

Junction Temperature Evolution of IGBTs under Power Cycling conditions

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Abstract

This paper presents a thermal simulation study to evaluate the temperature change of a transistor (IGBT) junction under power cycling conditions in an ambient temperature range from -20°C to 55°C.

A three-dimensional transient thermal model was developed based on a steady-state initial solution with full turn-on heating applied to the power semiconductor devices. Power cycling was implemented using a repeated turn-on and turn-off profile with durations of 180 s and 120 s, respectively, while ramp-up and ramp-down transitions of 900 s were applied to the ambient temperature to represent realistic operating conditions and avoid abrupt thermal shocks.

The total simulation time was set to 7200 s, and forced air cooling with an air flow velocity of 3 m/s was applied together with a customer-specific heat sink design. The power losses of the high-side and low-side IGBTs and diodes were individually defined and applied as heat sources to accurately capture the spatial distribution of heat generation within the inverter module. The junction temperature was monitored throughout the simulation to assess the temperature difference and transient response of the IGBTs under varying ambient conditions. The results show that, even under identical current and power cycling profiles, the junction temperature evolution of the IGBTs differs significantly between -20 °C and 55 °C due to the combined effects of temperature-dependent power losses and thermal boundary conditions. This study provides valuable insight into the thermal behavior of IGBTs in inverter applications and supports more reliable thermal design and power cycling reliability evaluation.

1 Introduction

Intelligent power modules (IPMs) are widely used in home appliance and industrial inverter systems because of their compact integration, simplified system design, and high reliability. As inverter applications continue to demand higher power density and operation over wider temperature ranges, thermal management of IPM modules has become a critical factor in ensuring stable operation and long-term reliability.

During inverter operation, IGBTs within IPM modules are subjected to repetitive power cycling caused by load variations and switching operation. Such power cycling leads to cyclic junction temperature fluctuations, which induce thermo-mechanical stress in packaging structures such as solder joints, substrates, and interconnections. These stresses are closely associated with degradation mechanisms and lifetime reduction of IPM modules, highlighting the importance of understanding junction temperature behavior under realistic operating conditions.

While the thermal characteristics and power cycling reliability of power semiconductor modules have been investigated in previous studies, many analyses rely on simplified assumptions, such as steady-state conditions or constant ambient temperatures. However, IPM modules used in home appliance and industrial inverter systems are often exposed to varying thermal environments, which significantly affect heat dissipation and temperature distribution within the module. A detailed investigation of junction temperature behavior considering such operating environments is therefore required to support reliable IPM thermal design and power cycling reliability assessment.

Unlike previous studies focusing primarily on steady-state or single ambient conditions, this work emphasizes the combined influence of power cycling operation and ambient temperature variation on junction temperature evolution in IPM modules.

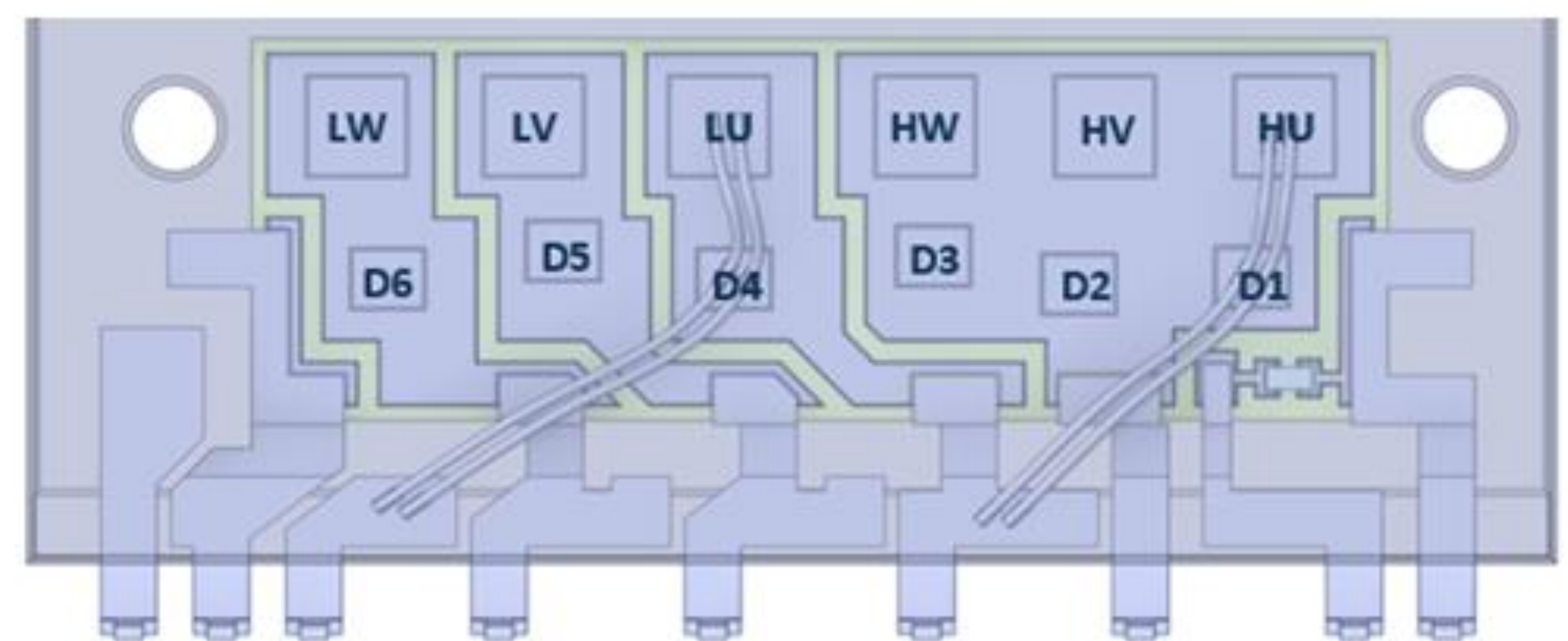


Fig. 1 Onsemi's Intelligent power module

2 Theoretical Background

2.1 Junction Temperature and Thermal Path in IPM Modules

The junction temperature (T_j) of an IGBT is a critical parameter that directly influences electrical performance, thermal stress, and long-term reliability of IPM modules. Heat generated at the semiconductor junction is transferred through a series of thermal paths, including the chip, die attach layer, DBC, TIM, heat sink, and finally to the surrounding environment. The effectiveness of this heat dissipation process determines the temperature distribution within the IPM module during operation.

Under ideal steady-state conditions, the junction temperature can be expressed using a thermal resistance model as:

$$T_j = T_{ref} + P_{loss} \cdot R_{th(j-ref)}$$

2.2 Power Loss Characteristics of IGBTs

The total power loss of an IGBT consists of conduction loss and switching loss, both of which contribute to heat generation at the junction. Conduction loss occurs when the device is in the on-state and can be expressed as:

$$P_{cond} = V_{CE(sat)}(T_j) \cdot I_C$$

where $V_{CE(sat)}$ is the collector-emitter saturation voltage and I_C is the collector current. Switching loss is generated during turn-on and turn-off transitions and can be expressed as:

$$P_{sw} = (E_{on} + E_{off}) \cdot f_{sw}$$

where E_{on} and E_{off} are the switching energies and f_{sw} is the switching frequency. Both conduction and switching losses exhibit temperature dependence, leading to increased power dissipation as junction temperature rises. This temperature-dependent behavior introduces a coupling effect between electrical loss and thermal response.

2.3 Power Cycling and Junction Temperature Evolution

Power cycling refers to repetitive on-off operation of power semiconductor devices, resulting in cyclic variation of junction temperature. Unlike steady-state operation, power cycling causes the junction temperature to evolve dynamically with time, depending on the applied power profile and thermal boundary conditions.

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The amplitude of junction temperature fluctuation (ΔT_j) during power cycling is a key factor influencing thermo-mechanical stress within IPM modules. Repeated temperature cycling induces mechanical fatigue in packaging materials such as solder joints and substrates, which is closely related to reliability and lifetime degradation. Therefore, evaluating the transient junction temperature evolution under power cycling conditions is essential for understanding thermal stress behavior in IPM modules.

Therefore, the findings highlight that both power cycling operation and ambient temperature variation must be simultaneously considered in thermal analysis and reliability assessment of IPM modules.

The proposed in thermal analysis and reliability assessment of IPM modules. The proposed simulation approach provides practical insight into junction temperature behavior and can be effectively used for thermal design optimization and reliability evaluation of inverter systems in home appliance and industrial applications.

3 Thermal Simulation Setup and Boundary Conditions

Figure 2. illustrates the thermal simulation boundary conditions and power cycling profile applied in this study. The ambient temperature is varied between -20°C and 55°C with ramp-up and ramp-down transitions of 900 s. Repetitive power cycling is applied using an on-off profile, while the corresponding power losses of the high-side and low-side IGBTs and diodes are individually assigned as heat sources in the three-dimensional thermal

- Three-dimensional model, steady thermal analysis
- Full turn on heating solution
- Ambient Temperature: 55°C and -20°C transient 900s
- Apply ramp down and ramp rising transient 900s
- Start Time: 0s, End time : 7200s, Monitor point : 60s
- Air flow rate : 3m/s
- Apply customer heat sink design
- Simplified 3D modeling

Die device	Power loss	Transient
HS IGBT	11.378w /each die	Turn on : 180s Turn off : 120s
LS IGBT	9.742w /each die	
HS Diode	0.951w /each die	
LS Diode	3.917w /each die	

Power loss data

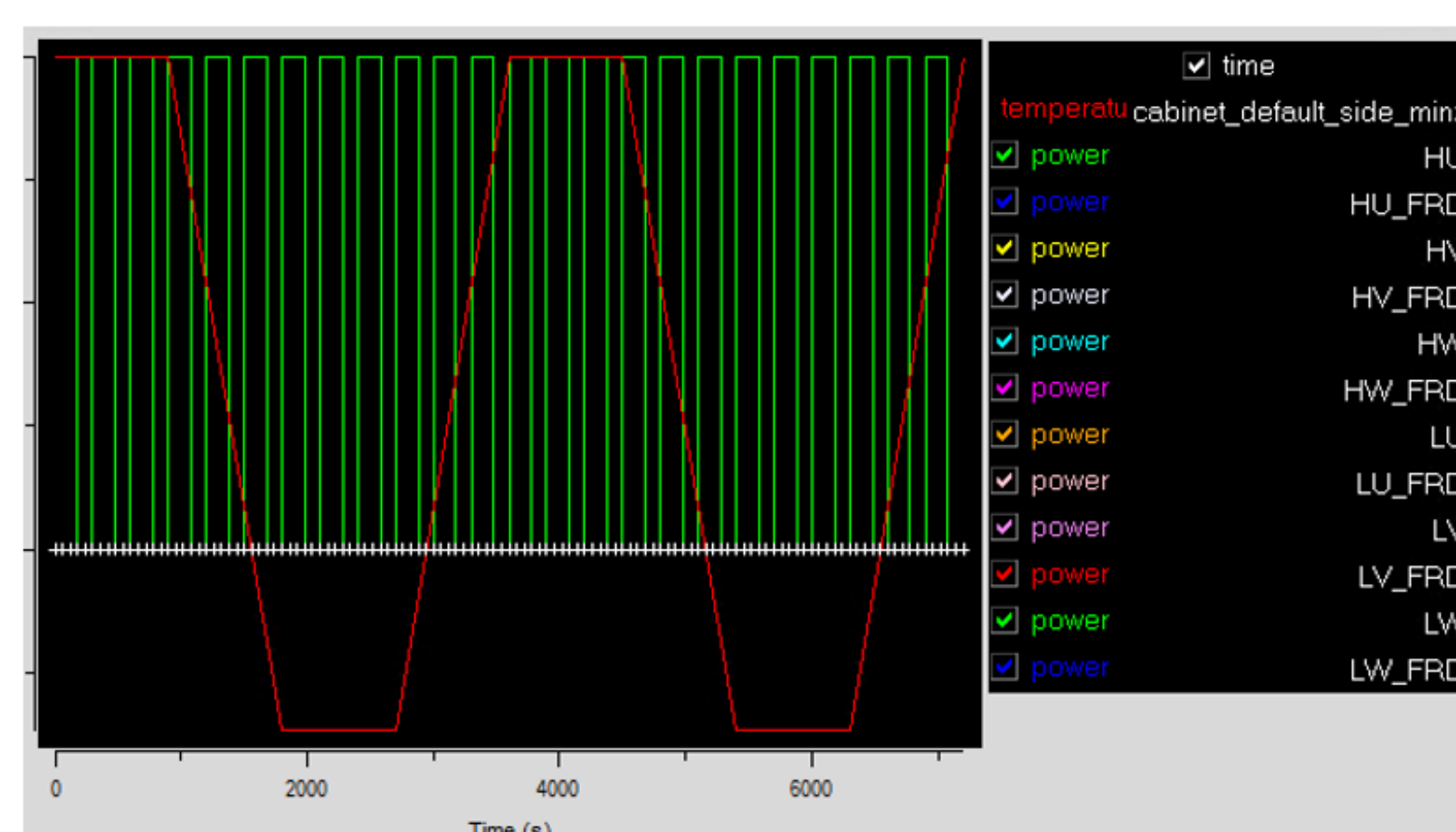


Fig. 2. Thermal simulation boundary conditions and power cycling profile used for junction temperature analysis

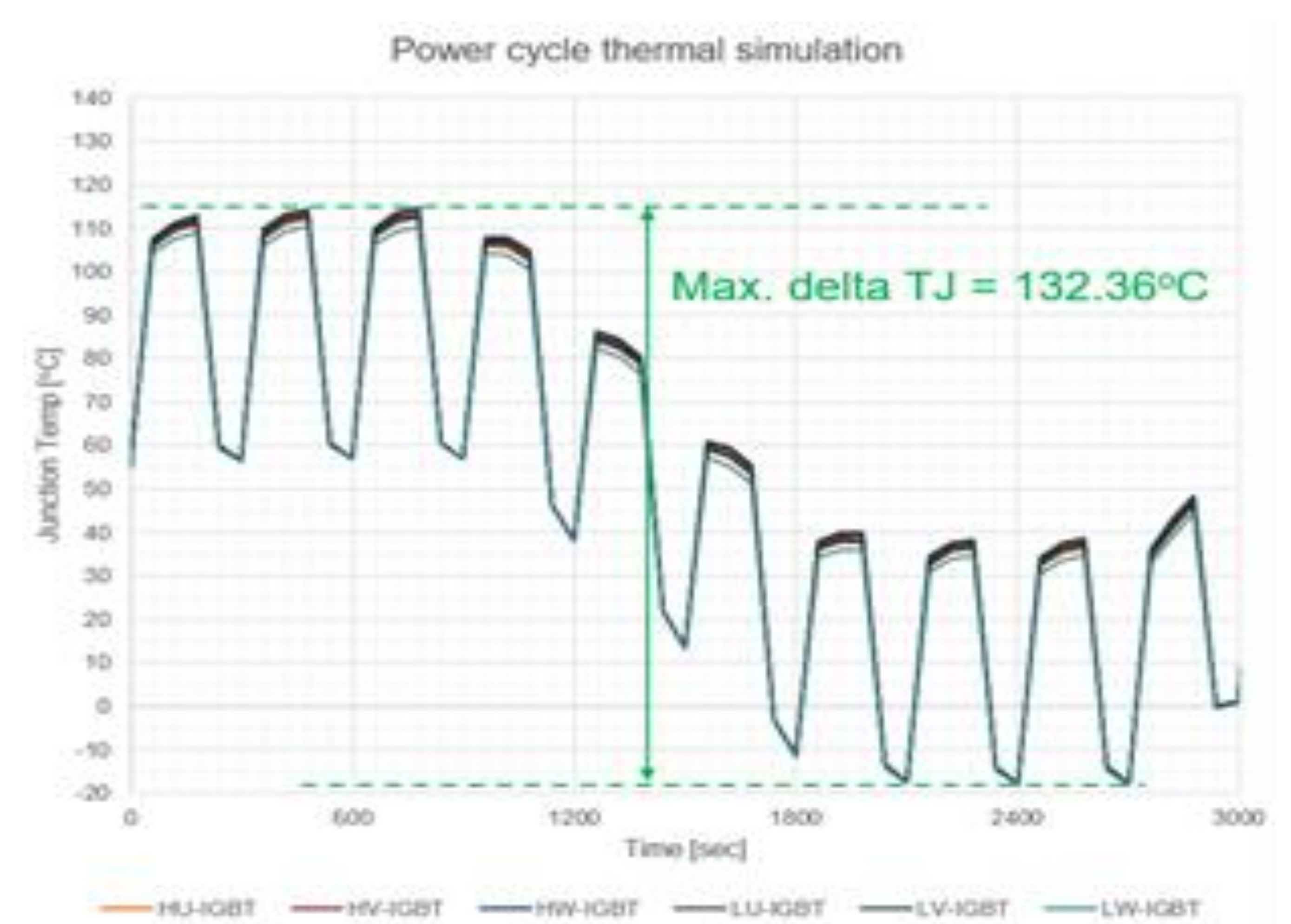
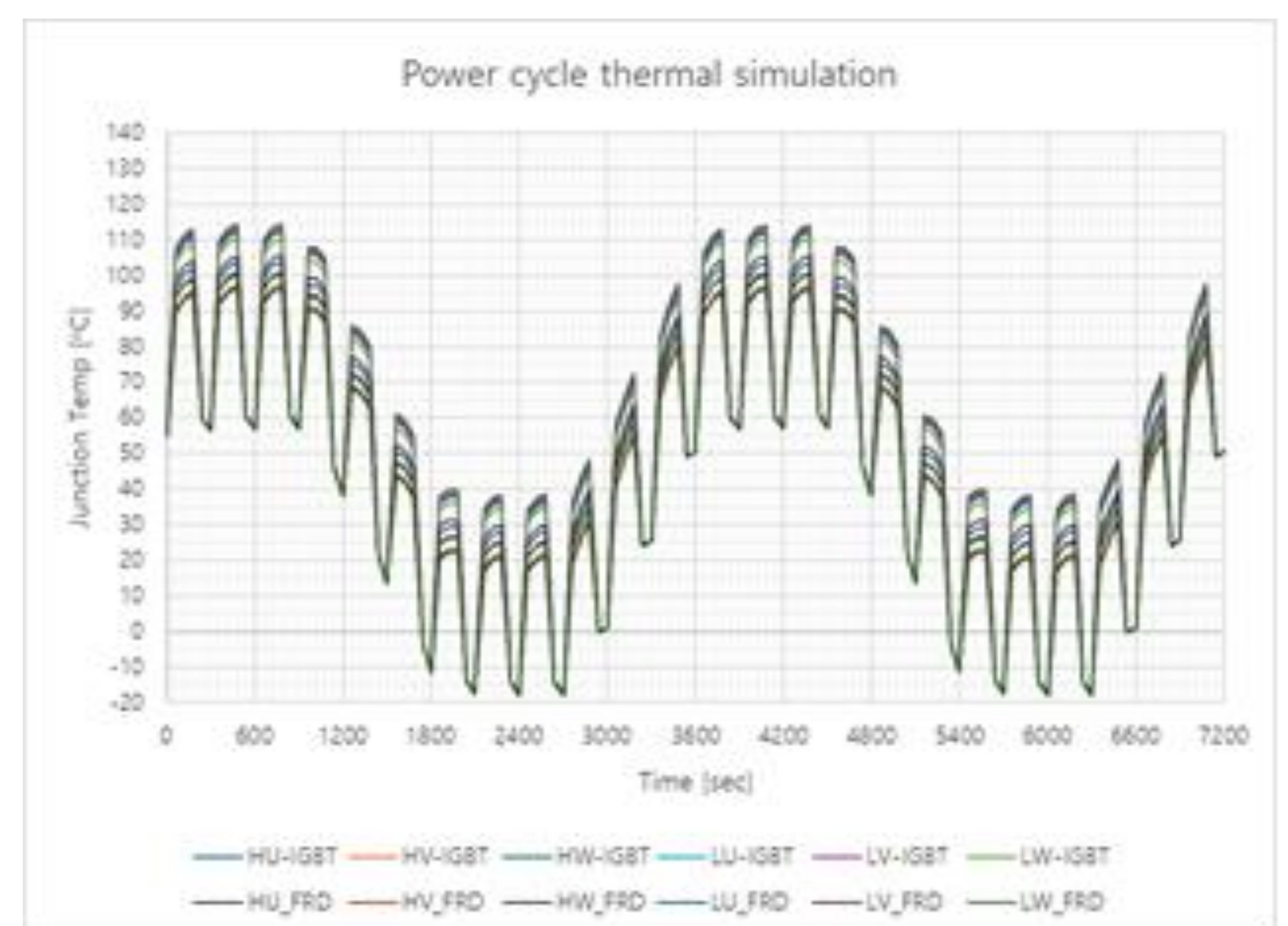
As shown in Fig. X, the thermal simulation considers ambient temperature variation between -20°C and 55°C together with repetitive power cycling operation to evaluate the junction temperature evolution of the IPM module.

4 Results and Discussion

In this study, the junction temperature evolution of IGBTs in an IPM module was investigated through transient thermal simulation under power cycling conditions. The simulation results revealed a strong dependence of junction temperature behaviour on ambient temperature variation.

From the analysis, the maximum junction temperature was observed to reach 114.53°C at the high-side IGBT, while the minimum junction temperature dropped to -18.129°C at the low-side IGBT under low ambient conditions

The results clearly demonstrate that the junction temperature variation becomes substantially larger when the ambient temperature condition changes over a wide range. In particular, the repetitive heating and cooling cycles combined with ambient temperature ramping lead to large thermal excursions within the IPM module. Such a high ΔT_j is known interconnections, which can accelerate degradation and reduce device lifetime.



5 References

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- [2] Z. Khatir et al., "Thermal Stress Analysis Comparison in IGBT Power Modules between DC and Switching Power Cycling," *IEEE Transactions on Power Electronics*, vol. 38, no. 9, 2023.