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Introduction

In the quest for higher efficiency in high wattage power supplies, designers are turning to the digital implementation of these power systems in greater numbers. This article features the implementation of peak current mode control, typically relegated to the external analog implementation of power supply control, in the digital domain utilizing the integrated analog functions of C2000™ Piccolo™ microcontrollers from Texas Instruments (TI). This integration reduces the burden on not only external support components but software implementation, as well.

Implementing peak current mode control of a switch-mode power supply with a single microcontroller

Peak current mode control is not a new topic to power supply designers but has traditionally been relegated to analog control schemes. In advanced power supply systems, current mode control offers many advantages including improved load line regulation, cycle-by-cycle current limiting and protection, and better flux balancing. However, due to the nature of peak current mode control, it has been difficult to implement in a digital architecture due to the requirement of slope compensation, which meant additional support circuitry. A complete, digitally controlled system has been difficult and expensive to implement until recently with the advent of digital signal processors (DSPs) with integrated hardware dedicated to performing the task.

Today's microcontrollers bring even greater precision, power efficiency and reduced cost to a wide range of power applications, including:

- Server and rectifier power supplies
- Industrial power supplies
- Medical, military and high performance consumer power systems

TI understands the challenges developers face in designing these high-performance power supply systems. Manufacturers seek to introduce advanced control algorithms to differentiate their products and increasing government regulation requires more efficient power consumption and reduced Electromagnetic Interference (EMI).

To aid developers in meeting these diverse challenges, TI offers the C2000 Piccolo microcontrollers, which have an optimized architecture integrating specialized peripherals that:

- Enable the use of real-time algorithms for more precise and accurate control
- Support control of multiple power stages with a single device
- Simplify design through peripheral integration
- Reduce system complexity and cost

These microcontrollers also come with a dedicated developer network for digital power and visual programming resources.

The Piccolo MCU advantage

Leveraging TI's high-performance TMS320C28x™ core, Piccolo microcontrollers provide all of the necessary performance and peripherals needed to control a system with a single stand-alone controller. With its ample headroom and specialized peripherals, Piccolo microcontrollers enable developers to implement more advanced control algorithms to further improve performance while lowering system cost.

The Piccolo microcontroller architecture has been optimized for digital control applications with advanced architectural features to enhance high-speed signal processing. Piccolo's main CPU core has built-in DSP capabilities such as a single cycle 32×32-bit multiply and accumulate unit, which greatly speeds computations. Furthermore, the control peripherals, such as the analog-to-digital converter (ADC) and pulse width modulators (PWMs) are designed to be very flexible and easily adapt to almost any use, requiring very little software overhead. For example, the ADC has an auto-sequencer which developers can program to cycle through samples in a specific order so that values are ready when the application needs them. With more intelligent control peripherals and a powerful CPU core, control loops run tighter, both improving the dynamic nature of control algorithms and resulting in better disturbance behavior.

Important Piccolo microcontroller features include:

- 40 to 90 MIPS of processing performance
- Single 3.3-V supply for full operation
- Dual-internal, high-precision oscillators; no external crystal necessary
- 12-bit ADC with 16 channels and a maximum sampling frequency of 4.6 mega-samples per second
- Up to 19 channels of PWM output with configurable automatic dead band
- Up to 8 of the 19 PWM channels can operate in high-resolution mode with a resolution as low as 150 picoseconds
- Integrated analog comparator and sSlope compensation reference digital-to-analog converter (DAC), tied directly to PWM outputs for implementing peak current mode control functions

Precise and accurate control with high performance PWMs

Because the Piccolo microcontroller architecture provides impressive processing capacity, ranging from 40 to 90 million instructions per second (MIPS), developers can concurrently monitor and control multiple motors and also execute more complex control algorithms for higher accuracy, smoother performance and better power consumption. For example, a single Piccolo microcontroller is capable of an active power factor correction (PFC) rectifier stage and still has sufficient processing capacity for implementing peak current mode control (PCMC) of a secondary DC-DC conversion stage.

Pulse Width Modulation (PWM) plays an important role in the control of a switch mode power supply. Recent improvements in control algorithms enable developers to implement highly accurate algorithms providing dynamic control that adapts to real-time variations in system behavior. By utilizing the high-resolution PWM capabilities (shown below in Figure 1 as V_o) of the Piccolo microcontroller series of devices, system designers are now able to utilize an effective 16-bit resolution PWM signal at switching frequencies of about 100Khz – thus alleviating duty cycle limiting issues.

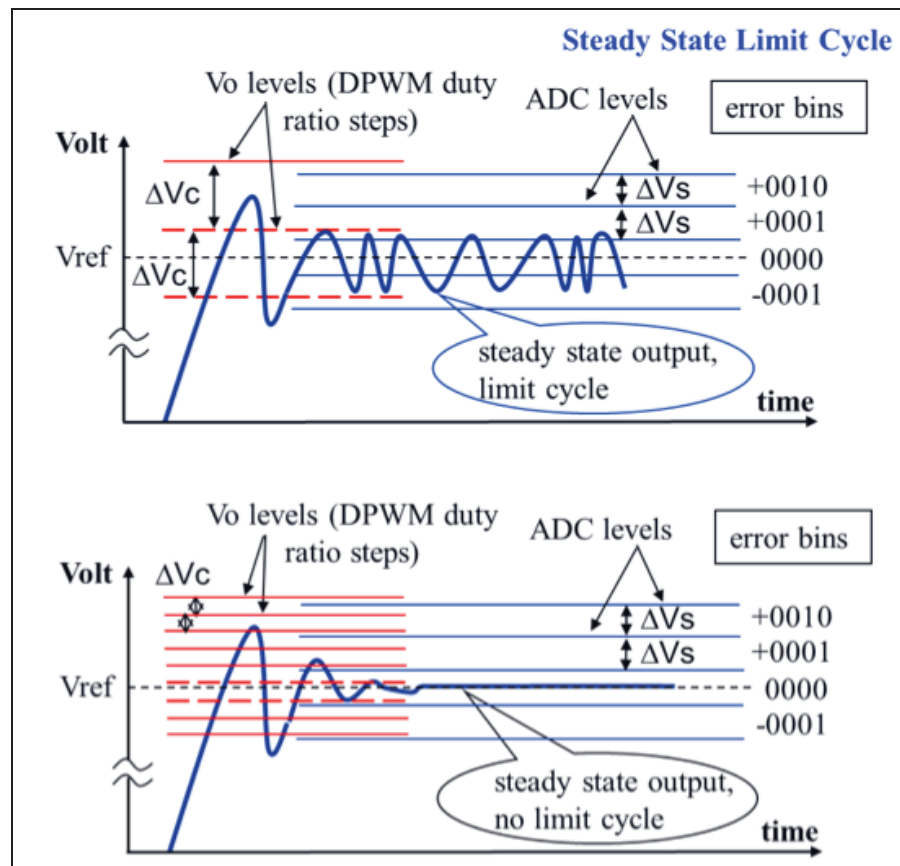


Figure 1. Low-resolution PWM steps (top) vs. high-resolution PWM steps

Peak Current Mode Control (PCMC) – Analog versus digital implementation

In both implementations of PCMC, there is a "plant" (our actual power stage) and a control function. Power stage aside, in the analog domain, our control function is implemented with a series of amplifiers, resistors and capacitors and various other analog components which must be calculated for optimal performance and efficiency of the power "plant." Figure 2 below refers to a basic analog implementation of PCMC of a buck regulator power stage.

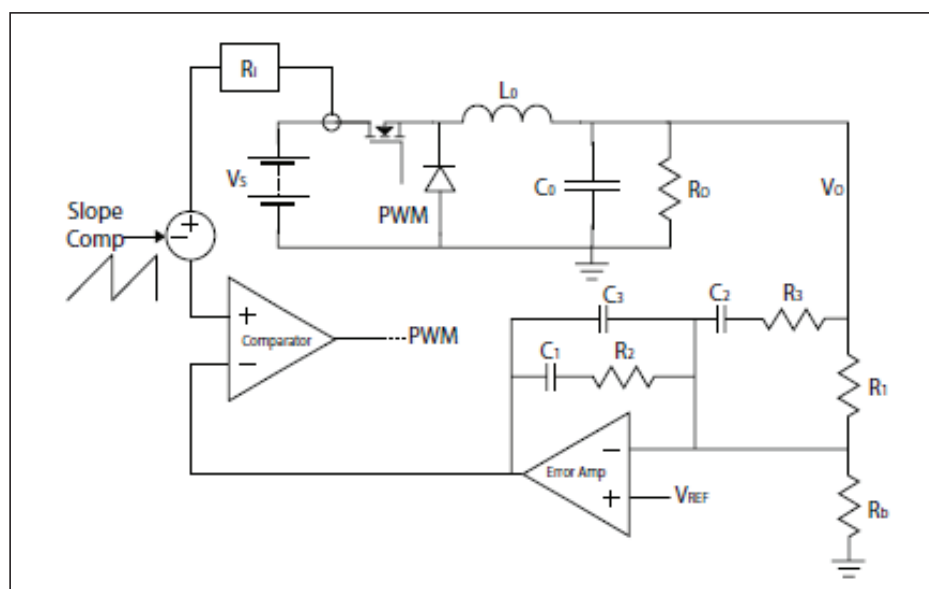


Figure 2. Analog implementation of a PCMC buck converter

When transitioning to the digital control domain, all of the control resources of the analog controller are implemented on a single microcontroller. All of the necessary analog components, ADCs, comparator, slope generation DAC and PWM output, are all integrated into a single device. Notice however, that the actual power stage remains the same. Figure 3 below represents the digital implementation with the integrated functions of the microcontroller in exploded form.

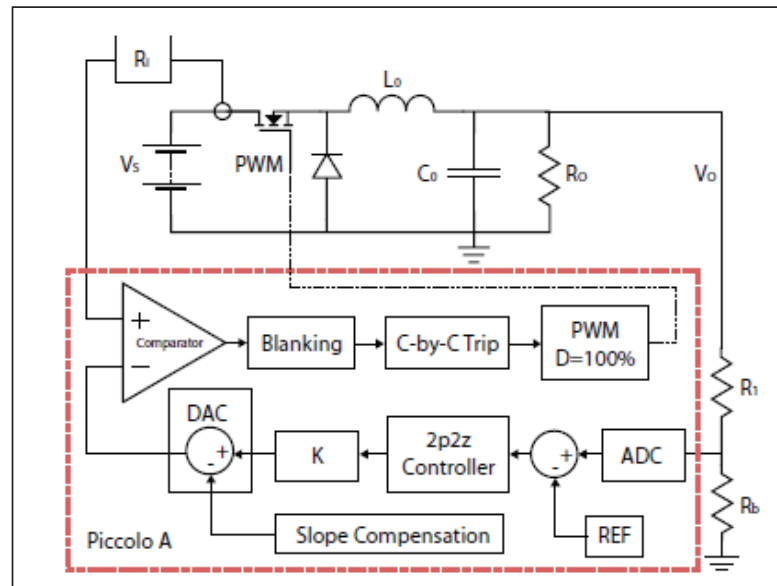


Figure 3. Digital microcontroller implementation of a PCMC buck converter. Red boxed area indicates functions included in the microcontroller.

When implementing a PCMC system, the outer voltage mode control loop for control of the circuit must be set up. This is outlined in the diagram below, showing the relationship between the ADC input, the 2P2Z control loop, and finally driving the PWM outputs of the controller.

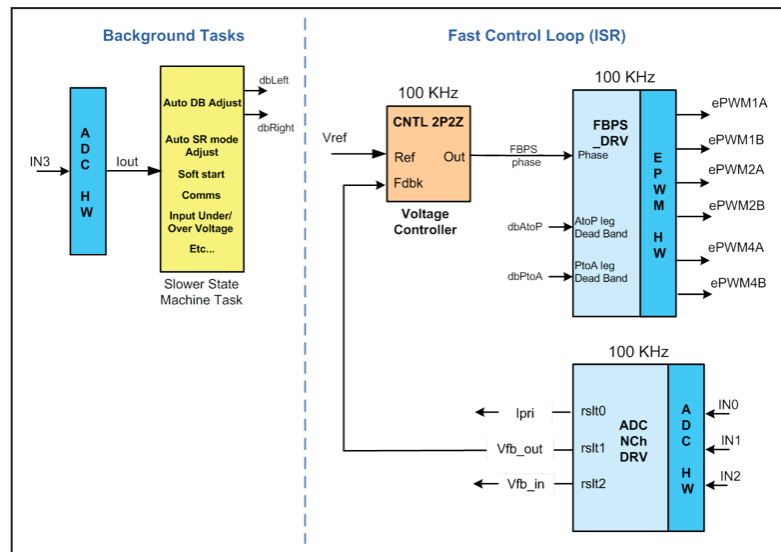


Figure 4. Implementing a voltage mode control loop

The PCMC implementation can now utilize this voltage mode control loop with the addition of a comparator and slope compensation circuit. In the PCMC implementation, the inner current mode control loop created by these two components now determines our peak current reference signal. While most microcontrollers can handle the voltage mode control, the addition of a comparator and slope compensation DAC is a requirement for PCMC, both of which have been incorporated into the Piccolo microcontroller series. This enables a PCMC controlled design that utilizes less external hardware, as well as reducing the processing requirements of the microcontroller, allowing for a lower cost implementation. A visual representation of the PCMC control loop and internal hardware connections when using the Piccolo microcontroller is shown below in Figure 5.

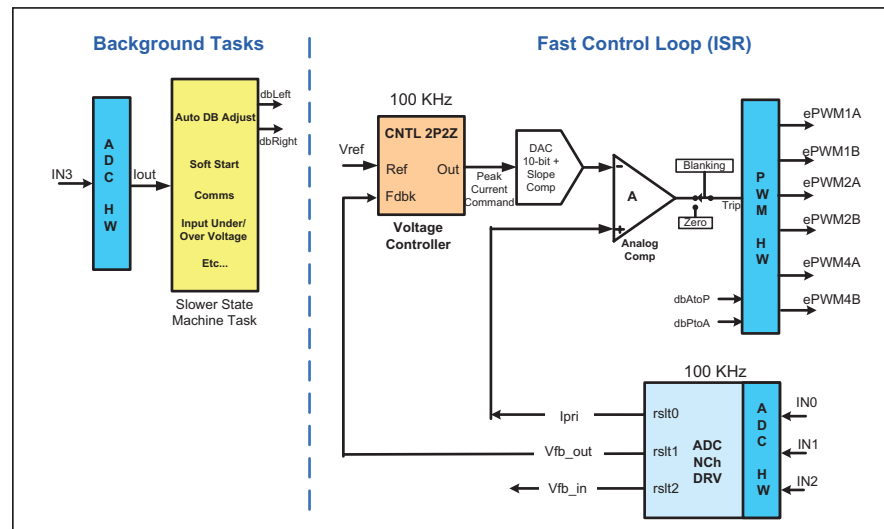


Figure 5. Implementing a PCMC Loop

Notice the same 100 KHz two-pole, two-zero control loop is utilized, but now it is feeding the output of this into a 10-bit slope compensation ramp DAC. One of the internal analog comparators is then used to trigger the PWM pulses to turn off at the appropriate times. The purpose of slope compensation in a PCMC system is to limit sub-cycle oscillations which occur when the system duty cycle is greater than 50 percent. Without slope compensation, these oscillations will cause the output to become unstable, with large deviations from the normal operating parameters.

In the PCMC system, measuring the inductor current, “leading edge blanking” should also be added to our comparator input. This is due to the current spike in the initial inductor charging and could potentially cause comparator to prematurely trip off due to sensing a higher than anticipated current. Piccolo microcontroller’s comparator modules have this functionality integrated directly into them as a flexible module, alleviating any design concerns that may arise. Figure 6 and 7 (below and on the following page) show the relationship of the PWM outputs to the sensed inductor current (with and without) leading edge blanking in the comparator module.

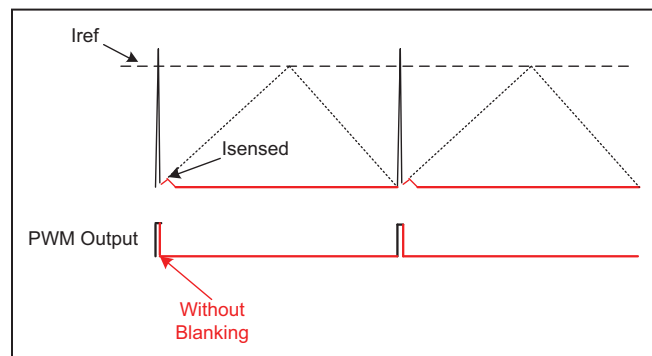


Figure 6. PWM outputs versus sensed inductor current with no leading-edge blanking.

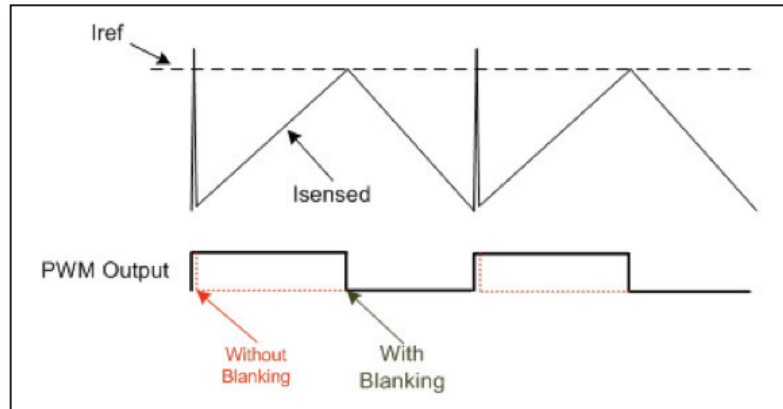


Figure 7. PWM outputs versus sensed inductor current with leading-edge blanking enabled.

To fully implement the peak current mode control system, the Piccolo microcontroller's RAMP DAC function is utilized and easily implemented within the microcontroller. With the proper system tuning, the RAMP DAC function is setup to provide a decreasing voltage signal (V_{ref}) in correspondence to the increasing V_{in+} signal to the comparator. In turn, this controls the shutdown trip-point of the comparator trip frequency, and its corresponding shutdown of the PWM generation unit. This is shown below in Figure 8 of a VisSim modeling and simulation diagram. (software provided by Visual Solutions)

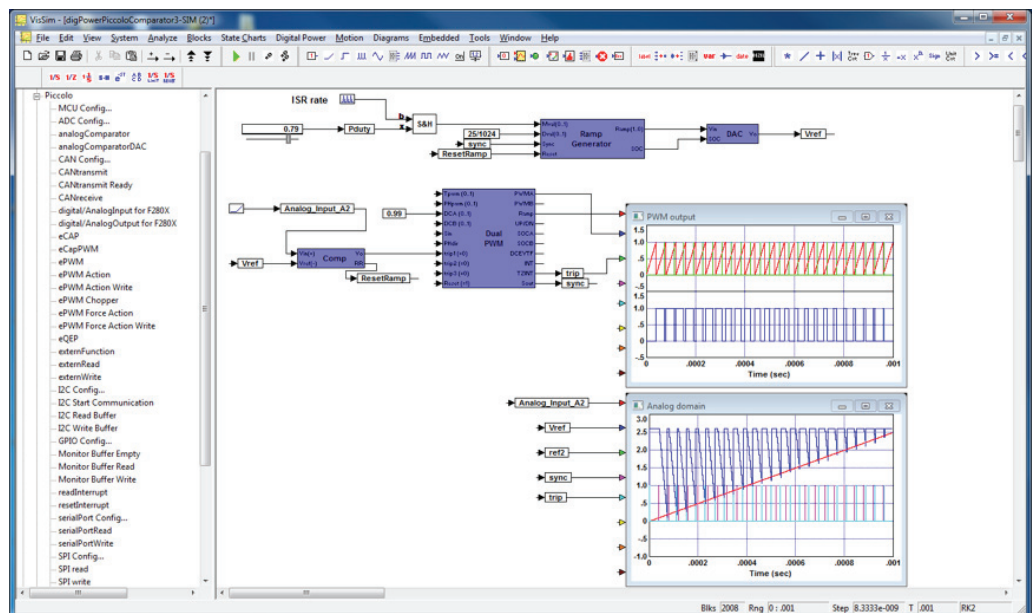


Figure 8. Simulation of PCMC in VisSim

Getting Started

TI offers a variety of development hardware for a myriad of applications, including those that help with the implementation of PCMC. The full bridge development kit TMDSHVPSFBKIT is representative of a complete, high-voltage phase shifted full bridge system, with both voltage mode control and peak current mode control options, with an easy to use GUI interface to set different parameters. This kit features a 400VDC input, 12VDC output and is rated up to 600 watts. This is an isolated topology, utilizing a Piccolo F28027 microcontroller on the secondary (output) side of the isolation boundary. Hardware schematics and implementation software for the peak current mode control functions of the phase shifted full bridge kit are available in the TI controlSUITE™ software system, as well. Figure 9 shows a block diagram of the evaluation kit and an image of the unit.

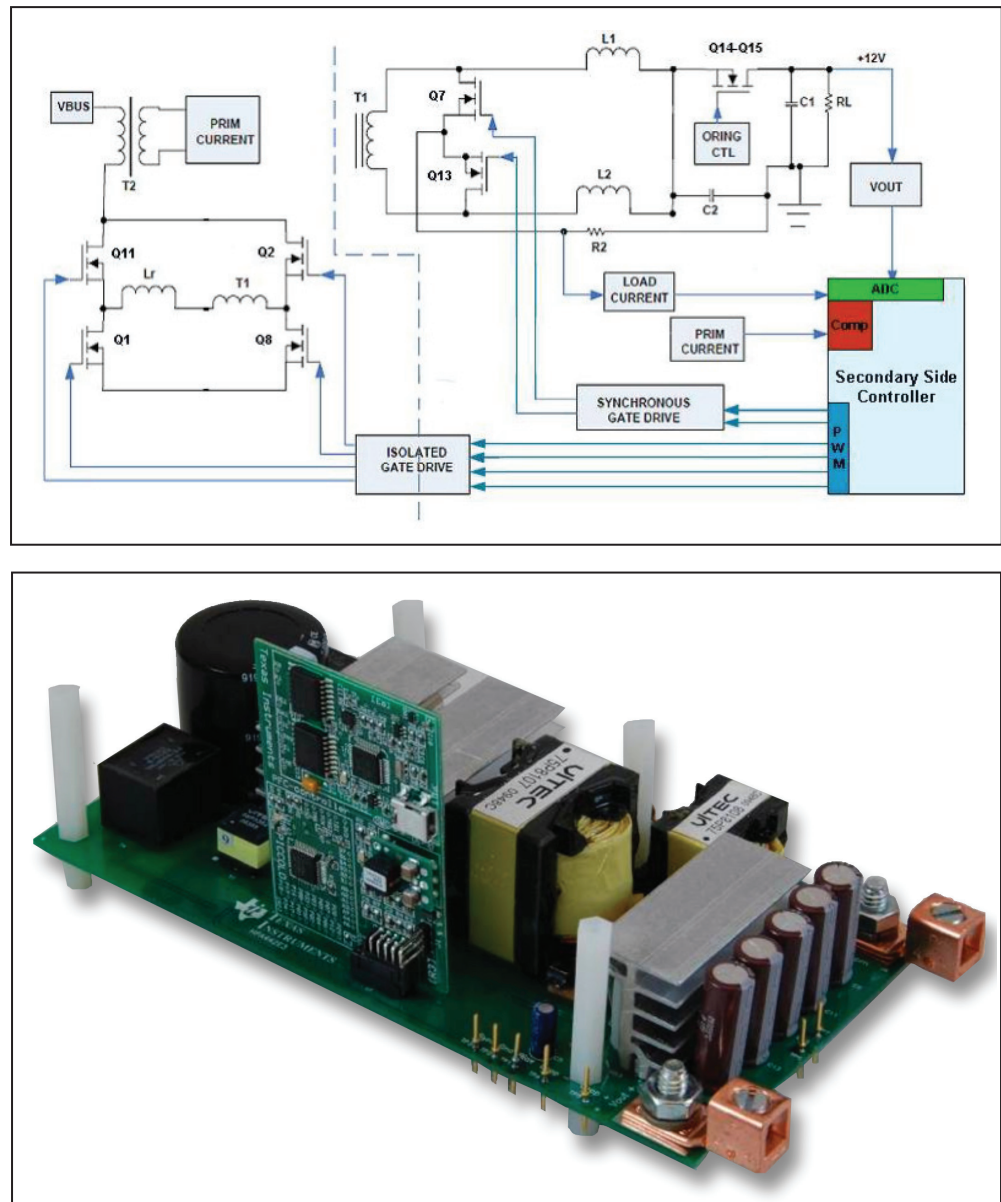


Figure 9. Block diagram of TMDSHVPSFBKIT and image of TMDSHVPSFBKIT

For developers looking to implement PCMC on other power supply designs, TI also offers an easy to use C2000 development tool called the C2000 LaunchPad. This is a low cost, evaluation kit that costs only \$17 and includes a Piccolo F28027 microcontroller and a pair of breakout pins offering access to the device peripherals. This board also includes a built-in, isolated USB-to-JTAG programming interface, offering protection to the user's PC when working with high voltage designs. The PCMC control code for the phase shifted full bridge kit is compatible with this evaluation tool, as well but will require modifications and tuning to work with a custom power supply.

For developers interested in developing other digitally controlled power supplies, TI's high voltage digital power developer's kits based on Piccolo microcontrollers are designed to give developers a robust platform that accelerates development and troubleshooting of complicated digital power systems. These kits include:

- Phase Shifted Full Bridge with PCMC– TMDSHVPSFBKIT (mentioned above)
- Resonant LLC Developers Kit – TMDSHVRESLLCKIT
- Bridgeless Power Factor Correction Kit – TMDSHVBLPFCKIT
- Interleaved Power Factor Correction Kit - TMDSHVPFCKIT

The available digital power kits provide direct access to all of the enhancements and features of the Piccolo microcontroller architecture. Extensive software libraries and thorough documentation lead developers through the process of creating a complete digital power system utilizing real-time algorithms. These kits also enable developers to determine quickly the processing resources required to implement power control. From this baseline, they are then able to bring in advanced algorithms to trade-off the remaining processing capacity for greater accuracy, better performance, higher power efficiency, control of multiple power stages and a myriad of other options. In this way, developers can architect systems specifically optimized for their application constraints and requirements.

C2000 Piccolo microcontrollers are available across a wide roadmap of configurations to ensure that developers can find a processor optimized in terms of performance, memory and peripherals for their application. TI also supplies all the analog components necessary for voltage and current sensing, as well as a wide range of standard and advanced MOSFET and GaN drivers. For more information on TI's digital power development kits, technical application notes, and programming resources, please visit

www.ti.com/controlsuite

For More Information

For Further information on Visual Solutions VisSim Graphical Modeling, simulation and programming software, please visit www.vissim.com.

For further reading on the implementation of Peak Current Mode Control, please see these technical application notes:

Step-by-Step Design Guide for Digital Peak Current Mode Control: A Single-Chip Solution

Dr. Ali Shirsavar

Digital Peak Current Mode Control With Slope Compensation Using the TMS320F2803x

Dr. Ali Shirsavar and Richard Poley

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