Overcurrent Detection Method by Monitoring Gate Voltage While Periodically Repeating Discharging and Charging of Constant Gate Charge in IGBTs

Haifeng Zhang[1], Hiromu Yamasaki[1], Katsuhiro Hata[1], Ichiro Omura[2], and Makoto Takamiya[1]
[1] The University of Tokyo, Tokyo, Japan
[2] Kyusyu Institute of Technology, Fukuoka, Japan

***Abstract*— A new overcurrent detection method by "monitoring gate voltage while periodically repeating discharging and charging of constant gate charge (MGDC)" is proposed, which enables overcurrent detection while IGBTs are ON by measuring gate-to-emitter voltage (V_{GE}). In MGDC, while the IGBTs are ON, constant gate charge is periodically discharged and charged, and when V_{GE} dropped by each discharge is less than the reference voltage, it is detected as the overcurrent. In a single-pulse test of an inductive load at 300 V for an IGBT with a pulse rating of 150 A, a current-source 6-bit digital gate driver IC was used to perform MGDC with 1.3-μs cycle, and MGDC successfully detected an overcurrent of 250 A with a relative loss increase of only 0.8 %.**

Keywords—overcurrent, detection, gate voltage, IGBT

I. INTRODUCTION

The detection and protection of IGBT overcurrent are important technologies to realize reliable power electronic systems. The target of this work is to develop an IGBT overcurrent detection (OD) method measurable from gate terminals while IGBTs are ON for large-current, short-pulse current generator circuits with inductive load [1]. When OD is done from the gate terminal of IGBTs, OD can be integrated into the gate driver IC, thus enabling low-cost OD method.

Methods for detecting overcurrent by measuring collector current (I_C) [2-5], collector-to-emitter voltage (V_{CE}) [3, 6], and gate-to-emitter voltage (V_{GE}) [7-10] of IGBTs have been proposed. I_C measurement requires a current sensor, and V_{CE} measurement for desaturation detection requires a high-voltage diode, which are expensive. All conventional OD methods by V_{GE} measurement [7-10] have the disadvantage that overcurrent during ON of IGBTs cannot be detected because V_{GE} is measured during the turn-on transient. To solve the problems, in this paper, a low-cost OD method by "monitoring gate voltage while periodically repeating discharging and charging of constant gate charge (MGDC)" that can detect overcurrent during ON of IGBTs from V_{GE} and can be integrated into gate driver ICs is proposed.

II. PROPOSED OVERCURRENT DETECTION METHOD BY MGDC

Figs. 1 and 2 show a circuit schematic and a photo of the measurement setup for a single-pulse test of an inductive load of 34 μH at 300 V for IGBT (SIGC57T120R3LE, 1200 V rating) with a pulse rating of 150 A, respectively. The IGBT module including IGBT (Q_1) and the diode (D_1: SIDC30D120H8, 1200 V, 50 A rating) was self-made. The high-side diode (D_2) is GB2X100MPS12-227 (1200 V, 1000 A pulse rating). A current-source 6-bit digital gate driver IC [11], where the gate current (I_G) is variable with 6-bit control signals (n_{PMOS} [5:0] and n_{NMOS} [5:0]) and I_G is proportional to n_{PMOS} and n_{NMOS} which are integers from 0 to 63, is used to perform MGDC.

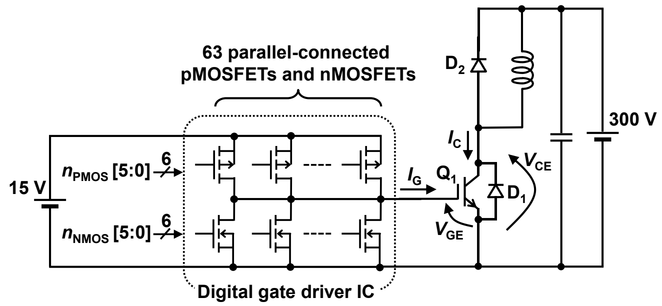

Fig. 1: Circuit schematic of measurement setup.

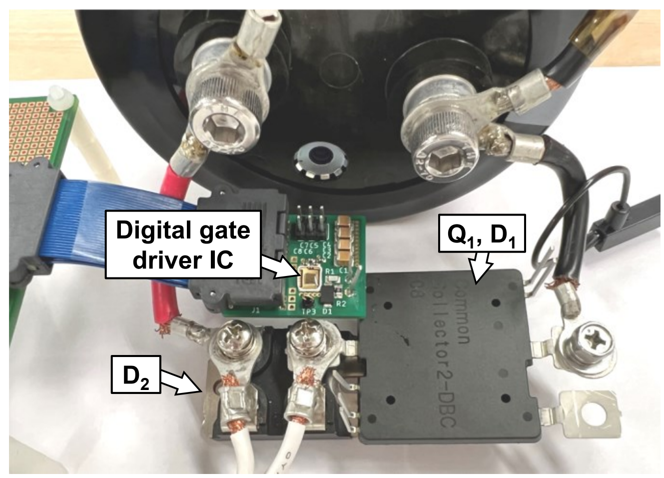

Fig. 2: Photo of measurement setup.

Figs. 3 (a) and (b) show timing charts for OD of the conventional V_{CE} measurement for desaturation detection and the proposed MGDC, respectively. In the conventional desaturation detection shown in Fig. 3 (a), overcurrent is detected when V_{CE} exceeds a reference voltage (V_{REF}). In contrast, the proposed OD method by MGDC has three steps: gate discharging, V_{GE} comparison, and gate charging. In the proposed MGDC shown in Fig. 3 (b), a constant gate charge

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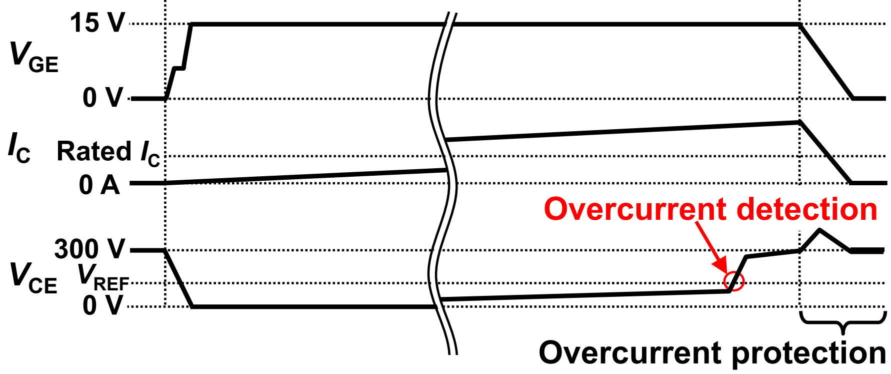
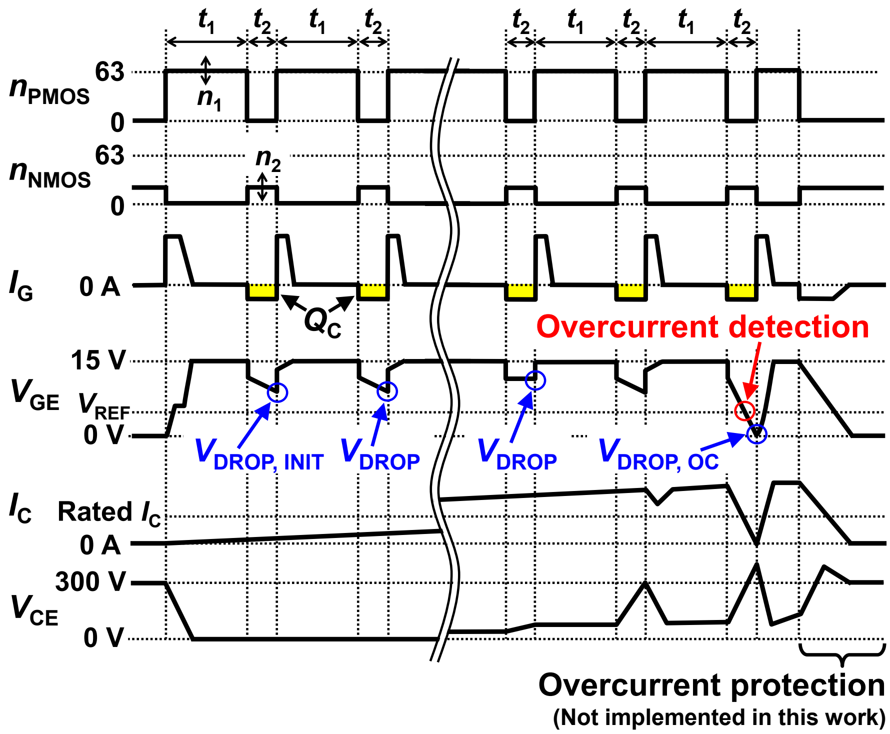


(a)



(b)

Fig. 3: Timing charts for overcurrent detection. (a) Conventional V_{CE} measurement for desaturation detection. (b) Proposed MGDC.

(Q_C) (= $I_G \times t_2$) is periodically discharged with the $t_1 + t_2$ cycle, and if the resulting drop in V_{GE} (V_{DROP}) is greater than V_{REF}, it is judged normal, and if V_{DROP} is less than V_{REF}, it is judged overcurrent. V_{GE} is recharged to 15 V in the t_1 period after each discharge.

Fig. 4 shows the principle of operation of the proposed OD by MGDC with a schematic of V_{GE} vs. gate charge (Q_G) curve. The black graph shows the characteristics for $I_C = I_1$, the red graph for $I_C = I_2$, and the blue graph for $I_C = I_3$, where $I_1 < I_2 < I_3$ and I_3 shows the overcurrent. When Q_C is discharged from Point A of $V_{GE} = 15$ V, the operating point changes from Point A to Point B when the IGBT is normal, while the operating point changes from Point A to Point C when the IGBT is overcurrent, because the gate capacitance decreases when the overcurrent occurs. Since V_{GE} at Points B and C are different, the overcurrent can be detected by comparing V_{GE} and V_{REF} using a comparator.

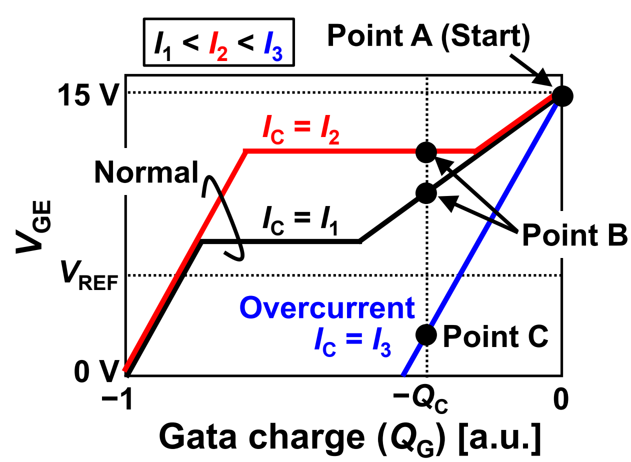


Fig. 4: Principle of operation of proposed MGDC.

III. Measured Results

Fig. 5 shows the measured waveforms of the conventional OD method by monitoring V_{CE}. When I_C exceeds 250 A, the IGBT enters the desaturation region and V_{CE} increases rapidly. In the conventional desaturation detection, the overcurrent is detected by the V_{CE} increases. The energy loss (E_{CONV}) caused by $I_C \times V_{CE}$ in Fig. 5 is 17.5 mJ, which is the value that will be used later as a reference for comparison with the proposal.

The proposed MGDC has four parameters (t_1, t_2, n_1, and n_2) shown in Fig. 3 (b). n_1 is n_{PMOS} during t_1 and n_2 is n_{NMOS} during t_2. The design guidelines for the parameters are as follows. The measurement cycle ($t_1 + t_2$) should be shorter than the short-circuit withstand time of the IGBTs so that the overcurrent is not overlooked. Q_C, which is proportional to $n_2 \times t_2$, is the most important parameter in MGDC. If Q_C is too small, the overcurrent cannot be detected. If Q_C is too large, the energy increase due to MGDC is excessive and unacceptable, because in MGDC, V_{GE} drops temporarily on a periodic basis, increasing the conduction losses of the IGBTs. Therefore, it is very important to set Q_C to an appropriate value.

Fig. 6 shows the measured waveforms of the proposed OD method by MGDC with different Q_C's. Q_C is varied by changing n_2 from 10 to 60 at t_2 = 300 ns. In this paper, t_1 = 1

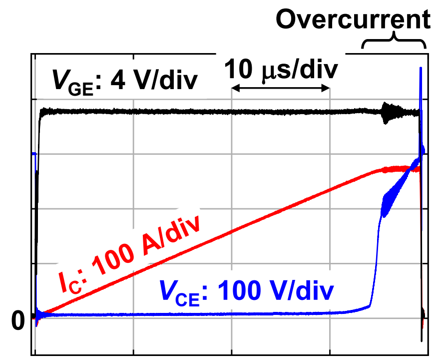


Fig. 5: Measured waveforms of conventional overcurrent detection method by monitoring V_{CE}.

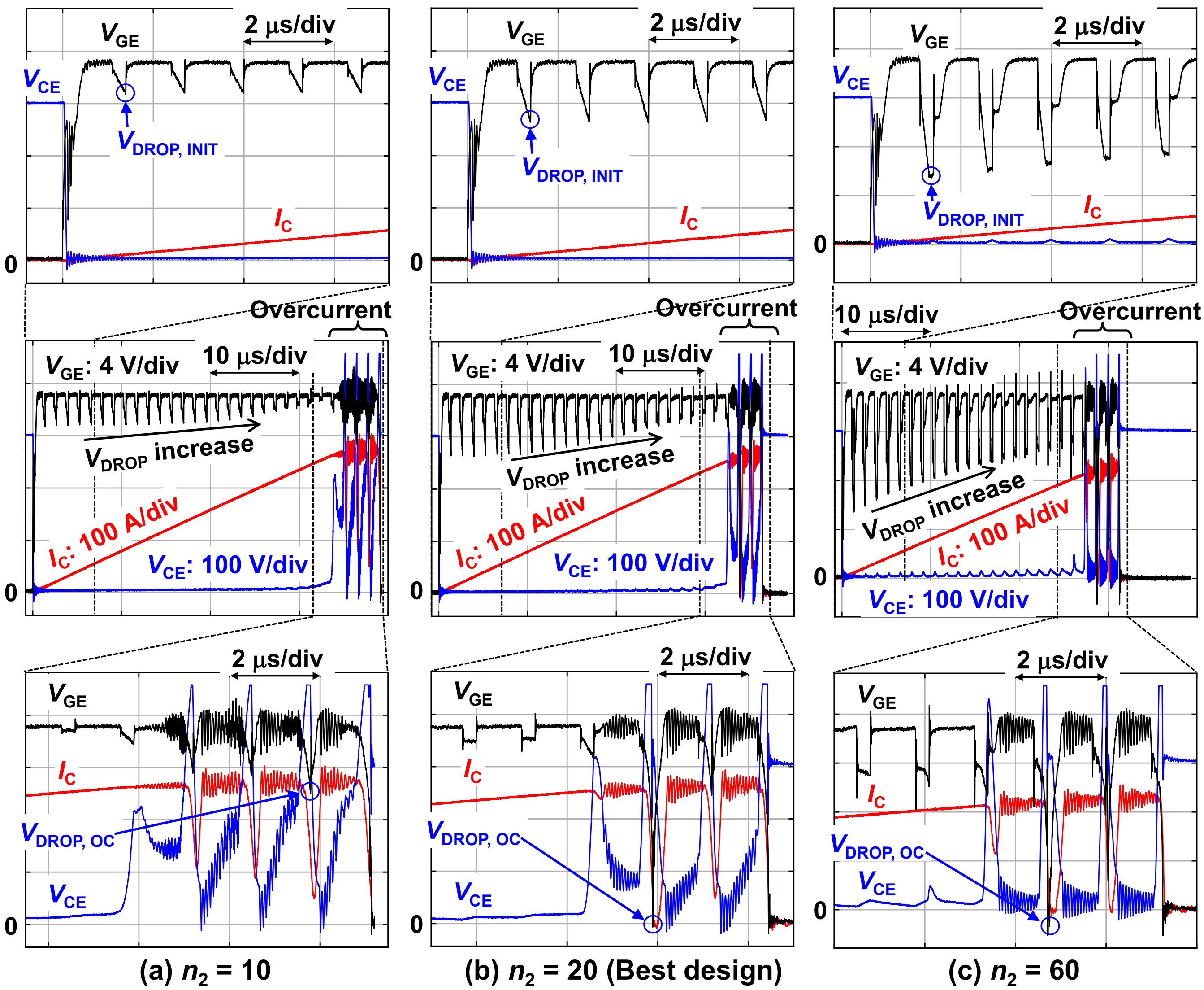
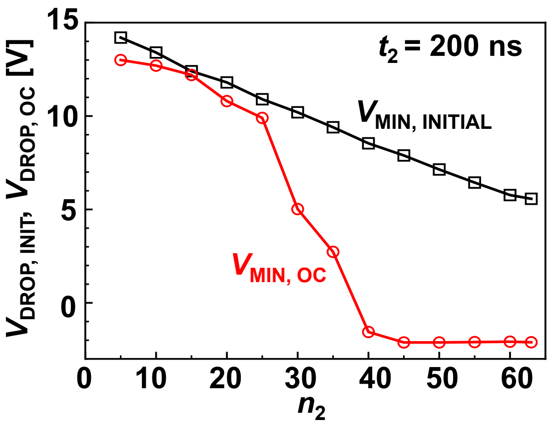


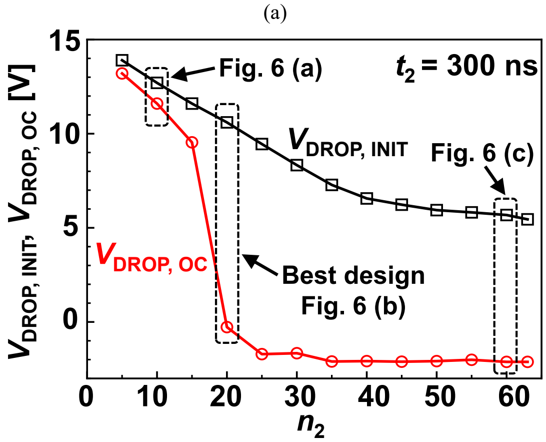
Fig. 6: Measured waveforms of proposed MGDC with different Q_C's. Q_C is varied by changing n_2 at t_2 = 300 ns. (a) n_2 = 10. (b) n_2 = 20 (best design). (c) n_2 = 60.

μs and n_1 = 63 are fixed. As shown in Fig. 3 (b), the initial V_{DROP} is defined as $V_{\mathrm{DROP,\,INIT}}$, and the minimum value of V_{DROP} in the overcurrent region is defined as $V_{\mathrm{DROP,\,OC}}$. In Fig. 6 (a) with $n_2 = 10$, V_{DROP} increases with increasing I_{C} since the Miller plateau voltage increases, and $V_{\mathrm{DROP,\,OC}}$ hardly decreases even in the overcurrent region, thus failing to detect overcurrent. In contrast, in Figs. 6 (b) and (c) for n_2 = 20 and 60, V_{DROP} increases with increasing I_{C}, and in the overcurrent region, $V_{\mathrm{DROP,\,OC}}$ decreases rapidly to around 0 V, indicating successful OD. As a result, an overcurrent of 250 A in the IGBT with the pulse rating of 150 A is successfully detected.

To discuss the optimal value of Q_{C}, Figs. 7 (a) and (b) show the measured n_2 dependence of $V_{\mathrm{DROP,\,INIT}}$ and $V_{\mathrm{DROP,\,OC}}$ at t_2 = 200 ns and 300 ns, respectively. Figs. 8 (a) to (d) show n_2 dependence of the energy loss increase in gate driver (E_{GD}) and the energy loss increase in main circuit (E_{MAIN}) caused by $I_{\mathrm{C}} \times V_{\mathrm{CE}}$ due to MGDC, total loss increase (E_{TOTAL} (= $E_{\mathrm{GD}} + E_{\mathrm{MAIN}}$)), and relative loss increase (E_{TOTAL} / E_{CONV}) due to MGDC, respectively. The integration period for energy calculation is from the beginning of I_{C} flow in Fig. 6 to just before the overcurrent region. E_{GD} is calculated as $I_{\mathrm{G}} \times 15\ \mathrm{V} \times t_2 \times$ number of times of MGDC, where I_{G} is proportional to n_2. E_{MAIN} is obtained from the measured waveforms of I_{C} and V_{CE}. E_{GD} is sufficiently smaller than E_{MAIN} hence E_{GD} can be ignored. In Fig. 7, since $V_{\mathrm{DROP,\,INIT}} >> V_{\mathrm{DROP,\,OC}}$ is required for stable OD, it is necessary to set $n_2 \geqslant 40$ for t_2 = 200 ns and $n_2 \geqslant 20$ for t_2 = 300 ns. In contrast, as shown in Fig. 8, excess n_2 leads to the loss

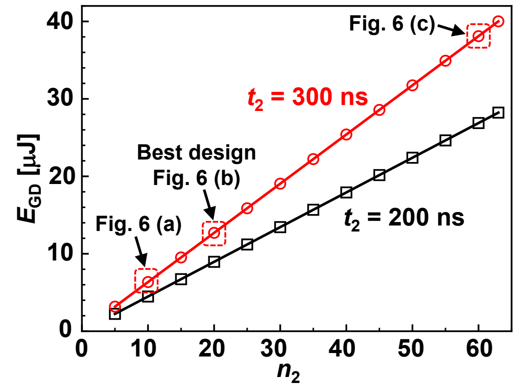


(a)

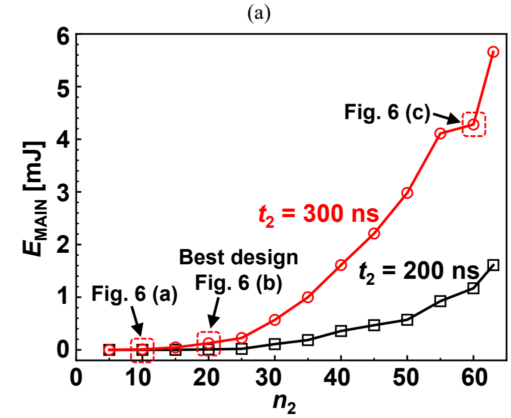


(b)

Fig. 7: Measured n_2 dependence of $V_{\mathrm{DROP,\,INIT}}$ and $V_{\mathrm{DROP,\,OC}}$ at (a) t_2 = 200 ns and (b) t_2 = 300 ns.



(a)



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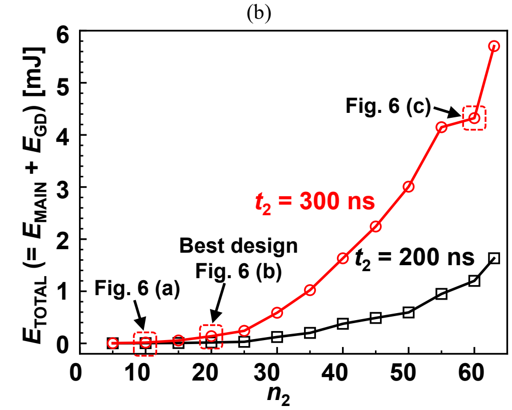

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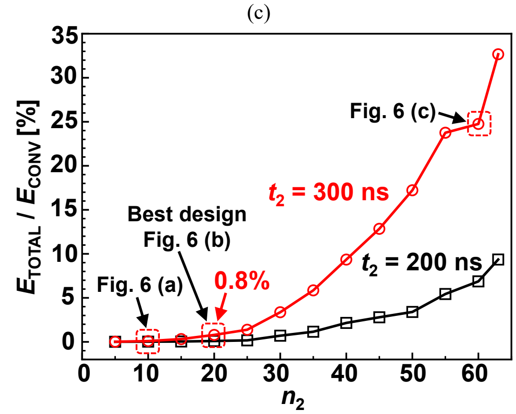

(d)

Fig. 8: n_2 dependence of (a) energy loss increase in gate driver (E_{GD}), (b) energy loss increase in main circuit (E_{MAIN}) caused by $I_{\mathrm{C}} \times V_{\mathrm{CE}}$ due to MGDC, (c) total loss increase (E_{TOTAL} (= $E_{\mathrm{GD}} + E_{\mathrm{MAIN}}$)), and (d) relative loss increase (E_{TOTAL} / E_{CONV}) due to MGDC.

increase. Thus, the best design point for detectable overcurrent and minimum loss increase is at t_2 = 300 ns and n_2 = 20, where the relative loss increase is only 0.8 %.

Table I shows a comparison table of OD methods. This paper is the first work to achieve OD while IGBTs are ON by measuring from the gate terminal. MGDC can be integrated into the gate driver IC, thus enabling low-cost OD method.

TABLE I. COMPARISON TABLE OF OVERCURRENT DETECTION

Reference	[2-5]	[3, 6]	[8-9]	[10]	This work
Method	Current monitor	Desaturation	Gate charge	V_{GE} at Miller plateau	MGDC
Measured value	I_C	V_{CE}	Q_G, V_{GE}	V_{GE}	V_{GE}
Measurement from gate terminal	No	No	Yes	Yes	Yes
Overcurrent detection during ON	Yes	Yes	No	No	Yes
Additional circuits except comparators	Current sensor	High voltage diode	Integrator	Filter	Constant charge discharger

IV. CONCLUSIONS

The proposed OD method by MGDC with 1.3-μs cycle successfully detected the overcurrent of 250 A by measuring V_{GE} while IGBTs are ON with a relative loss increase of only 0.8 %. Since this paper only demonstrated the principle of operation of OD by MGDC, future research topics are (1) OD using comparator circuits, (2) overcurrent protection, and (3) integration of MGDC into gate driver ICs.

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