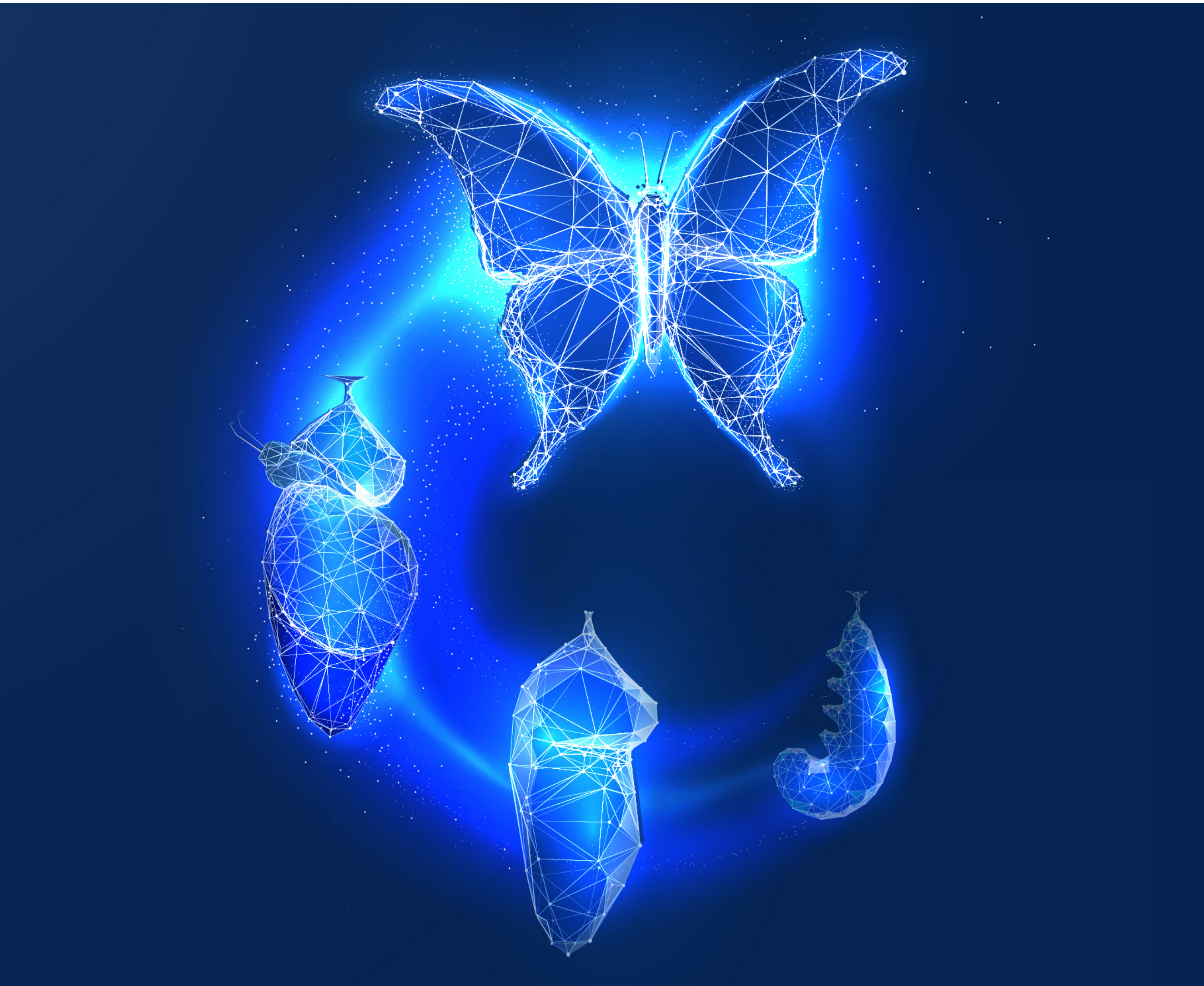
THE EVOLUTION OF ROBUST & COST-EFFECTIVE, ISOLATED DC/DC CONVERTERS



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INTRODUCTION

The isolated power converter has a rich history in bringing modern, complex, efficient, and SAFE electronics to fruition. Though of great historical contribution, the key characteristics of a power converter that dictate isolation properties are also important to keep a focus on because they are driving many of the leading factors that go into today's cutting-edge power supplies by keeping them continuing to support the pace of Moore's Law on the load side, while optimizing the manufacture, cost, and reliability of critical components such as magnetics and driving other advanced packaging techniques on the supply side.

A BRIEF OVERVIEW OF ISOLATED DC/DC CONVERTERS

The isolated DC/DC converter has enabled countless applications that would not otherwise be possible without these power electronics innovations. Some prominent examples are medical power supplies, high-speed communication busses, offline power solutions, motor drives, and high-voltage use cases.

Aside from enabling applications, one could argue the most valuable contribution of isolated DC/DC converters relates to the isolation itself. Being able to SAFELY process high voltages and/or large amounts of power has been a critical contribution of power electronics to society and the rest of the world.

Many people may not be aware of all of this and therefore not have an appreciation for these enabling technologies, but I am sure they are happy with the results in their daily lives. As power electronics engineers (or related), we are very much accustomed to being the unsung heroes that "secretly" make all the electronics of the world operate even if considered "black magic" or unbeknownst to the user.

First off, we should define what isolation is and how it applies to DC/DC converters. Electrical (a.k.a. – galvanic) isolation is the physical separation of conductors to prevent the direct flow of current between them [1]. The quickest test for evaluating if any level of isolation is present in a system is to evaluate the ground potentials between two targets. The grounds between isolated circuits should be at independent (a.k.a. – floating) potentials. In addition to safety needs, there are several, practical uses of floating grounds in DC/DC converters, which will be covered a little later.

There are too many different types, methods, and implementations of isolation used in power conversion circuits so we shall quickly overview the most salient here. The classification of isolation depends completely on the physical isolation techniques, often accomplished in the transformer assembly/construction, and also by physical spacing. The table below comes from a more comprehensive overview of isolation in DC/DC converters and their implementation.

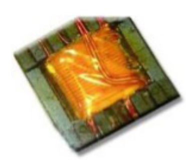
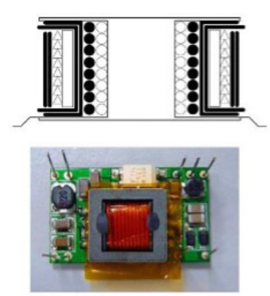
ISOLATION GRADE CLASS	DESCRIPTION	EXAMPLE USE CASES
FUNCTIONAL	The output is isolated, but there is no protection against electric shock	 Ring Core Transformer with Functional Isolation
BASIC	The isolation offers shock protection as long as the barrier is intact	 Bobbin Transformer with Basic Isolation
SUPPLEMENTARY	An additional barrier to basic, required by agencies for redundancy	
REINFORCED	A single barrier equivalent to two layers of Basic insulation	Example of a Reinforced Transformer Construction with a Basic and Supplementary Layer of Insulation (shown as the thick black lines in the diagram)

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

It is very important to note the requirements and aspects of isolation needs are dictated by many different industrial/safety standards, which can be highly dependent on the application and/or geographical location of usage. So be sure to capture any safety/certification requirements for your system early in the design process. It is imperative to research the specific requirements of the application at hand as the metrics, spacings (in 2D & 3D), isolation levels, and verification test methodology/setups can vary greatly and often be the difference maker between a smooth development and unexpected cost/time budget overruns. For instance, please see the excerpt below for voltage spacing requirements of uninsulated conductors from IPC-9592B. While it clearly calls out minimum spacing based on conductor potentials, it also notes that creepage/clearance requirements in a related standard (IEC 60950 in this case) may be more stringent and should take precedence. Supporting a medical and/or high-reliability application will also come with many application-specific guidelines/requirements in this regard.

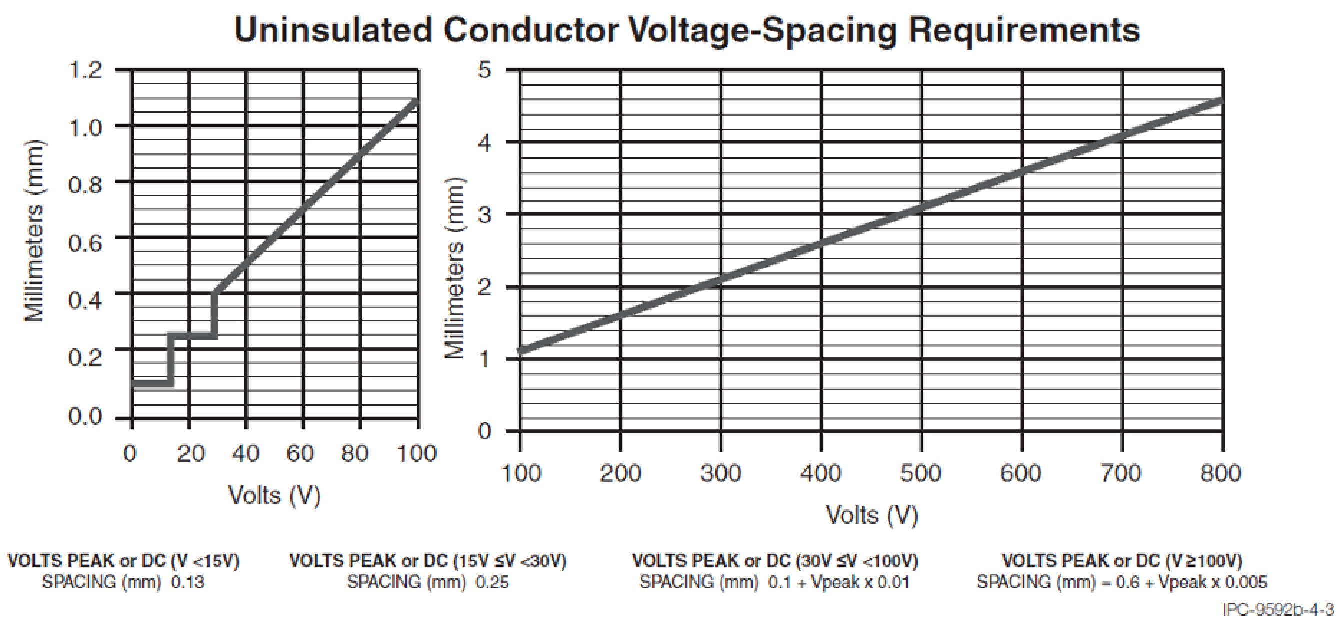


Figure 1 – IPC-9592B Uninsulated Conductor Voltage-Spacing Requirements Excerpt [3]

While isolation is commonly accomplished in the transformer construction, it can also be implemented in other ways, particularly for smaller-signals (i.e. – control feedback, digital communications, etc.). It is very common to isolate communication buses, such as that of CAN-bus in automotive and industrial applications, by using a small, isolated DC/DC or even capacitive isolation for digital signals. The small-signal feedback information from an isolated power converter's output can be fed back to the input via an optoisolator that converts a signal's electrical energy to optical, then back to electrical, thus passing along the critical control info, while preserving the galvanic isolation between input and output.

Modern improvements in transformer construction/materials, 3D power packaging (3DPP) techniques, and other novel geometries and manufacturing processes have made great strides in this space. Higher levels of reinforced insulation along with improved assembly techniques enable a design to meet isolation requirements, while still shrinking the overall size of the solution and utilizing the benefits of more automated manufacturing processes. This enhances overall quality and reliability, while concurrently taking advantage of economies of scale so the robustness and power density improvements do not come at the detriment of cost. A prime example is how previously manually-wound toroids are now automatically controlled by implementing in a planar structure that embeds windings in printed circuit boards (PCB) and incorporates the magnetic core materials directly into the surrounding geometry.

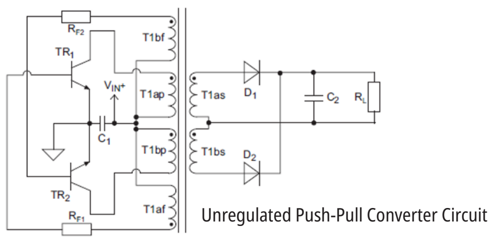
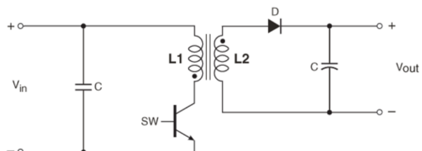
IMPACTS OF ISOLATION ON CONVERTER DESIGN

As highlighted in many resources regarding the design and optimization of power solutions, the most common figures of merit (FOM) for a system are its size, weight, and power (a.k.a. – SWaP factors) characteristics. When combined with a cost metric, this can also be referred to as SWaP-C factors [4]. Given the different methods and levels of isolation a design may require, these support needs can have big impacts to overall SWaP-C factors, particularly in filter components. Most systems cannot ship without signoff/certification for meeting (sometimes) multiple safety and functional standards so these are not "nice to have" kind of solutions, but can annoyingly become the critical path to market as well inject cost and time into a project development schedule that did not account for the resources required to support these contingencies.

For instance, the table in the last section demonstrated the tradeoff in voltage versus spacing needs when packing conductors at different potentials into tight spaces. The class of isolation grade determines how many isolation protection features must be present and their minimum characteristics (i.e. – in terms of material, thickness, and/or redundancy) for meeting the isolation spec (typically conveyed in terms of voltage level and withstand time for a exposure to such voltage(s) to still be functionally viable). This translates into a very typical tradeoff analysis between wanting to shrink overall solutions for optimizing SWaP, yet also coming at the detriment of cost when more expensive components (such as triple-insulated wire or TIW) can help to meet requirements in more compact arrangements.

Other technical factors such as thermal mitigation and supporting wide, high-voltage ranges may drive the compactness of a solution. Like any engineering development, reasonable compromises need to be made between meeting the core, functional/safety requirements of the system, cost impacts to development schedules/budgets, warranty/reliability needs, and time-to-market (TTM) targets. Given magnetics manufacturing remains amongst the last of manual component assembly needs on the line, it should be reiterated that relegating as much of that to automation and non-hand-soldered assembly as possible can help optimize many of the most crucial elements of optimizing SWaP-C and improving reliability in a design.

At this point it seems prudent to provide a quick mapping of isolated solutions to common power topologies and implementations. While a comprehensive topology overview is beyond the scope of this paper, this is meant to give a brief overview on 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 • Low-cost 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

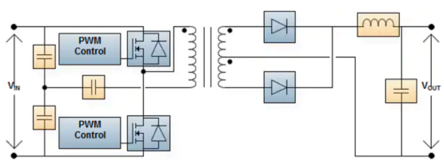
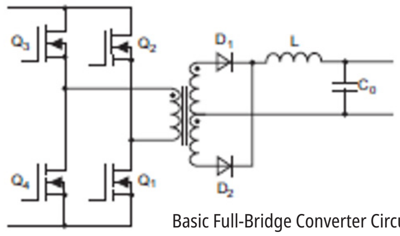
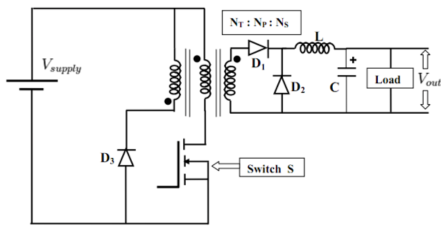
TOPOLOGY	FUNDAMENTAL CIRCUIT	IMPACTS OF ISOLATION/REGULATION
HALF-BRIDGE (PUSH-PULL)	 Basic Half-Bridge Converter Circuit	• V_{out} > OR < V_{in} • Two Switches • Isolated Topology - Highest Efficiency for Higher Power • Utilizes full line cycle for energy extraction/ commutation • Can Be Regulated or 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

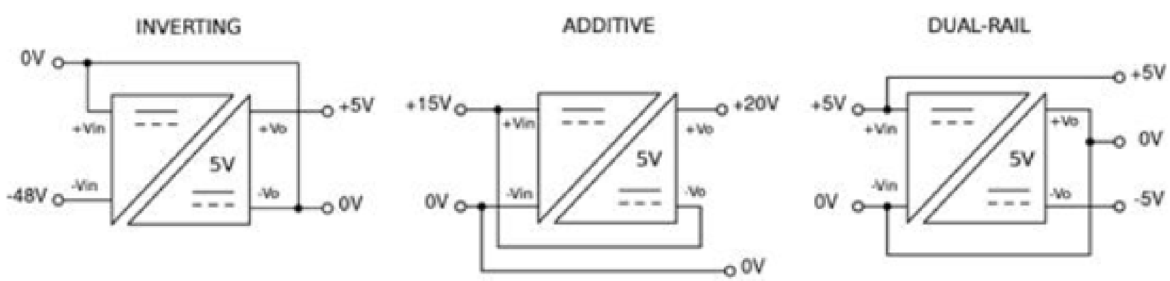


Figure 2 – Non-safety Applications for Isolated Solutions, From "Understanding isolation in DC/DC converters" Blog [2]

A natural and very common question to ask is about when to apply what topology and determine the appropriate level of isolation (if any) required by the application. Unfortunately, there are no direct answers because so many factors driving decisions are highly dependent on the use case, SWaP-C targets, and safety needs. There are even applications in which isolation is used to simplify the production of certain voltage outputs, irrespective of any needs for safety isolation. Taking advantage of the floating ground can easily enable an inverted output, a higher output, or multiple outputs as **shown in the figure above**.

Systems that provide external inputs/outputs in the way of ports, wires, and direct tissue exposure (such as with some medical equipment) are common candidates for isolated power solutions. The requirements to support high-speed communications concurrent with power lines (i.e. – universal serial bus or USB, Power over Ethernet or PoE, etc.) may come with specialized needs for multiple ground potentials and/or stringent isolation to protect end users and/or maintain data and power integrity over physically-long busses. Even in very low-power applications, the use of a small isolated supply for the end output or to drive the gate of a higher-power switch can be a very pragmatic, affordable, and robust solution.

WHEN TO LEVERAGE THE PAST? WHEN TO TAKE ADVANTAGE OF THE STATE-OF-THE-ART (SOTA)?

There is a constant push-pull feeling in the pressure to always want to take advantage of the state-of-the-art (SOTA), but in careful balance with an economic development model that leverages the most and best from the past so as to reuse known-good designs and take advantage of the associated cost savings and proven reliability. Given that isolation in DC/DC circuits is often tied to the design of the magnetics, it can be a grueling choice to take a risk on a newer solution when so much blood, sweat, and tears went into the design, iteration, and qualification of a mature, shipping design. Conversely, the perpetual pressure to improve SWaP-C factors is ever-present in just about any market or application space.

While it may push some designers out of their comfort zone, it can be a very worthwhile exercise to keep a finger on the pulse of power supply technologies, especially those related to advanced packaging, since such innovations are really the most attainable path to constant SWaP-C optimization in the future. Perhaps the best compromise is found in starting with a robust, proven, legacy design and breaking it down to see where the SOTA can bring improvement, address the most challenging pain points of a previous design, and mitigate reliability/warranty/packaging costs with the use of more robust, highly-automated and scalable solutions, such as a transition from wound magnetics to planar integration.

Another strategy is to disaggregate traditional power solution system design and match subsystem developments to better-align with the realistic pace of roadmaps for that given subsystem or family of components. As a reminder, Moore's Law only applies to semiconductors and will continue driving the power density of the loads, but there is no such pace to the generational improvements of roadmaps for critical components in magnetics and energy storage. 3DPP and advanced packaging techniques certainly the lead way to mitigate the gap between Moore's Law driving loads down and wanting to enable the power solutions to keep the pace as close as possible [5]. For instance, the power density improvements yielded from pushing switching frequencies with wide bandgap power switches (WBG, such as gallium nitride or GaN and silicon carbide or SiC) or from heterogeneous integration of components with 3DPP will yield faster, generational improvement than advancements in high-frequency magnetics or a bigger battery. Finding the right balance provides sustainable roadmap growth, while still taking advantage of the SOTA for power electronics.

One other well-known challenge that Moore's Law brings is an increase of core load current draw as technology nodes drive transistor voltages down, while power density nearly always tends to increase. Increasing the current on a voltage rail introduces several design challenges with the exponential losses proportional to current moving in the same conductor (e.g. – same resistance) along with the voltage drop challenges in longer conductors. These challenges drive a push for increasing bus voltage, which can translates right back to the need for isolation, particularly for bus voltages growing from 24-48 V to beyond the threshold of 60 V for safety extra-low voltage (SELV) and still needing to maintain safety requirements.

SUMMARY & CONCLUSIONS

Isolated converters have a long history in the world of power electronics and associated powered systems that have made our modern world possible, while also being safe. Given the many power supply topologies that can be a highly-convoluted web of design tradeoffs and seemingly endless variables to consider, it is helpful to note that some have endured for good reasons, whether they be for their simplicity, robustness, cost, and sometimes not-so-logical factors (i.e. – apprehension to SOTA, leverage/reuse pressure, or just plain "'Cause that's how we always did it, that's why!").

In just about any use case or application space, there is great pressure to improve SWaP-C factors even when the prioritization of optimizing each of these factors may differ. As explored in this discussion, the key factors, components, and assembly processes most impacted by the use of isolation techniques also just happen to be the ones driving SWaP-C so the investment to understand the implications and SOTA in this space yields the complementary benefits of optimizing SWaP-C factors. Given isolation is one of the greatest tools we have in the quest for safety (for system protection and ESPECIALLY for users), it is imperative to see generational improvement through the lens of enhanced isolation techniques as well.

Isolation requirements can be far more stringent (and therefore challenging) in some applications versus others. It is very important to fully review and internalize any standards/guidelines associated with an application space and dig into the specifics of meeting certain safety/testing requirements, such as passing a hi-pot test or another diagnostic validating effective isolation in a design. Checking a box from reading a datasheet or reviewing a test report in search of a metric or "PASS" message is not the same as having an appreciation for why these standards exist and why we go through so much pain and effort to ensure they are properly met. It should never be assumed that meeting spacing/isolation needs for one standard implies compliance with any other unless explicitly stated.

As one looks from the historical perspective to the SOTA, it can be seen how isolated power conversion remains a staple of enabling technological innovation in the world of shrinking electronics, but is challenged by the outpacing of ancillary system components that can take advantage of Moore's-Law-like trajectories of year-over-year improvement to SWaP-C factors. Luckily, recent progression in 3DPP and supporting, packaging technologies are allowing somewhat of a leveling of the playing field for power solutions to mitigate as many of these SWaP-C bottlenecks as possible.

REFERENCES

[1] Wikipedia contributors, “Galvanic isolation,” Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Galvanic_isolation&oldid=1137872797 (accessed February 15, 2023).

[2] “Understanding isolation in DC/DC converters,” RECOM Blog, Aug 14, 2019, https://recom-power.com/en/rec-n-understanding-isolation-in-dc!sdc-converters-69.html (accessed February 15, 2023).

[3] Power Conversion Devices Standard Subcommittee (9-82), “IPC 9592B: Requirements for power conversion devices for the computer and telecommunications industries,” IPC, Bannockburn, IL, Nov 2012, pg. 20. Available: https://shop.ipc.org/ipc-9592/ipc-9592-standard-only.

[4] “Power Supply Design for maximum Performance,” RECOM Blog, Oct 21, 2022, https://recom-power.com/en/rec-n-power-supply-design-for-maximum-performance-229.html (accessed February 15, 2023).

[5] 3D Power Packaging® for Low Power DC/DC converters, https://recom-power.com/en/applications/high-power-density/3dpp/3dpp.html (accessed January 23, 2023).