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
Typical Topology of Solid State Pulse Modulator Systems

- **Grounded klystron load**
  - Isolation with 50Hz transformer or
  - Isolated DC-DC converter
29 MW\textsuperscript{(35MW)} / 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 Solid State Modulator – System Overview
CLIC Modulator – Grid/Isolation Transformer

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

- Higher efficiency
  - Better core material
  - Copper winding
  - Efficiency

## Voltage

3×400 V to 3×400 V @ 250 kVA

Silicon steel

Aluminium

890 kg

98.8%

\( P_{Core} = 700 \text{W} \) & \( P_{Wdg} = 2.3 \text{kW} \)

## Core material

- Silicon steel

## Winding material

- Aluminium

## Weight

890 kg

## Efficiency

98.8%

\( P_{Core} = 700 \text{W} \) & \( P_{Wdg} = 2.3 \text{kW} \)

## Higher efficiency

- Better core material
- Copper winding
- Efficiency

E.g. Amorphous \( P_{Core} = 60\% \)

Higher conductivity \( P_{Wdg} = 35\% \)

\( \Rightarrow \approx 99.2\% \) (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 $P_{Cond}$ & $P_{SW}$
E.g. higher volume / lower $f_{SW}$$\Rightarrow \approx$ 99%

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Grid

Isolation Transformer

PFC Rectifier

AC

DC

Boost Converter

DC

Bouncer
(Drop Compensation)

Switching Unit

Pulse Transformer

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ETH Zürich High Power Electronic Systems
- 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
  \(\Rightarrow C_s/R\) for balancing
- Boundary cond. mode
- 6-fold interleaving: \(6 \times 40\) kW

**Diagram:**

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

**Equations:**

\[ V_{DC} = V_{Cd,tot} + V_{Cs,tot} \]

**Graph:**

- Time intervals: \(T_1, T_2, T_3, T_4, T_5\)
- Currents: \(I_{L_{max}}, I_{L_{min}}\)
- Voltages: \(V_{Cd,tot}, V_{Cs,tot}\)
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%

![Diagram of CLIC Modulator](image)

- Fans
- Inductor
- Output capacitors
- Input capacitors
- PCB with isolated gate drives
- HV output
- Power input
- Input fuse

- Fans Inductor
- PCB with isolated gate drives
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- Input capacitors
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- Snubber Capacitor 2%
- Boost Inductor 11%
- Diode Conduction 20%
- Diode Switching 3%
- MOSFET Switching 6%
- MOSFET Conduction 58%

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- MOSFET Conduction 58%
CLIC Modulator – "SiC" Boost Converter

- **Voltages**
- **Switching frequency**
- **Higher efficiency**
  - 4×1.2 kV SiC MOSFETs
  - 4×1.2 kV SiC Diodes
  - Efficiency

\[ 750 \text{ V} \rightarrow 3 \text{ kV} \]
\[ 70 \text{ kHz} \rightarrow 240 \text{ kHz} \]

2×C3M0016120K
2×IDW40G120C5B
≈ 98.6 % (Old: 97.2 %)

- MOSFET Conduction 46%
- MOSFET Switching 3%
- Diode Conduction 22%
- Boost Inductor 25%
- Snubber Capacitor 4%
- Efficiency ≈ 98.6 % (Old: 97.2 %)

**Graph:**
- W (Watts)
- MOSFET Conduction
- MOSFET Switching
- Diode Conduction
- Diode Switching

**Diagrams:**
- Electrical circuit diagram
- Efficiency breakdown diagram

**Notes:**
- 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

\[ 2 \times \text{C3M0016120K} \]
\[ 2 \times \text{IDW40G120C5B} \]
≈ 98.6 % (Old: 97.2 %)

**Diagram Depictions:**
- MOSFET Conduction 46%
- MOSFET Switching 3%
- Diode Conduction 22%
- 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 \times 2.4 \text{kA} \quad (@ P_p = 29 \text{ MW})

98.6\% \quad (\text{Switching losses: 87\% of } P_{\text{tot}})

SiC MOSFETs
- (assumption: 1.2 kV devices)
- (4 in series / 3 parallel)
- \rightarrow 99.5\%

\begin{itemize}
  \item Grid
  \item Isolation Transformer
  \item AC
  \item PFC Rectifier
  \item DC
  \item Boost Converter
  \item DC
  \item Bouncer (Droop Compensation)
  \item DC
  \item Switching Unit
  \item Pulse Transformer
\end{itemize}
CLIC Modulator – Bouncer

- Output voltage: $0 \ldots 300 \text{ V (10\% droop)}$
- Input voltage: $450 \text{ V}$
- 24-fold interleaving
- Ultra low ripple
- Semiconductors: IGBTs

Diagram:

- $V_{\text{b,out}}$ vs. $V_{\text{main}}$
- $V_{\text{main}} = 300 \text{ V}$
- $V_{\text{total}} = 3kV$
- Active Bouncer Module

System components:

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

Description:

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

Visual elements:

- Graphs showing voltage relationships
- Circuit diagrams
- Circuit symbols

Additional notes:

- 24-fold interleaving
- Ultra low ripple
- IGBTs as semiconductors
CLIC Modulator – Bouncer Operating Principle

- **Output voltage**: 0…300 V
- **Input voltage**: 450 V
- **Output current (pulse)**: >600 A (per module)

![Active Bouncer Module](chart)

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

**Vout** shortened

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

![Graph](chart)
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
With IGBTs

- Total AVG losses
- Module efficiency
  - Efficiency

- HS IGBTs
  - Conduct: 7%
  - Switching: 51%
- LS diodes
  - 14%
- LS IGBTs
  - 4%
- SC IGBTs
  - 3%
- HS diodes
  - 3%

Inductor losses: 18%

Active Bouncer Module

$\text{Si}$

With IGBTs

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

$\text{Si}$

$625\text{A}$

$\text{i}_b$

$\text{t}_k$

$\text{HS IGBTs conduct.} \quad 7\%$

$\text{Inductor losses} \quad 18\%$

$\text{HS IGBTs switching} \quad 51\%$

$\text{HS diodes} \quad 3\%$

$\text{SC IGBTs} \quad 3\%$

$\text{LS IGBTs} \quad 4\%$

$\text{LS diodes} \quad 14\%$
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

![Active Bouncer Module Diagram]

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

- SiC-based converter:
  - HS switch conduction: 12%
  - LS diodes: 27%
  - SC SW: 4%
  - LS SW: 9%
  - HS SW switching: 8%
CLIC Modulator – Pulse Transformer

- Matrix transformer
- Turns ratio
- Core material

- 2 cores / 4 primary windings
- 62 ⇒ 4:(2×124)
- 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%
  (Trafo + Pulse shape)

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- "Dissipated" pulse "energy"
- Flat top (Used pulse "energy")
- Allowed droop
- Time to flat top
- Fall time: <3 µs
- Flat top: 140 µs
- Efficiency: 96.7%
  (Trafo + Pulse shape)

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- Winding Losses: 4%
- Core Losses: 8%
- Pulse Shape: 88%
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%

Improved System

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

Comparison:

- Original: 98.8% 97.5% 97.2% 99.4% 98.6% 96.7%
- Improved: 99.2% 99.0% 98.6% 99.7% 99.5% 97.5%

Conventional SiC-based

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

Efficiency:

- 98.8% 97.5% 97.2% 99.4% 98.6% 96.7%
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: $\approx 0.9 \mu s$

$\Rightarrow$ Pulse shape $\approx <82 \%$
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: \( \leq 150\, \mu s \)
- Repetition rate: 14 Hz

Electrical Network:
- Similar to RF powering cell #1

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

RF powering cell #N
- Klystron B
- RF power
- SC cavity #B

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: ≤ 150 µs
- 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: ≤ 150 µs
- 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: 6 x 650V MOSFETs (STY139N65M5)
  - Rectifier diode: 221 W (179 W $P_{Cond}$)
  - Series inductor: 78 W (APT60DQ120SG)
  - Series capacitor: 132 W (Air core with litz)
  - Series capacitor: 56 W (NP0 / 896 pieces)
  - Parallel capacitor: 18 W (NP0 / 864 pieces)
- $\Sigma$ 505 W (per module)
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**

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

- 107.8 µs (0→99%)
- 83.5 µs (100→10%)
- 97.8 %
- 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
  - $L_s \Rightarrow 2 \times L_s @ \frac{1}{2} I$: $2 \times$ volume / $\frac{1}{3}$ losses
  - New core material: N97 instead of N87
  - **New efficiency** $\approx 94.4\%$ (+1.5% / Old: 92.9%)

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

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**Graph:**
- Si-based Converter
- SiC-based Converter

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**Diagram:**
- SPRC IPOS modulator system
- 800 V 2 x SPRC-Bm2 IPOP
- 800 V 2 x SPRC-Bm8 IPOP
- 800 V 2 x SPRC-Bm1 IPOP
- 800 V 2 x SPRC-Bm8 IPOP
- 800 V 2 x SPRC-Bm2 IPOP
- 800 V 2 x SPRC-Bm1 IPOP
- 800 V 2 x SPRC-Bm8 IPOP
- 800 V 2 x SPRC-Bm2 IPOP
- 800 V 2 x SPRC-Bm1 IPOP
- 800 V 2 x SPRC-Bm8 IPOP
- 800 V 2 x SPRC-Bm2 IPOP
- 800 V 2 x SPRC-Bm1 IPOP
- 800 V 2 x SPRC-Bm8 IPOP
- 800 V 2 x SPRC-Bm2 IPOP
ESS Modulator – System Efficiency & Loss Distribution

- Resonant converter: Si-based 92.9% vs. SiC-based 94.4%
- PFC charging: Si-based 97.5% vs. SiC-based 99.0%
  - Electrical system: Si-based 90.5% vs. SiC-based 93.5%
- Pulse shape: Si-based 97.8% vs. SiC-based 97.8%
  - Total efficiency: Si-based 88.5% vs. SiC-based 91.4%

**Si-based and SiC-based Efficiency Comparison:**

- **Si:**
  - Pulse Shape: 17.8%
  - PFC Charging: 20.3%
  - Transformer: 10.0%
  - Resonant Tank: 19.3%
- **SiC:**
  - Pulse Shape: 25.4%
  - H-bridge: 19.2%
  - Rectifier: 14.0%
  - Transformer: 17.8%
  - Resonant Tank: 12.1%
  - Total efficiency: 88.5% vs. 91.4%
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
  - Core material
  - Insulating oil
  - Transformer design
  - Short load cable
  - Fix operating point

Wide band gap devices (parallel SiC MOSFETs...)
SiFE 25 µm lamination or Amorphous
Use of uncut cores
Ester 7131 \( \varepsilon_r = 3.2 \Rightarrow \) Mineral oil \( \varepsilon_r = 2.2 \)
Critical damping (slightly underdamped)
Larger volume / Core splitting

![Diagram showing efficiency and power density](image-url)