Analysis and Design of a Resistor-Less DC-Bus Active Discharge and Dynamic Braking Scheme Using IGBTs in the Active Region

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***Abstract*—During shutdowns, emergency conditions, and dynamic braking, fully discharging the dc-bus capacitor or clamping the dc-bus voltage in industrial systems is typically managed using power resistors and additional switches. This conventional approach increases system cost, size, and complexity. This article introduces a compact, cost-effective, resistor-less method for two functions: 1) active discharge and 2) dynamic braking in low-power industrial systems. The proposed technique operates IGBTs in their active region with low gate-emitter voltages (V_{GE}), creating high impedance in the discharge path to limit current. For active discharge, a constant-power strategy is implemented using pulse frequency modulation (PFM), where the on-time (t_{on}) of each pulse is fixed and the pulse frequency is ramped up to accelerate energy dissipation. This approach enables complete discharge of a 600-V dc-bus within 1 s, handled entirely by a single IGBT. The method is validated across three different IGBT vendors, showing consistent results and long-term reliability with no parameter degradation after over 200 000 completed discharge cycles. For dynamic braking, the PFM method with fixed pulse frequency enables continuous power dissipation between 50 and 150 W for over 30 min. It effectively replaces conventional internal braking resistors typically rated from 20 to 200 W with resistance values of 5–120 Ω. The system can also tolerate brief overloads up to 50% beyond IGBT current ratings for 10–20 s, providing sufficient time to complete braking without failure, as confirmed by test results. All these benefits are achieved through a simple gate driver modification that supplies partial V_{GE} levels (3–10 V), eliminating bulky resistors, reducing cost by at least 50%, and saving space-making the solution ideal for high-volume industrial applications.**

***Index Terms*—Active discharge, active region, dc-bus capacitor, dynamic braking, IGBT, industrial drives, Si IGBT.**

I. Introduction

IN INDUSTRIAL motor drives and inverter-based systems, dc-bus capacitors are commonly employed to stabilize voltage and handle transient energy [1], [2]. During shutdown sequences, power resistors-often referred to as discharge, or braking resistors are widely used to safely discharge dc-bus capacitors [3], [4]. In scenarios such as emergency stops, active discharge, or dynamic braking, these resistors are connected across the capacitor bank to dissipate stored energy and meet safety standards [5], [6]. Typically, they are controlled by switches such as IGBTs or FETs, contactors, or relays, and are sized to handle worst-case energy conditions. However, these resistors introduce energy loss, increase system size and cost, and require additional mechanical components-making them less suitable for compact or high-efficiency designs. As a result, alternative discharge methods are gaining interest. One approach uses existing devices like IGBTs to actively control the dc-bus capacitor voltage. With a low gate-emitter voltage, an IGBT can operate in its active (quasi-saturation) region and behave like a voltage-controlled current source or a controllable resistor. In this mode, it allows precise current control during discharge. Energy can be dissipated directly in the IGBT, eliminating the need for power resistors. This improves system efficiency and reliability.

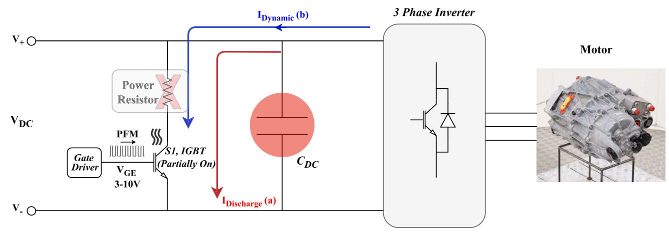

Fig. 1. Conceptual illustration of (a) active discharge and (b) dynamic braking mechanism of the proposed technique.

Unlike conventional switching applications where IGBTs operate in fully ON or OFF states, this article proposes a new resistor-less method by operating IGBTs in their active region through optimized gate-emitter voltages (typically between 3 and 10 V), avoiding full turn-on. As illustrated in Fig. 1, the active discharge process is managed by a partially turned-on IGBT, S1. This switch provides a high-impedance path and acts as a controllable resistive element. By adjusting the gate-emitter voltage using a specially designed gate driver that provides partial voltage levels (between 3 and 10 V), unlike traditional industrial gate drivers that typically offer only a single value, the discharge current is regulated. It enables the safe dissipation of the capacitor's stored energy through S1. This

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approach eliminates the need for power resistors, enabling fast and controlled discharge while ensuring operation within the IGBT's safe operating area (SOA) to prevent thermal runaway. A constant-power discharge technique is adopted, and pulse generation is achieved using a pulse frequency modulation (PFM) scheme that dynamically adjusts the pulse frequency based on real-time monitoring of the capacitor voltage. Experimental results using TO-247 packaged discrete IGBTs from three different vendors demonstrate successful discharge of a 600-V dc-bus within 1 s. The dynamic braking process is similarly controlled using a partially turned-on IGBT, S1. In this case, lower gate-emitter voltages are used—similar to the active discharge method—so that S1 functions as a resistive element, allowing the regenerative energy from the motor to be safely dissipated. While the same PFM technique is employed for pulse generation, a fixed pulse frequency is used during dynamic braking rather than voltage-dependent modulation. The proposed method demonstrates that TO-247 packaged discrete IGBTs from three different vendors can effectively handle continuous power dissipation between 50 and 150 W for over 30 min. This shows its potential as a reliable replacement for conventional internal braking resistors, which typically range from 5 to 120 Ω and have dissipation capabilities between 20 and 200 W in low-power industrial systems and servo applications [7], [8].

Various methods are proposed for rapid dc-bus capacitor discharge, including motor winding-based approaches [9], [10], inverter short-circuit techniques [11], and external resistor methods [3], [4]. Winding-based and inverter-based methods are limited by system dependence and potential overstress of power stages, respectively. External resistors are bulky, require long cooling times, and increase system cost. Prior work, such as [11], explores IGBT operation in the active region to discharge dc-bus capacitor but lacks closed-loop control, long-term validation, and practical integration. These limitations motivate a more compact, reliable, and cost-effective alternative.

The main novelty of this work lies in the design-oriented development and experimental validation of a resistor-less energy dissipation method that operates IGBTs in their active region under a closed-loop control scheme based on PFM. A custom gate driver dynamically modulates gate voltage and pulse frequency in response to real-time dc-bus measurements. This enables pseudo-constant-power discharge and thermally controlled braking while ensuring safe operation within the IGBT's SOA. The method is validated through over 200 000 discharge cycles and up to 150 W continuous braking dissipation using discrete TO-247 IGBTs from multiple vendors. This study is the first to demonstrate long-term reliability and scalable operation of IGBTs in the active region for both rapid discharge and dynamic braking, providing a practical and cost-effective alternative to conventional resistor-based solutions in industrial drive systems.

Table I provides a comprehensive comparison between existing methods and the proposed method. The key contributions of this study are as follows.

1) Introduces a novel, design-oriented, resistor-less approach for dc-bus: 1) active discharge and 2) dynamic braking, offering a cost-effective and space-efficient solution for low-power and servo applications by enabling precise energy control without the need for external braking resistors.
2) The proposed method enables seamless integration into existing IGBT gate driver architectures by introducing partial gate-voltage control, without necessitating major design modifications.
3) Ideal active discharge conditions are characterized by sweeping V_{GE} from 3 to 10 V and t_{on} from 1 to 10 μs, confirming safe operation and long-term reliability across 200 000 + cycles through theoretical and experimental validation.
4) Ideal dynamic braking conditions are determined by sweeping V_{GE} from 3 to 10 V and t_{on} from 1 to 11 μs, with device behavior, temperature, and power dissipation monitored over 30 + min to verify thermal safety and model compliance.
5) This article demonstrates that: 1) active discharge of a 600-V dc-bus is completed within 1 s and 2) up to 150 W is dissipated during dynamic braking, both achieved using only an IGBT without the need for internal power resistors.

II. Active Region Operation, Discharge-Braking Strategies, and IGBT Selection Criteria

The selection of the IGBT is critical for the safe and effective implementation of: 1) active discharge and 2) dynamic braking in industrial systems. Unlike conventional switching applications that involve fully turning the device on and off, the IGBT is operated in its active region to rapidly reduce the dc-bus voltage by applying a low gate-emitter voltage, allowing it to be partially on. In this controlled conduction mode, the IGBT must absorb and dissipate energy internally, which places unique demands on the device. To ensure reliable operation, the IGBT must be capable of handling repetitive pulsed conduction at high voltage, tolerate significant instantaneous power without exceeding thermal limits, and allow precise current regulation through gate control to shape the desired discharge profile.

1) Active Region Operation of IGBTs:

The active region, also known as the linear mode, is characterized by the IGBT operating with a gate-emitter voltage (V_{GE}) slightly above the threshold voltage ($V_{\text{GE(th)}}$) but below full enhancement, as illustrated in Fig. 2. Unlike saturation mode, where collector–emitter saturation voltage (V_{CE}) drops to a low value, the active region maintains a relatively high V_{CE}, allowing the device to act like a voltage-controlled current source or an equivalent resistor [12]. This operating point allows fine control over the energy dissipation rate—a key requirement in both: 1) active discharge and 2) dynamic braking applications. The collector current (I_C) in this region can be approximated as [13], [14]

$$I_C = k * (V_{\text{GE}} - V_{\text{GE}}\,(\text{th}))^{\alpha} * (1 + \lambda * V_{\text{CE}}) \quad (1)$$

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TABLE I
COMPARATIVE STUDY OF CONVENTIONAL AND PROPOSED APPROACHES TO RAPID ACTIVE DISCHARGE AND DYNAMIC BRAKING

Aspect	**Conventional Method: Resistor + Switch**	**Proposed Method**	**Advantage of Proposed Method**
Power Dissipation Element	Braking Resistors	IGBT (In active region)	Eliminates resistors
Energy Dissipation	Fixed resistor dissipates energy as heat, requiring cooling for 2-10 minutes before reuse.	Controlled pulses maintain constant power dissipation. Same total energy dissipated as conventional method.	Controlled power dissipation prevents excessive stress on components, improving thermal handling.
Control Requirement	Simple ON/OFF switch control.	Intelligent control using PWM with pulse frequency modulation (PFM).	Enables precise control over discharge and braking profile with current shaping.
Discharge Time	Defined by $\tau = RC$, fixed by resistor and capacitor values. Typically $> 2s$ for safe resistor sizing.	Precisely controlled to 1s using frequency-adjusted pulse modulation.	Faster, adjustable, and more responsive to system needs.
Braking Time	Limited by thermal capacity of resistors; continuous braking limited to short bursts.	Handles 50-150 W braking continuously without thermal issues.	Enables sustained low-power braking without additional internal power resistors.
Initial Power Dissipation	High at the beginning due to $P = \frac{V^2}{R}$.	Starts at low frequency to limit peak power.	Prevents high inrush currents, reduces stress on components, and avoids sudden spikes.
Power Dissipation Profile	Power dissipation decreases as voltage drops.	Maintains nearly constant power dissipation throughout discharge and braking.	Ensures consistent energy distribution, avoiding sudden power surges and minimizing component stress.
Peak Current	Dependent on resistor value; initially very high.	Controlled by partial turn-on of IGBT; current is actively shaped.	Prevents overshoot and peak current stress.
Switching Frequency	Single transition per discharge cycle.	Starts at low frequency and ramps up for active discharge (<100 kHz) and fixed frequency for braking.	Enables controlled and efficient energy dissipation over time, improving system reliability.
Component Size & Cost	Requires resistor and dedicated switch.	Uses IGBTs only	Eliminates extra components, reducing cost and board space, making it a more cost and space effective solution.
Thermal Handling	Heat concentrated in a single resistor, requiring large heat sinks.	Dissipates heat through IGBT during operations	Improves thermal management, reducing the need for large heat sinks and ensuring more even heat distribution.

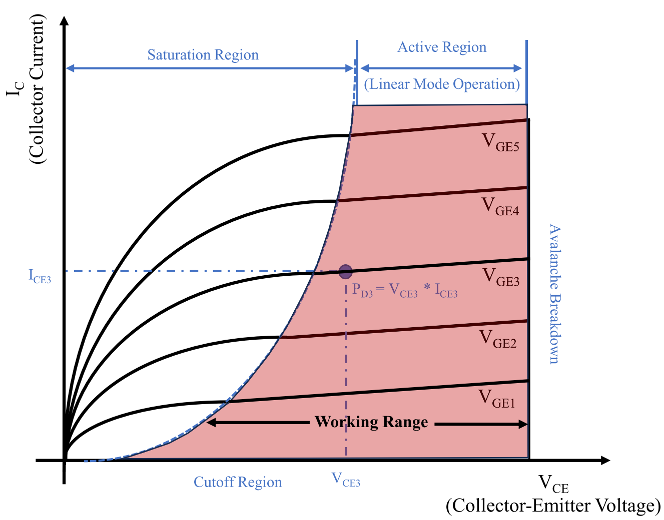

Fig. 2. IGBT output characteristics.

where k is a device-specific constant depending on temperature and process, α is a nonlinearity coefficient (typically between 1 and 2), and λ is the channel-length modulation parameter. This expression shows that I_C increases with V_{GE} and slightly with V_{CE} in the active region. The term $\lambda * V_{\mathrm{CE}}$ reflects the output conductance in the active region—i.e., as V_{CE} increases, the collector current increases slightly even for fixed V_{GE}, which must be accounted for in thermal analysis.

2) Constant-Power Discharge Strategy via Short Pulses:

In active discharge, the goal is to dissipate the energy stored in the dc-bus capacitor within a defined time (e.g., 1 s)

$$E_{\mathrm{CAP}} = \frac{1}{2} * C * V_{\mathrm{bus}}^2. \tag{2}$$

This is achieved by operating the IGBT in its active region using a PFM method. The IGBT is pulsed with short gate signals of fixed pulsewidth (e.g., in the range of 1–10 μs), while the pulse frequency is gradually increased from a starting value f_{start} (around 1 kHz) to a final value f_{end} (around 50 kHz). The pulse frequency is increased gradually to prevent device failure: at the beginning of discharge, the IGBT experiences high voltage and current, leading to significant heating, so a lower frequency helps manage thermal stress. As the voltage drops during discharge, it becomes safer to increase the frequency since the generated heat decreases. The gate-emitter voltage is kept constant, which sets a fixed collector current during each conduction period. As a result, discharge current remains consistent per pulse, and by increasing the pulse frequency over time, the average discharge power is maintained nearly constant while the capacitor voltage drops

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to a safe level. Assuming a constant discharge power P, the total energy to be dissipated over time t is

$$E = P * t. \tag{3}$$

If each pulse delivers an energy E_p, the total number of pulses N required is

$$N = \frac{E}{E_p}. \tag{4}$$

The energy per pulse E_p can be calculated based on the conduction time, collector–emitter voltage, and collector current as

$$E_p = V_{\mathrm{CE}} * I_C * t_{\mathrm{on}}. \tag{5}$$

The junction temperature rise ΔT_j per pulse is then estimated using

$$\Delta T_j = \frac{E_p * R_{\mathrm{th}}}{\tau} \tag{6}$$

where R_{th} is the junction-to-case thermal resistance, and τ is the time between pulses. Thermal simulations below verify that the junction temperature remains within safe limits throughout the discharge period.

3) Dynamic Braking Strategy With Fixed Frequency and Duty:

For dynamic braking in low-power industrial applications, the goal is to safely dissipate regenerative energy from the motor using the IGBT in its active region, without relying on braking resistors. The gate of the IGBT receives periodic short pulses with fixed frequency and duty. This method provides a predictable energy dissipation profile per event. The critical design consideration is ensuring the IGBT can absorb this energy without exceeding its instantaneous power or thermal limits. The instantaneous power during each conduction pulse is given by

$$P_{\mathrm{pulse}} = V_{\mathrm{CE}} * I_C. \tag{7}$$

For a braking event where a total energy E_{brake} must be dissipated over a time t_{brake}, the average power is

$$P_{\mathrm{brake}} = \frac{E_{\mathrm{brake}}}{t_{\mathrm{brake}}}. \tag{8}$$

To ensure reliable dynamic braking operation, the IGBT must remain within its safe thermal and electrical operating limits during each braking event. This requirement is quantified by comparing the average power dissipated during braking with the maximum power dissipation rating of the IGBT. To satisfy this, the following condition must hold [15]:

$$P_{\mathrm{brake}} = P_{\mathrm{pulse}} * D * f < P_{\mathrm{tot}} \tag{9}$$

where D is the duty cycle of the pulsed gate drive signal, f is the repetition frequency of the pulses, and P_{tot} is specified in the IGBT datasheet. This equation captures the time-averaged power based on how often and how long the IGBT conducts current in its active region. To ensure thermal and electrical safety, this average power must not exceed the maximum continuous power dissipation rating of the device.

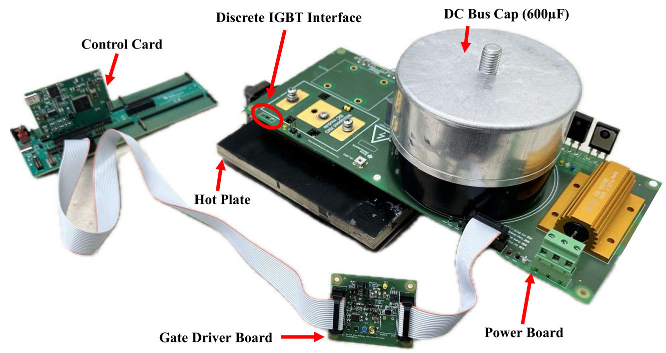

Fig. 3. Active discharge experiment setup and connections.

In addition to power constraints, it is critical to evaluate the junction temperature rise resulting from the braking pulses. This is estimated as

$$\Delta T_j = P_{\mathrm{brake}} * R_{\mathrm{th}}. \tag{10}$$

To avoid thermal overstress, the following condition must also be satisfied:

$$T_{\mathrm{case}} + \Delta T_j < T_{j\mathrm{max}} \tag{11}$$

$T_{j\mathrm{max}}$ is the maximum allowable junction temperature specified in the IGBT datasheet, and T_{case} is the case temperature during braking. By satisfying these constraints, the selected IGBT is validated for safe operation under dynamic braking, enabling compact and cost-effective energy dissipation for low-power systems.

4) IGBT Selection Criteria

IGBT selection for active discharge and dynamic braking applications requires careful consideration of key datasheet parameters. The gate-emitter threshold voltage ($V_{\mathrm{GE(th)}}$) is the voltage at which the IGBT starts to conduct. It defines the point above which the IGBT can be controlled to regulate current flow, with higher gate voltages allowing more current. The continuous and pulsed current ratings (I_C) must accommodate the peak current per pulse to prevent thermal runaway. While saturation voltage ($V_{\mathrm{CE(sat)}}$) is not directly used in active region operation, it offers insight into ON-state losses. Total power dissipation (P_{tot}) is essential, as it must exceed the average pulse energy dissipated during operation. The junction-to-case thermal resistance (R_{th}) plays a key role in predicting temperature rise during each pulse, and maximum junction temperature ($T_{j\mathrm{max}}$) defines the thermal boundary [16]. Among all datasheet parameters, peak and continuous current, maximum average power dissipation, thermal resistance, and junction temperature rating are the most critical for determining the suitability of operations. Properly selecting an IGBT with these parameters ensures the safe and effective operation of active discharge and dynamic braking in industrial systems [17].

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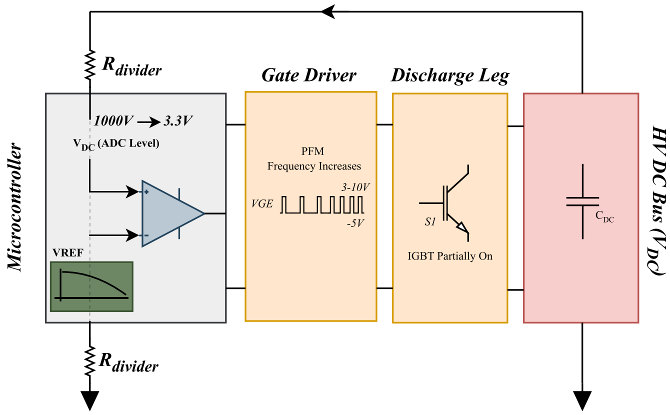

Fig. 4. High-level block diagram showing the main components and their connections in the active discharge system.

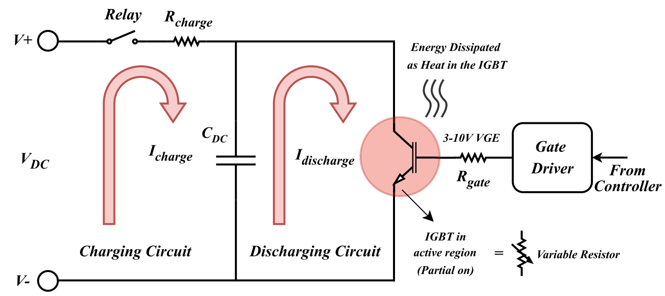

Fig. 5. Circuit schematic illustrating discharge control handled by the gate driver.

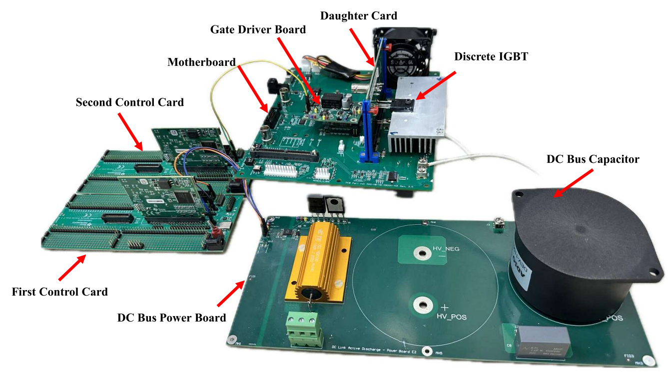

Fig. 6. Dynamic braking experiment setup and connections.

III. Design, Simulation, and Experimental Assessment of Resistor-Less Active Discharge and Dynamic Braking Method

A. Active Discharge Test Setup

Fig. 3 illustrates the experimental setup for active discharge operation. The power board, designed to test discrete IGBTs, operates within a voltage range of 0–1200 V dc. It includes an interface for current measurement, a high-voltage divider to monitor the dc-bus voltage, and a digital IC relay that disconnects the dc-bus capacitor from the power supply once it is fully charged.

A key feature of the gate driver board in this study is its variable gate-emitter voltage range of 3–10 V, which differentiates it from conventional gate drivers. This capability enables partial turn-on of IGBTs instead of fully turning them on, effectively limiting the collector current and preventing excessive values. The control unit utilizes PFM, starting with a low frequency and gradually increasing it throughout the discharge process. This strategy helps regulate thermal runaway, control the discharge rate, and maintain a stable power discharge profile, meeting the goal of a 1-s discharge time.

This platform's strength lies in its robust monitoring and control functions, ensuring safe and efficient power component testing while offering operational flexibility and detailed system feedback. Fig. 4 illustrates the system's main components and interconnections, operating in two stages. In the first stage, once the dc-bus capacitor is fully charged, the relay disconnects the capacitor from the dc supply. The capacitor voltage is then continuously monitored using analog-to-digital converter (ADC) channels. In the second stage, the processor generates a reference voltage corresponding to a user-defined constant-power discharge profile. This profile is configured based on parameters such as discharge time, pulse on-time, and the desired gate-emitter voltage. The reference voltage is compared with the measured capacitor voltage, and the resulting error signal is used to control the gate driver. The gate driver then supplies appropriate gate signals to the IGBT. A reduced gate-emitter voltage-typically between 3 and 10 V, ensures the IGBT operates in its active region, functioning as a variable resistor, as illustrated in Fig. 5. PFM is employed to achieve controlled switching, enabling safe and consistent capacitor discharge.

Fig. 5 illustrates the use of PFM and the gate driver's role in partially turning on IGBTs in the active region to achieve a constant power discharge profile. PFM adjusts the switching frequency while maintaining a fixed on-time to control energy dissipation. In this configuration, the IGBT acts as the primary energy-dissipating component, replacing traditional power resistors. Test results are presented in Section III-D.

B. Dynamic Braking Test Setup

Fig. 6 presents the experimental setup for dynamic braking operation. The dc-bus power board is designed to maintain the dc-bus capacitor voltage at 400 V throughout operation. The first control card regulates the charging process of the dc-bus capacitor. A motherboard and its daughter card are used to test discrete IGBTs. The motherboard includes interfaces for the gate driver board, daughter card, and current measurement circuits. The daughter card provides the necessary connections for discrete devices and gate drivers.

As in the active discharge setup, the gate driver board plays a crucial role in dynamic braking. Unlike conventional gate drivers that switch between high and low voltage levels (−5 to V_{GEmax}), this gate driver supports a variable gate-emitter voltage that can be manually adjusted from the power supply. This feature enables partial turn-on of IGBTs, limiting collector current and enhancing control.

The second control card generates a dedicated pulsating waveform with a fixed on-time and frequency. This waveform

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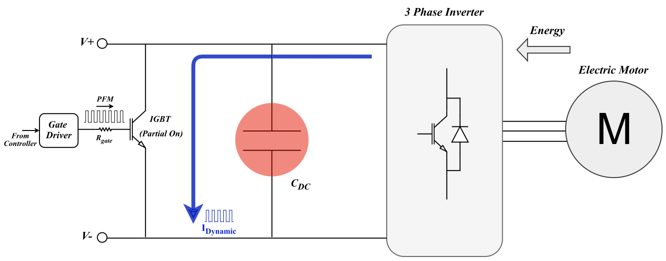

Fig. 7. Circuit schematic illustrating dynamic braking operation.

ensures safe operation by keeping IGBTs within their SOA while effectively dissipating energy as shown in Fig. 7. This method is optimized for low-power dynamic braking applications, particularly those utilizing internal resistors for energy dissipation.

Dynamic braking is achieved by converting kinetic energy into electrical energy, which is dissipated through controlled switching. The IGBT operates in the active region, functioning as a current-controlled source. By applying a pulsating control signal, sudden current surges are prevented, and a gradual energy dissipation profile is maintained. This controlled approach ensures stable braking performance. The test results are presented in Section III-E.

C. Simulation Studies

1) Active Discharge Simulation: The simulation setup for active discharge is identical to the testing approach, which involves generating dedicated pulsating waveforms for the gate while partially turning on the IGBT to maintain a constant-power discharge. The most critical phase occurs at the initial stage, where high voltage and low current are present. This condition can lead to localized thermal instability within the die, commonly known as the Spirito effect in semiconductor devices [18]. If not controlled properly, this effect may contribute to current crowding, increasing the risk of thermal runaway. Proper control of the gate-emitter voltage and operating frequency is essential to ensure stable operation.

Key parameters include the selection of gate-emitter voltage based on the device's threshold voltage and the starting frequency when using a fixed on-time per pulse. In the simulation, a 2 μs on-time per pulse and a 7-V gate-emitter voltage are applied to the first device from vendor 1 at 1 kHz. For the second device of vendor 2, a 2 μs on-time per pulse and a 6-V gate-emitter voltage are used at the same frequency. LTspice models, including thermal properties provided by manufacturers, are utilized to ensure accurate representation of device behavior. These vendors are also tested in real experiments in Section III-D to validate the consistency between the simulation and experimental results.

Fig. 8 presents the electro-thermal simulation results. The case temperature is set to 75 °C in the simulation model, representing the estimated temperature of the operating system. Initial junction temperatures of 77 °C and 85 °C are observed for vendors 1 and 2, respectively, with peak currents of 1.8 and 8 A. These temperatures remain steady for a period before gradually decreasing as the capacitor voltage drops.

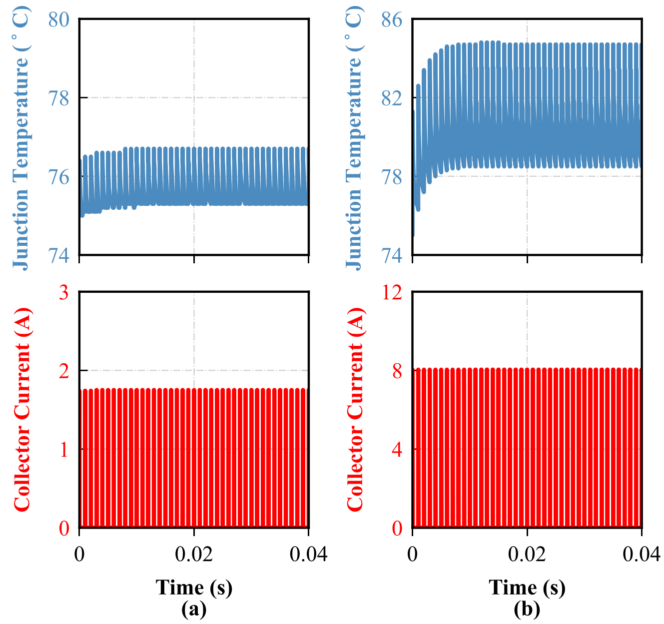

Fig. 8. Simulation results for two different DUTs. (a) Vendor 1 under 7 V V_{GE} with 2-μs pulse widths and a frequency of 1 kHz. (b) Vendor 2 under 6V V_{GE} with 2-μs pulse widths and a frequency of 1 kHz.

This indicates that these are the maximum junction temperatures experienced by the IGBTs. These values remain within safe limits, preventing thermal runaway. The results confirm that 1 kHz is a safe starting frequency for active discharge in the real experiment. Simulation studies in LTspice validate the design's energy dissipation requirements, ensuring that the proposed method meets thermal and operational constraints.

2) Dynamic Braking Simulation: The simulation setup models an ac motor for low-power applications, focusing on energy dissipation through the IGBT. The system includes an inverter, motor, and braking resistor network. The inverter runs in regenerative braking mode, directing excess energy to the braking resistors instead of the battery. Key parameters such as motor speed and current are considered. PSIM is used for circuit-level validation, ensuring realistic voltage and current representation during braking. The braking process is simulated by transitioning the inverter into braking mode, where the generated back EMF drives current through the IGBT in the dynamic braking leg, as illustrated in Fig. 7. Similar to the test setup in Section III-C, the control algorithm employs PFM to regulate the duty cycle. It generates pulses with fixed on-time and frequency, partially switching the IGBT to maintain a safe dc-bus voltage.

In this setup, a motor with a fan load is decelerated from 1000 to 0 r/min over 10 s. The energy to be dissipated through the braking resistor is approximately 1.6 kJ, resulting in an average dissipation of around 150 W over 10 s. A 45 Ω braking resistor is used, with the objective of keeping the dc-bus voltage below 400 V. Although allowing effective control through low-duty pulsed switching-specifically, at 1000 Hz with a 5% duty cycle. Simulation results, shown in Fig. 9, validate this strategy by successfully maintaining the dc-bus voltage near 400 V while smoothly bringing the

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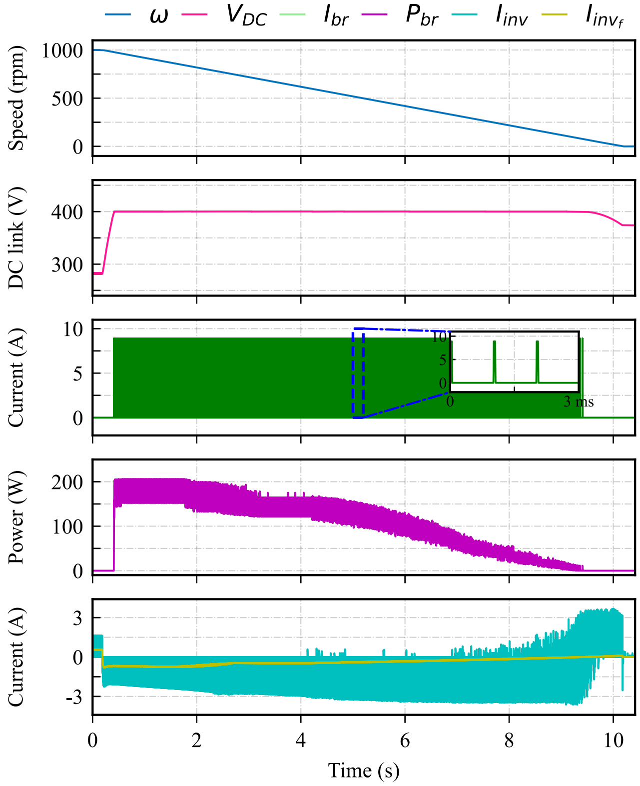

Fig. 9. Simulation results demonstrate controlled motor stop and stable 400 V dc-bus, validating safe switching and IGBT-based energy dissipation without high-wattage resistors.

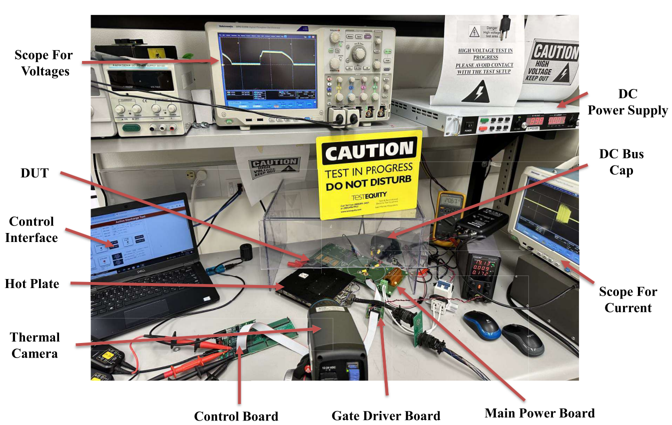

Fig. 10. Test bench setup for active discharge experiment, showing all key components.

motor to a stop. These case studies also inform the selection of safe switching frequency, on-time, and gate-emitter voltage values for low-power applications without requiring continuous dissipation through high-wattage resistors. IGBTs can replace this resistor since they are capable of handling this amount of energy using the proposed method, as confirmed in Section III-E.

D. Active Discharge Performance

Fig. 10 shows the test setup for active discharge operation. A thermal camera monitors the device case temperature.

TABLE II
ACTIVE DISCHARGE TEST RESULTS UNDER VARIOUS CONDITIONS AT 600-V DC-BUS WITH 2 μs ON-TIME

DUT	V_{GE}	**Discharge time**	I_{peak}
Vendor1	7, 8, 9 V	1 s	2.2 A at 7 V V_{GE}
Vendor2	5, 6, 7, 8, 9 V	1 s	9.1 A at 6 V V_{GE}
Vendor3	7, 8, 9 V	1 s	5.5 A at 7 V V_{GE}

A hot plate, set to 75 °C, simulates real-world conditions, such as EVs' chassis typically operate at 70 °C–80 °C on roads [19]. Discrete IGBTs are placed on the hot plate, which also acts as a heat sink. The control interface sets the gate-emitter voltage, pulse on-time, and discharge duration. This data is sent to the main controller. The control board generates the reference voltage and monitors the dc-bus capacitor voltage. It then applies the appropriate gate-emitter pulses to the IGBT, completing the operation on the main power board.

Three discrete IGBT devices (1200 V, 20 A) in TO-247 packages are used for testing. Each device comes from a different vendor but shares the same specifications. They are primarily trench field-stop IGBTs, which feature a trench structure where the gate is embedded within the trench. This design allows for better utilization of the silicon area, resulting in improved current density [20]. A 600-μF dc-bus capacitor is used to test real-world scenarios, where capacitors typically range up to 1.5 mF depending on the application, as seen in low-power industrial drives [21]. In addition, the typical drive operates within a voltage range of 120–690 V dc, depending on the application and motor type. For this test, a dc-bus voltage of 600 V is selected to replicate the most demanding conditions [22]. Demonstrating successful performance at this voltage ensures reliable operation at lower voltage levels as well.

Fig. 11 displays the actual experimental profiles of the capacitor voltage and discharging current. The main dc-bus capacitor voltage closely follows the reference voltage, and all DUTs from different vendors successfully discharge the fully charged 600 V dc-bus capacitor within the target 1-s time frame without any issues. Table II provides a summary of the test results under different conditions, showing that successful discharge is influenced by the V_{GE}. According to Table II, devices with higher threshold voltages initiate successful discharge at higher V_{GE} values, while those with lower threshold voltages can discharge the dc-bus at lower V_{GE} values. Experimental results show that vendors 1 and 3 have higher threshold voltages, typically around 6 V, meaning the IGBT behaves as a high resistance below this level. However, at 7 V and above, sufficient current can flow to dissipate the stored energy as heat in the IGBT. In contrast, vendor 2 has a lower threshold voltage, allowing it to dissipate the stored energy at lower V_{GE} values and given peak current values without any problems. This underscores the need for precise gate-emitter voltage adjustment via the gate driver to ensure successful active discharge for each device.

Based on these experimental results, a reliability analysis is necessary for each device to assess how many discharge cycles the IGBTs can withstand and how their key parameters, such

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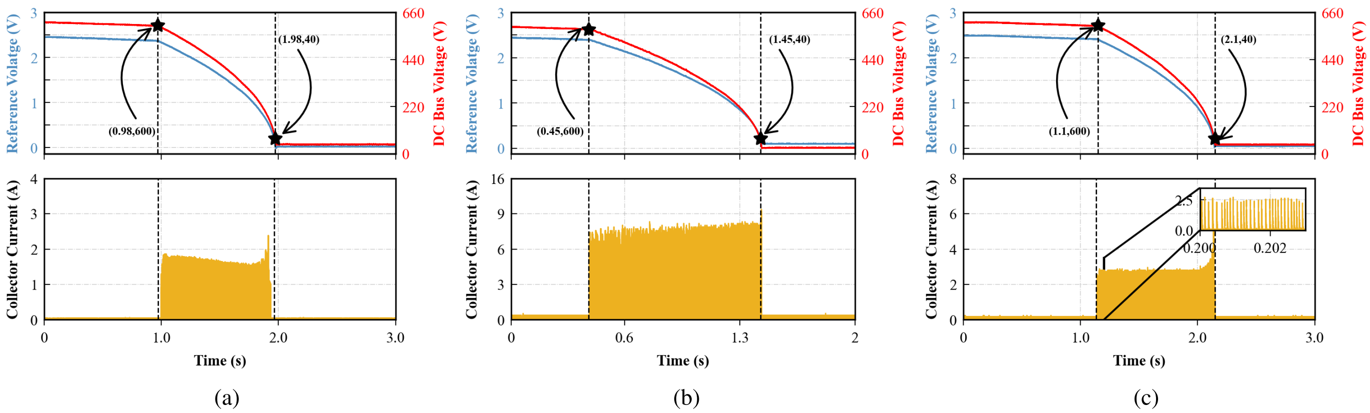

Fig. 11. Active discharge test results at 600-V dc-bus with 1-s discharge duration. (a) Vendor 1 at 7 V V_{GE}, 2 μs on-time. (b) Vendor 2 at 6 V V_{GE}, 2 μs on-time. (c) Vendor 3 at 7 V V_{GE}, 2 μs on-time. Stars indicate the starting and finishing points of the active discharge, along with their corresponding time and voltage coordinates.

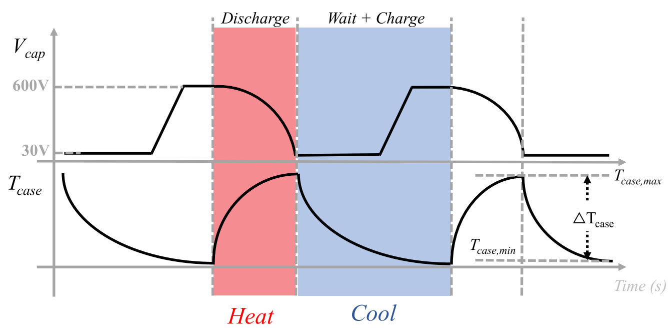

Fig. 12. Illustration of applied discharge cycles during reliability test.

as threshold voltage and collector–emitter saturation voltage, may degrade over time. For each device, a 200 000-cycle discharge test is completed to evaluate long-term reliability and monitor changes in key parameters of the IGBT. The reliability test scenario is shown in Fig. 12. During each cycle, the dc-bus capacitor undergoes a discharge phase, where its voltage drops from 600 to 40 V, causing heat generation in the IGBT due to conduction losses, followed by a cooling phase during the wait and recharge period. This results in cyclic thermal stress, with the case temperature (T_{case}) fluctuating between $T_{\mathrm{case,\,min}}$ and $T_{\mathrm{case,\,max}}$. The temperature swing (ΔT_{case}) is a critical factor influencing the device's lifetime, as repeated thermal cycling can lead to parameter shifts and potential degradation. By monitoring these variations over 200 000 cycles, the study evaluates the long-term robustness of each device under real-world operating conditions. Fig. 13 illustrates an example from the reliability test for one DUT. The top plot shows the dc-bus voltage (red) and the reference voltage (blue), demonstrating how the capacitor is charged and then discharged within each cycle. The discharge phase rapidly reduces the dc-bus voltage, while the charging phase restores it for the next cycle. The bottom plot presents the collector current, which exhibits distinct pulses during discharge events, indicating the current conduction through the IGBT. These patterns validate the controlled operation of the device, ensuring that each charge-discharge cycle is executed as intended. By continuously monitoring these parameters, variations in electrical and thermal performance can be analyzed to

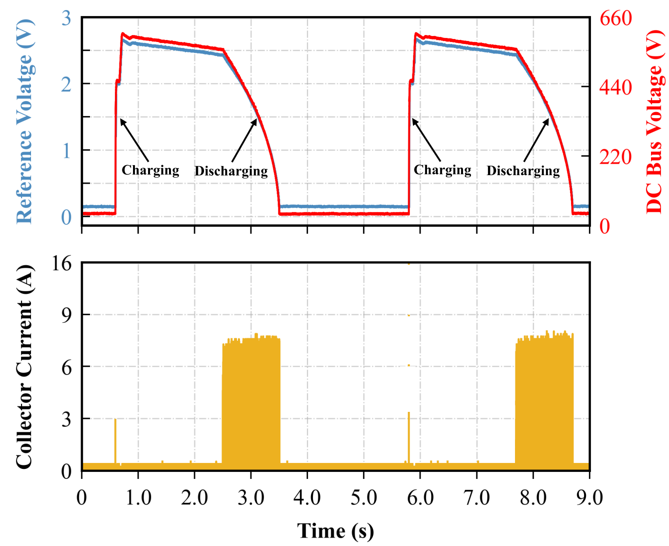

Fig. 13. Example from the reliability test for one DUT (vendor 2), showing dc-bus voltage, reference voltage, and collector current during discharge cycles.

assess long-term reliability and potential degradation effects on the DUT.

Fig. 14 presents the post-cycling measurements of six key IGBT parameters, including the breakdown voltage ($V_{\mathrm{BR(CES)}}$), which do not reflect the operational dc-bus voltage during drive operation. The plot illustrates typical parameter variations for DUTs from three different vendors under standardized test conditions, showing no noticeable shifts and thereby confirming the robustness and stability of the devices after extended cycling. A Keysight B1560 model curve tracer is used to analyze device parameters. The device characteristics are measured according to the test conditions specified in each vendor's datasheet, with the relevant parameters entered into the curve tracer as outlined in the datasheet. Additionally, the influence of linear mode operation on parameter variations is considered during the measurements to account for potential deviations from standard datasheet conditions. This approach helps assess the impact of partial voltage operation on conduction characteristics and ensures consistency with expected

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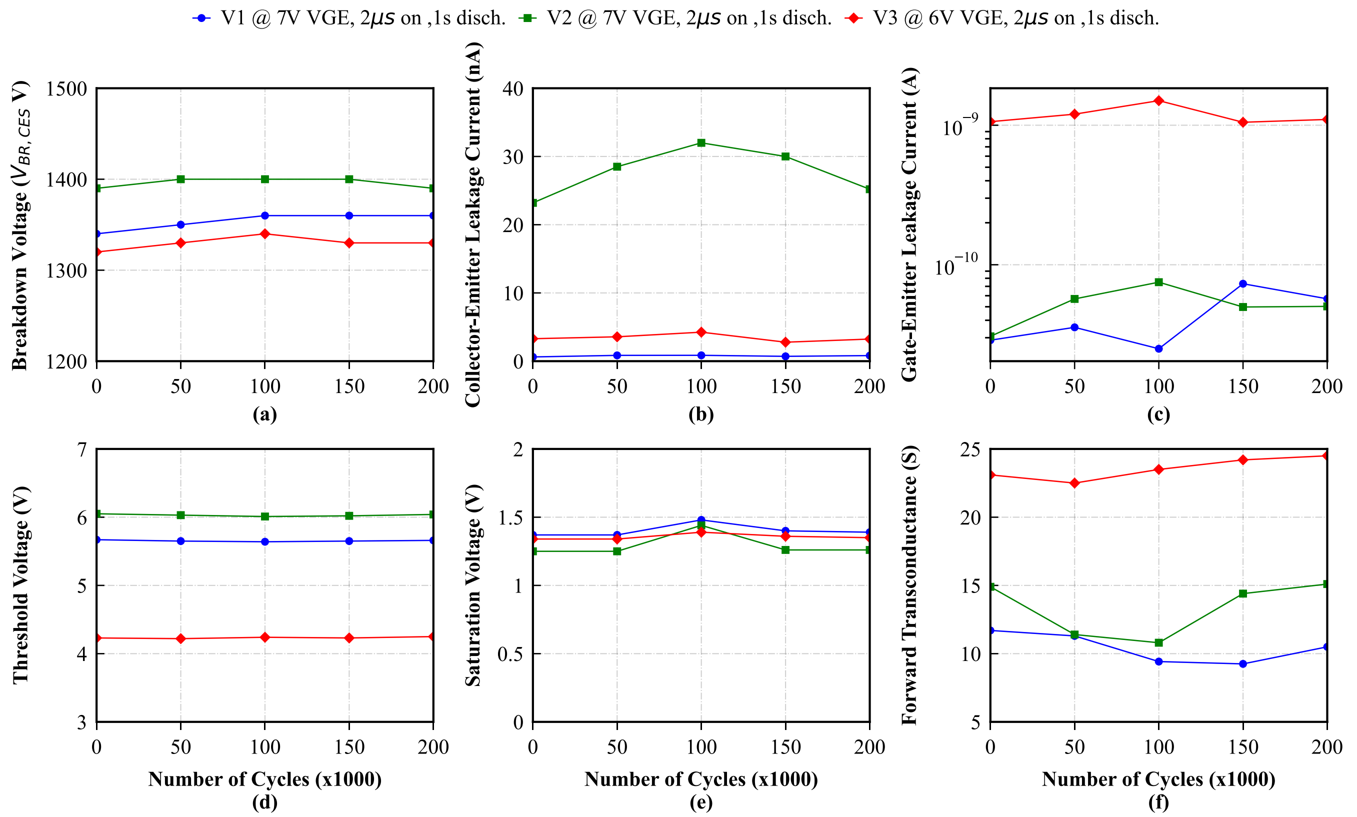

Fig. 14. Typical variations in device parameters after more than 200 000 discharge cycles under different labeled conditions show no observable change in any parameter. (a) Breakdown voltage $V_{\mathrm{BR(CES)}}$. (b) Collector–emitter leakage current. (c) Gate-emitter leakage current. (d) Threshold voltage. (e) Saturation voltage. (f) Forward transconductance.

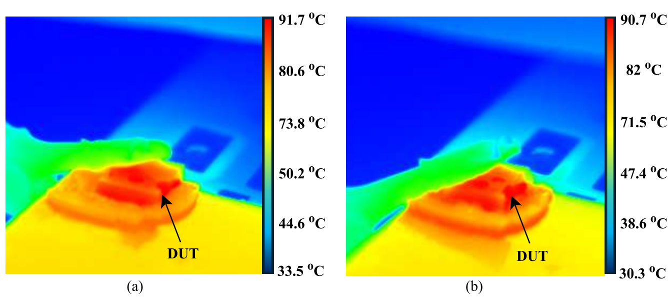

Fig. 15. Temperature variations on the DUTs after more than 200 000 discharge cycles. (a) Example of temperature from vendor 1 at the end of reliability testing. (b) Example of temperature from vendor 2 at the end of reliability testing.

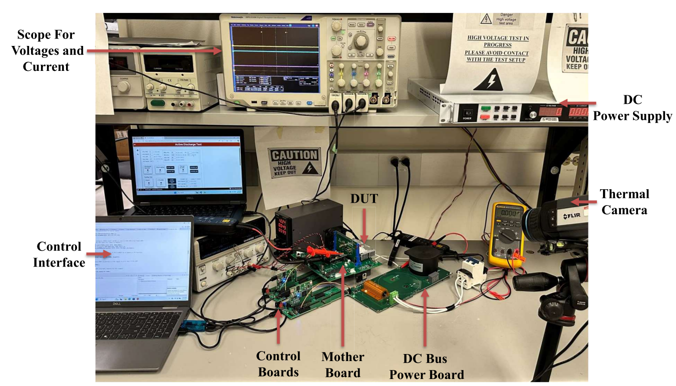

Fig. 16. Test bench setup for dynamic braking experiment, showing all key components.

performance. Parameters are also periodically measured by pausing the test after a set number of discharge cycles to monitor changes in the device's characteristics. The results of the reliability test conducted under a 600-V dc-bus for all vendors are presented in Table III. Based on the conditions specified in the table, no significant shifts in device parameters are observed for any of the vendors. These findings confirm the stability of the device parameters under the tested conditions, demonstrating the long-term reliability of the components. In addition, Fig. 15 illustrates the temperature variations after 200 000 cycles for vendors 1 and 2, supporting the results in Table III. The temperature remains almost constant throughout all charge-discharge cycle tests, further increasing the reliability of using IGBTs for this application without causing thermal runaway. Although not shown in Fig. 15, vendor 3 also demonstrates similar temperature behavior, with no notable rise in case temperature, further supporting thermal consistency across evaluated devices.

E. Dynamic Braking Performance

Fig. 16 shows the test setup for dynamic braking operation. A dc power supply is used to charge the dc-bus capacitor, while the dc-bus power board controls the charging process.

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TABLE III
ACTIVE DISCHARGE RELIABILITY TEST RESULTS WITH DIFFERENT TEST CONDITIONS AFTER 200 000 DISCHARGE CYCLES

DUT	V_{DC} Bus	V_{GE}	Pulse Width	Discharge time	Peak Current	Temperature	Shifts in Parameters
Vendor 1	600 V	7 V	2 μs	1 s	2.5 A	90.7 °C	No Shift
Vendor 2	600 V	5 V	2 μs	1 s	9.5 A	91 °C	No Shift
Vendor 3	600 V	7 V	2 μs	1 s	5.6 A	86 °C	No Shift

TABLE IV
DYNAMIC BRAKING OPERATION RESULTS

Vendor	V_{rated} (V) I_{rated} (A)	Pulse Freq (Hz)	Peak Current (A)	Energy Per Pulse (mJ)	Average Power (W)	Max T_{case} (°C)	Test Duration	V_{GE} (V)	Pulse width (μs)
Vendor X	650, 25	1000	19.5	50	50	87	$>$ 30 min	5.4	8
	650, 80	500	60	200	100	60	$>$ 30 min	7.8	5
	1200, 82	1000	80	300	150	88.7	$>$ 30 min	8.1	5
	650, 30	1000	45	105	105	120	14 sec	7.3	8
Vendor Y	1200, 75	500	48	101.3	50.5	38	$>$ 30 min	5.9	10
	650, 50	1000	48	101	101	54	$>$ 30 min	5.6	10
	650, 25	1000	37	130	130	120	19 sec	9.7	11
	650, 25	1000	42	140	140	120	8 sec	9.8	11
Vendor Z	650, 40	500	45	130	65	44	$>$ 30 min	8.2	10
	650, 71	1000	63	130.2	130.2	80	$>$ 30 min	7.2	11
	650, 40	1000	55	125	125	120	5 sec	8.1	11

As mentioned in Section III-B, the motherboard is connected to the dc-bus power board to maintain a stable dc-bus voltage during dynamic braking. A thermal camera is used to monitor the DUT's case temperature.

In this study, the dynamic braking test evaluates the thermal and electrical performance of TO-247 packaged discrete IGBTs under controlled conditions. Devices from three major vendors-vendor *X*-, *Y*-, and *Z*-rated for 650 V, 1200 V, and 20 to 80 A, are tested at fixed switching frequency and pulsewidth (on-time). These vendors are different from vendors 1, 2, and 3 used in the active discharge tests, allowing evaluation across different manufacturers and current classes to support greater design flexibility. For each test case, the gate-emitter voltage is set to a constant value and adjusted across cases to achieve desired peak current levels, enabling evaluation of the devices' ability to dissipate 50–150 W within the IGBT. These devices are primarily trench field-stop IGBTs, which feature a trench structure where the gate is embedded within the trench. This design enhances the utilization of the silicon area, resulting in an improved current density. The dc-bus voltage is maintained at 400 V, mimicking real-world braking scenarios.

The dynamic braking results in Table IV demonstrate that TO-247 discrete IGBTs from multiple vendors can reliably dissipate 50–150 W under continuous operation. This is valid as long as the peak current stays within or below the device's rated current. For example, vendor *X*'s 82 A-rated device operates safely at 80 A peak, dissipating 150 W with a case temperature of 88.7 °C, as shown in Fig. 17. It maintains stable operation for over 30 min, which indicates good thermal handling. A similar trend is seen with vendor *Y* and *Z*. Vendor *Y*'s device handles 101 W at 48 A, and vendor *Z*'s device handles 130 W at 63 A. Both maintain safe operation for over 30 min, as long as their rated currents—50 A for vendor *Y* and 71 A for vendor *Z*—are not exceeded.

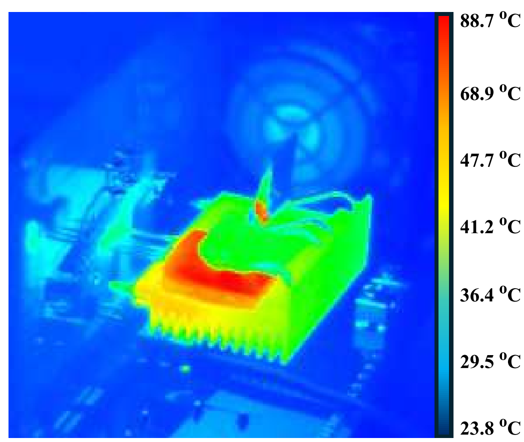

Fig. 17. Case temperature rise to 88.7 °C during 150 W dynamic braking operation as captured by a thermal camera.

However, when the current goes beyond the rated value, the safe operation time drops significantly due to thermal limits. Vendor *X*'s 30 A-rated DUT reaches 45 A, and the case temperature hits 120 °C in just 14 s. Similarly, vendor *Z*'s 40 A-rated device reaches 55 A and hits 120 °C in 5 s.

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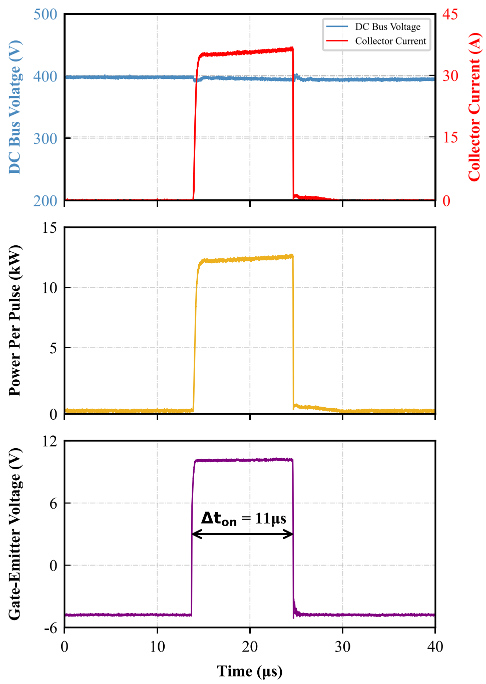

Fig. 18. Waveforms for Vendor Y's IGBT under 130 W dynamic braking at 1000 Hz. Peak current is ≈ 37 A with 11 μs on-time, yielding ≈ 130 mJ/pulse.

Despite this, it still dissipates 125 W during that short period. These results show that high-power pulses can be tolerated briefly if there is enough time to cool down afterward. This makes pulsed braking strategies a viable option in some use cases. Vendor Y's 25 A-rated IGBT shows a similar thermal behavior when pushed beyond its rated current. At 37 and 42 A peak values, the case temperature climbs to 120 °C. Protection triggers after 19 and 8 s, respectively. Even though the power dissipation is around 130–140 W, the rapid temperature rise limits safe operation. These consistent trends highlight the importance of matching the braking profile to the device's current rating. If not, intermittent pulsing with cooling periods becomes necessary.

Fig. 18 shows the scope waveforms for the 130 W dissipation case at 37 A peak current, where the collector current, dc-bus voltage, instantaneous power per pulse, and gate-emitter voltage are captured. The waveform illustrates that during the 11 μs on-time, the device handles current and voltage stress, peaking close to 37 A with the gate driven to 9.7 V, while the power pulse reaches over 10 kW, resulting in a cumulative dissipation of 130 mJ/pulse. This energy value is obtained by integrating the instantaneous power waveform over the conduction time. The energy per pulse is given by

$$E_{\text{pulse}} = \int_0^{t_{\text{on}}} P(t)\, dt \tag{12}$$

where $P(t)$ is the instantaneous power and is the on-time duration of the IGBT. Since the power waveform is nearly flat during conduction, the integration simplifies to

$$E_{\text{pulse}} \approx P_{\text{peak}} * t_{\text{on}} = 11,800 \text{ W} * 11 * 10^{-6} \text{ s} \approx 130 \text{ mJ}. \tag{13}$$

To calculate the average power dissipation, the energy per pulse is multiplied by the switching frequency

$$P_{\text{avg}} = E_{\text{pulse}} * \text{freq} = 130 * 10^{-3} \text{ J} * 1000 \text{ Hz} = 130 \text{ W}. \tag{14}$$

This confirms the IGBT's dissipation level under this high-current switching condition. The same methodology and similarly shaped waveforms are observed across other test cases; however, only this representative example is shown for clarity. These observations consistently confirm that maintaining peak current levels at or below the rated current ensures reliable dynamic braking operation, even at high-power levels. Exceeding these limits leads to rapid temperature rise and significantly reduced operation time, highlighting the importance of current and thermal margin in system design. As in the active discharge tests, no parameter shift is observed in the IGBT's electrical key parameters during dynamic braking, suggesting stable operation and suitability for long-term repetitive use. Section IV explores the industry feasibility and scalability of active discharge and dynamic braking methods, highlighting potential challenges and limitations in real-world implementation. It also explores their application in electric vehicles (EVs), with a focus on cost analysis and the integration of these technologies into existing systems.

IV. Discussion on Practical Implementation

A. *Industry Feasibility and Scalability*

The active discharge method utilizing an IGBT offers a technically feasible solution for industrial dc-bus capacitor discharge. Unlike traditional passive braking resistors, this method enables precise and rapid discharge of the dc-bus within seconds. The elimination of dedicated discharging resistors results in significant reductions in cost, space, and system size. The implementation of the IGBT-based discharge method remains straightforward, and internal testing validates its reliability and safety. Furthermore, the method is scalable, easily adapting to different voltage levels and capacitor sizes by adjusting the pulse frequency and on-time. This scalability makes it suitable for a wide range of industrial applications, from low- to medium-power systems, and allows for easy integration into existing setups with minimal changes, primarily requiring gate drivers that provide partial voltage levels in real-time. The feasibility of using IGBTs for dynamic braking in low-power industrial applications is confirmed through internal testing. These tests demonstrate that IGBTs can dissipate the necessary power levels (50–150 W) for braking without exceeding thermal limits, ensuring safe operation. Compared to traditional braking resistors, the controlled activation of the IGBT offers a technical advantage by managing peak currents and preventing damaging surge currents during braking. Replacing internal braking resistors (ranging from 20 to 200 W) with controlled IGBTs leads to significant cost and space savings. Integrating an IGBT leg for dynamic braking into existing motor drive and power converter systems is straightforward, without impacting the system's primary functions. By staying within the IGBT's thermal limits, the reliability of this method is ensured. Even

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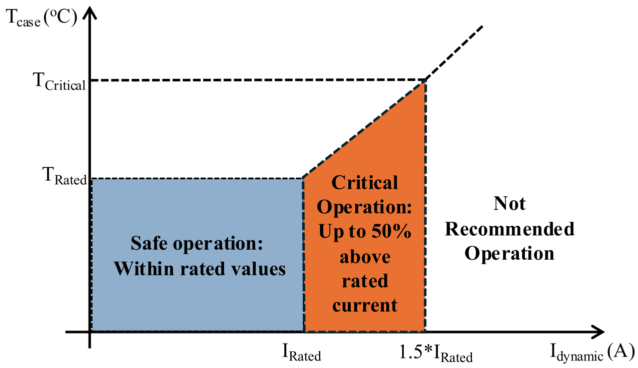

Fig. 19. Dynamic braking operational and critical regions for an IGBT: safe operation within rated values, critical up to 50% above rated current, beyond which is not recommended based on test results.

when the IGBT operates up to 50% beyond its rated current, it stays functional for 10–20 s, which is enough to finish most brakings safely, as shown in Fig. 19 This approach aligns with industry practices that use internal braking resistors, offering a more controlled and space-efficient alternative using existing semiconductor components. The method is scalable, adapting to a range of power levels, and can be applied to different system sizes by adjusting the IGBT's power handling and control strategy.

B. Potential Challenges and Limitations

Implementing the proposed resistor-less active discharge and dynamic braking method introduces several design challenges and application-specific limitations that must be carefully addressed.

1) Gate Driver Design Modifications: Unlike conventional gate drivers that apply fixed gate-emitter voltages for fully switching IGBTs on or off, this method requires partial gate control between 3 and 10 V to operate the device in its active region. Gate drivers must therefore be capable of real-time voltage modulation using programmable outputs or PWM-based voltage shaping. While this adds design complexity, it is achievable using existing driver architectures with minor modifications. In fact, new-generation gate drivers are being developed with such capabilities, and this study contributes to that direction with a practical implementation and validation.

2) Device-Specific Pre-Characterization: Due to part-to-part variations in threshold voltage and conduction behavior, each IGBT requires initial characterization to determine the optimal gate-emitter voltage range for safe and efficient operation. However, instead of characterizing each device individually, a closed-loop control system can dynamically adjust the gate voltage in real-time. This ensures consistent performance without manual tuning. Such an approach is generally preferred by industry for its scalability and practicality.

3) Control Strategy Complexity: Active discharge relies on closed-loop regulation to maintain a pseudo-constant-power profile. This necessitates real-time feedback to adjust pulse frequency or width dynamically. Although this adds to control complexity, dynamic braking mode can be implemented with fixed frequency and pulsewidth, allowing for a simplified open-loop operation.

4) Thermal Management Requirements: Operating IGBTs in the active region increases power dissipation and raises junction temperature. Continuous operation at 50–150 W is validated over 30 min in this study; however, thermal compliance must be ensured via adequate heatsinking and airflow to prevent long-term degradation.

5) Energy Dissipation and Application Scope: The instantaneous energy absorption capability is significantly limited by the die area (typically 10–30 mm^2) and the junction-to-case thermal resistance (typically ~0.3 °C/W) of discrete TO-247 IGBTs. As such, the method is best suited for braking durations longer than 5 s and is not optimized for high-energy, sub-second braking scenarios. Safe operation is constrained by the maximum junction temperature (175 °C) and thermal impedance, requiring precise thermal control. Compared to power modules, discrete devices offer lower thermal mass and are more susceptible to hotspot formation during soft short-circuit or high-current conditions. Consequently, the method is most appropriate for low-to-moderate energy events in servo and light industrial drive systems. High-speed or high-inertia braking events may exceed the SOA of the IGBT, unless thermal stress is properly managed using enhanced cooling or parallel device configurations.

C. Application to EVs

EVs utilize high-voltage battery packs to supply energy to traction and auxiliary systems. Power electronics such as inverters, dc-dc converters, and chargers operate from a centralized dc-bus, typically ranging from 350 to 900 V. The energy stored in the dc-bus capacitors must be rapidly discharged during maintenance, accidents, or key-off events to mitigate electric shock risks, a critical concern in EV safety. International standards such as ISO 6469-4 mandate that these capacitors be discharged to a safe level, typically below 60 V, within 5 s [23].

In the context of ISO6469-4 compliance, it is important to distinguish between dynamic braking and safety-related discharge. The 5-s requirement pertains to post-crash or maintenance scenarios, not to braking performance or kinetic energy recovery. The goal is to ensure electrical safety when the system is shut down or damaged.

The proposed IGBT-based active discharge method directly addresses this requirement by safely reducing a 600 V, 600 μF dc-bus to below 60 V in approximately 1 second, with manageable thermal stress on a single TO-247 IGBT (see Fig. 11). Beyond compliance, this method offers additional advantages for EV powertrains. Unlike passive discharge resistors, which generate heat and lack control, this approach uses a partially turned-on IGBT to dissipate energy internally. This enables faster, more precise voltage reduction, especially beneficial for rapid shutdowns that reduce electrical hazard exposure. Moreover, the method can be integrated into existing vehicle safety systems, enabling automated and reliable discharge initiation upon detection of critical events. Overall, this active strategy offers a robust, controllable, and compact solution

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TABLE V
DETAILED COST COMPARISON OF CONVENTIONAL AND PROPOSED METHODS: A CASE STUDY

System	Component (Rated Values)	Cost (USD)	Role in System
Conventional	Internal Braking Resistor (150 W, 50 Ω)	$17.05	Large, chassis-mounted resistor for dynamic braking and discharge. Requires thermal interface and increases system size.
	IGBT (650 V, 5 A)	$1.49	Switch for controlling current through resistor; limited current handling.
	Industrial Gate Driver (5 A)	$7.73	Opto-isolated gate driver; commonly used in commercial drives.
	Total	**$26.27**	Higher total cost and mechanical complexity. Requires cooling and mounting hardware.
Proposed	IGBT (Vendor X, 1200 V, 82 A)	$6.58	Used in active region for controlled discharge. Eliminates internal braking resistor.
	Custom Gate Driver (LDOs + feedback resistors + core)	$7.00	Low-speed, low-complexity driver circuit. Sufficient for active-mode operation.
	Total	**$13.58**	Nearly 50% cost savings with simplified integration and footprint.

to ensure occupant and service personnel safety by swiftly mitigating high-voltage risks in modern EV architectures.

Typical EVs employ regenerative braking to recover kinetic energy without relying on external dissipative systems. However, in high-power applications such as trucks, mining vehicles, or trains, regenerative braking may be unavailable or insufficient, necessitating dynamic braking using external resistors rather than internal ones. These systems must dissipate significant amounts of energy due to the high-power levels involved. In contrast, this article focuses on low-power applications, where such demanding requirements do not arise. As a result, dynamic braking in high-power vehicles falls outside the scope of this work. These scenarios often involve more complex braking systems that are required to handle larger energy flows, maintain thermal safety, and coordinate with other control units in real-time. Such considerations are not addressed in this study.

D. Cost Analysis

Unlike this study, conventional braking and discharge circuits use resistors to dissipate dc-bus energy during shutdown or emergency events. While effective, this method adds cost and occupies considerable PCB or chassis space, limiting factors in compact or cost-sensitive designs. Table V presents a cost comparison using real component prices from a major distributor's sites. In the conventional setup, a 50 Ω, 150-W internal braking resistor costs U.S. 17.05, and a low-power IGBT (650 V, 5 A) is U.S. 1.49. Adding a typical gate driver used in a conventional setup at approximately U.S. 7.73 brings the total bill of materials (BOM) cost to U.S. 26.27.

In contrast, the implemented solution uses a single high-power IGBT—e.g., vendor *X* (1200 V, 82 A), priced at U.S. 6.58, alongside a custom gate driver composed of an LDO, feedback resistors, and a core driver circuit totaling approximately U.S. 7.00. The overall BOM cost is therefore reduced to U.S. 13.58, yielding a cost reduction of nearly 50%. Beyond BOM savings, the proposed solution simplifies mechanical integration. High-power braking resistors are physically large, require chassis mounting, and need thermal isolation or airflow-adding design overhead. Discrete IGBTs, in contrast, are more compact, support case temperature monitoring, and reduce heatsink demands due to their smaller size. It is also worth noting that the gate driver requirements in this application are less demanding than high-speed switching circuits. The simpler gate drive architecture not only reduces cost but also enhances robustness in slow-switching, high-thermal-load environments.

The proposed method reduces component cost by approximately 50%, while also enabling system miniaturization, easier thermal design, and better scalability. These advantages make it particularly attractive for high-volume, space-constrained industrial applications.

V. CONCLUSION AND FUTURE WORK

This study presents a new, compact, cost-effective, and resistor-less solution for both: 1) active discharge and 2) dynamic braking operations in low-power industrial systems. For active discharge, a constant-power discharge technique is employed using PFM, where the on-time is fixed and the frequency is ramped from low to high. This enables rapid energy dissipation through a single IGBT, completing the discharge of a 600 V dc-bus within 1 s. The method is verified across three different IGBT vendors, confirming reliability and vendor independence. Long-term testing shows no degradation or parameter shift in key IGBT parameters after more than 200 000 discharge cycles. This proves its robustness for frequent shutdowns and emergency stops. For dynamic braking, a fixed-frequency and short-pulse method safely controls the IGBT within its rated power limits. The system handles continuous power dissipation between 50 and 150 W for over 30 min. It replaces conventional internal braking resistors typically rated at 20–200 W with resistance values from 5 to 120 Ω. Even when exceeding the IGBT's rated limits by up to 50%, the device remains operational for 10–20 s. It provides sufficient time to complete braking events without failure. This makes the method well-suited for industrial drives and a strong candidate to replace bulky internal braking resistors in the systems. All these benefits are achieved by simply modifying the IGBT gate driver to support low gate-emitter voltages (e.g., 3–10 V), rather than always supplying the full gate-voltage typical in standard industrial gate drivers. This approach enables enhanced control, reduces system cost by up to 50%, and saves significant board space, making it highly attractive for high-volume production lines. This work intentionally focuses on the device and reliability level, while commercial drive integration is a planned next step in the method's evolution. In future work, the proposed braking concept will be extended and evaluated for moderate- and high-power systems, using IGBT modules capable of handling power dissipation beyond 1 kW during braking events.

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