Tank Design and Overload Protection for Switch Mode / Class D LF Transmitters

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The old Decca LF transmitters had a novel protection circuit that prevented damage if they were operated into any mismatched load. The technique described is applicable only to this type of class-D voltage source switch mode transmitters that employ a series resonant tank circuit. (Class-E designs seem to do a particularly good job of looking after themselves)

I use this protection method in my 700 Watt 137kHz transmitter [1] and it has proved extremely reliable, allowing considerable abuse of output load, including short circuit, open, wrong frequency operation and repeated use of a make-before-break switch as the output transformer tap selector , switched live and hot at full RF power!

A Recap

The switch mode transmitters used by many of us have a generic design of output stage a bit like that shown in Figure 1. A pair of FETs are switched alternately between the supply rails to deliver a square wave into the load resistance. A series tuned tank circuit selects the fundamental and returns unused harmonic energy back to the supply. Efficiencies of 75% to 80% are readily achieved from either half bridge or full bridge configurations. Full bridge gives a doubling of the peak –peak voltage into the load. The power delivered is defined completely by the load resistance and supply voltage; the latter sets the peak or pk-pk of the square wave generated. An output transformer then transforms this load resistance to that required by the antenna or feed arrangement

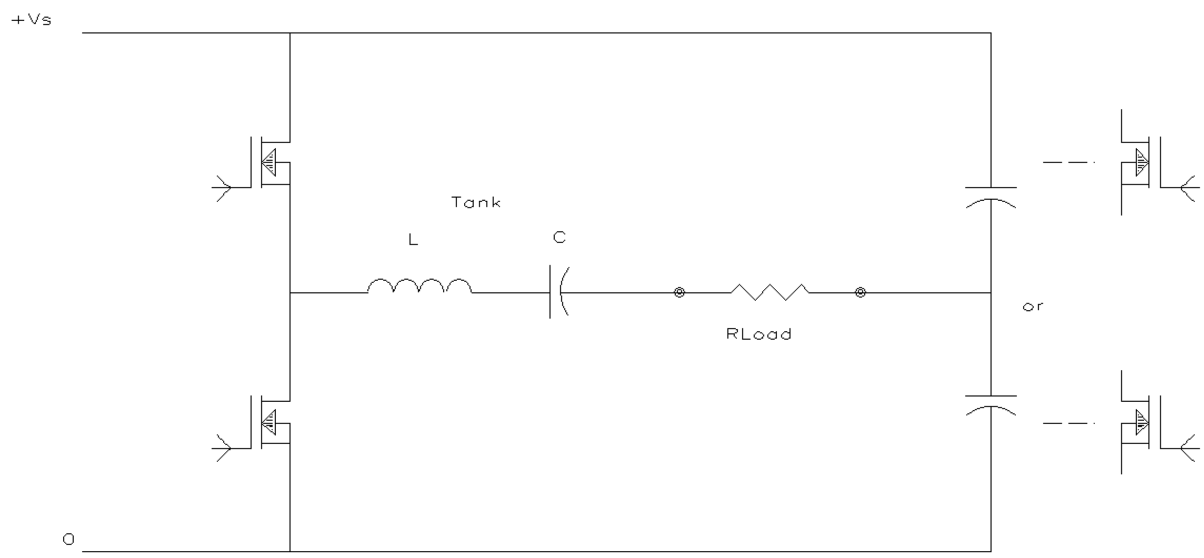

Figure 1 Typical Switch Mode Transmitter Output Stage

Another popular transmitter configuration has a pair of devices and a centre tapped transformer to give push-pull operation. The transformer serves the dual purpose of impedance transformation as well as push-pull balance. If such transmitters are followed by the same type of series tank to give the filtering then the technique described here can probably be adapted to suit, but it has not (to my knowledge) been tested on this transformer coupled type of PA.

Tank Circuit Calculations

The series tuned tank has to pass the fundamental components and reject the harmonics of the drive waveform. The values of the inductor and capacitor are selected based on the load impedance. Typically a compromise Q of around 6 is used. This means the reactance of both C and L in the tank is six times that of the load resistance, and means that Q times the output voltage voltage appears across each component. Choosing the Q value is a compromise. Higher values of Q give better rejection of harmonics but result in higher voltage and increased losses (mostly in the tank coil). Lower values give reduced harmonic rejection. A value of 6 appears about optimum in this position.

One thing to remember in calculating values for such designs is the equation for the amplitudes of the sine components making up a square wave:

$Vn = 4/\pi * \{ SIN(F) + 1/3\ SIN(3.F) + 1/5\ SIN(5.F) + \ldots 1/n\ SIN(n.F) \}$

So the peak value of the fundamental is therefore 4/ π or 1.273 times the amplitude of the input square wave. This ***modified value of Vpeak must be used*** when calculating a suitable load resistance for a specific power output. The RMS value for power calculation is then 4/π /√2. Which all works out at the rather convenient and remarkably close approximation:
$V_{RMS} = 0.45 * V_{SUPPLY}$ (0.9 for full bridge designs)

Worked Example:

Supply voltage = 200V, half bridge configuration for 200 Watt power output.
Square wave amplitude = 200V pk-pk or 100V peak
*Equivalent fundamental sine component = 0.45 * 200 V = 90V RMS*

R_L for 200W from 90V RMS, $P = V^2/R$, so R = 40.5 ohms
*For a loaded Q of 6, both L and C must have a reactance of 6 times this, or 243Ω each. At 137kHz this corresponds to 4780pF and 282µH respectively. The voltage across each component at resonance is about 6 * 90 = 540V. The current flowing in each is simply V_{RMS} / R_L or 2.2A*

Protection

Such a switch mode design, essentially a voltage source, can be damaged very quickly and spectacularly when excess current is drawn – such as when its output is shorted. The tank makes the damage potential even worse, since a reduction of load resistance leads to increased Q with its inherent voltage multiplication. The high resulting voltage further damages components. A make-before-break switch used to select taps on an output transformer can wreck havoc too (been there, done that !) Note also, that a low pass filter can transform an output open circuit into a short at the transmitter, or into some other complex impedance. A unprotected switcher output stage is clearly a major liability.

The Decca transmitters overcome this by adding a link winding, closely coupled to the tank coil. A series capacitor C1 broadly resonates with this , although the Q of the resulting resonator is extremely low, often below unity. The output from the link winding is full wave rectified with the output from this connected to the power supply rails. The full arrangement can be seen in Figure 2.

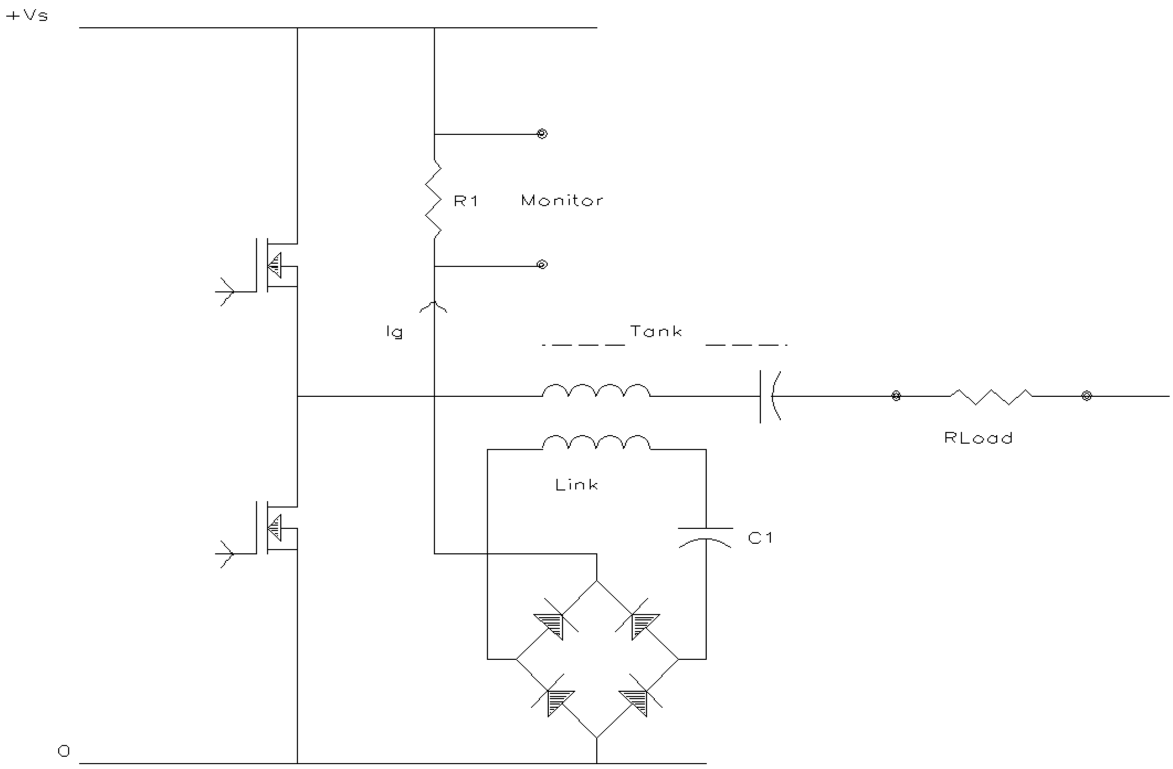

Figure 2 The Decca Overload Protection Circuitry.

It works as follows: At maximum output power, we know that the voltage across the inductor is Q times the rms. voltage across the load. Imagine the auxiliary winding over the tank coil were a perfect transformer. The voltage output from the link winding is therefore proportional to the Q-multiplied value, modified by the turns ratio which we will call N:1 (step down) When rectified, the resulting DC is near enough the peak, or √2 times this. We now select N so that at full output power the resulting rectified DC is exactly equal to the supply voltage. Ignoring diode drops, this is given by :

$$Q * 0.45 * \sqrt{2} * V_{SUPPLY} / N = V_{SUPPLY} \quad \text{or} \quad N \approx 0.64 * Q \quad \text{(1.27 for full bridge)}$$

If any attempt is made to draw more current, by lowering the load resistance, this voltage will try to rise. But since it is clamped to the supply it cannot possibly go any higher. So instead it drives current backwards, offsetting that input from the power supply and forcing a constant power draw. The result is to limit the maximum current drawn from the PSU to the design value and the devices and components are now protected from overload for any actual load resistance that may be presented.

Practicalities and Setting Up

A real tank coil is usually a large air wound inductor. Secondary windings on such coils never have 100% coupling – there is always some leakage, meaning more turns are needed on the link winding. It can't be calculated precisely, so adjustment and setting up is needed at the build stage. Start off with something like twice the number of turns the calculation suggests should needed for 100% coupling. Make sure the link is a decent over-wind to maximise the coupling that is achieved.

The capacitor C1 in series with the link winding serves to remove any residual inductance that may upset the rectifier. Its value is not particularly critical, and ideally will resonate with the link inductance. But as it can only come into play at the onset of overload, its effect is particularly difficult to see, and Q will be very low indeed. The link winding will affect the inductance of the main tank slightly – it is close-by metalwork after all – but the effect is barely significant.

To avoid the very damage this arrangement is designed to prevent, setting up must be done with a current-limited and / or reduced-voltage PSU. Use an adjustable load (any switch - tapped transformer ultimately intended for output matching can be useful here). Use the voltage dropped across R1 in Figure 2 to monitor the current from the protection circuit. This is called the guard current or I_G. Reduce the value of load resistance below the design value, looking for the onset of I_G . Any current at all means the protection circuit is starting to operate. Reduce (or increase if you're unlucky) the number of turns on the link winding until I_G only appears when R_{Load} is reduced below its design value; or a value you consider to be an acceptable overload during operation.
And that should be it...

Run at full power and tentatively and progressively overload the output – make sure the DC input power stays reasonably constant. Take a deep breath and short the output. All should be well (I did this - it was) and that's it.

In my 700 Watt transmitter, with a Q of 6, the optimum turns ratio ended up close to 4:1. The theoretical value should be $6 * 0.64 = 3.84$, which does suggest the coupling is reasonably tight.

In the final unit, the voltage across R1 could be monitored with an LED, such as the one in an opto-coupler to give DC level shifting, to provide a warning of any guard current.

Transformer Coupled Push Pull Stage

A transformer used for push pull output is always associated with load matching, so this type of PA stage does not lend itself to incorporation of a series tank in the conventional place. However, there is no reason why a tank shouldn't be used on the output of the transformer instead of the usually specified Pi or T low pass filter. In which case the same concept of an overwinding generating guard current could be used.

But now calculation (estimation) of the overwinding is made more complicated. The turns ratio of the push-pull transformer comes into the equation as well as Q. Most practical amplifiers with this topology will probably run from a low supply voltage, so the rectified voltage developed from the link will have to be that much lower – and deliver a higher guard current. Thus the number of turns on the link will be fewer, N larger. Coupling will not be so tight with fewer turns, possibly making it more difficult to set up. This may not be a problem, but only building and experiment will prove things.

[1] http://www.g4jnt.com/137tx.pdf Published in QEX Nov/Dec 2002