Generic High Voltage Power Module for Electrical Propulsion

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Michael Boss [1] , Frank Herty, [1] , Kurt Rogalla [1], Matthias Gollor [2]

[1] *EADS Astrium, Electronics Division, 88039 Friedrichshafen, Germany*
Email: michael.boss@astrium.eads.net; frank.herty@astrium.eads.net; Kurt.rogalla@astrium.eads.net
[2] *EADS Astrium, Electronics Division, 88039 Friedrichshafen, Germany and*
Fachhochschule Konstanz - University of Applied Science - Dept. of Electrical Engineering
78462 Konstanz, Brauneggerstr. 55D, Germany, Email: gollor@fh-konstanz.de

Abstract: High Voltage Power Modules for Electrical Propulsion have been developed for the European Space Agency`s GOCE and ALPHABUS missions, featuring Kaufmann-Type Ion Thrusters with power levels between 520W and 4.8 kW and output voltages from 1200V to 2000V. Based on these developments a new concept has been established for modular generic power modules being able to drive various types of ion thrusters, including new HEMP technology. Initial result have demonstrated that module efficiency can be increased to 97% by introduction of the Flattop ZVS converter especially designed for high voltage applications.

I. Introduction

The coming generation of commercial, scientific and earth observation missions are going to increasingly demand for electric propulsion systems instead of chemical propulsion in order to get advantage of ultra-precise attitude and orbit control as well as satellite life extension by fuel efficient mission scenarios.

Several actual and future satellite projects of the European Space Agency (ESA) have established challenging requirements for high accuracy in positioning (LISA mission, prepared by LISA Pathfinder), in pointing (DARWIN mission) and for drag compensation (GOCE mission) or long-duration flights (Bepi-Colombo mission). As a consequence various developments of Ion Thrusters and related Electronic Equipment have been initiated in the last couple of years.

A core equipment of an Ion Thruster Unit is the High Voltage Power Supply (HVPS), which is dedicated to condition the electrical power from the spacecraft main bus. Key issues of these power equipments are

- the generation of high voltage in the range of 1..2 kV for Kaufmann-Type and RIT-Type ion engines and up to 13 kV for Field Emission Type thrusters /1,2/.
- a precise regulation of output power in order to allow fine adjustment of thrust levels.

Since the selection of a thruster type from the choice of various principles and manufacturers is very mission specific, the authors have favoured the approach of developing a generic high voltage power supply. Some key data of realized designs are shown in Table I-1.

Program	Max. Voltage	Power	Thruster Type & Manufacturer
RITA	1000 V	500 W	RIT Ion
GOCE MPE	13 kV	10 W	ARCS FEEP“
GOCE IBCV	1200 V	520 W	Qinetiq Ion Thruster T5
AlphaBus	2000 V	4800 W	Qinetiq Ion Thruster T6

Table I-1- Key Data of recently developed High Voltage Power Supplies for Ion Propulsion

Generic elements have been already used in recent and actual projects. Increasing power demand of above 4.8 kW for the ESA AlphaBus mission has driven the need for a “Generic HVPS – Next Generation”.

AlphaBus, an ESA technology mission of a communications satellite, has already completed a technology phase. In the recent activities an electrical demonstrator (DEM) was designed, manufactured and tested together with the Ion Thruster.

Based on the experience with the DEM the way has now been paved for EM-program, where the AlphaBus HVPS is intended to be the cornerstone element of a “Generic HVPS _ Next Generation”.

The roadmap for an AlphaBus program together with a generic usability of the HVPS design needs to put special focus on

- the High Power (4.8 kW) converter topology
- New generic high voltage design (transformer core, winding, isolation, mass and volume reduction, increase of efficiency etc.)
- EEE parts reduction
- High accuracy measurement of housekeeping values
- Thermal management of the high voltage unit
- Assessment of new parts and materials (e.g. SiC)
- Scalability for low to medium power HV converters
- Optimisation of series production
- Very high voltage, low power converter

An R&D program has been defined to follow this roadmap, based on the technologies of the GOCE and the ALPHABUS DEM program.

Fig. II-1: Artist's impression of the GOCE Satellite in Orbit (Image: ESA)

II. GOCE Ion Propulsion Assembly

A. ESA's Gravity Mission GOCE

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) is dedicated to measuring the Earth’s gravity field and modelling the geoid with extremely high accuracy and spatial resolution.

Mission Objectives

- To determine the gravity-field anomalies with an accuracy of 1 mGal (where 1 mGal = 10-5 m/s2).
- To determine the geoid with an accuracy of 1-2 cm.
- To achieve the above at a spatial resolution better than 100 km.

Mission Elements

- Single rigid octagonal spacecraft of approximately 5 m long and 1 m in diameter with fixed solar wings and no moving parts.
- Gradiometer – 3 pairs of 3-axis, servo-controlled, capacitive accelerometers.

- 12-channel GPS receiver with geodetic quality.
- Laser retroreflector enabling tracking by ground-based lasers.

B. The drag-free and attitude-control system

The advanced drag compensation and attitude-control systems a key feature required to keep the sensor heads in near ‘freefall motion’ and to maintain the average orbital altitude at about 250 km. The system is based on ion-propulsion technology, a new and exciting way of moving spacecrafts. By contrast, ion thrusters propel spacecraft with an inert gas (Xenon) which is ionised by electric power generated from solar panels and controlled by an Ion Propulsion Control Unit (IPCU), the main electronic part of the Ion Propulsion Assembly (IPA).

C. Ion Propulsion Assembly

The Ion Propulsion Assembly (IPA) provides variable thrust in the range of 1.0 to 20 mN for compensation of the atmospheric drag force in the satellite flight direction during measurement phases. In addition, the IPA supports the gradiometer calibration and satellite maintenance phases by providing sufficient thrust for orbit raise manoeuvres and atmospheric drag compensation.

Launch vehicle

GOCE will be launched by one of the modified Russian Intercontinental Ballistic Missile (ICBM) SS-19 launchers, which are being decommissioned in the process of the Strategic Arms Reduction Treaty (START). The adaptation of the SS-19, called ‘Rockot’, uses the original two lower liquid propellant stages of the ICBM, which has an excellent record of successful flights, in conjunction with a new third stage for commercial payloads. Rockot is marketed and operated by EUROCKOT, a German-Russian joint venture. Launch is from the Plesetsk Cosmodrome in northern Russia.

Fig. II-1: Spacecraft view, firing one of the redundant thrusters (Poster: ESA)

The following performance criteria are essential to the GOCE scientific mission:

- the capability to accurately adjust the thrust level commanded by the power supply and control electronics over the specified thrust range. Electrical power is mainly provided by the Ion Beam Converter (IBCV)
- the very low thrust noise
- the capability of delivering very small thrust increments
- the provision of delivering continuous thrust and avoidance of thrust force interruptions
- the minimization of any degradation throughout the entire mission compliant with the specified performance characteristics at end of life
- the minimization of thrust vector migration throughout life time

D. IPA Function & Architecture

The IPA consists of

- Ion Thruster Assembly (ITA)
- Ion Propulsion Control Unit (IPCU) including the Ion Beam Converter (IBCV)
- Proportional Xenon Feed Assembly (PXFA)
- Xenon Storage Tank (XST)

as well as xenon tubing, the harness in between all components.

Connections Overview

The physical harness and propellant tube connections between the IPA equipments and the spacecraft platform are physically implemented as shown in the diagram below. In reality the system is of redundant design.

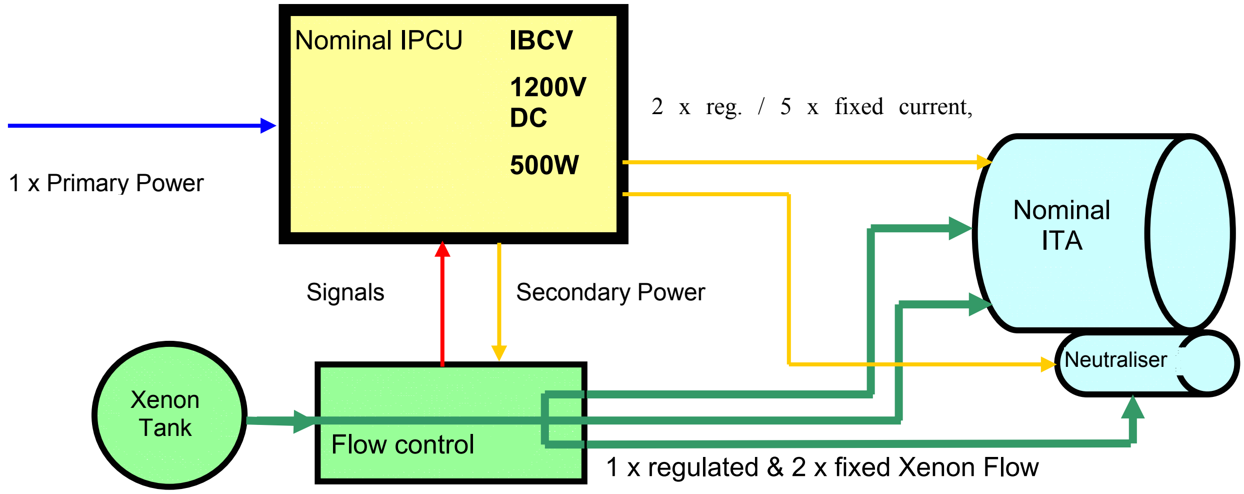

Fig. II-2: IPA General Arrangement (shown as non redundant system)

Controlled High Voltage Generation

The Ion Beam Converter takes power from the unregulated 28VDC main bus input. A two-stage architecture with a preregulator and a resonant converter principle is used to convert DC to an AC power output. This AC power is rectified at the output stage providing a very stable and well controlled high voltage output (1176 V) that supplies the ITA anode, as well as gives the reference potential to the inner housing of the HV isolation box. Additionally very precise analogue house keeping values are provided for voltage and current telemetry with an accuracy of better than 0.5%.

Architecture

The IBCV provides switch-able high voltage DC power to the Ion Beam Thruster assembly on-board the GOCE spacecraft. It is housed together with the other IPCU power supplies, integrated within the IPCU box. The top level IBCV configuration is illustrated below.

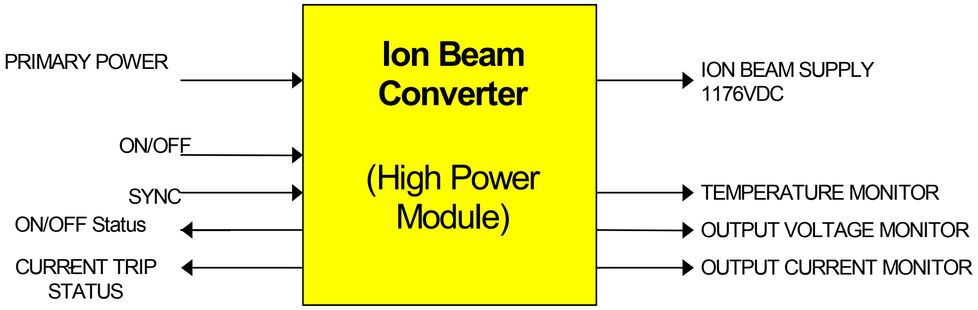

Fig. II-3: IPCV Configuration

The IBCV receives low voltage (22-34V) DC power from the unregulated primary power bus via an upstream LCL (Latching Current Limiter) and outputs isolated high voltage (nominally 1176V) DC power to the Anode of the Ion Thruster Assembly (ITA). It can be enabled and disabled by opto-coupled telecommand and provides the following nominal performance characteristics:

Achieved Output Characteristics:

Output Voltage	1176 VDC
Voltage regulation:	0.8 V (between 0% and 100% load), which is < 0.07%
Output ripple:	< 8 Vpp
Output current:	355mA nominal, 400mA max.
Efficiency:	90% through 94% for loads from 190W to 420 W

Voltage TM

Accuracy at begin of life conditions (BOL): 0.08%
Accuracy at end of life conditions (EOL): 0.2%

Current TM

Accuracy at BOL conditions: 0.26%
Accuracy at EOL conditions: 0.34%

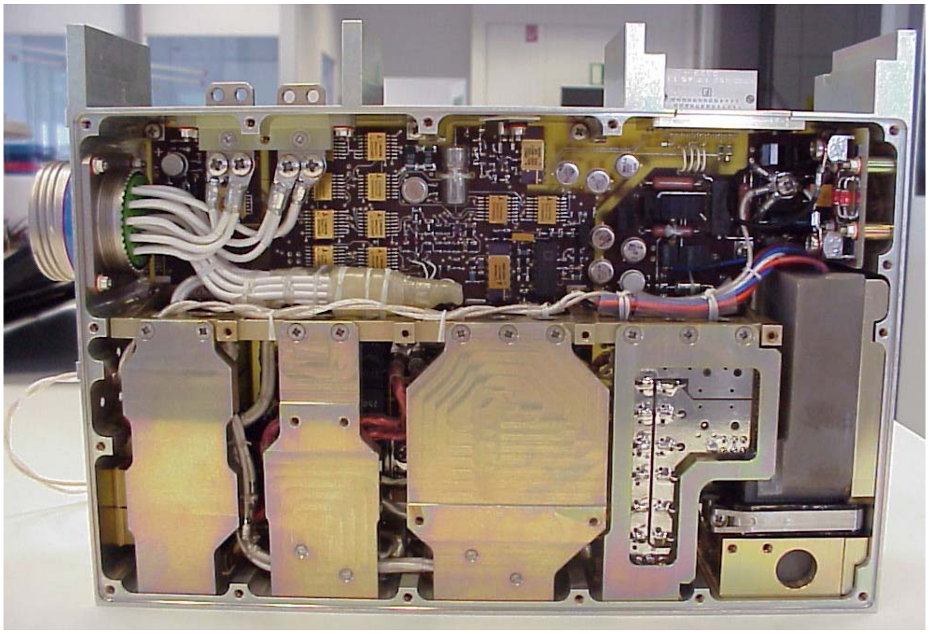

Fig. II-4: View of open box of Ion Beam Converter Module, including Low and High Voltage sections;. Mass: 3.4kg

E. Actual Status of GOCE IBCV

The High Power Module (Ion Beam Converter) has been designed, manufactured, tested, and integrated with the Ion Propulsion Control Unit. Its excellence high voltage performance has been demonstrated under qualification levels and fulfills therefore the ambitious requirements of supplying the Ion Thruster assembly for its task of very high resolution measurement requirements. The main objective of the High Power Module is to provide very stable output power as function of thrust demand and environmental conditions like temperature, radiation and aging. Additionally a very high resolution performance of housekeeping measurements has been demonstrated. All is integrated in light weight housing.

III. ALPHABUS IPCV DEMONSTATOR

A. Ion Thruster and Mission

Alphabus is the new large communications satellite platform initiated by The European Space Agency (ESA). The platform is featured with high-power electric propulsion based on QinetiQ's T6 Kaufman gridded ion engine. This high-power design offers efficient satellite station-keeping, orbit-topping as well as end-of-life de-orbiting.

In the frame of the Alphabus development, EADS Astrium was involved in power supply development since 2004. As a part of the propulsion assembly, EADS Astrium contributes the ion beam converter unit (IBCV) required for supporting the electrical field for ion acceleration. The IBCV is part of the Power Switching and Control Unit (PSCU) supplied by Astrium CRISA.

B. Architecture

The development was based on an electrical demonstrator approach. The demonstrator fulfills the desired electrical properties but it was not optimized in mechanical aspects. The main characteristics of the Ion Beam Converter are

- Nominal bus input voltage :100V
- Input current: 50A max
- Output voltage: 1850V
- Output power: 4625W max.
- Mass: 20kg, Size: 500mm x 260mm x 260mm (LxWxH)
- Efficiency: 91% at nominal operating conditions

In order to handle the high power a modular design is used. The power is equally shared by four modules, which are principally identical: Functionality required only one times is implemented at the first module called master module. The other remaining modules are identical and operate as slaves modules. Other advantages of this modular approach are:

- Four-phase operation: The ripple of the output voltage is significantly reduced to the phase-shifted distribution of the switching clock.
- Inter-module redundancy: A potential failure of one module would reduce the available output power but it will not lead to the failure of the complete IBCV. However, for simplicity the IBCV demonstrator has no redundant interface and voltage control capability.
- Each module is equipped with its own current limiter - this provides partial redundancy
- Power rating can be easily customized by increasing or decreasing number of modules.

The IBCV provides a fixed output voltage. This voltage is to be held constant since the load current - depending on the trust level - is variable. The inverter itself is based on a zero voltage switching (ZVS) full bridge.

Basically, each module consists of the following sections:

- Common/differential mode input filter
- Current limiter
- Fully controllable single stage inverter
- Potted high voltage section for galvanic insulation, voltage conversion, rectification and filtering.

- Space qualified high voltage insulation comprising the high voltage transformer, rectifier and output filter /3/.
- Telemetry and communication interface (master only)

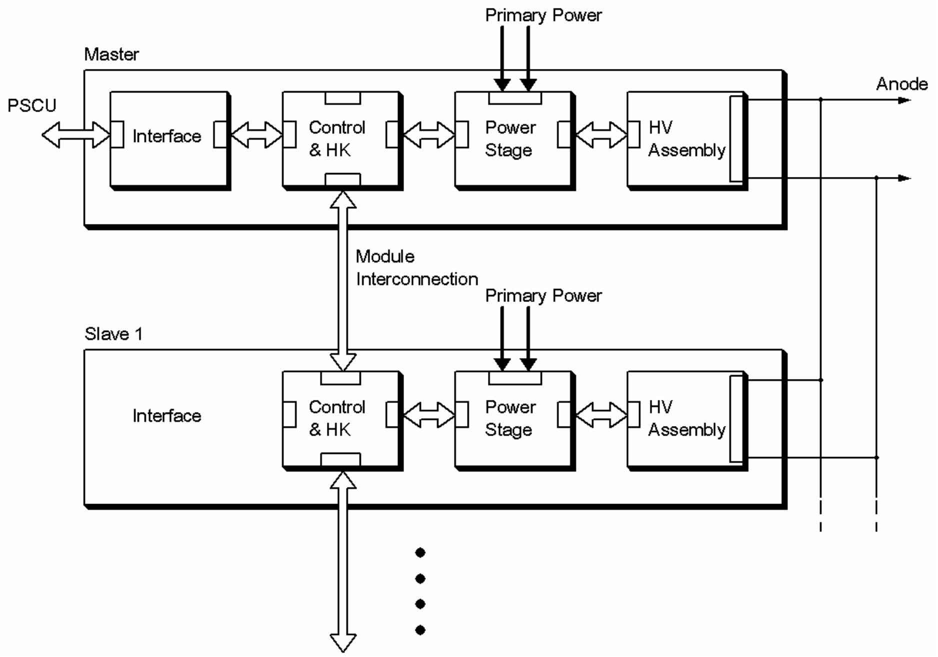

Fig. III-1: ALPHABUS IBCV Architecture

The zero voltage switching technique exploits the generally undesirable parasitic elements present at the high voltage transformer. However, these parasitic elements are utilized to drive near lossless switching transitions for all power MOSFETs. Converters operating with ZVS belong to the group of quasi-resonant converters. Resonance is used only at intervals of current commutation but not during energy transfer. This is the major difference to the full resonant types.

The ZVS Bridge converts the dc voltage of the primary bus directly to an ac voltage. A storage inductor is used to control the ac amplitude by the length of the energy transfer cycles. Then, the ac voltage is fed into the high voltage transformer. After rectification and filtering on the secondary side the high voltage is available at the output.

Furthermore, the bridge is controlled by phase shift modulation since conventional pulse width modulation resonant topologies, which cannot be controlled over a wide range of load, no pre-regulating buck or boost stage is necessary. This leads to a minimum of switching elements at the power path and increases efficiency. Additionally, the large (due to high ac currents) resonance capacitor is not required. Instead, the high voltage transformer is directly coupled. Although this method provides no inherent transformer flux balancing, it can be also achieved by a cycle-by-cycle current control loop. This loop does not only control the primary peak-to peak current of the high voltage transformer but it also keeps the dc component to zero.

Since all modules behave as controllable current sources parallel connection of modules becomes possible without any load balancing problems. One dedicated module - the master - contains the voltage regulator. Owing to the need for electric propulsion the regulator loop is designed to be very robust. Operation on different thruster types is possible without changing loop parameters. Especially thrusters needing high start-up currents can be supported. Moreover, severe load drops can be handled without significant voltage rise.

The IBCV provides several inhibits for converter and thruster protection like over-voltage, over-current and short-circuit detection. Precise telemetry data for thrust calculations and housekeeping are provides by the IBCV interface section.

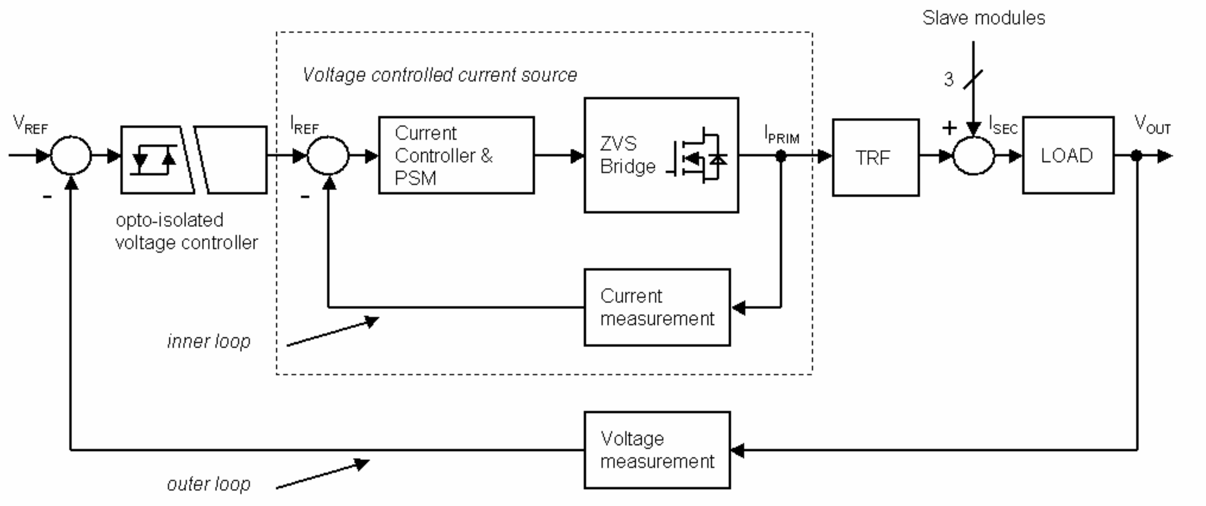

Fig. III-2: Structure of current and voltage control loops of ALPHABUS IBCV Architecture

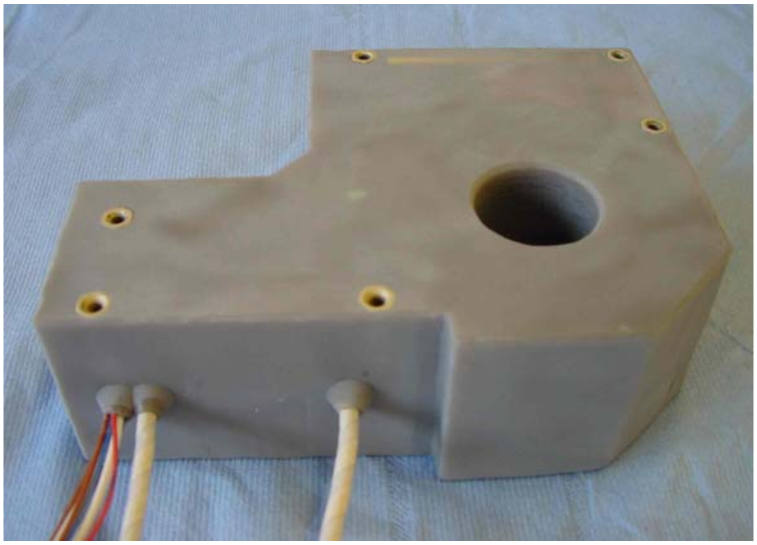

Fig. III-3: Potted high voltage assembly consisting of transformer, rectifier and output filter

In 2005, the IBCV was successful tested in conjunction with QinetiQ's T6 engine.

HEMP thruster

During Alphabus development, EADS Astrium has derived a single-module (master only) version of the IBCV in order to supply the grid-less HEMP thruster. While the module power was increases to 1200W, the output voltage was changed to 1250V. Besides that, a second output channel providing 700V was added. This supply operates successfully with the HEMP thruster.

IV. NEXT GENERATION HVPS (ALPHABUS & HEMP)

A. Generic HVPS Concept

Derived from the experience gained at the demonstrator models, EADS Astrium continues improvement of high voltage power supplies. This leads to the introduction of the Next Generation HVPS. Major improvements of the Next Generation supplies are high efficiency and reduced volume.

B. Improvements

Under laboratory conditions, the module efficiency was increased to 97%. Compared to the original Alphabus demonstrator (91%), this extraordinary result was achieved by introduction of the Flattop ZVS converter especially developed for high voltage applications. In contrast to the original ZVS Bridge, conduction losses are significantly reduced. An additional benefit of this converter topology allows reducing switching frequency without the need for large energy storage inductors. This facilitates saving volume, mass and cost. Like the original ZVS Bridge, the flattop converter is fully controllable. Furthermore, its current ripple is reduced. This leads to less filter capacitance at both, input and output filters. Additionally, low ripple is especially useful for single-module operation where phase-shifted clocking cannot be applied.

C. Future Work

Silicon high voltage rectifier diodes suffer from reverse recovery. As a consequence, high conduction losses deteriorate efficiency and cause EMC problems. EADS Astrium intends to introduce Silicon Carbide (SiC) Schottky Diodes for HV applications. SiC diodes exhibits no reverse recovery.

The HV transformer assembly will be featured with electrostatic shielding in order to reduce common mode distortions. This leads to the approach of a combined commend mode/differential mode input filter consisting of only one main magnetic component.

V. CONCLUSIONS

The experience with the GOCE and ALPHABUS DEM projects with high voltage power modules of 520W to 4.8 kW and output voltages between 1200V and 2000V has outlined the need to establish a universal module with high efficiency. The work has demonstrated that a power conversion efficiency of initially in the order of 90% can be increased to 97%. By using ZVS bridge, flattop converter technology and advance Silicon Carbide high voltage rectifier diodes the power processing can be downsized in mass and in thermal dissipation, giving the chance to make electrical propulsion in general more attractive for a wide band of space mission including commercial telecom satellites.

VI. REFERENCES

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