

# On Stability and Performance of Frequency-Offset Cartesian Feedback for RF Power Amplifiers of MRI Transmitter Arrays

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**Introduction:** We have previously proposed the use of Frequency-Offset Cartesian electronic feedback (FOCF) to deal with the rising challenges associated with control over the RF transmission fields in arrays of coils [1] [2]. In comparison to back-off, high transistor counts and other linearization methods, Cartesian feedback—like Vector Iterative Predistortion, VIP [3]—does not trade efficiency for performance and is robust to changes in the amplifier behavior and loading; unlike VIP, it is a real-time method. In comparison to traditional Cartesian feedback, our FOCF method and system is not affected by DC-offsets and baseband mismatches which may affect image quality by eliciting bright spots and quadrature ghosts, respectively. Before imaging can be performed, critical milestones of the system development process are (a) to guarantee that the conditions for stability exist and can be found automatically at the beginning of the imaging procedure, (b) to demonstrate that the amplifier can be driven up to its maximum rated power without loss of efficiency or stability, (c) to verify that the system response is fast enough for a wide variety of MRI pulses to be performed, and (d) to measure the increased performance (in terms of reduced distortion and errors) of the amplifier controlled by the FOCF system for several control variables including but not limited to output voltage, output current, and coil current. In this work, we present the results of these milestone tests.

**Material Methods:** Our improved FOCF system includes a Medusa MRI Console [4], which synthesizes the RF input to the FOCF transmitter and can digitize an exact replica of the fed-back control variable, and a commercially available pair of TTL switches placed in the feedback and forward loop paths, which allows the automatic determination of the loop stability requirements prior to closing the loop around a 200 W RF power amplifier near 64 MHz. Figure 1 shows a simplified diagram of the control system with autotuning capabilities. One version of the system includes a bidirectional coupler (by Werlatone) at the amplifier output, to sample forward (Vfwd) and reverse (Vrev) voltages that can be combined by using 0° (Vfwd+Vrev=Vtot, total voltage) or 180° (Vfwd-Vrev=Itot, total current) combiners (by Mini-Circuits). Vtot (or Itot) is sent as the fed-back variable to the FOCF transmitter. With this configuration, we loaded the power amplifier with a dummy load (56+j4 Ω) and investigated the ability of the feedback system to correct the amplifier distortion and errors by exciting a train of transmit rectangular pulses of linearly increasing amplitude. By changing the properties of the closed-loop (feedback gain, forward gain, phase shift), we studied their effects on the system performance. With the same configuration, we have also studied the ability of the system to control the amplifier by exciting MRI-like windowed and non-windowed sinc pulses and triangular pulses. In a slight variation of this configuration, we loaded the amplifier with a tuned transmit coil and fed a sample of the coil current—provided by a current sensor integrated in the coil—to the feedback loop [1]. In addition to characterizing stability and linearization performances of the control system experimentally, we have also developed a theoretical model for the study of stability of a single control system and of an array of control systems, with and without coupling of the coils loading the elements of the array. The model is based on the application of the Middlebrook criterion [5], a corollary of the Nyquist criterion applied to cascade control systems. Figure 2 shows the simplified schematic of an array of two control systems used to model the array stability. The coupled systems have been modeled as a cascade system by using an equivalent circuit of the coupled coils based on the concept of mutual inductance [6].

**Results:** In all of our experiments, we have successfully found the conditions for stability and operated the system safely up to the full rated power of the amplifier. Figure 3 shows the output voltage of the amplifier driven by a fixed-frequency input of linearly increasing amplitude. The phase error is below 2° and the voltage non-linearity below 1%, which represent over a ten-fold improvement with respect to the amplifier without control. Similar performances have been demonstrated while controlling the coil current directly (Figure 4). The system responds fast to the high-frequency input pulses typical of an MRI sequence, settling within less than 10 μs and offering less than 2% amplitude error and 3° phase error with both windowed (Figure 5) and non-windowed sinc pulses. Here the system proved to reduce memory effects otherwise evident in the pulse shape at the output of the amplifier. Robust stability was not only shown experimentally, but also confirmed by our modeling of stability of a single loop. Our preliminary results of modeling the stability of arrays of loops suggest that perfectly identical loops, if stable uncoupled, will be unconditionally stable even when coupled. Severe mismatches in the overall loop phase transmission may create the conditions for instability of the array; however, these conditions can be both predicted and avoided by careful electronics design that minimizes the differences between loops.

**Conclusion:** We have demonstrated FOCF to be a high-performing, versatile method for correcting non-ideal power amplifier behavior, including AM-AM and AM-PM distortion, phase errors, and memory effects. By controlling the RF output signal, the FOCF system may enhance the image quality of standard MRI transmitter arrays, or, permit the use of lower-priced RF power amplifiers, thereby reducing the growing cost of these arrays. During imaging, FOCF's ability to improve pulse performance may reduce distortion in the RF excitation profile and improve background suppression. Having successfully passed all critical milestones for safe and effective operation in an MRI scanner, the system is ready to be tested in the imaging suite.

**References:** [1] D. Hoult *et al.*, JMR 171(1):64–70, 2004; [2] M.G. Zanchi *et al.*, “FOCF Control System for MRI Power Amplifier,” Proc. 17<sup>th</sup> ISMRM; [3] Kurpad *et al.*, “Implementation of coil integrated RF power MOSFET as voltage controlled current source in a transmit phased array coil,” Proc. 12<sup>th</sup> ISMRM; [4] P. Stang *et al.*, “VIP: an auto-calibration method for transmit arrays,” Proc. 17<sup>th</sup> ISMRM; [5] R.D. Middlebrook *et al.*, “Advances in switched-mode power conversion,” TESLACO 1983; [6] R.F. Lee *et al.*, MRM 48:203–213, 2002.

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**Fig. 1:** Simplified FOCF system with switches for autotuning and Medusa. **Fig. 2:** Schematic of two systems

loaded by coils for stability analysis based on Middlebrook. **Fig. 3:** Linearized output voltage (Pmax 200 W). **Fig. 4:** Linearized coil current; inset shows the Tx coil with current sensor. **Fig. 5:** Sinc pulse amplitude (bottom) and phase (top) errors in the system without control (left) and with voltage control (right). Memory effects are visible in the case without control.

