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Loss Calculation Methods of Half-Bridge Square-Wave Inverters

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Introduction

The insulated gate bipolar transistors (IGBTs) are widely used in many modern fields of power electronics that are related to power conversion, transmission and distribution. Today IGBTs with blocking voltages up to 6.5 kV are commercially available, allowing simple and robust two-level topologies to be used in applications with nominal DC voltages up to 3.6 kV without the need of series connection of several IGBTs. The other advantages of IGBTs are easy driving and snubberless operation. On the other hand, the high-voltage IGBTs have limited current capability and high power losses, resulting in limited switching performance due to thermal issues. Therefore, thermal management became one of the most important aspects in the development of high-voltage IGBT converters. The accurate estimation of power losses is an important step in thermal management system design [1–3]. A number of calculation methods have been proposed. One of the approaches is based on the switching functions or coefficients obtained through measurements to guide the simulation during switching transients [4, 5]. However, this method requires a number of parameters to be extracted from the test waveforms. Another approach is based on the use of simple functions derived for losses based on typical switching waveforms [6, 7]. This method was extended in [1, 8] by deriving a set of formulae for switching losses based on the predicted current and voltage waveforms of the device. In this method the predicted waveforms conform to the physics of the switching process and take into account the dependency of the switching losses on various factors such as the switching voltage, switching current, stray inductance and the reverse recovery process of the freewheeling diode [8]. Another advantage is that it requires a smaller number of parameters from the test waveforms.

If a power electronic system prototype is unavailable, the losses can be estimated by the help of the datasheet parameters of the devices using linear interpolation of characteristic curves [9, 10]. This approach is generally limited in accuracy, however could be considered as a first approximation.

This paper will focus on the improvement of the calculation methods using manufacturers' datasheet parameters of semiconductors for inverters with the square-wave output [11]. The second part presents an analytical method of estimating losses, including the losses caused by parasitic components of the circuit.

Definitions

The power loss of each switching operation for the given current and voltage waveforms of the IGBT is divided into three sections as illustrated in Fig. 1 [12]. The leakage loss is only a small part of the total loss so that neglecting it the error is usually insignificant. Therefore, the total energy losses during each operating cycle of the IGBT are the sum of the turn-on and turn-off loss, saturated conduction loss as well as the reverse-recovery loss of the integrated freewheeling diode (FWD) [8]

$$E_{tot} = \int I(t) \cdot U(t) \cdot dt \,, \quad (1)$$

where *I(t)* and *U(t)* are transistor current and voltage, respectively.

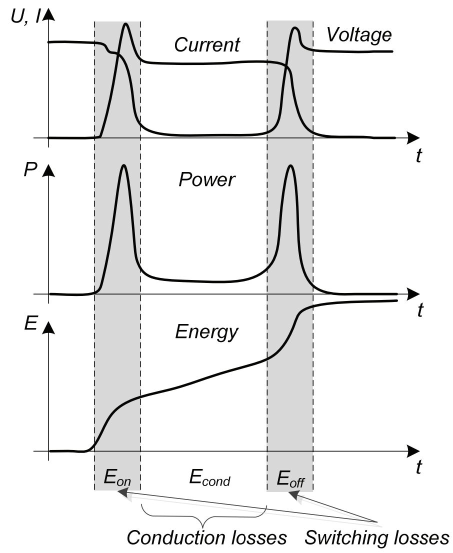


Fig. 1. Three sections of losses

Table 1. Characteristic values of 200 A 6500 V IGBT (FZ200R65KF2)

Parameter	Symbol	Value
Collector-emitter voltage	U_{CES}	6500 V
DC collector current	$I_{C(nom)}$	200 A
Collector-emitter saturation voltage	$U_{CE(sat)}$	5.3 V
Turn-on delay time	$t_{d(on)}$	0.72µs
Rise time	t_r	0.40 µs
Turn-off delay time	$t_{d(off)}$	6.00 µs
Fall time	t_f	0.50 µs
Critical rate of rise of current	dI_t/dt_{cr}	1000 A/µs
Turn-off delay time	$t_{d(off)}$	11 µs
Turn-on energy loss per pulse	E_{on}	1900 mJ
Turn-off energy loss per pulse	E_{off}	1200 mJ
Diode's repetitive peak current	I_{FRM}	400 A
Diode's forward voltage	U_F	3.90 V
Diode's peak reverse-recovery current	I_{RM}	330 A
Reverse-recovery energy	E_{rec}	550 mJ

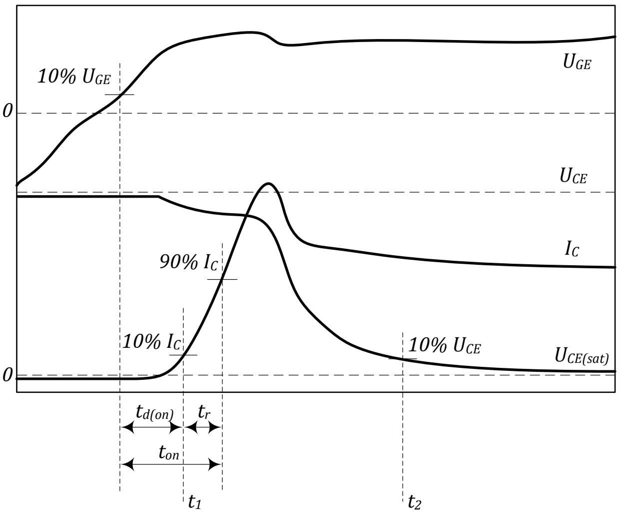


Fig. 2. IGBT switching times and energy defenitions during turn-on

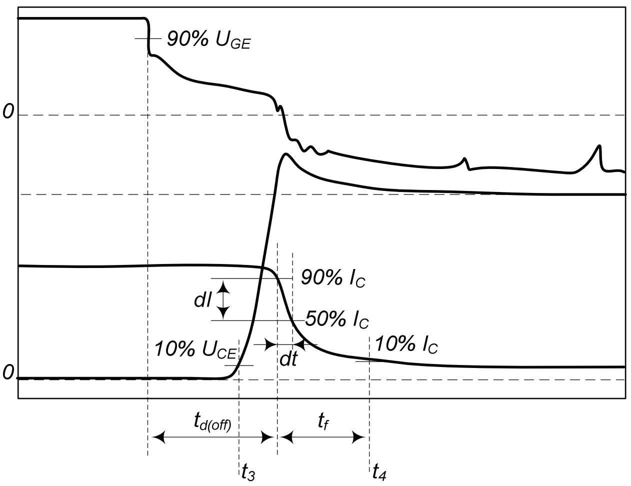


Fig. 3. IGBT switching times and energy defenitions during turn-off

The datasheets of IGBTs contain typical information about switching transients, on-state behaviour and energy losses during a single operation pulse. These characteristics refer to a specific test circuit which simulates a clamped inductive load operating with a specific diode [6]. Typical datasheet values of Infineon 200 A 6.5 kV IGBT module are presented in Table 1.

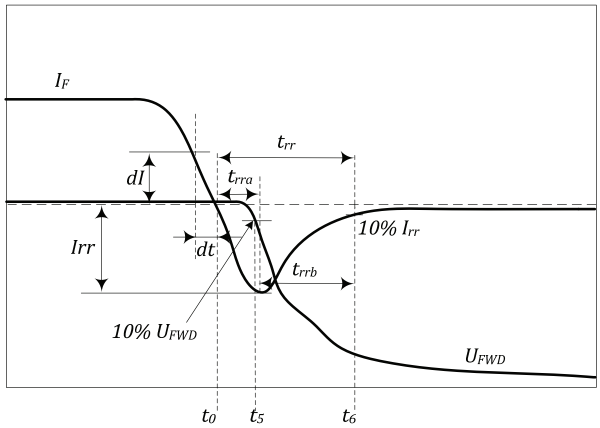


Fig. 4. FWD switching times and energy definitions during reverse-recovery

For high-voltage IGBT modules, the turn-on energy loss E_{on} is generally defined as the integral of the product of the collector current and the collector-emitter voltage over the interval from when the collector current rises above 10% of the test current to when the voltage falls below 10% of the test voltage (Fig. 2). The turn-off energy loss E_{off} is the integral of the product of the collector current and the collector-emitter voltage over the interval starting from when the collector-emitter voltage rises above 10% of the test voltage to when the collector current reaches 10% of the test current (Fig. 3). The diode reverse-recovery energy E_{rec} is the integral of the product of the diode current and voltage over the interval starting from when the voltage across the diode rises above 10% of the test voltage to when the diode reverse current drops to 10% of its peak value (Fig. 4).

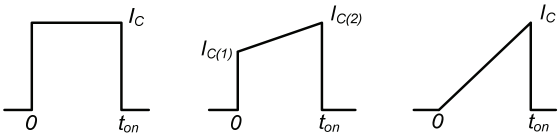
Loss calculation method using datasheet parameters

General equations. The on-state voltage drop of the non-punch-through (NPT) IGBT device generally increases with a higher collector current and the junction temperature. Moreover, it could vary from one device to another. The datasheets typically indicate the typical and the maximum values. The maximum values generally refer to the worst case device that the manufacturers consider as qualitative. For example, the 200A 6.5 kV IGBT collector-emitter saturation voltage varies from 5.3 V (typical) to 5.9 V (maximal) for the 200 A collector current at the junction temperature of 125°C. Generally, use of typical values at the maximum junction temperature could be considered reasonably accurate. The conduction losses are estimated by

$$P_{cond} = \frac{1}{T_{sw}} \cdot \int_{0}^{t_{on}} I \cdot U_{CE(sat)}\left(I, T_j, k_{(sat)}\right), \qquad (2)$$

where T_{sw} is the switching period, t_{on} is the on-state time, I is the IGBT current, T_j is the switch junction temperature, $k_{(sat)}$ is the scale factor based on the properties of the device considered.

The switching energy loss of a device is variable due to the device's current, voltage, gate resistance and junction temperature.



a) b) c)

Fig. 5. Typical transistor current waveforms operating in inverters with the square-wave voltage output

Generally, the latter dependency is not indicated in the datasheets, while the energy loss versus current and gate resistance are indicated at the maximum junction temperature. Since the losses increase with increased temperature, it is assumed in the following that the junction temperature will be 125°C as a worst case [9]. In general, the turn-on and turn-off energies are obtained by:

$$E_{on} = \int_{t_1}^{t_2} I \cdot U_{CE} \cdot dt\,, \qquad (3)$$

$$E_{off} = \int_{t_3}^{t_4} I \cdot U_{CE} \cdot dt\,. \qquad (4)$$

Calculation equations, linear approximation. To achieve fast analytical calculations, the on-state voltage drop can be characterized by a dynamical resistance r_T and a constant voltage drop U_{T0}. The voltage drop across the IGBT with rms collector current is then determined by

$$U_T = U_{T0} + r_T \cdot I_C^{rms}\,, \qquad (5)$$

where U_{T0} is the device's threshold voltage, r_T is the device's slope resistance and I_C^{rms} is the transistor RMS collector current.

For inverters with the square-wave output voltage the on-state energy dissipation for typical output current waveforms (Fig. 5) could be obtained by simple equations.

Case A.

$$I(t) = I_C\,. \qquad (6)$$

Conduction energy losses for the given pulse length

$$E_{cond} = \left(U_{T0} \cdot I_C + r_T \cdot I_C^2\right) \cdot t_{on}\,. \qquad (7)$$

Case B.

$$I(t) = I_{C(1)} + \left(I_{C(2)} - I_{C(1)}\right) \cdot \frac{t}{t_{on}}\,. \qquad (8)$$

Conduction energy losses for the given pulse length

$$E_{cond} = \begin{bmatrix} U_{T0} \cdot \dfrac{I_{C(1)} + I_{C(2)}}{2} + \\ + \dfrac{1}{3} \cdot r_T \cdot \left(I_{C(1)}^2 + I_{C(1)} \cdot I_{C(2)} + I_{C(2)}^2\right) \end{bmatrix} \cdot t_{on}\,. \qquad (9)$$

Case C.

$$I(t) = I_C \cdot \frac{t}{t_{on}}\,. \qquad (10)$$

Conduction energy losses for the given pulse length

$$E_{cond} = \frac{1}{6} \cdot I_C \cdot t_{on} \cdot \left(3 \cdot U_{T0} + 2 \cdot I_C \cdot r_T\right). \qquad (11)$$

The conduction power losses can then be calculated by

$$P_{cond} = f_{sw} \cdot E_{cond}\,. \qquad (12)$$

No simple expression can be found for the voltage and current during a switching transient. The datasheet parameters concerning the switching losses can be used in this case. To simplify the analysis for different current levels, the datasheet energy loss curves could be replaced by their linear interpolations using simple equations:

$$E_{on} = A_{on} \cdot I_C + B_{on}\,, \qquad (13)$$

$$A_{on} = \frac{\Delta E_{on}}{\Delta I_C} = \frac{E_{on(2)} - E_{on(1)}}{I_{C(2)} - I_{C(1)}}\,, \qquad (14)$$

$$B_{on} = E_{on(2)} - A_{on} \cdot I_{C(2)}\,, \qquad (15)$$

where $I_{C(1)}$, $I_{C(2)}$ are currents and $E_{on(1)}$, $E_{on(2)}$ corresponding energy loss values taken from the datasheet graphs. The turn-off coefficients A_{off} and B_{off} are calculated in the similar way.

Since the actual operation parameters of semiconductors are in most cases different from the reference circuit, datasheet values should be scaled accordingly. If the gate resistor of a user's gate drive does not have the same value as the gate resistor in the test circuit specified in the datasheet some corrections may be necessary. This can be done with the help of the datasheet using graphs $E_{on}=f(R_G)$ and $E_{off}=f(R_G)$. The scale factor is obtained by the relation between the switching losses with the used-specific gate resistance R_{G-on}^{US} and the one specified in the datasheet R_{G-on}^{DS} [4]

$$k_{(R_{G-on})} = \frac{E_{on}\left(R_{G-on}^{US}\right)}{E_{on}\left(R_{G-on}^{DS}\right)}\,. \qquad (16)$$

The turn-off resistor scale factor $k_{(R_{G-off})}$ is calculated in the similar way.

Generally, the switching losses scale almost linearly with U_{CE}, hence the following approximation of the scale factor for the actual commutation voltage could be considered reasonably accurate

$$k_{(U_{CE-on})} = \frac{U_{CE-on}^{US}}{U_{CE}^{DS}}\,, \qquad (17)$$

where U_{CE-on}^{US} is DC voltage across the IGBT during the off-state before the beginning of the turn-on transition, U_{CE}^{DS} is the collector-emitter voltage cpecified in the datasheet graphs $E_{on}=f(I_C)$, $E_{off}=f(I_C)$. The scale factor for the actual commutation voltage $k_{(U_{CE-off})}$ during the turn-off is obtained in the similar way

$$k_{(U_{CE-off})} = \frac{U_{CE-off}^{US}}{U_{CE}^{DS}}, \tag{18}$$

where U_{CE-off}^{US} is DC voltage at IGBT after the end of the turn-off transition.

The switching energy losses for typical current waveforms (Fig. 5) can be approximated by the following expressions.

<u>*Case A.*</u>

$$E_{on} = \left(A_{on} \cdot I_C + B_{on}\right) \cdot k_{R_{G-on}} \cdot k_{U_{CE-on}}, \tag{19}$$

$$E_{off} = \left(A_{off} \cdot I_C + B_{off}\right) \cdot k_{R_{G-off}} \cdot k_{U_{CE-off}}. \tag{20}$$

<u>*Case B.*</u>

$$E_{on} = \left(A_{on} \cdot I_{C(1)} + B_{on}\right) \cdot k_{R_{G-on}} \cdot k_{U_{CE-on}}, \tag{21}$$

$$E_{off} = \left(A_{off} \cdot I_{C(2)} + B_{off}\right) \cdot k_{R_{G-off}} \cdot k_{U_{CE-off}}. \tag{22}$$

<u>*Case C.*</u>

$$E_{on} = 0, \tag{23}$$

$$E_{off} = \left(A_{off} \cdot I_C + B_{off}\right) \cdot k_{R_{G-off}} \cdot k_{U_{CE-off}}. \tag{24}$$

Diode reverse-recovery losses. The data available to calculate the diodes' reverse recovery losses differs from one manufacturer to another. Furthermore, these losses depend on the current slope during the transition which in standard VSIs is basically determined by the inductance of the circuit, IGBT *dI/dt* during turn-on and operation temperature [12]. If the reverse-recovery energy in the datasheet is provided only for one operating point, then the scale factor k_{rr} can be calculated according to [13]

$$k_{rr} = \frac{E_{rr}^{DS}}{Q_{rr}^{DS} \cdot U_{CE}^{DS}}, \tag{25}$$

where E_{rr}^{DS}, Q_{rr}^{DS} and U_{CE}^{DS} are revese-recovery energy, reverse-recovery charge and voltage specified in the datasheet, correspondingly.

The reverse-recovery energy can now be approximated as

$$E_{rr} = k_{rr} \cdot Q_{rr}^{US} \cdot U_{CE}^{US} = k_{rr} \cdot \frac{I_{rr} \cdot t_{rr}}{2} \cdot U_{CE}^{US}. \tag{26}$$

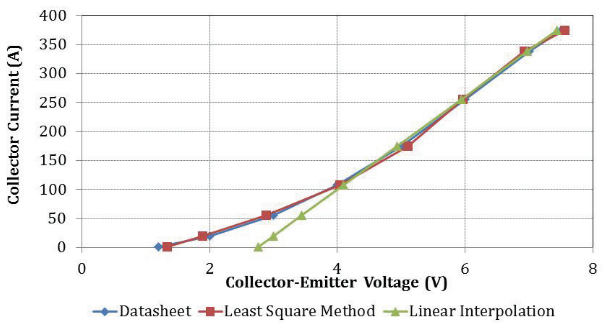


Fig. 6. Collector-emitter saturation voltage comparison with collector current using different interpolation methods

Calculation equations, least square approximation. The drawback of the above presented equations is generally related to the limited accuracy of the linearly interpolated characteristics of U_{CE}=*f*(I_C), E_{on}=*f*(I_C) and E_{off}=*f*(I_C). A better result, especially at lower currents, can be achieved by approximating these curves with the following function

$$f(x) = A \cdot x^3 + B \cdot x^2 + C \cdot x + F. \tag{27}$$

The coefficients *A*, *B*, *C* and *F* of the proposed function can be estimated from the datasheet curves using the least square method with the help of software, such as SOLVER in EXCEL. The comparison of results obtained with different interpolation methods is shown in Fig. 6.

The conduction losses can then be expressed as

$$P_{cond} = \frac{1}{T_{sw}} \cdot \int_0^{t_{on}} I(t) \cdot U_{CE(sat)}\left(I(t)\right) \cdot dt, \tag{28}$$

where *I(t)* could be expressed according to Eqs. 6, 8 and 10.

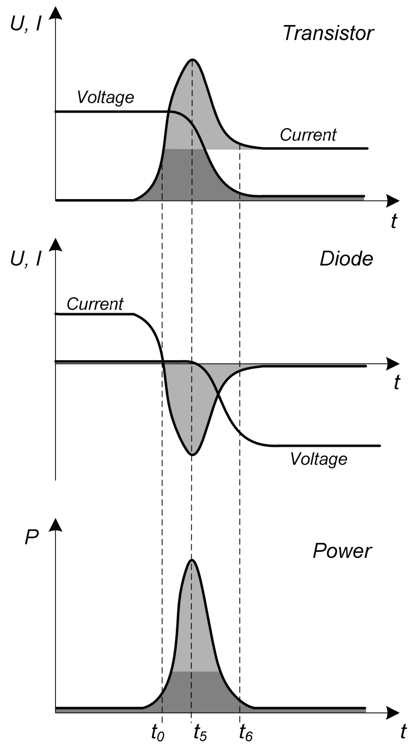


Fig. 7. Typical transistor voltage,current and power waveforms during turn-on

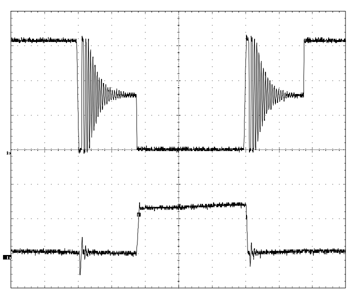


Fig. 8. Experimental waveforms of IGBT collector voltage (top) and current (bottom) during the tests of the inverter prototype (D=0.32), 20 A/div, 50 us/div

Analytical loss estimation method of two-level VSI

The turn-on energy losses indicated in the datasheet of the IGBT typically include the losses caused by the reverse-recovery current of turning-off freewheeling diode (Fig. 7).

No simple expression can be provided for these additional losses, as they depend on a number of factors: turn-on *di/dt*, citruit inductance and diode characteristics. The following equation assumes that the voltage across the diode stays close to zero volts during the interval t_0-t_5, rising to the supply voltage during t_5-t_6 (Fig. 4)

$$E_{on} = U_{CE-on}^{US} \cdot I_C \cdot \left[\left(1 + \frac{1}{2} \cdot \frac{I_{rr}}{I_C}\right) \cdot t_{0-5} + \frac{1}{4} \cdot \frac{I_{rr}}{I_C} \cdot t_{5-6}\right] = = U_{CE-on}^{US} \cdot \left(I_C \cdot t_{0-5} + Q_{t_{0-5}} + \frac{1}{2} \cdot Q_{t_{5-6}}\right), \quad (29)$$

where I_{rr} is the peak reverse-recovery current.

However, in the square-wave two-level half-bridge converters, the reverse-recovery process of freewheeling diodes is finished during the freewheeling state. Hence, there is no additional current during the turn-on of the IGBT, resulting in lower losses. Due to the leakage induction of the isolation transformer and the parasitic capacitances of HV-IGBT modules there are oscillations after the IGBT turn-off (Fig. 8). The energy stored in the circuit is lost during this process, moreover the IGBT modules seem to sustain additional reverse-recovery losses. This process was studied in [11] and the energy lost during the oscillation period is

$$E_{osc} = \frac{1}{2} \cdot L_E \cdot I_{osc}^2, \quad (30)$$

where L_E is the total parasitic inductance of the circuit, I_{osc} is the peak value of the oscillating current.
The proposed improved approximation of the transistor switching process is shown in Fig. 9. The turn-on energy is calculated by integrating multiplied turn-on voltage and current ramp. As the current changes slower than the voltage at the turn-on, the power loss equation is divided into two parts. In the first part both the voltage and current are changing, in the second part only the current changes. This energy is multiplied by the switching frequency f_{sw}. The result of this equation is the IGBT turn-on power loss

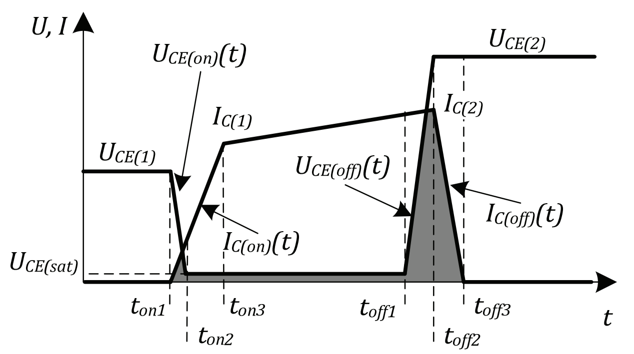


Fig. 9. Generalised IGBT waveforms in the two-level half-bridge voltage-source inverter

$$P_{on} = f_{sw} \cdot \left[\begin{array}{l} \int_{t_{on1}}^{t_{on2}} U_{CE(on)}(t) \cdot I_{C(on)}(t)dt + \\ + \int_{t_{on2}}^{t_{on3}} U_{CE(sat)}(I_C) \cdot I_{C(on)}(t)dt \end{array}\right], \quad (31)$$

where t_{on1} to t_{on3} is the total IGBT turn-on time; t_{on1} to t_{on2} is the IGBT collector-emitter voltage fall time from operation to saturation level, and t_{on1} to t_{on3} is the IGBT collector current rise time. $U_{CE(on)}(t)$ is the IGBT collector-emitter voltage at turn-on and $I_{C(on)}(t)$ is the collector current function during the turn-on of the IGBT. To simplify the calculations, voltage and current waveforms can be replaced by the linear functions:

$$U_{CE(on)}(t) = U_{CE(1)} - \frac{(t - t_{on1}) \cdot \left(U_{CE(1)} - U_{CE(sat)}\right)}{t_{on2} - t_{on1}}, \quad (32)$$

$$I_{C(on)}(t) = \frac{(t - t_{on1}) \cdot I_{C(1)}}{t_{on3} - t_{on1}}. \quad (33)$$

Transistor turn-off losses could be calculated assuming the current through the IGBT stays close to $I_{C(2)}$ during the interval t_{off1}-t_{off2} and the voltage across the IGBT is close to $U_{CE(2)}$ during the interval t_{off2}-t_{off3}. The turn-off energy loss can then be approximated by

$$P_{off} = f_{sw} \cdot \frac{U_{CE(2)} \cdot I_{C(2)} \cdot (t_{off3} - t_{off1})}{2}. \quad (34)$$

Table 2. Results of the analytical loss calculation

E_{on} (mJ)	E_{off} (mJ)	E_{rr} (mJ)	E_{cond} (mJ)	E_{osc} (mJ)	E_{total} (mJ)
5.2	254.3	16.6	10.1	9.3	295.5

Using the analytical approach (Eqs. 25-34) and the measured waveforms of the converter prototype the switching losses of the IGBT module are estimated (Table 2). Using the proposed analytical loss estimation method it is possible to estimate the contribution of the turn-on or turn-off losses in the total switching losses, which could be beneficial in estimating the feasibility of implementation of different loss reduction methods in semiconductors, such as passive or active snubbers. As known, the IGBT turn-on energy loss decreases while turn-off energy loss increases with the stray inductance. Both effects almost compensate each other [13]. In the studied converter due to the high stray inductance of the isolation transformer this effect is clearly observed.

Conclusions

As a result of increased heat dissipation from electronic devices, thermal management appears to be one of the most important issues of power converter design. The estimation of power dissipation of semiconductor devices is essential to determine operation parameters and cooling system requirements of a power converter. This paper presented an overview of different methods for loss calculation in inverters with the square-wave output, using IGBT module parameters extracted from the manufacturer's datasheets and test waveforms. A better method of approximating datasheet curves for fast analysis at different current levels is proposed. Further, an improved analytical loss calculation method using test results of the half-bridge converter prototype is introduced.

Acknowledgements

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References

1. **Andriukaitis D., Anilionis R.** Thermal Oxidation Process Influence to the Three–Dimensional Integrated Structures // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 8(96). – P. 81–84.
2. **Balaišis P., Eidukas D., Gužauskas R., Valinevičius A.** Modeling of Efficiency of Dynamic Electronic Systems // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 6(86). – P. 55–59.
3. **Rajapakse A. D., Gole A. M., Wilson P. L.** Electromagnetic transients simulation models for accurate representation of switching losses and thermal performance in power electronic systems // Power Delivery, IEEE Transactions, 2005. – Vol. 20. – No. 1. – P. 319–327.
4. **Azuma S., Kimata, M., Seto M., Jiang X., Haiwei L., Dewei X., Lipei H.** Research on the power loss and junction temperature of power semiconductor devices for inverter // Vehicle Electronics Conference (IVEC '99), 2009. – Vol. 1. – P. 183–187.
5. **Wong C.** EMTP modeling of IGBT dynamic performance for power dissipation estimation // Industry Applications Conference, 1995. – Vol. 3. – P. 2656–2662.
6. **Jinrong Q., Khan A., Batarseh I.** Turn–off switching loss model and analysis of IGBT under different switching operation modes // Industrial Electronics, Control, and Instrumentation (IECON), 1995. – Vol. 1. – P. 240–245.
7. **Bland M., Wheeler P., Clare J., Empringham L.** Comparison of calculated and measured losses in direct AC–AC converters // Power Electronics Specialists Conference (PESC), 2001. – Vol. 2. – P. 1096–1101.
8. **Rajapakse A. D., Gole A. M., Wilson P. L.** Approximate Loss Formulae for Estimation of IGBT Switching Losses through EMTP–type Simulations // 6th International Conference of Power System Transients, 2005.
9. Calculation of Major IGBT Operating Parameters // Infineon Application Note – ANIP9931E, 1999.
10. **Graovac D., Pürschel M.** IGBT Power Losses Calculation Using the Data–Sheet Parameters // Infineon Application Note, Ver. 1.1, 2009.
11. **Blinov A., Jalakas T., Vinnikov D., Janson K.** Switch–Off Behaviour of 6.5 kV IGBT Modules in Two–Level Voltage Source Inverter // Scientific Journal of Riga Techical University: Power and Electrical Engineering, 2010. –Vol. 27. – P. 121–126.
12. **Ahmed M. M. R., Putrus G. A**. A method for predicting IGBT junction temperature under transient condition // Industrial Electronics – 34th Annual Conference of IEEE (IECON'2008), 2008. – P. 454–459.
13. **Feix G., Dieckerhoff S., Allmeling J., Schonberger J.** Simple methods to calculate IGBT and diode conduction and switching losses // Power Electronics and Applications (EPE'09), 2009. – P. 1–8.

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This paper presents methods of loss calculation of IGBT modules, operating in two-level half-bridge inverters with square-wave output. The equations for calculating IGBT module losses for typical collector current waveforms using linearly interpolated datasheet curves are presented. Since this method is generally limited in accuracy, a better approximation of datasheet curves is introduced. In the second part the switching waveforms of experimental two-level half-bridge inverter based on two 6.5 kV Infineon IGBT modules are analysed. Ill. 9, bibl. 13, tabl. 2 (in English; abstracts in English and Lithuanian).

A. Blinov, D. Vinnikov, T. Jalakas. Nuostolių įvertinimo metodų taikymas kvadratinės bangos keitikliuose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 7(113). – P. 9–14.

Analizuojami IGBT tranzistorių, naudojamų dviejų lygių keitikliuose, nuostolių įvertinimo metodai. Pateiktos formulės IGBT tranzistoriaus nuostoliams apskaičiuoti. Pateiktos tiesiškai interpoliuotos kolektoriaus srovės kreivės. Pristatytas naujas aproksimacijos, kuria siekiama padidinti ribotą analizuojamojo metodo tikslumą, pavyzdys. Atliktas eksperimentas naudojant du 6,5 kV IGBT tranzistorius „Infineon”. Il. 9, bibl. 13, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).