An Envelope-Tracking Transmit Array Amplifier

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Introduction

Modern MRI pulse sequences demand high-fidelity RF transmit reproduction at multi-kilowatt power levels. Typical MRI power amplifiers are Class-AB architectures which excel at predictable linear performance, yet become inefficient when operated at less than their peak power. The simultaneous competing demands of high linearity and large peak-to-average power ratios common in MRI transmit pulses present a design challenge for RF amplifiers, and has spawned interest in alternate approaches such as Kahn Envelope-Elimination and Restoration (EER) [1] and its Class-E [2] and Current-Mode Class-D variants [3]. We present an envelope-tracking linear RF power amplifier system to explore the potential efficiency gain and performance impact of this method in the context of MRI transmit arrays.

Theory

A linear RF amplifier operates by delivering current at radio frequencies from a DC source to a RF load (eg. 50Ω). The resulting voltage swing in the load yields delivered power, while the voltage differential remaining in the amplifier must be dissipated as heat. Thus, an RF amplifier operates with maximum efficiency at maximum output, when it fully utilizes the available DC supply voltage, minimizing its own dissipation. Envelope tracking seeks to provide the amplifier with a DC supply voltage that dynamically tracks requested RF output power, thereby reducing dissipation and increasing efficiency. MRI is particularly well suited to envelope tracking as RF Tx pulses are known in advance, and sequences require widely varying pulse amplitudes (consider large-tip FSE vs. small-tip SSFP).

Methods

Our envelope-tracking RF amplifier system (Fig 1) is composed of a 200W Class-AB linear RF amplifier, a pulse-width modulation (PWM) controlled power supply, and a Medusa MR console to coordinate RF and envelope tracking operations. The 50V 25A PWM stage is a synchronous switching power supply architecture operating at 30-200KHz using an Intersil HIP4081 gate driver and Fairchild HRF3205 MOSFETs followed by an LC low-pass output filter. The PWM stage produces a modulated 10-30V DC supply for the 200W amplifier (Fig 2) – a minimum of 10V is maintained to keep the RF amplifier biased for operation. Notably, no gating is required for the power stage since it can be shut down by reducing its DC supply to a standby level or to zero.

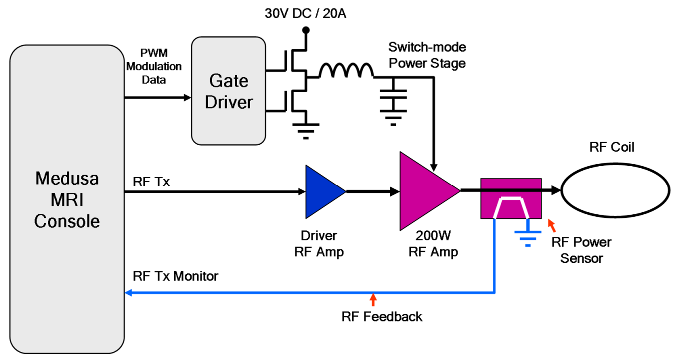

Figure 1: The 200W RF power amp is supplied with DC power from a switch-mode power stage whose voltage output dynamically tracks RF power demand to minimize dissipation in the amplifier. A Medusa MRI console is used to synthesize the RF and digital PWM control, as well as to monitor the output.

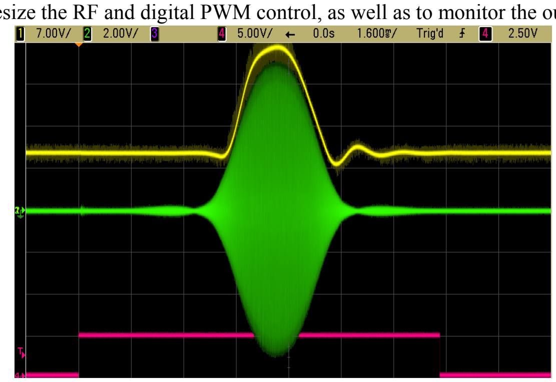

Figure 2: The envelope of a 180W RF sinc pulse (green, center) is tracked by the PWM-modulated DC supply rail (yellow, top) raising the supply voltage of the amplifier from 10V to 28V only as needed for higher power.

Results

The linearity and phase response of the RF amplifier with and without envelope-tracking is shown in Figure 3, with little difference between the two modes. The efficiency improvement from envelope tracking varies with both pulse shape and amplitude, however for sinc pulses, preliminary measurements show DC power consumption reduced by 20-35% compared to operation at full supply rail while delivering the same RF output.

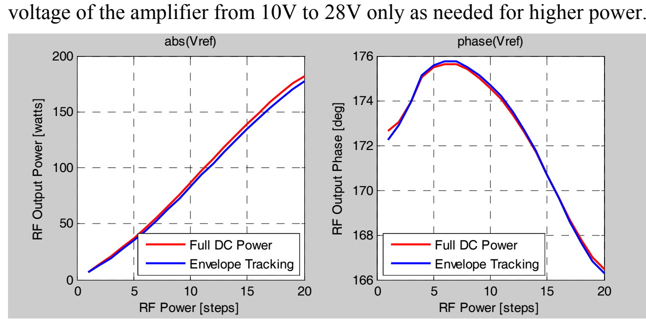

Figure 3: *Left:* As desired, the amplifier linearity response changes little with envelope tracking enabled (blue) vs. standard full-rail operation (red). *Right:* The phase response worsens slightly, potentially due to the varying bias experienced by the RF transistors. While these linearity/phase errors are correctable with pre-distortion methods, native amplifier performance is shown here to highlight changes caused by the envelope tracking method.

Discussion

A significant concern with envelope tracking methods is PWM switching-frequency leakage, exhibiting as unwanted AM sidebands on the RF. While MRI pulses are dynamic, they do not require the high-rate power modulation common in communications systems [4], nor the strict out-of-band suppression. As a result, the PWM low-pass output filter can be tailored to balance feed-through at the expense of modulation rate or efficiency. Additionally, with a-priori knowledge of the pulse, filter delays can be counteracted by time-advancing the DC supply envelope waveform. Another issue is the modulation of RF transistor capacitances (eg. C_{gd}, C_{gs}) by varying bias voltages present at device terminals, affecting the phase response of the amplifier. Indeed, we observe a small increase in amplifier phase excursion from +/-4.2 degrees on steady-state rails to +/-4.5 degrees when envelope tracking is enabled. The linearity and phase errors can be readily corrected using pre-distortion methods such as VIP [5], but this is not done here to avoid masking the true response of the amplifier.

Conclusions

We have successfully demonstrated envelope tracking on a linear Class-AB RF power amplifier while substantially preserving the amplifier response characteristics in linearity, phase, and output power. DC power consumption is reduced as much as 35 percent, significant considering power levels common in MRI. Future work will focus on determining the limits of efficiency improvement and scaling to higher power amplifiers (eg. 1kW peak).

References [1] L.R.Kahn, Proc. Inst. Radio Eng., 1952. [2] F.H.Raab ISMRM 19:1850 2011. [3] J.Heilman, ISMRM, 16:1097, 2008. [4] Shrestha, IEEE Soild-State Circuits 44,4:1272-80 2009. [5] P.Stang, ISMRM, 17:491 2009. Grant support: NIH R01EB008108, R21EB007715, R01EB005407.