On-Line Estimation of IGBT Junction Temperature Using On-State Voltage Drop

Yong-Seok Kim and Seung-Ki Sul

School of Electrical Engineering
Seoul National University
San 56-1 Sillim-Dong, Kwanak-Ku, Seoul, Korea(ZIP : 151-742)
Phone: +82-2-880-7243 Fax: +82-2-878-1452
E-Mail: hermit1@plaza.snu.ac.kr , http://eepel.snu.ac.kr

Abstract - **In this paper, noninvasive and accurate on-line estimation method for IGBT junction temperature is proposed. To optimize the heat management of IGBTs, it provides accurate information about junction temperature The proposed method requires a few additional passive circuit components for the estimation and it can be easily incorporated into the conventional gate driver circuit. The proposed method consists of two processes, one is off-line characterization of the IGBT under test and the other one is on-line estimation of junction temperature based on the characterized data. The simulation and experimental results confirm the validity of the proposed estimation method.**

I. INTRODUCTION

Owing to the capability of high-frequency switching with low saturation voltage and small driving power, IGBT is widely used in many power electronics applications[1~4]. In designing the power electronics systems using IGBT, the junction temperature of an IGBT is critical in determining its survival and lifetime which affect directly the reliability of the system[5,6]. Therefore, the clarification of the junction temperature is an essential part of the design process. The accurate information about IGBT junction temperature is very useful for enhancing the reliability, cost and performance of power electronics system. But it is difficult to obtain actual junction temperature because it cannot be measured directly by noninvasive method.

Traditionally, IGBT junction temperature was estimated from the junction temperature of heat sink using a thermal sensor adhered to the heat sink. The estimation of the junction temperature using thermal sensors has some incorrectness due to the followings;

- errors in thermodynamic model and variation of its constants.
- variation of thermodynamic time delay according to setup position of thermal sensor on heat sink.
- local heating problem in multi IGBT's on the same heat sink.

Recently, to overcome these problems, an estimatation method of IGBT junction temperature using on-state voltage drop was reported[7]. In that method, IGBT junction temperature can be obtained by applying the short pulse of small magnitude current when the collector current is nearly zero. However, since the on-state voltage drop is more severely influenced by the collector current than by the junction temperature at nearly zero collector current, it is impossible to detect the junction temperature exactly due to the difficulty in finding out the precise zero crossing point of collector current.

This paper proposes a new estimation method of IGBT junction temperature. In the proposed method, the junction temperature is estimated using the characteristic of IGBT that the on-state voltage drop is the function of the junction temperature and the collector current. The method consists of two processes, where one is off-line characterization of the IGBT under test and the other one is on-line estimation of junction temperature based on the characterized data. It requires a few additional passive circuit components and they can be incorporated into the conventional gate driver circuit easily. In order to show the validity of proposed method clearly, some tests are performed on a SKiiP (Semikron Integrated Intelligent Power) pack which has a thermal sensor attached to the silicon die of IGBT.

II. IGBT ON-STATE VOLTAGE DROP

For the estimation of IGBT junction temperature using on-state voltage drop, it is necessary to analyze the characteristics of IGBT as the function of the junction temperature. The electro-thermal models of IGBT have been proposed for the electro-thermal analysis of IGBT. Fig. 1 shows a structure of the Electro-thermal model of IGBT[8]. Analyzing the characteristics of IGBT based on the model in Fig. 1, the on-state voltage drop between collector and emitter is a complex nonlinear function[9]. Fig. 2 shows the simulation result of the electro-thermal model of IGBT based on Ref. [9,10]. In Fig.2, the on-state voltage drop of IGBT

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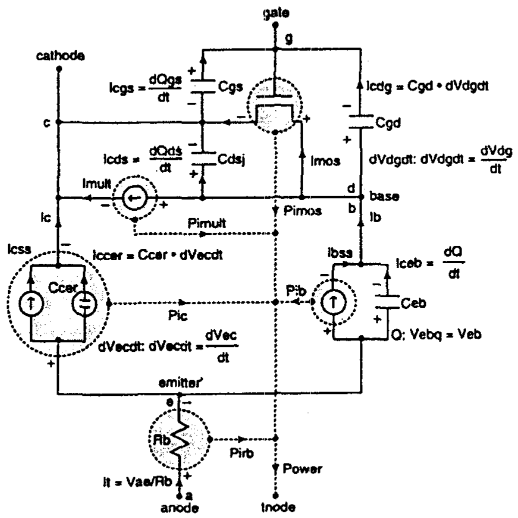

Fig. 1. Electro-thermal structure of IGBT

is the nonlinear function of the collector current and the junction temperature. But if the error bound is set within a certain level, the on-state voltage drop of IGBT can be approximated as

$$\begin{aligned} V_{ce(sat)}(T_j, I_c, V_{ge}) &= V_{ceo} + \Delta V_{ceo}(T_j - T_{jo}) \\ &\quad + I_c\left[r_o + \Delta r_o(T_j - T_{jo})\right] \\ &\quad - \alpha_{ge} \cdot \Delta V_{ge} \end{aligned} \tag{1}$$

where $V_{ce(sat)}$, T_j, I_c and V_{ge} indicate the on-state voltage drop, junction temperature, collector current and gate-emitter voltage, respectively. V_{ceo} and r_o represent the on-state voltage drop and ohmic resistance at the reference junction temperature T_{jo}, ΔV_{ceo} and Δr_o are the temperature coefficients(the dependence of the parameter on temperature) for V_{ceo} and r_o respectively. α_{ge} is the proportional constant for gate-emitter voltage difference ΔV_{ge}. From (1) the on-state voltage drop is the function of junction temperature, collector current and gate-emitter voltage. If the current and gate-emitter voltage is constant, (1) can be simplified to the function of only the junction temperature as

$$V_{ce(sat)}(T_j, I_{co}, V_{geo}) = V'_{ceo} + \Delta V_{ceo}(T_j - T_{jo}). \tag{2}$$

where V'_{ceo} is the on-state voltage drop at reference temperature, current and gate-emitter voltage. It is possible that the gate-emitter voltage can be maintained as a fixed constant value in steady state. Therefore if the collector current is measured and gate-emitter voltage at steady state is constant, junction temperature can be estimated effectively using on-state voltage drop. Simulation result of (2) is represented in Fig. 3 compared with original nonlinear

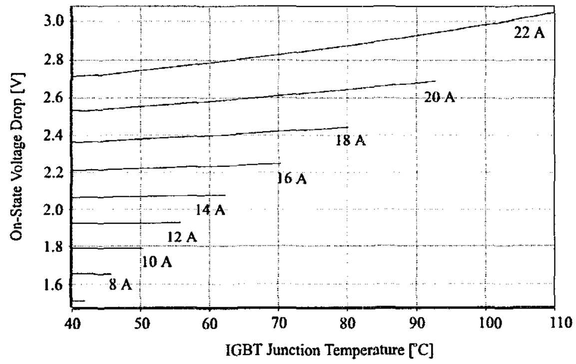

Fig. 2. Simulated nonlinear characteristics of IGBT

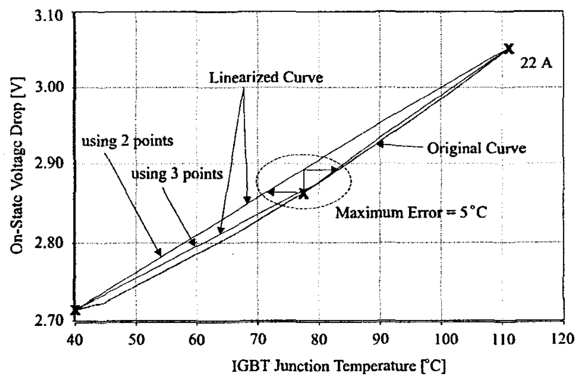

Fig. 3. Linearization of the on-state voltage drop

characteristics. In Fig.3, upper linearization curve is linearized using two reference points and lower one is linearized using three reference points. The linearization error is bounded within 5 °C on upper linearization curve and within 3°C on lower one in this IGBT model. Hence, a few reference data is enough to estimate the junction temperature using on-state voltage drop based on (2).

For the simulation of on-line junction temperature estimation, electro-thermal simulation based on (2) is performed with Saber™. The simulation circuit for the junction temperature on-line estimation is shown in Fig. 4, which consists of half bridge inverter, digital controller and electro-thermal network. The digital controller consists of the junction temperature estimator, current regulator, PWM signal generator and gate driver. It is designed with MAST(the modelling language for Saber™ simulator). The IGBT model based on [9] and electro-thermal network based on [10] are used. Fig. 5 shows that the on-state voltage drop is dependent on the junction temperature at constant load current and gate-emitter voltage. From the result of simulation, if the collector current is measured and the gate-

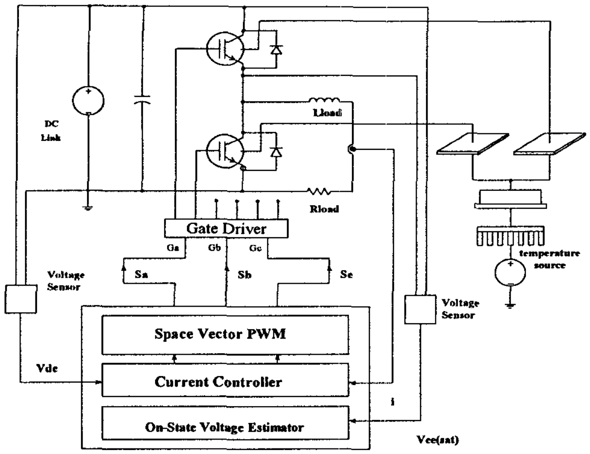

Fig. 4. Simulation circuit for the on-line estimation of the IGBT junction temperature.

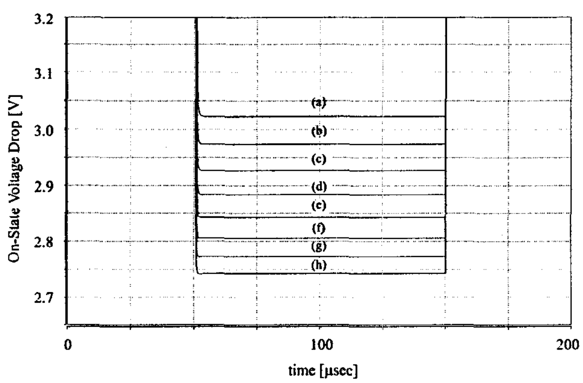

Fig. 5. The temperature dependence of the on-state voltage drop. (a) 110°C. (b) 100°C. (c) 90°C. (d) 80°C. (e) 70°C. (f) 60°C. (g) 50°C. (h) 40°C.

TABLE I
CIRCUIT PARAMETERS UNDER SIMULATION

Switching frequency	f_{sw}	5	*kHz*
Load resistance	R_{load}	0.3	Ω
Load inductance	L_{load}	2.0	mH
Gate-emitter voltage	V_{ge}	15	V
Thermal resistance			
• junction to heat sink	$R_{th(j-h)}$	0.080	°C/W
• heat sink to ambient	$R_{th(h-a)}$	0.036	°C/W

emitter voltage is constant at on-state, the junction temperature of IGBT is estimated using (2) by measuring the on-state voltage drop. Also, the simulation result shows that if the collector-emitter voltage at off-state is blocked effectively, the on-state voltage drop can be measured during the operation of system.

III. EXPERIMENTAL RESULTS

A. Off-line Characterization Of IGBT

Generally, the parameters in (1) and (2) cannot be obtained from vendors of IGBT. Even if they are available, the parameters are nominal values and they differ according to batch to batch. If the IGBT for the system is fixed, the parameters can be extracted by off-line tests. Through the tests, the parameters of specific IGBT can be extracted and the on-state voltage drop can be tabulated according to the junction temperature and collector current. For blocking the high voltage at off-state and delivering the accurate information of the voltage drop at on-state with no negative effects on controller and measurement circuit, two kinds of measurement circuit are proposed in Fig. 6. The circuits in Fig. 6(a) and Fig. 6(b) are proposed for medium V_{ce} and high V_{ce} respectively, where 'medium' means that 0~600V is applied between collector and emitter at off-state, and 'high' for 600~2000V. The configuration of experimental setup is shown in Fig. 7. It consists of half bridge circuit using SKiiP, proposed measurement circuit and DSP controller using TMS320C31 for current regulation. The junction temperature is controlled in the chamber, which can keep the temperature constant set value. Specification of IGBTs and experimental conditions for off-line measurement are represented in table II and table III, respectively. After the temperature in the chamber is in a steady state and load current comes to desired value using the control of A$^+$ IGBT, a short current pulse is applied to the IGBT under test(B$^+$ IGBT). The level of test current can be controlled by the A$^+$ IGBT and the on-state voltage drop is monitored at each case.

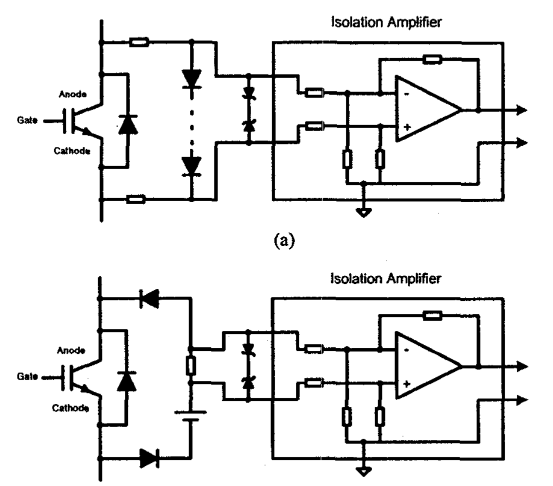

Fig. 6. Circuit configuration for measurement of the on-state voltage drop. (a) For medium V_{ce} (0V~600V). (b) For high V_{ce} (600V~2000V).

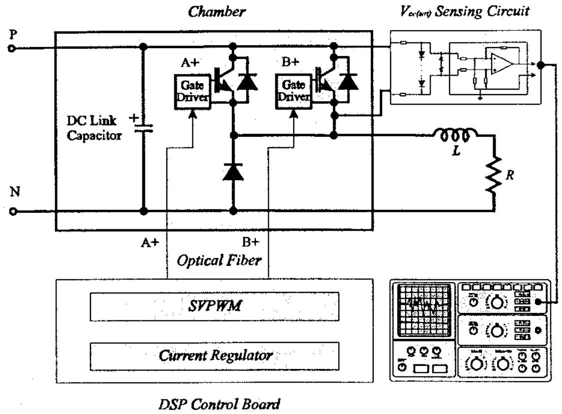

Fig. 7. Configuration of experimental setup for off-line estimation of reference value.

TABLE II
SPECIFICATION OF IGBT USED IN EXPERIMENT

Type :	SKiiP 292 GD 170 - 372 WT		
DC Link Voltage (max)	V_{ces}	1700	V
Collector Current (at 25°C)	I_c	250	A
On-state Voltage Drop	$V_{ce(sat)}$		
• I_c=187A, T_j=25(125) °C		3.30 (4.60)	V
• I_c=250A, T_j=25(125) °C		3.75 (5.65)	V
Thermal resistance			
• junction to heat sink	$R_{th(j-h)}$	0.080	°C/W
• heat sink to ambient	$R_{th(h-a)}$	0.036	°C/W

TABLE III
EXPERIMENTAL CONDITIONS

Switching frequency	f_{sw}	5	*kHz*
Test pulse width		100	μsec
Load resistance	R_{load}	2.72	Ω
Load inductance	L_{load}	3.0	mH
Gate-emitter voltage	V_{ge}	15	V

The on-state voltage drops with respect to the various collector current at T_j = 70°C is represented in Fig. 8. The junction temperature is assumed to be constant during the short pulse (about 100μsec pulse). The on-state voltage drops with respect to the various junction temperature at I_c=150A is represented in Fig. 9. The junction temperature measured by the thermal sensor in SKiiP is also used for verification. The sensor is directly attached to a silicon die of IGBT. It is certified from the measurements that the on-state voltage drop of IGBT is a function of the junction temperature. As the temperature coefficient ΔV_{ceo} increases in proportion to the junction temperature in NPT(Non Punch Through) IGBT, the on-state voltage drop increases in proportion to the junction temperature. Also, it is the characteristics of NPT IGBT that the on-state voltage drop increases as the collector current increases. The experimental results of off-line characterization are summerized in Fig. 10.

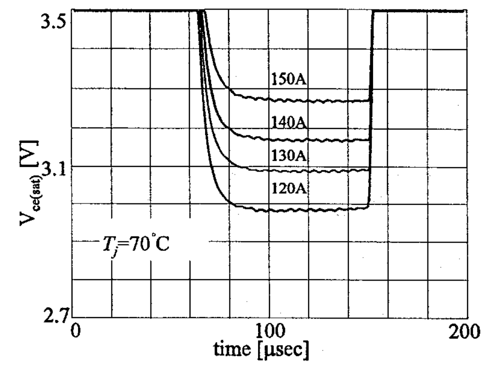

Fig. 8. On-state voltage drop with respect to the collector current.

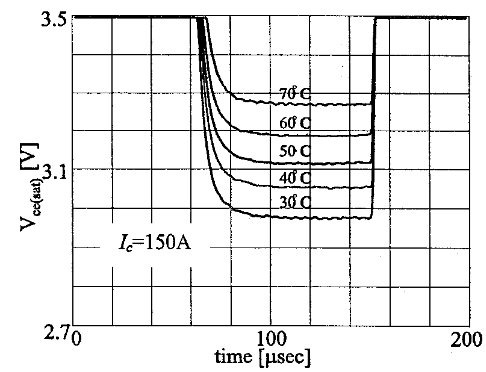

Fig. 9. On-state voltage drop with respect to the junction temperature.

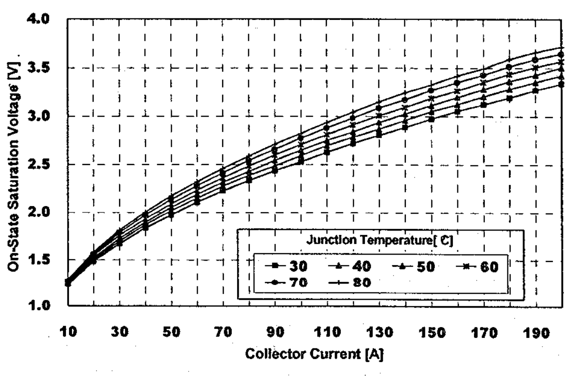

Fig. 10. Off-line characterization of IGBT on-state voltage drop for various collector current and junction temperature.

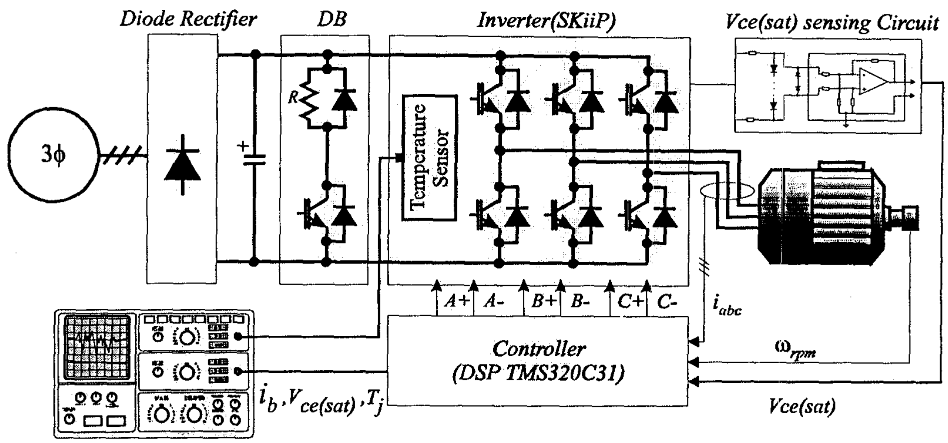

Fig. 11. Configuration of experimental setup to get the transient response of on-line estimation.

B. On-line Estimation

After the off-line measurement of the reference value, on-line estimation of the junction temperature has been performed using the extracted parameters. Two types of experiment have been carried out for the verification of proposed method. First, in order to show the validity of steady state characteristics,on-line junction temperature estimation has been performed with constant collector current. Second, in order to show the dynamic characteristics , on-line estimation has been performed with induction motor drive.

For the first experiment, the system configuration in Fig. 7 is used. In this experiment, resistor of 1.04 Ω and dc reactor of 6mH are used. On-line estimation is performed for various current level. As shown in Fig. 12, IGBT junction temperature can be estimated using on-state voltage drop in real time. The results are also verified by the thermal sensor attached to the silicon die of IGBT and it is observed that the signal of the thermal sensor is equivalent to a low pass filtered one of the actual junction temperature because of the characteristic of the sensor. The farther from IGBT junction the thermal sensor is, the more delay time it takes and the more inaccurate for measuring the real junction temperature because of the thermal capacitance and resistance[9,10].

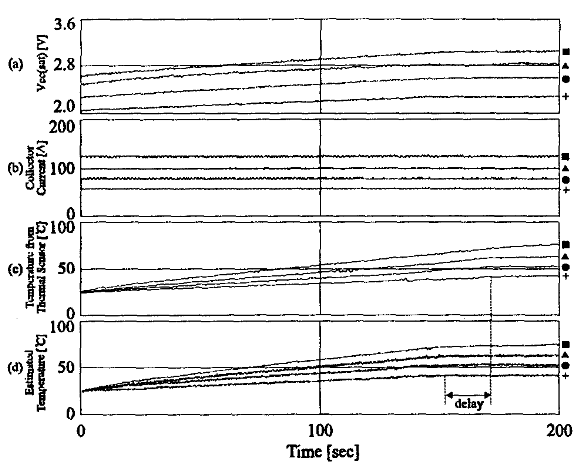

Fig. 12. Steady state response of on-line estimation. (a) On-state voltage drop. (b) Collector current (■ : 120A, ▲ : 100A, ● : 80A, ✚ : 60A). (c) Measured temperature by a thermal sensor. (d) Estimated temperature.

To get the transient response, induction motor drive system is used in the second experiment. The configuration of experimental setup for the second is shown in Fig. 11. Table IV shows the rated values and the nominal parameters of a tested induction machine. Induction machine control has been carried out with the 5 kHz switching frequency and the sampling period of current and speed control is 100 μsec and 2 msec, respectively[11]. In Fig. 13, load current flows through B^+ side IGBT as b phase current is positive and it flows through B^- side diode as negative, so IGBT junction temperature has to be estimated at positive b phase current. As shown in Fig. 10, variation of on-state voltage drop with

TABLE IV
RATINGS AND PARAMETERS OF INDUCTION MACHINE UNDER TEST

Rated power output[kW]	37
Rated Torque[N-m]	200
Rated voltage[V]	170
Rated current[A]	158.9
Number of pole	4
Efficiency[%]	92.0
Stator resistance[Ω]	0.032
Rotor resistance[Ω]	0.02175
Mutual inductance[mH]	4.9
Stator leakage inductance[mH]	0.417
Rotor leakage inductance[mH]	0.417

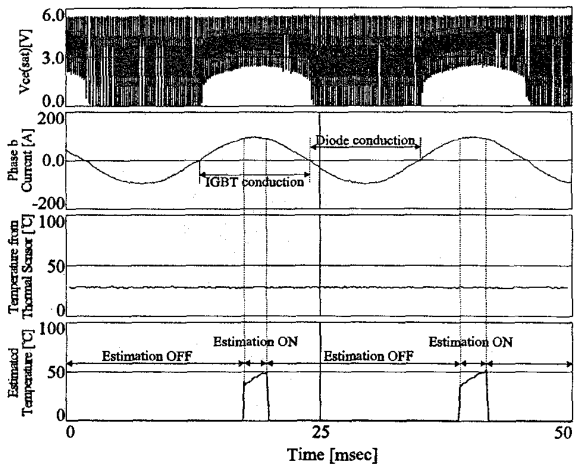

Fig. 13. Transient response of on-line estimation.

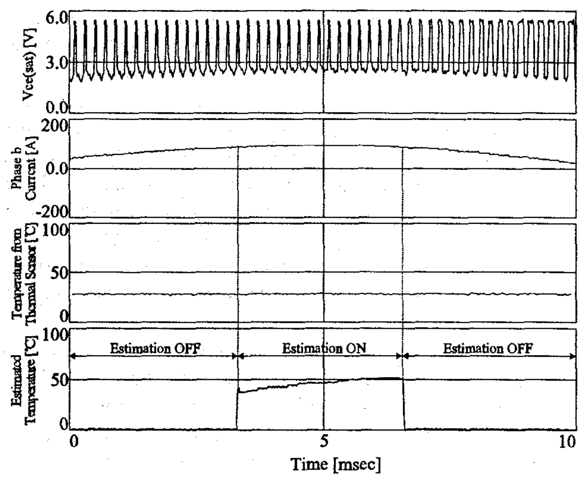

Fig. 14. Transient response of on-line estimation in expanded time scale of 10 msec

respect to junction temperature is very small at small current, therefore junction temperature should be estimated above a certain current level to reduce the estimation error. $V_{ce(sat)}$ in Fig. 13 is measured by proposed circuit in Fig.6 and time scale is expanded at Fig.14. At off-state, $V_{ce(sat)}$ is 5.4V which is the sum of the diode forward voltage drops in the measurement circuit and at on-state it features on-state voltage drop of the tested IGBT. In contrast to the first experiment (Fig.12), there is a difference between the estimated temperature and measured value by the thermal sensor in the second (Fig.13~15). The thermal capacitance of IGBT junction itself is so small that the time constant of the junction temperature is less than a few milli-seconds. Fig. 13 and 14 show that the proposed method responds to the instantaneous change of junction temperature while the

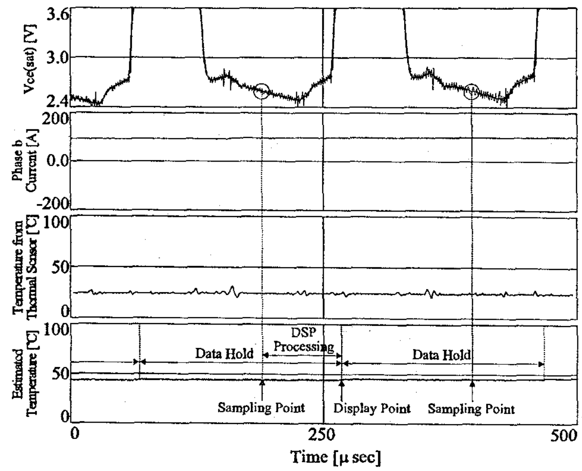

Fig. 15. Transient response of on-line estimation in expanded time scale of 500μsec.

thermal sensor does not respond to such a fast transient. As shown in Fig. 15, to reduce the error of measurement, on-state voltage drop is sampled at the center of switching period. After the data processing for several tens of micro-seconds, D/A converter of the controller displays the estimated junction temperature and holds it to next output. As shown in Fig. 15, while the output of the thermal sensor can not respond the junction temperature variation rapidly, the proposed method well represents the variation.

IV. CONCLUSIONS

This paper presents the on-line estimation method of IGBT junction temperature using on-state voltage drop. For the precise estimation of the IGBT junction temperature over all operating range, the circuit measuring IGBT on-state voltage drop has been designed. To acquire on-line estimation reference data for IGBT under test, off-line tests have been preceded. Based on the off-line test results, IGBT junction temperature has been estimated in real time and compared with measured one by the thermal sensor. Through the experimental results, it can be seen that the proposed on-line estimation method has both good dynamic response and accurate steady state performance. By adding the simple measurement circuit to gate driver without any invasive manipulation on IGBT, the accurate thermal information can be obtained with the help of the proposed method.

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