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Asymmetric Pulse Width Modulation for Improving the Reliability of Motor Drive Inverters

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***Abstract*—In multi-chip power modules, each power device could have different thermal impedance due to an asymmetric internal layout of the power module. This may lead to different thermal loadings and thereby having lifetime difference of the power devices in practical applications. Both lifetime and power rating of motor drives are limited by the most stressed device. Therefore, the reliability of motor drive can be improved by increasing the lifetime of the most stressed device. In this paper, the asymmetric Pulse Width Modulation (PWM) method to increase the reliability of inverters in motor drive systems has been proposed. The effect of an asymmetric layout of IGBT modules on the reliability of motor drives is studied based on a 3-phase motor drive application. Then, an asymmetric PWM method is proposed. Finally, the lifetime of the IGBT is compared before and after the proposed method is applied.**

I. INTRODUCTION

Adjustable speed motor drives have been widely used in various applications such as ship propulsion, rail traction, wind generation system, water pump system, home appliance, aerospace, electric vehicle, etc for high system efficiency and performance [1]-[2]. Adjustable speed motor drive system typically consists of three main sections; 1) The front-end power converter, which converts AC power from the main grid to DC power, 2) an energy storage unit, called DC-link, and 3) an inverter as the rear end power converter, which converts the DC power to AC power with demanded voltage and frequency for the motor [2]. Among them an inverter is one of the main failure source in motor drive system [3] and therefore, this study is focused on the reliability of an inverter.

Power devices are one of important parts of an inverter in motor drive system in terms of size, cost, and also failure. Therefore, the reliability performance of power devices is an essential aspect to be considered when an inverter is designed [4]. The reliability of power devices depend on the inherent capability and the operational condition in the field operation.

In practical application, power device modules are dominantly used in the range of more than 10 A [5], which consists of multiple power devices and different materials [6]. Wire-bonded/soldered power modules are the most widely used packaging technology. Typically, electro-thermal stresses are the main stressor, which leads to wear-out failure of power device module [7]. Much research have been performed on the reliability of power device modules in respect to electro-thermal stresses such as modeling of junction temperature, active thermal control, and lifetime estimation. In multi-chip power modules, each power device could have different thermal impedances due to an asymmetric layout. It may apply different thermal loadings to each device in practical operation, which will result in lifetime differences among the devices in the module. The detailed results on this effect can be found from [8], [9]. Both lifetime and power rating of an inverter are limited by the most stressed device. Therefore, the reliability of an inverter in motor drive system can be improved by increasing the lifetime of the most stressed device.

In this paper, the asymmetric PWM method to improve the reliability of inverters in motor drive systems has been proposed. A case study based on a 3-phase motor drive inverter is performed. The lifetime of IGBTs are estimated under the given mission profile of the motor drive system in order to show the effect of asymmetric layout on the lifetime difference among devices in the IGBT module. Then, the asymmetric PWM method is proposed. Finally, the lifetime of IGBTs is compared before and after the proposed method is applied.

II. LIFETIME ESTIMATION OF POWER DEVICE MODULE IN A MOTOR DRIVE INVERTER

A. *Variable speed motor drive inverter*

Fig. 1 shows the configuration of a 3-phase adjustable speed motor drive inverter with Permanent Magnet Synchronous Motor (PMSM). The related parameter of this system for the case study is listed in TABLE I.

Fig. 2 shows the mission profile of the inverter for the case study, composed of information on torque and speed profiles. This is a typical start-run-stop process in motor drive applications.

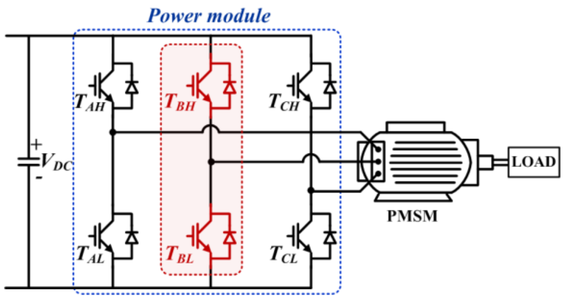

Fig. 1. Configuration of a 3-phase adjustable speed motor drive inverter with PMSM for the case study.

TABLE I. PARAMETERS OF PMSM FOR THE CASE STUDY

Parameters	Symbol	Value	Unit
Nominal power	P_N	5	[kW]
Nominal torque	T_N	24	[Nm]
Nominal speed	n_N	2000	[rpm]
Line-to-line peak voltage per 1000 RPM	$V_{L\text{-}L}$	130	[V]
Rotor inertia	J	0.0055	[Kgm^2]
Number of pole pairs	N_{PP}	4	[-]
Stator resistance	R_s	0.39	[Ω]
Stator inductance	L_s	4.9	[mH]
DC-link voltage	V_{DC}	400	V
Switching frequency	f_{SW}	15	kHz

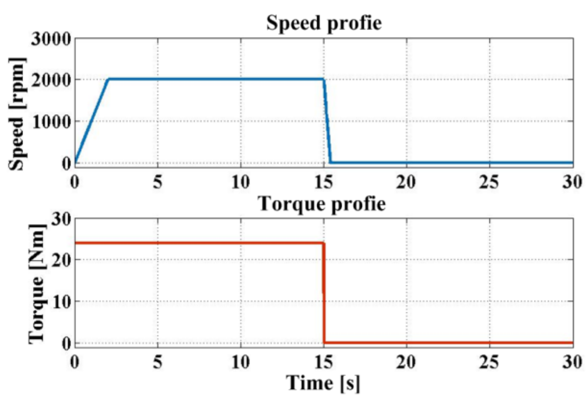

Fig. 2. Mission profile of the motor drive for the case study.

B. Thermal impedances of IGBTs in the module

Transfer molded IGBT modules are widely used in low power motor drive applications due to their advantages such as compactness, low cost, and high reliability [10]. Fig. 3(a) shows the appearance of transfer molded IGBT module, which is the target IGBT module in this paper. The power rating of the IGBT module is 600 V and 30 A. It consists of 6 IGBTs and 6 diodes.

Fig. 3(b) shows the internal layout of the IGBT module. It can be seen that the internal layout is asymmetric. In the inverter operation, typically, the power losses in IGBTs are dominant and thus they have higher temperature stress than diodes. Therefore, this paper is focused on the IGBTs.

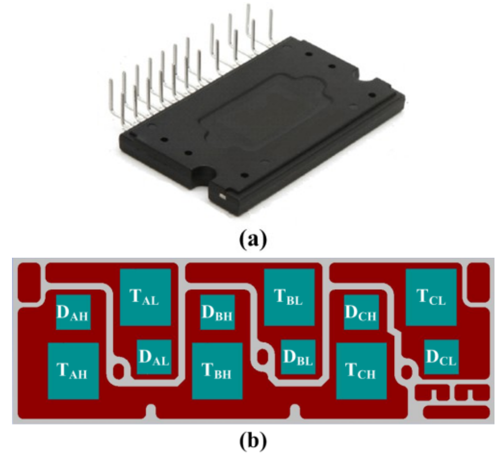

Fig. 3. Transfer molded IGBT module with six transistors and six diodes (a) appearance (b) Internal layout

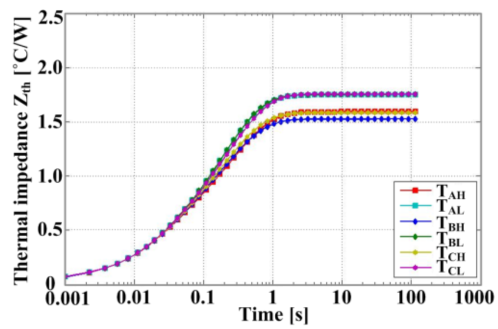

Fig. 4. Thermal impedance of IGBTs in transfer molded IGBT module.

The thermal impedance of each IGBT is extracted by Finite Element Method simulations as shown in Fig. 4. They have almost the same impedance when the transient time is short but the lower IGBTs (T_{AL}, T_{BL}, T_{CL}) have a higher thermal impedance than the upper IGBTs (T_{AH}, T_{BH}, T_{CH}) as the transient time is relatively long, above 0.05 s. From this, it can be expected that the power loss variation by periodical commutation of the power device at low fundamental frequencies of the output and the power loss variation by the load changes, which is typically in the second range or above, leads to different thermal loadings of the IGBTs due to the difference in thermal impedance. Finally, it results in a lifetime difference among the IGBTs.

C. Lifetime estimation of IGBTs under a given mission profile

The study to show the effect of the asymmetric internal layout on the lifetime of the devices in the IGBT module has been studied first in [8], [9].

There are mainly four steps in the lifetime estimation procedure of power device as shown in Fig. 5 [11]. The power loss profiles of power devices should be obtained first from the input data such as device characteristics, converter characteristics and mission profiles of power converter applications.

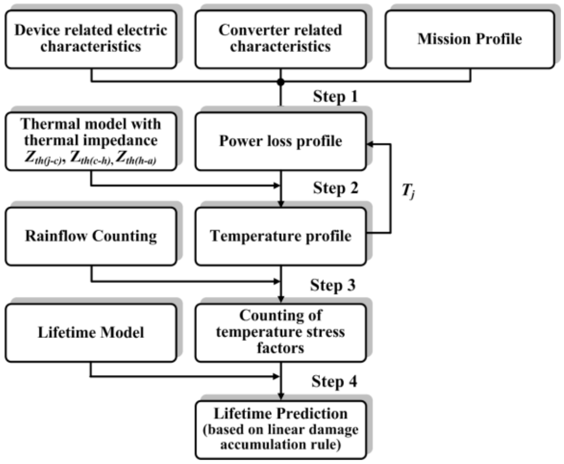

Fig. 5. Lifetime estimation procedure of IGBTs in the module [10].

Then, the power loss profiles of power devices are converted to temperature profiles using a thermal model of the power device modules. In step 3, the different temperature stress factors such as junction temperature swing (ΔT_j) and mean junction temperatures (T_{jm}) are counted from the temperature profiles by using a Rainflow counting method. Finally, the lifetime of the power device modules is predicted based on the Linear Damage Accumulation (LDA) principle by putting the accounted temperature stress factors into the lifetime model. The IGBTs in phase-B (T_{BH}, T_{BL}) as shown in Fig. 1 is selected for the case study due to the largest thermal impedance mismatch.

1) Power loss profile: The total power loss of the IGBT is composed of conduction loss (P_c) and switching loss (P_{sw}). The average conduction loss for switching cycle can be represented as

$$P_{c(T_H/T_L)} = V_{CE\_ON(T_H/T_L)} \cdot I \cdot d \tag{1}$$

where I is the collector current, d is the duty cycle and $V_{CE\_ON(T_H/T_L)}$ is the on-state collector-emitter voltage at a certain reference junction temperature T_H or T_L.

The switching loss of the IGBT is calculated as

$$P_{sw(T_H/T_L)} = f_{sw} \cdot E_{sw} \tag{2}$$

where f_{sw} is the switching frequency and E_{sw} is the switching energy of the IGBT at a certain reference junction temperature T_H or T_L.

Both switching and conduction losses are varied depending on the junction temperature. Therefore, when the power losses are calculated, the junction temperature information of the power device should be included as

$$P_{c/sw(T_j)} = \frac{P_{c/sw(T_H)} - P_{c/sw(T_L)}}{T_H - T_L}(T_j - T_L) + P_{c/sw(T_L)} \tag{3}$$

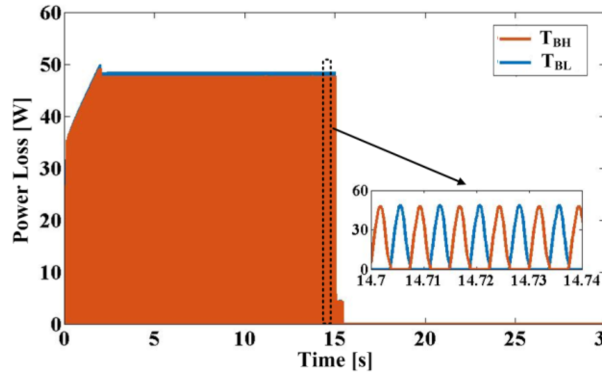

Fig. 6. Power loss profiles of T_{BH} and T_{BL} under the given mission profile shown in Fig. 2.

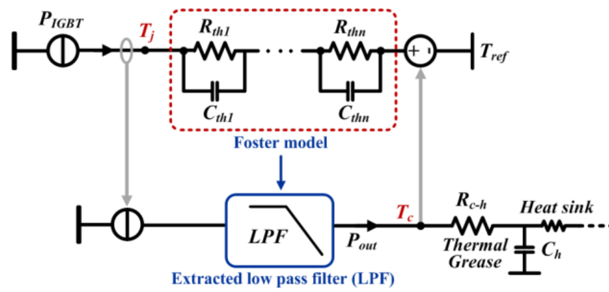

Fig. 7. Thermal model to obtain thermal loadings in the module [11].

Fig. 6 shows the loss profiles of T_{BH} and T_{BL} under the given mission profile shown in Fig. 2.

2) Thermal profile and lifetime estimation: The thermal loading of each device can be obtained from the power loss profiles with the thermal model. In this paper, the thermal model proposed in [12] is used as shown in Fig. 7. This thermal model has two thermal paths. The first thermal is used for the junction temperature estimation inside power device module by uisng the multi layer RC Foster thermal network, represented as

$$Z_{th(j-c)}(t) = \sum_{i=1}^{n} R_i (1 - e^{-t/\tau_i}) \tag{4}$$

where $Z_{th(j-c)}$ is the junction to case thermal impedance, $\tau_i = R_i * C_i$ and i means the different layers of a module for the Foster model.

The second thermal path is used for the temperature estimations outside power device module such as the case and heat-sink temperatures. The filtered power loss by low pass filter (LPF) is used to model the loss behaviors flowing out of the device, where the parameters for LPF can be extracted from the Foster thermal network.

The $Z_{th(j-c)}$ of T_{BH} and T_{BL} and the case to heat-sink thermal impedance ($Z_{th(c-h)}$) for this study are listed in the TABLE II. In this study, it is assumed that the heat-sink temperature is constant, 35 °C.

TABLE II. JUNCTION TO CASE, CASE TO HEAT-SINK AND HEAT-SINK TO AMBIENT THERMAL IMPEDANCES

Impedance	IGBT		i: 1	2	3	4
$Z_{th(j-c)}$ (Junction to case)	T_{BH}	R	0.6667	0.4060	0.3720	0.0801
		C	0.2419	0.0583	1.3502	0.0162
	T_{BL}	R	0.4221	0.8770	0.3717	0.0820
		C	1.1793	0.1937	0.0642	0.0170
$Z_{th(c-h)}$ (Case to heat-sink)	-	R	0.04132	-	-	-
		C	13.06	-	-	-

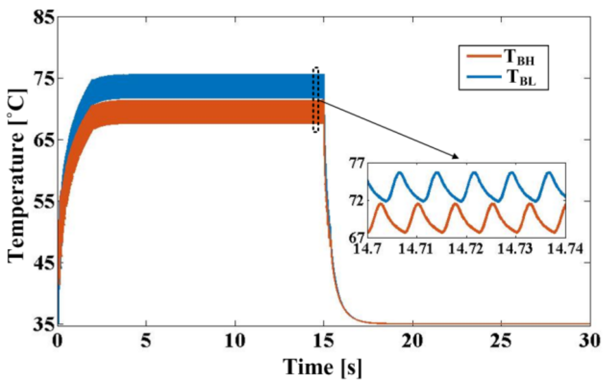

Fig. 8. Thermal loadings of T_{BH} and T_{BL} under the given mission profile of the motor drive system shown in Fig. 2.

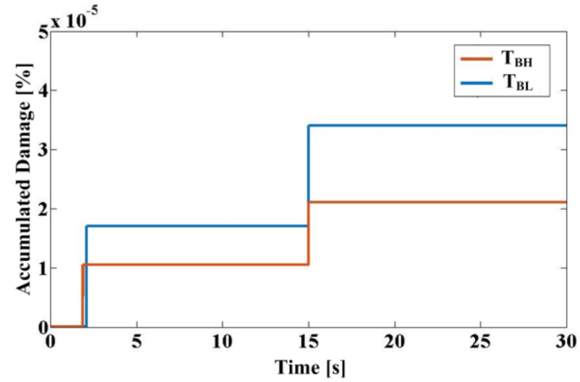

Fig. 9. Accumulated damages of T_{BH} and T_{BL} during a period of the mission profile based on the lifetime model in [5].

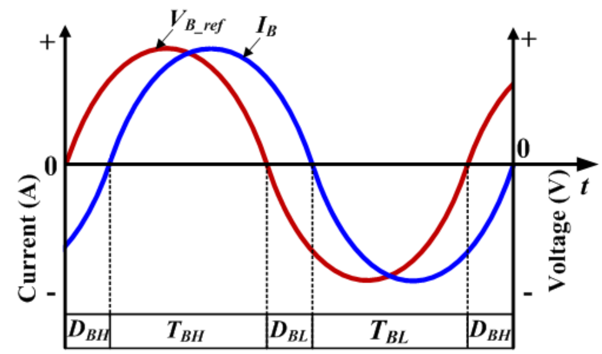

Fig. 10. Devices in phase-B, where the current flows depending on output current and reference voltage polarities.

Fig. 8 shows the temperature profile of T_{BH} and T_{BL} under the given mission profile. As expected, they have different thermal stress in terms of junction temperature swing and mean junction temperature by the load variation. T_{BL} has the higher thermal loading than T_{BH} and therefore, T_{BL} has a shorter lifetime than T_{BH}. After the corresponding thermal loadings of the IGBTs are obtained, the lifetime of the IGBTs can be estimated by mapping the thermal loading profiles to the lifetime model. A rainflow counting method is performed first in order to translate thermal loading to the number of cycles of different magnitudes of temperature stress factors. Then, the lifetimes are calculated based on the LDA rule. In this paper, the lifetime model presented in [5] is used for the lifetime estimation because there is no existing lifetime model for the target IGBT module in this paper. Therefore, the lifetime value should be considered only for the purpose of lifetime comparison.

Fig. 9 shows the accumulated damage of T_{BH} and T_{BL} based on the lifetime model for a period of mission profile and the corresponding lifetimes of T_{BH} and T_{BL} are estimated based on this result. If it is assumed that the motor system is operated for 12 hours per day, the corresponding estimated lifetimes of T_{BH} and T_{BL} are about 9 years and 5.6 years, respectively. It can be seen that the lifetime of T_{BL} is about 38 % shorter than T_{BH}. In other words, the lower group of the IGBTs (T_{AL}, T_{BL}, T_{CL}) are the most reliability-critical devices and thus the lifetime of the inverter could depend on the lower group of the IGBTs.

III. PROPOSED ASYMMETRIC PWM METHOD

As analyzed in §II, junction temperature is affected by both thermal impedance and power loss of the device. Therefore, through the optimization of internal layout of the module, the thermal impedance of the lower group of the IGBTs can be reduced so that upper and lower groups of IGBTs have the same temperature stress. This method is more appropriate for module designers. The other way is to reduce the power losses of the lower group of the IGBTs so that they have the same thermal loadings with the upper group of the IGBTs. This method is more suitable for power electronics engineers.

Discontinuous Pulse Width Modulation (DPWM) is the most widely used method to reduce power losses of IGBTs in motor drives. Fig. 10 shows the devices in phase-B, where the current flows depending on output current (I_B) and reference voltage (V_{B_ref}) polarities. When both I_B and V_{B_ref} are positive the current flows through T_{BH} and current flows through D_{BL} when V_{B_ref} is negative. On the other hand, in the case of negative I_B, the current flows through T_{BL} and D_{BH} when V_{B_ref} is negative and positive, respectively, where the current from motor drive to PMSM is positive. The power loss of T_{BL} can be reduced by applying DPWM when I_B and V_{B_ref} are only negative. Therefore, it can be expected that thermal loading of T_{BL} is lower than that of T_{BL} under typical Space Vector Modulation (SVM).

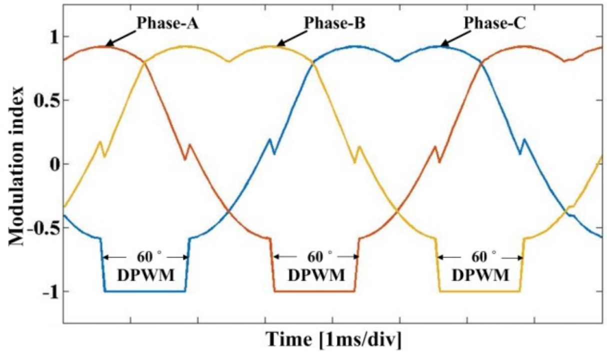

Fig. 11. Modulation waveform of the proposed asymmetric PWM.

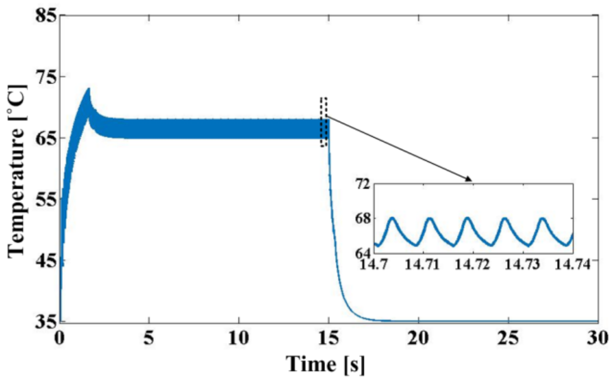

Fig. 12. Thermal loading of T_{BL} when the proposed asymmetric PWM is applied.

Fig. 11 shows the modulation waveforms of the proposed asymmetric PWM, where 60˚ DPWM is applied in this case study when output current and reference voltage of each phase are negative in order to reduce the power losses of lower group of IGBTs (T_{AL}, T_{BL}, T_{CL}). On the other hand, typical SVM is applied when the current is positive.

It is worth to note that the proposed asymmetric PWM is applied in order to balance the lifetime between the upper group of IGBTs and the lower group of the IGBTs when the modulation index is above 0.65 because the DPWM leads to large harmonic distortion under the low modulation index. The period in modulation waveform and modulation index, where DPWM is applied could be varied depending on different IGBT module structures and mission profiles.

Fig. 12 shows the thermal loading of T_{BL} when asymmetric PWM is applied. It can be seen that T_{BL} has lower thermal loading in terms of junction temperature swing (ΔT_j) and mean junction temperatures (T_{jm}) due to load variation compared with the thermal loading under the typical SVM shown in Fig. 8. This is because the asymmetric PWM reduce the power losses of T_{BL}.

Fig. 13 shows the accumulated damage of T_{BL} when the proposed asymmetric PWM is applied. It can be seen that the accumulated damage for the one period of the mission profile when the proposed asymmetric PWM is applied is lower than the accumulated damage under typical SVM and it is very similar to the accumulated damage of T_{BH} under the SVM shown in Fig. 9. The corresponding lifetime is also about 9 years as the lifetime of T_{BH}.

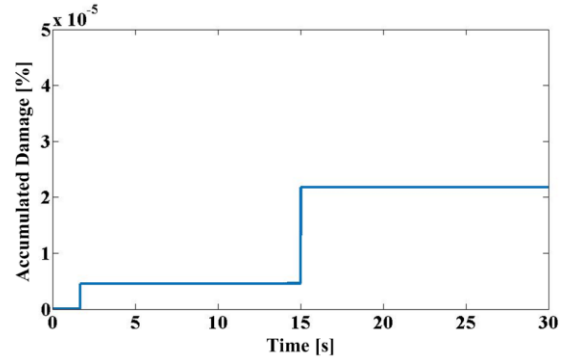

Fig. 13. Accumulated damages of T_{BL} during a period of the mission profile when the proposed asymmetric PWM is applied.

Consequently, the lifetime of the inverter has been extended as a result of applying asymmetric PWM which balances the lifetime between the upper and the lower IGBTs by increasing the lifetime of the lower group of the IGBTs (T_{AL}, T_{BL}, T_{CL}).

IV. Conclusion

In this paper, the asymmetric PWM method to improve the reliability of inverters in motor drive systems has been proposed. The proposed method is verified with 3-phase molded IGBT module focusing on the IGBTs under the 3-phase motor drive application. Due to the asymmetric internal layout of the IGBT module, the 6 IGBTs have the different thermal impedances and especially the lower IGBTs have higher thermal impedances than the upper IGBTs. Because of this, the different thermal loadings are applied to the IGBTs under the given mission profiles of the motor drive application and finally that leads to discrepancy in lifetimes of the IGBTs. T_{BL} has about 38 % shorter lifetime which is 5.6 years than T_{BH} which is 9 years. Consequently, T_{AL}, T_{BL} and T_{CL} are the most reliability-critical devices and thus the power rating and lifetime of the inverter are limited by them. By applying the asymmetric PWM the power losses of the lower IGBTs are reduced and it results in lower thermal loadings. The lifetime of T_{BL} is extended from 5.6 years to 9 years, which is equal to the lifetime of T_{BH}. The proposed asymmetric PWM method balances the lifetimes of the power devices in the module by increasing the lifetime of the most reliability-critical devices. Consequently, the reliability of motor drive inverter can be improved.

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