Status and Trend of High Power IGBT Gate Drive Technology

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Abstract. High voltage and high current IGBT power modules are widely used in many fields. The gate drivers play important roles in ensuring safe, efficient and reliable operation of IGBT power modules. Based on the comparative analysis of existing products from domestic and foreign mainstream gate driver manufacturers, this paper analyzes and collates the main functions and different technical paths of IGBT gate drivers. By comparison, conventional analog drive method exists inherent defects, and digital drive method is the direction of future development. In this work, the system structure and main working principles of digital drivers are analyzed. Key technologies and development trends of the gate drivers are summarized, which lays the groundwork for further improving the efficiency, reliability and intelligence of IGBT power modules.

Keywords: IGBT · Gate drive · Digital drive · Parameter extraction · Failure analysis · Condition monitoring

1 Introduction

High power IGBTs play important roles in power conversion and energy transmission, and have been widely used in traction electric transmission, power transmission and conversion, active filtering and other power electronics fields. As the hub between the controller and the power module, the gate driver is the basis to ensure the normal switching on, off and safe operation of IGBT, and the key point to determine the reliable, stable and efficient operation of the traction electric power system of rail transit [1–3]. High performance IGBT gate driver can reduce switch delay and switch loss, so that IGBT can have a good switching performance. In the event of overcurrent or short circuit fault, the gate driver can also make quick protective actions, to avoid exceeding the thermal limit, occurring the holding effect and exceeding the device voltage. So that the reliable and safe shutdown of IGBT can be ensured [4, 5].

With the progress of technology and the intensification of market competition, more stringent requirements are put forward on the cost, efficiency, reliability and electromagnetic compatibility of power electronic equipment, and new demands are generated for gate drivers. The development direction of digitalization has been affirmed by the industry [6]. In this work, the characteristics of IGBT gate drive products from domestic and foreign mainstream manufacturers are summarized firstly. Then the main working principles of active gate drive are analyzed. Finally, the statuses of key technologies of gate driver are analyzed and its development trends are described.

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2 Development Status of IGBT Gate Drivers

2.1 Power Integration (Concept)

Swiss Concept Company has been committed to the development of IGBT gate drivers for 30 years. It has a number of patents, and is widely recognized in the international market. In 2016, it was acquired by Power Integration to become the global technology and market leader in the field of medium and high-power drivers. Using its unique, highly integrated Scale technology, the driver uses 85% fewer components than other common drivers. As shown in Fig. 1, the gate drive IC, drive core and plug and play driver can be used for high-power and high-voltage IGBT power modules with voltage between 600 V and 6500 V, and possess a variety of protection, active clamping, power monitoring, soft start and other functions, even can be suitable for driving high switching frequency wide band gap semiconductor devices.

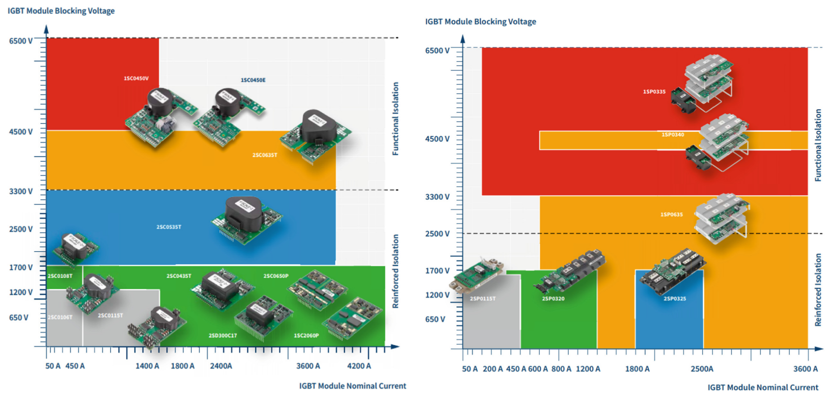


Fig. 1. SCALE-2 and SCALE-2+ gate drive core series products. SCALE-2 plug and play gate drive series products.

2.2 Inpower

InPower has nearly 20 year's history in supporting challenging applications. Its gate drive units are successfully deployed in transportation (traction), power generation (wind and solar power), power transmission (HVDC), industrial power supplies, industrial drives and induction heating. Inpower persists in the digital drive technology route, using digital control IGBT gate driver, combined with intelligent switch and the best classification protection. Through software programming to change the operating characteristics, it opens up a road for high reliability and low switch loss.

IPS-Driver is the representative product of Inpower. Its technical features include: all functions defined by software are realized based on programmable digital control technology; Through digitally adjustable gate resistance and continuous acquisition of di/dt, gate current and switching characteristics can be optimized, drive capability can be enhanced and switching losses can be reduced; Digital filtering technology ensures that unwanted signals will not affect the whole system; All parameters can be easily changed through interchangeable files, and users do not need to learn any software programming skills for this optimization; It has enhanced protection functions, including four-stage threshold digital desaturation protection, two-stage di/dt protection, active clamp and multi-step soft shutdown, etc. This digital technology has strong advantages in terms of reliability and flexibility.

2.3 Infineon

Infineon gate drivers offer a range of typical output current options from 0.1 A to 10 A, suitable for any power device model. Quick short circuit protection, programmable dead time, direct short circuit protection, active turn-off and other comprehensive gate drive protection features make these drivers suitable for all power devices including CoolGantM and CoolSiCTM. Infineon gate drivers also feature more advanced features such as integrated bootstrap diodes, enabling, fault reporting, input filters, OPAMP and DESAT protection. Active Miller clamp, and separate pull/charge current output pin functions also help improve design flexibility. Infineon EiceDRIVER™ series gate drivers offer advanced features such as programmable dead time, direct circuit protection, active Miller clamp, active turn-off, short circuit current clamp, soft turn-off and two-level turn-off, making it easier for customers to drive all power components and power modules (Fig. 2).

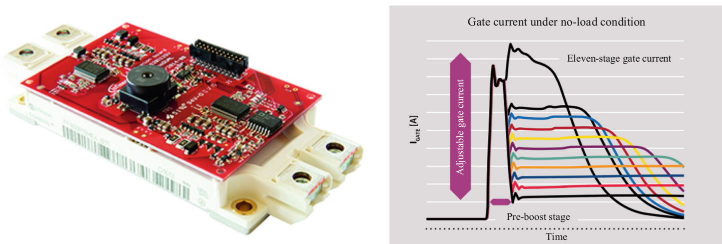


Fig. 2. 1EDS20I12SV real-time gate current control.

2.4 Amantys

The main product of Amantys is a highly reliable gate driver with condition monitoring function. The company's mainstream products feature the following technology: remote modification of configuration gate resistance value, key parameters of on-line real-time state monitoring power device, enhanced protection function (three-stage threshold desaturation protection, two-stage threshold active clamp, active feedback clamp, multiple soft shut-off with fast first-type short circuit protection). Amantys is developing a new driver technology called AdaptiveDrive, which is a flexible active gate control technology based on $\mathrm{d}i_C/\mathrm{d}t$ and $\mathrm{d}v_{CE}/\mathrm{d}t$ sampling. The process of switching on and off is divided into several stages, and the gate current of different stages can be controlled flexibly by programming, so as to reduce the loss under the premise of ensuring the fast and safe operation of IGBTs.

2.5 Bronze Technology

Bronze Technology was founded in 2009 by the doctoral team from Tsinghua University and Cambridge University. It used analog drive technology route, focusing on the development of drive core, such as the development of 2QD30A17K on the basis of 2SC0435T Concept company as an alternative version. On the basis of the drive core, the models of 2QP0115TXX-C, 2QP0320T/VXX-C and 1QP0635V33-C plug-and-play drives are developed, which are specially designed for Econodual3, PrimePACK3 and 3300V IHM-B packaged IGBTs, fully compatible with PI 2SP0115T, 2SP0320, 1SP0635, with a complete isolation of DC/DC power supply, driving power undervoltage protection function, saturation detection short circuit protection function and active clamp overvoltage protection function.

2.6 Firstack Technology

Hangzhou Firstack Technology Co., Ltd. is committed to intelligent IGBT driver. It optimizes the IGBT driver configuration for different working conditions, expands the working conditions boundary of the module, improves the module utilization and reliability, so as to meet the diversified needs of customers. Firstack integrates the reliable hardware circuit and the intelligent fault management algorithm, realizing the "not broken" driver, "communication" driver, contributing to power converter high long-term reliable operation and digital management. Its products have large-scale application in the new energy, ship propulsion, power system, high power traction, and many other harsh fields.

3 Main Working Principle of Active Gate Drive

3.1 Main Assembly

The main function modules of IGBT digital drivers are sorted out, which can be divided into five parts: power supply circuit, drive circuit, protection circuit, signal sampling circuit and logic control circuit. Its general functional block diagram is shown in Fig. 3.

3.2 Principle of DC/DC Circuit

As the connection between the control end and the power end, power supply of the driver directly affects the stability of the system. The application environment of high-power IGBTs is relatively complex, which requires that the power supply should have high isolation level and wide input voltage range. Moreover, IGBT takes into account the advantages of MOSFET and BJT, and its driving power is very small (generally several watts). Therefore, the switching power supply can be used to provide power for the gate

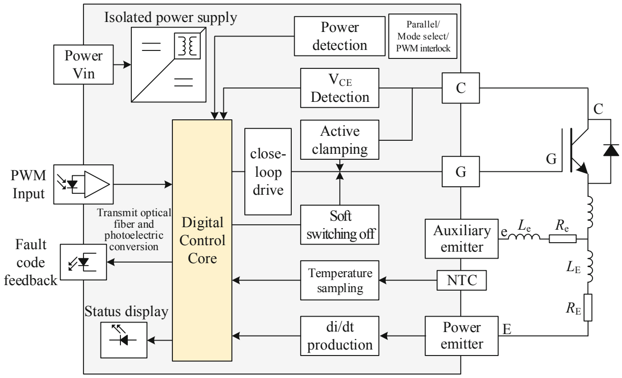


Fig. 3. The general functional block diagram of IGBT digital drivers.

drive. The auxiliary voltage provides DC power for the users, after the DC/DC converter isolation transformation to provide power for the secondary gate drive. The structure of commonly used transformer isolation type DC/DC converter includes forward, back, push pull, half bridge and full bridge.

Take the push-pull converter scheme for example, and its typical circuit is shown in Fig. 4. There are two switches, Q_1 and Q_2, which alternately turn on to generate alternating voltages at both ends of the windings N_1 and N_1', respectively. When Q_1 is on, the diode VD_1 is on; When Q_2 is on, the diode VD_2 is on; When both switches are off, VD_1 and VD_2 are in the on-state at the same time, each bearing half of the current; When one of Q_1 or Q_2 is on, the current through the inductor L will gradually increase, and when both switches are off, the current through the inductor L will gradually decrease. Both Q_1 and Q_2 withstand a peak voltage twice that of V_{in} when they are turned off. But if the switch Q_1 and Q_2 conduct at the same time, this is equivalent to short circuit in the primary side of the transformer, upper and lower bridge arm straight, which will cause damage to the switches. So it is necessary to prevent the two switches conducting at the same time. In practical applications, the duty ratio of each switch control signal is usually less than 50%, and a certain margin is reserved.

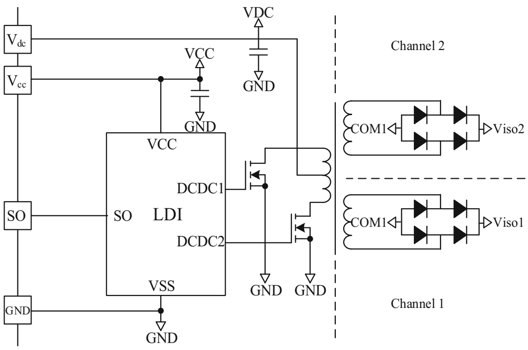
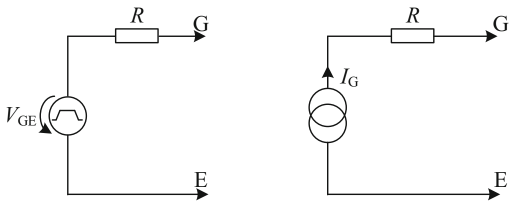


Fig. 4. Principle circuit of typical power supply.

3.3 Principle of Driving Circuit

IGBT is a voltage-controlled switching device. The switching on process of IGBT can be regarded as the charging process of the gate capacitor, and the switching off process can be regarded as the discharge process of the gate capacitor. According to the different structures of the gate driver, they can be divided into two forms: voltage control drive and current control drive.



a) voltage control b) current control

Fig. 5. Two control forms of gate drive.

Voltage controlled drive is the most commonly used drive mode at present. As shown in Fig. 5a), the charging and discharging of the gate capacitor can be controlled by the gate voltage and the gate drive resistance with appropriate resistance value, or different drive resistors can be used to control the opening and closing of IGBT respectively. Current controlled drive is a direct connection at the gate to a current source that can output both positive and negative current. As shown in Fig. 5b), in this method, current is injected into the gate through the current source during the IGBT opening process, and current is extracted from the gate through the current source during the shutdown process, so as to realize charging and discharging of the gate capacitance.

Two control methods have common disadvantages, the tolerance of MOSFET or IGBT gate capacitance will affect the switching time and switching loss of the transistor. In practical application, the drive structure is often used for voltage control, compared with current control, its advantage is that the power loss is on the gate resistance, rather than in the driving current source, and the structure and control method is relatively simple.

The traditional gate drive method controls the switching speed by changing the gate drive resistance, and the switching speed of the device can be controlled by changing the gate drive voltage, but it affects the on-off characteristics of the device and increases the on-off loss, which is not conducive to the overall performance optimization of the device. The limitation of the traditional gate drive determines that it is not suitable for the applications where the system requires high reliability, the control response is fast and the working state is frequently switched (Fig. 6).

By adopting digital control IGBT active gate driving mode and changing operation characteristics through software programming, the driving resistance can be switched between mΩ level and high resistance within ns level, and the balance optimization between turn-on loss and reverse recovery current can be realized, as well as the balance optimization between turn-off loss and turn-off voltage peak can be realized. In addition,

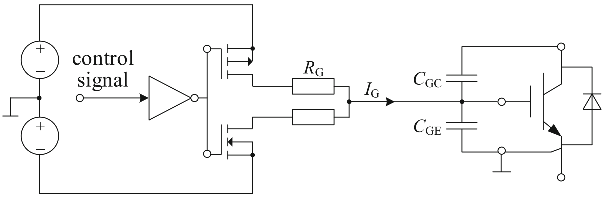


Fig. 6. Traditional gate drive mode.

the digital technology has greater advantages in terms of reliability and flexibility, all parameters can be easily changed in an interchangeable file, and the user does not need any complex operation to achieve this optimization.

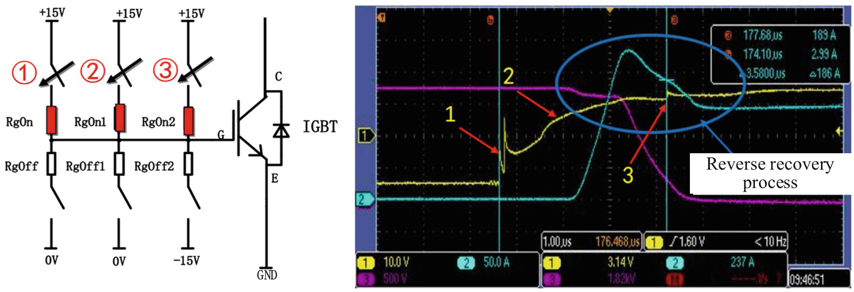


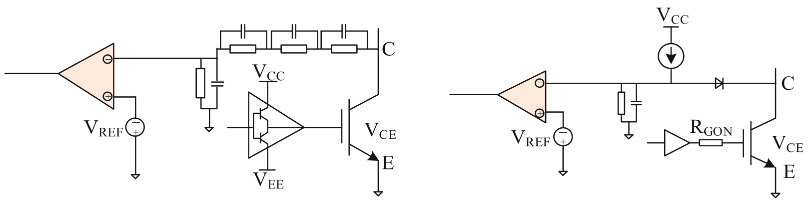
Fig. 7. Active gate resistor array drive mode – turn-on dynamic process.

3.4 Short Circuit Protection Principle Based on V_{CE} Detection

Under normal operation, the IGBT operates at saturation, which means that the voltage between the collector and emitter has dropped to a saturated value, V_{CEsat}. However, if the load I_C increases to more than four times the rated value, the IGBT will drop out of saturation, that is, the set-emitter voltage will rise, eventually reaching the DC bus voltage, V_{DC}. Therefore, a dynamic collector - emitter voltage (V_{CE}) detection circuit is installed in the gate driver to determine whether the IGBT is in short circuit by detecting the V_{CE} when the IGBT is turned on. There are two main methods for driver detection V_{CE} to enter the desaturation area, one is through resistance-capacitance partial voltage detection, the other is through diode detection (Fig. 8).

1) Resistance-capacitance partial voltage detection.

   Figure 7a) is the V_{CE} desaturation detection circuit which uses the resistance and capacitance partial voltage method to detect IGBT short circuit. It uses the resistance voltage to measure the collector voltage of IGBT. When IGBT short circuit occurs, the IGBT exits the saturated area, the collector voltage increases, and the partial voltage value on the corresponding resistance also increases proportionally. When its value is higher than the comparison value set by the comparator, the comparator reverses and sends a signal to turn off the IGBT.



a) Resistance-capacitance partial voltage detection b) Diode detection

Fig. 8. V_{CE} desaturation detection circuit.

2) Diode detection.
   Figure 7b) is a diode-type desaturation detection circuit, which uses the reverse blocking characteristic of the diode to detect the voltage between collector emitter terminals and compares it with the preset reference voltage. If the value exceeds, a fault signal will be sent to the control unit and the IGBT will be controlled to turn off quickly.

4 Key Technology of Gate Drive and Its Development Trends

Based on programmable control unit, the IGBT intelligent digital driver can set up the digital filtering and digital timer through software control, to realize adjustable door open/close off resistance, multilevel digital desaturation over-current protection, two level di/dt protection and active feedback clamping, multiple soft shut off, and other functions. It can cover all kinds of IGBT power modules and different applications, and provides a variety of algorithms for IGBT protection. Meanwhile, the integrated intelligent digital drive IGBT junction temperature monitoring, $V_{CE\text{-}sat}$ voltage high speed and high precision sampling function. Based on these, more kinds of fault can be identified, and based on the IGBT life model, the status monitoring algorithm can be realized, and maintenance advice can be provided for upper advice, improving the system safety, reliability and intelligent level.

4.1 High Precision IGBT Parameter Online Extraction Technology

At present, a very important development direction of power electronic converter technology is intelligence, medium and high voltage, large capacity, high power density, high maintainability and high reliability. Among them, high reliability is the most basic and important performance index that the power electronic converter system needs to achieve. According to the survey of the industry, nearly one third of the faults of power electronic converter system are caused by the damage of power electronic devices, especially the failure caused by over-voltage breakdown, so it is very important for the on-line monitoring of power device voltage [7].

Digital gate driver uses digital circuit as the core, and uses part of analog circuit as the assistant. The analog circuit is mainly to detect and adjust IGBT port power signal (u_{CE}, du_{CE}/dt, u_{Ge}, i_C and di_C/dt), after high-speed A/D collection they are sent to FPGA for calculating, storage and uploading. The measurement of transient collector voltage in IGBT turn-off is the basis of IGBT drive feedback control and overvoltage protection for digital drivers. The high precision measurement of saturation voltage during IGBT turn-on has an important reference role for IGBT fault protection such as short circuit and overcurrent and IGBT state recognition. In addition, the IGBT collector voltage data uploaded by the digital driver lays a foundation for the realization of DC bus voltage estimation and transducer less control of the converter. Combined with collector current, on-line estimation of IGBT junction temperature and life prediction can be carried out, and possible faults can be protected in advance, so as to improve the reliability of converter system. However, there is a big difference between the blocking voltage and the saturation voltage when IGBT is turned off, and the requirements for measuring circuit accuracy are also different under the two states [8]. At present, IGBT turn-off voltage often up to thousands of volts, which requires IGBT collector high voltage measuring circuit can withstand the corresponding voltage level; When IGBT is conducting, the saturation pressure drop is only a few volts, and the measurement accuracy is required to be 10 millivolts, so as to judge whether IGBT is overcurrent fault according to the saturation pressure drop, and realize the status identification, life prediction and on-line estimation of junction temperature of IGBT. As can be seen from the above, the IGBT collector voltage measuring circuit needs to break through the difficulties of wide measurement range and high low-voltage measurement accuracy.

4.2 Fault Identification and Protection Diagnosis Technology

Semiconductor power device driver generally has a protection and fault feedback function, for a complex electrical energy conversion system, its protection function should be very perfect. Ideal driver is to be able to give full play to the potential of power semiconductor devices, and fully protect the power semiconductor devices, making they are not damaged in all sorts of circumstances. But in the process of practical application, there is a certain difficulty, because the existing hardware circuit can't distinguish power component whether is really happened in normal working condition or fault. Assume that the threshold or testing time delay is set too high, once the real fault appears, gate drive can't turn off power device fast enough, causing damage to the device. And in some cases, there are safety risks and the power device health status can't be assessed, due to the cause of the failure cannot be located. On the other hand, the driver needs to provide comprehensive and effective power protection, short circuit protection, overvoltage protection, overtemperature protection, etc., and there are some difficulties in the design and implementation of signal sampling and processing, active clamping, hierarchical turn-off and timing management. Therefore, recent researches focus on collection of on-line monitoring and fault analysis for the integration of a new generation drive circuit, replacing the traditional drive circuit, improving the warning efficiency of controller for semiconductor device electrical damage, over-temperature, aging, and other failures. Thus contributing to quickly locate fault and analysis of incentive, further improve the system safety and reliability and intelligent level.

4.3 IGBT Status Assessment and Life Prediction Techniques

According to statistics, about 55% of the reasons for failure of electronic devices are caused by overheating and heat-related problems. Overheating will bring a series of effects on power electronic devices. Obvious temperature fluctuations will lead to fatigue fracture of packaging components or materials. Temperature changes will lead to changes in the properties of materials, and the resulting capacitance and impedance changes will affect the transmission characteristics of electrical signals.

The failure of IGBT is a complex process related to its dynamic characteristics, involving electrical, thermal, mechanical and other factors. Binding leads, binding points and solder layer packaging structure are the most vulnerable parts of IGBT, so its failure is mainly determined by the ability and strength of binding leads, binding points and solder layer to withstand thermal stress and deformation.

To summarize the analysis of IGBT reliability, there are mainly three methods: test testing, life prediction and reliability evaluation. It is difficult to effectively evaluate the reliability and state of IGBT in practical devices. Many foreign literatures have studied the failure mechanism of IGBT. Current state monitoring and reliability evaluation methods of IGBT can be summarized as: sensor-based condition monitoring and evaluation method, condition monitoring and evaluation method based on device surface end characteristics and evaluation method, and model-based state monitoring and evaluation method, etc.

5 Conclusion

The IGBT gate driver plays an important role in railway transport equipment. This paper summarizes the main functions and working principles of the digital driver through analyzing both foreign and domestic gate driver products. And the future development trend of digital driver is put forward, especially in high precision IGBT parameter online extraction, fault identification and protection diagnosis, and IGBT status assessment and life prediction.

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