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An Enhanced Dynamic Collector Voltage and Current Clamping Method for Semiconductor in Electric Vehicles

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ABSTRACT- The electric drive and the batteries are the two primary parts of an electric vehicle (EV). In order to increase the availability and dependability of the semiconductors used in traction converters, this research focuses on a new approach of semiconductor protection. The IGBT overshoot in voltage during a short circuit situation was successfully reduced by a newly created active voltage and current clamping circuit. This innovative method restricts IGBT's collector-emitter voltage during the turn-off event. As soon as the collector-emitter voltage of the IGBT crosses a predetermined threshold, the IGBT is partially turned on. The IGBT is then kept operating linearly, minimizing the rate at which the collector current falls and, consequently, and the collector-emitter over voltage. Simultaneously, during the short circuit, the current is monitored by a high precision hall-effect sensor allegro make IC, which detects over current and provides a fault output within 1µs. As a result of the combination of current and voltage monitoring, the likelihood of the IGBT failure is reduced drastically.

Keywords: Dynamic (active) voltage clamp, Current clamp, IGBT, Reliability, EV (Electric Vehicle), VCE (collector-emitter voltage), TVS (Transient Voltage Suppressor)

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1. INTRODUCTION

Electric vehicles (EVs) have gained recognition as the most eco-friendly transportation option, primarily due to their emission-free nature, emitting no CO2 [1]. The automotive industry as a whole is actively engaged in the development of EVs, with several already available on the market. To meet the demands for performance, the power output of EV motors now exceeds 100 kW [2].

One of the key factors contributing to their exceptional performance, including power density, switching frequency, energy efficiency, and cost-effectiveness, is the widespread utilization of insulated gate bipolar transistor (IGBT) power modules in various high-voltage and high-power applications, such as electric vehicles (EVs), wind turbines, smart grids, and industrial drives [3,4]. Ensuring the efficiency of power semiconductors is crucial for achieving cost competitiveness in EV inverter applications, as these components significantly influence almost half of the module's total cost.

Given their significance in the market, EVs cater to a wide mass audience that prioritizes both safety and cost efficiency. However, it is essential to address the vulnerability of semiconductors in the EVs' traction converter, as their failures could lead to sudden power or traction converter breakdowns, potentially resulting in severe accidents with human lives at stake [5].

In electric vehicles (EVs), semiconductor switches play a vital role in the power electronic system, serving as essential components responsible for controlling the flow of electrical energy. However, their lifespan is notably shorter than that of the overall drive system in the vehicle [6]. Due to this inherent characteristic, these semiconductor switches are regarded as "consumables." In other words, they are subject to wear and tear and need to be replaced multiple times throughout the system's lifespan or before the vehicle reaches a certain mileage or age, typically around 600,000 kilometers or 15 years.

This limited lifespan of semiconductor switches poses an important consideration for EV manufacturers and designers. It emphasizes the significance of optimizing the power electronic system to ensure efficiency, reliability, and overall performance throughout the vehicle's life cycle [7,8]. Three key aspects stand out in the evaluation of the power electronic system's performance in EVs:

Power Density: Power density refers to the amount of electrical power that the system can handle in relation to its size and weight. It is crucial to maximize power density in EV power electronic systems to ensure that the components can handle the required power demands while keeping the overall system compact and lightweight. High power density allows for more efficient use of space and resources within the vehicle, contributing to improved overall performance and range.

System Efficiency: The efficiency of the power electronic system directly impacts the energy consumption of the EV.

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Efficient power conversion ensures that minimal energy is lost as heat during the process of converting electricity from the battery to the motor, contributing to longer driving range and improved battery life. Optimizing system efficiency helps enhance the overall energy efficiency of the EV, reducing operating costs and environmental impact.

Reliability: With semiconductor switches being critical consumable components, their reliability is of utmost importance. A reliable power electronic system ensures that the switches operate consistently and without failure over extended periods. Improved reliability leads to reduced maintenance requirements and lower replacement costs, ultimately enhancing the overall lifespan and usability of the electric vehicle [7].
In conclusion, considering the limited lifespan of semiconductor switches in EVs, power density, system efficiency, and reliability are key focus areas for manufacturers and engineers to ensure the power electronic system performs optimally, contributing to a more sustainable and reliable electric vehicle driving experience.

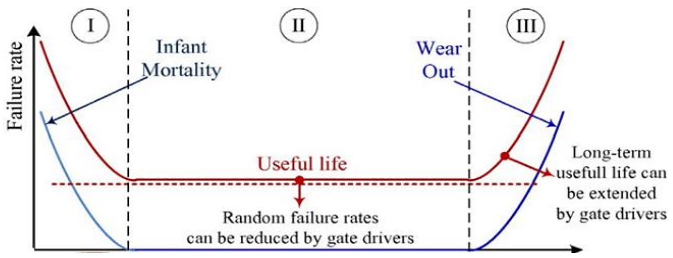

Figure 1. Paraent child hirarchy

In reliability engineering, the classic bathtub curve of semiconductor device showed in *figure 1* represents three stages of failures. The failures can be divided into three main stages: early failure, middle random failure and the wear-out failure period. The random failures rates and long-term wear out can be detected by the IGBT gate driver protective functions. *Table 1* shows the typical failure modes of IGBT, and major failure observed in operating device outside safe operating area.

Table 1. Typical Failure modes of semiconductor modules

Sr.No	External Abnormalities	Cause	Device failure mode
1	Short Circuit (Arm Short circuit, output short circuit, Ground short circuit)	Logic circuit malfunction, less dead band, Load short circuit or wrong wiring	Outside SCSOA
2	Overload	Over current protection error OR logic circuit malfunction	Overheating
3	Collector over voltage	Excessive input voltage, Failure of sensing circuit OR	C-E Over Voltage
4	Gate over voltage	Static electric charge OR Volt- age spikes due to long length wire	G-E Over Voltage
5	Mechanical Stress	Stress from external wiring	Disconnection from circuit

2. CONCEPT OF DYNAMIC COLLECTOR VOLTAGE CLAMPING

Dynamic (Active) clamping is new technique to limit the collector-emitter voltage of an IGBT during the turn-off event. The IGBT is partially turned on as soon as its collector-emitter voltage exceeds a pre-defined threshold. The IGBT is then maintained in linear operation, thus reducing the fall rate of the collector current and therefore the collector-emitter over-voltage. In the event of an IGBT short circuit, all IGBTs no longer have to be turned off in a dedicated sequence to avoid excessive IGBT collector-emitter voltages. Instead, the active clamping function limits the maximum collector-emitter voltage of the IGBTs to a safe level, enabling the IGBTs to be simply turned off as soon as the fault condition is detected. *Figure 2* illustrates the arrangement of TVS Zener diodes for dynamic clamp.

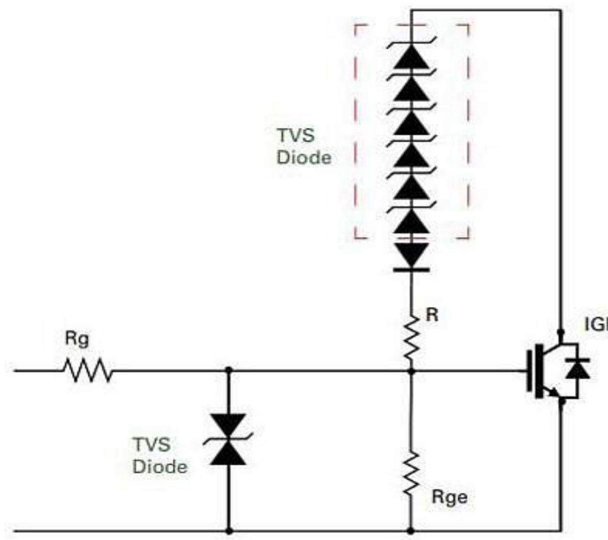

Figure 2. Dynamic collector voltage clamp using series connected Zener diodes

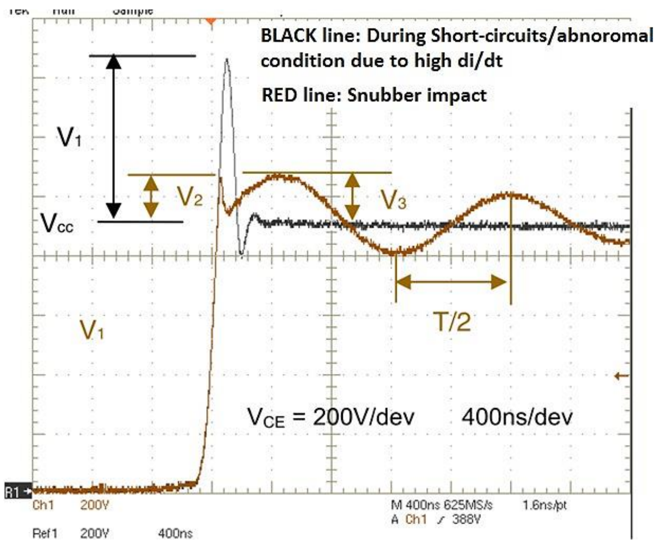

Figure 3. Switching characteristic during turned-off condition

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When the IGBTs are driven with a pulse that is shorter than the response time in the event of a short circuit, the fault is not detected, and the conventional driver turns off too quickly. Hence there are more chances of IGBT destroyed by the resulting over-voltage. The new technique focuses on improving the IGBT turn-off switching performance during the abnormal conditions. *Figure 3* shows a generic conventional turn off characteristic of IGBT. Dynamic performance of power semiconductor modules is determined by semiconductor characteristics and its gate driver reconfiguration. Gate driver's main responsibility is to guarantee semiconductors working reliably in their SOAs through its life.

Black line shows voltage V_1 across collector-emitter during short circuit condition. Red waveform shows the ringing due to LC resonance. So, it is trade-off between high values of snubber capacitor to reduce Vce overshoot.

$$V_1 = \sum \text{Ldc-link x di/dt}$$

Where,
Ldc-link = Lc + Ls + Lsnubber,
Lc = Module parasitic inductance
Ls = Stray inductance of laminated busbars, Lsnubber = Snubber capacitor series inductance

In this method the TVS (Transient Voltage Suppressor) chain is used to clamp the voltage across IGBT during short circuit scenarios. The selection of TVS is done in such way that the total breakdown voltage of TVS chain is less than rated voltage of IGBT.

While the collector current clamping achieved by measuring collector current with the high accuracy hall-effect Allegro make on-board current sensor ACS37002LMABTR. It is a fully integrated Hall-effect current sensor in an SOIC package that is factory-trimmed to provide high accuracy over the entire operating range without the need of any programming. A fast overcurrent fault output provides short circuit detection for IGBT protection with a fault threshold that is proportional to the current range and can be set with an analog input. This is fault feedback is within 1µs, which is much faster than any of the analog sensor.

This new technique of driving IGBT gives added advantage over conventional methods. See the *table 2*.

Table 2. Comparison table for IGBT protections

Protection	Conventional IGBT driver	Proposed IGBT driver
V_{CE} desaturation for short circuit protection	Yes	Yes
Soft turned-off after short circuit protection	Yes	Yes
Dynamic overvoltage protection	No	Yes
Dynamic overcurrent protection	No	Yes
Combined over voltage and short circuit protection	No	Yes

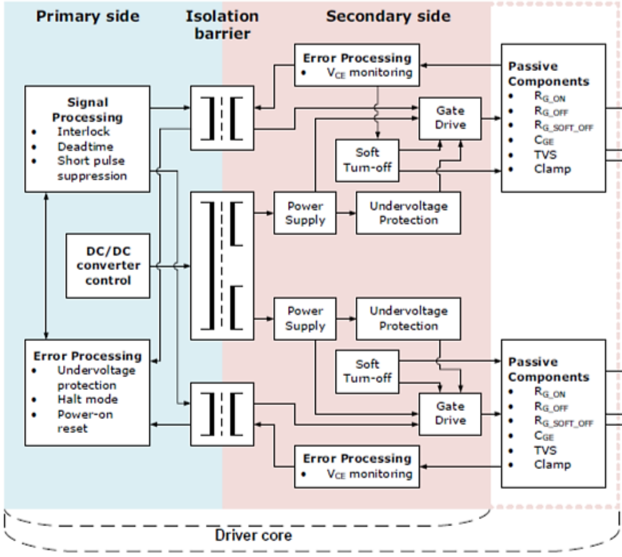

Figure 4. IGBT controller

3. EXPERIMENTAL RESULTS

The IGBT driver layout is design using ORCAD software, which has dead band generation circuit at the input. It is a two-layer PCB designed to drive IGBT up to the rating 1700V, 100A. Figure 4 shows the A modern two-channel driver circuit is constructed as in Figure 2 with the critical feature for safety being a clear delineation between primary (low voltage) and secondary (high voltage) sides. The controller is interfaced to the primary side, where logic provides short pulse suppression, interlock and/or dead time, and generally conditions the gating signals so that they can be transmitted across an isolation barrier. Additionally, an isolated power supply is needed to provide the positive and negative voltage rails that are used to turn the power devices on and off. Secondary side components include this as well as fast-acting protection feature dynamic voltage and current clamping.

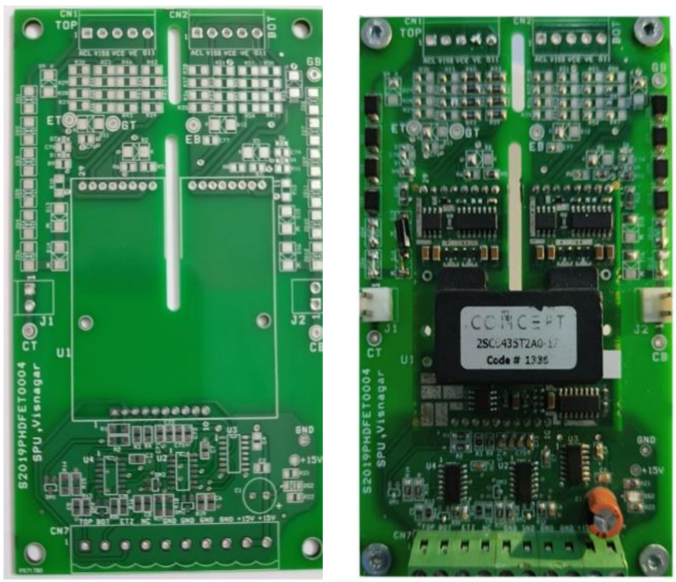

Figure 5. Hardware setup and bare PCB

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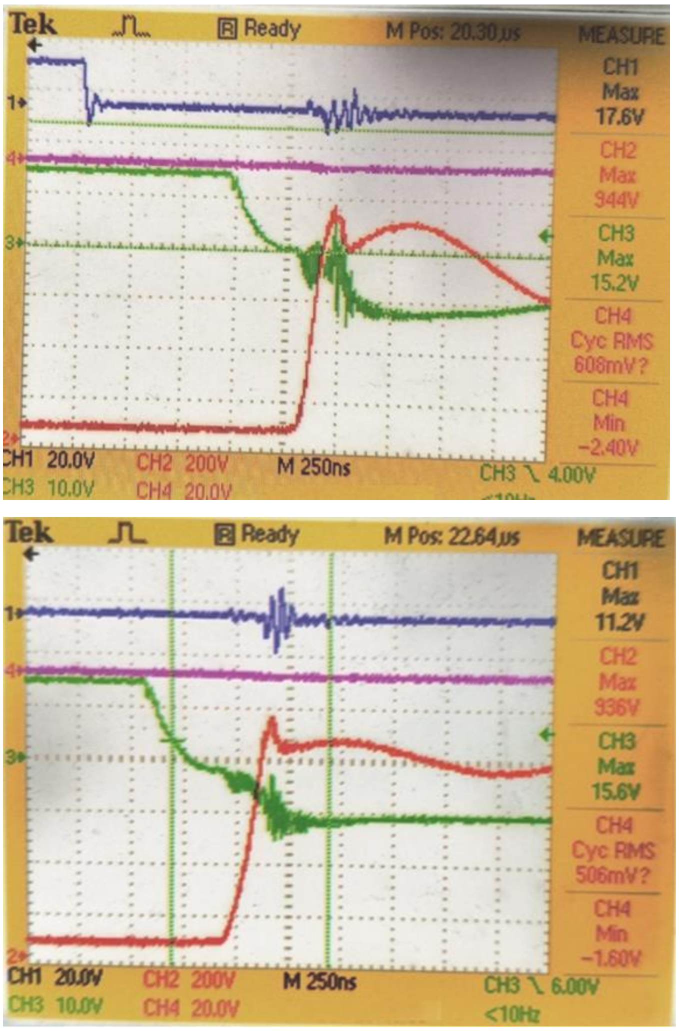

Figure 6. IGBT Collector voltage clamping

CH1 (Blue)	: Control side gate pulse
CH2 (Red)	: Vce (Collector emitter voltage of IGBT)
CH3 (Green)	: Vge (Gate emitter voltage)
CH4 (Pink)	: Vsat, IGBT saturation voltage

Figure 5 shows the dual IGBT driver hardware developed for IGBT SKM145GB176D. PCB is two layer and designed with low inductive path between the driver and semiconductor device. It is having the inbuilt feature of the deadband generation circuit at input which gives protection over the control malfunctions during the false pulsing. Also having the isolated DCDC converter which provides two isolated DC supply +15V/-7V for driving the high side and low side IGBT. It also has provision for adjusting the gate resistance to control the di/dt of switching.

Experiment carried out with conventional double pulse test method to using an external inductor to limit a fault or short circuit current. Gate pulse of IGBT gradually increased to reach the fault current limit. *Figure 6* shows the result waveform during the dynamic voltage clamping. It shows when the collector voltage Vce (Red) exceeds the predefined threshold which is sum of the breakdown voltage of all series connected Zener diode as shown in *figure 2*, then the gate signal Vge (Green) gets partially turn on to bring the collector voltage Vce down and protects the IGBT against the voltage overshoot caused by short circuit situation. Additionally, after detecting the short circuit gate signal Vge (Green) bring to the off condition with slower rate to avoid repeated voltage overshoot.

In similar way when Ic (collector current) increases beyond the threshold limit in normal as well as short circuit condition, the Allegro make hall-effect sensor gives the feedback to the driver in less than 1µs and IGBT driver stop the pulsing the IGBT. Thus, new driver gives combined protection the semiconductor against overvoltage during short circuit and overcurrent caused by any abnormal switching or load side faults.

4. CONCLUSION

The paper provides a comprehensive examination of dynamic collector voltage and current clamping in electric vehicle (EV) applications. This is achieved through the implementation of a gate driver with a dynamic turn-off transient control method, aimed at safeguarding the insulated gate bipolar transistor (IGBT) used in the system. The proposed method stands out due to its advantageous characteristics, including low cost, straightforward implementation, and high robustness, setting it apart from the state-of-the-art advanced gate drivers available. One significant challenge discussed in the paper relates to the correct selection of Transient Voltage Suppressor (TVS) components. The maximum clamping voltage (VC) of the TVS is considerably larger than the breakdown voltage, which poses difficulty during component selection. Breakdown voltage is specified within a wide tolerance range, making it challenging to precisely determine the ideal TVS component for the system. In summary, the paper introduces a novel approach for dynamic collector voltage and current clamping using a specialized gate driver. The method offers cost-effectiveness, ease of implementation, and a high level of robustness compared to existing advanced gate drivers. However, it also highlights the complexity in selecting appropriate TVS components due to the discrepancy between the maximum clamping voltage and the specified breakdown voltage range. These findings contribute to the advancement of EV power electronics systems and underscore the importance of careful component selection to ensure optimal performance and protection of critical components like the IGBT. This method of driving Si-IGBT can further be developed for new generation SiC & GAN semiconductors. Since the driving characteristics of SiC & GAN devices are different, detail analysis needs to be carried out for short-circuit & overvoltage situations.

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