Power balance considerations for RF transmit coil arrays

André Kuehne1,2, Sigurd Goluch1,2, Ewald Moser1,2, and Elmar Laistler1,2

1Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Vienna, Austria, 2MR Center of Excellence, Medical University of Vienna, Vienna, Vienna, Austria

Target Audience: Researchers interested in EM simulation, safety evaluation and optimization of parallel transmission coil arrays.

Purpose: In this work we aim to extend the quadratic form power correlation matrix (PCM) formalism [1] used for estimation of deposited power in lossy materials by a transmit coil array. A distinct PCM is derived for each term of the power balance – forward, reflected, absorbed, radiated, and lumped element loss power. The goal is to enable a straightforward calculation of losses for arbitrary excitations, transmit array worst-case loss analysis; and also to verify EM simulation integrity, which is imperative especially for complex workflows that are prone to mistakes.

Theory: The approach is based on the calculation of absorbed power $P$ via quadratic forms $P = v^T Q v$ for each term in the balance. In an $N$-channel array, $Q$ denoted an $N \times N$ PCM, $v$ the applied coil voltage column vector and $H$ the hermitian transpose. Knowledge of the coil array scattering matrix $S$, 3D $E$- and $H$ field distributions and lumped element (capacitor, inductor, resistor...) currents and voltages is assumed. All values are normalized to a unit excitation of 0.01W forward power, i.e. IV amplitude applied voltage at a source impedance $Z_0 = 50 \Omega$. The forward PCM, $Q_F = (2z)^{-1} I$, used to calculate the power incident into the coil, is a scaled identity matrix. Any power loss due to coupling or imperfect matching is computed using the coupling loss matrix derived from the scattering matrix as $Q_L = (2z)^{-1}(S^H S)$. For an $N$-channel coil with $M$ discrete lumped elements, the element voltages and currents can be arranged in a simple matrix calculation. Worst case power imbalance estimates allow a reliable provide access to the power balance for arbitrary excitations using simple matrix calculations. Worst case power imbalance estimates allow a straightforward plausibility check for EM simulations of arbitrary coil complexity. Values have been shown to vary significantly between different excitations, allowing a deeper insight into loss mechanisms than considering only a single mode. The maximum and minimum power imbalances for the investigated array were 0.018% and 0.002%, respectively. The worst- and best-case losses for each power balance term are detailed in Table 1. Figure 2 shows the complete power balance for the four clockwise rotating excitations ("Birdcage"-Modes) and the "Maxwell"-Mode (equal phase for all coil elements).

Discussion: The maximum power imbalance is negligible and thus in excellent agreement with theory. The small residual error can be attributed to multiple factors. Determination of radiated power via integration of the Poynting vector estimation via interpolation and lumped element (capacitor, inductor, resistor...) currents and voltages is assumed. In the brain magnet, bores comparable as well as in dielectric properties ($d = 18 \text{ cm}$, $\varepsilon = 50.6$, $\sigma = 0.66 \text{ S/m}$), was used as the coil load. Coil simulation was done with XFdtd (Remcom, State College, PA, USA) being used for 3D EM simulations and ADS (Agilent, Santa Clara, USA) for tuning, matching and decoupling. Particular care was taken to ensure accurate loss modeling. Metal losses were approximated by enabling a good conductor approximation in XFdtd; and capacitors assigned an ESR of 1001. The forward PCM, $Q_F$, with the conductivity $\sigma$, $\varepsilon$, $\mu$, $d$, $A$, $E$ denoting the electric field produced by a unit excitation of coil element $i$. By restricting the integration volume to certain materials (body, metal, substrate...), power correlation matrices can be obtained for each material of interest. A similar approach is taken for calculating the radiated power by integration of the pointing flux through a box enclosing the problem space. The radiated power of multiple interacting fields can be obtained via $P = 1/2 \text{Re} \left( \mathbf{E}^2 \mathbf{H}^2 \right)$, with the elements of $Q_R$ defined as $q_{ij} = \mathbf{E}_i \mathbf{H}^* j / dA$. Again restricting real part yields the power loss. The power balance can now be written as $P = Q_F + Q_L + Q_R$. Any residual imbalance of this equation can be attributed to factors such as non-convergence of FDTD simulations, insufficient sampling frequency, loss of precision due to simulation methodology or simply user errors. The by magnitude largest (smallest) Eigenvalue of the residual imbalance matrix represents the maximum (minimum) power balance error.