Automatic Search Method of Robust Gate Driving Vectors for Digital Gate Drivers Against Variations in Operating Conditions of IGBT's

Ting-Wei Wang[1, 2], Toru Sai[1], Ryuzo Morikawa[1], Katsuhiro Hata[1], Takayasu Sakurai[1], Po-Hung Chen[2], and Makoto Takamiya[1]

[1]The University of Tokyo, Tokyo, Japan
[2]National Chiao Tung University, Hsinchu, Taiwan

twwang.ee06g@nctu.edu.tw

***Abstract*—To solve the trade-off between the switching loss and the current/voltage overshoot of power transistors, a digital gate driver is effective. A temperature and load current dependent optimization of the gate driving vectors (GV) for the digital gate drivers, however, is required [7]. Robust gate driving vectors (RGV) to the temperature and load current variations are proposed in [9]. The test cost to search RGV, however, is very high. To reduce the test cost, a robust simulated annealing (RSA) for an automatic search method of RGV is proposed. In the proposed RSA, instead of changing the operating conditions, GV is varied in a single operating condition. Compared with the conventional method to search RGV [9], the proposed RSA reduces the measurement time by more than 85 % (from more than 5.5 hours to less than 50 minutes), which results in the reduced test cost.**

Keywords—Gate driver, IGBT, Switching loss, Temperature

I. INTRODUCTION

Active gate driving of power transistors, where the gate driving current is controlled during the turn-on/off transients, is effective to reduce both the switching loss (E_{LOSS}) and the current overshoot ($I_{OVERSHOOT}$) or voltage overshoot ($V_{OVERSHOOT}$) of power transistors, where E_{LOSS} and $I_{OVERSHOOT}$ / $V_{OVERSHOOT}$ are typically are trade-offs in the conventional fixed gate resistance driver. Among the active gate driving, digital gate drivers [1-10] are useful, because the gate driving current is programmable with gate driving vectors using a software. A 6-bit digital gate driver [6] with four 6-bit variables synchronized to the clock signal, where a simulated annealing algorithm is automatically finds an optimum gate driving vector (GV) out of 64^4 ($\sim 1.7 \times 10^7$) combinations, reduces E_{LOSS} by 55% at the same $V_{OVERSHOOT}$ and reduces $V_{OVERSHOOT}$ by 53% at the same E_{LOSS} at the turn-off of IGBT. As shown in [7], the optimum GV, however, changes depending on operating conditions such as temperature and a load current (I_{LOAD}). When an optimum GV at a particular temperature and I_{LOAD} is reused to another temperature and I_{LOAD}, E_{LOSS} and $I_{OVERSHOOT}/V_{OVERSHOOT}$ are sometimes worse than the conventional single-step gate drive [7]. Therefore, temperature and I_{LOAD} dependent GVs are required [7]. The digital gate drivers are not useful under temperature and load current variations, when sensors for temperature and/or I_{LOAD} are not available. To solve the problem, robust gate driving vectors (RGV) for the digital gate drivers to temperature and I_{LOAD} variations are proposed in [9]. RGV improves the trade-off between E_{LOSS} and $I_{OVERSHOOT}/V_{OVERSHOOT}$ across nine conditions including different temperatures and I_{LOAD} [9].

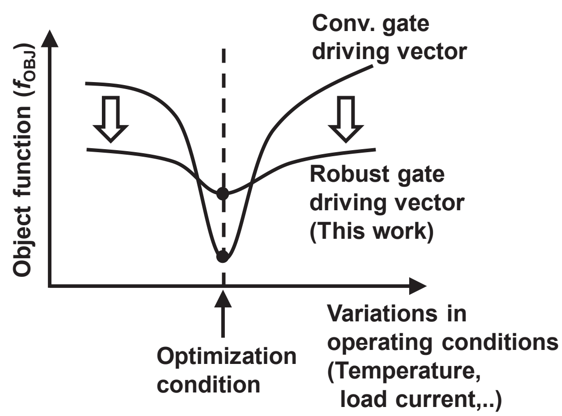
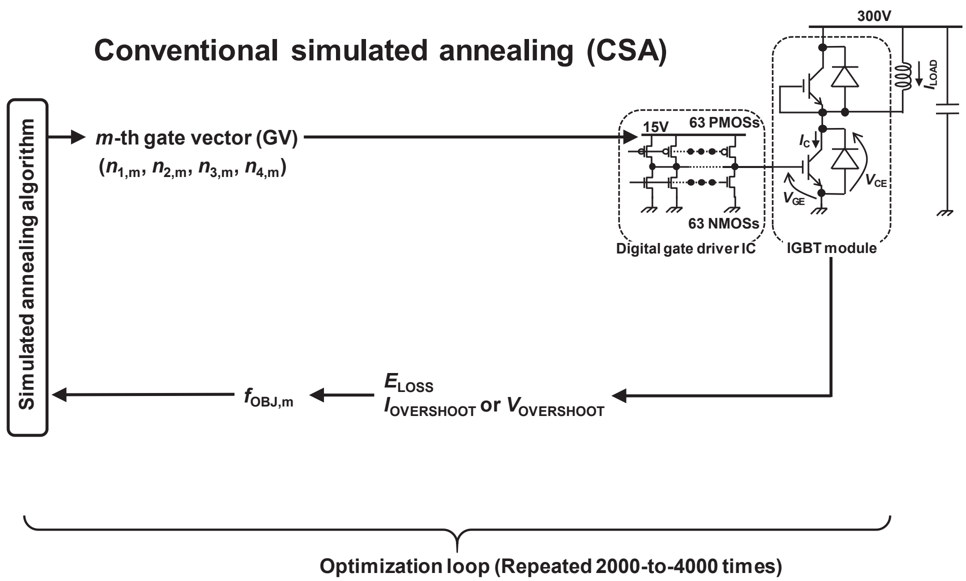


Fig. 1. Concept of robust gate driving vectors (RGV).

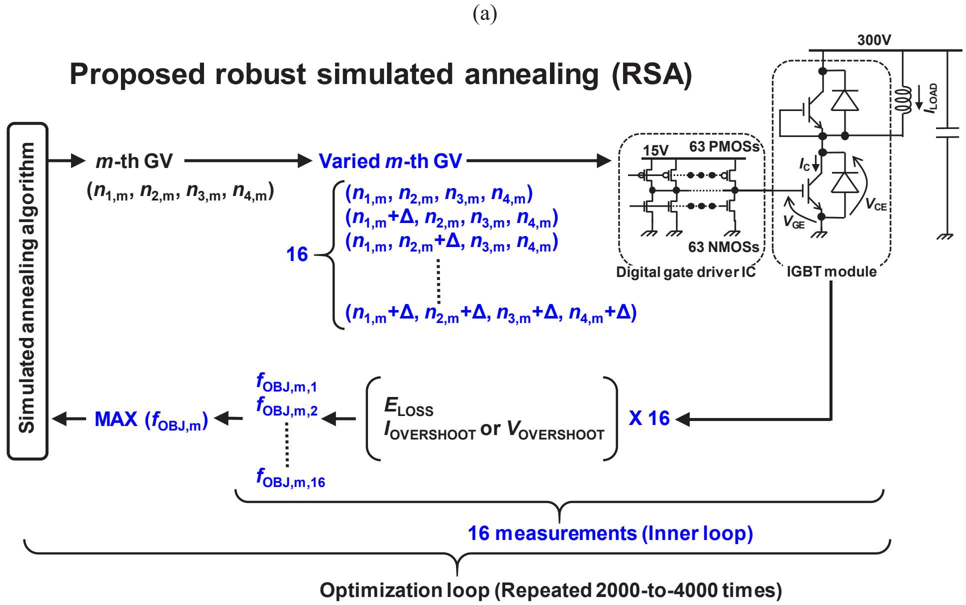
Fig. 1 shows a concept of RGV. The object function (f_{OBJ}) is a function of E_{LOSS} and $I_{OVERSHOOT}/V_{OVERSHOOT}$ and is used in the simulated annealing algorithm [5]. Small f_{OBJ} means small E_{LOSS} and $I_{OVERSHOOT}/V_{OVERSHOOT}$. RGV is a single universal GV that can be applied to different operating conditions. RGV is defined as a single GV which minimize the maximum f_{OBJ} when the operating condition changes [9]. From a practical viewpoint, as shown in Fig. 1, minimizing the maximum f_{OBJ} across variations in operating conditions is important, because product specifications are determined by the maximum f_{OBJ}, thereby RGV is important. The test cost to search RGV, however, is very high, because 90,000 measurements for full search of GVs across nine different I_{LOAD} and temperatures, which take more than 5.5 hours, is required in [9]. To reduce the test cost to search RGV, in this paper, a robust simulated annealing (RSA) for an automatic search method of RGV is proposed.

II. AUTOMATIC SEARCH METHOD OF ROBUST GATE DRIVING VECTORS

Fig. 2 (a) shows a conventional automatic search method [5] of the conventional GVs in Fig. 1 using a conventional simulated annealing (CSA). Fig. 2 (b) shows the proposed automatic search method of RGV using RSA. Fig. 3 shows the GV and waveforms in a 6-bit digital gate driver [5]. n_{NMOS} shows the number of activated NMOS transistors in 63 parallel NMOS transistors in the 6-bit digital gate driver [5]. In this paper, the GV is defined as (n_1, n_2, n_3, n_4) , where n_1, n_2, n_3, and n_4 are integers from 0 to 63. In this paper, only turn-



(a)



(b)

Fig. 2. (a) Conventional simulated annealing (CSA). (b) Proposed robust simulated annealing (RSA) for automatic search method of RGV.

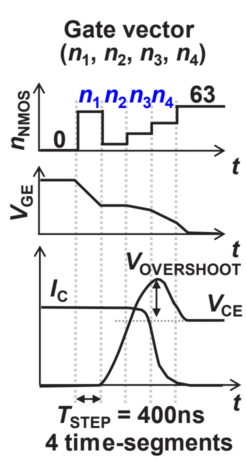


Fig. 3. Gate vector and waveforms in 6-bit digital gate driver.

off is shown for simplicity. As shown in Fig. 2 (a), a GV is given to the 6-bit digital gate driver. Then, the collector current (I_C) and the collector-to-emitter voltage (V_{CE}) waveforms of IGBT are measured in the double pulse test. After that, f_{OBJ} is calculated to evaluate E_{LOSS} and $V_{OVERSHOOT}$.

$$f_{OBJ} = \sqrt{\left(\frac{E_{LOSS}}{E_{LOSS,\,MAX}}\right)^2 + \left(\frac{V_{OVERSHOOT}}{V_{OVERSHOOT,\,MAX}}\right)^2} \qquad (1)$$

where the subscript MAX signifies the maximum of the corresponding quantity. Based on f_{OBJ}, the simulated annealing algorithm provides a new GV for the next measurement. By repeating the optimization loop more than 2000 times, an optimum GV is obtained [5]. The difference

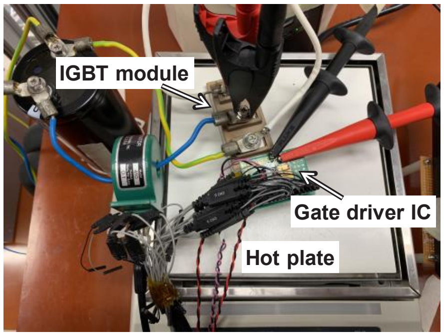


Fig. 4. Photo of measurement setup.

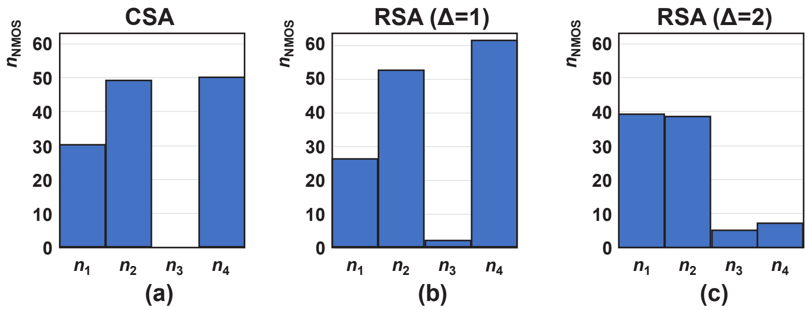


Fig. 5. Optimized gate vectors. (a) CSA. (b) RSA (Δ = 1). (c) RSA (Δ = 2).

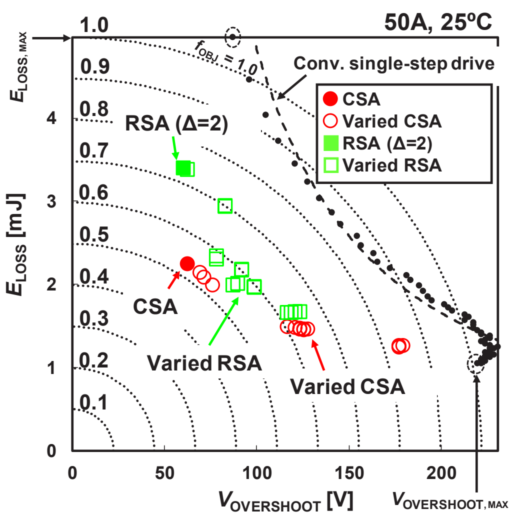


Fig. 6. Measured E_{LOSS} vs. $V_{OVERSHOOT}$ of five gate drives at 25 °C.

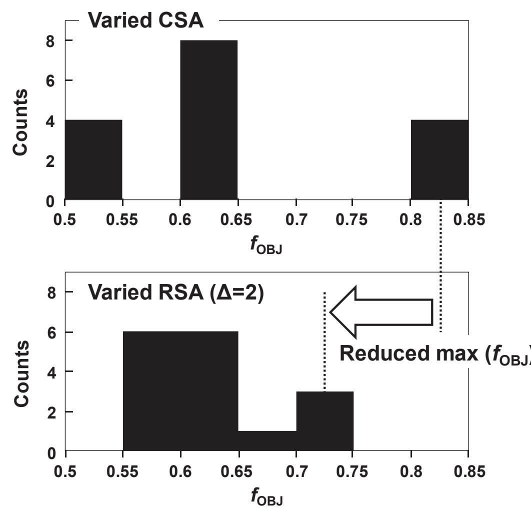


Fig. 7. Histograms of f_{OBJ} of varied CSA and varied RSA extracted from Fig. 6.

between CSA and the proposed RSA is shown in blue characters in Fig. 2 (b). In the proposed RSA, instead of changing the operating conditions in the automatic search of GVs in CSA, GV is varied in a single operating condition to reduce the test cost. In other words, for example, I_{LOAD} and temperature variations are emulated by the gate driving current variations. The emulation is very effective to reduce the test cost to search RGV, because the varied GV is done by a software instead of actually changing of the operating conditions. Specifically, as shown in Fig. 2 (b), a GV is augmented to 16 GVs by adding Δ (= 1 or 2) to the *m*-th GV ($n_{1,m}$, $n_{2,m}$, $n_{3,m}$, $n_{4,m}$), and 16 measurements are done using 16 GVs. Then 16 f_{OBJ}'s are calculated by using measured E_{LOSS} and $V_{OVERSHOOT}$, and the largest f_{OBJ} out of the 16 f_{OBJ}'s is given to the simulated annealing algorithm. As a result, RSA searches RGV which minimize the maximum f_{OBJ} across variations in operating conditions. In RSA, more than 32,000 (= 16 × 2000) measurements are required to search RGV.

III. Measured Results

Fig. 2 (b) shows a circuit schematic of the measurement setup for the double pulse test of IGBT (2MBI100TA-060-50, 600 V, 100 A) at 300 V. I_{LOAD} is fixed to 50 A. Fig. 4 shows the photo of the measurement setup. The IGBT module is put on a hot plate to control the temperature. The measurement setup is the same as [7] except for the automatic search method. In order to clarify the advantage of the proposed RSA over CSA, optimum GVs are searched using both RSA and CSA at 25 °C, and E_{LOSS}, $V_{OVERSHOOT}$, and f_{OBJ} using the optimum GVs at 25 °C, 75 °C, and 125 °C are compared. The optimum GVs are searched at 25 °C instead of 125 °C, because the test cost at room temperature (25 °C) is lower than that at an operating junction temperature of IGBTs (125 °C). Figs. 5 (a) to (c) show the optimum GV obtained by CSA, RGVs obtained by RSA with Δ of 1 and 2 at 25 °C, respectively. In CSA, it takes less than 9 minutes to search the GV by repeating less than 2400 optimization loops (= 2400 measurements). In contrast, in RSA, it takes less than 50 minutes to search the RGV by repeating less than 2500 optimization loops (= 2500 × 16 = 40,000 measurements). Compared with the conventional full search across nine different I_{LOAD} and temperatures, which take more than 5.5 hours [9], the proposed RSA at a single operating condition reduces the measurement time by more than 85 %, which results in the reduced test cost.

In order to confirm that RGV obtained by RSA has a smaller maximum f_{OBJ} than that by CSA under GV variations, Fig. 6 shows measured E_{LOSS} vs. $V_{OVERSHOOT}$ of the five gate drives in turn-off state at 25 °C. The black curve shows the trade-off curves of the conventional single-step gate drive with varied gate driving current [7]. The dotted concentric curves show the contour of f_{OBJ} defined in Eq. (1). In Fig. 6, "CSA" shows the optimum GV obtained by CSA, "Varied CSA" shows 15 varied GVs where Δ = 2 is added to "CSA" as shown in Fig. 2 (b), "RSA (Δ = 2)" shows the RGV obtained

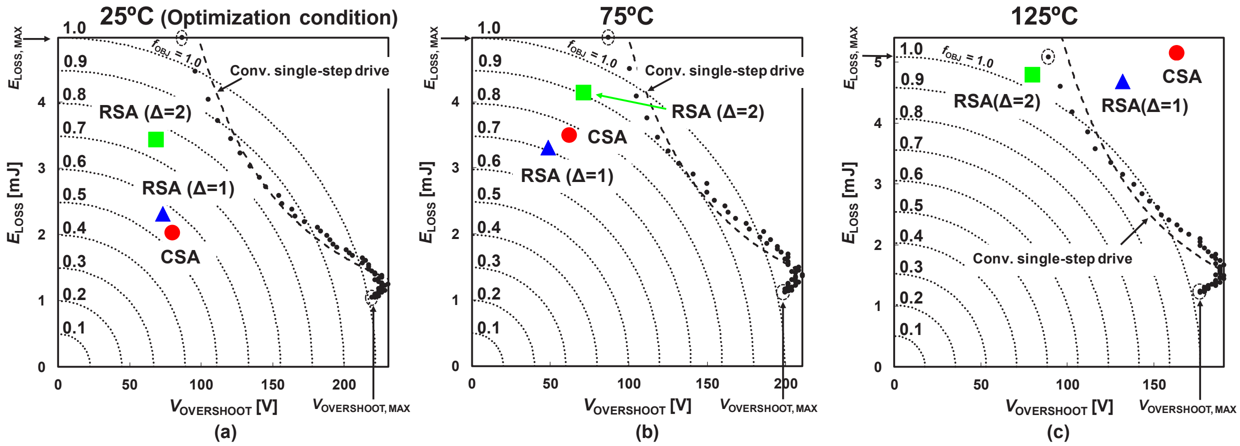


Fig. 8. Measured E_{LOSS} vs. $V_{OVERSHOOT}$ of four gate drives at (a) 25 °C, (b) 75 °C, and (c) 125 °C using gate vectors optimized at 25 °C in Fig. 5.

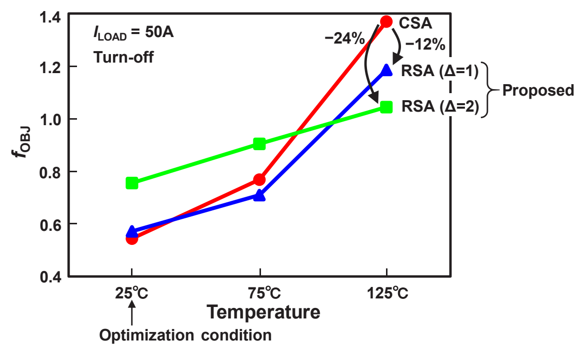


Fig. 9. Measured temperature dependence of f_{OBJ} for three gate drives extracted from Fig. 8.

by RSA with Δ = 2, and "Varied RSA" shows 15 varied GVs where Δ = 2 is added to "RSA (Δ = 2)". Note that "Varied CSA" has the largest f_{OBJ} because of the largest $V_{OVERSHOOT}$ of 180 V. Fig. 7 shows histograms of f_{OBJ} of "Varied CSA" and "Varied RSA" extracted from Fig. 6. The maximum f_{OBJ} of "Varied RSA" is clearly smaller than that of "Varied CSA", which supports that the concept of RGV shown in Fig. 1 is really achieved under GV variations.

In order to verify that RGV obtained by RSA has a smaller maximum f_{OBJ} than that by CSA under temperature variations, Figs. 8 (a) to (c) show the measured E_{LOSS} vs. $V_{OVERSHOOT}$ of the four gate drives in turn-off state at 25 °C, 75 °C, and 125 °C, respectively, using GVs optimized at 25 °C shown in Fig. 5. The black curves show the trade-off curves of the

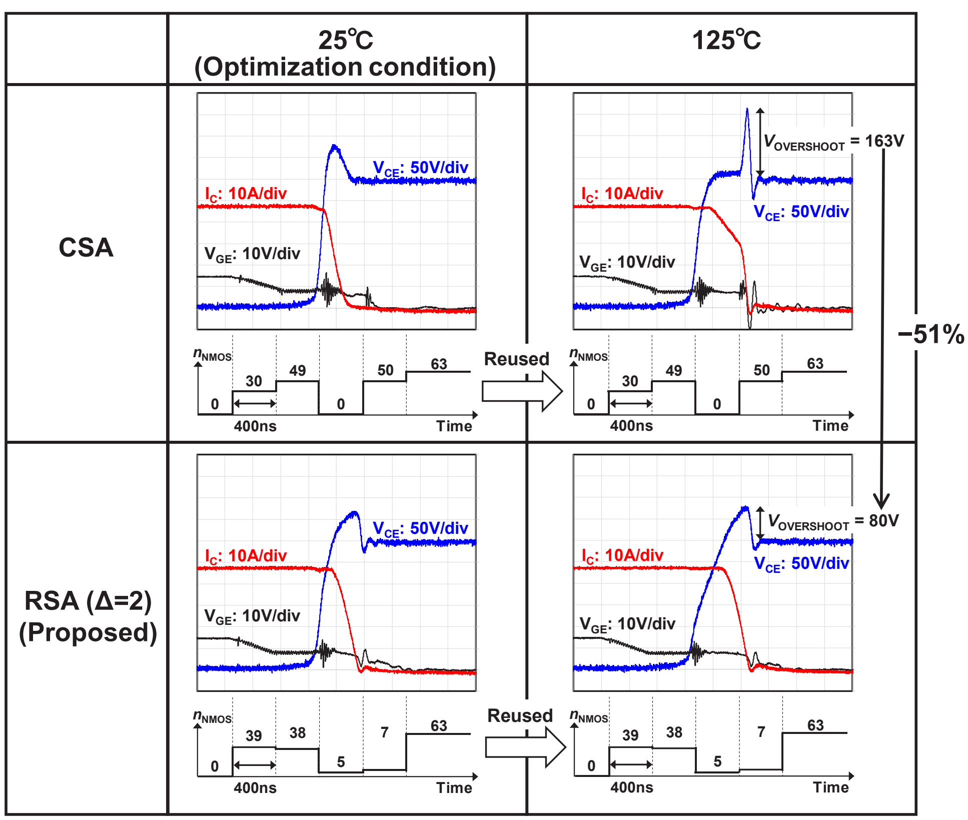


Fig. 10. Gate driving vectors and measured waveforms of CSA and proposed RSA (Δ = 2) at 25 °C and 125 °C.

conventional single-step gate drive with varied gate driving current [7]. At 25 °C in Fig. 8 (a), f_{OBJ}'s of CSA, RSA (Δ = 1), and RSA (Δ = 2) are smaller than those of the conventional single-step gate drives. In contrast, when the temperature is increased from 25 °C to 75 °C and 125 °C, f_{OBJ}'s of CSA, RSA (Δ = 1), and RSA (Δ = 2) are increased, because the GVs are optimized at 25 °C. Fig. 9 shows the measured temperature dependence of f_{OBJ} for CSA, RSA (Δ = 1), and RSA (Δ = 2) extracted from Fig. 8. At 25 °C, f_{OBJ} of CSA is the smallest as expected. In contrast, at 125 °C, f_{OBJ} of the proposed RSA (Δ = 2) is the smallest. Quantitatively, compared with f_{OBJ} of CSA and RSA (Δ = 1), f_{OBJ} of the proposed RSA (Δ = 2) is reduced by by 24 % and 12 %, respectively. Thus, under temperature variations, the maximum f_{OBJ} of the proposed RSA (Δ = 2) is the smallest among three GVs, which supports that the concept of RGV shown in Fig. 1 is really achieved. Fig. 10 shows the gate driving vectors and measured waveforms of CSA and the proposed RSA (Δ = 2) at 25 °C and 125 °C. The corresponding E_{LOSS} and $V_{OVERSHOOT}$ are shown in Figs. 8 (a) and (c). In CSA, when the GV searched at 25 °C is reused at 125 °C, large $V_{OVERSHOOT}$ of 163 V is observed, while $V_{OVERSHOOT}$ of RSA at 125 °C is 80 V. RSA reduces $V_{OVERSHOOT}$ by 51 %, which indicates that RGV obtained by RSA is really robust to temperature variations.

IV. Conclusions

In order to reduce the test cost to search RGV, which is a single universal GV that can be applied to different operating conditions, RSA for the automatic search method of RGV is proposed. Compared with the conventional full search method of RGV [9], the proposed RSA at a single operating condition reduces the measurement time by 86 %, which results in the reduced test cost. When GVs searched at 25 °C are reused to 125 °C, compared with CSA, the proposed RSA (Δ = 2) reduces f_{OBJ} and $V_{OVERSHOOT}$ by 24 % and 51 %, respectively.

Acknowledgment

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