910V
No Load Voltage at U_n (Tap 2)	/	930V	930V	/
Minimum Output Voltage at I_n (Tap 1)	500	650	650	500
Minimum Output Voltage at I_n (Tap 2)	/	500	500	/
Maximum Blocking Capability	1500V	1800V	1800V	1500V

- (b) the *bridge mode*, when the loads require injection of current, and the amplifier output voltage is proportional to the reference issued by PPCC (Plasma Position and Current Control) system;
- (c) the *blocking mode*, required for ~ 1 s during plasma formation and plasma current start-up, is achieved by the PDFA internal control reducing any residual load current to zero, forcing the thyristor bridges in full inversion, and then suppressing the gating pulses.

The current patterns generated by the PDFA in the divertor coils, are shown in Fig.4, including X-point sweeping.

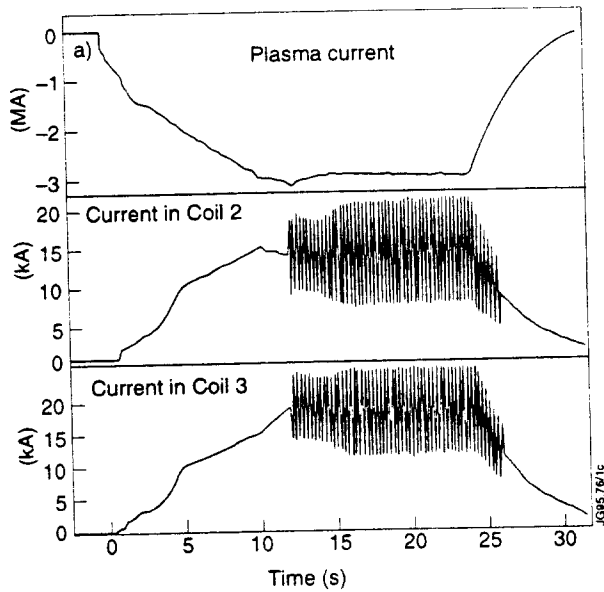


Fig.4a: The currents generated in the divertor coils D_2 , D_3 , by PDFA with X-point sweeping and currents in D_1 and D_4 =zero (JET Pulse No: 31732).

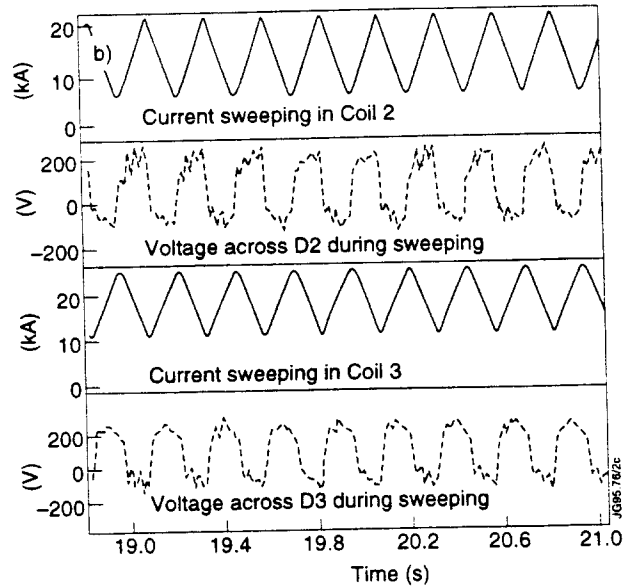


Fig.4b: Expanded scale for D_2 and D_3 coil currents and voltages during X-point sweeping (JET Pulse No: 31732).

The PDFAs have been designed to supply a current to the divertor coils in the same direction as the plasma current and cope with the consequences of plasma disruptions, namely, induced currents and voltages. Recently a new scenario requiring to feed the outer coils D1 and D4 with currents opposite to the plasma current has been studied. In case of plasma disruption, on the contrary to the present configuration where the current in the positive crowbar (opposite to normal bridge current) is only a short pulse (about 20ms), in this new configuration the induced current will flow in the positive crowbar during the complete current decay according to the time constants of the divertor coil system (from 0.5 to 0.8s).

Simulations of the complete PF circuit to determine the maximum induced currents in this new configuration as well as the subsequent temperature rise of the junction temperature have been carried out and power tests will soon take place to validate the simulations.

4.2. Fast Radial Field Amplifier (FRFA)

4.2.1. System description

The power supply concept is based on full four quadrant inverters (H-bridge) in which each arm consists of 2 Gate Turn Off (GTO) thyristors in parallel (Fig 5). GTO's appeared to be the most suitable devices, as they allow the required speed of control ($\sim 200\mu\text{s}$) to be reached and, due to their power handling capability, the number of GTO's required to cater for a peak power of 25MW is limited, if compared with otherwise suitable alternatives with IGBT's or MOSFET's. For the latter reason the largest GTO's available in 1992 were used (GTO SG 3000 GXH24 4.5kV, 3kA). FRFA is composed of four identical subunits. Each subunit includes a thyristor power supply, capable of regulating the 2.5kV DC voltage within $\pm 10\%$. The subunits can be connected in two configurations with 5kV or 10kV outputs. GTO's, freewheeling and snubber diodes and thyristors are water cooled^[5].

4.2.2. Rating and performance

The ratings of the amplifier for the two configurations A and B are given in Table II. To control the plasma vertical position the time of response is a critical issue. A subunit "nominal" pulse was specified for design purposes. The FRFA output switching frequency achievable is essentially limited by the admissible energy dissipation in the GTO's. However, although the nominal switching frequency of the chosen GTO is 625Hz, since more units are series

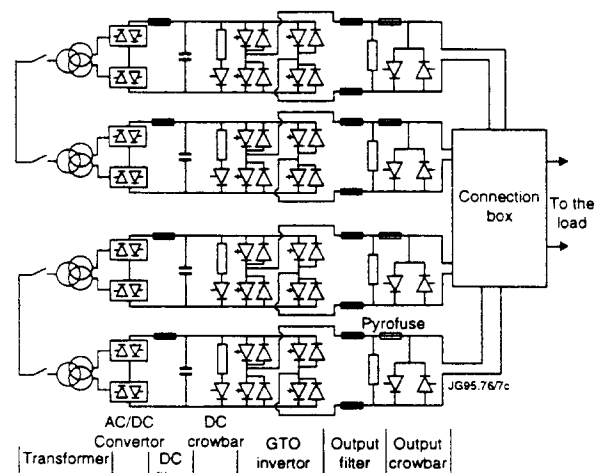


Fig.5: Schematic of the Fast Radial Field Amplifier (FRFA).

connected, they can be used alternatively to provide the required system output voltage at higher frequencies (for instance 2.5kHz between ± 2.5 kV).

Table II: Main Parameters of the FRFA

Parameter	Config. A	Config. B
Nominal Duty Cycle		30s/600s
Maximum Output Voltage	5000V	1000V
Base Output Current (29s)	1000A	500A
Short Time Output Current (1s)	5000A	2500A
Output Switching Frequency at Base Current	100Hz (full voltage swing)	
Maximum Response Delay Time	200 μ s	

The high energy stored in the JET radial magnetic field coils, (up to 537kJ) makes a 4 quadrant power supply necessary to limit the size of the DC filter capacitor. Nonetheless a relatively large capacitor bank (90mF, 2.75kV) is required for each subunit.

Each inverter arm is composed of 2 parallel connected GTO's, and the current sharing is passively controlled by a saturable reactor and actively controlled by firing the more loaded GTO with a delay proportional to the current unbalance.

Each subunit is provided with an output bipolar crowbar, for by-passing a unit in case of fault, so that the JET plasma can still be controlled. Furthermore, in case of a load overcurrent induced by a large and fast plasma vertical displacement, all 4 units can be by-passed, thus diverting the induced current (that can be as high as 20kA) from the GTO inverters. In addition a pyrofuse is installed at the output of each subunit, and is fired if the crowbar by-pass action fails, when the current exceeds 5kA. Finally, a real-time simulation of the GTO junction temperature protects the GTO's from over-dissipation[6].

The amplifier is normally operated in "open loop" mode, i.e. the reference signal, received from the PPCC defines directly the output voltage according to a multi-level hysteresis characteristics (5 levels in configuration A and 9 in B). A typical operating pattern of the FRFA is shown in Fig.6 (JET Pulse No:33415). The amplifier was in configuration A . The reference voltage

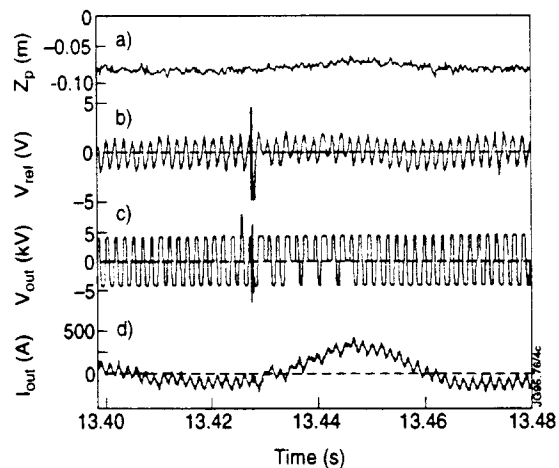


Fig.6: Typical operating waveforms of FRFA (JET Pulse No: 33415)

- a) Plasma vertical position, Z_p
- b) Reference signal to the FRFA, V_{ref}
- c) FRFA output voltage, V_{out}
- d) FRFA output current, I_{out}

received from the PPCC shows an oscillation of $\sim 4V$ peak to peak at 600Hz, which is reflected in the FRFA output voltage being switched between the 2 inner levels ($\pm 2.5kV$). The $\pm 5kV$ is applied occasionally in response to the demand from PPCC.

The operational experience with the FRFA has been fully satisfactory; the system has also shown to be quite flexible and, for instance, the multi-level input-output characteristics could be changed to better cope with a noisy reference signal produced by the magnetic probes detecting the plasma vertical movements.

4.3. Disruption Feedback Amplifier System (DFAS)

4.3.1. System description

The heart of the DFA is an H-bridge inverter module made up of 8 Insulated Gate Bipolar Transistors (IGBT-MG200Q1US1, 200A, 1.2kV) capable of generating DFA output frequencies of 10kHz and switching frequencies of 100kHz. Each switch of the H-bridge consists of two IGBT's connected in straight parallel. The schematic of one of the 4 amplifiers, including the saddle coils with their protecting crowbar are shown in Fig.7. The 2 thyristor

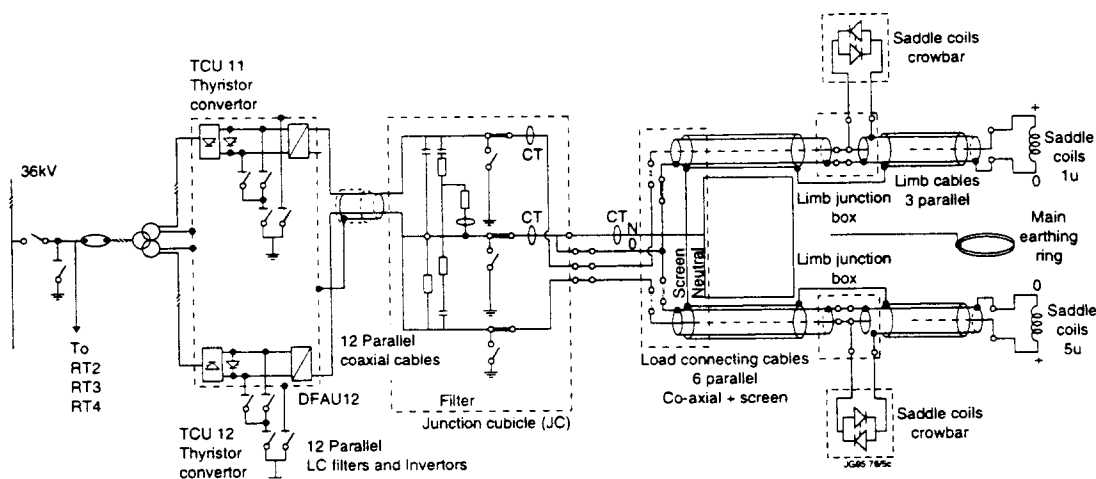


Fig.7: Schematic of a Disruption Field Amplifier, including cable connections, coil protection crowbars and saddle coils.

converter units feed the two inverter units made of 12 inverter modules each. Each pair of inverter units is connected in series, by connecting each module in series one by one. Each pair of modules in series is then connected to the junction cubicle by a single 60m coaxial cable and its impedance takes care of the current sharing between modules. Due to the low saddle coil impedance ($50\mu H$, $50m\Omega$), each saddle coil has been connected by six special parallel coaxial cables limiting the impedance of the connection to $2\mu H$ and $5m\Omega$ ^[7].

4.3.2. Rating and performance

The ratings of DFAS are summarized in Table III. Currents up to 3kA are required to stabilize plasma tearing modes at the smallest detectable level above the background noise. At 10kHz, the noise level is lower and only currents in the range 300-30A are required for mode stabilization. The dynamic error of DFAS is limited within 30° of phase shift and to ±5% of gain error in order to maintain the loop stability in all operating conditions.

Table III: Main Parameters of the DFA System.

Parameter	
Nominal Duty Cycle	$\hat{I}_{max}, 1s / 600s$ $0.2 * \hat{I}_{max}, 25s / 600s$
Maximum Output Voltage	1500V*
Maximum Output Current	3kA; $0 < f < 1kHz$ $3kA/f (kHz) 1 < f < 10kHz$
Output Frequency	0-10kHz
Maximum Switching Frequency at 300A	100kHz
Maximum Phase Shift	<30°
*Peak value of the fundamental	

The amplifiers can be used in voltage and current control. The control is based on a multi-level delta-modulation technique, where the amplifier voltage is changed up and down between its 5 voltage levels every time the output current error (I_{ref} minus I_{meas}) exceeds a preset level.

An extensive commissioning programme with plasma was undertaken to bring the DFAS into operational conditions. Oscillating currents and fields in the whole range of frequencies and amplitudes were produced, showing that, because the frequency is so high, the operation of DFAS does not introduce intolerable electromagnetic noise on plasma diagnostics. Voltage switch-off in less than 10-20µs has been proven during earth faults in the saddle coils, limiting to 20J the energy delivered to the fault. The response to a reference sinusoidal current of 300A, 10kHz added to a sinusoidal current of 300A, 1kHz is shown in Fig.8. The commissioning of the amplifiers has shown that, thanks to the IGBT's technology, magnetic fields can be controlled in a tokamak at a power level of 18MVA with a time constant of 10-20µs.

An extensive experimental plan is now assessing the effect of the Saddle Coils DC and AC fields on the MHD modes growth and rotation and the influence to these modes on the plasma current and energy confinement. A Digital Feedback Controller, now being commissioned, will allow to perform MHD feedback stabilisation experiments in the next few months. Afterwards the control system will be upgraded to adapt the controller to the plasma parameters, to make use of phase lock loop control techniques and to optimise the MHD modes detection system.

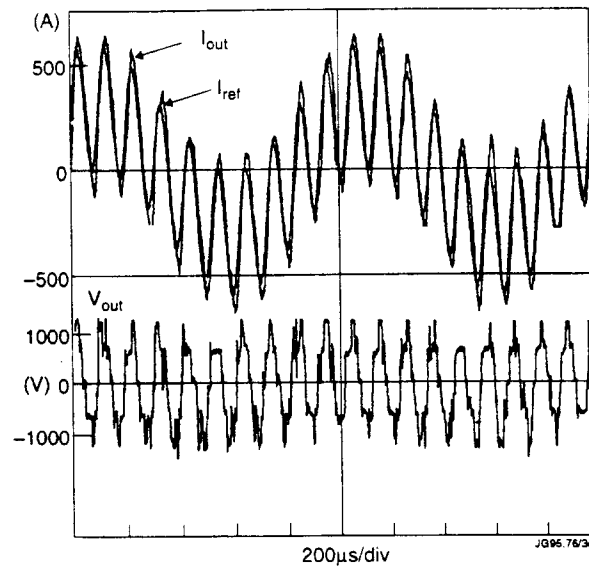


Fig.8: Response of DFAS to a 10kHz, 300A sinusoidal reference added to a 1kHz, 300A sinusoidal reference: I_{ref} (reference current), I_{out} (output current), V_{out} (output current).

5. CONCLUSIONS

- Magnetic fusion experiments require extensive use of AC/DC conversion systems;
- The plasma in a tokamak plays the dual role of burning fuel and of an electrical conducting medium in establishing the magnetic configuration for fuel confinement;
- The plasma is unstable both on the macroscopic and on the microscopic scale, thus requiring sophisticated feedback control methods;
- Most advanced power electronic technologies are required to make a tokamak experiment today and to produce a tokamak fusion reactor in the future, working in a reliable and efficient manner;
- The design of the International Tokamak Experimental Reactor Experiment, now underway in a cooperative effort involving Japan, the Russian Federation, the European Union and the United States, is taking advantage of the experience gained with large experiments, such as JET.

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