Status of the switched capacitor DC-DC converters for the upgraded LHC trackers

Michał Bochenek
Outline

- (Very) short overview of SC DC-DC converters
- DCDC013 test setup
- Results from the measurements:
  - time response of the converters
  - frequency, transfer and output characteristics
- Future plans
- Conclusions
Switched capacitor DC-DC converters in powering schemes for the silicon tracker upgrade

Initial schemes from the start of the project.

DC-DC conversion technique

Serial powering scheme
SC DC-DC converters: an overview

Step-up converter

Efficiency (SPICE) = 96%
Efficiency (measurement) = 91%

Design parameters:
- $C_L = 200 \text{ nF}$
- $C_X = 1 \text{ \mu F}$
- $f_S = 1 \text{ MHz}$

Project assumptions:
- $V_{IN} = 1.9 \text{ V}$
- $V_{OUT} = 0.9 \text{ V}$
- $I_{OUT} \approx 60 \text{ mA}$

Step-down converter

Efficiency (SPICE) = 96%
Efficiency (measurement) = 91%

Design parameters:
- $C_P1/P2 = 470 \text{ nF}$
- $C_L = 470 \text{ nF}$
- $f_S = 500 \text{ kHz}$

Project assumptions:
- $V_{IN} = 0.9 \text{ V}$
- $V_{OUT} = 1.55 \text{ V}$
- $I_{OUT} \approx 30 \text{ mA}$

Efficiency (SPICE) = 85%
Efficiency (measurement) = 84%
Long way to obtain the results from the converters

May 2010 (Submission)

February 2011 (ASICs at CERN)

Conclusions, improvements and new ideas

TWEPP 2010

TWEPP 2011

April 2011 (tests)
Setup

Schematic diagram of the setup used in DCDC013 measurements

POWER SUPPLY
Agilent E3631A

CLOCK GENERATOR
HP 8110A

DUT

3.3V
0.9V / 1.8V

CURRENT PROBE
Tecktronix TCPA300

OSCILLOSCOPE
Agilent Infinium 54631B

Irradiation cabinet containing the X-ray system

PCB for DCDCo13 tests (top)

PCB for DCDCo13 tests (bottom)
Step-up converter: time response

simulation (no parasitics)

- $f_s = 500$ kHz
- $I_{OUT} \approx 30$ mA
- $V_{OUT} = 1.53$ V
- $\eta = 84\%$

$V_{pp} \approx 600$ mV (for $L \approx 3/8$ nH)

simulation (with parasitics)

$V_{pp} \approx 1$ V (for $L = 1$ nH)

measurement

$V_{pp} \approx 5$ mV
Step-up converter: frequency characteristics

Simulation

\[ V_{IN} = 0.9 \, V \]
\[ R_L = 56 \, \Omega \]
\[ f_S : 50 \, kHz \rightarrow 10 \, MHz \]

No need for a precise clock

\[ \text{V}_{\text{OUT} \, (\text{MAX})} = 1.53 \, V \]
\[ I_{\text{OUT}} \approx 30 \, mA \]
\[ \eta_{\text{OUT}} \approx 84\% \]

\[ @f_S = 500 \, kHz \]

Measurement
Step-up converter: transfer characteristics

- **Simulation**
  - $V_{IN} = 0.7 \text{ V} \rightarrow 1.4 \text{ V}$
  - $V_{OUT} = 1.1 \text{ V} \rightarrow 2.5 \text{ V}$
  - $R_L = 56 \Omega$
  - $f_s = 500 \text{ kHz}$

Rapid increase of a driving capability

- **Measurement**
Step-up converter: output characteristics

V_{IN} = 0.9 V
f_s = 500 kHz
I_{OUT} : 17 mA → 55 mA
R_{OUT(SIM)} = 8 \, \Omega
R_{OUT(MEAS)} = 10 \, \Omega

V_{OUT(SIM)} = 1.7 \, V
P_{EFF(SIM)} = 85\%
R_{OUT(SIM)} = 8 \, \Omega
V_{OUT(MEAS)} = 1.7 \, V
P_{EFF(MEAS)} = 85\%
R_{OUT(MEAS)} = 10 \, \Omega

nominal load
Step-up converter: irradiation tests

Irradiation:
- X-ray photons
- up to 200 Mrad

Annealing:
- at 100°C
- for one week

The increase of the output impedance is visible.
Step-down converter: time response

- Simulation (no parasitics)
  - $f_s = 1 \text{ MHz}$,
  - $I_{\text{OUT}} \approx 60 \text{ mA}$,
  - $V_{\text{OUT}} \approx 0.88 \text{ V}$,
  - $\eta \approx 91 \%$.

- Simulation (with parasitics)
  - $V_{\text{PP}} \approx 300 \text{ mV}$ (for $L = 1 \text{nH}$)

- Measurement
  - $V_{\text{PP}} = 210 \text{ mV}$ (for $L \approx 3/8 \text{nH}$)

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Step-down converter: frequency characteristics

Simulation

<table>
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<tr>
<th>Frequency (MHz)</th>
<th>Voltage (mV)</th>
<th>Power Efficiency (%)</th>
<th>Peak-to-Peak Voltage (mV)</th>
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<tr>
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</table>

Measurement

- \( V_{\text{IN}} = 1.9 \text{ V} \)
- \( R_L = 15 \text{ \Omega} \)
- \( f_S : 100 \text{ kHz} \rightarrow 10 \text{ MHz} \)
- Optimal \( f_S \) slightly lower

@\( f_S = 1 \text{ MHz} \)
- \( V_{\text{OUT(MAX)}} = 0.88 \text{ V} \)
- \( I_{\text{OUT}} \approx 60 \text{ mA} \)
- \( \eta_{\text{OUT}} \approx 91\% \)

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Step-down converter: transfer characteristics

\[ V_{\text{IN}} = 1.0 \, \text{V} \rightarrow 2.6 \, \text{V} \]
\[ V_{\text{OUT}} = 0.43 \, \text{V} \rightarrow 1.21 \, \text{V} \]
\[ R_L = 15 \, \Omega \]
\[ f_S = 1 \, \text{MHz} \]

simulation

measurement
Step-down converter: output characteristics

\[ V_{\text{IN}} = 1.9 \, \text{V} \]
\[ f_s = 1 \, \text{MHz} \]
\[ I_{\text{OUT}} : 45 \, \text{mA} \rightarrow 115 \, \text{mA} \]
\[ R_{\text{OUT(SIM)}} = 0.4 \, \Omega \]
\[ R_{\text{OUT(MEAS)}} = 1.2 \, \Omega \]
Step-down converter: irradiation tests

Relative voltage drop after irradiation is less than 1.5%.

Observed small increase of the output impedance.

Irradiation:
- X-ray photons
- up to 200 Mrad

Annealing:
- at 100°C
- for one week
Future plans

The 2x2 mm² “VREG013” includes 2 Low Drop-Out (LDO) regulators with p-channel and n-channel pass device

Submitted in February 2011
Delivered to CERN in June 2011

Plans for combined tests of the front-end electronics with SC DC-DC converters and linear regulators.

Three chips on the PCB:
• SCT front-end (SCT32T130)
• SC DC-DC converters (DCDC013)
• Linear regulators (VREG013)
Conclusions

The voltage spikes observed at the output of the converters can be significantly reduced by:

- Chip bump bonded to the hybrid,
- Capacitors bump bonded directly to the DC-DC chip.

A new design of fully integrated switched capacitor DC-DC multiphase converters seems to be promising.

In order to avoid the efficiency drop after the irradiation, the use of Enclosed Layout Transistors (ELTs) in the final design should be considered.

SC DC-DC converters exist and operate with high power efficiency, up to 84% for the step-up converter and around up to 91% for the step-down converter.