Digital Power Supply, Design and Architectural Trade-offs

John Demiray, Sr. Product Marketing Manager

Class ID: AC03B
John Demiray: Sr. Product Marketing Manager

- Sr. Product Marketing Manager at Renesas Electronics America
  - Product expertise on Low Voltage and Mixed-Signal Power Products
  - End Market segments
    - Power Supplies, Power Tools, Servers, PCs, Smart Phones and Tablets, Solar Inverters
- 20+ Years of experience in marketing power products
  - Vishay
  - Exar
  - Conexant
- HW Design engineer at Alcatel Network Systems
- Ms. EE
- MBA
Renesas Technology & Solution Portfolio

Enabling the Smart Society

Microcontrollers
No.1 Market Share Worldwide

Advanced and Proven Technologies

System LSIs

Extensive, High-quality Portfolio

Analog & Power
Discrete and Integrated Power Products

30V-1500V in Application Optimized Processes
- Low voltage family optimized for Qgd x Rds(on)
- Separate family optimized for pure Rds(on) performance
- 600V Super Junction MOSFETs for SMPS

300V-1350V Discrete Devices
- Class-leading turn-off loss
- High-speed, short-circuit rated, and low Vce(on) optimized using thin wafers
- Multiple package options and bare die option available

SiC, Fast Recovery, SBD and Others
- SiC Schottky barrier diodes for very high switching speeds
- 3A to 30A, 600V parts available
- SBD optimized for high switching speeds

Optimized for Highest Efficiency & Compactness
- Dr MOS solutions for > 93% peak efficiency, up to 1.5MHz
- PFC ICs for solutions up to 98% peak efficiency
- Smallest CSP packages for POL, Battery Charger and Fuel Gauge Applications

Broad Line-up of Packages and Devices
- Current ratings from 0.8A to 30A rms
- Voltage ratings from 600V to 1500V
- Junction temperature to 150°C
‘Enabling The Smart Society’

**Challenge:**
“Efficient Digital Power designs, alongside with efficient analog power supply designs are required to enable smart society by optimizing Power Consumption”

**Solution:**

*This class will show you the trade-offs between analog and digital power design tools to achieve optimum efficiency, resulting in reduced energy consumption*
Agenda

- How increasing the efficiency and reducing power consumption enables smart society
- Comparison of digital and analog loop techniques
- Design optimization using analog and digital loop control
- How to handle challenges that come with digital loop design
  - How to optimize efficiency during light load
  - How to reduce PWM quantization efforts
- Digital Power Supply Reference Designs
  - RX62T interleaved digital PFC control design
  - PFC efficiency comparisons
- Summary and Q&A
Efficient Power Generation for a Smarter Society

Efficient Power = Longer Distances

Energy Management

Power Plant
Solar/Wind-Generated Power Plant

Electric Grid

Smart Meter

Smart Grid

Smart Home

Next-Generation Service Station

Smart Parking

ITS

Smart Transportation

Smart Car

Efficient Power = Longer Distances

Book
Map
Movie

Internet

Power Plant

Smart Grid

Smart Home

Smart Society

Smart School

Smart Building

Smart Store

Smart Factory

Smart Society
Agenda

- How increasing the efficiency and reducing power consumption enables smart society
- **Comparison of digital and analog loop techniques**
- Design optimization using analog and digital loop control
- How to handle challenges that come with digital loop design
  - How to optimize efficiency during light load
  - How to reduce PWM quantization efforts
- Digital power supply reference designs
  - RX62T interleaved digital PFC control design
  - PFC efficiency comparisons
- Summary and Q&A
Block Diagram of a Typical Loop Control

- Power supplies convert input voltage to different output voltage
  - Maintain a fixed output voltage $V_{out}$
  - Create a feedback loop
  - Compare with voltage reference
  - Adjust for reference/output voltage differences
  - Control the MOSFET’s

- Feedback and control loop determines analog vs. digital
DC DC Conversion Concepts

- Lower inductor value is preferred
  - Achieved by higher PWM frequency
  - Limited by MOSFET and PWM
- DC/DC conversion is achieved by varying the duty cycle
  - Shorter duty cycles $\rightarrow$ Higher conversion rate

PWM Clock

Period = 1 microsecond (1 MHz)

Duty Cycle = 30%

High Side/Low Side MOSFET

Inductor

Switching Losses
**Block Diagram of an Analog Loop**

- Feedback control loop is implemented using analog techniques.
  - Feedback loops samples the output
  - Voltage differences turned into error signal
  - PWM drives the Power MOSFET transistors
Feedback and control loop is digital
- The feedback signal converted to a digital number
- Digital number is generated, called the error term
- This error term is fed into a digital loop filter
Digital Loop Filter

- The filter is PID (Proportional Integral Derivative)
  - The P path is the gain of the error signal
  - The I path is the time integral of past error signals
  - The D path is the rate-of-change of the error signal

Error Signal Gain

Time Integral → Steady State Response

Rate of Change → Transient Response

- Performance improved with system knowledge
Advantages of Digital Loop Control

- Increased efficiency with system knowledge

![Efficiency Graph](image)

- New Generation Dr MOS
- Dr MOS #1
- Dr MOS #2
- 3.0% increase

Inductor
Feedback
Dr MOS
High Side/Low Side MOSFET Voltage

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Advantages of Digital Loop Control

- Ability to account for component value changes over temperature and time
  - Resistor, capacitor and inductor values can drift over time and temperature range

- Digital circuits can shrink faster than analog circuits
  - Digital designs can take advantage of new technologies such as 28 nm
  - Less component count means higher reliability designs
Advantages of Digital Loop Control

- Faster response to environmental/electrical variations
  - Faster response to voltage transients
  - Faster response to changes in temperature

- Increased efficiency results in high power designs
  - Google establishing a data center in Finland
  - Meet Energy Star Specifications
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  - How to optimize efficiency during light load
  - How to reduce PWM quantization efforts
- Digital power supply reference designs
  - RX62T Interleaved digital PFC control design
  - PFC efficiency comparisons
- Summary and Q&A
How to Optimize efficiency in Light Load

- Adjust internal parameters to varying line, load and temperature conditions
  - Efficiency curve can be made flat from full load to low output current by changing the switching frequency
    - Very critical for connected stand-by operation
How to Optimize efficiency in Light Load

- Adjust internal parameters to varying line, load and temperature conditions
  - Switching frequency can vary in relation to varying input line voltage
    - PWM frequency can be changed in response to light loads (fixed voltage)
    - PWM Duty cycle can be changed in response to output voltage requirements

PWM Clock

Frequency = 1 MHZ

Duty Cycle = 30%

Inductor

High Side/Low Side MOSFET

Switching Losses
How to take advantage of the flexibility provided by Digital Power?

- Programmable power consumption during light load

- Typical 1.2 KW design at 98% efficiency

100W Light Load

- 2% losses 24W

- 20W
  - Switching losses
  - MOSFET
  - Diode

- 4W
  - System Losses
  - Rectifies
  - Aux Power
  - Opto coupler
  - Diode

1.2KW Heavy Load

- 20W
  - Switching losses
  - MOSFET
  - Diode

- 4W
  - System Losses
  - Rectifies
  - Aux Power
  - Opto coupler
  - Diode

- 20W Represents 20%
Agenda

- How increasing the efficiency and reducing power consumption enables smart society
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- **How to handle challenges that come with digital loop design**
  - How to optimize efficiency during light load
  - How to reduce PWM quantization efforts
- Digital power supply reference designs
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  - PFC efficiency comparisons
- Summary and Q&A
How to handle challenges that come with flexibility

- **PWM Duty Cycle Quantization Error**
  - PWM clock frequency determines the PWM Duty cycle resolution.
    - Example: PWM Resolution = PWM Clock/PWM Switching Frequency;
      - 100MHZ Clock, 1MHZ PWM Switching = Resolution(1/100)
      - 50MHZ Clock, 1MHZ PWM Switching = Resolution (1/50)
    - For a 48V output
      - 100MHZ Clock = 48VDC/100 = 0.48V resolution
      - 50MHZ Clock = 48VDC/50 = 0.96V resolution

- **Faster Clock Frequency**
  - Faster Clock Frequency increases resolution
  - Also increases power consumption
How to handle challenges that come with flexibility

- Control delay
  - Too much delay causes instability
    - Solution
      - Faster processors
      - Better algorithms

<table>
<thead>
<tr>
<th>PWM Frequency</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 KHZ</td>
<td>100 microseconds</td>
</tr>
<tr>
<td>100 KHZ</td>
<td>10 microseconds</td>
</tr>
<tr>
<td>1 MHZ</td>
<td>1 microsecond</td>
</tr>
</tbody>
</table>

PWM Clock → Response Time

High Side/Low Side MOSFET
How to handle challenges that come with flexibility

- Requires very accurate A/D to reduce quantization error
  - 12-Bit A/D
    - 4096 levels,
      - 3 mV for 12 V output (12V/4096)
  - 10-Bit A/D
    - 1024 levels,
      - 12 mV for 12 V output (12V/1024)

- Requires fast conversion time to catch transients
  - 1 MHz sampling rate, 1 microsecond transients
Advantages of RX62x family

- Integrated FPU for digital loop control
  - Dedicated instruction for FPU units

![Bar chart showing comparison between Fixed Point and FPU for Math Functions and Math Tables.]

- High resolution PWM in RX62G, 312.5 ps vs 10 ns (1/100 MHZ)

![Diagram showing PWM Clock with Frequency = 1 MHZ and Duty Cycle = 30% = 333 ns.]

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  - How to reduce PWM quantization efforts
- **Digital power supply reference designs**
- Summary and Q&A
DPS Solutions

Digital Power Supplies Segment

Power Converters

CCM Interleave PFC

LCD TV PSU

AC/DC Power Supply for LCDTV

DC-DC Buck & Boost, DC-AC

I/F board 140x210[mm]

Power board 140x200[mm]

MCU board (RSK) 100x120[mm]

Solar Inverter

Grid-tied Solar Inverter

- DC-DC Buck & Boost and DC-AC share the same board design
The system has three configurations DC/DC Buck converter, DC/DC Boost converter and DC/AC inverter.

### Table 3-1 Specification for the DC/DC buck converter

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC input voltage range</td>
<td>45.6-50.4V(DC)</td>
</tr>
<tr>
<td>DC output voltage range</td>
<td>24V(DC)</td>
</tr>
<tr>
<td>DC output current range</td>
<td>0-10A(DC)</td>
</tr>
<tr>
<td>DC output maximum power</td>
<td>240W</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>50kHz</td>
</tr>
</tbody>
</table>

### Table 3-2 Specification for the DC/DC boost converter

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC input voltage range</td>
<td>22.8-25.2V(DC)</td>
</tr>
<tr>
<td>DC output voltage range</td>
<td>48V(DC)</td>
</tr>
<tr>
<td>DC output current range</td>
<td>0-5A(DC)</td>
</tr>
<tr>
<td>DC output maximum power</td>
<td>240W</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>50kHz</td>
</tr>
</tbody>
</table>

### Table 3-3 Specification for the DC/AC inverter

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC input voltage range</td>
<td>410V(DC)</td>
</tr>
<tr>
<td>DC output voltage range</td>
<td>100V(AC)</td>
</tr>
<tr>
<td>DC output current range</td>
<td>0-1.2A(AC)</td>
</tr>
<tr>
<td>DC output maximum power</td>
<td>120W</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>50kHz</td>
</tr>
</tbody>
</table>
Rx62T 32-Bit MCU
Interleaved Digital PFC Control
## Interleaved PFC Implementation - Analog versus Digital

<table>
<thead>
<tr>
<th></th>
<th>Analog PFC</th>
<th>Digital PFC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Complexity</strong></td>
<td>Simple Hardware</td>
<td>MCU can handle PFC and System Control</td>
</tr>
<tr>
<td><strong>Gate Drivers</strong></td>
<td>MOSFET/IGBT Driver Included</td>
<td>Needs MOSFET IGBT Gate Drivers</td>
</tr>
<tr>
<td><strong>Software Development</strong></td>
<td>Not Needed</td>
<td>Software Development needed</td>
</tr>
<tr>
<td><strong>Flexibility</strong></td>
<td>Little</td>
<td>Significant</td>
</tr>
<tr>
<td><strong>Additional Circuitry</strong></td>
<td>MCU may be required anyway, Motor Control etc</td>
<td>Timers and Sensors</td>
</tr>
</tbody>
</table>
Digital PFC for Motor Control Inverter

90 – 264 VAC

3 Phase Inverter stage

3 Phase Motor

AC voltage, DC voltage current

PWM

Current, voltage, temperature, OC-detection

Gate Driver

Speed, Position

MCU

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Renesas Digital Power Supply reference design

395V/3.8A CCM Interleave PFC

Diode: RJS6005TDPP-EJ

IGBT: RJH60F4DPK

IGBT: RJH60F4DPK

100 MHZ32-bit MCU 12 bit A/D and FPU

RX62T/100pin R5F562TAADFP

600V SiC

600V IGBT
# Digital PFC Control Demo System

- **Overview of components**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MCU</td>
<td>R5F562TAADFP (ROM: 256kB, RAM: 32kB, CLK: 100MHz, VCC: 5V)</td>
</tr>
<tr>
<td>2</td>
<td>Circuit system</td>
<td>Continuous conduction mode / 2-phase interleave</td>
</tr>
<tr>
<td>3</td>
<td>Switching device</td>
<td>IGBT (RJH60F4DPK: 600V/50A)</td>
</tr>
<tr>
<td>4</td>
<td>Input voltage</td>
<td>AC 85 to 264 V</td>
</tr>
<tr>
<td>5</td>
<td>Output voltage</td>
<td>DC 395 V</td>
</tr>
<tr>
<td>6</td>
<td>Maximum output current</td>
<td>3.8 A</td>
</tr>
<tr>
<td>7</td>
<td>Maximum output power</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>8</td>
<td>PWM frequency</td>
<td>35 kHz / 1 phase</td>
</tr>
<tr>
<td>9</td>
<td>Efficiency</td>
<td>&gt; 96 %</td>
</tr>
<tr>
<td>10</td>
<td>Power factor</td>
<td>&gt; 0.96</td>
</tr>
<tr>
<td>11</td>
<td>Cooling</td>
<td>Forced-air cooling by external browser</td>
</tr>
<tr>
<td>12</td>
<td>Board size</td>
<td>W * D * H = 195mm * 190mm * 50mm</td>
</tr>
</tbody>
</table>
PFC Performance Evaluation

Efficiency (Input voltage AC200V)

Power factor (Input voltage AC200V)

Load regulation (Input voltage AC200V)

※R2A20114FP : Include AUX power consumption

<table>
<thead>
<tr>
<th>Load [W]</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.993</td>
</tr>
<tr>
<td>1125</td>
<td>0.99</td>
</tr>
<tr>
<td>750</td>
<td>0.985</td>
</tr>
<tr>
<td>300</td>
<td>0.941</td>
</tr>
<tr>
<td>150</td>
<td>0.829</td>
</tr>
</tbody>
</table>

AC100V

<table>
<thead>
<tr>
<th>Load [W]</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.993</td>
</tr>
<tr>
<td>1125</td>
<td>0.989</td>
</tr>
<tr>
<td>750</td>
<td>0.977</td>
</tr>
<tr>
<td>300</td>
<td>0.974</td>
</tr>
<tr>
<td>150</td>
<td>0.964</td>
</tr>
</tbody>
</table>
Agenda

- How Increasing the efficiency and reducing power consumption enables smart society
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- Design optimization using analog and digital loop control
- How to handle challenges that come with Digital Loop Design
  - How to optimize efficiency during light load
  - How to reduce PWM quantization efforts
- Digital Power Supply Reference Designs
  - RX62T Interleaved digital PFC Control design
  - PFC Efficiency Comparisons
- Summary and Q&A
Summary

- Smart Power = Better Efficiency

- Digital Power Design provides an alternative to Analog Power Designs

- Trade-offs should be carefully considered
Questions?
‘Enabling The Smart Society’

- **Challenge:**
  “Efficient Digital Power designs, alongside with efficient analog power supply designs are required to enable smart society by optimizing Power Consumption”

- **Solution:**
  - *This class showed you the trade-offs between analog and digital power design tools to achieve optimum efficiency, resulting in reduced energy consumption*
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  ![Guidebook Logo]

  or

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