Experiment #5 – Gate Driver

High-Side and Low-Side Switches

A low-side switch is a MOSFET or an IGBT that is connected to the ground-referenced and is not floating. In a boost converter, the source terminal of the MOSFET is connected to the circuit ground, which is referred to a low-side MOSFET. To switch an N-channel MOSFET of a boost converter on, the V_{GS} should be in the order of 10 to 20V. Since the source terminal is grounded, this implies that the gate voltage must be 10 to 20V. This voltage level can be easily generated by having the input voltage of the boost converter and does not pose any challenge for gate driver circuit.

In a buck converter based on an N-channel MOSFET, the source terminal of the MOSFET is not connected to the circuit ground (not ground-referenced) and is floating. The N-channel MOSFET of a buck converter is a high-side switch. Drive circuits for the high-side switches are called high-side drivers and are more complicated than low-side drivers because of the required voltage translation to the supply and because it is more difficult to turn off a floating switch.

MOSFET Gate Drivers

The location of an N-channel MOSFET in a buck converter introduces a particular challenge to the power electronics engineer. As shown in Fig. 1, the MOSFET source terminal is not common with the gate voltage source V_G. This issue is expressed by applying the KVL in the loop shown on Fig. 1, as follows:

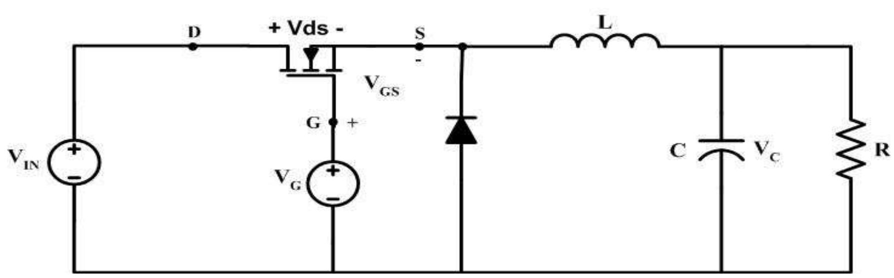

Fig. 1: Buck converter based on N-channel MOSFET.

$$-V_{IN} + V_{DS} - V_{GS} + V_G = 0 \quad ==\gg \; V_G = V_{IN} - V_{DS} + V_{GS} \tag{1}$$

To switch the MOSFET on, the V_{GS} should be in the order of 10 to 20V and ideally, the V_{DS}will be almost zero (considering a small on-state resistance). Consequently, (1) can be rewritten as:

$$V_G = V_{IN} + V_{GS} \tag{2}$$

This implies that the gate voltage must be 10 to 20V higher than the input voltage of the buck converter. For example, if the input source of a buck converter is a 12V battery, this would need a $V_G = 22$ V to turn the MOSFET on. Since typically, the required auxiliary voltages on a buck converter circuit are derived from the input voltage source, this poses a challenge for gate driver circuit.

The first solution is to replace the N-channel MOSFET by a P-channel MOSFET as shown in Fig. 2. In this case, the source terminal of the MOSFET is connected to V_{IN}. By applying KVL, we deduce

$$V_G = V_{IN} + V_{GS} \tag{3}$$

To turn a P-channel MOSFET on, the V_{GS} must go to -10V. Thus the gate voltage must vary between V_{IN}(MOSFET off) and $V_{IN} - 10V$ (MOSFET on). Although this is easily achievable, the P-channel MOSFET has characteristics that make this implementation less attractive. P-channel MOSFETs are built on P-type epitaxial material where the majority carriers are holes. Since holes have lower mobility than electrons, in the P-channel MOSFET, $R_{DS,ON}$ is two to three times larger than that of an N-channel MOSFET of similar size. Thus a P-channel MOSFET will have larger conduction losses and the buck converter will operate at a lower efficiency. Therefore, the P-channel MOSFETs are not investigated for buck converter circuit.

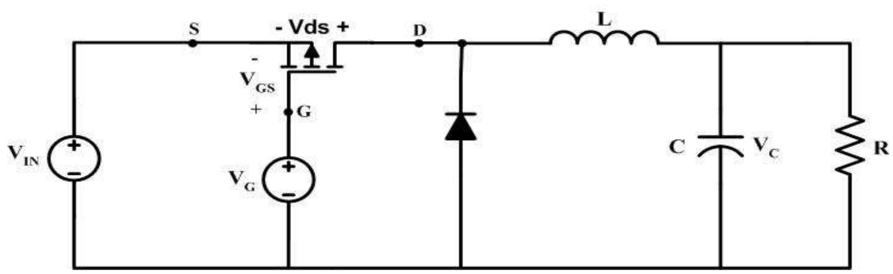

Fig. 2: Buck converter based on P-channel MOSFET.

N-Channel MOSFET Gate Drivers

As was discussed in the previous section, the issue with turning the N-channel MOSFET on in a buck circuit is referencing. That means that the source terminal of the MOSFET is not at the common ground; it will float depending on the status of the MOSFET. If the MOSFET is on, the source will be up almost equal toV_{IN}; if the MOSFET is off, the source will be near 0V (as the diode conducts). Thus to turn the MOSFET on, the gate driver needs to create an effective gate voltage that is higher than the input voltage. One approach that solves this challenge is the Boot-Strap circuit shown in Fig. 3.

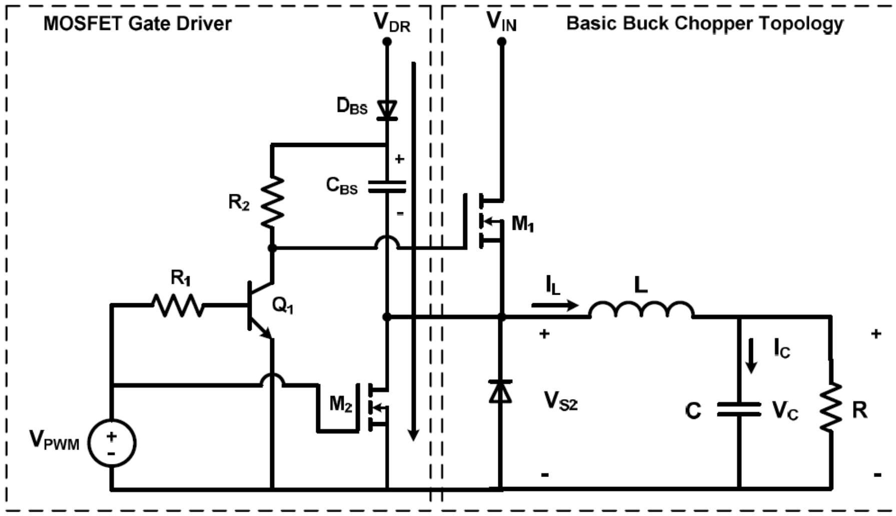

Fig. 3: Buck converter with boot-strap high-side gate driver.

In this circuit, V_{PWM} is a duty cycle control voltage toggling between 0V and +5V. The voltage V_{DR} is the gate driver voltage that will typically be between +10V and +18V. The circuit operates as follows. When $V_{PWM} = 5V$, the driver transistors Q_1 and M_2 are on. Consequently, the boot-strap capacitor C_{BS} and the gate of $M_1$to the bottom rail (0V). Thus M_1 is off and C_{BS} charges up to V_{DR} via the boot-strap diode as shown in Fig. 4. When $V_{PWM} = 0$ V, both Q_1 and M_2 turn off and the circuit becomes that shown in Fig. 5.

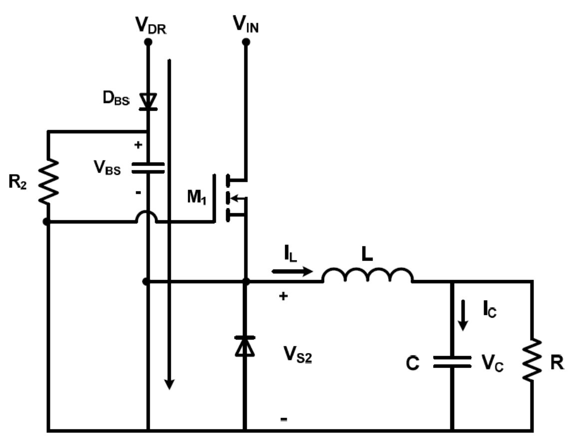

Fig. 4: Main MOSFET off and Boot-Strap capacitor recharges.

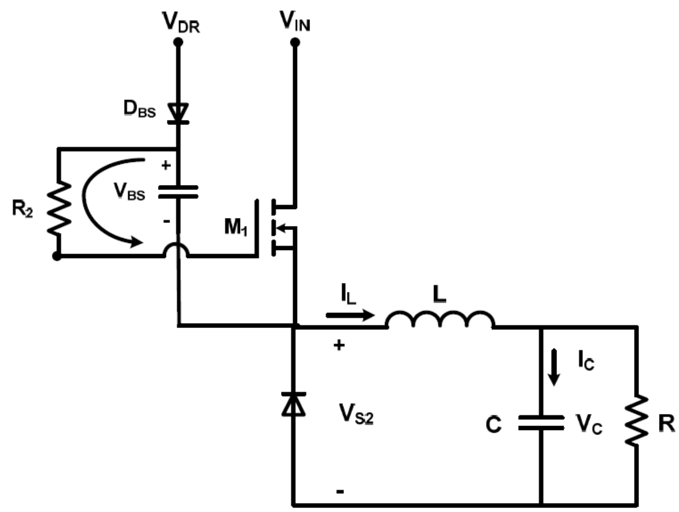

Fig .5: Boot-Strap capacitor discharges into main MOSFET gate.

The negative terminal of the boot-strap capacitor is now connected to the source of M_1 while the positive terminal is connected to the gate via R_2. C_{BS} begins to discharge, providing the gate current required to turn the M_1 on. When M_1 is on, its source terminal voltage rises up to near V_{IN} . The diode D_{BS} then prevents the capacitor from discharging into V_{DR} . When M_1 is commanded to get off again, V_{PWM} goes to +5V, Q_1 and M_2 turn on, the gate of M_1 is attached to ground, the M_1 gate capacitance discharges turning M_1 off, and C_{BS} recharges via V_{DR} and M_2 .

There are many gate drivers based on boot-strap circuitry available in the Integrated Circuit (IC) chips, though not necessarily using the exact circuit discussed above. A sample is the UCC27200/1 shown in Fig. 6. The UCC27200/1 is designed to drive both high-side and low-side switches. An external capacitor and diode provides the bootstrap circuit for the high-side MOSFET used in a buck converter. The low-side driver can be used to drive the low-side MOSFET of a boost converter.

The driver uses a supply voltage, V_{DD} in the range of 8~17 V. The inputs to the gate driver IC are the gating signals for the high-side and low-side MOSFETs coming from the TI microcontroller. The outputs of the gate driver IC are the voltages provided to the gates of the MOSFETs (HO for high-side MOSFET and LO for the low-side MOSFET).

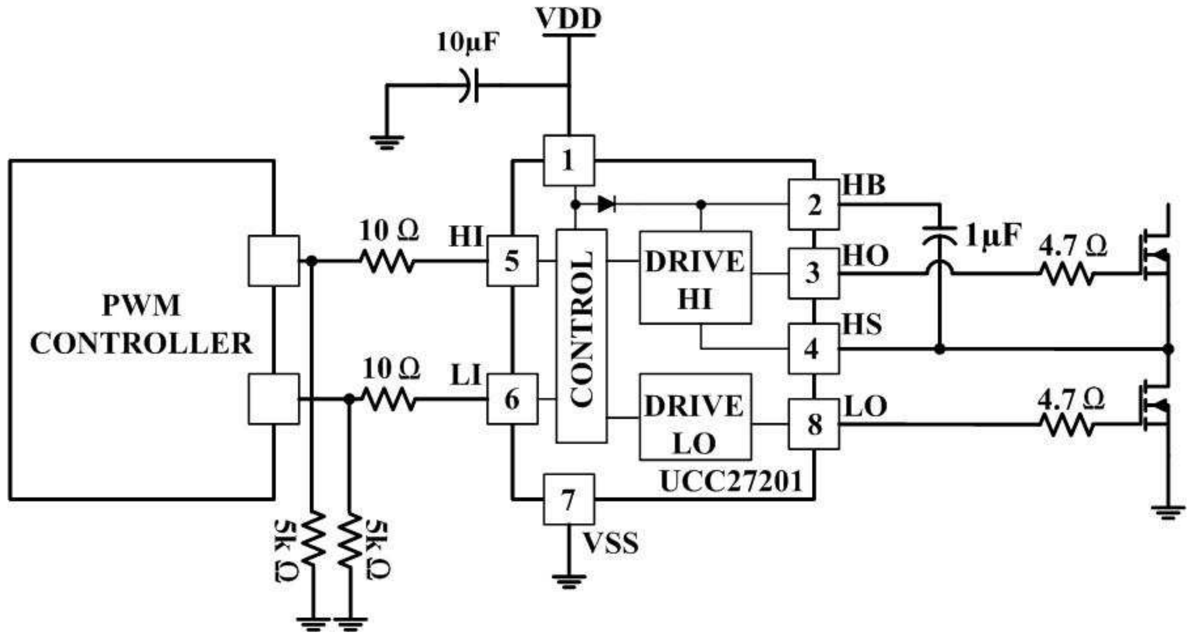

Fig. 6: Block diagram of UCC27200/1 gate driver.

Switching Characteristics of a MOSFET

Ideally, when the gating signal of a MOSFET is toggled between low and high voltage levels, (high when the MOSFET is commanded to turn on, and low, when the MOSFET is commanded to turn off), the output switching waveform of a MOSEFT looks like a square waveform, as depicted in Fig. 7. However, the actual switching characteristics of a MOSFET during turn-on and turn-off switching transitions are not changed step-wise, as shown in Fig. 7(c). The exact current and voltage waveforms of a MOSFET during switching transitions are shown in Fig. 8. As a result, the non-ideal current and voltage waveforms and the rise-time and fall-time intervals introduce the switching losses which can be calculated based on the triangular area shown in Fig. 9. The rise-time and fall-time intervals for MOSFET current and voltage waveforms can be found from the MOSFET specifications given by the datasheet.

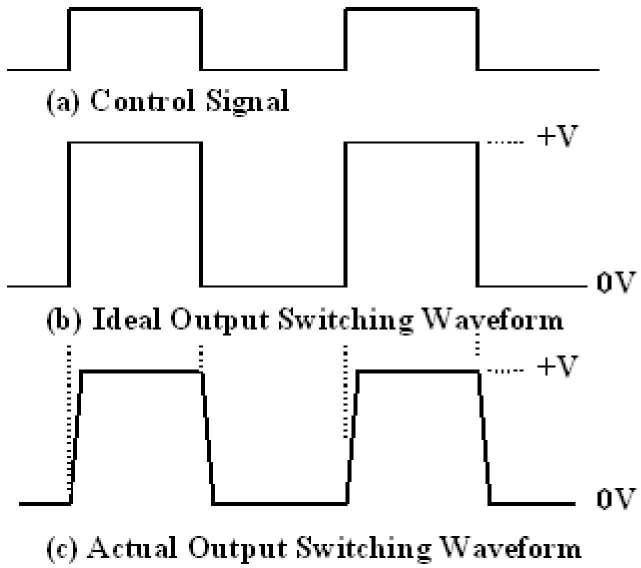

Fig. 7: Switching waveforms of MOSFET current and voltage.

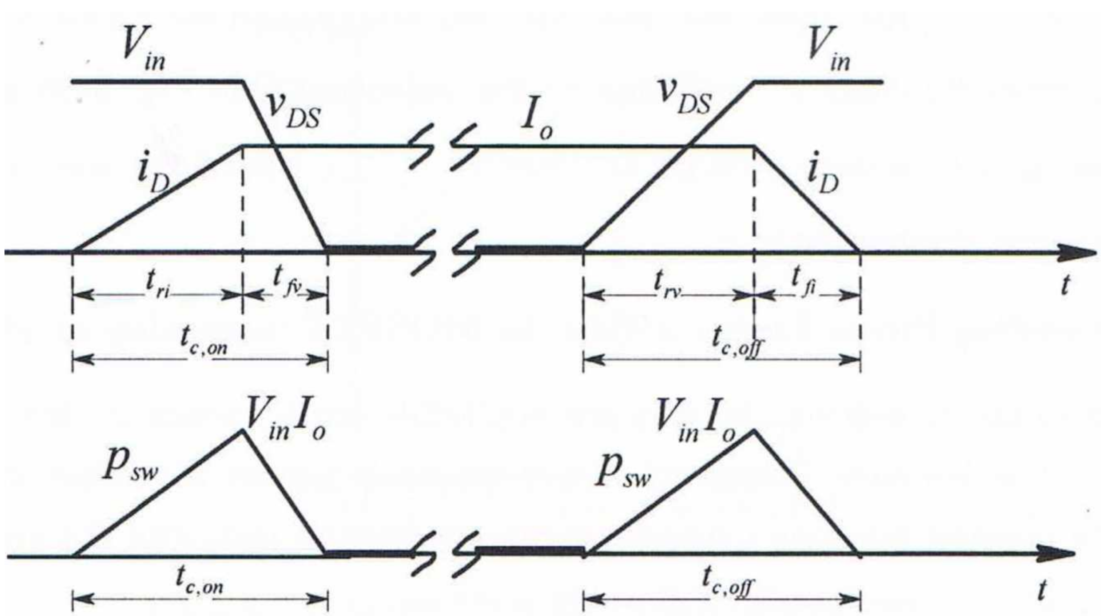

Fig. 8: Actual switching waveforms of MOSFET current and voltage.

Simulation Studies

Simulate the circuit of Fig. 10 and plot the voltage across the MOSFET, V_{DS}, and the current, I_D, during two full switching cycles, for a duty ratio of 50%. In simulation, you do not need to use the MOSFET gate driver IC.

- Adjust the MOSFET specifications of the simulation program based on the data provided in IRFIZ48NPb datasheet. Based on the simulation, measure the rise time and fall time of the voltage and current.
- Calculate the switching losses of the MOSEFT.
- Calculate the conduction losses.

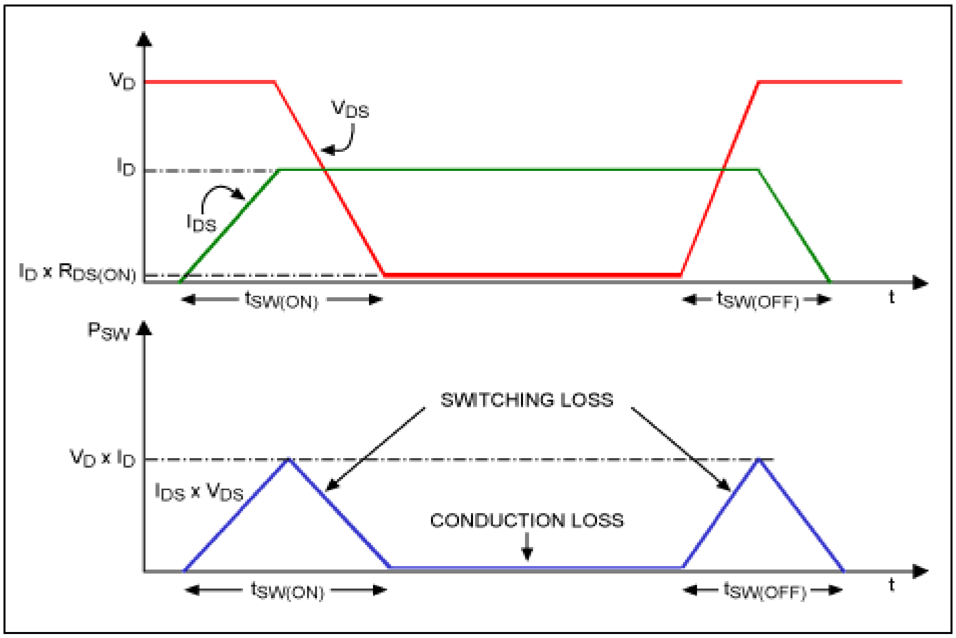

Fig. 9: MOSFET switching losses.

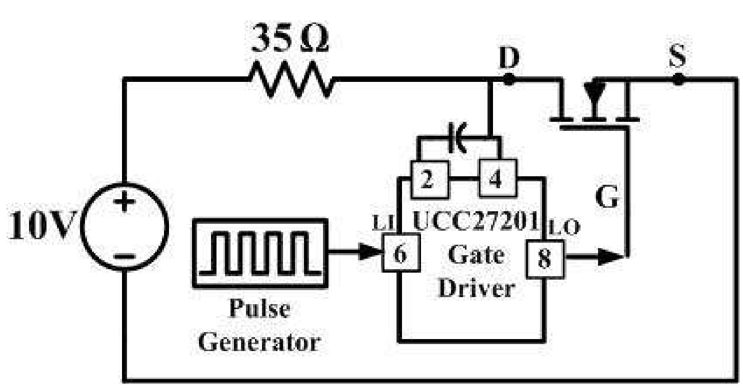

Fig. 10: MOSFET switching characteristic test circuit.

Experimental Studies

Construct the circuit of Fig. 10 in the laboratory using IRFIZ48NPb. Use a low-side gate driver (UCC27200/1) to switch the MOSFET. Once you are confident that your circuit is configured correctly, adjust the duty ratio to 50%. Use a differential probe to measure the drain-source voltage of the MOSFET. Measure:

- the MOSFET current. Adjust the time base to show the turn-on and turn-off characteristics of the MOSFET. Compare the turn-on and turn-off characteristics of the MOSFET with those from the MOSFET datasheet.
- the voltage drop across the MOSFET during the turn-on period and estimate the value of R_{DS}. Compare your estimation with the data based on the datasheet of the MOSFET.
- the switching losses of the MOSFET and compare the results with the simulation results and comment on them.
- the conduction losses of the MOSFET and compare the results with the simulation results and comment on them.

Construct the circuit of Fig. 11 in the laboratory. Use a low-side and a high-side gate driver (UCC27200/1) to switch the MOSFETs. Once you are confident that your circuit is configured correctly, adjust the duty ratios of both MOSFETs to 50%. Measure the drain-source voltages of both MOSFETs, compare the waveforms and report the results.

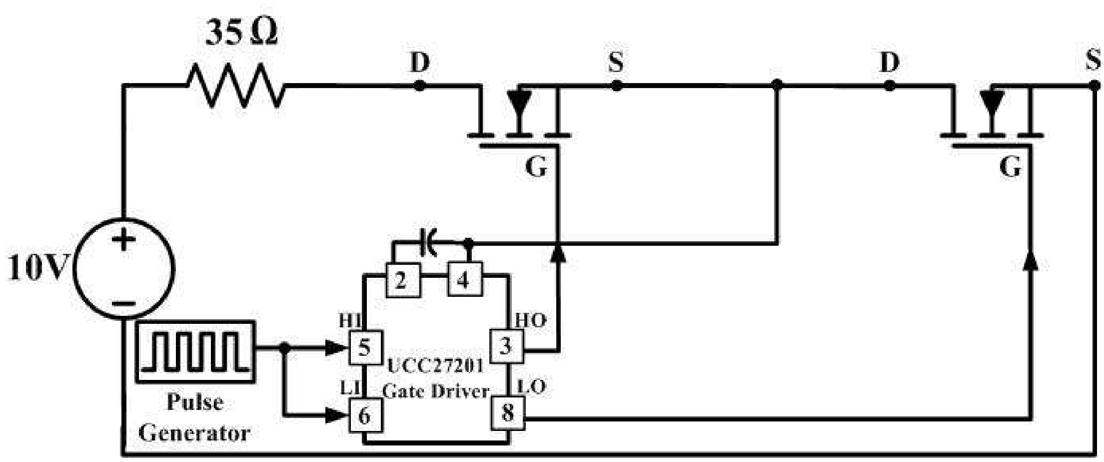

Fig. 11: Driving the MOSFETs by high-side and low-side gate drivers.