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Real-Time Thermal Evaluation of Power Converters in Microgrids by Device Current Reconstruction

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Abstract — **Real-time simulation is increasingly employed in the validation of power electronics and systems, showing great potential in terms of flexibility and efficiency. With it, electrical behaviors of power converters can be simulated with high accuracy. However, when evaluating the reliability of converters, the switching behaviors of power semiconductors should be simulated, which normally requires a rather high sampling rate and powerful computational capability of the hardware platforms, and such simulations usually take much time Therefore, an efficient approach is introduced in this article to evaluate the thermal performances of power devices. Compared to the prior-art methods, the required sampling rate is much lower, and the proposed approach is also simpler, as only the three-phase current is sampled. The junction temperatures can be simulated with high accuracy. Preliminary results have also validated the effectiveness of this approach.**

Keywords — Reliability analysis, thermal evaluation, power electronics systems, microgrids, real-time tests.

I. INTRODUCTION

Reliability of power electronics systems is crucial, where the degradation and failure of components are studied to prevent functional disability and economic loss. In modern microgrids, the increasing penetration of renewable energy sources (RES) and miscellaneous loads has become another driving force for reliability enhancement for adequate and secure power supply.

In power electronics systems, power semiconductors and capacitors are among the most fragile components [1]. Their failure mechanisms have been studied and modeled considering mission profiles [2], which is inspiring for reliability-oriented control like [3], [4]. For power semiconductors, the lifetime can be tested by repetitive experiments like power cycling tests [5] under certain electrical and thermal loadings, and in [6], [7], the lifetime is formulated to be determined by both the mean junction temperature and the junction temperature swing. Thus, the evaluation of junction temperature waveforms is showing much significance in reliability tests.

In the literature, the junction temperatures of power devices can be directly or indirectly measured with thermal sensors [5], [8], while this requires advanced and costly facilities, and it is difficult to be reconfigured for various applications. To this end, thermal evaluation using real-time testing platforms (e.g., OPAL-RT, dSPACE and RT Box) is becoming attractive. For example, in [9]-[11], the junction temperature is evaluated through device voltage and current, and in [12], it is mapped to the conduction and switching losses through a look-up table. These approaches have promoted the real-time thermal evaluation of power electronics systems in different application scenarios, thus providing more possibilities for enhancing the reliability.

However, in [9], the device voltage and current are still sampled using a physical circuit, and in [10]-[12], the simulation of switching transients is a must. These approaches can be challenging due to the requirement of high sampling rate, indicating that the hardware platforms should be facilitated with corresponding powerful sensors or tools. Under this scenario, it is thereby of importance to develop thermal evaluation methods that can be conveniently implemented on those real-time platforms.

Inspired by [9]-[12] and [13], this article introduces a simplified approach to evaluate the thermal performances of power devices based on device current reconstruction. Three-phase DC-AC converters in microgrids are selected as the study case. In the proposed approach, only the fundamental-frequency AC currents are sampled instead of the switching-frequency power device voltage v_{CE} in [14] and [15], whereas the junction temperature waveforms can still be achieved. Consequently, a much lower sampling rate is sufficient to perform the evaluation, and the computational capability of the hardware platforms can thereby be saved for the implementation of more complicated topologies or advanced control schemes in microgrid applications. The proposed approach is further applicable to power hardware-in-the-loop cases, where it is difficult to directly measure the junction temperatures. Case studies performed on a hardware platform are presented to demonstrate the proposed approach.

II. PROPOSED THERMAL EVALUATION BASED ON SIMPLIFIED MODELS

An exemplary power converter system generally used in microgrids is shown in Fig. 1, which is a three-phase DC-AC converter with an interface filter to reduce the current harmonics. In this case, a resistive load is connected to the converter, which can alternatively be, e.g., the grid or other converters. In DC-AC converters, the gate driving signals of the power devices are generated by pulse-width modulation (PWM), and the devices are working in the saturation region where they should be modeled as switches rather than as linear amplifiers. The switching frequency is around kHz for Silicon-based IGBTs, and higher for MOSFETs and Silicon-Carbide transistors (SiCs), and thus, the sampling rate for switching behaviors should be sufficiently high (e.g., up to MHz in [15]) to capture such dynamics in practice. However, in real-time simulations, the sampling rates are always supposed to be lower to reserve computational capability for the controllers or complicated topologies especially for microgrids. Hence, a commonly-used approach is to simplify the DC-AC converters into a controlled voltage source (as shown in Fig. 1(b)) to neglect the switching dynamics and reduce the computational burden.

The topology of the DC-AC converter in Fig. 1 can be expanded as shown in Fig. 2. In this article, it is assumed that the converter is a two-level converter with IGBTs and antiparallel diodes being the power devices, which are denoted as T$_k$ and D$_k$ respectively. There are three phases, each of which consists of upper and lower legs (H and L). The indices of the power devices are also labelled in Fig. 2.

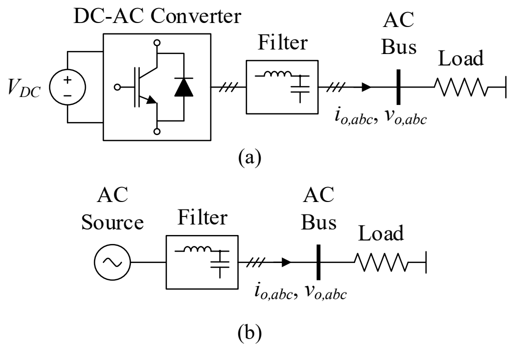


Fig. 1. Converters in microgrids, (a) a DC-AC converter under test, and (b) its equivalence as an AC source in real-time simulations.

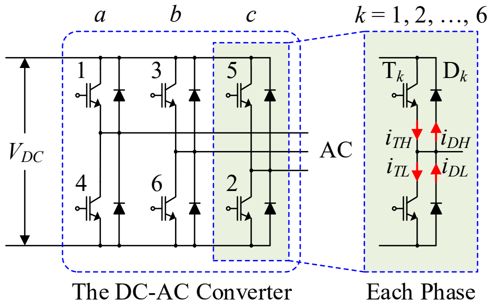


Fig. 2. Power devices in a DC-AC converter and the indices to be used in this article.

With this, the framework of the thermal evaluation is proposed as shown in Fig. 3, which basically includes three parts: the calculation of device currents i_T and i_D, the calculation of device power dissipation (losses), and the calculation of the junction temperatures. As the junction temperature variation is an accumulation of switching behaviors, an average-current-based approach is employed only by sampling the fundamental-frequency AC voltage v_o and current i_o, instead of the commonly-used real-time collector-emitter voltage v_{CE} during switching transients. This can reduce the high requirement of the sampling rate and lower the computational burden. The proposed procedures are elaborated in the following subsections.

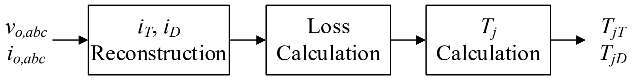


Fig. 3. Procedures of the proposed real-time thermal evaluation approach.

A. Reconstruction of Device Currents

The thermal behavior (or specifically, the junction temperature) of a power device is determined by the power dissipated as thermal loss and the thermal path (including the case, the thermal grease and the heat sink), where the current flowing through the power devices is decisive for the power loss. With this, the reconstruction of the device current is designed as the first step for the thermal evaluation.

The device currents principally follow the Kirchhoff's current law (KCL), and the normal operation states of a two-level converter in Fig. 4(a) can be divided into two modes, as shown in Fig. 4(b) and Fig. 4(c).

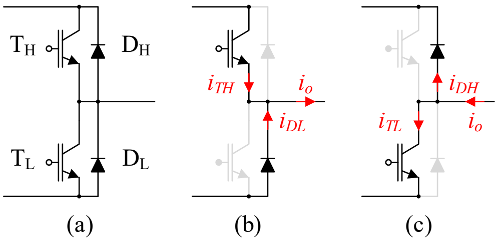


Fig. 4. Illustration of the current through the IGBTs and the diodes: (a) the upper and lower legs of a single phase, (b) when i_o flows out of the phase leg, and (c) when i_o flows into the phase leg.

When the AC current flows out of the AC terminal in Fig. 4(b) (defined as $i_o > 0$), the IGBT in the upper arm (T$_H$) and the diode in the lower arm (D$_L$) will be in the ON-state, while T$_L$ and D$_H$ will be in the ON-state in the opposite case ($i_o < 0$). Accordingly, the device currents should satisfy:

$$\begin{cases} i_{TH} + i_{DL} = i_{o,pos} = \begin{cases} |i_o| & \text{if } i_o > 0 \\ 0 & \text{otherwise} \end{cases} \\ i_{TL} + i_{DH} = i_{o,neg} = \begin{cases} |i_o| & \text{if } i_o < 0 \\ 0 & \text{otherwise} \end{cases} \end{cases} \tag{1}$$

where, $i_{o,pos}$ is the positive half of the output current i_o, and $i_{o,neg}$ is the negative half of i_o. The absolute value of the AC current is taken, such that the values of device currents will always be positive for the sake of real-time power calculation.

The relationship between the AC current and the device currents is illustrated in Fig. 5, where the case for $i_o > 0$ is taken as an example. The IGBT in the upper arm T$_H$ is in the ON-state when the PWM drive signal is 1, while the diode D$_L$ works as the freewheeling diode in the complementary situation. Similarly, when $i_o < 0$, T$_L$ and D$_H$ will work according to the duty cycle D and its complement $\overline{D}$ (namely $\overline{D} = 1–D$). Hence, the following equations are yielded by averaging the current over the switching periods given that the OFF-state leakage current is neglected:

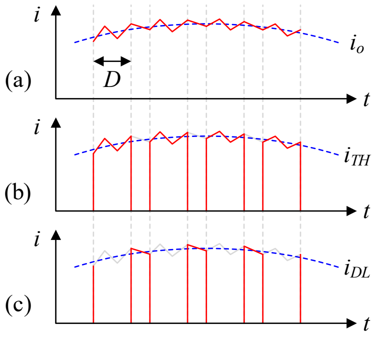


Fig. 5. Relationship between the AC current and the device currents, where the case for $i_o > 0$ is illustrated as an example: (a) AC current i_o, (b) upper IGBT current i_{TH}, and (c) lower diode current i_{DL}.

$$\begin{cases} i_{TH} = D i_{o,pos} \\ i_{TL} = \overline{D} i_{o,neg} \end{cases} \tag{2}$$

$$\begin{cases} i_{DL} = i_{o,pos} - i_{TH} \\ i_{DH} = i_{o,neg} - i_{TL} \end{cases} \tag{3}$$

With this, the current through the power devices (i_T for IGBTs and i_D for diodes) can be computed according to Fig. 6. This approach is aimed at reconstructing an average of the device current. For a certain phase, only the AC output current i_o is sampled and the modulation ratio is used for estimating the current through the devices, which enables a lower sampling rate to be employed.

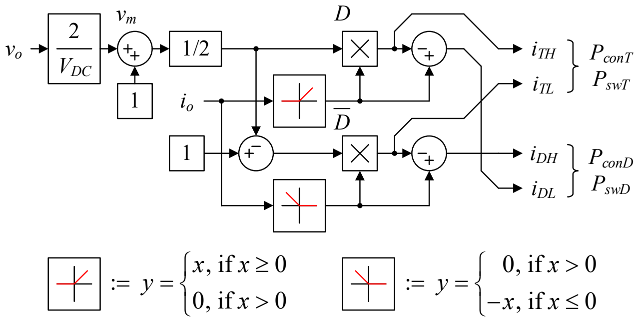


Fig. 6. Reconstruction of currents through the power devices using the AC voltage v_o and current i_o.

However, it should also be noted that the accuracy of this calculation could be affected by the switching ripples of the current [16]. Harmonics contributes to additional power losses of the power devices to some extent, but in normal operation where the device current is sinusoidal with low total harmonic distortion (THD), such influence could normally be negligible.

B. *Calculation of Device Power Dissipation*

The power loss of a power device that has impact on the junction temperature generally includes two parts, the conduction loss P_{con} and the switching loss P_{sw} [17]. The two parts are calculated as following:

1) The conduction loss P_{con} is the power dissipation during the ON-state. It is approximated as the multiplication of the averaged current (i_T or i_D) and the ON-state voltage (v_T or v_D) by ignoring the ripples. The voltage is obtained by the voltage-current (*V-I*) characteristics of the device from the datasheet and the reconstructed average currents.

$$P_{con} \approx i_T \cdot v_T \tag{4}$$

2) The switching loss P_{sw} is the power dissipation during the switching transients. In datasheets of power devices, the switching loss is normally given as an energy value E_{on} and E_{off}, which corresponds to the loss over a single switching action. Therefore, P_{sw} can be obtained by taking the average of all energy losses E_{on} and E_{off} over a switching period, given as:

$$P_{sw} = P_{on} + P_{off} = \frac{1}{T_{sw}}\left(E_{on} + E_{off}\right) \tag{5}$$

Therefore, the calculation of device power dissipation can be summarized as shown in Fig. 7. As the voltage-current (*V-I*) or loss-current (*E-I*) relationships are normally nonlinear, look-up tables with linear inter-/extrapolation or techniques like polynomial fitting could be used to simplify the computation.

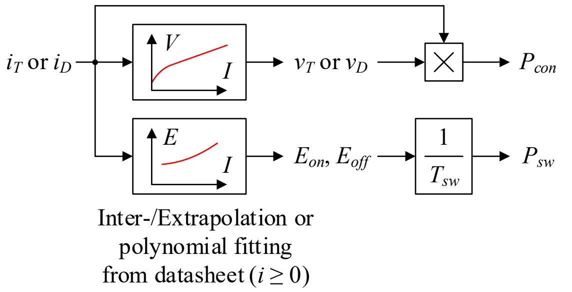


Fig. 7. Estimation of the power losses by the reconstructed device currents.

C. *Calculation of Junction Temperatures*

The obtained power losses of power devices are then used to calculate the junction temperatures via the thermal impedance network of power semiconductor modules [18], which also reflects the thermal dynamics. The equivalent thermal impedance network of a power module is shown in Fig. 8, where the thermal path can normally be modeled in the form of Cauer or Foster network [19]. Such a model can be easily programmed on real-time simulation platforms with a very low sampling rate due to its relatively slow dynamics.

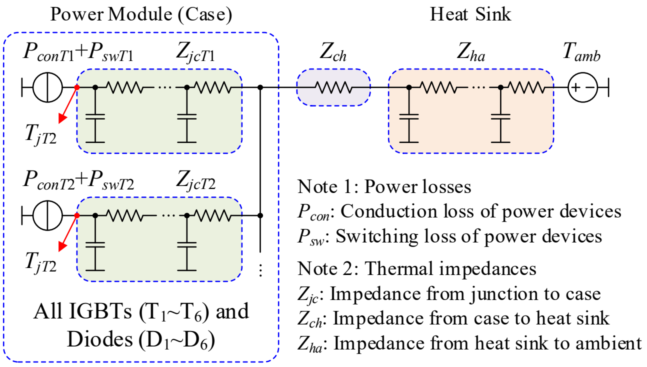


Fig. 8. Estimation of the junction temperatures by the power losses. The thermal path is modeled in the form of Cauer network.

Remark 1: The thermal impedance network can be further simplified according to the Thevenin and Norton theory. That is, to convert the Cauer or Foster network into a single thermal impedance in parallel with a power source, or in series with a temperature source.

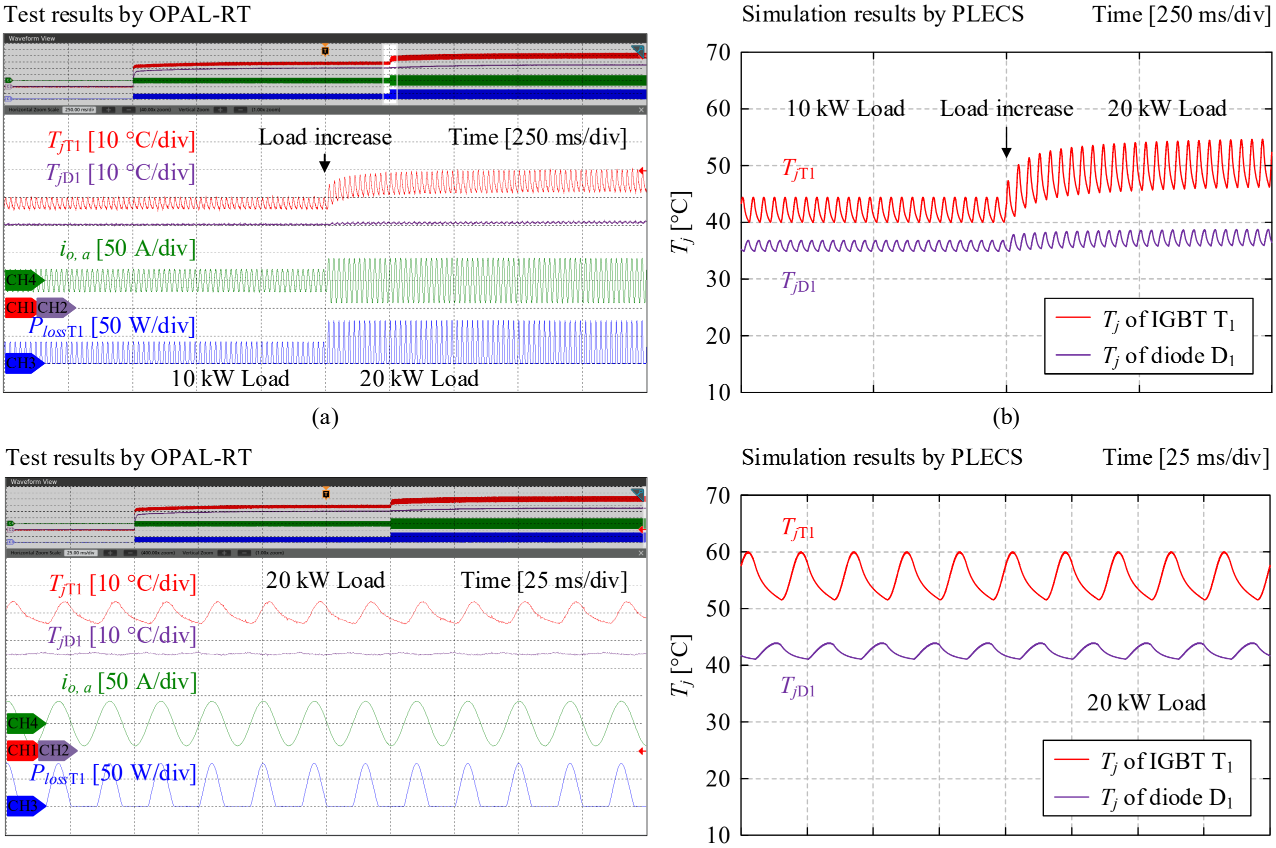
Remark 2: The thermal impedance network can also be constructed in a more complicated way, e.g., considering the thermal coupling among devices or other dissipation paths to the ambient [20]. The complexity will not increase much as the passive thermal impedances are linearly superimposable.

III. REAL-TIME TEST RESULTS

To validate the proposed approach, real-time simulations have been performed on an OPAL-RT platform. The system

TABLE I
KEY PARAMETERS OF THE STUDY CASE IN EXPERIMENTS

Parameters	Values
Rated phase voltage and frequency	230 V rms, 50 Hz
Resistive load power (three phases)	10 kW or 20 kW as specified
Parameters of the *LC* filter	L_f = 2.0 mH, C_f = 10 μF
Type of the power devices	Infineon FS75R12KT3 (1200 V/75 A, IGBT module)



(a) (b)

(c) (d)

Fig. 9. Comparison of the test results obtained by real-time simulations on an OPAL-RT platform ((a) and (c)) and the thermal simulation in PLECS ((b) and (d)). The dynamic performances are compared in (a) and (b), where a load increase of the converter is applied from 10 kW to 20 kW. The steady-state performances are compared in (c) and (d).

under test is configured with the same topology as Fig. 1(a), which is a three-phase two-level DC-AC converter, and the key parameters are listed in Table I. The step size of the real-time simulations is 10 µs (100 kHz sampling rate).

The thermal performances of power devices during load transient and steady state are shown in Fig. 9(a) and Fig. 9(c), respectively. The results are compared with those obtained from the switching model in PLECS (Fig. 9(b) and Fig. 9(d)), including the estimated junction temperature of T_1 and D_1 (as indexed in Fig. 2) as well as the total loss of T_1. With the proposed approach, the mean junction temperatures and the temperature swings can be simulated with a relatively low sampling rate (100 kHz, which can be further decreased given that the fundamental-frequency component is preserved), and the accuracy is acceptable for microgrid applications (e.g., around 10% for the mean value and the swing of IGBT junction temperature).

Meanwhile, it should also be noted that the error in T_{jD} could mainly result from (4), where the averaged i_T is used for power calculation instead of the instantaneous ON-state current i_{ON}. The accuracy may be influenced especially when the conduction time of the studied power device is much shorter compared to the switching period, which applies to, e.g., the current through freewheeling diodes. It turns out to be a tradeoff between evaluation accuracy and complexity, whereas further research could be accordingly carried out in the future to better address this issue.

IV. CONCLUSIONS

In this article, a novel approach is proposed and introduced to evaluate the thermal performances of power devices of converters in microgrid applications. By sampling the three-phase AC currents, the junction temperatures are estimated via the reconstruction of device currents and the calculation of losses. The approach can be used in real-time simulations where the computational capability of the platform should be spared for implementing topologies or control algorithms, especially for microgrid applications where the requirement is higher due to the increasing number of converters. It has also enabled the indirect estimation of junction temperatures in real-time controllers when the temperatures are difficult to measure. Case study results have also been obtained by real-time simulations on an OPAL-RT platform, preliminarily illustrating the feasibility of the approach.

This approach has simplified the real-time thermal evaluation for power converters in microgrids, which is convenient for time-domain validations of thermal or reliability-oriented control. In the future, the scope of this article can be extended to practical scenarios [21], such as the application to the reliability analysis on multiple power electronics converters in a microgrid where system-level stability should be considered. Meanwhile, the approach proposed in this article may also be further improved to be more accurate and better eligible for the implementation of real-time reliability tests where the harmonics are supposed to be considered in terms of, e.g., advanced controllers in more varied microgrids.

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