[HowTo] Kilowatt control.
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Power control remains a challenging prospect, but the low cost and high integration of modern semiconductors makes the prospect of driving kilowatts feasible, even for undergraduate projects on a shoestring budget.

Before you can start to design your power handling stage, you need to be cognisant of the behaviors of your load. In general, most loads you drive will be resistive, the trivial case, or inductive, reacting to a change in current with a sharp change in voltage. There are some loads including electroluminescent panels, LEDs, and motors running out of spec, who demonstrate capacitive current surges in response to a change in voltage. These loads will not be discussed further.

Inductive loads principally behave as a small resistor in series with a large inductor. This operates as a one-pole system with a time constant of the inductance over the equivalent series resistance. When voltage is changed, current slowly rises to the limit of the equivalent series resistance with a time constant of tau=L/R. The issue comes when current is changed rapidly, like when a load is switched off. When a current flow is stopped, the collapse of the magnetic field in the inductor induces a current flowing in the opposite direction. This current, unless properly handled, can develop voltages high enough to damage or destroy attached parts. As a result, the output of switching stages typically feature a combination of passive components - resistors, capacitors, and diodes, to ensure a low-impedance path to the voltage supply rails and prevent dangerous voltages from building up.

There are a broad array of semiconductor devices available for switching currents across a wide range of voltages. An abbreviated list, including functional notes, can be found below.

- SCRs or silicon controlled rectifiers, typically used for unidirectional current pulse applications, but feature high voltage ratings and high switching speeds.
- TRIACs are related to SCRs, but can be used for controlling current flow in both directions. Like SCRs, they shut off with a current flow near zero. This makes them useful for switching alternating current, and they are used extensively in 120VAC light dimming applications.
- BJTs, or bipolar junction transistors, were the first transistor mass produced, and were the only option available for power applications until FETs showed up in the open market at the end of the 20th century. They do not see much use for power applications in today's world.
- Darlington pairs are created from BJTs and were the tool of choice for medium-range power applications until low-end FETs showed up. The TIP120 and TIP125 are common in undergraduate classrooms.
- Insulated gate bipolar transistors, or IGBTs (pronounced ig-butts,) are the tool of choice for high-power, high-voltage applications in the ten to hundred kilohertz switching speed

range. They combine a FET and a massive bipolar transistor to deliver reasonable switching characteristics. They're commonly found on the secondary market, and as such tend to be used in a wide range of hobbyist projects. Their frequency restrictions and high cost on the primary market makes them less interesting than our next entry, and as such, they will not be the focus of this article.

- FETs, or field effect transistors, are your new best frienemy. They're fairly fragile, prone to both spectacular (explosions!) and obnoxious (fail-short) failure modes, but deliver a price-per-watt, price-per-amp, price-per-hertz, and efficiency unparalleled by any of the previously mentioned devices. They come in two primary flavors, nmos and pmos, with nmos being the most common, the cheapest, and generally the all-around best choice for switching applications.

For this application, FETs can be thought of voltage-controlled voltage-switches with a static "on" state resistance. They're three terminal devices with the drain-to-source conductance controlled by a gate pin. When the gate to source voltage is sufficiently high, the FET turns on, and has a resistance, R_ds, which is approximately static across most voltage combinations. This number is given in the datasheet, and usually includes a gate-to-source voltage and a drain-to-source voltage. So far, so these parts look pretty convenient, but it's only downhill from here. The gate of your FET acts like a capacitor to your source pin, with extremely low series resistance. This means that you must charge up you this capacitor every time you switch your load. This capacitor can be charged very fast, but all energy stored across it is wasted as heat. Additionally, driving the gate requires some care, as large currents can be sunk at high switching speeds (potentially damaging the driver,) and the gate-to-source voltage must be positive, increasing difficulty of use for high-side switching applications, with the nFET between the voltage source and the load. While the gate-source voltage is increasing, the nFET enters and exits a region of operation where the drain-source resistance is approximately directly proportional to the gate-source voltage, resulting in the FET acting like a large resistor. The power dissipated across the resistor is V**2/R, meaning that when the FET is in the linear region, it dissipates far more energy as heat than when it's fully "on," in saturation. Thus, care must be taken to drive the capacitor-gate of the nFET from "on" to "off" as fast as possible, lest the device overheat in the linear (or ohmic) region.

From the top:

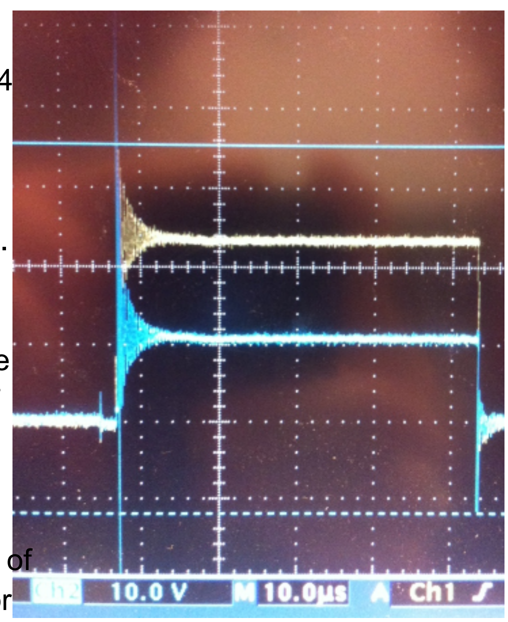
- voltage-controlled voltage-switches
- gate = "high"
- source = "low"
- gate = "capacitor"
- gate-source voltage must be sufficiently high to turn the device on
- change gate-source (capacitor) voltage fast to keep the device from getting hot
- R_dson tells you steady-state drain-source resistance (and thus power dissipation), of the device in saturation - get from datasheet

That's a long list of requirements, but fortunately, we have a powerful ally in our fight against the gate.

Enter.... the monolithic gate driver IC!

As FETs became more popular, semiconductor manufacturers focused on ease of use. With nFETs harder/better/faster/cheaper than pFETs, users needed an easy way to satisfy the gate voltage and current demands of their switching components. Simply put, gate-drivers use a diode, a capacitor, and a connection to the source of your high-side nFET to create a voltage above the drain (high-side) voltage. They typically do this by stacking the supply voltage of the chip (typ: 5-12V) on top of the source voltage. This concept is called "bootstrapping" and very common on modern FET drivers. This neat trick comes with a few caveats. First: the FET driver must have an electrical connection to the common output node of your two nFET half-h bridge. Second, the current used for driving the gate switching is stored in an voltage across an external capacitor, and leakage currents on the gate of the FET will discharge this capacitor over time, making bootstrapped FET drivers less well suited to applications with extremes of duty cycle in either direction.

While bootstrapped FET drivers solve our biggest issue of gate-source voltage, they still don't make gate drive a trivial endeavor. Remember that the gate-source characteristics are like that of a small, low-equivalent-series resistance capacitor. This yields a system with a very short time constant, but capable of sinking large amounts of current for appropriately short periods. When coupled with an inductor, such as that afforded by a sufficiently long piece of wire, pronounced ringing can occur at the resonant frequency given by F=1/(2*pi*sqrt(L_lead*C_gate). The following image shows this effect:



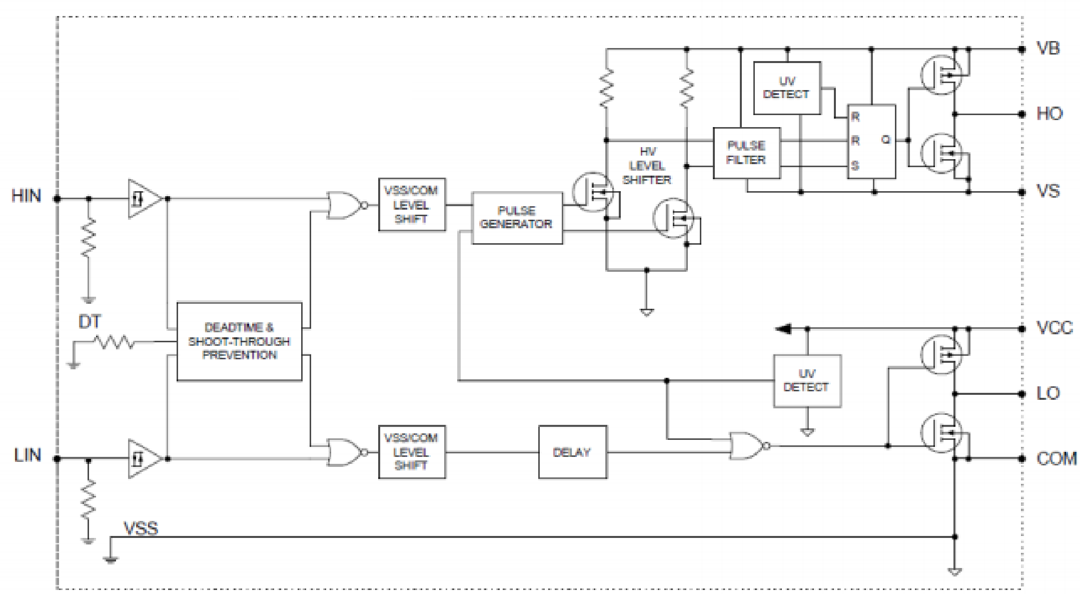
In this image, a power FET with a gate capacitance of 2154 picofarads was driven by an IR25606 bootstrapped gate driver through a 7cm wire. A 10 ohm series resistor was added to attempt to damp gate the parasitic high voltage oscillations, but this did not substantially modify the results. Only after the gate lead was reduced to 3cm and the resistance was increased to 100ohms did the oscillations cease. Note that the addition of a 100ohm resistor increase the gate charging time constant from 2e-8 seconds to 2e-7 seconds, but in practice this proved to be irrelevant.

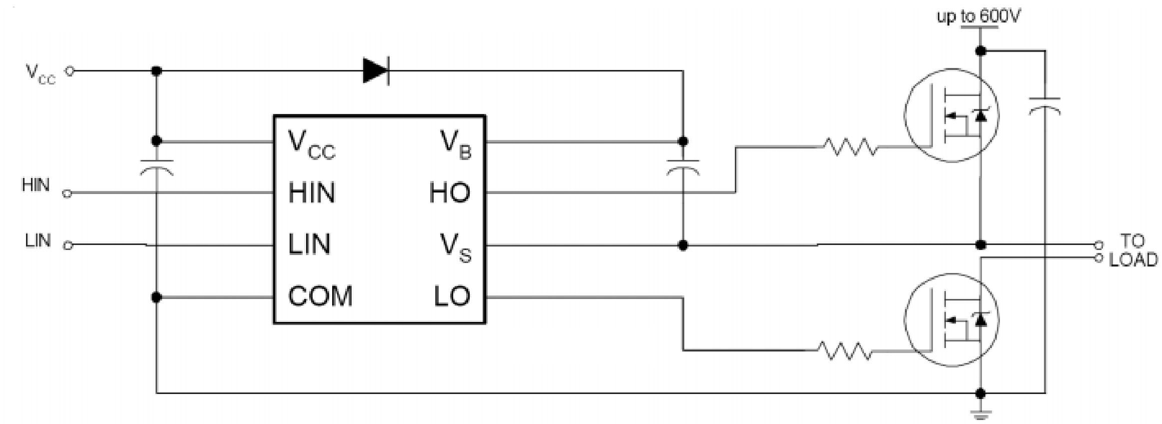
Should you encounter gate drive oscillations, endeavor to minimize the length of the connections between the output of your gate driver and the gate of your nFET. Additionally, for bootstrapped systems running off 12v, the addition of a 13v zener diode clamp from gate to source can typically effectively squeltch higher voltage oscillations. Should neither of these

solutions deliver satisfactory results, the addition of a 1kilohm or smaller gate drive resistor will decrease the peak current delivered to the gate, and thus the reactive current delivered by the parasitic inductor, without substantively reducing the system's drive efficiency.
When attempting to drive a capacitive load like the gate of a FET, the required current increases with frequency, which is limited by the series resistance of the drive circuitry. The current required to drive a gate can be calculated by multiplying the gate charge (from the datasheet) by the required switching frequency. The average power dissipated by switching can be calculated by P=C*F*Vgs. When selecting a gate driver chip, ensure that the current requirements of your FET at the desired frequency are 10x below the maximum current handling capability of the chip.

Most driver chips, and more importantly drive systems, have asymmetric high-low characteristics. This can mean that your high side and low side FETs do not switch on and off at the same rate. To prevent shoot through, when both FETs conduct simultaneously, resulting in excessive current draw and power surges, the addition of dead-time between the attempted turn-off of the active FET and turn-on of the previously non-conducting FET is usually a good idea. Many driver chips offer integrated deadtime, typically in the range of 100ns-1us, small enough to not substantively modify the drive waveform from ideal, but large enough to prevent cross-conduction. If your driver doesn't offer integrated deadtime, look for advanced waveform functionality in whatever device you're using to input control waveforms to the driver.

A block diagram of a bootstrapping FET driver from the IR25606 datasheet:





Wiring diagram from the IR25606 showing gate drive resistors, bootstrap diode / capacitor, decoupling capacitor, and pair of nFETs in a half-H configuration.