Solid State Modulators
– Efficiency Considerations focusing on SiC Devices –

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Typical Topology of Solid State Pulse Modulator Systems

- AC/DC rectifier unit
- DC/DC converter for charging C-bank / voltage adaption
- Pulse generation unit
- Load e.g. klystron
- Grounded klystron load
  - Isolation with 50Hz transformer or
  - Isolated DC-DC converter

Typical Topology of Solid State Pulse Modulator Systems

- AC Energy Storage
- Pulse Modulator
- Medium Voltage Grid
- DC

400V or MV

Intermediate Buffer

Capacitor Bank

Pulse Voltage

Klystron Load
29 MW\(\text{(35 MW)}\)/140 μs Modulator for CLIC

– System Efficiency –
CLIC System Specifications

- Output voltage: 150...180 kV
- Output power (pulsed): 29 MW (-35 MW)
- Flat-top length: 140 µs
- Flat-top stability (FTS): <0.85 %
- Rise time: <3 µs
- Settling time: <8 µs
- Repetition rate: 50 Hz
- Average output power: 203 kW (-245 kW)
- Pulse to pulse repeatab.: <100 ppm
CLIC Modulator – Grid/Isolation Transformer

- Voltage
- Core material
- Winding material
- Weight
- Efficiency

Higher efficiency
- Better core material
- Copper winding
- Efficiency

3 × 400 V to 3 × 400 V @ 250 kVA
Silicon steel
Aluminium
890 kg
98.8 %
($P_{\text{Core}} = 700$ W & $P_{\text{Wdg}} = 2.3$ kW)

E.g. Amorphous ($P_{\text{Core}} - 60\%$)
Higher conductivity ($P_{\text{Wdg}} - 35\%$)
$\Rightarrow \approx 99.2\%$ (Estimated)
(Larger volume $\Rightarrow$ Higher efficiency)
CLIC Modulator – AC/DC Converter Efficiency

- Type (B&R)
- Topology
- Switches
- Voltage conversion
- Efficiency

- Higher efficiency
  - 1.2 kV SiC MOSFETs
  - Optimised design
  - Efficiency

ACOPOSmulti 8BVP1650
2-level PFC-rectifier
1.2 kV Si IGBTs
400 V\(_{AC}\) → 750 V\(_{DC}\) (620 V – 800 V)
97.47 %

Lower \(P_{\text{Cond}}\) & \(P_{\text{SW}}\)
E.g. higher volume / lower \(f_{\text{SW}}\)
\(\approx 99\)

Grid
Isolation Transformer
PFC Rectifier
AC
DC

Boost Converter
Bouncer (Drop Compensation)
Switching Unit
Pulse Transformer
CLIC Modulator – Boost Converter Basic Operation

- Input voltage: 600 V – 800 V
- Output voltage: 3 kV
- Switching frequency: 70 kHz – 240 kHz
- Output power: 40 kW
- 650 V Si MOSFETs: 8 in series
  ⇒ $C_s/R$ for balancing
- Boundary cond. mode
- 6-fold interleaving: $6 \times 40\ kW$

![Diagram of CLIC Modulator and Boost Converter](image-url)

- Grid
- Isolation Transformer
- AC
- PFC Rectifier
- DC
- Boost Converter
- Bouncer (Droop Compensation)
- DC
- Switching Unit
- Pulse Transformer
- DC
- DC
- DC

**Input Voltage:** 600 V – 800 V

**Output Voltage:** 3 kV

**Switching Frequency:** 70 kHz – 240 kHz

**Output Power:** 40 kW

**650 V Si MOSFETs:** 8 in series
  ⇒ $C_s/R$ for balancing

**Boundary Condition Mode**

**6-fold Interleaving**
  ⇒ $6 \times 40\ kW$
CLIC Modulator – Boost Converter Efficiency

- Nom. voltages: 750 V → 3 kV
- Output power: 40 kW
- Switching frequency: 70 kHz – 240 kHz
- 8×650 V Si MOSFETs: 2× Infineon IPZ65R019C7
- 4×1.2 kV diodes: Microsemi APT75DQ120B
- Efficiency: 97.2%

Fans
Inductor
Output capacitors

MOSFET
Conduction 58%
MOSFET Switching 6%
Diode
Conduction 20%
Diode Switching 3%
Boost Inductor 11%
Snubber Capacitor 2%

Nom. voltages 750 V → 3 kV
Output power 40 kW
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Efficiency 97.2%

Si

Boost Inductor 11%
Diode Conduction 20%
MOSFET Conduction 58%
MOSFET Switching 6%
Snubber Capacitor 2%

Fan
Inductor
Output capacitors

Input capacitors
PCB with isolated gate drives

Power input
Input fuse
HV output

MOSFET
Conduction 58%
MOSFET Switching 6%
Diode
Conduction 20%
Diode Switching 3%
Boost Inductor 11%
Snubber Capacitor 2%
CLIC Modulator – "SiC" Boost Converter

- **Voltages**
  - 750 V → 3 kV

- **Switching frequency**
  - 70 kHz – 240 kHz

- **Higher efficiency**
  - 4×1.2 kV SiC MOSFETs
  - 4×1.2 kV SiC Diodes
  - Efficiency
    - Si-based Converter
    - SiC-based Converter

- **MOSFET**
  - Conduction: 46%
  - Switching: 3%

- **Diode**
  - Conduction: 22%

- **Boost Inductor**
  - 25%

- **Snubber**
  - Capacitor: 4%

- **Efficiency**
  - ≈ 98.6% (Old: 97.2%)

- **Switching frequency**
  - 70 kHz – 240 kHz

- **Efficiency**
  - ≈ 98.6% (Old: 97.2%)

- **MOSFET**
  - Conduction: 46%

- **Diode Conduction**
  - 22%

- **MOSFET Switching**
  - 3%

- **Boost Inductor**
  - 25%

- **Snubber**
  - Capacitor: 4%
CLIC Modulator – Switching Unit

- ABB StakPak (5SNA1250B450300)
- Active reset switch
- 4 units in parallel
- Pulse current
- Efficiency

- Higher efficiency
  - Semiconductors
  - Efficiency

4.5 kV / max. 3 kA (pulsed)

4 × 2.4 kA (@ $P_P = 29$ MW)

98.6% (Switching losses: 87% of $P_{tot}$)

SiC MOSFETs
(assumption: 1.2 kV devices)
(4 in series / 3 parallel)

⇒ 99.5%
CLIC Modulator – Bouncer

- Output voltage: 0...300 V (10 % droop)
- Input voltage: 450 V
- 24-fold interleaving
- Ultra low ripple
- Semiconductors: IGBTs

![Diagram of CLIC Modulator – Bouncer](image)

- Grid
- Isolation Transformer
- AC
- DC
- PFC Rectifier
- Boost Converter
- DC
- Bouncer (Droop Compensation)
- DC
- Switching Unit
- Pulse Transformer

- Output voltage: 0...300 V (10 % droop)
- Input voltage: 450 V
- 24-fold interleaving
- Ultra low ripple
- Semiconductors: IGBTs
CLIC Modulator – Bouncer Operating Principle

- Output voltage: 0...300 V
- Input voltage: 450 V
- Output current (pulse): >600 A

![Diagram of Bouncer Module](image)

**Diagram Explanation**

- **Active Bouncer Module**
- **Wait for trigger**
- **Pulse Resonant**
- **Interpulse Recharging**
- **Wait for next pulse**
- **Pre-charge**

**Graph**

- **$V_{Bout}$** shortened
- **$V_{main}$**
- **$V_{Bin}$**

- **$i_b$**

**Timeline**

- Pre-charge
- Pulse
- Resonant
- Interpulse Recharging
- Wait for next pulse
- Pre-charge
CLIC Modulator – Bouncer Components

- Output voltage
  - 0...300 V
- Input voltage
  - 450 V
- 4×6-fold interleaving
- Switching frequency
  - 100 kHz
- Per module:
  - \( S_{LS} \)-IGBTs
    - 2×IGW50N65H5
  - \( D_{LS} \)-Diodes
    - 4×IDW40E65D1
  - \( S_{HS} \)-IGBTs (w. diode)
    - 6×IKW50N65F5
  - \( S_{SC} \)-IGBTs (w. diode)
    - 6×IKW50N65F5
  - Inductor \( L_b \) = 26 \( \mu \)H
    - 4×Metglas AMCC32

Active Bouncer Module

Control board

Buck-boost switch

Short circuit switch
With IGBTs

- Total AVG losses: 1.56 kW
- Module efficiency
  - Efficiency: 91.0% Bouncer-Level
  - Efficiency: 99.4% System-Level

Active Bouncer Module

- Inductor losses: 18%
- HS IGBTs conduct: 7%
- HS IGBTs switching: 51%
- LS diodes: 14%
- LS IGBTs: 4%
- SC IGBTs: 3%
- HS diodes: 3%
- Inductor losses: 18%

Si
CLIC Modulator – SiC Bouncer Efficiency

- With IGBTs
  - Total AVG losses: 1.56 kW
  - Module efficiency: 91.0% Bouncer-Level
  - Efficiency: 99.4% System-Level

- With SiC MOSFETs
  - Total AVG losses: 0.79 kW
  - Module efficiency: 95.2% Bouncer-Level
  - Efficiency: 99.7% System-Level

With IGBTs

- Total AVG losses
- Module efficiency
  - Efficiency

With SiC MOSFETs

- Total AVG losses
- Module efficiency
  - Efficiency

![Active Bouncer Module Diagram]

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SiC

- Inductor losses: 35%
- HS diodes: 5%
- SC SW: 4%
- LS SW: 9%
- LS diodes: 27%
- HS SW conduction: 12%
- HS SW switching: 8%

SiC-based converter

- AVG losses: 0.79 kW
- Module efficiency: 95.2%
- Efficiency: 99.7%

Si-based converter

- AVG losses: 1.56 kW
- Module efficiency: 91.0%
- Efficiency: 99.4%

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With SiC MOSFETs

- Total AVG losses
- Module efficiency
  - Efficiency

W

800W
600W
400W
200W

W

Si-based converter
SiC-based converter

HS switch conduction
HS switch switching
LS diodes
LS switch
SC switch
CLIC Modulator – Pulse Transformer

- Matrix transformer
- Turns ratio
- Core material

2 cores / 4 primary windings
62 ➞ 4: (2 × 124)
SiFe / 50 µm

Grid
Isolation Transformer
PFC Rectifier
Boost Converter
Bouncer (Droop Compensation)
Switching Unit
Pulse Transformer

Matrix transformer 2 cores / 4 primary windings
Turns ratio 62 ➞ 4: (2 × 124)
Core material SiFe / 50 µm
CLIC Modulator – Pulse Shape/Transformer Efficiency

- Rise + settling time: 4.6 µs
- Fall time: <3 µs
- Flat top: 140 µs
- Efficiency: 96.7%

(Transformer + Pulse shape)
CLIC Modulator – Higher Transformer Efficiency

- Core material
  - SiFe 25 µm lamination
  - Amorphous material

- Insulating oil
  - Ester 7131 $\varepsilon_r = 3.2$ ➔ Mineral oil $\varepsilon_r = 2.2$

- Shorter load cable
- Transformer design
  - Critical damping (slightly underdamped)
  - Larger volume / Core splitting

- Estimated efficiency
  $\approx \geq 97.5\%$
CLIC Modulator – System Efficiency

Original System

- Pulse Shape/Transformer 28%
- Grid Transformer 10%
- Bouncer 5%
- Switching Unit 12%
- Booster 24%
- PFC 21%
- 24.8 kW

Improved System

- Pulse Shape/Transformer 39%
- Grid Transformer 12%
- Bouncer 5%
- Switching Unit 8%
- Booster 21%
- PFC 15%
- 13.4 kW

Conventional SiC-based

- Grid Isolation Transformer
- PFC Rectifier
- Boost Converter
- Bouncer (Droop Compensation)
- Switching Unit
- Pulse Transformer

98.8% 99.2% 99.0% 99.4% 99.6% 96.7% 98.6% 97.5% 93.6%
SwissFEL Modulator – Pulse Efficiency @ Short Pulses

- Free electron laser ➔ X-Rays
- Electron beam energy 5.8 GeV
- Wavelength range 1 Å – 70 Å
- Output voltage 370 kV
- Output power (pulsed) 127 MW
- Flat-top length 3 µs
- Rise time <1 µs
- Repetition rate 100 Hz
SwissFEL – Pulse Transformer

- Matrix transformer: 6 cores / 12 primary
- Turns ratio: $1:21 \times 6 \Rightarrow 1:126$
- Core material: SiFe / 50 µm
- Rise time: $\approx 1 \mu s$
- Fall time: $\approx 0.9 \mu s$

- Pulse shape: $\approx <82\%$

![Graph of voltage vs. time](image)
Solid State Modulators

2.88 MW / 3.5 ms Modulator for European Spallation Source (ESS)
ESS Modulator Specifications

- Pulse power: 2.88 MW
- Pulse voltage: 115 kV
- Pulse width: 3.5 ms
- Rise/fall time: ≤ 150 µs
- Repetition rate: 14 Hz

Diagram:

- Electrical Network
  - Klystron modulator (Power Supply)
  - RF powering cell #1
    - Electrical pulsed power
    - Klystron A
      - RF power
      - SC cavity #A
    - Klystron B
      - RF power
      - SC cavity #B
  - RF powering cell #N

Similar to RF powering cell #1
ESS Modulator – Basic Configuration

- Pulse power: 2.88 MW
- Pulse voltage: 115 kV
- Pulse width: 3.5 ms
- Rise/fall time: \( \leq 150 \mu s \)
- Repetition rate: 14 Hz
ESS Modulator – Basic Configuration

- Pulse power: 2.88 MW
- Pulse voltage: 115 kV
- Pulse width: 3.5 ms
- Rise/fall time: \( \leq 150 \mu s \)
- Repetition rate: 14 Hz
- Switching frequency: 105 kHz
- Modules: 2 parallel / 9 in series
ESS Modulator – Series-Parallel Resonant Converter Module

- **H-bridge**
- **Module loss distribution:**
  - H-bridge: 650 V MOSFETs (STY139N65M5)
  - H-bridge: 221 W (179 W $P_{Cond}$)
  - Rectifier diode: 78 W (APT60DQ120SG)
  - Series inductor: 132 W (Air core with litz)
  - Series capacitor: 56 W (NP0 / 896 pieces)
  - Parallel capacitor: 18 W (NP0 / 864 pieces)
  - $\sum$ 505 W (per module)

H-bridge: 6 x 650V MOSFETs in parallel

Diodes

$C_s$ 

$L_s$ 

$C_P$ 

SPRC-Bm1

Diodes

$C_P$
ESS Modulator – Step-up Transformer/Pulse Shape

- Transformer
- Losses (per module)
  - Core
  - Primary winding
  - Secondary winding
- Rise time
- Fall time
- Pulse shape (total)

2:40 / Midel 7131

- Transformer
  - 2:40 / Midel 7131
  - 73.4 W (2×4× UU126/20 / N87 ferrite)
  - 12.9 W (405 × 0.071mm / 18 parallel)
  - 11.1 W (1125 × 0.071mm)

- Rise time
  - 107.8 µs (0→99%)

- Fall time
  - 83.5 µs (100→10%)

- Pulse shape (total)
  - 97.8 %

![Diagram of transformer with labels for primary and secondary windings, core, and pulse shapes.](image)
ESS Modulator – Module Loss Distribution

- Resonant converter 92.9%
  (incl. transformer)
  (without pulse shape)
ESS Modulator – Converter with SiC

- **Improved efficiency**
  - 1.2 kV SiC MOSFETs: No balancing / Lower conduction losses
  - 1.7 kV SiC Diode: Lower losses in rectifier
  - $L_s \Rightarrow 2 \times L_s@\frac{1}{2}I$: 2 x volume / $\frac{1}{2}$ losses
  - New core material: N97 instead of N87
  - New efficiency: $\approx 94.4\%$ (+1.5% / Old: 92.9%)

- **Further improvements**
  - More parallel devices
  - Higher $f_{SW}$ → Shorter $t_r/t_f$
  - Higher overrating → Shorter $t_r/t_f$
  - New system optimisation

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**Graph showing efficiency comparison**

- Si-based Converter
- SiC-based Converter

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**Diagram showing circuit configurations**

- SPRC IPOS modulator system
- 2 x SPRC-Bm2 IPOP
- 800 V

ESS Modulator – System Efficiency & Loss Distribution

- Resonant converter 92.9%  
  Si-based 92.9%  
  SiC-based 94.4%

- PFC charging 97.5%  
  Si-based 97.5%  
  SiC-based 99.0%

  ⇒ Electrical system 90.5%  
  Si-based 90.5%  
  SiC-based 93.5%

- Pulse shape 97.8%  
  Si-based 97.8%  
  SiC-based 97.8%

  ⇒ Total efficiency 88.5%  
  Si-based 88.5%  
  SiC-based 91.4%

Si:
- Pulse Shape 17.8%
- Rectifier 9.9%
- Transformer 10.0%
- Resonant Tank 19.3%
- H-bridge 22.7%
- PFC Charging 20.3%

SiC:
- Pulse Shape 25.4%
- Rectifier 14.0%
- Transformer 12.1%
- Resonant Tank 17.8%
- H-bridge 19.2%
- PFC Charging 11.4%
**Conclusion**

- **Efficiency gain** (Assuming "drop-in" replacement)
  - CLIC Modulator: $\Delta \eta = +\approx 4.9\% \Rightarrow \eta_{SiC} = 93.6\%$
  - ESS Modulator: $\Delta \eta = +\approx 2.9\% \Rightarrow \eta_{SiC} = 91.4\%$

- **Higher Efficiency**
  - Switches/diode: Wide band gap devices (parallel SiC MOSFETs...)
  - Core material: SiFE 25 µm lamination or Amorphous
    - Use of uncut cores
  - Insulating oil: Ester 7131 $\varepsilon_r = 3.2 \Rightarrow$ Mineral oil $\varepsilon_r = 2.2$
  - Transformer design: Critical damping (slightly underdamped)
    - Larger volume / Core splitting
  - Short load cable
  - Fix operating point

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$\eta$ vs. Power Density

- Efficiency Limit
- Power Density Limit

$\eta-\rho$-Pareto-Front