

A Smart Gate Driver with Active Switching Speed Control for Traction Inverters

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ABSTRACT

The IGBTs are dominantly used in traction inverters for automotive applications. Because the Si-based device technology is being pushed to its theoretical performance limit in such applications during recent years, the gate driver design is playing a more prominent role to further improve the traction inverter loss performance. The conventional gate driver design in traction inverter application needs to consider worst case scenarios which adversely limit the semiconductor devices' switching speed in its most frequent operation regions. Specifically, when selecting the gate resistors, the IGBT peak surge voltage induced by fast di/dt and stray inductance must be limited below the device rated voltage rating under any conditions. The worst cases considered include both highest dc bus voltage and maximum load current. However, the traction inverter operates mainly in low current regions and at bus voltage much lower than the worst case voltage. This paper proposes a low-cost and simple gate driver circuit that can actively adjust the turn-off switching speed based on IGBT current levels. The proposed circuit utilizes the current sensing pin which is widely available for IGBTs used in current generation traction inverters. When the current is low, the switching is speeded up to minimize loss. Under worst cases, it can keep the maximum surge voltage same as the value of conventional gate driver. For applications that the system operates mostly in low current regions, the proposed method can significantly improve the system efficiency.

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INTRODUCTION

To meet the more stringent fuel efficiency requirement, the automotive industry is going through an evolutionary transformation to make smarter and more efficient electric vehicles (EV) and hybrid electric vehicles (HEV). The traction inverter in the electrified powertrain, as shown in Fig. 1, is one of the components that generate considerable losses. To further increase the vehicle fuel economy, it is desirable to improve the traction inverter efficiency. In a traction inverter, the IGBT and diode generate the majority energy losses in the form of switching and conduction losses. Over these years, the high power semiconductor devices have made significant performance improvements. The gate driver which is used to control the IGBT becomes more crucial if further performance improvement is desired. As shown in Fig. 1, each IGBT has a gate driver circuit to control its turn-on and turn-off. The gate driver circuit can adjust the switching transient, thus impact the switching loss.

This paper focuses on improving the IGBT turn-off switching performance. Fig. 2 shows a generic conventional gate driver circuit schematic. It simply includes a buffer stage, and turn-on and turn-off gate resistors. The gate driver receives a gate input signal from micro-processor and its output is connected to the IGBT gate terminal. The gate input signal is amplified by a buffer stage composed of BJTs or MOSFETs. In Fig. 2, the buffer stage includes a NPN BJT Q_1 and a PNP BJT Q_2 . When the gate input signal is high, Q_1 is turned on. The gate of IGBT Q is connected to gate driver

power supply, e.g. 15V, and gate capacitance is charged through turn-on gate resistor R_{on} . When gate input signal is low, the gate capacitance is discharged through turn-off gate resistor R_{off} and Q_2 . R_{on} and R_{off} determine the IGBT turn-on and turn-off switching speed respectively. L_s is the equivalent stray inductance existed in the IGBT high voltage loop. "E" represents the IGBT power emitter terminal and "e" represents the IGBT Kevin emitter terminal.

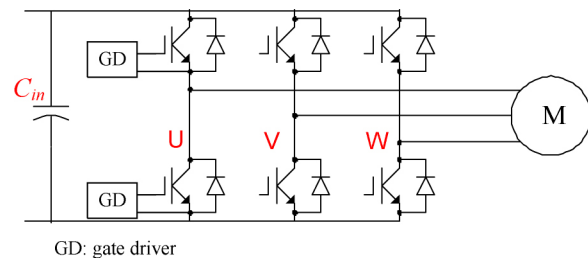


Figure 1. A generic HEV/EV traction inverter schematic.

A typical turn-off switching waveform using this circuit is shown in Fig. 3. The turn-off transient mainly includes four phases. Once the turn-off process begins, gate voltage V_{ge} starts to decrease. Before V_{ge} reaches miller plateau voltage, IGBT collector-emitter voltage V_{ce} and collector current i_c haven't changed a lot. This phase is turn-off delay phase. The longer the turn-off delay, the larger dead-time is needed to avoid potential shoot-through problem. Large dead-time could degrade the traction inverter output quality. The second phase is V_{ce}

rising period. V_{ce} reaches the dc link voltage at the end of this phase. During the third phase, i_c starts to decrease. Because of the stray inductance in the power circuit, di/dt will cause surge voltage across the IGBT. Therefore, V_{ce} continues to increase and exceeds dc link voltage. Due to the V_{ce} surge voltage, it raises the IGBT voltage rating requirement. In the fourth phase, V_{ge} discharges to zero and there is a tail current.

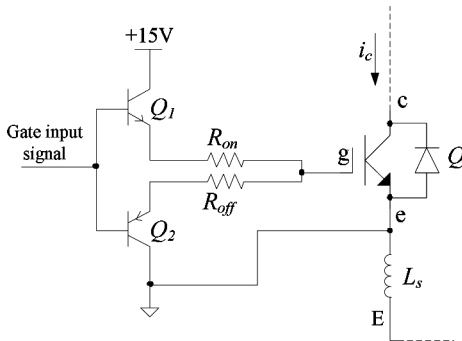


Figure 2. A generic conventional gate driver circuit schematic.

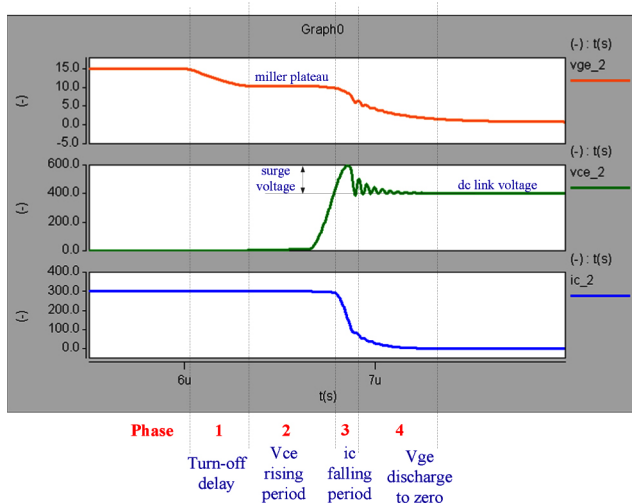


Figure 3. A typical turn-off waveform using conventional gate driver.

In designing the conventional gate driver for EV/HEV traction inverter, one needs to consider the tradeoff between switching losses and device stresses. For example, the gate resistances are selected at worst case scenario, i.e. maximum load current and highest dc bus voltage, to guarantee the device peak surge voltage always below its rating. This usually leads to large gate resistances. However, the selected large gate resistors unnecessarily slow down the switching speed at low current operation points. Since the traction inverter mostly operates at low current levels in typical driving cycles, the overall vehicle fuel economy is sacrificed to meet the worst case requirement.

The state-of-the-art advanced IGBT gate drivers target to improve the switching performances, and they can be classified as passive, open-loop and closed-loop types [1]. The passive method with added external capacitances or gate voltage shape generator [2] is simple, but the controllability of the switching waveforms is still limited. The open-loop control gate drivers incorporate switchable gate resistors, gate current sources or voltages [3, 4]. For each interval of the switching transient, a specific gate resistor, current source or gate

voltage is selected to independently control the waveform during that interval. Due to the dependence of IGBT characteristics on operation conditions, an operating point dependent profile is needed to control the switchable elements so that optimized performance can be achieved at each operation point. Usually, a lot of off-line calibration effort is required to generate the aforementioned control profiles. The closed-loop control concept can adjust the di/dt and dv/dt in real time during the transient by adding extra feedback circuits, control and logic circuits [1, 5, 6, 7], which increase the circuit complexity. Moreover, the added extra circuits could introduce delays, which make it not suitable for very fast switching applications.

PROPOSED GATE DRIVER CIRCUIT

This paper proposed a gate driver circuit that can actively adjust the turn-off switching speed based on different current levels. The circuit is shown as in Fig. 4. To increase the system reliability, the IGBT usually include a current mirror sensing pin which flows a fractional value of the IGBT collector current i_c . The signal is used for over-current and/or short circuit current protection [8]. In the proposed circuit, the signal is utilized to actively control the turn-off speed of the IGBT. When the current level is low, fast turn-off is enabled. When the current level is high, fast switching is disabled. To achieve fast turn-off under low current conditions, a fast gate discharge path composed of a MOSFET Q_3 and a small turn-off resistor R_{off_fast} is added.

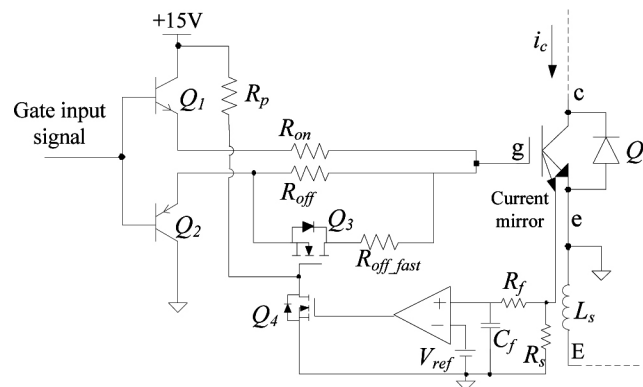


Figure 4. Schematic of the proposed gate driver circuit.

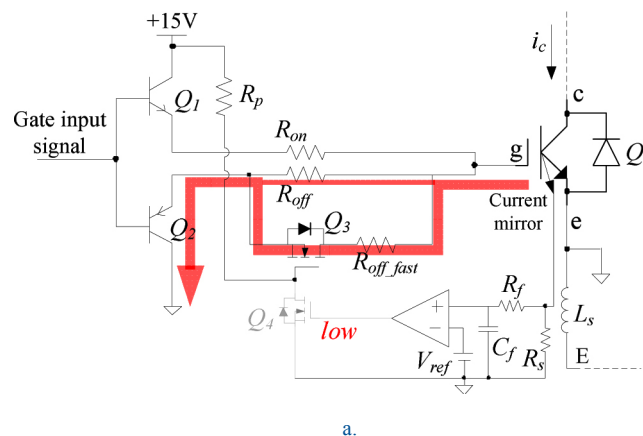


Figure 5. Different operation status of the proposed gate driver circuit (a) current is lower than the pre-set threshold and (b) current is higher than the pre-set threshold.