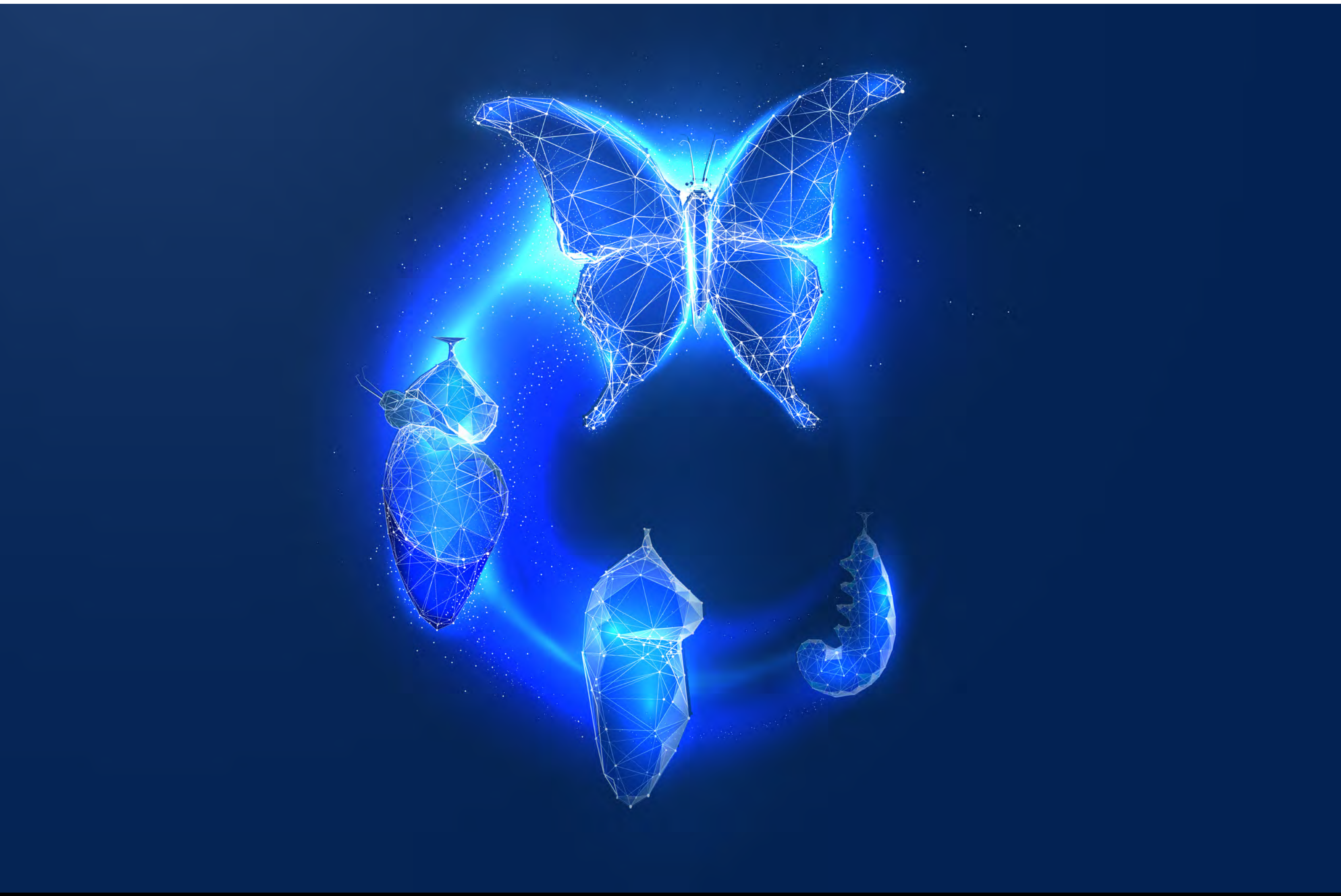
THE EVOLUTION OF ROBUST & COST-EFFECTIVE, ISOLATED DC/DC CONVERTERS



The isolated power converter has a rich history of bringing modern, complex, efficient, and SAFE electronics to fruition.

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INTRODUCTION

The isolated power converter has played a key role in advancing modern, complex, efficient, and SAFE electronics. Focusing on the key characteristics that determine isolation properties is crucial. These factors influence many of the leading aspects of today's cutting-edge power supplies, ensuring the continuation of Moore's Law on the load side while optimizing the manufacturing, cost, and reliability of critical components such as magnetics. These properties also enable the adoption of advanced packaging techniques on the supply side.

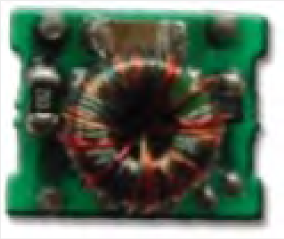
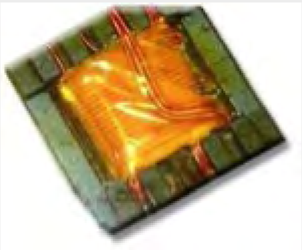
A Brief Overview of Isolated DC/DC Converters

The isolated DC/DC converter has enabled numerous applications that would not otherwise be possible, including medical power supplies, high-speed communication buses, offline power solutions, motor drives, and high-voltage use cases.

Perhaps the most significant contribution of isolated DC/DC converters is the isolation itself. The ability to SAFELY process high voltages and/or large amounts of power has been a crucial development in power electronics, benefiting society in ways that may go unnoticed. While many people may not fully appreciate these enabling technologies, they undoubtedly benefit from them in their daily lives. As power electronics engineers (or related fields), we are often the unsung heroes who "secretly" make electronics function—often seen as "black magic" or unknown to the end user.

First, let's define what isolation is and how it applies to DC/DC converters. Electrical (or galvanic) isolation refers to the physical separation of conductors to prevent the direct flow of current between them [1]. A quick way to test for any level of isolation in a system is to evaluate the ground potentials between two targets. The grounds between isolated circuits should have independent (floating) potentials. Beyond safety, there are several practical applications of floating grounds in DC/DC converters, which we will explore later.

Power conversion circuits use a variety of isolation techniques, and we will review the most relevant ones here. The classification of isolation depends entirely on the physical isolation techniques used, typically achieved through transformer assembly/construction and physical spacing. The table below provides a comprehensive overview of isolation in DC/DC converters and their implementation.

ISOLATION GRADE CLASS	DESCRIPTION	EXAMPLE USE CASE
FUNCTIONAL	■ the output is isolated, but there is no protection against electric shock	 Ring Core Transformer with Functional Isolation
BASIC	■ the isolation offers shock protection as long as the barrier is intact	 Bobbin Transformer with Basic Isolation

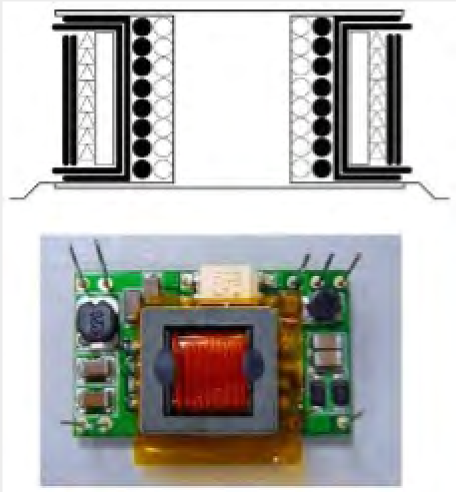
SUPPLEMENTARY	■ an additional barrier to basic, required by agencies for redundancy	 Example of a Reinforced Transformer Construction with a Basic and Supplementary Layer of Insulation (shown as the thick black lines in the diagram)
REINFORCED	■ a single barrier equivalent to two layers of Basic insulation	

Table 1: Common Isolation Grade Overview Table, From "Understanding isolation in DC/DC converters" Blog [2]

It is important to note that the requirements and aspects of isolation are governed by various industrial and safety standards, which can vary significantly depending on the application and geographical location. Therefore, it is crucial to identify any safety and certification requirements for your system early in the design process. Thorough research into the specific requirements of the application is essential, as factors such as metrics, spacings (in both 2D and 3D), isolation levels, and verification test methodologies can vary widely. These differences can often determine whether the development proceeds smoothly or faces unexpected cost and time overruns. For example, the excerpt below outlines the voltage spacing requirements for uninsulated conductors from IPC-9592B. It specifies minimum spacing based on conductor potentials and also highlights that creepage and clearance requirements in a related standard (IEC 60950 in this case) may be more stringent and should take precedence. Supporting medical and/or high-reliability applications also requires adhering to many application-specific guidelines and requirements.

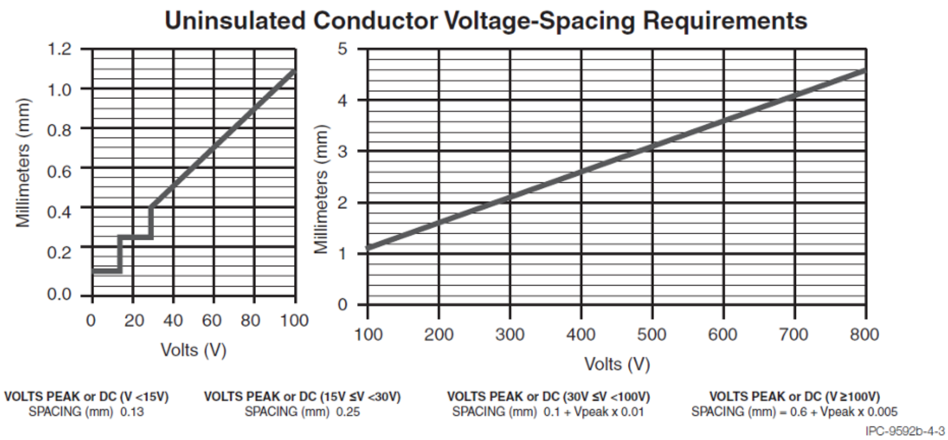


Figure 1: IPC-9592B Uninsulated Conductor Voltage-Spacing Requirements Excerpt [3]

While isolation is commonly achieved through transformer construction, it can also be implemented using other methods, especially for smaller signals (e.g., control feedback, digital communications, etc.). A common approach is isolating communication buses, such as CAN-bus in automotive and industrial applications, by using a small, isolated DC/DC converter or even capacitive isolation for digital signals. Small-signal feedback from an isolated power converter's output can be fed back to the input via an optoisolator. The optoisolator converts the signal's electrical energy to optical and then back to electrical, passing along critical control information while preserving galvanic isolation between the input and output.

Modern advancements in transformer construction, materials, 3D power packaging (3DPP®) techniques, and novel manufacturing processes have significantly improved this area. Higher levels of reinforced insulation, combined with improved assembly techniques, allow designs to meet isolation requirements while reducing the overall size. These improvements also leverage automated manufacturing processes, which enhance quality and reliability. Furthermore, they take advantage of economies of scale, ensuring that robustness and power density enhancements do not increase costs. A prime example of this progress is how manually-wound toroids are now automatically controlled by implementing a planar structure that integrates windings into printed circuit boards (PCBs) and incorporates the magnetic core materials into the surrounding geometry.

Impacts of Isolation on Converter Design

The most common figures of merit (FOM) for designing and optimizing power solutions are size, weight, and power (often referred to as SWaP factors). When combined with a cost metric, these are known as SWaP-C factors [4]. Given the varying methods and levels of isolation required by a design, these factors can significantly impact overall SWaP-C, especially in filter components. Most systems cannot ship without signoff or certification for meeting multiple safety and functional standards. These are not optional features but critical to market acceptance, often introducing additional cost and time into a project development schedule that may not have anticipated the resources needed to support these requirements.

For example, the table in the previous section illustrates the tradeoff between voltage and spacing when packing conductors at different potentials into tight spaces. The isolation grade class determines the number of isolation protection features required, along with their minimum characteristics (e.g., material, thickness, or redundancy) to meet the isolation specification, typically conveyed in terms of voltage level and withstand time for exposure to such voltages while maintaining functionality. This leads to a typical tradeoff analysis, where shrinking overall solutions to optimize SWaP can increase costs, particularly when more expensive components (such as triple-insulated wire or TIW) are required to meet these specifications in more compact designs.

Other technical factors, such as thermal mitigation and support for wide, high-voltage ranges, may drive the compactness of a solution. As with any engineering development, reasonable compromises must be made between meeting core functional and safety requirements, cost impacts on development schedules and budgets, warranty and reliability needs, and time-to-market (TTM) targets. Given that magnetics manufacturing remains one of the last manual component assembly processes on the production line, it is important to emphasize that shifting as much of this to automation and non-hand-soldered assembly can help optimize crucial elements of SWaP-C and improve the reliability of the design.

At this point, it seems beneficial to provide a quick mapping of isolated solutions to common power topologies and implementations. While a comprehensive overview of topologies is beyond the scope of this paper, the goal here is to give a brief summary of which power conversion topologies support isolation and why.

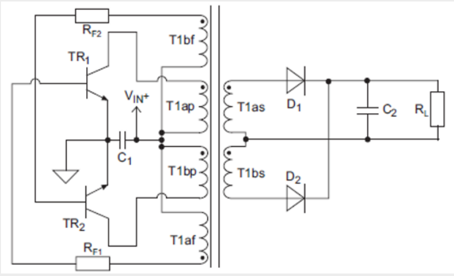
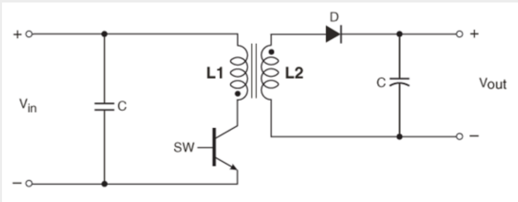
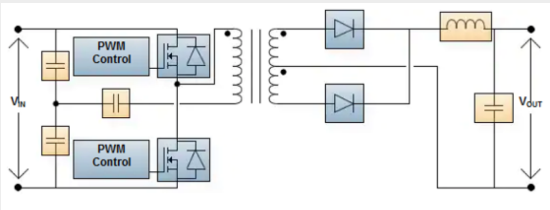
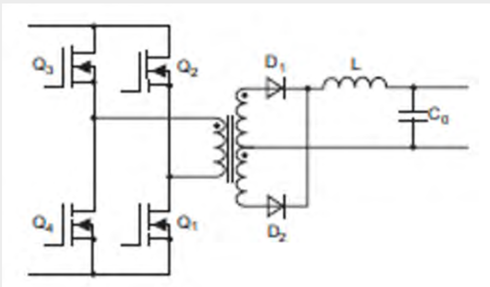
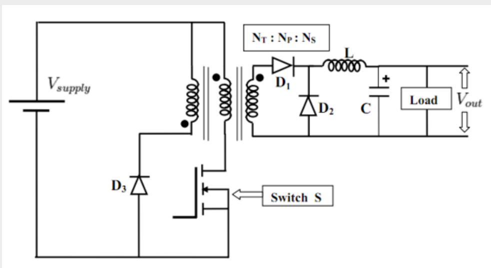
TOPOLOGY	FUNDAMENTAL CIRCUIT	IMPACTS OF ISOLATION/REGULATION
UNREGULATED PUSH-PULL (ROYER)	 Unregulated Push-Pull Converter Circuit	■ V_{out} > OR < V_{in} ■ Two switches ■ Isolated topology ■ Saturable-core transformer ■ cost-effective for higher/lower/inverted/bipolar outputs ■ Use with unregulated input
INVERTING BUCK-BOOST (FLYBACK)	 Basic Flyback Converter Circuit	■ V_{out} > OR < V_{in} ■ Single switch ■ Isolated topology ■ Higher efficiency for lower power, very robust (energy stored in transformer) ■ Most common offline power supply ■ Can be regulated or unregulated
HALF-BRIDGE (PUSH-PULL)	 Basic Half-Bridge Converter Circuit	■ V_{out} > OR < V_{in} ■ Two switches ■ Isolated topology ■ Higher efficiency for higher power ■ Utilizes half line cycle for energy extraction/commutation ■ Can be regulated or unregulated
FULL-BRIDGE	 Basic Full-Bridge Converter Circuit	■ V_{out} > OR < V_{in} ■ Four switches ■ Isolated topology ■ Highest efficiency for higher power ■ Utilizes full line cycle for energy extraction/commutation ■ Can be regulated or unregulated
FORWARD	 Basic Forward Converter Circuit	■ V_{out} > OR < V_{in} ■ Isolated topology ■ Higher cost, higher efficiency, complex magnetics assembly ■ Best for highest efficiency & power scaling, but complex control ■ Can be regulated or unregulated

Table 2: Power Converter Topology Isolation/Regulation Comparison Table

A common question is when to apply a specific topology and determine the appropriate level of isolation (if any) required by the application. Unfortunately, there are no straightforward answers, as many factors influencing these decisions are highly dependent on the use case, SWaP-C targets, and safety requirements. In some applications, isolation is used to simplify the production of certain voltage outputs, regardless of safety isolation concerns. For instance, taking advantage of the floating ground can easily enable an inverted output, a higher output, or multiple outputs, as illustrated in the figure below.

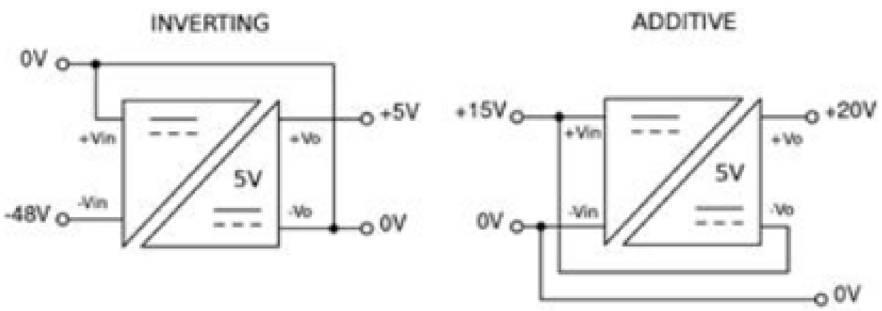


Figure 2: Non-safety Applications for Isolated Solutions, from "Understanding isolation in DC/DC converters" Blog [2]

Systems that provide external inputs and outputs through ports, wires, and direct tissue exposure (such as in some medical equipment) are common candidates for isolated power solutions. The need to support high-speed communications alongside power lines (e.g., universal serial bus (USB), Power over Ethernet (PoE), etc.) often requires specialized solutions for multiple ground potentials, stringent isolation to protect end users, and maintaining data and power integrity over long-distance buses. Even in low-power applications, using a small isolated supply for the end output or a higher-power switch can be a practical, affordable, and reliable solution.

Balancing Legacy Designs with State-of-the-Art (SOTA) Innovations

There is a constant push to take advantage of state-of-the-art (SOTA) technologies. However, it's crucial to maintain a balance with an economic development model that leverages the best of past designs, reusing proven solutions to capitalize on cost savings and established reliability. Since isolation in DC/DC circuits is often tied to the design of the magnetics, it can be a challenging decision to risk adopting a newer solution when considerable effort has been invested in the design, iteration, and qualification of a mature, well-established solution. At the same time, the pressure to improve SWaP-C factors remains a constant in nearly every market and application.

While this pressure may push some designers out of their comfort zone, it is beneficial to stay informed about emerging power supply technologies, especially those related to advanced packaging. Such innovations represent one of the most viable paths for ongoing SWaP-C optimization in the future. A practical compromise may involve starting with a reliable, proven legacy design and analyzing where SOTA innovations can improve the design, resolve the most challenging pain points, and reduce reliability, warranty, and packaging costs by using more robust, automated, and scalable solutions. A prime example is transitioning from wound magnetics to planar integration.

Another strategy is to break down traditional power solution system design and align subsystem developments with the realistic pace of roadmaps for that specific subsystem or component family. As a reminder, Moore's Law only applies to semiconductors, which will continue to drive the power density of loads. However, there is no comparable pace for the generational improvements in critical components like magnetics and energy storage. 3DPP® and advanced packaging techniques are leading the way in mitigating the gap between Moore's Law driving load reductions and the need to enable power solutions to keep pace as closely as possible. For instance, the power density improvements from pushing or switching frequencies with wide bandgap power switches (WBG, such as gallium nitride (GaN) and silicon carbide (SiC)) or from heterogeneous integration of components with 3DPP® will result in faster, generational improvements than advancements in high-frequency magnetics or larger batteries. Finding the right balance enables sustainable roadmap growth, while still leveraging SOTA technologies in power electronics.

One other well-known challenge with Moore's Law is the increase in core load current draw as technology nodes push transistor voltages down, while power density tends to increase. Increasing the current on a voltage rail introduces several design challenges, such as exponential losses proportional to current flowing through the same conductor (i.e., the same resistance), along with voltage drop challenges in longer conductors. These challenges drive the push for higher bus voltages, which in turn increases the need for isolation, particularly when bus voltages increase from 24–48V to above the 60V threshold for safety extra-low voltage (SELV) requirements, while still maintaining the necessary safety standards.

SUMMARY & CONCLUSIONS

Isolated converters have a long history in power electronics and the systems that have shaped the modern world. Given that many power supply topologies involve a complex web of design tradeoffs and seemingly endless variables, it is important to recognize that some have endured for good reasons — whether due to their simplicity, robustness, cost, or even less logical factors (e.g., apprehension towards SOTA, pressure to leverage/reuse existing designs, or simply "because that's how we've always done it!").

In nearly every use case or application, there is strong pressure to improve SWaP-C factors, even though the prioritization of optimizing each of these factors may vary. As discussed in this whitepaper, the key factors, components, and assembly processes most influenced by isolation techniques are also the ones driving SWaP-C. Therefore, investing in a deeper understanding of the implications and SOTA in this field brings complementary benefits for optimizing SWaP-C factors. Since isolation is one of the most powerful tools in ensuring safety — both for system protection and especially for users — it is essential to view generational progress through the lens of enhanced isolation techniques.

Isolation requirements can be significantly more stringent (and therefore challenging) in some applications compared to others. It is crucial to thoroughly review and understand the standards and guidelines relevant to a specific application, diving into the details of meeting safety and testing requirements, such as passing a hi-pot test or other diagnostics that validate effective isolation in a design. Simply checking off a box by reviewing a datasheet or test report for a metric or "PASS" message is not the same as understanding why these standards exist and the importance of meeting them properly. It should never be assumed that fulfilling isolation or spacing requirements for one standard automatically ensures compliance with another unless explicitly stated.

From a historical perspective, isolated power conversion remains essential in enabling technological innovations in the shrinking electronics landscape. However, it faces challenges from the rapid progress of ancillary system components that benefit from Moore's Law-like year-over-year improvements in SWaP-C factors. Fortunately, recent advancements in 3DPPR, along with supporting packaging technologies, are helping to level the playing field for power solutions and mitigate many of these SWaP-C bottlenecks as much as possible.

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