Minimal Acceptable Blocking Impedance for RF receive coils

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Introduction

In modern MRI systems the four main components are used to achieve imaging – main magnet, gradient coils, transmit coils and receive coils. During the transmit phase of the MR sequence the receiving coils are usually detuned to minimize the quadrature body coil B1 disturbance. This is typically achieved with passive or active decoupling parallel tank circuits. These circuits, when active, create very high impedance in coil elements so that the current induced into them is very small and does not affect the process of magnetization tipping. Coil designers usually characterize this effect by calling it B1 transmit field distortion due to the receive coil. Usual requirement for transmit B1 distortion is at maximum 5%. Coil designers typically need to attach to each coil element one or several decoupling boards to cumulatively having certain impedance sufficient to pass the 5% transmit B1 test requirement. When planning the build of a coil, the magnitude and the number of decoupling boards required for every receive element needs to be considered. In this work we deduce a simple rule for quick evaluation of the required blocking impedance per each element.

Theory

Let us suppose that the incident magnetic field generated by the transmit coils is $\mathbf{B}_i$ (which can be linearly or circularly polarized). It is typically under 50μT. If a loop is placed in the system, then the voltage generated along its perimeter will be $E_{emf} = -\partial_t \int_\Sigma \mathbf{B}_i d\mathbf{S}$, where Σ represents the total surface of the resonant contour. Knowing that magnetic field is frequency dependent $\mathbf{B}_i = \mathbf{B}_{i0} e^{-j\omega_0 t}$, with $\omega_0 = 2\pi f_0$ we can write the previous equation for a circular loop of radius r_0 as $E_{emf} = j\pi r_0^2 \omega_0 \mathbf{B}_{i0}\mathbf{n} e^{-j\omega_0 t}$, where $\mathbf{n}$ is the normal to the surface of the loop. If the loop has blocking impedance $Z_l = R_l + jX_l$, where R_l and X_l are real and imaginary part of the combined impedance of the coil and decoupling boards, then the current generated in the loop will be $I_l = E_{emf}/Z_l = j\pi r_0^2 \omega_0 \mathbf{B}_{i0}\mathbf{n} e^{-j\omega_0 t}/Z_l$. If in the loop a time variable current flows, then a secondary magnetic field is generated. For a circular filamentary loop the precise formulae are given [1]. Considering the absolute value of the total secondary magnetic field $|B|_s = \sqrt{|B_r|^2 + |B_z|^2}$ generated by induced currents in the coil, then the ratio between the two fields will be

$$\frac{|B|_s}{|\mathbf{B}_{i0}\mathbf{n}|} = \frac{\mu_0 f_0 \pi r_0^2}{|Z_l|} f_{form}(r,z,r_0) \quad (1), \quad \text{with} \quad f_{form}(r,z,r_0) = \frac{1}{\sqrt{(r+r_0)^2 + z^2}} \left[\frac{z}{r}\left(-K(k) + \frac{r_0^2 + r^2 + z^2}{(r-r_0)^2 + z^2} E(k)\right) + \left(K(k) + \frac{r_0^2 - r^2 - z^2}{(r-r_0)^2 + z^2} E(k)\right) \right]^{1/2} \quad (2)$$

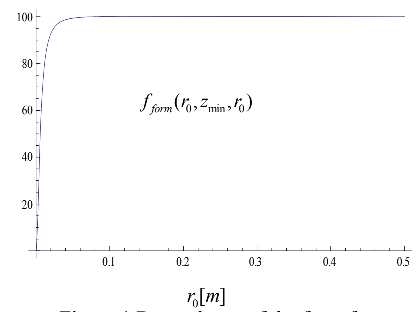

Figure 1 Dependence of the form factor function (z_{min}=1cm) as function of circular coil radius.

As can be observed from (1), the transmit field distortion $|B|_s / |\mathbf{B}_{i0}\mathbf{n}|$ is directly proportional to the system frequency f_0 and surface area encircled by the loop. It is inverse proportional to the absolute value of the blocking impedance $|Z_l|$. It is also found to be strongly dependent of the location of the loop relative to the field of interest (FOI). The strongest distortion occurs in the proximity of the loop's wire, therefore we will establish the minimum distance of the wire to the FOI to be 1cm (tipical minimal distance of the coil trace to the phantom or human). Let us plot the dependence of the function $f_{form}(r,z,r_0)$ evaluated for $r = r_0$ and $z = z_{\min} = 1\text{cm}$. As can be observed from Figure 1, the form function of the circular loop has a plateau starting with 4 cm loop radius. The result (1) with considerations described below it is possible to rewrite into a practical formula

$$|B|_s / |\mathbf{B}_{i0}\mathbf{n}| [\%] = 1.26 f_0[\text{MHz}] S[\text{cm}^2] / (|Z_l|[\text{Ohm}]) .$$

If we consider the acceptable maximum distortion to be 5%, then the corresponding blocking impedance according to previous equation approximately will be (3)

$$\left.\frac{|Z_l|[\text{Ohm}]}{S[\text{cm}^2]}\right|_{5\%} \approx \frac{1}{4} f_0[\text{MHz}] \quad (3) \qquad \left.\frac{|Z_l|[\text{Ohm}]}{S[\text{cm}^2]}\right|_{5\%} = \frac{1}{4}\zeta(d[\text{cm}]) f_0[\text{MHz}] \quad (4)$$

For very small coil with overall diameters less then 6 cm formula (3) would recommend higher impedance then necessary, therefore an augmented formula would be (4)
where correction function $\zeta(d)$ is defined from formula (2) and shown in Figure 2.

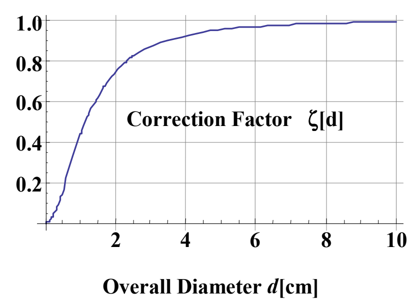

Figure 2. Small coil correction factor.

Results

Applying the formula (3) for 64 MHz for 14x14cm^2 loop we will get 3136 Ohm of blocking impedance to pass 5% B1 disturbance. For 128MHz it will be double.

Conclusion

When designing RF receive coils, it is always necessary to have a quick way of calculating how many decoupling boards are needed per each receiving element of the coil. Knowing RF components comprising the coil – capacitors, inductors, PIN diodes, etc. – it is generally know how much impedance each board can generate. The ultimate question then will be how many boards are needed to have maximal B1 distortion passed. Formula (3) allows quick calculation of the minimum impedance per surface area of the coil stating that "for passing 5% transparency test a quarter of the system frequency (taken in MHz) with attached [Ohm/cm^2] unit is needed". This rule can be extended to rectangular shapes of the elements, for which a precise Figure 1 like shape can be evaluated numerically.

References

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2. Kocharian A. et al., *Determination of appropriate RF blocking impedance for MRI surface coils and arrays*, Magnetic Resonance Materials in Physics, Biology and Medicine, Vol. 10 (2000), p80-p83.