Silicon Carbide GTO Thyristor
Loss Model for
HVDC Application
Why SiC?

• Low resistance – reduced drift region widths due to high band gap ⇒ hence less on state resistance

• High switching frequency – the high velocity saturation and thinner drift region ⇒ the device switches faster.

• Smaller heat sinks – thermal conductivity of silicon carbide is three times greater than silicon and hence better heat dissipation. This results in reduced thermal management system.

• High radiation tolerance and minimal shielding – the electrical characteristics of silicon carbide device do not vary with temperature.
Why SiC?

• Higher breakdown voltages- due to the high electric breakdown field (five times that of silicon), silicon carbide can block higher voltages.

• Higher junction operating temperature range

• Silicon carbide bipolar devices have excellent reverse recovery characteristics. With the less recovery current, switching losses and EMI are reduced and hence less need for snubbers.

• High temp operation capability and lower switching losses ⇒ high frequency operation (more than 20 kHz at > 1 MW) ⇒ less filtering; smaller passive components; saves space
How far is SiC from commercialization?

- Material availability and quality issues
  - micropipes
- SiC technology
  - polytype crystal growth (6H, 4H-SiC)
  - SiC-SiO₂ interface
  - ion implantation
- Cost of the material.
- Also, the increase in rating of auxiliary components and effective packaging techniques are important
Outline

SiC MATERIAL

SiC GTO Thyristor

HVDC System

Results

Conclusion
Gate Turn Off Thyristor (GTO)

- Three-terminal, four-layer structured device

- Turn off capability feature

- No commutation circuit - unlike conventional thyristors

- Most suitable for high-current, high-speed switching applications, and DC switching applications
GTO Turn On

Static Characteristics

\[ I_K = \alpha_{pnp} I_A + \alpha_{npn} I_K + I_L \]

\[ I_A = I_G + I_K \]

\[ I_K = \frac{\left( \alpha_{pnp} I_G + I_L \right)}{1 - \alpha_{pnp} - \alpha_{npn}} \]

\( \alpha_{pnp}, \alpha_{npn} \) - common base current gains

I_K - cathode current

I_G - gate current

I_L - leakage current

Two-transistor model equivalent circuit
GTO Turn On

Static Characteristics

\[ I_k = \frac{I_L}{1 - (\alpha_{npp} + \alpha_{npn})} \]

\[ \alpha_{npn} + \alpha_{pnp} = 1 \]

- SiC npn transistors have superior blocking voltage capability
- Both the transistors go into saturation region
- The device goes into latch-up similar to the thyristor

GTO Turn Off

\[ \beta_{off} = \frac{\alpha_{top}}{\alpha_{top} + \alpha_{bottom} - 1} \]

- Turn off gain is controlled by the gate signal

- Because of a large current gain of bottom transistor, the top transistor can be controlled with a small gate signal

- Wider range of control on the turn off gain is achieved for small current gains of bottom transistor
Structure

- Asymmetrical, complementary structure
- Partial ionization of p-type impurities – low conduction capability
- Reduced drift layer thickness compared to silicon
- P+ buffer layer – increase the turn off gain by decreasing the injection efficiency of npn transistor

Complementary asymmetric SiC GTO thyristor structure
Structure (cont.)

- npnp configuration

- Heavily doped N+ substrate

- Junction J2 is formed by N-base and P- drift region

- 1.5 the depletion width to accommodate the open base transistor voltage BVceo blocking capability of GTO.
Loss Model Equations

Conduction losses

\[ P_{\text{on-state}} = J \cdot (E_g / q) + J \cdot (3\pi / 8) \cdot (kT / q) \cdot \exp\left( \frac{3V_B}{2L_a E_c} \right) \]

\[ V_B = \varepsilon (N_a + N_d) \cdot E_c^2 / (2q \cdot N_a \cdot N_d) \]
\[ L_a = (D_a \cdot \tau_a)^{0.5} \]
\[ \tau_a = \tau_n + \tau_p \]
\[ D_a = 2 \cdot D_n \cdot D_p / (D_n + D_p) \]
\[ D_n = (kT / q) \cdot \mu_n \]
\[ D_p = (kT / q) \cdot \mu_p \]

Then final expression for conduction losses can be given as,

\[ P_{\text{on-state}} = J \cdot (E_g / q) + J \cdot (3\pi / 8) \cdot (kT / q) \exp(D) \]
\[ D = \left( \varepsilon (N_a + N_d) \cdot E_{bd} \cdot 1.5 / (2 \cdot q \cdot N_a \cdot N_d \cdot \sqrt{(K T / q) (\mu_n \cdot \mu_p) \cdot \tau_a / (\mu_n + \mu_p)}} \right. \]

This equation is dependent on doping densities, mobilities, temperature, applied voltage, and current.
Loss Model

- Si GTO thyristor losses are more ⇒ difference in the on-state specific resistance.

\[ R_{sp} = \frac{4 BV^2}{\varepsilon_s \mu_n E_c^3} \]

- Electric field for Si is lower ⇒ hence specific resistance is more

- For a given operating current, conduction losses vary with the second term in the equation, which is a function of the on-state specific resistance

\[ P_{\text{on-state}} = J \cdot \left( \frac{E_g}{q} \right) + J \cdot \left( \frac{3\pi}{8} \right) \cdot \left( \frac{kT}{q} \right) \cdot \exp\left( \frac{3V_B}{2L_a E_c} \right) \]
Loss Model

Switching losses

\[ E_{\text{off}} = \frac{1}{2} \cdot (\varepsilon_s \cdot E_c V / (1 - \alpha_{npn})) \sqrt{V/V_B} + J\alpha_{npn, \text{max}} \cdot \tau_a \]

\[ E_{\text{on}} = \frac{1}{3} \cdot \varepsilon_s \cdot E_c V \sqrt{V/V_B} + J^2 \cdot (3\tau_a \cdot V_B^2) / (\varepsilon_s \cdot \mu_n \cdot E_c^3) + (E_g / 2q) \cdot J\tau_a \]

The switching power losses can be calculated using the total energy loss equation as,

\[ P_{\text{switching}} = (E_{\text{on}} + E_{\text{off}}) \cdot f_s \]
Loss Model

SiC GTO has lower switching losses

- Reduced drift width ⇒ less stored charge ⇒ faster switching

- Smaller ambipolar diffusion length ⇒ smaller lifetimes & low mobilities of electrons and holes

The total power loss in the device is given as,

\[ \text{Total losses} = \text{Conduction losses} + \text{Switching losses} \]

\[ P_{\text{total}} = P_{\text{conduction}} + P_{\text{switching}} \]

\[ V = 5000V, J=200A/cm^2, f_s = 1kHz. \]
## Simulation Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>4H-SiC</th>
<th>Si</th>
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<tbody>
<tr>
<td>(Eg), Energy gap (eV)</td>
<td>3.2</td>
<td>1.1</td>
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<td>$\varepsilon_r$, relative permittivity</td>
<td>9.7</td>
<td>11.7</td>
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<tr>
<td>$\tau_p$, hole lifetime (s)</td>
<td>$575e^{-9}$</td>
<td>$575e^{-9}$</td>
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<td>$E_c$, critical electric field (V/cm)</td>
<td>$2.3e^{06}$</td>
<td>$0.3e^{06}$</td>
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<tr>
<td>$\tau_n$, electron lifetime (s)</td>
<td>$1150e^{-9}$</td>
<td>$1150e^{-9}$</td>
</tr>
<tr>
<td>$\mu_n$, electron mobility(cm$^{-3}$/V·s)</td>
<td>800</td>
<td>1360</td>
</tr>
<tr>
<td>$\mu_p$, hole mobility(cm$^{-3}$/V·s)</td>
<td>120</td>
<td>453</td>
</tr>
<tr>
<td>$V_{sat}$, saturation velocity(cm/s)</td>
<td>$2e^{07}$</td>
<td>$1e^{07}$</td>
</tr>
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</table>
Simulations

- The mobilities and lifetimes of holes and electrons are assumed to be constant.

- The device is doped for a desired breakdown voltage.

\[ V_B = \varepsilon (N_a + N_d) \cdot \frac{E_c^2}{(2q \cdot N_a \cdot N_d)} \]

- SiC GTO is rated at 20 kV, Si GTO is rated at 5000V and for comparison, Si devices are assumed to be connected in series for voltage rating.

- The frequency of operation is 1kHz.

- The temperature range is 300 K – 600 K. It should be noted that the silicon GTO cannot withstand more than 423 K, however, the model is tested for comparison purposes.

- The devices are subjected to a current density range of 100 A/cm² – 500 A/cm².
Simulations - Individual Device Simulation

\[ J = 100 \text{ A/cm}^2 \quad T = 300 \text{ K} \]

<table>
<thead>
<tr>
<th>Volts, V</th>
<th>( P_{\text{cond}} ) (W)</th>
<th>( P_{\text{cond}} ) (W)</th>
<th>( P_{\text{sw}} ) (W)</th>
<th>( P_{\text{sw}} ) (W)</th>
<th>( P_{\text{total}} ) (W)</th>
<th>( P_{\text{total}} ) (W)</th>
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<tbody>
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<td>518.5</td>
<td>550.5</td>
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<tr>
<td>SiC</td>
<td>800</td>
<td>236</td>
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<td>1037</td>
<td>590</td>
<td></td>
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<tr>
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<td>400</td>
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<td>12.5</td>
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<tr>
<td>10000</td>
<td>800</td>
<td>538</td>
<td>236</td>
<td>52.5</td>
<td>1037</td>
<td>590</td>
</tr>
<tr>
<td>15000</td>
<td>1200</td>
<td>538</td>
<td>354</td>
<td>165</td>
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<td>702.5</td>
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<tr>
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<td>1600</td>
<td>538</td>
<td>472</td>
<td>437.5</td>
<td>2074</td>
<td>975.5</td>
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</table>
Simulations- Individual Device Simulation

\[ V = 10000 \text{ V} \]
\[ J = 300 \text{ A/cm}^2 \]

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>( P_{\text{tot}}(\text{w}) )</th>
<th>( P_{\text{tot}}(\text{w}) )</th>
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<tr>
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<td>500</td>
<td>1725</td>
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</tr>
<tr>
<td>600</td>
<td>1794.5</td>
<td>3299</td>
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</tbody>
</table>
Simulations - Individual Device Simulation

#### Plot

- **Temperature:** 300 K
- **Current Density:** J = 500 A/cm²

#### Table

<table>
<thead>
<tr>
<th>Volts, V</th>
<th>P_{cond} (W)</th>
<th>P_{cond} (W)</th>
<th>P_{sw} (W)</th>
<th>P_{sw} (W)</th>
<th>P_{total} (W)</th>
<th>P_{total} (W)</th>
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<tbody>
<tr>
<td></td>
<td>Si</td>
<td>SiC</td>
<td>Si</td>
<td>SiC</td>
<td>Si</td>
<td>SiC</td>
</tr>
<tr>
<td>5000</td>
<td>2000.5</td>
<td>2151.5</td>
<td>1271.5</td>
<td>96.5</td>
<td>3272</td>
<td>2785.5</td>
</tr>
<tr>
<td>10000</td>
<td>4001</td>
<td>2151.5</td>
<td>2543</td>
<td>264</td>
<td>6544</td>
<td>2953.5</td>
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<td>6001.5</td>
<td>2151.5</td>
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<td>2151.4</td>
<td>5086</td>
<td>2100</td>
<td>13058</td>
<td>4789</td>
</tr>
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</table>
Mobility Model

The temperature dependent mobility model would affect the device model because the diffusion length, which is a function of lifetime, and mobility of electron and holes will vary with temperature.

\[ L_a = (D_a \cdot \tau_a)^{0.5} \]

\[ D_a = \frac{2 \cdot D_n \cdot D_p}{(D_n + D_p)} \]

\[ D_n = \left( \frac{kT}{q} \right) \cdot \mu_n \]

\[ D_p = \left( \frac{kT}{q} \right) \cdot \mu_p \]
Mobility

• Mobility is defined as the average velocity of free carriers in a semiconductor due to an applied electric field.

• Mobility affects the flow of electrons and hence current.

• Scattering of electrons causes reduction in mobility
  - bulk mobility is calculated neglecting the scattering at surface and has higher value
Mobility - Dependence factors

Temperature dependence
- Mobility reduces with increase in temperature due to lattice vibrations
- Low doping for high breakdown makes temperature dependence an important factor

\[
\mu = \mu_0 \times \left( \frac{T}{T_0} \right)^\gamma
\]

\(\mu_0\) value at room temperature \(T_0\)
\(\gamma\) constant and varies from -1.8 to -2.5 for n-type and p-type SiC materials.
Mobility - Dependence factors

Doping concentration

- Mobility decreases with increase in excess charge carriers due to coulombic scattering.
- At high doping levels the mobility becomes independent of doping.

\[ \mu_o = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left( \frac{N_D + N_A}{N_{\text{ref}}} \right)^\alpha} \]

- Mobility also decreases with increase in injection levels
Mobility - Dependence factors

Electric field

-Mobility decreases with increase in electric field.

-The average mobility is the ratio of drift velocity to the electric field at low doping levels.
-Drift velocity saturates at higher electric fields and is known as saturated drift velocity.

\[
\mu^E (E) = \mu \left( \frac{1}{1 + \left( \frac{\mu E}{\nu_s} \right)^\beta} \right)^{\frac{1}{\beta}}
\]

Average mobility for holes and electrons
Mobility Model

Caughey-Thomas Mobility Model

\[
\mu_o = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left(\frac{N_D + N_A}{N_{\text{ref}}}\right)\alpha}
\]

\[
\mu = \mu_o \left(\frac{E}{E_o}\right)^\gamma
\]

\[
\mu^E(E) = \mu \left(\frac{1}{1 + \left|\frac{\mu E}{V_s}\right|}\right)^\frac{1}{\beta}
\]

- \(N_A + N_D\) the total doping concentration,
- \(\mu_{\text{max}}, \mu_{\text{min}}\) minimum and maximum mobilities
- \(N_{\text{ref}}\) doping concentration calculated empirically
- \(\alpha\) curve fitting parameter, measure of how quickly the mobility changes from \(\mu_{\text{min}}\) to \(\mu_{\text{max}}\.
- \(\mu_o\) value at room temperature \(T_o\)
- \(\gamma\) constant and varies from -1.8 to -2.5 for n-type and p-type SiC materials.
- \(E\) applied electric field,
- \(V_s\) saturation velocity,
- \(\beta\) constant

- The device model has low doping concentration for high breakdown voltage and is rated for 20kV.

- Hence the mobility model dependency is dominated by temperature variation.
## Mobility Model Data

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum electron mobility, $\mu_{\text{minn}}$ [cm²/V·s]</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>Maximum electron mobility, $\mu_{\text{maxn}}$ [cm²/V·s]</td>
<td>1360</td>
<td>950</td>
</tr>
<tr>
<td>Minimum hole mobility, $\mu_{\text{minp}}$ [cm²/V·s]</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Maximum hole mobility, $\mu_{\text{maxp}}$ [cm²/V·s]</td>
<td>505</td>
<td>180</td>
</tr>
<tr>
<td>Electron ionization coefficient, $\alpha_n$</td>
<td>0.91</td>
<td>0.76</td>
</tr>
<tr>
<td>Hole ionization coefficient, $\alpha_p$</td>
<td>0.63</td>
<td>0.56</td>
</tr>
<tr>
<td>Reference electron concentration, $N_{\text{refn}}$ [cm⁻³]</td>
<td>8.5e16</td>
<td>2.2e17</td>
</tr>
<tr>
<td>Reference hole concentration, $N_{\text{refp}}$ [cm⁻³]</td>
<td>6.3e16</td>
<td>2.35e17</td>
</tr>
</tbody>
</table>
Lifetime

- Lifetime is measure of duration of a charge carrier before it recombines for equilibrium conditions.
- Recombination can occur in several ways when electrons drop from valence band to conduction band:
  - surface trap recombination
  - recombination center
- There are several different recombination processes:
  - Shockley-Read-Hall recombination
  - Auger recombination
Lifetime control

Methods of control:

- Thermal diffusion of impurities

High temperature diffusion at 800-900 °C causes homogenous distribution of impurities. These impurities reduce lifetime. Gold and platinum common dopants

- Creation of lattice damage

Bombardment of high energy particles create lattice damage. These damages act as recombination centers for carriers, thereby reducing the lifetime.
Effect of lifetime on device operation

- Higher lifetime results in high value of current density.
- Frequency of operation increases as lifetime decreases, and hence the current. So the DOA (device operating area) decreases.
- Switching-on time decreases with increase in lifetime, since the device can reach the on-state current faster.
- Switching-off time increases as it takes more time to sweep out charge carriers.
- Lifetime can be improved by increasing the doping levels of the respective layers of the p-n junction. However the breakdown voltage will be compromised.
- At low level injection the lifetime does not vary much with temperature.
Diffusion Length

- Diffusion length is the characteristic distance between the point at which the charge carrier enters the minority region and the point at which it is captured.
- Switching performance of a device is based on the diffusion length.
- Conduction losses are also determined by \( L_d \).
  - \( \text{ex: conductivity of the drift region depends on } L_d \) and hence the on-state losses.
- Hence it can be concluded that there is always a trade-off between switching frequency and on-state losses determined by mobility and lifetime of electrons

\[
L_a = (D_a \cdot \tau_a)^{0.5} \quad D_a = 2 \cdot D_n \cdot D_p / (D_n + D_p)
\]
Simulations: Device simulation for $J = 200 \text{ A/cm}^2$, $V = 5000\text{V}$

<table>
<thead>
<tr>
<th>T (K)</th>
<th>$P_{\text{cond}}$ (W)</th>
<th>$P_{\text{cond}}$ (W)</th>
<th>$P_{\text{sw}}$ (W)</th>
<th>$P_{\text{sw}}$ (W)</th>
<th>$P_{\text{total}}$ (W)</th>
<th>$P_{\text{total}}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>2491.5</td>
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<td>383.5</td>
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<td>2875</td>
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<td>400</td>
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<td>63</td>
<td>1.409e</td>
<td>4789</td>
</tr>
</tbody>
</table>
Simulations: Device simulation for J = 400 A/cm², V = 10000V

<table>
<thead>
<tr>
<th>T (K)</th>
<th>P°cond (W)</th>
<th>P°cond (W)</th>
<th>Psw (W)</th>
<th>Psw (W)</th>
<th>Ptotal (W)</th>
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<tbody>
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<td>SiC</td>
<td>Si</td>
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<td>SiC</td>
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<td>1.91E+04</td>
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</table>
**Simulations- Switching Losses**

**Switching Losses of SiC GTO Thyristor**

- The switch on losses are dominant at low voltage and low temperature.

- Drastic increase in switch off losses at high voltage ratings.

- Constant increase in switch on losses with increase in temperature, while the switch off losses were decreasing $\Rightarrow$ effect of mobility.
Conduction losses dominate because, at lower switching frequency the switching losses are low, and the main power loss is a function of on-state resistance.

It is found that the conduction losses of silicon GTO thyristor are at least twice more than silicon carbide device.

The switching losses of silicon carbide GTO thyristor are at least 12 times less than the silicon device.

The device operating area (DOA) limits can be improved due to reduced losses ⇒ the maximum frequency can be increased for a given current density and operating voltage

This difference in losses shows that SiC devices have high efficiency compared to silicon.

The number of SiC devices per converter leg required is less, due to the higher voltage rating of the device.
Outline

SiC MATERIAL

SiC GTO Thyristor

HVDC System

Results

Conclusion
HVDC System

- The configuration chosen for the study is a monopolar configuration.

- The transmission system is based on voltage source converter technology. Converter at both the ends is a voltage source converter also known as forced commutated converter.

- The system model is designed to emulate the ac characteristics.
HVDC System - VSC Technology

Basic configuration of VSC transmission

Phasor diagram

Equivalent circuit of VSC transmission

\[ P = V_{vsc} \cdot V_{ac} \cdot \sin \delta / X \]

\[ Q = \left( V_{vsc} \cdot \cos \delta - V_{ac} \right) \cdot V_{vsc} / X \]
Control system

The active power transfer in a system is given as,

\[ P = \frac{V_1 \cdot V_2 \cdot \sin \delta}{X} \]

\( V_1, V_2 \) - ac voltage magnitudes at the sending end and receiving end respectively.
\( X \) - inductive reactance of the dc cable
\( \delta \) - angle between the sending and receiving end voltages.
HVDC System

Overview of the Control System

\[ P = V_s \cdot V_r \cdot \sin(\delta_s - \delta_r) / X \]
HVDC System

System Simulations

- The system model and the various control systems were implemented using PSCAD/EMTDC software.

- PSCAD/EMTDC is a simulation tool for analyzing power systems. PSCAD is the graphical user interface and EMTDC is the simulation engine.

- The software also has an excellent feature of interfacing MATLAB/SIMULINK.

- The system model has been developed from an example of the PSCAD and modified for the specifications.
HVDC System - Simulation Specifications

- System ratings: 120 kV dc link, up to 75 MW power delivered to the receiving end
- Device ratings: SiC - 20kV/5kV, 200 A/cm², Si – 5kV, 200 A/cm² 400 A/cm²

- No of devices: For a rating of 120kV, 1000 A, which is the maximum voltage and current there are several possible arrangements based on the device rating.
  
  SiC devices: 5 parallel strings of 6 devices in series (for 20kV, 200A device).
  5 parallel strings of 24 devices in series (for 5kV, 200A device).
  
  Si devices: 3 parallel strings of 24 devices in series (for 5kV, 400A device).
  5 parallel strings of 24 devices in series (for 5kV, 200A device).

- The voltage and current profiles are obtained from the single GTO device valve of one phase leg in the converter.

- The model is tested for a temperature range of 27° C – 200 °C.
Results — Current and Voltage Profiles
Results — Power Loss Profiles

SiC GTO Power Loss

Loss Profile for SiC GTO (423 K)

Si GTO Power Loss

Loss Profile for Si GTO (423 K)
GTO Efficiency Calculation

• The GTO efficiency is calculated based on the power loss profile obtained for different operating conditions.

• It is the instantaneous loss as a function of the instantaneous current, which depends on the modulation index and the switching angles generated by the PWM.

• The average loss over few cycles of the fundamental is calculated to find the cyclic power loss (average power loss for each cycle of the output voltage).

• The maximum and minimum power loss for a single device, over a few cycles is measured from the plots, and the corresponding converter controlled switches efficiency is calculated.
Cyclic Power Loss Plots

Cyclic Power Loss Plots for Si 5kV, 200 A/cm² GTO

Cyclic Power Loss Plots for SiC 20 kV, 200 A/cm² GTO
GTO Efficiency Calculation

• Minimum efficiency = (dc power – \( P_{\text{loss(max)}} \))/dc power

\[ P_{\text{loss(max)}} = P_{\text{max}} \cdot (\text{No. of devices in the converter}) \]

• Maximum efficiency = (dc power- \( P_{\text{loss(min)}} \))/dc power

\[ P_{\text{loss(min)}} = P_{\text{min}} \cdot (\text{No. of devices in the converter}) \]

• No. of devices = (No. of devices for voltage sharing)\cdot(No. of devices for current dividing)\cdot6.
GTO Efficiency Plots

Maximum and minimum efficiencies of converters using Si GTO rated at 5 kV, 200 A/cm² and SiC GTO rated at 20 kV, 200 A/cm².

### Efficiency of Si GTO Converter’s Controlled Switches

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>( P_{\text{max}} )</th>
<th>( P_{\text{min}} )</th>
<th>Max.eff %</th>
<th>Min.eff %</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>433.3</td>
<td>262.7</td>
<td>99.68</td>
<td>99.48</td>
</tr>
<tr>
<td>373</td>
<td>1443.1</td>
<td>873.7</td>
<td>98.75</td>
<td>98.26</td>
</tr>
<tr>
<td>423</td>
<td>3041.2</td>
<td>1842.4</td>
<td>97.78</td>
<td>96.35</td>
</tr>
<tr>
<td>473</td>
<td>6301.9</td>
<td>3818.9</td>
<td>95.41</td>
<td>92.43</td>
</tr>
</tbody>
</table>

### Efficiency of SiC GTO Converter’s Controlled Switches

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>( P_{\text{max}} )</th>
<th>( P_{\text{min}} )</th>
<th>Max.eff %</th>
<th>Min.eff %</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>475.2</td>
<td>300.6</td>
<td>99.9</td>
<td>99.85</td>
</tr>
<tr>
<td>373</td>
<td>1245.6</td>
<td>771.8</td>
<td>99.76</td>
<td>99.62</td>
</tr>
<tr>
<td>423</td>
<td>2402.1</td>
<td>1472.8</td>
<td>99.55</td>
<td>99.77</td>
</tr>
<tr>
<td>473</td>
<td>4506.9</td>
<td>2749.3</td>
<td>99.17</td>
<td>98.64</td>
</tr>
</tbody>
</table>
GTO Efficiency Plots

Maximum and minimum efficiencies of converters using Si GTO rated at 5 kV, 400 A/cm² and SiC GTO rated at 20 kV, 200 A/cm².

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>$P_{\text{max}}$</th>
<th>$P_{\text{min}}$</th>
<th>Max.eff %</th>
<th>Min.eff %</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>737.6</td>
<td>445.1</td>
<td>99.67</td>
<td>99.46</td>
</tr>
<tr>
<td>373</td>
<td>2386.2</td>
<td>1442.8</td>
<td>98.96</td>
<td>98.28</td>
</tr>
<tr>
<td>423</td>
<td>5102.65</td>
<td>3088.3</td>
<td>97.77</td>
<td>96.32</td>
</tr>
<tr>
<td>473</td>
<td>10548</td>
<td>6388.4</td>
<td>95.4</td>
<td>92.43</td>
</tr>
</tbody>
</table>
GTO Efficiency Plots

Maximum and minimum efficiencies of converters using Si GTO rated at 5 kV, 200 A/cm² and SiC GTO rated at 5 kV, 200 A/cm².

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>$P_{\text{max}}$</th>
<th>$P_{\text{min}}$</th>
<th>Max.eff %</th>
<th>Min.eff %</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>57.5</td>
<td>40.05</td>
<td>99.9519</td>
<td>99.93</td>
</tr>
<tr>
<td>373</td>
<td>58.5</td>
<td>40.5</td>
<td>99.9514</td>
<td>99.929</td>
</tr>
<tr>
<td>423</td>
<td>59.6</td>
<td>41.1</td>
<td>99.9507</td>
<td>99.928</td>
</tr>
</tbody>
</table>
System Cost Calculation:

• Difference in losses,
  \[ dl = (P_{(\text{loss, Si})} \cdot \text{(No. of devices)}) - (P_{(\text{loss, SiC})} \cdot \text{(No. of devices)}) \]

• The converter operates for 365 days and 24 hours
  \[ \text{Losses/year} = dl \cdot 365 \cdot 24 \]

• Assuming a rate of 0.04 kW.hr,
  \[ \text{Savings} = (\text{losses/year}) \cdot (0.04) \text{ /yr.} \]
## System Cost Savings

The maximum and minimum cost savings using a SiC-based converter with 20 kV, 200 A/cm² GTOs instead of 5 kV, 200 A/cm² and 5 kV, 400 A/cm² Si GTOs.

<table>
<thead>
<tr>
<th>No. of devices</th>
<th>dl</th>
<th>Losses/yr</th>
<th>(Losses/yr) · 0.04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si -720</td>
<td>Max.savings</td>
<td>814.824 kW</td>
<td>7,137,858.24 kW</td>
</tr>
<tr>
<td>SiC-180</td>
<td>Min. savings</td>
<td>490.14 kW</td>
<td>4,293,626.4 kW</td>
</tr>
<tr>
<td>Si-432</td>
<td>Max.savings</td>
<td>806.824 kW</td>
<td>7,066,082.3 kW</td>
</tr>
<tr>
<td>SiC-180</td>
<td>Min. savings</td>
<td>484.365</td>
<td>4,243,042.656</td>
</tr>
</tbody>
</table>

SiC Converter’s Controlled Switches Cost Savings compared to Si-based Converter
Conclusion

- Since the losses of SiC GTO are less
  - the range of efficiency for SiC converter is higher.
  - operating cost of SiC converter is less.
  - reduced thermal management requirements.
  - device operating area (DOA) limits can be increased.
  - improved dynamic characteristics ⇒ less switching losses.
  - the ratio of number of devices in a SiC converter compared to a Si converter is less ⇒ higher voltage rating than their Si counterparts ⇒ one can afford to pay more for a SiC GTO.

- Currently GTO ratings are much lower, and their cost and losses are more than the Si thyristor. However, can be improved using SiC GTO thyristor.
- Hence, SiC close to commercialization can replace Si GTO thyrsitor.
Co-Author of Publications
