flex

Verification and Qualification Considerations for Digital Power Modules

Digitally-controlled power supplies introduce elements that can be unfamiliar to many power-system designers, threatening to complicate the qualification and verification processes that assure end-product quality. Yet analysis shows that the change from analog to digital inner-loop control is a well-proven evolution that provides rock-solid foundations for today's Quality Assurance processes.

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Digitally-controlled and managed power supplies represent a rapidly-growing part of the power conversion industry, and are breaking out of the telecom/datacom markets and on into far more mainstream applications where the superior performance and reliability of distributed power can deliver major benefits. This is an exciting area to work within or explore because of the many advantages that digital inner-loop control and integrated power-management subsystems offer over a conventional "dumb" analog control methodology.

Many recent articles and papers address the hardware and system impacts that "digital power" brings to a traditionally conservative market sector. Some of these effects may initially be unseen, such as the potential for slashing inventory and easing logistics by being able to program the same device to accommodate multiple output voltages and numerous other parameters besides. In this respect, a well-designed digital power converter echoes the difference between 7400/4000-series random logic and a CPLD or FPGA.

But just like their programmable-logic forbears, the full impact of highly-configurable digital power supplies extends beyond immediately obvious boundaries. For instance, a key impact falls upon the Quality Assurance (QA) processes that must now accommodate parameters and processes that were formerly alien to analog-converter environments. The underlying reason is simple – a conventional analog power converter is hard-wired to perform within well-defined and often relatively inflexible parameters, and over time the industry's QA regime has been perfected to suit this model.

With onboard firmware making it possible for users to program multiple parameters that determine the converter's operational behavior within the power industry's standard PMBus™ architecture, the sea-change in flexibility that digital power delivers breaks the regular QA model for analog power supplies.

Unfamiliar issues that cede from the digital hardware platform may also surface that are well known in other environments. For instance, the automotive industry had to learn how to qualify the crucial elements within digital control systems before deploying products that routinely have life-critical implications.

The auto industry took its lead from aerospace with the result that the accompanying qualification and verification overhead is immense, and generally only justifiable when people's lives may be at risk. The recently-released auto-industry functional safety standard ISO 26262-1:2011 endeavors to ensure that no unacceptable risk can arise due to failures in electrical and/or electronic systems, including elements such as software and memory integrity. Parts of this model may prove interesting to QA engineers seeking formal guidance in developing their own qualification and verification regimes.

The telecoms industry has traditionally sought "five-nines" availability for its networks – that is, 99.999% uptime – and this model has been seen by general industry as a beacon that mainstream systems endeavor to emulate. As a result, the challenge to QA engineers who are faced with digital power becomes one of ensuring that end products carry the same or better confidence than their analog predecessors.
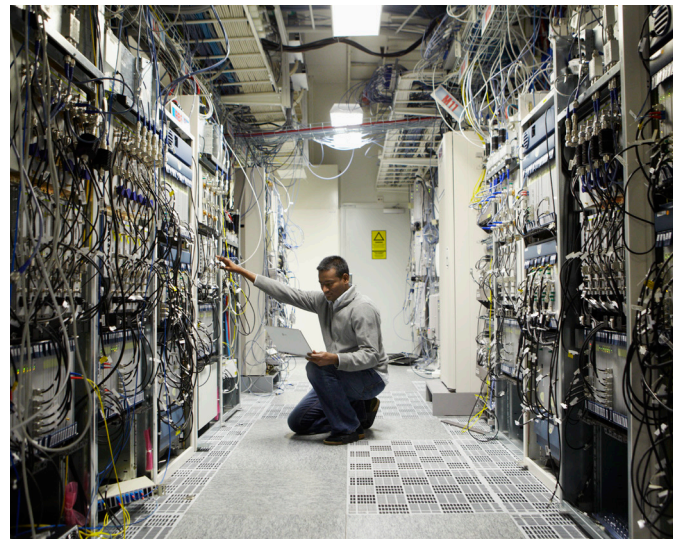

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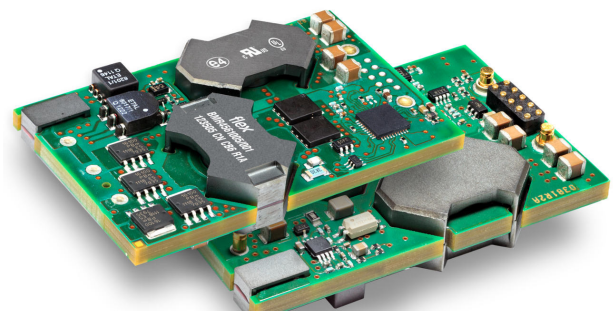
Digital Control

The illustration below compares the key differences between analog and digital control methodologies. Notice that much of the converter's hardware does not change when moving between these platforms – filtering, magnetics, and power semiconductors remain similar
if not exactly the same as before. What changes is the method of PWM (pulse-width-modulation) control that in the familiar example of a buck converter varies the duty cycle of the top (control) MOSFET and the lower (sync) switch.

Figure 1 shows that the digital power converter abandons analog control-loop dynamics in favor of a system that converts the feedback error-signal into numbers that are compared in a digital summing amplifier, filtered in a

proportional-integral-differential (PID) filter, and then fed into a logic block that's optimized for high-speed, high-resolution PWM generation. Mixed-signal technology makes it economically attractive to include the PMBus™ serial digital interface that's built upon the SMBus physical layer, which is a rugged evolution of the familiar I2C (inter-integrated-circuit) board-level bus. Crucially, PMBus features a standard command language and protocols that are specifically designed to implement robust power-control applications. The on-chip measurement and control subsystems that appear in PMBus-compatible products such as Flex's 3E series boast functionality that no conventional analog power converter can match, yet the devices are perfectly capable of standalone operation.
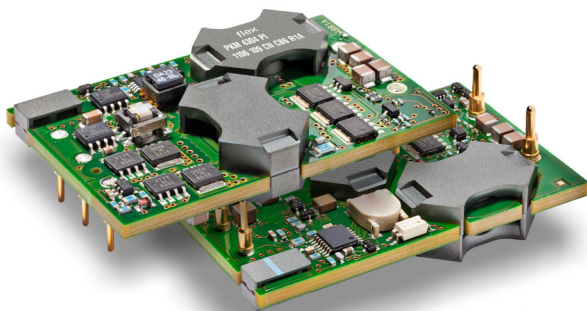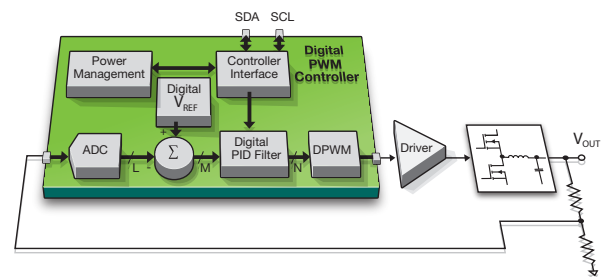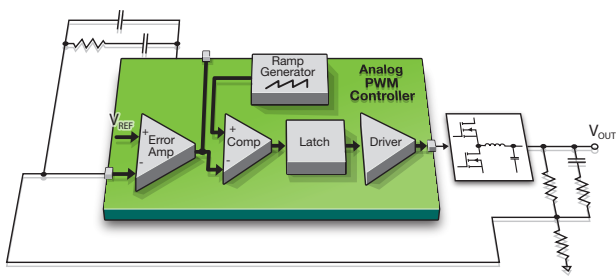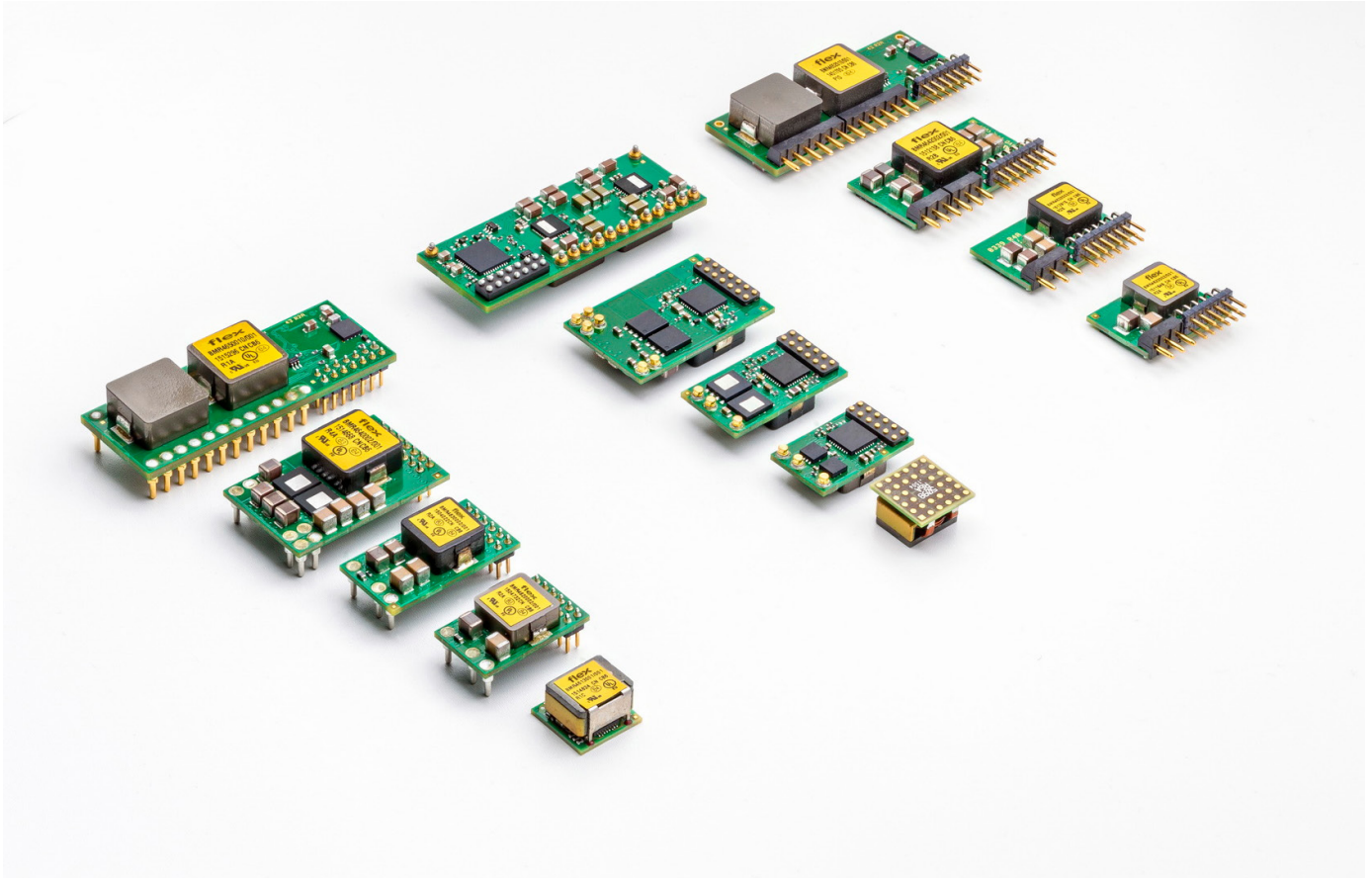

Analog DC/DC Converter

Digital DC/DC Converter

Figure 1. A digital buck-converter substitutes digital-signal-processing techniques for the traditional analog control loop.

Flex's 3E series of power modules includes a range of PMBus-compliant isolated Advanced Bus Converters and non-isolated Point-of-Load (POL) regulators. In an industry first, several recent products implement Flex's Energy and Performance Optimizer algorithms within their firmware to dynamically minimize power consumption.

The algorithms that control the digital core are generally factory-set and reside in protected, nonvolatile on-chip memory. Depending upon the converter's implementation, key parameters may be available for users to modify – such as the dead-time between the MOSFETs switching that has a profound effect upon conversion efficiency across the line/load spectrum, and the digital PID filter constants that balance stability and transient response for a given downconversion ratio and load bulk capacitance.

The digital approach offers superior performance in every way – higher efficiency across a larger operational envelope than analog designs; typically double the power density for equivalent or better regulation; vastly increased configurability at any point in the part's lifecycle; onboard power management that can work in stand-alone mode as well as within PMBus systems; simpler logistics as programmability means fewer parts are necessary to address applications; and faster time-to-market given that the supplier provides an accessible and robust development toolchain.

Digital control also raises potential concerns from a QA perspective, such as:

> how to manage this class of component given its unprecedented configurability
> any firmware/software component must be verified and qualified
> internal memory must be unquestionably reliable to ensure critical data retention
> how to configure and verify power supply performance during manufacturing/test

The Hardware/Firmware/ Software Divides

Let's consider factory-default behaviour that is coded into protected nonvolatile memory as "firmware". Its operation is hard to assess without access to a well-developed test suite that exercises every part of the code's range, and this challenge becomes evermore difficult as users layer custom parameters (in "software" that overrides the "firmware") on top of the basic control platform. The underlying physical logic is of course "hardware", and depending upon the depth of the QA regime concerns may range from assuring data retention in on-chip memory to ensuring that logic block elements and the core microcontroller (MCU) perform as expected under all foreseeable conditions. In addition, there is the application software that runs the end-user's product to assess. These are classic challenges that the military and aerospace industries in particular have struggled to overcome for many decades.

From the experiences of pioneers within these historically limitlessly-funded industries, general industry has learned how to approach qualification and verification issues to yield extremely high confidence levels at commercially-appropriate costs. For instance, the correct operation of hardware and firmware can together be assured by exercising the digital power converter under all circumstances of interest and independently monitoring the results – say by programming a range of output voltages and other parameters while subjecting the part to input voltage and temperature changes that span its operating envelope while monitoring the results using everyday test equipment.

In practice, the robustness of the hardware/firmware combination is invariably extremely high, yet a product may occasionally fail in unusual circumstances such as when the system designer fails to observe a critical boundary condition. Such conditions may include excessive dV/dT at the power converter's input, which might occur during power-up due to uncontrolled inrush currents or during operation if transients strike the part, especially if the grounding system presents excessive impedances. Accordingly, it is imperative to uncover any non-obvious requirements during end-product design, and these may not necessarily appear in manufacturers' datasheets – many of which are sketchy at best. By contrast, Flex strives to accurately describe the characteristics of each of its power converters, and help from the company's team of application engineers complements an array of web-based resources (please see www.flex.com/expertise/power/modules).
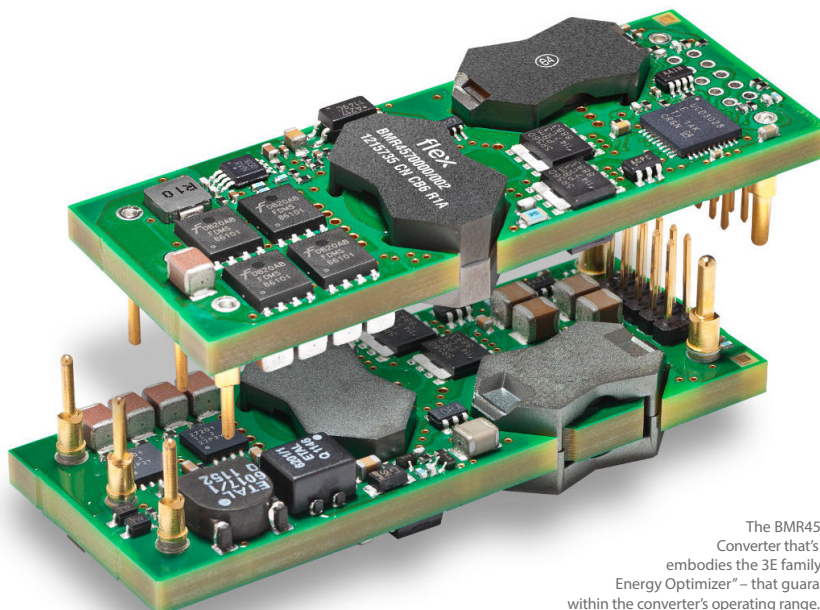
The BMR457 is a new-generation fully-regulated Advanced Bus Converter that's based on the 32-bit ARM architecture. The converter embodies the 3E family's most advanced firmware to date – Flex's "DC/DC Energy Optimizer" – that guarantees the best possible performance at any point within the converter's operating range. This capability extends to handling the line transients that can occur, for instance, when switching from Feed A to Feed B in AdvancedTCA

Application-specific code (that is, software) that appears in an end product may be more challenging to assess. This code typically contains operating parameters that affect the power supply's feedback control loop including output voltage settings, and in converters such as Flex's 3E series may include constants that directly affect the digital filter and other key hardware elements that could compromise the converter's stability. Common parameters include fault-detector limits, error-handling responses, on/off delays that can implement power-rail sequencing, and slew-rate controls that limit inrush currents and safeguard delicate components such as some ASICs and FPGAs.

Each digital power supply can operate over a broad range of many of these parameters. As part of the design and manufacturing process of an off-the-shelf digital power supply, default settings are defined, programmed into the product, and verified before shipment. In addition, several key settings are tested to ensure that the product operates reliably over its intended functional range. Clearly, there is a software element here that's necessary to program and exercise the product during its manufacturing process, which is originally the responsibility of the power-supply maker. Yet the flexibility

that digital supplies offer means that OEMs or even component distributors may re-program the supply to set e.g. a range of alternative output voltages using a single base device as part of an inventory-reduction program, meaning that their software and processes become an integral element of the QA inspection regime.

A further complication arises from OEMs using the product in a digital power-management environment, where supervisory intelligence such as a dedicated Board Power Manager – typically a microcontroller that's configured for local control and remote communications – implements some part of the overall application-programming task – see figure 2. This architecture provides maximum flexibility in sophisticated systems while significantly reducing implementation complexity. Yet from a QA perspective, it becomes necessary to consider the software element from its use within the vendor's product manufacturing process through OEM development and manufacturing and on to the product's deployment in the end system.
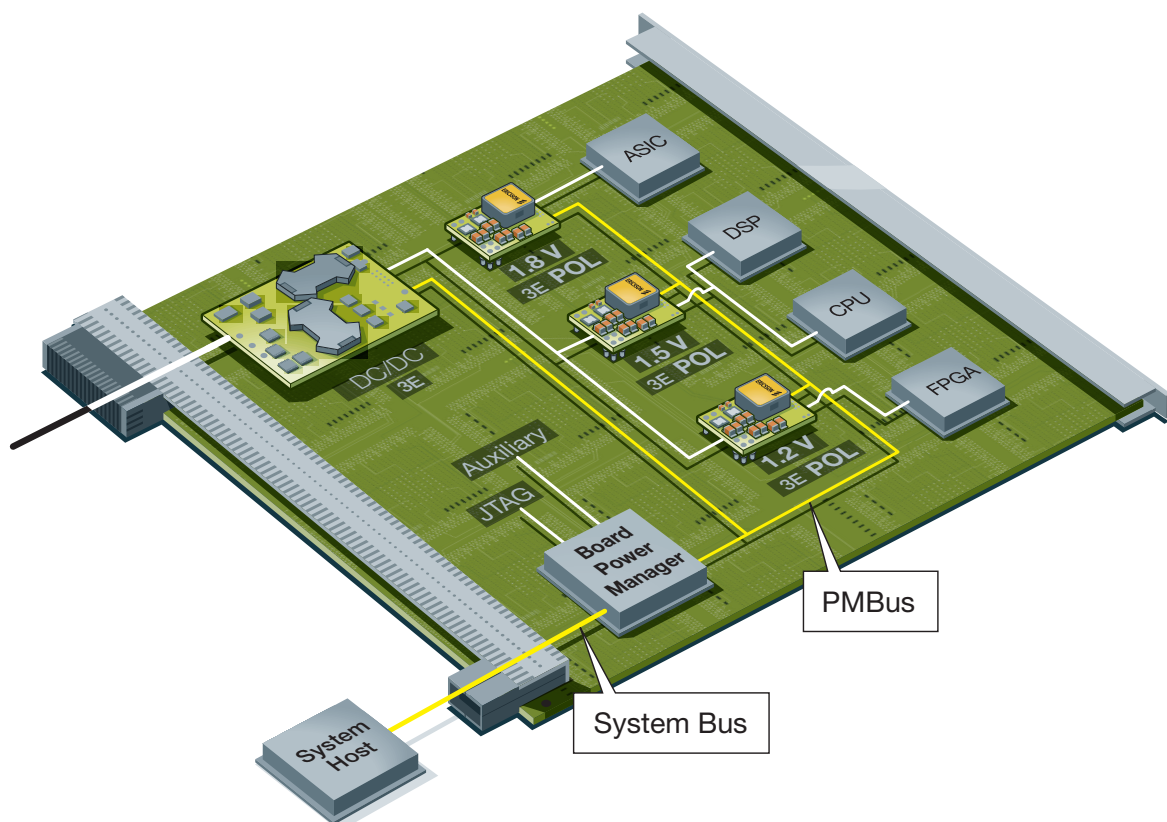

Figure 2. An application board may include a Board Power Manager that provides local supervisory control together with a link to the system host.

Quality Assurance Implications

Figure 3 provides an overview of Flex's internal QA processes that span material sourcing through to field support:

Figure 3. An overview of Flex's QA processes.

| Sourcing Raw Material | DVT SW/HM | Qualification SW/HW | Manufacturing | SW upgrade | RMA Handling |
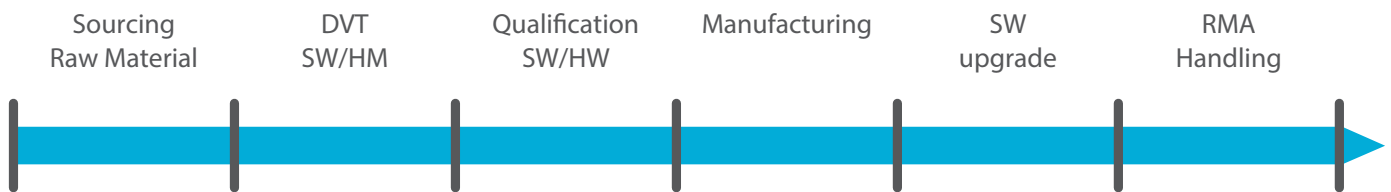
Material Sourcing

All materials are routinely of the highest-available quality and consistency. Digital power introduces some new challenges, notably in terms of the power-control chip that's almost invariably a complex mixed-signal device and specific to a single semiconductor maker. Flex works alongside the semiconductor industry's leaders in digital power conversion to develop parts and ensure their availability as second-sourcing is rarely possible! These are just some of the points that Flex's engineers consider when selecting a supplier:

> two or more equivalent manufacturing sites for the vendor's ICs
> highly robust non-volatile memory and communication interface
> built-in fault detection and diagnostic capability
> extensive QA testing during IC design and manufacture
> level control for firmware that's loaded during IC manufacture
> rigorous control of logistics flow during IC manufacture and shipment

Design Verification Testing (DVT)

Design Verification Testing (DVT) is performed close to the end of a product's design cycle to ensure that the product meets all of its design specifications in terms of functionality and performance. For an analog supply, there are relatively few 'corners' to test that generally reduce to familiar, well-defined parameters such as output voltage stability versus current drive and transient response across the device's input voltage and operating temperature range. Conceptually at least, the result is a three-dimensional space such as a cube – making measurements at each of its corners ensures that the product works across its entire operational range, as figure 4 outlines:

Figure 4. A conceptual representation of DVT complexity.
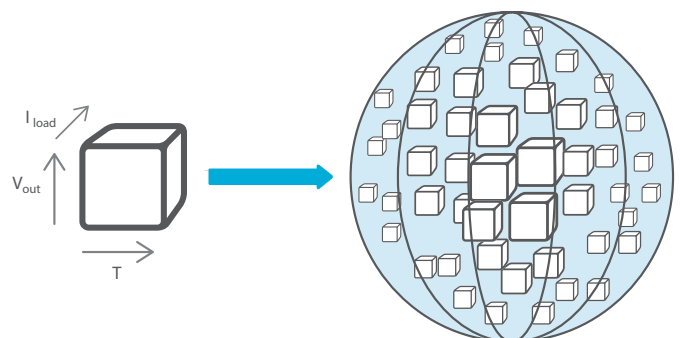
For digital power, DVT also applies to the firmware content within the product, much of which is proprietary to Flex and

represents massive investment. Essentially, the firmware makes it possible to define an almost infinite number of products that use an identical hardware base. This results in an exponential increase in DVT complexity as the number of corners are effectively infinite. Flex solves this conundrum with an intelligent DVT concept that considers the expected application profile of each product and tests accordingly.

For instance, any implementation will include externally-visible output voltage and fault monitoring/handling behavior specifications that are fixed and basically mirror the analog supply's case. There will be an array of additional internal definitions for parameters such as control-loop compensation settings, dead-time control, and various calibration trim values, yet it is easy to ensure that these values and the entire memory array are programmed correctly using conventional memory readback-and-compare techniques. Similarly, each device can ensure that its memory is good by performing a checksum self-test at power-up, providing a very high degree of operational confidence in the end application.

A very special area that Flex's engineers focus upon during DVT for digitally-controlled supplies is the electromagnetic susceptibility (EMS) performance of the controller chip and its memory. These are small-geometry ICs that are critical to the operation of the power supply, and they live in close proximity to the large currents and electromagnetic fields that accompany any switching power supply of more than a few tens of Watts. Their robustness in such an environment must be carefully verified so that data integrity is not compromised. This is in addition to ensuring freedom from alpha-particle induced soft errors, which has become an industry-wide concern with ever-shrinking geometries, and particularly so for leading-edge FPGAs. Yet observation suggests that if the controller chip withstands the large and often rapidly-changing electromagnetic fields that exist within a high-power advanced bus converter – almost 500 W from a quarter-brick footprint such as the BMR456 – it will be immune to other radiation hazards within any representative Earth-bound application.

Flex's BMR456 Advanced Bus Converter sources as much as 468 W from a quarter-brick footprint and features the 'Energy Performance Optimizer' FRIDA II firmware that is proprietary to the company. The firmware embodies a series of industry-first developments that continually optimize switching parameters to reduce energy consumption to an absolute minimum. Interoperability concerns make it essential that the chip's communications bus meets all appropriate specifications. For many engineers, this is a well-worn path that decades of I2C and similar developments have made routine – compared with say Bluetooth, USB, or even wired
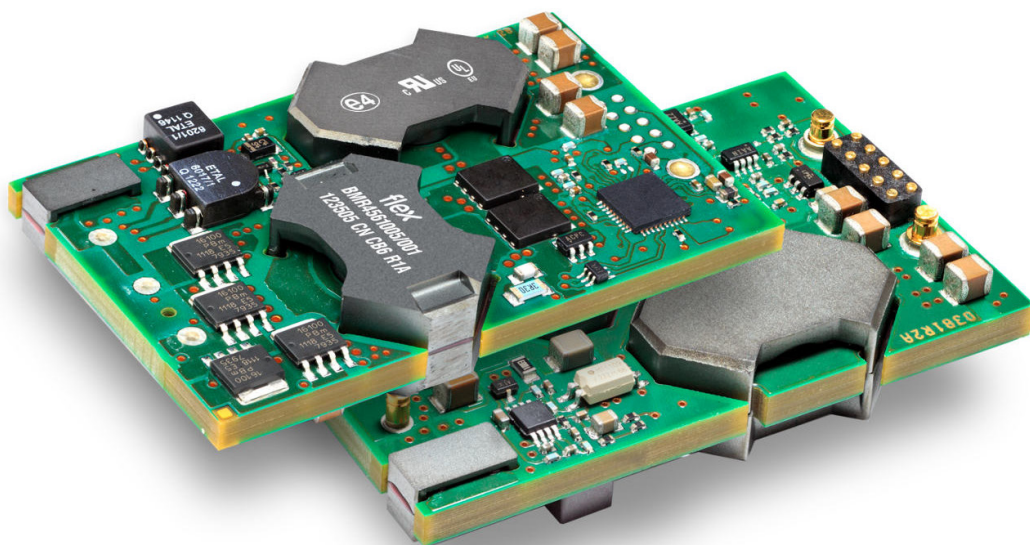
Ethernet, board-level serial protocols such as SMBus that underpins PMBus should take relatively little verification and qualification effort. While most engineers would expect this aspect to be guaranteed by design, Flex's team extensively tests any communications interface to ensure freedom from unexpected issues that in reality can still occur even with the simplest protocols.
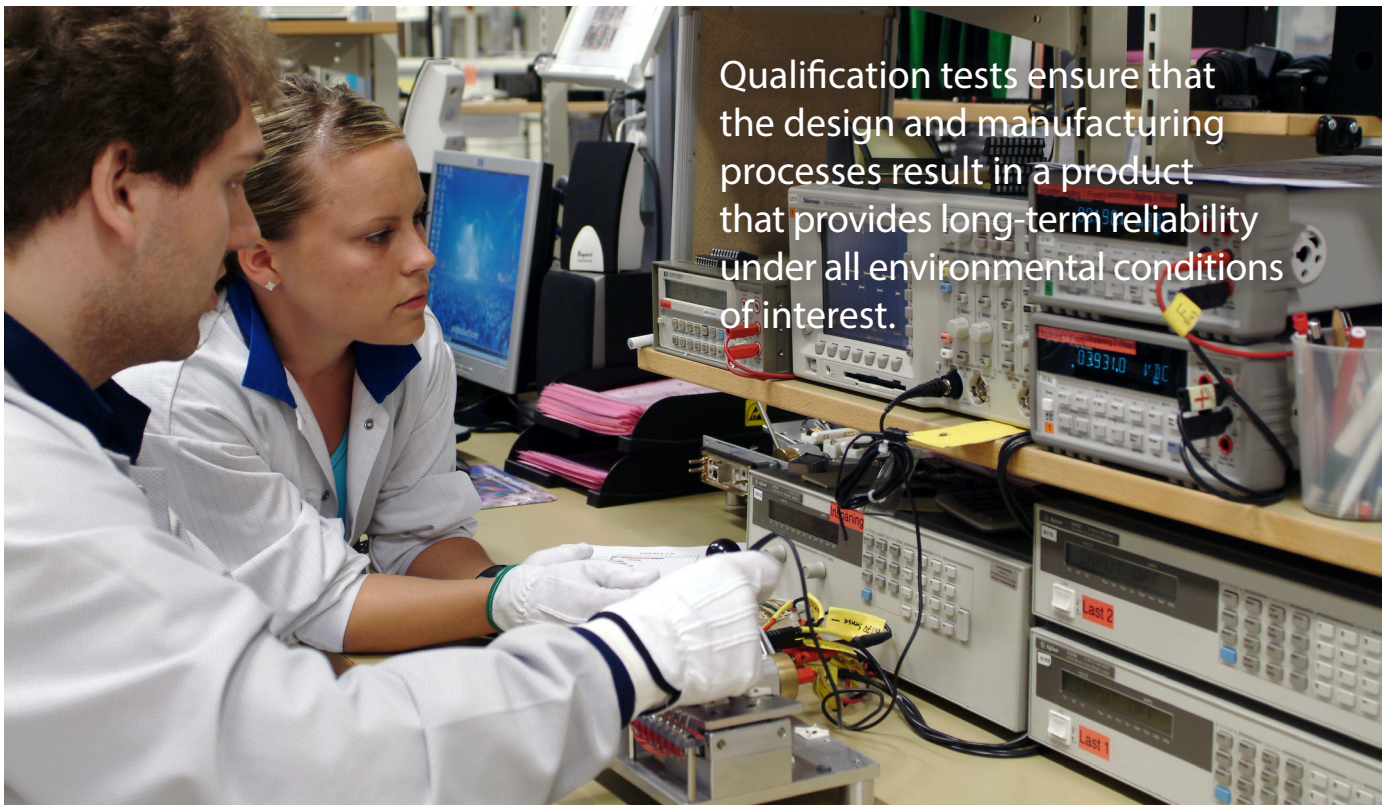
Qualification
Qualification tests ensure that the design and manufacturing processes result in a product that provides long-term reliability under all environmental conditions of interest. Such tests may be made at various levels within the end-product's process flow – for instance, initially at the component supplier and then at final board test, where functional testing via ATE provides high confidence in the end product.

Some engineers still worry that the key qualification challenge for digital power will be the long-term performance of the microcontroller and its memory with regard to software data integrity. Flex's experience has not borne this concern out, which from another view is hardly surprising given the semiconductor industry's efforts in developing radiation-hard MIL-spec components and applying its knowledge to everyday components. In fact, many MIL-spec components are no different from their commercial counterparts, but may enjoy better packaging and infinitely greater routine testing – all of which costs serious money.

In the commercial sphere, there is a balance to strike between the MIL-spec world's ultimate reliability model of testing that microscopically examines every component that's ever made under every conceivable operational condition versus making highly-reliable products available to everyone at affordable costs. Achieving that balance is a matter of experience and few world-wise production engineers are likely to disagree. But as a highly conservative supplier that services a highly conservative market sector, Flex continues to test beyond levels that the company publicizes.

Obvious tests for memory-based digital products include write endurance and data retention. These parameters should be guaranteed by design and way exceed the product's expected lifetime, but any spin around a representative selection of Flash-based microcontrollers reveals differences that may initially be surprising. For instance, a representative example of a now-mature ARM7TDMI design that's built using a 180 nm CMOS process quotes 20 years of data retention for its Flash memory, while a more recent Cortex-M3 machine from the same supplier that's built in a 140 nm process guarantees a minimum of 10,000 read/write cycles and 10-year data retention. The fact is that as semiconductor geometries shrink in the pursuit of ever-higher performance at ever-lower cost, memory-cell dimensions shrink and their long-term capability to retain charge – that is, their programmed state – diminishes alongside their potential ability to withstand strong local electromagnetic fields and space-

Qualification tests ensure that the design and manufacturing processes result in a product that provides long-term reliability under all environmental conditions of interest.

borne alpha-particle strikes. Recently, a leading maker of communications infrastructure ICs asserted that leading-edge 28 nm processes are technically no better than 40 nm processes and also more expensive. In a direct contradiction, the world's largest silicon foundry is trying to get a 20 nm process into production to compete with the 22 nm process that world's leading microprocessor maker has developed.

While mainstream microprocessor makers boast ever-shrinking line widths for their state-of-the-art devices that don't have to rely upon internal nonvolatile memories that must last for years, many companies that produce industrial-strength microcontrollers are reticent to publicize the relatively wide line widths that their products use because it doesn't sound technically competitive. It's useful to keep in mind that beyond the sub 90-nm publicity and the theory that this model will crash at 18 nm, well-judged conservative silicon geometries are proven reliable and economical to produce in a variety of foundries around the world – helping to assure the availability of sophisticated parts that are almost always single-sourced.

Manufacturing

The ultimate mission for QA is to eliminate all risks to ensure that customers receive their products on time, every

Arguably, there is another parallel here with the automotive electronics arena. For instance, no experienced engineer will run a CAN (controller-area-network) bus that was initially developed to control safety-critical ABS (anti-lock braking system) functions any faster than is absolutely necessary to meet throughput and deterministic response times. Similarly in our context, conservatively-dimensioned transistors deliver more reliable performance in several ways including far better control of the leakage currents that sap power.

Among other reliability assurance checks, Flex tests the data retention and integrity of on-chip memories by comparing the memory content before and after conventional hardware environmental tests, such as 1,000 hours at 85°C/85% RH — see figure 5. This routine is an experience-driven subset of the HASS (highly-accelerated stress screening) and HALT (highly-accelerated life testing) regimes that the semiconductor industry has refined over many years to ensure fundamental part quality and fitness-for-purpose.

time, and always within specification. This is what any holistic QA regime strives to achieve – 'making it right first
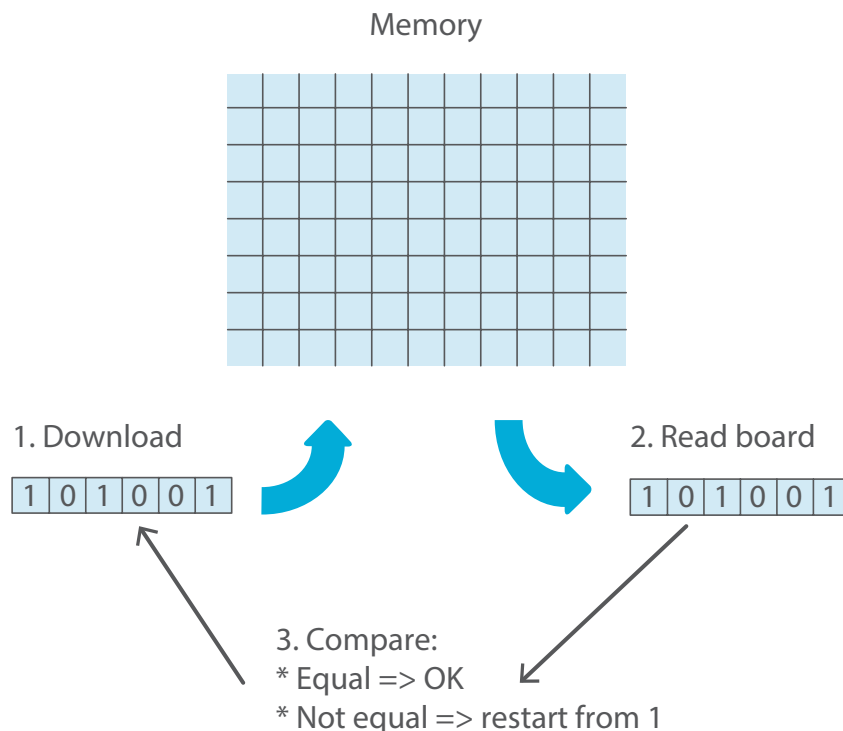

Figure 5. A readback-and-compare routine ensures memory integrity.

time, every time' saves time and expense for everyone including the environment and is a fundamental tenet of the several Japanese-inspired manufacturing philosophies that European industry has embraced in recent years.

The changes to conventional manufacturing processes to accommodate digital power products are minor, and primarily relate to programming parts during manufacture – an insignificant consideration given the predominance of today's ATE systems – yet it can be easy for people to 'lose track of the ball' and overlook the importance of simple points such as tracking version control for firmware/software elements. This is just one example of where a well-considered QA regime comes into its own, helping to keep manufacturing on-track while ensuring full traceability for every product that comes off the line.

Every Flex 3E power module has a unique serial number that's readable via PMBus, providing the foundation for traceability down to an individual module.

Software upgrades

Any holistic QA regime embraces the period after the base product leaves the factory and ideally tracks it through its entire lifecycle. This ideal can be difficult to achieve for multiple and entirely pragmatic reasons in the long term, but in the early days when OEMs and their customers take ownership of new systems should not be

difficult to follow for any organization that places importance upon customer care.

Often, enhancements to the firmware/software will occur after the product is deployed within an end user's equipment, as figure 6 illustrates. These changes could be driven by improvements that the power supply manufacturer develops, or they could be the result of specific customer requests and ongoing development by the OEM. It is important to have a reliable QA system in place for managing software changes and any upgrade activities.

Figure 6. Programmability makes it easy to upgrade firmware/software in the field.

Customer support when it matters most
If the worst-case scenario occurs and there are field failures that are attributable to the power supply system, it is utterly essential that processes are in place to handle such exceptions quickly and efficiently. Many

manufacturers – including Flex – have well-established Return Material Authorization (RMA) systems in place for this purpose. Significantly, digital power has the potential to improve the fault-detection and rectification process due to its innate ability to capture and record out-of-bounds conditions in realtime within the end system and store them in the host system's memory structure.

This ability speeds root-cause analysis and helps provide corrective action that can often be performed while the power supply remains installed within the customer's system, providing for very rapid response and resolution to most problems.

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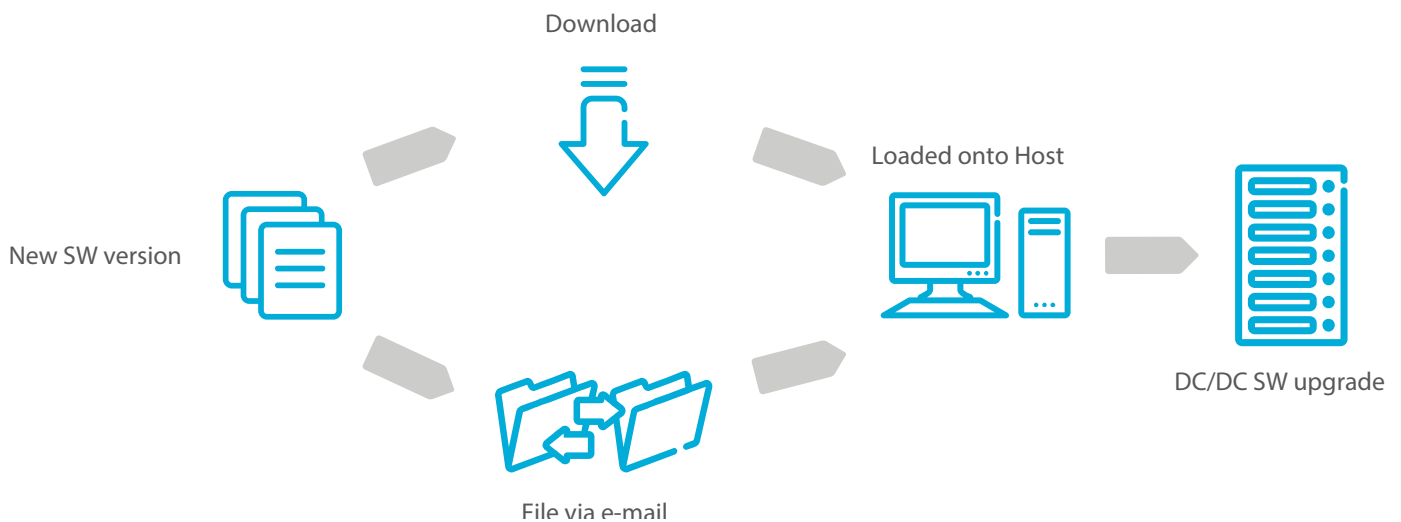
Have Some (Useful) Fun!

For many engineers, digital power initially appears as yet another hurdle to jump in a seemingly relentless technology race. Those of us who are old enough will remember the shift from analog circuitry built around transistors, op-amps, and occasionally specialist parts such as the Gilbert multiplier towards the 8080/6800 microprocessors that suddenly provided an entirely new way of working – one of numbers rather than continuous-time derivatives. It took us a little time to get comfortable, but witness the revolution that the digital revolution has delivered – lately for instance, it's difficult to see how to build a smartphone from op-amps and other discrete components!

Digital power follows a very similar model. It substitutes seemingly complex DSP (digital-signal-processing) routines for the familiar op-amp feedback loop while layering in a raft of programmable features that no conventional analog power converter can begin to match.

Because unfamiliarity can make people wary, Flex has developed the 3E evaluation kits that make digital power and PMBus control immediately accessible. It is truly eye-opening to be able to 'see inside' a running dc-dc converter in realtime for the first time, and anyone who has not enjoyed this experience is missing out — and it really is fun to watch and learn from making instantly-available adjustments to the digital converter's operating characteristics, with no need for a soldering iron and the selection of passive components that accompanies tuning an analog converter.

The 3E development kits offer system architects a range of ready-made boards to choose from that can easily be interconnected to represent a complete application. This makes it straightforward to develop, test, verify, and optimize the power architecture to ensure that it meets the overall functional requirement including the ever-present target of reducing energy consumption.

As figure 7 shows, available 3E development boards include:

> ROA 128 5151 – 3E Power Interface Modules
> ROA 128 3835 – 3E Advanced Bus Converter
> ROA 128 3836 – 3E Laydown POL
> ROA 128 5068 – 3E Single-in-Line POL
> ROA 128 5077 – 3E POL Paralleling

The kit also includes Flex's Power Designer software, a USB-to-PMBus adapter, and complementary cables and accessories.

Importantly, the hardware is strong enough to carry representative currents and unusually, the software will control any PMBus-compatible device. All the user has to do is to add a power supply and as much test equipment as necessary to monitor the parameters of interest. It is therefore possible to construct a verification and qualification system around a 3E design kit, power supply, PC, and a mid-range digital sampling oscilloscope for a fraction of the cost that may be expected.

Crucially, there is an opportunity for mutual learning that benefits everyone – power-supply manufacturers, OEMs, and end-users can all profit from the experiences that accompany delivering systems to the people who use them in earnest. This is especially true for digital power, as the unprecedented flexibility that the technology delivers is sure to stimulate new visions within the minds of innovative system architects that are likely to surprise even the power supply builder.

Please be sure to visit www.flex.com/expertise/power/modules and review the extensive archives of digital power resources that now includes the Digital Power Compendium – currently at 462 pages it's the industry's most complete publication on the subject.
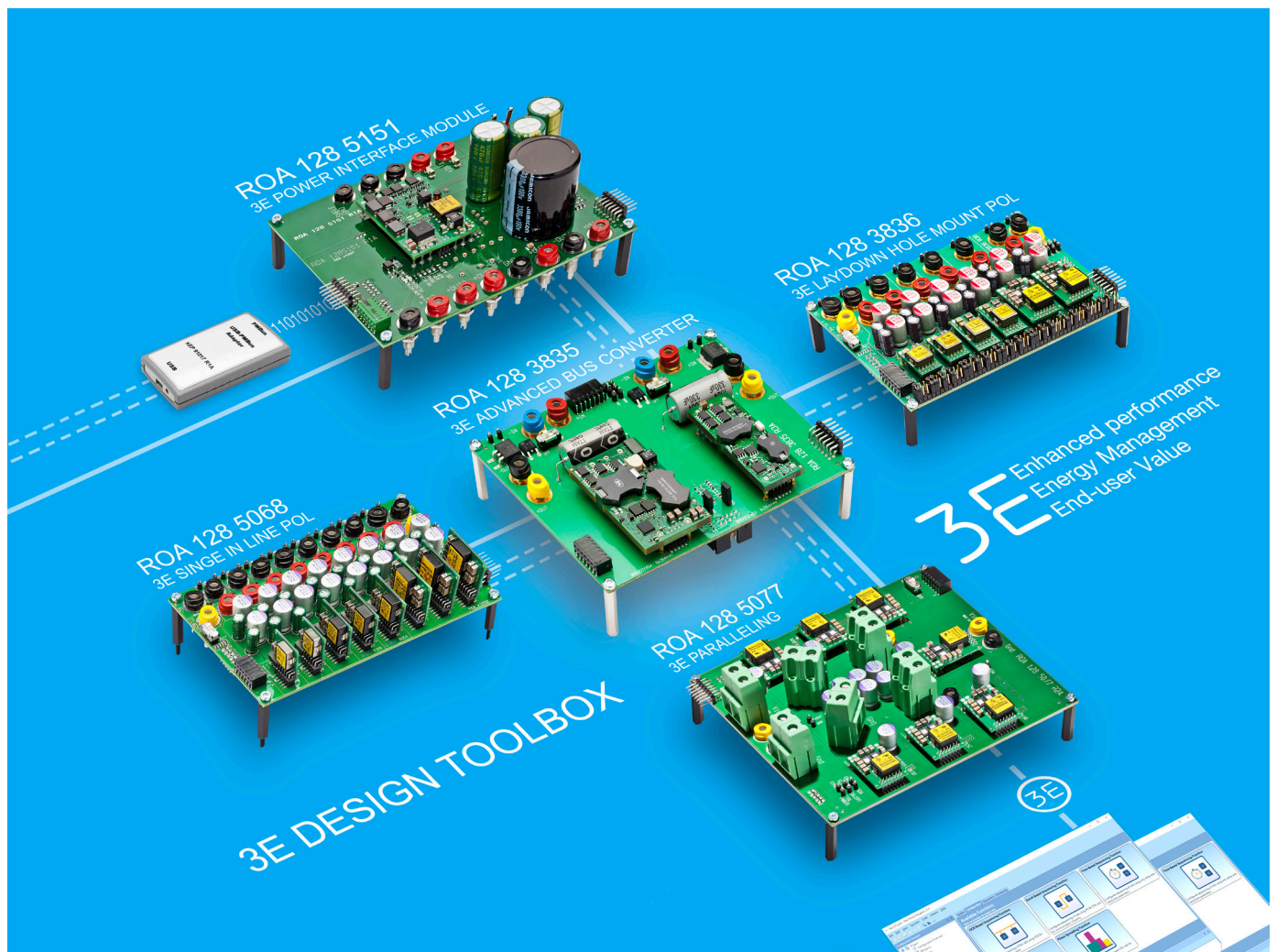

Figure 7. Available 3E development kit boards.

Glossary

3E	Enhanced performance, Energy management, End-user value
ABS	anti-lock braking system
AdvancedTCA	Advanced Telecommunications Computing Architecture
ASIC	application-specific integrated circuit
ATE	automated test equipment
CAN	controller-area-network
CMOS	complementary metal-oxide semiconductor
CPLD	complex programmable logic device
dV/dT	rate-of-change of voltage with respect to time
DSP	digital signal processing
DVT	design verification testing
EMS	electromagnetic susceptibility
FPGA	field-programmable logic array
GUI	graphical user interface
HALT	highly-accelerated life testing
HASS	highly-accelerated stress screening
I2C	inter-integrated-circuit (serial bus)
IC	integrated circuit
ISO	International Organization for Standardization
MIL	military (specification)
MOSFET	metal-oxide-semiconductor field-effect transistor
nm	nanometer
OEM	original equipment manufacturer
PC	personal computer
PID	proportional-integral-differential (filter)
PMBus™	Power Management Bus
POL	point-of-load (converter)
PWM	pulse-width-modulation
QA	quality assurance
RH	relative humidity
RMA	return material authorization
USB	universal serial bus
VDC	dc voltage