Study on Current-Driven IGBT Driver Circuit

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OUTLINE

• Research Background and Objective

• IGBT Evaluation Circuit

• IGBT Current Drive Simulation
  — Current Gate Driver Circuit
  — Simulation Results

• Gate Current Automatic Control

• Conclusion and Challenges
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IGBTs have advantages of both MOSFETs and bipolar transistors.

Used in a wide range of applications as power semiconductor devices.

Development of IGBT and its driver circuit is important.
IGBT and Driver Circuit

IGBT

(Insulated Gate Bipolar Transistor)

Input part is MOSFET
Output part is bipolar transistor

Advantages
- Fast operating speed
- Large current amplification factor (~1.2kA)
- High withstand voltage (~3.3kV)

Large gate capacitance → Driver circuit is difficult
Objective

IGBT circuit

Parasitic capacitance and tail current → Switching loss
Parasitic inductance → Excessive overshoot
Change drive resistance during switching → Complex control

Current Drive

Reduction of Switching loss and Excessive overshoot
Simplification of control design
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Voltage-Driven IGBT Evaluation Circuit (1/2)

Input voltage $V_1$

$V_g$ turns on IGBT

$I_c$ gradually flows

$L_1$ 500$\mu$H

$L_2$ 145nH

$R_g$ I$_g$ V$_c$ Tr$_1$

$V_1$ 16V

$V_g$ 16V

$V_c$ 360mA

$I_g$ -360mA

$I_c$ 500V

$I_c$ 50mA

0A

0$\mu$s 50$\mu$s 100$\mu$s
Voltage-Driven IGBT Evaluation Circuit (2/2)

- $V_1$ becomes 0
- $V_g$ turns off IGBT
- $I_c$ gradually decreases

Diagram:
- $L_1$: 500$\mu$H
- $L_2$: 145$n$H
- $R_g$
- $V_1$
- $V_g$
- $V_c$
- $I_g$
- $I_c$
- $D_1$

Waveforms:
- $V_1$: 16V, 0V
- $V_g$: 16V, 0V
- $I_g$: 360mA, -360mA
- $V_c$: 500V, 0V
- $I_c$: 50A, 0A

Timeline: 0$\mu$s, 50$\mu$s, 100$\mu$s
Overshoot and Switching Loss during Turn-off

Change gate resistance $R_g$ from 30Ω to 300Ω

![Circuit Diagram]

$\text{L}_1 = 500\mu\text{H}$

$\text{L}_2 = 145\text{nH}$

$I_c$ = 450V

$V_1$

$V_g$ = $V_c$

$V_2$

$I_g$

$R_g$

$\text{Tr}_1$

$\text{D}_1$

Switching Loss [mJ]

Overshoot [V]

300Ω

270Ω

240Ω

210Ω

180Ω

150Ω

120Ω

90Ω

60Ω

50Ω

40Ω

30Ω
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Current Gate Driver Circuit (1/2)
Current Gate Driver Circuit (2/2)

Consider 4 steps and draw different currents.
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IGBT Turn-off Characteristics

Control gate voltage by flowing $I_g$

Turn-on Current Source

Current Gate Driver Circuit

$L_1$: 500$\mu$H
$L_2$: 145nH

$V_g$, $V_c$

$I_c$, $450V$

$D_1$, $I_g$

$I_g$, $500\mu$A to 225mA

$V_g$, $16V$ to 0V

$V_c$, $500V$ to 0V

$I_c$, 0A to 50A

60.90$\mu$s, 61.65$\mu$s, 62.40$\mu$s
Control of Gate Voltage by Gate Current (Step1)

Step1

$V_g$: Saturation voltage to Miller voltage

No effects on switching loss and overshoot
Control of Gate Voltage by Gate Current (Step2)

Step 2

\( V_g \): Miller period of IGBT

Trade-off between switching loss and slew rate

Switching loss can be reduced
Control of Gate Voltage by Gate Current (Step3)

Step3

\[ V_g : \text{Miller voltage to threshold voltage} \]

\[ \text{Trade-off between switching loss and overshoot} \]

\[ \text{Overshoot can be reduced} \]
Step 4

\( V_g \) : Threshold voltage to 0

\( I_g \) : Uncontrollable due to I-V characteristics of MOSFETs

No effects on switching loss and overshoot
Comparison with Voltage Drive

Switching Loss : **-35%**, Overshoot : **-32%**
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Gate Current Automatic Control

Judge the operating region from the voltage value of the gate, and determine the control current.

4 regions:
- **I₂~I₅**
- **I₂**
- **I₃**
- **I₄**
- **I₅**

450mA
- **I₂**
- **I₃**
- **I₄**
- **I₅**

225mA

0mA

Current Source

Turn-on Current Source

Current Gate Driver Circuit

FF Circuit
FF circuit time chart

Automatic control only for the time in each operating region

Corresponding operating region

Current Mirror

I₁

S

S₁

S₂

S₃

S₄

Low

CLK

I₂

I₃

I₄

I₅

I₆

gate

RSFF

DFF

S

Q₁

Q₂

D

Q₂

CLK

Corresponding operating region

Max

min

S

1

0

R

1

0

Q₁

1

0

Q̅ (D)

1

0

CLK

1

0

Q₂

1

0
Comparison of Voltage Drive and Automatic Control Current Drive

Switching Loss : -31%, Overshoot : -31%
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Conclusion

- Proposal of current drive circuit to control gate voltage of IGBT

- During turn-off, when compared to conventional voltage drive:
  - Current Drive $\rightarrow$ switching loss (-35%), overshoot (-32%)
  - Automatic Control $\rightarrow$ switching loss (-31%), overshoot (-31%)

Challenges

- Automatic control of current value in each operating region