# *E-Match Igniter User's Guide and Design Overview*

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*If you wish to forgo this design and create your own igniter circuitry, please read the section on MOSFET gate drivers on page 5 at the very least.*

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## Introduction

This user's guide for the electronic e-match igniter created during the 2018/2019 SkyPilot avionics development program is written so future UBC Rocket teams do not need to create and validate new e-match igniter circuits. This igniter circuit flew on SkyPilot in June, 2019. While the main parachute failed to deploy during that flight (due to reasons unknown to the author of this paper as of August, 2019), the drogue parachute successfully deployed, and this igniter passed 100% of its pre-flight tests (~25 test fires).

### *Firing e-matches*

An e-match is ignited when sufficient current passes through the pyrotechnic tip of the match. This current is specified in the e-match manufacturer's documentation. E-matches are of very low resistance (~ 1-2 Ω), so connecting one end to ground and one end to a battery of sufficient voltage ( > ~ 7 volt) is usually more than enough to fire them (as per Ohm's law). This will only fail to ignite the match in the case of a discharged battery or a faulty e-match.

### *Electronic Control*

While e-matches are not difficult to ignite, problems become apparent when you consider the requirements of an e-match ignition system. The system needs to be electronically controlled by a microcontroller/microcomputer. The system needs to be light to keep its weight penalty to a minimum. The system needs to be efficient to reduce current draw on the battery system.

### *Design Decisions*

While a relay would work for the job, it is heavier than a MOSFET-based solution and requires a higher continuous current to fire (usually >30mA to operate the relay, vs no current for the MOSFET + ~10-15mA for the opto-isolator). A bipolar junction transistor-based solution is also possible but power electronics have been trending towards using MOSFETs since the 1980s.

Your first introduction to an opto-isolator driving a MOSFET would probably be first in ELEC 291. While logic-level MOSFETs are seen in ELEC 201, 301, 315, 402 and 403; it is not until [1]ELEC 451

[1] ELEC 451 with Ordonez might have been the best course I took at UBC, I highly recommend taking it

Power Electronics that issues specific to driving higher voltage and current MOSFETs are examined in detail.

## Brief Overview

The igniter circuit, as shown below, is fired with one digital output pin from a microcontroller (in addition to the shared ground, but current paths and star grounding techniques are outside the scope of this paper). This pin drives the LED in the optoisolator, whose photons drive the transistor in the optoisolator. This transistor connects the battery voltage (or other suitably high voltage level) to the gate of the MOSFET, and turns on the MOSFET. The MOSFET then "connects" the other end of the e-match to ground, and completes the current path through the e-match from the battery to ground. With a battery voltage around 11V, approximately 5-6A will flow through the e-match. After a short delay (~20 ms) to allow for the e-match to fire, the optoisolator (and the MOSFET by extension) should be switched off.

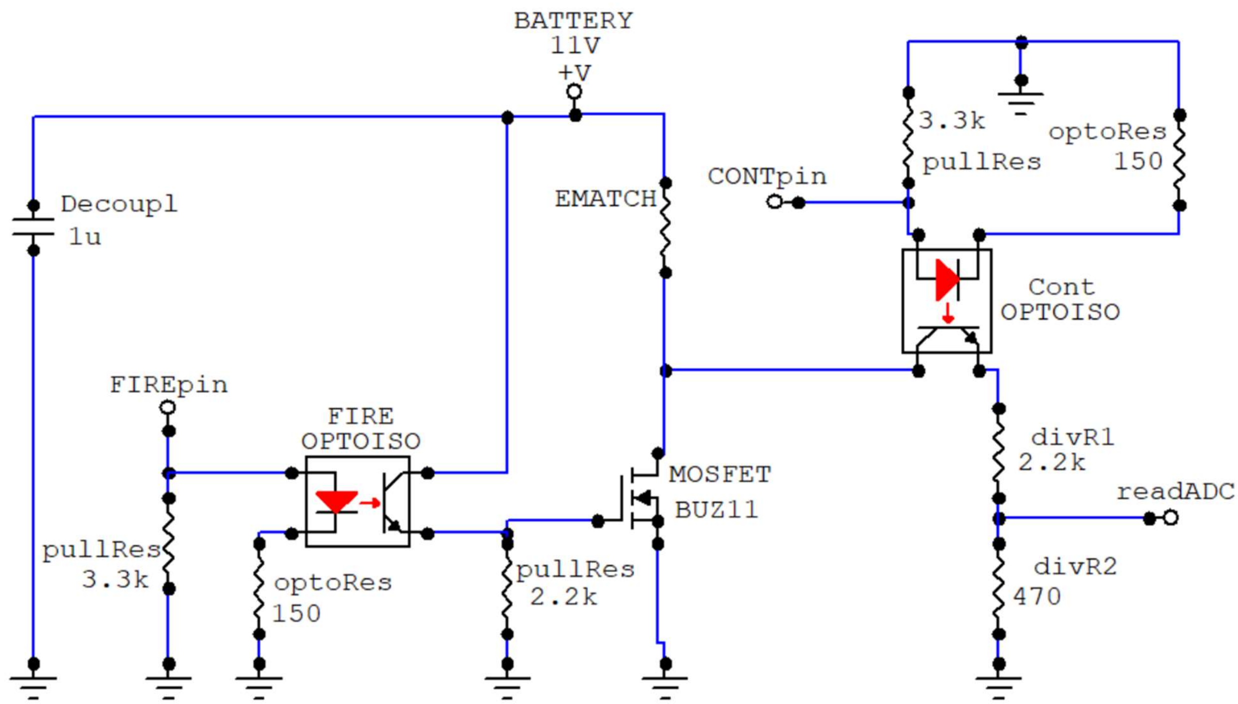
The continuity of the e-match is checked by activating the continuity check optoisolator. This serves to connect the ematch (and battery voltage behind it) to the continuity check voltage divider. The voltage at the midpoint of the voltage divider is then read with an ADC pin on the microcontroller. This value is compared to a calculated threshold that indicates a continuous and functional e-match.

## Off the Shelf Usage

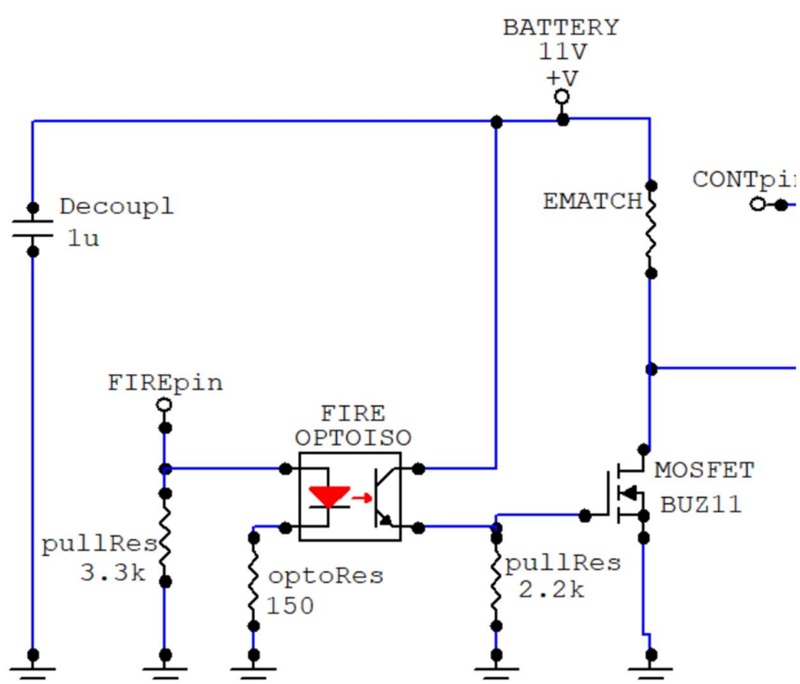
If you are using a battery ~ 11 volts, a microcontroller operating at 3.3V and do not wish to re-spec the components for the circuit - use the resistor values shown in the schematic below, in conjunction with the following components:

MOSFET - BUZ11 or IRLB8721PbF (for use with a maximum 20V battery)
Optoisolator - LTV-8x7 (where x is the number of channels 1, 2, or 4)

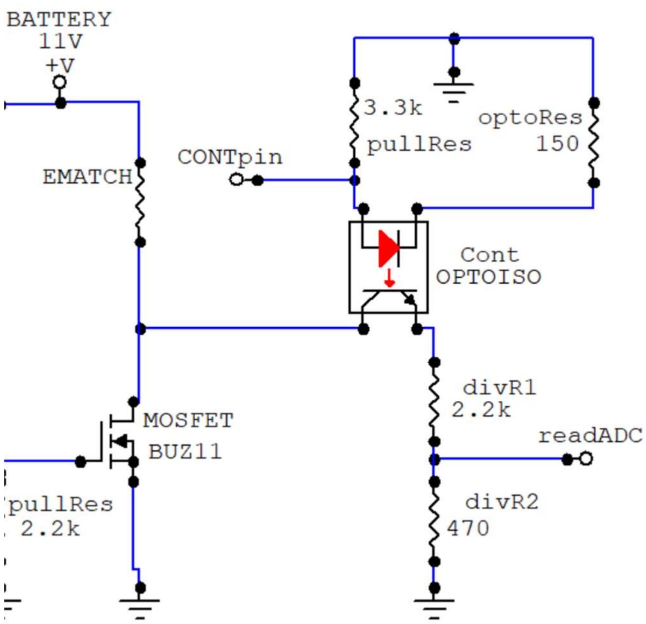
## The Igniter




***Fire Circuit:***



***Continuity Check Circuit:***




# Optoisolator

***Overview and Usage***

Optoisolators consist of an LED and phototransistor integrated into one package. As the transistor is controlled with photons instead of the typical current or voltage, it allows the controlling circuit to be electrically isolated from the controlled circuit. However, electrical isolation is not the issue that we are solving with the use of optoisolators in this circuit.

The advantage of using optoisolators in this circuit is their ability to be switched without having to bias the base of a BJT relative to its emitter. We can use the switching capabilities of the optoisolator at any voltage reference point in our circuit, and they will not switch off if the voltage at the emitter rises to the voltage of the battery.

***Selection Criteria***

Looking at the datasheet for optoisolators, there are a few criteria that must be met.

1) Collector-Emitter Voltage ($V_{CEO}$) > maximum battery voltage
2) Minimum Current Transfer Ratio (CTR) > 50% (well over 100% is ideal)
3) Response time -> any speed you are comfortable having it switch at, quicker is better.

# N-channel MOSFET

### *Overview and Usage*

The Power MOSFET is the component that directly controls firing the e-match. This is the crux of the igniter circuit, and is the most important component to spec properly. As with any n-channel MOSFET, a voltage applied at the gate pin (relative to the source pin) will "turn on" the transistor and allow current to flow from the drain to the source.

### *Why do we need a gate driver?*

The function of a gate driver is to switch a device from off to on and back. Minimizing the turn-off and turn-on times is usually the goal in order to keep the device in the active transition region for as little time as possible. A large initial current is required to shuttle enough charge to the gate to turn on a MOSFET quickly. After this initial current inrush (during the turn on period), only a large gate-source voltage is required to maintain the on-state of the MOSFET.

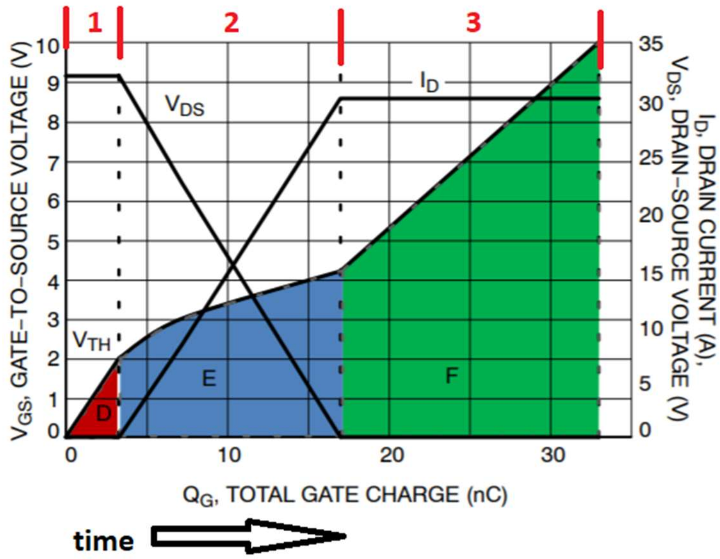
A microcontroller pin has no trouble operating logic-level MOSFETs as they are designed with a low turn on voltage ($V_{GS\ (TH)}$) and operate at lower voltages and currents. Higher rated power MOSFETs require turn on voltages that either exceed the voltage or current delivery capabilities of microcontroller pins (typically with a threshold gate-source voltage ~ 5V, with a fully on gate-source voltage > 7 V). These MOSFETs also require about 0.2-0.6A (or more, depending on the MOSFET specifications) of drive current for the duration of the turn on rise time (about ~100ns), which exceeds the capabilities of microcontroller GPIO pins (See *Appendix A* for a sample calculation).

What happens if this drive current is insufficient? Who cares if the MOSFET takes a little longer to turn on? As with any electrical device, their operational lifespan is related to how cool they run. MOSFETs only heat up (with the exception of the on resistance of the drain-source channel) when they are switched, for the duration of that switch.

When MOSFETs are switched on with a resistive load (this analysis does not hold for an inductive load), they go through 3 distinctive phases in order. For the purposes of the graphs below, the first phase is shown as section D. The 2nd is section E, and the 3rd is section F.

1. The gate-source voltage ($V_{GS}$) rises from 0. No conduction occurs until $V_{GS}$ reaches the threshold voltage $V_{GS\ (TH)}$.
2. The MOSFET begins to conduct, and the current passing through the device $I_D$ begins to rise to its maximum while the blocking voltage $V_{DS}$ begins to fall to its minimum (near 0).

3. With sufficient charge placed on its gate, the MOSFET channel has fully formed and it is completely on. The MOSFET is allowing maximal current to pass through it with minimal voltage drop between the drain and the source.




In regions 1 and 3, very little power is dissipated across the MOSFET. Either no current is flowing through the transistor, or there is no voltage drop across the drain and source. It is in these regions that you want your MOSFET to operate in as much of the time as possible.

In region 2, the MOSFET is dissipating a large amount of power (and therefore heat). There is current flowing through the MOSFET as well as a voltage difference between the drain and the source. In the chart above, the MOSFET is dissipating ~ 60W where the $V_{DS}$ and $I_D$ lines meet at the 'X'. In the igniter circuit, this maximal power dissipation is about 18 W.

If you attempt to drive the gate of the MOSFET with insufficient current (even if your microcontroller provides a voltage > $V_{GS\ (TH)}$, the MOSFET will be stuck in hell (region 2) for an extended period of time. Even if it is enough to turn on the MOSFET, it prolongs the time it spends dissipating heat. At least one MOSFET early in the 2018/2019 SkyPilot campaign explosively met its end this way.

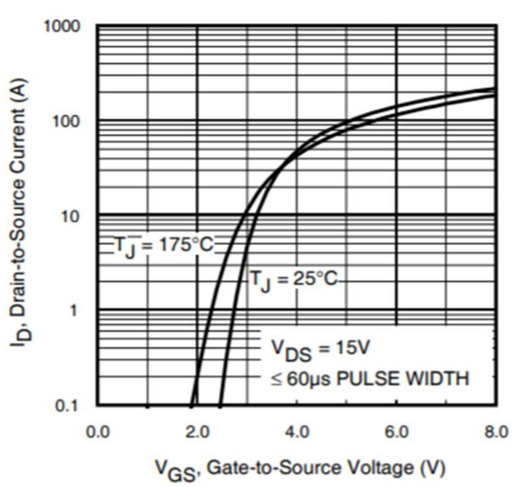
More can be read about drive circuits online or in chapter 2.11 and chapter 26 of Power Electronics: Converters, Applications, and Design 3rd Ed. by Mohan, Undeland, and Robbins (and you'll probably redesign this entire circuit if you read this text).
https://www.powerelectronictips.com/mosfet-drivers-need/ also serves for a quick and easy overview of the problem.

***MOSFET Selection Criteria***

Looking at the datasheet of prospective power n-channel MOSFETs, there are a few criteria that must be met.

| | Parameter | Minimum | Maximum | Notes |
|---|---|---|---|---|
| $R_{DS\ on}$ | Drain-to-source on resistance | | < 50mΩ | Minimize this for increased fire current |
| $BV_{DSS}$ | Breakdown drain-to-source voltage | >> battery voltage | | |
| $V_{GS}$ | Gate-to-source voltage | | > battery voltage | |
| $V_{GS\ (TH)}$ | Gate-to-source threshold voltage | | << battery voltage | As low as possible (least important parameter in this design) |
| $I_D$ | Continuous drain current | | > 3 x design fire current | ~ 20A min usually |
| $t_{d\ (on)}$ | Turn on delay time | | < 20 ns | |
| $t_r$ | Rise time | | < 150 ns | |

In addition to the above in the MOSFET datasheet, read the Vgs vs Id curves (ex. below) and verify the current pass through at the Vgs you are planning to operate the MOSFET at (battery voltage in this case).



## Pulldown Resistors

The pulldown resistors on many pins and gates are there to ensure that the voltage at those points do not float. This is to make sure that the system does not inadvertently fire. Pull up/down resistors need to be sized with a couple factors in mind. Lower R values result in higher current losses, but provide a stronger pull to the voltage of the rail. Lower R values also result in a quicker voltage response (smaller RC constant). The following articles give a good overview of pull up/down resistors and what to consider when sizing them.

https://learn.sparkfun.com/tutorials/pull-up-resistors/all
http://www.ti.com/lit/an/slva485/slva485.pdf

## Continuity Check

The continuity is checked by connecting the ematch to a voltage divider. The operation of the optoisolator completes a current path between the battery, through the e-match, and into a voltage divider. The voltage in the voltage divider can then be read by an ADC pin on the microcontroller. By characterizing the voltage of the e-match and transistor, one can design the voltage divider to drop the voltage below the maximum threshold of the microcontroller, and read it with the ADCs built into the microcontroller.

***Response time***

The response time of the ADC check is governed by the RC constant of the branch. In testing, the ADC was ready to read within 20 microseconds of the continuity select pin going high.

***Threshold Checking***

The resistors in the voltage divider must satisfy the following conditions:

1) $\frac{R_2}{R_1+R_2} <= \frac{V_{microcontroller\ maximum}}{V_{battery\ maximum}}$

2) $\frac{V_{battery\ maximum}}{R_1+R_2+R_{ema}} < I_{ema} \quad no\ fire$

The expected Analog Digital Converter value of a continuous e-match can be found as follows:

Expected ADC value $= \frac{R_2}{R_1+R_2+R_{ema}} \times V_{battery} \times \frac{ADC\ Resolution}{V_{microcontroll}}$

There should be a buffer below the expected value to allow for variations in resistance (temperature, manufacturing, etc…) but not with so much slack that a bum ematch passes the continuity test.

***Limitations***

The continuity check of the e-match cannot detect shorted e-matches. The resistance between a short (negligible) and a functional ematch (~ 1-2 Ω) is difficult to detect while both maintaining a current below the no-fire limit and reducing the check voltage in the divider below the maximum threshold of the microcontroller.

## Code

Sample code and a version of the igniter driver for use with a Teensy 3.6 or Arduino microcontroller can be found at https://github.com/a-duen/Ematch-Igniter

## Usage warnings

Power electronics, and MOSFETs in particular work least effectively in their linear ranges of operation. This means that they need to be fully on or completely off, with as little time as possible spent in the turning on or turning off phase.

### Nichrome Cutting Wire

If you want to utilize this circuit to control nichrome wire cutters, do not try to throttle the MOSFET with a PWM (pulse-width-modulation) signal at the control gate of the optoisolator. The optoisolator takes ~4us to turn on and your PWM signal may not turn the MOSFET on and off as you expect. Accurately measure the resistance of the wire and how it changes with temperature, and the on resistance of the MOSFET. Control either the length of time that the MOSFET is on (in one shot), or the resistance of the wire/MOSFET branch. An alternative is a circuit redesign to utilize logic-level MOSFETs or a gate driver chip to drive the power MOSFET (which have significantly quicker response times), where you can utilize PWM switching to throttle the current in the wire cutter.

## Future Development

### *Short Circuit Detection*

The current system is unable to detect short circuited e-matches. This is not a major problem, as e-matches tend to fail open rather than short. It is also quite difficult as the resistance of an ematch is relatively close to the resistance of a short circuit.

### *Improvements on this circuit*

This circuit was designed very late in SkyPilot's project cycle over the course of one afternoon, so there definitely are ways in which this design can improve. Immediate design changes like lowering the 2.2k pulldown resistor on the MOSFET gate to ~1k will more than halve the turn on/off time of the MOSFET. More advanced changes like adding a comparator/schmitt trigger or push-pull to the optoisolator can drive the MOSFET on and off with even more gusto. A typical drive circuit will include a dedicated gate driver IC between the optoisolator and the MOSFET gate (or even without an optoisolator). The textbook referenced above would be invaluable in designing new gate driver circuitry (and I wish I had read those chapters before I designed this circuit).

## Questions

This circuit is fairly straightforward, but if you have any further questions most upper year Electrical Engineering students should be able to deduce the design decisions made here. If there are still questions about the circuit, you can contact someone on the 2018/2019 SkyPilot avionics sensors team.

## References

https://learn.sparkfun.com/tutorials/pull-up-resistors/all
http://www.ti.com/lit/an/slva485/slva485.pdf
https://www.powerelectronictips.com/mosfet-drivers-need/
Power Electronics: Converters, Applications, and Design 3rd Ed. by Mohan, Undeland, and Robbins
http://ww1.microchip.com/downloads/cn/AppNotes/cn_00786a.pdf

Datasheets:
https://www.onsemi.com/pub/Collateral/AND9083-D.PDF
https://cdn-shop.adafruit.com/datasheets/irlb8721pbf.pdf

## Appendix A: Sample MOSFET Drive Current Calculations

There are several internal capacitances in MOSFETs (and any other transistor), but the total gate charge is used for the purpose of determining the switching time and the drive current needed.

These calculations are heavily approximated because I'm not paid enough.

***IRLB8721PbF Power MOSFET***

Datasheet: [https://cdn-shop.adafruit.com/datasheets/irlb8721pbf.pdf](https://cdn-shop.adafruit.com/datasheets/irlb8721pbf.pdf)

| | | | | | |
|---|---|---|---|---|---|
| $Q_g$ | Total Gate Charge | — | 7.6 | 13 | nC |
| $Q_{gs1}$ | Pre-Vth Gate-to-Source Charge | — | 1.9 | — | |
| $Q_{gs2}$ | Post-Vth Gate-to-Source Charge | — | 1.2 | — | |
| $Q_{gd}$ | Gate-to-Drain Charge | — | 3.4 | — | |
| $Q_{godr}$ | Gate Charge Overdrive | — | 2.0 | — | |
| $t_{d(on)}$ | Turn-On Delay Time | — | 9.1 | — | ns |
| $t_r$ | Rise Time | — | 93 | — | |
| $t_{d(off)}$ | Turn-Off Delay Time | — | 9.0 | — | |
| $t_f$ | Fall Time | — | 17 | — | |

With a worst case total gate charge of 13 nC, and a turn on time ($t_{d(on)} + t_r$) of 100.1 ns, 13nC of charge must be placed on the gate in 100.1 ns.

$I_{drive} = \frac{Q_{gate}}{t_{transition}} = \frac{13\ nC}{100.1\ ns} = 130\ mA$ for the duration of the switch.

***BUZ11 N-Channel Power MOSFET***

Datasheet: [https://www.onsemi.com/pub/Collateral/BUZ11-D.PDF](https://www.onsemi.com/pub/Collateral/BUZ11-D.PDF)

In this case, the gate charge is not specified in the datasheet. Fear not, one can still find the approximate gate drive current. We can approximate the equivalent capacitance of the MOSFET by summing the input, output, and reverse transfer capacitance of the MOSFET.

| | | | | | | |
|---|---|---|---|---|---|---|
| Input Capacitance | $C_{ISS}$ | $V_{DS} = 25V$, $V_{GS} = 0V$, f = 1MHz (Figure 10) | - | 1500 | 2000 | pF |
| Output Capacitance | $C_{OSS}$ | | - | 750 | 1100 | pF |
| Reverse Transfer Capacitance | $C_{RSS}$ | | - | 250 | 400 | pF |

In this case, the worst case capacitance is 3.5 nF.

The total gate charge can be found with $Q_{gate} = (C_{equivalent})(V_{GS})$

For $V_{GS}$, we will use the $V_{GS}$ specified in the turn on time specifications.

| | | | | | | |
|---|---|---|---|---|---|---|
| Turn-On Delay Time | $t_{d(ON)}$ | $V_{CC} = 30V$, $I_D \approx 3A$, $V_{GS} = 10V$, $R_{GS} = 50\Omega$, $R_L = 10\Omega$ | - | 30 | 45 | ns |
| Rise Time | $t_r$ | | - | 70 | 110 | ns |
| Turn-Off Delay Time | $t_{d(OFF)}$ | | - | 180 | 230 | ns |
| Fall Time | $t_f$ | | - | 130 | 170 | ns |

$$Q_{gate} = 3.5\,nF \,*\, 10\,V \;=\; 35\,nC$$

The quickest possible turn on time $t_{d(on)} + t_r$ is 100 ns.

$I_{drive} = \dfrac{Q_{gate}}{t_{transition}} = \dfrac{35\,nC}{100\,ns} = 350\,mA$ for the duration of the switch.