A METHOD FOR PREDICTING IGBT JUNCTION TEMPERATURE UNDER TRANSIENT CONDITION

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Abstract– **In this paper, a method to predict junction temperature of the solid-state switch under transient condition is presented. The method is based on the thermal model of the switch and instantaneous measurement of the energy loss in the device. The method for deriving thermal model parameters from the manufacturers data sheet is derived and verified. A simulation work has been carried out on a single IGBT under different conditions using MATLAB/SIMULINK. The results show that the proposed method is effective to predict the junction temperature of the solid-state device during transient conditions and is applicable to other devices such as diodes and thyristors.**

I. INTRODUCTION

Power semiconductor switches, especially IGBTs are widely used in many power electronics application such as rectifier drive inverters, converters, switching-mode power supply, solid-state circuit breakers and fault current limiting and interrupting devices (FCLID) [1-3]. In designing the power electronic circuit, accurate information about the actual junction temperature of the switch is critical in determining the dynamic performance, life-time and reliability of the device [4]. Therefore, the assessment of the junction temperature of the switching device is an essential part of the design process. The on-line monitoring of IGBT junction temperature is very useful for enhancing the reliability, cost effectiveness and performance of the power electronic system. However, it is difficult to obtain the actual junction temperature because it can not be measured directly by a non-invasive method [5]. In this paper a new method for predicting the junction temperature of the IGBT under transient condition is presented. The current, voltage and switching frequency are measured and fed to the computer which calculates the average power loss and the junction temperature. Given the intial and boundary condition, the junction temperature of the IGBT can be predicted on-line to allow the power electronic system to operate as long as the maximum allowable junction temperature has not exceeded. Computer simulation results are presented to evaluate the validity and the effectiveness of the proposed method.

II. EQUIVALENT TRANSIENT THERMAL IMPERDANCE

The transient thermal impedance of the semiconductor switch is an important tool in thermal design of the power electronic systems. The use of computers and a variety of software packages enable a simulational approach to thermal design [6]. Such this approach requires an accurate thermal model of the semiconductor switch. Figure (1) shows the transient thermal model of the semiconductor switch [7,8]. The transient thermal impedance may be expressed mathematically by sum of exponential terms.

$$Z_{thj-c}(t) = \sum_{i=1}^{n} R_{thi}(1 - e^{\frac{-t}{\tau_i}}) \tag{1}$$

Where R_{thi} is the thermal resistance of the i-th RC pair, K/W
τ_i is the time constant of the i-th RC pair, s

$$\tau_i = R_i C_i \tag{2}$$

The number of exponential functions needed to obtain a good representation of the Z_{thj-c} curve depends in general on the device topology. However, it has been found that four exponential terms are enough to model the Z_{thj-c} sufficiently well for the purpose of this model [10]. Table I list the values of the thermal resistances and time constants extracted from the manufacturer data sheet [9]. Figure (2) shows the good agreement between the fitted four exponential form and the manufacturer data sheet.

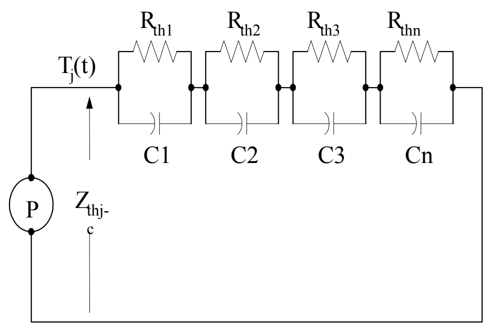

Fig. 1 Equivalent diagram of the transient thermal impedance

TABLE I
THERMAL MODEL PARAMETERS

No	R_{th}, K/W	τ_i, s
1st	0.064	0.00009
2nd	0.201	0.0007
3rd	0.7	0.0093
4th	1.1	0.09

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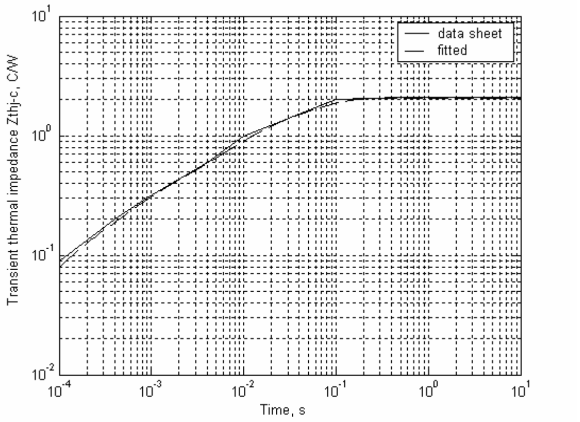

Fig. 2 Fitted and data sheet $Z_{thj\text{-}c}$ curve comparison

III. JUNCTION TEMPERATURE PREDICTION

The power loss of each switching operation for given current and voltage waveforms of the IGBT is divided into three sections as illustrated in Fig. 3. The leakage loss is only a small part of the total loss so that the error in neglecting it is not usually significant [11]. Therefore, the total power losses during each operating cycle of the IGBT are the sum of turn-on, turn-off loss and saturated conduction loss.

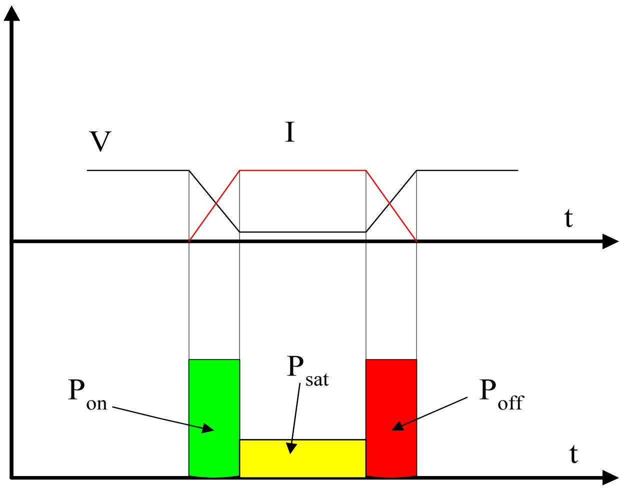

Fig. 3 Three sections of power loss

The average total power loss for one pulse is given by the following equation:

$$P_{av} = f_s \int_0^{\frac{1}{f_s}} v(t) \times i(t)\, dt \tag{3}$$

Where f_s is the switching frequency, $v(t)$ and $i(t)$ are the instantaneous voltage and current over one cycle of period $1/f_s$. From previous research it was found that all these losses changed with the increase in the junction temperature and can be expressed by the following equations as functions of the junction temperature:

$$P_{sat} = f(V_{CE}, I, T_J) \tag{4}$$

$$P_{on} = f(V_{supply}, I, T_J) \tag{5}$$

$$P_{off} = f(V_{supply}, I, T_J) \tag{6}$$

Where:

P_{sat} is the saturation power loss

P_{on} is the turn-on loss

P_{off} is the turn-off loss

V_{CE} is the collector-emitter voltage

V_{supply} is the supply voltage

I is the collector current

T_J is the junction temperature

Ta is the ambient temperature

The above relationships are numerically saved into look up tables. Based on the measured voltage and current then the power loss can be obtained by interpolation. This method only requires very limited experimental tests to have the power loss characteristics under different current and different junction temperatures [12]. In the proposed method, the voltage, current and switching frequency are measured. Then the measured voltage and current are multiplied together and integrated over a period T (where T > the time required to measure the average switching frequency) as shown in Fig. 4. In order to simplify the junction temperature calculation for all cases, we assumed that the duty ratio is 50 % for all waveforms with any duty ratio, Fig. 5 shows the modified power loss waveform. The simulation results in section 4 shows that this approximation does not affect the accuracy of the junction temperature prediction.

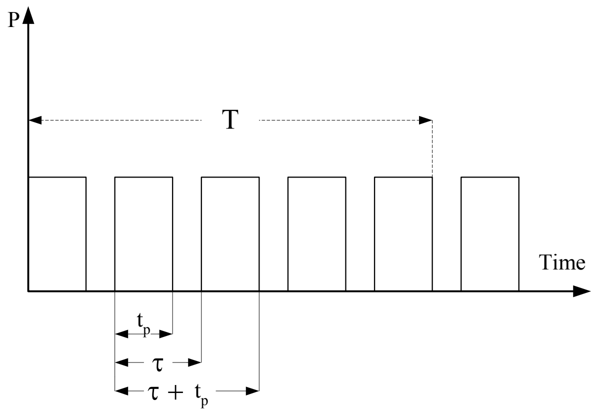

Fig. 4 Power loss waveform

So the average power loss over a period of T can be calculated by the following equation:

$$P_{av} = \frac{1}{T} \int_0^{T} v(t) \times i(t)\, dt \tag{7}$$

The power loss for the pulse can be calculated by the following equation:

$$P = \frac{2}{T} \int_0^{T} v(t) \times i(t)\, dt \tag{8}$$

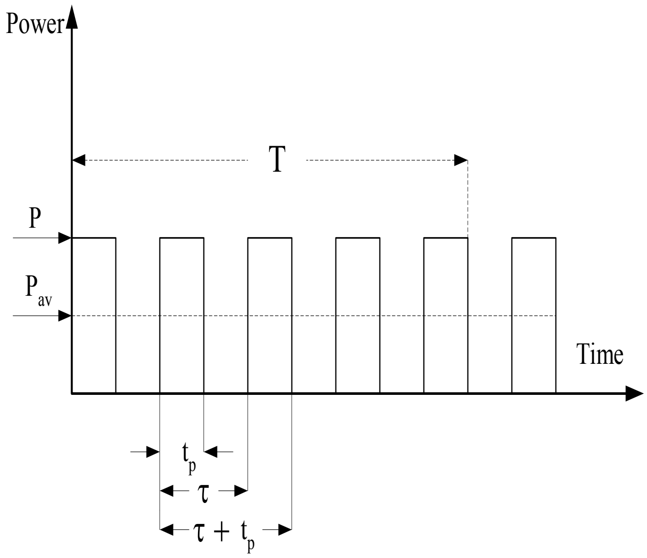

Fig. 5 Modified power loss waveform

The temperature rise at any time during transient condition for continuous repetitive pulses can be calculated by the following equation [11,13]:

$$\Delta T_j = p[\frac{t_p}{\tau} Z_{th}(t) + (1 - \frac{t_p}{\tau}) \cdot Z_{th}(\tau + t_p) - Z_{th}(\tau) + Z_{th}(t_p)] \quad (9)$$

$$T_j = \Delta T_j + T_a \quad (10)$$

A computer program was developed to calculate the average power loss, solve the thermal network and predict the junction temperature. The flow chart is shown in Fig. 6. In the flow chart, program first read the measured V, I, f_s, T_a. Second, it calculate the average power loss over a period T. Third, it calculate the transient thermal impedance based on the measured frequency. Finally, the program outputs the predicted junction temperature.

IV. Simulation Results

As an application example of the temperature predication, a simple chopper circuit using single IGBT was executed with MATLAB/SIMULINK. Fig. 7 shows the schematic diagram of the whole simulation. In this diagram there are two methods one to measure the instantaneous junction temperature by measuring the voltage and current of the device and multiplying them together. Then, the calculated power is fed to the transient thermal impedance RC model (block B). The voltage drop across the RC model gives the change in the junction temperature (actual data). The second method (block A) is the proposed method to predict the junction temperature. In order to show the effectiveness of this method, three tests have been carried out, Table II shows the simulation test parameters. Figs. 8, 9 and 10 show the comparison between the predicted and actual junction temperature with different duty ratio 30 %, 50 % and 70 % respectively.

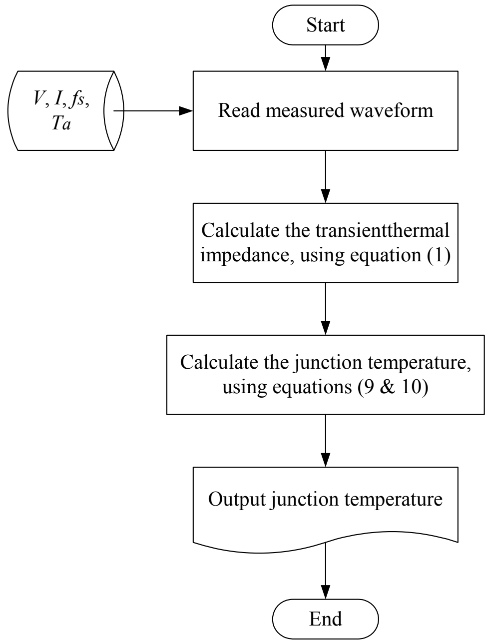

Fig. 6 Flow chart of the junction temperature prediction

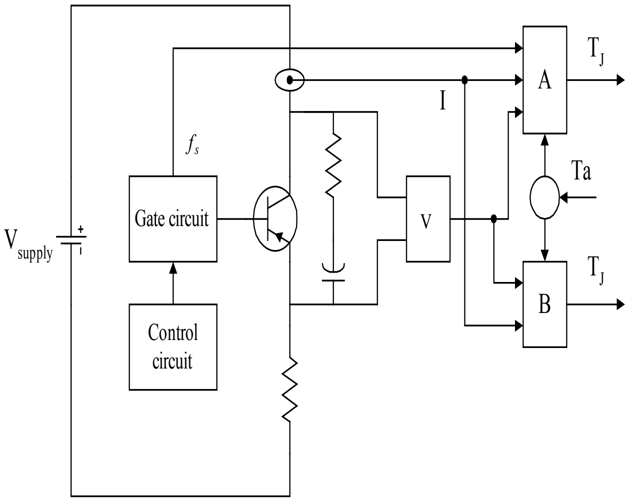

Fig. 7 Chopper circuit simulation in Matlab/Simulink

TABLE II
COMPARISON SIMULATION TEST PARMATERS

DC Voltage (V)	250
Load current (A)	12
Switching frequency (Hz)	240

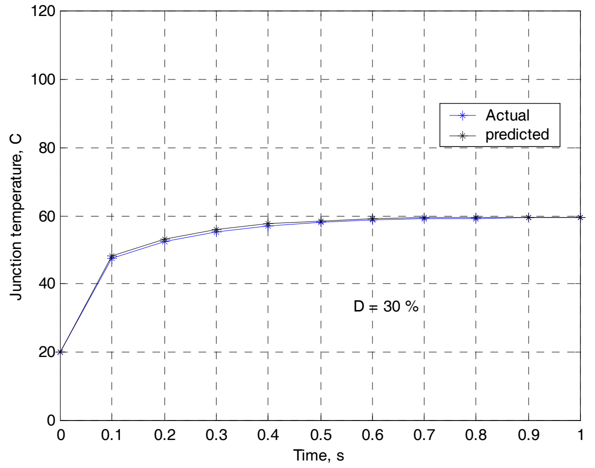

Fig. 8 Comparison between predicted and actual junction temperature

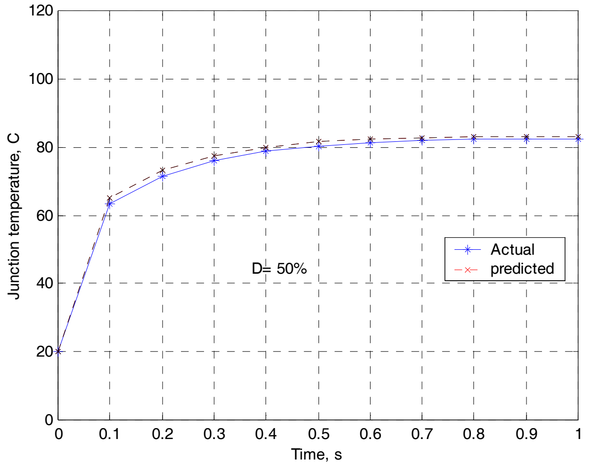

Fig. 9 Comparison between predicted and actual junction temperature

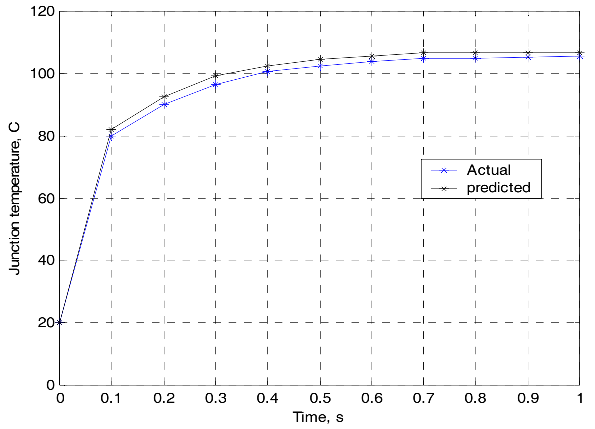

Fig.10 Comparison between predicted and actual junction temperature

V. Experimental Results

In order to verify the simulation results, the test circuit shown in Figure (7) has been implemented where the power circuit components are assembled on one board to minimize the circuit stray inductance. The current pulses through the IGBT are set to be of fixed amplitude 12 A, waveshape and switching frequency 240 Hz. Meanwhile, voltage, current waveforms and frequency were recorded into storage oscilloscope for the sake of temperature prediction with the program. . The IGBT temperature is predicted and measured during the operation from a few milliseconds up to a second, by feeding the program directly with the measured waveform. Figures (11, 12 and 13) show the comparison between the predicted and measured junction temperature with duty ratio 35 %, 50 % and 65 % respectively.

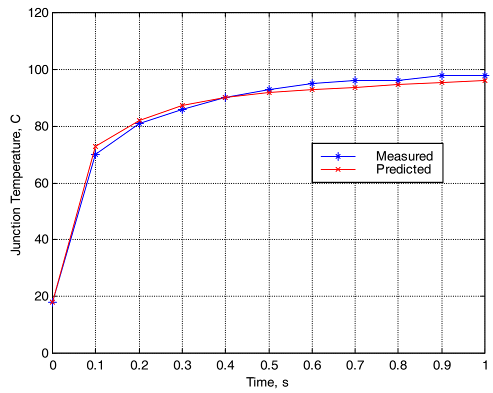

Figure 11 comparison between predicted and measured junction temperature

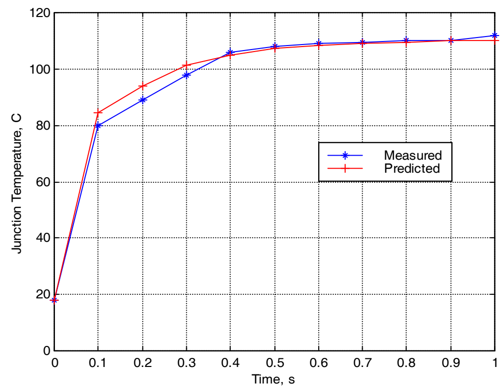

Fig. 12 comparison between predicted and measured junction temperature

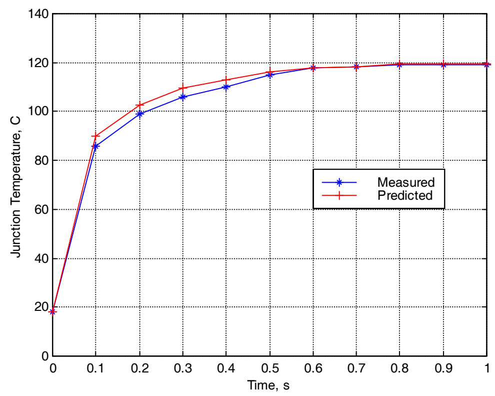

Fig. 13 comparison between predicted and measured junction temperature

Table III shows the whole results and percentage error. It can be seen that the errors within the 300 ms are within ± 7.2%, then it decreased to 3.5% or some time zero. This error is quite small as compared with other techniques used before (the error was 20%) [14]. The accuracy of the proposed method depends up on the accuracy of the measuring devices and on the accurate transient thermal impedance data of the used switch.

TABLE III
COMPARISON BETWEEN PREDICTED AND MEASURED JUNCTION TEMPERATURE

	Duty ratio 35 %			Duty ratio 50 %			Duty ratio 65 %		
Time, s	T_m, C	T_m, C	Error %	T_m, C	T_p, C	Error %	T_m, C	T_p, C	Error %
0	18	18	0	18	18	0	18	18	0
.1	52	55	5.76	62	66.5	7.2	68	72	5.8
.2	63	64	1.58	71	76	7	81	84.5	4.3
.3	68	69.1	1.6	80	83.3	4.12	88	91.5	3.9
.4	72	72	0	88	87	-1.13	92	95	3.2
.5	75	74	-1.3	90	89.2	-0.89	97	98	1.03
.6	77	75	-2.59	91	90.5	-0.54	100	100	0
.7	78	75.5	-3.2	91.4	91.2	-0.22	100.2	100.4	0.19
.8	78	76.8	-1.53	92	91.5	-1.6	101.2	101.4	0.19
.9	80	77.2	-3.5	92	92	0	101.2	101.4	0.19
1	80	78	-2.5	94	92	-2.1	101.2	101.4	0.19

VI. PREDICTING OF THE FCLID OPERATING TIME

For the safety operation of the FCLID the maximum allowable junction temperature is set to 120 C. The transient thermal impedance at T_J can be calculated from equation (10) and expressed in equation (12).

$$Z_{th}(t)=2\cdot[\frac{\Delta T_j}{p}-((1-\frac{t_p}{\tau})Z_{th}(\tau+t_p)-Z_{th}(\tau)+Z_{th}(t_p))] \quad (12)$$

In order to predict the FCLID operating time, the transient thermal impedance equation was simplified to one exponential term as expressed in equation (13). Figure (14) shows the comparison between the simplified and actual curve.

$$Z_{th}(t) = R_{th}\cdot(1-e^{\frac{t}{\tau}}) \quad (13)$$

The FCLID operating time can be expressed by equation (14).

$$t = \tau\cdot\ln(\frac{R_{th}-Z_{th}(T_J=120)}{R_{th}}) \quad (14)$$

Table IV shows the values of predicting FCLID operating time and predicting junction at this time (based on the four exponential term) and the errors.

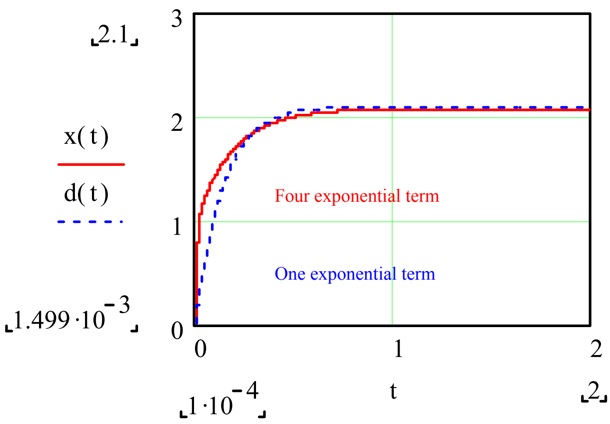

Fig.14 Comparison between simplified and actual transient thermal impedance curve

TABLE IV
PREDICTING FCLID OPERATING TIME

Time, s	0.206	0.33	0.461	0.52	0.758	0.8
T_J, C°	124.5	119.2	118	118	118.4	118.45
Error, %	+ 4.5	- 0.8	- 2	-2	- 1.6	- 1.55

VII. CONCLUSION

In this paper, a new method for predicting the junction temperature of the IGBT during transient condition has been presented. The prediction method is performed in three main steps. First, the device energy loss and switching frequency are measured and fed to the computer. Second, the transient thermal impedance is obtained. Finally, a computer program is used to predict the junction temperature for any current and duty ratio based on the calculated power loss and thermal impedance at different time periods based on the measured frequency. Both the simulation and experimental results show the validity and the effectiveness of the proposed method.
The advantages of this method:

- Reduce the time consumption for modeling the device characteristics (forward voltage and power loss).
- It can predict the junction temperature of the semiconductor switch at any instant during transient condition.
- It will prevent damage for the switching devices during transient or fault condition by sending a signal to the controller to reduce stress on these devices (reducing the current or the switching frequency).
- This method can be used for other electronic apparatus such diodes and thyristors.

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REFERENCES

[1] G. Eason, B. Noble, and I.N. Sneddon, "On certain integrals of Lipschitz-Hankel type involving products of Bessel functions," *Phil. Trans. Roy. Soc. London,* vol. A247, pp. 529-551, April 1955.

[1] R.K. Smith, P.G. Slade, and H. Mehta, "Solid-state distribution current limiter and circuit-breaker application requirements and control strategies", IEEE Trans. on Power Delivery, vol. 8, July 1993, pp.1155-1164.

[2] Y. Shakweh, "Power devices for medium voltage PWM converters", IEE Power Engineering Journal, 1999, pp. 297-307.

[3] Thomas G. and Raymound G.S., "Ratings of semiconductors for ac drives", IEEE Transactions, Vol. 37, No. 2, 2001, pp.434-441.

[4] M.M.R. Ahmed, and G. Putrus, "Investigation into custom power technology" UPEC'99, 519-522.

[5] R. Perret, CH. Schaeffer and E. Farjah "Temperature evaluation in power semiconductor devices: measurement techniques and simulation", IEE Colloquium on Measurement Techniques for Power Electronics, 1992, pp. 10/1-10/7.

[6] G.L. Skibinski and W.A. Sethares, "Thermal parameter estimation using recursive identification", IEEE Industry Application Annual Conference, 1990, pp. 1581-1588.

[7] P.E. Bagnoli, C. Casarosa and E. Dallago, "Thermal Resistance analysis by induced transient (TRAIT) method for power electronic devices thermal characterisation- part-I: fundamentals and theory, pp. 1208-1219 and part-II: practice and experiments, pp. 1220-1228, IEEE Transactions on Power Electronics, Vol. 13, No. 6, 1998.

[8] V. Blasko, R. Lukaszewski and R. Sladky, "On line thermal model and thermal mangament strategy of a three phase voltage source inverter", IEEE Industry Application Society 34th Annual meeting, October, 1999, pp. 1423-1431.

[9] International Rectifier, "IGBT data book", 1999

[10] F. ProFumo, A. Tenconi, S. Facelli, and B. Passerini, "Instantaneous junction temperature evaluation of high-power diodes (thyristors) during fast current transients", IEEE Transactions On Power Electronics, Vol. 14, No. 2, 1999, pp. 154-158.

[11] W.W. Barry, "Power Electronics: devices, drives, applications and passive components", Macmillan Press, 1992.

[12] S. Azuma, M. Kimata, X. Jian, H. Lu and D. Xu, "Research on the power loss and junction temperature of power semiconductor devices for inverter", Proceedings of the IEEE International Conference on Vehicle Electronics, Vol. 1, 1999, pp. 183-187.

[13] P.C. Sen, "Power electronics", Tata McGaw Hill, New Delhi, 1995.

[14] Z. Pan, X. Jiang, H. Lu and L. Huang, "Junction temperature analysis of IGBT", IEEE, pp. 1068-1073.

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