MAIN HIGH VOLTAGE SOLID STATE GYROTRON POWER SUPPLY 60kV / 80A *

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Abstract

This paper will describe the preliminary design of a 4.8 MW Main High Voltage Power Supply, rated 60kV/80A, especially conceived to supply the voltage between Cathode and Collector of a Gyrotron. A full solid state technology, named SWM (Stair-Way Modulation) for the full scale Electron Cyclotron (EC) Test Facility at CRPP, Lausanne. The ITER EC system may also make use of a similar system, in alternative to the present baseline design based on naturally commutated thyristor converters and series high voltages solid state switches. The 60kV output is reached by adding more than 120 high voltage modules in series connection, with ad hoc control criteria to allow a regulation at full performances in the range of 45kV-60kV, a square wave modulation and a fast switch-off in less than 10us.Components choices and simulations of the system will be highlighted in order to demonstrate the fulfilments of the technical specification before the manufacturing stage. This solution can be extended to several applications in the High Voltage domain and is aimed to enhance the reliability, decrease costs, provide redundancy, plug-in modularity, component de-rating and component standardization.

INTRODUCTION

The ITER Heating and Current Drive (H&CD) system, includes the installation of an Electron Cyclotron system based on CPD type Gyrotrons (170GHz). This type of RF sources requires two power supplies, one Main High Voltage Power Supply (MHVPS) between cathode and collector (typically V = 50 ÷ 60kV, 80A) and an Acceleration Power Supply, which, with the MHVPS, establishes the voltage between body and cathode, typically 80 ÷ 100 kV. The modulation frequency specified in the ITER reference design is 1 kHz but in the developments on-going in Europe, 5 kHz are considered for the stabilization of Neoclassical Tearing Modes (NTM). The continuous developments of solid state devices, available for both higher voltages and higher switching frequencies, have highlighted several advantages of the fully static solutions which could conveniently replace the more traditional systems based on vacuum tubes (e.g. tetrodes). On the basis of the above considerations, OCEM has performed a conceptual study of a Solid State Body Power Supply (BPS) [1] for ENEA Frascati, with support from EFDA. The first fully solid state BPS has now been completed [2] and installed at ENEA Frascati. For the new EC Test Facility in Lausanne, EFDA is now procuring, on behalf of European Commission, both power supplies (MHVPS and BPS). The results of a competitive tendering showed that the above described modular topology was economically convenient beside yielding some important technical advantages.

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OUTLINE SPECIFICATIONS

The performance specifications are listed in Table 1:

Table 1: Main Performance Specifications

Description	Value
Duty Cycle	8 / 24 hours
AC input Voltage	20kV / 50Hz (±10%)
Nominal Output Voltage	-60 kV DC
Output Voltage range	-1 kVDC < V_{DC} < -60kVDC regulation at full performances -45kV to –60kV
Nominal Output Current	80 A
Modulation freq.(ON/OFF)	5kHz
Output Voltage Accuracy: Static Reproducibility Dynamic transient Ripple	 <± 1% of V_{DC} nominal <± 0.5% of V_{DC} nominal <± 1500V <± 2%@600Hz, <±0.5% for higher frequencies
Voltage Settling time	<15us
Shutdown time	<10us
Max Energy delivered to the load in case of arc	10J
Protection Transm. delay	<1us
Measurement Accuracy Voltage Current	 +/-0.1% in DC +/-0.2% at 10kHz +/-0.3% at 50kHz <± 1% of nom. value
Measurement Bandwidth	≥500kHz

MHVPS TOPOLOGY

The preliminary design of the MHVPS is based on a series connection of elementary power modules which do not require direct series connection of semiconductors. Each module, is provided with its own DC power supply so that the voltage is evenly shared during normal operation. The total output voltage is hence controlled by the number of switched-on modules in quantization steps of voltage. This topology, together with an ad hoc control strategy developed by OCEM, the Multi Pulse Width Modulation (MPWM), has been named Stair-Way Modulation (SWM). This type of modulation has the advantage of an averaged power distribution among all the modules, with a consequent minor stress of the main transformers. Also the achievement of a high bandwidth is not related to the increasing of the switching frequency of only a few modules. In a SWM system the maximum switching frequency of each module remains equal to all the modules. This leads to reach a very high value of bandwidth, according to the constraints due to the particular specifications. The overall system also foresees a level of modularity in a redundant and fault tolerant configuration. Hence, in case of fault of a single module, the faulty module can be easily excluded from the main circuit, ensuring continuous operation.

The MHVPS consists mainly of the following blocks:

- **Input circuit breaker** with a protection relay, to connect the P.S. to the medium voltage grid (20kV, 50Hz, three-phase) through a soft start equipment.
- **Multi Secondary Transformer system**, to adapt the input voltage from the grid to the voltage required by the downstream parts, with the proper insulation level.
- **Power modules** in series connection, to transform the 50 Hz supply voltage from the transformer system in a regulated DC voltage.
- **Control electronics**, to provide regulation, protection and interface.

The main parts of the MHVPS are described in the following subsections.

Multi Secondary Transformer System

Due to the design constraints (mainly the 120kVdc insulation voltage, the reduced available space on the installation site and the requested very low harmonic content in the input current) the transformer system is based on two cast-resin transformers, made of several secondary, each feeding one power module.

The secondary coupling of these two transformers is either of the star type or of the delta type, in order to obtain an overall primary current from the grid with low harmonics. Finally, soft-start devices are integrated between the transformers and the main grid.

Power Modules

The general scheme diagram of the power module is shown in Figure 1.

The switched-on power modules, controlled by a modulation index, determine the total output voltage. By using this technique and a proper switching strategy, the modulation can be performed in order to obtain the

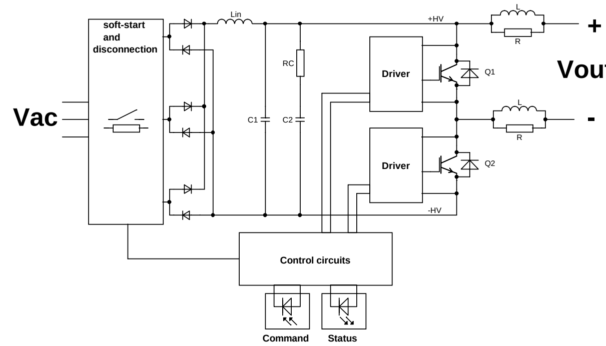

Figure 1: General schematic of a Power Module.

desired value of output voltage within the specification requirements. The Module is ON when the switch Q2 is closed and Q1 is open; a voltage step of -Vdc is added to the total output voltage. The Module is OFF when the switch Q2 is open and Q1 is closed; the module is bypassed. The two switches Q1 and Q2 must be never ON simultaneously. Using this structure it is relatively simple to perform a fast switch-off: there is enough time to simultaneously open the series switches (Q2) of each module, and then to close all the parallel switches (Q1); this operation can be very fast, in the order of 2-3 us.

Each module has an output L-R filter, which is a portion of the total output filter seen by the load. The filter has been conceived for:

- smoothing the output voltage ripple;
- limiting the di/dt and the peak current during the arc;
- obtaining a correctly damped overall system;

Calculations show that in order to minimize the energy delivered to the system it is necessary to consider an additional resistor of some ohms (4 ohms) in series with the load; this will permit to dissipate a portion of the energy before that this energy is delivered to the Gyrotron. The module is designed for an output voltage of 560V. This leads to a series connection of more than 120 modules with the consequence of a relatively high complexity of transformer and cabling. However the components mounted on each module can be low voltage devices, with an advantage in terms of cost and availability. Moreover, each stair of voltage is lower than the allowable peak to peak ripple, leading to have an additional degree of freedom in the dimensioning of the output filter.

Control Electronics

The control electronics has been designed to perform the following functions:

- measurement of the output voltage and current;
- regulation: to keep the output voltage at the desired value and within the allowed fluctuations;

- protection: to guarantee an effective protection in case of internal faults or external overloads;
- interface: to communicate with the main control system and to allow the local or remote command of the power supply.

The user interface, data log and Ethernet connections are based on commercially available electronics, with custom designed software. The regulation system (fully digital, based on an high performance FPGA card) determines the number of modules that must be ON in each time interval, providing a proper "rotation" in the module sequence. This allows to equally share the stresses among the modules. During commutations, with a proper modulation strategy for the semiconductor switches, the switching frequency seen by the load is equal to the frequency of the single module multiplied by the number of modules. This allows an high output switching frequency (seen by the load) with the advantage of a relatively low switching frequency seen by the components of the modules.

In steady state, when the output voltage is between an acceptable range around the set value, the algorithm foresees a lock modulation input that stops the switching of the modules and the rotation. This prevents an unnecessary power dissipation.

Components Choice

After a careful market inspection, the main standard components have been chosen. The IGBTs is a V_{CES}=1200V / I_C=140A @80°C (I_C=200A @25°C) device based on the SPT technology which offers a good compromise between the V_{CE_ON} and the switching speed (switching losses). The size of the IGBT was chosen also looking at its overload behaviour: it has a short circuit capability of 1000 pulses at ten times I_C and self limiting current capability to 6•I_C. The IGBT driver choice was made looking firstly to its delays which are extremely small. The input DC filter topology is an LC-parallel damped filter. The damping is chosen to avoid excessive over-voltages during power connection or load disconnection and to limit the filter peak output impedance to less then 0.5 Ohm.

PRELIMINARY SIMULATIONS RESULTS

The preliminary simulations for the MHVPS have been performed by considering the overall system which will be installed in Lausanne and which include the CPD Gyrotron, the BPS and MHVPS in order to verify the adequate compatibility of the MHVPS to the already designed BPS now under construction.

The model of the whole system has been developed using Pspice and Matlab/Simulink. Figure 2 shows the step up of the whole system simulation (with Simulink): the ramp up of the MHVPS current and voltage are shown in the first and third rows respectively. In the second row the switch-on of the BPS is simulated. This leads to the increase of the Body to Cathode Voltage up to the maximum value 100kV, as shown in the fourth row.

In Figure 3 it is sketched how the MHVPS and the overall system behave during the required 5kHz modulation. The first two rows show the commands given to the BPS and MHVPS for starting the modulation; both power supplies start modulating as specified, and the voltage patterns can be observed in rows 3 (BPS) and 4 (MHVPS). The total output voltage between Body and Cathode is the result shown in row 5 (100kV peak). Last row is the MHVPS current which shows a promising behaviour of the overall system during the 5kHz modulation.

Finally, Figure 4 reports a simulation of the overall system in case of an arc between Cathode and Collector. The arc is simulated by adding in the Simulink model a voltage generator of 100V. At 200 us the arc occurs and Body to Cathode voltage collapses by leading to an increase of the amount of charge in the Gyrotron (fifth row). The 0,1 limit value depicted in the fifth row, represents the amount of charge delivered to the load and, considering an arc voltage of 100V, corresponds to the maximum value of energy that could be delivered as per technical specification (10 Joules). However it can be

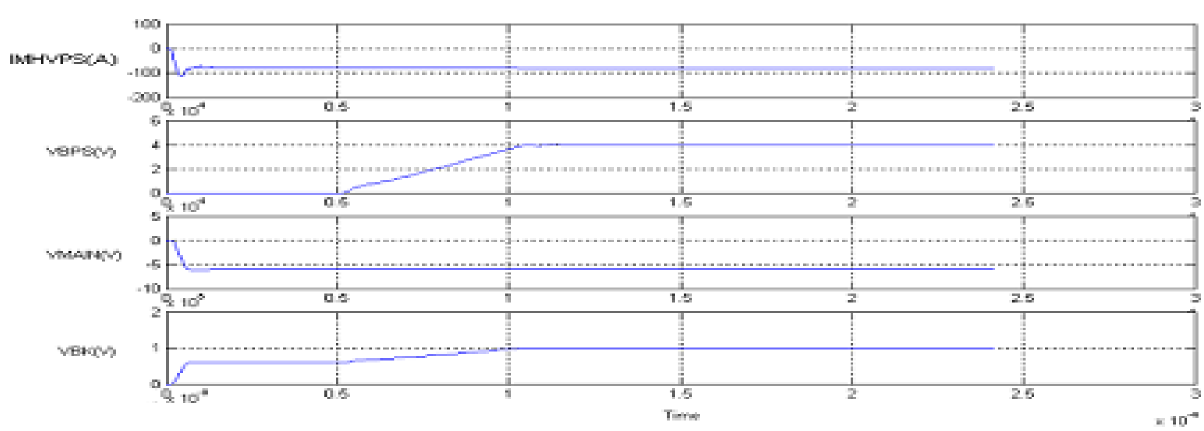

Figure 2: Simulation of the Step up of the whole system (MHVPS+BPS+Gyrotron)

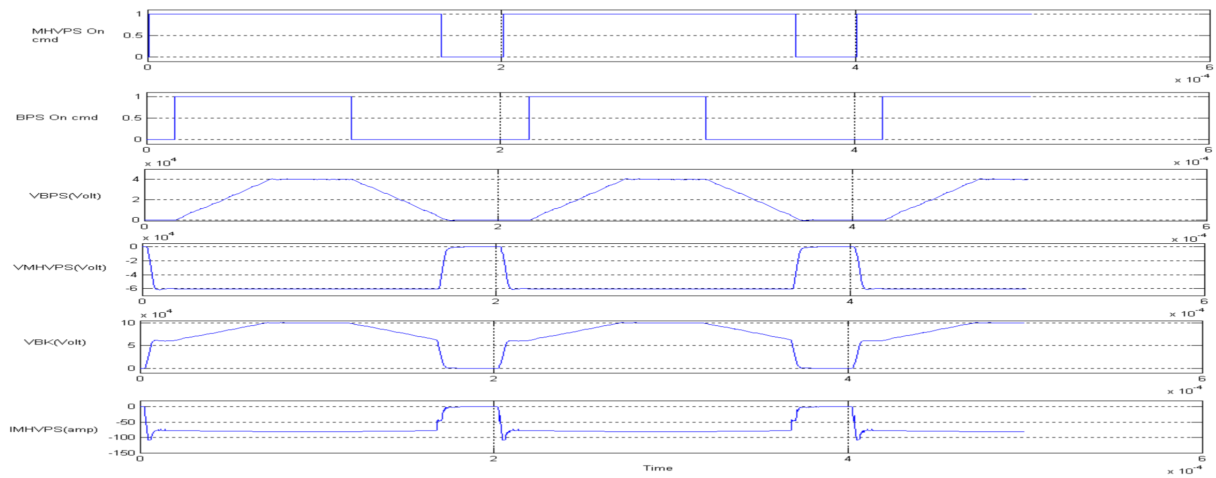

Figure 3: Simulation of the 5kHz Modulation

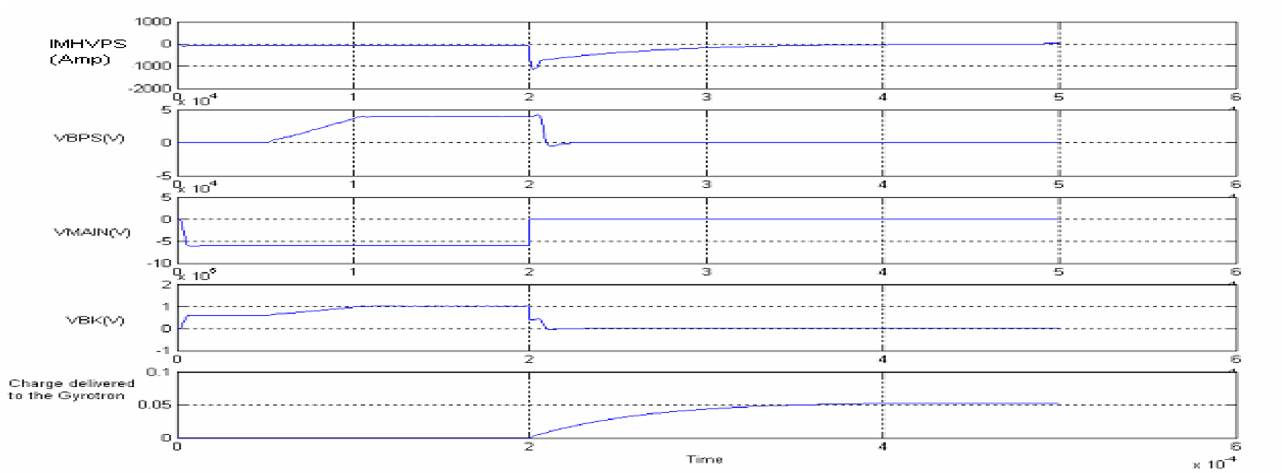

Figure 4: Simulation of the Step up of the whole system with an arc between K-C at 200us

CONCLUSIONS

This paper has described the preliminary design of a 4.8 MW Main High Voltage Power Supply, rated 60kV/80A, especially conceived to supply the voltage between Cathode and Collector of a Gyrotron. This topology has been chosen for the EC Test Facility at CRPP, Lausanne (CH). Similar systems could be adopted for ITER, which includes the installation of an Electron Cyclotron system based on CPD type Gyrotrons (170GHz) in alternative to the present baseline design.

The first simulations have demonstrated the correct behaviour of the MHVPS not only as a stand alone modulator but as part of a complete system which will be installed in Lausanne, and which include the MHVPS, the BPS and the CPD Gyrotron. Three main situations have been depicted in the simulation sketches: the step-up and the steady state, the 5kHz ON/OFF modulation and the behaviour of the system in case of an arc between Cathode and Collector. The first results are very encouraging and the design phase can enter into a further final detail before entering the manufacturing stage. The installation of the overall system in Lausanne is foreseen to be starting by September 2007.

REFERENCES

[1] T. Bonicelli et alia, “High Frequency/High Voltage Solid State Body Power Supplies for CPD Gyrotrons”, SOFT’02, Helsinki, September 2002, p. 543-548.

[2] G. Taddia et alia, “High Voltage Solid State Gyrotron Body Power Supply”, 14th Joint Workshop on Electron Cyclotron Resonance Heating, Santorini, May 2006, p 95.