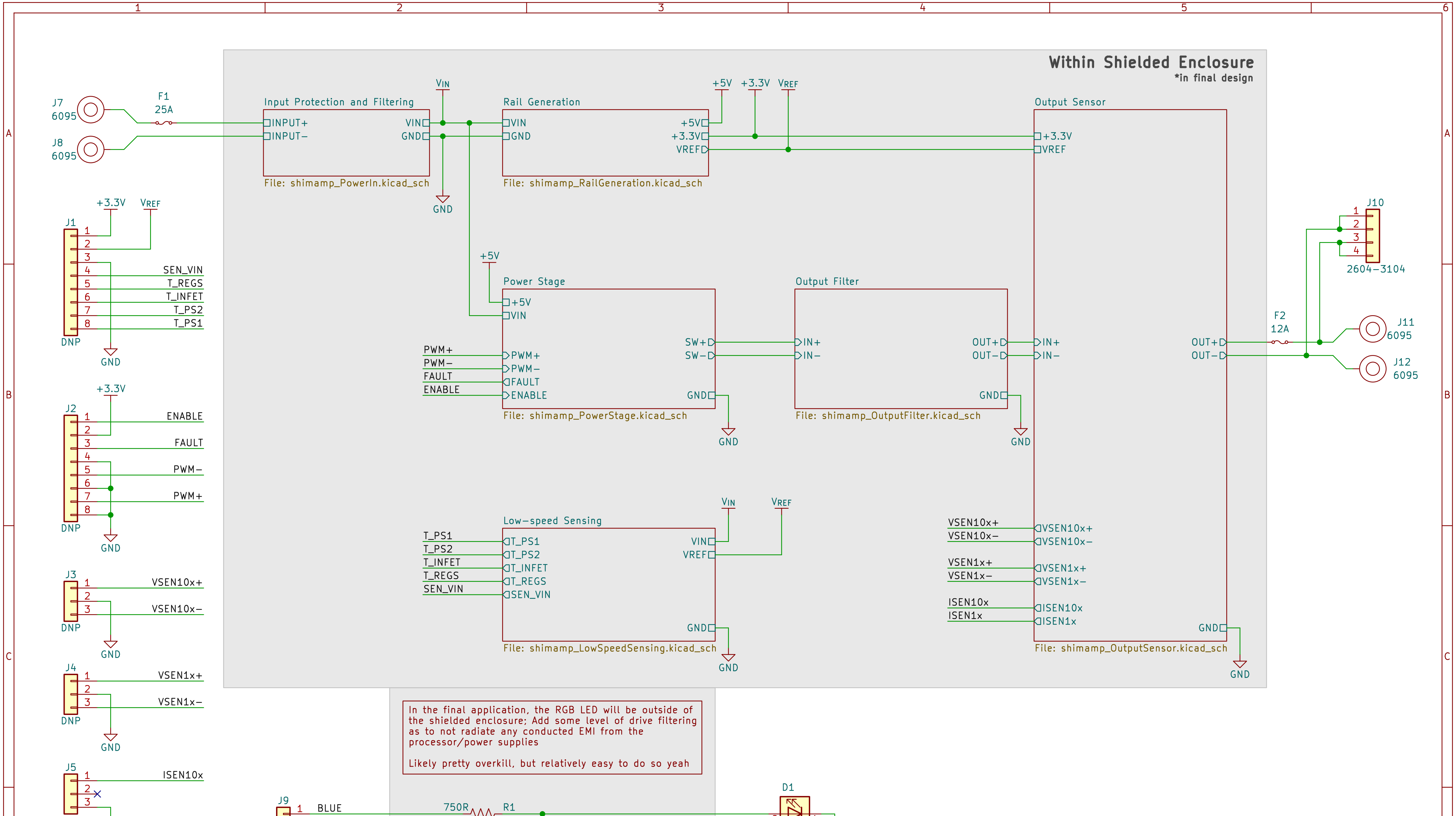


Ishaan Govindarajan

Sheet: /

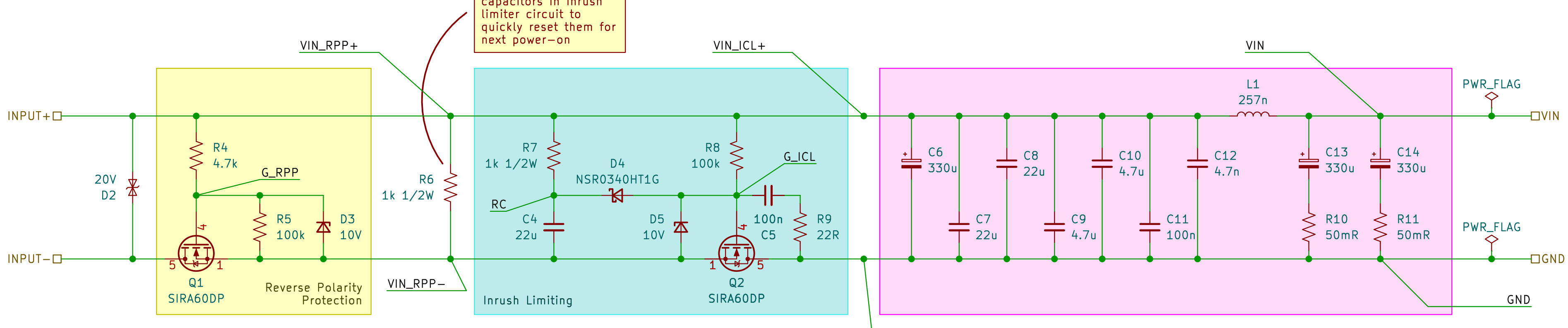
File: Class-D Prototype revA.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 Date: 2023-08-01 **Rev: A.1**

KiCad E.D.A. kicad 7.0.5 Id: 1/15

Resistor is necessary to discharge capacitors in inrush limiter circuit to quickly reset them for next power-on



Relatively standard way to do low-loss reverse polarity protection

Can do this on the low-side since our communications will be optical, i.e. galvanically isolated

Based on Motorola App Note AN-1542; I've used and tested this circuit in other designs and it works really well especially for a discrete solution

1.6V $V_{GS,Th}$, 12V nominal supply voltage; means 10.4V across gate resistor.
Aiming for 10ms turn on; use I = C * dVds/dt which equates to 100e−9 * −12V/0.01s or −120uA.
To achieve this current, we'll pull the gate up with 100k to the supply rail.

10ms for the particular selected FET allows for (I = C * dV/dt) 3 = C * 12/0.01 or 2500uF of capacitance to be safely charged; the '3' came from the SOA curve for the particular FET

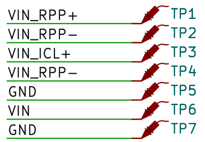
Just a note, there are some eFuse/inrush limiting ICs designed for 12V rail applications that could make sense here. Check out the following part numbers:
- STEF12H60
- MP5981GLU
- NCP81292MNT

Power supply filter−−aims to attenuate switching harmonics from escaping out to the power supply

Most of this attenuation needs to happen at frequencies greater than or equal to the switching frequency (1.25MHz)

Capacitor series resistors ~critically damp the LC tank formed by these and the main filter inductor

Additional output bypassing for power stage and linear regulators on their respective schematic sheets



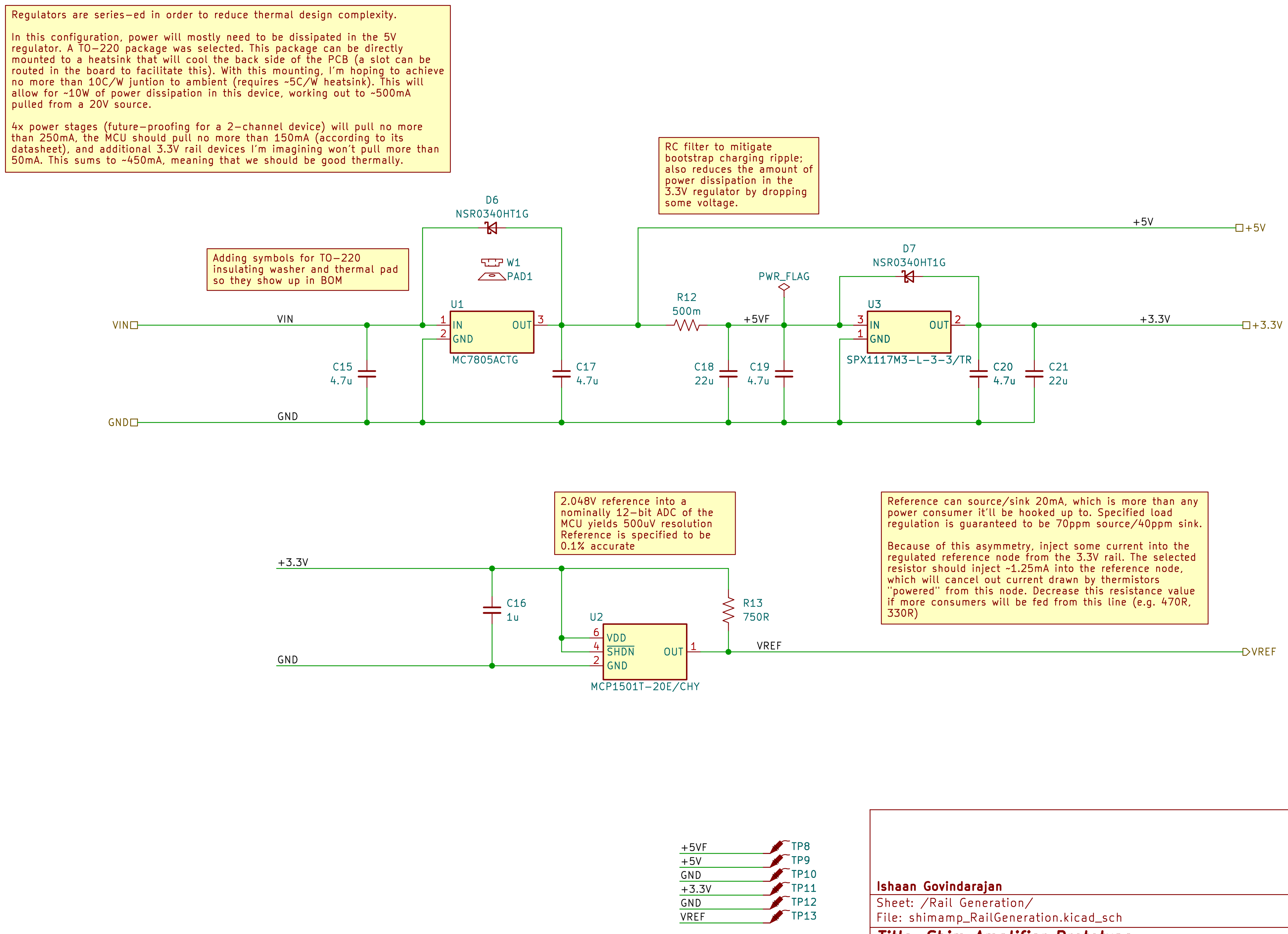
Ishaan Govindarajan

Sheet: /Input Protection and Filtering/
File: shimamp_PowerIn.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 | Date: 2023-08-01 | **Rev: A.1**

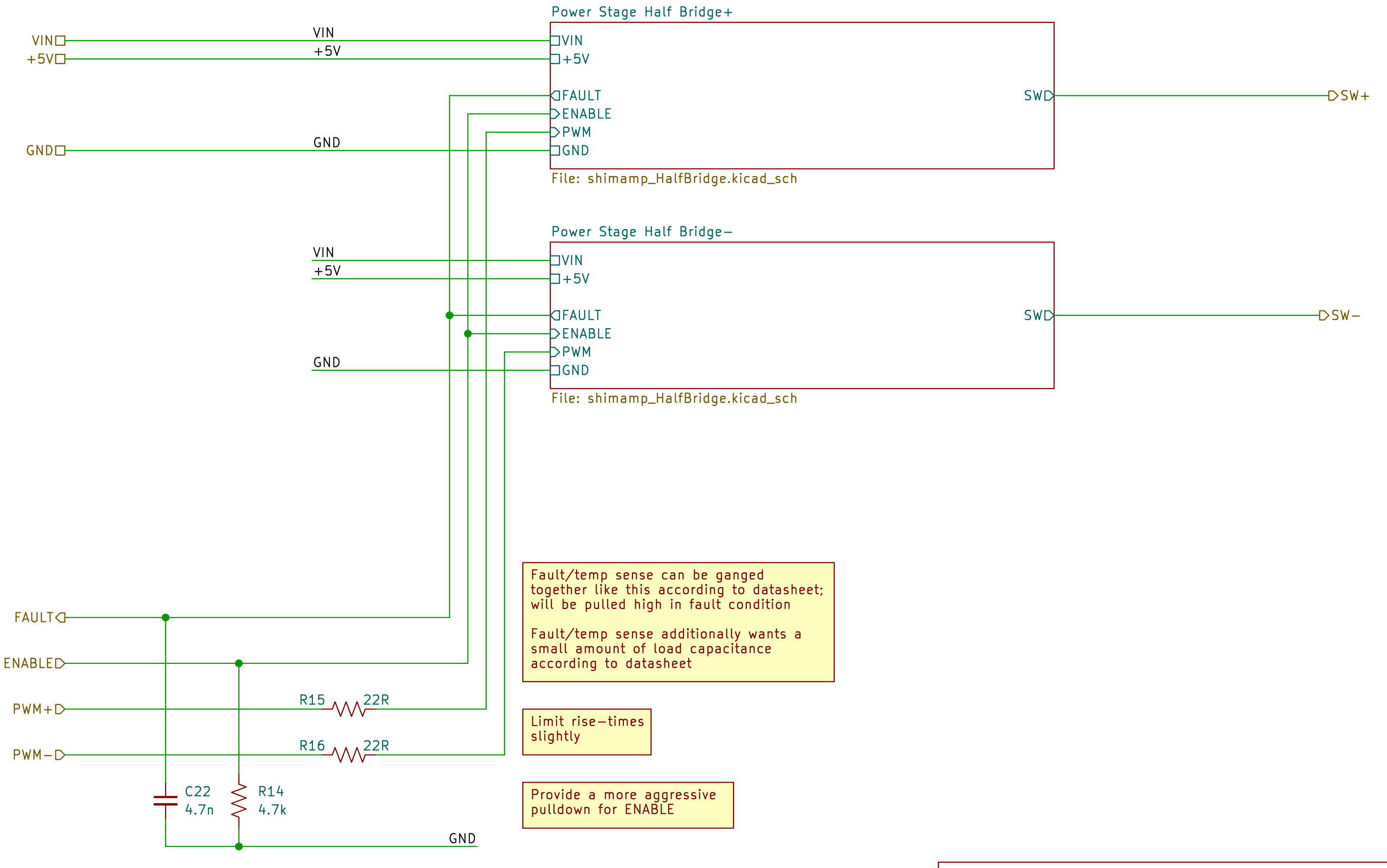
KiCad E.D.A. kicad 7.0.5 | Id: 2/15



Ishaan Govindarajan
Sheet: /Rail Generation/
File: shimamp_RailGeneration.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 | Date: 2023-08-01 | **Rev: A.1**
KiCad E.D.A. kicad 7.0.5 | Id: 3/15



Fault/temp sense can be ganged together like this according to datasheet; will be pulled high in fault condition

Fault/temp sense additionally wants a small amount of load capacitance according to datasheet

Limit rise-times slightly

Provide a more aggressive pulldown for ENABLE

Ishaan Govindarajan

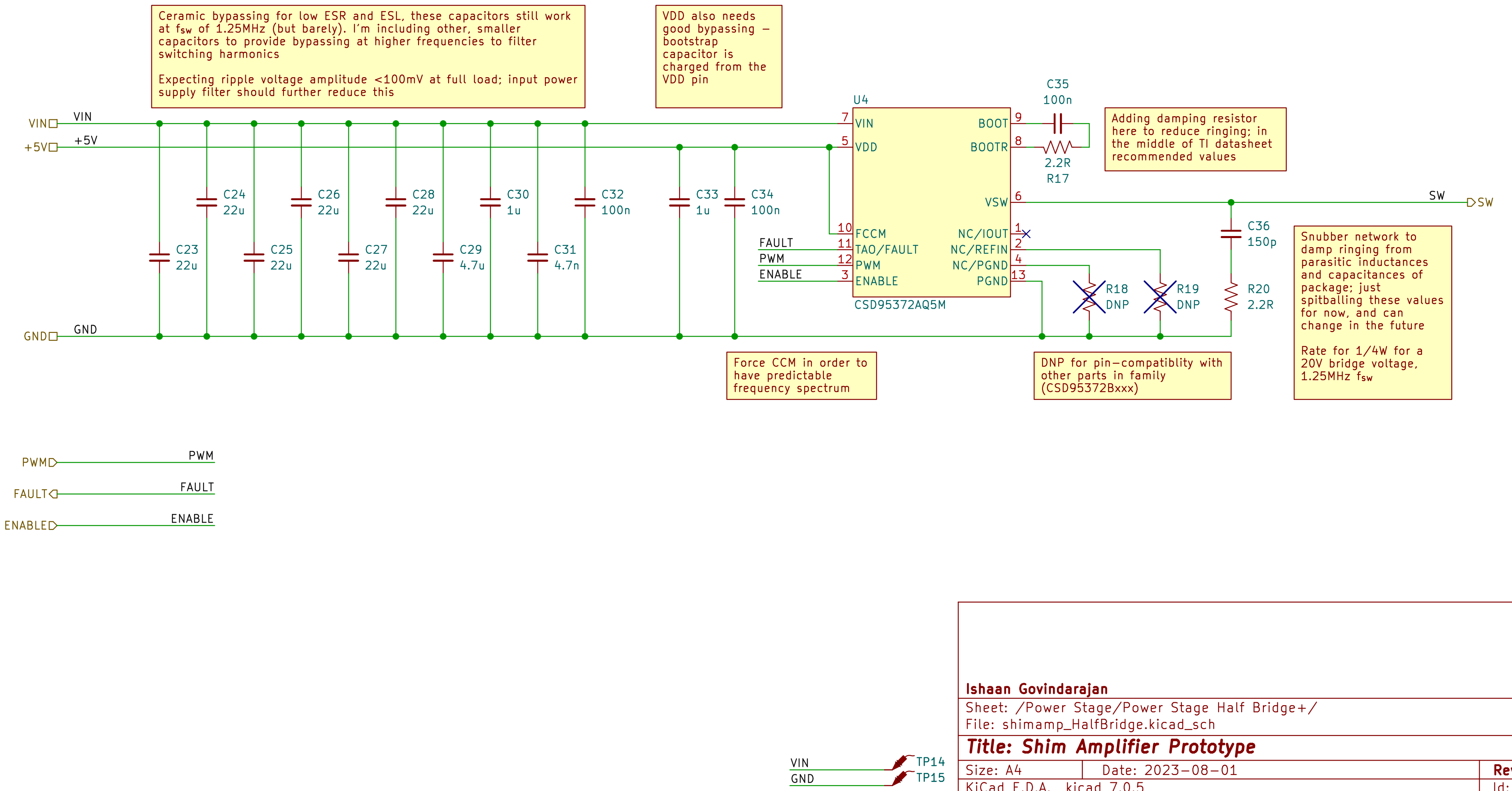
Sheet: /Power Stage/
File: shimamp_PowerStage.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 | Date: 2023-08-01 | **Rev: A.1**
KiCad E.D.A. kicad 7.0.5 | Id: 4/15

Worst-case combined power stage dissipation is ~7.68W when:
- Outputting near the supply voltage rail (i.e. high duty cycles)
- Outputting 20A load current

Nominal dissipation expected to be ~2-3W combined when driving 100-200mR shim coils



Ishaan Govindarajan

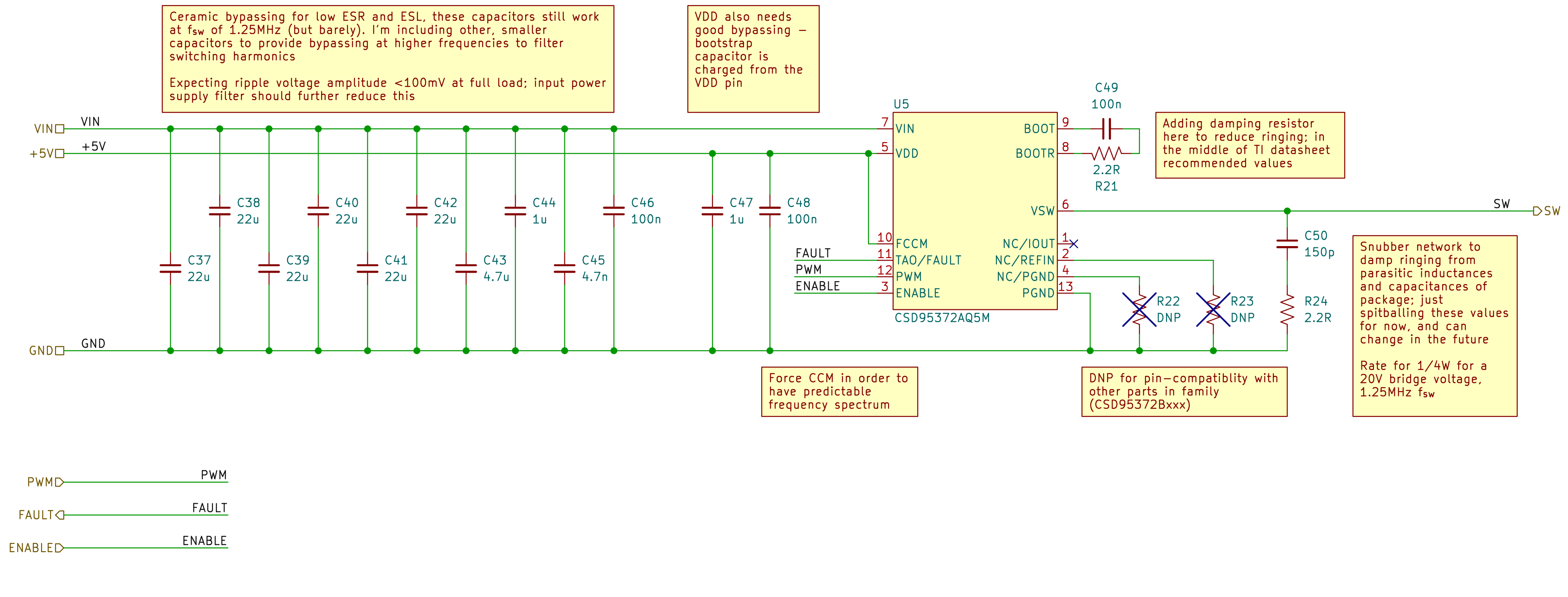
Sheet: /Power Stage/Power Stage Half Bridge+/
File: shimamp_HalfBridge.kicad_sch

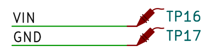
Title: Shim Amplifier Prototype

Size: A4	Date: 2023-08-01	**Rev: A.1**
KiCad E.D.A. kicad 7.0.5		Id: 5/15

Worst-case combined power stage dissipation is ~7.68W when:
- Outputting near the supply voltage rail (i.e. high duty cycles)
- Outputting 20A load current

Nominal dissipation expected to be ~2-3W combined when driving 100-200mR shim coils





Ishaan Govindarajan

Sheet: /Power Stage/Power Stage Half Bridge-/
File: shimamp_HalfBridge.kicad_sch

Title: Shim Amplifier Prototype

Size: A4	Date: 2023-08-01	**Rev: A.1**
KiCad E.D.A. kicad 7.0.5		Id: 6/15

Calculations for this filter (and control design) can be found under the 'simulations' folder in my Dropbox

Output filter is implemented as two common−mode filters (which have a byproduct of also attenuating differential mode). Each sheet contains one half of the filter.

Ishaan Govindarajan

Sheet: /Output Filter/
File: shimamp_OutputFilter.kicad_sch

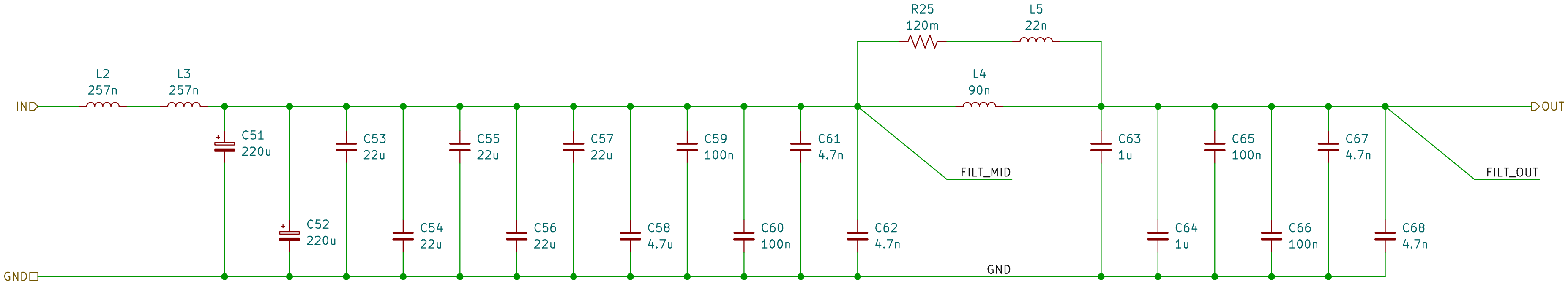
Title: Shim Amplifier Prototype

Size: A4	Date: 2023−08−01	**Rev: A.1**
KiCad E.D.A. kicad 7.0.5		Id: 7/15

This is one half of a 2-stage, 4th-order filter that provides both differential and common-mode filtering. Since the control loop bandwidth is greater than the resonant frequency of the first filter stage, it can remain undamped. However, this is not the case with the second stage, requiring the inclusion of a damping leg. This was applied across the series element (the inductor) because the shunt elements are formed by the series combination of the capacitors from the first and second stages of the filter. As such, damping via the shunt elements would require damping across both stages of the filter, adding to cost/complexity/area, etc.

Damping leg can safely handle up to 4A; I have some uncertainty whether this damping leg is adequately sized for circuit behavior between controller cutoff frequency and switching frequency. My theoretical understanding says that given a band-limited current setpoint signal (<20kHz) up to 20A in amplitude, this damping leg should have a 2x safety factor.

Calculations for this filter (and control design) can be found under the 'simulations' folder in my Dropbox



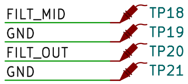
In the board design, give the smallest capacitors the tightest loops; this will minimize parasitic inductance for those components where it matters most.

Paralleled aluminum polymer capacitors for lower ESR and higher ripple rating; good for 100's of kHz;

Inductor Ripple current ~4.75A worst case (50% duty cycle) with 12V supply, 1.25MHz switching; should result in <40mV ripple at the end of the first stage

- Aluminum Poly caps are good up to about ~2-300kHz
- 22u ceramics are good to ~1MHz
- 4.7u, 1u ceramics are good to ~8MHz
- 100n ceramics are good to ~20MHz
- 4.7n ceramics resonate at ~150MHz

Ceramics will derate about 75% (i.e. 25% of their value) at 12V DC Bias
Except for the 1u caps those only derate by 15% for whatever reason--it's not even like a tolerance reason; +/-10% 10u caps still aggressively derate at those levels of DC bias. I'll investigate if it's a capacitor family reason.



Ishaan Govindarajan

Sheet: /Output Filter/Output Filter+/
File: shimamp_OutputFilterHalf.kicad_sch

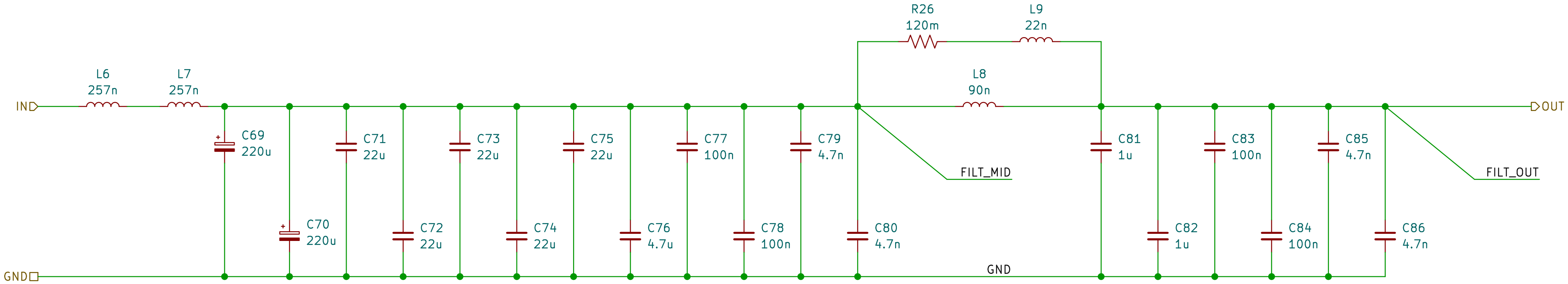
Title: Shim Amplifier Prototype

Size: A4 Date: 2023-08-01	Rev: A.1
KiCad E.D.A. kicad 7.0.5	Id: 8/15

This is one half of a 2-stage, 4th-order filter that provides both differential and common-mode filtering. Since the control loop bandwidth is greater than the resonant frequency of the first filter stage, it can remain undamped. However, this is not the case with the second stage, requiring the inclusion of a damping leg. This was applied across the series element (the inductor) because the shunt elements are formed by the series combination of the capacitors from the first and second stages of the filter. As such, damping via the shunt elements would require damping across both stages of the filter, adding to cost/complexity/area, etc.

Damping leg can safely handle up to 4A; I have some uncertainty whether this damping leg is adequately sized for circuit behavior between controller cutoff frequency and switching frequency. My theoretical understanding says that given a band-limited current setpoint signal (<20kHz) up to 20A in amplitude, this damping leg should have a 2x safety factor.

Calculations for this filter (and control design) can be found under the 'simulations' folder in my Dropbox



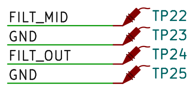
In the board design, give the smallest capacitors the tightest loops; this will minimize parasitic inductance for those components where it matters most.

Paralleled aluminum polymer capacitors for lower ESR and higher ripple rating; good for 100's of kHz;

Inductor Ripple current ~4.75A worst case (50% duty cycle) with 12V supply, 1.25MHz switching; should result in <40mV ripple at the end of the first stage

- Aluminum Poly caps are good up to about ~2-300kHz
- 22u ceramics are good to ~1MHz
- 4.7u, 1u ceramics are good to ~8MHz
- 100n ceramics are good to ~20MHz
- 4.7n ceramics resonate at ~150MHz

Ceramics will derate about 75% (i.e. 25% of their value) at 12V DC Bias
Except for the 1u caps those only derate by 15% for whatever reason--it's not even like a tolerance reason; +/-10% 10u caps still aggressively derate at those levels of DC bias. I'll investigate if it's a capacitor family reason.



Ishaan Govindarajan

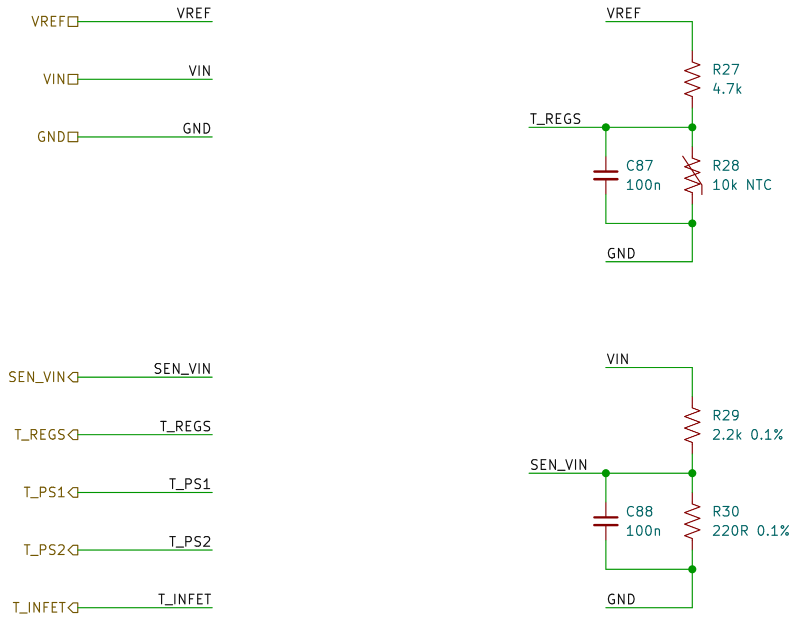
Sheet: /Output Filter/Output Filter-/

File: shimamp_OutputFilterHalf.kicad_sch

Title: Shim Amplifier Prototype

Size: A4	Date: 2023-08-01	Rev: A.1
KiCad E.D.A. kicad 7.0.5		Id: 9/15

These signals will be measured at a lower speed by the auxiliary ADC. These signals include the following:
- Input voltage to the power stages
- Center voltage reference for current sense amp
- Power stage temperature x2
- Input stage temperature
- Linear regulator temperature



Ishaan Govindarajan

Sheet: /Low-speed Sensing/

File: shimamp_LowSpeedSensing.kicad_sch

Title: Shim Amplifier Prototype

Size: A4	Date: 2023-08-01	**Rev: A.1**
KiCad E.D.A. kicad 7.0.5		Id: 10/15

This schematic page captures the output voltage and current sensing circuitry. A feedback loop will be closed around both voltage and current, allowing for the stabilization of plants with slightly different dynamics. These sensors must provide minimal distortion up to the controllers' unity gain frequency while maximally attenuating energy at frequencies beyond. Additionally, sensing circuit must have good common-mode rejection (CMR) to minimize sensitivity to power stage switching.

To achieve these objectives, a fully-differential amplifier topology was chosen for voltage sensing. The fully-differential topology maximizes CMR (>75dB from the amplifier, more from the MCU, ADC), and allows for the implementation of a high-order active filter. The cutoff frequency of this filter was chosen such that it has near-zero phase up to the voltage controller crossover frequency (~40-50kHz). This improves stability and phase margin.

For current sensing, an INA241x series amplifier was chosen for its low offset, noise, and high CMR (~80dB @ 1MHz). Due to its higher CMR, current measurements will be made with a simpler single-ended sensing technique, filtered with a simpler first-order RC filter. The zero-current reference is selected to place a reading of 0A in the middle of the MCU ADC range.

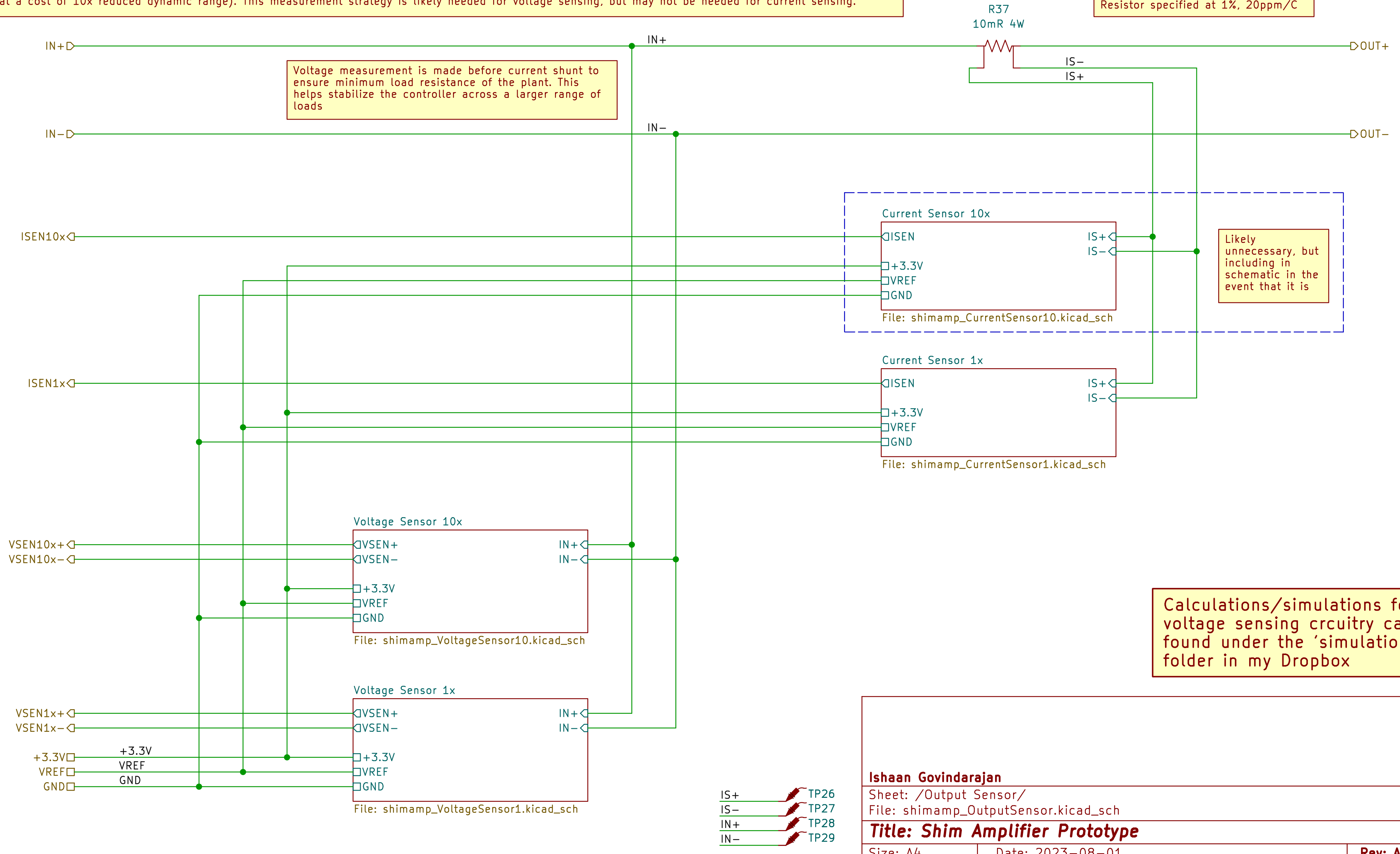
Additionally, both of these measurements benefit from a large dynamic range, and may run into resolution limits with the MCU's 12-bit ADC. As such, ADC channels may be "stacked"--one ADC channel will handle the full voltage/current range, and the other will handle measurements close to zero with a 10x greater resolution (at a cost of 10x reduced dynamic range). This measurement strategy is likely needed for voltage sensing, but may not be needed for current sensing.

Current shunt resistor sized for +/-10A; will dissipate ~1W, so power rating is derated for extra stability and general headroom

Resistor specified at 1%, 20ppm/C

Voltage measurement is made before current shunt to ensure minimum load resistance of the plant. This helps stabilize the controller across a larger range of loads

Likely unnecessary, but including in schematic in the event that it is



Calculations/simulations for the voltage sensing crcuitry can be found under the 'simulations' folder in my Dropbox

Ishaan Govindarajan

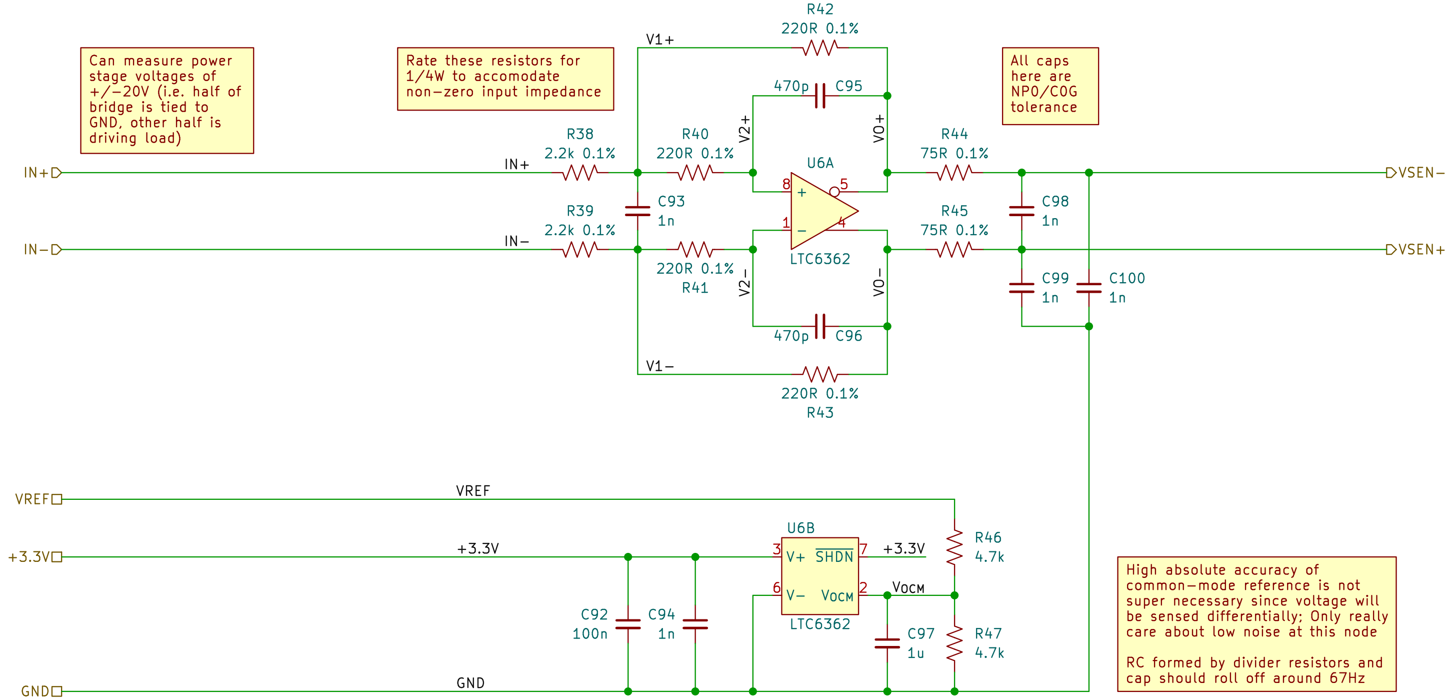
Sheet: /Output Sensor/
File: shimamp_OutputSensor.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 Date: 2023-08-01 **Rev: A.1**
KiCad E.D.A. kicad 7.0.5 Id: 11/15

3rd-order butterworth mutiple feedback filter with ~750kHz cutoff frequency (slight mismatch to the 10x amplifier), *10x* attenuation

Want high-accuracy resistors and capacitors to ensure good matching between positive and negative branches; this ensures good CMR



Can measure power stage voltages of +/−20V (i.e. half of bridge is tied to GND, other half is driving load)

Rate these resistors for 1/4W to accomodate non-zero input impedance

All caps here are NP0/C0G tolerance

High absolute accuracy of common-mode reference is not super necessary since voltage will be sensed differentially; Only really care about low noise at this node

RC formed by divider resistors and cap should roll off around 67Hz

LTC6362 chosen for good offset/noise performance; THS453x may also be a good part candidate (similar pinout but slightly different package)

Ishaan Govindarajan

Sheet: /Output Sensor/Voltage Sensor 10x/
File: shimamp_VoltageSensor10.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 | Date: 2023-08-01 | **Rev: A.1**
KiCad E.D.A. kicad 7.0.5 | Id: 12/15

3rd–order butterworth mutiple feedback filter with ~730kHz cutoff frequency (slight mismatch to the 10x amplifier), *1x* attenuation

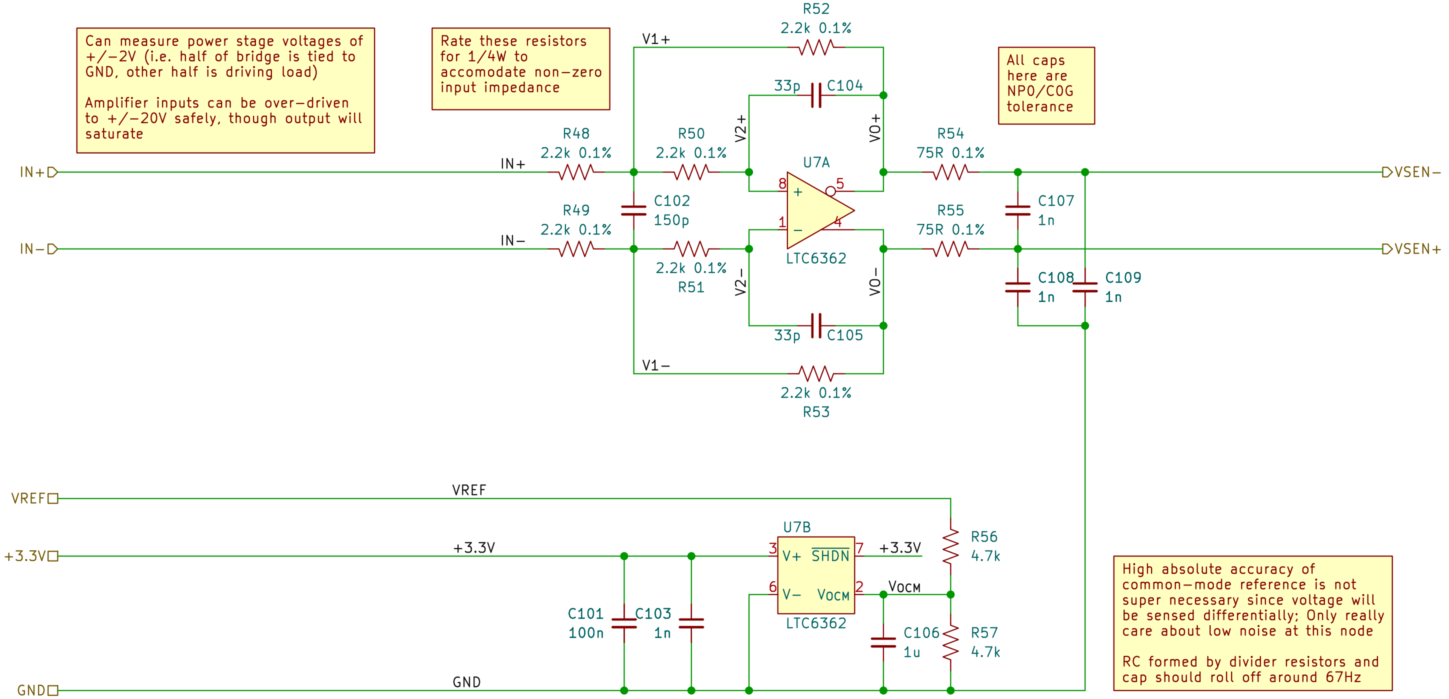
Want high–accuracy resistors and capacitors to ensure good matching between positive and negative branches; this ensures good CMR

Can measure power stage voltages of +/–2V (i.e. half of bridge is tied to GND, other half is driving load)

Amplifier inputs can be over–driven to +/–20V safely, though output will saturate

Rate these resistors for 1/4W to accomodate non–zero input impedance

All caps here are NP0/C0G tolerance



High absolute accuracy of common–mode reference is not super necessary since voltage will be sensed differentially; Only really care about low noise at this node

RC formed by divider resistors and cap should roll off around 67Hz

LTC6362 chosen for good offset/noise performance; THS453x may also be a good part candidate (similar pinout but slightly different package)

Ishaan Govindarajan

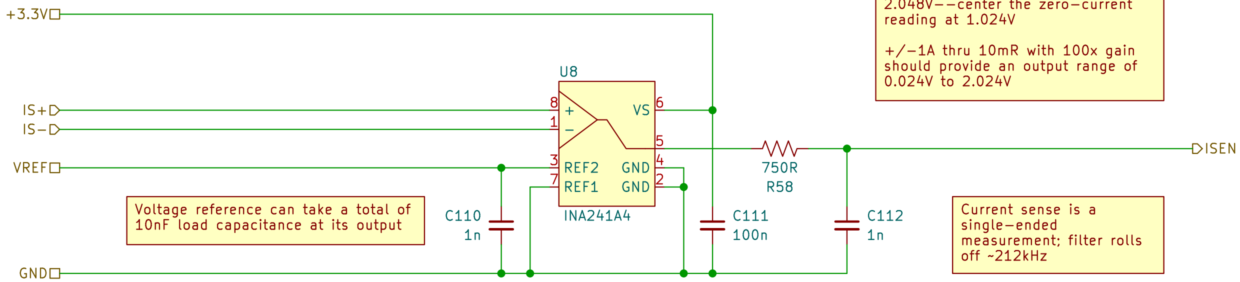
Sheet: /Output Sensor/Voltage Sensor 1x/

File: shimamp_VoltageSensor1.kicad_sch

Title: Shim Amplifier Prototype

Size: A4 | Date: 2023–08–01 | **Rev: A.1**

KiCad E.D.A. kicad 7.0.5 | Id: 13/15



ADC range is from 0 to 2.048V−−center the zero−current reading at 1.024V

+/−1A thru 10mR with 100x gain should provide an output range of 0.024V to 2.024V

Voltage reference can take a total of 10nF load capacitance at its output

Current sense is a single−ended measurement; filter rolls off ~212kHz

Reference divider is like insanely (ratiometrically) accurate, +/−0.005% maximum for the grade of part specified in this schematic;

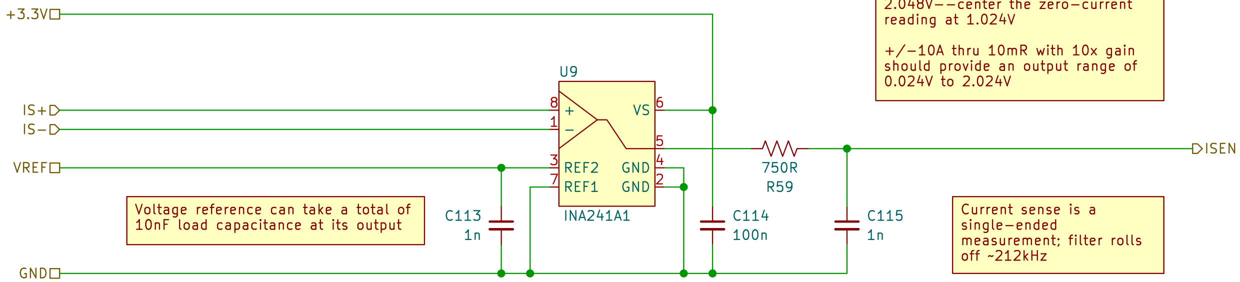
We'll never be able to easily generate something that accurate, so let's just leverage the chip's divider accuracy to generate the "zero−current reference voltage". This will center the amplifier output to be at half of the ADC range. It should be accurate enough that we don't even need to sense what the voltage actually is

Ishaan Govindarajan

Sheet: /Output Sensor/Current Sensor 10x/
File: shimamp_CurrentSensor10.kicad_sch

Title: Shim Amplifier Prototype

Size: A4	Date: 2023−08−01	**Rev: A.1**
KiCad E.D.A. kicad 7.0.5		Id: 14/15



ADC range is from 0 to 2.048V−−center the zero−current reading at 1.024V

+/−10A thru 10mR with 10x gain should provide an output range of 0.024V to 2.024V

Voltage reference can take a total of 10nF load capacitance at its output

Current sense is a single−ended measurement; filter rolls off ~212kHz

Reference divider is like insanely (ratiometrically) accurate, +/−0.005% maximum for the grade of part specified in this schematic;

We'll never be able to easily generate something that accurate, so let's just leverage the chip's divider accuracy to generate the "zero−current reference voltage". This will center the amplifier output to be at half of the ADC range. It should be accurate enough that we don't even need to sense what the voltage actually is

Ishaan Govindarajan

Sheet: /Output Sensor/Current Sensor 1x/
File: shimamp_CurrentSensor1.kicad_sch

Title: Shim Amplifier Prototype

Size: A4	Date: 2023−08−01	**Rev: A.1**
KiCad E.D.A. kicad 7.0.5		Id: 15/15