WHITE PAPER

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Simplifying the transition to digital power for greater efficiency at a lower cost

Introduction

Traditionally, power systems have been implemented as analog hardware designs. However, the availability of low-cost, high-performance microcontrollers have more and more developers turning to digital implementations of power systems. The switch to software-based control mechanisms significantly simplifies hardware design. The adaptability of software-implemented control allows digital power systems to provide higher power conversion efficiency across a wider range of operating conditions such as load currents and line voltages. The inherent flexibility of a software approach allows developers to leverage power systems across multiple designs, thus speeding time-to-market as well as potentially lowering overall system costs. In addition, developers can introduce control mechanisms such as advanced filtering or dynamic compensation that have been too complex or costly to implement using analog components.

Digital power impacts a broad range of applications, including server/telecom rectifiers, uninterruptible power supplies, hybrid electric vehicles, street and building lighting, power grid management, and products based on alternative energy sources like solar and wind. Just as the shift from analog to digital can bring many potential benefits, it also uses new design methodologies which can raise concerns for developers not familiar with them.

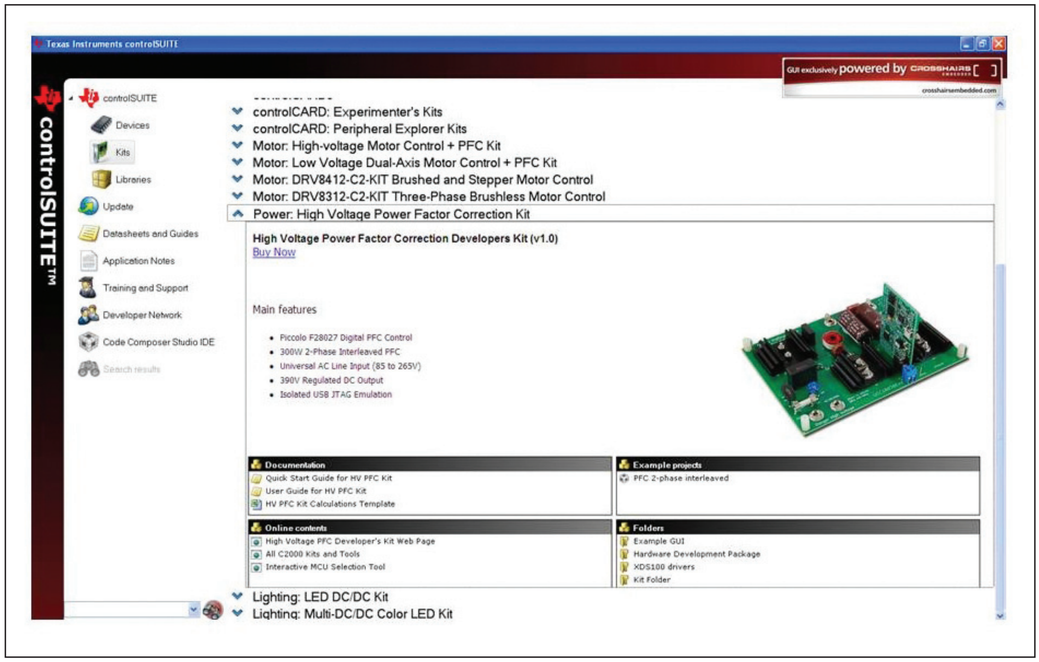
The reality of going digital

Power systems designers are a special breed of engineer. They understand analog dynamics at a level that seems like magic to other engineers and are comfortable implementing and tuning logic in hardware. However, many power systems designers have little experience with software. If they have used a microcontroller (MCU), it typically has been a straightforward and relatively simple 8-bit architecture. For such engineers, while taking a digital approach to power control clearly offers significant advantages, the idea of migrating to a sample and conversion-based architecture can seem intimidating.

With its extensive systems expertise, Texas Instruments understands not only the tradeoffs between analog and digital implementations, but also the challenges this transition poses for analog engineers. To simplify the process of shifting to digital power, TI has created a comprehensive suite of tools – including development kits, libraries, and complete application software – to specifically address the most common concerns of analog engineers.

Will moving to a digital implementation mean substantial software development?

There is a lot of software behind a digital power system. Fortunately, TI has already written most of the code a digital power system requires. Each of TI's digital power development kits is based on a Piccolo™ MCU and comes as a complete package with comprehensive technical documentation and full application source code so designers can get started in less than 10 minutes and learn quickly. TI also includes its industry-leading controlSUITE™ digital power library to facilitate adaptation. For developers who are not used to working with an extensive code base, the controlSUITE platform manages the complexity of software through a graphical user interface (GUI) that allows designers to select the resources they need for specific hardware, including target device, evaluation kit, etc. The controlSUITE tool downloads the selected files to a user's computer and puts everything in the right directories and folders. This includes software source code, technical documentation, hardware design packages, as well as libraries and header files. This also includes complete software projects. Building an initial design is as simple as clicking a few buttons (Fig 1).



▲ ***Fig. 1** – TI's free controlSUITE™ software includes more than 25 modular digital power software blocks. The platform minimizes software development time and reduces programming challenges.*

Additionally, TI supplies a simple GUI in every application kit that can greatly simplify the configuration and tuning of an application. If a modification is made to the software or hardware, the GUI can be used to speed up the debugging and tuning of the modified application. Since the source code and framework are supplied, customers can also easily port the GUI to their end application and use it to speed up the tuning and debugging of their product design.

The integration of the controlSUITE platform and its range of options provide analog engineers with a comprehensive development environment. This allows them to capitalize upon the benefits of going to digital while simplifying the migration from an analog-based approach.

Will periodic sampling achieve adequate transient responsiveness?

Moving to digital power requires a significantly different approach to design than analog implementations. Voltage and current feedback and output control adjustment for an analog system is instantaneous, giving excellent transient responsiveness. Digital systems – due to the need to sample, convert to digital, process, convert back to analog, and output – take time to respond to feedback and adjust control output, which may cause the design to fail transient response and stability specification.

The speed of today's MCUs and high-speed ADC/DAC peripherals enable the implementation of control loops that well exceed a system's transient and stability margin requirements. In fact, these controllers are so fast they can perform additional signal data processing that is not cost effective to implement in analog systems. Perhaps the most important example is peak load efficiency.

Analog implementations can only be optimized for a single load value, typically the load at which the system operates most frequently or the load for which accuracy is the most critical. While operating at this load, the system performs with the highest efficiency. However, the system likely operates at a variety of loads; the peak load may not even occur the majority of the time the system is in operation. As the load moves away from the peak load, its efficiency drops. For example, consider that the load on a server depends upon how many computers are accessing it at a time and how quickly. What this means for many applications is the system is operating at less than peak efficiency most of the time. For systems that consistently operate at lighter loads, efficiency will suffer significantly.

With digital implementation, parameters used in the compensation algorithms and output configurations including the compensation algorithms and output configurations themselves can be dynamically adjusted to match the current load. In the case of a server, as more computers request access, the adaptation algorithm adjusts the compensation loop and other parameters such as the deadband of PWM outputs to match the changing power requirements. This adaptation requires more controller cycles, but because of its added flexibility, the result is significantly improved efficiency across the entire operating load. The same is true when it comes to adapting to other operating conditions such as input AC line voltage. A digital implementation not only provides sufficient transient response and stability margin, it can also significantly improve the overall power efficiency of the system compared to an analog implementation.

With the extra processing capacity of a digital power controller like TI's Piccolo MCUs, developers can introduce enhancements, such as oversampling, to achieve more accurate measurements and output regulation. Developers can also introduce extra filtering to remove a known frequency component that is present in the expected operating environment.

Another example is Power Factor Correction (PFC). PFC is, by default, a required power conversion stage in a server AC/DC power supply, but it is also required in other applications such as variable frequency HVAC systems in China. The reason for this is first to reduce transmission loss and hence also infrastructure cost. But, more and more HVAC systems are adopting the highly efficient type permanent-magnet AC compressor. A front-end PFC stage allows the compressor to run at higher speeds making better utilization of the same AC line voltage. The extra CPU headroom of fast digital controllers can be very critical for these applications. The availability of powerful and cost competitive digital controllers is making PFC more prevalent across the embedded and industrial industries.

Will tuning a digital system be significantly more complex than tuning an analog system?

At first glance, the idea of making adjustments to complex compensation algorithms for PFC, isolated DC/DC and other power functions can appear overwhelming, especially to engineers new to the sample and convert approach of digital systems. By using the controlSUITE platform and the simple GUI in the application evaluation kits, developers can both quickly evaluate different power topologies and accelerate final product design. All software is provided as modules with clearly delineated inputs and outputs, enabling developers to take a component/parameter-based approach to design. The available GUI source code and framework allow developers to introduce new custom functions, such as a waveform display and watch window for additional variables, to accelerate analysis and troubleshooting.

To shorten the learning curve, each application code has been built to support incremental build steps that allow developers to work with only a portion of the project at one time. For example, when working with the full bridge kit, developers can first configure and evaluate voltage and current sensing before moving to closing the current and speed control loops.

TI has also specifically designed the GUI to simplify tuning of the adaptive compensation loop by giving developers access to the critical parameters of the system. In this way, developers can test a wide range of parameters and configurations to quickly converge on the most efficient implementation. This means developers can complete and tune a design without writing a single line of code or loading Code Composer Studio™ IDE, TI's integrated development environment. For those developers wishing to add additional functions, proprietary enhancements or optimizations, all source code is provided. Technical documentation, including lab reports and models, provides a full description of how each algorithm in the system has been implemented.

Will a digital power controller system be more expensive to develop and manufacture?

For a simple, inexpensive power supply where efficiency doesn't matter and there is no need for advanced features, analog-based systems cannot be beat. However, for applications where efficiency, responsiveness, accuracy, and other additional system functions such as input power monitoring are important, the savings from going digital can be significant:

Higher operating efficiency: Providing end-customers with more efficient equipment results in ongoing OPEX savings. Not only does this differentiate systems from competing products, it offers a significant value-add that can justify a higher sales margin.

Controller integration: Analog power control systems like those in a server/telecom AC/DC power supply typically employ a system controller as well. With a digital implementation, the functions of the analog controller and system controller can be integrated into one digital power controller. If the power supply has a redundancy controller and/or also shares the load in parallel with another power supply, these controllers can be integrated as well. A single controller can replace several controllers to reduce system cost and complexity.

Component count reduction: The ability to integrate functionality onto an MCU results in other component reductions as well. For example, if the system requires both over and under voltage protection, the two separate operational amplifier (op-amp)-based circuits for an analog approach can be replaced with a single op-amp-based circuit that feeds the signal into the digital controller. In fact this can be the same signal amplification circuit required by the voltage control loop, saving another op-amp circuit. In addition to lower system cost, reducing component count also has the positive side-benefit of improving reliability by reducing the number of points of failure in the system.

Added system intelligence and functionality through communications: Efficiency can also be measured across a network or grid of devices, and when a communications interface is integrated into the system controller, it becomes possible to coordinate interactions between different devices. For example, monitoring the performance of individual cells in a solar array enables the system to maximize the efficiency of each cell, rather than being limited to analyzing the performance of the array as a whole. Network-level efficiency can be further improved through features such as input power monitoring, load sharing, and redundancy management. Advanced monitoring also allows for more accurate measurement of power production and consumption. For example, rather than paying a set estimate to power street lights, cities can remotely monitor actual consumption and pay for exactly what they use, resulting in substantial savings.

Flexible topologies: Given the dynamic and flexible nature of a software-based digital approach, developers can easily reconfigure digital power systems for different equipment configurations or operating environments. Since differences can be accommodated in software, the hardware control card and controller can stay the same even if factors such as the power rating or number of rails change. For example, rather than customize a resistor divider to handle a new output voltage or change the output margin and have to stock this new board in inventory, a new voltage can be implemented simply by changing a single parameter in the control code.

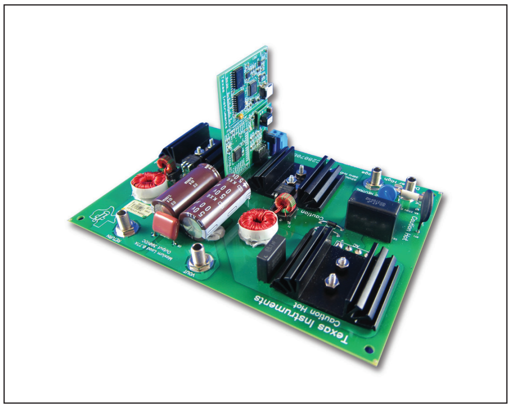
Simplified power topology design

To aid engineers in quickly developing a power system that provides the required efficiency at the lowest price, TI offers digital power evaluation kits that support the four most common and important power topologies in use today. Each kit is based on TI's powerful Piccolo microcontroller architecture and provides fully functional, standalone hardware that doesn't require an emulator to operate. Each kit comes complete with software so that developers can begin design at an advanced stage. These foundations help developers make the appropriate adjustments and optimizations of the compensation loops to adapt the design for their applications. Target applications are broad, and can range across communication, telecom, industrial test equipment, naval/aerospace, HVAC, lighting, renewable energy, and other applications requiring efficient power design.

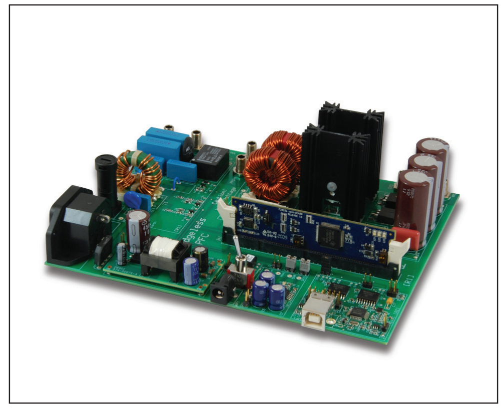
The kits are appropriate for both AC/DC and DC/DC power supplies. For AC/DC designs, developers will use one of the PFC topologies integrated with one of the DC/DC topologies. For DC/DC designs, developers need only one of the DC/DC topologies. The front-end PFC topologies can handle real-world voltage levels up to 265VAC input and 400VDC output. The isolated DC/DC topologies step the voltage down to the appropriate level (i.e., 12V for servers, 48V for telecom, and so on).

The kits have been designed to integrate seamlessly. Each of the PFC kits outputs between 380-400VDC, which is the input voltage for the isolated DC/DC kits. Since each design is controlled by one of TI's industry-leading Piccolo digital power controllers, developers can easily migrate between topologies without having to change controller platforms or extensively modify software.

PFC Topologies



▲ ***Fig. 2a*** *– High Voltage 2-Phase Interleaved PFC*



▲ ***Fig. 2b*** *– High Efficiency (Bridgeless) PFC Developers Kit*

The 2-phase Interleaved PFC and Bridgeless PFC Developers Kits are ideal for a variety of applications, including telecom and server AC/DC power, uninterruptable power supply (UPS), electric vehicle battery charging, and other industrial and commercial applications such as HVAC systems, lifts, cranes, drilling equipment, welding machines, and so on.

The 2-phase interleaved PFC kit (Fig. 2a) is based on a fairly standard topology which should be familiar to most power supply engineers. The bridgeless PFC kit (Fig. 2b) provides a modern approach to PFC design and is quickly becoming more popular than the standard 2-phase interleaved topology because of its generally higher efficiency. The term bridgeless comes from the fact that the traditional diode bridge has been eliminated, reducing internal power consumption compared to a standard interleaved topology. The primary tradeoffs for going bridgeless are increased magnetics for the same power level and a slight increase in compensation complexity to differentiate between positive and negative half-cycles.

Both kits offer:

Rated power: 300W

Full load efficiency: >90% / >94%, 2-phase interleaved / bridgeless

Power factor: >0.99% peak, 0.90% + at 20% load

– THD (only evaluated for bridgeless PFC): 4% peak, 5.3% at 20% load

Input range: 85 to 265VAC at 50 and 60 Hz

Output: Up to 400VDC

– 200 kHz switching frequency

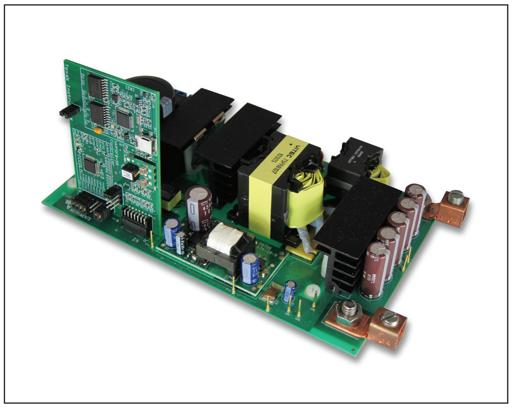
Protection: Over current (OCP), over voltage (OVP), under voltage (UVP)

Support for multiple control modes:

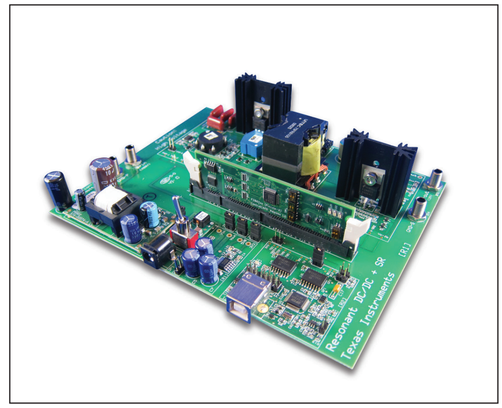
– Soft start, average current PID control, CCM/DCM, DCM current feedback compensation, software implemented multiplier, software implemented digital filter for voltage feedback, etc.

The bridgeless kit, in addition to providing greater efficiency, also offers a half-cycle (AC) RMS feed forward loop, faster DC Bus voltage response, RMS input VF monitoring, an on-board EMI filter, and auxiliary power supply.

DC/DC Topologies



▲ ***Fig. 3a*** *–Isolated Phase-Shifted Full Bridge (PSFB) DC/DC Kit*

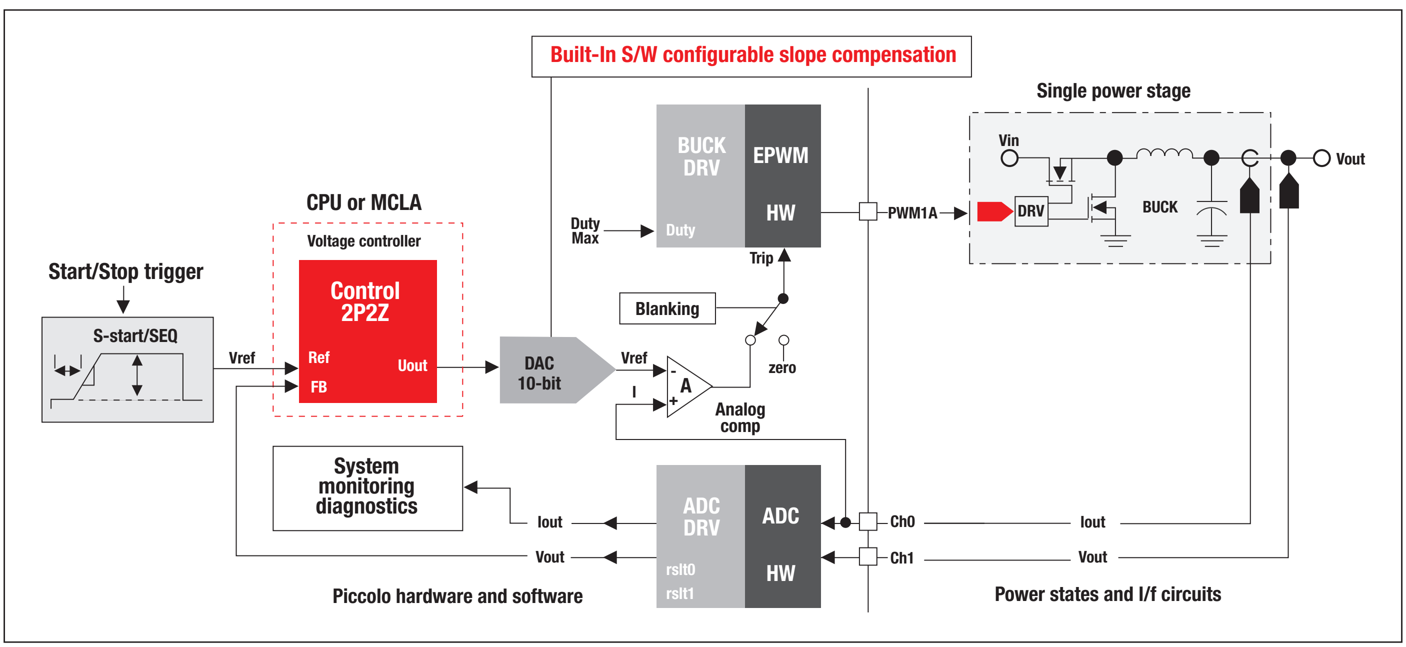


▲ ***Fig. 3b*** *–Isolated LLC Resonant DC/DC Kit*

The Isolated PSFB DC/DC Kit (Fig. 3a) and Isolated LLC Resonant DC/DC Kit (Fig. 3b) provide optimal efficiency for many applications, including hybrid electric vehicles, servers, and telecom power supplies, industrial AC/DC and DC/DC, and solar DC/DC.

The Isolated PSFB DC/DC topology is targeted for 400W to 5kW power supplies and is the most popular for advanced AC-to-DC applications. Piccolo digital power controllers support peak current mode control with slope compensation without the need for extra off-chip circuitry that designs based on other controllers must have (Fig. 4).

Peak current mode control with slope compensation



▲ ***Fig. 4*** *–TI's new kits allow developers to jumpstart digital power designs, enabling and simplifying more complex power supply functions that are in high demand, such as Peak Current Mode Control (PCMC) with Slope Compensation, using no additional external circuitry.*

The Isolated LLC Resonant DC/DC topology is generally considered to be the most efficient and cost-effective topology available today. TI's Isolated LLC Resonant DC/DC digital power kit is designed for 300W, but it is a directly applicable reference for high wattage applications, typically in the range of 300W to 1kW+, which need to be physically small and require high efficiency at peak load as well as light or no load. It is also ideal for applications such as audio which have low EMI requirements of their power supply.

Both kits offer:

Rated power: 300 / 600W, for the LLC / PSFB kits respectively

Efficiency: LLC kit - 93.6% (peak), 90% (@ 17% of rated power), 85% (@ 10% of rated power);
PSFB – 95%+ (peak), 90%+ at 10%+ load

Input range: 380 to 400VDC Nominal

Output: 12VDC with output regulation to +/- 0.3%

Output transient response: <+/-3%, <0.25 mS with 80% load change at 1.0 A/us

Switching frequency: 100 to 140 KHz (LLC Resonant), 100 KHz (Phase-Shifted Full Bridge)

Sampling frequency: 100 KHz

Protection: Over current (OCP), over voltage (OVP), under voltage (UVP)

Support for multiple control modes:

- **Both:** Soft start, adaptive ZVS, optimized synchronous rectification control
- **Phase-Shifted Full Bridge:** Average current mode, peak current mode, voltage mode
- **LLC Resonant:** Frequency controlled resonant mode, PID voltage controller

Each of these digital power kits supports full-voltage operation so that they more closely simulate real-world applications. For example, rather than force developers to extrapolate lab results measured at 12V to applications operating at 400V, these kits allow evaluation and verification of performance and efficiency at the proper high voltages and reasonably high power levels. In addition, the modular nature of the control software supports multiple control modes so that developers can pick the one ideal for their application.

Once developers have experimented with or selected a power topology, they need to be able to evaluate how well the underlying controller will be able to meet the specific requirements of their application. The most critical aspects to consider when evaluating a digital power controller are control loop latency, input and output resolution, flexibility, headroom, optimization, system-level support and cost.

Evaluating digital power controllers

Control loop latency: In order to achieve equivalent performance to the instantaneous responsiveness of analog control loops, digital control loops need to reduce the sample-to-output delay to as little as possible.
Piccolo digital power controllers achieve this by optimizing the entire signal chain, from signal capture to processing to output:

ADC conversion speed: At 4.6 Msamples/s, Piccolo digital power controllers capture signals faster than any other controller available in its class.

CPU speed: Operating at up to 60 MIPS, the Piccolo MCU architecture offers the industry's fastest digital power controllers.

- ***DSP-based processing:*** The DSP foundation of the Piccolo MCU is built for high-performance execution of complex algorithms with the ability to perform operations like a single-cycle multiply-accumulate (MAC) which takes tens of cycles on traditional MCUs.
- ***Optimized architecture:*** Piccolo power controllers integrate hardware-based components like the Control Law Accelerator (CLA) which executes floating-point control software in parallel to the main CPU and offload processing to substantially accelerate control loop processing.
- ***PWM resolution:*** At 150 picoseconds, the Piccolo MCU's pulse width modulators (PWM) can update the output 8 times faster than the nearest competitor at the same PWM resolution.

Input and output resolution: Because of their sampling nature, digital systems are discrete in time and values are stored as integers with finite resolution. Higher resolution directly minimizes signal losses and reduces the introduction of random noise:

- ***ADC resolution:*** With 12-bit sampling, the Piccolo MCU provides among the highest resolution for a digital power controller.
- ***Dynamic range:*** The 32-bit CPU word length of Piccolo digital power controllers provides a dynamic range that maximizes calculation accuracy and precision. The optional CLA for applications that require extra processing power is 32-bit in word length and is also floating point, further extending the dynamic range, accuracy, and precision in calculation.
- ***PWM resolution:*** The 150 picosecond PWM resolution ensures the accuracy of the output signal wave adjustment, even at extremely high PWM frequencies.

Flexibility: Every power system is different, and the more flexible the controller, the more efficient and accurate the output regulation. An ADC must offer prioritized triggering and a variety of sequencing options while the PWM must be flexible in order to support the different topologies and waveforms an application may require. With the application codes and libraries in the controlSUITE platform, all of the required software has been provided to sample and process signals in whichever manner or sequence needed.

Headroom: TI offers the broadest portfolio of digital power controllers so that developers can select a device with varying processing capacity and on-chip resources, many being pin-to-pin compatible. This wide selection, when combined with software blocks optimized for both the Piccolo MCU's CPU and CLA, provides sufficient headroom to implement advanced digital control functions without compromising real-time performance or reliability.

System-level support: TI is the world leader in providing the silicon, software, and support required to develop efficient and cost-effective power systems. TI has built its digital power portfolio based on extensive silicon and system-level expertise, learned from real-world applications by assisting its customers around the globe. Developers have access to the company's application and system design experience through comprehensive development kits, evaluation boards, system-level design tools like the controlSUITE platform, and TI's Engineer-to-Engineer (E2E) Forum which is widely used by the engineering community. In addition, TI's free, open source modular digital power library and application software not only eliminate software royalties but also accelerate time-to-market by providing tested and well-tuned code for every main power topology.

Optimization: Once developers have completed their evaluation of the different power topologies, they must be able to easily optimize the design for their own application. From a hardware perspective, for example, customers must now migrate to their own power board at the appropriate rated power level with more carefully considered magnetics, passive components and board layout. Customers may use the same control card used in these kits or develop a new control card customized for their application based on the hardware package provided in the kit. From a software perspective, the control loop can be tuned by adjusting system parameters using the TI-supplied GUI.

Communication: At some point, a communication link may need to be added to the power supply design. TI offers the drivers library for a variety of interfaces, including PMBus, I^2C, UART, and SPI. TI also offers a complete powerline communications (PLC) solution, backed by the powerful plcSUITE™ development environment.

Cost: Local regulations such as Energy Star V2.0 are driving demand for more efficient topologies in both commercial equipment and consumer goods. Given the high volumes of these markets, cost is a significant consideration when designing a power system and the Piccolo MCU architecture offers developers the most cost-effective implementation for achieving efficiency power system design.

TI's digital power kits provide an excellent foundation for introducing analog developers to digital power and evaluating the Piccolo microcontroller architecture. With hardware that operates at real-world voltages and currents, combined with software that provides a complete application framework, developers can quickly discover the benefits of digital power for themselves.

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