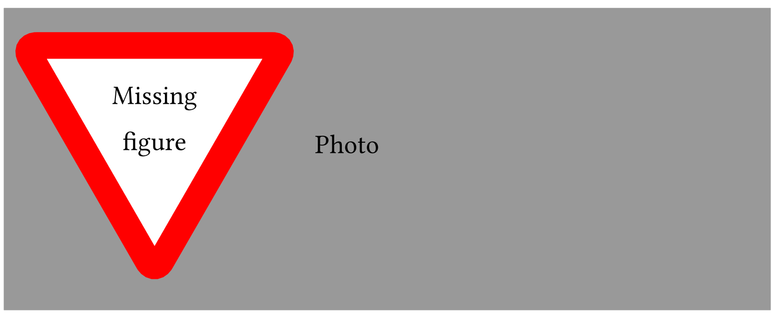
OWNER'S AND SERVICE MANUAL

Gain/Phase Analyzer



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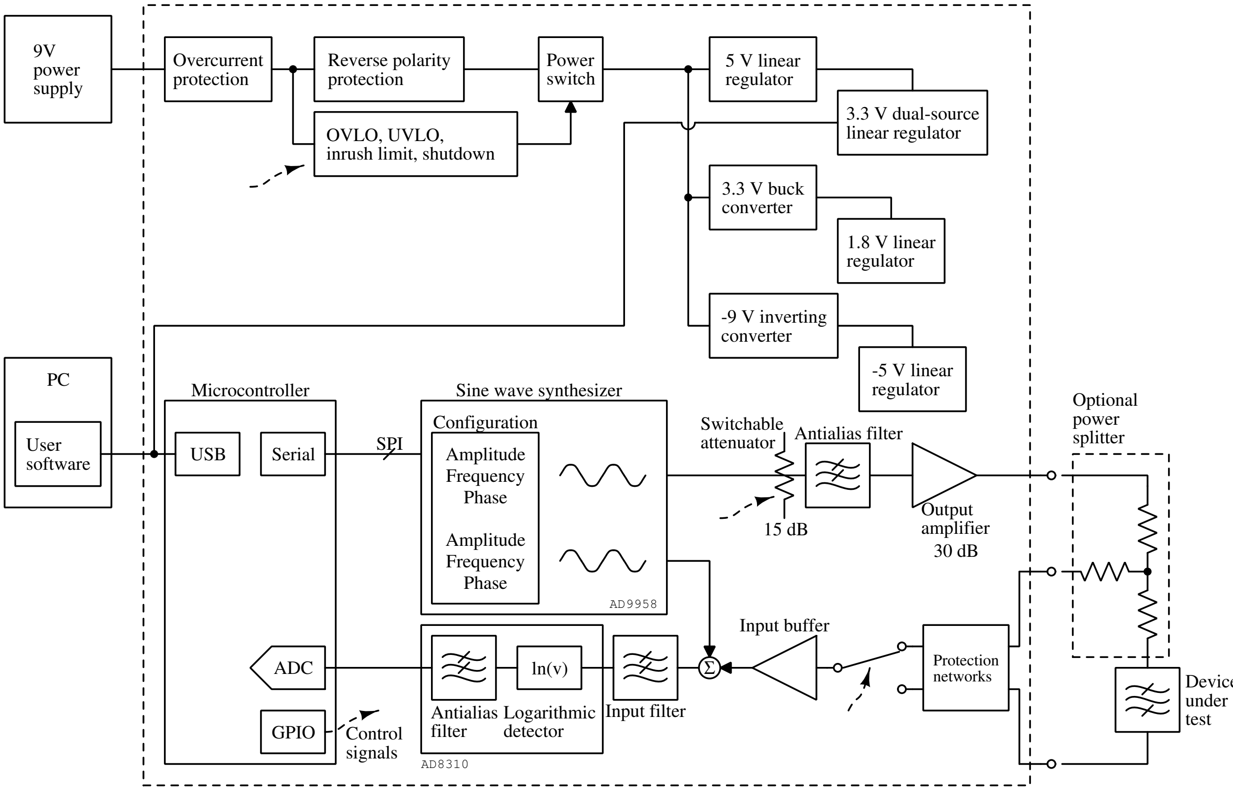

Figure 1: Block diagram

4 Theory of Operation

This section contains a decription of the operation of the gain/phase analyzer. Explanations range from simple and broad to very specific. It is expected that the reader has an understanding of the basics of gain/phase analysis itself, which is explained in the Introduction chapter.

Also, it will be beneficial to look at the main system schematics when reading through this section. Small pieces of the schematic are excerpted when helpful in explaining their function, but are not always shown.

4.1 Block Description

The block diagram is shown in figure 1. A microcontroller drives the instrument, configuring a dual sine wave synthesizer via a serial interface. The first output passes through an optional, switchable attenuator, allowing output amplitude to be configured beyond the practical amplitude range of the synthesizer. The signal is then filtered to attenuate Nyquist aliasing, and then amplified by 30 dB before being passed to the output.

Signals returning from the Device Under Test (DUT) pass through input protection networks, then enter a double-throw RF switch allowing one of them to be analyzed. An input buffer prevents signals from further circuitry from feeding back out the input and affecting the DUT. A summing network combines the input signal with the second output of the synthesizer, and the sum passes through an input filter and into a logarithmic detector. The logarithmic detector outputs a voltage corresponding to the signal amplitude in decibels, and this is further filtered to allow slow sampling, and returns to the microcontroller via the on-chip analog to digital converter.

A power supply system provides overcurrent protection, reverse polarity protection, overvoltage lockout, undervoltage lockout, inrush limiting, and microcontroller-driven shutdown (used in cases of USB suspend). It produces regulated voltage rails of +9 V and −9 V (for the final output amplifier stage), +5 V and −5 V (for general linear circuitry), +3.3 V (for the synthesizer), +1.8 V (for the synthesizer), and a second, weaker +3.3 V rail that can be powered by the USB port in the absence of the main power input (for the microcontroller).

A USB interface connects to a computer, where software sends control commands to the instrument and plots received data.

4.2 Detailed Circuit Description

Power Input Circuit

This instrument is complex and has many somewhat expensive parts, so a full input subsystem was designed to ensure that these parts are always supplied correctly with power. This subsystem provides the following features:

- Overcurrent protection
- Reverse polarity protection
- Undervoltage lockout
- Overvoltage protection
- Inrush current limiting

Overcurrent protection

The first piece of this input system, and possibly the simplest, is R81. R81 is a *resettable fuse*, a type of resistor with a positive temperature coefficient. Its resistance is very low (around 0.5 Ω) at room temperature. As the current flowing through it increases, it heats up, and as it heats up, its resistance increases. Eventually, it will reach a point where this process 'snowballs', and its resistance is high enough that almost no current can flow through it. This allows it to act like a fuse, but without permanently blowing: as soon as it cools back down, it will conduct again.

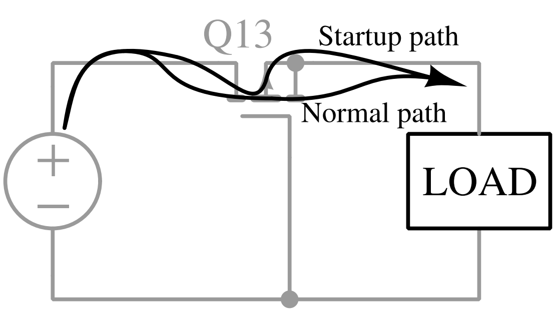

Figure 2: MOS reverse polarity protection circuit, simplified

Reverse polarity protection

Once input current has passed through the resettable fuse, it encounters Q13. A simplified form of this part of the circuit can be seen in figure 2. Remember that a MOSFET has 'parasitic' diodes connected from the transistor's channel to its substrate; in a standard power MOSFET, one ends up connected between the two ends of the channel (the other ends up shorted to itself). In a P-channel MOSFET, this diode points from the source to the drain. In this circuit, when power is applied with the correct polarity, this diode allows current to initially take the path labeled *startup path*. When it does so, the voltage applied to the load begins to rise, but the gate stays low, as it is tied to ground. Eventually, the voltage rises high enough that the gate-source voltage switches on the MOSFET, and current begins to flow through the *normal path* instead. This path takes the current through the low-impedance MOSFET channel, rather than through the diode where the forward threshold voltage of the diode would be lost.

If power is applied in the incorrect polarity, the substrate diode never conducts, so the MOSFET never switches on.

Power switch

After the reverse polarity protection, the current must flow through Q14, which is connected as a traditional switch. R88 holds its gate and source together when the power is switched off, keeping the MOSFET also turned off.

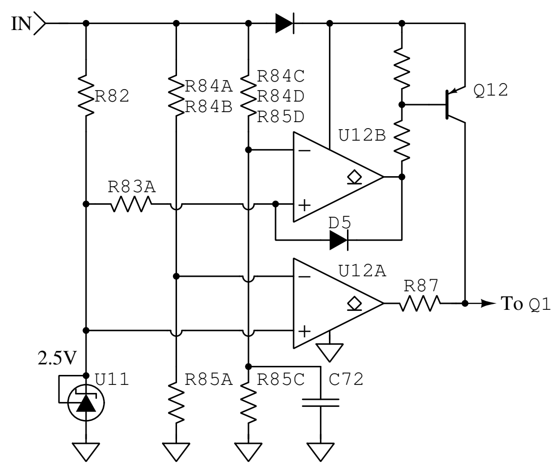

Figure 3: UVLO and OVLO circuit

To simplify things, the subcircuit in figure 3 is powered through a single diode for its own reverse-polarity protection. Bandgap voltage reference U11 does not need this, as its internal circuit has an antiparallel diode built in [8].

Undervoltage lockout

U11 provides an accurate 2.5 V level against which the input voltage can be compared. As the input voltage rises, the voltage at the output of the R84A/R84B/R85A voltage divider also rises. When this divided voltage reaches the 2.5 V reference level, the input voltage is at 7.5 V, the undervoltage threshold. Comparator U12A switches low, allowing power switch Q14 to switch on and allow the full system to operate.

Overvoltage protection

If the input voltage continues to rise, the voltage at the output of the R84C/R84D/R85D/R85C voltage divider will eventually reach the reference level when the input voltage is at 10 V. C72 provides a low-pass effect which prevents simple noise and short transients from causing this. When this happens, comparator U12B switches low. At this point, two things happen. First, Q12 switches Q14 off, powering down the circuit. Second, D5 pulls the reference level as seen by U12B down to about 1 V, locking the system in this shutdown mode until the input voltage drops back as low as 4 V — at which point it must climb again to the 7.5 V undervoltage threshold. In practice, the system must be powered off and back on. This latch prevents the instrument from accidentally being powered by too high an input voltage.

Inrush current limiting

Q14 does not act *only* as a power switch. When it switches on, it starts in the 'cutoff' region of operation, and moves to the 'saturation' region. However, it must pass through the 'linear' region. We can take advantage of this.

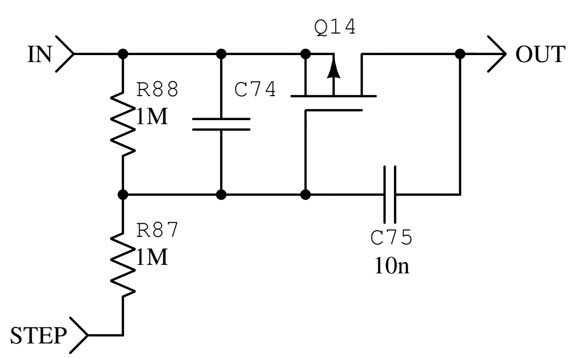

Figure 4: Miller integrator

The circuit in figure 4, when Q14 is in the linear region, is known as a 'Miller integrator' [2, pg. 283]. Because R87 and R88 form a voltage divider, the input voltage to the integrator will be half the input supply voltage at half the resistance (nominally, 4.5 V at 500 kΩ). The integrator capacitance is simply C75, which is 10 nF. Because the voltage across C74 changes only negligibly, its effect on the circuit will also be negligible.

At startup, C75 would tend to hold the gate above the source, switching the transistor fully on and bypassing any limiting effect. The much larger C74 swamps this effect, holding the gate to the source until a DC source of current is provided via R87.

The input signal to this integrator will be a step, because comparator U12A switches directly from 'off' to 'on'. Integrating a step gives a ramp, with a slope of:

$$\frac{dv}{dt} = \frac{v_{in}}{RC} = \frac{4.5\text{ V}}{(500\text{ k}\Omega)(10\text{ nF})} = 900\text{ V/s} = 0.9\text{ V/ms}$$

This means it will take about 10 ms for the voltage to ramp from zero to the full input voltage of 9 V.

Because the inrush current to be limited is the current charging the system's capacitance, we can calculate the worst-case inrush current. Charge is held on-board by approximately 200 µF worth of capacitors. Given this capacitance and the voltage slope, the current is calculated as follows:

$$I = C\frac{dv}{dt} = (200\ \mu\text{F})(900\text{ V/s}) = 180\text{ mA}$$

During this charging time, the power dissipated in Q14 will be high. The worst-case is when the full input voltage is dropped across it, giving a power dissipation of (9 V)(180 mA) = 1.62 W. The average power for the entire time will be:

$$\begin{aligned} P &= IV \\ P_{avg} &= \frac{1}{10\text{ ms}}\int_0^{10ms} iv\ dt \\ &= \tfrac{1}{2}(1.62\text{ W})(10\text{ ms})/(10\text{ ms}) \\ &= 810\text{ mW} \end{aligned}$$

Thus, a MOSFET must be selected that can handle an 810 mW pulse for 10 ms. This pulse-handling capability is shown in the datasheet as the "forward-biased safe operating area", and we selected an AOD417 which can easily handle this pulse with excess [1].

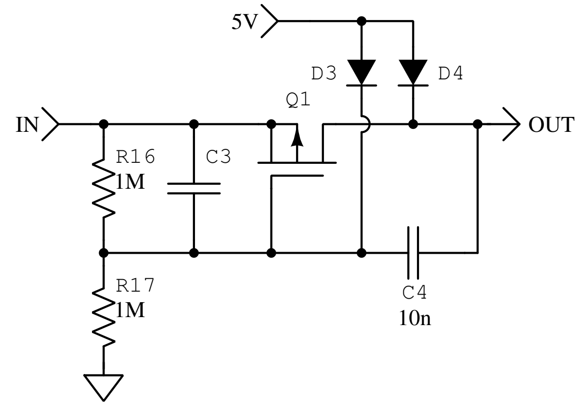

Figure 5: USB power input circuit

USB Power Input Circuit

The USB specification is very demanding with respect to the amount of inrush current that a USB device may consume. We used the same Miller-integrator inrush limiting circuit on the USB power supply input.

In this case, the resistance has not changed (still a Thévenin-equivalent 500 kΩ), and the input step is equal to 2.5 V, half the input voltage. The integrating capacitance is C4, which has a value of 10 nF, and the maximum input capacitance being charged is approximately 20 µF.

$$\frac{dv}{dt} = \frac{v_{in}}{RC} = \frac{2.5\text{ V}}{(500\text{ k}\Omega)(10\text{ nF})} = 500\text{ V/s}$$
$$I = C\frac{dv}{dt} = (20\ \mu\text{F})(500\text{ V/s}) = 10\text{ mA}$$

The power dissipation in this case is very small (no more than 50 mW for only a few milliseconds), so we used a smaller and less expensive MOSFET that was already in use elsewhere for this particular integrator.

No reverse polarity protection was deemed necessary on the USB input.

Diodes D3 and D4 allow the on-board power supply to power the circuitry downstream from the USB port whenever that supply is powered, so that this circuitry can draw larger amounts of current without the trouble of making sure that this current draw is within USB specifications. D3 shuts off Q1, and D4 provides power in Q1's absence.

Switching DC-DC Converters

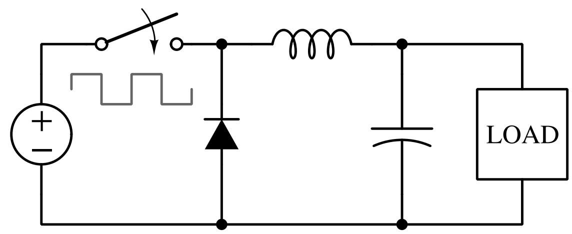

Figure 6: Basic buck converter circuit

Buck converter theory

The basic idea of an inductor is that it translates electric current flowing through it into a magnetic field around it. There is energy stored in this magnetic field, so the inductor tends to hold the current fixed (as changing the current would require adding or removing energy from the field). The 'buck converter' is a voltage down-converter circuit that takes advantage of this.

A more mathematical approach is that inductors integrate the voltage applied to them, producing a current:

$$i = \frac{1}{L}\int v\, dt$$

A buck converter must have at least one switch, as shown in figure 6. The switch is initially closed for a brief period. This applies a positive voltage to the inductor, causing the current through it to begin to increase (remember that the integral of a step is a ramp). This current flows through to the output of the converter, and the output voltage begins to rise.

Now, the switch is opened. The inductor keeps the current flowing, though, through the diode this time. The voltage across the inductor is now negative (the voltage on the left side had to fall negative in order to forward-bias the diode and make it conduct), so the current starts ramping downward, and the output voltage begins to fall. [4, pp. 356–357]

By repeating this cycle, the output voltage can be made to rise and fall around a desired point, and by placing a large capacitor at the output, the rising and falling current can translate to very small variation in output voltage, though it must rise and fall at least a small amount. This allows the output voltage to be any arbitrary voltage smaller than the input voltage, but does not theoretically lose power, unlike a linear regulator (whose entire mechanism of operation is intentional power loss).

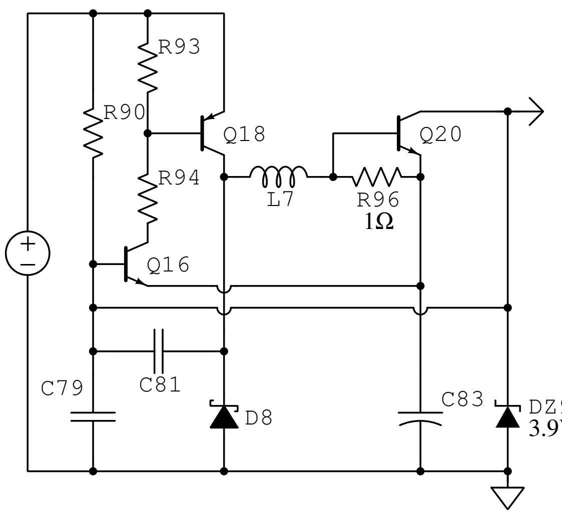

Figure 7: 3.3 V buck converter circuit

3.3 V buck converter

In this instrument, we have used a simple, three-transistor regulated buck converter circuit. It is inexpensive, reliable, and though it is not hugely efficient, it generates relatively little switching noise (due, in part, to its low speed compared to more modern designs).

In the first phase of the switching cycle, Q16's base voltage is low. R90 charges C79, and eventually the base voltage rises high enough that Q16 switches on. It pulls Q18's base voltage down, switching on that transistor too. Q18 is equivalent to the main switch in figure 6, and the inductor current starts to rise.

In the next phase of the switching cycle, something draws current towards ground out of C79 and away from Q16's base. This starts a chain reaction: Q16 and Q18 start to switch off, and are no longer driving the inductor. The inductor's tendency to keep current flowing makes the voltage on its left side sharply decrease. This decrease is coupled through C81, which drags Q16's base voltage even lower, switching it off quite solidly. The converter will remain switched off until C79 charges back up through its resistor.

Two things can be the 'something' of the previous paragraph, initiating the switch from phase 1 to phase 2. First, note that Q16's emitter is connected to the output voltage, so when it is switched on, its base will be about 0.65 V above that. When the output voltage reaches about 3.25 V, the base voltage is at about 3.9 V, and Zener diode DZ9 starts to conduct. This means that the output voltage will not be allowed to rise above about 3.25 V, providing the voltage regulation function.

The inductor current must also flow through sense resistor R96. If the current exceeds about 650 mA, the base-emitter voltage applied to Q20 will be high enough to switch it on, and Q20 will draw the shutdown current. This provides the current-limiting function.

-9V inverting regulator

It is possible to repurpose a buck converter circuit as an inverting (buck-boost) circuit that generates a negative voltage [9]. The circuit is otherwise the same, with two exceptions. First, the Zener diode, now DZ10, is a 10 V part, giving a regulated output voltage of about 9.35 V. Second, because the current through the output capacitor has more hard edges in a buck-boost converter, a 1 µF ceramic capacitor (useful to higher frequencies and currents) has been added in parallel with the main output capacitor.

Linear Regulators

A series-type linear regulator works by acting as a controlled resistance, regulating itself to exactly the resistance required to give the correct output voltage considering the amount of current flowing through it. This means that power loss is a required property of linear regulators. For example, a linear regulator taking an input voltage of 9 V, giving an output voltage of 5 V, and passing a current of 100 mA, will lose $(9-5)(0.1)$ W $= 400$ mW of power, dissipated as heat. The loss is sometimes a fair trade for simplicity and low output noise. This instrument uses four linear regulators, which provide power supplies of 5 V, -5 V, 1.8 V, and a low-power 3.3 V supply (a high-power 3.3 V supply for the synthesizer comes from the buck converter).

These regulators are U13, U14, U15, and U16. They are monolithic devices with no external circuitry except for filter capacitors, and as such will not be addressed further. See their datasheets for more information: [7] [6] [3] [5].

Microcontroller

USB Communications

Synthesizer

Synthesizer Output Amplifiers

Output System

Attenuator and Filter

Gain Stages and Termination

Input System

Protection

Switching

Buffer and Filter

Logarithmic Detector

4.3 Software Description

Signal Processing

Sampling

Null Search

Calibration

User Interface

5 Full schematics

References

[1] Alpha & Omega Semiconductor, "AOD417 P-Channel Enhancement Mode Field Effect Transistor," AOD417 datasheet, 2008. http://aosmd.com/pdfs/datasheet/AOD417.pdf

[2] S. W. Amos and M. James, "Sawtooth generators," in *Principles of Transistor Circuits*, 9th ed. Oxford: Newnes, 2003, ch. 14, pp. 281–292.

[3] Diodes Incorporated, "Low Dropout Linear Regulator," AZ1117C datasheet, October 2014 [Revision 3–2]. http://www.diodes.com/datasheets/AZ1117C.pdf

[4] P. Horowitz and W. Hill, "Voltage regulators and power circuits," in *The Art of Electronics*, 2nd ed. Cambridge: Cambridge, 1989, ch. 6, pp. 307–389.

[5] Microchip Technology, "Low Quiescent Current LDO," MCP1700 datasheet, October 2013 [Revision C]. http://ww1.microchip.com/downloads/en/DeviceDoc/20001826C.pdf

[6] ON Semiconductor, "500 mA Negative Voltage Regulators," MC79M00 series datasheet, July 2013 [Revision 15]. http://www.onsemi.com/pub_link/Collateral/MC79M00-D.PDF.

[7] STMicroelectronics, "Precision 500 mA regulators," L78M datasheet, June 2014 [Revision 20]. http://www.st.com/web/en/resource/technical/document/datasheet/CD00000447.pdf

[8] Texas Instruments, "TL43xx Precision Programmable Reference," TL431 datasheet, Aug. 2004 [Revised Jan. 2015]. http://www.ti.com/lit/ds/symlink/tl431.pdf

[9] J. Tucker, "Using a buck converter in an inverting buck-boost topology," *Analog Applications Journal*, Texas Instruments, fourth quarter 2007, pp. 16–19. http://www.ti.com/lit/an/slyt286/slyt286.pdf