Rebuilding and Optimization of a High Voltage Power Supply for the Additional Heating Systems of ASDEX Upgrade

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One of the unique features of ASDEX Upgrade is the heating power with respect to the size of the plasma. The power at the separatrix divided by the major plasma radius P_{sep}/R representing the normalized heat flux at the divertor is 10 MW/m for 3 s. This is 2/3 of the power expected for a fusion power plant. In order to achieve this goal, the additional heating systems have been strengthened by four new ECRH gyrotrons. For power supply two 30 years old 70 kV / 2.5 MW high voltage AC power controllers have been rebuilt, equipped with a modern digital control system, integrated into the ASDEX Upgrade HV power supply system and optimized for the new task. The paper describes the reconstruction and installation of the power circuits and control system, commissioning, system optimization, operational experiences, present state and findings.

Keywords: ASDEX Upgrade; Plasma heating; Gyrotron power supply; High voltage power supply; Star point controller

1. Introduction

The ASDEX Upgrade (AUG) Tokamak experiment generates thermal plasmas to examine possible scenarios for future fusion reactors. The research program is focused on the construction and operation of the ITER fusion experiment and the next step DEMO reactor. ASDEX Upgrade has a pulsed nature with a plasma flattop time of maximum 10 s. The high current (HC) converters for magnetic confinement and the high voltage (HV) converters for additional heating are supplied by three large flywheel generators with pulsed power up to 571 MVA and stored energies up to 2782 MJ (see Fig. 1, [1]).

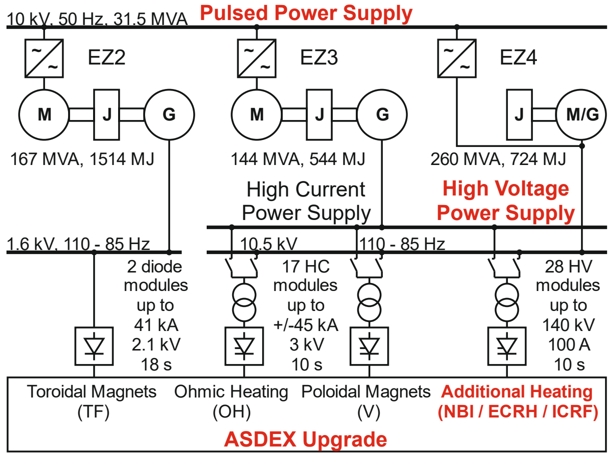

Fig. 1. AUG pulsed power supply network.

The power supply systems have to cope with the progressing and increasing requirements of the steadily improving plasma scenarios of the ASDEX Upgrade research program [2]. For high voltage power supply of four new 1 MW / 140 GHz ECRH gyrotrons (ECRH-3) installed between 2013 and 2018, two 30 years old 70 kV / 2.5 MW high voltage AC power controllers had to be rebuilt, equipped with a state of the art control system, integrated into the AUG HV power supply system and optimized for the multiple heating scenarios.

2. Application

ASDEX Upgrade operates 28 HV power supply modules for 8 neutral beam (NBI), 8 electron cyclotron resonance (ECRH) and 4 ion cyclotron resonance (ICRF) heating systems.

While at current experiments (AUG, DIII-D, JET) neutral beam injection is dominating plasma heating, at ITER and DEMO it will mainly be electron heating. In order to increase the fraction of electron heating at ASDEX Upgrade, another 4 MW / 140 GHz / 10 s (3.2 MW / 105 GHz) ECRH system with four gyrotrons has been installed (see Fig. 2, [3]).

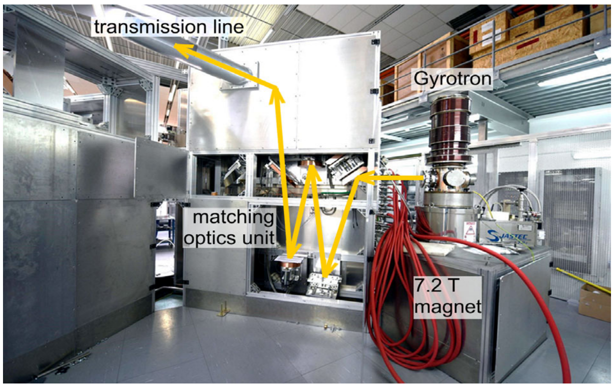

Fig. 2. ECRH-3 gyrotron with superconducting magnet, matching optics unit and transmission line

3. Reconstruction and installation

The two 70 kV / 37 A klystron HV power supplies left to IPP by the Deutsche Elektronen-Synchrotron

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DESY in Hamburg were in operation since 1981. As a first step the transformers and rectifiers were sent to factory for major inspection and modification in 2013/14. In parallel a new HV building was constructed. Installation of the assembly took place in 2015/16 and intensive commissioning, testing and optimization of the systems in 2017/18.

3.1 Power Circuits

In order to detect possible damages at the core-and-coil assembly, tap changer, rectifier or bushings, the transformer and rectifier tanks had to be opened and the inner parts to be dismantled (see Fig. 3). Luckily no damages could be found.

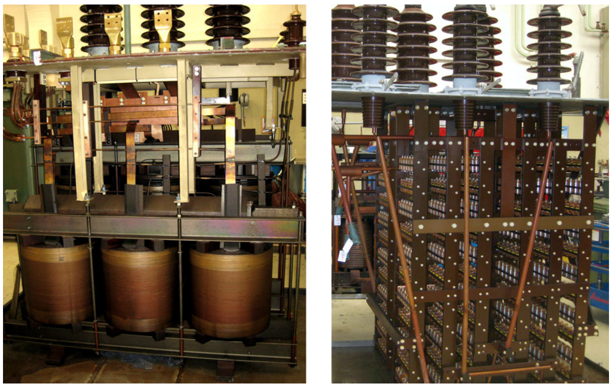

Fig. 3. Disassembled transformer and diode rectifier

Since the system - originally used for continuous operation - was designed as AC power controller, it had to be converted into a star point controller for the new pulsed duty with an overload factor of more than 2.5 (70 kV / 100 A / 12 s). To achieve this goal the star point connections of the intermediate circuit had to be disconnected and wired to additional bushings (see Fig. 4) and the output reactor of the rectifier was removed requiring an adapted new rectifier tank.

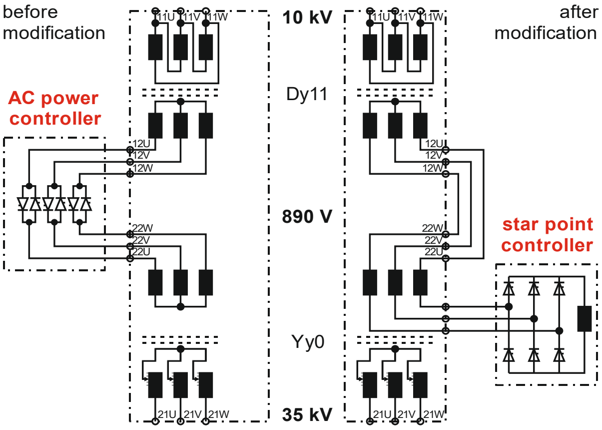

Fig. 4. Modification of intermediate circuit

The modules are directly connected to the 10.5 kV / 50 Hz surge load network. An integrated SF6 metal-clad switchgear was purchased for this purpose. Both transformers of a module together with its rectifier form a 12-pulse system. Thyristors of the AC power controller could be reused and rearranged inside the original converter cabinet. Cooling was changed from water to air natural because of the pulsed duty. Converter and control cabinets were installed in a 20′ dry-container. Neutral reactors are set up on top of the container. A second container includes the HV DC system with polarity reversal switches, resistive and direct short-circuit switches, earthing switches and current and voltage measurement. Smoothing capacitors are mounted on top of the HV container. The complete installation is put up inside a newly constructed weatherproof hall. For single line diagram of the installation see Fig. 5. A layout drawing is given at Fig. 6.

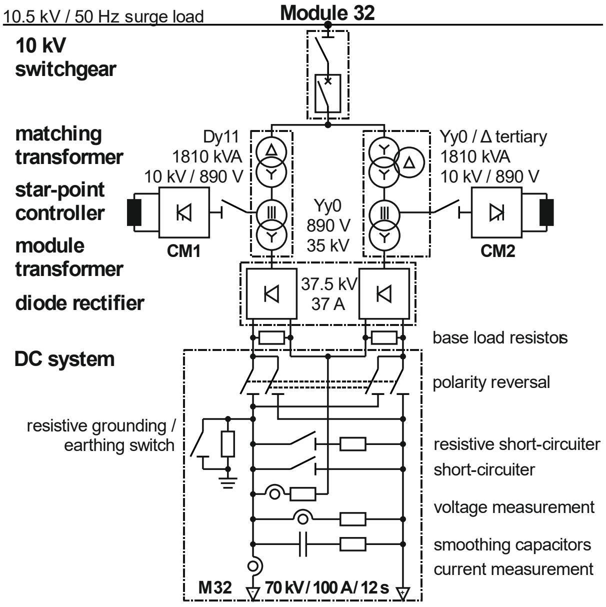

Fig. 5. Single line diagram HV module

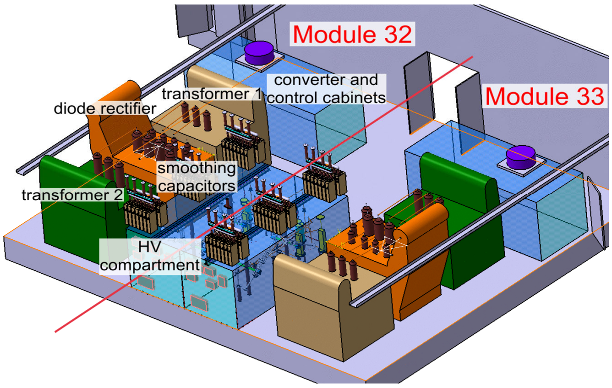

Fig. 6. Layout of installation

3.2 Control System

The control module - including supplement unit and external gate pulse transformers - of the SIMOREG DC-Master 6RA70 converter assembly is used as control system. The DC-Master is equipped with a fully digital logic and feedback control. Its common use is to feed armature and excitation windings of variable-speed DC drives. Flexible software enables it for special applications as for the star-point controller. Gate control of the thyristors is directly carried out by the DC-Master.

Higher level control is performed by a Simatic S7-300 including WinCC flexible operator panel. For remote control from the ECRH control room the existing and reliable standard analog control interface is used. Further on the new system had to be integrated into the emergency stop circuitry and load allocation of the HV plants.

For AC current measurement existing 1500/1 A current transformers (c.t.) are used. DC current measurement is realized by two LEM electronic c.t. and DC voltage measurement by shunt resistors and LEM c.t.

The focus of control is on the effort to meet the strict requirements for voltage stability during turn on (undervoltage) and turn off (overvoltage). This is even more difficult since the gyrotrons have to reliably operate in continuous waveform mode (c/w pulse) and at modulation frequencies up to 500 Hz with variable pulse duty factors between 0 and 100 %. Parameters can be changed during a plasma pulse at will. DC voltage is switched on and off very fast by tetrodes.

To achieve high dynamic, the DC Master provides a feedforward control in parallel to the PI voltage controller. As soon as a current flow is detected and thus before the DC voltage breaks down, the thyristor firing-angles are advanced starting to feed energy into the DC circuit and thus boosting the voltage. The voltage controller acts for steady state stability of the voltage. An overview of the control loops finally implemented after all investigations described below is given in Fig. 7.

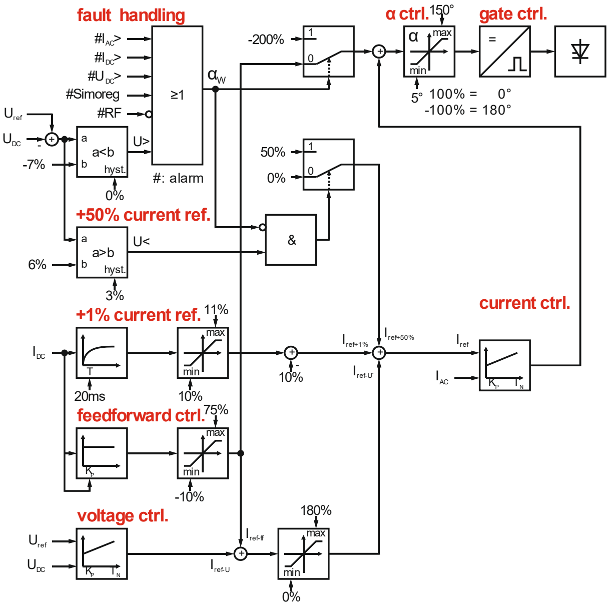

Fig. 7. Control loops

4. Commissioning and system optimization

During commissioning of the HV power supplies in spring of 2018 the ECRH-3 system was not yet available. Therefore all tests of both HV modules were performed on a single modulator and a dummy load at 60 A. Full load tests with two gyrotrons connected to each module and final adjustments of the control loops could only be performed after completion during ASDEX Upgrade operation.

The tolerable voltage variation was -10 % for voltage dips and +5 % for overvoltage. The rise time of the control is 6.6 ms. Unfortunately there is an additional statistic dead time of 3.3 ms. Therefore during commissioning a sophisticated external fast analog feedforward control with P / DT1 behavior based on Simadyn C hardware has been established to operate the DC power supplies within the challenging conditions described above. Since feedforward control is unfavorable during modulation, a modulation detection based on an ATMEL ATtiny 45 microcontroller was added. As soon as modulation is identified, feedforward control is smoothly reduced to zero within 250 ms. To further improve voltage stability, the smoothing capacitance was increased from 64 µF to 96 µF per module. Since ECRH-3 operates at about 51 kV only, a reduction of the AC link voltage to 27.125 kV (tap 4 / 77.5 %) was favorable to allow an improved phase control factor. In order to improve no-load characteristic, a base load resistor of 240 kΩ was added to each half-module.

5. Operational experiences

During plasma operation a few critical events occurred close to the power limits. Critical events cannot be handled by the in-phase modulators anymore and the gyrotrons have to stop operation. Load steps of the DC current I_{DC} are 40 A and 80 A (40 A per gyrotron). Most problems happened with both gyrotrons of a HV module being switched on. To avoid tripping, -10 % / +5 % under- and over-voltage detection was disabled at the expense of longevity of the modulators.

5.1 Intermittent current flow

After switching on the second gyrotron, star-point controller CM2 showed intermittent current flow alternating with increased AC current I_{AC} up to AC overcurrent trip level. DC voltage U_{DC} dropped down below 40 kV stopping gyrotron operation. (see Fig. 8). The feedforward peak of the DT1 element together with the low stiffness of the system resulted in oscillations of the AC current controller.

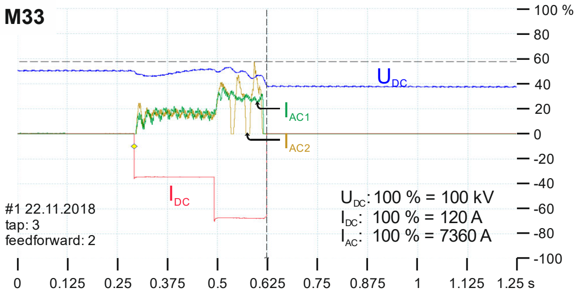

Fig. 8. Intermittent AC current flow

5.2 Excessive voltage rise

300 ms after switching on the gyrotron - DC voltage has not recovered completely, yet - voltage suddenly started rising sharp resulting in an overvoltage of 62 kV instead of target 52 kV (see Fig. 9). Modulation was detected because of the short blip at the beginning of the pulse and feedforward was reduced down to zero. At the next control cycle 260 ms later the feedforward controller noticed that there is no modulation anymore

and feedforward started again, resulting in overvoltage since the voltage controller could not counteract quickly enough.

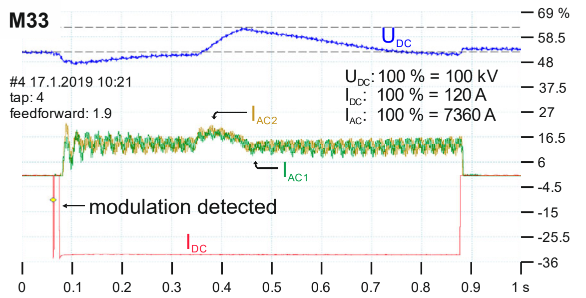

Fig. 9. Excessive voltage rise

5.3 Modulation detection

Modulation detection noticed the quite irregular modulation and disabled feedforward control. DC voltage was quite stable. An extended idle period after about 2 s resulted in DC overvoltage and the voltage controller was cut back. Since feedforward was disabled the following current pulse resulted in a voltage dip that could not be compensated by the voltage controller any more (see Fig. 10).

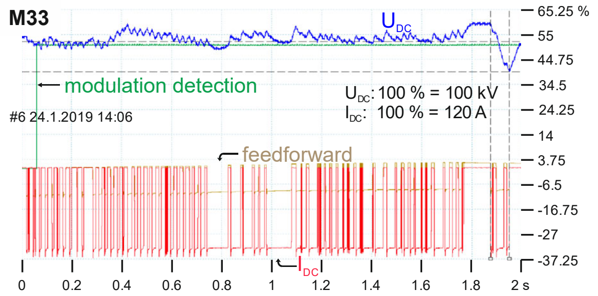

Fig. 10. Modulation detection

6. Present State and Findings

After lots of measurement and deep investigation, behavior of the system was very well understood and further modifications were implemented: 1) The DT1 function of the feedforward control is disabled. DT1 resulted in a reduced step height of feedforward at successive pulses since it was already precharged from the previous pulse. 2) Gain of feedforward control is increased as a function of load current resulting in an improved control behavior. 3) Feedforward is limited to 75 % and prevents heavy overshooting and high AC current peaks if two gyrotrons are switched on. 4) Ramp-up time of the feedforward signal after enabling is increased from 100 ms to 500 ms resulting in a more gentle reaction. 5) Modulation is now checked every 32 ms instead of every 261 ms only. Reducing feedforward can be stopped and reversed early resulting in an improved behavior if modulation and continuous current periods alternate. 6) Originating from armature current control, the PI current controller is disabled and its integral component reset as soon as the reference value becomes zero. The firing angle jumps towards 150° and the integrator has to start from zero at the next current pulse. Modulation behavior could therefore be improved adding an additional 1 % reference value as soon as the mean value of the DC load current exceeds 10 %, preventing the reference current becoming zero during interpulse periods of modulation. 7) If overvoltage occurs (difference between reference and actual voltage exceeds -7 %) the trigger delay angle is immediately set to its maximum value $\alpha_{max} = 150°$. At undervoltage (difference between reference and actual voltage exceeds +6 %) the current reference value is increased by 50%. Both measures reduce voltage deviation substantially if feedforward control is disabled.

7. Conclusion

After three years of on-site installation and two further years of gradual delivery and commissioning of the gyrotrons and body modulators, the complete ECRH-3 additional heating system is in operation at ASDEX Upgrade since end of 2018. With the modifications described above, a stable operation of the two HV power supply systems was achieved fulfilling the requirements of the ASDEX Upgrade experiments.

The AUG ECRH system with the four additional ECRH-3 gyrotrons is the most powerful ECRH system on a Tokamak experiment worldwide. The new system allows for more flexible profile tailoring while maintaining central heating, resulting in more current drive and higher P_{sep}/R. It is an important element increasing the heating and pulse power capabilities of ASDEX Upgrade towards achieving a stationary behavior of the current profile and plasma wall interaction under reactor relevant conditions. The total heating power is now in the range of 34 MW and the phase of high heating power is significantly extended to more than 5 s. Further on, the availability of the installation has been improved, resulting in a more efficient operation close to the limits of the systems.

Acknowledgments

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References

[1] C.-P. Käsemann, E. Grois, F. Stobbe, M. Rott, K. Klaster, ASDEX Upgrade Team, Pulsed Power Supply System of the ASDEX Upgrade Tokamak Research Facility, 2015, https://doi.org/10.1109/EEEIC.2015.7165545.

[2] C.-P. Käsemann, A. Kallenbach, J. Stober, J.-M. Noterdaeme, C. Hopf, N. Arden, I. Goldstein, ASDEX Upgrade Team, Extension of Heating and Pulse Power Capabilities at ASDEX Upgrade, 2017, https://doi.org/10.1016/j.fusengdes.2017.05.035.

[3] J. Stober et al., High power ECRH and ECCD in moderately collisional ASDEX Upgrade Hmodes and status of EC system upgrade, 2015, https://doi.org/10.1051/epjconf/20158702004