Digital Active Gate Driving Automatically Minimizing Switching Loss While Keeping Surge Current Below User-Specified Target

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***Abstract*-- To address the user-specified surge current targets and the trade-off problem between surge current and switching loss in gate drivers, a digital active gate driving method is proposed that automatically minimizes the switching loss while keeping the surge current below the user-specified target. A 6.5 kV IGBT is driven at 3.6 kV and 56 A load current using a digital gate driver (DGD) IC that can change the gate current in 64 levels from 0 A to 1 A in 480 ns steps. For each of the four user-specified surge current targets at turn-on, the optimum parameters of DGD are searched by repeating the double-pulse test 2500 times using the simulated annealing algorithm. As a result, the switching loss is successfully reduced by 18 % to 27 % compared with the conventional gate driving while automatically meeting the surge current targets.**

***Index Terms*-- Gate driver, switching loss, surge current, IGBT.**

I. Introduction

Digital gate drivers (DGDs), which digitally change the gate current (I_G) multiple times in fine time slots during the switching period of power devices, are attracting attention as a technology that can solve the trade-off problem between the switching loss (E_{LOSS}) and surge voltage/current [1-9]. In DGD, E_{LOSS} and surge voltage/current are programmable within a certain range, because I_G is software-controlled and can be automatically optimized [1-2, 9]. In gate driver design, there is a high demand for minimizing E_{LOSS} while keeping surge voltage/current below the user-specified target. Previous DGD papers [1-2, 9], however, minimize both E_{LOSS} and surge voltage/current with the same weights and do not achieve the above need. To solve the problem, in this paper, a digital active gate driving method is proposed that automatically minimizes E_{LOSS} while keeping the surge current ($I_{OVERSHOOT}$) below the user-specified target.

II. Proposed Digital Active Gate Driving Method

Figs. 1 and 2 show a circuit schematic and a timing chart of the developed DGD IC, respectively. In the following, turn-on is discussed for simplicity, whereas the exact same is true for turn-off. This open-loop DGD IC is modified from the closed-loop DGD IC [6-7]. The modifications are the following three points. (1) The sensor for the closed-loop active gate driver is removed and "Timing" input is added to define the timing to change I_G. (2) The number of slots for I_G change at turn-on is increased from 3 to 9. (3)

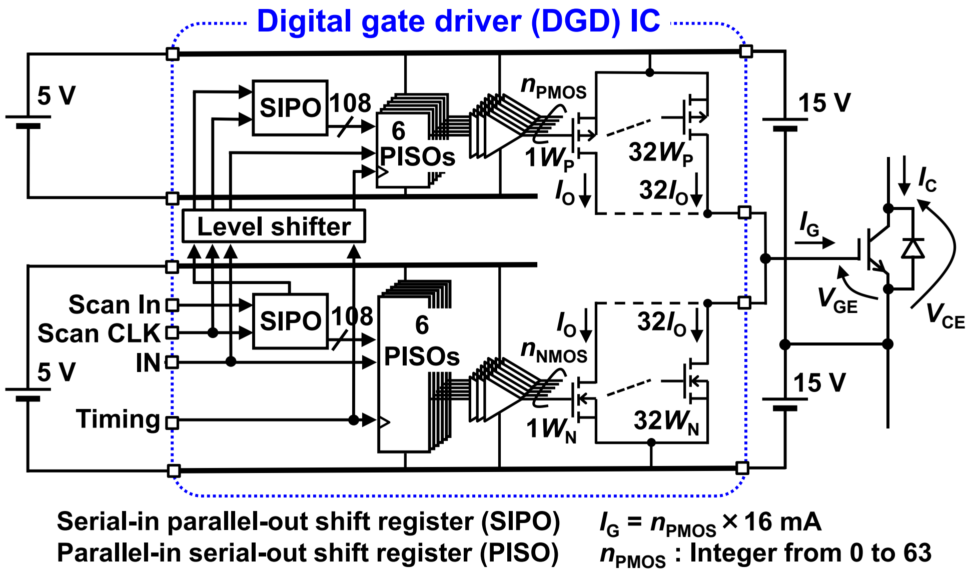

Fig. 1. Circuit schematic of developed DGD IC.

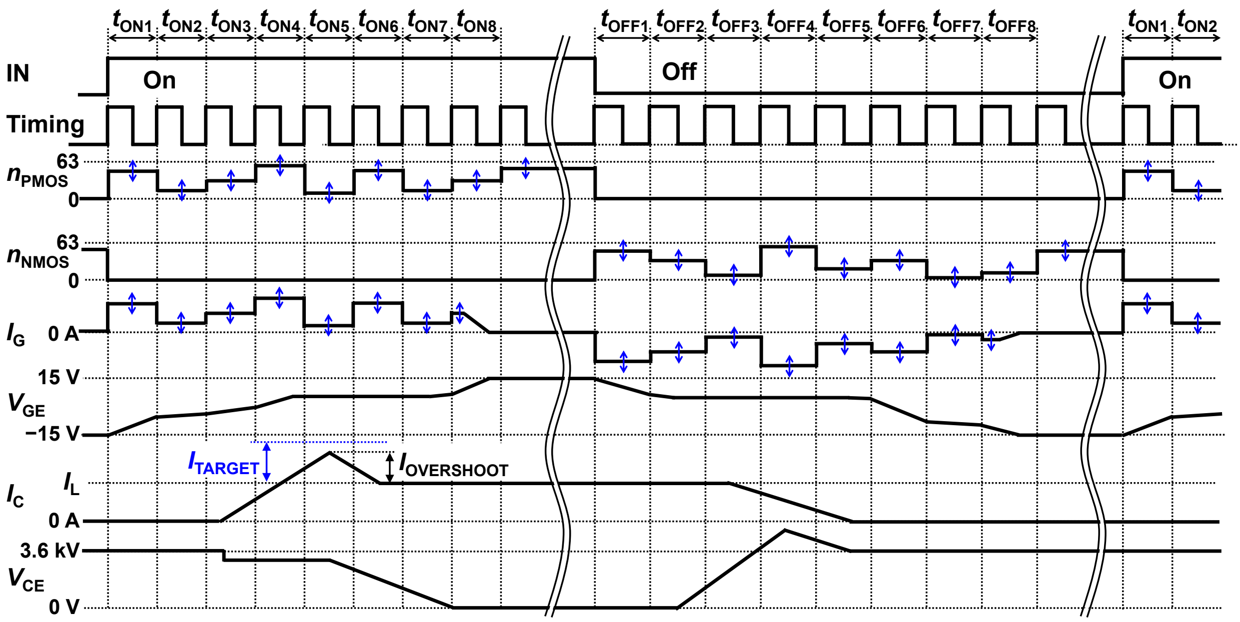

Fig. 2. Timing chart of developed DGD IC.

The maximum I_G value is reduced from 3 A to 1 A, because the gate charge of the target IGBT is small. The equation for I_G is shown in Fig. 1. As shown in Fig. 2, I_G can be varied 9 times with 6 bits (= 64 levels) in time steps from t_{ON1} to t_{ON8}. t_{ON1} to t_{ON8} are determined by the period of "Timing". t_{ON1} to t_{ON8} need not be identical and can be different values for each. Definitions of the load current (I_L), $I_{OVERSHOOT}$ and the surge current target (I_{TARGET}) are shown in Fig. 2. Figs. 3 and 4 show photos of DGD IC fabricated with 180-nm BCD process and a gate driver PCB including DGD IC, respectively. The die size is 2.0 mm by 2.5 mm. The gate driver PCB also includes a signal isolator (IL260-3E), two 15 V isolated DC-DC converters (MGS1R50515), and two 5 V isolated DC-DC converters (MGS1R50505). Figs. 5 and 6 show a circuit schematic and a measurement setup of the double pulse test at 3.6 kV and I_L = 56 A using the developed DGD IC and two 6.5 kV IGBT modules, respectively. Figs. 7 (a) and (b) show timing charts of the conventional single-step gate driving (SGD) and the proposed active gate driving (AGD) at turn-on for comparison, respectively. In SGD, n is varied, which emulates a conventional gate driver with varied gate resistance. In AGD with 480 ns × 4 slots and last long slot, five parameters (n_1 to n_5) are varied. n and n_1 to n_5 are integers from 0 to 63. To achieve the proposed digital active gate driving method, the double pulse tests are repeated 2500 times, and each time E_{LOSS} and $I_{OVERSHOOT}$ are measured to calculate an evaluation function (f_{OBJ}) defined in Eq. (1), and the combination of the five parameters (n_1 to n_5) that minimizes f_{OBJ} is searched using the simulated annealing algorithm [1]. The search takes 37 minutes.

$$f_{OBJ} = \sqrt{\left(\frac{E_{LOSS}}{E_{LOSS,\,MAX}}\right)^2 + 10^5\left(\frac{\max\left(I_{OVERSHOOT}, I_{TARGET}\right) - I_{TARGET}}{I_{TARGET}}\right)^2} \quad (1)$$

where $E_{LOSS,MAX}$ is the maximum of E_{LOSS} in SGD. The intent of defining this f_{OBJ} is to keep $I_{OVERSHOOT}$ below I_{TARGET} in the first priority and minimize E_{LOSS} in the second priority. For the purpose of differentiating between the first and second priority, 10^5 is multiplied by the later

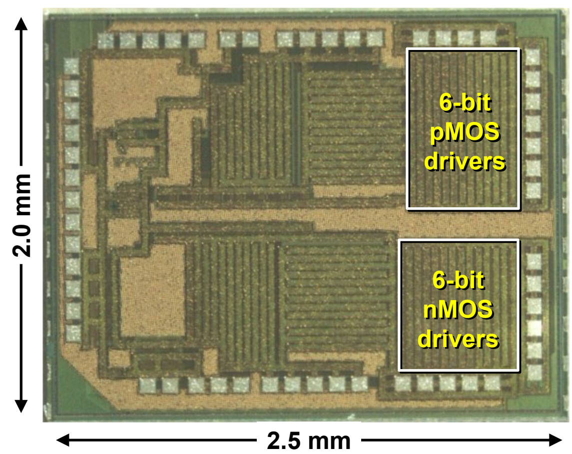

Fig. 3. Die photo of DGD IC.

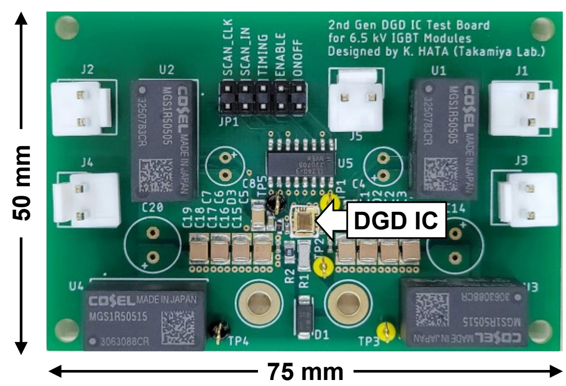

Fig. 4. Photo of gate driver PCB including DGD IC.

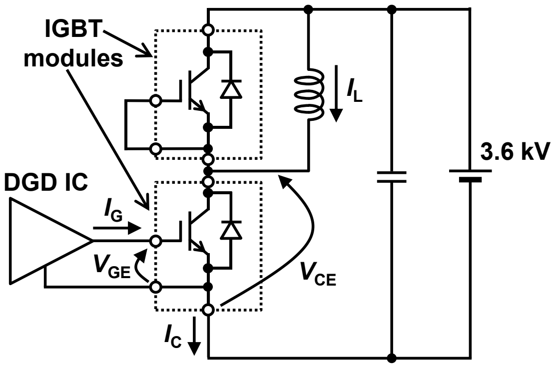

Fig. 5. Circuit schematic of double pulse test.

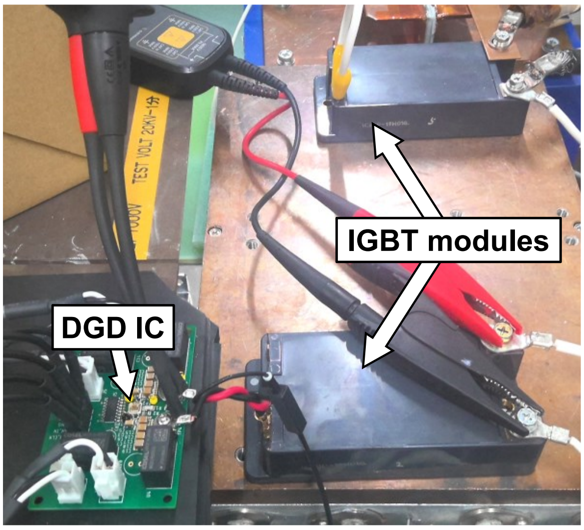

Fig. 6. Measurement setup of double pulse test.

term, where 10^5 has no physical meaning and can be any large number. The definition of f_{OBJ} differs from the previous papers [1-2, 9] that minimize both E_{LOSS} and $I_{OVERSHOOT}$ with the same weights.

III. Measured Results

Fig. 8 shows the measured E_{LOSS} vs. $I_{OVERSHOOT}$ of the conventional SGD and the proposed AGD. The black curve is the trade-off curve for SGD with varying n. The proposed AGDs at user-specified I_{TARGET} of 50 A, 60 A, 70 A, and 80 A are Points A, B, C, and D, respectively, where each has successfully achieved minimizing E_{LOSS} while keeping $I_{OVERSHOOT}$ below I_{TARGET}. Points E and F are the conventional SGD points with $I_{OVERSHOOT}$ approximately the same as the proposed Points A and D, respectively. Compared with SGD (Points E and F), the proposed AGD (Points A and D) reduces E_{LOSS} by 27 % and 18 % under $I_{OVERSHOOT}$-aligned condition, respectively.

Figs. 9 (a) to (f) show the measured waveforms of Points A to F in Fig. 8, respectively. In the proposed AGDs (Points A to D), for each of four I_{TARGET}, E_{LOSS} is minimized while keeping $I_{OVERSHOOT}$ below I_{TARGET} by automatically searching for the optimum five parameters (n_1 to n_5). Comparing the waveforms of Points D and F with $I_{OVERSHOOT}$ = 80 A, the proposed Point D (Fig. 9 (d)) suppresses $I_{OVERSHOOT}$ by $n_2 = 4$ while reducing E_{LOSS} by $n_4 = 54$, compared with the conventional Point F (Fig. 9 (f)) with the constant $n = 12$.

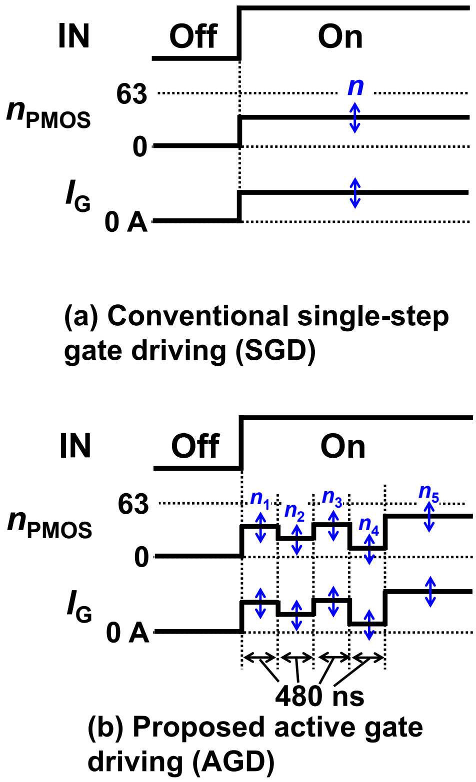

Fig. 7. Timing charts at turn-on. (a) Conventional single-step gate driving (SGD). (b) Proposed active gate driving (AGD).

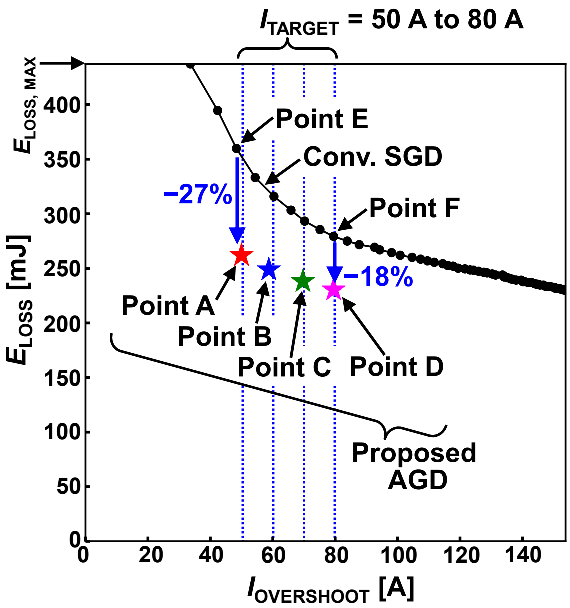

Fig. 8. Measured E_{LOSS} vs. $I_{OVERSHOOT}$ of conventional SGD and proposed AGD at user-specified I_{TARGET} of 50 A, 60 A, 70 A, and 80 A.

IV. Discussion

A. Lower Limit of I_{TARGET}

Not surprisingly, the proposed digital active gate driving method is not a perfect solution, and there is a lower limit of I_{TARGET} that can be achieved. Therefore, the lower limit of I_{TARGET} in the proposed digital active gate

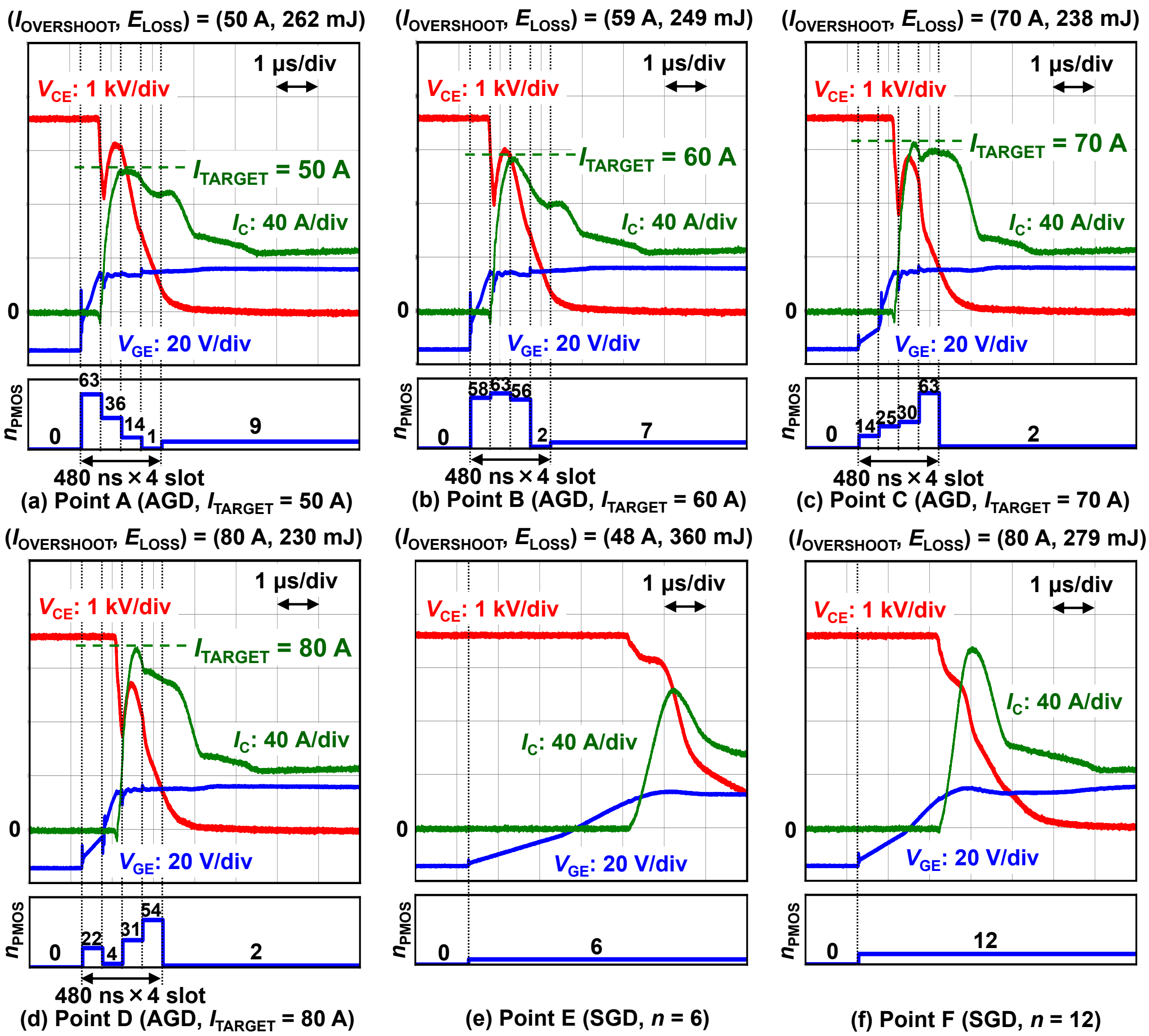

Fig. 9. Measured waveforms of Points A to F in Fig. 8.

driving method is discussed below. In Fig. 10, Point G of the proposed AGD at user-specified I_{TARGET} of 40 A is added to Fig. 8. $I_{\mathrm{OVERSHOOT}}$ at Point G is 42 A and fails to keep $I_{\mathrm{OVERSHOOT}}$ below I_{TARGET} of 40 A. The reason for this is discussed below. As a representative example of the proposed AGD, Fig. 11 shows the results of 2500 measurements performed to search for the optimal gate driving waveform at I_{TARGET} = 50 A, with blue dots. The best AGD with the smallest f_{OBJ} among 2500 points is Point A. In the proposed digital active gate driving method, by varying the five parameters (n_1 to n_5) controlling the gate driving waveform using the simulated annealing algorithm, it can be clearly seen that the best gate driving waveform (Point A) that minimizes E_{LOSS} while keeping $I_{\mathrm{OVERSHOOT}}$ below 50 A is searched over a wide range of E_{LOSS} and $I_{\mathrm{OVERSHOOT}}$. Among the 2500 measurements, the minimum value of $I_{\mathrm{OVERSHOOT}}$ is 42 A. This means that AGD defined in Fig. 7 (b) would not be able to achieve $I_{\mathrm{OVERSHOOT}}$ of less than 42 A, which is the reason why Point G failed to achieve $I_{\mathrm{OVERSHOOT}}$ below I_{TARGET} of 40 A in Fig. 10.

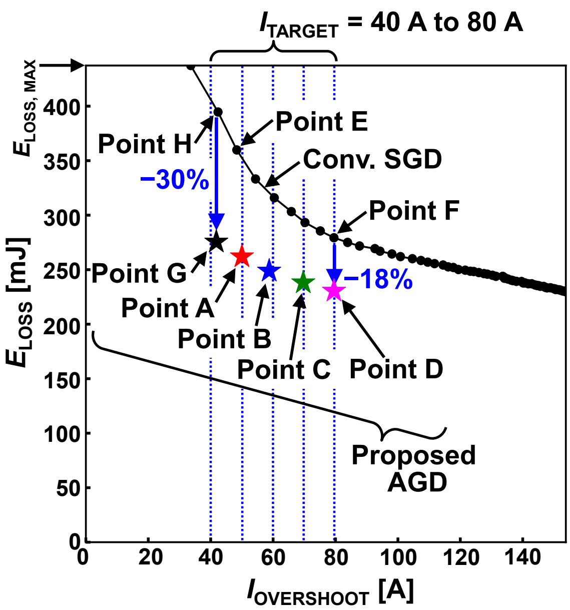

Fig. 10. Measured E_{LOSS} vs. $I_{\mathrm{OVERSHOOT}}$ of conventional SGD and proposed AGD at user-specified I_{TARGET} of 40 A, 50 A, 60 A, 70 A, and 80 A.

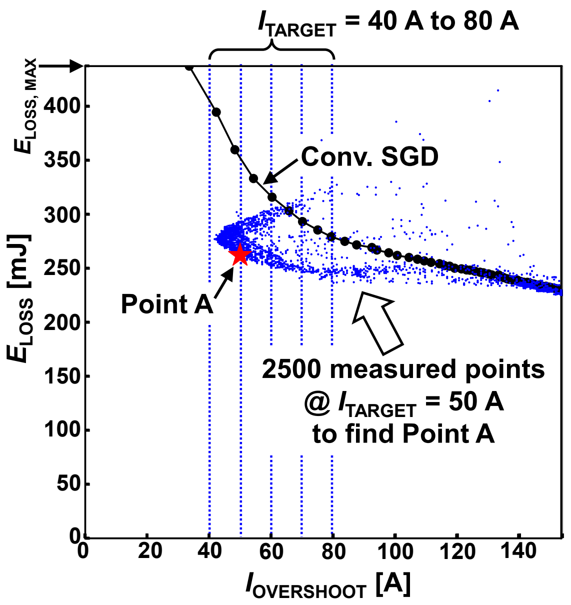

Fig. 11. Measured E_{LOSS} vs. $I_{\mathrm{OVERSHOOT}}$ of conventional SGD and proposed AGD at user-specified I_{TARGET} of 50 A.

B. I_{TARGET} Dependence of E_{LOSS} Reduction Rate

In Fig. 10, I_{TARGET} dependence of the E_{LOSS} reduction rate of the proposed AGD to the conventional SGD is discussed. Compared with SGD, the proposed AGD reduces E_{LOSS} by 30 %, 27 %, 21 %, 19 %, and 18 % at I_{TARGET} = 40 A, 50 A, 60 A, 70 A, and 80 A under $I_{\mathrm{OVERSHOOT}}$-aligned condition, respectively. Thus, as I_{TARGET} increases, the E_{LOSS} reduction rate decreases. The reason for this is that, as shown in Fig. 11, in SGD, E_{LOSS} increases rapidly when $I_{\mathrm{OVERSHOOT}}$ is reduced, while in AGD, focusing on the lower envelope of the blue point group, E_{LOSS} increases slowly when $I_{\mathrm{OVERSHOOT}}$ is reduced.

Figs. 12 (a) and (b) show the measured waveforms of Point G and Point H in Fig. 10, respectively, where Point H is the conventional SGD with $I_{\mathrm{OVERSHOOT}}$ approximately the same as the proposed Point G. Compared with Point H, Point G reduces E_{LOSS} by 30 % from 395 mJ to 275 mJ under $I_{\mathrm{OVERSHOOT}}$-aligned condition.

V. Conclusions

The proposed AGD minimizes E_{LOSS} while keeping $I_{\mathrm{OVERSHOOT}}$ below user-specified I_{TARGET} by automatically searching for the optimum parameters of DGD, which will enable prompt development of low-loss power converters while meeting customer surge specifications. In the double pulse tests at 3.6 kV and 56 A for 6.5 kV IGBT, compared with the conventional SGD, the proposed AGD reduces E_{LOSS} by 27 % and 18 % at I_{TARGET} = 50 A and 80 A, respectively.

Acknowledgment

This work was partly supported by NEDO (JPNP21009).

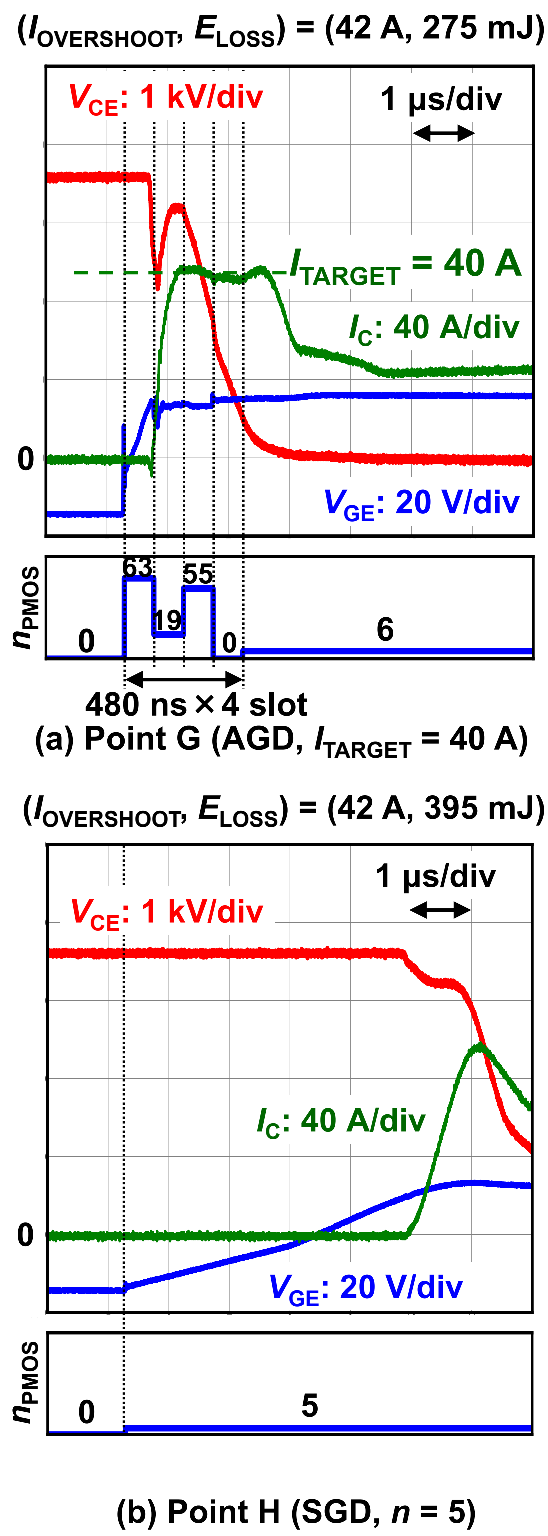

Fig. 12. Measured waveforms of Point G and Point H in Fig. 10.

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