

---

# Component Design for LV2 Power Electronics (Except Main Battery?)

There are errors here! Fully discharge Li+ cells are 2.5V (not 2V). (2.5, 3.6, 4.2)

Don't forget IC's for div 6.5 circuit! (HC161 + 2xExOR+small cap) (PIC-300series, don't know Andrew's numbers)

# CAN Node Switch Mode Power Supply (SPS) (200)

## Connector(s)

- CX200/201 No Earthly Idea ???

## Integrated Circuit(s)

- U200 LT1767, 1.25+MHz, 1.5A, DC-DC buck converter (DigiKey LT1767EMS8-ND 6.00\$ea)

The selection criterion include size, efficiency, complexity and frequency. This MSOP-8package can reach 87% efficiency supplying 5V @ around 100mA output @ 1.5MHz (synchronized). With 10 $\mu$ A shutdown current, about 1mA quiescent current, and potentially 1A output current while tolerating a 8-20V input range.

- U201 LTC1442, ultra low power dual comparator w/ reference (DigiKey LTC1442IS8-ND 4.88\$ea)

Functionally this chip identifies over-voltage and under-voltage conditions. Since it must operate constantly off the Li+ backup battery, micropower is essential. This unit is a single package SO-8or MSOP-8solution which draws only 3.5 $\mu$ A (typ) or 5.7 $\mu$ A (Max).

- U202 Any single 'HC NOR gate (DigiKey SN74AHC1G02DBVR 0.56\$ea) SOT-23-5

This gate blocks the synchronization signal during power fail. This is required because the backup power can keep the synchronization signal active even when U200 is shut down. If the synchronization signal passed directly to U200, U200 would be powered through its input protection diodes during positive excursions of the sync signal. U202 is not required on SPS' which do not include backup power.

Since a full discharged Li+ battery is only 2.5V the logic should run in the range of about 2V to 5.2V. Most current CMOS products will do this.

## Transistor(s)

### ■ Q200 IRF7455 SO-8 N-FET (DigiKey IR7455-ND1.53\$ea)

International Rectifier IRF7455

SO-8	package
30V	V <sub>DSS</sub>
29mV/C	Break down temp.co. 25C, I <sub>D</sub> =1mA
7.5mΩ	R <sub>DS(on)</sub>
(, 37, 56)nC	total gate charge @ V <sub>GS</sub> =5V
3480pF	typ. input capacitance
15	I <sub>D</sub> Max (dissipation limited)
120A	Max pulse current
±12V	V <sub>GS</sub> Max
1.2V	Max body diode forward voltage @ 25C, 2.5A, V <sub>GS</sub> =0V
96ns	Max body diode reverse recovery time
150nC	Max body diode reverse recovery charge
200mJ	Max pulse avalanche Energy
0.25mJ	Repetitive avalanche Energy
150C	T <sub>J</sub> Max
50C/W	Max θ <sub>JA</sub> on standard 1"sq. copper clad board, t < 1s.

Crowbar element for CAN node. Q200 shorts the incoming power bus when an over-voltage condition exists at the output of the SPS. Dissipation is not high because of the short duration of activation. Must respond to 5V gate drive and sink minimum of 8A at 5V. Voltage rating 25V minimum.

A very cheap part in the SO-8package is the IRF7463, R<sub>DS(on)</sub>=8mΩ, V<sub>DS</sub>Max=30V, 1.55\$.

Almost as suitable in the MSOP-8style, IRF7603, R<sub>DS(on)</sub>=35mΩ, V<sub>DS</sub>Max=30V, 1.92\$.

Perhaps smallest, but pushing it, SOT-223,IRLL014, R<sub>DS(on)</sub>=140mΩ, V<sub>DS</sub>Max=55V, 0.68\$

The SOT-223 package is spec'd (See irll014n.pdf p.5) as having 10% response to a single 100ms pulse. The effective thermal resistance is therefore at most 12C/W. assuming a 16A pulse, the max power is about 36W or 430C temperature rise. Obviously too much. What is the impedance of a 4Ahr 4 cell Li+ battery? Ans: about 0.1Ω.

Figuring 0.1Ω per cell, and accounting for the transistor at 0.28Ω and the choke at 0.14Ω the short circuit current of a full battery pack is

$$4.2 * 4 / (4 * 0.1 + 0.28 + 0.14)$$

$$20.4878$$

Safety suggests figuring 30A. In which case the SOT-223 is too small.

Going to the MSOP-8? Ooo the Farchild NDT455N is much better! (R<sub>DS(on)</sub>=20mΩ), but still too small.

Even the MSOP-8is too small ... sigh. So it's the SO-8for us.

Ok, just to disprove insanity, here's the justification. Surge current 30A for 50ms Max.

R<sub>DS(on)</sub> @ 150C is < 12mΩ, so P<sub>D</sub>(Max) is < 11W, transient thermal resistance (equivalent, see irf7455.pdf p.5) is < 7C/W so temperature rise is < 77C. Therefore maximum operating ambient is > 73C, which is pretty damn hot, so there.

## ■ Q201 ZXMN2A01F SOT-23-3 N-FET (DigiKey ZXMN2A01FCT-ND0.48\$ea@10)(Changed to bipolar)

Zetex ZXMN2A01F

SOT-23-3	package
20V	V <sub>DSS</sub>
120mΩ	R <sub>DS(on)</sub> V <sub>GS</sub> =4.5V, 25C
3.1nC	typ. total gate charge @ V <sub>GS</sub> =4.5V
299pF	typ. input capacitance
1.8	I <sub>DMax</sub> (dissipation limited)
10A	Max pulse current
±12V	V <sub>GSM</sub>
(.84, .95)V	Max body diode forward voltage @ 25C, 0.6A, V <sub>GS</sub> =0V
11.2ns	typ. body diode reverse recovery time
3.64nC	typ. body diode reverse recovery charge
(-55, 150)C	T <sub>J</sub> range
200C/W	Max $\theta_{JA}$ on FR-4, t < 5s.

The problem with the micro-6 & Fairchild part is the cases have mutually incompatible board layout between each other and between the std. SOT-23. DigiKey has a decent SOT-23-3 (4.2A) but only in tape&reel :(.

Oooo, compare Fairchild NDC651 (maybe better)

International Rectifier IRLMS1503

Micro6	package (Similar to SOT-23-6)
30V	V <sub>DSS</sub>
37mV/C	Break down temp.co. 25C, I <sub>D</sub> =1mA
200mΩ	R <sub>DS(on)</sub> V <sub>GS</sub> =4.5V, 25C
(, 6.4, 9.6)nC	total gate charge @ V <sub>GS</sub> =5V
210pF	typ. input capacitance
2.6	I <sub>DMax</sub> (dissipation limited)
18A	Max pulse current
±20V	V <sub>GSM</sub>
1.2V	Max body diode forward voltage @ 25C, 2.2A, V <sub>GS</sub> =0V
54ns	Max body diode reverse recovery time
58nC	Max body diode reverse recovery charge
(-55, 150)C	T <sub>J</sub> range
75C/W	Max $\theta_{JA}$ on FR-4, t < 5s.

Q201 has been changed to bipolar PNP because it turns out there is an O.C. pin on the PIC, and the bipolar works better with the O.C. (The bipolar is generic 3906-ish.

Q201 isolates the HAP-powered PIC from the possibly shutdown U200. This can be a generic logic level mosfet. Prefer SOT-23-3 package. Best if Voltage ≥20V.

Couldn't find a DigiKey part with cool ratings and SOT23-3. IRLMS1503 is in a Micro6. I think a PCB can be laid out for either package.

## ■ Q202 See Q201

Q202 performs a switching function similar to Q201, see Q201 for details.

## Diode(s)

### ■ CR200 Panasonic Schottky MA2Q705 (MA10705) (DigiKey MA10705CT–ND0.64\$ea/10)

Panasonic MA2Q705 (MA10705)

NMiniP2 package, proprietary, but similar to other 2 pin types

30V  $V_R$

1.5  $I_{DMax}$  (dissipation limited)

30A Max pulse current

0.37V Max forward voltage @ 25C, 1A

50ns Max reverse recovery time

(–40, 125)C  $T_J$  range

This is the main diode for the buck topology. The voltage rating requirement is  $\geq 25V$ .

Average current is given by

$$I_d = I_o \frac{(V_i - V_o)}{V_i} / . \{ I_o \rightarrow 1, V_i \rightarrow 18, V_o \rightarrow 5 \} // N$$

$$I_d = 0.722222$$

A reasonably conservative choice would be a 1A Schottky diode.

### ■ CR201 1N4448HWS (DigiKey 1N4448HWSDICT–ND0.30\$ea/10)

Diodes Inc. 1N4448HWS

SOD-323 package, 2 pin type possible to shoot a trace

80V  $V_R$

100nA Max reverse current @  $V_R$  @ 25C

50 $\mu$ A Max reverse current @  $V_R$  @ 150C

200mW Max power (assume 25C at leads)

1V Max forward voltage @ 25C, 100mA

4ns Max reverse recovery time

3.5pF Max capacitance

625C/W  $\theta_{JA}$  @ 25C

(–65, 150)C  $T_J$  range

Considered BAV16WS, but 1N4448HWS has slightly better specs.

Diodes Inc. BAV16WS (1N4148WS)

SOD-323 package, 2 pin type possible to shoot a trace

75V  $V_R$

1 $\mu$ A Max reverse current @  $V_R$

200mW Max power (assume 25C ???)

1V Max forward voltage @ 25C, 50mA

4ns Max reverse recovery time

2pF Max capacitance

(–40, 125)C  $T_J$  range

Also considered the SOD-123 package, which is longer, similar to 1206. Smaller package is nice and according to preliminary analysis, will still give 1206 interchangeability.

Diode provides boost current for U200's internal switch. Ordinary signal type diodes are adequate. Something we could shoot a lead through is probably good. Voltage rating  $\geq 25V$ .

## ■ CR202 not used

Formerly this diode prevented reverse current flow from the HAP into the main bus. This is no longer required because of the diode added to the battery backup section of the HAP. Recommend removal of this component. In fact this has been done as of SPS-0.3.

## ■ D200 BAT42WS, Schottky diode (DigiKey BAT42WSCT-ND0.52\$ea/10)

Diodes Inc. BAT42WS  
 SOD-323 package, 2 pin type possible to shoot a trace  
 30V  $V_R$   
 200mA Max continuous forward current  
 500mA Peak repetitive forward current  
 4A Peak non-repetitive forward current  
 500nA Max reverse current @  $V_R$  @ 25C  
 100 $\mu$ A Max reverse current @  $V_R$  @ 100C  
 200mW Max power (assume 25C at leads)  
 (, 0.26, 0.33)V Max forward voltage @ 25C, 2mA  
 1V Max forward voltage @ 25C, 200mA  
 5ns Max reverse recovery time  
 10pF Max capacitance  
 625C/W  $\theta_{JA}$  @ 25C  
 (-55, 125)C  $T_J$  range

D200 is intended for current limiting. When the SPS output voltage is low during start up, loss of bus power, or due to excessive current draw, the Pwr\_Fail signal causes D200 to pull low via Q202. The idea here is to limit the maximum current available by preventing  $V_c$  from rising above a certain value. The difficulty with this idea is that it's uncertain exactly what current limit value should be chosen or exactly what the  $V_c$  switching cutoff voltage is.

The datasheet gives typical values as  $G_m=2.5A/V$ ,  $V_c$  @ 0% duty=0.35V,  $V_c$ @1.5A switch current=0.9V.

The maximum current from the error amp over temperature is sink(70, 110, 180) $\mu$ A, source(80, 120, 160) $\mu$ A

The original concept was to use a Schottky diode to clamp the switch current at about 0.4V or 1/8A. But this is probably too low, and too easily effected by threshold variations. An ordinary Si diode clamping at 0.5-0.65 V probably gives adequate start up current, and better consistency, but the clamp current is so high forgetting the whole thing seems reasonable. Alternately a resistor might be used to give a more linear and consistent current limit.

The overarching question is whether a current limit is really required. That is can the SPS withstand a continuous short on it's output if the internal current limit (1.5, 2, 3)A is used? The answer at this time is maybe. The ratings seem close. What temperature will U200 reach?

For the time being, a Schottky will be selected here because having a signal-level Schottky on hand seems prudent.

## ■ D201 Green SMD LED in 0805 package

D201 is by request. Its purpose is to aid bench testing. It simply lights up when SPS power is present.

We anticipate disconnecting the LED for flight. A cuttable jumper has been provided to make this easy.

## Inductor(s)

### ■ L200 Coiltronics MP2A-1R5, 1.5μH, See PM-4112.pdf

Coiltronics MP2A-1R5

1.5 μH nominal inductance

1.54 μH measured @ 100kHz, 0.25V RMS, 0.0A DC, ±20%

73 mΩ DC Ohms @ 20C typ.

2.02 A RMS current producing +40C temperature rise (excluding core loss)

3.22 A Saturation current defined by 30% loss of inductance. Measured at 20C

2.09 V·μs Volt-time product of 300kHz waveform which when applied across inductor produces core loss equal to 10% of power loss producing +40C temperature rise previously determined.

-40to +125C storage temperature range

-40to +85C operating temperature range

molybdenum permalloy core

rated to 500kHz ??? —I don't see any reason for this.

Body Length exclusive of leads 5.88 mm, Length with leads 7.5 mm. Width 5.2 mm, Height 1.8 mm.

Maximum available current = max switch current -p-p inductor current / 2

Derivation (buck converter)

Equal volt-seconds implies

$$V_o = D V_i$$

The current increase through the inductor in one cycle ( $\Delta I$ ) is

$$\frac{V_i - V_o}{L} * T_{on}, \quad T_{on} = T * D = \frac{1}{f} * D \Rightarrow \Delta I = \frac{1}{f} \frac{V_o}{V_i} \frac{V_i - V_o}{L}$$

Average current is

$$I_o = I_p - \Delta I / 2 = I_p - \frac{V_o (V_i - V_o)}{L f V_i} / 2 = I_p - \frac{V_o (V_i - V_o)}{2 L f V_i}$$

The peak current is limited by the IC to 3A Max. Inductor saturation will not destroy the IC due to this current limit.

Inductor parameters

L	inductance
μ	core permeability
ℓ	magnetic path length
A	cross sectional area
g	air gap thickness (maybe)
B	magnetic field strength (Max BM (saturation))
N	number of turns
I	winding current (Peak $I_p$ , Avg. $I_{avg}$ )
$I_p$	peak winding current
$\Delta I$	ripple current (p-p current change, current increase during on time)
E	energy stored
Vc	volume of core

Inductor formula [ A and ℓ in cm]

$$L = 0.4 \pi \times 10^{-8} \frac{\mu A N^2}{\ell + \mu g} [\text{H}]$$

$$B = 0.4 \pi \frac{\mu I N}{\ell + \mu g} [\text{Gauss}]$$

$$E = \frac{I^2 L}{2} [\text{J}]$$

The core should not saturate. That is  $B < B_M$  when  $I = I_p$ .

Use the inductor formula to eliminate  $N$

$$\text{Solve}[L = k \text{ ee } \frac{\mu A N^2}{\ell + \mu g}, N^2][[1, 1]] // \text{FullSimplify}$$

$$N^2 \rightarrow \frac{L (\ell + g \mu)}{A \text{ ee } k \mu}$$

$$B^2 = \left( k \frac{\mu I N}{\ell + \mu g} \right)^2 / . N \rightarrow \sqrt{\frac{L (\ell + g \mu)}{A \text{ ee } k \mu}} // \text{PowerExpand} // \text{FullSimplify}$$

$$B^2 = \frac{k L I^2 \mu}{A \text{ ee } \ell + A \text{ ee } g \mu}$$

Note that

$$V_c = A \ell$$

$$\text{Solve}[B^2 = \frac{k L I^2 \mu}{V_c \text{ ee } + A \text{ ee } g \mu}, V_c][[1, 1]] / . L I^2 \rightarrow 2 E$$

$$V_c \rightarrow \frac{-A B^2 \text{ ee } g \mu + 2 k E \mu}{B^2 \text{ ee}}$$

The minimum core volume for a given maximum flux  $B$  and energy storage  $E$  is therefore

$$V_c = \mu \left( 2 E \frac{0.4 \pi}{B^2 \times 10^{-8}} - A g \right) = \mu \left( I^2 L \frac{0.4 \pi}{B^2 \times 10^{-8}} - A g \right)$$

Note that lengths above are in cm, otherwise normal.

Putting  $A \ell$  back in for  $V_c$  and solving for  $E$  gets

$$\ell + g \mu = \left( 2 \mu E \frac{0.4 \pi}{A B^2 \times 10^{-8}} \right)$$



$$E = A (\ell + g \mu) \frac{B^2 \times 10^{-8}}{2 \mu 0.4 \pi}$$

So the energy handling capacity is proportional to the faky pathe length ( $\ell + g\mu$ ). The inductance as stated before is inversely proportional to the same factor, hence trade-off.

Found a cool formula for DC resistance in an19fa.pdf

$$R_{dc} = \frac{N \bar{\ell}}{12} 10^{\left( \frac{AWG}{10} - 4 \right)} [\Omega]$$

Here N is number of turns,  $\bar{\ell}$ –baris the average turn length in inches, and AWG is the American Wire Gauge number. Example, 35 turns of 2.4 in average in #14 wire  $\Rightarrow 0.0176 \Omega$

For AC losses, see an19fa.pdf, they also do ferrite core losses.

Our particular case. It would be prudent to peak at about 1 A, 1/2 A is a good minimum goal. The typical peak switch current is 2A, assume a 15V input, limiting the peak current (peak being = 1/2 p-p) to 1A implies a certain inductance

$$f_{nom} = N[10^{*6} / 6.5] (* \text{ design operating frequency } *)$$

$$1.53846 \times 10^6$$

$$f_{min} = 1.1^{*6} (* \text{ Assumes loss of sincronization } *);$$

$$\frac{V_o (V_i - V_o)}{2 L f V_i} /. \{V_o \rightarrow 5, V_i \rightarrow 15, f \rightarrow f_{nom}\}; (* I_{avg} *)$$

$$\text{Solve}[1 == \%, L][[1, 1]]$$

$$L \rightarrow 1.08333 \times 10^{-6}$$

So even 1 $\mu$ H will satisfy the current requirements.

The peak inductor current is

$$V_{iMax} = 4.2 * 4; V_{iMin} = 2 * 4; V_{shore} = 18; (* \text{ some input voltage limits } *)$$

$$I_p = I_o + \frac{V_o (V_i - V_o)}{2 L f V_i} /. \{V_o \rightarrow 5, V_i \rightarrow V_{shore}, f \rightarrow f_{min}, L \rightarrow 1^{*-6}, I_o \rightarrow 1\}$$

$$I_p == 2.64141$$

It's desirable for the inductor to saturate above this current.

Consider Coiltronics SD18–1R2, 5.2 mm square, 1.8 mm tall. Shielded bobbin style.

Coiltronics DR73 series is adequate, but oversized.

Coiltronics MP2 series torroid for SMT. 5.88mm x about 4mm, 1.8 mm tall.

Coiltronics MP2A is same but better. Same size. See PM–4112.pdf

Part	L [ $\mu$ H]	I@+40 C [A]	Isat@70 % [A]	RDC [m $\Omega$ ]	V $\mu$ s typ.
SD18 - 1 R2	1.2 $\pm$ 20 %	2.97	2.95	29.4	2.55
MP2 - 1 R0	1.0 $\pm$ 20 %	1.67	2.1	103	□
MP2A - 1 R0	1.0 $\pm$ 20 %	2.11	3.63	67	2.00
MP2A - 1 R5	1.50 $\pm$ 20 %	2.02	3.22	73	2.09

Volt $\cdot\mu$ s typ. is Vs product required to generate core loss equal 10% of total losses for 40 C temperature rise (@ 100 kHz for SD18, 300kHz for MP2A)

For our case the Vs product equation is

$$(V_i - V_o) T_{on} = V_o T_{off}$$

$$V_i T_{on} = V_o T$$

$$(V_i - V_o) \frac{V_o}{V_i f} = D V_i T_{off}$$

$$\frac{V_o}{f} \left( 1 - \frac{V_o}{V_i} \right) =$$

Evidently the product is a maximum when Vi is maximum

$$\frac{V_o}{f} \left( 1 - \frac{V_o}{V_i} \right) /. \{V_i \rightarrow V_{shore}, V_o \rightarrow 5, f \rightarrow f_{nom}\} // N$$

$$2.34722 \times 10^{-6}$$

This seems acceptable.

In some ways I dislike this procedure, there is no technical data on core loss, frequency characteristics, etc. Even the core material is unspecified, though it's probably that Mn<sub>x</sub>Zn<sub>x</sub> stuff. On the other hand the manufacturer claims to have optimized the design, so yay if they're not full of it. Alas tempus fugit.

This inductor value will cause discontinuous operation when the output current is below (worst case)

$$\frac{V_o (1 - V_o / V_i)}{2 f L} /. \{V_i \rightarrow V_{iMin}, V_o \rightarrow 4.5, f \rightarrow f_{nom}, L \rightarrow 1.5 \times 10^{-6}\}$$

$$0.426562$$

This is the usual situation. However this is not a big problem unless the regulator is cycle-skipping. Even skipping isn't necessarily a big problem, but it could be a source of RFI. Since I can't find a minimum on-time spec for this part, assume 70ns, which seems pretty reasonable. The minimum peak current is

$$\frac{V_{iMin} - 5}{L} * 70 \times 10^{-9} /. L \rightarrow 1.5 \times 10^{-6}$$

$$0.14$$

The decay time for this current is

$$\frac{I_p L}{5} /. \{I_p \rightarrow \%, L \rightarrow 1.5 \times 10^{-6}\} // \text{EngineeringForm}$$

$$42. \times 10^{-9}$$

So the average output current is

$$f I_p T_{offmin} / 2 /. \{f \rightarrow f_{nom}, T_{offmin} \rightarrow \%, I_p \rightarrow \%\}$$

$$0.00452308$$

The minimum load will be more than this so everything is fine.

## ■ L201, L202      Coiltronics CMS1–11, 120μH, See PM–4313.pdf

Coiltronics CMS1–11

120 μH      nominal inductance (100kHz, 0 DC A, 0.1 Vrms)

1.35 A      Irms Max (160 C max temp)

70 mΩ      DC Ohms @ 20C typ. (per leg)

1.10 μH      Leakage inductance

2.9 pF      Interwinding capacitance

–40to +125C storage temperature range

–40to +85C operating temperature range

300 VDC      maximum voltage

internal "hot spot" temperature limit 130C

molybdenum permalloy core

rated to 500kHz ??? —I don't see any reason for this.

Maximum dimensions: Body Length 9.4 mm, Width 7.2 mm, Height 2.6 mm.

This part is a common mode choke. It was chosen hurristically on the basis of reasonable package size and low DC losses. Based on a quick search, to get greater antenuation requires either a larger package or 30+% more DC resistance. The current rating is adequate.

## Capacitors(s)

## ■ C200      Panasonic ECJ–3YB0J226M(DigiKey PCC2242CT–ND17.34\$/10)

Panasonic ECJ–3YB0J226M

22 μF      nominal capacitance

6.3V      WV DC

X5R      dielectric

1206      case size

±20%      tolerance

–35to +85C operating temperature range

Height 1.6 mm.

The output capacitor for a high frequency buck switching power supply. The dynamic properties of this capacitor affect the loop stability so a moderately stable X7R or X5R type is typical. A tantalum cap. will work fine here, but is probably bigger. The ceramics seem so much cooler. Voltage rating ≥ 6.3V.

RMS ripple formula (from 1767f.pdf, check this???(Correct up to factor 0.58)).

$$\Delta I_{rms} \rightarrow 0.29 \frac{V_o (V_i - V_o)}{f L V_i} /. \{f \rightarrow f_{nom}, L \rightarrow 1.5 \times 10^{-6}, V_o \rightarrow 5, V_i \rightarrow V_{iMin}\} // N$$

$$\Delta I_{rms} \rightarrow 0.235625$$

Output ripple current is maximized at high input voltage.

$$\Delta I_{rms} \rightarrow 0.29 \frac{V_o (V_i - V_o)}{f L V_i} /. \{f \rightarrow f_{nom}, L \rightarrow 1.5 \times 10^{-6}, V_o \rightarrow 5, V_i \rightarrow V_{shore}\} // N$$

$$\Delta I_{rms} \rightarrow 0.453796$$

5mV would be a good target for for the output ripple.

$$5 \times 10^{-3} == \frac{\Delta I_{rms}}{f_{nom} C} /. \%$$

$$\frac{1}{200} == \frac{2.94968 \times 10^{-7}}{C}$$

`Solve[%, C][[1, 1]] // EngineeringForm`

$$C \rightarrow 58.9935 \times 10^{-6}$$

an-19p.23 contradicts this

$$C \geq \frac{1 / (8 L f^2)}{V_{pp} / (V_o (1 - V_o / V_i))} /. \{V_{pp} \rightarrow 5 \times 10^{-3}, f \rightarrow f_{nom}, L \rightarrow 1.5 \times 10^{-6}, V_o \rightarrow 5, V_i \rightarrow V_{shore}\} // N // EngineeringForm$$

$$C \geq 25.4282 \times 10^{-6}$$

The biggest in the DigiKey catalog is only 22 $\mu$ F, sad.

## ■ C201 Panasonic ECJ-4YB1E106M(DigiKey PCC2243CT-ND12.39\$/10)

Panasonic ECJ-4YB1E106M (used to be ECJ-4YF1E106Z)

10  $\mu$ F          nominal capacitance  
 25V          WV DC  
 X5R          dielectric  
 1210          case size  
 +/-20%      tolerance  
 -35to +85C   operating temperature range  
 Height 2.5 mm.

This is an input capacitor for a high frequency buck switching power supply. The standard choice is a 1-5 $\mu$ F ceramic capacitor. The Y5V or similar dielectrics are suitable. Voltage rating should be at least 20V.

Input ripple current (buck) is (This formula is from 1767f.pdf, is this really correct???)

$$\Delta I_{rms} \rightarrow I_o \sqrt{V_o (V_i - V_o) / V_i^2} /. \{I_o \rightarrow 1, V_o \rightarrow 5, V_i \rightarrow V_{iMin}\} // N$$

$$\Delta I_{rms} \rightarrow 0.484123$$

The ripple in the capacitor is

$$V = Q / C$$

Try  $2.2\mu F$

$$\frac{\Delta I_{rms}}{f_{nom} C} /. \{ \%, C \rightarrow 2.2 \times 10^{-6} \}$$

$$0.143036$$

This seems ok, but check the web for a better value in 1206.

I can get  $10\mu F$  in 1210 size, X5R, this should be excellent.

## ■ C202 Any 25+V $0.1\mu F$ ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND 0.35\$ea)

Panasonic ECJ-4VB1H104K

$0.1\mu F$  nominal capacitance

50V WV DC

X7R dielectric

1206 case size

$\pm 10\%$  tolerance

$-55$ to  $+125^\circ C$  operating temperature range

Height 1.0 mm.

Boost cap for U200. Voltage at least 20V. Linear recommends  $0.1\mu F$ , who are we to argue?

## ■ C203 Panasonic TEL series EEJ-L1ED336R (DigiKey P11298CT-ND3.30\$ea)

Panasonic TEL series EEJ-L1ED336R

$33\mu F$  nominal capacitance

25V WV DC

tantalum dielectric

7343 case size

$\pm 20\%$  tolerance

0.08 Max dissipation factor

$8.3\mu A$  Max leakage spec. (also stated leakage  $< CV/100$  but not less than  $1/2\mu A$ )

$0.2\Omega$  ESR @ 100kHz

866mA Max ripple current

$-55$ to  $+125^\circ C$  operating temperature range

Height 2.8 mm.

This is not a critical component. Its primary function is as a noise filter. The secondary function is local energy storage. Voltage rating should be  $20+V$ . High value and low ESR are desirable. Tantalum was chosen for compactness and low ESR. It's desirable to limit package size, which becomes the primary constraint.

The selected component is quite expensive, perhaps a re-think is in order???

## ■ C204 Panasonic ECJ-3VB1E334K (DigiKey PCC1889CT-ND0.25\$ea)

Panasonic ECJ-3VB1E334K

0.33  $\mu\text{F}$  nominal capacitance

25V WV DC

X7R dielectric

1206 case size

$\pm 10\%$  tolerance

-55to +125C operating temperature range

Height 0.85 mm.

This is a non-critical component. It's function is as a very high frequency noise filter. To be effective in this application requires low ESR which suggests a ceramic type capacitor. It's also desirable to select a fairly low cost component. Voltage rating  $\geq 20\text{V}$ .

DigiKey has 0.33 $\mu\text{F}$  caps for 25¢ while the 1 $\mu\text{F}$  version is 45¢, given the current mood the 0.33 $\mu\text{F}$  version should suffice.

## ■ C205/C206

Frequency compensation component. See R206 for explanation.

## ■ C207 Panasonic ECJ-3VB1C684K (DigiKey PCC1880CT-ND0.44\$ea/10)

Panasonic ECJ-3VB1C684K

0.68  $\mu\text{F}$  nominal capacitance

16V WV DC

X7R dielectric

1206 case size

$\pm 10\%$  tolerance

-55to +125C operating temperature range

Height 0.85 mm.

Partly determines comparator response. See R211 for explanation.

## ■ C208/C209

Frequency compensation component. See R206 for explanation.

## ■ C210 Any 25+V 0.1 $\mu\text{F}$ ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND 0.35\$ea)

Check out C202

Effects dynamic characteristics of power-down shutdown. See R209 for explanation.

This is a de-glitch capacitor. It also adds some time-constant delay. The value may as well be 0.1 $\mu\text{F}$ .

```
 $\tau \rightarrow RC /. \{R \rightarrow r1 r2 / (r1 + r2)\} /. \{r1 \rightarrow 60 \wedge 3, r2 \rightarrow 10 \wedge 3, C \rightarrow 0.1 \wedge -6\} // N //$ 
EngineeringForm
```

```
 $\tau \rightarrow 857.143 \times 10^{-6}$ 
```

Basically 1ms, that's fine.

## Resistors(s)

### ■ R200 8.25kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-8.25KFCT-ND 1.17\$/10)

N.B. This needs to be re-calculated for the HAP, which uses a slightly different output voltage.???

Panasonic P-60.4KFCT-ND

8.25kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

-55to +125C operating temperature range

Height 0.6 mm.

thick film composition

R200-203 form a voltage divider which serves 3 purposes. As the voltage measuring element of the regulator feedback loop, as the measuring element for the over voltage protection, and as the measuring element for the undervoltage detection/current limiting mechanism.

The LT1767 data sheet provides a formula for the divider values based on the nominal reference voltage and the expected FB-pin output current of 25μA (50μA Max)

The reference voltage is fairly tight. ±2% over temperature.

$$RA \rightarrow \frac{V - V_{fb}}{V_{fb} / RB - I_b} \quad /. \{V \rightarrow 5, V_{fb} \rightarrow 1.2, I_b \rightarrow 25 \times 10^{-6}\} \quad /. RB \rightarrow 10 \times 10^3 \quad // N //$$

EngineeringForm

$$RA \rightarrow 40. \times 10^3$$

To keep bias current errors in the 1/4-1/2 % range, keep RB below 10-20k

$$RA \rightarrow \frac{V - V_{fb}}{V_{fb} / RB - I_b} \quad /. \{V \rightarrow 5, V_{fb} \rightarrow 1.2, I_b \rightarrow 25 \times 10^{-6}\} \quad /. RB \rightarrow 20 \times 10^3 \quad // N //$$

EngineeringForm

$$RA \rightarrow 108.571 \times 10^3$$

Current could be saved by going to 20kΩ, but the increased sensitivity isn't a good idea since we're hooking other opamps to this divider, the total divider current with a 10k base is only ~100μA, which is ok here.

Overvoltage definition: (6.0, 6.1, 6.2)V. Undervoltage definition: (4.6, 4.7, 4.8)V.

With a 50k total resistance, the correct tap points are easily found. The nominal reference voltage of U201 is 1.182V.

First solve for the over voltage tap (Vref is the reference voltage of U201)

$$V_{ref} = V_{fb} \frac{r_0}{r_0 + r_1} \quad /. V_{fb} \rightarrow (I_b RA + V) \frac{RB}{RA + RB} \quad // FullSimplify$$

$$V_{ref} == \frac{r_0 RB (I_b RA + V)}{(r_0 + r_1) (RA + RB)}$$

```
Solve[{%, RB == r0 + r1}, {r0, r1}] [[1]] // FullSimplify
```

$$\left\{ r0 \rightarrow \frac{(RA + RB) V_{ref}}{I_b RA + V}, r1 \rightarrow RB - \frac{(RA + RB) V_{ref}}{I_b RA + V} \right\}$$

```
% /. {RA -> 40.0^3, RB -> 10.0^3, Ib -> 25^-6, Vref -> 1.182, V -> 6.1}
```

$$\{r0 \rightarrow 8323.94, r1 \rightarrow 1676.06\}$$

Now solve for the under voltage tap

```
Vref == Vfb + \frac{V - Vfb}{RA} r2 /. Vfb -> (Ib RA + V) \frac{RB}{RA + RB} // FullSimplify
```

$$V_{ref} == \frac{I_b (-r2 + RA) RB + (r2 + RB) V}{RA + RB}$$

```
Solve[{%, RA == r2 + r3}, {r2, r3}] [[1]] // FullSimplify
```

$$\left\{ r3 \rightarrow -\frac{(RA + RB) (V - V_{ref})}{I_b RB - V}, r2 \rightarrow \frac{I_b RA RB + RB V - (RA + RB) V_{ref}}{I_b RB - V} \right\}$$

```
% /. {RA -> 40.0^3, RB -> 10.0^3, Ib -> 25^-6, Vref -> 1.182, V -> 4.7}
```

$$\{r3 \rightarrow 39528.1, r2 \rightarrow 471.91\}$$

These have to hit standard values, try 8.25k , 1.69k , 475Ω , 39.2k

```
Solve[RA == \frac{V - Vfb}{Vfb / RB - Ib}, V] [[1, 1]] // FullSimplify
```

$$V \rightarrow -I_b RA + V_{fb} + \frac{RA V_{fb}}{RB}$$

```
Solve[Vref == \frac{r0 RB (Ib RA + V)}{(r0 + r1) (RA + RB)}, V] [[1, 1]] // FullSimplify (*overvolt*)
```

$$V \rightarrow -I_b RA + \frac{(r0 + r1) (RA + RB) V_{ref}}{r0 RB}$$



```
Solve[Vref ==  $\frac{I_b (-r2 + RA) RB + (r2 + RB) V}{RA + RB}$ , V] [[1, 1]] //
FullSimplify (*undervolt*)

V →  $\frac{I_b (r2 - RA) RB + (RA + RB) Vref}{r2 + RB}$ 
```

```
sub = {RB → r0 + r1, RA → r2 + r3, Ib → 25.0*^-6, Vfb → 1.2, Vref → 1.182};
```

```
val = {r0 → 8.25*^3, r1 → 1.69*^3, r2 → 475., r3 → 39.2*^3};
```

```
Vo → Vfb  $\left(1 + \frac{RA}{RB}\right) - RA Ib /. sub /. val$  (* output voltage *)

Vo → 4.99786
```

```
Vov → Vref  $\frac{(r0 + r1) (RA + RB)}{r0 RB} - Ib RA /. sub /. val$  (* over voltage *)

Vov → 6.1166
```

```
Vuv →  $\frac{I_b (r2 - RA) RB + (RA + RB) Vref}{r2 + RB} /. sub /. val$  (* under voltage *)

Vuv → 4.69551
```

Definitely close enough.

■ **R201** 1.69kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-1.69KFCT-ND 1.17\$/10)

See R200 for details

■ **R202** 475Ω , Any 1% or better film resistor in 1206 package (DigiKey P-475FCT-ND 1.17\$/10)

See R200 for details

■ **R203** 39.2kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-39.2KFCT-ND 1.17\$/10)

See R200 for details

## ■ R204 4.70MΩ , Any 2% or better film resistor in 1206 package (DigiKey 311-4.70MFCT-ND 1.35\$/10)

Phicomp 311-4.70MFCT-ND

4.70MΩ nominal resistance

200V WV DC or RMS

1206 case size

±1% tolerance

±100ppm temp.co.

-55to +125C operating temperature range

Height 0.6 mm.

thick film composition

R204, 205 form a hysteresis network for U201 (LTC1442).

Here are the specs

Vref 1.182±1.5% over temperature

Current source for ΔVref=1mV, (100, 200, )μA

Current sink for ΔVref=2.5mV, (10, 20, )μA

Voltage noise [100, 100k]Hz = 100μVrms typ.

Vhyst range [Vref-50mV, Vref]

If a 100mV hysteresis is assumed on over voltage and under voltage trip, then 1st the divider ratio is needed.

$$\{1.182 / 6.1, 1.182 / 4.7\}$$

$$\{0.19377, 0.251489\}$$

$$\sqrt{\text{Times}} \text{ @@ \%}$$

$$0.220751$$

$$50 \text{ mv} * \%$$

$$11.0376 \text{ mv}$$

So Vref-11mV should be applied to the Vhyst pin.

As a 1st try, set the hysteresis divider current to 0.25μA

$$RA \rightarrow Vh / Ih /. \{Vh \rightarrow 11^{*-3}, Ih \rightarrow 250^{*-9}\} // N // \text{EngineeringForm}$$

$$RA \rightarrow 44. \times 10^3$$

$$RB \rightarrow \frac{Vref - Vh}{Ih} /. \{Vref \rightarrow 1.182, Vh \rightarrow 11^{*-3}, Ih \rightarrow 250^{*-9}\} // N //$$

**EngineeringForm**

$$RB \rightarrow 4.684 \times 10^6$$

Possible standard values are 4.70M & 44.2k

Check

$$V_h \rightarrow V_{ref} \frac{R_A}{R_A + R_B} /. \{V_{ref} \rightarrow 1.182, R_A \rightarrow 44.2 \times 10^3, R_B \rightarrow 4.70 \times 10^6\} // N //$$

EngineeringForm

$$V_h \rightarrow 11.0123 \times 10^{-3}$$

Seems fine.

### ■ R205 44.2kΩ , Any 2% or better film resistor in 1206 package (DigiKey P-44.2KFCT-ND 1.17\$/10)

See R200 for typical specs.

See R204 for calculations.

### ■ R206 ???kΩ , Any ???% or better film resistor in 1206 package

R206, along with C205,206, and possibly C208,209, forms the frequency compensation component of the SPS switching supply.

As a basic reference take an-19 p.48-50. A more detailed reference is an76.

Adequate testing includes using the actual power source (to account for source impedance) and testing load transients over input/output range and temperature. Check transients on start up and short circuit.

The goal is to have the highest possible cross over frequency while maintaining a phase margin of 45+° and a gain margin better than -10dB.

1st estimate DC loop gain (gm is error-amp gain, R\_ea is error-amp load resistance to ground, Gm is output stage gain, and R\_L is the output load resistance = Vo/Io.) Load resistance ranges from about 10Ω to 200+Ω (from 500mA to ≈20mA). Not sure which is worse for stability.

$$\frac{V_{fb}}{V_o} (g_m * R_{ea}) (G_m * R_L) /. \{g_m \rightarrow 850 \times 10^{-6}, G_m \rightarrow 2.5, V_o \rightarrow 5.0, V_{fb} \rightarrow 1.2, R_{ea} \rightarrow 412 \times 10^3, R_L \rightarrow 10\}$$

$$2101.2$$

Gain (66dB) increases at lower output currents, up to factor >20.

The highest corner frequency is at highest current. Target here is 500mA ⇒ R\_L = 10Ω

$$f_0 \rightarrow 1 / (2 \pi R_L C_o) /. \{R_L \rightarrow 10, C_o \rightarrow 22 \times 10^{-6}\} // N$$

$$f_0 \rightarrow 723.432$$

Conventional buck design proceeds from the assumption that voltage-mode control is bad because the inductor and output capacitor form a tank circuit (double pole) at a resonant frequency within the gain-range of the supply. Hence current-mode control whose gain roll-off is dominated by the R\_L\*C\_o output pole. Conventionally the phase lag is limited by the zero created from C\_o and C\_o's ESR. For ceramic output caps this doesn't work (ESR too low). The classic solution is to add a zero to the error amplifier's response by inserting a series resistor (R\_c) into the compensation capacitance (C\_c) (See data sheet for LT1375/1376 13756fc.pdf, p 21). Increasing R\_c raises loop BW and therefore improves transient response. However, as R\_c increases, gain at higher frequencies makes V\_c susceptible to noise injected from the switching node. This can be filtered with a parallel capacitor (C\_f) from V\_c to ground. The pole of this capacitor is typically at 1/5th the switching frequency to provide significant switching noise attenuation, but still be high enough not to disturb loop dynamics. (13756fc.pdf p.22 is excellent on loop testing). It's desirable that the gain of the loop be <1 at the switching frequency.

Additionally two capacitors CA and CB (C208, 209 in this case) have been added. These are not usually required but can be beneficial. CA is a speed-up capacitor. Its zero produces a bump in the the phase plot "Ideally, the peak of this bump is centered over the loop's

crossover frequency." (See an76 p.5). CB usually functions as a noise filter. Typical pole frequencies are 1/2 to 1/3 of the switching frequency. It may interact with CA, and can be used to swamp fb-pin input capacitance if that is important (it isn't).

An76 p.9 fig.8 has an alternate load pulser for SPS testing which looks good.

Here are the most basic equations for buck SPS

$A_{v(fb)} = V_{ref} / V_o$	Voltage gain due to feedback divider
$A_{v(ea)} = g_m * R_{ea}$	Voltage gain of error amp
$A_{v(mod)}$	Voltage gain of modulator section
$DC\ gain = A_{v(fb)} * A_{v(ea)} * A_{v(mod)}$	Total DC voltage gain
$f_{p_o} = (2 \pi R_L C_o)^{-1}$	Output pole frequency
$f_{z_o} = (2 \pi ESR_o * C_o)^{-1}$	Output zero frequency (unusably high for ceramic caps)
$f_{p_{ea}} = (2 \pi R_{ea} C_c)^{-1}$	error amp pole frequency
$f_{z_{ea}} = (2 \pi R_c C_c)^{-1}$	error amp zero frequency
$f_{p_{fb}} = (2 \pi R_c C_f)^{-1}$	compensation feedback pole frequency
$f_{z_A} = (2 \pi R_A C_A)^{-1}$	speed-up zero frequency
$f_{p_B} = (2 \pi R_B C_B)^{-1}$	slow-down pole frequency

The basic idea is to begin with "reasonable values" and apply transient loads similar to expected loads at several values of DC output current. This is done for all interesting voltage input, input resistance, and temperature conditions.

Initially  $C_c$  is chosen large and  $R_c$  small. Loop response is checked (overdamped expected otherwise raise  $R_c$ , if required raise  $C_c$ ). Then  $C_c$  is reduced in 2:1 steps until ringing begins, then  $R_c$  is increased by 2:1 steps until ringing ceases. Then  $C_c$  is again reduced, etc. until no further improvement is possible.

The other components can be guessed at and tried. 10:1 experiments will verify the ballpark ranges.

Variational testing is done by replacing compensation components over the 2:1 range at room temperature and average conditions. No significant transient response deviations should be noted.

Final check out is done with the selected compensation component values over the full voltage/load/temperature matrix. Using the final input supply and output load is helpful at this stage.

A good starting point for U200 should be  $C_c = 2.2nF$  and  $R_c = 0\Omega$ .

Note that "small signal"  $\equiv$  "closed loop" response is indicated by 1) symmetric response on both edges of transient, 2) linear range at  $V_c$  pin 3)  $dV/dt$  @  $V_c$  pin less than slew rate limit (calculate from  $V_c$  pin impedance, ea drive).

## ■ R207 100k $\Omega$ , Any 5% or better film resistor in 1206 package (DigiKey P-100KFCT-ND 1.17\$/10)

See R200 for typical specs.

Changed this to the pull-up for a bipolar because Buck\_Off was changed to an O.C. output, same value should work.

R207 discharges the gate on Q201. While not strictly required, this provides some noise immunity, and assures that Q201 stays off if Buck\_Off is tri-stated.

100k $\Omega$  is reasonable. A harsh RF environment would be required to overcome a 100k shunt, yet the increase in current when on is still smallish.

## ■ R208 10.0k $\Omega$ , Any 5% or better film resistor in 1206 package (DigiKey P-10.0KFCT-ND 1.17\$/10)

See R200 for typical specs.

Changed Q201 to bipolar, still same deal here.

R208 separates the gate of Q201 from direct connection to the PIC. A direct connection would certainly work, but the resistance isolates the gate from any funny business in the PIC powersupplies. What is more reliable depends on the spectrum of failure modes. Intuition and some experience sez that direct connection to a FET gate could be problematic.

Even at 4.5V, the gate voltage will reach 4V

$$4.5 * 100 / 110 // N$$

$$4.09091$$

Since the threshold voltage is under 3V, the scheme should work.

## ■ R209 60.4kΩ , Any 2% or better film resistor in 1206 package (DigiKey P-60.4KFCT-ND 1.17\$/10)

See R200 for typical specs.

R209,210 form a resistive voltage divider which shuts down U200 when the input bus voltage falls below a certain value. It also serves to activate U200 when bus voltage is present or restored.

Shutting down U200 when the bus voltage is low does two things. It decreases the chance of over-discharge of the main battery, and it makes the transition to backup power crisper. A crisp transition is less noisy, and seems less risky.

The Anticipated range of the bus voltage is:

20 V Should never get this high

18 V Shore Power

16.8 V Maximum Battery Voltage (4.2 V / cell)

14.4 V Nominal Battery Voltage (3.6 V / cell)

10 V Minimum Battery Voltage (2.5 V / cell)

9 V Should never get this low

The LT1767 datasheet helpfully specifies:

Shutdown voltage range (over temperature) (1.27, 1.33, 1.40)V (generally higher when hotter)

Shutdown current (threshold + 60mV) (over temperature) (7, 10, 13)μA

Shutdown current (threshold -100mV)(over temperature) (4, 7, 10)μA (This appears wrong???)

The two shutdown current entries represent a hysteresis mechanism. When running U200 sources about 10μA into the shutdown pin. In the shutdown state U200 sources only about 3μA. (The data sheet appears wrong about this spec.???)

The datasheet gives design formula. Using 9.75±0.2V as the target range gives:

$$RA \rightarrow \frac{VH - VL}{7^{*-6}} /. \{VH \rightarrow 9.95, VL \rightarrow 9.55\} // N // EngineeringForm$$

$$RA \rightarrow 57.1429 \times 10^3$$

$$RB \rightarrow \frac{Vcenter}{(VH - Vcenter) / RA + 3^{*-6}} /. \{VH \rightarrow 9.95, VL \rightarrow 9.55, Vcenter \rightarrow 1.33, \%\} // N // EngineeringForm$$

$$RB \rightarrow 8.64478 \times 10^3$$

Using standard resistors, this would be 57.6K, 8.66K.

$$ra = 60.4^{*3}; rb = 10.0^{*3};$$

$$Vth = 1.33;$$

Check:

Nominal

```
Solve[(V - Vth) / ra - Vth / rb == 10^-6, V]
```

```
{{V → 9.9672}}
```

```
Solve[(V - Vth) / ra - Vth / rb == 3^-6, V]
```

```
{{V → 9.5444}}
```

Worst case

```
Vth = 1.40; Solve[(V - Vth) / ra - Vth / rb == 13^-6, V]
```

```
{{V → 10.6412}}
```

```
Vth = 1.27; Solve[(V - Vth) / ra - Vth / rb == 2^-6, V]
```

```
{{V → 9.0616}}
```

Worst case includes manufacturing spread, so probably this is ok. Shut down hysteresis current is fairly flat w/ temperature, so if we test and trim away from 10V, SPS should work over the whole battery range. An trim could be added to fine-tune this action if needed.

#### ■ R210 10.0kΩ , Any 2% or better film resistor in 1206 package (DigiKey P-10.0KFCT-ND 1.17\$/10)

See R200 for typical specs and calculations.

#### ■ R211 590Ω , Any 5% or better film resistor in 1206 package (DigiKey P-590FCT-ND 1.17\$/10)

See R200 for typical specs and calculations.

R211 forms part of a low pass filter on the reference output of U201. The low pass filter is intended to prevent false triggering due to noise on the reference output, particularly due to switching noise or other interference on the power input lines. The associated capacitor, C207, should be as large as convenient. The 16V Y5V style is available as a 2.2μF unit only 0.85mm high. The LTC1442 datasheet specifies 300Ω minimum resistor for stability. 390Ω gives a quite adequate safety margin.

While filling out the spec, the mind changed. The problem is Y5V loses a lot of capacitance at elevated temperature. Lower capacitance values require more resistance for stability. So at the minimum the resistance should be figured based on minimum capacity over temperature. This would be 0.44μF (−80%) implying a resistance of about 700Ω. An X5R or similar dielectric holds  $\leq \pm 10\%$  of its initial value, so it is a better choice here.

A 0.68μF X7R type can be had for 44¢ and 0.85mm tall, this should be fine. The required resistance is about 550Ω. Choose 590Ω as a safe bet.

#### ■ R212 ~1.8kΩ , Any 5% or better film resistor in 1206 package

Current limiting resistor for SPS power indicator LED, see D201.

Assuming a high efficiency LED, we can probably use 2mA, a typical forward voltage is 1.5V.

$$r \rightarrow (5 - 1.5) / (2^{-3})$$

$$r \rightarrow 1750.$$

## Miscellaneous

### ■ F200 Littelfuse "1206" (3216) 429-series Fast Acting fuse (DigiKey F1234CT-ND 0.70\$ea)

Littlefuse 429-FH

1A nominal current

63V Max interrupting voltage

3216 (1206) case size

-55to +125C operating temperature range

Height 1.2 mm.

Blow times @ 25C

100% > 4hr

200% < 5s

300% < 0.2s

800% < 50ms, > 2ms

Fast acting fuse. Protects each CAN node in the event of catastrophic fault and likewise protects the power bus.

The exact value is dependent on complex details, and really should be measured. However if we assume the maximum SPS output is 1A @ 5V the maximum input should be about

$$\frac{I_o}{\eta} \frac{V_o}{V_{imin}} /. \{I_o \rightarrow 1, \eta \rightarrow 0.75, V_o \rightarrow 5.2, V_{imin} \rightarrow 2.5 * 4\} // N$$

$$0.693333$$

We seek to interrupt fast, which requires ~800% overload. The 1A model should not present a problem.

### ■ TVS200 Diodes Inc. SMBJ18A Transient Voltage Suppressor (DigiKey SMBJ18ADICT-ND 0.71\$ea/10)

Diodes Inc. SMBJ18A

18V nominal voltage

SMB package

20V minimum breakdown voltage (1mA)

23.3V Maximum breakdown voltage (1mA)

20.5A Max peak pulse current

29.2V Max clamp voltage at 20.5A

100A Max peak current using single 8.3ms 1/2 sine wave

5μA Max reverse leakage

-55to +150C operating temperature range

Height 2.6 mm.

Protects the node in the event of over-voltage condition. Must be capable of blowing the fuse before U200 is destroyed. U200's maximum input voltage is 25V.

The SMBJ18A is possibly just a little under-rated, but it's quite close. I think for any plausible faults it's fine.

### ■ W200 (probably eliminate)

This wire jumper exists to power U201 when the HAP is not present. Since the UPS and SPS power lines both run to the application area, probably eliminate this line and substitute a wire jumper in the application area on non-HAP versions.

### ■ W201 Power LED cuttable jumper

Cut this to disconnect the power-indicator LED. The jumper can be easily re-connected, either with a SMD zero-ohm jumper in 1206-ish package, or just a hunk of fine gauge wire.

### ■ W202

This wire jumper bypasses U202, which is only present on HAP versions. W202 is cut prior to installation of U202.



# High-Availability Sub-Node Power Supply (HAP) (400)

## Integrated Circuit(s)

### ■ U400 LTC3401, 3MHz, 1A, DC-DC boost converter (DigiKey LTC3401EMS-ND5.50\$ea)

The selection criterion include size, efficiency, complexity and frequency. This MSOP-10 package can reach 90+% efficiency supplying 5V @ around 100mA output @ 1.5MHz (synchronized). With  $<1\mu\text{A}$  shutdown current,  $<1\text{mA}$  quiescent current, and potentially 1A output current while tolerating up to 6V input or output.

### ■ U401, 402 NC7SZ14, Single Schmitt inverter (DigiKey NC7SZ14M5CT-ND0.96\$ea)

What is really better is a dual inverter in a SOT-6-style package (e.g. NC7WZ14), but digikey doesn't have them.

These inverters snap-up the lowpass filtered PwrGood signal from U400 making it crisp for the power switch-over circuitry and providing some hysteresis. Two inverters are used to properly drive Q400 and provide a positive logic Power\_Good signal. Other single gate styles could be substituted but the 1.8V rating on the selected part is nice because of the potential low battery voltage operation.

### ■ U403 TC54VC4502ECB713, voltage monitor (DigiKey 158-2066-1-ND0.83\$ea)

This threshold detector is chosen for low quiescent power, suitable output drive (active pull up) and compatible voltage range.

U403 does two essential things. It wakes the HAP up when SPS power is available and is shuts the HAP down when SPS power is down and it is commanded by the PowerDown signal.

Additionally it exhibits the parasitic effect of shutting down the HAP in the event of a HAP brown-out. This behavior could be construed as a feature.

### ■ U404 LTC1734, Lithium-Ion Battery Charge controller (DigiKey LTC1734ES6-4.1-ND2.75\$ea)

Selection criterion include small package, small total parts count. The ability to properly charge the battery.

The '1734 uses an external pass transistor, but is otherwise a reasonably complete system. The 4.1V version might be selected because it is adaptable to any Li chemistry, however the 4.2V version may be more appropriate???

## ■ U405 TC7W53FK, 2 Channel Analog Multiplexer (DigiKey TC7W53FKCT–ND0.56\$ea)

Toshiba TC7W53FK  
 SSOP8–P–0.5A package  
 (2,, 7)V V<sub>CC</sub> Range  
 (0,, –6)V V<sub>EE</sub> Range  
 (, 55, 120)Ω R<sub>DS(on)</sub> 25C @ 4.5V  
 >1GΩ typ. off resistance (but consider feedthrough capacitance)  
 150Ω Max @ –40C, 4.5V  
 150Ω Max @ 85C, 4.5V  
 ±(, , 60)nA Leakage 25C  
 ±600nA Max leakage @ 85C  
 (, 11, 20)pF input capacitance  
 (, 0.75, 2)pF feedthrough capacitance  
 200mW P<sub>DMax</sub> (dissipation limited)  
 –40C– 85C operating temperature range

U405 is a single analog multiplexer. Powered from the UPS (battery) supply.

The multiplexer isolates the PIC from the battery voltage when the PIC is powered off. In fact this function maybe unnecessary, but it is very cheap because the mux also selects between the Pwr\_Fail and the Batt\_Curr (Battery Current) signals. When the battery is under charge, the battery current is selected, otherwise the Pwr\_Fail signal is selected. If the Power\_Bad signal is asserted, both signals are disconnected.

The Toshiba part is adequate in terms of resistance and operating voltage (it's spec'd to run down to 2V).

## ■ U406 TC4S66F, single analog switch (DigiKey TC4S66FCT–ND0.68\$ea)

Toshiba TC4S66F  
 SMV-5 package  
 18V V<sub>DSS</sub> Max  
 (, 290, 950)Ω R<sub>DS(on)</sub> 25C  
 >1GΩ typ. off resistance (but consider feedthrough capacitance)  
 800Ω Max @ –40C  
 1200Ω Max @ 85C  
 (, 0.1, 100)nA Leakage 25C  
 1μA Max leakage @ 85C  
 10pF typ. input capacitance  
 0.5pF typ. feedthrough capacitance  
 200mW P<sub>DMax</sub> (dissipation limited)  
 –40C– 85C operating temperature range

U406 is a single analog switch. It is powered from the UPS (battery) supply. (In fact typical specs require 3V to operate. The minimum on UPS is approximately 2.2V. This should still work. All that is required is that U404, 405 remain off at low supply voltages, this should be checked???

This switch isolate the PIC from the battery voltage when the PIC is powered off. Fairly high on resistance can be tolerated because the input impedance of the PIC's ADC is reasonably high. 1kΩ is definitely good enough.

## ■ U407 NC7SZ14, Single Schmitt inverter (DigiKey NC7SZ14M5CT–ND0.96\$ea)

This could be a plain inverter, but a Schmitt was specified to reduce the number of different parts. Either way is ok.

## Transistors(s)

### ■ Q400 See Q404

Turns HAP supply off.

### ■ Q401 See Q201

### ■ Q402 Eliminated in HAP version 0.3

### ■ Q403 Zetex FCX717 SOT89 PNP (DigiKeyFCX717CT-ND0.87\$ea)

Zetex FCX717

SOT89 package

12V  $V_{DSS}$

(, 0.11, 0.15)V  $V_{CE(Sat)}$   $I_c=1A$ ,  $I_b=10mA$

100nA Max collector cut off current

10A Max pulse current

300 round value for  $H_{fe}$

500mA  $I_b$  (Abs. Max)

(-55, 150)C  $T_J$  range

1W Max Power on FR-4 (15×15×0.6)mm

This is the PNP series pass transistor required by U404.

The input voltage hovers near 4.75V. The cell voltage varies down to 2.5V. Assuming 420mA maximum charge current the dissipation is

$$(4.75 - 2.5) 0.420 (* \text{ Watts } *)$$

$$0.945$$

To handle this power level a thermal resistance of 50°C/W would be desirable. 70C/W is about the max.

The SOT89 package probably can dump about 1W. This should be ok because the very low voltages during recharge are of short duration, and the ratings to handle the power are there.

The beta is fairly high on this unit, so be careful of overall loop stability.

## ■ Q404 IRF(2nd source) P-Channel MOSFET Si4435DY (DigiKey SI4435DY-ND1.50\$ea)

International Rectifier (2nd source) Si4435DY

SO-8	package
30V	V <sub>DSS</sub>
19mV/C	Break down temp.co. 25C, I <sub>D</sub> =1mA
35mΩ	R <sub>DS(on)</sub> @ V <sub>GS</sub> =4.5V
(, 40, 60)nC	total gate charge @ V <sub>GS</sub> =10V
2320pF	typ. input capacitance
6.4A	I <sub>DMax</sub> (dissipation limited) V <sub>GS</sub> =10V
50A	Max pulse current
±20V	V <sub>GSMax</sub>
1.2V	Max body diode forward voltage @ 25C, 2.5A, V <sub>GS</sub> =0V
51ns	Max body diode reverse recovery time
50nC	Max body diode reverse recovery charge
150C	T <sub>JMax</sub>
50C/W	Max $\theta_{JA}$ on standard FR-4 board, t < 5s.

Q404 functions as a saturable rectifier. When the Pwr\_Fail signal is false (i.e. SPS is good) the gate-source voltage on Q404 is zero or negative and Q404 acts as a normal diode, in this case blocking current from V<sub>BK</sub> into the battery. If the V<sub>BK</sub> voltage falls below V<sub>BB</sub> for any reason the body diode of Q404 will conduct providing power to the HAP.

Theoretically the only way V<sub>BK</sub> can fall below V<sub>BB</sub> is if SPS fails, in this case Pwr\_Fail will be asserted and U407 will in turn provide gate voltage to Q404 decreasing the voltage drop to near zero.

If the SPS voltage suddenly rises the Pwr\_Fail signal will rapidly ( $\mu$ -seconds) drop. During the switch over fairly large currents may flow into the battery (though limited by the SPS switch limit) but the duration is so short that no harm will be done.

For conservative design Q404 should be capable of dissipating the load current in the un-saturated state ( $\sim 1/2A \times 0.7V \approx 400mW$ ), though this could be pushed.

## ■ Q405,406 See Q201

### Diode(s)

## ■ CR400 See CR200

## ■ CR401 Renumbered to D401

## ■ CR402 Diodes Inc. Fast Si-Diode MURS120 (DigiKey MURS120DICT-ND0.60\$ea)

Diodes Inc. MURS120, 1A Super-Fast rectifier

SMB	package
200V	V <sub>R</sub>
1.5A	I <sub>DMax</sub> (dissipation limited)
40A	Max pulse current
0.875V	Max forward voltage @ 25C, 1A
0.710V	Max forward voltage @ 150C, 1A
25ns	Max reverse recovery time
(-65, 175)C	T <sub>J</sub> range

Originally this diode was configured as a N-Fet saturable rectifier similar to Q404. This was not successful because the LTC3401 is spec'd at 120ns minimum on time. This implies a maximum input voltage of 4.07V to maintain constant frequency switching. In fact the slight

discontinuous mode switching that results from excessive input voltage *might* not be a big problem. It's the uncertainty over the consequences of the added noise that drives us to eliminate it.

The 4.07V limit can be eased by raising the HAP output voltage to 5.2V (should work). The maximum input voltage rises to 4.24V. This works fine for the Li+ cell, which is never over 4.2V anyway, but the battery charger wants more like a 4.55V input (4.68V to be really happy). Of course limiting the input voltage to the battery charger also decreases power dissipation in the pass transistor, which is good.

As a 1st cut, try to make every one happy. Let the input to the battery charger be 4.78V (to allow for some slop). CR402 should drop a minimum of 0.54V at around 10mA, but be capable of passing the maximum switch current of U400 (1.6A, but only around 1/2A average) with an as low as possible additional voltage drop.

If the actual minimum drop is 0.64V there would be a little slack in meeting the 4.24V constraint. This should make everything happy.

The selection search, which will be brief, consists of finding a Si-diode (for the high initial voltage drop) that maintains a fairly low voltage drop into the 1A range.

The minimum operating voltage for the battery charger is 4.55V, assume 4.6V is more realistic. Let the nominal target for SPS voltage be  $4.69V \pm 2\% = [4.60, 4.78]V$

## ■ D400 1N4448HWS (DigiKey 1N4448HWSDICT-ND0.30\$ea/10)

See CR201.

D400 allows the  $\mu P$  to activate the reset function, but not to countermand it. This de-glitches the PowerDown cycle.

## ■ D401 See D200

## Inductor(s)

## ■ L400 Coiltronics MP2A-1R5(Same as L200), 1.5 $\mu$ H, See PM-4112.pdf

Coiltronics MP2A-1R5

1.5  $\mu$ H nominal inductance  
 1.54  $\mu$ H measured @ 100kHz, 0.25V RMS, 0.0A DC,  $\pm 20\%$   
 73 m $\Omega$  DC Ohms @ 20C typ.  
 2.02 A RMS current producing +40C temperature rise (excluding core loss)  
 3.22 A Saturation current defined by 30% loss of inductance. Measured at 20C  
 2.09 V $\cdot\mu$ s Volt-time product of 300kHz waveform which when applied across inductor produces core loss equal to 10% of power loss producing +40C temperature rise previously determined.

-40to +125C storage temperature range

-40to +85C operating temperature range

molybdenum permalloy core

rated to 500kHz ??? —I don't see any reason for this.

Body Length exclusive of leads 5.88 mm, Length with leads 7.5 mm. Width 5.2 mm, Height 1.8 mm.

Manufacturer (Linear) recommends  $L > 3/f$  [H]. Ripple constraints suggest:

$$L > \frac{V_{imin} (V_{oMAX} - V_{imin})}{f \times \Delta I \times V_{oMAX}} [H]$$

Maximum available current = (max switch current - inductor ripple current/2)  $\times$  efficiency / boost-ratio

Derivation (boost converter)

Equal volt-seconds implies

$$(1 - D) (V_o - V_i) = D V_i$$

$$V_o = \frac{V_i}{1-D}, D = 1 - \frac{V_i}{V_o}$$

The current increase through the inductor in one cycle is

$$\frac{V_i}{L} * T_{on}, T_{on} = T * D = \frac{1}{f} * D \Rightarrow \Delta I = \frac{D}{f} \frac{V_i}{L}$$

Average current is

$$I_{avg} = I_p - \Delta I / 2 = I_p - \frac{D V_i}{2 L f} = I_p - \frac{D V_i}{2 L f}$$

This current is decreased by the same factor the voltage is increased, (1-D), less (by definition) the efficiency. We therefore get the maximum boost-current available as

$$I_o = \eta (1-D) \left( I_p - \frac{D V_i}{2 L f} \right)$$

As a rule of thumb, the ripple current is typically 20–40% of the peak current

$$I_o = \eta (1-D) (I_p - 0.3 I_p / 2) \text{ (* Rule of Thumb *)} // \text{FullSimplify}$$

$$I_o = -0.85 (-1 + D) I_p \eta$$

Using the 3401 numbers, assuming 5.2V out, 4.25V in gets

$$\% /. \{ \eta \rightarrow 0.92, I_p \rightarrow 1.6, D \rightarrow 1 - \frac{4.25}{5.2} \}$$

$$I_o = 1.02262$$

Of course we'll actually get something less than this, but this is ball-park. Now find L by using the rule of thumb.

$$Ip_{3401} = 1.6 \text{ (* peak switch current limit for LTC3401 *)};$$

$$\text{Solve} \left[ \Delta I = \frac{D V_i}{L f}, L \right] \llbracket 1, 1 \rrbracket // \text{FullSimplify}$$

$$L \rightarrow \frac{D V_i}{f \Delta I}$$

$$\% /. \{ D \rightarrow 1 - \frac{V_i}{V_o} \} /. \{ f \rightarrow f_{nom}, \Delta I \rightarrow 0.3 * Ip_{3401}, V_i \rightarrow 4.25, V_o \rightarrow 5.2 \} //$$

**EngineeringForm**

$$L \rightarrow 1.05143 \times 10^{-6}$$

So basically one micro-Henry.  $I_{sat}$  should be >1.6A, ferrite core, and for ~1/8W DC loss, we want  $\lesssim 50m\Omega$ .

Referring to the calculations for L200, it seems either MP2A-1R0 or MP2A-1R5 would be ok. To minimize inventory, the 1R5 should be selected but for fun run both.

The maximum inductor ripple current for  $1\mu\text{H}$  is

$$\text{VbkH} = 4.25 ; \text{VbkL} = 3 ; \text{VHAP} = 5.2 ; (* \text{ HAP voltage limits } *)$$

$$\Delta I \rightarrow \frac{D V_i}{L f} /. \{D \rightarrow 1 - \frac{V_i}{V_o}\} /. \{V_i \rightarrow \text{VbkL}, V_o \rightarrow \text{VHAP}, f \rightarrow f_{\text{nom}}, L \rightarrow 1 \times 10^{-6}\} // N$$

$$\Delta I \rightarrow 0.825$$

For  $1.5\mu\text{H}$

$$\Delta I / 1.5 /. \%$$

$$0.55$$

This is closer to the rule of thumb's 30%. The slightly increased DC resistance of the  $1.5\mu\text{H}$  unit probably lowers the efficiency v. the  $1\mu\text{H}$  inductor (probably the reduced AC core loss doesn't make up for the upped DC loss). Considering the advantage of reduced inventory, the  $1.5\mu\text{H}$  unit seems the way to go.

Going back to the originally stated constraints

$$L > \frac{\text{VbkL} (\text{VHAP} - \text{VbkL})}{f_{\text{nom}} \times 0.3 \text{ Ip3401} \times \text{VHAP}}$$

$$L > 1.71875 \times 10^{-6}$$

Close enough.

Note this inductor does not meet the IC manufacture's recommended value of  $\geq 3/f[\text{H}]$  which would be  $2\mu\text{H}$  in this case. Obviously it is close. I don't see why this should be a problem.

The volt  $\times$  second product for this case is

$$\frac{D V_i}{f} == \left(1 - \frac{V_i}{V_o}\right) \frac{V_i}{f}$$

Maximize this

$$\text{Solve}\left[D\left[\left(1 - \frac{V_i}{V_o}\right) V_i, V_i\right] == 0, V_i\right][[1, 1]]$$

$$V_i \rightarrow \frac{V_o}{2}$$

In our case this means  $V_i$  is minimum

$$\left(1 - \frac{V_i}{V_o}\right) \frac{V_i}{f} /. \{V_i \rightarrow \text{VbkL}, V_o \rightarrow \text{VHAP}, f \rightarrow f_{\text{nom}}\} // N // \text{EngineeringForm}$$

$$825. \times 10^{-9}$$

This is quite small, which should mean AC losses are small.

## Capacitors(s)

### ■ C400 Panasonic ECJ-3YB0J226M(DigiKey PCC2242CT-ND17.34\$/10)

Panasonic ECJ-3YB0J226M

22  $\mu$ F nominal capacitance

6.3V WV DC

X5R dielectric

1206 case size

$\pm 20\%$  tolerance

-35to +85C operating temperature range

Height 1.6 mm.

Output capacitor for a high frequency boost switching power supply. The dynamic properties of this capacitor affect the loop stability so a moderately stable X7R or X5R type is typical. A tantalum cap. will work fine here, but is probably bigger. The ceramics seem so much cooler. Voltage rating  $\geq 6.3V$ .

Basic ripple formula

$$V_{pp} = \frac{\Delta I V_i}{C V_o f} \quad /. \{ \Delta I \rightarrow 0.55, V_{pp} \rightarrow 5^{-3}, V_i \rightarrow 4.25, V_o \rightarrow 5.2, f \rightarrow f_{nom} \} // N$$

$$0.005 == \frac{2.92188 \times 10^{-7}}{C}$$

`Solve[%, C] [[1, 1]] // EngineeringForm`

$$C \rightarrow 58.4375 \times 10^{-6}$$

I think this is p-p, so i get a free factor of two, and anyway what i got is a 22 $\mu$ F cap, so that's what to use.

### ■ C401 Panasonic ECJ-3YF1A106Z(DigiKey PCC1894CT-ND4.91\$/10) (might use the SPS units instead, see C201)

Panasonic ECJ-3YF1A106Z

10  $\mu$ F nominal capacitance

10V WV DC

Y5V dielectric

1206 case size

+80/-20% tolerance

-25to +85C operating temperature range

Height 1.6 mm.

This is an input capacitor for a high frequency boost switching power supply. The standard choice is a 1-5 $\mu$ F ceramic capacitor. The Y5V or similar dielectrics are suitable. Voltage rating should be at least 6.3V.

The ripple in the capacitor is

$$V = Q / C$$

Try 2.2 $\mu$ F



$$\frac{\Delta I_{rms}}{f_{nom} C} /. \{ \Delta I_{rms} \rightarrow 0.55, C \rightarrow 2.2 \times 10^{-6} \}$$

$$0.1625$$

I like to stick w/the 10 $\mu$ F, there is an inexpensive style available. It might however, be better to use the expensive units used in the SPS, since there are only one or two HAP's and we could save stocking multiple types.

### ■ C402 Any 25+V 0.1 $\mu$ F ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND 0.35\$ea)

See C202.

C402 introduces delay into the \shutdown circuit of U400. The largest convenient value is 0.1 $\mu$ F. With on order 1k $\Omega$  source resistance, the time constant is

$$0.1 \times 10^{-6} \times 1 \times 10^3 \text{ (* seconds *) // EngineeringForm}$$

$$100. \times 10^{-6}$$

The time required to drop the voltage on C402 1V assuming the maximum input current of U403 (4.2 $\mu$ A) is

$$\frac{1 \times 0.1 \times 10^{-6}}{4.2 \times 10^{-6}} \text{ (* seconds *) // EngineeringForm}$$

$$23.8095 \times 10^{-3}$$

This seems about right.

### ■ C403 Panasonic ECJ-3VF1C225Z(DigiKey PCC1898CT-ND4.17\$/10)

Panasonic ECJ-3VF1C225Z

2.2  $\mu$ F nominal capacitance

16V WV DC

Y5V dielectric

1206 case size

+80/-20% tolerance

-25to +85C operating temperature range

Height 0.85 mm.

Output filter for HAP supply. C400 is the main filter. C403 is positioned after switch Q400. Assuming on order 1nH of stray inductance, the resonant value of C403 is about.

$$\text{Solve}\left[F_{drive} = \frac{1}{\sqrt{LC}}, C\right] \llbracket 1, 1 \rrbracket // \text{FullSimplify}$$

$$C \rightarrow \frac{1}{F_{drive}^2 L}$$

```
% /. {Fdrive → 1.53846*^6, L → 1*^-9} // N // EngineeringForm
```

```
C → 422.501 × 10-6
```

So resonance won't be a problem.

The largest practical value in 1206 size is 2.2 $\mu$ F, which is the value chosen.

#### ■ C404 Any 25+V 0.01 $\mu$ F ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND 0.35\$ea)

Panasonic ECJ-4VB1H104K

0.01  $\mu$ F nominal capacitance

50V WV DC

X7R dielectric

1206 case size

$\pm 10\%$  tolerance

-55to +125C operating temperature range

Height 0.6 mm.

C404 deglitches the PwrGood signal from U400. The value is non-critical, and really to be determined.

#### ■ C405 See C412

Forget this, use the same as C412.

Panasonic ECS-T1AY106R

10  $\mu$ F nominal capacitance

10V WV DC

Tantalum dielectric

EIA-A case size

$\pm 20\%$  @ 20C tolerance

CV/100 A DC leakage @ 20C, (or 0.5 $\mu$ A, whichever is greater)

<0.06 Tan- $\delta$

-55to +125C operating temperature range

Height 1.6 mm.

This capacitor provides high frequency bypassing for U404's feedback loop. The manufacturer's recommended value is 10 $\mu$ F, so that's what we've used.

#### ■ C406 Any 25+V 0.01 $\mu$ F ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND 0.35\$ea)

See C404

C406 is solely to deglitch and delay the shutdown signal to Q401. It is redundant in the graph-sense with C410. C406 may be unnecessary, whether this is true is best determined by observation of the hardware. A preliminary specification has been given anyway.

#### ■ C407-C409

Frequency compensation component. See R403 for explanation.

#### ■ C410 Any 25+V 0.01 $\mu$ F ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND 0.35\$ea)

See C404

See C406

## ■ C411

Beware, C411 was reassigned in HAP version 0.3. Frequency compensation component. See R403 for explanation.

## ■ C412 Panasonic ECJ-3YF1A106Z(DigiKey PCC1894CT-ND4.91\$/10) (might use the SPS units instead, see C201)

Panasonic ECJ-3YF1A106Z

10  $\mu$ F nominal capacitance  
 10V WV DC  
 Y5V dielectric  
 1206 case size  
 +80/-20% tolerance  
 -25to +85C operating temperature range  
 Height 1.6 mm.

This could be a ceramic (Y5V) unit or a Tantalum, which is best? See C401, 405, 201.

This is the input bypass cap for the battery charger. The manufacturer recommends 1-10 $\mu$ F, we have no compelling reason not to use a 10 $\mu$ F unit as chosen here.

## Resistors(s)

## ■ R400 1.00k $\Omega$ , Any 5% or better film resistor in 1206 package (DigiKey P-1.00KFCT-ND 1.17\$/10)

Panasonic P-1.00KFCT-ND

1.00k $\Omega$  nominal resistance  
 200V WV DC  
 1206 case size  
 $\pm$ 1% tolerance  
 $\pm$ 100ppm temp.co.  
 -55to +125C operating temperature range  
 Height 0.6 mm.  
 thick film composition

R400 serves as a wire-OR'ing element for input voltage from the SPS and UPS node. If SPS voltage is zero, the input to U403 will be equal to UPS, less the voltage drop across R400. The supply current for U403 (TC54VC45) is 4.2 $\mu$ A Max. The minimum anticipated value for the SPS voltage is 4.60V. The maximum voltage threshold for U403 is 4.59V. 10mV drop at 4.2 $\mu$ A gives

$$10^{-3} / 4.2 \times 10^{-6}$$

$$2380.95$$

Choosing a value of 1k $\Omega$  will assure a sufficiently low voltage drop while maintaining acceptably low current during override operations. R408 must be able to pull down U403 to the low voltage threshold. The minimum threshold voltage is  $4.5 \times 0.98 = 4.4$ V. Assume an input voltage of 5.2V, the maximum resistance value for R408 is

```
Solve[ $\frac{r408}{r400 + r408} = \frac{V_o}{V_i}$ , r408][[1, 1]] // FullSimplify
```

$$r408 \rightarrow \frac{r400 V_o}{V_i - V_o}$$

```
% /. {r400 → 1000, V_o → 4.4, V_i → 5.2} // N
```

```
r408 → 5500.
```

For simplicity, choose  $R_{408} = 1\text{k}\Omega$ .

### ■ R401 36.5k $\Omega$ , Any 1% or better film resistor in 1206 package (DigiKey P-36.5KFCT-ND 1.17\$/10)

Panasonic P-36.5KFCT-ND

36.5k $\Omega$  nominal resistance

200V WV DC

1206 case size

$\pm 1\%$  tolerance

$\pm 100\text{ppm}$  temp.co.

$-55\text{to} +125\text{C}$  operating temperature range

Height 0.6 mm.

thick film composition

R401, 402 form the feedback divider for the HAP boost converter. The reference voltage is  $1.25 \pm 0.03\text{V}$ . The desired output voltage is 5.2V. The error amp input current is under 50nA, so a very high divider impedance ( $\sim 2\text{M}\Omega$ , value limited by capacitive parasitics) could be used, but noise considerations suggest working closer to the  $100\text{k}\Omega$  level. Somewhat arbitrarily set the target divider impedance to  $150\text{k}\Omega$  then the values are

```
Solve[{Vfb == V_o * R401 / Rt, Rt == R401 + R402}, {R401, R402}][[1]] // FullSimplify
```

```
{R402 → Rt -  $\frac{R_t V_{fb}}{V_o}$ , R401 →  $\frac{R_t V_{fb}}{V_o}$ }
```

```
% /. {Rt → 150*^3, Vfb → 1.25, V_o → 5.2} // N // EngineeringForm
```

```
{R402 →  $113.942 \times 10^3$ , R401 →  $36.0577 \times 10^3$ }
```

Try 115k and 36.5k

```
Vfb → V_o * R401 / (R401 + R402) /. {V_o → 5.2, R401 → 36.5*^3, R402 → 115*^3} // N
```

```
Vfb → 1.25281
```

$$V_{fb} / 1.25 / . \% // N$$

$$1.00224$$

Seems OK.

### ■ R402 115kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-115KFCT-ND 1.17\$/10)

Panasonic P-115KFCT-ND

115kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

−55to +125C operating temperature range

Height 0.6 mm.

thick film composition

See R401

### ■ R403 ???kΩ , Any ???% or better film resistor in 1206 package

R403, along with C408,409 form the frequency compensation component of the HAP switching supply. C407 also affects the mix by providing a feed-forward component to the output sensing voltage divider.

The notes for R206 also cover frequency compensation. The basic references an-19 p.48-50 and reference an76 still apply.

The DC loop gain is the product of modulator gain and the error amp gain. The error amp gain is around 2000, while the modulator gain is  $\approx 2 V_{in}/I_{out}$ .

The Output filter pole (current mode control) is basically  $1/(2\pi R_{out} C_{out})$ Hz.  $R_{out}$  is just  $1/2 * V_{out}/I_{out}$  (??? explain this). Thus the output pole break frequency is

$$f_{0pole} \rightarrow \frac{1}{2\pi R_o C_o} /. R_o \rightarrow \frac{1}{2} \frac{V_o}{I_o} (* Hz *) // FullSimplify$$

$$f_{0pole} \rightarrow \frac{I_o}{C_o \pi V_o}$$

The output zero is

$$f_{0zero} \rightarrow \frac{1}{2\pi R_{esr} C_o}$$

The boost regulator also has a right-half-plane-zero (RHP0), which can lead to instability (no response through the feedback path). The frequency is given by

$$f_{RHP0} \rightarrow \frac{V_i^2 R_o}{2\pi L V_o^2} (* Hz *)$$

This frequency can be low if  $R_o$  (the load resistance) has a low value. The typical strategy is to roll off the loop gain prior to the RHP0.

Following the nomenclature from the note under R206, the compensation capacitor and series resistor ( $C_c$ ,  $R_c$ ) and the filter compensation capacitor ( $C_f$ ), the compensation network introduces two poles and a zero as before.

The leading pole (assuming  $C_c \gg C_f$ , which is the usual case) is formed by  $C_c$  and the modulator input resistance, which is around 20MΩ

$$f_{p1} \rightarrow \frac{1}{2 \pi R_i C_c} (* \text{ Hz } *) /. \{R_i \rightarrow 20^{*6}, C_c \rightarrow 100^{*-12}\} // N$$

$$f_{p1} \rightarrow 79.5775$$

The 1st pole is quite close to DC, even with a fairly low value of  $C_c$  (here assumed to be 100pF).

Here is the remaining pole and zero

$$f_{p2} \rightarrow \frac{1}{2 \pi R_c C_f}$$

$$f_{z1} \rightarrow \frac{1}{2 \pi R_c C_c}$$

As before, the input voltage divider is bypassed by a speedup capacitor (CA) and a noise filtering, and counter balancing capacitor (CB).

The break frequencies produced by CA and CB are at

$$f_A \rightarrow \frac{1}{2 \pi R_A C_A}, f_B \rightarrow \frac{1}{2 \pi R_B C_B}$$

See also R206

#### ■ R404 27.4kΩ , Any 2% or better film resistor in 1206 package (DigiKey P-27.4KFCT-ND 1.17\$/10)

Panasonic P-27.4KFCT-ND

27.4kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

−55to +125C operating temperature range

Height 0.6 mm.

thick film composition

R404 sets the center frequency of U400's oscillator. For synchronization, the center frequency should be about 30% less than the desired synchronization frequency, according to the manufacturer.

$$\text{Solve}[F_{osc} == 3^{*10} / R_{osc}, R_{osc}] [[1, 1]] // \text{FullSimplify}$$

$$R_{osc} \rightarrow \frac{30000000000}{F_{osc}}$$

$$\% /. F_{osc} \rightarrow (10^{*6} / 6.5) (0.70) // N // \text{EngineeringForm}$$

$$R_{osc} \rightarrow 27.8571 \times 10^3$$

27k would be fine, 28k is good too. 5% is fine, 2% perhaps a bit better.

## ■ R405 Eliminated

### ■ R406 47.5kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-47.5KFCT-ND 1.17\$/10)

Panasonic P-47.5KFCT-ND

47.5kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

-55to +125C operating temperature range

Height 0.6 mm.

thick film composition

This is the pullup resistor for the PwrGood output signal. The value should be >>R400. As a compromise try 47k.

## ■ R407 No value selected

Ideally, R407 would be dropped. It's function is to assure the \Shutdown signal to U400 is asserted when U403 is unpowered. U403 operates down to about 0.7V. It is possible that U400 would operate down to 0.5V so a window exists for unintended operation. This seems unlikely so no value for R407 was selected. If used the value should be fairly high if possible to minimize operating dissipation.

### ■ R408 1.00kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-1.00KFCT-ND 1.17\$/10)

See R400.

### ■ R409 20.0kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-20.0KFCT-ND 1.17\$/10)

See RT400.

### ■ R410 32.4kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-32.4KFCT-ND 1.17\$/10)

See R411.

### ■ R411 3.57kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-3.57KFCT-ND 1.17\$/10)

Panasonic P-3.57KFCT-ND

3.57kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

-55to +125C operating temperature range

Height 0.6 mm.

thick film composition

R410, 411 set the fast and trickle battery charging rates.

Here is the basic formula

$$I_{bat} = 1500 / R_{set}$$

The fast charge current is not very critical. The nominal value is 420mA, but if this was a problem for the supply it could be reduced to 300mA. For now assume 420mA is ok, then the programming resistor is

$$R_{set} \rightarrow 1500 / 0.42 // N$$

$$R_{set} \rightarrow 3571.43$$

Since this is a standard value, go for it.

The nominal trickle charge rate is C/10 or in this case 42mA. This can successfully be any similar figure but sticking to definite C/x values should give a charge-time profile that is independent of battery capacity, which might be good.

These assumptions enable a calculation for R410 to be made

$$R_{set} * (10 - 1) / .\%$$

$$32142.9$$

Pick 32.4k as the next standard value.

$$1500 / (3570 + 32.4 \times 10^3) // N // \text{EngineeringForm}$$

$$41.7014 \times 10^{-3}$$

#### ■ R412-413      47.5kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-47.5KFCT-NDI.17\$/10)

See RT406.

These are pull downs for the battery charge control lines.

#### ■ R414 (Removed) 2MΩ , Any 5% or better film resistor in 1206 package (DigiKey P-2.00MFCT-NDI.17\$/10)

It's desirable to monitor the status of the input supply to the HAP. This should be done with a minimum of input pins on the PIC. The program current pin (PROG) on the Li+ charger (U404) can serve four functions. Connecting a resistor between the pin and ground can set the peak charging current. The true charging current can be determined by reading the voltage at the PROG pin. If the voltage rises above 2.25V(Max) the battery charge circuitry is disabled. The PROG pin is pulled up by a 3μA current source internal to U404. However, if the input voltage drops to zero, essentially zero current will flow from the PROG pin, and the action of R414 will be to pull the voltage at PROG down to zero volts. Thus, a reading of zero volts on the PROG pin indicates a main power failure except during charging, when it could indicate charge termination.

In the case of main power failure during charge, the loss of battery current could be mistaken for charge termination. For the anticipated algorithm, this is not the case, but even if a misidentification of the cause of a zero current reading was made, the ordinary response would be to terminate charging. If the mains were available, the PROG voltage would immediately increase. If the mains failed, the PROG voltage would remain zero, breaking the ambiguity.

The value of R414 must be large enough to allow the voltage to rise to the shutdown threshold under the action of the nominal 3μA current source. The minimum current is 1.5μA



$$1.5 \times 10^{-6} \times 2 \times 10^6$$

$$3.$$

3V is fine as the minimum threshold is 2.25V.

R414 must be small enough to pull the PROG pin low during "Sleep" mode, when the input voltage is  $\sim 0V$ . The leakage current in sleep mode is not specified on the data sheet. The maximum leakage for the whole chip over temperature is given as  $\pm 1\mu A$ .

## Miscellaneous

### ■ B400 Sanyo UF611948, rectangular Li-Ion cell

Sanyo UF611948 (See Sanyo\_Rectang\_UF611948.pdf)

420mAh	nominal capacity
3.7V	nominal voltage
4.2V	maximum charging voltage
420mA	maximum rated charging current
2.5Hr	expected recharge time for fully discharged cell
273Whr/liter	volumetric energy density
135Whr/kg	gravimetric energy density
(0, 40)C	allowable charging ambient temperature
(-20, 60)C	allowable discharge ambient temperature
(-20, 50)C	storage temperature range
48×19.5×6.1mm	Case dimensions
11.5g	cell mass

The main question here is how big a battery is required. A 1Hr mission durability is probably adequate. Assuming the low current requirements we have estimated are correct ( $<100mA$ ) the capacity of this battery is clearly sufficient. The AA type are easier to come by but they seem harder to mount??? and have slightly worse gravimetric energy density???

The 420mA recharge current may be somewhat high for the SPS target of 500mA (but maybe not) but if this was a problem, the current could probably be safely reduced 50% without complications except longer recharge times. Alternately the SPS inductor value could be raised, raising available output current.

By the way, the chemistry of the Sanyo cell is approximately

Lithium Cobaltate ( $LiCoO_2$ ),  $\rho=4.95$ ,  $mp=1130C$ , black odorless powder  
 Graphite electrode (C) (as opposed to Coke),  $\rho=2.09\sim 2.2$ , black odorless powder  
 Organic Solvent  
 Polyvinylidene difluoride (PVdF)

### ■ RT400 Thermometrics NHQM103R10, negative temperature coefficient thermistor (DigiKey 235-1116-1-ND.75\$ea/10)

Thermometrics NHQM103R10 (DigiKey claims NHQM103B375T10)

10k $\Omega$	nominal resistance @ 25C
$\pm 10\%$	tolerance
3750	$\beta$ (25C, 85C) $\pm 200$ K
0805	case size
$<5s$	thermal time constant
1.5mW/K	thermal dissipation factor
(-40, 125)C	operating temperature range
1.3 mm tall	

This is the same unit used on the LV1b FC and IMU. The consistency is regarded as an advantage. Possibly an IC unit with linear response should be substituted.

Based on LV1b design, the series resistance should be 20k $\Omega$ .

# Pyrotechnic Sub-Node High Voltage Igniter Trigger (PYRO) (2100)

Connector(s) ???

Integrated Circuit(s)

## ■ U2100 LT1310, 4MHz, 1.5A, DC-DC boost converter

The selection criterion include size, efficiency, complexity and frequency. This MSOP–10package can reach 85% efficiency and output upto 35V. It can be synchronized to above 4MHz, has under  $1\mu\text{A}$  shutdown current, about 12mA quiescent current, and potentially above 1A output current while tolerating a 3–18V input range.

Particularly constraining here is the requirement of high voltage output, to minimize the number of stages in the voltage multiplier, and high frequency operation.

I really want to use the LT1310. The difficulty is that the maximum duty cycle is only about 80%, this is less than what's required to get 100V off a tripled output. An LT1930 reaches 84%, which is sufficient, but this part cannot be synchronized.

If it's allowable to resort to typical characteristics, the LT1310 will function marginally with a tripler at 100V. This might be a problem at low temperatures. If i can assume Schottky diodes at 0.25V, the implied duty cycle is

$$(100 + 5 * 0.25) / 3 (* \text{ voltage required } *)$$

$$33.75$$

$$1 - \text{VHAP} / \% (* \text{ required duty cycle } *)$$

$$0.845926$$

This is almost the same duty cycle as would be achieved with silicon diodes.

$$(100 + 5 * 0.7) / 3$$

$$34.5$$

1 - VHAP / %
0.849275

I think this problem can be solved by using the discontinuous conduction mode, which will lower the effective duty cycle for a given output voltage. Alternatively a tapped inductor could be used (see an-19 p.43). Since a tapped inductor is a U-wind-it solution, it's currently not the preferred method.

## ■ U2101-2104 IR2118S, Single channel inverting high voltage, high side driver

International Rectifier IR2118S

<600V maximum offset voltage

10-20V drive voltage range

<200ns propagation delay

SO8 package

8.4V UV lockout center voltage

(,120, 580) $\mu$ A quiescent current

-40to +125C operationg temperature range

This integrated circuit accepts a 10-20Vpower supply and a 5V logic input and drives a high side mosfet switch up to 600V.

Selection criterion include quiescent current, voltage and drive capacity, and parts count.

## ■ U2105 SN74AHC1G126DBVR (DigiKey 296-8746-1-ND.56\$ea)

Texas Instruments SN74AHC1G126DBVR

5.5V maximum supply voltage

8mA recommended output current

<10ns propagation delay

SOT-23-5 package

Buffer drives a voltage tripler to supply boost power for the high side drivers.

## Transistor(s)

## ■ Q2100 ZVN3320 SOT-23-3 N-FET (DigiKey ZVN3320FCT-ND0.86\$ea@10)

International Rectifier IRL1110

SOT-223package

100V V<sub>DSS</sub>

12mV/C Break down temp.co. 25C, I<sub>D</sub>=1mA

760m $\Omega$  R<sub>DS(on)</sub>, V<sub>GS</sub>=4V

<6.1nC total gate charge @ V<sub>GS</sub>=5V

250pF typ. input capacitance

1.5A I<sub>DMax</sub> (dissipation limited)

12A Max pulse current

$\pm$ 10V V<sub>GSMax</sub>

2.5V Max body diode forward voltage @ 25C, 1.5A, V<sub>GS</sub>=0V

130ns Max body diode reverse recovery time

650nC Max body diode reverse recovery charge

50mJ Max pulse avalanche Energy

0.31mJ Repetitive avalanche Energy

150C T<sub>JMax</sub>

60C/W Max  $\theta_{JA}$  on standard 1"sq. copper clad board, t < 1s.

Zetex ZVN3320

SOT-23-3 package

200V  $V_{DSS}$

25Ω  $R_{DS(on)Max} V_{GS}=10V, 25C$

1000Ω  $R_{DS(on)Max} V_{GS}=3V, 25C$

1A  $I_{DMax} (pulse)$

60mA  $I_{DMax} (dissipation\ limited)$

330mW Recommended dissipation

This transistor passes current from the high voltage cap (C2100) to the voltage measurement divider. When on this allows the voltage on C2100 to be measured by the microprocessor. Also the measurement divider serves to discharge C2100 when that is desired. The current requirements for Q2100 are miniscule, but the voltage rating must be at least 100V.

I think 5V should get  $R_{DS}$  down to ~100Ω, but the divider should be designed to accept 1kΩ with rated accuracy. The PIC ADC is 10bit. The maximum threshold is 3V. Compress 100V to 2V @ 5/1024V resolution. The voltage quanta is

$$\frac{100}{2} * \frac{5}{1024} V // N$$

$$0.244141 V$$

About 1/4V. The 5V test voltage is thus 20 quanta. At best, if say 5V was scaled to 150V, 5V would read

$$5 / \left( \frac{150}{5} * \frac{5}{1024} \right) // N$$

$$34.1333$$

Preliminarily, it looks like all is working.

Suppose we wish to discharge in 3 seconds to 95%  $\Rightarrow \tau \approx 1s$ . For  $10\mu F \Rightarrow R=100k\Omega$ . Initial current ~1mA. This should be ok w/  $V_{GS} > 2V$  using IRL110. Map 100V to 2V.

$$\text{Solve} \left[ \left\{ r_{2108} + r_{2107} = 100^{*3}, \frac{100}{r_{2108} + r_{2107}} r_{2107} = 2 \right\}, \{r_{2108}, r_{2107}\} \right]$$

$$\{ \{r_{2108} \rightarrow 98000, r_{2107} \rightarrow 2000\} \}$$

## ■ Q2101-2104 IRLR3410 D-PAK N-FET (DigiKey IRLR3410-ND1.16\$ea/10)

International Rectifier IRLR3410

TO-252AA (D-PAK) package

100V  $V_{DSS}$

122mV/C Break down temp.co. 25C,  $I_D=1mA$

105mΩ  $R_{DS(on)}, V_{GS}=10V$

<34nC total gate charge @  $V_{GS}=5V$

800pF typ. input capacitance

17  $I_{DMax} (dissipation\ limited)$

60A Max pulse current

±16V  $V_{GSMax}$

1.3V Max body diode forward voltage @ 25C, 9A,  $V_{GS}=0V$

210ns Max body diode reverse recovery time

1100nC Max body diode reverse recovery charge

150mJ Max pulse avalanche Energy

7.9mJ Repetitive avalanche Energy

175C  $T_{JMax}$

50C/W Max  $\theta_{JA}$  on standard 1"sq. copper clad board,  $t < 1s$ .

These transistors discharge the high voltage capacitor triggering the associated pyrotechnic charge. They require sufficient voltage and current ratings while maintaining low  $R_{DS(on)}$ . Unfortunately this makes them huge.

## ■ Q2105-2108 See Q201

## Diode(s)

### ■ D2100 BAV21W (DigiKey BAV21WDICT-ND0.32\$ea/10)

See D2101.

Must withstand the full high voltage. Use the same as the high side drivers.

### ■ D2101-2104 BAV21W (DigiKey BAV21WDICT-ND0.32\$ea/10)

Diodes Inc.	BAV21W
SOD-323	package, 2 pin type possible to shoot a trace
200V	$V_R$
$0.1\mu A$	Max reverse current @ $V_R$
250mW	Max power (assume 25C ???)
1V	Max forward voltage @ 25C, 100mA
50ns	Max reverse recovery time
5pF	Max capacitance
(-40, 125)C $T_J$ range (maybe a bit more)	

These diodes provide current to the high side driver bootstrap circuits. They must withstand the full high voltage and be fast recovery. The current requirement is quite low, only 150mA (See C2103). The reverse recovery time should be under 100ns.

### ■ D2105-2109 1N4448HWS (DigiKey 1N4448HWSDICT-ND0.30\$ea/10)

See CR201.

High voltage tripler diodes. Max voltage is ~35V, average current pretty low. These will work for the high side driver supply tripler too.

### ■ D2110-2114 1N4448HWS (DigiKey 1N4448HWSDICT-ND0.30\$ea/10)

See D2105.

## Inductor(s)

### ■ L2100 Coiltronics MP2A-1R5, 1.5μH, See PM-4112.pdf

Coiltronics MP2A-1R5

1.5 μH nominal inductance

1.54 μH measured @ 100kHz, 0.25V RMS, 0.0A DC, ±20%

73 mΩ DC Ohms @ 20C typ.

2.02 A RMS current producing +40C temperature rise (excluding core loss)

3.22 A Saturation current defined by 30% loss of inductance. Measured at 20C

2.09 V·μs Volt-time product of 300kHz waveform which when applied across inductor produces core loss equal to 10% of power loss producing +40C temperature rise previously determined.

–40to +125C storage temperature range

–40to +85C operating temperature range

molybdenum permalloy core

rated to 500kHz ??? —I don't see any reason for this.

Body Length exclusive of leads 5.88 mm, Length with leads 7.5 mm. Width 5.2 mm, Height 1.8 mm.

The LT1310 has a switch current limit of 2.8A Max. Assuming a 33V output voltage and a 5.2V input voltage the following seem to apply.

Nominal output voltage is up to 100V, assuming silicon diodes in tripler configuration

$$V_{\text{boost}} = (100 + 5 * 0.7) / 3 (* \text{ input to voltage multiplier } *)$$

$$34.5$$

$$D = 1 - V_{\text{HAP}} / V_{\text{boost}}$$

$$D = 0.849275$$

The data sheet only guarantees 78% maximum duty cycle over temperature at 1.5MHz

$$V_{\text{HAP}}$$

$$1 - 0.78$$

$$23.6364$$

That's sort of pathetic. If the layout was modified to include a doubler on the HAP output, then even assuming a 2 diode drop loss, the resulting duty cycle is only

$$D = 1 - (2 V_{\text{HAP}} - 3 * 0.7) / V_{\text{boost}}$$

$$D = 0.75942$$

On the other hand, changing to a quadrupler on the pyro output and trying for 100V means 7 diode drops

$$(100 + 7 * 0.7) / 4 \text{ (* required voltage using quadrupler *)}$$

$$26.225$$

$$D == 1 - V_{HAP} / \%$$

$$D == 0.801716$$

This fails, barely. If schottky diodes were used in the quadrupler

$$(100 + 7 * 0.3) / 4$$

$$25.525$$

$$D == 1 - V_{HAP} / \%$$

$$D == 0.796278$$

The design still will not meet specs.

It therefore appears that the HAP should be modified for doubler operation. This is complicated by the need to completely shut off the HAP supply. Doing this would require another high-side switch, which is a bad deal.

Consider discontinuous mode operation.

The current during the on time builds up to

$$\Delta I == \frac{V_i}{L} T_{on}$$

By definition, in discontinuous mode, the off time exceeds the time required for the inductor current to fall to zero. This time is given by volt · seconds balance

$$\text{Solve}\left[T_{offmin} \frac{V_o - V_i}{L} == \frac{V_i}{L} T_{on}, T_{offmin}\right][1, 1] // \text{FullSimplify}$$

$$T_{offmin} \rightarrow \frac{T_{on} V_i}{-V_i + V_o}$$

$$T_{offmin} == T_{on} \frac{V_i}{V_o - V_i}$$

The duty cycle concept ceases to be meaningful in discontinuous mode. The average current into the load is given by an integral (ignoring efficiency effects)

$$I_{avg} == I_o == f \int I_{off} dt$$

During off time the current is falling linearly

$$I_o = f \frac{I_p t_{offmin}}{2} = \frac{f}{2} \frac{V_i}{L} T_{on} * T_{on} \frac{V_i}{V_o - V_i} = T_{on}^2 \frac{f}{2 L} \frac{V_i^2}{V_o - V_i}$$

For a boost-mode supply, an-19 gives these formula (note the 3rd formula is mis-stated in an-19 and the 3rd equation is also plain wrong, see derivations below)

Smallest inductor that results in continuous mode operation

$$L_{cont} \geq \frac{V_i^2 (V_o - V_i)}{2 f I_o V_o^2}$$

The minimum inductance to supply a given current in discontinuous mode (ignoring efficiency)

$$L_{dis} \geq \frac{2 I_o (V_o - V_i)}{f I_p^2}$$

Peak inductor current ( $V_f$  is diode forward voltage drop,  $R$  is switch on-resistance) (for continuous mode operation)

$$I_p = I_o \frac{(V_o + V_f) - (I_o V_o R / V_i)}{V_i - I_o V_o R / V_i} + \frac{V_i (V_o - V_i)}{2 f L V_o} \quad (* \text{ WRONG! } *)$$

Here are some derivations of the above

$$L_{cont} = \frac{V_i^2 (V_o - V_i)}{2 f I_o V_o^2} = \frac{V_i^2 D}{2 f I_o V_o} = T_{on} \frac{V_i^2}{2 I_o V_o}$$

$$2 I_o \frac{V_o}{V_i} = T_{on} \frac{V_i}{L_{cont}} = \Delta I$$

So the mode is just barely continuous when the current change during  $T_{on}$  is equal to twice the average current output times the voltage ratio. This derives the 1st equation.

Now find  $I_o$  in terms of  $L_{dis}$  and frequency. Using what was done above

$$I_o = f \frac{I_p t_{offmin}}{2} = \frac{f}{2} I_p T_{on} \frac{V_i}{V_o - V_i}$$

In discontinuous mode,  $I_p = \Delta I$ , so the  $\Delta I$  formula can eliminate  $T_{on}$

$$\text{Solve}\left[I_o = \frac{f}{2} I_p \left(\frac{I_p L}{V_i}\right) \frac{V_i}{V_o - V_i}, L\right][1, 1] // \text{FullSimplify}$$

$$L \rightarrow -\frac{2 I_o (V_i - V_o)}{f I_p^2}$$

Now the 3rd formula

$$I_p = I_o \frac{(V_o + V_f) - (I_o V_o R / V_i)}{V_i - I_o V_o R / V_i} + \frac{V_i (V_o - V_i)}{2 f L V_o}$$

$$= I_o \frac{V_o + V_f - V_{on}}{V_i - V_{on}} + T_{on} \frac{V_i}{2 L}$$



The 1st term is the transformer relation for the average current corrected for diode drop and finite switch on voltage. The 1st term is wrong. The numerator should not contain the  $V_{on}$  voltage. The second term is the  $\Delta I$  contribution. The correct equation is

$$I_p = I_o \frac{V_o + V_f}{V_i - V_{on}} + \Delta I / 2 = I_o \frac{V_o + V_f}{V_i - I_o V_o R / V_i} + \frac{V_i (V_o - V_i)}{2 f L V_o}$$

There's no decent reason I see why the same inductor can't be spec'd here as before.

The continuous mode current threshold is

$$I_o \geq \frac{V_i^2 (V_o - V_i)}{2 f L V_o^2} /. \{V_i \rightarrow V_{HAP}, V_o \rightarrow V_{boost}, f \rightarrow f_{nom}, L \rightarrow 1.5 \times 10^{-6}\}$$

$$I_o \geq 0.144221$$

$\Delta I$  continuous mode

$$\Delta I = \frac{V_i (V_o - V_i)}{2 f L V_o} /. \{V_i \rightarrow V_{HAP}, V_o \rightarrow V_{boost}, f \rightarrow f_{nom}, L \rightarrow 1.5 \times 10^{-6}\}$$

$$\Delta I = 0.95685$$

This is within the LT1310 limit of (1.5, 2.1, 2.8)A

## Capacitors(s)

### ■ C2100 American Capacitor Corp. DW2D106K

Electrocube 230B1B106K, <Electrocube 230 Series–MetallizedPolyester.pdf>

10  $\mu$  nominal capacitance  
 100V WV DC  
 Oval shape  
 <1.25% dissipation factor @ 1000Hz  
 metallized polyester dielectric  
 0.46 x 0.63 x 1.15 " case size  
 $\pm 10\%$  tolerance  
 0.032" lead diameter (AWG #20)  
 -55to +85C operating temperature range (voltage derated to 125C)

Electrocube 230C1B106K, <Electrocube 230 Series–MetallizedPolyester.pdf>

10  $\mu$  nominal capacitance  
 100V WV DC  
 Flatish shape  
 <1.25% dissipation factor @ 1000Hz  
 metallized polyester dielectric  
 0.27 x 0.66 x 1.4 " case size  
 $\pm 10\%$  tolerance  
 0.0253" lead diameter (AWG #22)  
 -55to +85C operating temperature range (voltage derated to 125C)

American Capacitor Corp. DW2D106K, <ACC\_MetallizedMylar–DDData.pdf>

10  $\mu$  nominal capacitance  
 100V WV DC  
 <1.25% dissipation factor @ 1000Hz  
 metallized polyester dielectric  
 0.46 x 0.63 x 1.17 " case size

±10% tolerance  
 0.032" lead diameter (AWG #20)  
 -55to +85C operating temperature range (voltage derated to 125C)

For details see DesignNotes???

Volume of 230B, 230C

```
{0.46 * 0.63 * 1.15, 0.27 * 0.66 * 1.4} // N
```

```
{0.33327, 0.24948}
```

Measured dimensions of 230B, 230C

```
b = ( .420 .426 .418 .433
      .576 .572 .587 .575
      1.163 1.163 1.169 1.174 );
```

```
c = ( .269 .274 .272 .264
      .703 .697 .696 .700
      1.386 1.383 1.391 1.386 );
```

```
Times @@ b (* Volume *)
```

```
{0.281353, 0.283391, 0.286833, 0.292297}
```

```
Times @@ c (* Volume *)
```

```
{0.262102, 0.264123, 0.263333, 0.256133}
```

So, interestingly, the ovals are a little smaller than advertised, the flats are a bit larger. Still the flats are smaller overall.

Mass of 4 together (full leads)

```
bm = 24.05 / 4
```

```
6.0125
```

```
cm = 22.05 g / 4
```

```
5.5125 g
```

For "C" flats, recommend 1.7" spacing on holes. For "B" ovals, recommend 1.5" spacing.

## ■ C2101 Panasonic ECJ-3YF1A106Z(DigiKey PCC1894CT-ND4.91\$/10) (might use the SPS units instead, see C201)

See C401.

This is an input capacitor for a high frequency boost switching power supply. The standard choice is a 1-5μF ceramic capacitor. The Y5V or similar dielectrics are suitable. Voltage rating should be at least 6.3V. Choose the same type as used in the HAP to minimize inventory.

■ **C2102, 2104, 2106, 2108** Any 25+V 0.1 $\mu$ F ceramic cap in 1206 package (DigiKey PCC104BCTCT–ND0.35\$ea)

See C202.

These capacitors are simple bypassing caps. 0.1 $\mu$ F values are adequate. Voltage rating should be at least 25V.

■ **C2103, 2105, 2107, 2109** Any 25+V 0.33 $\mu$ F ceramic cap in 1206 package, Panasonic ECJ–3VB1E334K (DigiKey PCC1889CT–ND0.25\$ea)

See C204.

These capacitors are bootstrap components for the high side switch. Ref. dt98–2.pdf.

Let  $Q_{bs}$  be the charge delivered by the bootstrap capacitor per cycle,  $Q_s$  be the total gate charge required by the mosfet,  $I_{qbsMax}$  be the maximum quiescent current used in the bootstrap circuit,  $Q_{ls}$  be the charge required by the level shift circuitry,  $I_{cbsleak}$  be the leakage current in the bootstrap capacitor, and  $f$  the operating frequency. The basic bootstrap equation is

$$Q_{bs} = 2 Q_s + I_{qbsMax} / f + Q_{ls} + I_{cbsleak} / f$$

$Q_s$  is specified by the mosfet manufacturer, in the case of the IRLR3410 this is approximately

$$34 \times 10^{-9} + 5 \times 800 \times 10^{-12} (* nC *) // N // EngineeringForm$$

$$38. \times 10^{-9}$$

Call this 40nC. The IR2117 datasheet gives the maximum bootstrap quiescent current as 240 $\mu$ A. And the level shifting charge is 5nC. Assume a low leakage capacitor, thus

$$Q_{bs} \rightarrow 2 Q_s + I_{qbsMax} / f + Q_{ls} + I_{cbsleak} / f$$

$$(* nC *) /. \{f \rightarrow 10^6 / 6.5, Q_s \rightarrow 40 \times 10^{-9}, I_{qbsMax} \rightarrow 240 \times 10^{-6}, Q_{ls} \rightarrow 5 \times 10^{-9}, I_{cbsleak} \rightarrow 0\} // N // EngineeringForm$$

$$Q_{bs} \rightarrow 85.156 \times 10^{-9}$$

Assume the minimum input voltage is 12V, and the maximum diode voltage is 0.7V.

The manufacturer recommends a capacitor value equal to

$$30 * Q_{bs} / (V_{cc} - V_{diode}) /. \% /. \{V_{cc} \rightarrow 12, V_{diode} \rightarrow 0.7\} // N // EngineeringForm$$

$$226.078 \times 10^{-9}$$

Since we've already spec'd some 0.33 $\mu$ F parts, we may use them.

Incidentally, the diode forward current is

$$Q_{bs} * f /. \% /. f \rightarrow 10^6 / 6.5 (* A *) // N // EngineeringForm$$

$$131.009 \times 10^{-3}$$

## ■ C2110 KEMET C1206C224K5RACTU (DigiKey 399-1251-1-ND0.18\$/10)

KEMET C1206C224K5RACTU

0.22  $\mu$  nominal capacitance

50V WV DC

X7R dielectric

1206 case size

$\pm 10\%$  tolerance

-35to +85C operating temperature range

Height ?? mm.

This is the 1st output capacitor for the pyrotechnic voltage tripler. Ripple can be very high compared to typical applications, but stability suggests a reasonable value should be used. The dynamic properties of this capacitor affect the loop stability so a moderately stable X7R or X5R type is typical. Voltage rating  $\geq 35V$ .

Basic ripple formula

$$V_{pp} = \frac{\Delta I V_i}{C V_o f} /. \{ \Delta I \rightarrow 0.144, V_{pp} \rightarrow 50^{-3}, V_i \rightarrow 5.2, V_o \rightarrow 34.5, f \rightarrow f_{nom} \} // N$$

$$0.05 == \frac{1.41078 \times 10^{-8}}{C}$$

`Solve[%, C] [[1, 1]] // EngineeringForm`

$$C \rightarrow 282.157 \times 10^{-9}$$

This is a very modest value

## ■ C2111 - C2113 See 2110

These are the remaining ladder caps of the pyro voltage tripler. I don't see why the same 0.22 $\mu F$  values can't be used. Recharge time should still be sub-second.

## ■ C2114 Any 25+V 0.01 $\mu F$ ceramic cap in 1206 package (DigiKey PCC104BCT-ND0.35\$ea)

Filter capacitor for Pyro voltage measurement. 0.01 $\mu F$  gives ~200 $\mu S$  time constant.

## ■ C2115 Any 25+V 0.33 $\mu F$ ceramic cap in 1206 package, Panasonic ECJ-3VB1E334K (DigiKey PCC1889CT-ND0.25\$ea)

See C204.

This is the output capacitor for the high side driver supply. The maximum steady load is

$$(240 + 340) 1^{-6} * 4 (* A *) // N // EngineeringForm$$

$$2.32 \times 10^{-3}$$

At the operating frequency this represents a small charge of

```
% / f /. f → 10*^6 / 6.5 (* nC *) // N // EngineeringForm
```

```
1.508 × 10-9
```

If a the ripple is set to 100mV, the required capacitance is

```
% / .1 (* F *) // N // EngineeringForm
```

```
15.08 × 10-9
```

This is tiny. Triggering the driver will pull 40nC

```
15 * 40 / 1.5 (* nF *) // N
```

```
400.
```

Since the 0.33 $\mu$ F caps have already been spec'd keep using 'em.

■ **C2116-2120** Any 25+V 0.33 $\mu$ F ceramic cap in 1206 package, Panasonic ECJ-3VB1E334K (DigiKey PCC1889CT-ND0.25\$ea)

See C2115.

■ **C2121-2124** Frequency compensation components, see R2110.

■ **C2125** 1500pF ceramic cap in 1206 package (DigiKey PCC152BCT-ND1.17\$/10)

Panasonic ECU-V1H152KBM

1500pF nominal capacitance

50V WV DC

X7R dielectric

1206 case size

±10% tolerance

-55to +125C operating temperature range

Height 0.6 mm.

LPF for PLL. Manufacturer recommended value is 1500pF.

■ **C2126** Not Present

LPF for PLL. Should not be required.

## ■ C2127 100pF NPO (DigiKey PCC101CCT-ND)

Panasonic ECU-V1H101JCH

100pF nominal capacitance

50V WV DC

NPO dielectric

1206 case size

±5% tolerance

–55to +125C operating temperature range

Height 0.6 mm.

Sets the center frequency of the PLL. For synchronization, set ~33% higher than target frequency.

$$\frac{9+3}{9} \frac{10^{*6}}{6.5} (* \text{ Hz } *) // N // \text{EngineeringForm}$$

$$2.05128 \times 10^6$$

The recommended capacitor for this frequency from the datasheet is 100pF. This value is cheap enough in NPO.

## Resistors(s)

### ■ R2100 47.5kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-47.5KFCT-ND 1.17\$/10)

See R406.

Pull down for Pyro-Charge input signal. Pretty much standardized on 47k.

### ■ R2101-2104 Any 5% or better film resistor in 1206 package of around or about 10Ω's (guess). (DigiKey P-10.0FCT-ND 1.17\$/10)

These resistors slow down the transitions of the mosfet switches. Typical values are between 3.3Ω and 47Ω. Typical indications for there use are excessive supply bounce or VHF oscillation in the mosfet gate. Just for fun we have spec'd 10Ω's.

### ■ R2105 39.2kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-39.2KFCT-ND 1.17\$/10)

Panasonic P-36.5KFCT-ND

39.2kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

–55to +125C operating temperature range

Height 0.6 mm.

thick film composition

R2105, 2106 form the feedback divider for the PYRO boost converter. The reference voltage is 1.255±0.016V. The desired output voltage is 33V. The error amp input current is under 150nA, so a moderately high divider impedance ~500kΩ, could be used, but noise considerations suggest working closer to the 100kΩ level. Somewhat arbitrarily set the target divider impedance to 150kΩ then the values are

```
Solve[{Vfb == Vo * R2105 / (R2105 + R2106), 1 / Rt == 1 / R2105 + 1 / R2106},
{R2105, R2106}][[1]] // FullSimplify
```

$$\left\{ R2106 \rightarrow \frac{R_t V_o}{V_{fb}}, R2105 \rightarrow \frac{R_t V_o}{-V_{fb} + V_o} \right\}$$

```
% /. {Rt -> 150*^3, Vfb -> 1.255, Vo -> 33} // N // EngineeringForm
```

$$\{R2106 \rightarrow 3.94422 \times 10^6, R2105 \rightarrow 155.93 \times 10^3\}$$

Scale R2106 to 1MΩ

```
R2106 / 1*^6 /. %
```

```
3.94422
```

```
{R2106, R2105} / %% /. % // N // EngineeringForm
```

$$\{1. \times 10^6, 39.5338 \times 10^3\}$$

Try 1M and 39.2k

```
Vfb -> Vo * R2105 / (R2105 + R2106) /. {Vo -> 33, R2105 -> 39.2*^3, R2106 -> 1*^6} // N
```

```
Vfb -> 1.2448
```

```
Vfb / 1.255 /. % // N
```

```
0.991875
```

Seems OK, though not great.

## ■ R2106 1.00MΩ, Any 1% or better film resistor in 1206 package (DigiKey P-1.00MFCT-ND 1.17\$/10)

Panasonic P-1.00MFCT-ND

1.00MΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

-55to +125C operating temperature range

Height 0.6 mm.

thick film composition

See R2105

## ■ R2107 2.00kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-???KFCT-ND 1.17\$/10)

Panasonic P-22.1KFCT-ND

22.1kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

–55to +125C operating temperature range

Height 0.6 mm.

thick film composition

**Calculation superceeded, see Q2100**

R2107 along with R2108 form the high voltage measurment divider. For convinience at the  $\mu\text{P}$ , it's desirable to keep the impedance less than 20kΩ. We wish to compress a zero to ~150V range down to 0–5.2V. Perhaps the most natural division is into 1/2 volt quanta (full scale 128V). Here are the equations.

```
Solve[{1/Rt == 1/RA + 1/RB, Vo/Vi == RA/(RA + RB)}, {RA, RB}] [[1]] //
FullSimplify
```

$$\left\{ R_B \rightarrow \frac{R_t V_i}{V_o}, R_A \rightarrow \frac{R_t V_i}{V_i - V_o} \right\}$$

```
% /. {Rt -> 20*^3, Vi -> 128, Vo -> 5.2} // N // EngineeringForm
```

$$\left\{ R_B \rightarrow 492.308 \times 10^3, R_A \rightarrow 20.8469 \times 10^3 \right\}$$

An OK compromise would be  $R_A \rightarrow 22.1\text{k}$  ,  $R_B \rightarrow 523\text{k}$ , this is open to discussion.

## ■ R2108 97.6kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-???KFCT-ND 1.17\$/10)

See R2107.

## ■ R2109 4.99kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-4.99KFCT-ND 1.17\$/10)

Panasonic P-4.99KFCT-ND

4.99kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

–55to +125C operating temperature range

Height 0.6 mm.

thick film composition

This resistor charges the high voltage discharge capacitor to the supply voltage (5.2V nominal). The maimimum permissible value is that resulting in the no-fire igniter current, which is about 100mA. The maximum value is that which results in a time constant of ~1/2s. These two constraints are



```
R > 5.2 / .1 // N (* Ohms *)
```

```
R > 52 .
```

```
R < 0.5 / 10*^-6 // N (* Ohms *)
```

```
R < 50000 .
```

5000Ω seems a convenient figure.

## ■ R2110 frequency compensation component

This resistor, along with C2121-2124 form the feedback compensation network. As explained for the HAP, the component values are to be determined.

## ■ R2111 3.01kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-3.01KFCT-ND 1.17\$/10)

Low pass filter for PLL. Manufacturer recommended value.

## ■ R2112-2120 47.5kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-47.5KFCT-ND 1.17\$/10)

See R406.

Pull down for high side driver input signal. Pretty much standardized on 47k.

## ■ R2121 10kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-10.0KFCT-ND 1.17\$/10)

Gate resistor for Q2100 Pyro measurement divider switch.

The gate resistor isn't a necessity, but by slowing the transitions it eliminates any unwanted high frequency effects. Also in the event of oxide failure, the gate resistor will limit the current to the microprocessor. 10k isn't too big to be slow, and will limit the peak current to around 10mA.

# DTMF Demodulator for 2m radio (DTMF) (2200)

## Integrated Circuit(s)

### ■ U2200 HT9170D, DTMF Receiver

A single chip dual tone decoder. Requires an external 3.579545 MHz crystal or ceramic resonator.

Holtek HT9170D

2.5 - 5.5V operating range

(, 3, 7)mA operating current

(, 10, 25) $\mu$ A standby current

SOP18 package

3.579545 $\pm$ 0.004 MHz Input frequency range

$\pm$ 1.5% frequency acceptance range

$\pm$ 3.5% frequency rejection range

(-29,, -6)dBm Input signal range — dBm are referenced to 1mW, The conversion to voltage assumes (we think) 600 $\Omega$ 's

Solve for power

```
Solve[dBm == 10 * Log[10, P / P0], P][[1, 1]]
```

```
P → 10dBm/10 P0
```

Find the voltage

```
Solve[Evaluate[P == V2 / R /. %], V]
```

```
{ {V → -10dBm/20  $\sqrt{P0}$   $\sqrt{R}$  }, {V → 10dBm/20  $\sqrt{P0}$   $\sqrt{R}$  } }
```

Assuming 600 $\Omega$ 's find the voltage

```
%[[2, 1]] /. {R → 600, P0 → 1*^-3} // N // FullSimplify
```

```
V → 0.774597 e0.115129 dBm
```

```
vdBm[dBm_] := 0.7745966692414833 e0.1151292546497023 dBm
```

vdBm [ - 29 ]
0 . 0274837

vdBm [ - 6 ]
0 . 388218

So the correct voltage range for the input ( GS pin ) is ~ 50 - 300 mV, a good target would be 100mV.

## Capacitors(s)

- **C2200, 2201** Panasonic ECU-V1H102JCH(1206, DigiKey PCC102CCT-ND1.98\$/10 — not for new design)  
Panasonic ECJ-2VC1H102J(0805, DigiKey PCC102CGCT-ND1.13\$/10)

Panasonic ECU-V1H102JCH(1206)/ ECJ-2VC1H102J(0805)

1 nF nominal capacitance

50V WV DC

NP dielectric

1206/0805 case size

±5% tolerance

-55to +125C operating temperature range

Height 0.6 mm

Part of the DTMF input active filter. These caps should have equal value. NPO 1206 are available.

For Calculations see Diff-BP-FilterDesign

- **C2202, 2203** 2nF, See C2200

Part of the DTMF input active filter. These caps should have equal value. Since 2nF is not a standard value in the digikey catalog, make a 2nF using two caps of the C2200 variety. This should improve tracking as well.

- **C2101** Panasonic ECJ-3YF1A106Z(DigiKey PCC1894CT-ND4.91\$/10) (might use the SPS units instead, see C201)

See C401.

This is an input capacitor for a high frequency boost switching power supply. The standard choice is a 1-5 $\mu$ F ceramic capacitor. The Y5V or similar dielectrics are suitable. Voltage rating should be at least 6.3V. Choose the same type as used in the HAP to minimize inventory.

- **C2102, 2104, 2106, 2108** Any 25+V 0.1 $\mu$ F ceramic cap in 1206 package (DigiKey PCC104BCTCT-ND0.35\$ea)

See C202.

These capacitors are simple bypassing caps. 0.1 $\mu$ F values are adequate. Voltage rating should be at least 25V.

## ■ C2103, 2105, 2107, 2109 Any 25+V 0.33 $\mu$ F ceramic cap in 1206 package, Panasonic ECJ-3VB1E334K (DigiKey PCC1889CT-ND0.25\$ea)

See C204.

These capacitors are bootstrap components for the high side switch. Ref. dt98-2.pdf.

Let  $Q_{bs}$  be the charge delivered by the bootstrap capacitor per cycle,  $Q_s$  be the total gate charge required by the mosfet,  $I_{qbsMax}$  be the maximum quiescent current used in the bootstrap circuit,  $Q_{ls}$  be the charge required by the level shift circuitry,  $I_{cbsleak}$  be the leakage current in the bootstrap capacitor, and  $f$  the operating frequency. The basic bootstrap equation is

$$Q_{bs} = 2 Q_s + I_{qbsMax} / f + Q_{ls} + I_{cbsleak} / f$$

$Q_s$  is specified by the mosfet manufacturer, in the case of the IRLR3410 this is approximately

$$34 \times 10^{-9} + 5 \times 800 \times 10^{-12} (* nC *) // N // EngineeringForm$$

$$38. \times 10^{-9}$$

Call this 40nC. The IR2117 datasheet gives the maximum bootstrap quiescent current as 240 $\mu$ A. And the level shifting charge is 5nC. Assume a low leakage capacitor, thus

$$Q_{bs} \rightarrow 2 Q_s + I_{qbsMax} / f + Q_{ls} + I_{cbsleak} / f$$

$$(* nC *) /. \{f \rightarrow 10^6 / 6.5, Q_s \rightarrow 40 \times 10^{-9}, I_{qbsMax} \rightarrow 240 \times 10^{-6},$$

$$Q_{ls} \rightarrow 5 \times 10^{-9}, I_{cbsleak} \rightarrow 0\} // N // EngineeringForm$$

$$Q_{bs} \rightarrow 85.156 \times 10^{-9}$$

Assume the minimum input voltage is 12V, and the maximum diode voltage is 0.7V.

The manufacturer recommends a capacitor value equal to

$$30 * Q_{bs} / (V_{cc} - V_{diode}) /. \% /. \{V_{cc} \rightarrow 12, V_{diode} \rightarrow 0.7\} // N // EngineeringForm$$

$$226.078 \times 10^{-9}$$

Since we've already spec'd some 0.33 $\mu$ F parts, we may use them.

Incidentally, the diode forward current is

$$Q_{bs} * f /. \% /. f \rightarrow 10^6 / 6.5 (* A *) // N // EngineeringForm$$

$$131.009 \times 10^{-3}$$

## ■ C2110 KEMET C1206C224K5RACTU (DigiKey 399-1251-1-ND.18\$/10)

KEMET C1206C224K5RACTU

0.22  $\mu$  nominal capacitance  
 50V WV DC  
 X7R dielectric  
 1206 case size  
 $\pm 10\%$  tolerance  
 $-35$  to  $+85^\circ\text{C}$  operating temperature range  
 Height ?? mm.

This is the 1st output capacitor for the pyrotechnic voltage tripler. Ripple can be very high compared to typical applications, but stability suggests a reasonable value should be used. The dynamic properties of this capacitor affect the loop stability so a moderately stable X7R or X5R type is typical. Voltage rating  $\geq 35\text{V}$ .

Basic ripple formula

$$V_{pp} = \frac{\Delta I V_i}{C V_o f} /. \{ \Delta I \rightarrow 0.144, V_{pp} \rightarrow 50^{-3}, V_i \rightarrow 5.2, V_o \rightarrow 34.5, f \rightarrow f_{nom} \} // N$$

$$0.05 == \frac{1.41078 \times 10^{-8}}{C}$$

`Solve[%, C] [[1, 1]] // EngineeringForm`

$$C \rightarrow 282.157 \times 10^{-9}$$

This is a very modest value

## ■ C2111 - C2113 See 2110

These are the remaining ladder caps of the pyro voltage tripler. I don't see why the same  $0.22\mu\text{F}$  values can't be used. Recharge time should still be sub-second.

## ■ C2114 Any 25+V $0.01\mu\text{F}$ ceramic cap in 1206 package (DigiKey PCC104BCT-ND0.35\$ea)

Filter capacitor for Pyro voltage measurement.  $0.01\mu\text{F}$  gives  $\sim 200\mu\text{s}$  time constant.

## ■ C2115 Any 25+V $0.33\mu\text{F}$ ceramic cap in 1206 package, Panasonic ECJ-3VB1E334K (DigiKey PCC1889CT-ND0.25\$ea)

See C204.

This is the output capacitor for the high side driver supply. The maximum steady load is

$$(240 + 340) 1^{-6} * 4 (* A *) // N // EngineeringForm$$

$$2.32 \times 10^{-3}$$

At the operating frequency this represents a small charge of

```
% / f /. f → 10^6 / 6.5 (* nC *) // N // EngineeringForm
```

```
1.508 × 10-9
```

If a the ripple is set to 100mV, the required capacitance is

```
% / .1 (* F *) // N // EngineeringForm
```

```
15.08 × 10-9
```

This is tiny. Triggering the driver will pull 40nC

```
15 * 40 / 1.5 (* nF *) // N
```

```
400.
```

Since the 0.33μF caps have already been spec'd keep using 'em.

■ **C2116-2120** Any 25+V 0.33μF ceramic cap in 1206 package, Panasonic ECJ-3VB1E334K (DigiKey PCC1889CT-ND0.25\$ea)

See C2115.

■ **C2121-2124** Frequency compensation components, see R2110.

■ **C2125** 1500pF ceramic cap in 1206 package (DigiKey PCC152BCT-ND1.17\$/10)

Panasonic ECU-V1H152KBM

1500pF nominal capacitance

50V WV DC

X7R dielectric

1206 case size

±10% tolerance

-55to +125C operating temperature range

Height 0.6 mm.

LPF for PLL. Manufacturer recommended value is 1500pF.

■ **C2126** Not Present

LPF for PLL. Should not be required.

## ■ C2127 100pF NPO (DigiKey PCC101CCT-ND)

Panasonic ECU-V1H101JCH

100pF nominal capacitance

50V WV DC

NPO dielectric

1206 case size

±5% tolerance

−55to +125C operating temperature range

Height 0.6 mm.

Sets the center frequency of the PLL. For synchronization, set ~33% higher than target frequency.

$$\frac{9 + 3}{9} \frac{10^{*6}}{6.5} (* \text{ Hz } *) // N // \text{EngineeringForm}$$

$$2.05128 \times 10^6$$

The recommended capacitor for this frequency from the datasheet is 100pF. This value is cheap enough in NPO.

## Resistors(s)

### ■ R2100 47.5kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-47.5KFCT-ND 1.17\$/10)

See R406.

Pull down for Pyro-Charge input signal. Pretty much standardized on 47k.

### ■ R2201 Any 5% or better film resistor in 1206 package of around or about 10Ω's (guess). (DigiKey P-10.0FCT-ND 1.17\$/10)

R2201 is part of the input network of the opamp. We want to do 3 things with the opamp network. 1) Provide a fixed gain. 2) Block DC components, 3) Filter high frequency AC components.

DTMF covers a frequency range from 697 - 1633 Hz.

### ■ R2105 39.2kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-39.2KFCT-ND 1.17\$/10)

Panasonic P-36.5KFCT-ND

39.2kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

−55to +125C operating temperature range

Height 0.6 mm.

thick film composition

R2105, 2106 form the feedback divider for the PYRO boost converter. The reference voltage is  $1.255 \pm 0.016\text{V}$ . The desired output voltage is 33V. The error amp input current is under 150nA, so a moderately high divider impedance ~500kΩ, could be used, but noise considerations suggest working closer to the 100kΩ level. Somewhat arbitrarily set the target divider impedance to 150kΩ then the values are

```
Solve[{Vfb == Vo * R2105 / (R2105 + R2106), 1 / Rt == 1 / R2105 + 1 / R2106},
{R2105, R2106}][[1]] // FullSimplify
```

$$\left\{ R2106 \rightarrow \frac{R_t V_o}{V_{fb}}, R2105 \rightarrow \frac{R_t V_o}{-V_{fb} + V_o} \right\}$$

```
% /. {Rt -> 150*^3, Vfb -> 1.255, Vo -> 33} // N // EngineeringForm
```

$$\{R2106 \rightarrow 3.94422 \times 10^6, R2105 \rightarrow 155.93 \times 10^3\}$$

Scale R2106 to 1M $\Omega$

```
R2106 / 1*^6 /. %
```

```
3.94422
```

```
{R2106, R2105} / %% /. % // N // EngineeringForm
```

$$\{1. \times 10^6, 39.5338 \times 10^3\}$$

Try 1M and 39.2k

```
Vfb -> Vo * R2105 / (R2105 + R2106) /. {Vo -> 33, R2105 -> 39.2*^3, R2106 -> 1*^6} // N
```

```
Vfb -> 1.2448
```

```
Vfb / 1.255 /. % // N
```

```
0.991875
```

Seems OK, though not great.

## ■ R2106 1.00M $\Omega$ , Any 1% or better film resistor in 1206 package (DigiKey P-1.00MFCT-ND 1.17\$/10)

Panasonic P-1.00MFCT-ND

1.00M $\Omega$  nominal resistance

200V WV DC

1206 case size

$\pm 1\%$  tolerance

$\pm 100\text{ppm}$  temp.co.

$-55\text{to} +125\text{C}$  operating temperature range

Height 0.6 mm.

thick film composition

See R2105



### ■ R2107 2kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-???KFCT-ND 1.17\$/10)

Panasonic P-22.1KFCT-ND

22.1kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

–55to +125C operating temperature range

Height 0.6 mm.

thick film composition

**Calculation superceeded, see Q2100**

R2107 along with R2108 form the high voltage measurment divider. For convinience at the  $\mu\text{P}$ , it's desirable to keep the impedance less than 20kΩ. We wish to compress a zero to ~150V range down to 0–5.2V. Perhaps the most natural division is into 1/2 volt quanta (full scale 128V). Here are the equations.

```
Solve[{1 / Rt == 1 / RA + 1 / RB, Vo / Vi == RA / (RA + RB)}, {RA, RB}] [[1]] //
FullSimplify
```

$$\left\{ RB \rightarrow \frac{R_t V_i}{V_o}, RA \rightarrow \frac{R_t V_i}{V_i - V_o} \right\}$$

```
% /. {Rt -> 20*^3, Vi -> 128, Vo -> 5.2} // N // EngineeringForm
```

$$\left\{ RB \rightarrow 492.308 \times 10^3, RA \rightarrow 20.8469 \times 10^3 \right\}$$

An OK compromise would be  $RA \rightarrow 22.1\text{k}$  ,  $RB \rightarrow 523\text{k}$ , this is open to discussion.

### ■ R2108 98kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-???KFCT-ND 1.17\$/10)

See R2107.

### ■ R2109 4.99kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-4.99KFCT-ND 1.17\$/10)

Panasonic P-4.99KFCT-ND

4.99kΩ nominal resistance

200V WV DC

1206 case size

±1% tolerance

±100ppm temp.co.

–55to +125C operating temperature range

Height 0.6 mm.

thick film composition

This resistor charges the high voltage discharge capacitor to the supply voltage (5.2V nominal). The mainimum permissible value is that resulting in the no-fire igniter current, which is about 100mA. The maximum value is that which results in a time constant of ~1/2s. These two constraints are

$$R > 5.2 / .1 // N (* \text{ Ohms } *)$$

$$R > 52 .$$

$$R < 0.5 / 10^{-6} // N (* \text{ Ohms } *)$$

$$R < 50000 .$$

5000Ω seems a convenient figure.

## ■ R2110 frequency compensation component

This resistor, along with C2121-2124 form the feedback compensation network. As explained for the HAP, the component values are to be determined.

## ■ R2111 3.01kΩ , Any 1% or better film resistor in 1206 package (DigiKey P-3.01KFCT-ND 1.17\$/10)

Low pass filter for PLL. Manufacturer recommended value.

## ■ R2112-2115 47.5kΩ , Any 5% or better film resistor in 1206 package (DigiKey P-47.5KFCT-ND 1.17\$/10)

See R406.

Pull down for high side driver input signal. Pretty much standardized on 47k.

## Miscellaneous

## ■ B400 Sanyo UF611948, rectangular Li-Ion cell

Sanyo UF611948 (See Sanyo\_Rectang\_UF611948.pdf)

420mAHr	nominal capacity
3.7V	nominal voltage
4.2V	maximum charging voltage
420mA	maximum rated charging current
2.5Hr	expected recharge time for fully discharged cell
273WHr/liter	volumetric energy density
135WHr/kg	gravimetric energy density
(0, 40)C	allowable charging ambient temperature
(-20, 60)C	allowable discharge ambient temperature
(-20, 50)C	storage temperature range
48×19.5×6.1mm	Case dimensions

The main question here is how big a battery is required. A 1Hr mission durability is probably adequate. Assuming the low current requirements we have estimated are correct (<100mA) the capacity of this battery is clearly sufficient. The AA type are easier to come by but they seem harder to mount??? and have slightly worse gravimetric energy density???

The 420mA recharge current may be somewhat high for the SPS target of 500mA (but maybe not) but if this was a problem, the current could probably be safely reduced 50% without complications except longer recharge times. Alternately the SPS inductor value could be raised, raising available output current.

By the way, the chemistry of the Sanyo cell is approximately

Lithium Cobaltate ( $\text{LiC}_{??}\text{O}_2$ ),  $\rho=4.95$ ,  $\text{mp}=1130^\circ\text{C}$ , black odorless powder

Graphite electrode (C) (as opposed to Coke),  $\rho=2.09\sim 2.2$ , black odorless powder

Organic Solvent

Polyyvinilidene difluoride (PVdF)

## ■ RT400 Thermometrics NHQM103R10, negative temperature coefficient thermistor (DigiKey 235-1116-1-ND, \$0.75/ea/10)

Thermometrics NHQM103R10 (DigiKey claims NHQM103B375T10)

10k $\Omega$  nominal resistance @ 25 $^\circ\text{C}$

$\pm 10\%$  tolerance

3750  $\beta$  (25 $^\circ\text{C}$ , 85 $^\circ\text{C}$ ) $\pm 200$  K

0805 case size

<5s thermal time constant

1.5mW/K thermal dissipation factor

(-40,125) $^\circ\text{C}$  operating temperature range

1.3 mm tall

This is the same unit used on the LV1b FC and IMU. The consistency is regarded as an advantage. Possibly an IC unit with linear response should be substituted.

Based on LV1b design, the series resistance should be 20k $\Omega$ .