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Benchmarking of Digital Gate Driven IGBTs: New Eoff-Vsurge Trade-off Approach

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***Abstract*— Digital gate driving methods have been recently proposed to control the IGBT switching transient by dynamically changing the drive power according to the input digital pattern. It has been reported that both surge voltage suppression and turn-off loss reduction can be consistently achieved. In the prior papers, however, the effect is evaluated based on only one optimum point, so that the effect of digital gate driving technology have not been accurately benchmarked for practical use. In this paper, we proposed a new benchmarking method for digital gate driven IGBTs using an approach of Eoff -Vsurge Trade-off shifts. We applied the proposed method to 12 types of IGBT samples and analyzed the benchmarking results.**

Keywords— IGBT, Benchmarking Method, Digital Gate Drive, Trade-off Shift, Turn-off Loss, Surge Voltage

I. INTRODUCTION

Digital gate driver (DGD) have been recently proposed to control the IGBT switching transient by dynamically changing the gate driving power according to the input digital pattern. Whereas conventional gate drivers drive IGBTs with constant gate resistances, the DGDs drive with variable gate current [1-3] or gate resistance [4-6] changing with switching transient to optimize the switching characteristics. Several research result have been reported on improvement of switching loss and surge voltage trade-off by searching the optimum input digital pattern.

In the prior reports, however, the effect is evaluated based on only one optimum point of Eoff –Vsurge along the axis, so that the effect of digital gate driving technology have not been accurately benchmarked for practical use. In this paper, we proposed a new benchmarking method for digital gate driven IGBTs using a unique approach of Eoff -Vsurge trade-off shifts. We applied the proposed method to 12 types of IGBTs and analyzed the benchmarking results.

II. EXPERIMETAL SYSTEM

The experimental system consists of a controller, a pattern generator, a digitizer, a digital gate driver, a main circuit for double pulse test, and a high-voltage power supply (Fig.2) [7],[8]. The controller, digitizer, and pattern generator are integrated in the chassis with PXIe back plane bus to minimize data transfer time.

A. Digital Gate Driver

A 24-bit DGD with a wide output range was prepared for various samples of IGBT with different current ratings and chip size. As shown in Fig. 3, among the 24 bit inputs, 12 bits are used for driving control at turn-on, and the others are used for control at turn-off. As the result, the drivability has a range of 4000 times. Inputs and outputs are isolated in the driver for digital equipment protection and safety.

The digital signal generated by the pattern generator is input to the buffer ICs via the digital isolator. Inverting buffer ICs are used to drive source side 12 pnp transistors and non-inverting buffer ICs to drive sink side 12 npn transistors. The total gate resistance is controlled with input digital signal by changing the combination of transistors turned on. Since resistors of 2.0Ω to 4 kΩ are connected to 12 transistors respectively, the total gate resistance has the range of 1.0Ω to 4 kΩ.

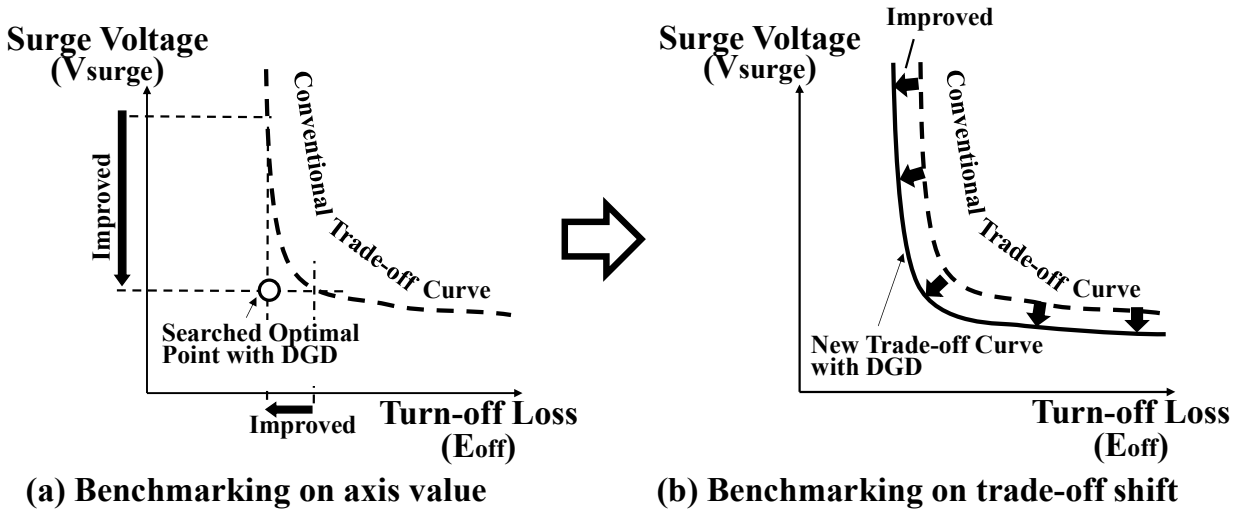

Fig.1. Benchmarking method for DGD IGBTs

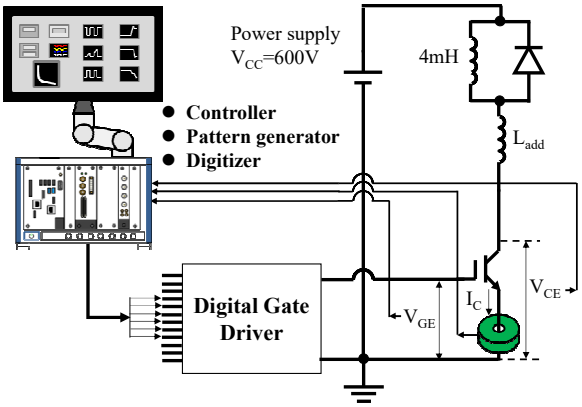

Fig.2. Experimental system

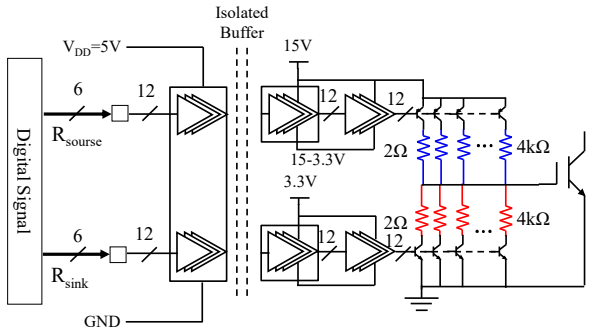

Fig.3. DGD circuit diagram

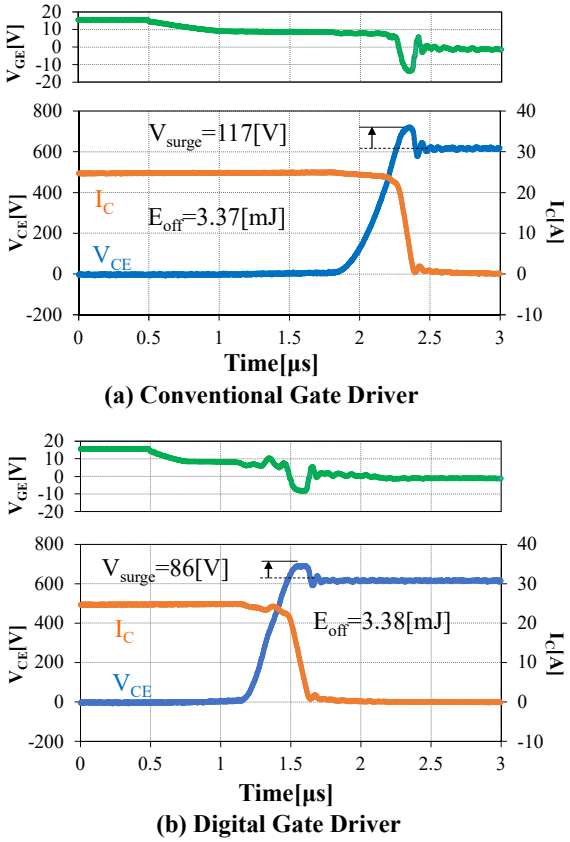

Fig.4. Switching waveform examples
(a) Conventional Gate Driver (b) Digital Gate Driver

B. Simulated Annealing

In the DGD, it is necessary to specify a combination of gate resistors that can achieve both reduction of turn-off loss and suppression of surge voltage from a huge number of combinations of gate resistors. In this study, we constructed a simulated annealing (SA) method [7], [8] as an optimization method, and SA searched the optimum digital pattern for DGD. The SA method is one of the optimization methods that uses an algorithm to converge a solution within a certain search range to the optimum state, and it is possible to approach the optimum state without being limited to a local solution. The SA method is mainly used in analyzing combinatorial optimization problems such as this study.

In this study, the SA method is implemented into the system using MATLAB and LabVIEW on the controller so that the evaluation function equation (1) shown below is minimized. By minimizing the evaluation function, the optimum point at which the turn-off loss and surge voltage can be reduced most can be obtained.

$$J = \sqrt{\alpha^2 \left(\frac{E_{off}}{E_{off\_max}}\right)^2 + \beta^2 \left(\frac{V_{surge}}{V_{surge\_max}}\right)^2} \quad \cdots\cdots\cdots\cdots\cdots (1)$$

Figure 4 shows improvement example of turn-off waveform by the experimental system. Surge voltage was suppressed from 117V to 86V under identical turn-off loss.

III. Benchmarking on Axis Value

We evaluated degree of improvement of an optimal point searched by SA method compared by the value on the conventional trade-off curve along the axis as shown Fig. 1 (a). In the search using the SA method, the gate resistance at turn-off was switched every 400 ns to drive the IGBT. The range of gate resistance was selected according to the characteristics of the IGBT.

The basic characteristics and experimental conditions of the IGBT sample used in the experiment are shown Table 1, the benchmarking results are shown Fig. 4. We confirmed the improvement in all of the IGBT sample. The degrees of improvement varied from -5% to -70% and the results can be under- or over-estimated since it does not consider practical degree of improvement based on the trade-off obtained with DGD.

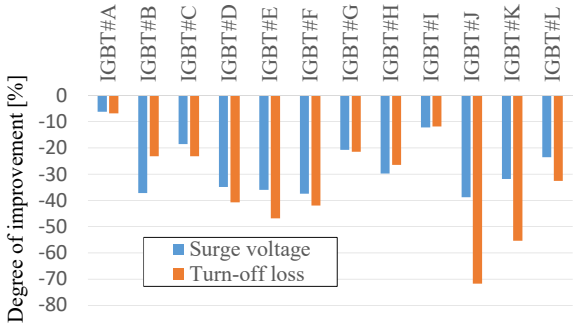

Fig.4. DGD IGBT benchmarking on axis value

Table.1. Basic characteristics and experimental conditions of IGBT samples

No.	Basic characteristics					Experimental conditions		
	Rated collector-emitter voltage [V]	Rated DC collector current[A]	Collector-emitter saturation voltage[V]	Input capacitance [pF]	Chip size [mm2]	V_{CC} [V]	I_C [A]	R_g range [Ω]
IGBT #A	1200	50	4.2	4190	62.27	600	25	7.5~240
IGBT #B	1200	50	3.5	3100	54.88	600	25	15~470
IGBT #C	1200	50	2	4800	92.16	600	25	7.5~240
IGBT #D	1200	50	1.85	2800	49.59	600	25	15~470
IGBT #E	1200	50	1.75	3270	57.56	600	25	15~470
IGBT #F	1200	50	2	3269	56.62	600	25	15~470
IGBT #G	1200	57	1.9	5100	108.16	600	28.5	7.5~240
IGBT #H	1200	100	1.9	9000	153.76	600	50	4~120
IGBT #I	1200	150	2	12500	222.01	600	75	4~120
IGBT #J	1200	15	1.7	1100	21.16	600	7.5	30~1k
IGBT #K	1200	40	1.7	2500	29.76	600	20	15~470
IGBT #L	1200	60	1.7	3700	31.36	600	30	15~470

IV. Benchmarking on Trade-off Shift

We evaluated the degree of improvement by comparing the trade-off curve when using the DGD with respect to the conventional trade-off curve. The trade-off curve when using DGD is obtained by changing α and β and controlling the search direction. When α is increased, the search proceeds in the direction of giving priority to the switching loss, on the other hand, when β is increased, the search proceeds in the direction of giving priority to the surge voltage. Therefore, by changing α and β and searching while controlling the direction, the turn-off loss and surge voltage when using the DGD can be measured over a wide range (Fig. 5).

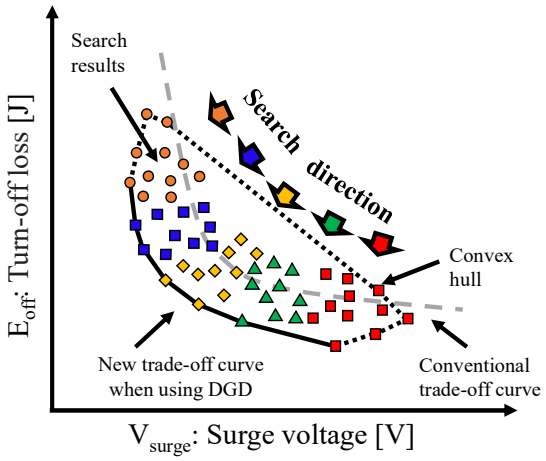

Fig.5. How to obtain the trade-off curve when using the DGD

In this study, we found a convex hull that includes all the results with different search directions, and extracted a part of it to derive a trade-off when using the DGD. Figure 6 shows the trade-off curves of the six IGBT samples A to F when using the conventional gate driver and the DGD.

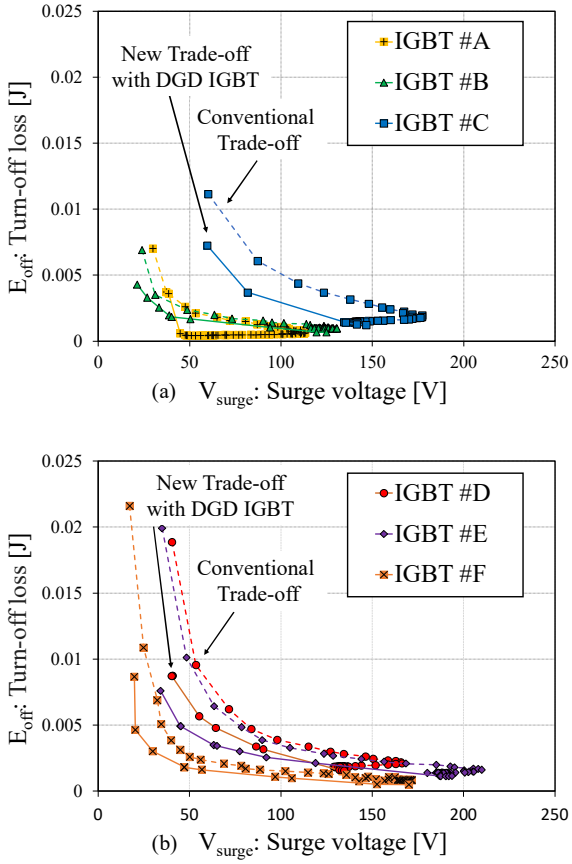

Fig.6. Trade-off comparison of each IGBTs
(a) Results of IGBT #A, #B, #C (b) Results of IGBT #D, #E, #F

The degree of improvement is calculated by comparing the points in the trade-off curve where the evaluation function is the smallest. We can compare the entire trade-off curve by changing the weighting of the evaluation function. Benchmarking results for the 12 type of IGBT samples are shown Figure 7. We confirmed the sweet spot with the minimum improvement in all IGBT samples. The degree of improvement in the sweet spot varied from -15% to -35%, and the results are not underestimated or overestimated since we are evaluating the entire trade-off (Fig.8).

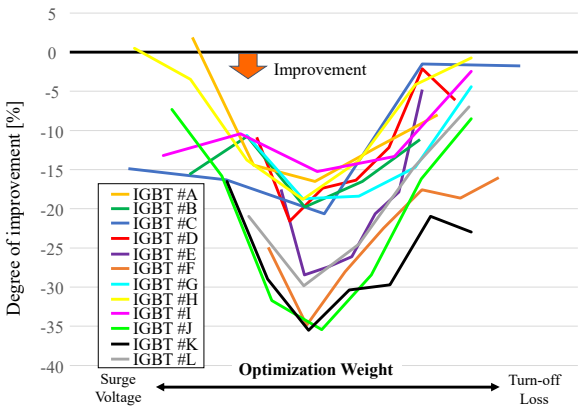

Fig.7. DGD IGBT benchmarking on trade-off curve shift

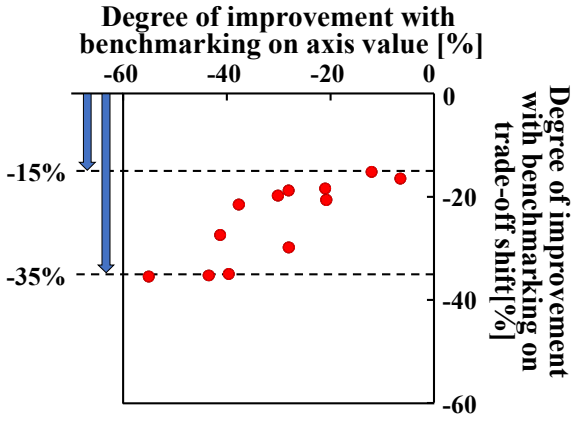

Fig.8. Comparison degree of improvement for two benchmarking methods

V. Conclusion

DGD, which is a new driving method of IGBT, can improve transient characteristics such as turn-off loss and surge voltage, and much research has been done. In the prior papers, however, the effect is overestimated or under estimated therefore the effect of digital gate driving technology have not been accurately benchmarked for practical use.

In the evaluation by the trade-off shift comparison proposed in this study, the degree of improvement of -15% to -35% was observed in all IGBT samples. As a result, it was confirmed that the proposed method was accurately benchmarked for practical use. In the future, integrated design of devices and circuits based on the combination of IGBT and DGD will be required.

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