Digital Power Simplified

ABSTRACT: As power supply designers embrace the transition from analog to digital controller based solutions, foremost on their minds is the challenge of crafting firmware that would accomplish all the power supply tasks using a processor with a well-defined, but limited computation capability. A popular school of thought subscribes to the idea of separating the time-critical tasks in the power supply from others that are less so, and executing these tasks using specialized hardware blocks that run autonomous of the processor. This dramatically simplifies the firmware development effort and also offers the opportunity to accomplish more with the processor. Using an example from Texas Instruments' portfolio, this webinar introduces the approach described above and shares details about the implementation to illustrate how digital power can be simplified for one and all.

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Presented by:
Ramanan Natarajan
Director, Systems Solutions, Texas Instruments
Outline

• Introduction
  – Key Tasks in a Switch Mode Power Supply (SMPS)
  – High Speed vs Low Speed Tasks in a SMPS
  – Firmware Development Challenge in High-frequency SMPS

• Controller Architectures for SMPS

• State Machine Architecture for Digital Power
  – Introduction
  – UCD3138 Block Overview
  – Application Examples of Digital Power Supplies

• Doing ‘More’ with Digital Power using State Machine Architecture

• Summary
A Typical IT Infrastructure Power Supply

**Energy Source**

\[ V_{IN}, I_{IN}, P_{IN} \]

**Power Supply**

**Basic Power Supply Control**
- Output regulation vs. Source/Load variations
- Fault Protection

**Housekeeping & System Communication**
- Thermal management
- Fan speed control
- Communication with Host MCU
- Enabling Special Operating modes eg. Light-load, Stand-by
- Telemetry (\( P_{IN}, I_{IN}, V_{IN} \) Temp. etc)

\[ V_{OUT}, I_{OUT}, P_{OUT} \]

**Server Motherboard or Telecom Network**

**Communication (I2C, PMBUS)**

Host MCU

Offline AC/DC

Isolated DC/DC

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High Speed vs Low Speed SMPS Functions

### High-Speed Functions

- Voltage regulation, Feedback Loop
- Control & Transient Response
- Cycle-by-Cycle (CBC) Fault Protection

\[ I_{LOAD}, V_{OUT} \]

- Dynamic Mode-switching Between States
  - PWM Mode: (Fixed Frequency, Vary Duty %)
  - LLC Mode: (50% Duty Cycle, Vary Frequency)

Sensing, Decision-making & Response within the same or within few switching cycles (100s of kHz \( \rightarrow \) few \( \mu \)-sec)

### Low-Speed Functions

- Communication with Host
- Temperature Sensing and Fan-speed control

Current Sharing

Time budget of several milli-sec
# Analog ➔ Digital Power Supply

## Traditional Power Supply

### Analog Controller

**Basic Power Supply Control**
- Output regulation vs. Source/Load variations
- Fault Protection

### General Purpose MCU

**Housekeeping & System Communication**
- Thermal management
- Fan speed control
- Communication with Host MCU
- Enabling Special Operating modes eg. Light-load, Stand-by
- Telemetry ($P_{IN}$, $I_{IN}$, $V_{IN}$ Temp. etc)

## Digital Power Supply

### Digital Power Controller

**Basic Power Supply Control**
- Output regulation vs. Source/Load variations
- Fault Protection

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- Thermal management
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- Enabling Special Operating modes eg. Light-load, Stand-by
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Controller Architectures for SMPS

**Analog Controllers**

**PRO:**
1. Simple
2. High PSU bandwidth
3. Fast time-to-market

**CON:**
1. Fixed Function, not a platform device
2. External components
3. No housekeeping, needs MCU

**Programmable, featuring an integrated MCU**

**PRO:**
1. High integration
2. No f/w development
3. Fast time-to-market
4. No computation speed concerns for bandwidth

**CON:**
1. Fixed Function, not a platform device
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**Fixed Function, only GUI configurable**

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**Fully Software Executed Digital Power Controllers (DSP/MCU based)**

**PRO:**
1. Very Flexible, platform device for SMPS
2. Supports complex controls
3. High Integration
4. Housekeeping support

**CON:**
1. More involved f/w development effort
2. Processor computation capability drives PSU bandwidth
3. Learning curve for familiarity with device h/w
4. Complex controls limited by device hardware

**Hardware Implemented Digital Power Controllers (State Machine based)**

**PRO:**
1. Very Flexible, platform device for SMPS
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4. Complex controls limited by device hardware

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Firmware Development Challenges

Availability of Computation Power for desired SMPS switching frequency & bandwidth

Say 50Mips CPU is the right device for a 200kHz SMPS that needs 20kHz bandwidth
- Sampling, compensation calculations and pulse adjustment must happen WITHIN ~60% of switching period
- Rest to account for interrupt latencies and the less time-critical tasks
- 60% of 5\(\mu\)s = 3\(\mu\)s
- Excluding ADC conversion delays, say only 2.5\(\mu\)s available for CPU \(\Rightarrow\) only about 125 instructions for PID, Is this enough?
- What if there are nested loops (such as Average current mode control)? Now 2 loops to be managed within this time?
- What if there are 2 control loops (such as a dual output converter)

To “Interrupt” or not?
- What tasks to include in interrupt loop (time-critical) and what in the background/idle loop (less time-critical)?

Prioritization of time-critical tasks
- When multiple time-critical tasks, then prioritization is needed
- How many levels of interrupt priority available in architecture?

Assembly Language for “tight code”
- PID software routine runs at switching frequency, must be efficient
- Lower level programming

SMPS Hardware & Firmware design becomes intricately intertwined
- Firmware development becomes a more ‘involved’ process
Power Supply Controllers Architectures

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4. Housekeeping support
5. Housekeeping support

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1. More involved f/w development effort
2. Processor computation capability drives PSU bandwidth

**Fully Software Executed Digital Power Controllers**

(DSP/MCU based)

**PRO:**
1. Flexible, platform device for SMPS
2. High integration
3. Easy f/w development
4. No processor computation concerns for PSU bandwidth
5. Housekeeping support

**CON:**
1. Learning curve for familiarity with device h/w
2. Complex controls limited by device hardware

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**Analog** vs. **Digital**

**Fixed Function** vs. **Programmable**

**Hardware Driven** vs. **Processor Driven**

**Texas Instruments**
**UCD3138 Digital Controller – Architecture**

- **Fully programmable architecture targeted for high frequency SMPS**
- **Configurable State Machine + a General Purpose Microcontroller**

**State machine executes time-critical power supply functions with no dependence on processor**

(V/I feedback loop control, protection and other specialized SMPS functions)

**Fully Programmable MCU for Configuring & Initializing State Machine and running Housekeeping, Communications, Telemetry**

**State machine features hardware peripherals that support most common power supply topologies/functions**

(Boost PFC, Resonant LLC, Phase Shifted & Hard-switched Full-bridge, Buck & Peak Current Mode, Burst mode and more)

**MCU also available for lower speed power supply control functions**

(such as PFC Voltage loop, Current Sharing)

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### Architecture Overview

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<tr>
<td>4 KB RAM</td>
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<td>32 KB Flash</td>
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<td>OSC</td>
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<td>Timer</td>
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<td>GPIOx</td>
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<td>UART x2</td>
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**Texas Instruments**
Benefits of Architecture

Reduced entry-barrier to get into Digital SMPS, Fast time-to-market

Ease of F/w Development
Program state machine by assigning bit values to registers
All compensation calculations implemented in high-speed h/w
No need for complex time-slicing of CPU resources

Lower Power Consumption
Sub-100mA during normal operation
Can shut down portions of chip for lower power ~25mA

High Bandwidth in High-frequency Digital SMPS
No reliance on slower firmware decisions from CPU
Clear benefit at high-frequencies when switching period is short
Control multiple voltage/current loops simultaneously, or in multi-output power supplies

High Level of Integration
One device for both Power supply control and housekeeping
Eliminate discrete MCU
Small package sizes for high density applications
UCD3138 – Block Level Overview

Key Attributes

State Machine Hardware is comprised of dedicated peripherals for:
- Feedback control of 3 simultaneous loop
  - with Interconnection mechanism between loops
- High-speed 50-ns analog comparators & advanced fault management
- Common power supply functions
  - Burst Mode, Fast $V_{\text{INPUT}}$ Feedforward

Microcontroller:
- 31.25MHz, 32-bit ARM7 CPU
- On-chip memory: Program & Data Flash, RAM and ROM
- 14-Ch, 12-bit, 265kHz general purpose ADC
- Communication ports: UART, I2C, PMBus and JTAG
- GPIOs, Timers, Capture modules
- Bias power monitors: BOD/POR blocks
Hardware Power Peripheral Blocks

- 3 independent feedback loops capable of operating simultaneously
- Loop Mux to allow ‘Nesting’ one loop inside another, transferring control signals between loops
- Peripherals for commonly needed SMPS functions – Peak Current Mode, Constant Power/Constant Current, Burst Mode, PWM/LLC Mode Switching, Fast Input Voltage Feedforward and more

**Feedback Loop (x1)**

- Sensing & Error Generation
- Output Pulse Generation
  - Modulations: PWM/FM/Ph-M
  - Resolution: Pulse width - 250ps,
  - Freq & Phase – 4ns

**Feedback Loop (x2)**

- Analog Controller
  - Error Amplifier
  - COMP pin with external R/C network
- Digital Controller
  - Front End block
  - PID based Filter
  - DPWM (Digital Pulse Width Modulator)

- Loop Mux
- EAP0, EAP1, EAP2
- EAN0, EAN1, EAN2
- Loop Mux to allow 'Nesting' one loop inside another, transferring control signals between loops

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Hardware Power Peripheral Blocks (Contd.)

Front End Module

Analog Differential Amplifier

Adjustable Gain Error Amplifier

16MHz Error Analog to Digital Converter

Digitized Error Signal Sent on to Digital Compensator

Effective 14-bit DAC driven from:
- ARM7 (soft-start, set-point)
- a different loop (nesting)
- Other peripherals

Peak Current Mode control with programmable slope compensation

3 Front-end modules facilitate 3 independent high-speed feedback loops, support operation up to 2MHz switching frequency simultaneously
Analog Comparators

• 7 High-speed 50-ns analog comparators, for cycle-by-cycle protection (e.g., current limiting)

• Advanced Fault management between various Source Inputs (analog/digital comparators, GPIOs) and Pulse Generation modules (DPWM0-3)
General Purpose MCU

14-Ch, 12-bit, 267khz Analog-to-Digital Converter

- ADC12 Control
- Sequencing, Averaging, Digital Compare, Dual Sample and hold
- Internal Temperature Sensor
- Current Share Analog, Average, Master/Slave
- Analog Comparators
- Fault MUX & Control
- Cycle by Cycle Current Limit
- Digital Comparators

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Isolated DC/DC Converter with **UCD3138**

Phase Shifted Full Bridge Converter with Synchronous Rectification

- 1 Voltage Loop (several kHz bandwidth) and 2 Current Loops
- Fully implemented using State Machine hardware

**Diagram Description**

- **Primary MOSFET PWM**
- **SR MOSFET PWM**
- **Isolated Gate Transformer**
- **PWM Control**
- **Voltage Loop**:  
  - V_{OUT} Feedback Loop
  - V_{OUT} OVP
  - V_{OUT} OCP
- **Current Loop**:  
  - I_{PRI} Feedback Loop
  - I_{OUT} Sense
  - I_{PRI} Sense
  - I_{OUT} Sense
- **Current Share**
- **State Machine Hardware**
- **Phase Shifted Full Bridge Converter**

**Key Components**

- **D1, D2, T1, T2**
- **Q1, Q2, Q3, Q4**
- **C1, C2, L1, R1, R2**
- **Q7**
- **VOUT**
- **VOUT Sense**
- **D1, D2, D3, D4**
- **Q1, Q2, Q3, Q4**
- **L1, L2, L3**
- **C1, C2, C3**
- **R1, R2, R3**
- **VIN, VA, VOUT**
- **I_{PRI}, I_{OUT}, I_{PRI} Sense, I_{OUT} Sense**
- **V_{REF}, V_{CTRL}, V_{OUT}**

**Texas Instruments**

**400VDC I_{PRI} Sense**
Power Factor Correction with **UCD3138**

AC/DC, 2-ph Interleave, Boost Power Factor Correction Converter

1. 2 Fast Current Loops (5-10kHz bandwidth) controlled by state machine hardware
2. Fast current loop “nested” inside slow voltage loop for Average Current Mode
3. PFC Voltage loop typically ~10Hz cross-over, slow loop which allows ARM7 MCU control
Multi-Output Converter Using UCD3138
DC/DC Dual Output Converter - Half-Bridge Resonant LLC + Downstream Buck

- 2 Voltage Loops (several kHz & several tens of kHz bandwidth) & 1 current loop
- Fully implemented using State Machine hardware
Using State Machine to ‘Do More’
Average Current Mode Control

CCM Operation
Mid Point Sample of Rising Current = AVG of Switching Cycle

DCM Operation
Mid Point Sample of Rising Current > AVG of Switching Cycle

EADC Hardware Oversampling + Hardware Averaging
- Increase to 8X samples / Sw Cycle
- Achieve More accurate Average Current estimation

State Machine Hardware Facilitates FAST calculation
- 65kHz Fsw → Sampling ~520kHz
- Calculation time < 2μsec

AC/DC Power Factor Correction
8X Oversampling Enables 2-4% Improvement in iTHD

MCU Availability to ‘Do More’
On-the-Fly Firmware Upgrade of Power Supply without Shut-down

State Machine running autonomous of processor increases MCU availability for specialized housekeeping functions

Upload and commission NEW firmware without shutting down power supply

- Dual Memory Bank architecture device, UCD3138064
  - Capable of Execution from one block, while simultaneously writing to another block

- On-the-fly upgrade in systematic steps:
  1) Write new firmware in Block 2
  2) Check integrity of Block 2 Write step
  3) Stage for a live switch in execution from block 1 to block 2 (save values of old variables, initialize new variables, create structures)
  4) Perform Live switch

Reduced Downtime in server datacenters during SMPS performance upgrades, bug fixes etc
MCU Availability to ‘Do More’
On-the-Fly Firmware Upgrade of Power Supply without Shut-down

Example: DC/DC Resonant LLC Firmware Upgrade
- Add Constant Power (CP) regulation function for overload protection
- Replace $I_{OUT}$-based overcurrent protection (OCP) function with $I_{PRI}$-based cycle-by-cycle (CBC) protection function
## Summary

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<th>State Machine Based Digital Power Controller</th>
<th>Processor Based Digital Power Controller</th>
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<tr>
<td>Voltage/Current feedback loop, high-speed functions controlled by digital state machine h/w</td>
<td>Software running on processor controls all loops</td>
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<td>Critical decisions without processor intervention, no latency involved</td>
<td>Powerful (co-)processor at the core of every decision made</td>
</tr>
<tr>
<td>Power topologies supported depend on state machine h/w in architecture – Quick decision making</td>
<td>All Functions supported based on CPU resource – detailed Upfront calculations needed for assessment &amp; decision making</td>
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<tr>
<td>UCD3138 - Dedicated high-speed data converters for each feedback loop (3x EADC) + hardware peripherals – no need for resource sharing</td>
<td>Typically 1, maybe 2 data converter(s) + CPU of known capability shared across all functions</td>
</tr>
<tr>
<td>Full availability of processor for housekeeping, communications, telemetry and specialized functions (such as on-the-fly firmware upgrades in-system without shut-down)</td>
<td>Processor must be shared between both power supply control and housekeeping</td>
</tr>
<tr>
<td>Firmware development involves configuring state machine hardware for desired power supply topology and architecting low speed functions in software using MCU</td>
<td>All desired functions must be architected in software with MCU/DSP, with proper attention to timing and priorities between high and low speed functions</td>
</tr>
</tbody>
</table>

**Simplification of firmware development, Reduced entry-barrier & Fast time-to-market**
Additional References

http://www.ti.com/product/UCD3138

Digitally controlled 1/8th Brick DC/DC Telecom Power Module

http://www.ti.com/tool/PMP8877

Power Factor Correction Evaluation Module

http://www.ti.com/tool/UCD3138PFCEVM-026

Phase Shifted Full-Bridge Evaluation Module

http://www.ti.com/tool/UCD3138PSFBEVM-027

On-the-Fly Firmware Update of Digital Power Supplies

http://b Cove.me/mk5kk1wd

Fast input-voltage transient response with digitally-controlled isolated DC/DC converters


Digital current balancing for an interleaved boost PFC


Using UCD7138 and UCD3138A for Advanced Synchronous Rectification Control

Ramanan Natarajan, from Texas Instruments, is focusing on analog & digital power management controllers and gate driver devices for offline, isolated switch mode power supplies and other power electronics. Ramanan Natarajan has over 16-years experience in the area of power electronics. He holds Masters degrees in Materials Engineering and Electrical Engineering from Rensselaer Polytechnic Institute, Troy, NY where he worked on power electronics packaging and IGBT device physics respectively. He also holds a Bachelors degree in Metallurgical Engineering from Indian Institute of Technology-Madras, India.