A High-Efficiency Linear MRI Transmit Amplifier using Envelope-Tracking

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Introduction

Typical MRI power amplifiers use Class-AB architectures which excel at predictable linear performance, yet are exceptionally inefficient when operated under the large peak-to-average power ratios common in MRI pulse sequences. This inefficiency combined with multi-kilowatt RF power levels leads to high instantaneous heat dissipation in the amplifier with detrimental effects on performance, stability, and component lifetime. Alternate architectures such as Kahn Envelope-Elimination and Restoration (EER) [1] and its Class-E [2] and Current-Mode Class-D [3] variants have been proposed but can introduce linearity and spectral distortions unacceptable to MRI. Here, we consider the addition of envelope-tracking to classic linear amplifiers to achieve higher efficiency, reduced thermal memory effects and stress, and improved performance stability.

Theory

A linear RF amplifier must straddle the voltage drop between its DC supply rail and the RF amplitude delivered to the load. Power is dissipated in the amplifier as heat when current is delivered to the load across this voltage drop. Thus linear amplifiers operate with maximum efficiency at maximum output, when fully utilizing the available DC supply voltage and minimizing internal dissipation. By dynamically adjusting the DC supply voltage to track the requested RF amplitude in real-time (envelope tracking), the amplifier can be kept in a high-efficiency regime despite widely varying pulse shapes and amplitudes (consider large-tip FSE vs. small-tip SSFP).

Methods

Our envelope-tracking RF amplifier testbed (Fig 1) consists of a 200W Class-AB linear RF amplifier, a digital pulse-width modulated (PWM) power supply, and a Medusa MR console [4] to coordinate RF and envelope tracking operations. The 94%-efficient 50kHz PWM stage produces a modulated 10-32V DC supply at 25A capacity for the 200W amplifier – a minimum 10V supply is maintained to keep the RF amplifier biased for operation. A data acquisition system independently records delivered DC voltage and current in-sync with pulse playback to assess net DC power consumption (Fig 2).

Results

As seen in Figure 3, envelope-tracking has no negative effect on the raw linearity and phase response of the RF amplifier, and no 50kHz PWM spurs leak into the excitation spectrum. The efficiency impact of envelope tracking depends on pulse shape and amplitude, with Figure 4 showing comparative DC-to-RF efficiency for equal-area sinc and hard pulses over 20 steps from 5-100% amplitude. Efficiency is improved at all power levels, with ~3.5x gains observed for pulses at midrange amplitudes, translating into 15-40% reductions in amplifier DC power while delivering the same output. Results from voltage and current sensors corroborate that power reduction is obtained through lower voltage headroom while net delivered current over the pulse is conserved.

Discussion

A-priori knowledge of the MRI pulse sequence is a key advantage in envelope-tracking, allowing design-time computation of the DC supply waveform required to produce the RF pulse. This is critical for pulses with fast rise-times (hard pulses) where the DC power must be ramped-up in advance to compensate for filter delays and limited slew rate. While envelope tracking involves additional power supply and control complexity, it can be retrofitted to existing linear RF amplifiers and may reduce the need for complex thermal performance compensation. Moreover, it can provide intrinsic gating for the power stage by reducing the DC supply to a standby level or to zero as needed.

Conclusions

Our envelope-tracking linear Class-AB RF amplifier achieves substantial efficiency improvement while preserving amplifier response characteristics in linearity, phase, and power output. Future work will examine amplifier long-term thermal response stability and additional MRI pulse profiles.

References [1] Kahn. 1952. [2] Raab, ISMRM 2011. [3] Heilman, ISMRM 2008. [4] Stang, ISMRM 2007. Grants: NIH R01EB008108, R21EB007715, R01EB005407.

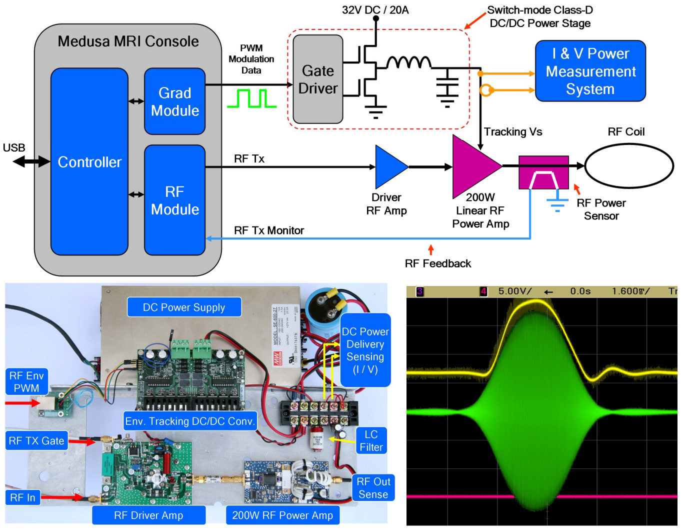

Figure 1: A functional diagram (top) and photo (bot) of our envelope-tracking testbed. The 200W linear MRI RF power amp is supplied with DC power from a switching power stage that dynamically tracks peak RF power demand to minimize dissipation in the amplifier. A Medusa console is used to synthesize the RF and digital PWM control, as well as to monitor the RF output quality.

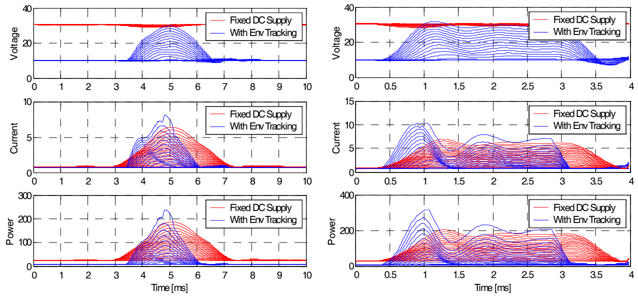

Figure 2: The DC voltage, current, and power delivered to the RF amplifier over the course of a sinc pulse (left) or a hard pulse (right). Voltage is envelope-modulated between 10V to 32V only as needed for RF delivery.

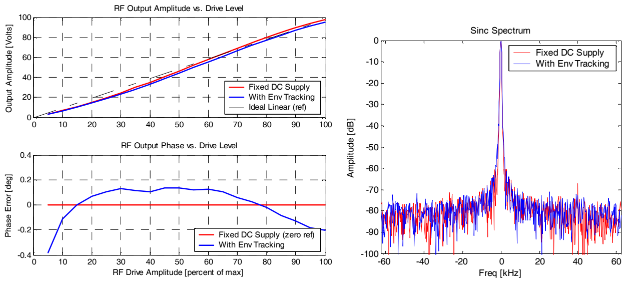

Figure 3: Amplifier linearity and phase response (left) and pulse spectrum (right) is little changed with envelope tracking enabled (blue) vs. standard full-rail operation (red). Phase response worsens by just +/-0.2 deg.

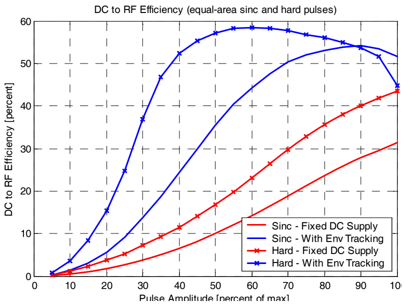

Figure 4: Envelope-tracking exhibits broad efficiency improvement (blue vs. red), with gains up to 3.5x when operating at mid-range power levels of 30-80% particularly important for pulses like sincs that deliver power over a range of amplitudes.