Gate-driver circuit with a variable supply voltage to influence the switching losses

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Abstract: The lifetime of semiconductor devices used in power electronics depends on the junction temperature. With a suitable junction temperature control system, the lifetime of semiconductor devices is extended. These control systems require a possibility to influence the power losses of the semiconductor devices and therefore the junction temperature. The proposed gate-driver circuit has a variable supply voltage in order to influence the switching speed of the semiconductor devices. This affects the switching losses. In addition, the adjustable switching speed can be used to prevent voltage overshoots during the switching transition or to decrease electromagnetic emission. The main advantage of this gate-driver circuit is its simple structure. This study focuses on the switching losses.

1 Introduction

The reliability of power electronic devices becomes more and more important. One possibility to extend the lifetime of power semiconductor devices is to reduce the thermal stress, to which they are exposed. In particular, large temperature swings damage these components. The reason is their mechanical structure. Power semiconductor devices consist of many different material layers with different thermal expansion coefficients. If temperature swings occur, caused by alternating load conditions, each material layer expands in a different way. This leads to mechanical strain, which damages the device [1–3].

A suitable junction temperature control system is able to decrease the thermal stress. Therefore, these control systems influence the junction temperature by controlling the power losses. This can be done by varying the switching frequency, using different modulation techniques or by applying a reactive current through the semiconductor device [4–6]. One drawback of these methods is that the power losses of all transistors of the entire power electronic are influenced at the same time. So the junction temperature of the different transistors cannot be controlled independently.

The proposed gate-driver circuit is able to affect the switching speed by adjusting the supply voltage. The switching speed itself influences the switching losses. Thus, the supply voltage can be used as a correcting variable for junction temperature control systems. The supply voltage of each gate driver is varied independently from each other. This offers the possibility to realise a junction temperature control system for every single transistor. Another aspect is the voltage and the current slope during the switching transition. They significantly affect the electromagnetic emission (EME) [7–10]. In addition, a high current slope together with the parasitic inductance of the connectors also causes voltage overshoots, while the power semiconductor device turns off [11]. By varying the supply voltage of the gate driver, the voltage and current slopes are affected as well. Therefore, the proposed gate-driver circuit could be used to reduce EME or to prevent voltage overshoots. This study discusses the effects on the power losses.

2 Gate-driver circuit

2.1 Concept

The switching speed and the voltage and current slopes depend on the gate current witch charges or discharges the gate capacitance \(C_G\). The higher the gate current, the higher the switching speed, thereby increasing the voltage and current slopes. Using a voltage source gate driver, the gate current \(I_G\) depends on the supply voltages \(V_{CC}\) and \(V_{EE}\), and the gate resistance \(R_G\). With the simplification that the gate capacitance \(C_G\) is constant and the gate-driver circuit is decoupled from the power path, the gate current is calculated as follows:

\[
I_G(t) = \frac{V_{CC} + V_{EE}}{R_G} \cdot e^{\frac{1}{R_G C_G}}
\]

To scale the gate current, it is possible to change either the gate resistance or the supply voltage. The realisation of a variable supply voltage is easier than the realisation of a variable gate resistance. If the gate resistance is very large, there is a high impedance between the gate driver and the gate. Thus, disturbances at the gate of the transistors could lead to an unwanted switching transition of the power transistor. With a small impedance between the gate driver and the gate, the gate-source voltage is almost equal to the corresponding supply voltage at any time. Due to the simple design and the small impedance between the gate and the gate-driver circuit, the variation of the supply voltage was chosen; see Fig. 1.

In this case, the supply voltage \(V_{CC}\) is variable. It is also possible to vary the supply voltage \(V_{EE}\). The principle is explained for a variable voltage \(V_{CC}\). However, the measurement results show both cases.

In the steady state, the supply voltage is equal to the gate-source voltage. This means that the variation of the supply voltage \(V_{CC}\) affects the conduction characteristic of the power semiconductor device; see the example in Fig. 2 (SCH2080KE, SiC-MOSFET from Rohm).

If the gate-source voltage is too low, the metal-oxide-semiconductor field-effect transistor (MOSFET) activates in the saturation area. This has to be prevented. Assuming that the drain...
current is always <30 A, for this example, the allowed range of the gate-source voltage lies between 13 and 20 V. The lower the gate-source voltage, the higher the on-resistance of the transistor and the higher the conduction losses. Therefore, both switching and conduction losses change in the same way by different gate-source voltages. This is helpful in order to realise a junction temperature control system by using the supply voltage of the gate driver as a correction variable.

In contrast to the variation of $V_{CC}$, the variation of $V_{EE}$ does not affect the conduction characteristics of the power transistor.

2.2 Design

The gate-driver circuit consists of a half-bridge to charge the gate either with the positive supply voltage $V_{CC}$ or with the negative supply voltage $V_{EE}$. The supply voltage $V_{CC}$ is a variable voltage. The buck converter converts the fix supply voltage $V_{CC}′$ into the variable supply voltage $V_{CC}$; see Fig. 3.

The inductance $L_{BC} = 10$ µH and the capacitor $C_{BC} = 100$ µF smooth the supply voltage $V_{CC}$. A conventional isolated gate driver (1EDI60N12AF from Infineon) is used to realise the half-bridge of the buck converter. The switching frequency of the buck converter is 100 kHz. This leads to a voltage ripple $\Delta V_{CC} < 100$ mV which is small enough to not influence the switching behaviour too much.

The gate-driver half-bridge is realised with the same device. The duty cycle $D$ of the buck converter is the ratio between the output and the input voltage:

$$D = \frac{V_{CC}}{V_{CC}′}$$

3 Measurements

3.1 Setup

The gate-driver circuit is tested in a half-bridge with an inductive load $L$, see Fig. 4.

The MOSFETs S1 and S2 are driven by the proposed gate-driver circuit. The drain current $I_{D}$ is measured with a coaxial shunt resistance $R_{Shunt}$. The drain-source voltage $V_{DS}$ and the gate-source voltage $V_{GS}$ are measured with voltage probes.

The switching behaviour at different supply voltages is investigated with the double pulse method; see Fig. 5. First, the transistor S2 is turned on, while S1 is turned off ($t = t_1$). The current through the inductor $L$ rises in this period. As the current reaches the value $I_{test}$ at which the experiment should run ($t = t_2$), the transistor S2 is turned off and S1 is turned on. The current now commutates from S2 to S1. A short time after that, S2 is turned on and S1 is turned off again ($t = t_3$). At this time, the turn-on transition of transistor S2 is measured. As the transition is finished, the turn-off transition of S2 starts ($t = t_4$). Therefore, S2 is turned off and S1 is turned on again. The turn-off transition is measured at this time.

The very short conduction time of the power transistors minimises the self-heating of the power transistors during the experiment.

3.2 Results

The measurements are recorded at a drain current of $I_{D} = 28$ A, a DC-link voltage of $V_{DC,link} = 550$ V, a gate resistance of $R_{G} = 10$ Ω, and different supply voltages $V_{CC}$ and $V_{EE}$. The junction temperature is equal to the room temperature (25°C). The switches S1 and S2 are realised with the SiC MOSFETs from Fig. 2.
The first experiment is made at different supply voltages $V_{CC}$ and at the fixed supply voltage $V_{EE} = 5\,\text{V}$. The results are shown in Figs. 6 and 7.

The switching speed at the turn-on transition significantly depends on the supply voltage $V_{CC}$; see Fig. 6. The lower the supply voltage, the smaller the rate of change of the drain current $I_D$ and the drain-source voltage $V_{DS}$. With a supply voltage of $V_{CC} = 10.3\,\text{V}$, the transistor operates in the saturation area. This means that the transistor is not completely turned on, which is not allowed in normal operation. Thus, the drain current cannot reach the final value of 28 A.

The switching speed of the turn-off transition is independent from the supply voltage $V_{CC}$; see Fig. 7. The reason is that the waveforms of the gate-source voltage are identical for each supply voltage $V_{CC}$ during the actual switching transition.

In the second experiment, the supply voltage $V_{EE}$ is variable. The supply voltage $V_{CC}$ is set to a fixed value of 20 V. The turn-on transition does not depend on the supply voltage $V_{EE}$; see Fig. 8. The almost similar course of the gate-source voltage during the switching transition is the reason for that. The variation of $V_{EE}$ influences the switching behaviour of the turn-off transition; see Fig. 9. The smaller the supply voltage, the slower the switching transition. In addition, the voltage overshoot is reduced with smaller values of $V_{EE}$.

In fact, the variation of $V_{CC}$ has a bigger impact on the switching speed than the variation of $V_{EE}$.

### 3.3 Evaluation

To prove if the variation of the supply voltages $V_{CC}$ and $V_{EE}$ is usable as a correction variable for a temperature control system, the switching energies $E_{on}$ and $E_{off}$ are calculated for each measurement. Therefore, the course of the drain current and the drain-source voltage are multiplied to get the course of the power loss. This course is integrated during the corresponding switching transition:
Using the values of Fig. 2, the calculated conduction losses increase from ~67.5 to 148.5 W by reducing $V_{CC}$ from 20 to 14 V.

The supply voltage $V_{CC}$ significantly influences the total losses, which makes the usage of a variable $V_{CC}$ as a correction variable for junction temperature control suitable. Fig. 11 shows the results of the experiment with a variable supply voltage $V_{EE}$ and a fixed supply voltage $V_{CC}$.

The influence of the supply voltage $V_{EE}$ on the switching losses is small. The conduction losses are not affected by the variation of $V_{EE}$. The outcome of this is that the variation of $V_{EE}$ is not suitable in order to realise a junction temperature control system. However, a variable supply voltage $V_{EE}$ can be used to reduce voltage overshoots during the turn-off transition; see Fig. 9.

4 Conclusion

This article presents a simple gate-driver circuit with an adjustable supply voltage, which makes it possible to vary the switching speed of the power transistor. This affects the switching losses. The supply voltage is changed by a small buck converter while the power electronic is working. Therefore, the supply voltage can be used as a correction variable in a junction temperature control system. This gate-driver circuit can also be used to prevent overshoots during the switching transitions or to decrease electromagnetic interference.

The experimental results show that it is suitable to vary the supply voltage $V_{CC}$ of the driver, because the variation of $V_{CC}$ affects the power losses more than the variation of $V_{EE}$.

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\[ P_{\text{con}} = \int_{t_{\text{on}}}^{t_{\text{off}}} I_D \cdot V_{DS} \, dt \]  

\[ E_{\text{on}} = \int_{t_{\text{on}}}^{t_{\text{off}}} I_D \cdot V_{DS} \, dt \]  

\[ E_{\text{off}} = \int_{t_{\text{off}}}^{t_{\text{on}}} I_D \cdot V_{DS} \, dt \]

Table 1 Borders of the integrals

| Border   | Condition   |
|----------|-------------|
| $t_{\text{on},1}$ | $V_{DS} > 0 \text{ V}$ |
| $t_{\text{on},2}$ | $V_{DS} \leq 11 \text{ V}$ |
| $t_{\text{off},1}$ | $V_{DS} < 10 \text{ V}$ |
| $t_{\text{off},2}$ | $I_D < -0.5 \text{ A}$ |