Digital Power Supply, Design and Architectural Trade-offs
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

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

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

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

- Smart Factory
- Smart Building
- Smart School
- Smart Home
- Smart Grid
- Smart Meter
- Electric Grid
- Power Plant
- Solar/Wind-Generated Power Plant
- Efficient Power = Longer Distances
- Efficient Power = Less Emission
- Energy Management
- ITS
- Smart Parking
- Next-Generation Service Station
- Book
- Map
- Movie
- Internet

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
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- 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 Vout
  - 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

<table>
<thead>
<tr>
<th>Period = 1 microsecond (1 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty Cycle = 30%</td>
</tr>
</tbody>
</table>

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

Performance improved with system knowledge
Advantages of Digital Loop Control

- Increased efficiency with system knowledge
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
Agenda

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  - How to handle challenges that come with digital loop design
    - How to optimize efficiency during light load
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- 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

![Efficiency graph](image-url)

**Efficiency**

- Efficiency $\eta$ [%]
- Output Power [W]

- Red: R2A20114FP
- Blue: RX62T

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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

![Diagram showing PWM Clock, Frequency = 1 MHZ, Duty Cycle = 30%]
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
  - Octo coupler
  - Diode

1.2KW Heavy Load

- 20W
  - Switching losses
  - MOSFET
  - Diode

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

- 20W Represents 20%
Agenda

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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>
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

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

Frequency = 1 MHz
PWM Clock
312.5 ps
Duty Cycle = 30% = 333 ns
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- **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 and DC-AC share the same board design

Solar Inverter
- Grid-tied Solar Inverter

Power board 140x200[mm]
I/F board 140x210[mm]
MCU board (RSK) 100x120[mm]
DPS Solutions

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</strong></td>
<td>Not Needed</td>
<td>Software Development needed</td>
</tr>
<tr>
<td><strong>Development</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flexibility</strong></td>
<td>Little</td>
<td>Significant</td>
</tr>
<tr>
<td><strong>Additional</strong></td>
<td>MCU may be required anyway, Motor Control</td>
<td>Timers and Sensors</td>
</tr>
<tr>
<td><strong>Circuitry</strong></td>
<td>etc</td>
<td></td>
</tr>
</tbody>
</table>
Digital PFC for Motor Control Inverter

- 90 – 264 VAC
- AC voltage, DC voltage current
- Current, voltage, temperature, OC-detection
- Gate Driver
- Speed, Position

MCU

Gate Driver

PWM
Renesas Digital Power Supply reference design

- 395V/3.8A CCM Interleave PFC
- Diode: RJS6005TDPP-EJ
- IGBT: RJH60F4DPK
- IGBT: RJH60F4DPK
- RX62T/100pin R5F562TAADFP
- 100 MHZ 32-bit MCU 12 bit A/D and FPU
- 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><strong>1</strong></td>
<td><strong>MCU</strong></td>
<td>R5F562TAADFP (ROM: 256kB, RAM: 32kB, CLK: 100MHz, VCC: 5V)</td>
</tr>
<tr>
<td><strong>2</strong></td>
<td><strong>Circuit system</strong></td>
<td>Continuous conduction mode / 2-phase interleave</td>
</tr>
<tr>
<td><strong>3</strong></td>
<td><strong>Switching device</strong></td>
<td>IGBT (RJH60F4DPK: 600V/50A)</td>
</tr>
<tr>
<td><strong>4</strong></td>
<td><strong>Input voltage</strong></td>
<td>AC 85 to 264 V</td>
</tr>
<tr>
<td><strong>5</strong></td>
<td><strong>Output voltage</strong></td>
<td>DC 395 V</td>
</tr>
<tr>
<td><strong>6</strong></td>
<td><strong>Maximum output current</strong></td>
<td>3.8 A</td>
</tr>
<tr>
<td><strong>7</strong></td>
<td><strong>Maximum output power</strong></td>
<td>1.5 kW</td>
</tr>
<tr>
<td><strong>8</strong></td>
<td><strong>PWM frequency</strong></td>
<td>35 kHz / 1 phase</td>
</tr>
<tr>
<td><strong>9</strong></td>
<td><strong>Efficiency</strong></td>
<td>&gt; 96 %</td>
</tr>
<tr>
<td><strong>10</strong></td>
<td><strong>Power factor</strong></td>
<td>&gt; 0.96</td>
</tr>
<tr>
<td><strong>11</strong></td>
<td><strong>Cooling</strong></td>
<td>Forced-air cooling by external browser</td>
</tr>
<tr>
<td><strong>12</strong></td>
<td><strong>Board size</strong></td>
<td>W * D * H = 195mm * 190mm * 50mm</td>
</tr>
</tbody>
</table>
PFC Performance Evaluation

Efficiency (Input voltage AC200V)

※R2A20114FP : Include AUX power consumption

Power factor (Input voltage AC200V)

Load regulation (Input voltage AC200V)

AC200V

<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

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