Digital power approach with STM32G4 in unidirectional/bidirectional totem pole PFC

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Agenda

1. Unidirectional totem pole PFC solution
2. Bidirectional totem pole PFC solution
3. ST key products on solution
4. Takeaways
Uni-directional totem pole PFC solution
3 kW CCM totem pole PFC solution

- Input AC voltage: 90–264 VAC
- DC output voltage: 400 VDC
- Switching frequency: 70 kHz
- Operation mode: CCM
- Peak efficiency: 98.5% @ 230 VAC
- Power Factor: >0.98 @ 100% load
- iTHD: <5% @ 100% load
- Peak inrush current: <30 A

Key features

Key components
- STM32G474RBT (32-bit MCU)
- SCTW35N65G2V (SiC Gen2) → SGT40R65ALD (SiC Gen3)
- STGAP2D (gate driver)
- STW70N65DM6-4 (DM6 SJ MOS)
- VIPER26HD (Aux. SMPS)

Target application
- Telecom & 5G PSU
- Datacenter & Server PSU

Design material

Demo video
(Key words on ST.COM STDES-3KWTPFC)
PFC digital platform - STM32G474

Arm® Cortex®-M4 up to 170 MHz

Floating-point unit (FPU)
- Control loop computation (reserved for future use)

32-Kbyte CCM-SRAM
- Zero wait-state for critical code execution

CORDIC for trigonometric functions acceleration
- Software phase-locked loop (reserved for future use)

FMAC filter mathematical accelerator
- Hardware digital filter (CPU off-load) for loop computation

Hi-Resolution PWM Timer (184 ps)
- Mainly for high frequency (HF) MOSFET control at 70 kHz

Multiple ADCs (4 Msps) up to 5
- AC voltage, PFC voltage/current, and hotspot temperature sensing

Comparators and DACs up to 7
- PFC OVP and critical current protection

UART, SPI, CAN and USB
- UART for internal/external communication
**AC positive cycle** \((V_{AC} > 0)\)

**Major behavior**

- **Active switch**: \(S_2\) controls the input current to charge to PFC choke for making a sinusoidal waveform
- **Synchronous switch**: \(S_1\) is the complementary switch that provides a path to discharge inductor current
- **Always-on switch**: \(S_4\)
- **Always-off switch**: \(S_3\)
AC positive cycle \((V_{AC} < 0)\)

**Major behavior**

- **Active switch**: S1 controls the input current to charge to PFC choke for making a sinusoidal waveform.
- **Synchronous switch**: S2 is the complementary switch that provides a path to discharge inductor current.
- **Always-on switch**: S3
- **Always-off switch**: S4

**S1 on, inductor current charging**

- S1, S2: High switching frequency
- S3, S4: Low switching frequency

**S1 off, inductor current discharging**
Current sampling strategy in TTP

Sampling consideration and configuration

- Active switch is swapped according to AC polarity
- Inductor current is sampled at middle duty of active switch
- Sampling at both of period and reset of PWM count for software filtering (interrupt is double to switch frequency)

Positive cycle

Negative cycle

PWM count in center-aligned mode (up-down mode)

• Positive cycle: current sampling at PWM count period and then doing PI computation
• Negative cycle: current sampling at PWM count reset and then doing PI computation
PFC control block diagram

Dual loops with SW phase locked loop

- Voltage loop: performed at 10 kHz
- Current loop: performed at 70 kHz
- SW loop: performed at 10 kHz

- Current loop
  - Inner loop for shaping AC current that is executed by built-in hardware filter (FMAC)

- Voltage loop
  - Outer loop for bulk voltage regulation and with input voltage feedforward compensation

- SW loop
  - SW PLL (frequency + phase tracking) to synchronize AC phase to achieve blanking time and soft-start scheme
Design challenge: current spike at AC zero-crossing

- At a zero-crossing when the AC input is going from positive to negative.
  - Before zero-crossing, $V_{coss\_S3}=400\,\text{V}$, $D_{boost}=0.99$ to $S_2$, $(1-D_{boost})=0.01$ to $S_1$
  - After zero-crossing, $V_{coss\_S4}=400\,\text{V}$, $D_{boost}=0.99$ to $S_1$, $(1-D_{boost})=0.01$ to $S_2$

- Right at zero-crossing, if $D_{boost}$ changes abruptly, the $V_{coss\_S3}$ will cause a current spike.
Solution for eliminating current spike

All MOSFETs are turned OFF to ensure a safe permutation of the power switches control and to avoid to short-circuit of the output DC capacitor.

S1 or S2 active switches are controlled with a soft duty cycle.
Experimental results @230 Vac

![Efficiency Curve]

- **Peak efficiency:** 98.55%

- **230 Vac/50 Hz startup**
  - Peak inrush current < 18A
  - Input current is smooth & aligned with Vac
  - Unit operates without protection triggered

- **230 Vac 100% load**
  - PF ≥ 0.99
  - iTHD ≤ 5

- **230 Vac 100% load 50 Hz → 60 Hz**

- **CH1 (yellow): Input voltage**
- **CH2 (blue): DC bus voltage**
- **CH4 (green): Input current**
Bidirectional totem pole PFC solution
6.6 kW bidirectional totem pole PFC solution

**Key features**

- Grid voltage: **180-265 VAC**
- DC bus voltage: **380-580 VDC**
- Switching frequency: **100 kHz**
- Operation mode: **CCM**
- Peak efficiency: **98.5% @230VAC**
- Power factor: **>0.99 @100% load**
- iTHD: **<5% @ 50%-100% load**

**Key components**

- STM32G474VBT (32-bit MCU)
- SCTWA60N120G2-4 (SiC Gen2) → SCT040W120G3-4AG (Gen3)
- STGAP2SICS (gate driver)
- STP75NF20 (N-ch power MOS)
- VIPer 319HD (Aux. SMPS)

**Target application**

- Energy storage system (ESS)
- Power conditioning system (PCS)
PFC digital platform—STM32G474

**Arm® Cortex®-M4 up to 170 MHz**

- Floating-point unit (FPU)
  - Control loop computation (reserved for future use)
- 32-Kbyte CCM-SRAM
  - Zero wait-state for critical code execution
- CORDIC for trigonometric functions acceleration
  - Software phase-locked loop (EPLL)

**Configurations of MCU key functions on digital PFC**

- **Hi-Resolution PWM Timer (184 ps)**
  - Mainly for high frequency (HF) MOSFET control at 67 kHz
- **Multiple ADCs (4 Msps)** up to 5
  - Grid voltage, inductor current, DC bus voltage/current and hotspot
- **Comparators and DACs** up to 7
  - PFC OVP / OCP
- **FMAC filter mathematical accelerator**
  - Hardware digital filter (CPU off-load) for loop computation (reserved)
- **UART, SPI, CAN and USB**
  - CAN for internal/external communication

➢ Control loop computation (reserved for future use)
➢ Zero wait-state for critical code execution
➢ Mainly for high frequency (HF) MOSFET control at 67 kHz
➢ Grid voltage, inductor current, DC bus voltage/current and hotspot
➢ PFC OVP / OCP
➢ CAN for internal/external communication
Dual loops with enhanced phase locked loop

- Voltage loop: performed at 10 kHz
- Current loop: performed at 100 kHz
- EPLL loop: performed at 100 kHz

Control block diagram: rectifier mode (charging)

Current loop
- Inner loop for shaping AC current with $V_{AC}$ and $V_{DC}$ feedforward compensation

Voltage loop
- Outer loop for bulk voltage regulation and with current feedforward compensation

EPLL loop
- Enhanced PLL to synchronize AC phase to achieve blanking time and soft-start scheme
Control block diagram: inverter mode (off-grid)

Dual loops with SW VCO for sine generation

- Voltage loop: performed at 100 kHz
- Current loop: performed at 100 kHz
- SW VCO: performed at 100 kHz

Current loop
- Inner loop for controlling AC current and with $V_{AC}$ feedforward compensation

Voltage loop
- Outer loop for shaping AC voltage and the reference is from SW sine table basically

Theta $\Theta$ generation
- Simple software VCO for AC phase ($\Theta$) generation
Control block diagram: inverter mode (on-grid)

Current loop only for grid-tied feature

✓ Current loop: performed at 100 kHz
✓ EPLL loop: performed at 100 kHz

Current loop
- Inner loop for with $V_{AC}$ feedforward compensation, and AC current reference is from VR (due to no DCDC section)

EPLL loop
- Enhanced PLL to synchronize AC phase to achieve grid connection and phase control
Experimental results

Rectifier mode

Efficiency (220Vac/380Vdc)

- Peak efficiency: 98.48%

Inverter mode (off-gird)

Efficiency (550Vdc/220Vac)

- Peak efficiency: 98.46%

Inverter mode (gird-tied)

Efficiency (550Vdc/220Vac)

- Peak efficiency: 98.45%

- CH1 (yellow): Vds of upper high-speed MOSFET
- CH2 (blue): Vds of upper low-speed MOSFET
- CH3 (purple): Inductor current

230Vac/50Hz, 550 Vdc with 6600 W load

550 Vdc, 220Vac/50Hz with 6600 W load

550 Vdc, 220Vac/50Hz with 6600 W R load

20
ST key product on solution
## SiC MOSFET range

### High voltage and fast switching for high density applications

<table>
<thead>
<tr>
<th>Gen</th>
<th>Optimization</th>
<th>Voltage Range</th>
</tr>
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<tbody>
<tr>
<td>Gen1</td>
<td>Optimized Ron and Tj for motor drive applications</td>
<td>1200–1700 V</td>
</tr>
<tr>
<td>Gen2</td>
<td>Balanced Ron and Qg for a broad range of automotive &amp; industrial applications</td>
<td>650 V, 1200 V, 2200 V</td>
</tr>
<tr>
<td>Gen3</td>
<td>Ultrafast series optimizing Ron and Qg for very high frequency applications</td>
<td>650 V, 750 V, 900 V, 1200 V</td>
</tr>
<tr>
<td>SiC VHV 2200 V*</td>
<td>Very high voltage SiC extend the advantages of SiC technology to higher voltage ranges</td>
<td>2200 V</td>
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* industrial grade
STGAP gate driver
1700V/6kV galvanic isolated single- & dual-channel

**STGAP2SM**
- 3V3 / 5 V logic inputs
- Up to 26 V supply voltage
- 4A sink / source driver current capability
- 100 V / ns CMTI
- Propagation delay 80 ns
- Standby function
- High-voltage rail up to 1700 V
- Temperature shut down protection

**STGAP2SCM**

**STGAP2D** (3 kW PFC)
- High performance
  - Galvanic isolated up to 1700V
- Robustness
  - Interlocking
  - Negative gate drive ability

**STGAP2SICS** (6.6 kW PFC)
- High performance
  - Galvanic isolated up to 6 kV optimized for SiC MOSFET
STM32G474 MCU

Hi-resolution PWM and comprehensive set of analog peripherals for digital control

- 170 MHz 32-bit Arm® Cortex®-M4 core with FPU
- Routine booster of CCM-SRAM up to 32 KB
- Mathematic hardware accelerators (CORDIC / FMAC)
- High-resolution timer (184 ps) for precise PWM control
- Rich advanced analog
- USB Type-C® Power Delivery (PD)
- ±1% internal clock
STM32G4 hardware solutions

Accelerate evaluation, prototyping, and design

STM32 Nucleo
Flexible prototyping
- NUCLEO-G431RB
- NUCLEO-G474RE
- NUCLEO-G431KB

Evaluation boards
Full feature STM32G4 evaluation
- STM32G484E-EVAL
- STM32G474-EVAL

Motor control Pack
Full feature for motor control and analog
- P-NUCLEO-IHM03

Discovery kits
Key feature prototyping
- B-G474E-DPOWER
- B-G431B-ESC1
STM32G4 software tools

Complete support of Arm® Cortex®-M ecosystem

STM32CubeMX
- Configure and generate code
- Conflicts solver

IEDs compile and debug
- Partners IDE, like IAR and Keil
- Free IDE based on Eclipse, like STM32CubeIDE

Flexible solutions

STM32 programming tool
- Flash and/or system memory
- GUI or command-line interface
Digital power workshops with Biricha

Combining industry leading ST MCUs with Biricha’s tools and training

STM32 PSU/PFC design
Step-in Digital Power technology

Biricha digital power:

- World leading expertise and training in digital power
- Workshop based on STM32F334/G474 Nucleo and dedicated digital power expansion board
- Learn how to implement digital power supplies and power factor correction
Takeaways
Digital control with STM32G4 allows unidirectional/bidirectional solutions based on bridgeless totem pole topology

Totem pole PFC offers inherent bidirectional power flow control and can be used for various applications.

ST 3 kW reference design for telecom rectifier application demonstrates a conventional unidirectional solution.

6.6 kW reference design demonstrates bidirectional capability, including rectifier, off-grid, and on-grid.

STM32 ecosystem provides a complete design environment and rewarding development experience.
Our technology starts with You

Find out more at www.st.com