Generic High Voltage Power Supplies (HVPS) with Optimum Efficiency and Multi-Range

IEPC-2007-20

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

Matthias Gollor*), Michael Boss, Frank Herty, Bernhard Kiewe
Astrium GmbH – Friedrichshafen – Germany
Dept. Electronics Equipment Germany – ASE2

) Professor, University of Applied Science Konstanz (Germany) – Electrical Engineering

The European Space Mission GOCE, the AlphaBus Platform and the new High Efficiency Multistage Plasma (HEMP) thruster for future telecom missions, have triggered the development of a Generic High Voltage Power Supply referred as "HVPS - Next Generation" at Astrium. Focusing to a generic approach a high voltage module has been designed as a core functional block. It can be manufactured for high voltage levels between a few hundreds Volts up to 2000 Volts at maximum power of 1.4kW per module. Higher power levels can be supported by connecting the necessary number of modules in parallel. The HVPS portfolio comprises basically three different converter topologies which are optimized either for a fixed or a variable output voltage. The high voltage module can be used for all three converter types. The innovative single-staged "Optimum" converter is designed for almost constant bus- and output voltage conditions. Initial results from full vacuum testing together with a HEMP thruster have demonstrated module efficiency of >97%. The dual-staged "Multi-Range" converter types, however, are featured with additional wideband capability, i.e. they can handle variable input (bus) and output voltages.

I. Introduction

Generic High Voltage Power Supply (HVPS) – Next Generation – is a response to the growing number of applications for electric propulsion (EP): Several actual and future satellite projects of the European Space Agency (ESA) have established 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). In addition commercial telecom satellite manufacturers are interested in cost effective EP solutions. As a consequence various developments of electric propulsion thrusters and related electronic equipment have been initiated in the last few years.

A core equipment of the power processing unit of an EP-system is the High Voltage Power Supply (HVPS), which is used to condition the main electrical power of an electric thruster from the spacecraft power bus. Typical key aspects of these power equipments are

- the generation of high voltage in the range of 1 kV to 2 kV for Kaufmann-Type, RIT-Type and HEMP Type electric engines and up to 13 kV for Field Emission Type thrusters /1,2,3,4,5/.
- a precise regulation of output power in order to allow fine adjustment of thrust levels depending on mission requirements.

Some examples of realized or intended designs are shown in Table I-1. Since the selection of a thruster type from the choice of various principles and manufacturers is very mission specific, the authors have favored the approach of developing a "Generic High Voltage Power Supply", which shall allow serving all the different needs with a single development.

An R&D program funded by the German Space Agency DLR has been initiated encouraging new technologies and significant improvements in order to provide a space-qualified HVPS module for flexible use.

Program	**Max. Voltage**	**Power**	**Thruster Type & Manufacturer**	**Status of Power Supply**
GOCE MPE	13 kV	10 W	FEEP (ARCS, Seibersdorf, Austria)	Pre-development
GOCE IBCV	1176 V	520 W	Ion Thruster – Type T5 (QinetiQ, UK)	Flight Configuration Tests finished
AlphaBus	1850 V	4800 W	Ion Thruster – Type T6 (QinetiQ, UK)	Demonstrator
HEMP	1000 V	1400 W	HEMP-Thruster 3050 Plasmathruster (Thales, Ulm, Germany)	Generic Demonstrator Model Coupling test successfully performed in vacuum
HEMP	1200 V	7500 W	HEMP-Thruster 3052 Plasmathruster (Thales, Ulm, Germany)	Under Development

Table I-1: History of Key Data of recently developed High Voltage Power Supplies for Electric Propulsion

II. ROADMAP TO NEXT GENERATION HVPS

An initial roadmap of "Generic HVPS - Next Generation" has been established two years ago and has been nearly completed and realized as a demonstrator model today:

Roadmap Task	**Achievement**
Low-inductive electro-mechanical lay-out	Use of stacked copper rails for high current paths. Saves additionally wiring effort.
Thermal management of the high voltage unit	Mechanical Design with optimum heat conduction path to the baseplate is realized.
High voltage transformer development:	Ultra-compact toroidal high voltage transformer with an

Roadmap Task	**Achievement**
Optimization in: size, core and losses	integrated heat-sink and double electrostatic shielding.
Assessment of new parts and materials (e.g. SiC)	Silicon Carbide diodes are used to reduce switching losses and to achieve overload capabilities
Development of a scaleable, high efficiency high power converter topology	Development of single staged high voltage converter module "Optimum" with efficiency > 97% completed.
Development of parallel operation functionality including single-failure tolerant operation	Load-sharing techniques developed. Modules can also be synchronized by an additional clock distribution net.
EEE parts reduction	Achieved by single stage concept
Scalability for low to medium power HV converters	Scalability from few hundred Watt to 1.4 kW per module is given. Higher output power possible by parallel switching.
Optimization of series production	Reduced number of items for module assembly and minimization of adjustment steps.
Very high voltage, low power converter	Very high voltage, low power converters as a splinter development, see publication /5,6//.

Table II-1: Generic HVPS – Next Generation Roadmap with Main Tasks

Due to the actual needs of various EP subsystems the development program has been extended and the roadmap has been accomplished by focusing two application scenarios:

- Generic HVPS NG "OPTIMUM" providing highest efficiency at fixed input and output voltages
- Generic HVPS NG "MULTI-RANGE" covering high efficiency at various output voltages and/or variable input voltage

Both applications are leading to generic HVPS modules with a high degree of common functional blocks.

III. Generic HVPS "Optimum"

A. The "OPTIMUM" Concept

Major design goal for the Generic HVPS – Next Generation "Optimum" was the development of the single-stage power conversion concept with highest efficiency at fixed input and output voltage. The single-stage topology was chosen as baseline to minimize conversion losses and to reduce number of components. In contrast to the task-sharing approach of operation at dual-stage designs, (i.e. a single-stage converter has to accomplish both: to transfer energy to the high voltage output and to provide means of regulation in order to keep the output voltage to a desired level and providing galvanic isolation), the objective to control the energy flow and the dc-to-ac conversion can only be realized by a converter topology which can be controlled over the full range of load.

Starting from the AlphaBus demonstrator – which was already a single stage design – the conversion efficiency was improved step-by-step. The improvements have lead to the "Optimum" HVPS which operates with (almost) rectangular HV transformer currents The "Optimum" HVPS is based on the so-called Flattop converter which is named according to the shape of the transformer current. This leads to reduced I^2R losses due to the reduced form factor of the current. Components of the inverter bridge and the rectifier circuit were analyzed regarding to their contribution to the total converter losses and their potential for optimization. The milestones of improvements are shown at Fig. III-1.

Reverse recovery losses at the HV rectifier were eliminated by replacing the silicon rectifier diodes by silicon carbide types. Proximity losses at the HV transformer secondary and primary winding were identified and an improved winding scheme was developed leading to another significant improvement in efficiency. Owing to the special behavior of the Flattop converter not to increase current ripple when lowering the switching frequency, residual frequency-dependent losses (switching losses for instance) were minimized by that way.

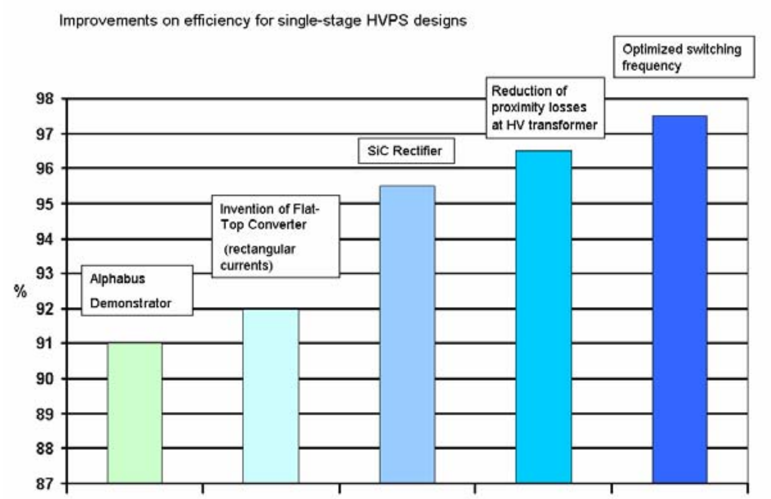

Fig. III-1: Survey of Efficiency Improvements

With the increased efficiency – which means low conversion losses – the thermal fluxes within the converter module are reduced, which allows a very compact mechanical design.

B. Architecture

The Flattop converter is a new development (Astrium Patent) of controllable single stage converter optimized for constant input and output voltages. A Flattop-Converter module can be grouped into the primary power section, the secondary power electronics and the auxiliary low voltage electronics responsible for regulation, monitoring and interface functionality – as shown in Fig. III-2. The input filter prevents the main converter current from common and differential- mode distortions coming from the voltage supply bus. In addition, it suppresses conducted emissions generated by the switched-mode of operation of the main converter. A current limiter passes the input power via the dc-link to the main converter. The limiter cuts the supply bus in case of an internal failure of the module. Beside the main converter, a 10W auxiliary flyback dc-dc converter is also connected to the dc-link providing all required supply voltages at primary and secondary side.

The main converter is responsible for generation of the AC voltage to be transformed up to the desired high voltage level. This is done by the high voltage transformer. This transformer provides galvanic isolation between primary (bus voltage return) and secondary (high voltage return) side. Consequently, the auxiliary dc-dc supply must be also equipped with galvanic isolation. At the secondary side of the HV transformer, the AC voltage is rectified and the voltage and current ripple is smoothed by a capacitive output filter (see Fig. III-3)

A digital voltage regulation is used to ensure a constant output voltage independent of the load conditions. The control and monitoring circuit consists of a signal conditioning stage followed by digital-to-analogue conversion.

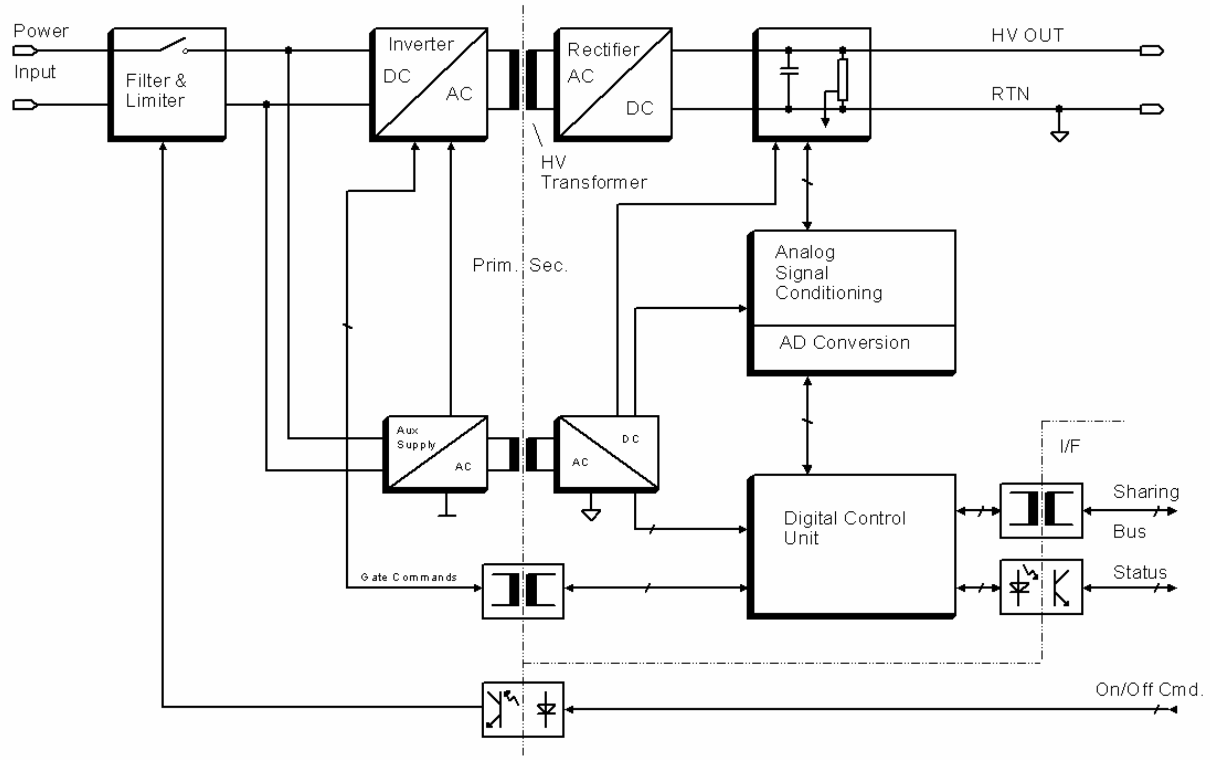

Fig. III-2: Top-level Block Diagram of the Converter Module

The Flattop converter consists of a full bridge configuration with an additional diode branch. Two zero voltage switching (ZVS) capacitors are connected in parallel to the low-side power switches. In addition, two storage inductors are used: The storage inductor L_S is switched in series to the High Voltage Transformer (HVT). Further, the auxiliary inductor L_K is switched between the diode branch and the C/D branch. Basically, both inductors have the same inductance and current capability but when dimensioning of L_s, the stray inductance of the HVT must be included. The transfer ratio of the HVT is set equal to the ratio of the input and output voltage.

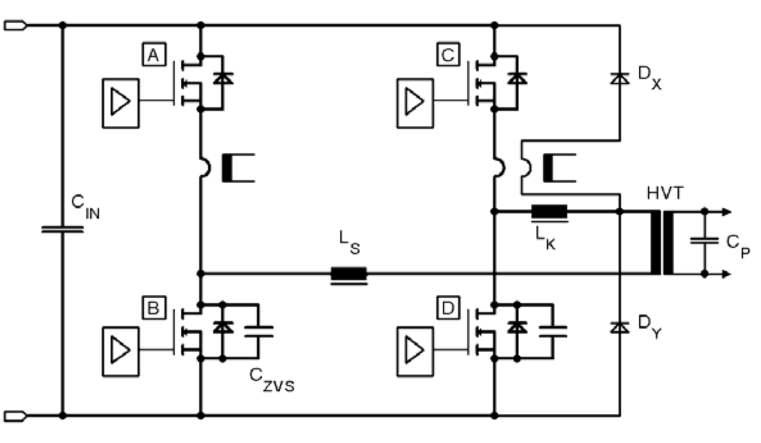

Fig. III-3: Schematic of the Flattop-Converter for HVPS Next Generation

The parasitic winding capacitance is also required element for the Flattop principle. It is used together with an external capacitor C_P in order to obtain sufficient capacitance which is needed for the reversal of the transformer current.

C. Modular Concept and Redundancy

A High Voltage Power Supply based on the new architecture may consist of an array of up to eight identical modules. Depending on the power requirements given for a specific electric thruster, n modules are switched in parallel sharing the total output current. An additional module can be added to provide still rated output power capability in case of a module failure. In case of low-voltage variants (having a single rectifier stage only) an optional protection diode can be connected in series to the output. This method prevents the complete assembly to fail if one of the module has a short-circuit failure at the output stage

D. High Voltage Assembly

A key functional block of a HVPS module is the high voltage assembly. The high voltage module combines the high voltage transformer, the rectifier stage(s), the output filter, the output voltage divider and the output current sensing devices. Although a gap-less toroidal core transformer is used – the flattop converter needs no magnetizing current – the same design is also feasible for resonant-type converters. Instead of an air-gap, energy needed for soft-switching of the HV rectifiers can be stored in a separate magnetizing inductor outside of the high voltage module. Proximity losses of the high voltage transformer can be identified as the dominant type of transformer losses. For that reason, a special winding scheme of the transformer primary and secondary windings was developed; refer also to Fig. III-4. Moreover, the transformer is featured with two electrostatic shielding foils. One of them is connected to the secondary ground and the other to the primary ground. This method avoids a direct capacitive coupling of the primary and secondary winding. Since each shield encloses the secondary winding completely, high voltage cannot propagate to the primary system in case of an insulation failure.

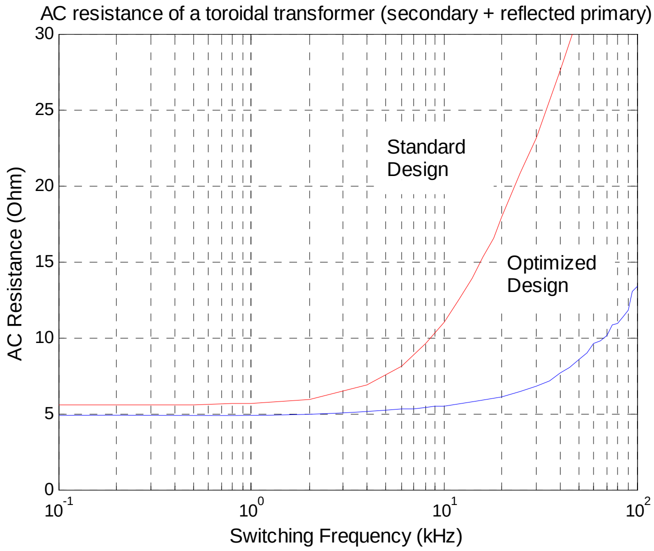

Fig. III-4: Comparison of the proximity effect in terms of ac resistance of a hypothetical transformer

The high voltage assembly is completely potted using the space qualified DOS-E potting material. This material was originally developed for the 15kV-EPCs required for the ERS radar satellites and it was used on many space (and also commercial) products since then. The accumulated in-orbit operation time of the DOS-E potting material sums up to 540 years (status quo 08/2007) without any failure. A typical configuration of module is a 1000V, 1.4A type having two 1200V Silicon-Carbide (SiC) rectifier bridges and two output filters connected in series. This is to protect the output bus in case of a rectifier or capacitor failure. Two heat sinks are integrated to conduct the heat directly into the baseplate of the HVPS module.

E. Mechanical Design

The structure of a High Voltage Power Supply Module is based on an inverted T-shaped design consisting of a base-plate and a center frame carrying two printed circuit boards (PCB). The module electronics is divided into a power and a signal conditioning PCB in order to minimize electromagnetic interference from power tracks to signal tracks.

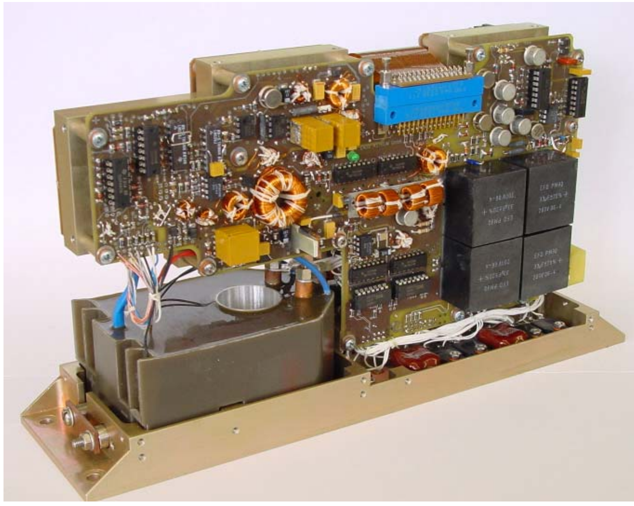

Fig. III-5: High Voltage Power Supply Module (EM)

The mechanical properties of a HVPS module "Optimum" as shown at Fig. III-5 (without enclosure) are:

- The mass of the 1400W module including baseplate is 2900g
- The dimensions are: Footprint 300 x 96 mm2 , Height 160mm

F. Characterization of Engineering Model "Optimum"

An engineering model (EM) of the Generic HVPS NG "Optimum" has been built and tested. Since the generic concept is scalable, the output and input voltage for this EM are reflecting "typical" requirements of a high power thruster:

- Input Voltage: 100V +/-2V (regulated power bus)
- Output Voltage: 1000 V
- Maximum Output Power: 1400W

The EM was tested under ambient conditions and in thermal vacuum. A 48h vacuum test was successfully performed together with a HEMP 3050 thruster of Thales /9/. As an important test result, it was demonstrated that the module's efficiency did not change compared to a resistive (test) load despite of the significant current oscillations inherently generated by the HEMP thruster. Using the resistive test load, the efficiency versus output power was measured under ambient conditions. An overall efficiency above 97% power levels from 700W to maximum power (1400W) could be demonstrated (see Fig. III-6).

With the mass properties given in chapter E the resulting mass to power ratio is about 2 kg/kW

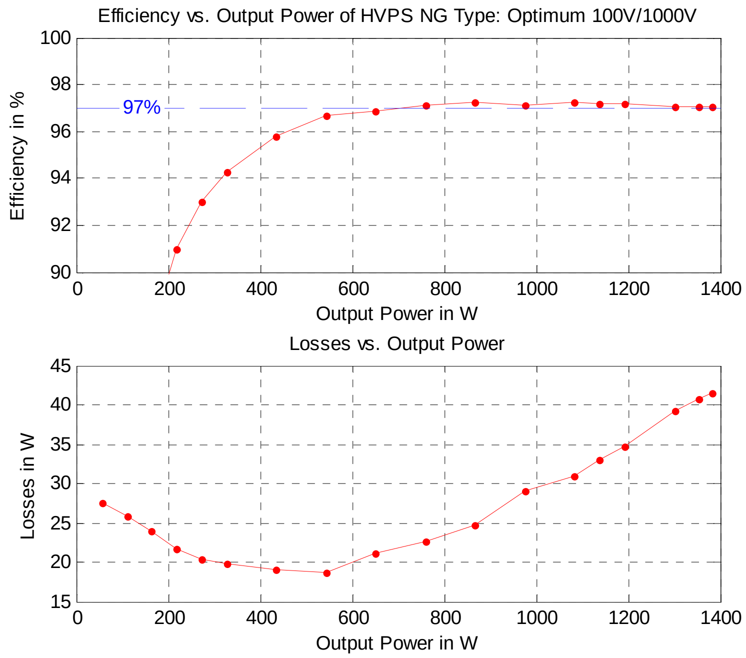

Fig. III-6: Measured Efficiency of a the "Optimum" Module

Summary: the Generic HVPS "OPTIMUM" provides a single stage, controllable concept with high efficiency due to rectangular currents and low switching frequency. Stable operation is ensured even for unknown load dynamics due to the very simple transfer function of the converters, which represents a single-pole system. Moreover, the pole frequency is practically not shifted when the load changes, leading to a very robust voltage control loop. Mass savings are achieved due to comparatively small filter capacitors and inductors.

IV. Generic HVPS "MULTIRANGE"

The single stage concept achieves highest efficiency at fixed (regulated) bus voltages and at constant output voltages. On the other hand, some thruster applications require operation at variable bus voltages or have to drive thrusters in different operating modes. As a consequence, the single stage concept needs to be extended by an additional stage.

The implementation of a Multirange concept offers the choices of two different basic topologies. Common for both is the usage of two converter stages and the capability of compensating variations of the power bus voltage or the adjustment of output voltages in a wider range. Both are currently under assessment.

A. Pre-Regulator Concept

For low-quality or unregulated power busses, the bus voltage is converted into a stable intermediate (dc-link) voltage. This is done by a step-down pre-regulator. In a second stage the dc-link voltage is converted to the desired high voltage by means of an unregulated voltage follower based on a full resonant bridge.

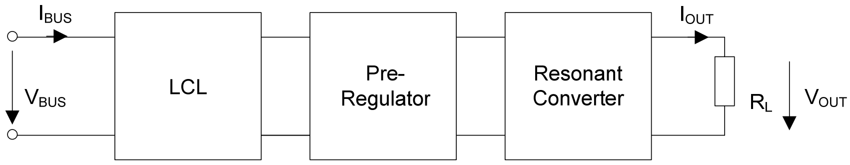

Fig. IV-1: Two Stage Concept with Pre-Regulator followed by an Resonant Converter

Owing to the pre-regulator, the converter is able to compensate voltage fluctuation at the power bus side and simultaneously to generate a variable output voltage.

Fig. IV-2 shows the transfer characteristics of the proposed concept: Considering the step-down as a perfect current source, the overall transfer function of the whole converter is composed of the 2-pole transfer function of the resonant stage and the pole contributed by the capacitive output filter and load. The resulting three-pole system generally exhibits a significant resonance peak and is therefore hard to stabilize. Voltage noise or oscillations, which are inherent on many thruster types, can correlate to that resonance frequency. This is also true for single event distortions (beam outs) occurring on gridded ion engines. Moreover, the pre-regulator has to provide full output power plus the losses of the second stage. Due to the wideband capability it is designed as a hard-switched converter, giving some drawback with respect to efficiency.

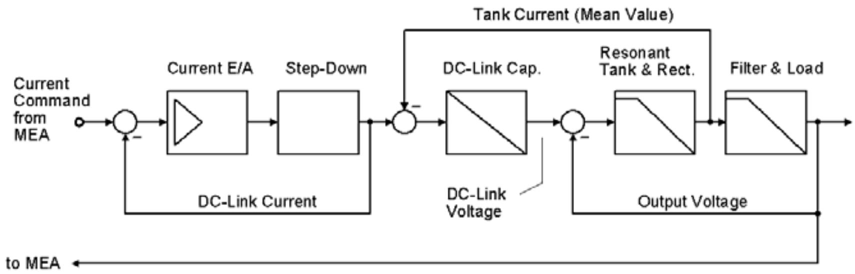

Fig. IV-2: Cycle Based Averaged Model of the Step-down and Resonant stage

B. Series Regulator Concept

For power bus systems which are principally regulated but having some voltage droop for certain conditions, there is no need for full wideband capability. Obviously, the major part of output power needs not to propagate through two conversion stages.

Instead, it is possible to connect the uncontrolled voltage follower directly to the main bus. At the output side, both converters are switched in series. Since the follower delivers the major part of the output voltage and power, a small, controllable converter is used to complete the required amount of output voltage. This concept is shown in Fig. IV-3.

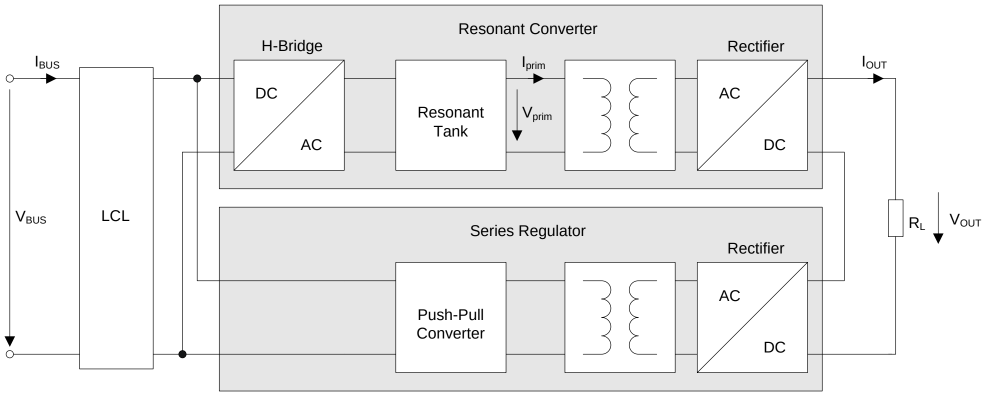

Fig. IV-3: Block Diagram DC-Output Series Connected Converter

Since the 2-pole transfer function of the resonant stage is not part of the voltage control loop, the transfer function of the complete converter is basically identical to the transfer function of the series regulator -which is a single-pole system in case of a hard-switched forward converter type. This makes it easy to achieve sufficient control loop stability and speed. Moreover, the major part of output power is provided by the soft-switching resonant stage operating with low dissipation. This results in a high total efficiency.

However, the series regulator converter itself requires high (>20dB) wide-band capability on the output side. As a consequence, a hard-switched topology must be used since resonant types cannot be controlled over a wide range with low effort. Despite of this, the complete converter has no wideband capability, i.e. only small variations of bus voltage can be compensated. This is because of the small power capability (contributing only 10%-15% of total output power) of the series regulator.

C. Resonant Converter Stage

The resonant converter (see Fig. IV-4) consists of a full bridge, a series resonant tank, a high voltage transformer, rectifier and output filter. Due to series resonant operation mode, the transformer primary and secondary currents are shaped almost sinusoidal. This stage is designed to operate with the same high voltage module as the "optimum"-type converter; only C_p is omitted.

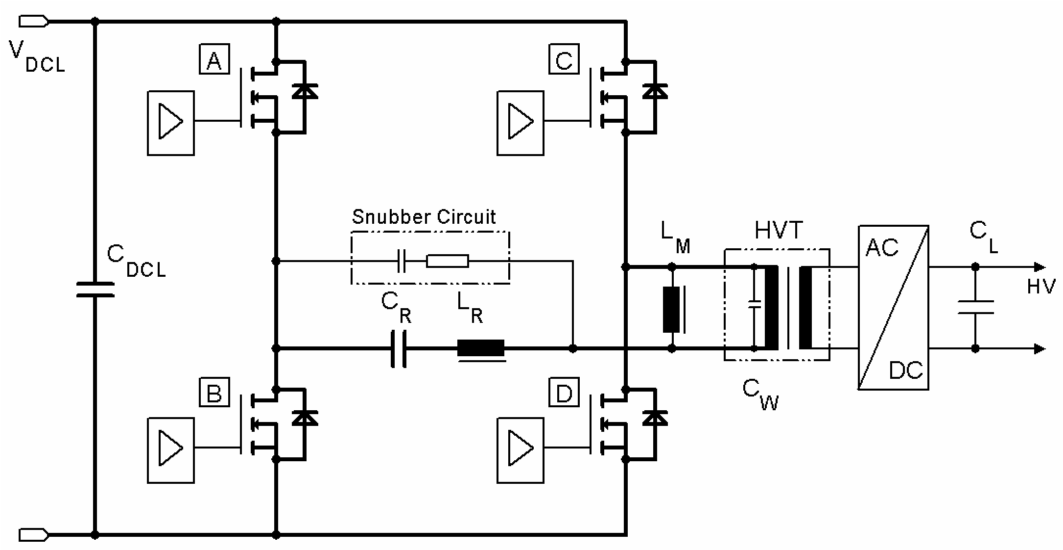

Fig. IV-4: Block Diagram of the Resonant Converter Stage

The resonant tank is build by a series capacitor and a series inductor, both located at the low voltage side. Although the leakage inductances of the high voltage transformer already contribute to the resonant tank a discrete inductor is necessary since the leakage of the toroidal high voltage transformer is very small. In a similar manner, the magnetizing inductance of the toroidal transformer is quite large to store sufficient energy required for soft-switching of the high voltage rectifier diodes. For that reason, an external parallel storage inductor L_M is required, (see Fig. IV-4).

Although this component contributes to total mass, the difficult adjustment of the transformer's air-gap width (by inserting different spacers or sheets) is then replaced using a tunable test inductor. Another benefit of using an external inductor is to have now access to the net carrying the major part of the "magnetizing" current. For that reason, a very effective snubber circuit connected to the L_R/L_M junction can be used.

During commutation, the magnetizing current reaches a certain peak value. This is used to control the charge of the transformer's winding capacitance in a way to increase the reverse voltage of the rectifier diodes slowly enough to avoid any reverse current. However, if the soft-switching conditions are not exactly met - for example due to drift effects of the timing electronics or due to parameter drifts of the power circuit components - a reverse current may occur leading to switching losses. In order to reduce these drift effects the timing pattern of the resonant bridge is made by a quartz-based logic instead of using analogue R-C delay stages.

In order to avoid frequency beat effects, the switching frequency of the resonant stage is synchronized to the half of the frequency used for the step-down converter. Since the full bridge rectification doubles the ripple frequency again, the ripple of both converters are in phase.

V. Example For Generic HVPS Application – Gimbal Free HEMP Thruster System

Many existing satellite propulsion concepts require gimbal mechanisms in order to achieve efficient thrust vectoring. Nevertheless, the use of these mechanisms is a significant cost driver and affects the reliability of the propulsion systems. An alternative to complex gimbal systems could be the use of distributed individual thrusters.

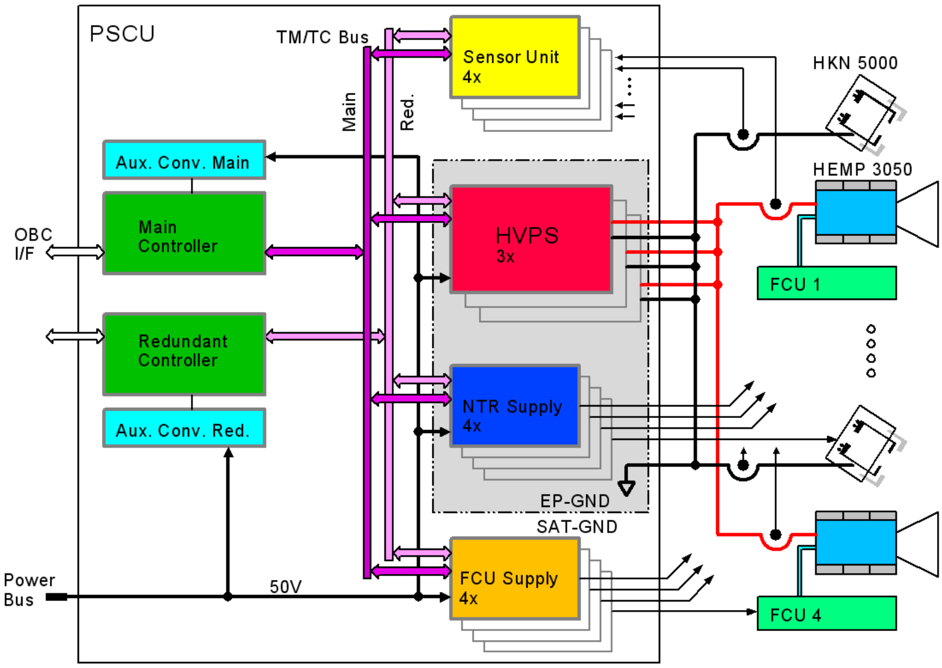

Fig. V-1: Power Supply Control Unit (= Power Processing Unit) for HEMP Thruster Unit

A high potential candidate for a gimbals-free thrust vectoring concept is given by the HEMP3050 Thruster /8/. As shown in Fig. V-1, this Thruster requires only one anode voltage (of 1 kV) and two voltages for the neutralizer (heater and keeper). Thus, it is viable to drive up to 4 thrusters from a single Power Supply and Control Unit (PSCU).

Future mission scenarios may involve the newly developed HEMP3050 Thruster of Thales in Ulm (Germany). Four of these thrusters can be operated at one common power supply, since the anode current depends on the Xenon-gas flow through the thruster. Thrust vectoring can be achieved by individual throttling of multi-thruster configurations. The benefit of this solution is its simplicity since the HEMP-Thruster does not require a lot of complex regulated power supplies. An initial outline of a four-thruster PSCU is shown in Fig. V-1.

The HEMP Thruster PSCU contains a control interface based on MIL-Bus Standard communication links and analogue telemetry/command lines:

- Two serial TM/TC interfaces acc. to MIL-STD 1553 specification
- Control of the thruster operation on command from the on-board computer
- Acquisition of analog and digital status signals from the modules
- Provision of the telemetry data as a serial data stream on command from the on-board computer
- Generation of auxiliary supply voltages for the data interface modules and all electronics requiring secondary power in the PCDU
- On/off control of the auxiliary converter on discrete commands from the on-board computer

VI. CONCLUSIONS

A “Generic High Voltage Power Supply Module” has been developed as a core part of next generation Power Processing Units respectively Power Supply and Control Units for electric propulsion subsystems. Many experiences from foregoing electric propulsion projects like GOCE and ALPHABUS have led to a new approach of converter design. The so-called “OPTIMUM”-Converter allows high voltage generation in a single stage by using the innovative “Flat-Top” principle in order to reduce the mass to power ratio, increases the power conversion efficiency and to ensure a robust voltage control loop. In combination with new Silicon Carbide Diode technology an overall efficiency 97% has been demonstrated in a thermal vacuum test together with a HEMP3050 thruster. Next steps are the qualification of the HVPS in connection with a fight opportunity in a European On-Orbit Demonstration Program.

The single stage concept achieves highest efficiency at fixed bus voltages and at fixed output voltages. Since some thruster applications require the operation at variable bus voltage or have to drive thrusters in different operating modes, the single stage concept is to be extended by an additional stage, without modifying the majority of the functional blocks from the “OPTIMUM” concept. Concept implementation is currently ongoing.

An on-board demonstration program is scheduled to be performed on the innovative small telecom platform SGEO (2011). Further flight opportunities might be by the European space missions AlphaBus, Bepi-Colombo, and commercial Telecom Missions.

VII. REFERENCES

1. N. Koch, H.-P Harmann and G. Kornfeld, “Development and Test of the THALES High Efficiency Multistage Plasma (HEMP) Thruster Family” Proceedings of the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005 - IEPC-2005-297

2. H. Meusemann, M. Winter et. al. „Electric Propulsion in Germany: Current Program and Prospectives” Proceedings of the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005, IEPC-2005-130

3. Tajmar, M., Genovese, A., and Steiger, W., "Indium FEEP Microthruster Experimental Characterization", AIAA Journal of Propulsion and Power, Vol. 20, No. 2, 2004, pp. 211-218

4. G. Kornfeld, N. Koch, H.-P. Harmann, P. Micheli, H. Meusemann, E. Gengembre: „High Power HEMP-Thruster Module, Status and Results of a DLR and ESA Development Program“, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Sacramento, California, July 2006, Paper AIAA 2006- 60150

5. M. Gollor, K. Breier, „Compact High Voltage Power Conditioners for Field Emission Electric Propulsion (FEEP)”, Proceedings of‘Seventh European Space Power Conference’, Stresa, Italy, 9-13 May 2005 (ESA SP-589, May 2005)

6. M. Gollor, M. Boss „Micro-Newton Electric Propulsion Subsystems for Ultra-Stable Platforms“ 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 2006, Sacramento, California, Paper AIAA 2006-4825

7. M. Gollor, K. Rogalla, "High Voltage Design of Vacuum Insulated Power Supplies for Space Applications" - IEEE Transactions of Electrical Insulation, Vol. 28, No. 4, August. 1993, pp. 667-680

8. Kornfeld, G., Koch, N., Harmann, H.-P. „Gimbal Free EP Thrust Gimbal Free EP Thrust-Vectoring System” Proceedings of the ESA Workshop: Propulsion Technologies for Space Exploration, Noordwijk, The Netherlands, 04.May.06

VIII. ACKNOWLEDGEMENT

A significant part of the described work of the “Generic High Voltage Supply – Next Generation” has been funded by the German Space Agency DLR (FKZ 50 JR 0542 "HVPS NG")