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* Manuscript

FINAL TEST OF THE W7-X CONTROL COILS POWER SUPPLY AND ITS INTEGRATION INTO THE OVERALL CONTROL ENVIRONMENT

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Abstract

In order to be able to vary the magnetic configuration of WENDELSTEIN 7-X (W7-X) at the plasma edge and allow sweeping of the power across the divertor target plates 10 „control coils" are installed inside the plasma vessel behind the baffle plates of the divertor. The coils are made of eight turns of a hollow copper profile. The dimensions of the coils are 2,05 m x 0,35 m x 0,35 m with a three dimensional shape to fit into the narrow space between the baffles and the wall of the plasma vessel.

Each of the ten coils is supplied by independent power supplies each providing bi-directionally a direct current of 2500 A with high accuracy and low ripple.

To allow sweeping the power deposition from the plasma across the target plates the power supplies provide an alternating current of up to 625 A with frequencies up to 20 Hz which is synchronised between the ten supplies in order to maintain the symmetry of the magnetic field.

The total output current of a power supply is a superposition of a direct current and an alternating current, where both parts have to be independently adjustable.

All ten power supply units and auxiliary systems have meanwhile been installed and finally tested at the W7-X site in Greifswald.

The paper focuses on the results of the final tests and measures to integrate the power supply system to the overall control system including the central PLC and PC's for experiment control, data acquisition- and security systems.

Key words: WENDELSTEIN 7-X, control coils, power supply

1. Introduction

The main magnetic field of W7-X is provided by 50 non planar and 20 planar coils. To ensure a variety of magnet field configuration at the plasma boundary of the W7-X main magnetic field, to avoid symmetry breaking error fields and to sweep high peak plasma depositions across the target plates, additional normal conducting coils are located behind the baffle plates of the divertor inside the plasma vessel.

The dedicated power supplies have to provide a direct current of 2500 A bi-directionally with high accuracy and low ripple, which can be superposed with an alternating current of 625 A with frequencies up to 20 Hz [1]. The detailed requirements are summarised in Table 1.

The complete system consists of ten independent power supplies modules (PSM), a supply distribution module (SDM) providing the mains and generating the auxiliary power, a cooling water module (CWM) for cooling the most heat excessive parts as there are the rectifier diodes, the inverter MOSFETs and the transformers. For the remote operation of the power supply a superordinated control unit (SCU) basically a master PLC belongs to the system as well. For low power density, hence low voltage drop and heat load in the torus hall, 4x630 mm^2 cables have been chosen to connect the power supplies to the control coil.

The inverter stage of the power supply is built up by a 24 kHz "H-bridge" converter being fed by a 12 pulse link rectifier with interphase coils. A filter composed of a capacitor and an inductance is connected to the output assuring the low voltage and current ripple requirements (Fig. 1).

2. Results of the final tests

After the installation and commissioning of the power supplies by the contractor Grupo Jema (Spain) each individual PSM has been tested with respect to its functionality and current performance. After these tests have been finished successfully the SCU was installed and connected to the power supply. In the final test the overall system had to prove all main parameters given in Table 1 during combined operation from the SCU. For testing the power supplies a set of ten water cooled test coils has been purchased representing the electrical parameters as expected for the control coils which are namely the ohmic resistance of 3,9 mΩ and the inductance of 188 µH.

2.1 DC Current

For the current measurement the internal measurement devices of the PSM have been used after have been tested sufficiently during the tests of the individual PSM. The measurement signals coming from the ten power supplies have been collected by the experimental data acquisition system (XDV) of IPP for further evaluation. With the data gained during the test campaign the current precision was measured for different current scenarios. The measured currents are well within the specified precision with values like 500 A to 505 A for a set point of 500 A, 1500 A to 1510 A for set a set point of 1500 A and 2495 A to 2510 A for a set point of 2500 A. Several more scenarios have been tested showing the same behaviour of the current with a deviation of less then 1%. Furthermore, the influence of drastic current changes in one PSM to the performance of the other PSMs due to the coupling of stray inductances of the parallel installed power lines for several PSMs was checked by changing the set point value of one PSM from 2500 A to -2500A while working at full DC and AC current. No undesired reactions in the currents were observed. As the measurement signal coming from the internal current transducer of the PSM already contains a certain noise level in a range of 0,5 A_{pp} to 1 A_{pp} it was decided to simulate the current ripple based upon a voltage ripple measurement. A simulation model of the dummy coil has been developed using the simulation tool SIMPLORER© containing the ohmic resistance, inductance and also the parasitic capacitance of the coil, which has been calculated from the dummy coil design and afterwards verified with a measurement at the resonance frequency of the coil. With the values from the DC voltage measurement and the coil model the current ripple was then calculated via simulation (Fig. 2 and 3).

As expected the higher frequencies are well smoothed by the inductance of the output filter and the load itself. The Effect of the commutation frequency of 24 kHz and its higher harmonics is negligible due to the capacitance of the output filter which is dedicated to high frequency voltage peaks coming from the inverter, whereas the sub harmonics from the 600 Hz inter phase coils have the main impact on the residual current ripple. The ripples itself stayed inside the requirement of less than 1 V_{pp}. for the output voltage and 1A_{pp} for the current.

2.2 AC Current

First of all the AC current provided by the power supply was tested regarding the sine wave quality. Measurement data gained with an oscilloscope were analysed regarding the frequency and evaluated by a Fourier analyses to get the THD of the sine wave. The results show that the frequency of 20.02 Hz is very close to the specified value of 20 Hz which means a deviation of 0,1 %. The Fourier analyses revealed that the total THD is mostly composed of the third harmonic with less then 4 %.

As the data acquisition system which was used for the measurements of the DC current is limited to a sample frequency of 200 Hz it was decided to use the oscilloscope also for the measurement of the AC current precision. AC current on its own and composed with the DC current has been tested at various scenarios. The current values for the AC current were all within a current precision of less than 1%. Superposed to various DC current the precision of DC and AC current stayed the same as during the individual tests of the currents.

The synchronisation of the AC current is determined by the controller of one of the PSMs. For each zero crossing of the reference sine wave created in the controller a synchronisation interrupt is processed in all the other modules. To evaluate quality of the synchronisation the AC current coming from this one module is taken as the reference for the measurement of the phase shift (Fig. 4). The deviation of the zero crossings of all other modules has been measured by 1,3° to 1,8° in different current scenarios and is therefore within the specified value.

3. Integration into the central control environment

As part of a complex system consisting of numerous individual components the power supply of the control coils has its dedicated control system enabling the operator to control each individual power supply from a local operator panel (local operation) as well as from a visualization system for combined operation of all power supply modules and its auxiliary systems for maintenance and test operations (autonomous operation).

In order to integrate this component and its control to the W7-X central control system [2] for the so called "segment operation" [3] during the experimental campaigns several interfaces have been defined (Fig. 5).

The Control system of the power supplies and the W7-X central control are based upon SIEMENS S-7 hardware technology. The main interface between the power supply system and the W7-X central control is established by the SCU of the power supply system and the Fast Control Station (FCS) of the W7-X central

control. The SCU consists of one PLC and the dedicated communication hardware, being the master for all control tasks of the individual PLCs of the different modules during the autonomous operation and a visualization PC as Human Machine Interface based upon SIEMENS WinCC software. Connected via Ethernet to the W7-X central control this PLC then works as a slave during segment operation. Internal communication between all modules of the system is also established by Profibus DP. The FCS is a local interface between its dedicated component and the central segment control being part of the W7-X central control [2]. The central segment control provides the essential data for running a segment as part of the experiment campaign and distributes them to the local control stations of the different components taking part in the experiment. The FCS then sends these data to the SCU operating the system. Furthermore, the FCS collects the feedback data of the currents coming from the power supply to distribute them back to the W7-X main control and the XDV. The FCS has already been installed and connected to the power supply system while the main control exists only in a preliminary status. All functionalities to test the operation of the power supply have been implemented containing the defined data packages for command, status, alarm and feedback signals as well as certain test segments providing the set point and limit values for the power supply. During the final test of the power supply of the control coils the functionality of the normal operation together with the existing prototypes of the W7-X main control was established successfully. For the visualization system, a standardized screen has been developed by IPP showing all main parameters of a component which are exchanged between the SCU and W7-X central control. This screen was implemented into the visualization system provided by the manufacturer of the power supply. As the power supply can be operated from three different places it has to be assured that no misuse of the system can occur while working in a certain operation mode (local, autonomous or normal). This is managed by the so called “user rights”. User rights between SCU and the local PLC of each module is determined in the SCU itself. For changing the user rights to the W7-X central control a standardized software application for the WinCC has been developed by IPP. It allows the switching of the user rights of the operator at the SCU and W7-X central control under defined conditions as well as the forcing of the user rights back to the SCU in case of emergency. This software application was also scope of the test in combined operation and passed this test successfully.
Apart from the software based control system an additional hardwired security bus system is foreseen to ensure the overall personal and machine safety. First of all it has to be assumed that each component of the W7-X complies with the certain rules of personal and machine safety. Nevertheless, a residual risk exists due

to the interactions with other components while being operated combined during the normal operation of W7-X. This has a significant influence on the operation regime for certain components as well as for the operating staff, e.g. the access control to experiment hall. Based upon a security analyses for the power supply the potential danger coming from the power supply while working in normal operation was determined and classified. It is planned to use the power supplies for the control coils as a test bed for a first prototype of the security bus system to test different hardware configurations for the security control. In a first step a "system save" condition has been defined determined by the status of the main breakers of each PSM. An auxiliary contact of each main breaker will create this signal to be provided to the security bus for further assessment. Further signals will be generated and integrated to the security bus system.

4. Conclusions

The ten power supplies for the control coils has been finally installed, commissioned and completely tested. The control system has been tested too. It is compatible to the preliminary main control system of W7-X which is currently under design. Ongoing activities will be the adjustment of the control system to further modification and completion of the W7-X main control and the establishing of the security bus system. As the first control coil will arrive soon in Greifswald the power supply will be prepared to supply this coils for further internal tests.

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Table 1 Main properties of a power supply for one control coil

Designation	Value	Unit
DC current	0 to ±2500	A
AC Current	625	A_p
Maximum peak current	3125	A
Frequency of the AC current	0 - 20	Hz
Ripple of the DC current	≤ 1	A_{pp}
Deviation from setpoint value	≤ 16	A
THD of the AC current	≤ 10	%
Phase shift between AC currents	≤ 2	°
Effective voltage	30	V
Ripple of the DC voltage	1	V_{pp}
Power losses	10	kW

Fig. 1 Scheme of the power supply for the control coils

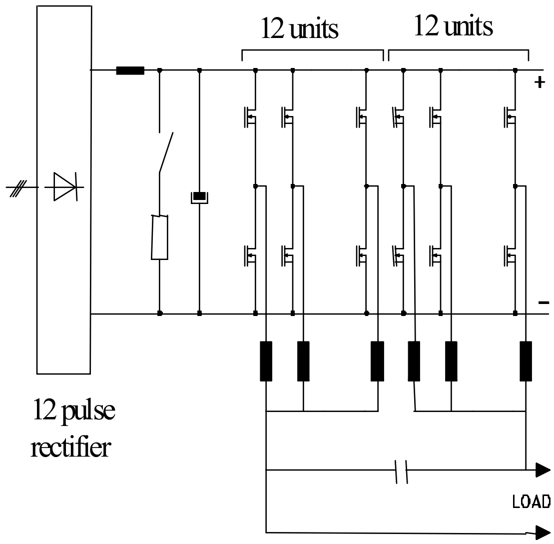


Fig. 3 Simulated current ripple at 2500 A

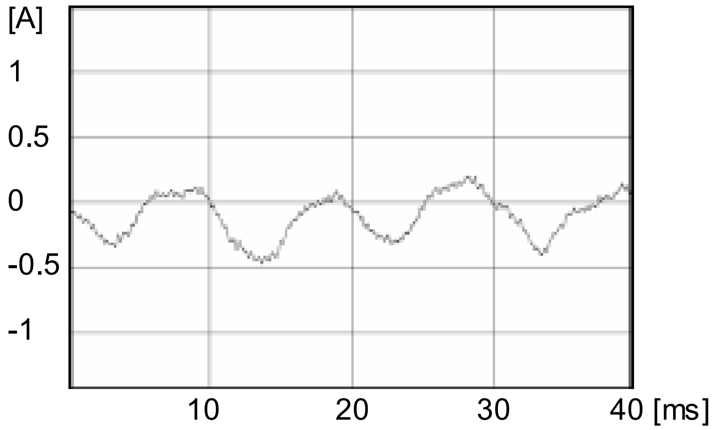


Fig. 2 Measured voltage ripple at 2500 A

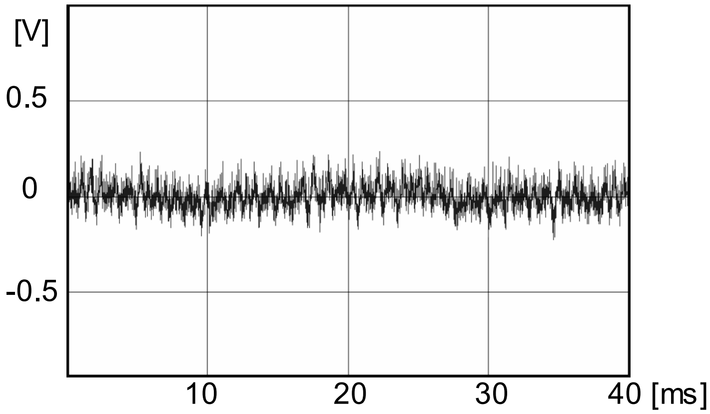


Fig. 4 Ref. AC current (top) and three adjacent modules

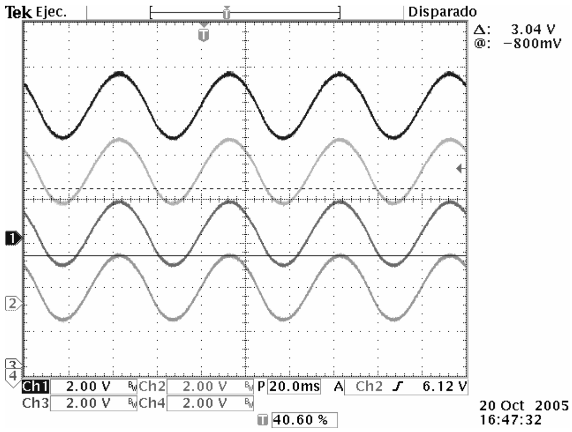
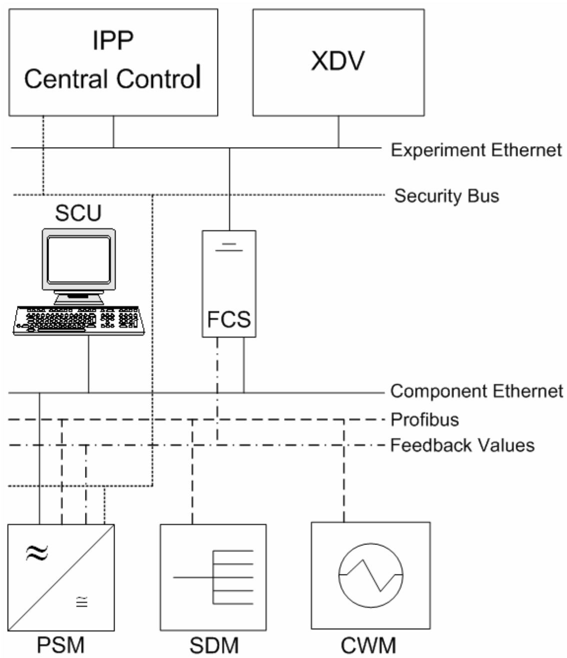


Fig. 5 Control layout of the power supply system



Detailed Response to Reviewers

This piece of the submission is being sent via mail.