Power Architecture Evolution in Data Centers

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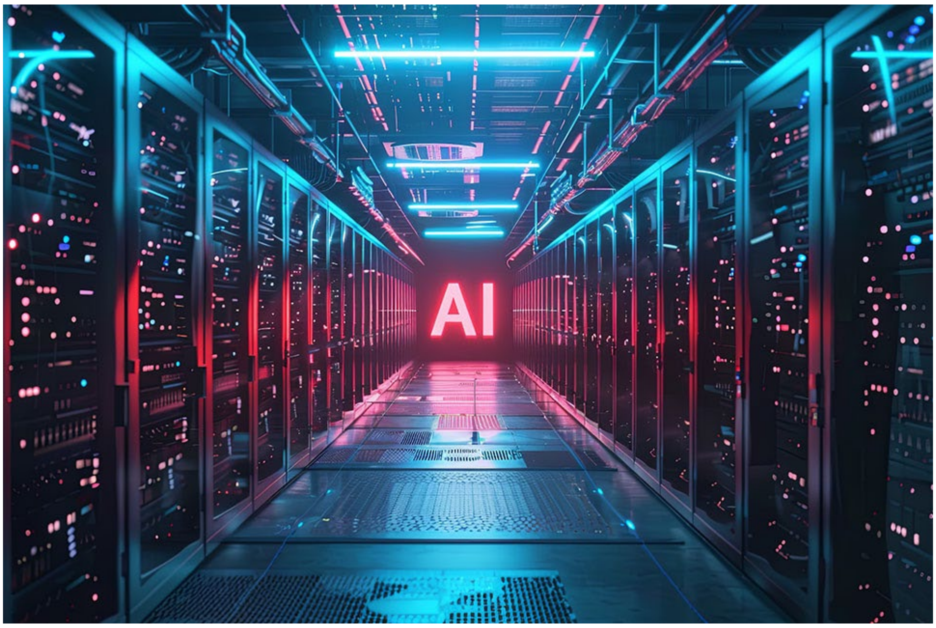


Executive Summary

The explosive growth of AI and its consequent hardware evolution have brought a dramatic increase in power levels of data center IT racks – up to several hundred kW already today. This factor is forcing the evolution of the conventional architecture of power distribution inside the rack, based on the OCP standard 48 V architecture. Higher voltage distribution inside the rack is required and 800V (2 or 3 wires) is going to be selected in order to reduce distribution losses and copper requirements. As a fundamental element of the new architecture, a high-power density isolated 16:1 DC/DC converts 800V down to 48V to quickly reuse most of the available ecosystem.

As a technology enabler, mid-voltage GaN plays a relevant role on the primary side, enabling an increase in switching frequency while granting efficient performance. The LLC Direct Current Transformer (DCX) topology, operating open-loop at constant fs can provide tightly unregulated 48V output with an efficiency of 98%. In this paper a detailed analysis of that converter will be described together with the key components

enabling performance in control, drive and active switches. The high-voltage architecture is prone to further evolution and enhancement in the search for the best density and efficiency. In that scope, further efforts are ongoing to explore approaches achieving fewer stages of conversion with different possible permutations of converters and intermediate bus values, leveraging the possibilities of efficiency boosts offered by lower voltage technologies, including low-voltage GaN. Another area where GaN will play an enabling role for the architecture is the newly defined sidecar rack, where the 3-phase AC to high-voltage DC conversion is implemented. Mid-voltage bi-directional GaN will realize topology simplification in front-end rectification. The architecture evolution will continue across the next generations of xPUs in line with higher power requirements. Renesas has been leading the IBC Power solution and Core supply for several generations and is now expanding the footprint in high-voltage infrastructure, collaborating with Nvidia on the new 800V architecture for data centers.

Renesas is contributing to the innovation of technologies from Grid to Core which can enable this transition through reference solutions aimed to evaluate best technical alternatives, offering highest FOM cost and reliability and generating the best evolution of the data center infrastructure architecture.

Introduction

Data centers are undergoing major disruption with AI hardware proliferation: new technology gets released by xPU and ASIC OEMs with very fast cycles (12-15 months vs traditional 30 months), with Hyperscalers realizing capex investments much higher than standard server upgrades and with semiconductor suppliers engaged in supporting this hardware revolution.

Power consumption at the xPU is increasing dramatically (multi-kW, see Figure 1) bringing the total power in the GPU rack quickly up to several hundred kW already in the next year with VR200 in NVL144, more than twice as high as today's NVL72 of GB300.

AI and networking drive significant increases in current, exceeding the current peak within the next two years. CPU power requirements will also increase, but not as quickly as those for AI. Moore's law has been steadily progressing with 2x increase every three years. Now AI is demanding 2x every 12-18 months (Huang's Law), driven by parallelism.

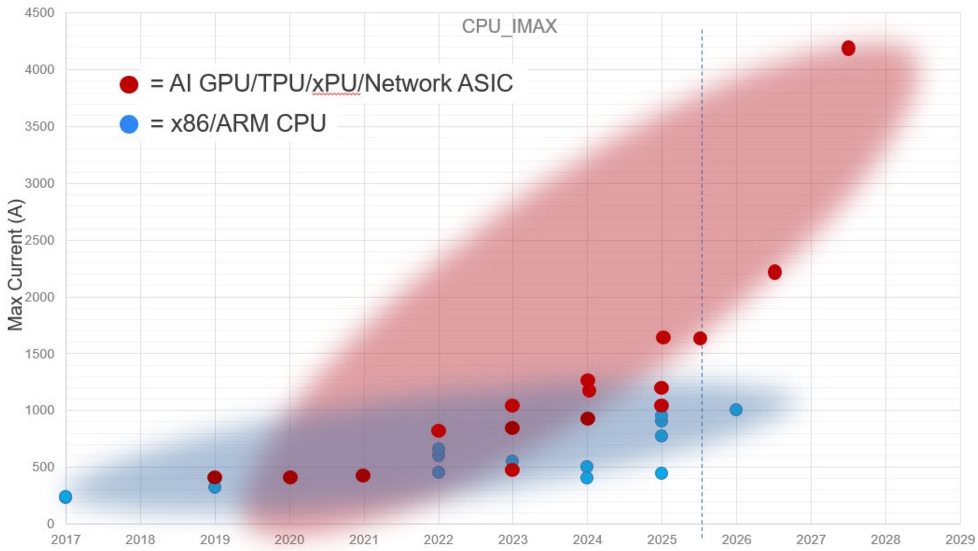
For this reason, the conventional power distribution architecture inside the rack, based on a 48V intermediate bus generated from the AC main as standardized by the Open Compute Project (OCP), needs to be modified to manage this dramatic increase of power. The current structure of the rack and architecture cannot manage the power increase without incurring huge distribution losses or massive use of copper for bus bars.

A higher voltage DC bus will be introduced by the Hyperscalers and supported in R&D by the OEMs and PSU / energy systems suppliers (Figure 2). The chosen value will reduce copper weight by almost 50%.

The two wire solution implementing 800V enables higher copper utilization, while the three wires will have lower isolation requirements, with penalty of more complex control for load balancing.

The DC high-voltage bus will be generated in an external sidecar rack starting from the main AC (3-phase 480Vrms line to line), while the IT rack will be supplied by this DC voltage and will contain all the GPUs or TPUS required to increase the computational performance of the AI infrastructure.

In this paper, we analyze a few examples of converters and topologies which will fit in the new architecture, as well as the technologies and components that enable them. Inside the sidecar rack, the AC/DC front-end may be simplified in structure and cost by the bi-directional GaN switch (GaN BDS) using a Vienna topology as in Figure 4 to generate the 800V DC bus. The power level of the AC/DC building block for the sidecar rack is trending about 20kW or higher.



Note: Thermal design current is ~ 50-70% of peak current for CPUs, ~70% for AI and ~90% for networking

Figure 1. Trends in SoC Power – Max Current

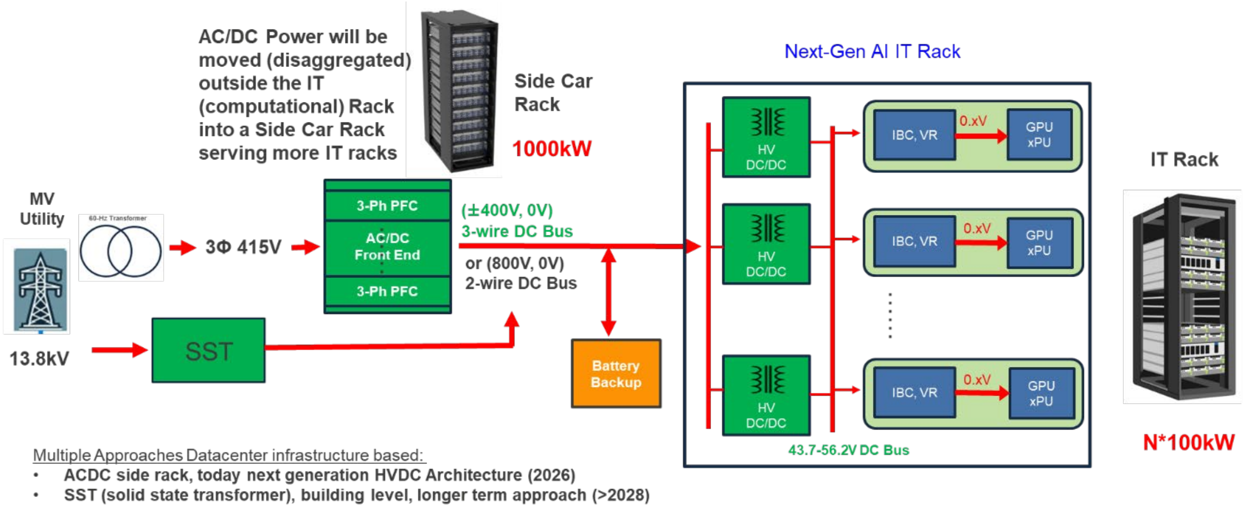


Figure 2. Next-generation 800V HVDC power delivery architecture

Inside the IT rack, the DC/DC topology implementing the 16:1 conversion down to 48V can be effectively implemented by an LLC Direct Current Transformer (DCX) topology but using a stack of two stages in series to support the entire DC input voltage (Figure 5). Also here GaN switches play a key role, due to the capability to switch at MHz level with manageable losses and as a consequence, enable a smaller size and the high power density required by the huge power level of these new racks. On the low-voltage side, the DCX generates the intermediate 48V which allows reuse of the entire existing ecosystem, both Silicon MOSFETs or GaN HEMTs can be alternatives to achieve the performance and size requirements. This DC/DC converter topology could be also used to implement a 64:1 conversion to eventually remove one stage of conversion by eliminating the 48V IBC and moving to 12V, if the efficiency can beat the 96% achievable today with two stages. Another even more direct approach may be the effort to convert the 48V down to core voltage, an approach that requires another DC/DC topology to satisfy all the efficiency specs (>90%), current density (>2A/mm2) and transients (>3kA/µsec). But several other permutations are possible in the effort to increase the overall performance, with the actual IBC converter 4:1 being replaced by an 8:1, for example with an eight-switch Hybrid Switch Cap with GaN (1000W/in3) to step down to 6V, where the conversion to core may benefit in efficiency of the lower voltage rating of the power stages.

In fact, other challenges have to be resolved also at lower voltage where the current required by the GPU will also increase, with values that trend toward a few kW. This requires providing power to the load in unconventional ways, with vertical delivery from the opposite side of the SoC with the aim of reducing distribution losses. This vertical power delivery (VPD) can be implemented by discrete solutions or more integrated modular approaches to reduce size and parasitics, combining inductors and capacitors with active elements in advanced packaging, all having extremely reduced height to fit into the blade max size. Finally, high frequency Integrated Voltage Regulators (IVR) may realize the final stage of conversion. The system architects within Renesas are currently working on all these alternative approaches to generate the best assessment of performance, standing the available technologies and those currently in roadmaps to support OEMs and Hyperscalers as they define their next generation architecture.

Renesas has been a supplier of data center power for several generations, supporting all sockets in the blades inside the IT rack as well as for all these new architectural elements by leveraging GaN and Si switches portfolio, digital controllers for IBC and multiphase core solutions, drivers and digital and analog PoL and BMS controllers (Figure 3).

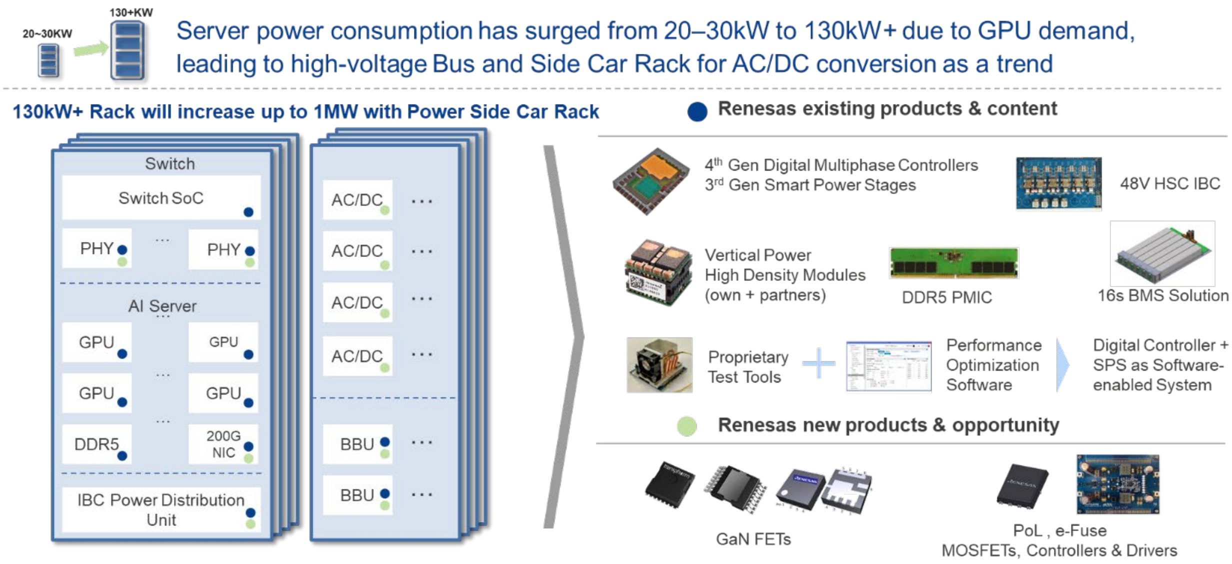


Figure 3. Renesas power portfolio supports today’s AI power solutions in data centers

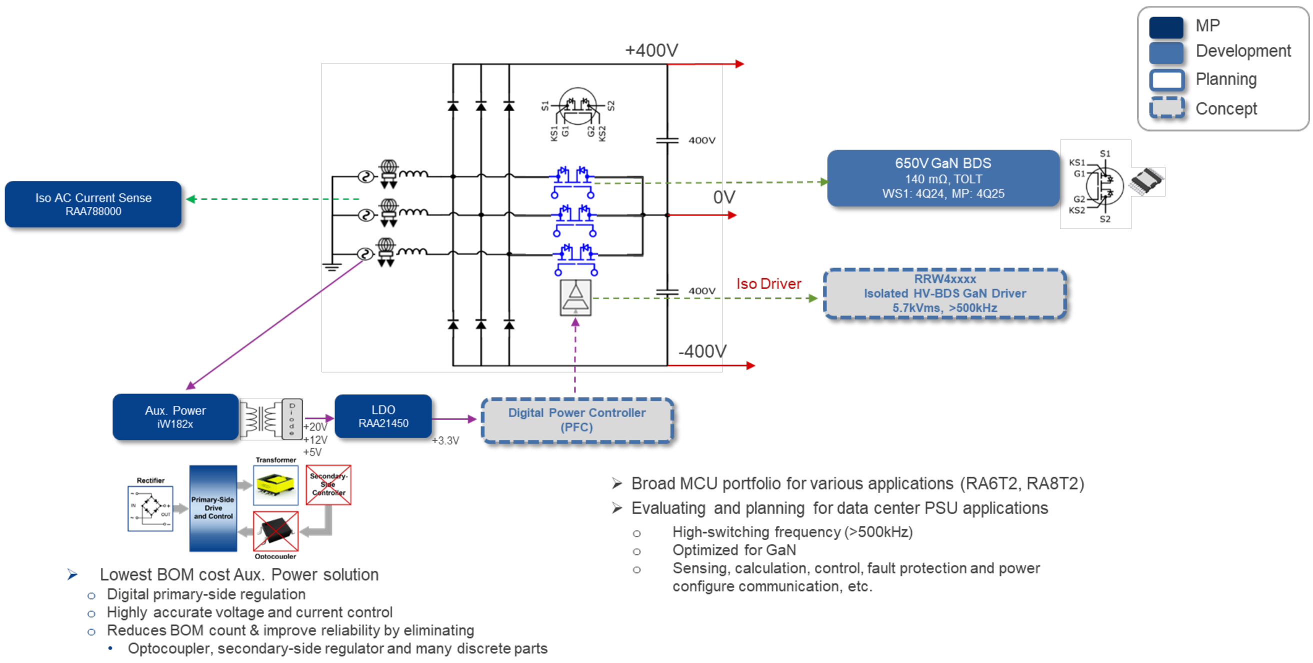


Figure 4. 3-Phase PFC Vienna rectifier for next-gen sidecar racks with BDS GaN

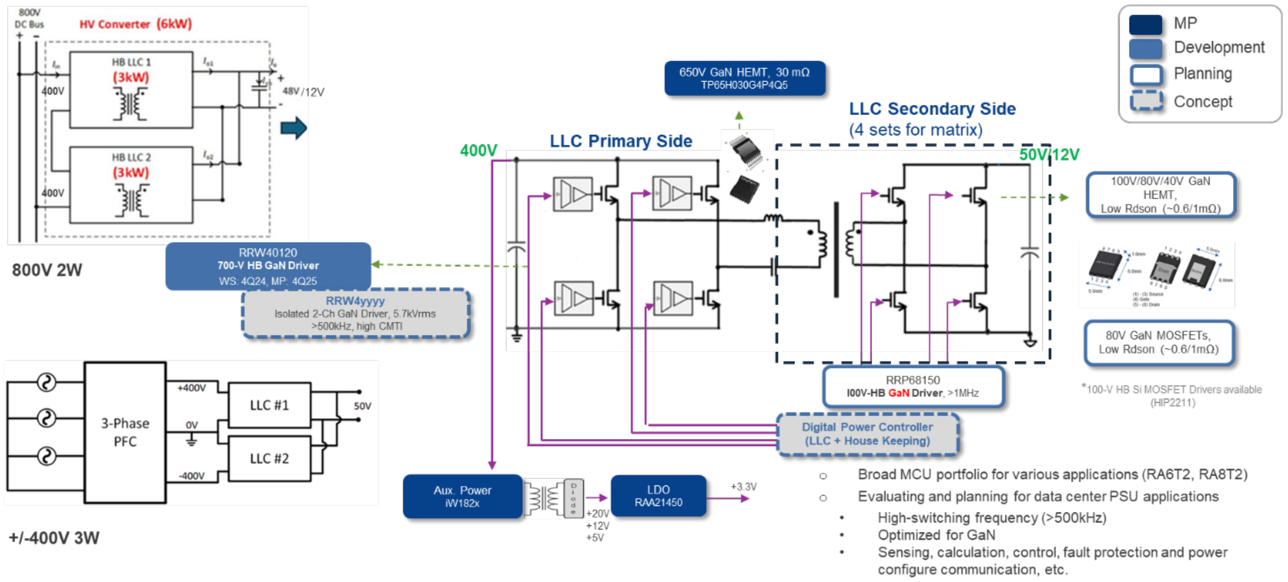


Figure 5. HV Bus data center DC/DC for next generation IT racks

Compliance with Open Compute Project Tenets

The described topic is generated in compliance with OCP tenets. The scope is to showcase a standard and open topological approach to resolve the new challenges brought by the new architecture, as well as to inspire adoption across the industry. This brings clear impacts in terms of copper saving across the IT rack and overall efficiency advantage from grid to core, for a sustainable implementation of the IT rack. The DC/DC approach, validated on a power level of 12kW around a full brick size is scalable, standing a potential power change, but also in perspective of the intermediate voltage value shift from actual 48V to a lower value to further improve overall efficiency and power density of the blades and IT rack itself. These technologies involved in the circuit implementation of the new architecture and components can also be leveraged in the sidecar AC/DC rack, where GaN BDS and UDS devices can increase efficiency and cost with the use of simplified topologies.

16:1 800V DC/DC Converter Design for the IT Rack

Figure 6 illustrates the selected system architecture and topology for an 800V-48V HV DC/DC converter, with power level of about 12kW. Two (2) units of 6kW converters can be designed and built separately and then both their inputs and outputs are put in parallel to handle the higher power (12kW). Each unit of the 6kW 800V-48V HV DC/DC consists of stacking two units of 3kW 400V-48V LLC DCX converter – inputs in series to handle 800V input and outputs in parallel to handle higher power (6kW). As a result, the 3kW 400V-48V LLC DCX becomes the basic building block in HV DC/DC systems. This is a scalable architecture supporting multiple blocks in parallel or in series.

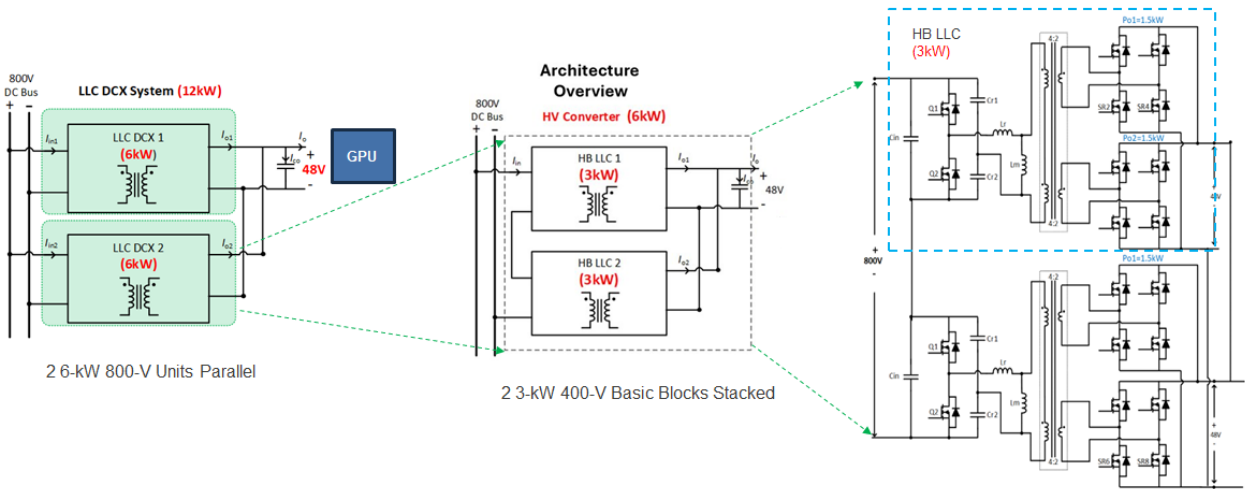


Figure 6. Architecture for 12kW 800V-48V HV DC/DC system

KEY SYSTEM TECHNOLOGIES TO ENABLE HIGH EFFICIENCY AND POWER DENSITY

There are two key system technologies that enable high efficiency and high-power density in HV DC/DC systems—LLC DCX and matrix transformer.

LLC DCX

The LLC resonant converter is widely adopted for its ability to achieve soft-switching, reducing losses and electromagnetic interference (EMI). The LLC can achieve all this while operating at high frequencies resulting in high-power density. Moreover, thanks to the unique nature of the new 800V DC/DC architecture, the LLC DCX operation can be explored, which results in additional benefits of higher efficiency and simplified control. In the new HV DC/DC, the 48V or 12V output can be unregulated since the downstream low-voltage DC/DC stages can take care of the voltage regulation and provide regulated DC voltage to power the GPU devices.

This provides the opportunity to design and operate the LLC in a DCX mode. Unlike a standard LLC converter which regulates its output by varying switching frequency, an LLC DCX always operates at or near the resonant frequency which has near unity gain, with ZVS achieved for the primary-side switches and ZCS for the secondary-side switches. It relies on its inherent characteristics to transfer power efficiently as a well-defined input-output ratio, which is determined by the transformer turns ratio. Therefore, an LLC DCX operates at the fixed conversion ratio, acting like a transformer (thus the DCX name, see Figure 7). In a standard LLC converter, closed-loop control is required for voltage regulation, which typically requires high-speed ADC sampling of multi voltage/current signals and execution of real-time feedback control algorithms within each switching cycle. However, due to its unique operation, the LLC DCX requires open-loop control. It does not need output voltage regulation, eliminating the need for time-consuming control loops. There is no real-time control needed as it runs in open-loop mode with a predefined switching frequency. There is no need for fast ADC as the system may only need slow ADC monitoring for certain high-level protections. As a result, it is possible to use standard MCUs to perform the control implementation of LLC DCX. Further, the exploration of LLC DCX may lead to new opportunities to define optimized digital power controllers dedicated to 800 VDC architecture for AI data centers.

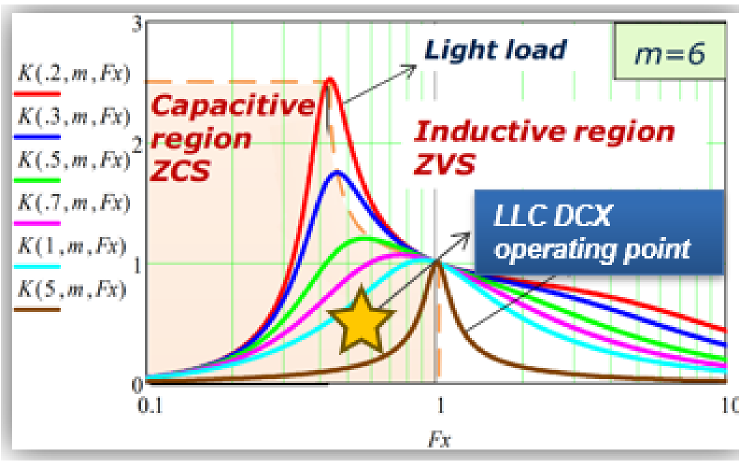


Figure 7. Typical LLC operating curve

Matrix Transformer

The matrix transformer is crucial to achieving LLC DCX's superior power density and efficiency. Unlike traditional transformers where different windings use separate magnetic components, the matrix transformer is designed and built as an array of elements inter-wired and sharing the same magnetic components so that the whole functions as a single transformer. The windings can be integrated into the main power PCB, combining synchronization rectification (SR) and output capacitors into a compact co-designed structure essential to the PCB layout and fabrication. As illustrated in Figure 8, the major benefits of matrix transformers are the following:

- Legs of multiphases sharing the same core creating flux cancellation
  - Precise leakage control among phases for better current sharing
  - Inter-phase winding configuration to create flux cancellation effect and reduce core loss and size
- Multiphase small transformers can merge into a single core, optimizing size and minimizing magnetic losses
- No need to parallel devices compared to single phase transformer
- Less termination loss compared to single phase transformer

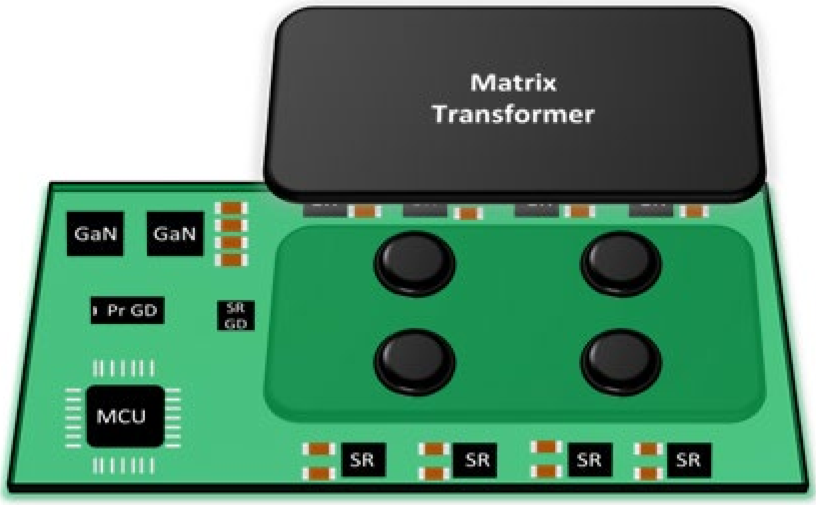


Figure 8. LLC DCX with a matrix transformer

BASIC BUILDING BLOCK DESIGN – 3kW 400V-48V LLC DCX

The circuit is based on half-bridge (HB) LLC topology, as in Figure 9. Two Renesas TP65H030G4PRS 650V, 30 mΩ GaN FETs in TOLT package are selected as the primary-side devices. This is the optimal choice for the primary-side HV switch of a 400V-48V/12V, 3kW LLC DCX module, as it provides the best combination of parameters that achieve the lowest performance loss in an LLC DCX topology. This GaN device offers a convenient top-side cooling package.

The secondary side consists of two phases of full bridge (FB) SR circuits, each using four new parts in development Renesas RBE024N08R1SZN6 80V, 2.4 mΩ MOSFETs in BSC packages. Each phase of the SR circuit handles around 1.5kW power. The primary consideration of using two-phase SR circuits is the ease of managing the power loss, thermal, parasitic effects and gate driving when handling high power and high current and avoid the need to parallel devices and the associated difficulties on leakage control. Of course, if aiming to modify the circuit for achieving a 12V output, the number of secondary phases will be increased and a center-tapped configuration will be used with a low side driver. In the 48V output version, a matrix transformer structure is used in the design, where the two secondary-side windings of the 2-phase SR circuits are wound on two legs in the same transformer core. This helps optimize core size and minimize magnetic losses. From the circuit operation and control perspective, the HB LLC is designed and controlled as a DCX, which always operates at the resonant frequency and achieves ZVS over the entire operating range, with switching frequency from 650kHz – 1MHz to enable high power density. The controller selected is the Renesas RA6T2 MCU**.** As discussed previously, LLC DCX does not require output voltage regulation, eliminating the need for time-consuming control loops or real-time control, and the Renesas MCU’s processing capability and internal resources are sufficient for the unregulated open-loop PWM control and SR control for the secondary side, together with supervision and fault handling functions. Since the HB-LLC operates in a forward mode, the SR switching signals basically follow the PWM signals for the primary-side switches, which reduces the control requirements for the MCU. On top of the basic LLC and SR control methods, there are various advanced control algorithms to minimize the loss and maximize efficiency, which are beyond the scope of this paper. Both primary and secondary PWM signals are generated by the same MCU, which stands on the secondary-side ground. The PWM signals for the primary-side switches are sent across the galvanic isolation, and isolated high-voltage high-speed gate drivers are used to drive the switches with desirable switching performance. Isolated gate drivers are not required on the secondary side, but they need adequate driving strength for the high-current FETs with high-switching frequencies, handling the power dissipation and thermal challenges. Renesas 100V HB gate driver HIP2211 is used as a secondary-side driver, with 4 devices in one LLC DCX design. Of course, GaN switches could be also used on secondary side, together with an appropriate driver and this version of the design would ultimately offer better efficiency.

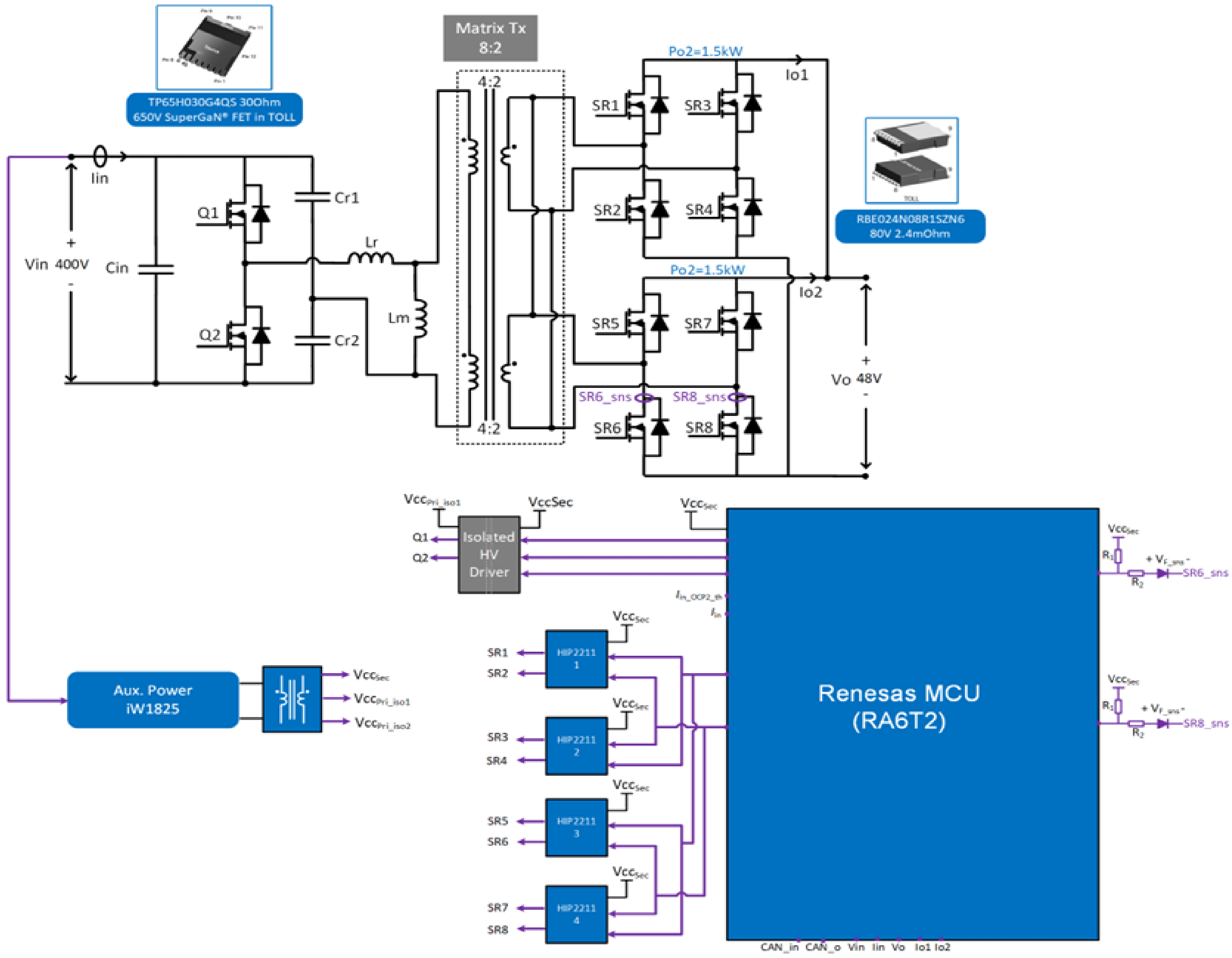


Figure 9. HVDC building block design – 3kW 400V-48V LLC DCX

Auxiliary power supplies are critical in the HVDC system, as well. They not only need to power the MCU, gate drivers and various peripherals circuits with different voltage levels meeting voltage and current regulation and galvanic isolation requirements, but also need to handle the special start up and shutdown sequence when powering up/down and connecting/disconnecting with the 800V DC bus**.** Renesas iW1825 flyback converter is selected as the auxiliary power supply for the 3kW 400V-48V LLC DCX design. iW1825 is a flyback converter that integrates a 700V power MOSFET with a high-performance digital AC/DC controller. It uses Renesas primary-side sensing technology to eliminate the need for an optocoupler and other secondary-side feedback circuits while achieving excellent line and load regulation, which not only reduces the BOM cost, but also enhances the reliability.

Transformer Design

Traditional transformers used in LLC applications typically require separate ferrite core with windings. But traditional transformers are not preferred in applications requiring ultra-high-power density due to their large size, difficulty controlling the leakage inductance and inability to integrate SRs and capacitors as in the case of planar transformers. Planar-based matrix transformers are preferrable for LLC DCX applications. With a non-integrated structure, the flux distribution is not uniform which results in higher core loss. With the integrated structure, the flux is uniformly distributed ensuring minimum core loss. In this application, the transformer has been developed together with Renesas partner Payton Group. A 3D model is developed in Ansys tool with two limb structure as shown in Figure 10 and analyzed with several variations to minimize conduction and core losses. The equal airgap on all parts of the core provides several advantages: flux and losses are spread out, the core is fully utilized and lower core losses are achieved.

Test Results – 3kW 400V-48V LLC DCX

We have designed the 3kW 400V-48V LLC DCX, built a hardware prototype and tested it. As we continue to optimize the design, we expect to further reduce the board size, with the aim to fit the entire 12kW system in a size slightly higher than a standard full brick module. Reinforced isolation requirements together with clearance and creepage requirements generate significant challenges to the form factor of the converter in the form of an onboard converter. As shown in Figure 11, the desired LLC DCX operation is achieved with switching frequency at ~650kHz, ZVS for primary switch and ZCS for secondary switch.

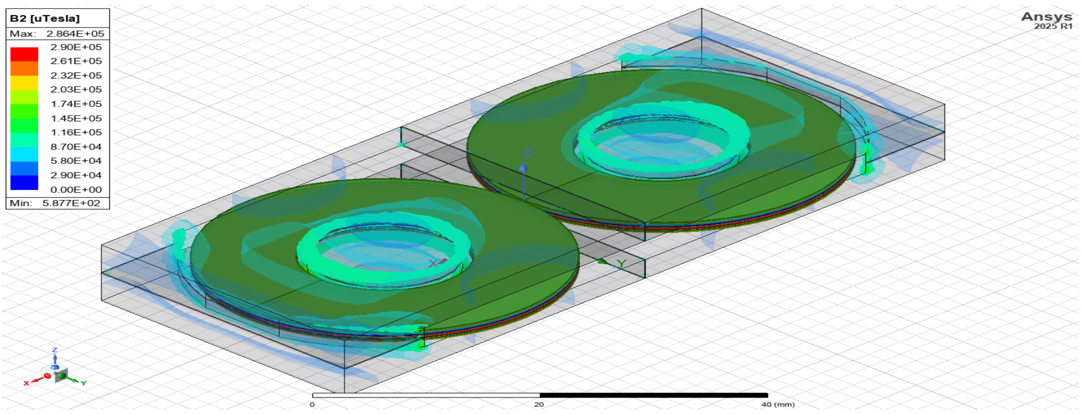
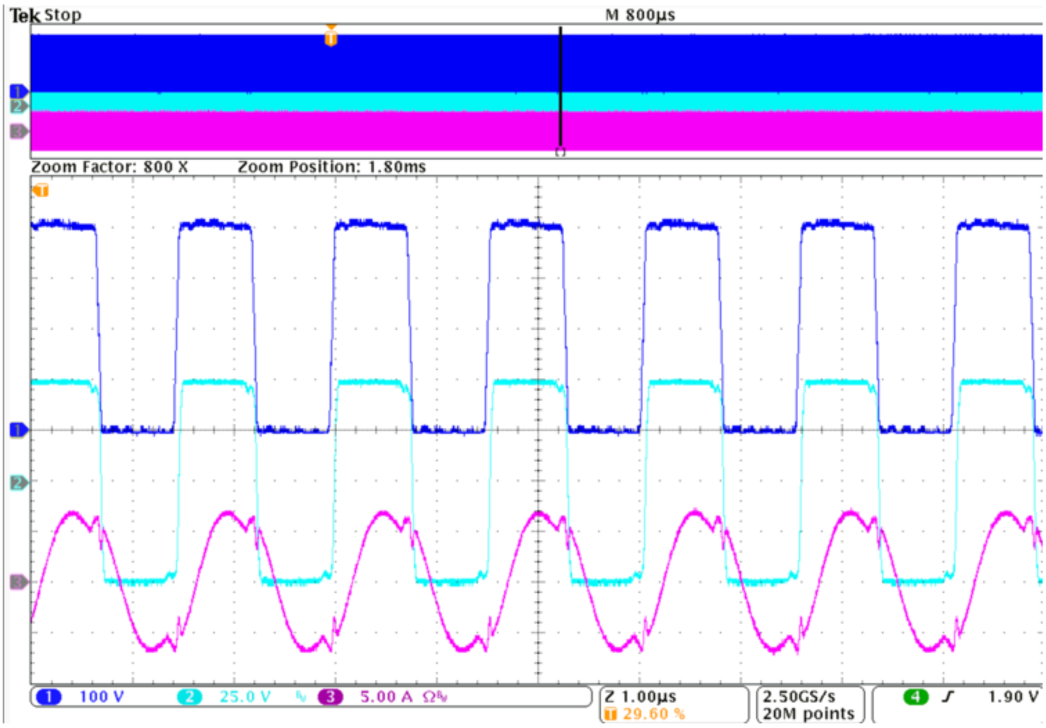


Figure 10. Ansys 3D view for equal airgap showing lower flux density distributed across the core



CH1: Primary-side switching node voltage (100V/div)
CH2: Secondary-side transformer output voltage (25V/div)
CH3: Primary current (5A/div)

Figure 11. Test waveforms of the LLC DCX prototype

64:1 800V DC/DC Converter extension

The 800V to 12V LLC DCX system architecture is similar to 800V to 48V, as shown in Figure 12. The LLC DCX topology with 8x secondary center tap configuration is preferred due to reduced secondary SR current and reduced conductional loss, thereby improving overall efficiency. This design is ongoing and different alternatives have been evaluated with the use of two transformers, a single one and different number of outputs to achieve the best performance and best power density.

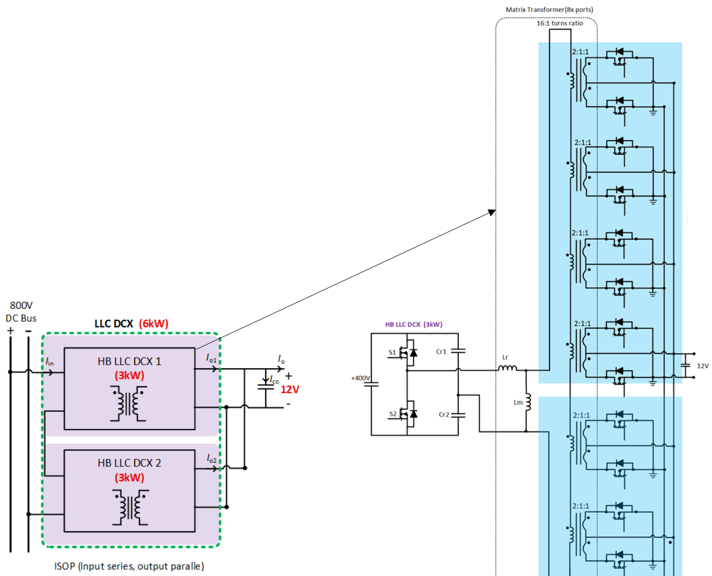


Figure 12. LLC DCX configuration with 12 V output

With support of the simulation study carried out in Simplis tool (Figures 13 and 14), efficiency at various load conditions have been benchmarked to get to the selected configuration of the topology. The efficiency performance is estimated for 3 kW output in about 96.7% which is about 1% lower than the 48V output results but shows a significant value in the approach of reducing one step of conversion.

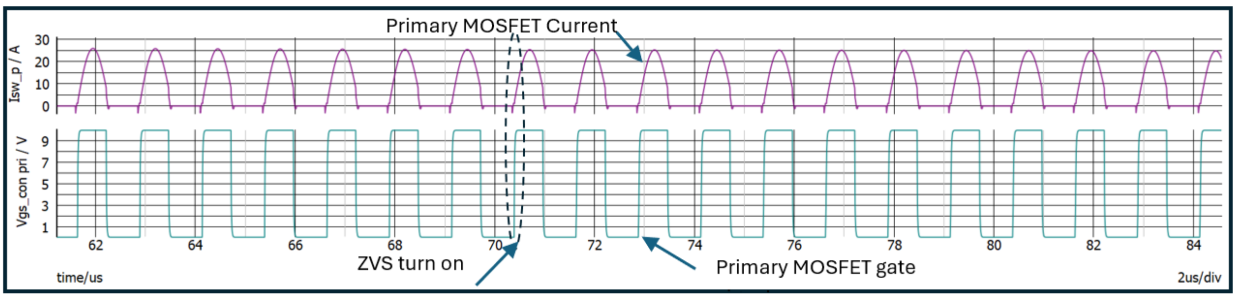


Figure 13. Primary resonant tank current and secondary switch current

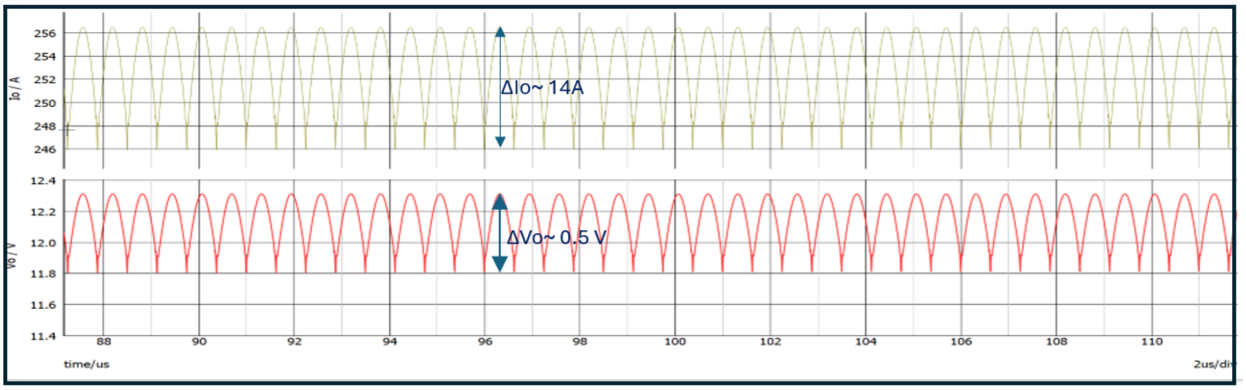


Figure 14. Output Voltage and current at 3 kW of load power

AC/DC (Front-end) PFC Converter

As shown in Figure 4, a key element inside the sidecar rack is the AC/DC front-end converter.

This AC/DC PFC interfaces with the utility grid to maintain unity power factor and is responsible for producing regulated a 800V DC bus to the downstream section. The Vienna rectifier is one of the most popular topologies for an AC/DC PFC converter in uni-directional power flow applications. The high-level block diagram shows the integration of bi-directional GaN devices which makes this topology configuration more attractive for high-power density applications compared to the conventional method of using two back-back switches in series. Key advantages of using BDS GaN in Vienna rectifier are low conduction loss, implementation of just three floating HV drivers and reduction in boost inductor size due to higher switching frequency, enabling higher power density.

The bi-directional switch which enables the ideal 4-quadrant switch, while still a lateral structure, enables dissipation through the substrate (source-down) but eventually also to add top heat dissipation capabilities. Standing the quasi no reverse recovery and fast switching, performance in switching losses is excellent. Losses are mainly due to conduction and for this reason, the active area of the devices needs to be maximized. One of the new Renesas bi-directional high-voltage GaN switches can replace two standard power transistors, reducing power stage size while increasing efficiency performance and potentially saving cost vs two transistors in series with half of the Rds_on and which normally shows higher total gate charge.

Conclusion

To meet the megawatt-scale power demands of modern AI data centers, this work presents an overview of the new high-voltage architecture as it is evolving according to the latest power demands from the new AI cores. And in line with the architecture evolution, the white paper explores in detail two building blocks for the IT rack and sidecar rack, highlighting open and scalable topology and technological approaches to achieve the performance in terms of efficiency and power density required by the application.

GaN is playing a key role in both approaches with UDS and BDS, offering lower switching losses and enabling an increase of switching frequency in the 16:1 DCX with matrix transformer and simplification of the topology in the AC/DC front-end, for a reliable overall performance. Detailed design implementation results for 3kW 400V-48V LLC DCX converter have been shown, together with electronical and thermomechanical simulations for its extension.

The principles and methodology established provide a crucial foundation to tackling the next challenges in AI data center power delivery. More architectural building blocks are being designed, built and tested to assess and benchmark performance of the potential paths of evolution. This approach can be leveraged by the data center OEMs and Hyperscalers to partner with semiconductor suppliers like Renesas toward the scope of defining the next generation's improved power solutions performance and enable implementation of more power-hungry and advanced AI hardware.

References

Renesas Power Management Solutions and Technology

NVIDIA 800 VDC Architecture Will Power the Next Generation of AI Factories

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