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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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ABSTRACT

The JET plasma requires a radial magnetic field to control its vertical position and the bulk field is produced using relatively slow (line commutated) amplifiers. Should fast (possibly of order 100μs) disturbances arise, the plasma can move from its reference position very quickly and this must be controlled using a high speed amplifier. As part of a wider project to upgrade the plasma control system, a new, more powerful, Enhanced Radial Field Amplifier (ERFA) will be installed to replace the existing Fast Radial Field Amplifier (FRFA).

The company JEMA has designed the ERFA and it comprises four series-connected Units with a total rated output voltage of ±12kV, in 3kV steps, and a maximum output current of ±5kA. The ERFA is being manufactured at JEMA's works during 2008 so that it can be installed, tested and then commissioned on the JET radial field load coils in spring 2009.

INTRODUCTION

The JET plasma requires a radial magnetic field to control its vertical position, the bulk of which is produced using relatively slow amplifiers employing line-commutated thyristors. Should the plasma's vertical position be disturbed from its reference position, for example during scenarios with Edge Localised Modes (ELMs) [1], it must be controlled with a radial magnetic field produced by a high-speed amplifier connected to external poloidal-field coils to prevent the plasma touching the vessel wall and causing a disruption. Since 1992 the vertical stabilisation amplifier on JET has been the Fast Radial Field Amplifier (FRFA) [2]; constructed with inverters employing Gate Turn-Off thyristors (GTOs), FRFA is normally configured to output up to ±10kV and ±2.5kA.

The EP2 enhancement project [3] to increase the plasma heating capability and equip JET with an ITER-like first wall, will allow JET to operate in scenarios that are expect to produce vertical displacements of the plasma requiring a vertical stabilisation system with an amplifier performance in excess of FRFA's capabilities. The necessity for a new amplifier with enhanced performance was identified, and a conceptual design for the Enhanced Radial Field Amplifier (ERFA) produced by the JET operator, UKAEA and RFX [4]. In July 2007 the Spanish power electronic company JEMA were awarded a European Commission contract to design, build, test, and install ERFA on JET. Construction of the ERFA amplifier took place at JEMA's works during summer 2008.

2. THE ERFA SYSTEM

ERFA is made-up of four Units with their outputs connected in series. As shown in figure 1, each ERFA Unit consists of a 12-pulse controlled rectifier converter stage fed by a matching transformer, a dc-link capacitor bank nominally charged to 3kV, an Insulated Gate Bipolar Transistor (IGBT) inverter stage rated at 5kA, and an output filter to limit the rate of change of voltage applied to the load coils. ERFA is required to operate for a pulse length of 60 seconds every 10 minutes.

ERFA is designed to operate as an energy exchange system. When current is required in the load coils, electrostatic energy stored in the dc-link capacitor is transferred through the inverter to electromagnetic energy stored in the inductance of the load coils, thereby causing the dc-link voltage to fall and the load current to rise. When a reduced load current is required the process is reversed and the dc-link voltage rises as energy is recovered from the load into the capacitor. This results in the matching transformer and converter stage being sized to overcome the system losses and not the much larger peak power flow in and out of the load.

The 36kV, 450kVA pulse rated matching transformer has two separate, phase shifted 1550V secondary windings, each feeding one of a pair of series connected six-pulse thyristor bridges. Whilst this converter is used to control the dc-link capacitor voltage, a dissipative chopper can intervene to remove energy from the dc-link should its voltage begin to rise excessively, a thyristor crowbar providing additional over-voltage protection should the chopper fail to stem the voltage rise.

The 5kA inverter stage in each Unit consists of ten parallel IGBT ‘H’-bridges, using output inductors to ensure static and dynamic current sharing between the parallel inverter modules. By controlling the state of the IGBTs in the inverter, each Unit can be made to apply either +3kV, 0V or –3kV to the load, and by controlling the inverter stages of all four series connected Units, ERFA can output between +12kV and –12kV in nine discrete levels.

In order to limit stress on the insulation of the JET coils, the ERFA output is required to limit the rate of change of applied voltage to 800V/ºs. This is largely achieved with output filters that make use of the inverter output inductance and an R-C element in parallel with the Unit output. Conversely, to ensure rapid response to the control system reference signal, the ERFA output is required to change from 12kV in one sense, to 12kV in the other sense and then back to 12kV in the original sense, all within 100ºs;. the filter design must therefore not slow the output response excessively.

Should an ERFA Unit trip during a pulse, its output will be rapidly bypassed with the bi-polar thyristor crowbar, followed-up by a parallel vacuum switch capable of conducting the current from the remaining Units for the full pulse length. This allows the vertical stability system to continue to control the plasma’s position after an ERFA fault, albeit with a reduced output voltage swing.

3. DESIGN AND CALCULATIONS

The conceptual design for ERFA [4] relied on the converter to supply some of the energy delivered to the load inductance, and then made use of the chopper, consisting of a high power resistor in series with a semiconductor switch to dissipate the excess energy recovered as the load current reduces. In contrast, JEMA has dimensioned the dc-link capacitors so that the maximum energy stored in the load (250kJ, or 5kA in 20mH) is 18.5% of the total ERFA capacitors bank energy (1350kJ, or 3kV in 75mF of each Unit). This results in a maximum dc-link voltage swing of less than 10%, which meets the ERFA specification without having to rely on power delivered from the converter.

Three main benefits are obtained with this larger dc-link capacitor bank:

- The dissipative chopper is not needed for normal operation and is only required for protection -system power losses are therefore significantly reduced.
- The ERFA input stage, comprising the step down transformer and thyristor rectifier can be made smaller as the chopper losses do not need to be compensated for in normal operating conditions.

- The dc-link voltage control system is simplified, since the chopper is now only used for protection.

Thorough simulations have been carried out to determine the maximum power losses produced by ERFA in the different operation scenarios defined in the specification. These simulations take into account IGBT and diode conduction and commutation power losses in the inverter, output filter losses, and losses in the load cables and coils. The input stage has been sized to overcome the 1.2MW power loss resulting from the worst-case simulation scenario.

Another important design decision was the choice of power semiconductor switching technology used in the inverter. The existing FRFA uses GTOs, however subsequent advances in power electronics has resulted in IGCTs (Integrated Gate Commutated Thyristor) and IGBTs (Insulated Gate Bipolar Transistors) superseding GTOs in drives of comparable power rating to ERFA. A solution based on IGBTs has been adopted for the following reasons:

- IGBTs offer better switching performance than IGCTs (at the expense of higher conduction loss) - analysis of ERFA's switching behaviour has shown minimisation of switching losses to be beneficial.
- A typical IGBT package can control less power than a typical IGCT. This has resulted in more components connected in parallel and has led to a solution with higher modularity.
- With diligent busbar design, snubber components can be avoided in IGBT inverters. IGCTs however require passive networks to limit both the dI/dt and dV/dt experienced by the device.

The cooling system has been given careful consideration in ERFA's design. Natural air cooling of all the thermally loaded power components has been chosen over forced air and liquid cooling for the following reasons:

- The pulsed nature of ERFA allows the cooling system to exploit the 10 minutes between JET pulses without increasing the rating of the semiconductors. The heatsinks act as a temporary thermal capacitance, absorbing the peak power dissipated during a pulse.
- Natural air cooling increases the system reliability significantly.
- The average power losses are evacuated from the Unit shelters by means of several fans. Failure of an individual fan does not cause ERFA to trip.

Selecting the ERFA output filter components to limit the rate-of-change of output voltage required careful analysis to limit the voltage overshoot without causing excessive losses in the filter resistor. The final filter design uses a distributed inductance of 200μH, a 12μF capacitor and an 8 Ohm resistor for each ERFA Unit. The selected values ensure a dV/dt lower than 800V/μs for all the normal operation and fault scenarios. The slight under-damping of the filter reduces the power losses and the resulting maximum commutation overshoot is mitigated by a staggered switching technique discussed in the following section.

Every ERFA Unit is housed inside a 12×3×2.8m shelter (Fig.2). The 4 matching transformers are located in two 6×3×2.8m shelters.

4. CONTROL SYSTEM

The ERFA control system is key for the amplifier performance to meet the speed of response required with the flexibility to achieve this for an unpredictable reference and for a wide range of load coil configurations (from 5mH to 25mH). It can be divided into the following sub-systems for each Unit:

– Real time regulation of the thyristor rectifiers and IGBT inverters.
– PLC based control system.
– Data acquisition system.

Each ERFA Unit has a "Low Voltage Controller" referenced to local earth and a "High Voltage Controller" referenced to the negative polarity of the dc-link. The Low Voltage Controller uses two cards based on DSP (Digital Signal Processor) and FPGA (Field-Programmable Gate Array) devices to control the converter and inverter in real time to regulate the dc-link voltage and control the output voltage and current. The thyristor firing angle and inverter switch states are output from this controller on optical-fibres and this data is sent to the High Voltage Controller where the commands are directed to the converter thyristors or the 10 inverter modules as appropriate.

In addition to this real-time regulation, another DSP based card calculates the instantaneous power losses generated by the system. This information is used to calculate the maximum IGBT junction temperature, which is then communicated to the JET Plasma Position and Current Controller (PPCC) to allow corrective action to be taken as the IGBT operating limits are approached, and helping to avoid the ERFA tripping on its own protective limits.

The rectifiers are controlled by a control loop regulating converter current, with a feed-forward component of the required dc current obtained from the calculated system power losses. The dc-link voltage regulator control loop is found upstream of this current loop, the reference for which is calculated from the ERFA output current and nominal load inductance; the controller ensuring the total stored system energy (in the dc-link capacitors plus the load inductance) is kept constant.

In normal JET operations, ERFA operates as an open-loop amplifier with its output voltage set by a reference signal from the Plasma Position and Current Controller (PPCC). The controller for the Unit's inverters stages must:

– Set the output voltage of every unit, i.e. +3kV, 0V or –3kV.
– Ensure the sum of the four Unit outputs equals the JET PPCC reference.
– Manage the switching sequence of the IGBTs to equalize the power loss between devices.
– Manage the rotation of switching between Units to equalise the flow of energy to/from the load from all four Units dc-link capacitors.
– When switching all four Units to achieve the maximum output voltage ERFA implements a 'Staggered Switching' technique (Fig.3). The commutation of one of the units is delayed for a few microseconds after the first three are switched to significantly lower the voltage overshoot.
– Modulate the inverter outputs to implement a current limit if the output current exceeds 5kA.
– If a Unit trips and its output is bypassed, the switching of the remaining active Units must take the reduced performance into consideration.

Most of the required analogue feedback parameters (voltages, currents, etc) are derived from transducers referenced to high potentials and their signals need to be isolated for transmission to the Low Voltage Controller. JEMA's standard 12 bit analogue fibre-optic links cards with 1MHz bandwidth are used for this purpose.

Each ERFA Unit has a PLC referenced to local earth and this is linked to a slave PLC in the Unit's high-voltage area by an optical-fibre PROFINET link; this allows each ERFA Unit to be tested individually. All four Unit PLCs are linked by PROFIBUS-DP, with communications to the JET control interfaces routed through the supervisor PLC located in Unit 1. Unit 1 also includes a SCADA PC; this can be used to monitor the plant status and view system alarm information. The other three Units incorporate a smaller control display which allows individual Unit testing in local mode.

Each Unit incorporates a data acquisition module which allows relevant local analogue signals to be stored at up to 100 kSample/s for the full 60s pulse length. Data is stored locally until the end of the pulse, whereupon it can be transferred to the JET data acquisition system.

5. FUTURE WORK

ERFA factory testing will start in August 2008 and is expected to be completed by the end of November. Factory tests include combined ERFA tests on dummy load at full power and will include the contractual waveforms.

Installation at the Culham facilities and tests on the JET coils will be performed in early 2009.

ACKNOWLEDGMENT

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REFERENCES

[1]. M. Bécoulet et al., "Edge Localized Mode Physics and Operational Aspects in Tokamaks", Plasma Physics And Controlled Fusion **45** (2003) A93–A113

[2]. P.L. Mondino, T. Bonicelli, D. Hrabal, R. Klein, V. Marchese, R. Ostrom, H.P. Timmert, "The New Fast Radial Field Amplifier for the Control of the Plasma Vertical Position in JET", Fusion Technology 1992, Elsevier, 1993, pages 907–911

[3]. A. Lioure et al., "JET Enhancement Programmes: Key Steps in the Preparation of ITER", Proceedings of the 21st IEEE/NPSS Symposium on Fusion Engineering, 26th - 29th September 2005, pages 17-22

[4]. V. Toigo, L. Zanotto, M. Bigi, E. Gaio, J.H. Hay, R. Piovan, S.R. Shaw and JET-EFDA Contributors, "Conceptual Design of the Enhanced Radial Field Amplifier for Plasma Vertical Stabilisation in JET", Proceedings of the 24th Symposium on Fusion Technology, Warsaw, Poland 11th - 15th September 2006

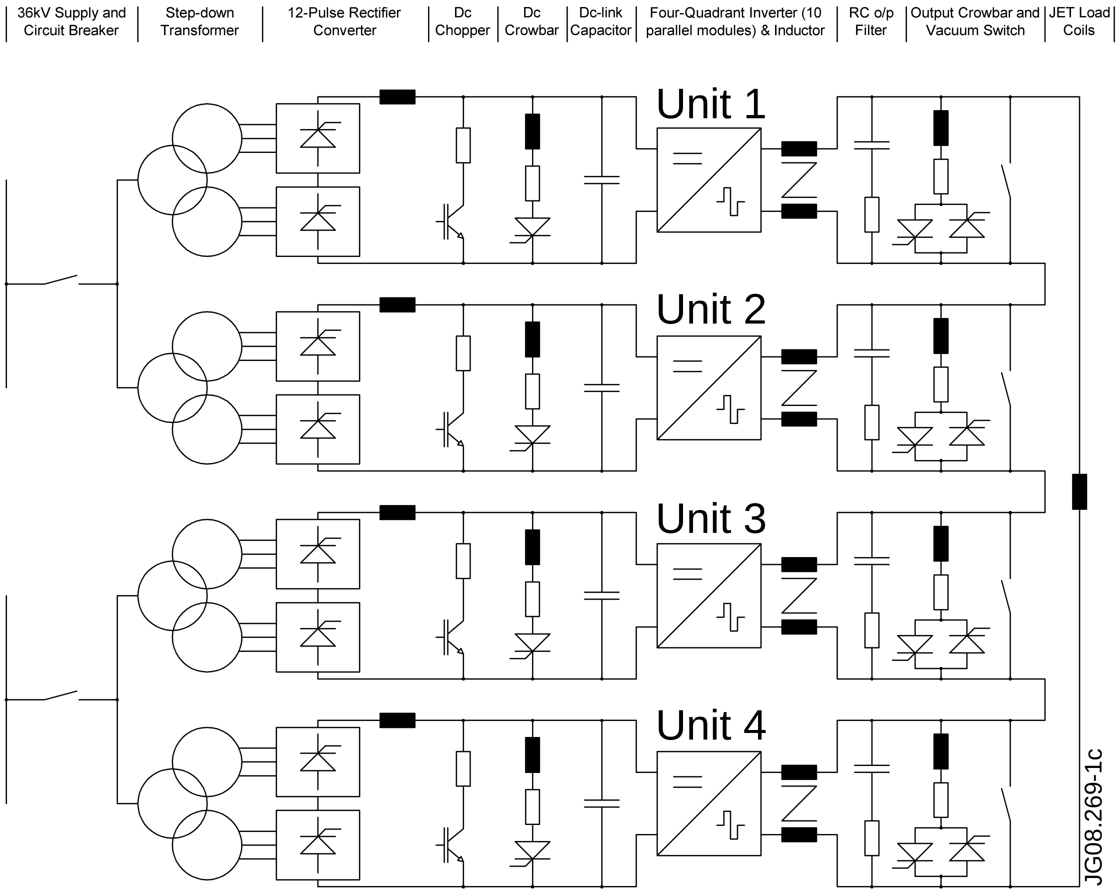

Figure 1: ERFA Single Line Diagram

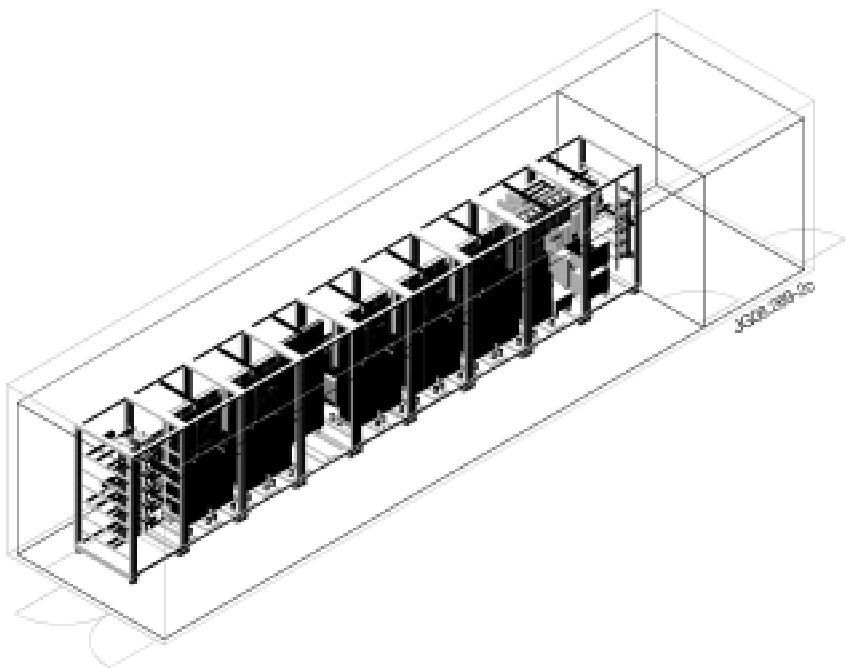

Figure 2: An ERFA Unit Inside Its Shelter

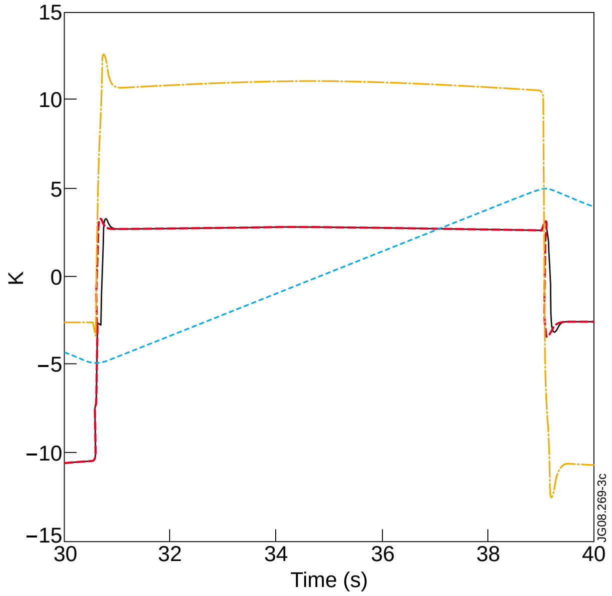

Figure 3(a): ERFA Output Voltage without Staggered Switching

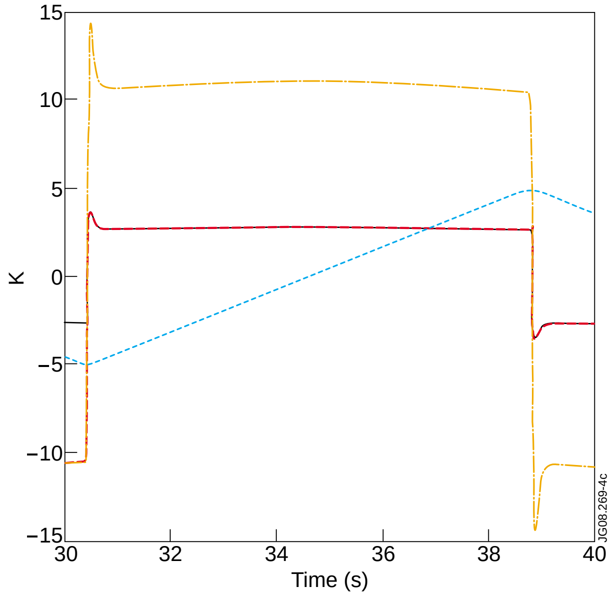

Figure 3(b): ERFA Output Voltage without Staggered Switching