3x.15 High-Voltage Pulsers

High-voltage power MOSFETs are widely available; and, happily, they are quite inexpensive. The FQPF8N80, for example, rated at 800 V and 8 A, costs just \$1 in single quantities. We owe our good fortune here to a host of important commercial applications in power control that provide incentive to the semiconductor manufacturers: line-powered ac–dc conversion, inverters for three-phase variable-speed motor drive, fluorescent lighting, and so on. For many of these applications there's a need also for an isolated high-side driver, to provide gate drive to the "flying" upper *n*-channel MOSFET switch of a push–pull pair, as for example in the classic half-bridge circuit (Fig. 9.73C). Here too the semiconductor manufacturers have responded, with inexpensive offerings that do the job (many of which cost less than a dollar, even in single quantities); some examples are listed in Table 3x.5 on page 250.

Quite apart from such commercial power applications, these high-voltage MOSFETs and drivers can be used to make impressive pulse generators for laboratory applications. We've designed pulsers for applications including particle trapping, electro-optic light modulation, generation of terahertz radiation, electroporation in cell biology, rapid bubble production in nanopores, and, at a more mundane level, testing the pulse-energy endurance of electronic components such as resistors and transient voltage suppressors.

In this section we present several useful designs for laboratory-scale high-voltage pulsers.

3x.15.1 Two-switch +600 V pulser

Figure 3x.107 shows the basic form of a unipolarity (positive only) pulse generator. A pair of *n*-channel[107] MOSFET switches (shown notionally as an ordinary SPDT switch) are used to connect the output either to ground or to a positive dc voltage. There are two outputs: For applications where you want to drive a hefty current into the load, the output is taken directly from the switch; but for ap-

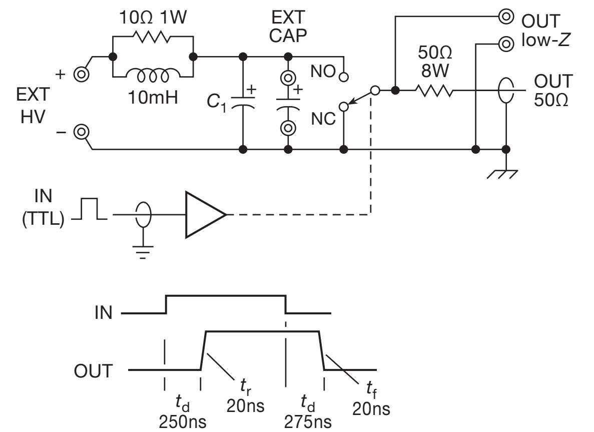


Figure 3x.107. Block diagram of the pulser of Figure 3x.109.

plications where you want to deliver a clean pulse at the open (unterminated) end of a length of coax, there's a 50 Ω "back-terminated" output (see Appendix H). There's provision to attach a large external energy-storage capacitor, if you want to deliver high-current pulses without droop. The MOSFET switches respond to a logic-level input, with control circuitry to ensure non-overlapping conduction. The switch transitions are fast (∼20 ns), but the drive circuitry imposes significant delay time (∼250 ns), as indicated.

Before moving on to the full circuit, let's briefly visit the business of high-side drivers, a topic seen earlier in §3.5.6 and revisited in §9x.10 in the context of lower voltages. We need to generate a ∼10 V gate–source drive to the upper *n*-channel MOSFET switch, whose drain is tied to the positive rail and whose source terminal is at the output potential. This is a "flying MOSFET" with flying gate, for which the driver has to generate its V_{GS} (of 0 V or +10 V) relative to the source terminal, the latter jumping between ground and +HV at a prodigious rate. To get a sense of the problem, note that a 500 V step in 20 ns is a slew rate of 25 *kilo*volts per microsecond! And, as with MOSFET drivers generally, the high-side driver may need to supply dynamic drive currents in the range of an amp, in order to charge and discharge the gate capacitance on timescales of 10 ns; after all, a power MOSFET gate charge value of, say, $Q_g \approx 25$ nC requires a gate current of 2.5 A to switch in 10 ns. For our circuit it's important also to have good control over the relative timing of the high-side and low-side switches, to prevent conduction overlap; that's why a half-bridge driver chip, with its paired outputs, is just what we need here.

For this circuit we chose the IR2113 driver, for which a simplified diagram is shown in Figure 3x.108. The low

[107] We use *n*-channel switches because the highest voltage *p*-channel MOSFETs top out at 600 V, and we want to go higher; *p*-channel parts of comparable voltage and current ratings also have poorer performance characteristics (higher R_{ON} and C_{iss}), and they are quite a bit more expensive.

side has a straightforward push–pull output stage, able to source or sink 2 A, and powered from a +10 V to +20 V supply (V_{CC}) referenced to an output COM terminal that must be within a few volts of input logic ground. The high-side push–pull driver floats atop the high-side MOSFET's source terminal (V_S), powered also from +10 V to +20 V relative to its common terminal V_S; i.e., $10V \leq V_B - V_S \leq 20V$. Both the low-side and high-side drivers are shut down if their supply voltages fall below a preset undervoltage lockout (UVLO) threshold of approximately 8 V; this ensures that the MOSFETs are fully driven (or not at all), thus preventing partial conduction that would cause excessive dissipation and overheating. An interesting design feature of this class of driver IC is the use of short pulses (rather than levels) to signal the intended high-side state; this minimizes power dissipation in the high-voltage level-shifters. This is quite effective, except at high switching frequencies where the dissipation rises: The datasheet graphs show minimal heating effects below ~10 kHz, but rising to maximum permissible junction temperatures at frequencies in the 100 kHz–1 MHz range. The heating effect is linear in switching frequency and in high-side supply voltage V_B, but it depends also upon the value of series gate resistor (R_1 and R_2 in Fig. 3x.109).

The IR2113/2213 drivers do their level shifting with internal high-voltage transistors, with ratings to 1.2 kV. It's also possible to do the job with transformer coupling, as in the ADuM6132 (see Table 3x.5 and Fig. 12.44G,H), or with optical coupling (see Fig. 3x.113).

Now for the full circuit (Figure 3x.109). Working from left to right, we generate true and inverted input signals for the high-side and low-side driver-chip inputs, matching delays with a pair of XOR gates. The IR2113/2213 itself creates a non-overlap interval of approximately 25 ns, which is the difference between its ON and OFF propagation delay times (120 ns and 94 ns, typ, respectively), but we have added ~15 ns of additional safety factor with the slow-on/fast-off gate circuits shown. We've done this because we've seen power MOSFETs take as long as 50 ns to completely cease drain conduction after V_{GS} is brought to zero.[108]

The output switches Q_1 and Q_2 are driven with small series gate resistors R_1 and R_2, paralleled with Schottky diodes to reduce turn-off time (for further overlap prevention). The 1 kΩ gate–source resistors prevent switch conduction if, for example, the high voltage is applied before the low voltage supplies. The bulk capacitor C_1 provides the low impedance path of pulsed output current; it can be supplemented with additional external capacitance. The power inductor L_1 (with 10 Ω damping resistor) isolates the HV supply from abrupt high-current transients.

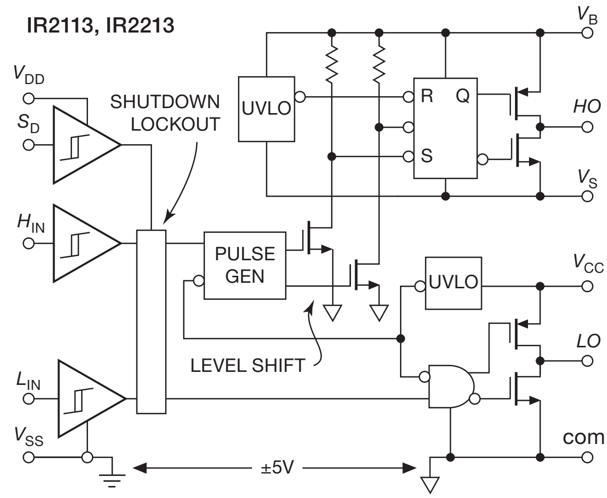
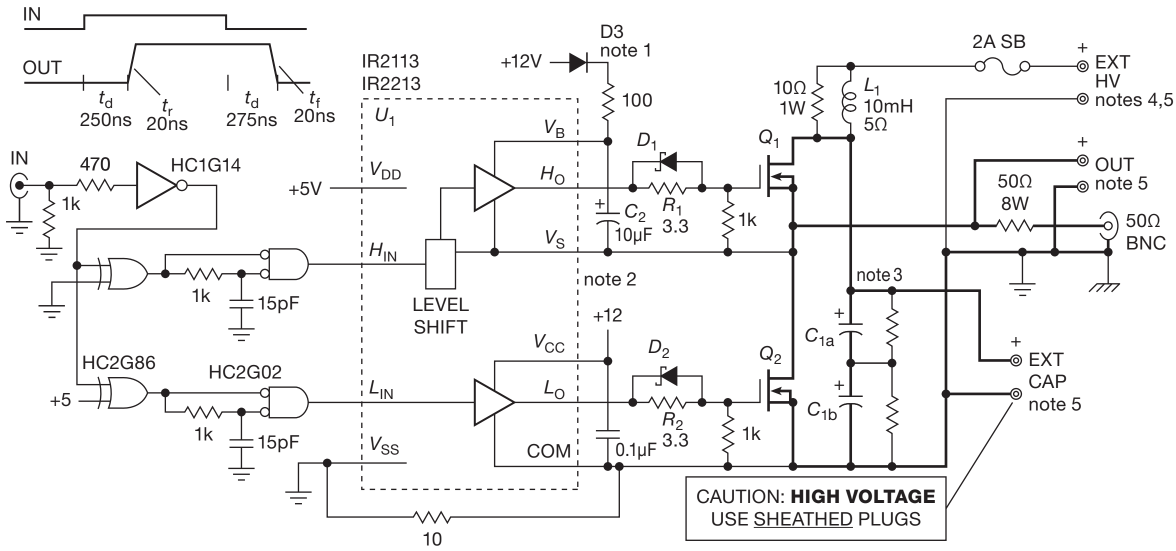


Figure 3x.108. Block diagram of the IR2113-style isolated high-side driver with matched non-isolated low-side driver. The high-side driver is implemented as a flip-flop, with level-shifted pulsed SET and RESET inputs. Both drivers implement undervoltage lockout.

Diode D_3 deserves some comment: The high-side driver requires its own 12 V dc supply, whose common terminal necessarily flies with the output. That could be an ac-powered dc supply – but beware, such a supply will have to slew at kilovolts per microsecond, no easy task for a conventional line-powered supply because of the inter-winding capacitance of the transformer.[109] The trick in Figure 3x.109 is to use a relatively large storage capacitor (C_2) on the high-side supply, and let the low-side +12 V supply replenish its charge through D_3 during times when the output is low. That works fine if the output is low most of the time, or if the pulse rate is high enough. It would not work, though, if the output sits high for long intervals; in that case you'd have to arrange a flying supply. Alternatively you could take advantage of a half-bridge driver like the ADuM6132 (used in our three-switch design, §3x.15.5), which integrates its own flying high-side supply and requires only an external storage capacitor.

[108] The MOSFET channel itself switches very fast in response to the overlying gate electrode; but the resistance of the gate runners combines with the gate capacitance to cause an *RC* signal delay to the distant MOSFET cells. This varies widely among different MOSFETs and manufacturers, and is generally not specified.

[109] Which must be insulated to withstand the full output voltage. We've successfully used the PCP-series of miniature PCB-mounting transformers, rated at 2500 V isolation.



Notes:

1. C_2 charges to 12V via D_3 when OUT = LOW. V_B quiescent drain 0.23mA typ; for long positive pulses or for switched DC, add a floating 12V supply across C_2.

2. Driver U_1, MOSFETs, R_{DS}, max HV EXT:

IR2113	FQA19N60	0.3Ω	600V
IR2213	IXFK26N120	0.46Ω	1200V

3. C_1 electrolytic; e.g., for 600V use two series 680μF, 350V caps, with parallel 470k 1W bleed resistors, plus large parallel mylar cap. Optional Ext Cap, e.g., CDE type CGS, 3300μF, 450V, ESR = 0.04Ω, priced at $228.

4. Ext HV, current limited to charge caps.

5. Banana jacks spaced 0.75" -- DANGER: High Voltage! Use spring-loaded sheathed plugs.

Figure 3x.109. High-voltage pulse generator. The *RC* delays at the input gates ensure non-overlapping conduction (“shoot-through”). The back-terminated BNC output drives unterminated 50 Ω coax, delivering full-swing pulse or dc output to a high-impedance load; the direct output delivers high-current short-pulse output. Bold lines indicate the output current path.

3x.15.2 Two-switch +500 V 20 A fast pulser

For several exotic applications we needed a faster HV pulser (<20 ns) with lots of peak current capability (to 20 A) and the ability to operate to several megahertz. For these requirements the IR2113 or IR2213 drivers are hopeless, with their sluggish ∼100 ns or ∼250 ns respective propagation times. Happily, there are some faster non-isolated drivers, for example the UCC2753x series; the UCC27538 we chose has typical propagation times of 17 ns (and that into a whopping 1.8 nF load, nearly twice the 1 nF that the IR2113/2213’s specify). And to keep the load capacitance low we chose silicon carbide (SiC) MOSFETs, which are superior to silicon in several important parameters: Compared with silicon, SiC has an order of magnitude higher electric-field breakdown strength, three times higher thermal conductivity, and triple the bandgap. As a consequence, SiC MOSFETs of equivalent voltage rating and ON-resistance can be made much smaller (see Fig. 3x.110), with correspondingly lower gate capacitance. That’s helpful for our application, permitting significantly greater switching speed with the drivers we’ve chosen.

The circuit is shown in Figure 3x.111, where we’ve omitted some details that only a nerd could love. As with the previous pulser, we’ve tailored the drive signals for delayed-ON/fast-OFF (both with the frontend gates and with the MOSFET gate drive resistors). For the high-side driver we chose the fast Si8610 digital isolator (8 ns propagation time, dc–150 Mbps, and isolation rated to 5000 Vrms and 60 kV/μs). High-side dc power comes from U_4, an isolated dc–dc module intended for SiC gate drive, where it’s common to use gate swings to +20 V and −5 V. These are available from several manufacturers (two are listed on the drawing), with isolation ratings of 3.5 kVac (and 6 kVdc), and an astonishingly low isolation capacitance of just 3.5 pF. For convenience we used the same converter type for the low-side driver (where no isolation is needed).

Some details: (a) This circuit runs *hot*, particularly when switching fast, and into a low-impedance load. So we mounted the MOSFETs and the output terminating resistor R_3 (a non-inductive TO-247 type) onto a microprocessor-style heatsink with blower. (b) Note the high-current path at the output, best implemented with generous copper pours, and of course storage capacitors of low inductance.

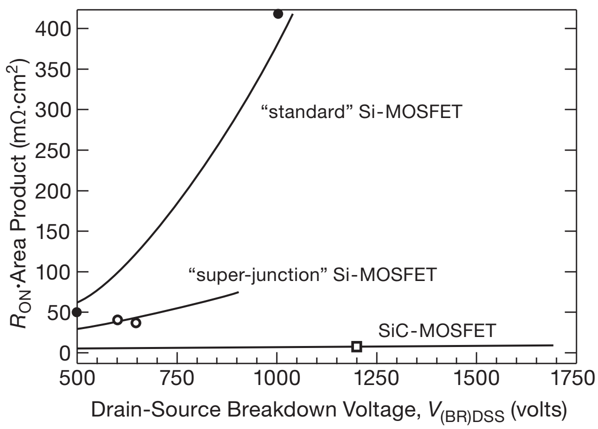


Figure 3x.110. Owing to silicon carbide's higher breakdown strength, the die size of SiC MOSFETs are far smaller than conventional silicon MOSFETs of comparable ON-resistance, as seen in this plot of $R_{ON}A_{die}$ figure-of-merit versus rated breakdown voltage. (Adapted from Rohm App Note 14103EBY01, to which we've added measured datapoints.)

(c) These particular gate drivers provide separate pull-up and pull-down outputs, convenient for setting ON and OFF delays; most drivers don't let you do that, so you use a resistor/diode combination, as in Figure 3x.109. (d) Because the low-side MOSFET driver U_3 rides on a -4 V "ground," its input signal is level-shifted by Q_1 (see for example Fig. 12.44A,C).

The good news is that this circuit works well, at least for pulse rates to $\sim$2.5 MHz: Figure 3x.112 shows a 500 V 5 A pulse with FWHM$\approx$20 ns. But things go bad when you try to push it higher: we cranked it up to 10 MHz, and the gate drivers *exploded*, taking out a bunch of other components with them! The problem is that those fast drivers come only in tiny SOT-23 packages, an odd situation given that they are rated to peak currents of 2.5 A (sourcing) and 5 A (sinking). Drivers you can get in power packages (e.g., TC4422, in a TO-220) are slower (t_p=30 ns, typ), and their greater self-capacitance requires more supply current (e.g., 170 mA at 2 MHz with no load) than the isolated converters U_4 and U_5 can supply (maximum dc output $\pm$100 mA). Desperate for operation to 10 MHz, we reconfigured the circuit with TC4422 heatsink-mounted drivers, powered by three paralleled dc–dc converters. Pretty crude, but it works.

3x.15.3 Two-switch reversible kilovolt pulser

Positive pulses are fine ... but sometimes you want *negative* high-voltage pulses. With the previous circuit you're stuck with positive polarity only, because the low-side driver's COM terminal must be close to logic ground. But you can circumvent this limitation by using a dual driver in which both outputs are fully HV isolated, as in Figure 3x.113. Here we've used a dual optocoupler from Avago, with logic-level outputs (5.5 V maximum), pretty good speed ($t_p \approx$40 ns), isolation to 1 kV, and slew rates[110] to 20 kV/μs. Because the optocoupler's output is intended for driving logic (i.e., 5 V swing, and 10 mA maximum), we add TC4420 gate drivers to bring the gate-drive swing to 10 V, and with sink or source peak currents to 6 A. That should do the job!

Because both drivers and their floating supplies are fully isolated, polarity reversal is as simple as switching which terminal of the HV supply is connected to ground. Here we've used a mechanical relay for the job, energized by the polarity input choice. Relays are slow ($\sim$ milliseconds), and so this circuit is not intended for rapid polarity reversals (for example, in a train of pulses of alternating polarity). We'll address that challenge in the last example of this section (§3x.15.5 on page 249).

The rest of the circuit is straightforward, and to save space in the drawing we've omitted some details: the gate drive resistors and diodes, the HV fuse and peak current limiting inductor, the direct (low-Z) output, and provision for an external HV capacitor.

3x.15.4 Output monitor

For most applications of these pulsers you'd like to know the actual output waveform, delivered at manageable 'scope voltages (say within a range of $\pm$10 V), and with enough fidelity to reveal details at the rapid timescales of the pulse waveform ($\sim$10 ns). A simple 100:1 resistive divider will not do the job, because (just as with a 'scope probe) stray capacitance distorts the waveform. But, as with a 'scope probe, we can compensate the stray shunt capacitance of the upper resistor with a trimmable capacitor across the lower resistor, as in Figure 3x.114.

Here we've chosen a precision high-voltage resistor for R_1, forming a 100:1 divider with R_2. Compensation capacitor C_2 combines with the estimated $\sim$0.05–0.1 pF self-capacitance of R_1 to maintain the 100:1 divider at high frequencies; you trim it for best waveform fidelity, in the manner of 'scope probes. The 2 MΩ value of R_1 may seem surprisingly low – for example, it dissipates 0.5 W at V_{out} = 1 kV. But, as in engineering generally, its value

[110] This specification is the minimum common-mode output slew rate for which the output state is guaranteed to be correct.

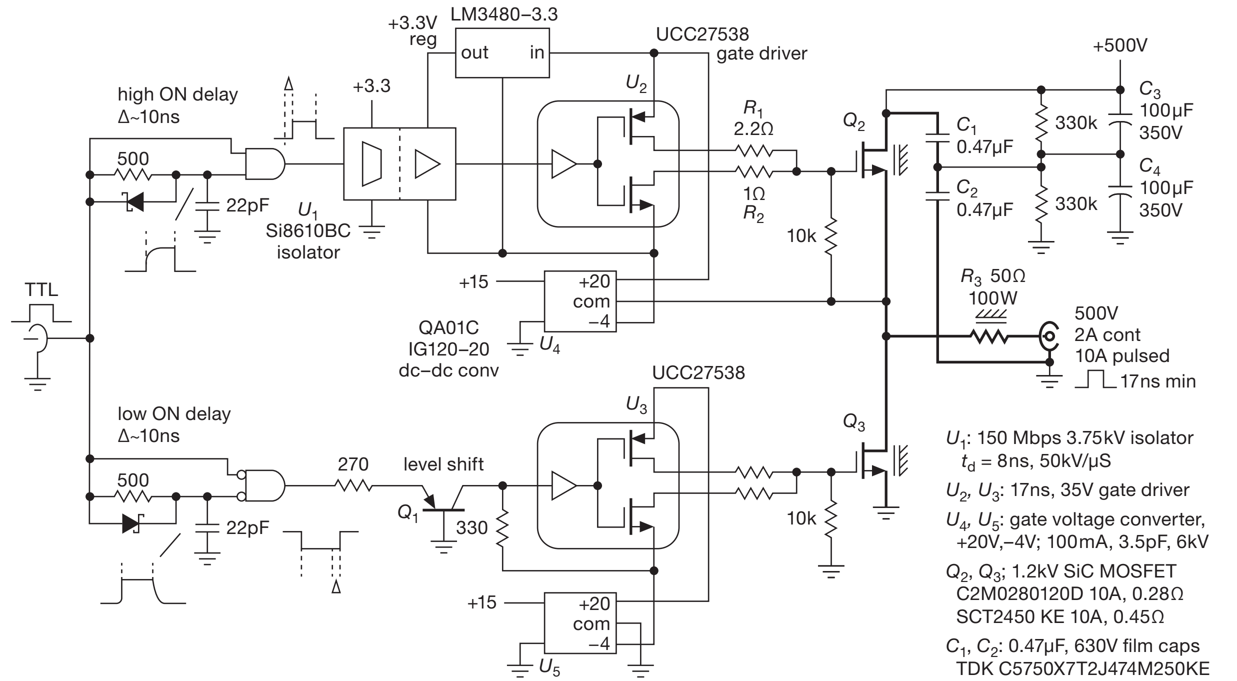


Figure 3x.111. Fast 500 V 10 A unipolarity pulser. The low capacitance of silicon carbide MOSFETs Q_2 and Q_3 allows the use of fast low-power drivers U_2 and U_3 and associated isolated gate supplies U_4 and U_5.

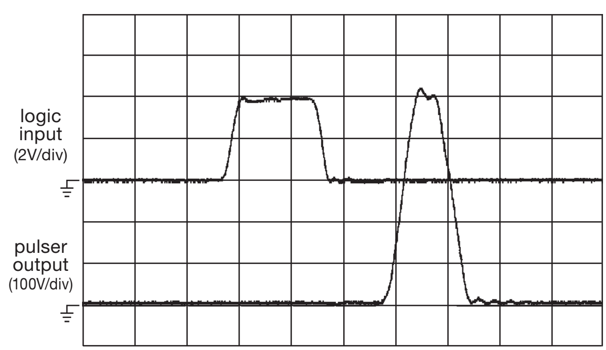


Figure 3x.112. Output waveform (upstream of 50 Ω series resistor) when driving 50 Ω power load. Horizontal: 20 ns/div.

is a compromise, in this case balancing resistor dissipation against the voltage error produced by U_1's input current.

The latter buffers the divided signal (whose source impedance is 20 kΩ, thus unsuitable for any cable or capacitive loading, even that of a high-Z 'scope probe). The LT1363 was chosen for its high speed (> 500 V/μs) combined with relatively low offset current (120 nA, typ), and ability to operate from ±15 V supplies. A 10 V swing into the 100 Ω of the terminated output requires 100 mA, here provided by the wideband unity-gain BUF634 (160 MHz, 2000 V/μs). The latter is muscular (output currents to ±250 mA), but inaccurate (V_{os} = 100 mV, would you believe? It's a muscle-car, with a terrible driver!), so we close the loop around U_1 as shown.

To minimize dc error we match source resistances into U_1 with a 20k feedback resistor (R_3), shunted at signal frequencies by C_4 (crossover at 800 Hz); series resistor R_4 allows C_3 to take over at frequencies above 30 MHz, forming a direct signal path around U_1 for high-frequency stability. The final result is a 200:1 monitor output into a 50 Ω termination that can follow a full-swing 1 kV HV output step in 20 ns (500 V/μs), and with a maximum untrimmed dc offset of 0.7 V (referred to the HV signal); the latter is caused mostly by U_1's worst-case offset current of 350 nA, and could be trimmed to zero with its NULL pins.

This is pretty good, and simple enough. But you can do better, if you want, by separating the low- and high-frequency paths, processing them with optimized amplifiers (for LF: slow, low-bias, accurate; for HF: just fast), and combining the signals into the output buffer. Such an arrangement is some 50× less vulnerable to errors from stray capacitive coupling, and in addition has far better untrimmed dc accuracy.

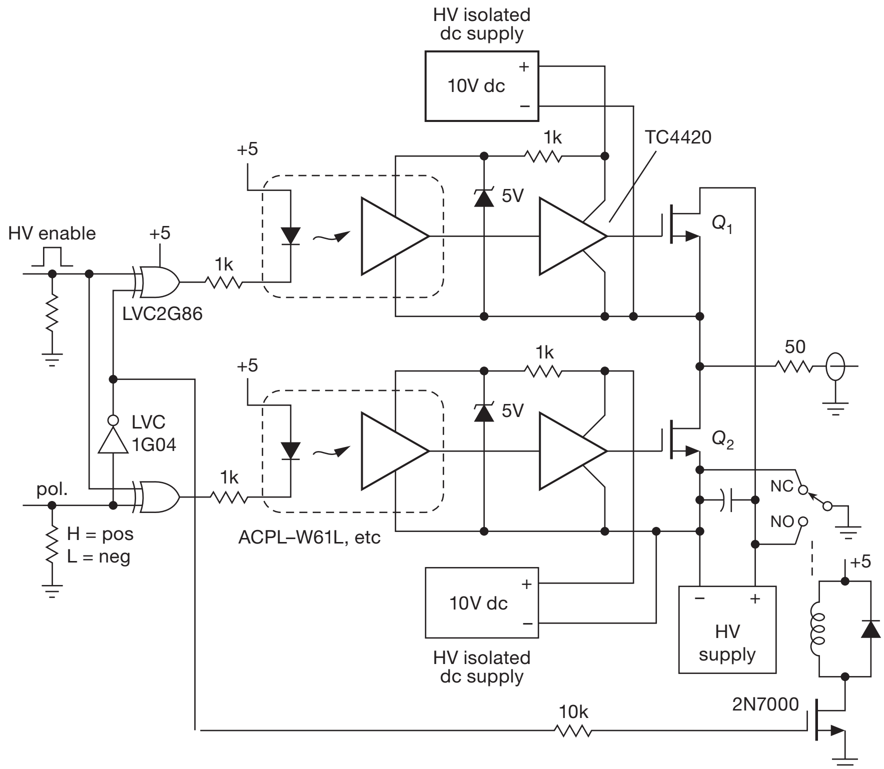


Figure 3x.113. By using a pair of high-voltage optocouplers, each with its own floating gate driver supply, the simple topology of Figure 3x.109 can be adapted to generate pulses of either polarity.

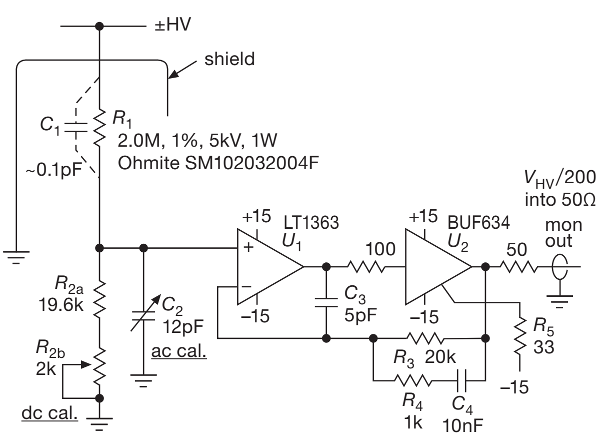


Figure 3x.114. High-voltage output monitor circuit with 30 MHz bandwidth and 10 ns pulse response, suitable for pulses of either polarity to ±1 kV.

3x.15.5 Three-switch bipolarity kilovolt pulser

Finally, with the addition of a third switch element we can make a high-voltage pulser with output pulses of either polarity, switchable at full pulser speed. Figure 3x.115 shows the scheme. Here we've used the elegant ADuM6132 half-bridge driver,[111] which incorporates internal transformer-coupled high-side isolated dc supply and driver, with 15 V output swing and ±200 mA drive capability. For faster switching we've appended TC4420 gate drivers, powered by the same isolated dc.

The middle switch may confuse. The *n*-channel MOSFET series pair Q_3Q_4 act as a bidirectional switch: when the gate is driven high, both switches are in conduction, bringing the output back to ground from its previous residence at either polarity. The body diodes (present in all power MOSFETs) are drawn explicitly here, so you can see that nothing bad happens when one of the series pair experiences reverse polarity: The body diode carries the reverse current if $I_{out}R_{ON}$ would be greater than a diode drop, otherwise the MOSFET is quite happy to conduct in the reverse direction. As with Figure 3x.113, we've omitted details such as the non-overlap delay circuits at the input, the

[111] It has also a matched non-isolated low-side driver, sitting idle in this application.

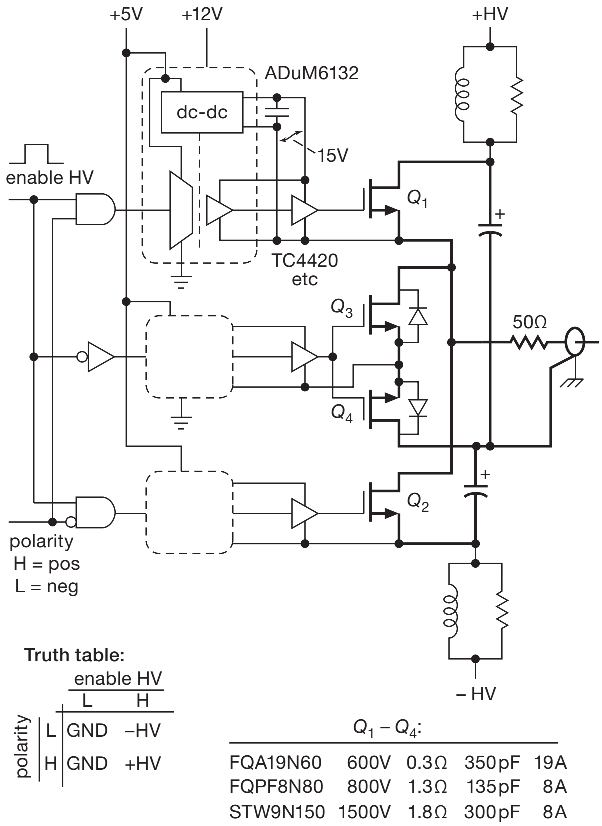


Figure 3x.115. A third electronic switch to ground (series pair Q_3Q_4) permits rapid generation of pulses of either polarity (or from one rail to the other), to be contrasted with the slower polarity switching (via mechanical relay) of Figure 3x.113.

Table 3x.5: High-Voltage Half-Bridge Drivers[a]

Part #	V_S^m HV (V)	I_{out}^t pos (A)	I_{out}^t neg (A)	Delay t_{on} (ns)	Delay t_{off} (ns)	UVLO[m] (V)	HI & LO inputs	Shutdown	Separate GNDs[v]
IR2113[p]	600	2.5	2.5	120	94	9.7	•	•	±5V
FAN7392	600	3.0	3.0	130	150	9.9	•	•	±5V
FAN7390M1	600	4.5	4.5	140	140	9.8	•	-	±7V
IR2101[i]	600	0.13	0.27	160	150	9.8	•	-	no
NCP5111	600	0.25	0.5	750	100[d]	9.9	-	-	no
FAN7382	600	0.35	0.65	170	200	10.0	•	-	no
IRS2108[e]	600	0.12	0.25	220	200[e]	9.8	•	-	±5V
IRS2109[e]	600	0.12	0.25	750	200[e]	9.8	-	•	±5V
IR2213	1200	2.0	2.5	280	225	11.7	•	•	±5V
with de-saturation detectors									
IR22141	1200	2.0[s]	3.0	440	440	11.4	•	•	±5V
self-oscillating									
IR21531	600	0.21	0.42	osc1[o]		9.9	-	•	-
NCP1392	600	0.5	1.0	osc2[o]		12.0	-	•	-
transformer-coupled									
ADuM6132	2500	0.2[u]	0.2	60	60	12.3	•	-	no

Notes: (a) all have isolated high-side driver; all accept "TTL" input logic levels, and most have Schmitt-trigger inputs. (d) 650ns deadtime. (e) IRS2108 and IRS2109 have 540ns deadtime; the '21084 and '21094 variants are deadtime programmable to 5μs. (i) IR2102 for inverted logic. (m) maximum. (o) osc1: 555-type oscillator, to 100kHz; osc2: to 480kHz. (p) IR encourages use of their IRS-series, rather than IRxxx parts. (s) 8V desaturation detector, causes shutdown after 10μs. (t) typical. (u) includes 15V 22mA floating supply, add capacitor and gate-driver IC. (v) for logic input and LOW driver output; i.e., separate V_{SS} and COM pins.

gate resistors and diodes, the HV fusing, the direct (low-Z) output, and provision for an external HV capacitor. For more details, inquire about our RIS-688.

A high-voltage switch with three states is unique. One of our colleagues (Gabriel Hosu) made a 1.5 kV version of this circuit for his experiment. He was using an EO (Electro-Optic) deflector, with a pinhole, to make a fast laser-light shutter. For the required deflection he needed to apply 1500 V, but the EO restricted him to 750 V, so he switched it with ±750 V. The manufacturer also warned against a shortened EO lifetime if it was kept at high voltage for long durations, so he had his program set the 3-state switch to zero except when his experiment momentarily needed fast shutter operation (and a mechanical shutter was used the rest of the time).