A Class D AM Transmitter for 75 Meters

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2.26.2012

What started out as a curiosity about whether transformer coupled AM was feasible with solid state amplifiers, turned into a bit of a bigger project. I had heard some say that it's not practical to do high level modulation of solid state amplifiers with a transformer because of the low modulation impedance. As I happened to be looking around the shack I remembered I had a 1000W 50Vdc power supply that is based on a toroidal 60Hz transformer. I decided to evaluate the suitability of the transformer for use in an amplitude modulator. If practical and reasonable audio bandwidth could be realized, I thought this would be a good platform with which to build a high efficiency legal limit AM transmitter. The design goals were as follows:

- High enough efficiency to operate the RF Deck and the Modulator from a standard 120Vac 15A outlet
- Use an off-the-shelf high efficiency audio amplifier as the audio source for the modulator

Background:

Solid state RF power amplifiers typically have a very low modulation impedance due to their relatively low power supply voltage. Typical RF power devices generally operate from supply voltages in the range of 13.8Vdc to 50Vdc with few exceptions. The modulation impedance is calculated by simple ohms law, Vdd/Idd. For the case of a typical linear 1kW RF module operating from 50Vdc this works out to 1.66 ohms.

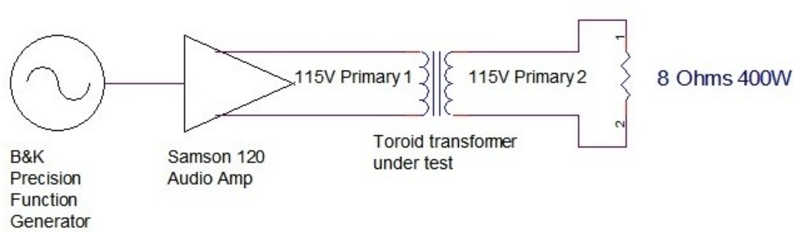
Such a low impedance would be impractical to match with a traditional modulation transformer intended for tube transmitters, and most audio transformers in general are simply not suited for such high current. Also, transformers constructed with laminated electrical steel cores require careful design to achieve bandwidth into the audio range beyond a kHz or even less.

Transformers used in 400Hz aircraft power applications are frequently wound on toroidal cores. For the sake of efficiency these cores are typically “tape wound” where a single continuous thin flat strip of high silicon electrical steel is coated and rolled up like a roll of tape and potted to provide a smooth winding surface. For this reason I decided to test the frequency response of a high power tape wound transformer, similar to those used in high end audio gear. One such transformer is rated for 1000 watts continuous duty with “generous overload margin” in its conservative ratings, available from Antek (not to be confused with the computer power supply company Antec). Various models from low power to 1500 VA can be purchased at www.antekinc.com.

The transformer model tested and used in the transmitter is AN-10440 which is available for about $100. Construction quality on these transformers is superb.

Test:

The best way to test for frequency response is while loaded with the approximate intended input and output impedance, to ensure accurate measurement. The test setup is shown in the following diagram:

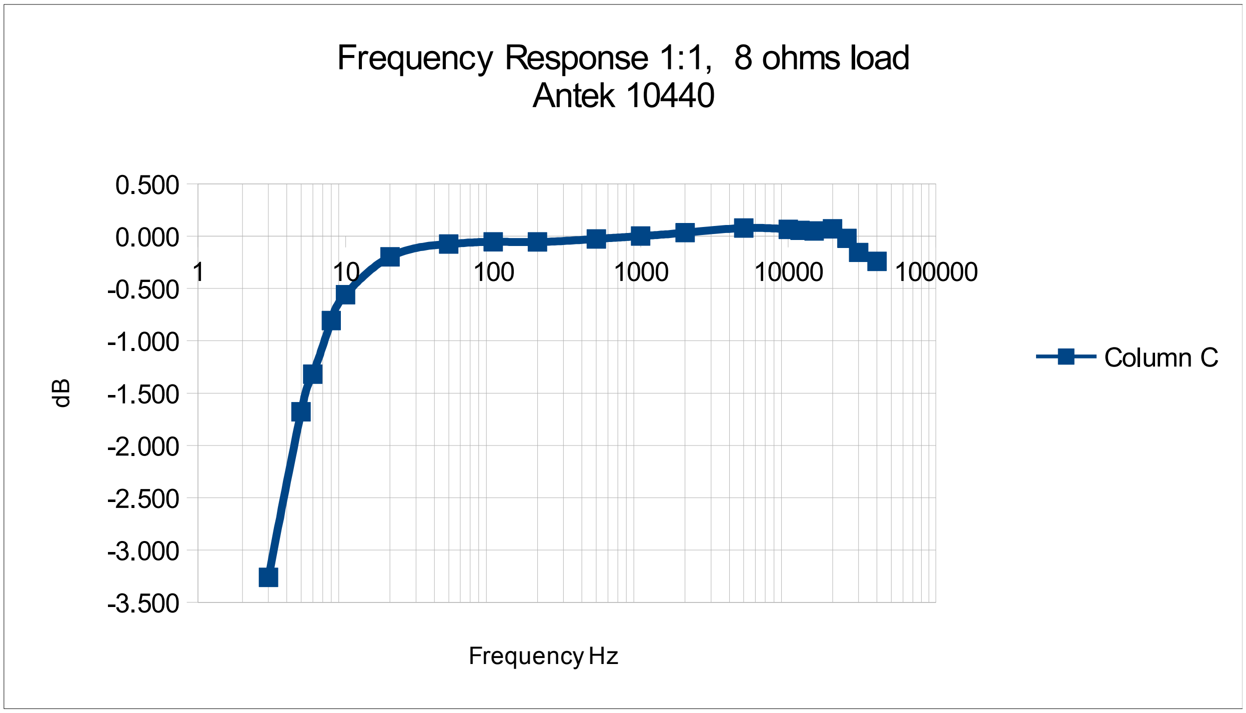


Test Setup Diagram

Voltage and frequency were measured across an 8 ohm audio load resistor, and the transformer under test was driven by a 120 watt audio amplifier in bridged mode.

Results:

The results are surprisingly good. The chart below shows the frequency response measured. Measurements were normalized to 10Vac RMS across the load at 1000Hz.



This transformer is absolutely flat to over 20 kHz and the -3dB point is 3.3Hz on the low end.

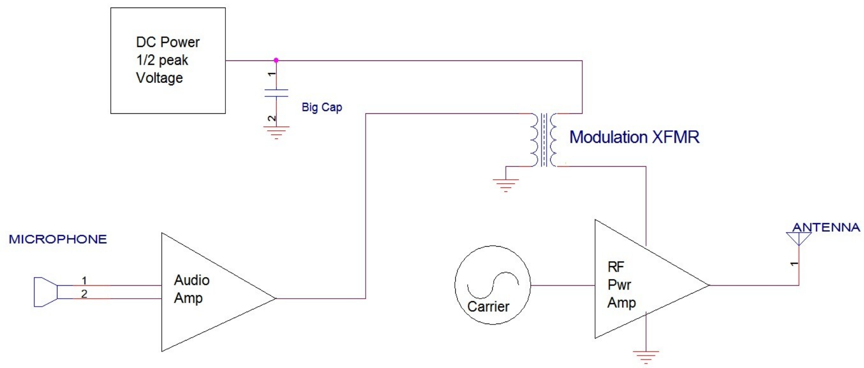
Application:

This test supports the possibility of using off-the-shelf high power audio gear with low impedance output, as the audio source for modulation. Bear in mind the average audio power needed is still 50% of the average carrier output power of the transmitter, so a monstrous audio amplifier is needed for 100% modulation of a 1.5 kW transmitter.

While any audio amp with the necessary output capability could be used, for any reasonable efficiency the audio amp should be a Class D type since they are nearly 90% efficient from the AC plug to audio power delivered.

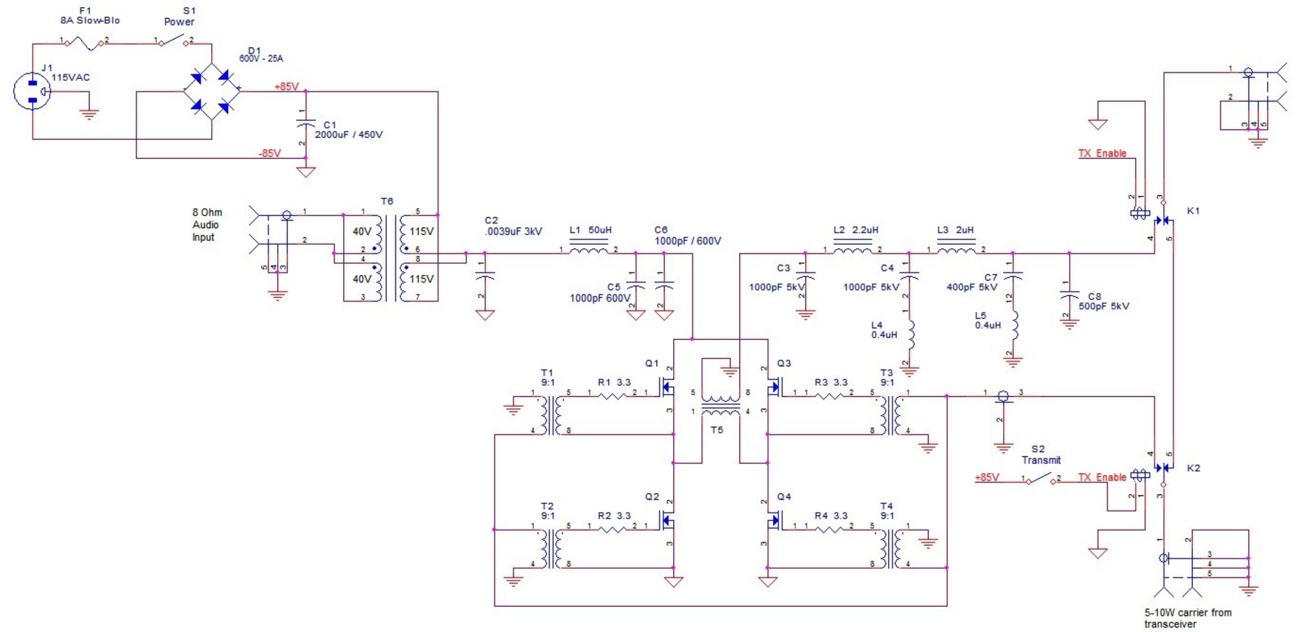
Much has been written about Class E RF amplifiers and there is quite a large contingent of active users on the air presently. Class E was considered for this design but ultimately Class D was chosen for the RF deck. As such the details of Class E are outside of the scope of this paper. A simple Google search will bring forth much info on this subject.

The ideal RF stage to use would be running Class D or E for efficiency, but also because it can be run at much higher voltages than typical specialty RF transistors can tolerate. For example, a 1kW Class E RF amp for the low bands running at 160 Vdc (straight rectified 120Vac line) can be built with cheap and readily available power FETs[1, 3]. With Class E however, the FET maximum Vdd must be rated at 4x the supply voltage for reliability, so when considering operating a Class E amp above 150V, there are very few device choices with sufficient voltage rating. Many builders end up using lower supply voltage and pairing many FETs to handle the current required. With a Class D "H-Bridge" configuration however, device Vdd_max can be up to the maximum Vdd value the devices are rated for without consequence. Ideally you would use devices rated at 1.5x the peak supply voltage under modulation or more for safety margin and good engineering practice. The down side of Class D is, it is an untuned amplifier and requires an aggressive low pass output filter due to rich harmonic content. The upside to Class D is, it may be possible to get two or three bands out of it without the careful tuning Class E stages require to maintain the efficiency sweet spot. A typical AM transmitter topology diagram employing an external audio amplifier with transformer coupling is shown below.



Let's look at some numbers for a Class D RF stage running at 320Vdc (peak under modulation), assuming 1.5kW PEP output and 83% efficiency. The modulation transformer secondary would need to carry only 5.64 amps peak. This puts the modulation impedance at 56 ohms. The impedance ratio of a transformer is the square of the turns ratio. The voltage ratio is equal to the turns ratio. To properly load the audio amp at 8 ohms the impedance ratio needed is 7:1 or a turns ratio of, $\sqrt{7}$ or 2.64:1. Since our transformer has 115Vac windings a 2.64:1 ratio would mean 115 / 2.64 = 43.28, so a 40V winding would be pretty close. It will be operated in step up and the audio amp would feed the 40 volt winding and the 115V winding would carry the DC for the RF stage and provide the requisite 56 ohms. This Class D RF amp would require a no-modulation signal supply of 160Vdc at 2.82A. This suggests the carrier output would be 374.4 Watts at 83% efficiency.

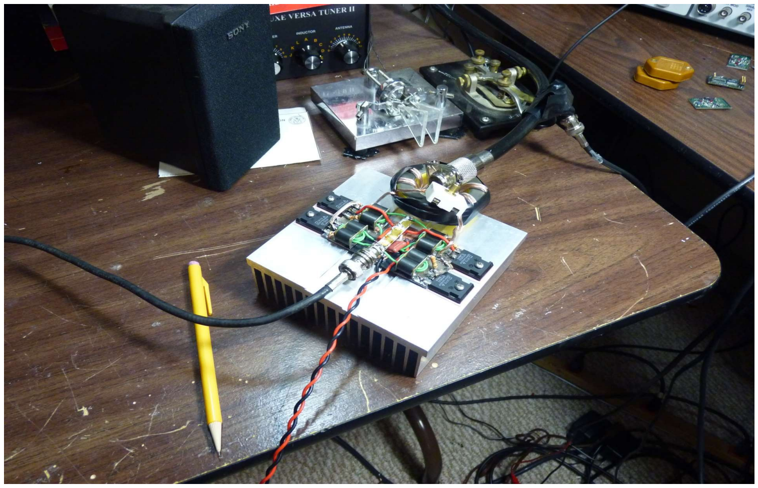
It seems clear that a Class D stage running at a modulated peak of 320Vdc, and 160Vdc dead carrier would be the right choice. The schematic for the Class D amplifier is shown on the following page.



Amplifier Design:

In this amplifier, four devices[1] are used, costing $4.12 ea. They are rated at 500V and 16A maximum, and use the TO247 package. The gate capacitance of these is about 2600pF. While “logic level drive” could be implemented using gate driver ICs, optical isolators, and isolated power supplies for the high side gate drivers, it was concluded that 9:1 ferrite loaded broadband transformers would greatly simplify the design eliminating the need for isolated high side power supplies. The other advantage of step down driver transformers is, it makes the amplifier less sensitive to damage from inadvertent overdrive. The gates on these FETs will tolerate +/- 40V without damage, yet only 10V is needed for full saturation. Even though the input VSWR is very high with 9:1 gate transformers, at only a few watts drive from a 100W transceiver this high VSWR is of no consequence to the transceiver. Broadband driver transformers are readily available from suppliers that carry parts for solid state RF amplifiers. I used RF400-77-9 types from Communications Concepts Inc[2]. They are under $5 each. The output transformer is wound on a T225-6 powdered iron toroid of mix #6.

From the modulation impedance calculation above we get 56 ohms modulation impedance. With an H-Bridge, this is also the output impedance so a 1:1 output transformer is appropriate. I had some 14AWG speaker type zip cord and wound 12 turns on the 2.25” diameter core. With 1000pF across the output side of the transformer to cancel the leakage inductance, I made some efficiency measurements at 160Vdc from straight rectified AC line voltage. This was possible without any isolation transformer because both the RF input and output of the amplifier are isolated with RF transformers. Without any low pass filter, more than 90% drain efficiency was achieved at 3.88MHz, and 95% drain efficiency at 1.88MHz. Approximately 5W of drive was necessary to drive the devices to saturation, and output was 375 Watts carrier on 75m, and 400 Watts on 160m. A picture of the RF Deck measuring 5” x 5” x 1.7” appears on the following page.



RF Deck

Integrating the modulation transformer and mounting everything in an old audio amplifier case was not too difficult. A picture of the nearly complete transmitter is shown below.

Transmitter Assembly

Low Pass Filter:

One challenging aspect of this was my efforts to realize two band operation, both 160m and 75m. I modeled and tested several low pass filter designs attempting to include a trap at 5.64MHz, serving the dual purpose of suppressing the 3rd harmonic of 160m and providing a sharp cutoff above 4 MHz for 75m operation. While I was able to design a filter that met these requirements, I was not able to locate enough surplus transmitting grade capacitors. I tried paralleling several smaller value “pulse rated” 1kV polyester film caps, and they worked well until modulation was applied. Ultimately after 6 revisions and many blown caps, I decided that 75m was sufficient for now. I was able to find a configuration based on the available values of molded mica transmitting caps I had on hand to realize efficient operation on 75m, without risk of over-current in the caps. In fact the low pass filter was more difficult than the rest of the amplifier. All spurs and harmonics are now better than -50dBc on 75m, however the 3rd harmonic of 160m with this filter is -40dBc which is illegal. The requirement is all spurs and harmonics must be >-43dBc. So it will not be operated on 160m until the correct parts are installed and retested.
The T/R switch is made from two Omron 16 amp relays with 120Vac coils. I am running them on the raw 160Vdc supply and they work fine, the coils do not over-dissipate.

The Audio Amplifier:

I originally bought a Behringer EPQ1200 audio amplifier for use as a modulator with this rig. When it arrived I did some initial bench testing on it and found some issues. That amplifier is a Class H type with switchmode power supply. That design is the best of both worlds in that it operates Class AB except that when approaching saturation, the power supply is increased as necessary to avoid clipping and distortion. I measured the output at 685 Watts RMS at 8 ohms which was sufficient for the job, however during bench testing I realized the cooling fan was inoperative. After doing more testing at medium power CW causing the thermal protection circuit to kick on, the fan never did, and after several conversations with the national service manager for Behringer we determined this one was defective, and it was returned. I will say working with the service manager and generally all interactions with Behringer was an excellent experience and I would nonetheless strongly recommend their products.

But the quest here was for efficiency as well as high quality audio. As such, I purchased a Crown XLS1000 Class D amplifier. While it has slightly less output it is still more than sufficient for the task. The Crown has proven to be extremely rugged, as I was to become very thankful for in final testing of the whole system.

System Testing:

There are a couple of characteristics of this topology I did not anticipate in the design. The first is a very large power spike appearing at the modulation input that occurs when carrier drive is cut. The drop in the current in the primary of the modulation transformer is effectively stepped down and delivered to the audio amp input winding. This spike has kiloJoule level of energy due to the very low DC resistance of the modulation transformer windings. Concerned for my new audio amp, I found I had to roll off the carrier drive from my Kenwood TS930 transceiver with the carrier adjust pot rather than just turn off the send switch. While this eliminates the spike it does reduce operating convenience.

The second unforeseen characteristic is the saturation characteristics of the modulation transformer. This core begins to saturate just as I hit 100% modulation because it is trying to drive the intrinsic body diodes in the RF deck FETs into conduction as Vdd tries to go negative. That causes a rapid nose-dive in the load impedance presented to the audio amplifier, and it would regularly trip the protection circuit. Thank you Crown for designing an amp that can survive a full power load dump going from about 8 ohms to 0.05 ohms (the DC resistance of the 40V windings) over one cycle! At first this problem appeared to be a showstopper. I was concerned that this design could never see 100% modulation. Then I had the idea to put a 4 ohm 200W load between the amplifier and the transmitter, so that when the 100% modulation occurred the audio stage would see a jump from 12 ohms load to 4 ohms instead of a dead short. While it wastes some of the audio power in the load, this has proven to be an effective solution. It also solves the spike problem, limiting the spike energy applied to the audio amp output when the drive carrier is cut going from transmit to receive.

On the air testing so far has resulted in very positive reviews of the audio quality. It is of course essential to control the audio bandwidth of the signal going in, since this transmitter can easily produce a 30kHz wide signal. Also, much was done in eliminating EMI to my stereo system upstairs after I got nice clean audio reports from my wife Deb while she was upstairs trying to watch TV.

The next phase of development will be to implement some form of linearization through either EER or outphasing or some combination of existing techniques, except with emphasis on keeping it simple and low cost.

Acknowledgments

I must tip my hat to Bruce Franklin, K7DYY[4] for inspiration on this project. While I have done several things differently than his designs to accommodate the goal of using off the shelf audio gear, Bruce has done a superb job on his design and construction of his AM transmitters. I have heard many of them on the air and they work extremely well and are of tremendous value. His use of the concept of isolating the RF and not needing an isolated power transformer, provided some of the inspiration to build this transmitter.

I would also like to thank Horace N1HC for donating the transmitting caps, Mike N1FBZ, Dan N1FYL, Bob W1FP, Doug KB1PJM, Brian WB2JIX, Joe KZ1J, Bob W1ICW, Ben K1AUE, Les W1UT, and Joe WB8DNO without whose contributions, encouragement (and tolerance) from all, I would not have finished this phase of the project.

[1] *IXFH16N50P data sheet: http://ixdev.ixys.com/DataSheet/99357.pdf*
[2] *RF400 driver transformers: http://www.communication-concepts.com/prod02.htm*
[3] *"A Quick Build 75 meter Class E transmitter" WO1U November 2010 http://hrselectronics.com/amtx/amtx.html*
[4] *http://www.k7dyy.com/*