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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT

The ERFA is a major part of the upgrade to the plasma vertical stabilisation system for JET. As well as improvements to the plasma controller, there was a requirement for a new power supply with increased voltage and current capability over its predecessor the Fast Radial Field Amplifier (FRFA).The ERFA had to be factory tested, installed at JET, power and signal connections made, all signals tested and then installed adjacent to FRFA. The connection to the JET coils had to be achieved in a planned 7-week pause in operation dedicated to this installation activity and perform to its full capability from the JET restart. The ERFA project achieved all of its aims and, following a minor upgrade, met or exceeded the performance specifications.

1. INTRODUCTION

The vertical position of the JET plasma is of critical importance during a JET discharge. Up until 1991 stability was controlled by a (relatively) slow Poloidal Radial Field Amplifier (PRFA) which is now reassigned to other JET coils. A faster, more powerful amplifier, the Fast Radial Field Amplifier (FRFA), was used from 1992 up until 2009 and was able to deliver ±10kV; ±2.5kA with a response time approaching 200μs. The wider Plasma Control Upgrade project identified pulse types that would be beyond the stabilising capability of even the FRFA [1,2], and therefore a project to replace the FRFA with the ERFA was initiated in 2006. ERFA would be able to deliver more current and voltage to the JET coils (±12kV; ±5kA) and at speeds of up to 100μs from an input reference request. The usual method for a fast amplifier to deliver energy in very short timescales to a load is from a DC stored energy source, typically high energy capacitors. In the ERFA a converter/inverter arrangement is used with the output voltage able to be switched from positive to negative using an H-bridge arrangement of Insulated Gate Bipolar Transistors (IGBT). Using four individual Units each capable of ±3kV; ±5kA connected in series the desired output is achieved (Figure 1).

A significant constraint imposed upon the project was to connect the ERFA to the JET coils in a relatively short 7-week suspension of pulsing operations. Replacement included not only the output power section but also the many control, indication, protection, interlocks and data acquisition systems. All of this was achieved within the tight time frame available.

2. INSTALLATION

The general arrangement of ERFA is shown in Figure 1 with design details previously given by D.Ganuzua et al [3].

ERFA had to be installed in such a way as to present the power output cables to the terminations in the FRFA connection box of existing load cables that run uninterrupted to the JET coils around ~200m away. This connection box also contained the load earth switch and two output current transducers. The ERFA is constructed in a modular way for ease of factory testing, transportation and installation. This includes four main Unit shelters, two transformer shelters (each containing two transformers) and a dedicated connection box.

It made good economic and technical sense to avoid the use of large quantities of insulating /

cooling oil within the ERFA e.g. in HV transformers or large power capacitors. The technical specification dissuaded its use in order that costly oil capture bunds in the civil works could be omitted. As such the site civil works needed only to supply concrete plinths for the shelters to stand on and a short road with some linking pathways. Installation of the main components was completed in two days of delivery employing a 500-tonne crane with sufficient reach to clear other power buildings in between. Careful planning ensured that as much of the ancillary infrastructure as possible was installed prior to the shelter delivery (new power connection box, signal patching cubicle, overhead cable trays, outdoor lighting etc) which significantly reduced the time to first energisation. High voltage tests were performed on the final installation; some initial breakdowns identified indoor power section electromagnetic screens (fitted after delivery to site) with insufficient electrical clearance. The addition of strategically placed insulating pieces quickly resolved this. There were also breakdowns in the transformer secondary output tails tested to the transformer frame. Additional insulating sheeting by the winding tails corrected this. The opportunity was taken to increase the rating of the transformer secondary output insulators to 20kV giving a much greater safety margin.

3. RADIAL FIELD COIL MODIFICATIONS

In order to maximise the advantages of the new amplifier it was necessary to reduce the effective inductance of the P2/P3 radial field windings and increase the volts per turn from 140V/turn to 500V/turn. This was achieved by adding new busbars at the coil termination points that would allow a sliding connection to select the turns required. Once completed it allowed the windings in the P3 radial field pancakes to be adjustable between 0 and 20 turns in one turn steps rather than fixed at 20 turns. The P2 radial pancakes were already adjustable at 0, 8 and 16 turns. There remained an issue about the large voltage to ground that could be induced on P2/P3 shaping circuit windings (in the same coil packs as the radial field windings). This was addressed by re-configuring the supply busbars in the shaping circuit so as to cancel out induced voltages and avoid ‘voltage piling’.

4. INTERFACES AND SIGNAL TESTING

The contract demanded that all four Units making up the complete system be fully tested in the factory before despatch. However the interfaces to which it would connect at the JET plant were many and complex so whilst good preparation simplified the power connections there was to be significant work in the area of signals, control etc. The many interfaces used by JET had to be manipulated in a way that would make ERFA insertion completely compatible with the FRFA it replaced and included:

- Central Interlock and Safety System (CISS) – back-up safety trip protection
- Direct Magnet Safety System (DMSS) – trips in the event of load coil fault detection
- CODAS (Control and Data Acquisition System) remote mimics and touch panels
- CODAS analogue data acquisition – 40 high speed pulse data channels
- CODAS alarm handling package – for the 700 new signals to and from ERFA
- JET Coil Protection System (CPS)

- Central Timing System (CTS) – provided timing enable widows
- Plasma Position and Current Control (PPCC) – supplied in analogue (as with FRFA) but also in digital for ERFA this being the (now) normal mode of operation

In total 1047 new and existing signals had to be connected and commissioned both with the ERFA and with the many remote interfaces; this significant task occupied around half of the 10 weeks from delivery on site to connection to the JET coils.

In addition the High and Low Voltages (HV and LV) supplies had to be redeployed including: Auxiliary electrical supplies 36kV power connections (two feeds)

5. ERFA TESTING

ERFA operates as part of a stability control system therefore the voltage reference from PPCC is somewhat random in its nature and cannot be accurately predetermined. In order to define performance requirements for ERFA the technical specification of the ERFA contract included a number of test waveforms that were designed to exercise the amplifier in a variety of ways thus ensuring the systems performance is fit-for-purpose, namely stabilizing the plasma's vertical position.

5.1 Tests with ERFA Connected to the Dummy Load

The ERFA 36kV supply was energised for the first time on 29th April 2009. There then followed a period of system commissioning and testing which included exercising each Unit in isolation. These Unit dummy load tests were comprised of the contractual test waveforms, adjusted to represent the contribution from a single Unit. Full system testing with all four Units energized and connected in series with the dummy load began on 28th May 2009. This included the following contractual tests:

Waveform 1 - Triangular current waveform

With ERFA switching between a nominal output voltage of +12kV and -12kV, this 60s test consists of a ±500A peak triangle current waveform for the first 59s, followed by a ±5kA peak triangle current waveform for the final 1s.

Waveform 2 - Current Offset with 5kA "Kicks"

This test demonstrates ERFA's ability to be 'kicked' with a large current and voltage request. With ERFA switching between a nominal output voltage of +3kV and -3kV at 2.5kHz to control a 500A dc current, this 60s test has 10ms long 5kA "kicks" every 260ms during which ERFA switches between a nominal output voltage of +12kV and -12kV at 1kHz.

Waveform 3 - Current Offset with 7.5kA Current Changes

This test uses a larger current swing coming from an offset value; 2.5kA is this case. With ERFA switching between a nominal output voltage of +3kV and -3kV at 200Hz to control a -2.5kA dc current, this 60s test has current excursions at around 12.5Hz (at 20mH) to +5kA by applying a nominal output voltage of +12kV, before returning back to -2.5kA by modulating the output voltage between -12kV and zero at 200Hz with 50% duty cycle.

Waveform 4 - Sinusoidal Current
This test demonstrates ERFA's ability to operate in a closed-loop, current control mode (as opposed to the normal open-loop, voltage control mode) by modulating the output voltage so that the output current follows an analogue current reference signal.

Waveform 5 - Open-loop Control at 1kHz
This test demonstrates ERFA's ability to switch rapidly in response to a burst of activity in the voltage reference; it also shows the effect that the filter and staggered switching scheme has on output voltage rate-of-change and overshoot. ERFA successfully switched at 1kHz for 5s both with and without a dwell at the 0V crossing and with a dummy load inductances of 5mH, 10mH, 20mH and 25mH. Figure 4 shows the ERFA output voltage switching at 1kHz with a 20mH dummy load; the effect of the staggering (delaying) [4], the switching of the 4^{th} Unit by 100μs is apparent on the output voltage. Note that the amplifier output voltage overshoot is limited to a peak of about ±14.2kV with a "settled" voltage of ±12kV.

Waveform 6 - ERFA Response Time
ERFA is required to have a minimum response time of 100μs; this is defined in the contract as "the time to swing from full output of one polarity via full output voltage of the opposite polarity and back to full output voltage of the original polarity". To demonstrate this ability ERFA was tested with a 10kHz voltage reference signal; this was successfully achieved for around 200ms before the amplifier tripped on IGBT junction temperature protection (as expected).

ERFA performed extremely well with all dummy load commissioning in various combinations of load from 1.25mH (single Unit test) up to 25mH (all Units in series). In all cases the specification was achieved and in many cases exceeded giving good confidence that a reasonable operational safety margin is in-built.

5.2 Tests with ERFA Connected to the JET Coils

Following successful completion of the full system dummy load tests, ERFA was connected to deliver power to the JET coils for the first time on the 8^{th} July 2009. To assess the optimum ERFA load for JET operations, a sub-set of the dummy load test waveforms described in section 5.1 were repeated with the P2/P3 JET coils connected in four different configurations; these had effective load inductances of 20mH, 12mH, 10mH and 8mH.

Compared to the dummy load tests, it was apparent from the tests on the JET machine that significant energy was lost to the mechanical structure (modelled in [5]). In order that all contractual waveforms were fully achieved a minor upgrade was made in August 2009. This included increasing converter DC output current from 100A to 300A for periods up to 20s. Thereafter the nominal 100A would be permitted with thermal protections ensuing the transformers were protected backed up by protection relays associated with each transformer.

After the converter was upgraded ERFA was tested on the optimum coil configuration again with a subset of the dummy load test waveforms. Figure 5 show a variation of test waveform 3 but with the 7.5kA current changes repeated at 11.8Hz.

CONCLUSIONS

The contractual, programming and technical constraints imposed on the delivery into service of the ERFA were considerable. By influencing the design, careful planning and early progress of site works the delivery schedule was met. The extremely demanding level of performance required was achieved – and exceeded – by pushing industrial components to far exceed their normal duty. The avoidance of oil made the civil work significantly more straight-forward, cheaper and quicker. The project also learned that the complexity of the signal interfacing imposed as much, if not more, of a burden on time and resources than the civil and power work. The ERFA project demonstrated that installation and testing of high specification power equipment, technically very complex and modular in its design can be achieved with careful planning right from the design stage up to acceptance. Ensuring large power plants are delivered to time, cost and perform to the requirements is a major challenge for other large projects including ITER.

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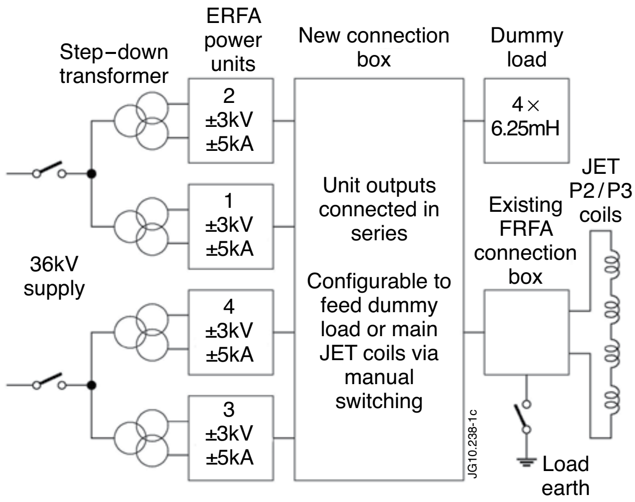

Figure 1: General Arrangement of the ERFA with loads and connection boxes.

Figure 2: Installation of the last power Unit of ERFA.

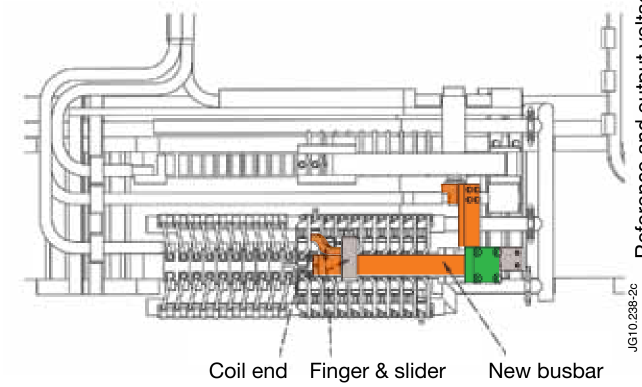

Figure 3: Modification of P3 Coil with Slider and busbar.

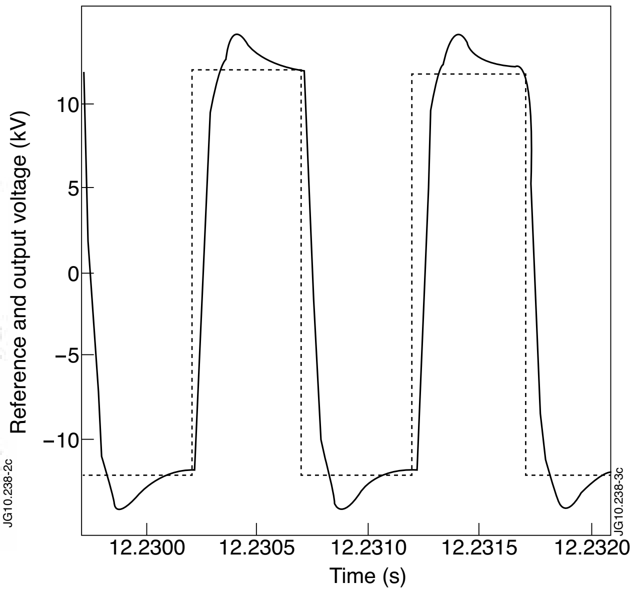

Figure 4: Voltage Reference (dotted) and Output Voltage (solid) for the ERFA Switching at 1kHz.

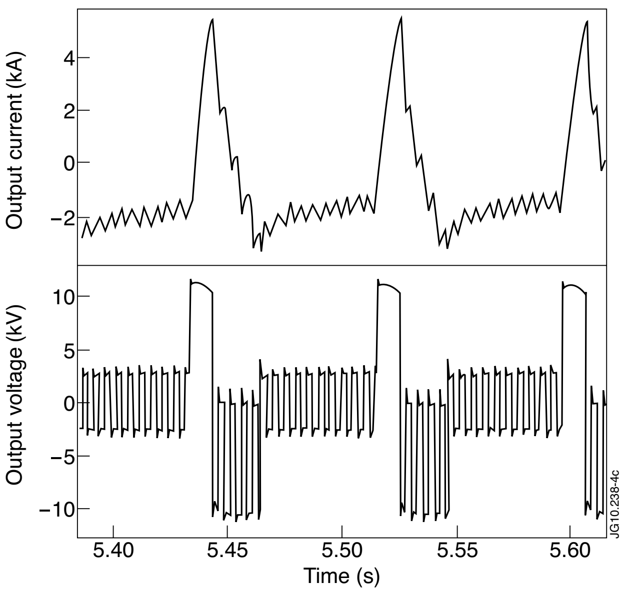

Figure 5: JET Pulse No: 78876, Upper trace ERFA Output Current, Lower trace ERFA Output Voltage.