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HIGH-POWER MODULAR GAN BASED POWER SUPPLY FOR MEDAUSTRON SCANNING MAGNETS

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Abstract

MedAustron is a synchrotron-based ion therapy center in Wiener Neustadt, Austria, constantly working towards the performance improvement of cancer treatment. A major improvement opportunity comes from the scanning magnets system – a crucial element of dose delivery system at MedAustron - that is influenced by the bandwidth and power density of the magnet power supplies. Therefore, a novel highly modular power converter, based on the latest gallium nitride technology is being developed to tackle the aforementioned requirements. One sub-module of this power supply is based on two H-bridges that are operated in hard parallel and are integrated into a standardized euro-crate form factor with target output power specifications of 720 kW. This design also includes a 4th-order output Bessel filter to meet the ripple requirements for clinical operation. Furthermore, those sub-modules offer the possibility of being connected, cascaded or interleaved, in order to meet different output power requirements, providing a high modularity aspect. The status of this development in terms of requirements, global topology, and control structure is presented.

INTRODUCTION

Particle accelerators for research and medical applications have a demand for high performance magnet power supplies. The corresponding requirements vary with respect to the magnet families used in different sections of the accelerator. In case of the so called scanning magnets that is most importantly high accuracy and bandwidth. Therefore, a power converter based on GaN (gallium nitride) components is currently under development for this specific magnet family. The expected benefits are high modularity, power density, bandwidth, current stability, and simultaneous better maintainability [1, 2]. The given prerequisites, are tailored for utilizing GaN switches in the design, to avoid increased losses that would in contrast occur with conventional silicon switches. This paper compares possible control structures of such a highly modular device. The most promising design setups are presented in detail and the paper concludes with an outlook on a possible final setup candidate.

REQUIREMENTS

To aid the reader in understanding the different nomenclature, an illustration of a possible power converter (PCO) setup is presented in Fig. 1. The design scope includes a four-quadrant DC-DC converter. It consists of two H-bridges operated in hard parallel with an output filter stage. This setup is from now on referred to as a submodule. Three of these submodules make up a whole module that shall be inhabited by a standardized 19" crate. Prospected specifications are summarized in Table 1. The pulse width modulation (PWM)

Table 1: Specifications of one sub-module and scanning system.

Parameter	Value
DC-link voltage	300 V
Output Current (I)	33 A
f_{-3dB}	50 kHz
Switching Frequency	$\geq$ 150 kHz
Maximum Load Inductance	3 mH
Maximum Load Resistance	50 mΩ
Scanning Max. I Ramp Rate	450 $\frac{kA}{s}$
Scanning Step settling time	150 µs
Steady state I_{pp} ripple	100 ppm

signals or references are provided externally and interleaving is implemented inside each module to further decrease the current ripple. Measurements for currents are local to submodules and the voltage measurement is global on module level. The layout for the output filters follows a fourth order Bessel-design [3] with designated -3 dB frequency f_{-3dB} at 50 kHz. For desired output specifications of 1200 V and 600 A, multiple modules have to be interconnected on a PCO level. In the particular case of this investigation, 24 modules have to be connected in total. Hence, six paralleled modules are required. This assembly is called hexaGaN. Four serialized hexaGaN make up the whole PCO.

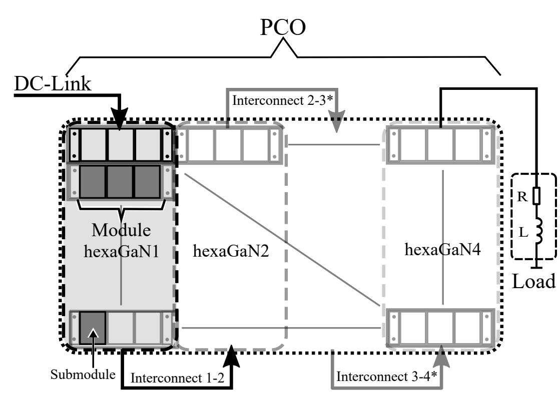

Figure 1: Schematic illustration of a possible power converter setup scenario. For output of 1200 V and 600 A, six modules are parallelised (dashed) to a so called hexaGaN, and four of these assemblies are serialised (dotted) - also illustrated as the interconnect line between hexaGaNs.

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HARDWARE SETUP OPTIONS

In total four possible hardware setups (HWS1 to HWS4) are investigated in the course of this paper. The overview from Fig. 1 serves as a basis for the upcoming nomenclature and illustrations. Comparisons for other power converter setups also serve as a basis for this investigation [4].

Central Controller (HWS1)

The first setup is visualized in Fig. 2. The hexaGaN closest to the load is depicted and the ones beyond are just hinted at. In the illustration shown, they would be serialized in a sort of zig-zag fashion. The same control strategy applies for all modules. Same holds true for all other upcoming setups. Henceforth, these circumstances are not mentioned in detail from here on. The heart-piece of the first setup is a central controller that is alone responsible for the whole control methodology. It also has the task to provide isolated PWM signals to the individual sub-modules. A possibility to implement this are optocouplers (hinted at in the illustration) on the receiving end or a fiber optic transmission setup. In any case the amount of PWM interfaces would add up to a total of 288 (4 PWM signals, for each hard paralleled H-Bridges, in 3 Submodules contained within 6 Modules for each of the 4 HexaGaN. $4 \cdot 3 \cdot 6 \cdot 4 = 288$). Furthermore, also due to the centralized approach, all currents of the module outputs must be feedback to the controller for current-control and -balancing between the sub-modules. For the digital solution this can be implemented by means of the voltage droop method [5]. This control layer is the basis for a voltage control loop that receives the output voltage of a whole module. In the illustrations, the voltage measurement point is optionally chosen to be located after the second stage of the Bessel output filter. The exact placement is under assessment. As can be also seen, the voltage measurement must be galvanic isolated in order to prevent possible unwanted interaction between medium- and low-voltage levels. For the current measurement a Hall based sensor is utilized. Hence, these measurements are inherently isolated. A total number of 76 feedback signals would be required for this setup and hence a high number of precise ADC channels.

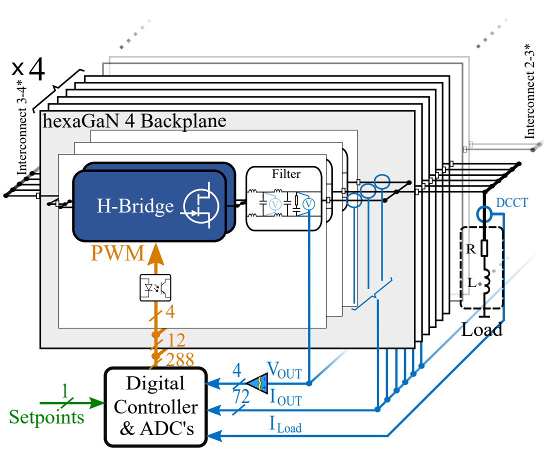

Figure 2: Centralized controller hardware setup option.

Central- and Co-Controller (HWS2)

The next setup under investigation is illustrated in Fig. 3. A centralized controller forwards an analogue reference to a decentralized controller which is responsible only for PWM generation. Same as in the previous option all currents and voltages must be fed to the central controller with the same isolation criteria as before. This setup drastically reduces the required signal interfaces to the individual sub-modules. To further improve the signal integrity for the reference, even multipoint-low voltage differential signal (M-LVDS) could be utilised with SPI as a protocol in a digital solution [6].

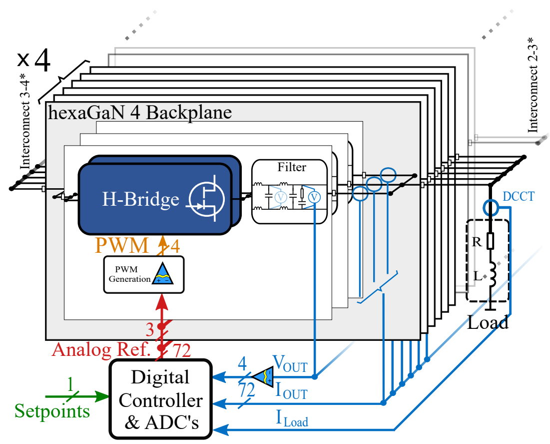

Figure 3: Centralized controller with decentralized slave controllers located on a sub-module level hardware option. Central controller provides analogue reference and current balancing is implemented digital.

Central- and Co-Controller with Analogue Current Balancing (HWS3)

The subtle difference between the preceding and this setup becomes apparent by closer inspection of the setup nomenclature as well as the illustration in Fig. 4. The current balancing is implemented by means of an analogue circuitry that receives the current measurements of the individual sub-modules. Here either an average or highest current method could be implemented [7]. Other than that the similar benefits and limitations as from the previous discussion hold true.

Full Scale Digital (HWS4)

The last setup under investigation is a fully digital implementation shown in Fig. 5. It implements a central master controller that receives the load current and is hence responsible for the precise current control. Also this setup relies on decentralized digital slave controllers on sub-module level that receive their reference via a bus that is based on the EtherCAT protocol. Therefore, the slave controllers are the backbone of the whole setup and implement a rough first stage current and voltage nested control loop. Despite EtherCATs gigabit capability, further investigation is required to ensure timely information distribution among the hexaGaN's.

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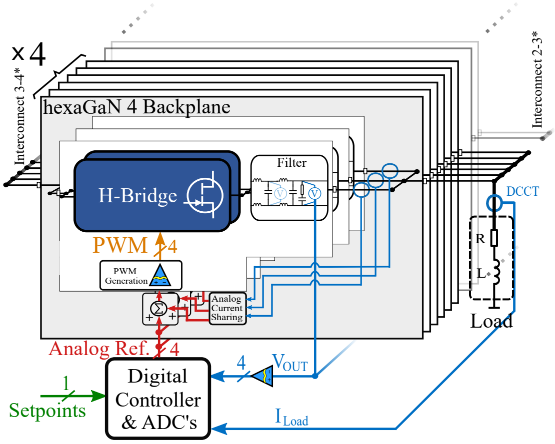

Figure 4: Centralized controller with decentralized slave controllers. Analogue reference is provided and analogue current balancing is implemented.

e.g., assuming a 2-Byte payload and 100 Mb/s, the frame time would be ≈7.7 µs. The propagation delay, assuming a pure EBUS solution and 5 nodes (Master+Slaves) would be 0.3 µs [8]. For a targeted controller frequency of 50 kHz this frame time + delay might be acceptable.

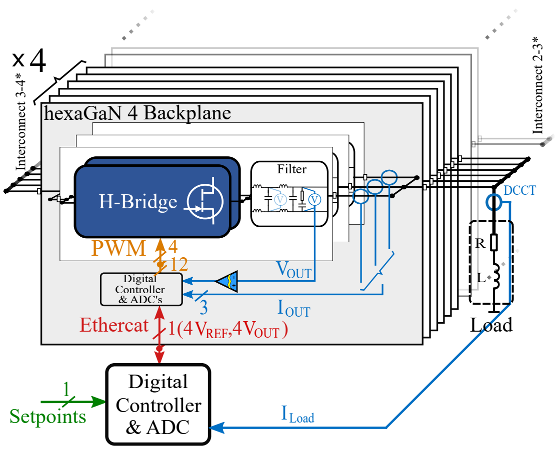

Figure 5: Centralized controller with decentralized slave controllers connected via a EtherCAT bus.

PROS & CONS

Cabling effort is highest for setup one. To that respect this setup also scales poorly with increasing number of modules or hexaGaN. Furthermore, an optical solution has to be considered since propagation time matching for the PWM signals might become crucial. The options with decentralized controller reduce the cabling effort drastically while the full scale digital solution offers the biggest relief. HWS3 requires the lowest number of references and feedbacks among the analogue solutions. For the computational effort also the first option encounters the largest drawbacks with its high number of signals. In that case a FPGA and ADC combination would be a likely controller candidate. HWS3 offers a slight relief in contrast to setup one due to the analogue implemented current balancing technique. For EtherCAT, the possibility of utilizing higher bandwidths (1000Base-T, full-duplex) needs to be assessed. Similar statements can be made for the interfacing techniques. Measurements are feedback either analogue or digital. Where the former offers higher transfer rates but is noise prone and the latter faces bandwidth limitations. Here all options suffer under similar implementation dependent drawbacks. Clearly, EtherCAT requires the already standardised Ethernet physical layer. It offers galvanic isolation by design. The analogue reference solutions (HWS2, HWS3) require fast DAC's or a swap to a fast and reliable digital solution (M-LVDS&SPI). Another aspect that requires further investigation and would apply for HWS1 to 3, is the option of generating reference setpoints on central controller level and trajectories are generated on module level. This would lower the burden on the signal integrity for the reference transmission drastically. Finally, first option must be fully isolated for voltage feedback and PWM. Same holds true for the decentralized solutions, except of the EtherCAT for stated reasons.

CONCLUSION

Within the limited scope of this paper, an overview and possible final hardware architectures for the novel modular scanning power converter assembly for the facility of MedAustron have been presented. A $f_{-3dB} = 50$ kHz, utilisation of GaN switches with a switching frequency of 150 kHz and final output specifications of 1200 V and 600 A require a prudent assessment of the complex designs. Taking all requirements into account, the full scale digital setup seems to be the most promising for further investigations. Especially, with respect to the mentioned desired bandwidth and output specifications. It offers the capability of providing the submodules with their corresponding PWM signals and receiving the required feedbacks with the lowest cabling efforts. A major point to be assessed further is the transmission time through the nodes for the dataframes. Moreover, in contrast to power converters that are confronted with a similar cycling behaviour as is the case for scanning magnets, such an implementation with the stated specifications is a novelty. At this point the CERNs modular SIRIUS power converters shall be mentioned that are operated in a similar fast cycling behaviour, but offer less power density [9]. Ultimately, the presented solution is also planned to be used for the largest majority of MedAustrons power supplies in the future. Furthermore, future work concerns the investigation in terms of control schemes within simulations and in combination with actual hardware as well as long term behaviour of the GaN switches.

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