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D.C Edwards, M. Bigi, D.P.D Brown, D. Ganuza, F. Garcia, Z. Hudson, T.T.C Jones,
A. Perez and JET EFDA Contributors

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D.C Edwards[1], M. Bigi[1], D.P.D Brown[1], D. Ganuza[2], F. Garcia[2], Z. Hudson[1],
T.T.C Jones[1], A. Perez[1] and JET EFDA Contributors*

[1]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon Oxon OX14 3DB, UK
[2]Grupo JEMA, E-20160 Lasarte-Oria, Guipúzcoa, Spain
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ABSTRACT.

The design features, on-site testing, commissioning and operation are described of two new 130kV/130A HV power supply units serving four upgraded 130kV/60A Positive Ion Neutral Injectors (PINIs) on JET. Both units were factory tested at full power and pulse length into dummy resistive load. Following on-site installation, the factory tests were repeated. The transition from dummy-load testing to PINI operation required full integration of the HVPS within the overall JET control system, and rigorous testing of the co-ordinated actions and protections of all PINI power supplies (filament and arc for plasma source and negative suppression grid). The implementation of these functions is described. Extensive use was made of parasitic integrated test pulses, where the other PINIs could be operated normally, with the HVPS energised under full remote control together with the corresponding PINI plasma sources, but with the HVPS connected to dummy load. The amount of NB operation time dedicated to commissioning was thereby minimised, yet gave a high degree of confidence of readiness for HV energisation of the PINI, and first beam operation followed less than 24 hours from HV connection to the PINI. The routine operating experience and performance, including load protection characteristics, of the new HVPS units are also described.

1. INTRODUCTION

The JET Neutral Beam (NB) upgrade increased the current of eight triode-type Positive Ion Neutral Injector (PINI) deuterium beam sources from 30A to 60A at 130kV d.c. acceleration voltage. Two new HV Power Supply (HVPS) units each rated at 130kV/130A (20s pulse length, 1/30 duty cycle) were procured, each to feed the accelerator grid (G1) of two 130kV/60A PINI accelerators connected electrically in parallel [1] (Fig.1). The new HVPS units are all solid-state switched-mode type, in which 120 high-frequency IGBT invertor modules feed 120 isolation transformers whose rectified outputs are connected in series. Regulation and fast switching for control and load protection are done on the LV side, and the isolation transformers provide a passive barrier to the transfer of energy to the load in case of failure of an IGBT device to block. Up to 255 re-applications per pulse allow for repetitive HV breakdowns in the PINI accelerator, detected when the load current exceeds a pre-defined first threshold (TH1), causing the invertors to block. Two independent optically triggered thyristor crowbars across the HV output are fired if the load current reaches a second threshold (TH2).

In parallel with the development and production of the new HVPS units, several levels of the existing distributed control system were re-implemented to replace many parallel hardwired functions by software driven serial links. The overall objective was to give flexibility, improved reliability and reduced down time for servicing etc. The control system is hierarchical, with full integrated control of the NB injector at Level 1 [2,3]. The modified controls were at the local level below Level 3, at the Local Control Cubicle (LCP) shown in Fig.2, which controls two PINIs served by a single HVPS integrating the control and protection actions for the associated auxiliary supplies: filament, arc, snubber, negative electron suppression grid (G3) and deflection magnet. Fast signals are transmitted from the LCP to the HVPS via discrete fibre optics. A separate link to the HVPS

PLC is used to transmit regulation set points, such as output voltage. The fail-safe external Fast Beam Interlock [4] permit is transmitted direct to the HVPS invertors.

2. POWER SUPPLY TESTING AND COMMISSIONING

Both HVPS were tested extensively in the factory, to demonstrate compliance, at an early stage, of the most crucial requirements of load protection and output voltage regulation. The plant components and configuration were, as far as possible, as used on the JET site, including a 200m triaxial cable connection to a resistive load. Firstly, high voltage was delivered at the output on no load. The full power performance of the equipment was then proven on a 1kΩ resistive load, then on a 2kΩ load configuration corresponding to single PINI operation. The critical breakdowns of the neutral injector were simulated by firing one of the two thyristor crowbars. Factory tests were completed on the first HVPS in December 2002. Most of the installation work on the JET site was finished by April 2003 ready for site testing of the individual components, including insulation tests of the insulation transformer tanks at 200kV d.c. and the load connecting cable at 173kV d.c. The HVPS output capacitance was also carefully measured in order to fully characterise the stored energy.

Integrated on-site commissioning progressed in stages from the 36kV 3-phase a.c. supply toward the load. First the 36kV / 670V step down transformers were brought into service followed by the thyristor rectifier. At this stage the new plant was in local control. The next step involved the invertors and saw the first high voltage delivered at the output to a 280kΩ resistor (light load). The equipment was run in the range of output voltage 10kV to 120kV for different speeds of switch on voltage ramp-up between 150-500μs, a parameter critical to PINI operation. Initial testing of the light triggered thyristor crowbars was also performed in this light load configuration. Co-ordination between protection and regulation was demonstrated by firing the crowbars in the presence of high voltage at the output. The response of the TH2 protection was also tested and showed that the invertors switched off within 2μs of the TH2 event.

The dummy load available at JET was 830Ω and in this configuration testing on resistive load commenced in June 2003. The equipment was run at output voltages ranging from 10kV to 120kV, for different ramp-up times and pulse lengths, up to the nominal duration of 20s. Pulses at 120kV, for an output current of 144A (above the rated 130A) were particularly significant. The load configuration was then changed to 2kΩ, to allow testing of the HVPS up to the rated voltage of 130kV at 65A (simulating a single PINI). Having established the basic performance, the focus shifted to testing the load protection requirements and specifically the response to simulated PINI breakdowns. In preparation for that, control of the new plant was moved from the local interface to the new LCP.

Initially, to demonstrate the capability of the new plant to remove its output voltage and reapply it periodically (both on-load and open-circuit), cycles of 40ms on/40ms off were programmed in the invertor control and performed at different voltages and up to the specified limit of 255 applications per pulse. To simulate more closely the conditions of a PINI breakdown, a physical short circuit was applied across the dummy load, by means of an ignitron crowbar, fired at a typical rate of 10 times per second. Overcurrent protection of the load was provided by the same electronics employed on the PINIs and utilised the LCP interface to request switch off of the HVPS.

By the end of July 2003, the first HVPS was ready for connection to the PINIs, four months from the start of commissioning. The second unit followed approximately 10 weeks later.

3. CONTROL SYSTEM TESTING, COMMISSIONING AND INTEGRATION

In line with high reliability engineering practice all new designs had a design validation route; all equipment had 100% testing to confirm correct manufacturing. All software was fully specified before it was designed, coded, tested and then integrated. A plant simulator was produced to allow the fast combination logic and the sequential logic to be fully bench-tested prior to its installation in the LCP.

The upgraded injector box had to remain available for JET operation throughout the 2003 campaigns and therefore the installation of new equipment and commissioning had to be planned in a highly optimised way. The only period available for final integrated and on-load commissioning (with PINI) to full power was within the six week JET restart commissioning period immediately before the first high power campaign. All functions of the new HVPS and associated controls and interlocks were commissioned in a fully integrated manner before energising the PINI accelerator. Integrated commissioning started with testing all six individual power supplies (HVPS plus auxiliaries) per PINI from the LCP under Local Control. This was carried out using simulated signals from other JET interfaces e.g. the external Fast Beam Interlock, or with over-rides designed to allow safe operation in testing and to allow a safe return to operation for the JET pulse. At this stage, the HVPS was connected either to dummy load or local light-load resistor, and the auxiliary power supplies were operated in open circuit. With confidence that all the power supplies were functioning correctly, control was then switched successively to the next higher levels of controls in the JET Control System, Levels 3 then 2. Once control, status, monitoring, personnel & plant safety had been proved satisfactory multiple power supply operation was tested from Level 1. The PINI plasma sources (gas, filament and arc) were operated normally, with the negative grid (G3) disconnected, but its power supply energised on open-circuit. With the HVPS still disconnected from G1, the complete PINI control system was thus tested including simulated HV breakdowns. During breakdowns of the PINI accelerator, the arc source was interrupted (“notched”) to avoid feeding energy into the breakdown. The complex timing requirements for notching and reapplication were checked in this configuration so when HVPS was connected to the PINI for the first time there was high confidence that it would operate and be fully protected. As a last step before connection to the PINI load, the HVPS was run on the dummy load synchronously with JET plasma discharges. Fig.3 shows waveforms for one of the last integrated test pulses (on light-load), used to check the relative timing of striking the arc in the ion source and application of the G3 and G1 voltages, compared with data from one of the earliest on-load beam pulses; first beam extraction then occurred within 24 hours of connecting the HVPS to the PINI. The typical on-load voltage regulation performance during the voltage ramp and settling phase is also seen in the PINI grid 1 voltage trace (VG1) for the beam pulse in Fig 3.

4. ROUTINE OPERATING EXPERIENCE

One difference between this type of HVPS, compared with conventional systems employing series switch tubes for load protection, is that a current path is maintained around the circuit when the invertors have blocked, via the HV-side rectifier diodes, and the circuit inductance continues to drive current through the fault until it is discharged. The dominant circuit inductance (≈1mH experimentally measured) is due to the eddy current core-snubber [2] modules located at the load, leading to current extinction times of order 100μs, compared with <<100μs for a conventional series switch tube circuit where the circulating current may be diverted through a resistive path.

The observed fault current extinction times are in line with predictions, but there is no observable effect on PINI reliability, as expected since the additional energy dissipated in the fault is estimated to be <0.1J. Figure 4 shows a comparison between the fault current extinction behaviour of the conventional switch tube and new HVPS. No particular problems have been experienced in routine operation up to typically 125kV, 55A per PINI (125kV, 110A per HVPS module) and up to 10s pulse duration, leading to achievement of highest ever deuterium NB power injected into JET (22.7MW) [5,6].

CONCLUSION

In specification and detailed design of the system, each element of the equipment's life cycle was taken into account i.e. development, manufacture, testing, installation, commissioning, servicing and finally operation. The design was not carried out in isolation but with the participation of a team consisting of NB physicists and engineers, software engineers, power supply engineers, C & I engineers, manufacturing personnel, testing and commissioning staff. The problems of installing and testing the system in parallel with JET being operational were fully considered at the design phase, so during installation and testing, solutions to known problems had already been implemented. The PINI loads were brought into operation remarkably quickly with the new HVPS modules, a consequence of extensive factory testing, the initial on-site stand-alone dummy-load tests, and the ability to carry out parasitic integrated commissioning.

ACKNOWLEDGEMENTS

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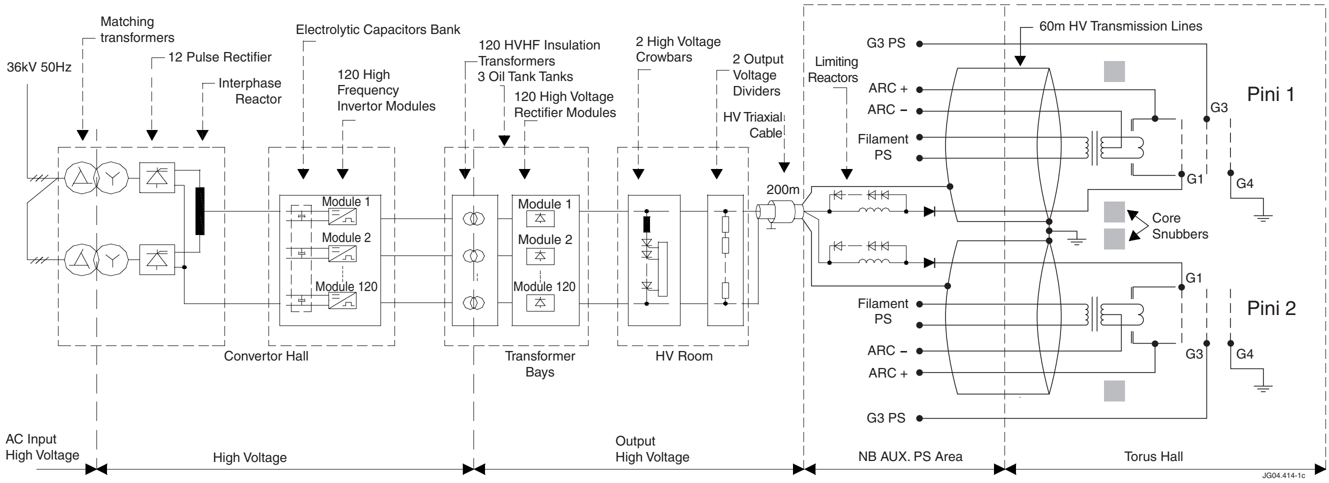

FigureMain Circuit Diagram of HVPS and Load

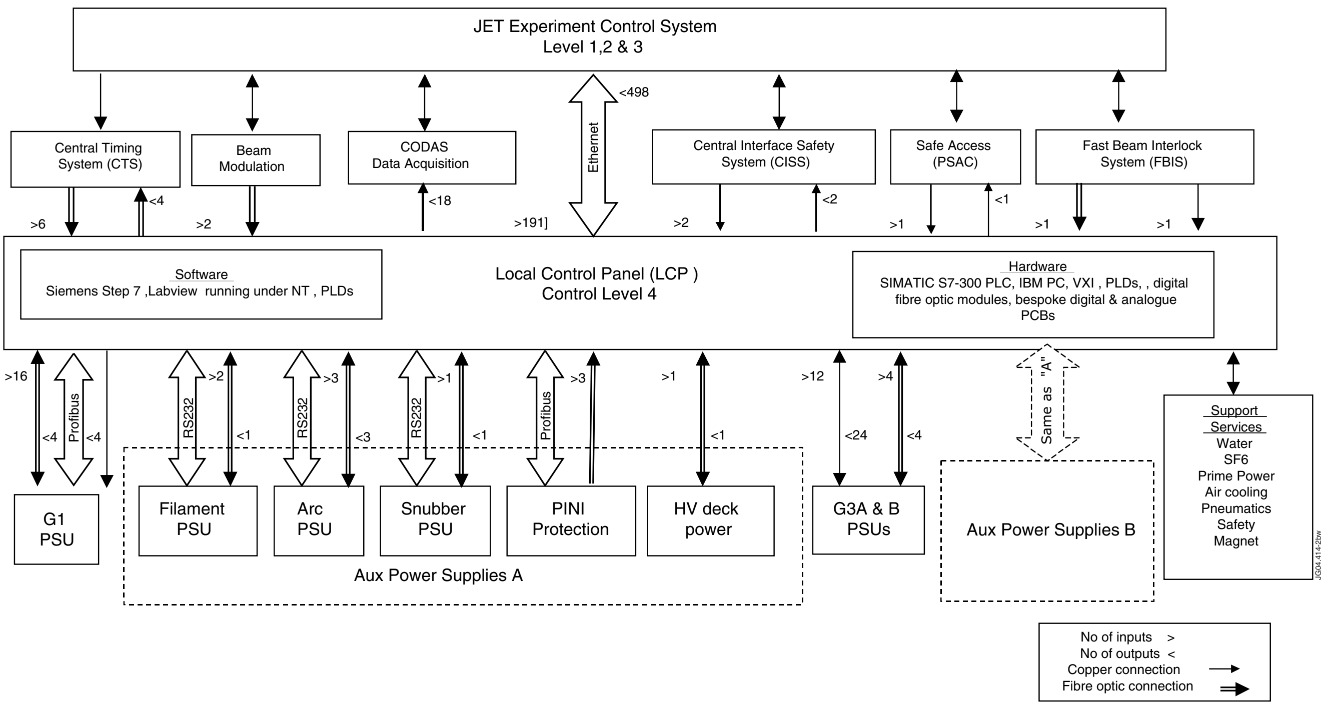

Figure 2: New Control System Block Diagram

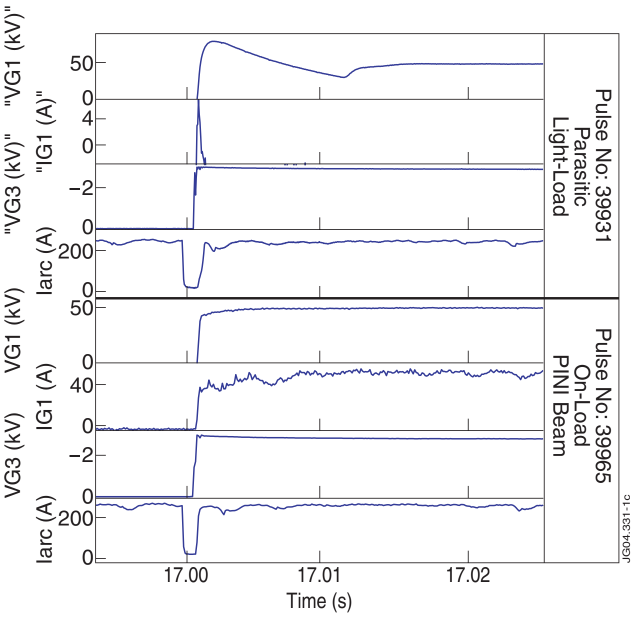

Figure 3: Parasitic integrated test waveforms (HVPS on light-load only, hence voltage overshoot) compared with one of the earliest beam commissioning pulses, illustrating how the interaction between the HVPS and auxiliary power supplies (e.g. relative timing) could be fully optimised before connecting to the PINI load.

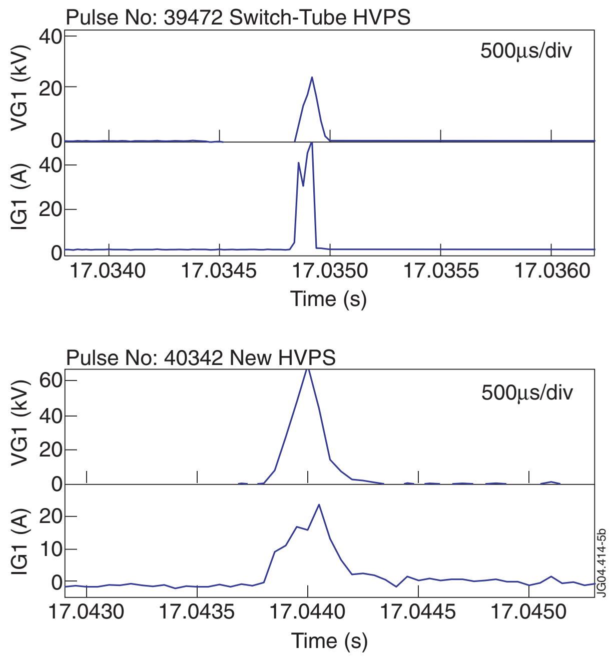

Figure 4: Comparison of behaviour of conventional switch-tube and new HVPS modules after blocking in response to load breakdown, here occurring during the voltage ramp phase during PINI conditioning at about 70kV. For the new HVPS the extinction time is longer (>100µs), as expected due to the continuous current path through the HV-side rectifier diodes, whereas the switch tube protection system extinguishes the fault current in << 100µs.