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High Side Switch with Current Sensing

Preface for Reader

Schematic PDF Details,

Page 1
- Remote Interface Communication circuit
  - Connects directly to the remote computer and relays info to the Local (high side switch/current sensing circuit) PCB via the RJ45 connector and CAT6 cable.

Page 2
- Local Interface Communication circuit
  - Connects to Remote circuit via RJ45 connector and CAT6 cable.
  - Located on same PCB as High Side Switch and Current Sensor.

Page 3
- Local current sensing and high side switch circuit
  - Located on same PCB as Local Interface Communication circuit.

Problem

Details from Email

Make any assumptions that you feel necessary about the aircraft design to complete your design. System should be hard-wired to the remote-computer.

Problem Statement

Create a high side load switch and current sensor circuit that can be controlled by a remote computer up to 100 ft away.

- Switch 12-60V DC into RL load.
- Measure load current
- Report it back to remote computer

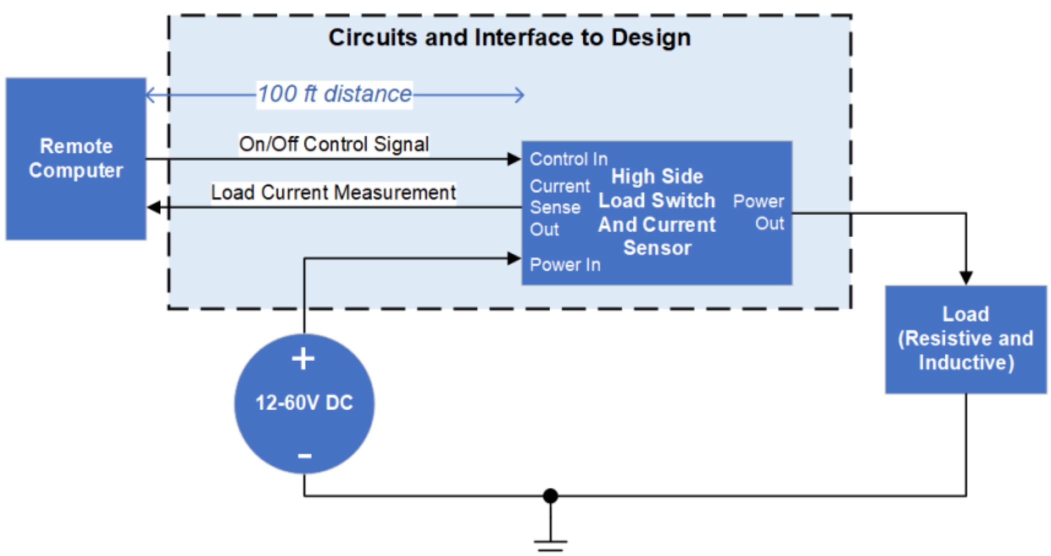

Figure 1

Component Details

Component details given by project instructions PDF.

Load Switch

- Must handle 12-60V DC into RL load.
  - L <= 5mH
  - 10A DC Max through load
- Must be continuously operable
  - f_sw is < 1Hz
  - (no one time use fuses)

Load Current Measurement

- Measure and report load w/ resolution of <= 10mA at 100Hz to remote computer
  - I_load may contain higher frequency content than DC
  - Only unidirectional current sensing needed

Remote Computer Interface

- Remote computer located 100ft away from load switch and current sensing circuits
  - Command ON/OFF switch
  - Report measured load current to computer

Environment of Airplane

- Temperature
  - -40 to +70C ambient temperatures
- Standard atmospheric pressure
- Some potential exposure to conducted and radiated EMI
- Moderate mechanical shock and vibration

Design

What am I designing?

I am creating an over current protection circuit that is able to be monitored and controlled via a hard-wired connection to a central computer interface. The design must account for the environmental conditions of an airplane.

Remote Interface Design

The communication interface that travels the span of 100ft between the remote computer and the high side switch/current sensor needs to be resistant to EMI and be capable of 100Hz bandwidth.

Communication Interface Research

- Ethernet
  - Ethernet and USB both define the physical and application layers as part of their standards. (overhead of application layer doesn't seem necessary)
  - Max cable length: 328.084 ft
    - This gives plenty of overhead
  - Resistant to EMI due to differential signaling
    - Use CAT5E or better cabling w/ shielding
    - Zdiff = 50ohm
  - Use EDF-RR packet scheduling to satisfy FAA safety requirements of flight-critical applications
  - CAT5E has bandwidth of 350MHz so 100Hz update is WELL within range.
- RS485
  - Only defines the physical layer, does not define a frequency bandwidth like Ethernet does because the cabling of the physical layer is not defined like it is in Ethernet.
    - Bandwidth in Hz is guaranteed with Ethernet because they know what medium (CAT5E, CAT6, etc.) that the signal will be traveling through.
  - Master-slave topology where master polls slave, waits for response, and then polls next slave.
    - Deterministic behavior avoids collisions of data packets (good for safety)
  - Frequency bandwidth not guaranteed because dependent on physical implementation
  - +/- 200mV input sensitivity

            - To recognize 1 or must see +200mV and -200mV respectively
    - VERY long length of cable possible
        - 4Mbps at 100ft
    - Differential Signaling (highly resistant to EMI)
    - Using CAT5E for physical cabling between remote computer and the high side switch/current sensing should allow us to achieve close to 350MHz bandwidth (well encompasses the 100Hz)
    - RS485 with UART Implementation
    - Design needs two processors (UART Interfaces)
        - HOST (remote computer)
        - SLAVE (microprocessor that can command gate and read voltage value corresponding to current through node
    - Design needs two RS485 Transceivers
        - 3-5.5V supply range
    - Twisted pair cable (impedance matched, I am going to choose RJ45 connectors and CAT6 cable 100 ohm characteristic impedance)
    - Termination resistors at input to each transceiver.
    - Doesn’t require use of specific bus voltage, only differential voltage.
- RS485 most often used in Half-Duplex Operation
    - Devices take turns using same line where the host will assert control of bus and send command with all other devices listening
    - RS485 Data layer typically impementled w/ UART, so UART is used in half-duplex in these cases
- UART
    - Asynchronous, does not include a clock
    - Host and slave devices must use their own internal clocks
        - Must know at which clock rate data will be transmitted (manually set)
    - “Normal Format”
        - Idle state, voltage high
        - Begin transmission, low pulse for start bit
        - Data, 8 bits following start bit
        - End Transmission, high pulse for stop bit

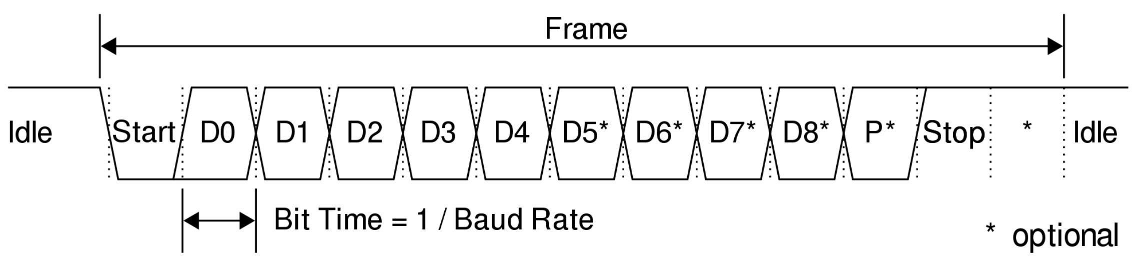

Figure 2

- RS485 implemented with UART
    - Host processor uses I/O pint to put RS485 transceiver in transmit mode then,
    - Sends byte from UART TX line to RS485 transceivers Data (D or DI) line
    - Transceiver then converts UART bit stream into differential bit stream on the A and B lines
    - Immediately after data leaves transceiver, host switches mode of the treansceiver to receive (high impedance tristate)
        - Slave system is identical except sends its data stream on the Host's RX line
    - RS485 allows multiple slaves on bus as the master makes calls to the individual slave devices
        - Accomplished by having slave specific commands or specific addresses, Avoids Collisions

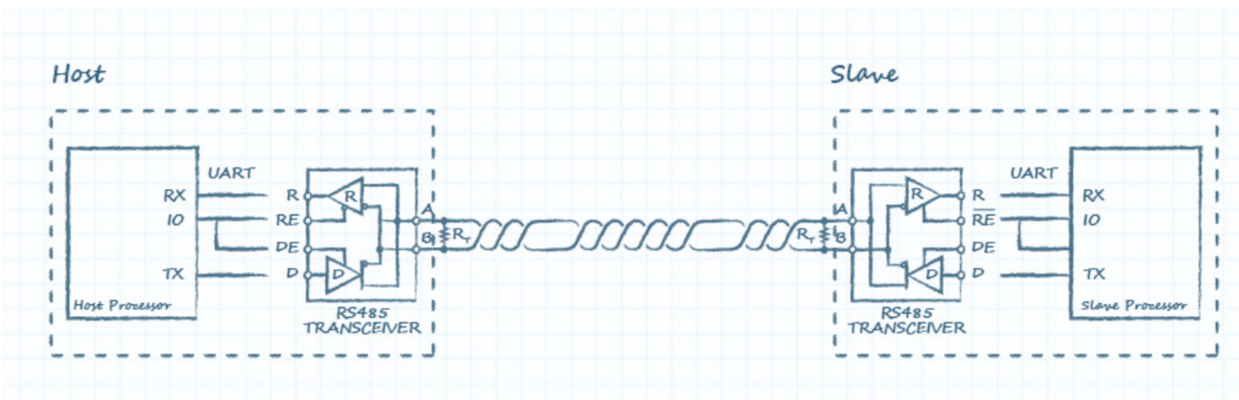

Figure 7: Common use of UART to RS-485

Figure 3

- RS485 Characteristics
    - Max Number of Drivers: 32
    - Max Number of Receivers: 32
    - Modes of Operation: Half-Duplex
    - Max Distance: 1200m
    - Network Topoloy: mulipoint
    - Max Speed @ 12m: 35Mbps
    - Max Speed @ 1200m: 100Kbps
    - Receiver Input Resistance: >= 12k ohm
    - Driver Load Impedance: 54 ohm
    - Min Voltage Diff: +/- 200mV
    - Receiver Input Range: -7 to 12V
    - Max Driver Output Voltage: -7 to 12V

- Min Driver Output Voltage: +/- 1.5V (w/ load)
- Nominal Characteristic Impedance: 120 ohms

Selected Communication Interface

I chose the RS485 communication interface implemented with UART as it seemed to best check the boxes for ease of hardware implementation, robustness to EMI, ability for signaling over long distances, and its flexibility of supply voltage.

Implementation Notes

Nominal Characteristic Impedance for the RS485 transceiver input is 120 ohms. I am choosing to use CAT6 cabling for the twisted pair to travel the length of the 100ft which has a characteristic impedance of 100 ohms. Since there is a mismatch between the transceiver input impedance and the characteristic impedance of the CAT6 twisted pair, there is a design decision to be made to prevent reflections.

Math for Load Reflection Coefficient with 120 ohm termination:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{120-100}{120+100} = 0.09$$

From the Reflection Coefficient being 0.09, this tells us that the voltage of the signal takes a loss of 9.09% in amplitude and that 9.09% will be reflected back towards the input.

Math for Voltage Drop over 100ft run of CAT6 Cable:

$$Vdrop = R_{cable} * I_{receiver} = (4.27 ohm) * (16 mA) = 0.068\,V$$

Worst Case Attenuated Voltage:

$$Vatten = V_{TX} - V_{drop} - V_{TX} * \Gamma_L = 3.3V - 0.068V - 3.3V * 0.09 = 2.935V$$

From the Math above, we can see that our signals voltage will be well above our 200mV voltage differential threshold defined by the RS485 standard.

If the reflections from the mismatch of impedance from the Transceivers to the twisted pair becomes an issue, I would implement a π-pad or O-pad matching network to clean up reflections.

The use of CAT6 cable should guarantee that we can get close to achieving 250MHz bandwidth, which will more than well encompass the 100Hz we are targeting for update speed of the current measurement.

For the pinout of the RJ45 connectors, Twisted Pair chosen is "Orange White" and "Orange" which are Pin 1 and Pin 2 respectively. T568B Pinout Used.

For the component selection of the RS485 transceivers I chose the SN65176BDR due to its attractive price point and being in stock on DigiKey. Otherwise nothing special about it in terms of the RS485 world of transceivers.

Current Sense Design

Unidirectional current measurement and must be able to handle 12-60V DC. Current measurement must have 10mA or less resolution and provide the measurements at a 100Hz update rate to the remote computer.

Current Sense IC Research

- High Side Current-Sense Amplifiers
  - Current from source flows through R_{SENSE} to load, creating a sense voltage V_{SENSE}
  - Negligible current flows through R_{G2} due to high input impedance of A1 (Op-amps draw ideally zero current at input of +/- terminals) so, sense amplifiers inverting input voltage equals
    - $V_{(-)} = V_{SOURCE} - (I_{LOAD})(R_{SENSE})$
  - Open loop gain of Amp forces noninverting input (+) to same voltage as inverting input (-) so, drop across R_{G1} is equal to V_{SENSE}.
  - So, we know the current $I_{RG1} = I_{SENSE}$ which is multiplied by β by the current mirror to give $I_{A2} = \beta * I_{RG1}$
  - Then, amplifier A2 is used to convert I_{A2} to a voltage and is sent through amplifier A3 to “OUT”
  - This output voltage on “OUT” is linearly proportional to the current I_{SENSE}

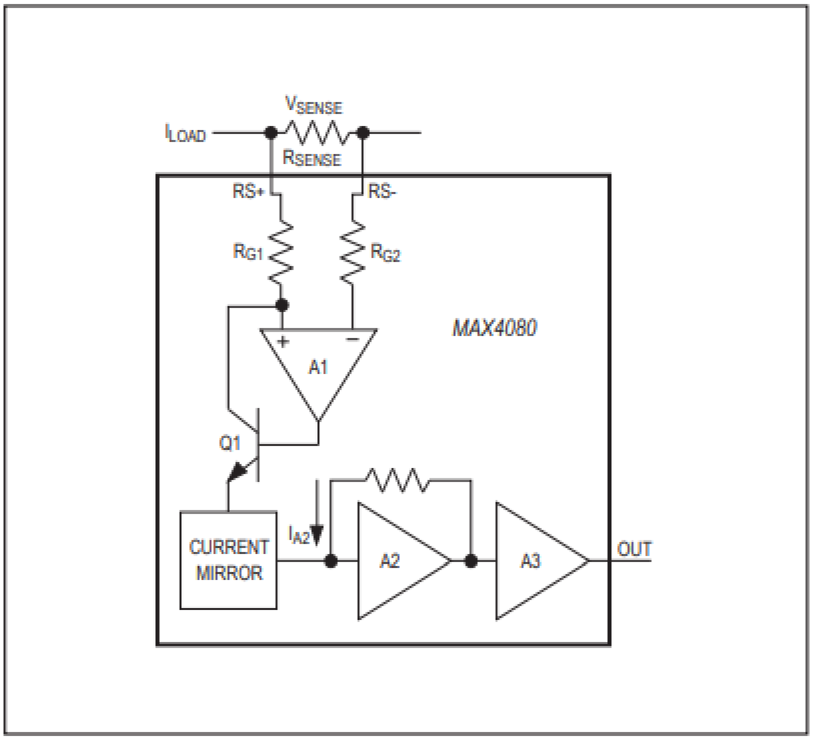

Figure 4

- MAX4080F
    - Unidirectional current sensing
    - 4.5 to 76V Vcc input
    - high side current-sense amplifier
        - does not interfere with the ground path of load being measured
    - 5 v/v gain scale
        - Designer selected external sense resistor sets the full-scale current reading and its proportional output voltage
    - -40C to +125C operating range
    - A high R_{SENSE} value allows lower currents to be measured more accurately
        - Want the smallest R_{SENSE} acceptable to reduce I^2R losses
    - Use 4-terminal current-sense resistor to limit delay and loss for more accurate measurement

Selected Current Sense IC

I selected the MAX4080F high side current-sense amplifier for measuring load current. Paired with the 10-bit ADC on the ESP8266, I am able to achieve 9.765mA resolution and able to update at well above 100Hz with the physical layer implementation I chose for the RS485 communication.

Implementation Notes

The resolution in which you are able to measure current with a high side current-sense amplifier is not inherent to the IC you choose but rather the sampling resolution you are able to achieve with your ADC. The V_{imeas} voltage outputted on the OUT pin of the MAX4080F IC is linear between 0 and 5V. The voltage level on the OUT pin directly correlates to the current flowing through the R_{SENSE} resistor. So in my implementation, 5V correlates to 10A and 0V correlates to 0A. With the ESP8266 microcontroller I selected we have a 10bit ADC accessible via the pin TOUT. With a 10bit ADC we are able to represent values between 0 and 1023.

Math for Resolution of Current Measurement:

$$I_{resolution} = \frac{I_{max}}{2^N} = \frac{10A}{2^{10}} = 9.765mA$$

The current sense resistor criteria is closely described in the datasheet for the MAX4080F.

Summary of R_{SENSE} Selection Criteria:

- 100mΩ for 10A full-scale I_{SENSE}
- 4-terminal current-sense resistor
- Metal film to keep inductance down

Needed to add voltage divider to step the 5V output of OUT to 3.3V to allow the ADC on the ESP8266 to sample. Decoupling capacitor added for voltage stability.

High Side Switch Design

Must handle switching 12-60V DC into an RL load (L <= 5mH) with a maximum I_{LOAD} of 10A DC. Needs to be capable of operating continuously (no one time use fuses). f_{sw} is less than 1Hz for turning switch ON and OFF.

Switch Research

- NMOS
  - Requires positive Vgs to turn ON
    - To achieve this on high side, you need a Vdd voltage source greater than the input voltage (this requires much more circuitry)
  - Comparison to PMOS
    - Less expensive
    - Low Rds(on)
    - Lower input capacitance
      - (Less conduction loss for fast switching applications)
- PMOS
  - Easier to switch high side because it requires a negative Vgs to turn ON
    - Vg = 0V, switch is ON
    - Vg = Vdd, switch is OFF
  - Why easier?
    - Does not require a voltage source higher than Vdd
    - GND is a much larger current sink than Vdd so it easily pulls the gate voltage Vg to zero volts giving us a Vgs = -Vdd
  - Comparison to NMOS
    - More expensive
    - Higher Rds(on)
    - Higher input capacitance
      - (More conduction loss for fast switching applications)
- MOSFET Gate Resistor Selection
  - Affects how quickly gate capacitor charges
    - Dictates switching time, power dissipation, power losses, voltage overshoot, gate ringing, and EMI
  - Small Gate Resistor
    - Higher $\frac{di}{dt}$
    - Gate ringing
    - Voltage overshoot
    - EMI

- Large Gate Resistor
  - Low switching speed
  - High power dissipation
- Tradeoff
  - Small gives High Efficiency, Large gives Low Noise

Selected High Side Switch Circuit

I have chosen to go with a high side switch circuit that implements an NMOS fet driven by the microcontroller to switch a PMOS fet that is connected in line with the load path. The design implements four passive resistors to adjust voltage levels for the Vgs of the high side switch PMOS, to set the gate current for the NMOS, and to add pull down to NMOS gate.

Implementation Notes

Since the high side switch will be switched at less than 1Hz, I decided a gate driver was not necessary. If the switching speed was approaching or exceeding 100Hz I would choose to implement a gate driver.

Reasoning for PMOS High Side Switch:

NMOS FET requires a Vg greater than the Vin to achieve the Vgs necessary to turn the switch ON. Therefore harder to drive than PMOS as a seperate supply is necessary. Since switching at less than a Hz the conduction losses of PMOS will be negligible and therefore I believe is the better choice for the application of a high side switch.

Gate Resistor Calculation:

$$R_{gate-min} = \frac{V_{GPIO}}{I_{GPIO-max}} = \frac{3.3V}{12mA} = 275\Omega$$

Since f_{sw} is less than 1 Hz, gate capacitor charge time is negligible so I chose to double the $R_{gate-min}$ value to keep I_{GPIO} safe in the middle of the GPIO current range at 6mA for the ESP8266.

Gate Resistor Selected:

$$R_{gate} = 550\Omega$$

The GT700P08D3 PMOS fet I chose has a $V_{GS-max} = \pm 20V$ which means since we have a V_S of 60V maximum we need to ensure we have 40V on our V_G. To accomplish this I chose to add a voltage divider to the gate of the PMOS. We also must make sure that with our smallest Vin of 12V that we are still able to meet the minimum threshold voltage of -4V.

Voltage Divider Calculation for Max Vin:

$$V_G = V_S * \frac{R21}{R21+R22} = 60 * \frac{2M}{2M+1M} = 40V$$

$$V_{GS} = V_G - V_S = 40V - 60V =- 20V$$

Voltage Divider Calculation for Min Vin:

$$V_G = V_S * \frac{R21}{R21+R22} = 12 * \frac{2M}{2M+1M} = 8V$$

$$V_{GS} = V_G - V_S = 8V - 12V =- 4V$$

To verify that my design would work in theory I implemented it in the online circuit simulation software [Falstad](). Screenshot of ON (Figure 5) and OFF state (Figure 6).

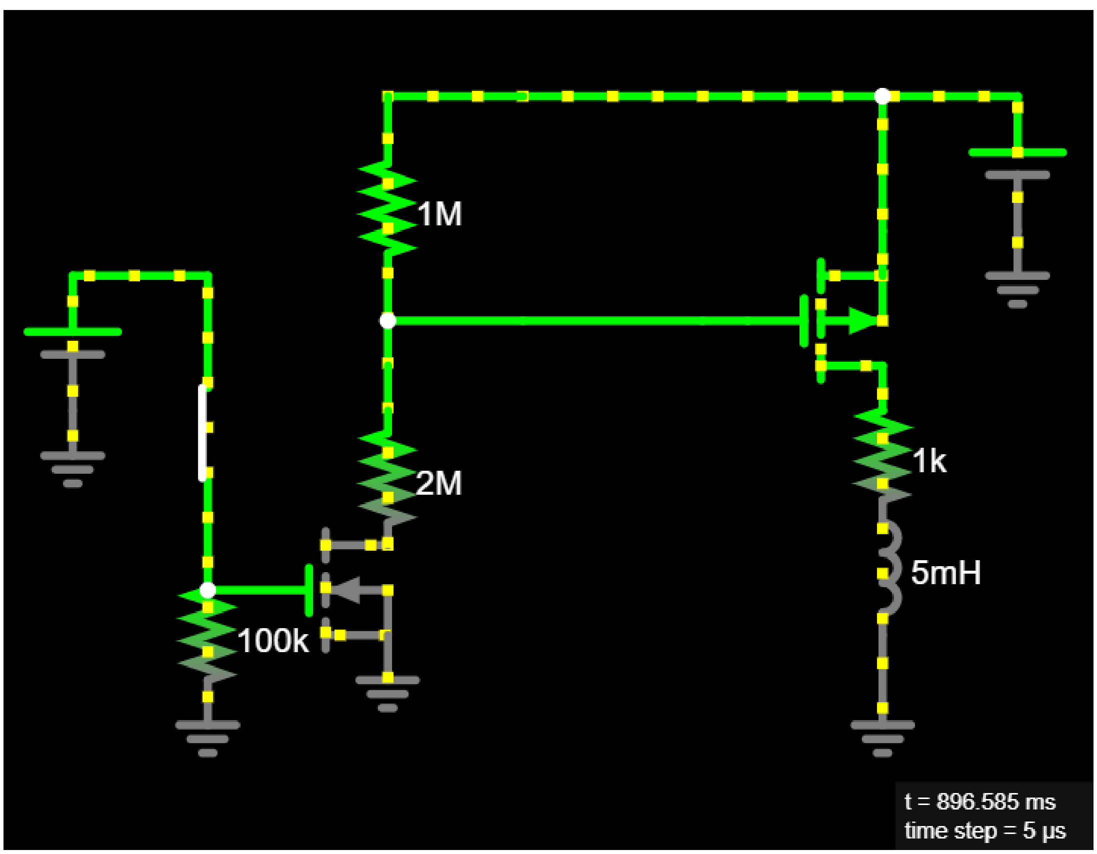

Figure 5

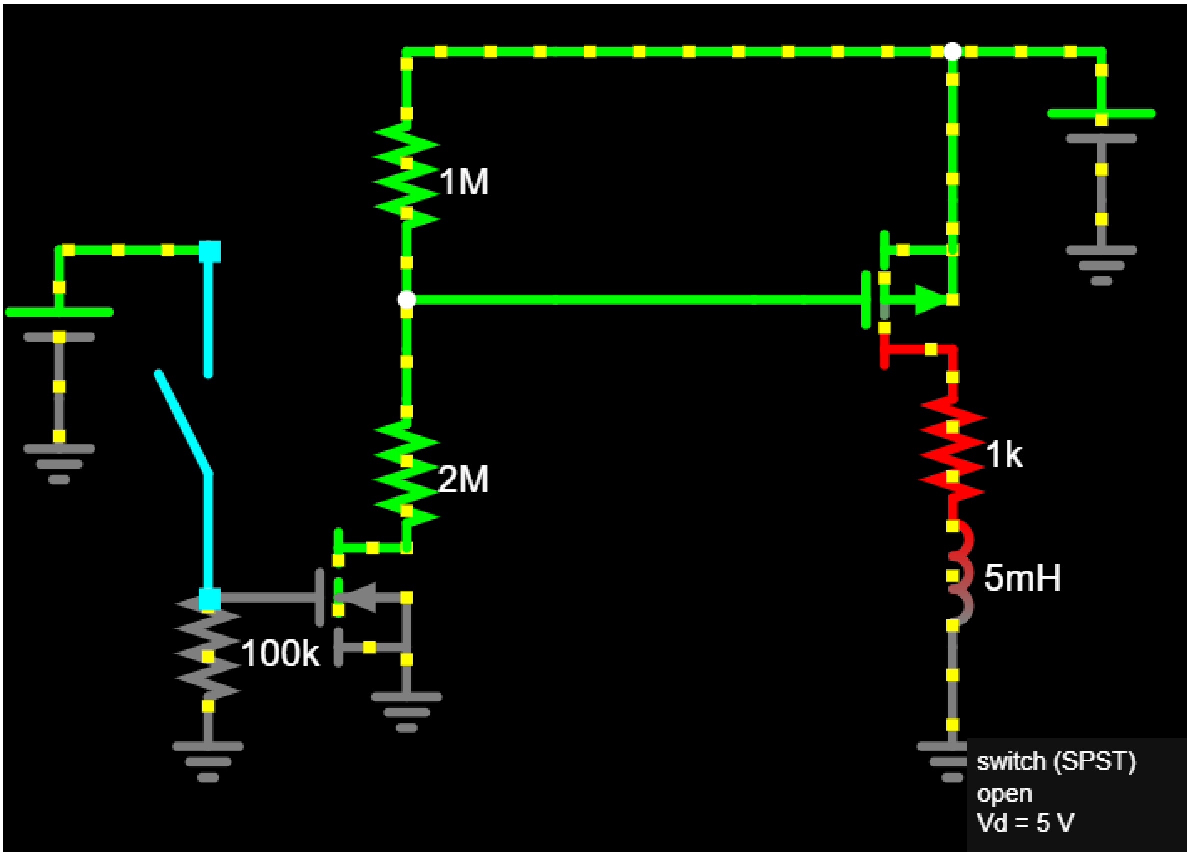

Figure 6

Conclusion

The design I devised to address the challenge of switching a load and transmitting current information over a 100ft distance is highly robust. It incorporates a remote interface communication board that connects directly to the remote computer via a USB link, which is then translated to UART for transmission to the microcontroller on the local board. The choice of RS485 as the communication standard, along with the implementation of Transient Voltage protection on both the remote and local transceivers, ensures reliable communication even in the presence of electromagnetic interference (EMI).

Furthermore, the use of a PMOS fet for the high-side switch simplifies the circuit and eliminates the need for an additional higher potential voltage supply, reducing overhead. The high-side current-sense amplifier, in conjunction with the onboard ADC of the ESP8266, provides an impressive 9.765mA resolution for current measurement. Thanks to my selection of the physical layer for RS485, we can easily achieve a 100Hz update rate to the remote computer.

In summary, the pairing of these circuit designs for the remote and local boards results in an elegant and effective solution to the presented problem.