Power Loss and Junction Temperature Analysis of Power Semiconductor Devices

Dewei Xu, Haiwei Lu, Lipei Huang, Satoshi Azuma, Masahiro Kimata, and Ryohei Uchida

***Abstract*—A newly developed electrothermal calculation method is implemented to estimate the power loss and working temperature of insulated gate bipolar transistor (IGBT) devices. Based on the measurement of the IGBT's characteristics, the exact estimation of power loss considering the junction temperature is introduced. Then, the thermal network is used to calculate the working temperature. The comparison between experimental and calculation results shows that this method is effective as a designing step with only the time-domain voltage and current data obtained from simulation results.**

***Index Terms*—Insulated gate bipolar transistor, junction temperature, power loss.**

I. Introduction

IN RECENT YEARS, power semiconductor devices, especially insulated gate bipolar transistors (IGBTs) have been widely used in the application of motor drivers, switching supplies, and other power conversion systems. The estimation of the power loss and junction temperature of semiconductor devices has become a major issue with the increase of the capacity and switching frequency of devices.

The common way to estimate the power loss of devices is based on the exact current and voltage waveforms of the device [1]. Obviously, it is very difficult to get the waveforms from simulating each pulse of pulsewidth modulation (PWM) exactly, with the variation of the voltage and the current. The accumulated error of loss would be generated with the error of such waveforms. Another difficulty is that some of the precise parameters of power semiconductor devices that are referred in the model [2], [3] are unavailable.

In the power application, the other factor we care most about is the junction temperature of devices that have a peculiar safe operating area. Usually, the power loss is calculated under the constant junction temperature [1], [4], [5]. However, the power loss does depend on the junction temperature, not only the loss of saturation, but also the loss of transient switching operation. Therefore, the power loss estimation and the junction temperature calculation should be combined to find out the working point of devices.

In the designing step of a power application, the only available item is the topology of the main circuit and its waveforms from simulation results and, in those simulations, IGBT devices are taken as ideal switches, which means the performance of the controlling system becomes more important. As shown in Fig. 1, the newly developed method analyzes the time-domain data of voltage and current from simulation or from experiment and resolves the record of time-domain data into several complete switching processes of power semiconductor devices. From that, the power loss calculation program calculates the precise power loss of each device by fitting every switching process into the precise power loss characteristics. Also, the program computes the working junction temperature of devices after importing the thermal network of a certain thermal radiator.

II. Power Loss Characteristics of Devices

The power loss of each switching operation of IGBTs in one branch is divided into three portions, which are illustrated in Figs. 2 and 3. Total power loss during each pulse of the IGBT is the sum of turn-on loss, turn-off loss, and saturation loss. Also, the losses of the antiparalleled diode are included.

It can be assumed that the transient power loss of turn-on or turn-off depends on the dc-link voltage and collector current of the IGBT. From application, it was found that the transient switching waveforms change with increase of junction temperature. It should be pointed out that the turn-on loss and turn-off loss are also functions of junction temperature which are expressed in (1), (2), (4), and (5). The saturation voltage of the IGBT and its antiparalleled diode is usually defined as the function of junction temperature and collector current which are shown in (3) and (6)

$$P_{s\text{-on}} = f_{s\text{-on}}(V_d, i, T_j) \tag{1}$$
$$P_{s\text{-off}} = f_{s\text{-off}}(V_d, i, T_j) \tag{2}$$
$$V_{s\text{-}st} = f_{s\text{-}st}(i, T_j) \tag{3}$$
$$P_{d\text{-on}} = f_{d\text{-on}}(V_d, i, T_j) \tag{4}$$
$$P_{d\text{-off}} = f_{d\text{-on}}(V_d, i, T_j) \tag{5}$$
$$V_{d\text{-}st} = f_{d\text{-}st}(i, T_j). \tag{6}$$

In order to get the precise switching process of the IGBT, the experiment was designed to measure the turn-on and turn-off waveform under variations of collector current, dc-link voltage, and junction temperature. As shown in Fig. 4, the circuit was adopted to measure the precise transient switching processes of the IGBT. The pulse generator that can generate two pulses con-

Paper IPCSD 01–075, presented at the 1999 Industry Applications Society Annual Meeting, Phoenix, AZ, October 3–7, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Power Electronics Devices and Components Committee of the IEEE Industry Applications Society. Manuscript submitted for review October 15, 1999 and released for publication July 1, 2002. This work was supported by Mitsubishi Electric Corporation.

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Publisher Item Identifier 10.1109/TIA.2002.802995.

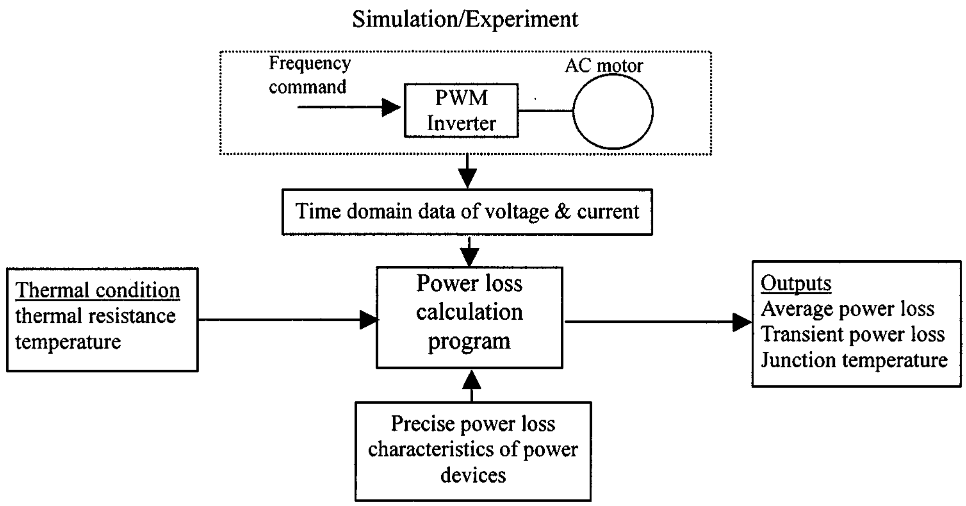


Fig. 1. Diagram of power loss and junction temperature analysis.

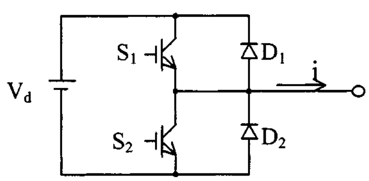


Fig. 2. Main circuit of IGBT branch.

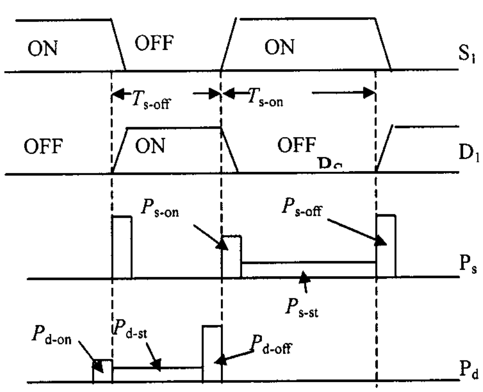


Fig. 3. Three sections of power loss.

trols the collector current. The first pulse is used to control the final current through the collector of the IGBT and the second one is for measurement. While testing, the heat unit is heated to a certain temperature that is taken as the junction temperature after the temperature is kept stable. The turn-on and turn-off switching processes are shown in Fig. 5.

After computing the product of voltage and current of the device, the transient power loss characteristics in IGBT module CM400DY-12H are obtained as shown in Fig. 6.

Based on (1)–(6), the voltage and current waveforms of the IGBT are measured under different conditions in order to construct power loss characteristic tables in detail. The functions in (1)–(6) are applied by searching the tables of power loss and finding out the loss result.

Three parameters, V, T, and I, represent dc-link voltage, junction temperature, and collector current of the pulse, respectively. P represents the corresponding loss. As illustrated in Fig. 7, there are eight points, O1–O8, in three–dimensional (3-D) space around a certain operation point (V, T, I). Each point of O1—O8 has its value of loss $P1$–$P8$, respectively, obtained by the experimental results. They are expressed in the following eight sets:

$$\begin{aligned}
\text{O1} &= (V_{i1}, T_{j1}, I_{k1}, P_1)\\
\text{O2} &= (V_{i1}, T_{j1}, I_{k2}, P_2)\\
\text{O3} &= (V_{i1}, T_{j2}, I_{k3}, P_3)\\
\text{O4} &= (V_{i1}, T_{j2}, I_{k4}, P_4)\\
\text{O5} &= (V_{i2}, T_{j3}, I_{k5}, P_5)\\
\text{O6} &= (V_{i2}, T_{j3}, I_{k6}, P_6)\\
\text{O7} &= (V_{i2}, T_{j4}, I_{k7}, P_7)\\
\text{O8} &= (V_{i2}, T_{j4}, I_{k8}, P_8).
\end{aligned}$$

The transient power loss of the point (V, T, I) in (1), (2), (4), and (5) can be found by (7)

$$\begin{aligned}
f(V,T,I) = &\left[\left(P_1\frac{I-I_{k2}}{I_{k1}-I_{k2}} + P_2\frac{I-I_{k1}}{I_{k2}-I_{k1}}\right)\frac{T-T_{j2}}{T_{j1}-T_{j2}}\right.\\
&\left.+\left(P_3\frac{I-I_{k4}}{I_{k3}-I_{k4}} + P_4\frac{I-I_{k3}}{I_{k4}-I_{k3}}\right)\frac{T-T_{j1}}{T_{j2}-T_{j1}}\right]\\
&\cdot\frac{V-V_{i2}}{V_{i1}-V_{i2}}\\
&+\left[\left(P_5\frac{I-I_{k6}}{I_{k5}-I_{k6}} + P_6\frac{I-I_{k5}}{I_{k6}-I_{k5}}\right)\frac{T-T_{j4}}{T_{j3}-T_{j4}}\right.\\
&\left.+\left(P_7\frac{I-I_{k8}}{I_{k7}-I_{k8}} + P_8\frac{I-I_{k7}}{I_{k8}-I_{k7}}\right)\frac{T-T_{j3}}{T_{j4}-T_{j3}}\right]\\
&\cdot\frac{V-V_{i1}}{V_{i2}-V_{i1}}
\end{aligned}\tag{7}$$

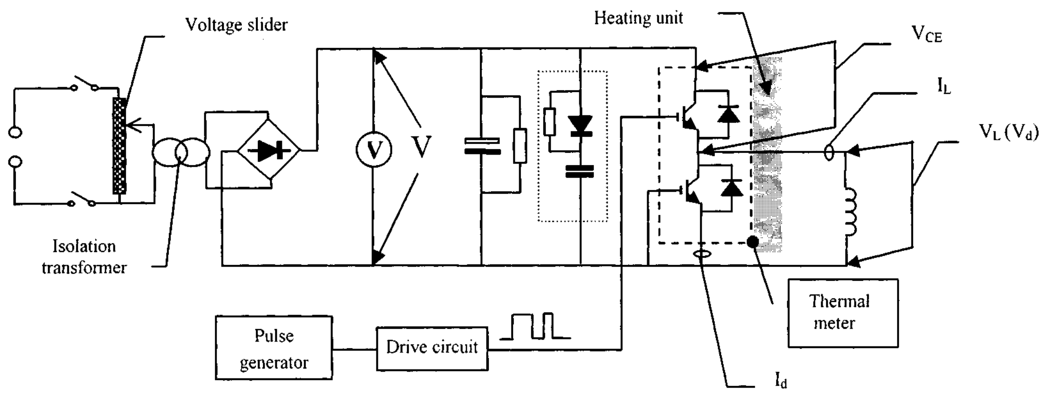
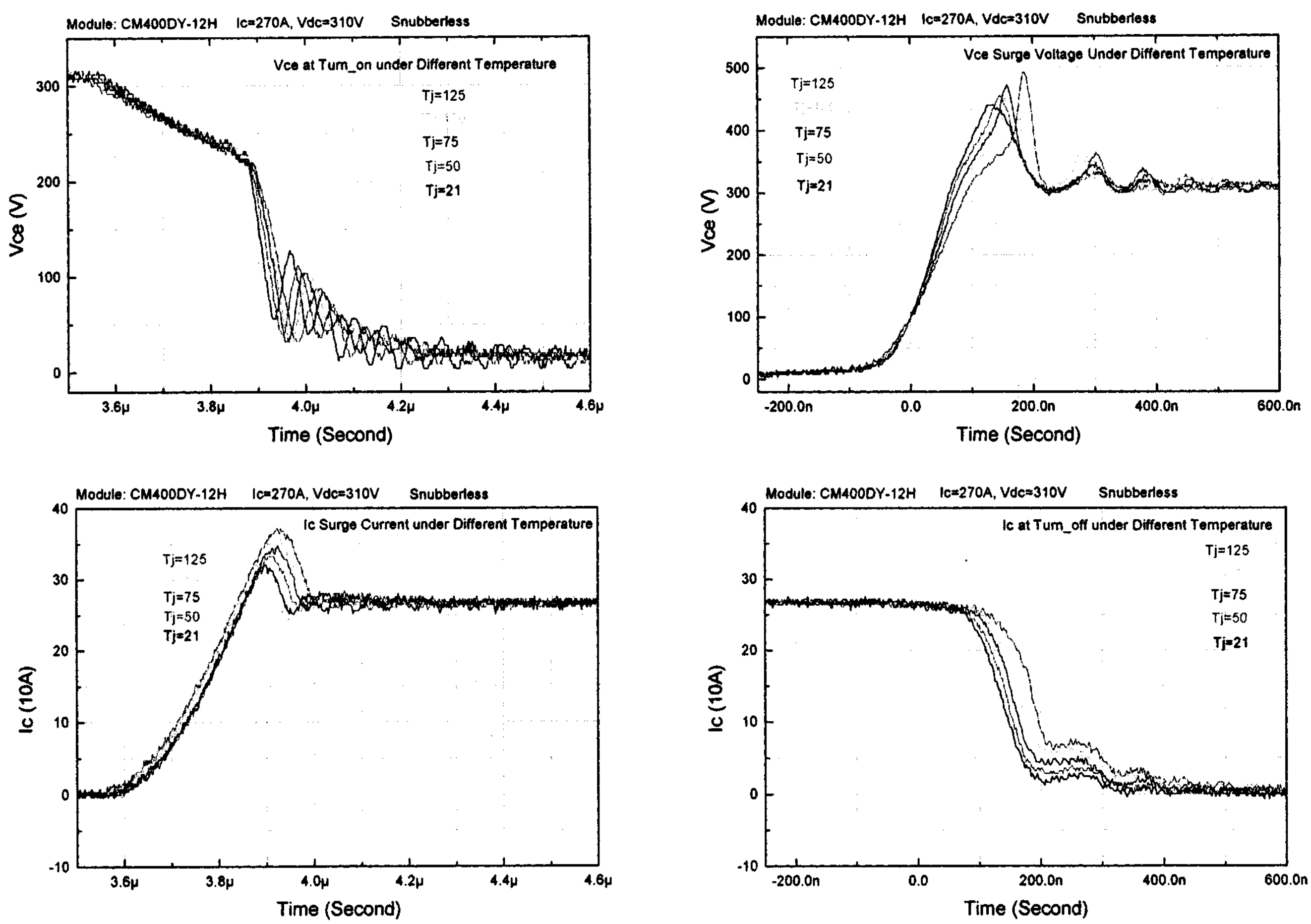


Fig. 4. Measurement circuit of transient switching process.



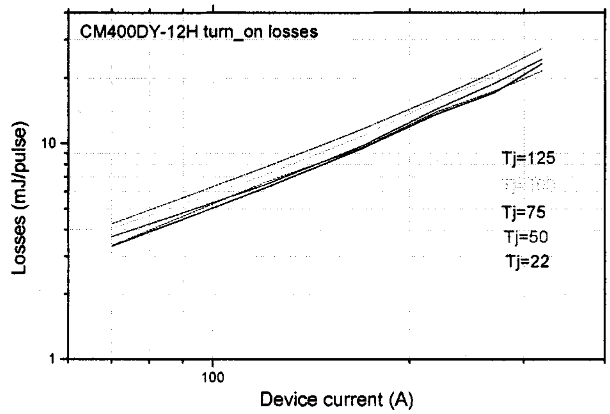
(a) (b)

Fig. 5. Transient switching processes under different junction temperatures (CM400DY-12H). (a) Voltage and current of turn-on. (b) Voltage and current of turn-off.

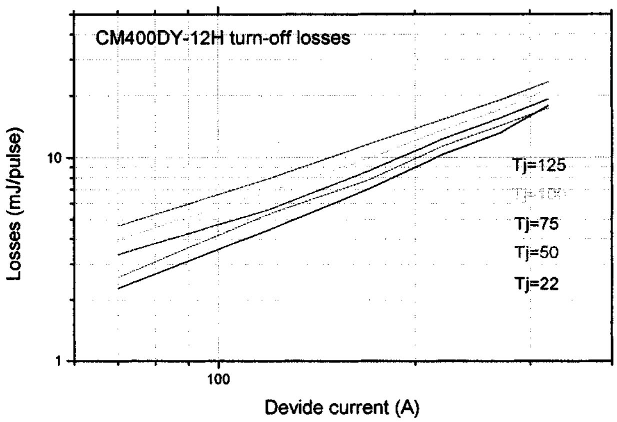
III. Power Loss and Temperature Estimation

In actual applications, the collector currents of devices vary according to the controlling command. The junction temperatures also rise up and fall down with the changes of the load. The average power of the number *1* IGBT can be estimated with (8)-(13)

$$P_{l,s\text{-on}} = \frac{1}{T}\sum_{k} f_{s\text{-on}}(V_d, i_{kl}, T_{jl}) \tag{8}$$



(a)



(b)

Fig. 6. Transient loss of CM400DY-12H. (a) Turn-on loss of IGBT. (b) Turn-off loss of IGBT.

$$P_{l,s\text{-off}} = \frac{1}{T}\sum_k f_{s\text{-off}}\left(V_d, i_{kl}, T_{jl}\right) \tag{9}$$

$$P_{l,s\text{-}st} = \frac{1}{T}\sum_k f_{s\text{-}st}\left(i_{kl}, T_{jl}\right)\Delta T_{kl,s\text{-on}} \tag{10}$$

$$P_{l,d\text{-on}} = \frac{1}{T}\sum_k f_{d\text{-on}}\left(V_d, i_{kl}, T_{jl}\right) \tag{11}$$

$$P_{l,d\text{-off}} = \frac{1}{T}\sum_k f_{d\text{-off}}\left(V_d, i_{kl}, T_{jl}\right) \tag{12}$$

$$P_{l,d\text{-}st} = \frac{1}{T}\sum_k f_{d\text{-}st}\left(i_{kl}, T_{jl}\right)\Delta T_{kl,s\text{-off}}. \tag{13}$$

Total loss is the sum of transient loss and saturated loss of all IGBTs and diodes

$$P_s = \sum_l P_{l,s\text{-on}} + P_{l,s\text{-off}} + P_{l,s\text{-}st} \tag{14}$$

$$P_d = \sum_l P_{l,d\text{-on}} + P_{l,d\text{-off}} + P_{l,d\text{-}st} \tag{15}$$

$$P_{total} = P_s + P_d. \tag{16}$$

In fact, the total loss is determined by the dc-bus voltage, the junction temperature of each device, and also the current of each device.

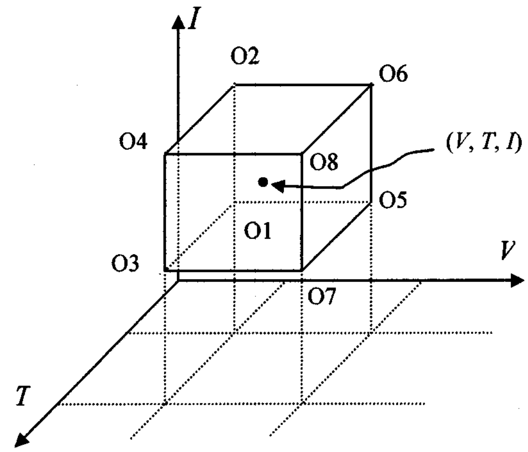


Fig. 7. Location of eight points in 3-D space.

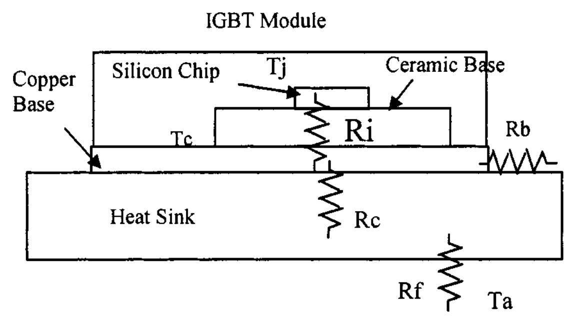


Fig. 8. Single chip with heat sink.

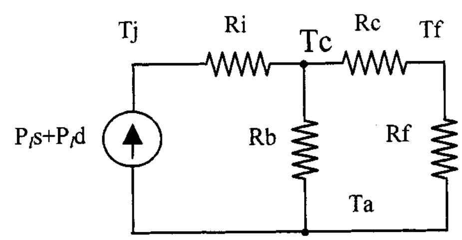


Fig. 9. Equivalent thermal circuit of IGBT module.

After getting the power loss of each IGBT and antiparalleled diode, the selected heat sink can be described as a thermal network of heat resistance. An ideal centralized equivalent thermal network of the IGBT is shown in Figs. 8 and 9. It is a bit complex to describe the network of the module because there are double pairs of chips on the copper base. However, we can assume that the junctions of the diode and IGBT have the same temperatures when the aluminum connectors are of good thermal conductance. On the other hand, it would be more difficult to describe the heat sink as a centralized network when it becomes big enough. Furthermore, it would be very complex to describe the network of the inverter with three modules all mounted together on the heat sink. Details of the thermal network are decided by the arrangement of modules and the size of the heat sink.

A new program was developed to calculate the power loss and solve the thermal network. The flowchart is shown in Fig. 10.

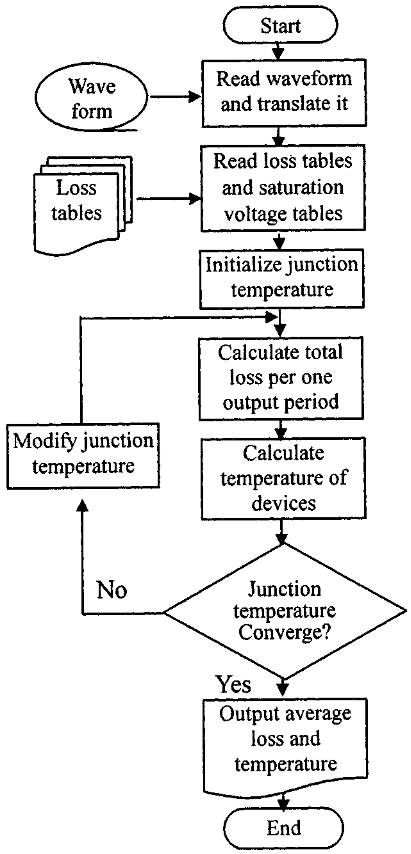


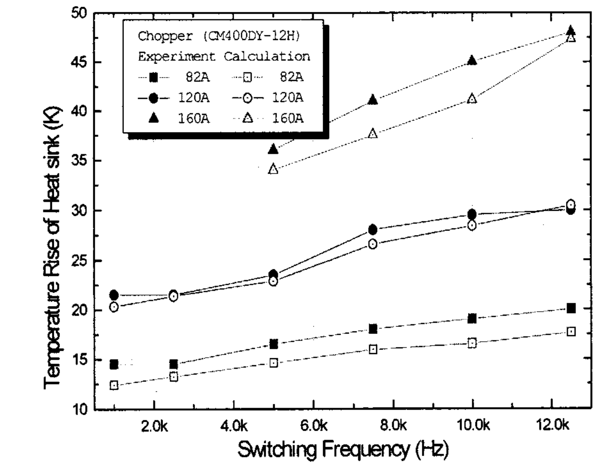
Fig. 10. Flowchart of loss calculation program.

In the flowchart, the program loads all loss tables that are established by the experimental result and searches the tables to find out the power loss. After that, it automatically constructs the equivalent matrix equation of the thermal network and finds the root of the equation. With the loop shown in the flowchart, the program judges the convergence of junction temperature. Finally, the program outputs the calculation result of temperature and estimated loss.

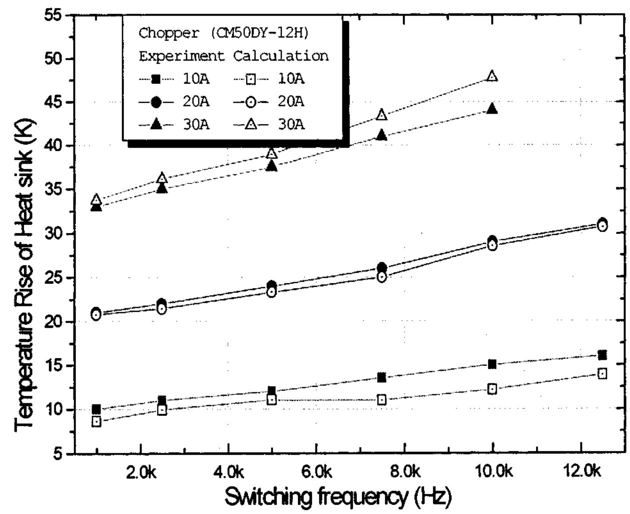
IV. Experimental Results

Two experiments were performed to verify the calculation result of the new program. First, a chopper circuit with a CM50DY-12H (50-A/600-V module with two devices) and CM400DY-12H (400-A/600-V module with two devices) was tested. This experiment was carried out by varying the switching frequency. It was proved that the risen temperature of the heat sink lineally increases with the power loss generated by modules and also the junction temperature in the centralized equivalent thermal network. Fig. 11 shows a comparison between calculation and measurement result with two modules under varying switching frequency conditions.

A test was also made on an inverter with a heat sink and a CM400DY-12H was developed to drive a permanent-magnet synchronous motor. Several switching frequencies were set for the comparison of calculation and measurement result. As is revealed from Fig. 12, the calculation results are acceptable in an engineering application without any problem.



(a)



(b)

Fig. 11. Comparison of temperature rise of chopper. (a) Comparison result of IGBT module CM400DY-12H. (b) Comparison result of IGBT module CM50DY-12H.

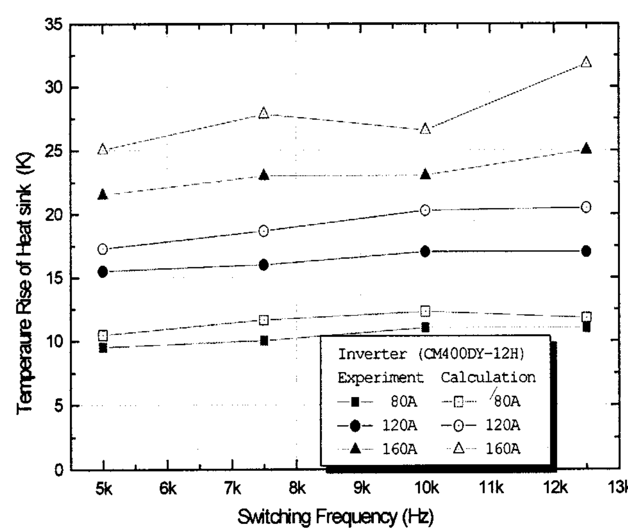


Fig. 12. Comparison of temperature rise of inverter (module: CM400DY-12H).

Several factors seemed to affect the deviation of calculation and measurement result. The major factor might be the thermal network. The centralized equivalent network would not work well if the heat sink is very big, which means the distribution of temperature on the heat sink should be considered carefully. The second factor might be the measurement of temperature. Because of the large thermal capacitor inside the heat sink, it takes a rather long time for the temperature on the heat sink to be stable. Another factor might be the condition that affects the loss tables data and test experiment. A different condition, such as the parasitic inductance of the dc bus, could affect the transient loss tables.

V. Conclusions

With the new method of the loss calculation, the power loss of IGBT devices and working temperature can be estimated in the power conversion system. The method is effective in determining the thermal radiator. It can be used to improve the efficiency of the inverter and the ultimate thermal design. Also, it can predict the working temperature of the IGBT and diode devices in order to avoid faults of the devices. Furthermore, the program is suitable for different types of topologies of the main circuits. Based on this calculation method for the steady junction temperature, we will consider the thermal capacitor and predict the transient junction temperature with the varying load in the future.

Acknowledgment

The study in this paper was completed at Tsinghua University in 1999. The authors wish to thank Prof. D. Zhu and X. Jiang of Tsinghua University and, also, M. Seto and Dr. M. Koyama of Mitsubishi Electric Corporation for their support and assistance in this research.

References

[1] C. Wong, "EMTP modeling of IGBT dynamic performance for power dissipation estimation," *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 64–71, Jan./Feb. 1997.

[2] H. A. Mantooth and A. R. Hefner, "Electro-thermal simulation of an IGBT PWM inverter," in *Proc. IEEE PESC'93*, June 1993, pp. 75–84.

[3] A. R. Hefner and D. M. Diebolt, "An experimentally verified IGBT model implemented in the saber circuit simulation," in *Proc. IEEE PESC'91*, June 1991, pp. 10–19.

[4] F. Blaabjerg, U. Jaeger, S. Munk-Nielsen, and J. K. Pedersen, "Power losses in PWM-VSI inverter using NPT or PT IGBT devices," in *Proc. IEEE PESC'94*, vol. 1, June 1994, pp. 434–441.

[5] F. Blaabjerg and J. K. P. Pedersen, "Optimized design of a complete three-phase PWM-VS inverter," *IEEE Trans. Power Electron.*, vol. 12, pp. 567–576, May 1997.

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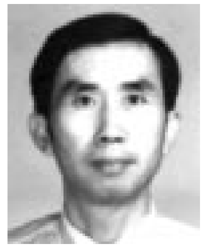

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