

Flying-Cap PFC And Three-Phase LLC Overcome Challenges Of AI Power Delivery

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Large language models are transforming how we access data. Artificial intelligence (AI) advancements are disrupting how industries and societies use data-center computing resources. Of course, this is just the tip of the iceberg. AI systems also can write code, generate pictures and videos, and transcribe and summarize meetings. All of these AI functions and queries require significant increases in power to operate (Fig. 1).



Fig. 1. Data center racks running advanced AI models are now expected to consume more than 1 MW of power by 2028.^[1]

Supporting the changes that AI is bringing to computing requirements has resulted in exponential growth in data-center power. Fig. 2 shows the first major evolutionary step in the power delivery process: the introduction of the sidecar.

The sidecar contains support peripherals for the computing functions in the IT rack. Its central purpose is to provide power through the power shelf, which converts power from the three-phase ac power lines to the high-voltage dc bus that provides power to the IT rack. This article describes innovative technologies used to create these power supplies.

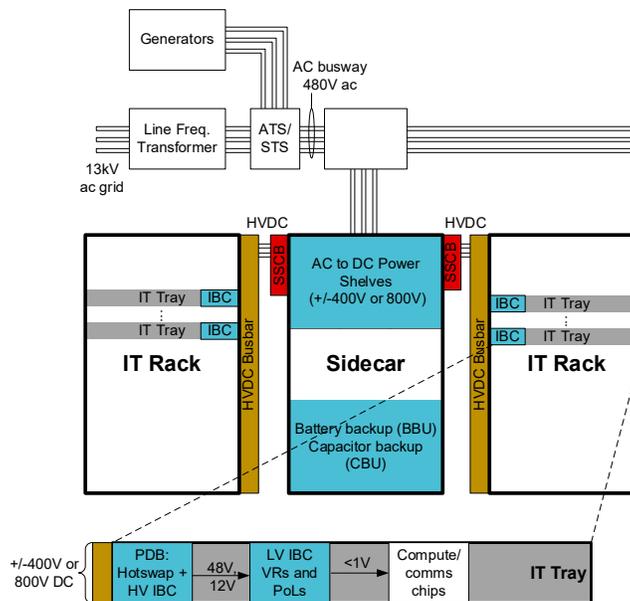


Fig. 2. A third-generation AI computing dc distribution sidecar.

Requirements For AC-DC Supplies With High-Voltage Output

The table lists the target requirements for the power supply discussed in this article. The Open Compute Project provides more detailed requirements for additional use cases in reference.^[2]

Table. Requirements for ac-dc power-supply unit (PSU) with 800-V dc output.

Parameter	Specification
Ac input voltage (line-to-line three-phase ac)	480 V
Output voltage	±400 V
Output power	30 kW
Peak power	48 kW for 50 ms

The third-generation architecture changes the input source from single-phase ac to three-phase ac to accommodate the rapidly increasing power demands. Each PSU requires approximately 30 kW of output power to meet high-voltage dc PSU system requirements.^[2] In addition to a dramatic increase in steady-state power, the power supply also must support large load transients.

The table shows a load step of 160% for 50 ms. However, reference 2 also describes a broader range of transient scenarios reaching as high as 175%.

Power-Supply Architecture

Converting power from three-phase ac with low total harmonic distortion requires a power supply capable of delivering high efficiency in a small space. One option that has recently gained more attention is the three-phase, three-level flying capacitor topology (Fig. 3).

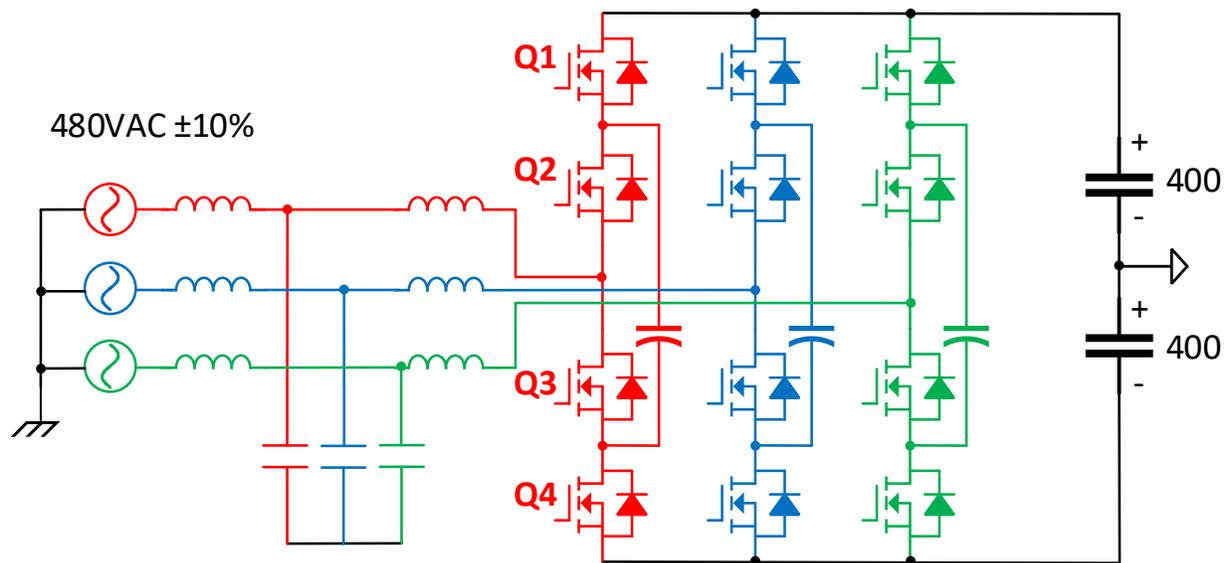


Fig. 3. Three-phase, three-level flying capacitor topology.

This topology uses four FETs for each ac phase. The capacitor connected between the midpoint of the bottom pair of FETs and the top pair of FETs is the flying capacitor, which earns its name because both terminals of the capacitor are switching rather than constantly connecting to a dc reference. When designers control the voltage across this capacitor so that it is equal to half the total output voltage (400 V in this case), each one of the 12 FETs in this topology needs to support only half the total output voltage. This topology provides significant benefits, since lower-voltage transistors have better cost-per-performance characteristics.

This topology also reduces the inductor voltage by presenting only half the total output voltage to the inductor terminal connected to the switch node. Alternating the control of the FETs in the series stack also doubles the switch frequency.

Fig. 4 shows the pulse-width modulation (PWM) pattern for one phase of the topology during the positive half cycle. When the input voltage is positive, the duty cycle of Q1 and Q3 exceeds 50%; when the input is negative, the duty cycle falls below 50%. A 50% duty cycle is equivalent to a zero current state on the input.

The reduction in the inductor voltage and the doubling of the switching frequency both reduce the effective inductor size in the design. A smaller inductor electrical value combined with a lower volt-second product makes it possible to increase efficiency and reduce the physical size of the inductors.

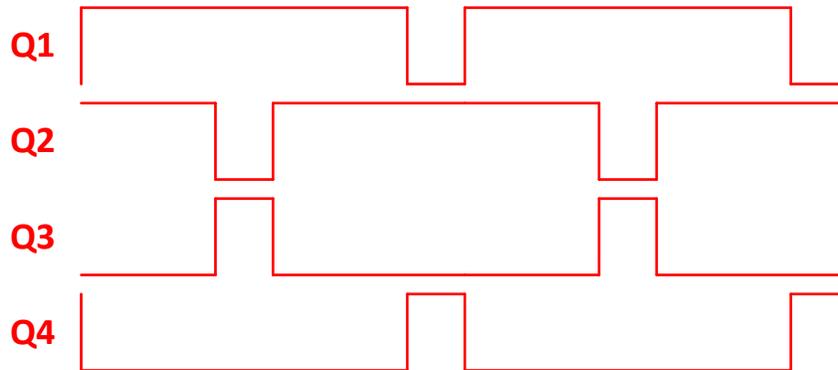


Fig. 4. Flying capacitor FET PWM pattern.

With the power factor correction (PFC) output not isolated from the ac mains, you'll need an additional power-conversion stage with isolation. This stage also provides energy holdup for ac dropout and fast transient response for the large dynamic loads demanded by AI IT racks. A strong topology option for this stage is the three-phase LLC converter (Fig. 5).

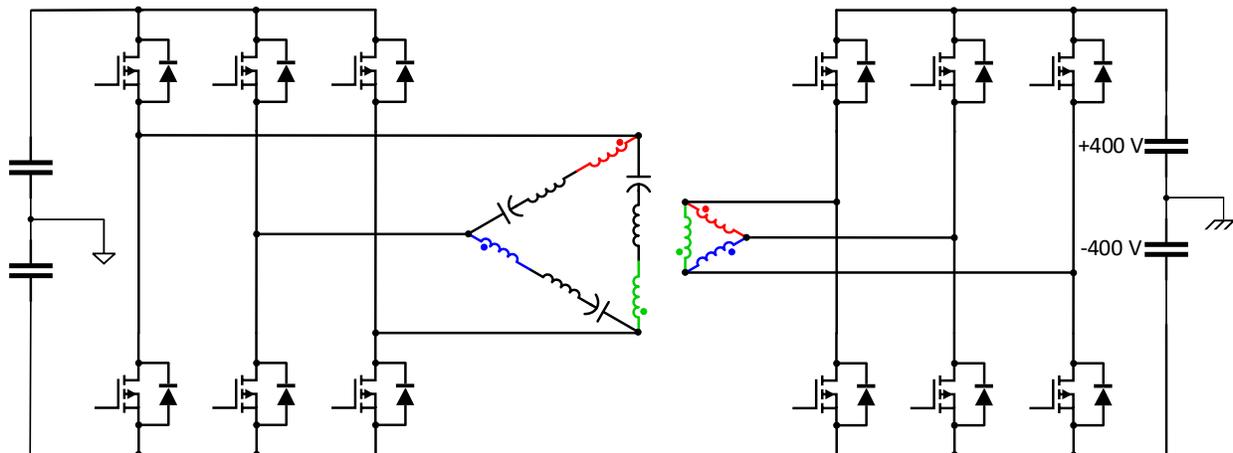


Fig. 5. A three-phase LLC converter.

This topology features three half bridges on the primary connected to the inductor-inductor-capacitor (LLC) resonant tank in a delta (Δ) configuration. Likewise, the secondary has a similar connection. Designers can connect primaries and secondaries of this topology in various ways.

Two technical considerations drove the delta-to-delta connection choice over alternatives: using the transformer leakage inductance as the resonant inductor and minimizing the root-mean-square (RMS) currents in the LLC resonant tank elements. The delta connection reduces the RMS currents by a factor of $\sqrt{3}$ compared to the wye connection. Additionally, the delta-connected primary puts the resonant inductor in series with the transformer winding, facilitating easy integration into the transformer. Reference 3 provides more detail about the different options and their tradeoffs.

To accommodate the large, fast transient load demands of AI processing, the LLC converter needs a control algorithm that can minimize the transient output voltage while keeping the output capacitance small. Hybrid hysteretic control (HHC) can control the voltage ripple across the resonant capacitor, enabling the control loop to respond to transient events faster while simultaneously maintaining excellent stability margin.^[4] Fig. 6 compares the loop dynamics of an HHC-controlled system with a traditional direct frequency controlled (DFC) system. The benefits of HHC to both the phase margin and system bandwidth are clear.

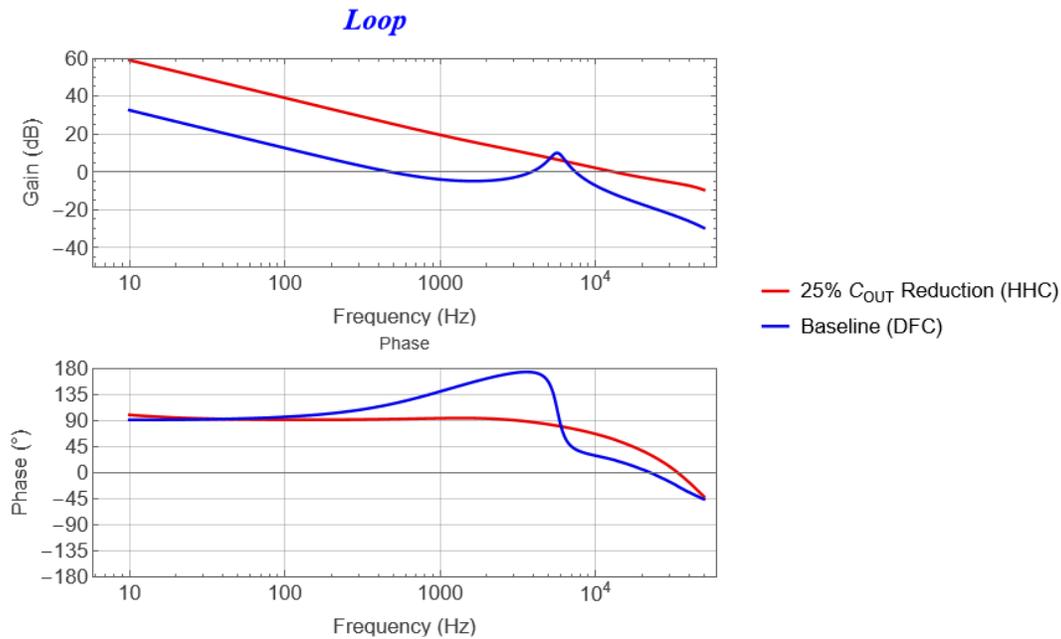


Fig. 6. HHC vs. DFC loop dynamics.

Conclusion

AI is completely changing the way IT rack power supplies are delivering power. The voltages, power levels and transient requirements require a new approach to designing these power supplies. The flying capacitor PFC and three-phase LLC with HHC are just two examples of novel approaches to solving these problems.

References

1. ["Data Centers Evolve to Meet AI's Massive Power Needs"](#) by Brent McDonald, Texas Instruments technical article, literature No. SSZTDB4, November 2025.
2. ["Diablo 400 Project: Rack and Power,"](#) v. 0.5.2, Open Compute Project, Austin, Texas, May 30, 2025.
3. ["PCB-Based Heterogeneous Integration of LLC Converters"](#) by Rimon Gadelrab, Ph.D. dissertation, Virginia Polytechnic Institute and State University, 2023.
4. ["Improving Transient Response in LLC Converters Using Hybrid Hysteretic Control,"](#) Texas Instruments application report, literature No. SLUA834B, April 2021.

Additional Resources

1. ["Five Major Trends in Power-Supply Designs for Servers"](#) by Richard Yin, Texas Instruments technical article, literature No. SSZTCW2, August 2022.
2. ["Grid-to-Gate: A Framework for Understanding Power-Management Challenges"](#) by Robert Taylor, Data Center Frontier, May 14, 2025.
3. ["High-Voltage DC Power: The Future of Data Center Power Architecture"](#) by Brent McDonald, Data Center Frontier, August 13, 2025.
4. ["High-Voltage DC: The Power Solution for AI Data Centers"](#) by Brent McDonald, Data Center Knowledge, September 11, 2025.
5. [±400-Vdc Rack for AI/ML Applications.](#)

About The Author



Brent McDonald is a system engineer and distinguished member of technical staff (DMTS) on Texas Instruments' data center systems team. A power conversion expert with 30 years of professional experience designing isolated and non-isolated ac-dc and dc-dc power conversion systems, Brent demonstrates deep proficiency in hardware design, simulation and mathematical modeling of circuits and systems. He is a recognized industry expert in both analog and digital control.

Brent is an established inventor with more than 40 patents and has authored 20 IEEE papers, two book chapters and multiple articles and white papers. He regularly contributes as an author and technical speaker at both APEC and the Texas Instruments Power Supply Design Seminar (PSDS) series. Brent earned a bachelor's degree in electrical engineering from the University of Wisconsin-Milwaukee and a master's degree from the University of Colorado.

For more on designing power supplies for data centers, see the [How2Power Design Guide](#) and select the "[AC-DC Power Supplies](#)" and "[Data Centers](#)" search results.