Tuning the Output Impedance of RF Power Amplifiers with Frequency-Offset Cartesian Feedback

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Introduction: Coupling between coil elements of a transmit array is one of the key challenges faced by designers of MRI transmitter arrays. To address this challenge, methods and systems have been developed to change the output impedance of the RF power amplifiers driving the array coils in order to suppress inter-element coupling effects. Chu [1], for example, proposed an output-matching network to drastically lower the drain-source impedance of the power amplifier output transistor; in contrast, Kurpad [2] demonstrated the active rung concept to turn the amplifier into a very high output impedance device; similarly, Lee [3] developed a current source design to present the amplifier load with a very high impedance. All of these methods—and others—assume linear behavior of the amplifier (whereas power amplifiers can be non-linear) and have limitations such as the lessening of the power amplifier efficiency, the inability to accurately predict the exact value of the output impedance of the amplifier, or the impossibility of maintaining the latter constant over a wide range of output power. We propose the use of the Frequency-Offset Cartesian Feedback (FOCF) method and system [4] [5] to manipulate the output impedance of power amplifiers for MRI transmitter arrays predictably, inexpensively, and without hampering the efficiency of the amplifiers. Through simulations and measurements on both single amplifiers (with and without terminating circulator) and balanced amplifiers (all three shown schematically in Figure 1), we demonstrate the ability to predictably manipulate the real and imaginary parts of the series output impedance of the power amplifier from very low (~ 2 Ω) to very high (~ 500 Ω) values.

Material Methods: The simplest architecture of our FOCF system includes only a directional coupler at the output of a 200 W amplifier loaded by Z_L, which samples both forward (Vfwd) and reverse (Vrev) voltages, and a 0º or 180º combiner to either sum or subtract these samples before they are sent to the down-mixer of the feedback path of the FOCF transmitter driving the power amplifier. By summing forward and reverse voltage, the system controls the amplifier total output voltage (Vfwd+Vrev=Vtot) and creates a very low amplifier output impedance; by subtracting these voltages, the system controls the total output current (Vfwd-Vrev∝Itot) and creates a very high impedance It is also possible to use only the Vfwd sample as the control variable (Vfwd∝Vtot+Z_O·Itot), which results in the system creating an output impedance that matches the coupler Z_O impedance. Almost any other arbitrary value of output impedance can be obtained when two vector multipliers are integrated in the FOCF system,—between the directional coupler and a 0º combiner—one multiplier weighting the forward voltage sample, the other, the reverse. For each value of the complex constant K=β/α, where α and β are the coupler weighting factors of the combination α·Vfwd+β·Vrev, a unique value of the complex impedance of the power amplifier Zamp is obtained. The FOCF system with active modulators is shown in Figure 2. In addition to the FOCF transmitter, power amplifier, directional coupler, combiners, and vector multipliers, our system includes autotuning capabilities, a Medusa console [6], and the components of a load-pull setup [7], to automatically search for the stability conditions of the system, drive the FOCF transmitter, and measure the output impedance of the amplifier. The system is operated entirely via PC, using Matlab (for Medusa) and a GUI interface (for the vector multipliers). In addition to actual measurements of output impedance obtained for over 80 different values of K, we present the results of simulating the complex impedance of the power amplifier as a function of module and phase of K.

Results: Figure 3 shows a plot of the very high, very low, and nearly 50 Ω amplifier impedance versus output voltage obtained using the basic FOCF system (without vector multipliers) controlling Vtot (0º combiner), Itot (180º combiner), and Vfwd, respectively. Figure 4 is a Smith chart of the 80+ values of output impedance obtained with the vector multipliers before the 0º combiner. Each of the three contours is obtained by varying the phase of K while |K| is constant and equal to 0.4, 0.6, and 0.8. These impedance values were obtained with the power amplifier loaded by Z_L=56+j4 Ω. Here the maximum output power was 100 W; however, we successfully controlled the amplifier output up to its maximum rated power (200 W). Figure 5 shows the simulated module of K needed to obtain the desired real and imaginary part of Zamp, with 0≤real(Zamp)≤500 Ω and -500≤imag(Zamp)≤500 Ω. Note that |K|≤1, that is, real(Zamp)≥0 Ω, or the system will synthesize a negative resistance and become unstable. Simulations and measurements of Zamp match well for lower values of K (|K|≤0.5); at higher values, deviations from theory result from the open-loop impedance of the amplifier and the finite value of the loop gain.

Conclusion: We have demonstrated a FOCF method and system to manipulate the output impedance of the RF power amplifiers for MRI transmitter arrays. The output impedance synthesized by FOCF can have any value within a large area of the Smith chart, and is stable over the power range. In principle, since Zamp is tunable, any length of coaxial cable can be used between the power amplifier and transmit coil.

References: [1] X. Chu *et al.*, MRM 61:952–961, 2009; [2] K. Kurpad *et al.*, Concepts in Magnetic Resonance Part B 29B(2):75–83, 2006; [3] W. Lee *et al.*, MRM 62:218–228, 2009; [4] M.G. Zanchi *et al.*, "Frequency Offset Cartesian Feedback Control System for MRI Power Amplifier," Proc. 17th ISMRM; [5] D. Hoult *et al.*, JMR 171(1):64–70, 2004; [6] P. Stang *et al.*, "Experiments in Real-Time MRI with RT-Hawk and Medusa.," Proc. 16th ISMRM; [7] G. Scott et al., "A Load Pull/Hot S22 Analyzer for Transmit Array Amplifiers," Proc. 17th ISMRM.

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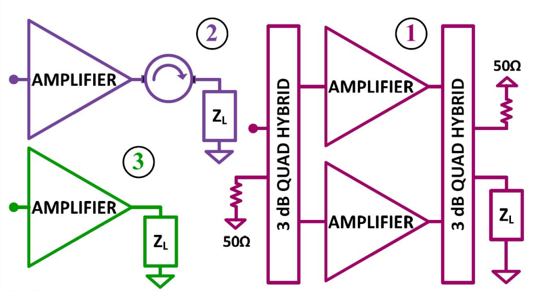

FIG. 1

FIG. 3

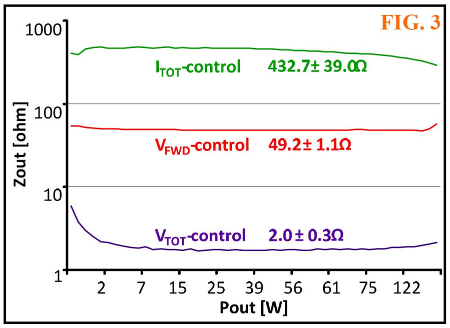

FIG. 4

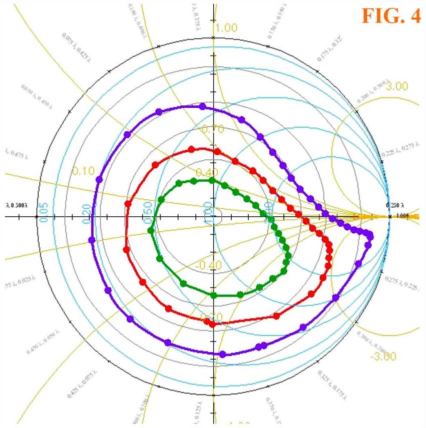

FIG. 2

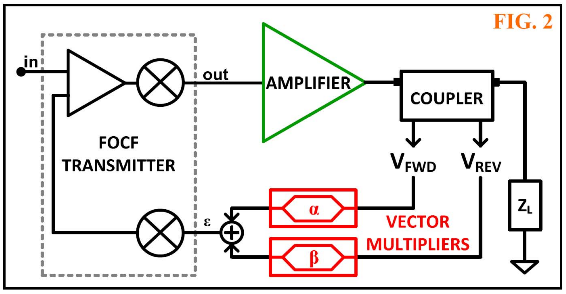

FIG. 5

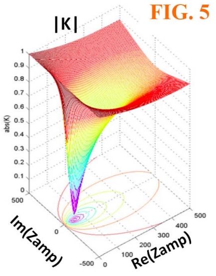

Fig. 1: Balanced amplifier (1) and single amplifiers, with (2) & without (3) circulator.

Fig. 2: Schematic of basic FOCF system including vector multipliers.

Fig. 3: Plot of the high, low, and ~ 50 Ω impedance of the power amplifier obtained using only a directional coupler and a combiner.

Fig. 4: Smith Chart of Zamp at varying K, each contour for fixed |K| (the green contour is for |K|=0.4; red, for |K|=0.6; blue, for |K|=0.8).

Fig. 5: Simulations of |K|, Real(Zamp), and Imag(Zamp).