Scheme of Bipolar current control based on PID controller

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I. Negative feedback with op-amp

1. Basic idea about op-amp

Connecting the output of an op-amp to its inverting (-) input is called negative feedback. This term can be broadly applied to any dynamic system where the output signal is “fed back” to the input somehow so as to reach a point of equilibrium (balance).

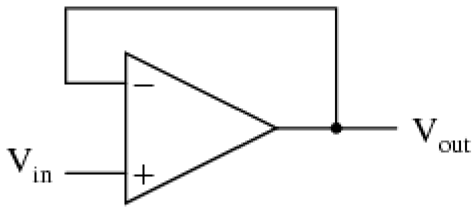


Figure 1

When the output of an op-amp is directly connected to its inverting (-) input, a voltage follower will be created. Because the op-amp’s gain is so high, the voltage on the inverting input can be maintained almost equal to V_{out}. (The higher the op-amp differential gain, the closer that differential voltage will be to zero)

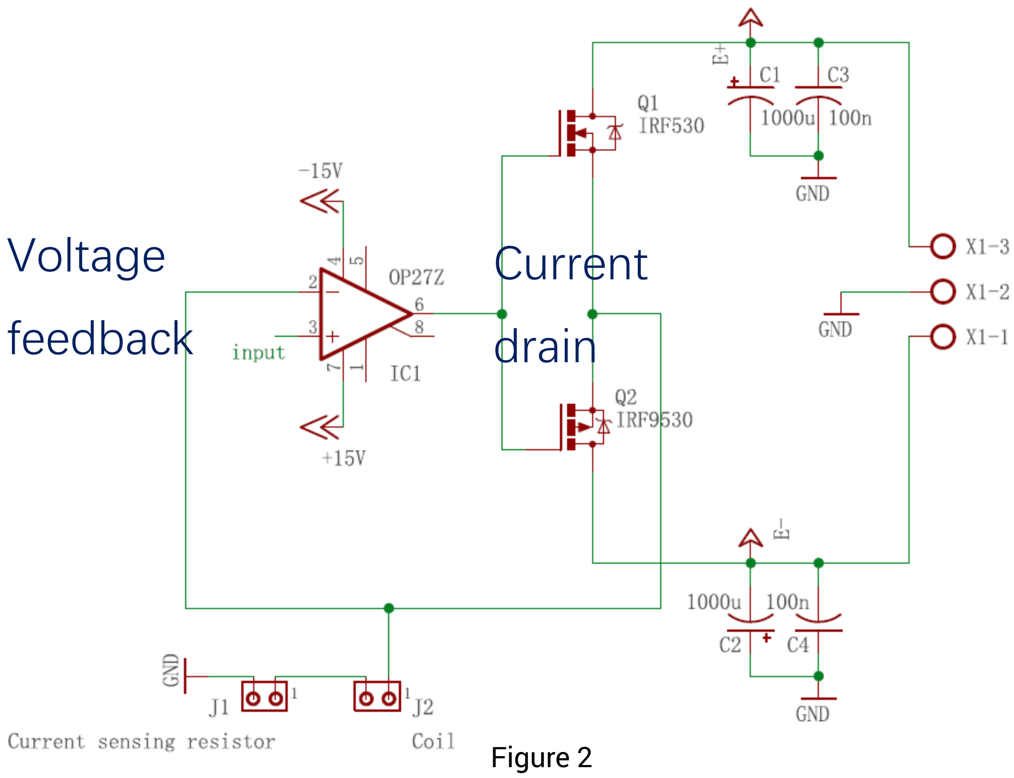


Figure 2

2. To fix the distortion and delay

In experiment, due to the threshold voltage of activating MOSFET, the voltage between coil, together with sensing resistor, and ground is distorted from the input voltage. In the schematic, we apply the idea above to compensate the threshold so that the distortion and delay is gone.

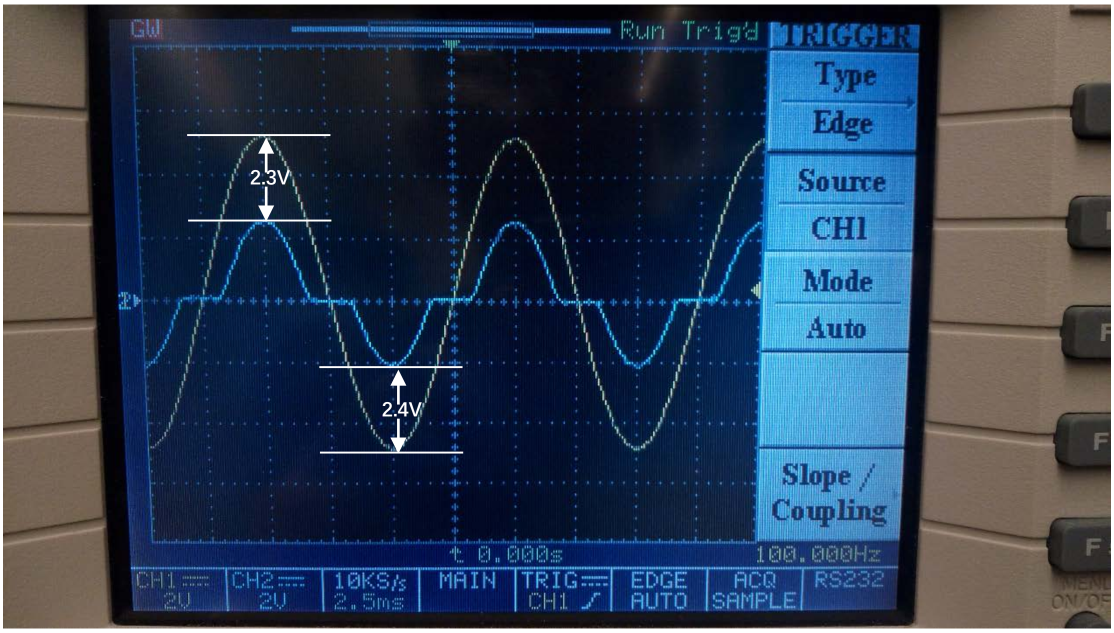


Figure 2 voltage of input (yellow) and 'coil+ sensing resistor' (blue) without voltage feedback. There is a time delay in order for gate voltage to be higher than threshold. We can read the threshold is approximately 2.3V for IRF530 and 2.4V for IRF9530.

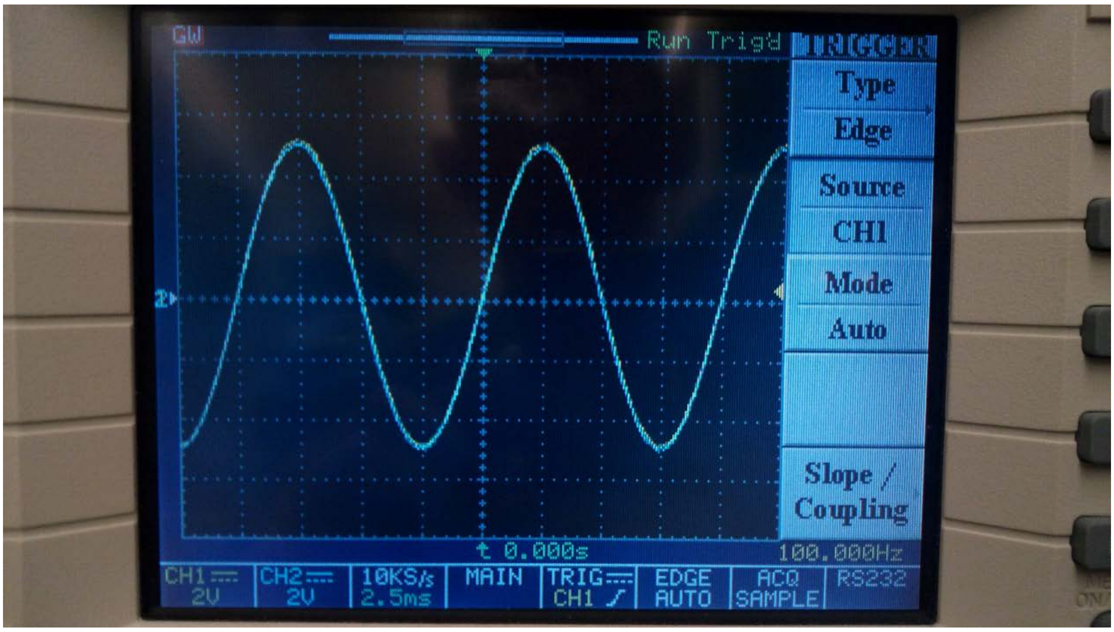


Figure 2 voltage of input (yellow) and 'coil+ sensing resistor' (blue) with voltage feedback where these two line nearly coincide.

3. To shorten the response time

Since the op-amp has a slew rate, in order to reduce the time for op-amp to reach the threshold voltage, we implement diodes to narrow the voltage gap in the **figure** above.

(The voltage drop of diodes is chosen to be less than threshold voltage of MOSFET)

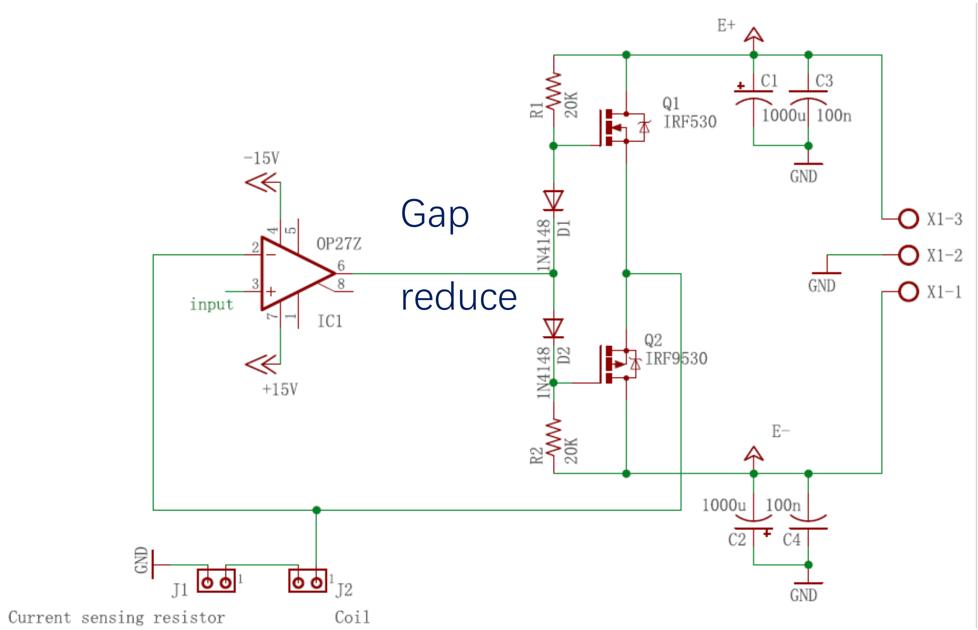


Figure 2

Thus the voltage at pin 6 which is needed to activate the MOSFET is reduced by the voltage drop of diodes, the result of which will make the op-amp response faster. See figures below:

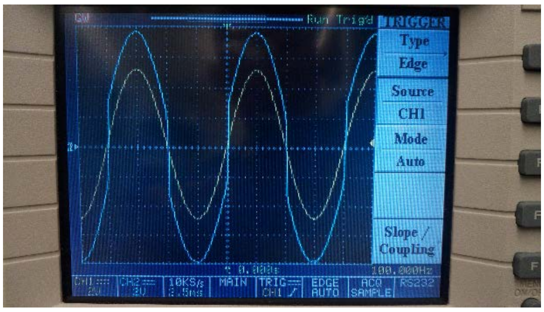


Figure 2(a)

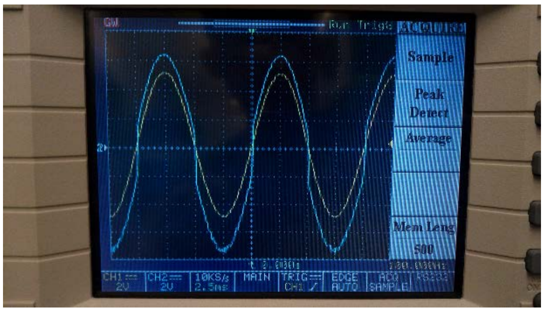


Figure 2(b)

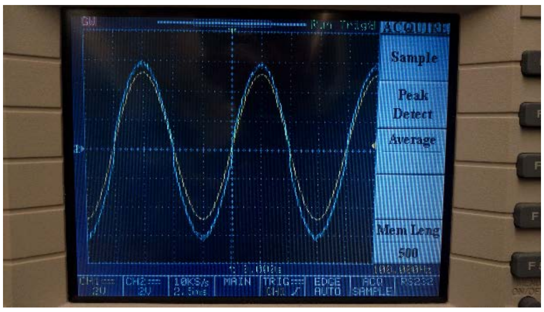


Figure 2(c)

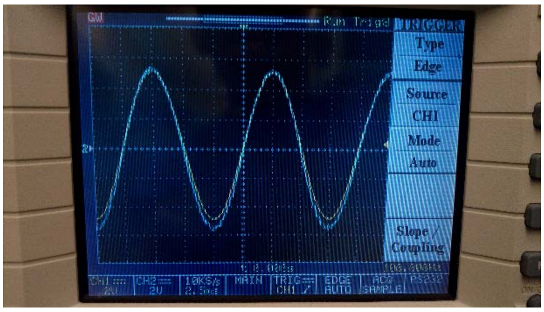


Figure 2(d)

Voltage at pin 6, where a is without diode, b with 1 diode on either side, c with 2 diodes on either side, d with 3 diodes on either side

As we add more diodes, the gap narrows significantly. At Figure 2(d), the gap nearly disappears which means extremely little respond time for op-amp comparing to Figure

2(a). However, we should also note that the diodes introduce more noise to the circuit. (actually we can short 1 or 2 diodes at one side to guarantee the signal of this side is clean depend on rising edge or falling edge we want to use
One point to highlight, the voltage drop of these diodes should be carefully chose so that it can optimally reduce the gap width and also not to trigger the MOSFET with zero input.

4. Fast oscillation/noise elimination

When do the testing, there is fast oscillation in the signal as if the wave has been modulated by a high frequency sine wave. That is because the response of op-amp is so rapid that a tiny deviation from input signal is over-fixed and the loopback tend to self-provoke which lead to oscillation.

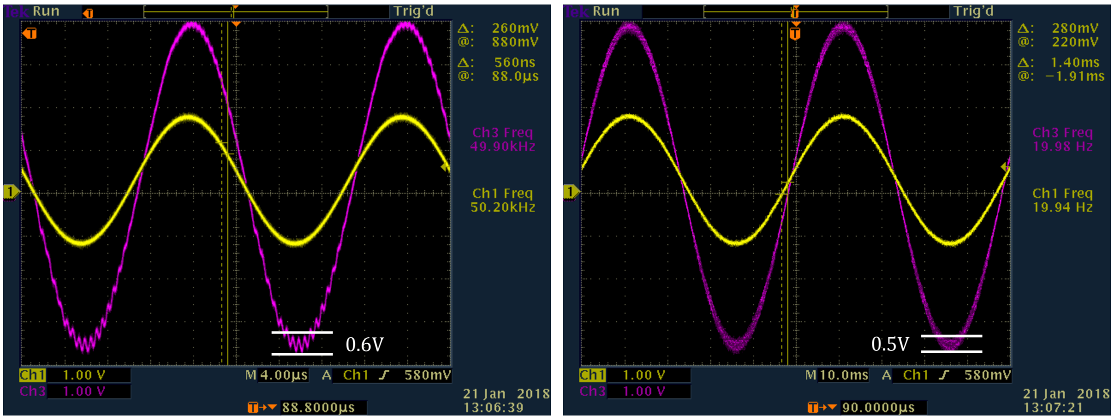


Figure Noise in the circuit

Yellow line (CH1) is voltage input from function generator; Purple line (CH3) is voltage of sensing resistor. Left is of 50 kHz, right of 20 Hz. As shown in the figure,

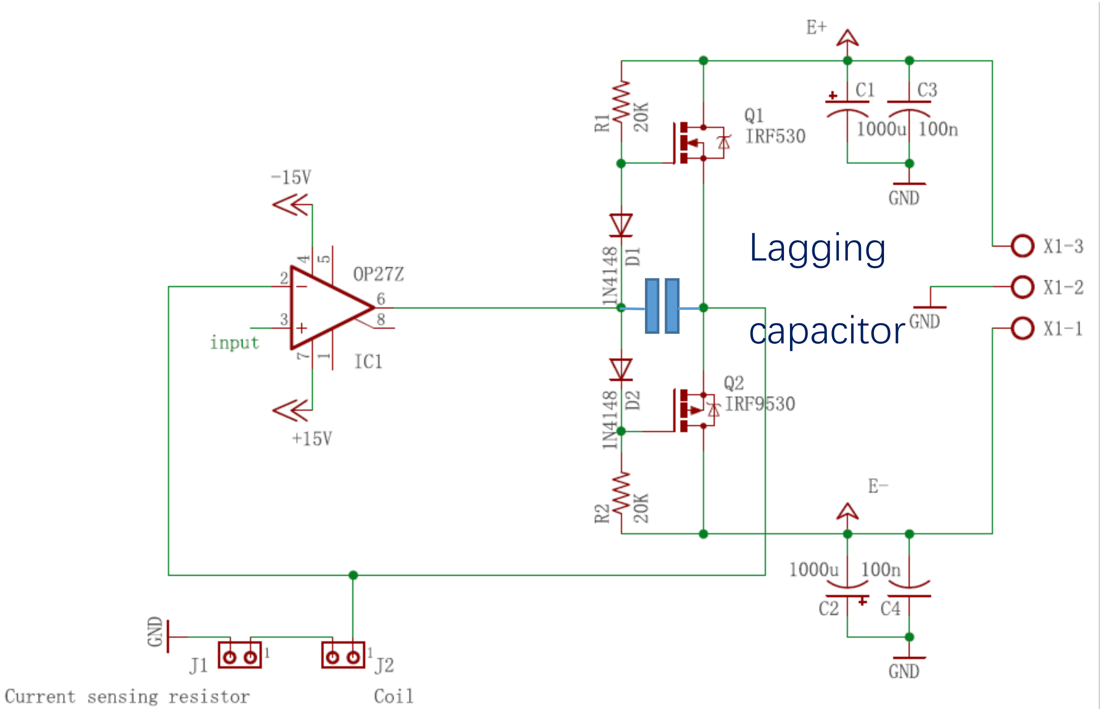


Figure　schematic

In order to fix that defect, we introduce capacitor between gate and source to retard the whole response so that the loop can reach to a relative steady state.
In reality, sometimes we **also have to introduce resistor**, installed in series with capacitor, to further reduce the amplitude of oscillation. With this combination, the annoying noise is eliminated as shown in the figure below.

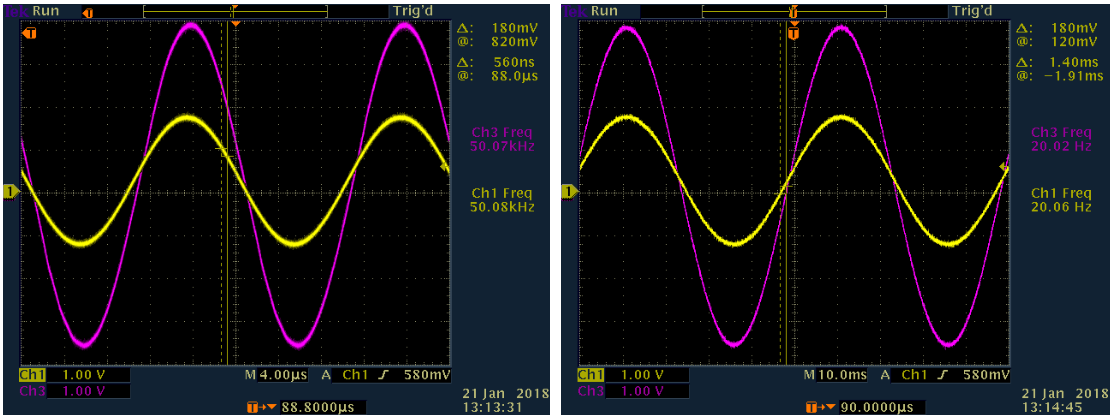
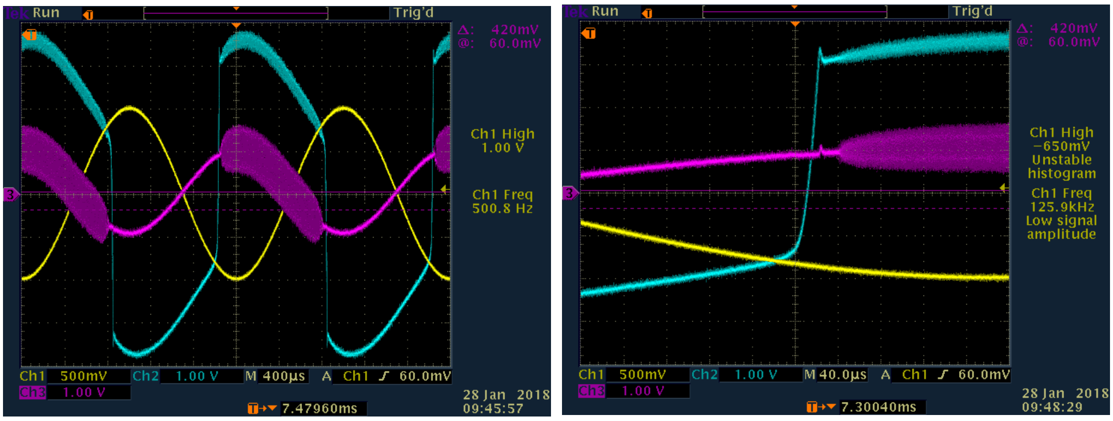


Figure　After implementing resistor and capacitor
Yellow line (CH1) is voltage input from function generator; Purple line (CH3) is voltage of sensing resistor. Noise of both frequencies disappear

*configuration clarification
In the circuit used to wipe off noise, $R = 40\Omega$, $C = 12nF$

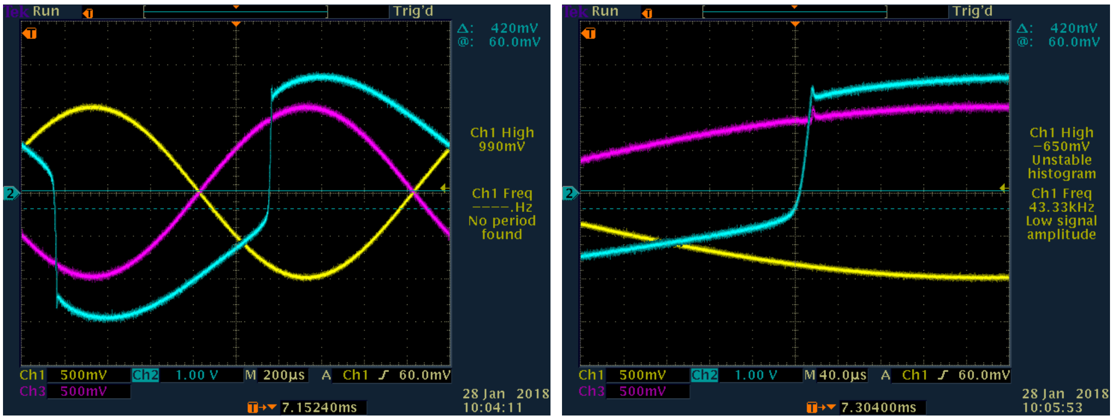
5. More about the lagging system

The combination of 'Resistor + Capacitor' is intended to slow down the instantaneous voltage drop stemmed from the feedback loop in which the op-amp manage to adjust the voltage on order to make a 'perfect follower'.
The time scale of gap is of the order of $40\mu s$ without the lagging system. With the implementation of lagging, it extends to $80\mu s$, which actually makes no significance difference to our system of which the time scale is $\sim 1ms$.
The experience is that if the 'jumping rate' is larger than $4V/40\mu s$, then the turbulence will occur.



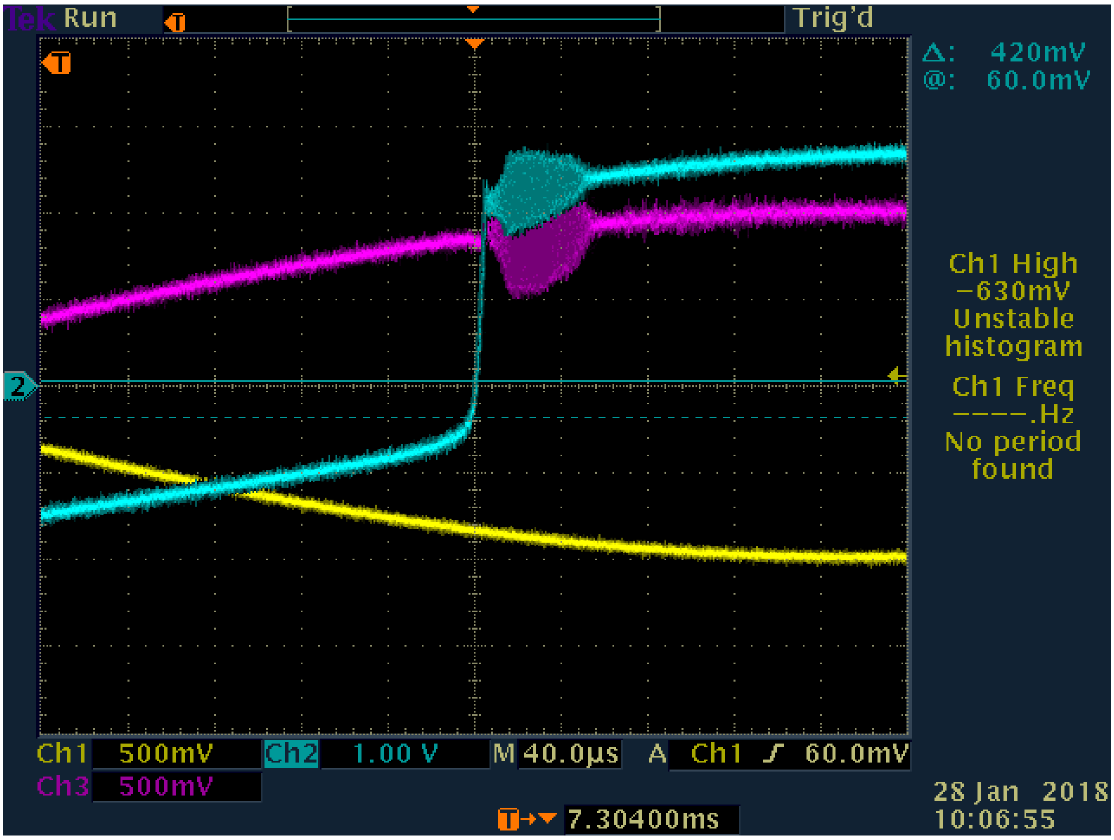
One diode forward bias with lagging

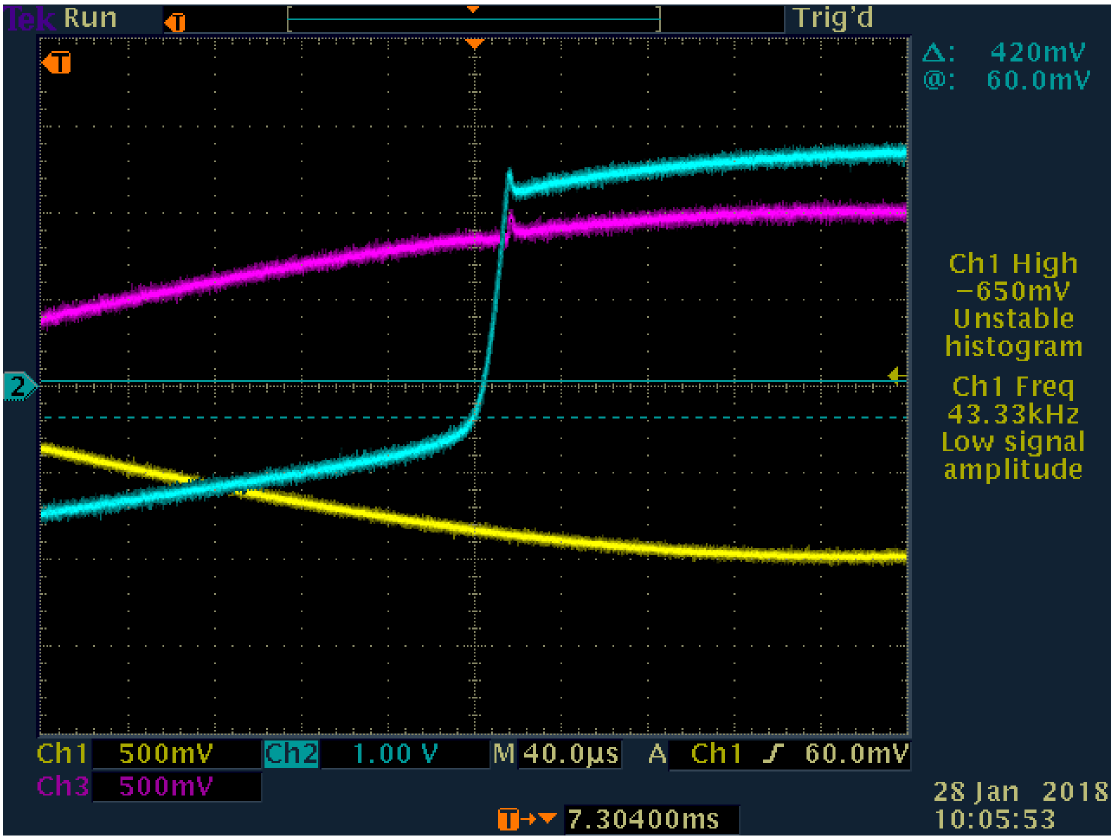
Yellow line (CH1) is voltage input from function generator; Blue line (CH2) is voltage of invert input of op-amp; Purple line (CH3) is voltage of sensing resistor. (the same below)



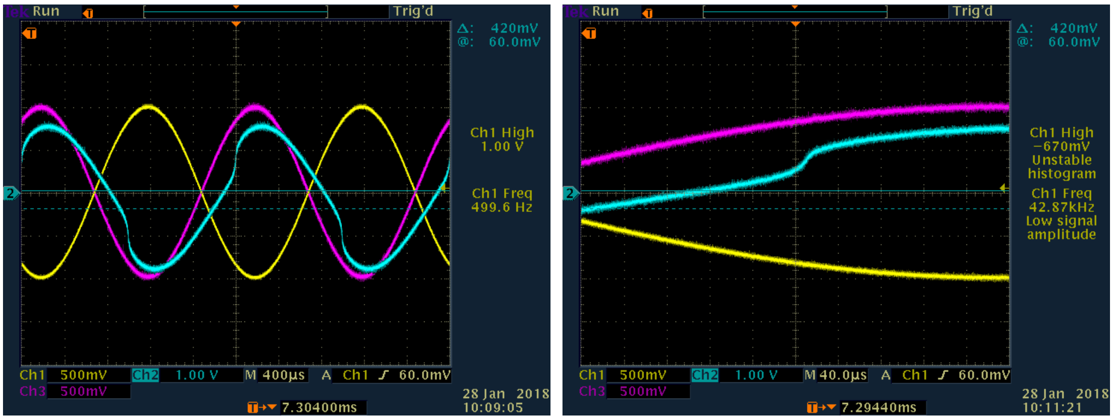
One diode backward bias with lagging

With these figures, we can directly observe the overshoot and the consequent peak and turbulence.





One diode backward bias with lagging but still overshoot which imply that further reduction should be implemented for smaller voltage gap



Two diode forward + backward bias---gap shrank

Finally, with $2.7\mathrm{V}$ bias voltage, the oscillation disappears.

6. Time scale

Times scale characterization without PID feedback

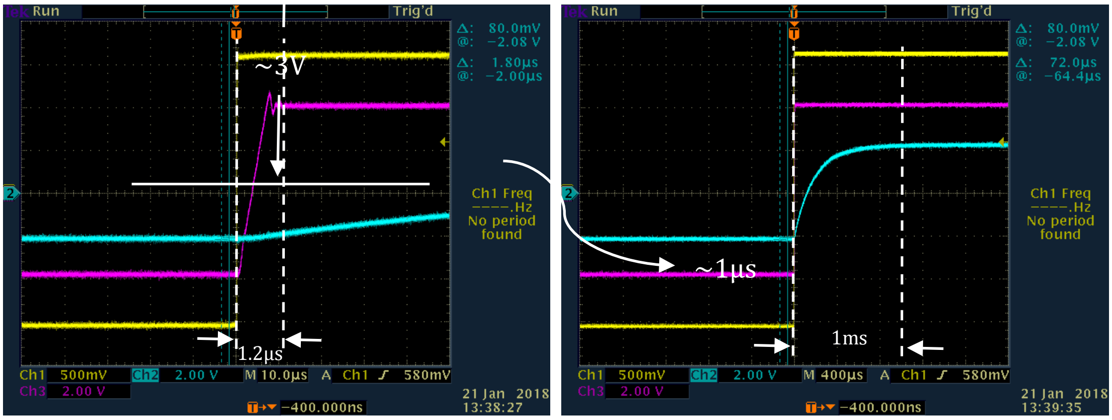


Figure 2 Yellow line (CH1) is voltage input from function generator; White line (CH2) is voltage of sensing resistor; Purple line (CH3) is voltage of pin3 of op-amp.

The rising time of input is $1\mu\mathrm{s}$, which is mainly due to the limited response time of instrumental amplifier implemented before. (also confirmed that the implement of capacitor as to reduce noise does not retard the rising edge magnificently, which means still remain within $1\mu\mathrm{s}$). The rising time of sensing resistor is of the order of $1\mathrm{ms}$ and the character time (half value time) of 'coil plus sensor' is $168\mu\mathrm{s}$. As shown in the right figure, the time scale of this system is determined by its longest value, which is $1\mathrm{ms}$.

Times scale characterization with PID feedback

As shown below, the time scale of system without PID is still $1\mathrm{ms}$, however the character time even decreases $\tau = 108\mu\mathrm{s}$.

During testing, we also notice that voltage implied on coil has drastically high-frequency oscillation with amplitude 3V and freq. 125kHz. However, somehow, it seems that this oscillation does not afflict the signal of coil and sensor: the behavior of this system is still desirable.

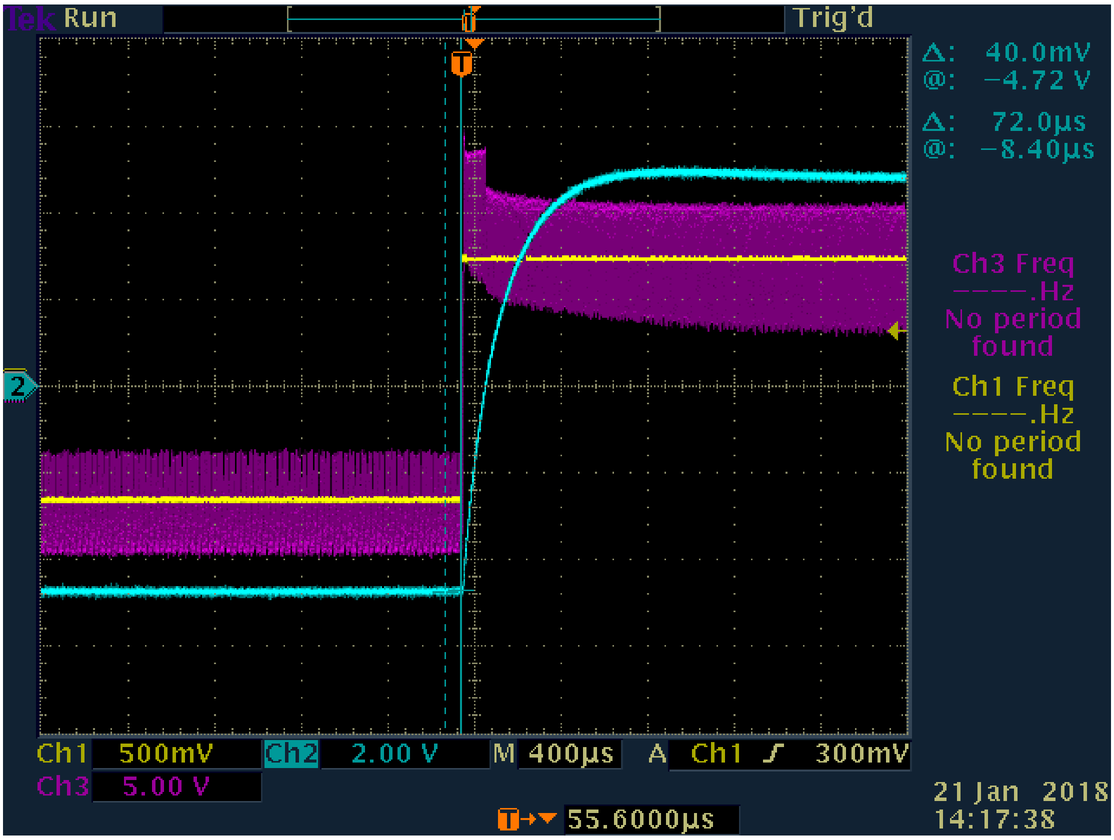


Figure 2 Yellow line (CH1) is voltage input from function generator; White line (CH2) is voltage of sensing resistor; Purple line (CH3) is voltage of 'coil plus sensor'.

*configuration clarification

In this setup, the amplification of current sensing feedback is $150k\Omega/22k\Omega$;

PI parameter $R_0 = 1k\Omega$, $R = 15.5k\Omega$, $C = 12nF$ also $K_P = 15.5$, $K_I = 83.3kHz$

**Voltage drop between drain and source: IRF530: 3.78V; IRF9530 4.3V

Resistance of coil $R_c = 5.5\Omega$; Resistance of sensing resistor $R_{sensor} = 10\Omega$

7. Achieve higher current

For the need of experiment, we reduce the resistance of sensing resistor in order to achieve higher current within ± 15V.

New resistance of sensing resistor $R_{sensor} = 1\Omega$

About scaling gain of current sensing feedback

In order to make the change of the existing PI value or input-output relationship as little as possible (to save the effort of tuning PID parameters), we want to scale the gain of feedback to such a desirable value. The idea is basically as follows:

The state we want to achieve is that after scaling, the range of input voltage (from computer) stays unchanged, i.e. the old maximum input voltage still corresponds to the new maximum current, which remind us that it is the ratio of sensor's voltage that be scaled.

$$\frac{R_{gain-new}}{R_{gain-old}} = \frac{\dfrac{R_{sensor-new}}{R_{coil} + R_{sensor-new}}}{\dfrac{R_{sensor-old}}{R_{coil} + R_{sensor-old}}}$$

According to this formula, the new gain resistor is set to be $150\mathrm{k}\Omega \times 1/4 = 37.5\mathrm{k}\Omega$
Noting change of time scale
Since the resistance of sensor has decreased, the 'coil plus sensor' system's time scale also prolongs according to $t_{\frac{1}{2}} = \sqrt{L/R}$

8. Something to note:

We can tune the value of resistor which is right after signal coming out of INA111P to scale the tuning range of input signal (usually the desirable value is $\pm 1\mathrm{V}$)

After changing the sensor, the time scale of 'coil + sensor' also changes. $\tau = \frac{\mathrm{L}}{\mathrm{R}}$

New noise-shaking resistor & capacitor $R = 40\Omega,\ C = 600pF$
Scaling of feedback gain

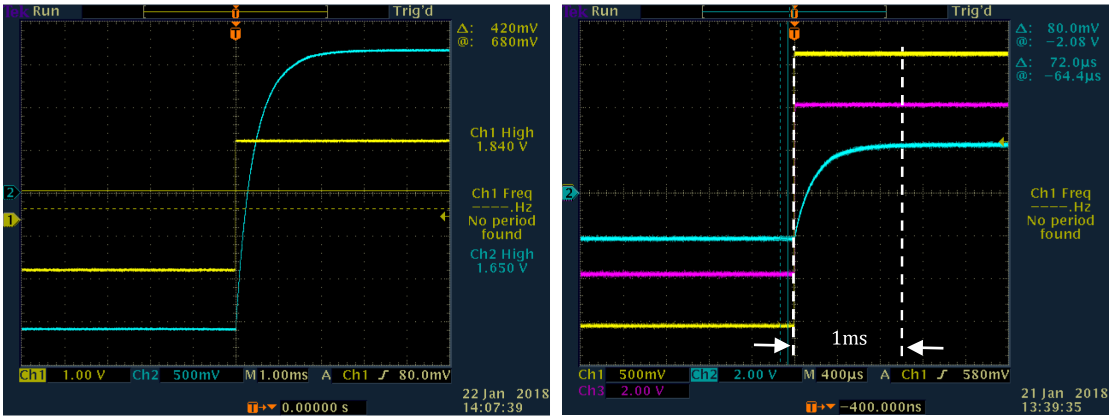


Figure 2 Yellow line (CH1) is voltage input from function generator; White line (CH2) is voltage of sensing resistor; Purple line (CH3) is voltage of pin3 of op-amp.

Rising edge and falling edge; Positive offset and negative offset, compare time scale
Falling edge noise since the two MOSFET has different gate threshold: one has closed and one haven't open yet.

9. Fixing noise of High Voltage path

After implementing the circuit, it is found that the ± 45 V path exhibit large noise and dramatic oscillation, as depict in the figure below

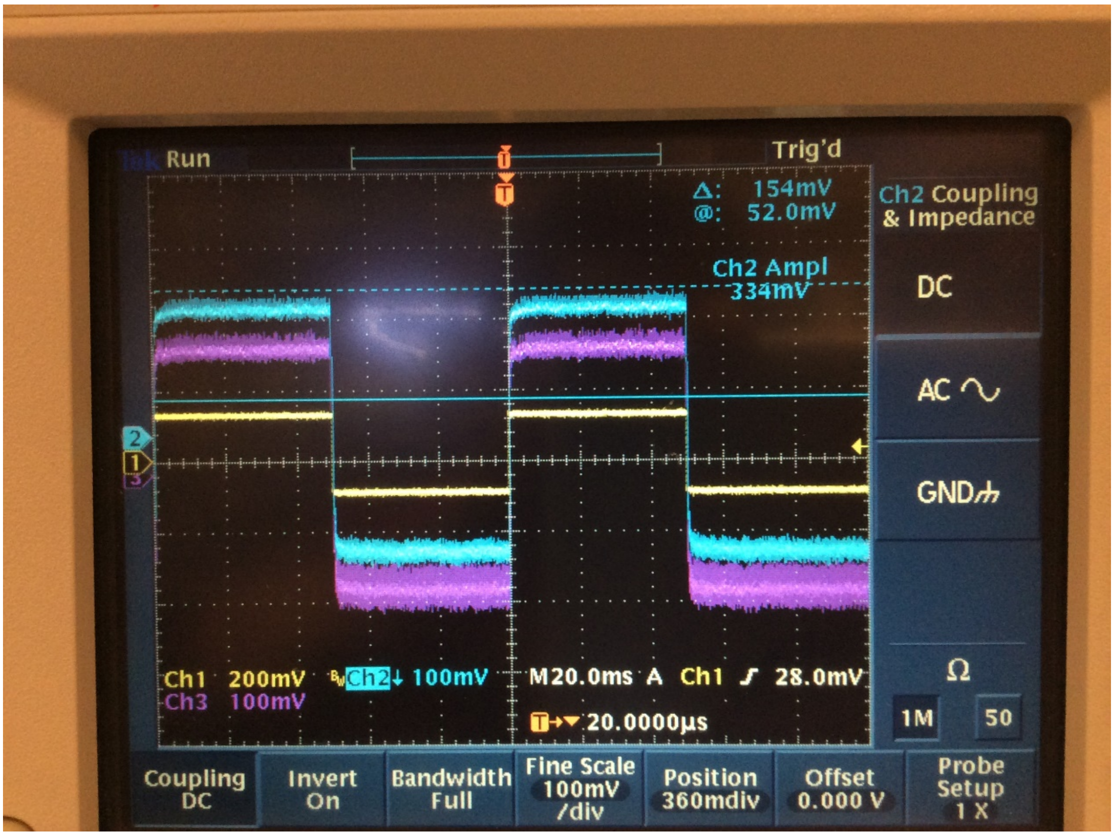


Figure Yellow line (CH1) is voltage input from function generator; White line (CH2) is voltage of sensing resistor; Purple line (CH3) is voltage of 'coil plus sensing resistor'

It is clear from the figure that although the coil filters out part of the fast oscillation, the total performance is still far from being satisfactory. There are two approaches to fix this noise, which are listed as fellow.

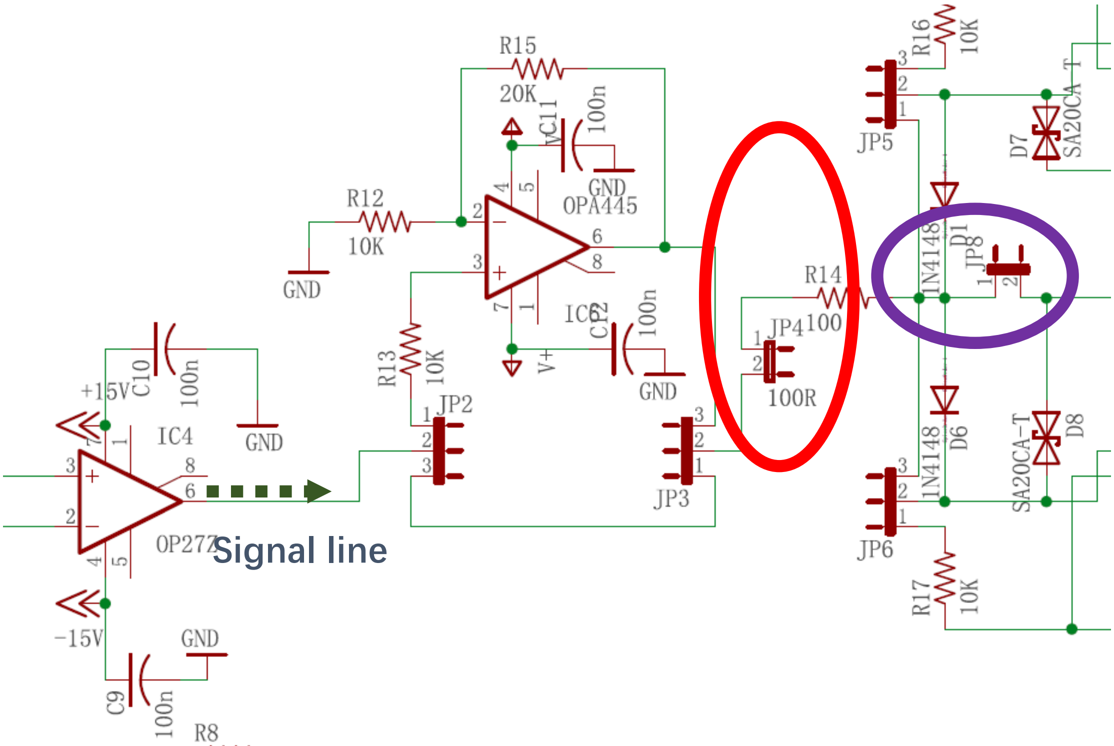
(The author first comes up with method A, but recommends method B)

Method A

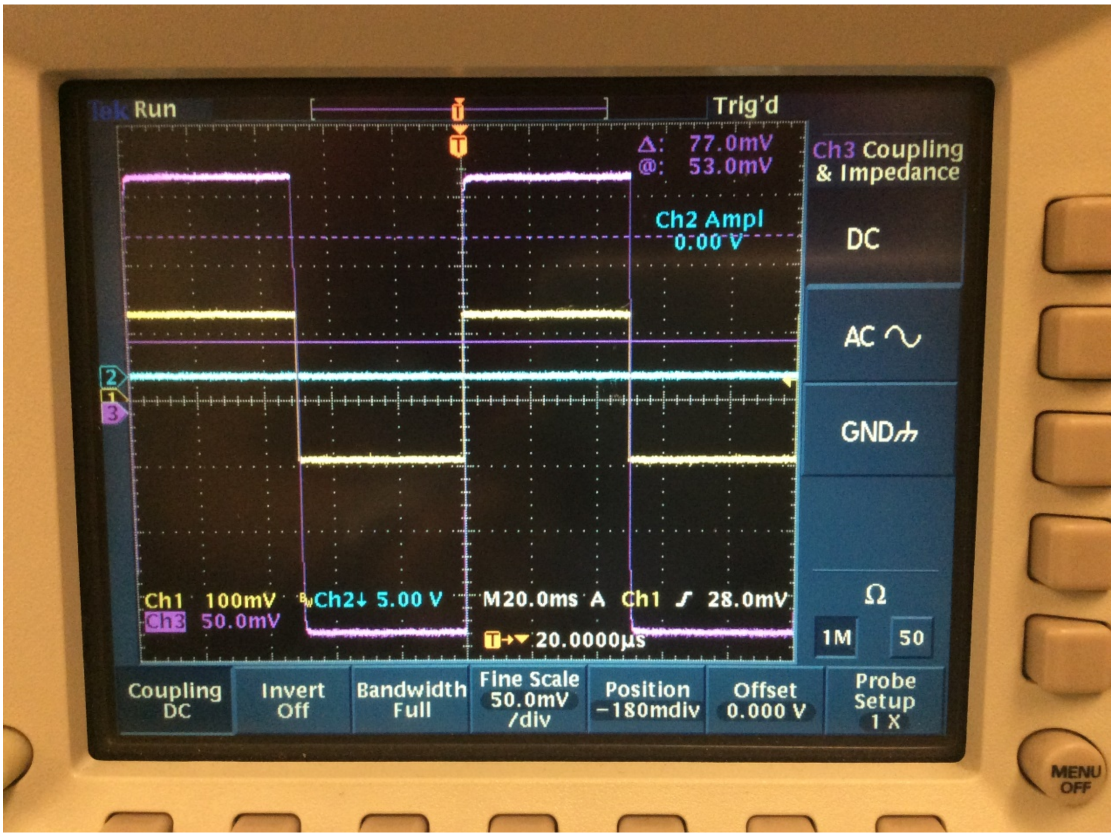
Experimentally we find that the current of the signal line is quite large when using the 45 V path, usually of the order of hundred mA. Thus one of the plausible reasons we surmise is that the current in the signal line is too large that the op-amp is overload by producing such a high power and also once the control current is high, the system is more likely to exhibit self-induced oscillation due to the intrinsic fluctuation of the circuit. However,

The reason there is a large current is that the lagging system is consecutively charging and discharging for the periodic signal. Once on resonance, this process is likely to get amplified and thus induce high current in the signal line. See the schematic below.

To fix this oscillation, we use the same trick as the lagging system, that is, adding a choke into the signal line. Strictly speaking, we need to add a capacitor JP4 and tune the value of this capacitor and R14 to eliminate the noise. In practice, we make a capacitor and a resistor in parallel and plug it into JP4 and it turns out the capacitance needed is quite small (of the order of 1nF) and one can simply make use of the induced capacitance between the two legs of the resistor. The result of the parameter tuning is to put a 10kΩ resistor into JP4 and the noise and oscillation is significantly reduced.



Schematic of the high voltage path. By shorting pin 1,2 of JP2 and pin 2,3 of JP3, we can go to the 45V route. The signal line is indicated by the dashed arrow and the red ellipse indicate the original resistance of the signal line which is of the order of 100Ω. The blue circle indicate the lagging system.



Signal after adding 10k resistor to the circuit. Yellow line (CH1) is voltage input from function generator; Purple line (CH3) is voltage of sensing resistor. It is clear the performance is back to normal compare to the original output

Here, we have to emphasize the defect of this method. Since we are using diodes two reduce the voltage correction, the whole control scheme relies heavily on the ability to control the current inject to the diode side, as depicted in the figure below.

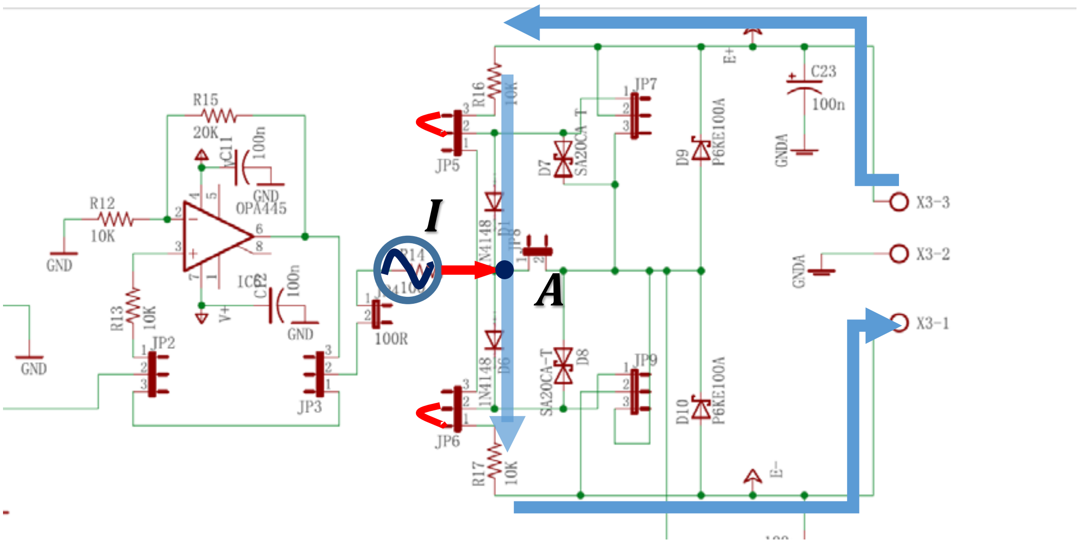


Illustration of the relation between signal line current and diode current. Once we short JP5 and JP6 as in the figure, there are current flowing in the blue arrow line even without signal input. Ideally, without single input, the voltage of middle point A should be zero.

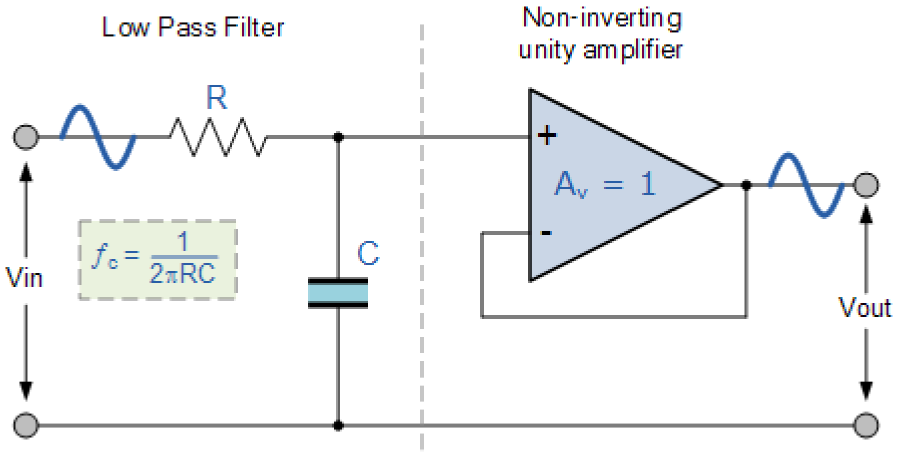
In order to raise the gate voltage, finite amount of current has to be injected into (or extracted from) the diode side to balance the current discrepancy due to the non-zero middle-point voltage. In this method, by adding a large resistor to the signal line, it simultaneously limits the maximum one can inject into point A, and thus the control range is restricted by this large resistor, which make the implementation of High-Voltage path less useful. (Experimentally we find that the optimized circuit can only reach 2A without significant noise which is far from the maximum theoretical value)

And also, this method does NOT clear the noise from the fundamental level: the added resistor acts more or less like a filter in the signal line to suppress the noise only after the resistor (the signal before resistor is still noisy). One can verify that if we increase the resistance of R16 and R17 symmetrically (e.g. from 10kΩ to 50kΩ), which in principle should allow us to be able to drive more current with the same amount of current injected into point A, actually significantly increase the noise level. That is because once the current in the blue arrow line is small, the current in the signal line should be of more precision, that is with larger signal to noise ratio. Unfortunately, this scheme cannot provide such fine control of the signal and thus is somewhat dissatisfactory.

Method B

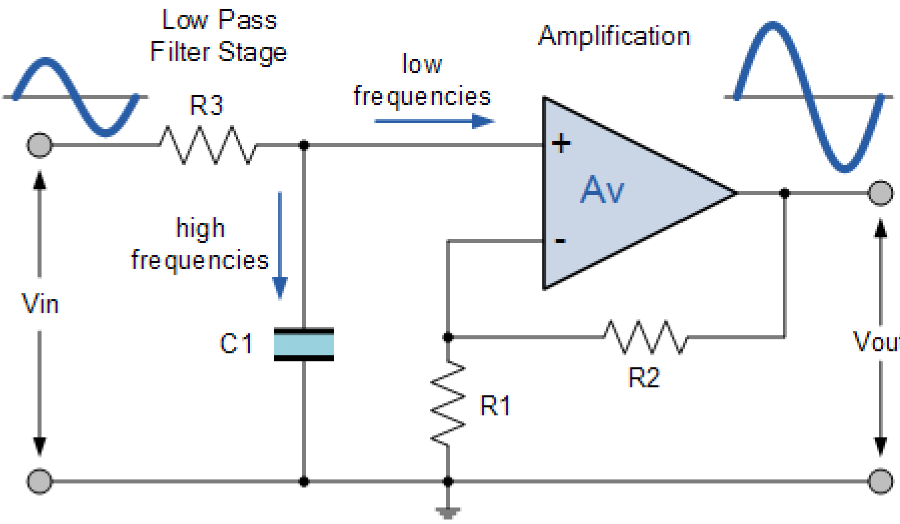
Based on the comment above, we are motivated to find another more efficient way to kill the noise, which means we have to literally clean it up in the signal line such that the maximum driving current is not limited either by noise itself or by **method A** which just seemingly eliminate the noise.

In order to achieve this, we resort to the **active** low pass filter (ALPF) scheme. Note we do *not* choose the commonly used *passive* filter since the main disadvantage of passive filters is that the amplitude of the output signal is less than that of the input signal, i.e., the gain is never greater than unity and that the load impedance affects the filters characteristics. Especially in our signal line, such an attenuation would destroy the whole feedback loop at some particular driving current value. The configuration is shown in the figure below.



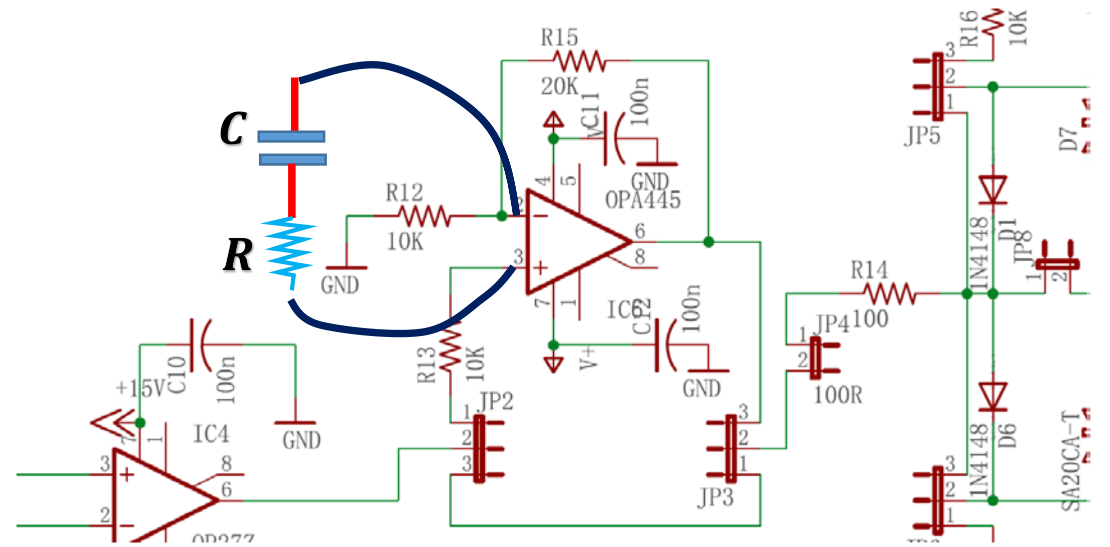
Scheme for the active low pass filter with unitary gain. The simplest form of a low pass active filter is to connect an inverting or non-inverting amplifier. Its principle of operation and frequency response is exactly the same as those for the normal passive filter, the only difference this time is that it uses an op-amp for amplification and gain control

The scheme above is with unitary gain. In order to make full use of the High Voltage op-amp, we adopt the active low pass filter with amplification as shown below.



Scheme for the active low pass filter with finite gain $1+\frac{R_1}{R_2}$(DC). And with the cut off frequency $f = \frac{1}{2\pi RC}$

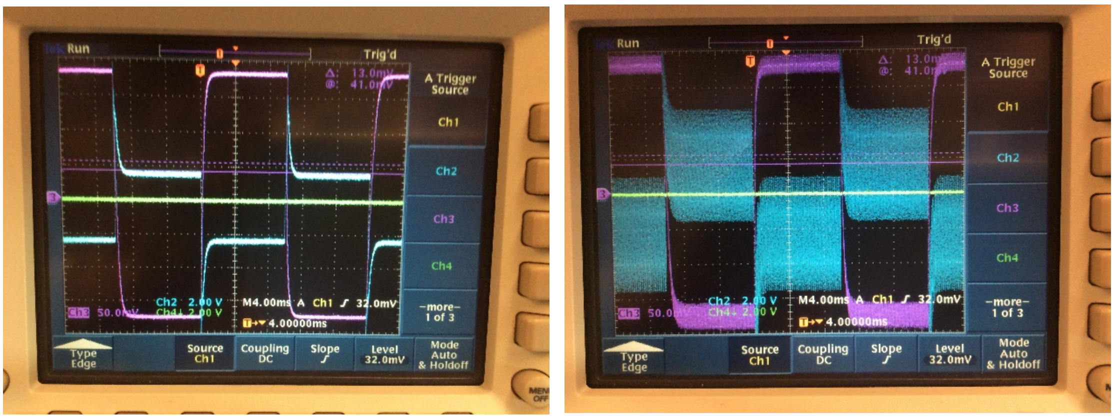
Such a configuration allows us to modify the circuit in the minimum extent, that is we simply add an capacitor (and a resistor) between pin 2 and pin3 of OPA445, as depicted in the figure below.



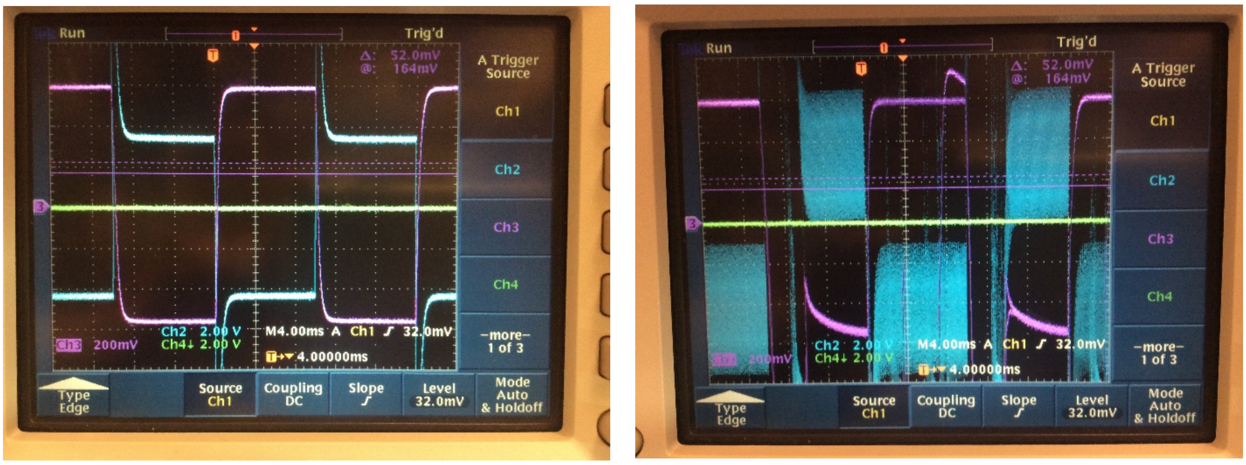
Scheme adopted in the real circuit, with the maximum usage of OPA445 and minimum modification. Experimentally, we find that the noise is more suppressed with an extra small resistor acting as a dissipation component.

Such a modification is actually a trade-off between the temporal stability and the performance of real-time error correction and response. However, since the circuit is intended to work at low frequency ($\leq 1\mathrm{kHz}$), and the noise frequency is normally at $500\mathrm{kHz}$, therefore the price is fairly acceptable.

Below we show the comparison of two methods at different driving current. We conclude that method B is the desirable way to eliminate the noise.



Comparison between method A(right) and method B(left). The purple trace is the voltage of point A and the white trace is the voltage of sensing resistor. The system is driven at 180 mV input and 0.15A, i.e. the low driving regime. Method A still exhibit oscillation although suppressed while method B is quite clean.



Comparison between method A(right) and method B(left). The purple trace is the voltage of point A and the white trace is the voltage of sensing resistor. The system is driven at 750 mV input and 0.92A, i.e. the relative high driving regime. Method A is essentially unstable, as seen in the figure, while method B fairly satisfactory.

10.A side note about the grounding issue

In the previous section, we fix the noise of high voltage. However, we should stress the potential problem of the fighting between two ground. In the circuit, we have several grounds defined by

a) Power supply of 15V op-amp and INA
b) The external signal input (functional synthesizer)
c) Power supply of coil
d) Power supply of 45V op-amp

we add a 100Ω impedance between c) and the rest of the circuit to isolate the high current of the coil. This works fine when the circuit is under 15V modes. But once it switches into 45V modes, empirically the ground of c) is likely to fight with the rest of grounds and make the whole circuit noisy. We suggest to connect all the ground together at the source of the power supplies to avoid such an issue which can not only stabilize the circuit but also not dump the large current of coil into a) through the board (which might generate a lot of heat).

II. PID controller

A proportional–integral–derivative controller (PID controller) is a control loop feedback mechanism widely used in applications requiring continuously modulated control.
Mathematical form

$$u(t) = K_p e(t) \ + \ K_i \int_0^t e(t')\mathrm{d}t' + \ K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}$$

Where K_p K_i K_d are coefficient(for negative feedback, all are non-negative) for the proportional, integral, and derivative terms.

$e(t)$ is the difference between a desired set point $SP = r(t)$ and a measured process variable $PV = y(t)$.

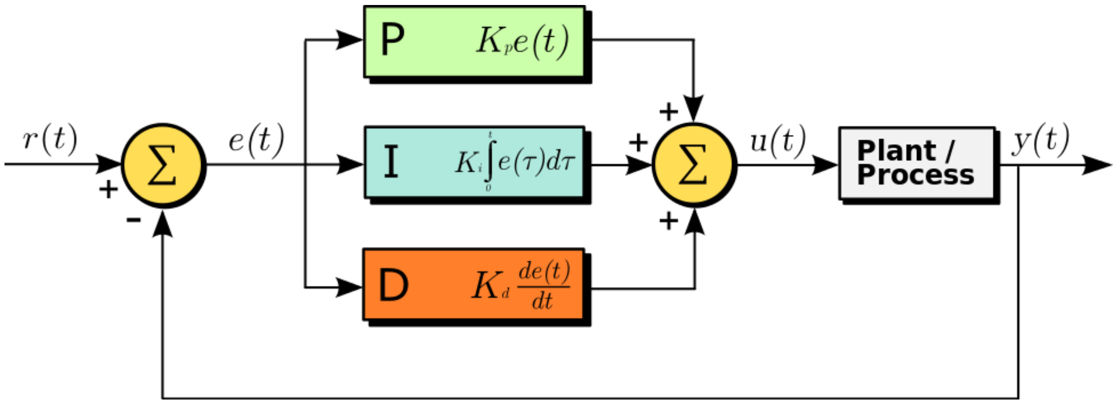


Figure: the controller attempts to minimize the error over time by adjustment of a weighted sum of the control terms.

Feature of three control terms

Proportional term: the main part of the output change, easy to tune but less sensitive to small change time-consuming

Integral term: eliminates the residual steady-state error produced by proportional term but may cause overshoot.

Derivative term: predicts system behavior and thus reduces settling time but sometimes system may go unstable and occurs fast oscillation

1. Frequency domain

The goal is to have the system's output $y(t)$ follow a control signal $r(t)$ as faithfully as possible. The general strategy consists of two parts: First, we measure the actual output $y(t)$ and determine the difference between it and the desired control signal $r(t)$, i.e., we define $e(t) = r(t) - y(t)$, which is known as the error signal. Then we apply some "control law" K to the error signal to try to minimize its magnitude (or square magnitude).

In frequency domain, we have the transfer function

$$y(s) = K(s)G(s)e(s) \quad \text{with } e(s) = r(s) - y(s)$$

$$\Rightarrow y(s) = \frac{K(s)G(s)}{1 + K(s)G(s)} \cdot r(s)$$

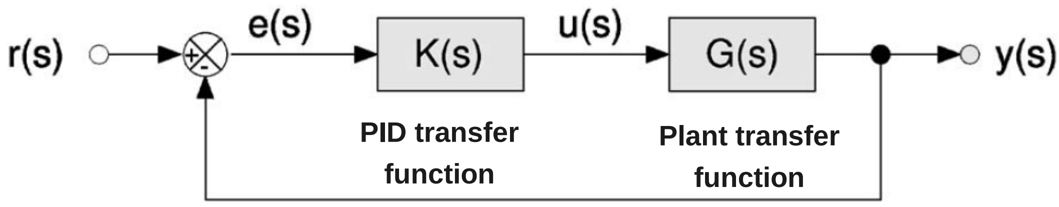


FIG. 6. Block diagram illustrating closed-loop control of a system $G(s)$. Controller dynamics are given by $K(s)$ where, in PID controller cases, is $K(s) = K_p + \frac{K_i}{s} + K_d s$

Realization in digital control loops

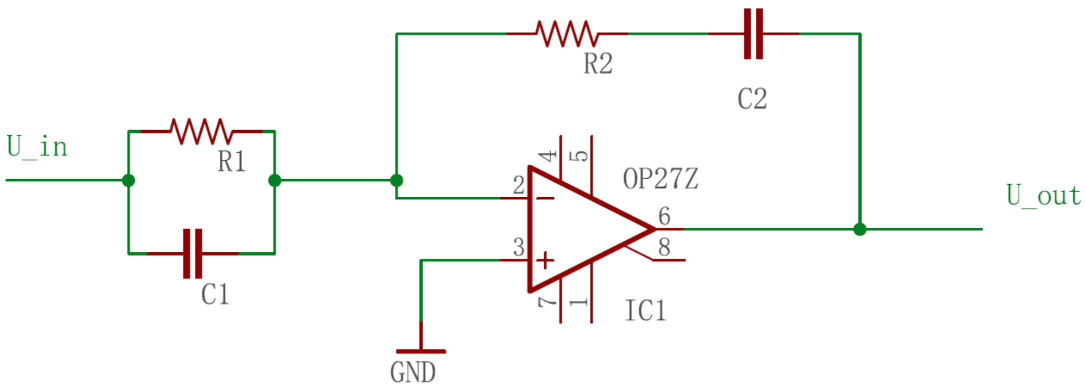


Figure 2 schematic of digital PID controller

$$\left(\frac{1}{C_2}\int \mathrm{d}t + R_2\right)\cdot\left(\frac{U_{in}}{R_1} + C_1\frac{\mathrm{d}U_{in}}{\mathrm{d}t}\right) = U_{out}$$

$$\Rightarrow \quad U_{out} = \left(\frac{R_2}{R_1} + \frac{C_1}{C_2}\right)\cdot U_{in} + \frac{1}{C_2R_1}\cdot\int U_{in}\mathrm{d}t + R_2C_1\cdot\frac{\mathrm{d}U_{in}}{\mathrm{d}t}$$

The corresponding coefficient

$$K_p = \left(\frac{R_2}{R_1} + \frac{C_1}{C_2}\right)$$

$$K_i = \frac{1}{C_2R_1}$$

$$K_d = R_2C_1$$

Then with the help of current feedback, we can implement PID controller to optimize the circuit

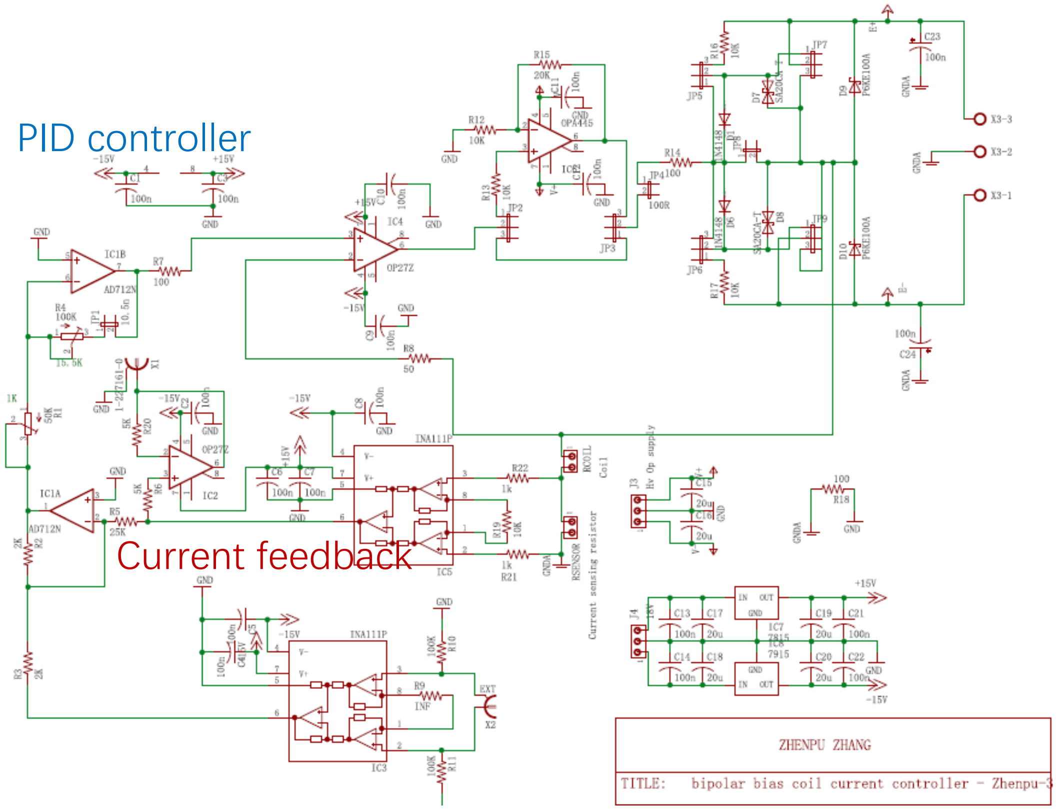


Figure 2 End schematic

2. Tuning of PID

Effects of increasing a parameter independently

Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade
K_d	Minor change	Decrease	Decrease	No effect in theory	Improve if K_d small

Ziegler–Nichols method------A heuristic tuning method:

First set K_i and K_d gains to zero. The proportional gain is increased until it reaches the ultimate gain, K_u, at which the output of the loop starts to oscillate, K_u and the oscillation period T_u are used to set the gains as follows:

Ziegler–Nichols method

Control Type	K_p	K_i	K_d
P	$0.50K_u$	–	–
PI	$0.45K_u$	$0.54K_u/T_u$	–

PID	$0.60K_u$	$0.12K_u/T_u$	$3K_uT_u/40$

3. Tuning Result

Layout statement

Input signal: square wave (to simulate step function) with frequency small enough to allow the system reach steady state.

$R_{coil} = 4.8\Omega \quad R_{monitor} = 10.0\Omega \quad L_{coil} = 3.86 \times 10^{-7}H \quad \tau = 162\mu s$