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MODULAR HIGH POWER HIGHLY STABILISED MAGNET POWER SUPPLIES FOR PARTICLE ACCELERATORS AND SYNCHROTRONS

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Abstract: *The aim of this paper is to present a power electronics building blocks (PEBB) concept for high power magnet (superconducting or classical) power supplies for physics research institutions such as nuclear accelerators and synchrotron sources. A PEBB system described in this paper is based on [13kA, 18V] high frequency Zero-Voltage/Zero-Current switching (ZVZCS) converters built by Transtechnik for Large Hadron Collider (LHC) Machine at CERN. After a basic system description, interconnection and parallel operation of the basic system in order to increase the output current/voltage will be presented.*

Key Words: ***Accelerators, Synchrotrons, Pulsed Power Supplies, Superconducting Magnets, Soft-Switching Converters.***

1. INTRODUCTION

Superconducting or classical magnet power supplies (PSU) for physics research institutions such as nuclear accelerators and synchrotron sources usually demand a very high level of performance from the power converters, the most important being:

- DC stability and accuracy (ppm area),
- Dynamic response (ideal profile tracking),
- High efficiency,
- Wide operating current range (1% to 100%)
- Electro Magnetic Compatibility (EMC),
- Ease of replacement,
- System redundancy (n+1 based).

To meet these requirements, modular (PEBB based) IGBT converters with soft-switching techniques are used as the state of the art. In addition, a modular approach increases fault tolerance and decreases the overall system cost.

A PEBB system described in this paper is based on [13kA, 18V] and high frequency Zero-Voltage/Zero-Current switching converters built by Transtechnik for Large Hadron Collider Machine at CERN. The chosen sub-converter topology is described in three parts - Part 1: Circuit-breaker and contactor together with a soft-start circuit, input rectifier on the AC mains with a damped LC passive filter. Part 2: Full-bridge soft switching inverter. Part 3: High frequency transformers, rectifier stage and 4th order L-C output filter.

Such PSUs are intended to supply the basic types of magnets, both superconducting and warm resistive ones, such as:

- Dipoles for beam bending and steering
- Quadrupoles for beam focusing
- Sextupoles and higher order magnets for the beam correction, chromaticity control etc.

After design, control and operation description of a highly stabilised PSU, an analysis of converter adaptation for different pulsed voltages/currents will be presented. Interconnection and parallel operation of the basic system in order to increase the output current/voltage will be discussed.

2. BASIC BUILDING BLOCK FOR HIGHLY STABILISED MAGNET SUPPLIES

The basic sub-converter for the [3.25kA, 18V] converter is split in three modules i.e. "building blocks inside a building block" (Figure 1):

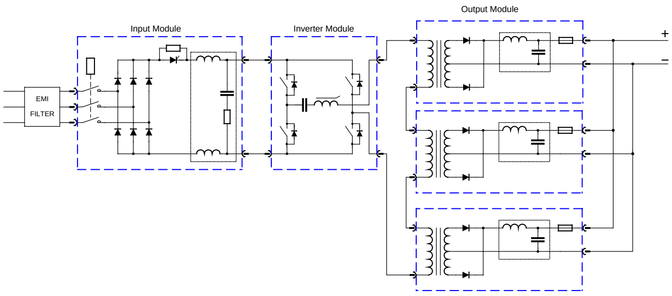

Figure. 1. *Basic building block: sub-converter for highly stabilized supplies*

- Input Module: a power contactor on the AC mains (3x400V, 50Hz), a diode rectifier with a damped L-C passive filter (70Hz)
- Inverter Module: Full-Bridge Zero Voltage Zero Current Switching Phase Shift inverter (FB-ZVZCS-PS) at 25kHz
- Output Module: high frequency transformers, rectifier stage and output filter. To fulfill the weight constraint, the module 3 is physically split in three modules of 1.1kA.

2.1 Input module:

The 3-phase mains voltage is rectified and filtered in the input module. An input contactor disconnects the complete sub-converter from the mains if there is no demand for power or in the case of a severe fault. The input module is equipped with a pre-charge circuit to limit the inrush current at the power-up. EMI Filter is provided at the modules input.

2.2 ZVZCS Inverter module:

The filtered DC-link voltage from the input module feeds the inverter running at 25 kHz. This stage employs a switch-mode inverter (ZVZCS = **Z**ero **V**oltage / **Z**ero **C**urrent **S**witching). The control of the power semiconductors (IGBTs) is done by introducing a phase-shift between the two legs of the bridge, instead of turning off the diagonally opposite switches in the bridge simultaneously as for a classical PWM. This phase-shift determines the output power whereas the switching frequency is fixed to 25 kHz. The needed energy to achieve soft-commutation conditions for the switching of the leading leg (ZVS) comes from the series inductance, the leakage inductance and the output filter inductance. This means that the energy stored is large enough to charge and discharge the parallel switch capacitances (parasitic and snubbers) and the parasitic capacitances of the transformer. To regulate the output voltage / current with high precision from 1% to 100% and over a wide load range, a modified phase-shifting principle is applied, as shown in Fig. 2. By using a DC blocking capacitor and a saturable inductance, the primary current is reset during the freewheeling period, which provides ZCS conditions for the lagging-leg switches.

2.3 Output module

- High frequency transformers and Schottky diodes:

To achieve the required output parameters (1100A, 18V) within one module (Figure 1), a special transformer with ferrite core UU93 and thin copper foil windings has been developed. The secondary is separated into 3 sections, each of them feeds a centre-tapped rectifier with 2 Schottky diode modules to handle the current with 20% safety margin. Considering the skin and proximity effects, the foils are wound in such a special way to enable the appropriate current sharing, that is - the current in each section and also in the Schottky diodes is almost identical. Furthermore, the series / parallel connection of the split modules guarantees a good current sharing between them.

- Passive filter:

To achieve the required output ripple of only 10mVpp at peak output current a quadruple stage output filter was implemented. The filter stages consist of iron powder cores and electrolytic capacitors with very low ESR and high reliability.

- Fuse and power connections:

A fuse is used to protect the output module against serious damage in case of a diode failure. All the output modules can be exchanged easily by pulling the units out via the special drawer system. A system of multiple single-pole high-current connectors is used for quick plug-in/plug-out to carry the high currents.

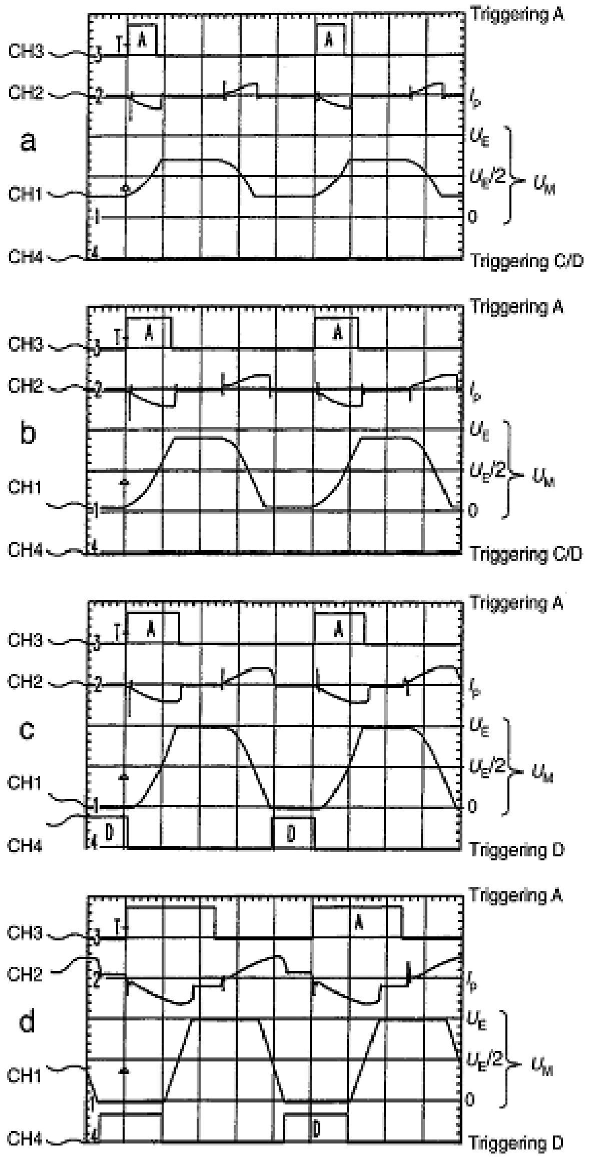

Figure 2. *ZVZCS Module in different modes: a) almost idle, b) low load, c) medium load, d) full load.* U_M*=DC-link mid-point voltage (100V/div),* I_P*=primary current (100A/div)*

3. BASIC BUILDING BLOCK FOR PULSED MAGNET SUPPLIES

The system architecture for pulsed power supplies is similar to the one presented in paragraph 2, with a difference that two- or four-quadrant operation is required. This requirement leads to elimination of HF galvanic isolation and introduces (if required) a LF one.

In addition, considering the pulse profile and magnet's duty cycle, it is not necessary and often not possible (because of the limited energy gradient through the equivalent supply inductance) for the input circuit to manage the complete power range. It is thus designed to handle the average power, while the power peaks are drawn from the DC-Link which at the same time provides the energy storage and the filtering function. Depending on (average power)/(peak power) ratio, peak power duration and magnet duty cycle, different energy storage methods can be used: electrolytic capacitors, batteries and super capacitors. Inverter or 2-quadrant chopper must be designed to handle the full load power.

Fig. 3. shows bipolar pulsed PSU with 4-quadrant chopper module designed for the steering dipole or trim quadrupole type magnets, while the figure 4. illustrates an energy recovery pulsed PSU with 2-quadrant chopper module for the kicker type magnets.

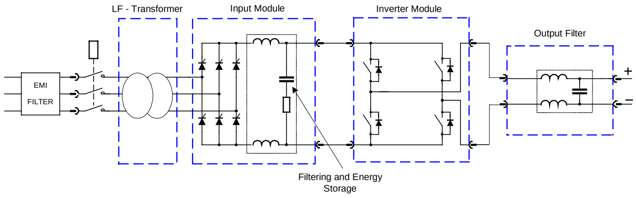

Figure 3. *Bipolar pulsed PSU with inverter / 4-quadrant chopper module*

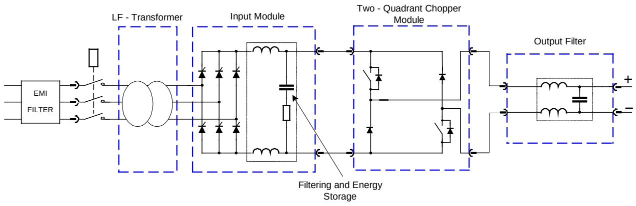

Figure 4. *Energy recovery pulsed PSU with 2-quadrant chopper module*

4. CONTROL OF CONVERTERS

To achieve the required high DC precision and stability, a triple cascaded control system have been implemented (Figure 5):

- a fast current loop at the sub-converter level (ZVZCS-inverter current control), having the task of attenuating the 6-pulse DC-link (300Hz) ripple, eliminating mains disturbances and of conversion of voltage-source to current-source converter for the purpose of sub-converters paralleling. The required bandwidth is 8 kHz
- a global voltage loop to control a global voltage source composed of (n+1) sub-converters with a required bandwidth of 700 Hz. Separate electronics handles the regulation of the whole converter and provides the reference and other control signals for all the sub-converters.
- a high precision current loop to control the magnet current with demanded high precision with a bandwidth of 1 Hz. A high precision current transducer, usually a Direct-Current Current-Transformer (DCCT), measures the output current of the power converters. With the Transtechnik converters for LHC, a CERN developed RST current control algorithm was used.

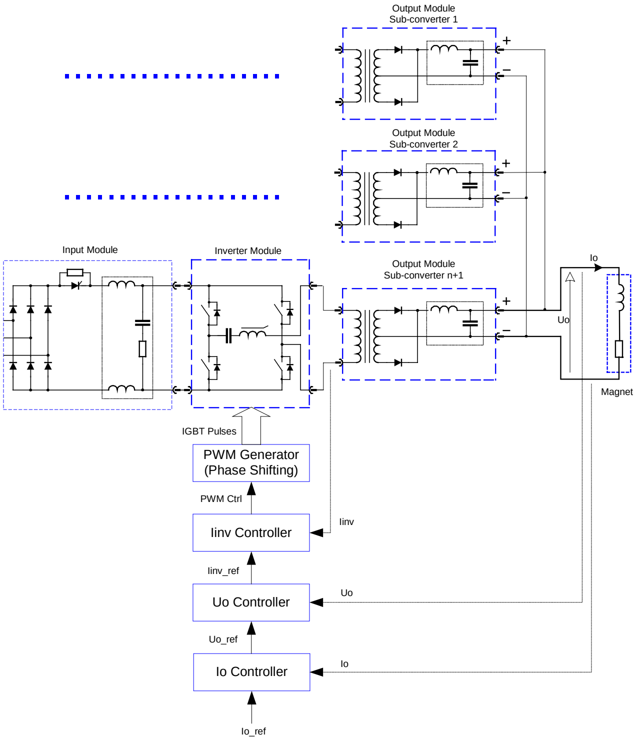

Figure 5. *Control structure*

Fig 6. shows an experimental frequency response of the fast current loop at sub-converter level, where:
Area [1], I_{REF} = 1.62500kA + 162.5A x sin (wt)
Area [2], I_{REF} = 4.71250kA + 162.5A x sin (wt)
Area [3], I_{REF} = 12,1875kA + 81.25A x sin (wt)

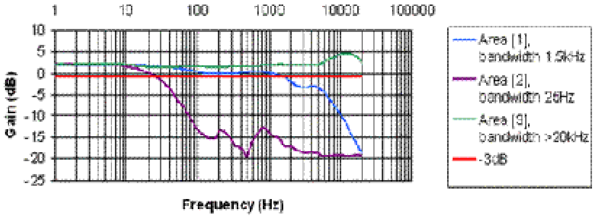

Figure 6. *Fast current loop frequency response*

Fig. 7 shows an experimental frequency response of the magnet voltage loop, where:
Area [1], U_{REF} = 0.540V + 0.18V x sin (wt)
Area [2], U_{REF} = 1.026V + 0.18V x sin (wt)
Area [3], U_{REF} = 2.700V + 0.18V x sin (wt)

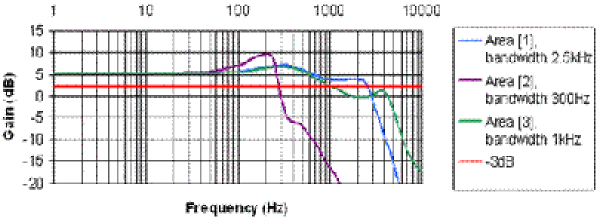

Figure 7. *Output voltage loop frequency response*

5. PARALLEL OPERATION/REDUNDANCY

The PEBB converter system has been designed in such way that several sub-converters can work in parallel. The voltage inverter topology used in the design means that the sub-converters are inherently voltage sources. In order to make the paralleling possible, a fast current loop, as discussed in paragraph 4, transforms the sub-converters into a controlled current sources.

For reasons of redundancy and availability, the converter has been designed to use one extra sub-converter in relation to the necessary power, as shown in Fig. 8. Fig. 9 shows the [13kA, 18V] converter (234kW nominal power) which make use of 5 [3.25kA, 18V] sub-converters with total available power 292.5kW. Fig. 10 shows the [20,5kA, 18V] converter (369kW nominal power) which make use of 7 [3.25kA, 18V] sub-converters with total power 430.5kW.

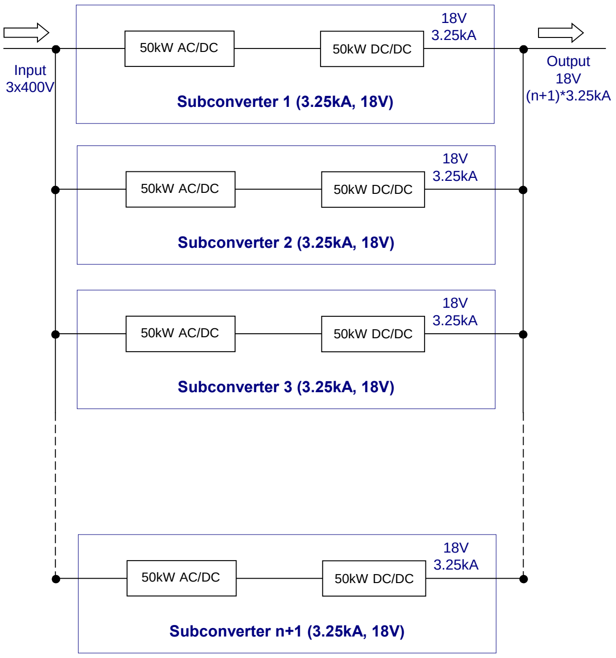

Figure 8. *n+1 redundancy concept*

Figure 9. *[13kA, 18V] converter*

Figure 10. *[20,5kA, 18V] converter*

The sub-converters are capable of being started independently and working alone. Under normal conditions, all the sub-converters are working in parallel with n/(n+1) capacity. If one of the sub-converters fails, the current reference for remaining sub-converters will increase, so that the current and voltage of the magnet do not change, as shown in Fig. 11. This feature is very important for the research institutions since the failure of one sub-converter does not lead to failure of the experiment in progress.

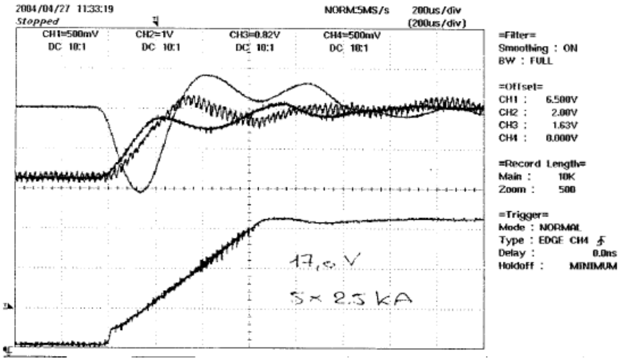

Figure 11. *Magnet voltage and sub-converter current when one sub-converter fails (time trace 200µs/div)*

With a simple inverter-transformer adaptation, it is possible to achieve a different voltage levels at the sub-converter output with the same PEBB design, provided the sub-converter power stays within the 58.5kW range. With the Transtechnik latest design the sub-converter power will be pushed to the 66kW, enabling larger power density.

6. PERFORMANCE

In addition to the features explained in the previous section, further converter performance can be summarised as:

- Current operating range from 1% to 100% of the 13kA/20.5kA maximum current with soft-commutation throughout the range (Figure 12, 13). The soft-commutation enables the use of only one inverter module per sub-converter.
- Measured efficiency is above 90% at full power.

- Output voltage ripple is less than 10 mV p-p in the 0 - 150 kHz frequency band, 2 mV r.m.s. for frequencies > 150 kHz and 1 mV r.m.s. for frequencies > 500 kHz (IEC 478-3-C for conducted EMI) (Figure 14).

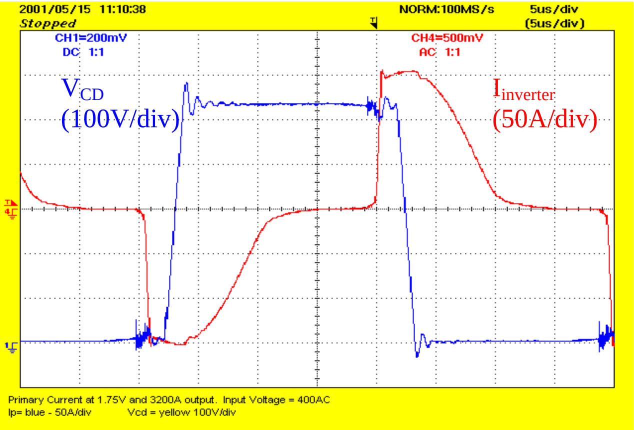

Figure 12. *Inverter current with high output current (3200A) and low voltage (1.75V)*

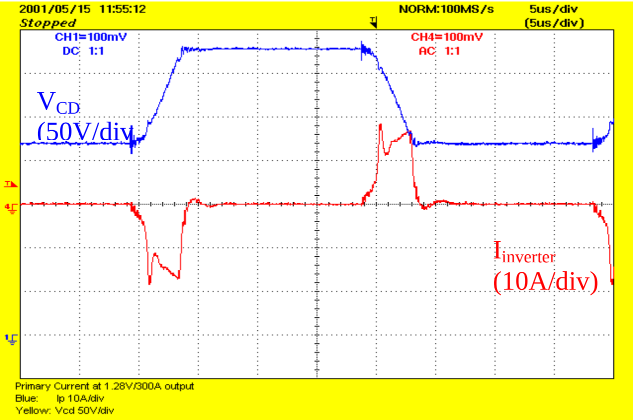

Figure 13. *Inverter current at low output power (300A, 1.3V)*

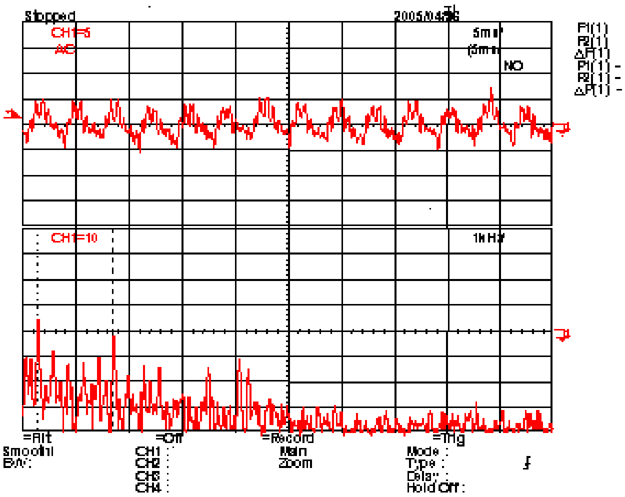

Figure 14. *Output voltage ripple and its frequency spectrum at full power*

7. CONCLUSION

A power electronics building blocks concept for high power magnet power supplies was presented in the paper. After design, control and operation description of a highly stabilised PSU, an analysis of converter adaptation for pulsed applications was presented. Interconnection and parallel operation of the basic system in order to increase the output current were discussed as well as the necessary steps to increase/decrease the output voltage.

It was shown that the PEBB concept enables the use of standardised sub-converters for the whole range of applications. Compared to classical "a specific supply for a specific magnet" design, the most important advantages of such concept are:

- Ease of replacement,
- System redundancy
- Fault tolerance
- Shorter stuff training time
- Reduction of the overall system cost

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