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JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

[1] *Siemens AG, Erlangen, Germany.*

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FACTORY AND SITE TESTS ON THE 25 MW GTO POWER AMPLIFIER FOR THE CONTROL OF THE JET PLASMA VERTICAL POSITION

T Bonicelli[1], P Baigger[2], D Hrabal[2], R Klein[2], V Marchese[1], PL Mondino[1], R Öström[1], S Shaw[1], HP Timmert[2], G Zullo[1]
([1]) JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK
([2]) Siemens AG, PO Box 3240, 8520 Erlangen, FRG

Abstract. The vertical position of the JET plasma is normally unstable and feedback stabilisation is therefore needed. A new power amplifier (Fast Radial Field Amplifier - FRFA) based on GTO inverters has been procured to cope with configurations characterized by plasma having a high degree of vertical instability, beyond the stabilising capability of the phase controlled thyristor converter used so far. The new power amplifier is composed of four identical subunits which can be connected in two different configurations to achieve output voltages up to 10 kV (at 2.5 kA) and output currents up to 5 kA (at 5 kV). The amplifier is characterised by a peak output power of 25 MW and by switching frequencies of the individual GTOs of 1 kHz.
The series connection of more inverters allows more voltage levels (up to nine) to be made available on the load. The paper presents the results of the extensive series of tests on a dummy load performed on the amplifier both at factory, where a complete subunit was assembled, and at the JET site. The tests included the achievement of the full performances and the assessment of the correct operation of all the required control modes.

Keywords. GTO, inverter, plasma, power test

1 - INTRODUCTION

The JET machine is the largest device in the world presently operating in the field of the research on nuclear fusion based on magnetically confined plasma, Rebut (1). In JET the plasma is heated in a toroidal vacuum vessel and is confined away from the vessel walls by magnetic fields produced by currents flowing in control coils.
The vertical position of the JET plasma is normally unstable; an essential feature of the stablisation system is that the response time of the power amplifier feeding the stabilisation coils is smaller than the inverse of the instability "open loop" growth rate, Bertolini (2).
Up to the end of the last experimental period of the JET machine, the power amplifier of the vertical position stabilisation system was based on a naturally commutated thyristor converter, Chiron (3). The response time of that amplifier at small amplitude variations of the reference signal is about 2 ms; for large variations of the control signal the response time increases to about 8 ms; those performances have shown some limitations in the control of the vertical stability in some of the most demanding plasma configurations.
Projections for future JET configurations suggest that the increased growth rate of the vertical instability will be beyond the stabilising capability of the thyristor converter and a response time smaller than .5 ms will be required, Noll (4). A new amplifier with faster response time has therefore been procured.

2 - DESCRIPTION OF THE SYSTEM

The new Fast Radial Field Amplifier (FRFA in the following) is based on high power GTO inverters, Mondino (5). The largest GTOs available at the time when the supply contract was placed are used (V_{DRM} = 4500, I_{TGQM} = 3000 A).
Fig. 1 shows a simplified schematic of the FRFA system. The amplifier is composed of four identical subunits. Each subunit is provided with an independent DC power supply capable to regulate the DC voltage at 2500 V within +/- 10%. The output ratings of each subunit are +/- 2500 V at +/- 2500 A .
The four subunits can be connected in two configurations giving at the output of the system +/- 5 kV at +/- 5 kA (Configuration A) or +/- 10 kV at +/- 2.5 kA (Configuration B).
The nominal duty cycle is of 30 seconds operation every 10 minutes (the JET machine is in fact operated on pulsed basis).

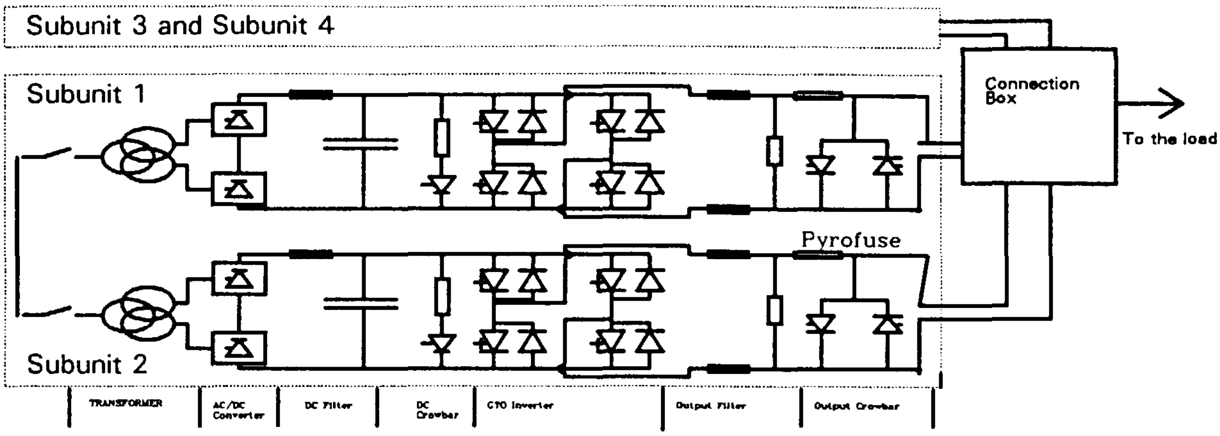

Fig. 1 - Simplified schematic of the FRFA system

The switching frequency achievable at the output of the FRFA is essentially limited by the admissible energy dissipation in the GTOs, the switching losses being, at frequency above a few hundreds hertz, dominant over the conduction losses. The switching pattern and the output current required during a JET pulse is quite unpredictable, being determined by the plasma behaviour. Under the contractual point of view, a "nominal" pulse was specified as shown in Fig. 2 (which applies to a single subunit). The "rated" performances of the FRFA system are summarised in Table I.

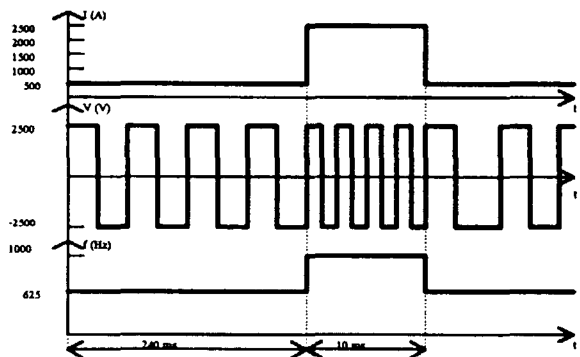

Fig. 2 - "Nominal" pulse (ideal): the sequence is repeated for the full lenght (30 s) of the pulse

TABLE I - "Rated" perfomances of the FRFA system

	Config. A	Config. B
Nominal Duty Cycle	30 s/600 s	30 s/600 s
Max Output Voltage	$\pm$ 5000 V	$\pm$ 10000 V
Base Output Current (29 s)	$\pm$ 1000 A	$\pm$ 500 A
Short-time Output Current (1 s)	$\pm$ 5000 A	$\pm$ 2500 A
Output voltage switching frequency at the base current	2.5 kHz (2500 V step)	2.5 kHz (5000 V step)
Output voltage switching frequency at the short-time curr.	1000 Hz (full voltage swing)	1000 Hz (full voltage swing)
Maximum voltage response delay time	200 μs	200 μs

The "base" switching frequency for each GTO is 625 Hz for the full length of the JET pulse. The output voltage of each subunit can therefore be switched by one level (for example between 0 and + 2500 V) at 1250 Hz.

The switching frequency of each GTO can be increased to 1 kHz for periods of 10 ms.

Since more subunits are series connected (two in Configuration A and four in Configuration B), they can be used alternatively to provide the required system output voltage allowing higher switching frequencies to be achieved (for instance in Configuration B the output voltage can oscillate between + 2500 V and - 2500 V at a frequency of 2500 Hz).

The response time (defined as the maximum delay between the request from the control signal for an output voltage level and the actual achievement of that level) of the amplifier was specified to be no more than 200 μs.

The load is quite complex since it is composed of the radial field coils coupled to the JET vacuum vessel and, during plasma operation, to the plasma current itself. To simplify it can be assumed that the equivalent load can be represented as a reactor of ca. 25 mH. It should nevertheless be kept in mind that the load can exhibit an "active" behaviour especially in case of fast vertical movements of the plasma ring which can induce high currents (up to 20 kA) in the radial field system.

Some of the most interesting features which had to be tackled by the design of the system were:
- the high energy stored in the coils (up to 537 kJ) makes a four quadrant DC power supply necessary to limit the size of the DC filter capacitor; even so a large capacitor bank of 90 mF (2750 V) is required for each subunit;
- each subunit is provided with a bipolar crowbar at the output. The crowbar allows a subunit to be by-passed in case of faults in such a way that a pulse can be terminated mantaining the control of the plasma vertical position with the other subunits. In case of overcurrent induced by large and fast plasma vertical displacements, all the four subunits can also be by-passed thus diverting the induced overcurrent from the GTO inverters;
- a pyrofuse is installed at the output of each subunit. The pyrofuse will be fired if the normal sequence of protective actions leading to the by-pass of the subunit fails and the subunit output current exceeds 5000 A;
- the actual switching pattern and the output current required during a JET pulse is quite unpredictable. To protect the GTOs from overdissipation a real time simulation of the junction temperature has been studied and adopted;
- a multilevel control structure (up to nine output voltage levels in Configuration B) based on a non-conventional hysteretic characteristic has been adopted. This would limit the switching frequency compared to a more classic PWM control, which is anyway available also for the FRFA system;
- each inverter arm is composed of two GTOs parallel connected. The current sharing between the GTOs was therefore an important issue and passive as well as active current control sharing techniques were adopted.
- a possible, optional, configuration based on the parallel connection of two inverters has been studied to increase the output voltage switching frequency.

Finally, it should be remarked that failure in controlling the vertical position of the plasma could result in severe and potentially damaging electrodynamical stresses being applied to the JET mechanical structures. The FRFA must therefore respond to requirements of reliability and availability similar, if not higher, to those found in more conventional industrial applications.

3 - TESTS ON THE PYROFUSE

The individual components of the system were extensively tested generally following IEC standards. A "special" test was carried out on the pyrofuse to assess the suitability of the device to interrupt highly inductive DC currents. The protection against output overcurrents of the FRFA system is normally achieved by switching off the inverter and, after a delay of 120 μs, the output bipolar crowbar is fired, thus diverting from the inverter any current possibly being induced by plasma movements. If the inverter is not successfully blocked, the firing of the crowbar causes a short at the inverter output, the current being now limited only by the output filter inductance (400 μH) and the output current increases therefore with a derivative of 6.9 A/μs. The pyrofuse is fired when the output current reaches 5000 A. Taking into account the delay for the pyrofuse intervention, a peak current of ca 10 kA can be reached. There was no experience of operation of pyrofuses in conditions similar to the ones occurring in the FRFA circuit and the Manufacturer could not guarantee the proper functioning of the device in absence of a test. The test circuit, shown in Fig. 3, reproduced as closely as possible the actual operating conditions.

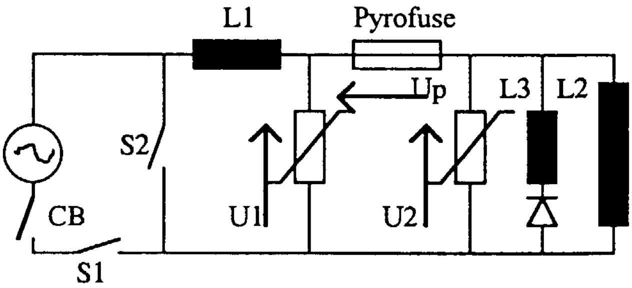

Fig. 3 - Pyrofuse test circuit

At the beginning of the test, CB was closed while S1 and S2 were open. The tests was performed as follows: S1 was closed on the zero of the voltage in order to achieve full asymmetrical current in the circuit; when the current had reached the required peak value, S2 was closed and CB was opened; finally, the pyrofuse was fired. Two ZnO non linear resistors are installed up and downstream the pyrofuse to limit the overvoltages during interruption. The diode in series with the L3 reactor (50 μH) simulated the presence of the output bipolar crowbar. The main test results are shown in Fig. 4.

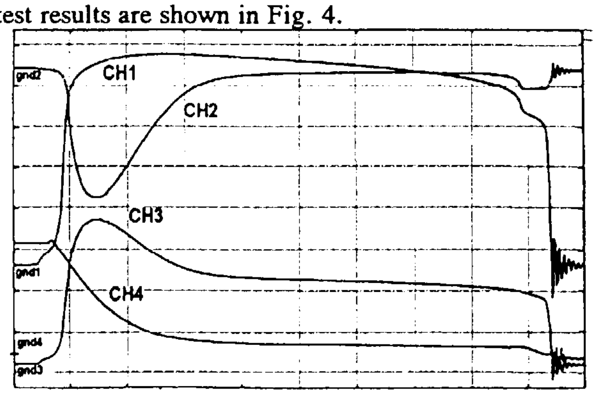

Fig. 4. Pyrofuse test waveforms.
CH1: U1 740 V/div.; CH2: U2 740 V/div.
CH3: Up 1850 V/div.; CH4: Ip 3500 A/div.
Time 145 μs/div.

The current in the L2 reactor (4 mH) before the intervention of the pyrofuse was 10.3 kA. The time intercurring between the pyrobreaker intervention and the actual melting of the fuse in parallel (pre-arcing time) was found to be ca 410 µs as required for the pyrobreaker to regain its dielectric rigidity. The voltage across the pyrofuse reached ca 6.5 kV in 150 µs while the current dropped to 800 A in 360 µs and stayed at that level as long as there was voltage applied from the "inverter" side, ie ca 3.8 kV in this case. That is an indication that the arcs inside the fuse were not estinguished due to the relatively low energy dissipated which does not allow the arcs lenght to be extended sufficiently. This actually helps in achieving a smoother limitation of the output current. The voltage at the "inverter" side of the pyrofuse was limited at 3.86 kV. The energy dissipated in the fuse was 14.8 kJ. The test was repeated once with consistent results.

4 - FACTORY TESTS ON A SUBUNIT

The specified performances of the FRFA are beyond the normal industrial practice. To try and anticipate difficulties, it was decided to assemble a complete subunit in factory and to perform a set of tests up to the achievement of the full performances. The subunit was operated on a dummy load composed of two 12.5 mH/2500 A reactors. Since the available supply voltage at the factory was 20 kV (the distribution voltage at JET is 36 kV), the primary winding of the transformer, normally star connected, was delta connected to obtain the correct secondary voltage. After the completion of the various preliminary tests (HV tests, check of control and protection signals, functional tests on auxiliary devices and safety switches, bench tuning of the control circuitries, etc) and the execution of the low power tests, the contractual tests were performed. The tests were executed making use of a simplified "Central controller" (Test Box) simulating the essential features of the control system supervising the whole FRFA system, which was not available at the time of the factory tests.

Check of switching waveforms on GTO. The proper functioning of the snubber circuitries (Marquardt-Undeland type) was checked especially with regard to the peak forward transient voltage, turn off voltage, snubber settling time, etc up to the maximum currents. The tests suggested some minor modifications to the values of the snubber capacitors and inductors which had been evaluated during design. A typical switch off transient is shown in Fig. 5; the DC voltage was 2500 V and the output (load) current 2500 A. The peak transient voltage is 340 V, the peak voltage is 2920 V and the snubber settling time is 50 µs.

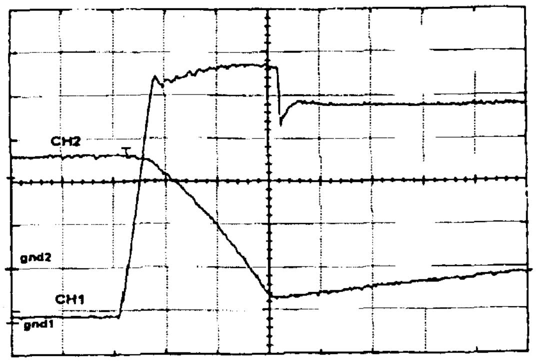

Fig. 5. Typical GTO switch-off waveforms.
CH1: GTO Vak 500 V/div.
CH2: Load current 1000 A/div.
Time 20µs/div.

Response time. The response time is mainly limited by the interlock times introduced in the GTO drivers (eg minimum on and off times, filtering times, blocking time) and, in less extent, by the delay in the control circuitries. For the FRFA the following interlock times have been adopted: t_{minon}= 88 µs, t_{minoff} = 98 µs, t_{block} = 48 µs, t_{fil} = 10 µs. The maximum delay is obtained when the same GTO is first switched off and, immediately after, the inverter control requires the same GTO to be switched on again. The results of the tests are shown in Fig. 6. Initially positive voltage was applied at the inverter output (CH2 Low). A notch in the reference voltage (CH1) lasting 40 µs was then produced thus initiating the transition to negative output voltage. After 10 µs the "positive" GTOs were turned off (CH2 High) and after 68 µs the "negative" GTOs were turned on (CH3 Low). The minimum On-time needed to elapse before the "negative" GTOs could be turned off and, finally, the positive voltage was reapplied with a delay of 181 µs from the request of re-application. This delay is in accordance with the performance specified in Table I.

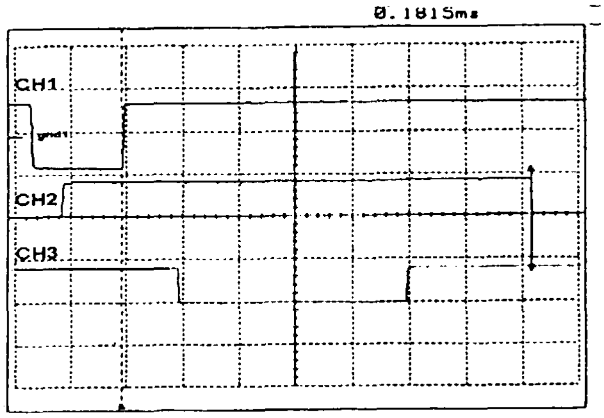

Fig. 6. Worst-case minimum response time.
CH1: voltage reference 3000 V/div.
CH2: +2.5 kV applied when Low.
CH3: -2.5 kV applied when Low.
Time 25µs/div.

Full Load Tests: maximum energy transfer back from the load. The most demanding condition as far as the control of the DC voltage is concerned occurs at full current (2500 A) when the voltage is reversed and the energy is therefore recovered from the load. The converter has in this case to transfer back to the distribution system part of the energy. The test was performed with the dummy load connected to give 25 mH; the current was made to oscillate between $\pm$ 2500 A at a frequency of ca 10 Hz. The main test results are shown in Fig. 7.

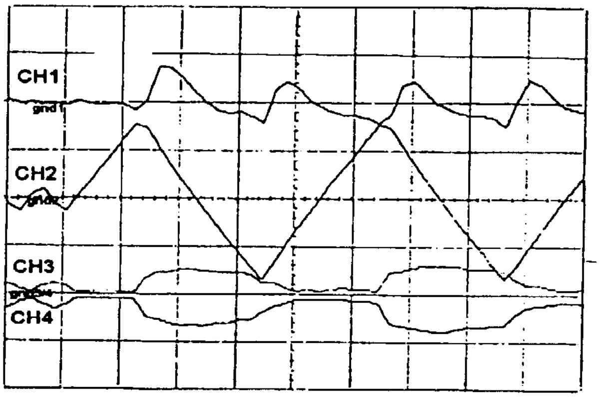

Fig. 7. Maximum energy transfer.
CH1: DC voltage 150 V/div.
CH2: Load current 600 A/div.
CH3: current misharing, left leg inverter 12.5 A/div.
CH4: current misharing, right leg inverter 12.5 A/div.
Time 25 ms/div.

The voltage on the DC capacitor was controlled between + 75 V/ - 90 V of 2.5 kV, well within the specified band (+/- 250 V). The control of the current sharing between parallel GTOs was very effective, the imbalance being always found to be less than 20 A (specified 125 A).

Full Load Tests : nominal pulse at full current and switching frequency. The specified nominal pulse shown in Fig. 2 was reproduced as closely as possible taking into account the finite time required to raise or lower the current between 500 A and 2500 A. A ripple of ca $\pm$ 160 A is superimposed to the 500 A current of $\pm$ 100 A to the 2500 A current. The dummy load was 6.25 mH. The thermal considerations are the most critical for this pulse. The thermal protection of the GTO is based on an on-line simulation of the junction temperature, Bonicelli, Öström et al (6).
Being the current unidirectional ("negative" in tis case), the junction temperature of the lower left arm was higher than the one of the upper left arm; during the high current period, lasting 10 ms, the lower arm GTO temperature rose of about 10 °C. At the end of the pulse, the lower arm junction temperature had risen to a peak of ca. 76 °C above the initial temperature. The current sharing between parallel GTOs was also checked and the imbalance was found to be negligible confirming the effectivness of the provisions adopted for the current sharing control, see Fig. 8. The tests was repeated with "positive" current obtaining consistent results.

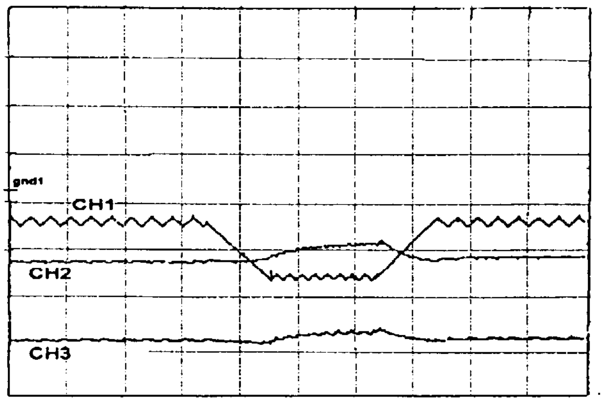

Fig. 8. Nominal pulse (expanded scale).
CH1: Load current 1500 A/div.
CH2: Junction temperature lower-left GTOs 24 °C/div.
CH3: Junction temperature upper-left GTOs 30 C/div.
Time 5ms/div.

To check the increase of temperature in "steady state" on the various components, the pulse was repeated seven times at the nominal duty cycle (one pulse every ten minutes). The temperature of all the components of the system remained within the design values.

Higher Duty Cycle Operation. The specification of the FRFA system calls also for a "higher duty cycle" operation characterised by the same switching pattern as for the nominal pulse in Fig. 2 but lasting for 60 seconds at 70% of the current. Also this operation was successfully tested. The temperature of the GTOs in the more loaded arms reached ca 67 °C above the initial temperature, slightly lower than the one achieved for the nominal 30 seconds pulse.

"Increased Output Switching Frequency" Operation. The supply contract includes as an option the possibility to increase the output switching frequency of the FRFA system by installing two inverters in parallel for each subunit; the current depending losses in each GTO decrease and the switching frequency can be correspondingly increased. The test was executed reproducing the pulse in Fig. 2 at a frequency increased by 25% (ie 780 Hz and 1250 Hz) and obtaining a temperature rise of 76 °C.

Check of the control modes of operation. All the specified control modes were fully tested. In particular a three level (hysteretic) characteristic was used both in voltage (open loop) mode and in current control mode. A typical example in current control is shown in Fig. 9. The dummy load was set at 25 mH;

a sinusoidal reference current of 200 A peak at 75 Hz was reproduced with an error of $\pm$ 30 A.
The PWM control mode was also sucessfully tested.

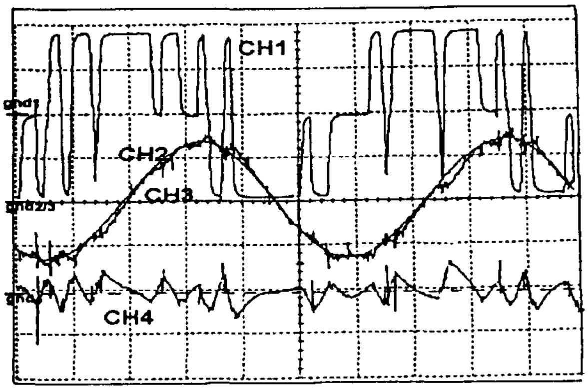

Fig. 9. Test in current control.
CH1: Load voltage 1500 V/div.
CH2: Reference current 150 A/div.
CH3: Load current 150 A/div.
CH4: Current error 50 A/div.
Time 2.5ms/div.

Overcurrent and pyrofuse operation test. Short circuit tests were performed starting from an output current of 2500 A; the fast protective switch off of the inverter limited the overcurrent below 3200 A.
The output bipolar crowbar was fired with a delay of 120 μs after the blocking of the inverter thus ensuring the correct voltage polarity for allowing the load current to be diverted into the crowbar itself.
The correct operation of the pyrofuse was tested in a "simplified" circuit. The GTO inverter was in fact bypassed during this test and the load was disconnected. After charging the DC filter capacitor at 2500 V, the output crowbar was triggered thus producing a short circuit at the output. The pyrofuse was fired when the output current reached 5 kA. The current was successfully interrupted at 8.5 kA.

5 - SITE TESTS

Tests on individual subunits

All the four subunits were tested at the JET site with the repetition of the power tests described in Section 4, with the exception of the pyrofuse operation test. The results were consistent with the one obtained at factory.

Tests on the full system in Configuration A

In Configuration A (Table I), the subunits are connected in such a way to make available on the load $\pm$ 5 kV (in steps of 2.5 kV) and $\pm$ 5 kA.

The same sequence of tests executed at subunit level were repeated at unit level (ie two subunits parallel connected) and, finally, on the full system with the two units series connected. The tests were carried out from the central controller (Supervisor) of the system.

Current imbalance between parallel subunits. The current sharing between parallel connected subunits was assessed for the first time: unlike the parallel connected GTOs in the inverter, no active control of the current imbalance is provided for the two subunits and the passive control is mainly provided by the 400 μH output filter reactors. The actual current sharing was very satisfactory, the current difference between parallel subunits being, in all the test conditions and up to the rated short time output current of 5 kA, always less than 100 A. A typical example is shown in Fig. 10: during this test, the output current was made to oscillate between + 5 kA and -5 kA by applying an alternating square voltage of about 5 kV on a dummy load of 6.25 mH. Each subunit therefore provided its rated short time current of $\pm$ 2.5 kA at $\pm$ 2.5 kV. The current imbalance did not go beyond 50 A and it is actually not noticeable in the data shown in Fig. 10.

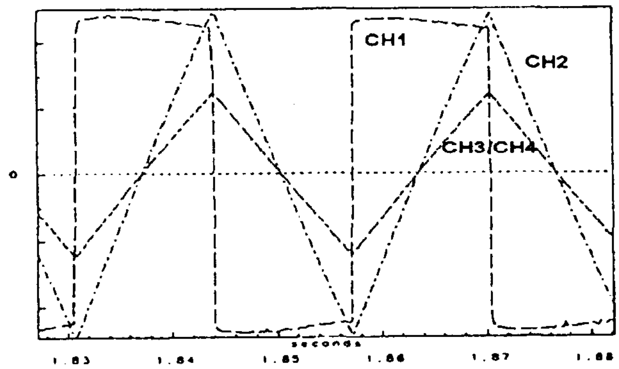

Fig. 10 Config. A full system: max. energy transfer
CH1: Load voltage 1000 V/div.
CH2: Load current 1000 A/div.
CH3 / CH4: Sub.1/2 output current 1000 A/div.

Control of the DC voltage. The operation of two subunits in parallel requires also the parallel connection of the DC filter capacitors to prevent large imbalances of the subunit output currents which would quickly build up in presence of even minute differences of the DC link voltages. The two DC power supplies are controlled following a master-slave strategy, the current reference for the "slave" subunit being the same as for the "master" subunit. The effectiveness of this control approach was tested during the execution of the same test shown in Fig. 10. The DC link voltage never dropped below -100 V of the set value, well within the -250 V allowed in the specification.

Nominal pulse at full current and switching frequency. A pulse equivalent to the one described in Fig. 2 but adapted for the rated current and voltage of the full system in Configuration A was performed. As shown in Fig. 11, the "low" current (1000 A) periods lasting 240 ms were characterized by switching the output voltage between + 2.5 kV and -2.5 kV at a frequency of 1250 Hz. Each subunit was actually switching between the same voltage levels at only 625 Hz. The "high" current (5000 A) periods lasting 10 ms were instead characterized by the output voltage being switched between + 5 kV and - 5 kV at 1 kHz; all the subunits were simultaneously switching at the same frequency in this case to provide the full voltage swing on the load.

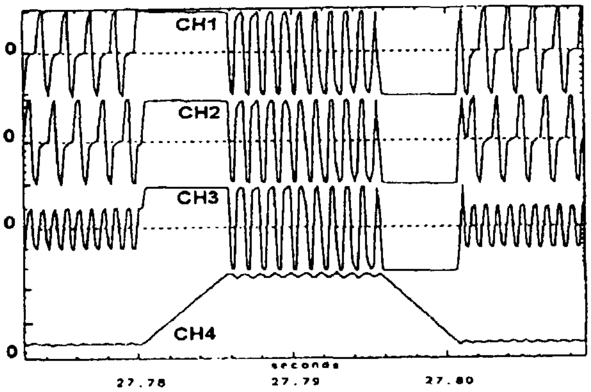

Fig. 11 Nominal pulse (expanded scale)
CH1 / CH2: Unit 1/2 output voltage 2500 V/div.
CH3: Load voltage 2500 V/div.
CH4: Load current 2000 A/div.

Check of the control modes of operation. During normal plasma operation the reference signal to the FRFA will be provided by the so-called Plasma Position and Current Control (PPCC) system.

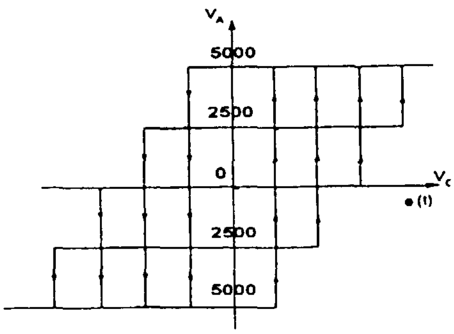

Fig.12 Hysterisis characteristic for Config. A.

The FRFA system can be operated either in "current control" or in "voltage (Open loop) control". In Configuration A, five voltage levels (-5 kV, -2.5 kV, 0, +2.5 kV and 5 kV) become available on the load, the output voltage being related to the "control" signal with a multilevel hysteretic characterstic of the type shown in Fig. 12 (it should be noted that in Configuration B a similar characteristic with nine levels is adopted). In current control, the "control" signal is the error between reference and actual value of the load current. In "voltage" control, the reference signal is directly interpreted as an output voltage request and becomes therefore the "control" signal (no voltage feedback is actually used in this case). Tests in both control modes were executed.

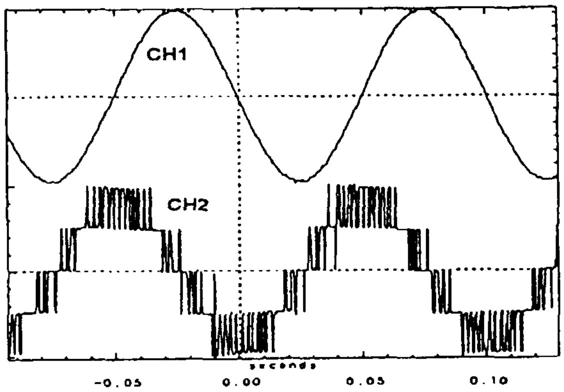

Fig.13 Test in current control
CH1: Load current 400 A/div.
CH2: Load voltage 1000 V/div.

Fig. 13 shows the output current obtained in current control mode with a sinusoidal reference of 2500 A peak at 10 Hz on a 25 mH dummy load. The current error was less than 70 A. The output voltage, also shown on the same figure, demonstrates the five level operation of the system.

Check of correct operation of protective actions. It was an important requirement for the FRFA system that a fault in a part of it (eg a subunit) would affect the remaining parts to the least possible extent, so that a plasma pulse can be continued mantaining the control of the vertical position and avoiding potentially damaging vertical instabilities.
In Configuration A, both the subunits which are parallel connected must be simultaneously subjected to the same sequence of protective actions in case a fault requiring the trip of one of the two subunits occurs.
The remaining two subunits should instead continue their operation.
The normal protection of a subunit is accomplished by:
1 - immediately, blocking the thyristor converter and the GTO inverter and firing the DC crowbar to quickly discharge the DC filter capacitor. If required, the command to trip the 36 kV circuit breaker is also issued;

2 - firing the output crowbar with a delay of 120 µs, to ensure the correct polarity of the voltage to divert the load current in the crowbar itself.
The main results of one of the tests are shown on Fig. 14.

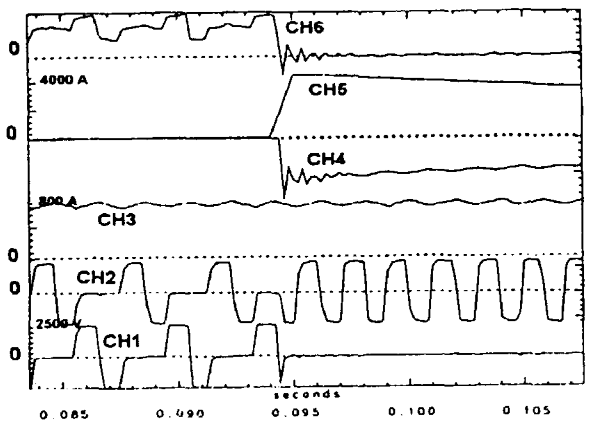

Fig. 14 Operation of protection.
CH1 / CH2: Unit 1/2 output voltage.
CH3 : Load current.
CH4: Output crowbar current (Sub.1).
CH5: DC crowbar curent (Sub.1).
CH6: Inverter output current (Sub.1).

Before the occurance of the fault at t = .0945 s, the system was supplying ca 800 A (CH3) to the load. The system output voltage was switching between + 2.5 kV and -2.5 kV at about 600 Hz which were obtained by alternatively using the two units series connected, as shown in Fig. 14. When the fault occurred (in this case a fault in subunit 1 was simulated), the inverters of subunit 1 and 2 were immediately switched off (CH6) and the DC and Output crowbars were fired (CH4, CH5, only the signals referring to subunit 1 are shown in Fig. 1 for better clarity). The remaining unit, composed of subunits 3 and 4, continued its operation switching its output voltage at double frequency (CH2) to make up for the trip of the faulty unit.

6 - CONCLUSIONS

A comprehensive series of tests was executed on the FRFA system up to the operation of the complete system at full performances. The tests covered all the control modes, the most demanding conditions of operation, the check of the execution of the protective actions and the assessment of the system performances.
The tests have proved that the specified requirements have been met and, in certain cases, outperformed.
The system is now undergoing the final stages of power testing in Configuration B; additional tests will be performed on the final load (the JET radial field coils) before operation with plasma will start.

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