Estimation of Power Losses, Temperatures and Power Cycle Lifetime for IGBT Modules by Using IGBT Simulator

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ABSTRACT

Fuji Electric has released its IGBT simulator free of charge on the website. It simulates the power dissipation and the junction temperature of Fuji Electric IGBT modules that are incorporated into power electronics systems, such as inverters. It supports 3-level circuits and many of the widely used pulse width modulation methods and provides the calculation of the dependence of the power loss on the junction temperature, allowing users to run more realistic simulations. Providing the power loss and the temperature rise transitions of IGBT modules helps users select modules and estimate their lifetime at the initial stages of design.

1. Introduction

In recent years, the continuous size reduction and densification of power electronics equipment has been accompanied by a wider utilization of insulated gate bipolar transistors (IGBT) in applications that are characterized by frequent and repeated load changes due to acceleration and deceleration, such as in the case of electric vehicles. Thermal fatigue due to repeated changes in the junction temperature T_{vj} of semiconductor elements is a problem related to the lifetime and reliability of the equipment. Therefore, it is necessary to adopt a design that sufficiently takes into consideration the power loss and temperature rise that occur in complex operation patterns. Fuji Electric has released an IGBT simulator[(1)] that is available free of charge to calculate the power losses and temperatures that occurs in IGBT modules. We have recently released Ver. 6 on our website*1 as a simulator that enables more realistic calculation of characteristics such as the temperature dependence of power loss.

2. Overview of IGBT Simulator Ver. 6

Figure 1 shows the operation screen of IGBT Simulator Ver. 6. The simulator is compatible with Windows 7*2 and higher. Compared with Ver. 5 of the simulator, Ver. 6 includes the following functionality:

(a) Supports 3-level circuits
(b) Includes 3-phase inverter PWM methods
(c) Enables calculation of the T_{vj} dependence of power loss.

*1: https://www.fujielectric.com/products/semiconductor/model/igbt/simulation/

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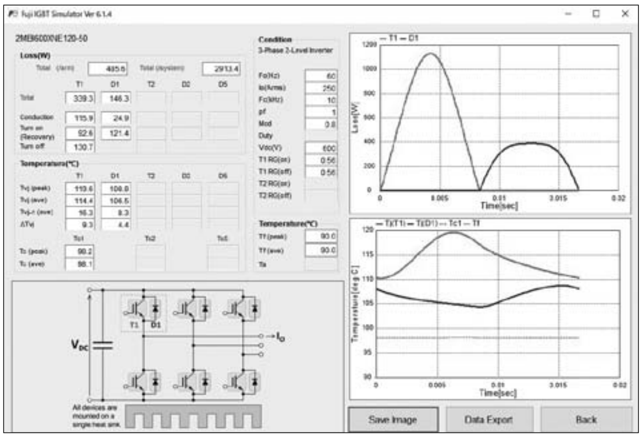

Fig.1 IGBT Simulator Ver. 6 operation screen

3. Calculation of IGBT Module Power Loss

3.1 Support for 3-level circuits

The IGBT Simulator supports 3-phase 2-level inverter circuits and boost and buck chopper circuits as conventionally done. In addition, it supports 2 kinds of 3-level circuits that are increasingly used in photovoltaic power generation, wind power generation and uninterruptible power systems (UPSs) (see Fig. 2).

3.2 Addition of 3-phase inverter PWM methods

In addition to previously supported sinusoidal pulse width modulation (PWM) and 2-phase modulation PWM (discontinuous PWM 1), it supports the following 3 widely used modulation methods:

(a) Space vector PWM
(b) 3rd harmonic injection PWM

*2: Windows 7 is a trademark or registered trademark of Microsoft Corporation

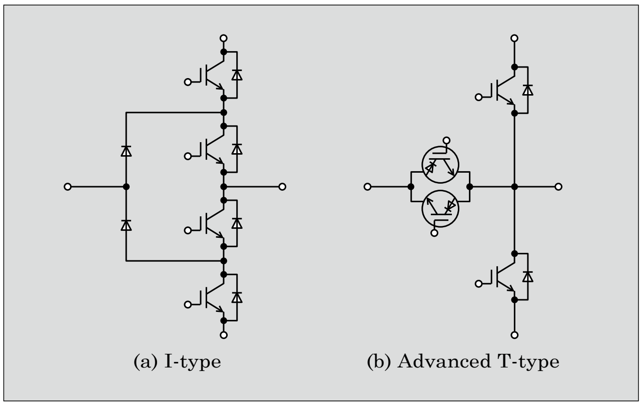

Fig.2 Newly supported 3-level circuits

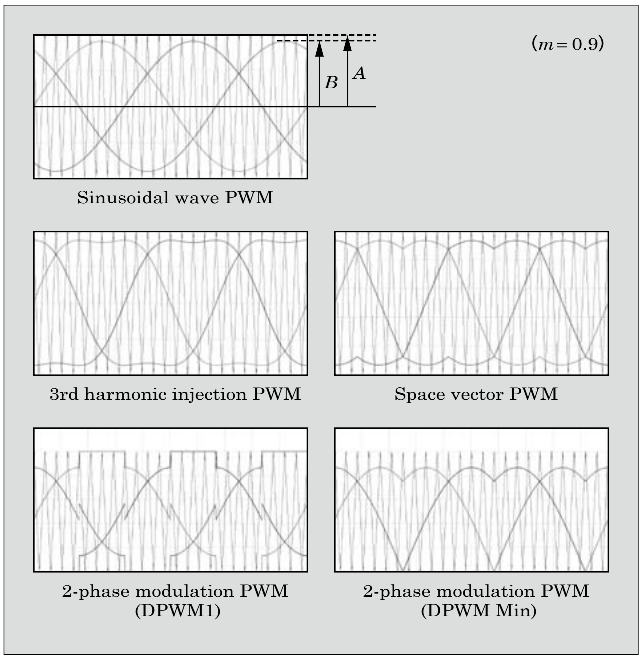

Fig.3 Control signal and triangular wave carrier signal waveforms for each modulation method

(c) 2-phase modulation PWM (discontinuous PWM Min)

Figure 3 shows the control signal and triangular wave carrier signal waveforms for each modulation method. In Ver.6, simulations can be performed by changing the control rate (modulation rate) m. m is defined as B/A, that is, the ratio of the amplitude A of a triangular carrier signal to the amplitude B of a control signal in the sinusoidal wave PWM as shown in the figure.

3.3 Power losses and temperature calculation flowchart

Figure 4 shows the calculation flowchart for the IGBT simulator. Power losses of an IGBT and a free wheeling diode (FWD), which constitute an inverter, are categorized into conduction loss (steady-state loss) generated during energization and switching loss generated during switching. Conduction losses are calculated on the basis of the output characteristics of the

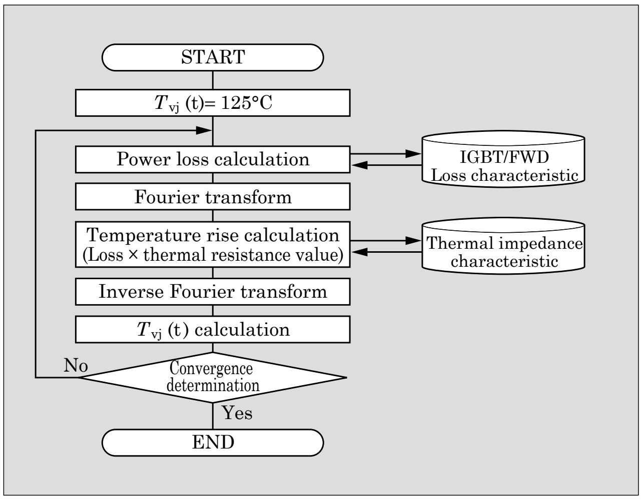

Fig.4 Calculation flowchart

IGBT and FWD, while switching losses are calculated based on current and gate resistance characteristics. For more details on how power loss is calculated, please refer to the reference material(1). In the IGBT simulator, the characteristic curve data at each temperature is stored as database content for each module, and is thereafter used in calculations.

4. Calculation of IGBT Module Temperature

4.1 Thermal resistance model

Figure 5 shows the one-dimensional thermal circuit model of a 3-phase inverter in the simulator. It consists of junction-to-case thermal impedance $Z_{th(j\text{-}c)}$, case-to-fin thermal impedance $Z_{th(c\text{-}s)}$, and heat sink-to-ambient thermal resistance $Z_{th(s\text{-}a)}$. In this model, the case temperature T_c and the heat sink temperature T_s are defined as temperatures directly below the chip. The ambient temperature T_a is treated as a constant.

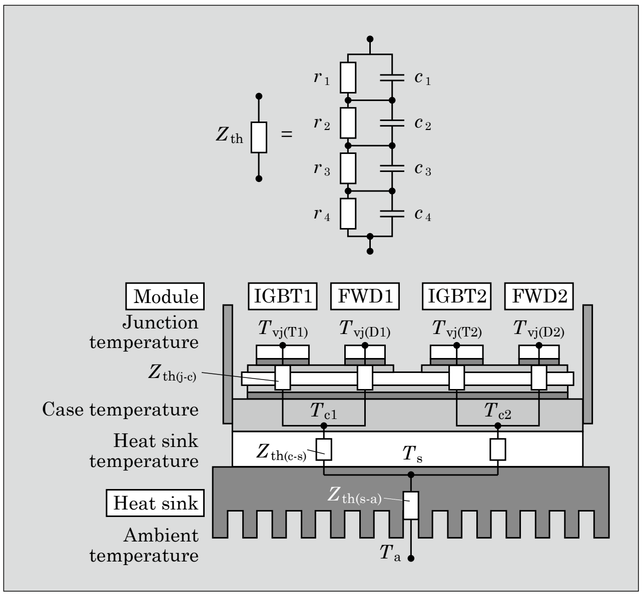

Fig.5 Inverter thermal circuit model

To calculate the transient temperature rise, each thermal impedance curve is expressed as a 4th-order Foster Network circuit represented by Equation 1, in which 4 parallel circuits of components R and C are connected in series. In the circuit, r_n and c_n are values calculated by the least squares method using the characteristic curve data for transient thermal impedance on the data sheet. As shown in Fig. 4, these values are registered in the database for each module of the simulator.

$$Z_{\mathrm{th}}(t) = \sum_{n=1}^{4} r_n \left\{ 1 - \exp\left(- \frac{t}{r_n c_n} \right) \right\} \quad \cdots\cdots (1)$$

Z_{th}: Thermal impedance
r_n: Resistance component in the Foster Network
c_n: Capacitance component in the Foster Network
t: Time

4.2 Calculation of temperature rise

To calculate the junction-to-case temperature rise $T_{(\mathrm{vj\text{-}c})}$ of an IGBT and FWD, loss waveform $P_{\mathrm{loss}}(t)$ generated by the IGBT is Fourier transformed, the obtained Fourier coefficient is multiplied by transient thermal resistance value, and is then inverse Fourier transformed. First, $P_{\mathrm{loss}}(t)$ is expanded in a Fourier series, and Fourier series a_0, a_m, b_m for each frequency component is obtained as expressed in Equation 1.

$$P_{\mathrm{loss}}(t) = a_0 + \sum_{m=1}^{g} \{ a_m \cos(m\omega t) + b_m \sin(m\omega t) \} \quad \cdots\cdots (2)$$

$P_{\mathrm{loss}}(t)$: Loss waveform
ω: Output angular frequency of the inverter
g: Arbitrary integer

Next, Fourier series c_m, d_m of the temperature rise waveform are obtained by the product of the determined Fourier coefficient and junction-to-case thermal impedance $Z_{\mathrm{th(j\text{-}c)}}$.

$$c_m = \sum_{n=1}^{4} \frac{(a_m - m\omega\tau_n b_m)}{1 + (m\omega\tau_n)^2} r_n \quad \cdots\cdots (3)$$

$$d_m = \sum_{n=1}^{4} \frac{(m\omega\tau_n a_m + b_m)}{1 + (m\omega\tau_n)^2} r_n \quad \cdots\cdots (4)$$

The $T_{(\mathrm{vj\text{-}c})}(t)$ waveform is obtained by applying an inverse Fourier transform to these series.

$$T_{(\mathrm{vj\text{-}c})}(t) = T_0 + \sum_{m=0}^{g} \{ c_m \cos(m\omega t) + d_m \sin(m\omega t) \}$$
$$= P_{\mathrm{loss(ave)}} \sum_{n=1}^{4} r_n + \sum_{m=0}^{g} \{ c_m \cos(m\omega t) + d_m \sin(m\omega t) \} \quad \cdots\cdots (5)$$

$T_{(\mathrm{vj\text{-}c})}(t)$: Junction-to-case temperature
T_0: Average value of temperature rise

Using the heat sink-to-ambient temperature $T_{(\mathrm{s\text{-}a})}$ and the case-to-heat sink temperature $T_{(\mathrm{c\text{-}s})}$, which is obtained by the same method as that used for the junction-to-case temperature $T_{(\mathrm{vj\text{-}c})}(t)$, Equation 6 gives the waveforms of the heat sink temperature T_{s}, case temperature T_{c}, and junction temperature T_{vj}.

$$T_{\mathrm{s}}(t) = T_{\mathrm{a}} + T_{(\mathrm{s\text{-}a})}(t)$$
$$T_{\mathrm{c}}(t) = T_{\mathrm{s}}(t) + T_{(\mathrm{c\text{-}s})}(t)$$
$$T_{\mathrm{vj(IGBT)}}(t) = T_{\mathrm{c}}(t) + T_{(\mathrm{vj\text{-}c})(\mathrm{IGBT})}(t)$$
$$T_{\mathrm{vj(FWD)}}(t) = T_{\mathrm{c}}(t) + T_{(\mathrm{vj\text{-}c})(\mathrm{FWD})}(t) \quad \cdots\cdots (6)$$

$T_{(\mathrm{c\text{-}s})}$: Case-to-heat sink temperature
$T_{(\mathrm{s\text{-}a})}$: Heat sink-to-ambient temperature
T_{s}: Heat sink temperature
T_{c}: Case temperature
$T_{\mathrm{vj(IGBT)}}$: IGBT chip junction temperature
$T_{\mathrm{vj(FWD)}}$: FWD chip junction temperature

4.3 Calculation in consideration of the T_{vj} dependence of power loss

In IGBT simulators Ver.5 and before, power losses are calculated with a constant junction temperature T_{vj} of 125 °C. However, in order to facilitate more realistic calculations, Ver. 6 comes equipped with a new calculation function that takes into consideration the T_{vj} dependence of power losses.

In the IGBT simulator, loss and temperature cannot be calculated simultaneously because the temperature is calculated after obtaining the power losses for the entire period of the calculation as shown in Fig. 4. Therefore, the T_{vj} dependence of power losses is calculated as below.

As an initial value, calculate power losses are from assuming junction temperature $T_{\mathrm{vj}}(t)$ = 125 °C for the entire period of the applicable calculation. Next, calculate the junction temperature $T_{\mathrm{vj}}(t)$ from each of the values of thermal impedance. After this, recalculate power loss based on the $T_{\mathrm{vj}}(t)$ obtained as described above. Finally, obtain the convergence value by repeatedly calculating loss and temperature in this manner.

Figure 6 shows the differences between the number

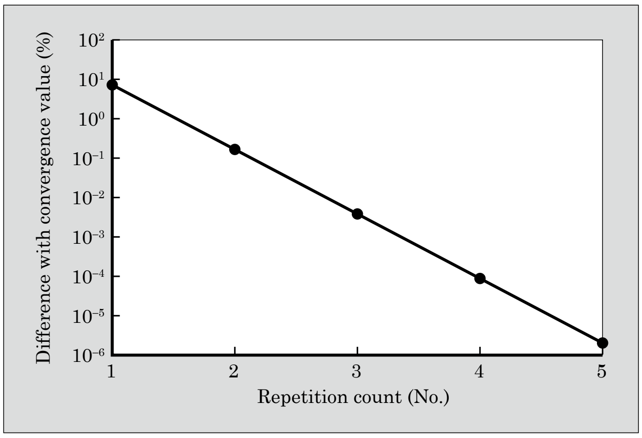

Fig.6 Difference between the number of recalculations and the convergence values

of recalculations of loss and temperature and the convergence value. The calculated IGBT loss for a single recalculation (assuming T_{vj} = 125 °C) has a margin of error of 7% with respect to the convergence value. On the other hand, when the number of recalculations is increased to 3, the difference with the convergence value is less than 0.01%, thereby providing a practical value that can be used without concern.

5. Comparison with Commercially Available Simulator

In order to verify if IGBT Simulator Ver. 6 correctly calculates loss while taking into consideration T_{vj} dependence, we compared its results with those of the commercially available circuit simulator PLECS(2)*3.

PLECS is an electrical circuit simulation software for power electronics systems. Switching devices are modeled as ideal switches. In addition, PLECS can determine the loss generated in a circuit's switching element by inputting the loss characteristics of the switching element. Temperature simulation is also possible by incorporating a one-dimensional thermal resistance model.

Table 1 shows the simulation conditions, and Table 2 and Fig. 7 shows a comparison of the simulation results. All of the results coincide extremely well, thereby verifying the validity of the calculation.

Table 1 Simulation conditions

Item	Condition
IGBT module	2MBI600XNE120-50
Circuit and control method	3-phase inverter Sinusoidal modulated PWM
AC output frequency	50 Hz
AC output current	300 A
DC bus voltage	600 V
Switching frequency	8 kHz
Power factor	0.9
Modulation rate	0.9
Gate resistance	0.56 Ω
Case temperature	90°C

Table 2 Comparison of simulation results

Item	IGBT Simulator Ver. 6 (Fuji Electric product)	PLECS Ver.4.1
IGBT conduction loss (W)	147.6	147.5
IGBT switching loss (W)	103	103.1
FWD conduction loss (W)	30.9	30.9
FWD switching loss (W)	49.9	49.5
IGBT junction temperature (°C)	106.5	106.6
FWD junction temperature (°C)	96.3	96.6

*3: PLECS is a trademark or registered trademark of Plexim GmbH

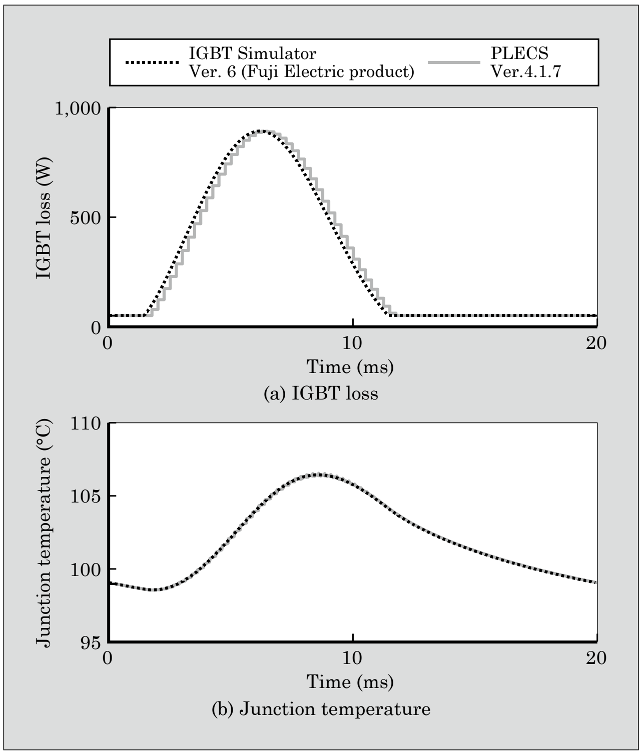

Fig.7 Comparison of IGBT loss and temperature calculation results

6. Estimation of the Power Cycle Lifetime

6.1 IGBT module power cycle lifetime

In servo drive systems and applications such as elevators and electric vehicles equipped with power converters that use IGBT modules, frequent and repeated acceleration and deceleration can fluctuate the junction temperature during speed changes, low frequency operation and motor lock mode, which in turn can cause failure in the IGBT module(3). Figure 8 shows an example of the ΔT_{vj} power cycle curve of an IGBT module, and Fig. 9, an example of a load cycle calculated by the IGBT simulator. The temperature waveform plot-

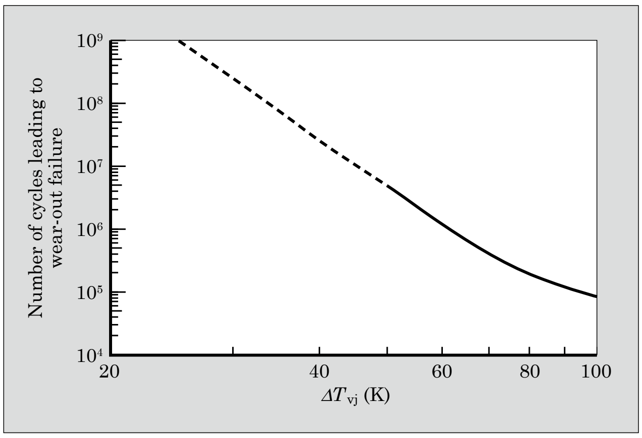

Fig.8 Example of IGBT module ΔT_{vj} power cycle curve

ted with solid line shows the maximum temperature for the inverter output period, whereas that with the dashed line shows the average temperature for the output period. For details, please refer to the manual[4] of the IGBT simulator.

Figure 8 shows the number of cycles (lifetime) leading to failure when a constant temperature change ΔT_{vj} is repeatedly applied to an IGBT module. However, since the actual load changes during the specified operation cycle of the specified period as shown in Fig. 9, the lifetime of the IGBT module cannot simply be estimated by using the ΔT_{vj} power cycle curve.

In general, module breakdown due to the ΔT_{vj} power cycle corresponds to wear-out failure*4. If there are multiple temperature fluctuations in a specified operating cycle, the power cycle lifetime can be estimated on the basis of the linear cumulative damage rule (Miner's rule).

Multiple temperature fluctuations occurring during a specified operation cycle are expressed as ΔT_{vj1}, ΔT_{vj2}, ΔT_{vj3}, …, ΔT_{vji}. Next, the number of repetitions until breakdown occurred at each temperature fluctuation is obtained from Fig. 8 and expressed as N_1, N_2, N_3, ..., N_i. If the number of times ΔT_{vj1}, ΔT_{vj2}, ΔT_{vj3}, ..., ΔT_{vji} occurs during the specified operation cycle is n_1, n_2, n_3, ..., n_i, the fatigue damage ratio D per operation cycle can be expressed by Equation 7.

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots + \frac{n_i}{N_i} \quad \text{..............................} (7)$$

n_i: Number of ΔT_{vji} occurrences during a single operation cycle
N_i: Number of power cycles until ΔT_{vji} fatigue damage occurs
D: Fatigue damage ratio per operation cycle

Module failure occurs if the cumulative fatigue damage ratio $N_{cycle} \times D$ is more than 1 when the operation cycle is repeated N_{cycle}. The number of operation cycles until module failure is determined by Equation 8.

$$N_{cycle} = 1/D \quad \text{..} (8)$$

N_{cycle}: Number of operation cycles until module failure

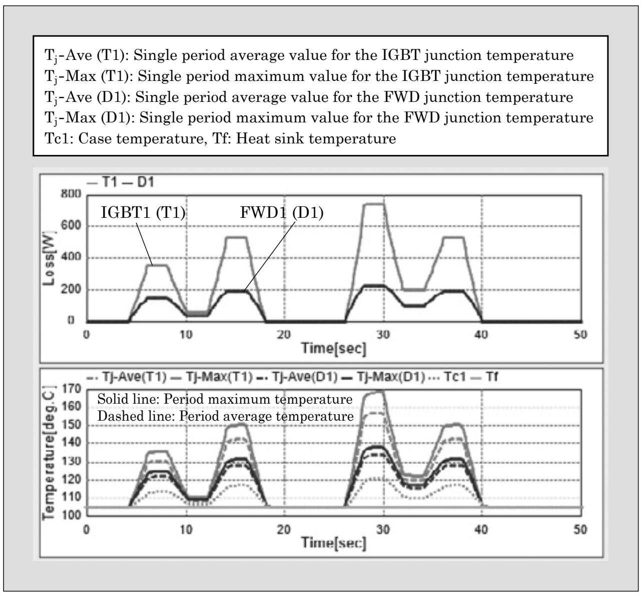

Fig.9 Example of load cycle calculation via IGBT simulator

6.2 Power cycle count via rainflow-counting method

The peak counting method, the range pair counting method and other methods are proposed for predicting the lifetime in wear-out failure. The rainflow counting is one of the major methods.

As an example shown in Fig. 10, the T_{vj} profile during an operation cycle that is repeated every 60 seconds was obtained via the IGBT simulator. Then, the number of occurrences n_i for multiple ΔT_{vj} obtained by using the rainflow-counting method from the T_{vj} profile is shown in Table 3.

N_i is the power cycle lifetime at each ΔT_{vj} obtained from Fig. 8. On the basis of these values, $N_{cycle} = 1.9 \times 10^6$ cycles can be obtained by using Equation 8 to calculate the number of cycles until the module is failed for the 60-second cycle, and from this, the IGBT module lifetime can be estimated to be 10.9 years when

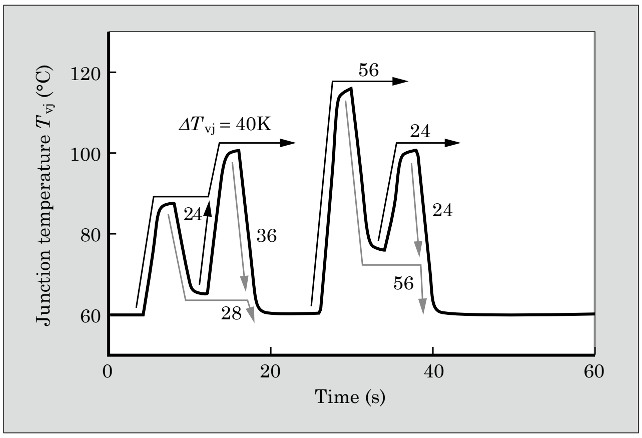

Fig.10 Power cycle count via rainflow-counting method

Table 3 Power cycle count calculated via rainflow-counting method

ΔT_{vj} (K)	Occurrences n_i	N_i	n_i/N_i
23 to 25	1.5	1.27×10^9	1.2×10^{-9}
27 to 29	0.5	4.19×10^8	1.2×10^{-9}
35 to 37	0.5	5.90×10^7	8.5×10^{-9}
39 to 41	0.5	2.56×10^7	2.0×10^{-8}
55 to 57	1.0	2.02×10^6	5.0×10^{-7}

*4: Wear-out failure: the failure rate curve can be separated into the 3 periods: initialization failure, accidental failure and wear-out failure. Wear-out failure causes the failure rate to increase over time due to wear and fatigue.

operated 8 hours a day with $N_{\text{cycle}} \times 60$ seconds = 1.1×10^8 seconds.

7. Postscript

In this paper, we described the estimation of power loss, temperature and lifetime of IGBT modules using our simulator. In addition to supporting 3-level circuits and many of the widely used PWM methods, it enables calculation of power loss depended on junction temperature in order to provide a more realistic simulation. Furthermore, we also explained how to estimate power cycle lifetime from simulation results in applications characterized by complex output fluctuations such as those of electric vehicles.

The described simulator, though in simple manner, helps users understand movements in the power loss and temperature rise of IGBT modules in a user-friendly manner. We recommend that this simulator be used during the initial stages of design to aid users in selecting modules and estimating lifetime.

References

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