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STANDARDS AND TECHNOLOGY
Driving System Design in Power Conversion

STANDARD AND TECHNOLOGY Driving System Design in Power Conversion

INTRODUCTION

USB Type C power distribution (PD) has been pushing adoption of USB as much as SuperSpeed USB. Users love faster data transfers but having a single connection to handle power chores everything from smartphones to laptops. USB PD also allows bidirectional power distribution support so a USB PC-based monitor can be powered by a laptop or recharge it depending upon the configuration. This ebook takes a look at the myths and magic behind USB PD.

Bill Wong
Editor, Senior Content Director

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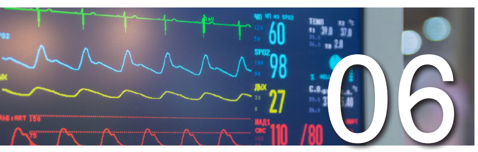
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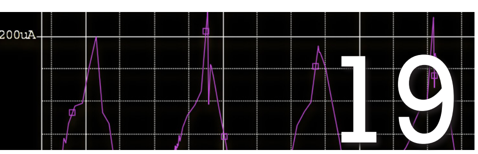
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CHAPTER 1:

What Can You Expect from the New Generation of Power Supplies?

STEVEN LEE, Application Engineer, Keysight Technologies Inc.

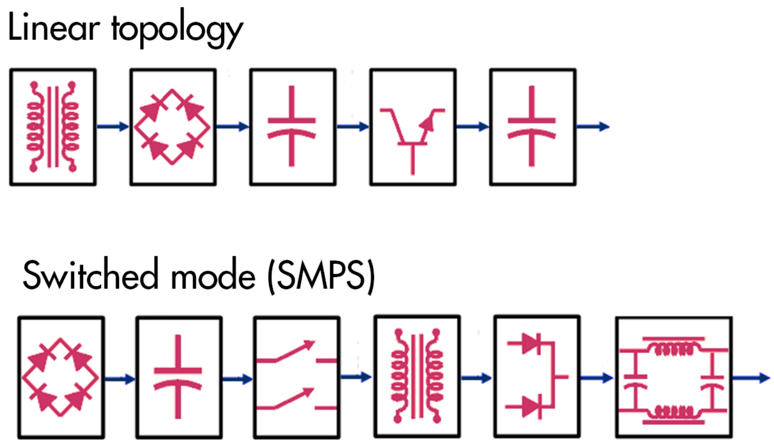
To get the most out of the advantages GaN transistors can offer in low-voltage, high-current POL converter design, pay close attention to several key guidelines.

Bench power supplies come in all shapes and sizes. Some fall into the general-purpose category, and others are very application-specific. Some only have a single output, while others offer multiple outputs.

Because today's designs place higher demands on the systems that power them, newer-generation bench power supplies are packed with very useful features that help engineers address those problems much earlier in the design process. This includes controlling multiple power-supply voltage sequences, measuring wide dynamic ranges of current, and varying the speed of the power-supply voltage to reflect real circuit characteristics.

Underlying all of this, bench power supplies need to be easy to use, deliver clean and stable dc power, and protect themselves and the development board (or DUT). It's not uncommon for bench power supplies to also be used in automated systems, so modern I/O connectivity might be

1. Shown are Keysight's E36300 Series triple-output dc power supplies.



2. This simplified block diagram represents the design topology between linear and switching power supplies.

another important consideration.

This article delves into problems that the new generation of power supplies *(Fig. 1)* can uniquely solve, and factors to consider when specifying or purchasing a power supply.

Design Topology: Linear vs. Switcher

A fundamental requirement of a power supply is an output signal with a high level of signal integrity, especially when working on a delicate design. The design topology of a power supply can tell you a lot about its signal integrity.

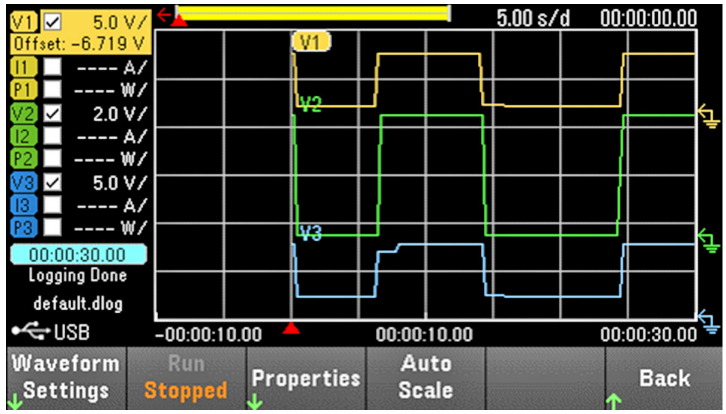
Generally, dc power supplies are developed with either linear or switch-mode technology, each offering different advantages. Linear power supplies tend to have low output noise, fast transient response, and high programming speed. However, they also come with a series of disadvantages, such as low efficiency, more cooling, higher level of low-frequency magnetic radiation, and (usually) larger-sized.

Switch-mode power supplies are typically smaller in size, provide higher efficiency, and require less cooling. Some of the disadvantages include slower transient response and higher output noise. However, design advances are enabling the newer generation of switch-mode power supplies to perform just as well as linear power supplies in those areas. Newer bench power supplies provide the best of both topologies. To achieve higher power in a smaller package, Keysight combined a linear output stage with a phase-controlled pre-regulator. Some of the benefits of this approach are better efficiency, double the output power, and lower acoustic fan noise *(Fig. 2)*.

High- and Low-Current Measurements

More and more applications require low current measurements such as idle/standby current on devices while in a low-current consumption state. These measurements can only be made with a power supply that accurately measures low-current values. Newer power supplies can measure dc current in the 100-µA range. However, be sure to check the datasheet for accuracy of measurement specifications at that range.

There may also be situations when more current is needed than can be provided by an older dc bench power supply. Newer bench supplies come with a built-in auto-parallel-mode capability that allows the engineer to combine two channels into a single, higher-current dc output channel rated as high as 25 V and 4 A. This eliminates the need to find and add another power supply into the test design. In a way, new bench power supplies



3. In Data Logger view, you can log data on multiple traces. Here, the voltage of output 1, output 2, and output 3 are captured over 30 seconds.

with auto-parallel capability perform the work of two power supplies.

Advanced Capabilities

Modern bench power designs fully take advantage of the latest graphical displays, microprocessors, and FPGAs. Thus, many advanced capabilities are built-into newer power supplies to save you time and money.

One example is the ability to synchronize multiple outputs on a power supply. Without this feature, a design engineer could spend hours writing code to perform this synchronization. Another example is the ability to create a dynamic user-defined output signal on a power supply to eliminate the need of a second setup requiring additional programming and instrumentation *(Fig. 3)*. With these and other advanced features, you will use less test equipment, set up tests faster and more simply, and reduce test setup errors—all of which save time and money.

Protection and Safety Features

When dealing with power, protection and safety come first. When a device fails, or goes up in smoke, it may be catastrophic. It's not only important for the power supply to protect itself, but also protect the device under test (DUT) and the operator. When a DUT fault occurs, protection circuits in the power supply can limit the voltage, limit the current, and shut off all outputs with a single button push.

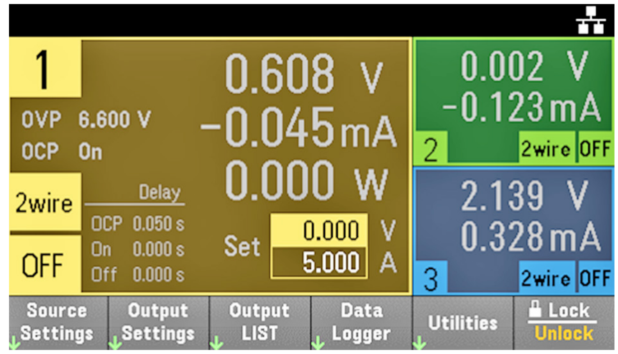
For example, the E36300 Series from Keysight integrates overvoltage, overcurrent, and over-temperature protection to prevent damage to the DUT. One push of a button on the front panel can shut down all power-supply outputs.

Enhanced User Experience

An intuitive user interface that allows you to easily navigate, control, and track each channel is another important feature with the latest power supplies. Equally important is a large graphical display that lets you see all of the output channels at the same time. With newer power supplies, you can set up advanced capabilities like remote sense, auto-parallel/auto-series, tracking mode, voltage sequencing, voltage steps, and data logging of V/I pairs over time with one push of a button.

In addition, modern I/O control such as built-in USB and LAN is typically available in modern power supplies. Support software can simplify automated measurement setup, recording, and analysis.

It's convenient to be able to see all channel readings and settings on the same screen *(Fig. 4)*. This may not be obvious, since many of the older power supplies make the user toggle back and forth to compare the channel setting and the reading. Newer power supplies make this information available on the same screen.



4. The user can view details of a single channel, including the measured power, OVP/OCP condition, and delays.

Performance Characteristics

Unfortunately, no standards have been established for power-supply datasheet specifications. Descriptions of the specification, as well as the specifications themselves, are determined by the manufacturer and will vary from one manufacturer to another. It's also at the manufacturer's discretion whether a characteristic is even specified. Some vendors specify more than others. Texas Instruments' experts wrote an application note, titled How to Read Your Power Supply's Data Sheet, to help you better understand power-supply datasheets and evaluate which power supply best meets your needs.

Total Cost of Ownership

The cost of an instrument includes the initial purchase price, as well as ongoing maintenance expenses plus the opportunity cost of downtime for calibration and repairs. Look for a manufacturer that will provide worldwide maintenance and support, a dedicated support team, and a solid track record for delivering products that last for 20 years or more.

For more information, visit www.keysight.com/find/E36300, or check out the application note "Seven Ways to Speed Up Your Testing with a Modern DC Bench Power Supply."

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Fig 1. Patient monitor with multiple connectors

CHAPTER 2:

USB Type C + PD Power Supplies: Advantages And Implementation

Universal ease of use of a standard USB-C connector with power delivery

ABSTRACT

Many powered devices will benefit from the universal ease of use of a standard USB-C connector teamed with power delivery (PD). By implementing the latest and highest-powered version of the USB PD standard, feature packed built-in versatility is available for medical and industrial markets. Learn about how USB-C + PD complies with USB and USB PD standards to provide system features and benefits including the reversible and robust USB-C output connector and USB-C + PD for higher power applications and reduced charge time of higher-capacity battery. In this article, the advantages and challenges of implementation associated with USB-C + PD are discussed. Although not limited to portable products, the solution for a hand-held imaging medical device is used for illustration.

BACKGROUND

Electronic product roadmaps tend to share some universal goals, regardless of industry, market or purpose. Design for user experience includes ease-of-use and improved portability, which requires smaller and lighter products with longer battery life. A good solution generally goes unnoticed, but the user is painfully aware of the inconvenience cause by a poor design. Such is the case with the seemingly mundane choices available for electronic connectors.

A product that requires data, sound, video and power will often have multiple connector ports, such VGA, HDMI, DB-9 and a DC power plug. Until relatively recently, each of these connectors served one purpose each, could be unreliable, have limited insertion lifeand could be difficult to locate. In addition to causing confusion, inefficiency and increased set-up time, which frustrates the user, multiple ports introduce multiple potential failure points for reliability and leads to an inherently bulky design. They also increase costs due to engineering time, higher tooling costs and increased part numbers on a final Bill of Materials(BOM).

DESIGN FOR USER EXPERIENCE INCLUDES EASE-OF-USE AND IMPROVED PORTABILITY, WHICH REQUIRES SMALLER AND LIGHTER PRODUCTS WITH LONGER BATTERY LIFE. THE UBIQUITOUS ADOPTION OF THE UNIVERSAL SERIAL BUS (USB) STANDARD ILLUSTRATES THE INDUSTRY'S FRUSTRATION WITH THE LACK OF OTHER OPTIONS FOR HIGH SPEED DATA AND POWER.

These cost and inconvenience factors are exacerbated in the case of industrial or medical applications, the patient monitor shown in *Figure 1*, for example. This is for technical reasons, such as ingress requirements for cleaning as well as unknown environmental conditions, and because of the critical naturre of the device's use model.

The ubiquitous adoption of the Universal Serial Bus (USB) standard illustrates the industry's frustration with the lack of other options for high speed data and power. Most applications, including consumer electronics products have adopted USB. Apple is the remarkable exception, which highlights the need for high speed data and power in a reversible port, and sets the expectation in the industry that USB type C enabled with power delivery for variable DC voltage on-demand will be the de facto solution in the coming years.

PRIOR USB STANDARDS

Below, the features of various types of prior USB connectors are outlined. The most commonly seen today are shown in *Figure 2*, alongside the newer USB-C.

- **Type-A:**
  - o Standard flat, rectangular interface
  - o Most computers have multiple USB-A ports for connecting peripherals
  - o Game consoles, TVs, and other devices
  - o Only inserts in one way
- **Type-B:**
  - o Almost square connector
  - o Mostly used for printers and other powered devices that connect to a computer
  - o No longer common, replaced by smaller options
- **Mini-USB:**
  - o Smaller connector type that was standard for mobile devices before micro-USB.
  - o On some cameras, the PlayStation 3 controller, MP3 players, and similar

Fig 2. Common USB connectors

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
GND	TX1+	TX1-	VBUS	CC1	D+	D-	SBU1	VBUS	RX2-	RX2+	GND
GND	RX1+	RX1-	VBUS	SBU2	D-	D+	CC2	VBUS	TX2-	TX2+	GND
B12	B11	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1

- Cable Ground
- SuperSpeed Data Path (TX for USB 3.1, or reconfigured in Alternate Mode)
- SuperSpeed Data Path (RX for USB 3.1, or reconfigured in Alternate Mode)
- Cable Bus Power (from 5V up to 20V)
- Configuration Channel
- Sideband Use
- USB 2.0 Interface

Two pins on the USB Type-C receptacle, CC1 and CC2, are used in the discovery, configuration and management of connections across USB type-C cable.

Fig 3. Receptacle pins for USB type C

- **Micro-USB:**
  - o Current standard (though slowly declining in popularity) for mobile and portable devices
  - o Smart phones, tablets, USB battery packs, and game controllers

USB DATA SPEEDS AND COMPATIBILITES

USB data speeds have increased over time increasing its functionality for streaming video and sound. There are two speeds still in use today: USB 2.0 and USB3.x.

- **USB 2.0** introduced many modern USB norms, including support for Mini and Micro cables. This is the slowest speed of USB still used today, but it is still common in flash drives and devices like mice and keyboards.
- **USB 3.x** is the current standard for USB speeds. It is faster than USB 2.0, and thus recommended for devices like external hard drives. One can typically identify a USB 3.x port or connector by its blue coloring. Many USB 3.0 ports also have an SSsymbol (which stands for Super Speed). Most new computers have at least one USB 3 port, and good-quality flash drives use this standard.

USB-C + PD: Advantages and Implementation

USB-C is the emerging standard for high speed data transfer of video and sound for several very simple and straight forward reasons. USB-C is, at once, robust and inexpensive, especially for the number of connections available. USB Type-C connector extends to the inclusion of a 24-pin connector. As seen in *Figures 3 and 4*, this provides four ground connections, four Vbus connection, two pairs of TX high-speed data path, two pairs of RX high-speed data path and two pairs of USB2.0 interface. It is compact and reversible which contributes to improved mechanical design and a positive user experience. The two CC channels enable USB-C connector to determine the orientation; the Vconn cable power and the other will be used for USB-Power Delivery(PD) communication. Finally, when paired with a PD chip, the format allows for higher power utilization or faster charging capabilities

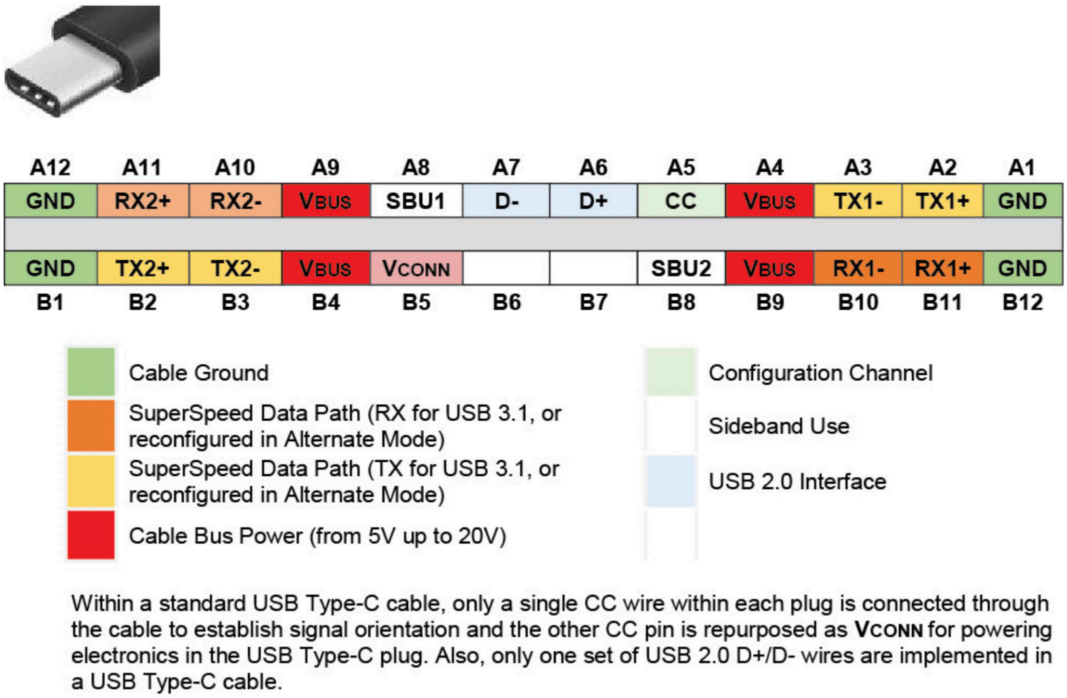

Figure 4: Plug pins for USB type C

of battery powered devices and the built-in versatility for power and voltage negotiation means that a single power supply could serve multiple products and result in a reduction of accessory part numbers and lowered costs due to standardization.

POWER DELIVERY VIA USB

A Device Policy Manager(DPM) communicates with a power supply to provide the required power (Voltage, Current) over Vbus. PD communication gives commands through DPM or Policy Engine(PE) to the power supply to requests the desired power level and modes while monitoring the performance and the PD chip that is integrated into the USB-C connector enables the communication between the source and the sink to elevate Vbus to supply voltage from 5V up to 20V and current up to 5A. USB Type-C PD supports dynamic power negotiation, allowing minimum charge time, maximum battery life and performance. Not only does it regulate the power output level, but also the PD chip features a single wire communication protocol that enables any source to become the power sink and vice versa.

CHALLENGES OF IMPLEMENTING POWER DELIVERY

To provide such high-power output, the desired voltage and current must be negotiated through USB power pins with DPM. For the power supply to achieve such efficiency and meet functional safety standards for medical product, PD verification process must be conducted during the design phase.

The initial power (source to sink) and data (host to device) relationship using the two CC1 and CC2 pins on the USB Type-C receptacle must established using the following methodology:

- The orientation of the connection is detected, with the connection the two pairs of CC pins, as a twisted-through connection or straight-through connection. If both ports try to act as the source or sink, a collision resolution is commenced.
- The USB-C + PD communication is established, and Bi-phase Mark Coded communications are carried on the CC wire of the USB Type-C cable.
- The communication will determine how to setup and manage the power and accessory modes and dynamically monitor the detach and re-attach.

Next the source defines the capability of USB-C cable through EMCA identifier and communicates to sink and the sink will ask for the specified power level at certain current/voltage.

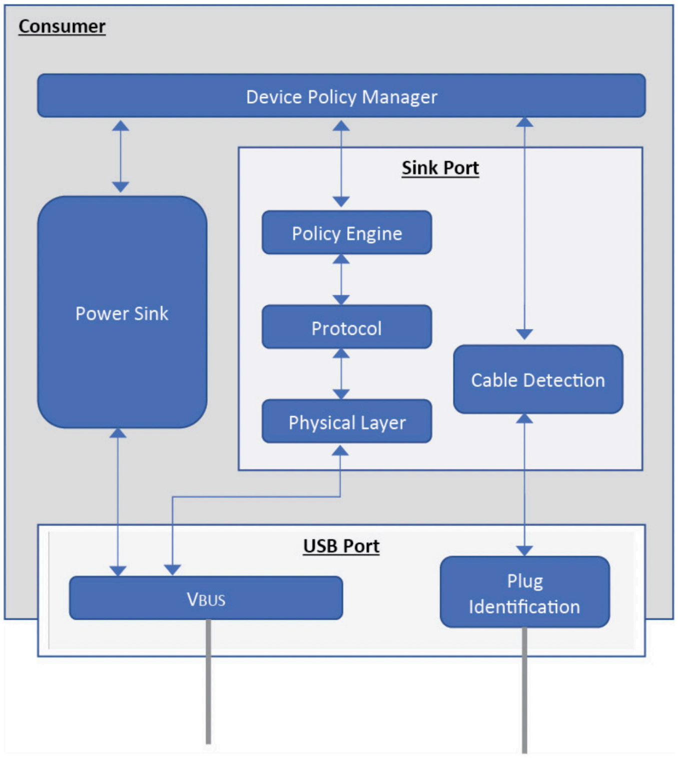

Figure 5: Communication schematic for security implementation

- The source will then evaluate the requested setting and EMCA caps to determine if the request is acceptable or not.
- The downstream facing port (DFP) capable of USB-PD communication will send Vconn message to initiate Vconn SWAP and enable the desired voltage to provide the power requested.
- Vconn will be established on one of the CC pins that was not used by USB PD communication, to supply power to the local plug.

SECURITY IMPLEMENTATION

The use of communication to authenticate power electronic peripherals is surprisingly important. The use of aftermarket products is very common and can result in reduced user satisfaction and liability for the OEM. Fortunately, the USB-C + PD products offer a few approaches with a varying degree of burden and security. The approaches for the Phasium products (outlined in the next section) are as follows; they are representative of the ways in which solutions are implemented:

- **Identifying the product ID by PD message of Get_ Manufacturer_Info and Manufacturer_Info**
  - o Easiest way to achieve the goal
  - o PD's standard command which is used to get the manufacturer information of devices
  - o TA can verify the information and enable more functions, e.g.extra power profile
  - o Difficult to prevent copy-cats
- **Implement Alternate-Mode and UVDM (unstructured VDM)**
  - o Use UVDM to exchange information with its port partner
  - o Use it to implement an simple authentication flow. E.g. SHA256 or something else for identifying the product ID
- **Implement USB Authentication flow by Security_Request and Security_Response**
  - o Customer can refer to the spec of USB_AUTHENTICATION R1_0, requires an extra chip
  - o Highest security, highest cost

The schematic for the communication protocol is shown in *Figure 5.*

CASE STUDY: Power supply for a medical imaging system

The information above outlines the advantages and reasoning for the presumed popularity of the USB-C + PD solutions. These include: the reduction in number of connectors; ease of use due to reversibility: for industrial and medical products, there are fewer ingress points; cost reduction and size reduction. A theoretical side-by-side of the Phasium USB-C + PD power supplies versus a conventional multi-port approach illustrates the simplicity of this approach.

The Phasium USB-C + PD Product Line

Phasium offers a line of power supply solutions for all USB-C+PD enabled products regardless of power and voltage incompatibilities. The products are offered at 24W, 40W, 60W and 100W with current limits at 3A (24W and 40W) or 5A (60W and 100W) and voltages and preset standards of 5V, 9V, 10.4V, 15V and 20V. An image of the 60W power supply is shown in *Figure 6.*

These power supplies offer the following features:

- **60601-1**
- **Class B**
- **4th ed EMC**
- **Reversable USB-C output**
- **Class I or II**
- **IP22**
- **High power density**
- **Custom options upon request**
- **Additional features**
  - o Embedded MCU with an OTP-ROM of 32kB and an SRAM of 1.5kB to perform role of Policy Engine
  - o Supports USB PD 2.0 and 3.0 & Other Proprietary Protocols
  - o Embedded BMC Transceiver
  - o In negotiation phase Vendor Defined Messages (VDMs) can be used for positive ID

Fig 6. Phasium USB-C + PD 60W power supply

- o Built-in Synchronous Rectifier Driver and Controller
- o Built-in Shunt Regulator for Constant-Voltage and Constant-Current Control (Battery Charging)
- o Programmable Cable Compensation
- o BLD Pin for Quick Discharge of Output Capacitor
- o USBP Pin for Direct Drive of External Blocking P-MOSFET
- o Power-Saving Mode in Standby Mode Protection
- o Adaptive Output Over-Voltage Protection
- o Adaptive Under-Voltage Protection
- o Firmware-Programmable Over-Current Protection
- o Firmware-Programmable Over-Temperature Protection

The Phasium USB-C + PD Compared to a Conventional Solution

The cost comparison in *Figure 7* may present as over-simplified but Occam's razor is most commonly described as 'the simplest answer is most often correct.' One can quibble

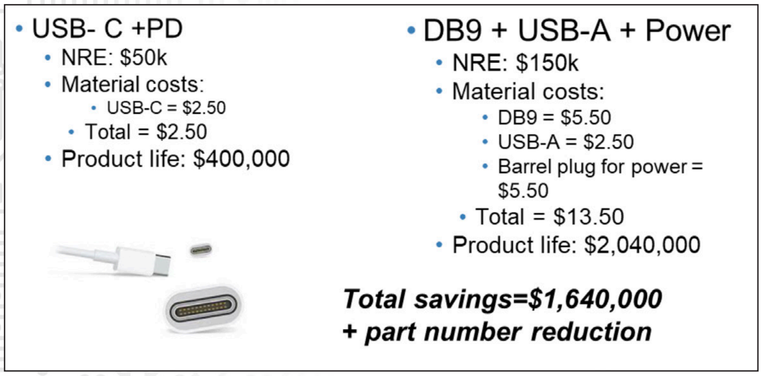

Fig 7. Cost comparison of USB-C + PD

about the philosopher's intent but in this case, the numbers speak for themselves.

If one uses the example of a typical medical imaging system, such an ultrasound unit or anything else with both video and sound, and compares the utilization of a USB-C +PD solution versus a conventional solution with a DB9 connector for video, a USB-A for data and a barrel plug for power, the reason the industry is gravitating toward USB-C + PD is obvious. Over a seven year product life, typical for medical products, a cost savings of more than $1.5M dollars could be expected. That is before one takes into account additional efficiencies such as part number reductions.

CONCLUSIONS

The USB-C + PD power supply solutions provide universal ease of use due their robust design and versatility and reversibility.

Cost savings are available to the OEM do to reduced engineering and tooling resource requirements in development and the reduction of part related costs in production.

Built in versatility for power and voltage means that a single power supply could serve multiple products and result in a reduction of part numbers.

Security is easily implemented protecting against liability due to the failure of aftermarket or counterfeit products.

Reduction in charge time for battery powered products is available with the high power enabled by PD.

Medical grade 13485 manufacturing and quality is available at a similar cost to off the shelf consumer products with the line of Phasium USB-C + PD products.

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CHAPTER 3:

11 Myths About Digital Power

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The second coming of power conversion or an unnecessary extravagance? We examine myths surrounding digital power conversion to better understand its challenges and benefits.

Analog power conversion has been a staple of power electronics for decades, and for many designers, digital power is a relative unknown. Depending on who you ask, it could be described as the second coming of power conversion or an unnecessary extravagance. The reality is the technology offers new features and system advantages for the designs that need them.

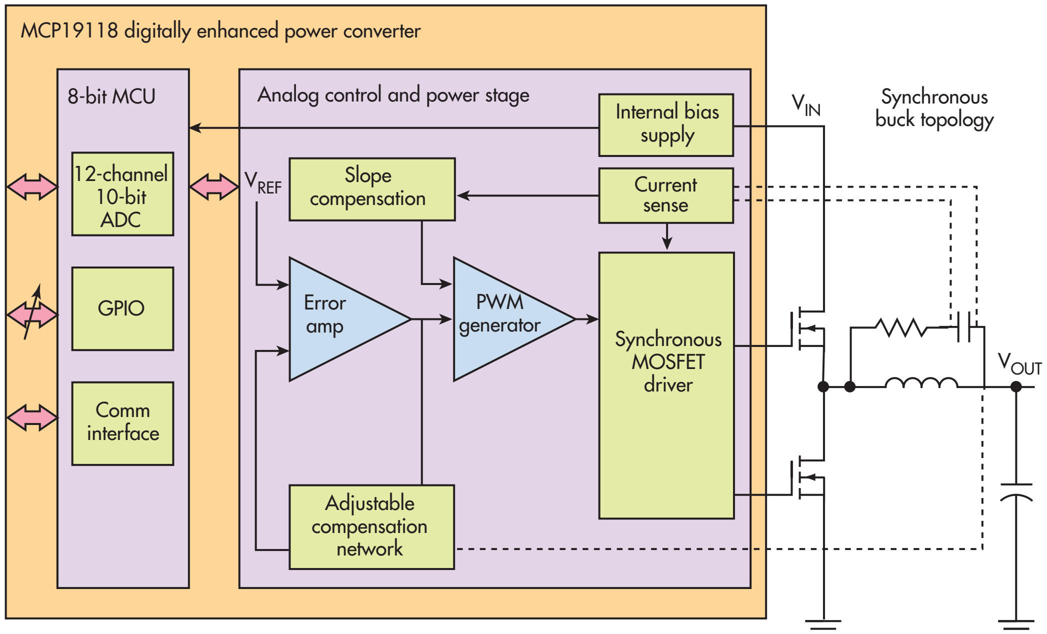
Digital power can mean a lot of different things, and digital technologies can bring many benefits if used judiciously. Let's take a closer look at several myths and legends to help understand the challenges, benefits, and appropriate use of digital technology for power conversion.

1. Switch-mode power supplies are exclusively analog or digital.

Switch-mode power conversion is an inherently mixed-signal system. The pulse-width-modulation (PWM) signals are digital and the feedback signal is analog. What goes on between those two nodes is an analog-to-digital conversion with very precise timing. That conversion could happen after an amplifier-based control network decides when to switch, or it could happen at the feedback signal, allowing a digital algorithm to decide when to switch.

More than ever, analog control chips include digital interfaces for external control, and digital microcontrollers incorporate analog components that allow for power-supply control *(Fig. 1).* It's always been possible to add a microcontroller to a power supply, but today that microcontroller can have more influence on system operation than ever before. Or, alternatively, the whole control loop can be implemented in a digital signal controller.

Either way, power supply designs can be more flexible, more adjustable, and respond



1. Shown here is the digital management of an analog control loop on the MCP19118.

more intelligently to environmental conditions or external inputs. These features can be added regardless of whether the control loop itself is implemented in a digital or analog domain. Today, switch-mode power supplies can have as much digital logic as required an application.

2. Digital features require digital control loops.

The control method is just one of the features of the power-conversion system. A microcontroller can be added to any analog system to allow for additional supervision or management, power supplies included. Historically, a microcontroller's ability to affect an analog control loop has been very limited, due to the very limited dynamic configurability of dedicated analog control parts.

However, newer analog control devices more commonly contain digital interfaces, with more configuration or programmability than previous generation devices. Similarly, there are integrated power converter products with microcontrollers on chip, which allow new dimensions of dynamic configuration. With smart component selection, digital communication interfaces, sleep modes, frequency shifts, synchronization, soft-start, intelligent fault protection, or output voltage/current changes can all be intelligently implemented in a power-conversion system—added to either analog or digital control-loop implementations.

3. Digital power is less robust than analog power.

Robustness is a complicated system feature, and many things can be done to improve the robustness of either analog or digital power supplies. Depending on the implementation, analog power supplies could have faster hardware fault responses, with quick acting undervoltage and overvoltage comparators, and true cycle-by-cycle current limiting.

However, those things can also be implemented in a digitally controlled power supply, possibly with dedicated analog structures present in more advanced digital control chips. Digital controllers may include analog current limit comparators. In addition, digitally featured power supplies (even those using analog control loops) have several distinct advantages that can't really be mimicked in a true all-analog solution. Digital program code can provide customized fault or brown out responses, including customized soft start, soft shutdown, trickle charge, timeout or retry approaches that would be difficult (or impossible) to implement using analog controllers.

Furthermore, digital control loops or integrated on-chip feedback networks reduce reliance on external passive components, which often shift or degrade over time. Finally, digital interfaces provide diagnostic and reporting information that can be used to identify future problems, avoiding hard system outages.

Adding all of these features can create a more robust system than a simple dedicated analog solution. Regardless of the implementation, all power supplies require careful testing to ensure good product lifetimes. However, there are no fundamental reliability limitations to digital power systems that will lead them to perform poorly compared to their analog counterparts.

4. Digital power is more expensive.

While designers are under the impression that digitally controlled power supplies are more expensive than their analog counterparts, this isn't always the case. Digital supplies can be less expensive because they may be designed around less precise, and therefore less expensive, components. They may also require fewer total components, reducing both the cost and solution size.

Digital supplies can also save money in terms of the total cost of ownership. In applications with variable load conditions, designers are able to implement nonlinear and adaptive algorithms to deliver the highest possible efficiency for any given set of operating conditions. Another reason that digital supplies may cost less to operate is that they can account for component aging over the life of the supply, notify users if preventative maintenance is required, and avoid catastrophic component failures (also resulting in expensive, unexpected downtime).

5. Digital power is more efficient.

Oftentimes, digitally controlled power supplies offer more energy efficiency across widely varying load conditions. They may utilize adaptive algorithms and even modify the topology of the system in response to changing conditions using techniques such as phase shedding. Digitally controlled supplies can use nonlinear and predictive algorithms to improve dynamic response to transients.

Analog power supplies can be every bit as energy-efficient as digital power supplies at a given design point. The challenge for analog supplies, though, is to maximize the efficiency if conditions such as load current move away from the optimum operational point.

On the other hand, the power required to run a digital controller can exceed the power required for an analog controller. Digital controllers are usually a better fit for higher-power applications, where their energy use overhead is easily offset by the additional energy savings made possible by the more comprehensive control algorithms enabled by digital technology.

6. A digital controller's latency negatively impacts transient response.

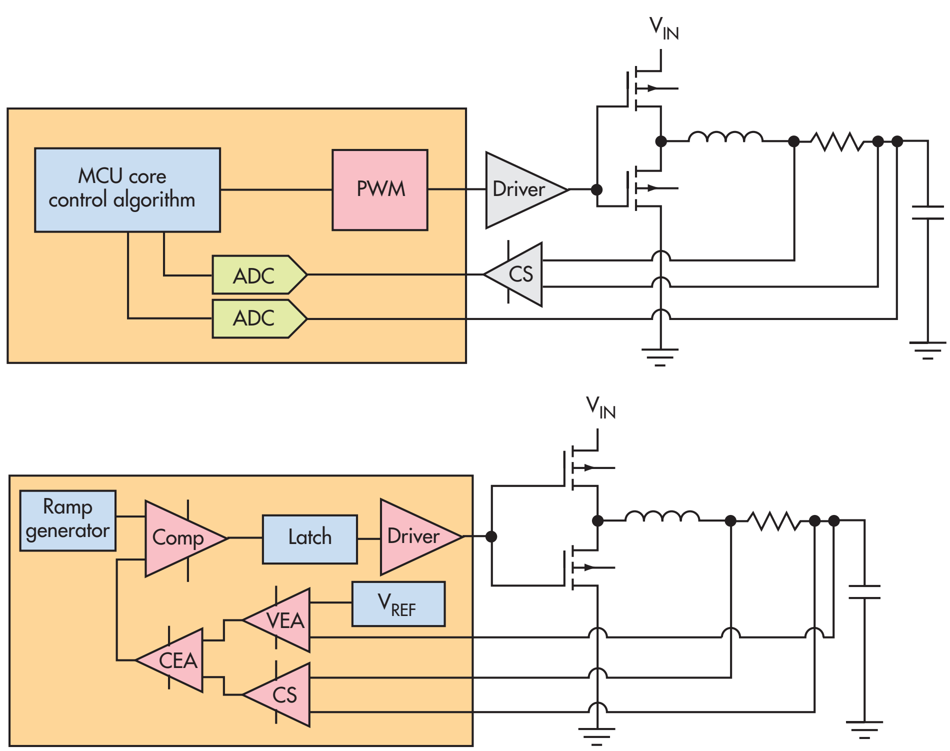
A digitally compensated system faces two major latency concerns: the sampling effects and the computation time.

With any power conversion, the crossover frequency (transient response) will always trade off against the phase margin (stability). Digital systems are fundamentally similar, but digital control systems are sampled. A periodic sampling (once per cycle) adds a phase shift to the transfer function. This can't be easily compensated for; the digital system requires a lower crossover frequency to achieve the same phase margin (if using the same compensation method). On top of that, the processor needs to perform the ADC reading and difference calculations within one switching cycle, or there will be an additional period of latency from the calculation time.

However, these negatives can be overcome with advanced nonlinear control methods and feed-forward techniques—algorithms that would be difficult (or impossible) to implement in an analog control system. The drawback is the processing requirements, which creates a tradeoff between processing speed, switching frequency, algorithm complexity, and transient response. This needs to be designed for, but doesn't necessarily cause a reduction in transient response due to the digital control.

7. No load current is a problem

Switching power supplies typically run in one of two modes: discontinuous conduction and continuous conduction. In discontinuous conduction operation, the inductor current falls to zero at the end of every PWM cycle. Continuous conduction operation maintains continuous current flow in the inductor.



2. The top diagram is the hardware required for a digital control loop in a switch-mode power supply; the bottom diagram shows the analog control loop equivalent.

The advantage of continuous conduction is that the inductor current doesn't have to ramp up from zero on every PWM pulse, thus delivering more current each PWM cycle. The disadvantage is that the error amplifier/loop filter must have the right combination of poles and zeros to maintain stability. Unfortunately, if the current in a continuous conduction design does go to zero, it can make the control loop unstable.

To combat this, older designs often either specify a minimum current or guarantee a minimum current by placing a load resistor on the output (forced continuous conduction, or FCC). Fortunately, a number of power-supply controllers today can handle both continuous and discontinuous modes of operation (PWM and pulse frequency modulation, or PFM) with monitoring circuitry to determine when to switch from one mode to the other. So, while this was once a limitation due to the design of power-supply controllers, newer controllers automatically handle the mode switching and the limitation is little more than a footnote in history.

8. Digital power supplies are difficult to design.

Designing a digitally controlled power supply isn't necessarily more difficult than designing an analog supply; it's just different. The powertrain design is very similar in both cases (for a hardware illustration, *see Fig. 2*). The control loop or compensator design is implemented in digital controller firmware rather than with analog circuitry.

The location of poles and zeros of the plant are used to define the compensator characteristics (same as an analog design). However, in the case of a digital compensator, software tools are often used to configure the optimum response for the control loop. For example, highly optimized software libraries, including common 2P2Z (type II) and 3P3Z (type III) compensator algorithms, for use on Microchip's family of dsPIC digital signal controllers, are available for free on the company's website. Designers don't need to write the software for those functions themselves. In addition, these algorithms are tuned for specific powertrains by providing coefficients that are derived by the design tools.

9. Digital power-supply design is easier than analog (because it's just software).

The fact that digital power supplies use software for the control algorithms doesn't discernibly simplify their design. Designers must still fully understand control systems and characterize the powertrain's frequency response to be able to properly configure the software-based compensator that's used. On the other hand, tweaking the operation of the supply to fine-tune results can be easier in software than it would be if hardware has to be modified to make the changes.

10. All you need is a DSP—digital power will replace everything else.

While many pundits push digital power as the silver bullet that solves all problems, it doesn't fit every application. For example, it doesn't make sense to put all of that processing power into a palm-sized MP3 player running on an internal lithium-ion cell, just to boost the supply voltage. On the other hand, platinum-level server power supplies need the capabilities of a digital power converter to efficiently generate the necessary power output and respond quickly to load changes.

For example, cell-phone towers have a high current requirement when the transmitter is on, but use much less power when it's off. The controller for the transmitter knows when it's going to turn on, so it alerts the power converter and coordinates a move up in the average current. Therefore, when the transmitter kicks on, the current is already there. That allows it to avoid a sag in the power while the loop filter responds, after the fact. This is one of the powerful features of digital power, and it justifies the additional complexity in the design.

On the other hand, a system with a relatively constant power requirement can use an analog system with its much simpler design, lower complexity, and lower cost. After all, it's pretty hard to beat the cost and simplicity of an ASIC-based regulator.

11. Software-defined power will take over.

A few years ago, the prediction was that software-defined radio (SDR) would take over as the default design for radio receivers. While SDR offered several advantages, it suffered from one major drawback: It required a processor with 10X to 100X MIPS to receive frequency. Even systems that used an analog mixer to translate the radio frequency (RF) down to a lower intermediate frequency (IF) would still require 10 to 100 MIPS, and demodulation would be all that the processor could handle. This is clearly not very cost-effective.

Now, when someone says that software-defined power (SDP) will take over, one shouldn't take it too seriously. There's nothing simpler and cheaper than a linear regulator. And, even if a processor with the necessary MIPS were available at the same price, you would still need the Linear 5-V regulator to bootstrap the power for the processor to get it started. SDP has a definite place in power, and really is the only thing that can do its job. However, it is not, nor will it ever be, a one-size-fits-all solution for power conversion.

Conclusion

Often, it's difficult to separate marketing fluff from hard information, particularly when the market is in flux, such as is the case with the current power market (no pun intended). Proponents for change typically extol the virtues of new technology, often forgetting to mention inherent challenges that come with it. The conservatives focus just on the challenges and argue "if it ain't broke don't fix it."

Of course, we don't live in either extreme. We typically have to design and work in the middle ground, take the new with the old, and find the right mix for our current design needs. That's why a company like Microchip has a portfolio of power solutions extends from traditional analog to digital power. Such firms realize that the world is not black and white; rather, it's a continuum, so they try to meet all customer needs.

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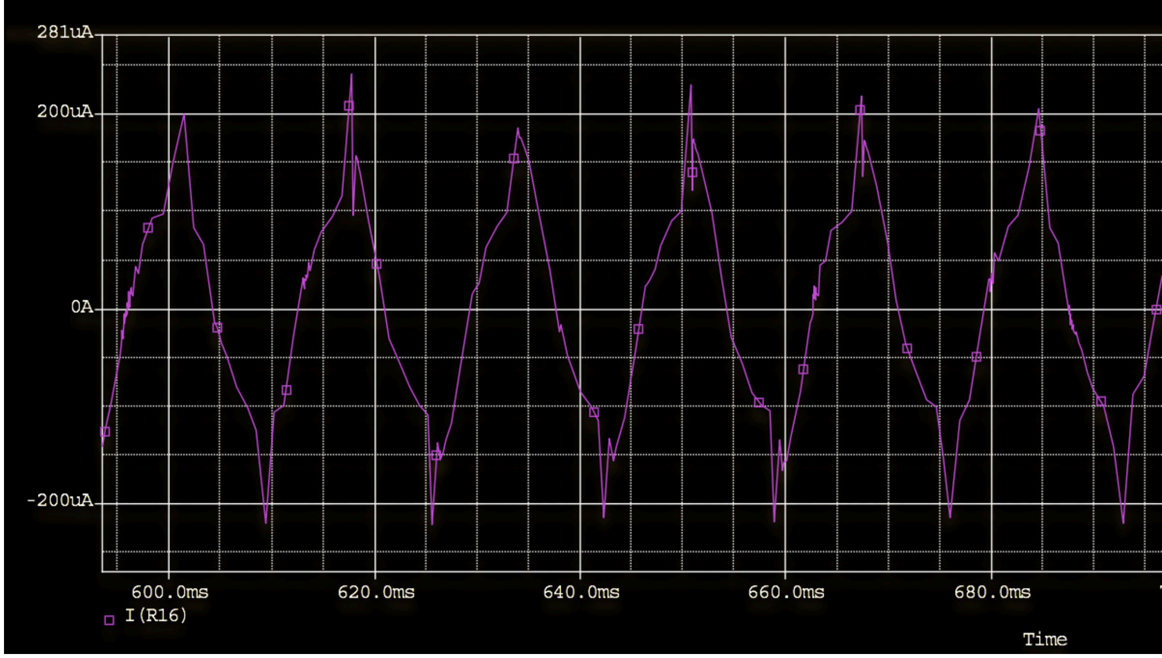

CHAPTER 4:

Leakage Current Estimation In Power Supply Design

Theoretical Analysis of Leakage Current in a Medical Power Supply System

ABSTRACT

This article provides a theoretical analysis method of leakage current in power supply systems. Medical power supply engineers should guide the design through theoretical analysis of leakage current of the system to ensure proper design margin, so that there is no risk of leakage current exceeding the standard requirement due to the error of Y capacitors in the mass production of medical power supplies. This helps to reduce production costs and improve quality while ensuring that all factory power supply products meet customer and safety leakage current requirements.

PROBLEM STATEMENT

In the design of medical power systems, multiple Y capacitors are generally used to solve Electromagnetic Interference (EMI) issues. The value of the leakage current of the power supply is verified, meeting the leakage current safety requirement or not, generally after the EMI is solved by choosing the Y capacitors by experimental methods. For power systems with multiple Y capacitors, designers often do not theoretically analyze the effect of each Y capacitor tolerance on the design margin of the power supply's leakage current; therefore, in mass production, the influence of the positive and negative errors of multiple Y capacitors on the leakage current can only be verified by batch production test to meet safety standards. There is no theoretical basis to prove whether the leakage current of the power supply in the design has a quality risk exceeding the safety requirements in production.

In our case study, Phasium takes a medical power supply as an example, the equivalent circuit of the patient leakage current of the power supply is obtained, and then the leakage current is estimated based on it. The function between the positive and negative tolerances of the Y capacitor and the variation of the leakage current leakage current of the medical power supply is derived by using the total differential error analysis method. This has important theoretical guiding significance for the design of leakage current of medical power

DESIGNERS OFTEN DO NOT THEORETICALLY ANALYZE THE EFFECT OF CAPACITOR TOLERANCE ON THE TOTAL DESIGN MARGIN OF THE POWER SUPPLY'S LEAKAGE CURRENT; THEREFORE, IN MASS PRODUCTION, THE INFLUENCE OF THE ERRORS OF MULTIPLE CAPACITORS ON THE LEAKAGE CURRENT CAN ONLY BE VERIFIED BY TESTING. IN OUR CASE STUDY, THE EQUIVALENT CIRCUIT OF THE PATIENT LEAKAGE CURRENT IS OBTAINED, AND THEN THE LEAKAGE CURRENT IS ESTIMATED BASED ON IT

supply, the selection of Y capacitance accuracy and the evaluation of leakage current margin, as well as mass production testing and quality management.

BACKGROUND: The Equivalent Circuit for Patient Leakage Current Calculation and Formula Derivation

One medical power adaptor schematic which contributes the main patient leakage current is shown in *Figure 1.*

The PATIENT LEAKAGE CURRENT test in *Figure 2* shows suitable test configuration for use in conjunction with the test PROCEDURES specified in IEC60601-1.

From the above schematic and Patient Leakage Current measuring test setup, it is known that the Patient Leakage Current of the power adaptor is mainly the superposition of two currents IC42 and IC39 in the branches C42 and C39, respectively. The simplified equivalent circuit for Patient Leakage Current IC42 contribution is shown in *Figure 3*.

C42 is connected in parallel with C3, and then they are connected in series with C2. But only the current in C42 branch needs to be calculated for Patient Leakage Current contribution. According to Figure 3, the formula for IC42 calculation can be derived as follows:

$$I_{c42} = \text{Vin} * \omega * \frac{C_{42} * C_2}{C_{42} + C_3 + C_2} \qquad (1)$$

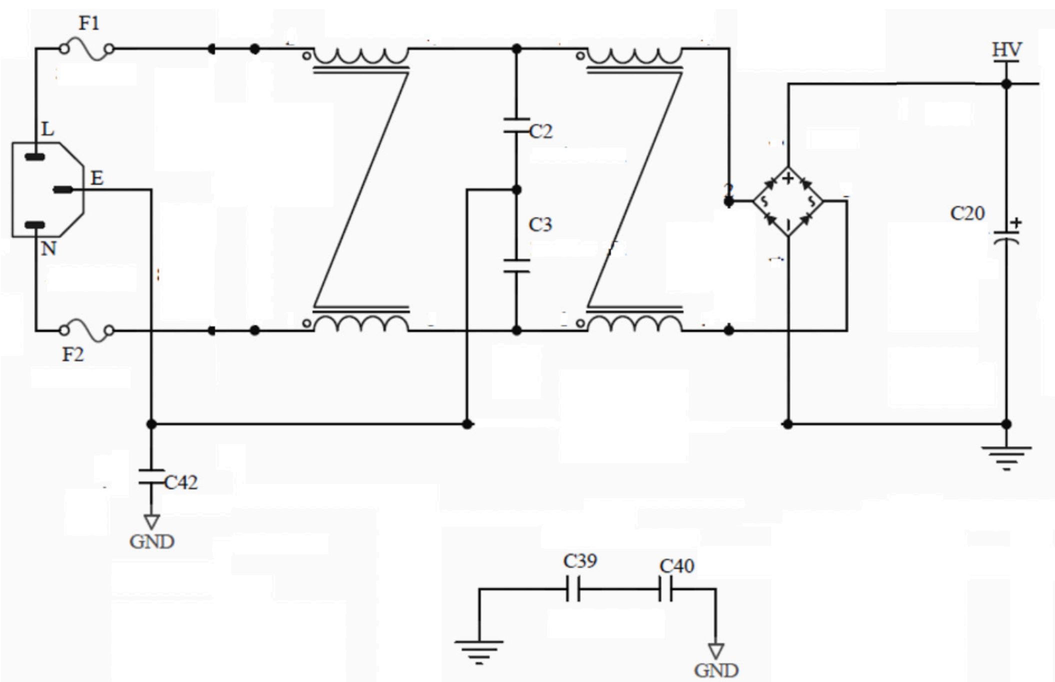

Fig 1. A Medical Power Supply Schematic

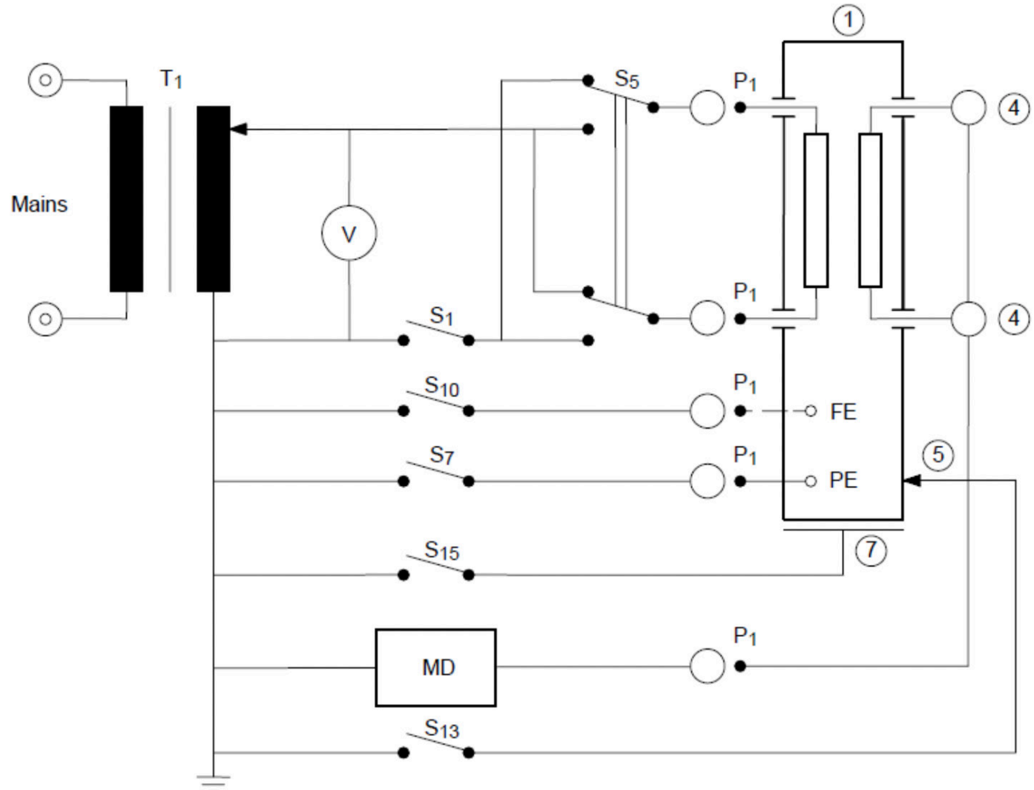

Fig 2. Measuring circuit for the PATIENT LEAKAGE CURRENT from the PATIENT CONNECTION to earth

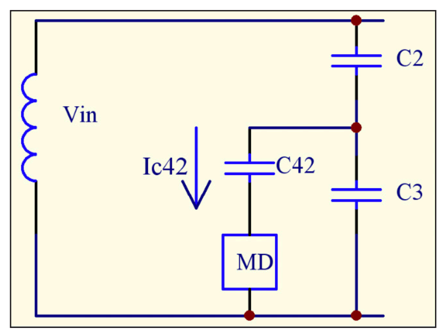

Fig 3. Equivalent Circuit for Patient Leakage Current IC42

Where ω=2πf and f is the frequency of the voltage.

The simplified equivalent circuit for Patient Leakage Current IC39 contribution is shown in Figure 4.

According to *Figure 4*, the branch IC39 consists of C39 and C40 in series. They are connected after the input rectifier bridge, so the voltage applied to C39 and C40 is the rectified half-wave sine voltage. Its Fourier Transformation is expressed as follows:

$$V_{halfwave} = \frac{V_{in}}{\pi} + \frac{V_{in}}{2}\sin(\omega t) - \frac{V_{in}}{\pi}\sum_{n=1}^{\infty}\frac{\cos(2n\omega t)}{4n^2-1} \quad (2)$$

Omitting the DC component in the half-wave sine voltage in the Equation (2), its fundamental is the half of the sinusoidal input voltage. Thus, the formula for Patient Leakage Current IC39 at fundamental can be obtained as follows:

$$I_{c39} = \frac{V_{in}}{2} * \omega * \frac{C_{39}*C_{40}}{C_{39}+C_{40}} \quad (3)$$

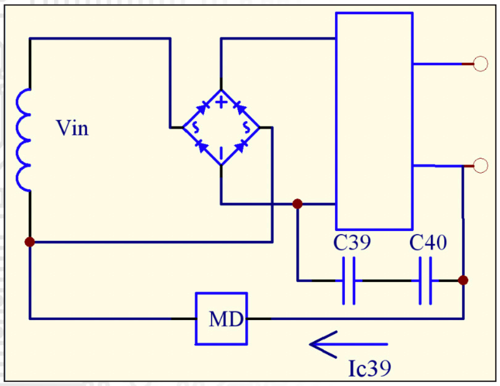

Figure 4: Equivalent Circuit for Patient Leakage Current IC39

The total Leakage current at fundamental is Ileakage1= IC42 + IC39, that is,

$$I_{leakage1} = V_{in} * \omega * \{\frac{C_{42}*C_2}{C_{42}+C_3+C_2} + \frac{1}{2} * \frac{C_{39}*C_{40}}{C_{39}+C_{40}}\} \quad (4)$$

The contribution of third harmonic voltage generated by rectifier bridge side to the leakage current must be also considered. The third harmonic voltage has an amplitude of V_in/3π . The third harmonic leakage current can be estimated by the following formula:

$$I_{leakage3} = V_{in} * 3\omega * \frac{1}{3\pi} * \frac{C_{39}*C_{40}}{C_{39}+C_{40}} = V_{in} * \frac{\omega}{\pi} * \frac{C_{39}*C_{40}}{C_{39}+C_{40}} \quad (5)$$

The total leakage current contributed by the fundamental and third harmonic can be calculated by

$$I_{leakage} = \sqrt{I_{leakage1}^2 + I_{leakage3}^2} \quad (6)$$

The leakage current variation as a function of the tolerances of the Y capacitors can be derived as follows:

In Equation (4), the leakage current at fundamental has been expressed in variables of Y capacitances.

$$i_{leakage1} = i_1(c_{42}, c_3, c_2, c_{39}, c_{40}) = \text{Vin} * \omega * \{\frac{c_{42}*c_2}{c_{42}+c_3+c_2} + \frac{1}{2} * \frac{c_{39}*c_{40}}{c_{39}+c_{40}}\} \quad (7)$$

The leakage current deviation of the power supply can be approximately expressed in the tolerances of the Y capacitors by using the definition of total differential on Equation (7).

$$\Delta i_{leakage1} \approx \frac{\partial i_1}{\partial c_{42}}\Delta c_{42} + \frac{\partial i_1}{\partial c_3}\Delta c_3 + \frac{\partial i_1}{\partial c_2}\Delta c_2 + \frac{\partial i_1}{\partial c_{39}}\Delta c_{39} + \frac{\partial i_1}{\partial c_{40}}\Delta c_{40}$$

$$= Vin * \omega * \{\frac{c_2*(c_3+c_2)}{(c_{42}+c_3+c_2)^2}\Delta c_{42} + \frac{-c_{42}*c_2}{(c_{42}+c_3+c_2)^2}\Delta c_3 + \frac{c_{42}*(c_{42}+c_3)}{(c_{42}+c_3+c_2)^2}\Delta c_2 + \frac{1}{2}\frac{{c_{40}}^2}{(c_{39}+c_{40})^2}\Delta c_{39} + \frac{1}{2}\frac{{c_{39}}^2}{(c_{39}+c_{40})^2}\Delta c_{40}\} \quad (8)$$

The Equation (8) clearly shows the amount of change in leakage current caused by each Y capacitor error. It is noted that only the deviation in capacitance of the Y capacitor C3 can cause the leakage current to change in the opposite direction, that is, as the C3 capacitance increases, the leakage current decreases. All other deviations in the Y capacitances cause the leakage current to change in the same direction, that is, the capacitance increases and the leakage current also increases.

Equation (8) can also be used to find the contribution of the deviation of each capacitor to the leakage current.

We can use the same strategy to obtain the third harmonic leakage current variation as a function of the tolerances of the Y capacitors. In Equation (5), the third harmonic leakage current has been expressed in variables of Y capacitances.

$$i_{leakage3} = i_3(c_{39}, c_{40}) = V_{in} * \frac{\omega}{\pi} * \frac{C_{39} * C_{40}}{C_{39} + C_{40}}$$

The third harmonic leakage current deviation of the power supply can be approximately expressed in the tolerances of the Y capacitors by using the definition of total differential on Equation (9).

$$\Delta i_{leakage3} \approx \frac{\partial i_1}{\partial c_{39}} \Delta c_{39} + \frac{\partial i_1}{\partial c_{40}} \Delta c_{40}$$

$$= Vin * \frac{\omega}{\pi} * \{\frac{{c_{40}}^2}{(c_{39}+c_{40})^2} \Delta c_{39} + \frac{{c_{39}}^2}{(c_{39}+c_{40})^2} \Delta c_{40}\}$$

All the deviations in the Y capacitances C39 and C40 cause the leakage current to change in the same direction, that is, the capacitance increases and the leakage current also increases.

CASE STUDY: Medical Power Supply

The following is an example using the actual parameters of a medical power adaptor to analyze the influence of the tolerance of the Y capacitor on the leakage current of the power supply.

Given that Vin=240Vac; f=50/60Hz,

C_42=2200pF;C_3=1000pF;C_2=1000pF; C_39=1000pF; C_40=1000pF;

Assuming the capacitance tolerances are ±10% and ±20%, respectively, we try to find the amount of change in leakage current caused by the Y capacitance error in the medical power supply.

Solution:

According to the testing requirements for patient leakage current in IEC60601-1, the mains supply voltage should be at 110% of the highest- RATED MAINS VOLTAGE and at the highest-RATED supply frequency. This means that a product rated for operation at 115 ~ 240 Vac, 50/60 Hz would be tested at 264 Vac and a line frequency of 60Hz.

The leakage current caused by the ideal Y capacitors (without deviations) of the medical power supply can be directly obtained by using Formula (4) in Excel:

Vin=	264	Vac			
f=	60	Hz			
C42=	2200	pF	=	2.200E-09	F
C3=	1000	pF	=	1.000E-09	F
C2=	1000	pF	=	1.000E-09	F
C39=	1000	pF	=	1.000E-09	F
C40=	1000	pF	=	1.000E-09	F
$I_{leakage1}$=	76.97	uA			
$I_{leakage3}$=	15.84	uA			
$I_{leakage}$=	78.588	uA			

Table 1: The Leakage Current to Ground Caused by The Ideal Y Capacitors without Deviations

At the 264Vac input, the ideal fundamental leakage current of the power supply is 76.97uA and the third harmonic leakage current is 15.84uA. The total ideal leakage current is 88.88uA. In the case where all the Y capacitance deviations are equal to zero, the Patient leakage current can meet the requirement of less than 100uA.

A Pspice simulation circuit for Leakage Current measurement is built in Figure 5 to verify the above calculation result.

The simulated patient leakage current measurement waveform for the ideal Y capacitors without errors is shown in *Figure 6.*

From Figure 6 we note that the leakage current is not a perfect sinusoidal waveform (including 3rd harmonic) due to the rectifier bridge. Its fundamental frequency component (at 60Hz) and 3rd harmonic (180Hz) are shown in Figure 7 and thus the Formula (4), (5) and (6) are good enough for leakage current estimation.

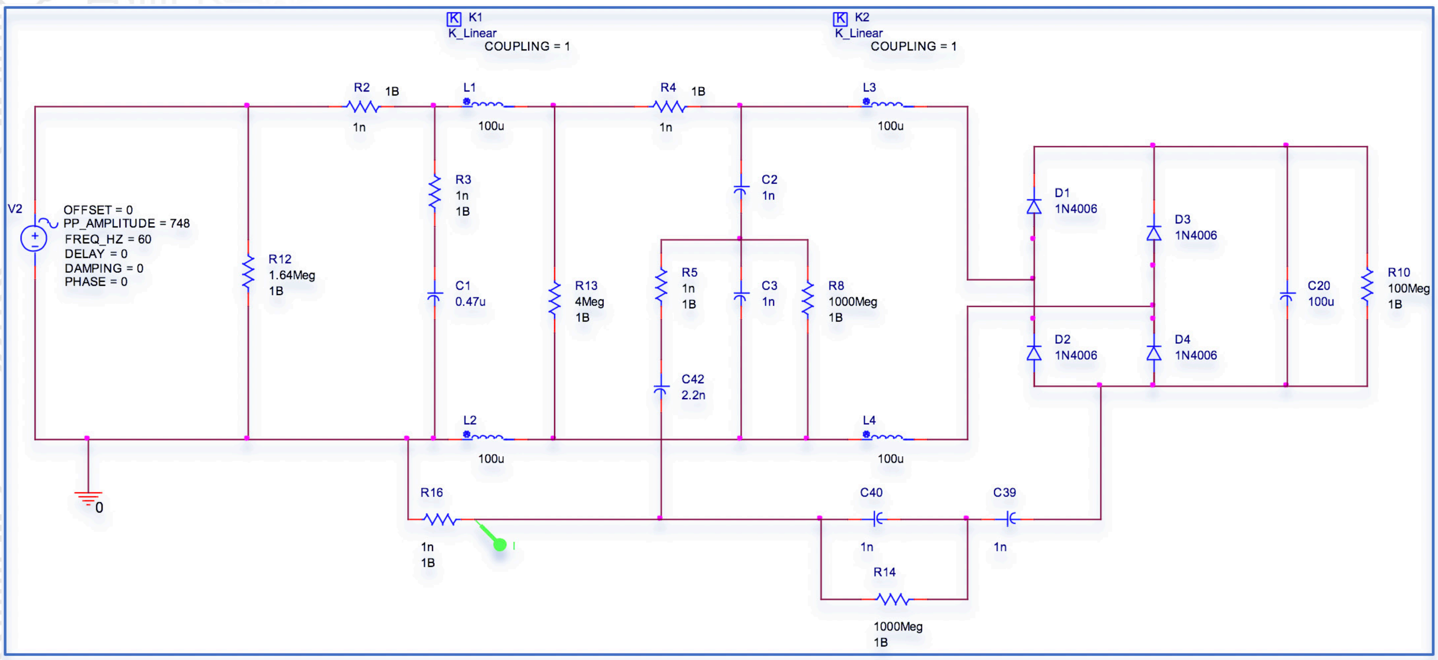

Fig 5. Simplified Pspice Simulation Circuit for Patient Leakage Current Measurement

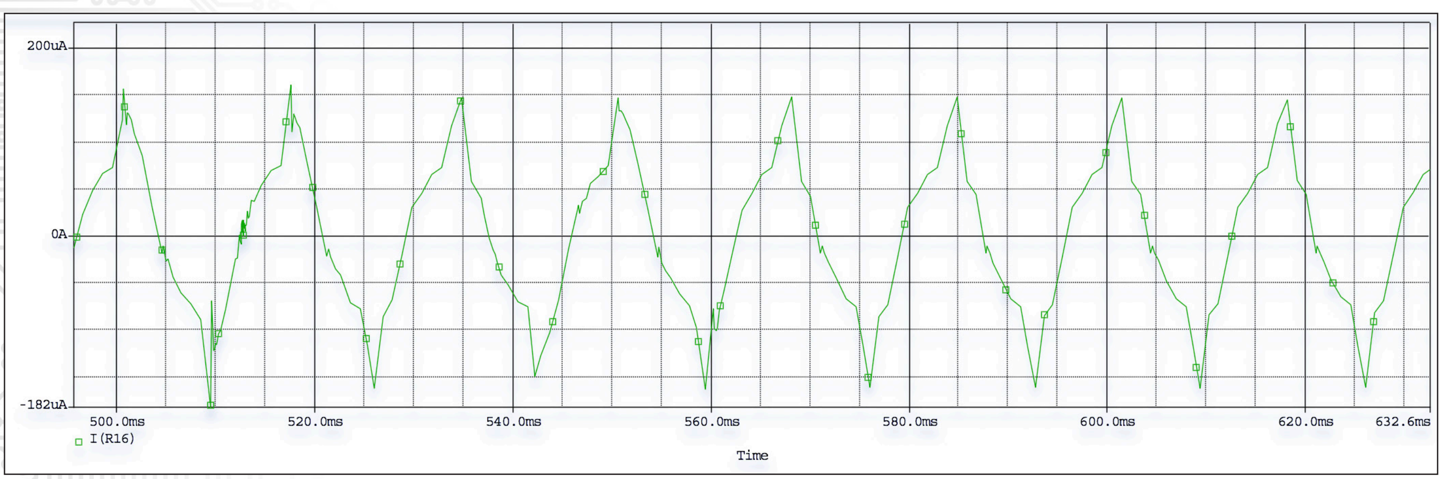

Fig 6. The Simulation Waveform for Patient Leakage Current Measurement with Ideal Y Capacitors without Errors

Table 2 is the leakage current of the extreme case where C3 has -10% tolerance capacitance and the remaining Y capacitances have +10% Tolerance and calculated in Excel. It can be seen from the calculation results that in this extreme case, the leakage current caused by the Y capacitors is 88.88 uA. If considering other distributed capacitances of the power supply, such as stray capacitors in transformer coupling, choosing 10% capacitor accuracy has some margin.

Under the same 10% Y capacitance tolerance, C2 and C42 contributes the most to the leakage current. Therefore, in the component selection process, the capacitor with a better Y capacitor accuracy can be considered for C2 and C42, for example ±5% tolerance.

For further analysis, *Table 3* below shows the leakage current 99.17uA in an extreme

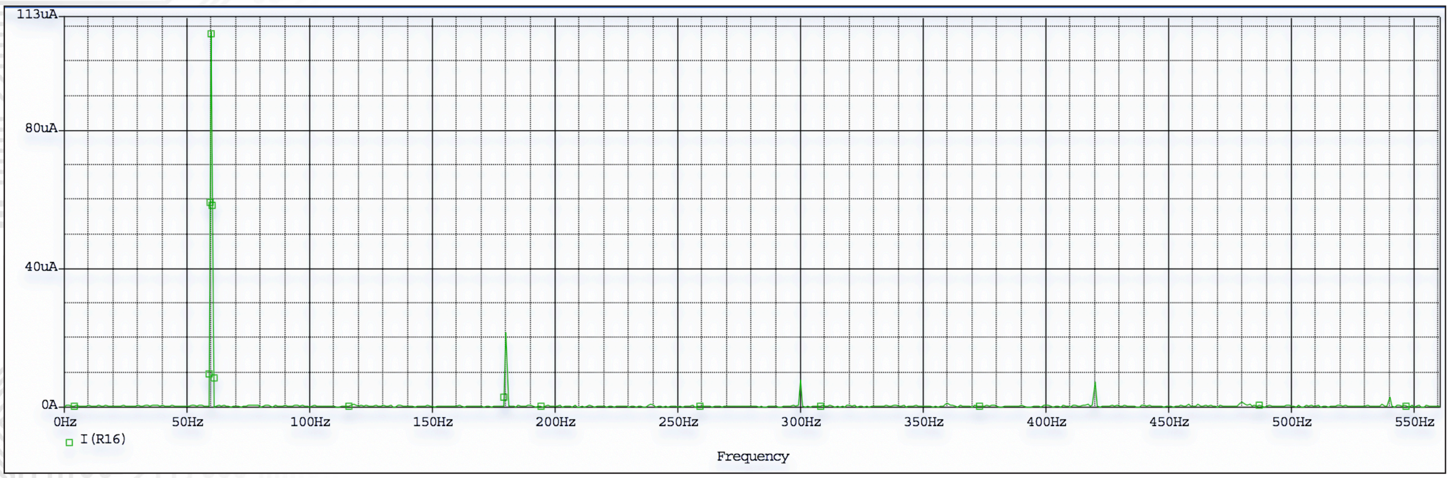

Fig. 7. The FFT for Patient Leakage Current Measurement with Ideal Y Capacitors without Errors

Vin=	264	Vac				Capacitor Tolerance	Capacitance Deviation ΔC		Fundamental Leakage Current Caused by Each Capacitor Error		Third Harmonic Leakage Current Caused by Each Capacitor Error	
f=	60	Hz										
C42=	2200	pF	=	2.200E-09	F	10%	2.200E-10		2.48	uA		
C3=	1000	pF	=	1.000E-09	F	-10%	-1.000E-10		1.24	uA		
C2=	1000	pF	=	1.000E-09	F	10%	1.000E-10		3.97	uA		
C39=	1000	pF	=	1.000E-09	F	10%	1.000E-10		1.24	uA	0.79	uA
C40=	1000	pF	=	1.000E-09	F	10%	1.000E-10		1.24	uA	0.79	uA
				Peak Value								
$I_{leakage1}$=	76.97	uA		108.86	uA	$\Delta I_{leakage1}$=	10.18	uA	10.18	uA		
$I_{leakage3}$=	15.84	uA		22.40	uA	$\Delta I_{leakage3}$=	1.58	uA	1.58	uA		
$I_{leakage}$=	78.59	uA		The Worst Case		Total $I_{leakage}$=	88.88	uA				

Table 2: The Leakage Current Calculated with -10% Tolerance for C3 and +10% Tolerance for All Other Y Capacitors

Vin=	264	Vac				Capacitor Tolerance	Capacitance Deviation ΔC		Fundamental Leakage Current Caused by Each Capacitor Error		Third Harmonic Leakage Current Caused by Each Capacitor Error	
f=	60	Hz										
C42=	2200	pF	=	2.200E-09	F	20%	4.400E-10		4.96	uA		
C3=	1000	pF	=	1.000E-09	F	-20%	-2.000E-10		2.48	uA		
C2=	1000	pF	=	1.000E-09	F	20%	2.000E-10		7.94	uA		
C39=	1000	pF	=	1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
C40=	1000	pF	=	1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
				Peak Value								
$I_{leakage1}$=	76.97	uA		108.86	uA	$\Delta I_{leakage1}$=	20.36	uA	20.36	uA		
$I_{leakage3}$=	15.84	uA		22.40	uA	$\Delta I_{leakage3}$=	3.17	uA	3.17	uA		
$I_{leakage}$=	78.59	uA		The Worst Case		Total $I_{leakage}$=	99.17	uA				

Table 3: The Leakage Current Calculated with -20% Tolerance for C3 and +20% Tolerance for All Other Y Capacitors

case of -20% tolerance for C3 and +20% tolerance for all other Y capacitors. In this case, the leakage current is very close to the limit 100uA in the IEC60601-1 requirements with very small margin.

Finally, considering another extreme case of -20% tolerance for C3, +25% tolerance for C42 and C2, and +20% tolerance for C39 and C40 in *Table* 4, the leakage current is 102.34 uA which exceeds the limit 100uA in the testing requirement.

The simulated patient leakage current measurement waveform for the Y capacitors with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors is shown in *Figure 8*. It is evident that the peak value of the simulated leakage current increases compared with that in Figure 6.

From the FFT of the above leakage current waveform in Figure 9, it is clearly known that the fundamental component peak value exceeds 145uA and 3rd harmonic peak is above 25uA.

CONCLUSIONS

The Patient leakage current is mainly contributed by Y capacitors in the power supply design. The fundamental and third harmonic components are dominant in the leakage current. The equivalent circuit and formulae for this leakage current estimation are derived and verified by the simulations.

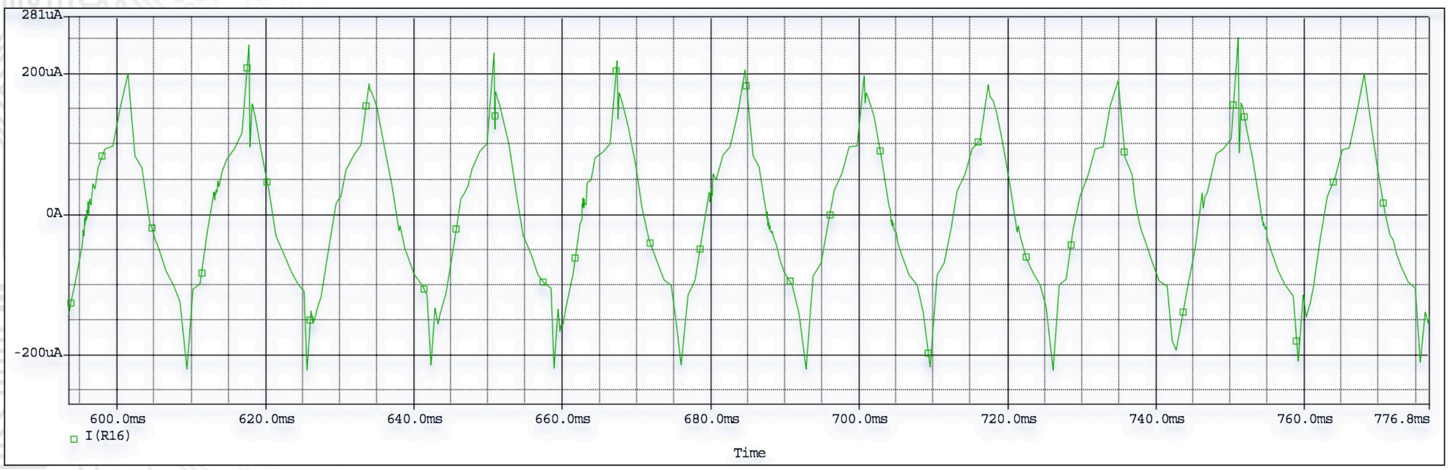

Fig 8. The Simulation Waveform for Patient Leakage Current Measurement with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors

Vin=	264	Vac				Capacitor Tolerance	Capacitance Deviation ΔC		Fundamental Leakage Current Caused by Each Capacitor Error		Third Harmonic Leakage Current Caused by Each Capacitor Error	
f=	60	Hz										
C42=	2200	pF	=	2.200E-09	F	25%	5.500E-10		6.20	uA		
C3=	1000	pF	=	1.000E-09	F	-20%	-2.000E-10		2.48	uA		
C2=	1000	pF	=	1.000E-09	F	25%	2.500E-10		9.92	uA		
C39=	1000	pF	=	1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
C40=	1000	pF	=	1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
				Peak Value								
$I_{leakage1}$=	76.97	uA		108.86	uA	$\Delta I_{leakage1}$=	23.58	uA	23.58	uA		
$I_{leakage3}$=	15.84	uA		22.40	uA	$\Delta I_{leakage3}$=	3.17	uA	3.17	uA		
$I_{leakage}$=	78.59	uA		The Worst Case		Total $I_{leakage}$=	102.34	uA				

Table 4:The Leakage Current Calculated with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors

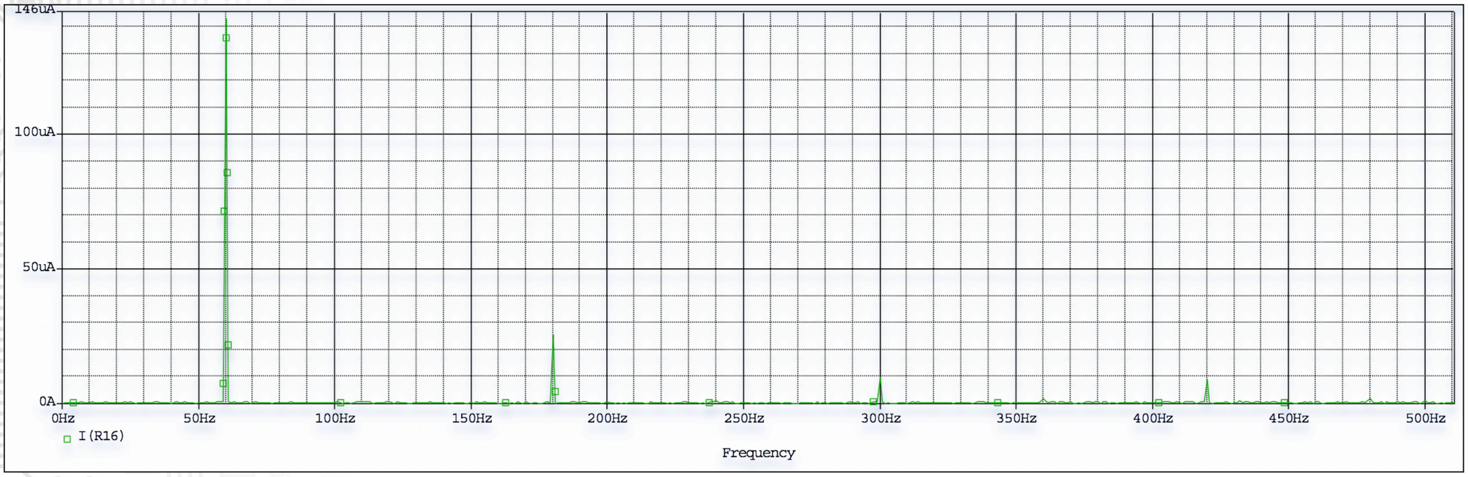

Fig 9. The FFT for Patient Leakage Current Measurement with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors

Using the partial differential error analysis method, the effect of each Y capacitor on the leakage current of the power supply is clearly obtained. This provides guides on the selection of each Y capacitor tolerance parameter of the power supply and the quality control in production.

Taking a medical power adaptor topology as an example to theoretically select the tolerance of the capacitor, the leakage current error is determined by the tolerances of 5 Y capacitors, that is, the output leakage current is controlled by multivariable (5 variables), and the total deviation of the multivariable circuit structure is the sum of the partial differential of the error of each component. Since the capacitors have positive and negative tolerances and are variables of the multivariable function of the leakage current of the power supply, this causes big scattering of the actual leakage current value measurement result of the power supply in production. Considering the influence of other distributed parasitic parameters of the power supply on the leakage current, the Y capacitance of the medical power adaptor should be selected with ±10% .

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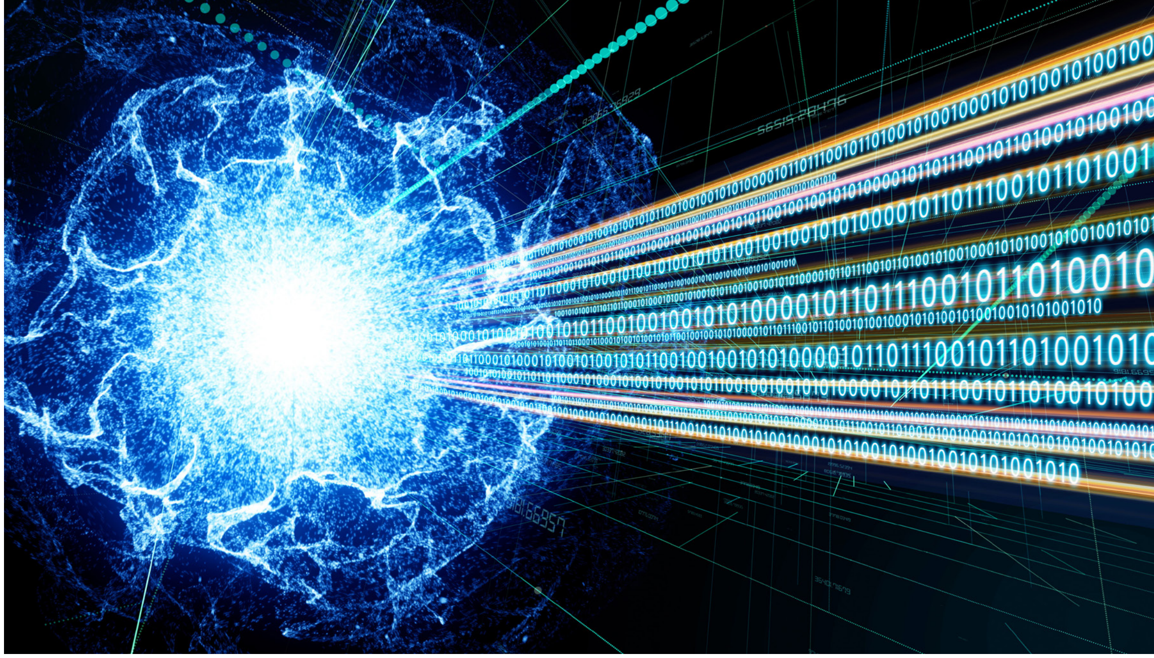


CHAPTER 5:

Digital Power Comes of Age

MARTIN HÄGERDAL, *Architects of Modern Power* Spokesman and President
MARK ADAMS, *Architects of Modern Power* Spokesman and Vice President
STEVE PIMPIS, *Architects of Modern Power* Spokesman and Vice President

This article looks at the evolution of distributed-power architectures since the introduction of the first high-frequency switching dc-dc converter modules back in 1984. It describes the factors that have driven this evolution and highlights some of the most significant innovations along the way.

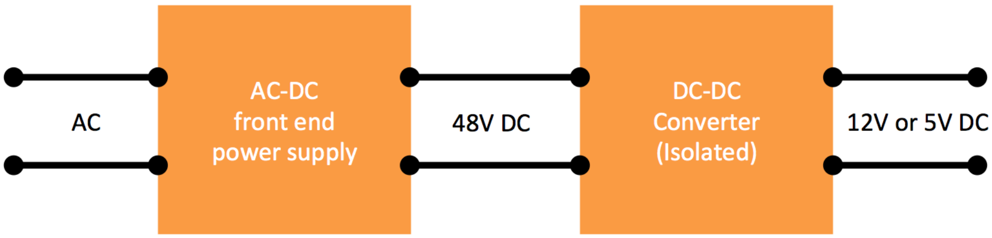
Distributed-power architectures now dominate in power-system designs for high-performance datacom and telecom networks, as well as data-center equipment. The change from centralized power—a simple ac-dc power supply, perhaps with battery backup, feeding the cards in a system rack—came about by necessity. Semiconductor operating voltages decreased as ever-smaller process nodes were developed to boost the processing power of ICs. The ICs became more powerful and their lower operating voltages demanded higher current.

On top of that, long printed-circuit-board (PCB) tracks would mean unacceptable I^2R losses, reducing power system efficiency. As a result, distributed-power architecture became the norm—a trend that continues today. Since the 1980s, the power demands of data centers have risen from 300 to 1200 W per board, and some forecast that it will reach 5 kW in 2015 as network IP traffic skyrockets over the next few years.

The economics of creating distributed-power systems were transformed back in 1984, when a group within Sweden's part of Ericsson AB, Ericsson Components – RIFA Power (later to become Ericsson Power Modules), launched the PKA series of dc-dc converters. The introduction of the PKA, described by Ericsson as "the world's first high frequency dc-dc switching power supply," meant that engineers no longer had to design relatively expensive and complex circuits from discrete components. They could now use a compact board-mounted module on each card, adding just a few external filtering and decoupling components, to create much more efficient and effective power systems.

The use of power modules also significantly improved system reliability. This was particularly important for those designing communications networks, where the target for operating life was sometimes 25 years or more.

Typically, the front-end ac-dc unit would have a –48-V output, and a dc-dc power module on each card would convert this to 12 V or 5 V, or a combination of both, to provide the

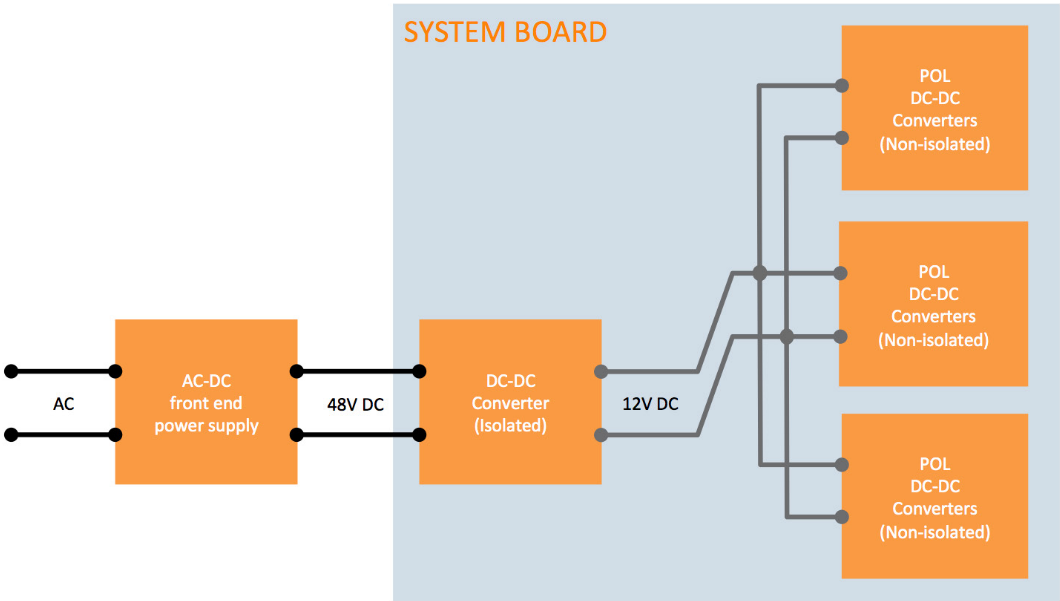


1. Early distributed-power solutions adopted a two-stage conversion with a typical intermediate bus voltage of –48 V and a single output at 12 V or 5 V.

correct operating voltage for semiconductors in the system. Then, 3.3-V semiconductors started to appear, and today we're down to 0.9 V for many with some processors drawing up to 90-A current at full load *(Fig 1)*.

The larger the differential between the input and output voltage(s) of a dc-dc converter, the less efficient the conversion process. It soon became clear that to achieve maximum system efficiency, it's best to handle the last conversion very close to the load, i.e., the processor, FPGA, or other device. Power supplies used in this final conversion are point-of-load (POL) converters. In addition to boosting efficiency, placing power converters as close as possible to their loads prevents instability due to stray impedances in long PCB tracks or system wiring. Datel, which was acquired by Murata as part of the Power Electronics Division of C&D Technologies in 2007, was an early pioneer of isolated dc-dc converters and POL modules during the 1980s and 1990s.

Distributed-power architectures can be implemented in a number of different ways, using regulated or unregulated bus voltages. About 15 years ago, as systems became more complex, demanding a number of different voltages (perhaps 12, 5, 3.3, 2.5 and 1.2 V), power-system designers began to adopt intermediate bus architectures (IBAs). Here, the



2. The proliferation of supply rails at the board level has resulted in an intermediate bus architecture (IBA) that requires multiple POL converters on the system board.

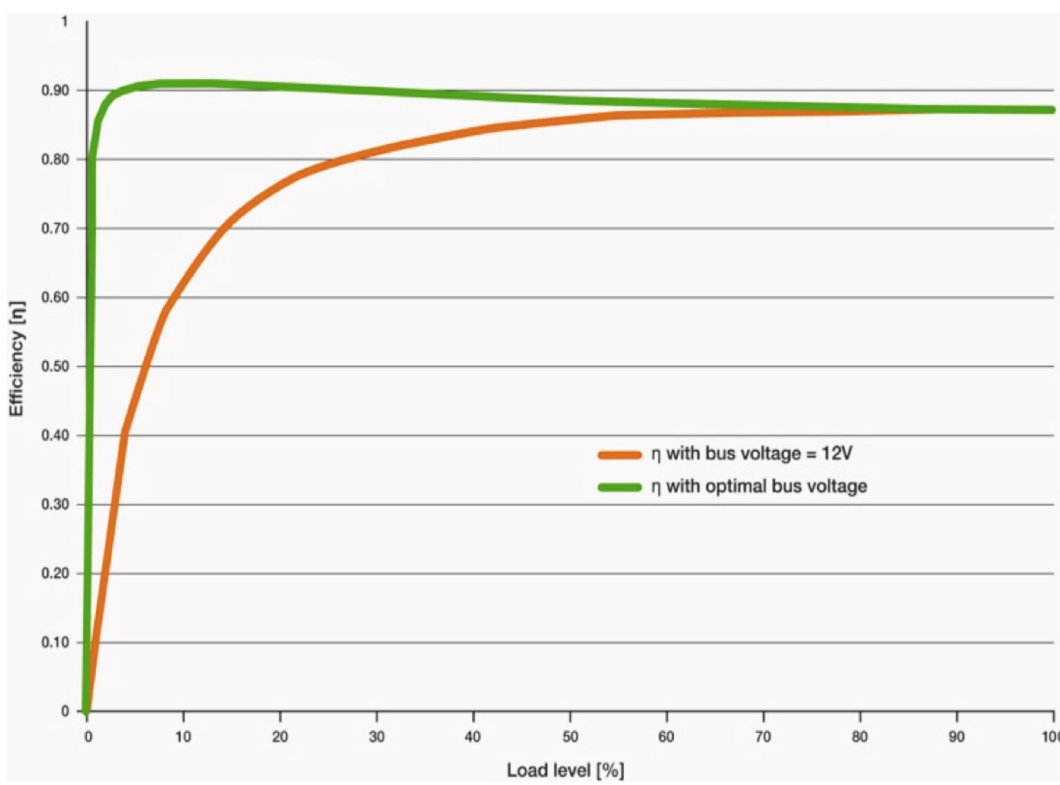
ac-dc power supply feeds an IBA converter at perhaps 24 V or –48 V. The isolated IBA converter outputs 5 to 14 V dc and feeds the required number of POL converters *(Fig 2)*.

Distributed Goes Digital

The demand to provide sophisticated power-management functions, including the sequencing of power supplies with controlled ramp rates as required by large FPGAs, along with a desire to reduce board space and the number of external components, drove more and more power-system designers to digital power over the past decade. Key to this movement are power-management ICs from companies like Texas Instruments, which in December 2002 introduced the industry's first digital-signal-processing (DSP) development kit specifically geared to power-supply applications.

What's accelerated adoption of digital power over the last five years, though? Simply put, it's the development of off-the-shelf digital power-converter modules. Digital converters have much in common with their analog counterparts, including similar power switches and output filters. However, the inner control loop provides digital flexibility for tailoring power delivery to the application, as well as enabling power systems to dynamically adapt to changes in operating conditions in real time. Communications, monitoring, and control are implemented over the industry-standard PMBus.

Digital control is particularly important in improving the efficiency of data-network power systems. Networking equipment draws more power with greater data throughput. At times of low data traffic, the network operates well below capacity, power supplies operate well below their maximum load, and processors can run at lower clock speeds.



3. Digital power is particularly effective for improving efficiency under low-load conditions. (Courtesy of Ericsson, EGG October 2014).

At low loads, the power supplies are relatively inefficient, resulting in excessive energy consumption and waste-heat generation, with undesirable technical, financial, and environmental consequences. By implementing a digital control loop encompassing both an intermediate bus and POL converters, the intermediate-bus voltage can be varied dynamically in response to varying loads. The input voltage to the POL converters is reduced under low load conditions, which increases conversion efficiency at low loads *(Fig 3)*.

Some digital power devices offer a dynamic-voltage-scaling (DVS) function to save energy. If the demand for computing power is low, the processor's clock frequency and its supply voltage can be reduced. DVS is usually implemented as an open-loop function with a lookup table holding pre-determined combinations of frequency and supply voltage.

More advanced than DVS, adaptive voltage scaling (AVS), adopts a closed-loop, real-time approach that adapts the supply voltage precisely to the minimum required by the processor, depending on its clock speed and workload. This technique also compensates automatically for process and temperature variations in the processor.

Most switching power supplies use a closed control loop with negative feedback from output to input. A compensation network is needed to adjust the loop's frequency response to achieve the optimum transient response without compromising stability. The design of the compensation network can be a time-consuming task involving considerable trial and error. Even then, the performance of the components in the network can change with variations in temperature or due to aging. In 2010, CUI Inc, a North American company, was the first manufacturer to develop and launch non-isolated POL converter modules featuring auto-compensation, a digital function that completely eliminates this problem.

Using digital power modules also simplifies or enables many other aspects of power system design. These include active current sharing, voltage sequencing and tracking, soft start and stop, and synchronization.

The Drive for Standardization

Wider adoption of dc-dc power modules has led to a greater push toward some level of standardization of products from different manufacturers. Due to concerns about supply-chain reliability, customers demanded second sources for products, leading to trade associations being formed by power-supply and component vendors.

As has often been the case, though, the alliances formed in this space succeeded in little more than agreeing to standard footprints and pin-outs for certain categories of power converters, such as non-isolated and isolated dc-dc converter modules. While this enabled a degree of interchangeability between products from different manufacturers, there hasn't been full consensus on how to implement all of the electrical functions of converters, making it less than straightforward to swap out one product for another. This is particularly true for digital power, which adds another layer of complexity to the challenge of ensuring compatibility between solutions.

More significantly, in 2004, Artesyn Technologies, Astec Power, and a group of semiconductor suppliers—Texas Instruments, Volterra Semiconductors, Microchip Technology, Summit Microelectronics, and Zilker Labs—formed a coalition to develop an open standard for communications with a protocol dedicated to power systems. This was the birth of the industry standard for the power-subsystem management known as PMBus.

Not all has been "clear sailing," though, and despite good intentions and a number of positive moves, various issues stalled developments by other manufacturers. Most notable was the patent-infringement lawsuit issued by Power One in 2005, intended to protect the Z-Bus technology used in its POL regulator ICs for monitoring and controlling power supplies. This held back the widespread adoption of PMBus for around four years, until the use of licensing royalty agreements became routine for such technology.

More recently, power-supply companies have been coming together once again to address these issues, particularly the more challenging requirements of digital power. In July 2011, CUI announced a cooperative agreement with Ericsson Power Modules, and in September of that year, demonstrated a new family of POL modules that are pin- and-function compatible with Ericsson's BMR46X series of converters.

A year later, CUI entered into a license agreement with Ericsson for the latter's 3E Advanced Bus Converter family, allowing it to offer customers an intelligent intermediate bus converter to pair with its portfolio of POL products. The companies agreed at that time to cooperate on a common standard for digital intermediate-bus converters going forward. Then, in July 2014, Murata and Ericsson announced a technical collaboration agreement—their goal is to accelerate the adoption of digital power products by offering customers fully compatible products from each company.

Meeting Future Needs

According to the *Ericsson Mobility Report*, annual IP traffic will reach 7.7 zettabytes by the end of 2017, up from 2.6 zettabytes in 2012. Video communications, cloud-based services, and the interconnection of physical objects, dubbed the Internet of Things (IoT), are the primary drivers of this unstoppable growth. This will place even greater demands on data-network power-system designers. They must fully exploit the functional and efficiency benefits provided by digital-power devices in order to meet this challenge.

Furthermore, the technology that started in datacoms and telecoms is spreading out into other industries and applications, such as in medical, industrial, and test/measurement equipment, as advanced processors and FPGAs become commonplace. This creates the need for a simple, intuitive, multisource solution across the board. The challenge is to achieve "perfect power conversion, under all conditions, all of the time." Hence, power-supply manufacturers are under greater pressure to accelerate their rate of innovation, to the extent where they must rely on much deeper collaboration.

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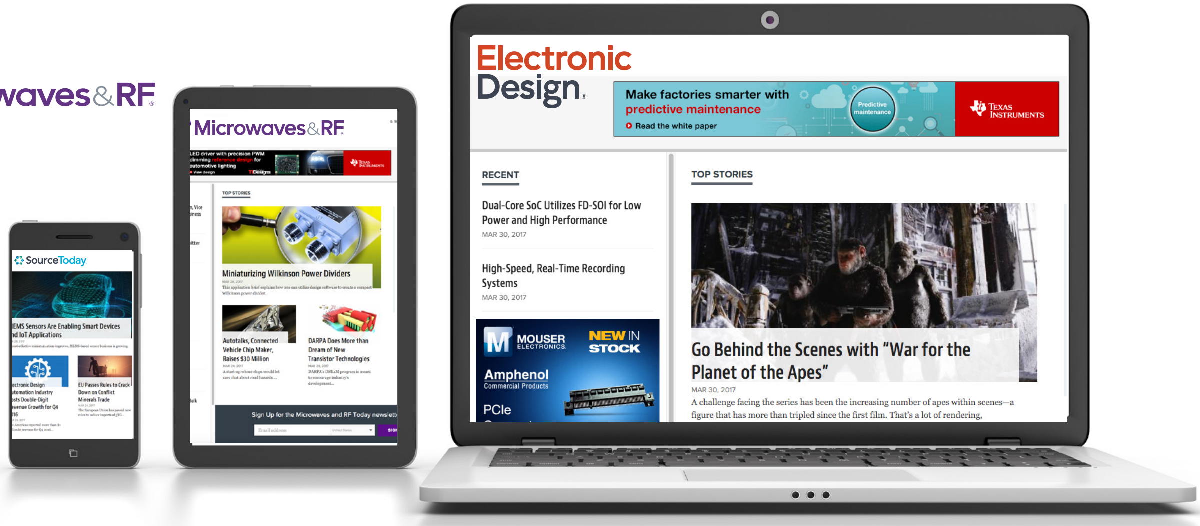

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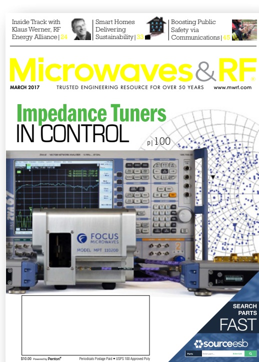

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