Introduction

RF power amplifier systems design is an exceedingly broad and complex engineering discipline. The goal of this tutorial is to identify the important architecture and design limitations relevant to MRI. All MRI pulse sequences assume that the RF power amplifier has high linearity, and maintains phase and amplitude stability over the entire pulse sequence duration. In typical pulse sequences, the time average power needs may be as little as 1-5% of the peak power requirements. Real RF power amplifiers have distortion, generate heat, and can suffer from various drift or memory effects. By the end of this presentation, the MRI pulse sequence or RF coil designer will have developed a more realistic understanding of RFPA operation. The following subtopics will be addressed:

RFPA Basics  RF power amplifier operation falls under a veritable alphabet soup of classes A, B, AB, C, D, E, F of which the A-B range refer primarily to linear but inefficient designs, and C-F are nonlinear but very efficient classes. It is one of the least appreciated mysteries of RFPA technology that simultaneously linear AND efficient power amplifier design goals are contradictory. We will introduce the basic model of the RF power transistor, including its intrinsic current source, nonlinear capacitor, and the concepts of load line match. This matching determines the optimum load impedance that allows the transistor to simultaneously swing through peak voltage and current, delivering maximum power to the load without device destruction. Amplifier output impedance, by comparison, is a much more nebulous and ill-defined quantity.

Nonlinearity and Memory Effects Depending on how a transistor is biased, amplifiers exhibit nonlinearity especially at low output amplitudes and as the gain compresses at the high power limits. These effects can be modeled by a static (time-independent) nonlinearity model. However, time dependent (memory) effects also exist. Semiconductor trapping, which occurs on the sub-microsecond time scale, is too short-lived to impact MRI, although it is an issue in wide-band wireless communications. Thermal heating of the transistor over the duration of an RF pulse occurs on the 100 us to ms time scale, creating a detectable temporal dependence. The envelope of MRI RF pulses creates large audio frequency current demands from the power supply which must be adequately bypassed to prevent indirect modulation of the transistor biasing. Indeed, certain RF pulses such as a rectangular “hard” pulse, demand infinite rise times in power supply currents, and are invariably distorted by the voltage rail linear systems dynamics.

Architectures for Linearity & Efficiency  High linearity and high efficiency tend to be mutually exclusive. Linearity can be improved simply by using higher bias currents, but this dissipates power. Since MRI is so narrowband, it is possible instead to apply narrowband RF feedback, or its quadrature input variant, Cartesian feedback. However, various closed loop stability criteria must be met, that must be tolerant to thermal drift and to coil loading changes. Instead, one can perform digital predistortion, which not only accounts for static nonlinearity, but can include behavioral models for thermal drift, such that predistortion weights can be updated in real-time. To improve efficiency several advanced architectures are feasible. In MRI, the Kahn Envelope Eliminate and Restore (EE&RI) has appeared in class E and current mode class D variants. Here, a high efficiency amplifier is only RF phase modulated, while the supply rails are modulated at audio frequency to vary output amplitude. Envelope Tracking (ET) instead uses a fully modulated input waveform, and also varies the supply rails but only to reduce the voltage headroom, minimizing power loss. In outphasing, or LINC (Linear Amplification by Nonlinear Components) two high efficiency amplifiers at constant RF amplitude, varying only in relative phase, are quadrature combined. Doherty designs switch in auxiliary amplifiers to artificially modulate the load, improving efficiency.

Power Combining  With solid state amplifiers, the maximum power a single transistor pair can control is now about 1KW through to 500 MHz. Given peak power needs reach 35 KW at 3T, multiple modules must be combined. This is achieved through quadrature combiners, or in phase combiners. Interestingly, transmit arrays represent a third form: spatial power combining. One critical issue is the impedance presented at the combiner output. If one uses quadrature combining of matched stages, the output impedance is ideally 50Ω. A similar result occurs at the output of a circulator. If 0 or 180 degree combiners are used, one ideally replicates the amplifier “output reflection coefficient”. Many experimentalists have mistakenly assumed a 50Ω resistor can mimic the output impedance in array testing, but this is true only for circulators and quadrature combined outputs.

Power Measurement  A very important issue is the tracking of RF power delivery. For very conservative estimates, one can simply track forward power, but this is wasteful. To correctly measure total power, a bi-directional coupler is needed. In the VHF to low UHF range, a very popular configuration is the the mono-match coupler, which employs two coupled lines, one on each side of the power transmission line. It is easy to show that transmission line voltage induces a common signal on both strips, but current induces opposite signals. From this, one can physically synthesize scaled versions of (V+ZoI)/2 and (V-ZoI)/2, namely forward and reverse wave amplitudes. These can be rectified by schottky diodes, but now a variety of vendors offer IC designs with log(Power) outputs.

Conclusions  MRI systems occupy similar frequency ranges to that of the broadcast bands, and can directly leverage the new high power transistors developed for FM radio and digital broadcast. In many ways, because MRI signals are so narrowband, this can simplify and make accessible linearization techniques, power measurement etc that may be more limited or difficult to implement in wider band applications. The topic of RFPA design is vast, with almost a century of research publications. For a basic introduction and further references [1,2] are very readable and offer excellent breadth into this fascinating discipline.

References: