

# Re: PWM Amp Design

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- *From:* "Larry Brasfield" <[donotspam\\_larry\\_brasfield@xxxxxxxxxxx](mailto:donotspam_larry_brasfield@xxxxxxxxxxx)>
  - *Date:* Sat, 9 Apr 2005 09:36:43 -0700
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"Chris Carlen" <[crobc@xxxxxxxxxxxxxxxxxxxxxxxxxxxx](mailto:crobc@xxxxxxxxxxxxxxxxxxxxxxxxxxxx)> wrote in message [news:d38qfa02aif@xxxxxxxxxxxxxxxxxxxxxxxx](mailto:news:d38qfa02aif@xxxxxxxxxxxxxxxxxxxxxxxx)  
> Larry Brasfield wrote:  
>> "Chris Carlen" <[crcarleRemoveThis@xxxxxxxxxxxxxxxxxxx](mailto:crcarleRemoveThis@xxxxxxxxxxxxxxxxxxx)> wrote in message  
>> [news:d36fkj022dd@xxxxxxxxxxxxxxxxxxxxxxxx](mailto:news:d36fkj022dd@xxxxxxxxxxxxxxxxxxxxxxxx)  
>>> I'm designing a PWM amp PCB module based on the Apex  
>>> Microtechnology SA60 chip.  
>>  
>>> Target specs are to be able to sustain 80V at up to 7.1A  
>>> continuously and 10A max. into a load of unspecified resistance.  
>>  
>> Specifying at least a range would help a lot. Does the load actually  
>> change once a system is built? Or do you just not know the load yet?  
>  
> My idea was that since I had to build an amp for about 3.5A RMS into the load of 2.5ohm+250uH for a specific application in which  
> the load will never change, that I might use the opportunity to make a somewhat more generalized hardware foundation which could  
> be used for similar applications in the future with different loads. Hence the "unspecified" load. Reasonably speaking, we would  
> be considering mostly slightly inductive loads such as motors and solenoids ranging from perhaps 0.5-20ohms, and 10-1000uH. I  
> doubled the current capability from my application's 3.5A RMS (but must be able to deliver 10A peak currents anyway, so the filter  
> inductors mustn't go flat at that current) to 7A just for flexibility.

Great. That makes the controller design a lot easier since it can be revised (but only slightly) for subsequent applications.

>>> That means for small load resistances, the output voltage might not  
>>> ever reach 80V, but for any load resistance, the output current  
>>> must be able to reach 7.1A continuously.  
>>  
>> Is current limiting an issue? (I would think so if the load is as  
>> ill-behaved as you have allowed here.)  
>  
> At this point, current limit isn't necessary. I don't like being unprotected from short circuit, but the complexity of

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- > implementing this vs. the timeframe for getting something running (this is an experimental lab apparatus application, not a commercial product) forces me to implement the simplest approach first. I can spend time on refinements later.

I would think it could be added later without much interaction with the basic system. (There could be control issues, of course, in whatever outer loop this PWM+mover ends up in.)

- > Current limiting would also be complicated by the fact that we need to be able to deliver accelerating currents of 10A to perhaps
  - > even the SA60's 15A peak capability, which the load coils can handle briefly, but not continuously. So a current limit designed
  - > to protect the load would have to allow short bursts of high current, but somehow take into account the average power limitations
  - > of the load as well as its transient thermal limitations.
- >
  - >>> Frequency response should be flat to  $-3\text{dB}$  at 10kHz or better.
  - >>
  - >> If phase delay up to 150 Hz is what you really care about, it would
  - >> be more useful to know that requirement.
- >
  - > 2 degrees.

I suppose I can translate that to flat delay within  $\pm 37\ \mu\text{s}$  from DC to 150 Hz and beyond that, don't care.

- >>> The PWM amp is closed loop with a differential output voltage sense
  - >>> amp feeding into a simple integrating summing amp driving the PWM
  - >>> control input, which also has the main input signal applied. Note
  - >>> that the output voltage sense is done prior to output filtering, so
  - >>> that a simple integrator compensation is able to maintain control.
- >>
  - >> I suggest that, with an appropriate controller, it would be fine to
  - >> control the filter output instead. That would likely simplify
  - >> getting the phase delay you want, by easing the derived and hence
  - >> subsidiary requirements.
- >>
  - >>> The output is filtered with a differential LC Butterworth
  - >>> arrangement, the LC values of course needing to be tuned to the
  - >>> load resistance.
- >>
  - >> That makes me think the load may be knowable after all.
- >>
  - >>> I have chosen a 125kHz switching frequency. The output filter
  - >>> cutoff will be 12.5kHz.
- >>
  - >> Is it a 2 pole LC LPF, nominally?
- >
  - > Yes.

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That, too, simplifies the controller and the math (if any) behind it.

>>> My present load will be a 2.5 ohm coil with 250uH of inductance.

>>> Thus the LC filter elements are 22.5uH and 7.2uF.

>>

>> Is there any reason you cannot adjust the controller response to

>> accomodate the load variation?

>

> There is no load variation in this case. The response would have to be adjusted for different load applications.

May I presume you are willing to use a 10% ceramic cap and 5% gapped core set for the inductor? (This may well be relaxed once the phase delay performance is simulated or analyzed with respect to sensitivity.)

>>> The inductive load requires equalization to cancel its reactance or

>>> else the LC filter for the PWM becomes resonant with the added load

>>> inductance, resulting in freq. response peaking.

>>

>> The controller could provide the damping without the necessity of

>> dissipation or extra HF output.

>

> That would be cool (in more ways than one.)

I've always liked electronic damping.

>>> To fix this, I have added a 2.5ohm resistor in series with a 40uF

>>> capacitor across the load.

>>

>> That is a hit with respect to ripple.

>

> Huh? Wouldn't crossover of load current at high frequency to the capacitive branch actually reduce ripple?

Oh wait, or does it

> modify the filter response so as to reduce the cutoff slope? No! That's the point of the equalization, to present to the filter

> an effective resistive load of 2.5 ohms at all frequencies. But from the real load's perspective...it sees its current dropping

> off as its own inductance kicks in. Actually, since the voltage across both the real load and the capacitive branch are the same,

> I don't think there is any effect on ripple. I'll have to check this.

Perhaps I misread your statement. I took it as (a 2.5ohm resistor in series with a 40uF capacitor) across the load

whereas you apparently meant

a 2.5ohm resistor in series with (a 40uF capacitor across the load).

At any rate, I would get rid of the resistor, except for

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a residual to be used for current sensing later.

>>> This all works fine except for some drawbacks. Obviously, at high  
>>> frequencies near and above the crossover frequency of the load RL  
>>> combination, the equalizer RC network begins to conduct substantial  
>>> current and dissipating massive power. Up to about 115W at the  
>>> output specs mentioned.

>>

>> EMI might suffer, too, depending on what the inductors really look  
>> like.

>

> Do you mean because they are having to conduct the full current expected from a resistive load at the cutoff  
freq. whereas if

> there was no capacitive equalizer, then their current thus radiated mag. field would drop off more quickly at  
HF?

I mean because of my misunderstanding of your network.

>>> I should point out that the application signal has an upper  
>>> bandwidth of only about 150Hz, so the 10kHz amplifier response is  
>>> way overkill. The point is that at 150Hz, I want very low phase  
>>> shift for a servo loop, so the wide band amp relative to the application is warranted. (Actually, perhaps  
only about 3kHz might  
>>> suffice).

>>

>> With a controller designed to bring the LC LPF poles where they would  
>> help form a traditionally design, controlled phase–delay filter, I  
>> expect the difference between your desired passband and the switching  
>> frequency will make it an easy job.

>

> Hmm.

Having sketched a quick root–locus for this, I am still convinced. I have two complex poles in G, near the imaginary axis, and two zeros in H near the real axis and about as far from the origin as the LPF poles. (And some poles way to the left to make it realizable.) With the right loop gain, the poles move to the left and around the zero pair, ending up just about wherever they are most useful for that controlled delay filter I mentioned.

What kind of DC accuracy do you need? Can gain variation induced by 80V supply variation be handled by an outer loop? Or does this power amp have to have very tight gain and offset specs? (Until it appears necessary, I hesitate to add a pole at zero just to reduce maybe tolerable error.)

>>> However, for more academic purposes I am still curious about what

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>>> other approaches other than an equalizing network one might try to  
>>> solve the reactance problem? It seems to me that one approach  
>>> might be to try to sense the PWM output post-filter, and then compensate for the peaking within the  
PWM amplifier control loop.

>>

>> Glad you are open to this.

>>

>>> Is this typically done?

>>

>> I don't know about typical. I've done exactly that for a system with

>> much less separation between the intended signal band and the

>> switching frequency.

>

> That's a good sign.

That was a bit of a challenge, but your task is  
enough easier that I wanted to offer that  
encouragement.

>>> I am as of yet unable to do this, because my AC model for the PWM

>>> amp power train is inadequate. I am aware of the state space averaging and other models which correctly  
predict the presence of

>>> a right plane zero in these circuits.

>>

>> The simple PWM with bridge does not have the RHP zero and its

>> response is quite consistent as long as the initial filter inductors

>> do saturate and the input supply is relatively stable.

>

> Saturate? Why would we want that? Perhaps you mean "don't saturate?"

Yes. (I don't know why proof-reading is so hard.)

> They will be designed to hold up at least 75% of their inductance to 10A.

Gapped parts would do better. If the open-loop  
response can be kept more predictable, it will be  
easier to control the close-loop phase delay. The  
LC poles do not have to be kept so far out.

>>> I think I need to be able to understand this and be able to compute

>>> the correct model for my PWM amp before I can attempt designing the

>>> correct loop compensation.

>>

>> The response is very simple. The transfer function is a constant

>> once the switching frequency is taken out. Write a few expressions

>> for the steady state DC output versus duty cycle and see for

>> yourself.

I should have said "for the quasi-steady-state from  
one cycle to another". The DC case is trivial and  
not of much use for a transfer function. The method

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I prefer, for fixed switching frequency, is to analyze cycle to cycle increments as a function of duty cycle and translate those to equivalent derivatives.

- > Yes, I have already done this. Quite a while ago I did a sim where it seemed things \*didn't\* work with this model, but did work
- > in reality. Kind of backwards from what usually happens. I thought because my AC model was missing the RHP. Perhaps you are
- > correct.

As long as the H-bridge switches are always on, either one way or the other, (and the inductor is constant!), it really is that simple. You can think of the bridge as simply a "DC" signal with some AC on it. (There is also a delay, on the order of a partial cycle, but that can be ignored when you are willing to filter off the AC anyway.) The "DC" part is just the mean as affected by duty cycle.

- > Now the other day I discovered that maybe my model wasn't so broke after all. I haven't pursued it very thoroughly because I knew
- > I could get away with a simple integrator and "turn the knobs until it works" design based on the simple topology in Apex's app
- > note AN33.

Two poles near the imaginary axis plus one at 0 is a formula for something that either oscillates or is very poorly damped.

- > But I hate to design things that way. Like I said, we need a result and I have already gotten burned once in this project for
- > spending too much time making sure things worked theoretically, while some other guy just empirically tinkered his way to a
- > working result (that's referring to the outer control loop in which this amplifier will fit).

I'd like to see him empirically stabilize a rocket.  
(But from quite a distance.)

>>> One possible advantage of post-filter PWM amp output voltage  
>>> sensing and control might be to eliminate the overshoot inherent in  
>>> the output filter (or I suppose the filter might be damped down to  
>>> a Bessel response as well).

>>

>> Yes.

>>

>>> It seems problematic that the output filters for a PWM amp must be  
>>> tuned to the load impedance, and if there is substantial load reactance, that additional compensating  
measures must be taken

>>> which either waste power or complicate the compensation required.

>>

>> That would depend on how far the poles are moved by the controller

>> relative to the variation in their open loop positions due to load

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>> variation. I do not see an inherent problem, depending on your final  
>> accuracy requirements.

>

> I need to spend some more time with pencil and paper to understand how the controller can "move the poles" of the filter. I think  
> you mean that the closed loop transfer function will have it's poles not in the same place as the open loop right?

Yes. As long as there is some loop gain, the poles are shifted from their open-loop positions.

> So far I haven't dealt with any cases of having complex poles in the open loop, so this is virgin territory.

That's were it becomes fun. With a few more answers, I am inclined to simulate a controller and idealization of your plant.

>>> Maybe linear amplifiers are not so bad after all. I tend to prefer  
>>> them since they are ripple free, but in this case I opted for the  
>>> PWM amp because 4 channels must fit along with 1200W of power  
>>> supplies, and bunch of other CPU type electronics in a 7" high rack  
>>> chassis. That just didn't seem feasible or power efficient with  
>>> linear amps.

>>

>> Given your requirements, PWM with appropriate feedback and control  
>> seems like a good choice.

>

> Yes, a linear amp would have needed water cooling to fit in the desired package.

>

> Thanks for the input.

>

> Good day!

You're welcome, and likewise.

—

—Larry Brasfield

email: donotspam\_larry\_brasfield@xxxxxxxxxxxx

Above views may belong only to me.

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• *Follow-Ups:*

◆ *Re: PWM Amp Design*

◇ *From:* Larry Brasfield

• *References:*

◆ *PWM Amp Design*

Re: PWM Amp Design

◇ *From: Chris Carlen*

◆ ***Re: PWM Amp Design***

◇ *From: Chris Carlen*

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