Review of IGBT Intelligent Gate Drive and Protection Strategies

Ruyingjing Zhang, Xinmei Li, Jiafeng Ding, Shijie Chen, Hao Yang, and Hangyu Guo

***Abstract*—In the realm of power electronics systems, gate drive and protection strategies are of paramount importance, bolstering reliability, efficiency, and safety. This article provides a comprehensive overview of existing methods for gate drive and short-circuit protection of insulated-gate bipolar transistor (IGBT), further elucidating the latest advancements with intelligent features. The structure of an intelligent driver with the trend of integrating more sophisticated features is presented first, followed by descriptions of its functions, such as overshoot optimization, electrical isolation, and sensor monitoring. The methods for gate drive are discussed and compared, particularly emphasizing the benefits of self-adaptive gate drive in reducing losses and overshoot. Subsequently, different strategies for short-circuit detection and shutdown protection are explored, complemented by discussions on recent short-circuit protection techniques. Finally, the promising approaches for future works are recommended. This review is intended to provide practical solutions for the design and development of IGBT operating circuits in the existing and emerging applications.**

***Index Terms*—Complex programmable logic device (CPLD), field programmable gate array (FPGA), insulated-gate bipolar transistor (IGBT), intelligent gate driver, short-circuit (SC) protection.**

I. Introduction

NOWADAYS, as one of the most important power devices in medium and high power converter applications, insulated-gate bipolar transistors (IGBTs) maintain their advantages and are widely used in various fields, such as renewable energy, electric vehicles, and industrial power electronics [1], [2], [3]. As the demands for energy efficiency and power density in these industries continue to increase, appropriate gate drive and protection circuits are crucial in ensuring the best performance of IGBTs in different applications.

Gate drivers directly manage the working status, switch time, and switch losses of IGBT, playing a vital role in ensuring its stable operation. Over the past decade, gate drivers have been upgraded from basic isolators and power amplifiers to intelligent control circuits with multiple functionalities. These enhancements not only ensure the proper turn-ON and turn-OFF of IGBT, but also progress in controlling current and voltage overshoots [4], improving switch performance [5], [6], and reducing noise and losses [3], [7], [8], [9], [10]. The protection circuit is used to prevent IGBT from damage under abnormal conditions, such as short-circuits (SCs), overcurrent, overvoltage, and overheating. Given the rapid response time, high fault current, and the ability to burn out switching devices associated with SCs, SC protection becomes essential for power converters [11], [12], [13]. The increasing urgency to optimize SC protection circuits to enhance the reliability of dedicated hardware has spurred the evolution of protective technologies in aspects like improving monitoring speed and stability [12], [14], [15], [16], [17], implementing reasonable soft shutdown processes [18], and exploring new control functions and evaluation models [18], [19].

Over the years, extensive research on the drive and protection strategies of power devices has led to increasingly refined and sophisticated solutions [20], [21], [22]. The review [20] discusses the latest developments in gate drive technology with intelligent characteristics, focusing on the challenges and opportunities associated with drivers for wide bandgap semiconductors. The concept of a three-dimensional safe operating area is proposed in [21] as the IGBT's operational boundary to divide the SC failure modes, giving a deep insight into the limiting effects of these failure modes on the device SC ruggedness. Furthermore, monitoring and maintenance technology are classified into four levels in [22] according to performance complexity, which impacts the extension of average power module lifetime in next-generation power electronic systems.

Compared with a comprehensive review of future power converters, this article aims to construct a framework for intelligent driving and protection circuits for IGBT, explaining the relationship between the model and its functionalities. The structure of this article is as follows. Section II proposes the framework of intelligent driving and protection circuits, elucidating their smart functionalities. Based on this circuit framework, Sections III and IV provide an in-depth review of the gate drive and SC protection strategies of IGBT, respectively, detailing the latest advancements. The effects of different gate drive methods in terms of controlling losses and overshoots are compared through relevant examples, and some latest innovative SC protection approaches are discussed. Lastly, this article anticipates how equipment reliability, intelligent monitoring and management,

Manuscript received 20 July 2023; revised 9 December 2023; accepted 18 February 2024. Date of publication 5 March 2024; date of current version 19 April 2024. Recommended for publication by Associate Editor K. Wada. *(Corresponding author: Xinmei Li.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPEL.2024.3372254.

Digital Object Identifier 10.1109/TPEL.2024.3372254

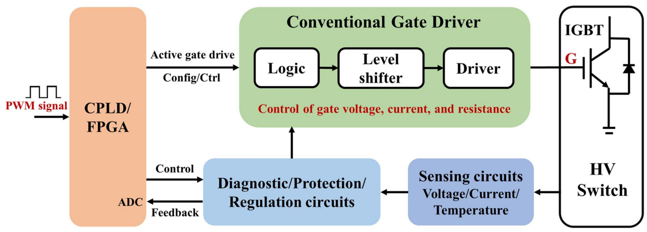

Fig. 1. Schematic diagram of intelligent gate driver.

and the third-generation semiconductors' characteristics can offer new directions for the development of drivers.

II. Intelligent Gate Driver

Modern gate drivers integrate increasingly complex features to protect and optimize the operation of power semiconductor devices [23], [24], [25], [26]. The intelligent gate drive circuit, composed of a sensor circuit, control unit, active gate drive circuit, and protection module, has been developed with an increase in integration [20], [27]. Fig. 1 shows the block diagram of the intelligent gate drive circuit.

A. Structure of Intelligent Gate Driver

1) Gate Driver: The primary task of the conventional gate driver (CGD) is to amplify power, ensuring the proper switching of IGBT without causing high voltage overshoot. However, the CGD's suppression effect on overshoot is rather limited and losses are inevitable. Increasing demands for performance and logic functions have spurred the integration of drive stages with digital controllers to achieve more complex and precise control. Active gate drivers (AGDs) have been proposed to balance conflicting features among switching time, switching loss, and overshoots, aiming to achieve good drive effects [28], [29], [30]. This article focuses on the analysis of active gate drive and self-adaptive gate drive technologies.

2) Sensing Circuits: Sensing circuits are effective tools in closed-loop drive and protection circuits as they provide essential status feedback and parameter signals. They monitor parameters, such as device current, device voltage, gate voltage, induced stray inductance voltage, and temperature, converting them into signals for diagnostic circuits or a microprocessor [12]. Various detection approaches exist, which depend on the desired protection objectives and circuit characteristics. These will be detailed further in Section IV.

3) Diagnostics, Protection, and Regulation Circuits: On one hand, the diagnostic circuits receive signals from the sensing circuits and controller, further triggering the protection and adjustment circuits. On the other hand, some strategies involve directly connecting from sensing circuit to the A/D converter, and the signal is then fed back to the controller to trigger either the internal protection circuit or the adjustment circuits to regulate the gate signal [31].

Different circuits are contained in this module based on their execution function and practical application. For instance, the complementary current source (CCS) in [32] and [33] utilizes control signals from field programmable gate array (FPGA) to regulate the current source and current sink, thereby adjusting the switching ON and OFF of the device. The state detection circuit proposed in [34] receives start signals and feedback, obtaining the IGBT's switching status in advance. This allows the switch stage to implement the designed switching scheme during a sequential appearance process.

B. Functions of Intelligent Gate Driver

1) Current and voltage transient control: The parasitic capacitance and inductance in power devices and circuits can lead to high voltage overshoot, voltage ringing, and high current overshoot [40]. These undesired switching responses increase power losses of devices and give rise to electromagnetic interference (EMI) related issues. Optimizing the circuit structure to reduce stray parasitic has limited effects [41], [42], [43]. A multistep driving method proposed in [44] effectively controls the stress of power semiconductor switches and antiparallel diodes, leading to a reduction of switching loss by up to 50%. Several manufacturers have adopted more intelligent drive techniques and designed commercially available gate drivers capable of limiting overshoot and controlling transient [45], [46].

2) Isolation technology: The isolator is primarily used for electrical and signal isolation [47], thereby enhancing the circuit's reliability and stability. The design of gate driver needs to consider the isolation requirements for different voltage levels. Low-voltage circuits, characterized by their durability and longevity, typically use nonisolated techniques. High-voltage circuits, which contain hazardous live parts, require functional isolation or even reinforced isolation. The development of commercial isolation drivers, especially those utilizing coreless transformer (CT) technology, enables them to withstand larger voltage fluctuations, while reducing power consumption and delay [39], [48], [49]. Since nonisolated circuits often suffer from severe electrical interference, isolation parts are often required in control signal paths. Based on different principles and mediums, Table I lists several types of isolation methods, comparing their characteristics, strengths, and weaknesses.

3) Sensing and Regulation: The demands of high-frequency and high-power applications, reliability, and longevity prediction of power electronic systems necessitate accurate and fast sensing of IGBT conditions [15]. Utilizing external devices to sense signals is costly and often results in noise interference. The current trend is to fully integrate sensors and regulation circuits into gate driver ICs, which allows monitoring data to be used for signal processing and precise timing control while minimizing losses. In [27], a fully integrated gate driver is proposed, requiring no extra discrete components. The integrated sensor in this design plays a key role in monitoring thermal behavior and is also temperature compensated.

4) Protection: Unpredictable failures always occur in the actual operation of circuits and lead to over-current, e.g., SCs. Most IGBT can withstand SC current for only a few microseconds because the fault current can quickly exceed several times the current limit. Without appropriate remedial measures, IGBT is at risk of burning out. Therefore, proper SC fault detection and

TABLE I
TYPICAL ISOLATION METHODS

Methods	Voltage level (kV)	Advantages	Disadvantages
Direct drive [35]	< 0.6	Simple and small circuit	Difficulty in layout, slow switching rate
Level shifter [36] [37]	0.6, 1.2	Simple circuit, easy to integrate	Large parasitic inductance, inability to transmit energy
Optocoupler	1.2	High withstand voltage, unlimited pulse width	Large delay error, inability to transmit energy
Optical fiber [10]	—	Long transmission distance, low transmission delay	Easy aging, severe interference, high cost
Pulse transformer [38]	1.2, 1.7, 3.3, 6.5	Low transmission delay, high switching frequency, transmit energy	Large volume, core saturation issues
Coreless transformer [39]	1.2, 2.3	Low transmission delay, easy to integrate	Inability to transmit energy, limited insulating capacity
Capacitive coupler	1.2	Low transmission delay	Large capacitor requirements, inability to transmit energy

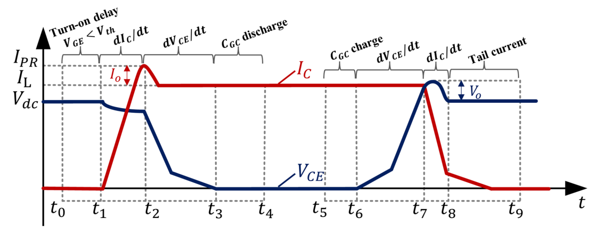

Fig. 2. Schematic current (I_C) and voltage (V_{CE}) waveforms at hard switching subdivided into characteristic intervals.

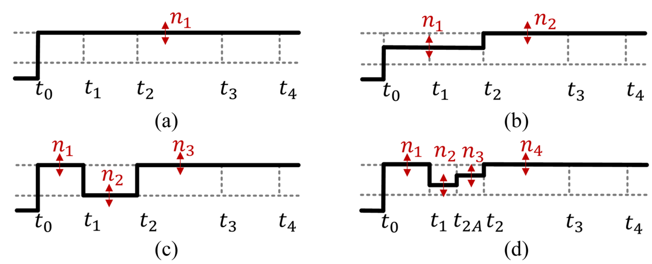

Fig. 3. Different gate control patterns. (a) Single-step conventional driving control. (b) Two-step gate control. (c) Three-step gate control. (d) Four-step gate control.

protection strategies are necessary as they can effectively prevent the IGBT from damage due to overwork or improper operation [50]. Additionally, the intelligent features of protection circuits cover fault reporting and evaluation, enabling state identification through model establishment and mathematical calculation [51], [52]. The soft-shutdown features of a gate driver can prevent overvoltage during fault-clearing incidents.

III. DRIVE TECHNOLOGY

IGBT drive technology involves the control of current, voltage, and gate resistance. The CGD, which adopts a fixed gate resistor to switch IGBT, can suppress voltage and current overshoots by increasing gate resistor R_g [53], [54], [55], gate capacitors C_{ge} or Miller capacitors C_{gc} [25]. Although CGD is widely used and cost-effective, it fails to guarantee optimal switching performance under varying working environments.

The AGD is designed to generate appropriate control signals tailored for various circuit operational conditions. This capability allows for effective suppression of overshoots, striking a balance between slow driving requirements of low noise and switching stress and fast driving requirements of high-speed switches and low losses [56]. Depending on whether feedback regulation is utilized, AGD can be classified into open-loop drive and closed-loop drive. The self-adaptive gate driver (SAGD) utilizes closed-loop control, which is more intelligent and requires high control accuracy. Hence, this section discusses the gate driver, and delves deeper into its latest advancements, which align with the functional requirements mentioned in Section II.

A. Active Open-Loop Driver

Compared to CGD, an active open-loop driver uses a control unit to adjust the input signal so that the gate input can be controlled according to preset specific values without relying on feedback signals [57].

Control of gate current or voltage can be achieved by the gate driver in a multistep strategy to optimize switching waveforms of the IGBT. Fig. 2 shows a typical IGBT switching waveform for an inductive load, sequentially divided into different stages corresponding to the charging and discharging states of the component. Since events during turn-OFF are symmetrical to those during turn-ON, control methods are similar. In Fig. 3, the control timing diagrams for four different gate driver methods during the on-state are discussed, including single-step methods (CGD) [see Fig. 3(a)], two-step methods [58] [see Fig. 3(b)], three-step methods [28], [29], [30] [see Fig. 3(c)], and four-step methods [44], [59] [see Fig. 3(d)].

In each interval, n_i (where $i = 1,2,3,4$) represents the varied gate current or gate voltage, which can be determined from the device datasheet or through optimization algorithms [60], [61]. In the two-step driving method, the current injected into the gate remains below the drive level until the collector current (I_C) reaches the load current (I_L) plus the peak reverse-recovery current (I_O). This design reduces current overshoot and increases switching delay [58]. Three-step control method provides another practical example of optimizing IGBT conduction performance [29]. *Stage I* (t_0-t_1) immediately follows the main commend at turn-ON, utilizing a high current to accelerate the switching process and minimize delay time. Gate input is reduced in *Stage II* (t_1-t_2) to prevent current overshoot. In *Stage III* (t_2-t_3), the gate is rapidly charged to reduce the tail voltage, thus decreasing the power loss during turn-ON. The four-step method, illustrated in Fig. 3(d), divides the step from t_1 to t_2 by t_{2A} when I_C reaches I_L [44]. Although the complexity of the control strategy escalates with each additional step, so too does the precision of the control effects. More sophisticated multistep

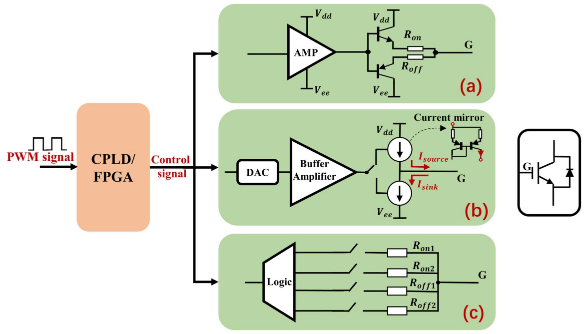

Fig. 4. Open-loop driving methods. (a) Adjustable gate voltage. (b) Adjustable gate current. (c) Adjustable gate resistance.

control methods have been extensively studied, and the time intervals can also be equally distributed based on the estimated total time [62].

Most drivers are voltage source-based, offering an advantage over current sources as power loss occurs in the gate resistance, not in the driver's current source. In Fig. 4(a), a schematic diagram of the adjustable gate voltage circuit is shown, which is composed of an amplifier and a complementary emitter follower circuit [63]. Operational amplifiers are used to increase signal amplitude. Commercial drivers with integrated programmable gain amplifiers enable configurable amplification and buffering the inputs of lower impedance blocks [64], [65]. The complementary emitter follower circuit, comprising bipolar transistors, is capable of achieving digital control [66], [67]. During the relevant stage, the behavior of IGBT is regulated by the control unit [complex programmable logic device (CPLD) or FPGA], which instructs the gate driver to output preset voltage values.

Compared with the emitter follower circuit, potential reversal on the gate can be easily achieved with an H-bridge circuit. However, this requires a separate isolated power supply, and transistor control becomes more complex [5]. MOSFET push-pull circuits are also suitable for digital control, offering the advantage of generating large gate currents from small control currents [29], [67]. Drivers utilizing MOSFET push-pull circuits do not require precise control in low-voltage applications, although careful selection of gate resistors is essential in high-power applications [68].

The structure of a current source-based AGD is more complicated, but it gives a better controllability over the switching dynamics as the gate current is directly controlled [33], [69]. Fig. 4(b) illustrates the schematic of the adjustable gate current circuit. The output signal from the FPGA controller is converted into an analog signal through the DAC, and then converted into a gate input by the buffer amplifier and current mirrors (CMs) [29], [63]. One CM is used for positive gate current, and the second CM is used for negative gate current. The difference between these two CMs is that the NPN and PNP transistors are interchanged [32], [69], [70]. A CCS composed of current sources and current sinks can also be used as an external circuit to compensate the gate current [71], [72]. The turn-ON and turn-OFF delay times must be shorter than the switching time of IGBT, and stability is needed. This stability can be assessed by evaluating whether the CCS maintains a linear proportion under different gate voltages [1].

Fig. 4(c) presents a schematic diagram of the adjustable gate resistance circuit. The values of gate resistance are switched during the switching phase to effectively suppress current and voltage overshoots [30]. Furthermore, the circuit's design must ensure that the IGBT operates within the safe operating area of the power semiconductor.

Compared to CGD, the digitalized open-loop driver can effectively shorten the switch delay time, reduce the peak reverse recovery current of the diode, decrease overvoltage, and minimize switch losses. However, its drawback lies in the complexity of control, which necessitates the precise detection of shifts in driving modes [66]. Under fluctuating environment, the method of predefining voltage and current based on ideal characteristics often constrain its utility and even cause irreversible damage on the circuit.

B. *Active Closed-Loop Driver*

A key aspect of active closed-loop driving lies in feedback sensing. Parameters such as the collector current I_C [44], the collector-emitter voltage V_{CE} [31], the gate voltage V_{GE} [4], [73], the current slope dI_C/dt [74], [75], [76], and the voltage slope dV_{CE}/dt [74], [76], [77] are often monitored as feedback signals to control the gate. Contrasting with open-loop drive systems, it is a dynamic control method that adjusts the devices based on feedback signals, thereby enhancing the system's robustness and control precision. Another key point lies in regulation methods, which are different between analog closed-loop systems and digitalized systems based on their own structure.

1) Analog Closed-Loop Feedback: Based on analog circuits, the drivers typically conduct a fast comparison between the sensor-obtained feedback signals and preset reference signals, and then employ the results of these comparisons to adjust the gate. It is feasible to employ a multistep method at turn-ON and turn-OFF by setting corresponding comparison values at each stage [24]. There, the input reference signals from reference waveform generator are set once at the beginning of every switching operation and kept at a constant value for the complete switching process [77]. In addition, analyzing of system's stability and robustness is important for closed-loop drivers.

In [58], a scaled feedback value of V_{CE} is compared with a defined signal to suppress voltage overshoots. The duration of each voltage interval can be adapted by detecting the beginning of the decrease of the voltage across the transistor during turn-ON and the break of voltage slope during turn-OFF. Parameters such as I_C, dI_C/dt, and dV_{CE}/dt are also utilized as feedback items in [78], [79], and [80].

Ideally, dV_{CE}/dt is zero during the collector current change and dI_C/dt is zero during the collector-emitter voltage change. Therefore, analog circuits can utilize the closed-loop control that combines both dI_C/dt and dV_{CE}/dt [59], [74], [80], [81], [82], [83]. Block diagram of a combined closed-loop current slope and voltage slope control extended by an additional gate current control is depicted in Fig. 5. The voltage parameter [see Fig. 5(a)] and current parameter [see Fig. 5(b)] are first processed

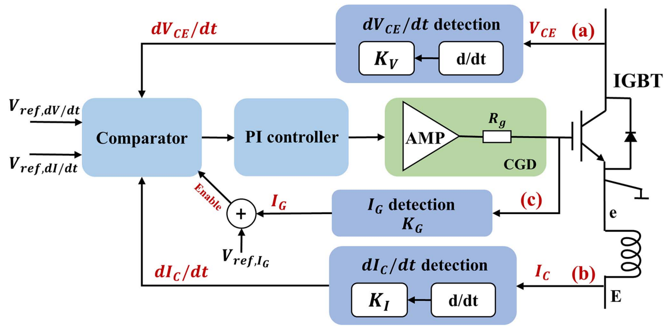

Fig. 5. Analog feedback control circuits. (a) dI_C/dt. (b) dV_{CE}/dt. (c) I_G [24].

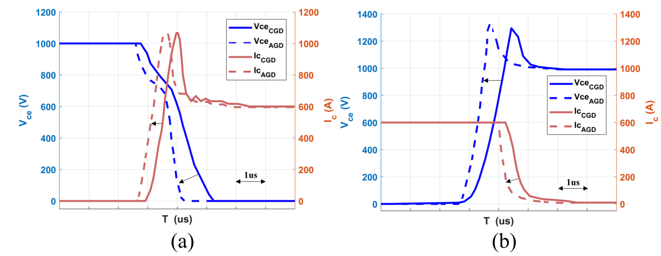

Fig. 6. Comparison of waveforms between CGD and AGD with a fixed gate resistance of 3.75 Ω and a load current of 600 A. (a) Turn-ON waveforms. (b) Turn-OFF waveforms [1].

through differentiation, and then scaled by the gains K_I and K_V. Since dI_C/dt and dV_{CE}/dt are, respectively, used during turn-ON and turn-OFF, $V_{ref,\ dI/dt}$ and $V_{ref,\ dV/dt}$ are set to a constant positive value [84]. Fig. 5(c) describes the feedback process for gate current, where the reference gate current is set to desired values corresponding to different switching stages to activate the gate control [24], [34]. As a switching variable, V_{GE} can also serve as a parameter reflecting the switching process of the device. Here, the input signal of gate is compared with the reference value, and the result of this comparison is then fed back to the input terminal of the amplifier, thereby controlling the amplifier's operating point [80]. To achieve better control effect, V_{GE} is often used in conjunction with other parameters as the feedback values, as in [73], both V_{CE} and V_{GE} are employed for feedback control.

Analog closed-loop gate drivers can regulate current and voltage overshoots with minimal compromise in switch time, and the switching losses are lower than the CGD with the same gate resistors. However, they lack flexibility in diverse application environments, and their bandwidth can be easily constrained by the limitations of analog devices, such as operational amplifiers.

2) Feedback With Digital Controller: Gate drivers with control units like FPGA or CPLD can provide enhanced precision, stability, flexibility, and programmability [31]. Additionally, they can integrate more functions and protective measures, as described in Section II.

Digital drivers can also be achieved based on multistep voltage/current/resistance control, with a focus on the detection of key parameters and the status of devices, as well as issues related to bandwidth limitations [44], [58], [59]. The digital circuits are the key components of the digital gate drive controller while some analog circuits are auxiliary. The basic function of the control unit is to act as a PWM generator, providing the gate pulse as illustrated in open-loop AGD section. Moreover, signals from external circuits such as the fast comparator and the reference signals generator are sampled by the A/D converter, and then sent to the FPGA for processing, storage, and upload [85].

A stage detection circuit that relies on the status-feedback signals is always necessary to detect switching stages. When the feedback value meets the criteria, it proceeds to the next control stage. This method typically requires a certain delay and robustness in the switching. In [1], three signals are utilized to detect the stage: the collector-emitter voltage V_{CE}, the voltage across the emitter inductance V_{Ee}, and the turn-ON and turn-OFF command signal. A CCS in this AGD is controlled by FPGA to provide compensation input into the gate. Fig. 6 shows the comparison of turn-ON and turn-OFF waveforms between CGD and AGD with a fixed gate resistance of 3.75 Ω and a load current of 600 A. The AGD significantly accelerates the delay times and voltage rising/falling rate, leading to increased switching speed and reduced loss.

Several studies have concentrated on identifying optimal parameters of the circuit such as gate resistance, gate-emitter capacitance, and ON–OFF gate threshold voltage by exploring control algorithms and establishing mathematical models, aiming to enhance operational performance [56], [68]. For instance, a neural network is established in [86] to predict the gate resistance during the three stages of turn-ON and turn-OFF, thus simplifying the drive circuits.

C. Self-Adaptive Gate Driver

Self-adaptive drive circuits build upon the concept of active gate drives but introduce a level of self-adaptability and integration. They are designed to automatically adjust control strategies and parameters in response to changes in system parameters or operating conditions. This adaptive behavior is often implemented using a feedback control system that adjusts the switching characteristics based on previously measured values. This process necessitates high-speed A/D and D/A converters for sampling variables effectively.

Intelligent functions are based on the efficient cooperation between external circuits of the driving stage with the control unit. In [87], strategies using high-speed feedback circuits are proposed to decrease switch delay and overshoots. Signals are processed through high-speed feedback and then input into the FPGA. This allows for recognition of each switch stage, thereby achieving voltage control. To circumvent the time delays introduced by D/A and A/D converters, a SAGD that is used to adjust gate voltage directly is proposed in [16]. The state feedback circuit indirectly detects the load current and dc bus voltage as time quantities. During the specific stages when voltage or current rise, the controller adaptively selects optimal increment of gate resistance, which makes the system exhibit stability in applications with variable load current or changes in dc bus voltage, and effectively balances overshoots and switch losses.

TABLE II
IGBT Gate Drive Methods

Methods		Features	Applications (module voltage and current)	Controller	Switching loss/delay time (E_{ON}, E_{OFF})(T_{ON}, T_{OFF})	Overshoots (V_o, I_o)	Comments
CGD		R_g ↓[53]	IGBT in series 600V 75A	None	E_{ON}, E_{OFF}↑	V_o↓	Poor voltage overshoot suppression effect
AGD	Open-loop	Adjustable current [63]	Matrix converter 600V 100A	GAL16V 8D	T_{ON}: ↓0~80% T_{OFF}: ↓0~75% (Compared to CGD for same Rg)	I_o↑	Large current overshoot
AGD	Open-loop	Adjustable voltage	Single IGBT 1200V 300A [66] 6500V 1000A [62]	None	E_{ON}: ↓25~45% (Compared to CGD for same Rg)	Same	Shutdown performance not studied
AGD	Closed-loop	V_{CE} [58] 2-step control	Single IGBT 1200V 300A	None	E_{ON}↑ (Compared to CGD for same Rg)	V_o↓, I_o↓	Increased switching losses
AGD	Closed-loop	I_C [44] 4-step control	Single IGBT 1700V 300A	FPGA	E_{ON}: ↓0~50% (Compared to CGD for same Rg)	I_o↓	Work in specific conditions
AGD	Closed-loop	I_C, V_{CE} [31]	Single IGBT 400V 320A	FPGA	E_{ON}: ↓0~20% (I_C<55A, compared to CGD for same R_g)	I_o↓	Shutdown performance not studied
AGD	Closed-loop	dI_C/dt [79]	Three-phase inverter 600V 400A	None	E_{ON}: ↓20~35% E_{OFF}: ↓15~33% (Compared to CGD for same R_g)	Same	Lack of in-line regulation, prolonged response
AGD	Closed-loop	dV_{CE}/dt [82]	IGBT in series 1200V 560A	FPGA	T_{ON}, T_{OFF}, E_{ON}, E_{OFF}↑ (Compared to CGD for same R_g)	dV_{CE}/dt adaptive Control	Current overshoot not studied
SAGD		dI_C/dt, dV_{CE}/dt [16]	Load current and dc bus voltage changing circuit 1200V 400A	FPGA	E_{ON}: ↓0~35.8% E_{OFF}: ↓0~64.7% (V_{CE}=700V; compared to AGD for same R_g)	V_o↑, I_o↑ V_o<V_{CGD} I_o<I_{CGD}	Balancing switching loss

Adjustable control and protection functions are included to simplify the design of highly reliable systems. The programmable features of commercial active driver ICs provide a design space for adaptive and precise control [39].

Enhancing switching speed while simultaneously suppressing EMI noise presents a contradictory characteristic in power semiconductor device driving, posing a challenging issue in balancing these conflicting properties [8]. The choice between CGD and AGD depends on different application scenarios, and the determination of gate drive parameters is influenced by various factors. For instance, in motor drives powered by drivers, due to insulation or EMI concerns, the rate of change of voltage slope is limited. It is common to reduce the gate current to keep the dV_{CE}/dt within its limit. Alternatively, in ultrahigh-voltage dc circuit breakers, applying an unconventional ultrahigh drive voltage to the device's gate can significantly enhance the instantaneous current capability of the IGBT, enabling it to control currents several times its rated value within a brief period [6].

To provide a clearer comparison of the characteristics of different drive methods, Table II gives an overview over the characteristics of various gate drive methods of IGBT in dealing with switch loss and voltage/current overshoots. It can be observed that the SAGDs demonstrate significant benefits in terms of IGBT operational performance.

IV. SC Protection

SC overcurrent can be categorized into two types: hard switching faults (HSF) and faults under load (FUL). HSF occurs at the instant IGBT turns ON, while FUL happens during the conducting state of the IGBT [88]. SC protection is the most critical protection function in power converters. Existing SC detection methods are mainly hardware-based, with less applications in the software. Generally, SC protection circuits need to meet the requirements as follows.

1) Rapid protection, with minimal delay, does not adversely affect the operational performance of the IGBT.
2) Restriction of peak fault current to lessen the high current stress on the device.
3) Robustness against interference and insensitivity to noise, such as transient overcurrent caused by diode recovery.
4) Capable of operating normally under fault conditions such as FUL and HSF.
5) Cost-effective and easy to implement.

Many researchers have extensively explored IGBT SC protection, including SC testing methods, detection technologies, and shutdown strategies [20], [89]. Therefore, this section introduces IGBT SC protection technology to deepen the understanding of SCs, thereby helping for better usage of IGBT devices.

A. Detection Technology

1) Desaturation Detection: Desaturation detection is widely employed in integrated IGBT drive chips and is effective in addressing the voltage division issues associated with series-connected IGBTs [90], [91].

Fig. 7(a) depicts the use of a diode for desaturation detection. In [92] and [93], the sensing diode monitors the voltage drop of the collector-emitter voltage V_{CE} during conduction, and then compared with a set threshold V_{th} to ascertain the presence of SCs in the IGBT. Upon detection of faults, the gate voltage is gradually and controllably decreased within a few microseconds, turning OFF the IGBT and thereby reducing the peak voltage on the collector.

Blanking circuits are employed in desaturation detection to prevent false triggering of SC protection at the moment of IGBT

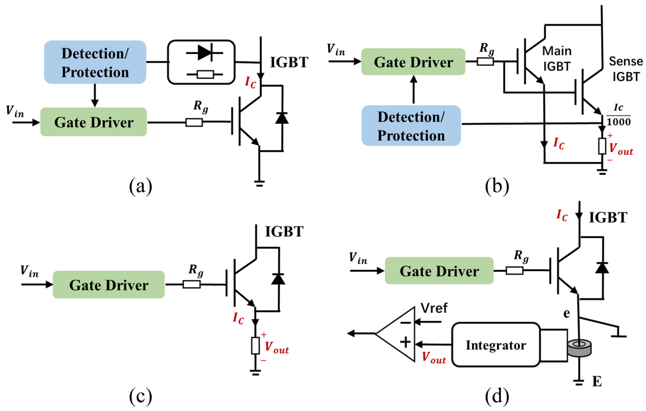

Fig. 7. Detection technology. (a) Schematic diagram of desaturation detection. (b) CM circuit. (c) Shunt resistor. (d) Rogowski coil sensing current.

turn-ON, and ensure that the collector current I_C drops to a low level before the protective mechanism operates. However, the design of the blanking circuit requires the consideration of different gate resistances and junction temperatures, which limits its adaptability. In [94], [95], [96], and [97], an adaptive blanking circuit utilizing the status feedback of V_{CE} and V_{GE} is designed to optimize performance. While employing multiple diodes can help to reduce the triggering threshold, this strategy could have some drawbacks. Specifically, an excessive number of diodes might cause uneven voltage distribution, which can potentially harm the circuit or diodes themselves [98].

2) Collector Current Transient dI_C/dt: There exist parasitic inductances between the Kelvin emitter and the power emitter, and induced voltage across the parasitic inductance under faults lasts much longer than that generated during normal switching. Therefore, measuring the induced voltage V_{Ee} across the parasitic inductance can effectively detect transient fault currents. The schematic diagram of dI_C/dt detection is shown in Fig. 5(b). Compared to using external sensors, measuring the voltage across the emitter's parasitic inductance to gain dI_C/dt is more cost-effective and simplifies the circuit [99], [100].

In [101] and [102], the detection circuits combining both V_{CE} and dI_C/dt monitoring can effectively and quickly identify faults and reduce the false alarm rate when no blanking circuits are present. Additionally, an automatic time constant matching method is designed in [103] to achieve adaptive and continuous measurement of I_C.

3) Gate Voltage V_{GE}: Under fault conditions, V_{CE} impacts the gate voltage through the Miller capacitance, thus measuring the V_{GE} can reflect the fault states [104], [105] and enabling early detections [106].

In [107], [108], and [109], novel overcurrent detection methods based on the characteristics of the gate voltage waveform are proposed. These methods, which involve monitoring the gate voltage, allow for the simultaneous detection of both HSF and FUL. The operating principle is grounded in the behavior of gate voltage during different states. Specifically, when SC occurs during the turn-ON transient, the gate voltage of IGBT will lose the Miller effect. Conversely, when SC occurs during the conduction state, the gate voltage of IGBT will increase. Besides, rapid fault detection can also be achieved by monitoring the gate charge and comparing it with a set threshold [110], [111].

In [112], the behaviors of dI_C/dt and V_{GE} are monitored simultaneously, which are significantly different under SC conditions. The aim of this method is to expedite detection.

4) Collector Current I_C: Various methods are available for monitoring the collector current I_C. One approach involves utilizing a CM circuit, which is based on the structure of the IGBT device [113]. Alternatively, some methods rely on external monitoring components like shunt resistors and current sensors [50], [91], [114].

a) CM circuit: The CM circuit is derived by integrating a sensing IGBT into the main IGBT. As depicted in Fig. 7(b), a sensing IGBT carries a proportionally reduced current (mirror current) of the main IGBT, typically at a ratio of 1/1000. Consequently, when the mirror current is generated, the voltage drop across a known resistor is minimal, facilitating fault detection [88], [113]. Intelligent power modules commonly employ this method for fault detection, with the additional incorporation of a temperature sensor.

A combined full-gate chip with sensor emission was proposed by Mitsubishi in 2017, aiming to enhance system performance and ensure that the overall EMI remains within acceptable limits [115]. This innovation is based on the use of a CM circuit to detect the instantaneous value of the collector current, and it provides feedback signal for the next conduction process [116].

b) Shunt detection: Shunt detection often relies on linear components such as resistors and coaxial shunts in the emitter. The schematic diagram of the shunt resistor is shown in Fig. 7(c). Under fault conditions, the fault current flowing through the resistor can induce a proportional voltage drop, thereby obtaining accurate measurements without delay [88], [95]. In [117], the problem of effective resistor selection under variable conditions is explored to facilitate current sensing. Meanwhile, in [118], a suitable resistor to the external emitter of the IGBT is introduced, which is utilized to adjust the operating point of the IGBT in the active region during SC, thereby effectively controlling the system current.

c) Current sensors: Current sensors, such as current transformers, Hall effect devices, and Rogowski coils, are prevalently utilized for current measurement [88], [113], [114]. Both current transformers and Hall effect devices require a magnetic core, which results in heavier current sensors and increased circuit size and cost [119], [120], [121]. The Rogowski coil is a nonmagnetic loop coil similar to an inductor, and it exhibits detection errors for dc components, making it primarily suitable for measuring alternating currents [99], [122], [123]. The schematic diagram is shown in Fig. 7(d). In [103], a method for measuring output current with a miniaturized printed circuit board (PCB) current sensor is proposed, making it possible to install a PCB current sensor based on Rogowski coils inside the IGBT module.

As high operating temperature of the IGBT can cause a drift in the sensor's output signal, consideration of thermal effects is crucial when selecting a detection method to achieve the best performance. For example, the shunt resistor is one

TABLE III
IGBT SC Detection Methods

Methods		Delay time (detection)	Advantages	Disadvantages	Temperature effects
Desaturation	Convention	HSF≈ 2.329μs; FUL≈ 1.3μs [97]	Simple circuit, low cost	Need blanking circuit and isolator	Sensitivity to the thermal characteristics of the IGBT [127]
	Adaptive blanking	HSF≈ 294*ns*; FUL≈ 35.3*ns* [97]	Accelerated detection	Not implemented in hardware	
Collector current transient		HSF≈0.6μs [124]	Fast measurement, easy integration	Heavily affected by parasitic inductance	Less affected by slow changes in temperature
Gate voltage		HSF≈0.6μs; FUL≈ 0.5μs [112]	Fast detection	Complex circuit	High ambient temperatures can lead to measurement inaccuracies
Collector current	Current mirror	≈0.1μs [113]	Simple principle, easy design	High cost	Good performance in a stable temperature range
	Shunt resistor	HSF≈380ns; FUL≈1.4μs [125]	High measurement accuracy	Large loss, increased inductance, high cost	Heat generation due to power loss at the resistor [126]
	Hall effect device	—	No blinding circuits	Low precision	Good accuracy and performance in a wide range of temperatures [128]- [130]
	Current Transformer	—	Transformer isolation, accurate ac sensing, high noise immunity	Poor dc measurement, lower bandwidth, large mounting area	
	Rogowski Coil	HSF≈ 0.5μs FUL≈1μs [99]	No saturable core, low inductance	No dc response lossy in integrator	

of the mainstream methods for current detection in industrial applications, but due to heat generation from its structure, it is not suitable for measuring large currents [126]. A common approach to minimize temperature drift is to design a temperature compensation circuit [127], [128]. Magnetic field detection methods, like current transformers and Hall effect devices, maintain stable performance despite temperature fluctuations [129], [130]. Table III summarizes the strengths and weaknesses of different detection methods. As the requirements for detection performance continue to increase, modern gate drivers can implement more optimized sensing strategies and improve reliability without increasing efficiency costs [131], [132].

B. Turn-OFF Strategies

When abnormal signals are detected, it is urgent to promptly turn-OFF the IGBT. However, utilizing hard turn-OFF methods could induce high overvoltage upon turn-OFF, potentially damaging the IGBT. Although the use of RC and RCD snubber circuits can reduce the dI_C/dt, thereby reducing voltage spikes during IGBT shutdown [133], it inevitably leads to substantial increases in system size, cost, and loss. Therefore, to effectively manage the shutdown speed and prevent overvoltage, soft shutdown techniques are commonly employed [20], [50], [102], [134]. The two common methods are as follows.

1) Large Resistance Shutdown: Upon detection of an SC signal, the employment of a larger shutdown resistor can slow down the rate of current decline, subsequently lowering the peak voltage [135]. However, although this method effectively suppresses overvoltage, it also increases the shutdown delay time and power loss, and may cause the IGBT to fail to turn-OFF within the limited time.

2) Active Clamping of Gate Voltage: During the turn-OFF process of the switching device, the voltage is initially controlled at a lower level, keeping the gate current at a relatively low state. After a certain delay, the SC current is shut down, thus preventing the large voltage overshoot [99], [135], [136]. Implementing a soft turn-OFF via the active clamping of gate voltage method necessitates the consideration of several factors, including voltage stability, switching speed, and noise suppression, which results in a relatively complex circuit structure.

The control unit plays a vital role in the implementation of soft shutdown technology. For example, it can modify the control algorithms to change the timing of the soft shutdown [101]. Furthermore, by adjusting signals of the switching devices, it can control the rate of change in both current and voltage [95].

V. Conclusion

As power electronics continue to evolve toward enhanced intelligence, integration, and stability, the design of gate drive and protection circuits with more constraints on efficiency, cost, and safety becomes increasingly crucial. This article presents a comprehensive discussion on the principles and characteristics of various gate drive methods, and further explores the latest developments in self-adaptive driver for IGBTs. Simultaneously, we overview the SC detection methods and SC shutdown technology for IGBTs, supplementing with some novel SC protection strategies that are not discussed in existing reviews. Clearly, intelligent gate drivers equipped with adaptive features and a high level of integration can greatly improve not only the accuracy of control operations, but also the effectiveness of warnings for aging and other fault conditions.

To meet the needs of IGBTs in different applications, the future research topics concerning IGBT drive and protection circuits primarily involve the following aspects.

1) *Increased robustness and reliability:* Given the often-harsh operating conditions of IGBTs, driver and protection circuits must be designed with high levels of robustness and reliability. This might involve using advanced design techniques to improve the circuit's tolerance to factors such as temperature variations, voltage transients, and EMI. Furthermore, the inclusion of intelligent features, such as self-adaptive control, fault detection, and

predictive maintenance, increases the complexity of the driver design. Managing this complexity while ensuring the robustness and reliability of the drivers can be a significant challenge.

2) *Intelligent condition monitoring and management:* At present, increasing effects are devoted to enabling adaptive health monitoring and diagnostics of power electronics and their packages. Detailly, predictive monitoring mechanisms can be integrated into the circuit to provide early warnings of potential issues, allowing for preemptive actions to be taken to avoid catastrophic failures. This can drastically improve the overall reliability and longevity of the IGBTs. Additionally, most of the existing state monitoring systems focus mainly on fault detection and diagnosis, with less attention on fault prediction and health management. This is a significant direction to develop more advanced algorithms and technologies to predict faults and provide health management schemes to extend the lifespan of the devices.

3) *Drivers for third-generation semiconductor devices:* Compared with traditional silicon devices, novel power devices made by silicon carbide and gallium nitride possess superior advantages, including higher energy efficiency, improved frequency response, and increased operating temperature range [47]. Due to their unique electrical characteristics, such as rapid switching, high voltage, and robustness against breakdown, it is necessary to investigate more comprehensive gate drive and protection strategies to fully harness the vast potential of these power devices.

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