Australian Journal of Basic and Applied Sciences, 9(16) Special 2015, Pages: 224-228

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Design and Analysis of Matching Network for 1.5 Tesla Magnetic Resonance Imaging RF Surface Coil

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A R T I C L E I N F O

Article history:
Received 20 January 2015
Accepted 02 April 2015
Published 20 May 2015

Keywords:
impedance matching
Quality factor
magnetic resonance imaging
radio frequency
smith chart
surface coil

A B S T R A C T

In the whole system of magnetic resonance imaging (MRI) machine RF coil plays a major role in producing a good quality medical image. Surface type RF coils are mainly preferred for 7 Tesla MRI without giving much importance to impedance matching techniques. In this article to further advance the approach, a surface type RF coil design is focused for 1.5 Tesla MRI with suitable impedance matching elements. The matching network consists of a lumped capacitor and inductor forming an L shaped structure. The quality factor based design procedure is followed to determine the value of matching network components. The performance of L section design is analyzed for different values of RF surface coil width. The workability of the proposed matching network has been verified using Advanced Design System (ADS) S-parameter simulation. The return loss result of S Parameter simulation shows the proposed L type matching network performs well at 63.87 MHz for wide variety of RF coil width values.

To Cite This Article: K. Thiyagarajan, T. Kesavamurthy, R. Ponkohila, Design and Analysis of Matching Network for 1.5 Tesla Magnetic Resonance Imaging RF Surface Coil. ***Aust. J. Basic & Appl. Sci.,*** *9(16): 224-228, 2015*

INTRODUCTION

In recent years, Magnetic Resonance Imaging (MRI) is one the most extensively used medical imaging technique to obtain the clear image of the anatomy, especially those of high-water-content tissues (Wu *et al*., 2007). The introduction of MRI technique into clinical practice gives a new dimension to the radiological study. The basic principle behind MRI is to radiate the high-power RF energy towards the object of the body and to capture the Nuclear Magnetic Resonance (NMR) induced signals emitted by the body. The whole action of RF energy radiation and reception is performed by RF coil under high-magnetic field intensity called static magnetic field (B0) (Chen & Hoult, 1989). The efficient way of signal transmission and reception at these high fields can also be achieved by using multi element RF transceiver coils (Aussenhofer & Webb, 2014; Adriany *et al*., 2008).

The entire MRI system consists of RF coil, gradient coil, magnet, power amplifier, low noise amplifier, pulse programmer, RF source and computer. There are several types of RF coils such as saddle coil, surface coil, volume coil and birdcage coil. Surface coils are better in producing high-signal-to-noise ratio of the reconstructed image and able to perform multichannel operation in comparison with volume coils (Dehkhoda *et al*., 2012). The operating frequency of the MRI RF coils is decided by the static magnetic field strength (Ibrahim *et al*., 2005) . If the static magnetic field strength of MRI system is selected as 1.5 Tesla, the desired Larmor frequency (42.58 MHz/Tesla for 1H protons) of operation is 63.87 MHz. The signal to noise ratio of the reconstructed image can also be improved by selecting high static field strength coils. These high resonance frequency RF coils are dimensionally small and consequently produce less field of view for imaging. That is the reason to concentrate on low field RF coils.

Impedance matching at the input of RF coil is necessary to deliver maximum power for the RF coil and to achieve minimum reflection at the source side. The circuits or antennas operating at higher range of RF and microwave frequencies uses microstrip based stub transmission line sections for impedance matching. These transmission lines are lengthier at low frequencies. As a result the passive networks are focused for impedance matching at low frequencies (Liao *et al*. 2012; Chamseddine *et al*., 2006; Chung, 2006; Thompson & Filder, 2004). The preferred

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configurations of the matching networks for single frequency matching are T, L and pi networks. The most important performance requirement of any matching network is the amount of return loss at the source side for the matching frequency concerned. This work mainly concentrates L type matching network due to the simplicity and lesser hardware requirements.

Related Work:

The structure shown in Fig.1 was introduced by kraff et.al (2009) for 7 Tesla MRI with four sections of L shaped transmission lines. In the earlier work of Thiyagarajan et.al (2014), the same structure is analyzed for 1.5 Tesla MRI with two C shaped transmission line sections as shown in Fig.2. In that a detailed design procedure is followed to convert 4 L sections into 2 C sections. The impedance matching is achieved by inserting a series resistance of 50Ω with the structure. The resonance was achieved at 63.87 MHz. The power loss across this 50Ω resistance is considered to be a serious drawback in the earlier work. This is rectified by using the proposed L section-matching network in series with the RF coil.

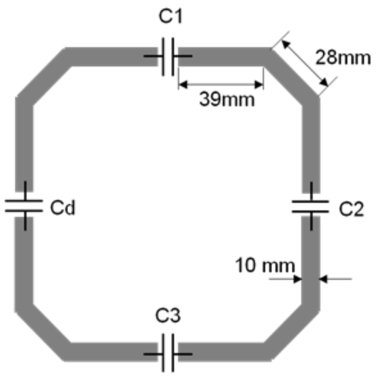

Fig. 1: Surface coil for 7Tesla MRI

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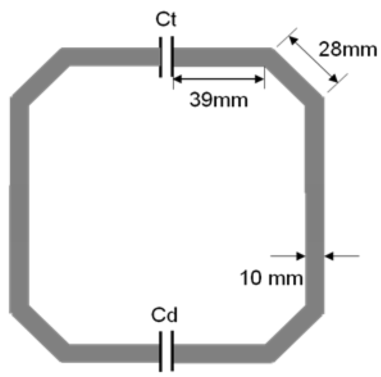

Fig. 2: Surface coil for 1.5Tesla MRI.

Proposed Work:

Matching Circuit Design:

Generally, the preferred impedance value of first section of any RF circuit is 50 Ω to avoid impedance matching issues. But directly selecting a microstrip based 50 Ω section at 63.87 MHz will lead to a lengthy transmission line, which is not suitable for practical applications. Therefore radiating structure shown in Fig.2 is selected as RF coil and it is matched to a 50 Ω source with the help of matching network.

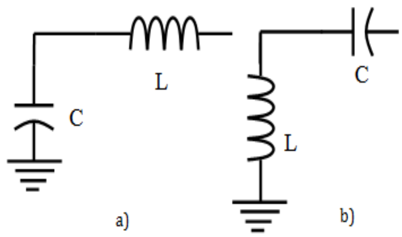

Fig. 3: L Type Matching Network a) Type1 and b) Type 2.

A wide variety of impedance matching techniques are available for RF and microwave applications (Wu *et al*., 2010; Best, 2005; Deng *et al*., 2006). Smith chart is one of the very useful tools in impedance matching applications (Pozar, 2012 ; Ludwig and Bogdanov, 2011). This work considers two types of L matching networks as shown in Fig.3. The above mentioned L Type matching circuits are effective in matching real loads. But the input impedance of the proposed surface type RF coil is Complex in nature. It has to be matched with 50Ω source impedance. So in order to eliminate the reactive part at the input side of RF coil, opposite type reactive element is added along with the L type structure shown in Fig 3. This newly added element is either Lad or Cad depends upon the type of reactive impedance present at the input side of RF coil.

Design procedure:

The matching network will make the surface type RF coil as radiating element. Resonance frequency of the RF coil is same as the matching frequency. Quality factor based relationship is used in the matching network design procedure. The input side of Type 1 network will have 50Ω source impedance (Rs) parallel with matching capacitor (C) and acts as a parallel resonant circuit. The output side of Type 1 network will have input resistance (Rin) of RF coil and acts as series resonant circuit. The input impedance of the RF coil is determined from smith chart plot of ADS S parameter simulation as shown in Fig. 4 & Fig. 5. The Real value (Rin) of the input impedance (Zin) is matched by using L matching procedure. The imaginary capacitive reactance is eliminated by adding suitable inductive reactance in series with RF coil.

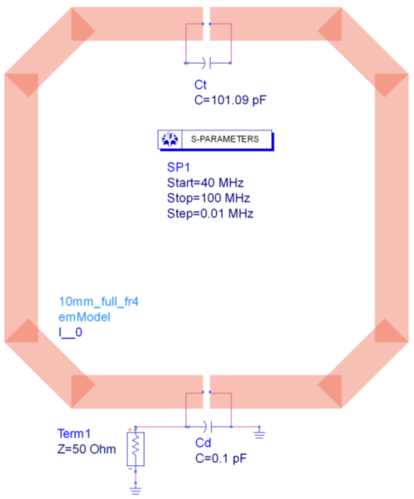

Fig. 4: Co-Simulation structure for Zin calculation.

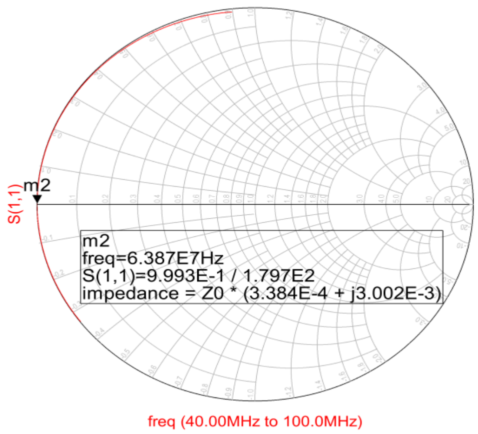

Fig. 5: Input impedance evaluation from smith chart.

In a series RLC circuit the resonance frequency is

$$f_0 = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}} \qquad (1)$$

In resonance circuit the quality factor is related with source (Rs) and load resistance (Rin) as,

$$R_s = \left(1+Q^2\right)R_{in} \qquad (2)$$

$$Q = \sqrt{\frac{R_s}{R_{in}} - 1} \qquad (3)$$

In Type 1 circuit Capacitor is in parallel with source resistance. So for parallel resonance,

$$Q = \frac{\text{Resistance}}{\text{Reactance}} = \frac{R_S}{X_C} = R_S C 2\pi f_0$$

$$C = \frac{Q}{2\pi f_0 R_s} \qquad (4)$$

Inductor is in series with RF coil input resistance. So for series resonance,

$$Q = \frac{\text{Reactance}}{\text{Resistance}} = \frac{X_L}{R_{in}} = \frac{L2\pi f_0}{R_{in}}$$

$$L = \frac{QR_{in}}{2\pi f_0} \qquad (5)$$

Similarly for Type 2 circuits L is used in Parallel resonance and C is used in Series Resonance.

$$C = \frac{1}{2\pi f_0 QR_{in}} \qquad (6)$$

$$L = \frac{R_s}{2\pi f_0 Q} \qquad (7)$$

Consider a RF surface coil of width 10 mm the input impedance obtained from smith chart plot is,

Zin=Z0*(3.384+30.02)x10^{-4}. The resonance frequency of the RF coil is 63.87 MHz. Equations (4)-(5) are used to calculate L and C values of the Matching section.

C= 2.7087 nF, L = 2.2916 nH,

From Fig.5 X_L= Z0*(0.003) = (50*0.003) Ω

$$C_{ad}\omega = 1/0.15$$

$$C_{ad} = \frac{1}{0.15x2\pi f_0} = 16.601\text{nF}$$

In a similar manner if we select type 2 circuit than first shunt element is inductor and the next series element is capacitor. These L & C values will be calculated by using Eq.(6)-(7). Then in order to cancel inductive reactance at the input side of RF coil, additional capacitive reactance Cad is used. The series configuration of C and Cad is finally converted as single equivalent capacitance Ceq. It will give only 2 matching components such as L and Ceq at the input side of RF coil. Whereas in type 1 circuit there are three matching components C, L and Cad.

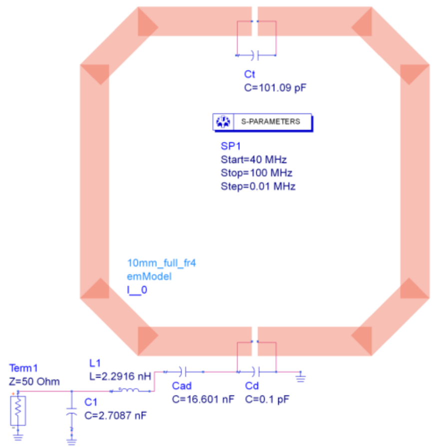

Fig. 6: Co-simulation structure of matched RF coil.

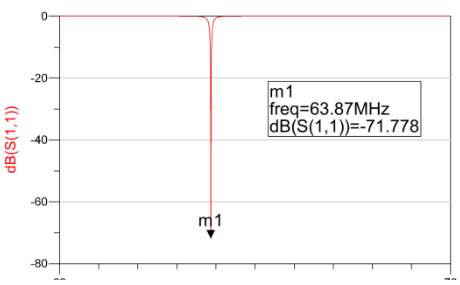

Fig. 7: Return loss result of S-parameter Co-simulation.

Simulation & Results:

The microstrip part of the proposed structure is implemented in a layout option of Advanced Design System (ADS) 2011. A 35 µm copper transmission lines of 10 mm width and 45^0 flaring as specified in Fig.2 is followed for two face to face C shaped transmission line sections. All the microstrip design discussed in this work is implemented in a FR4 dielectric material with 1.6 mm thickness. A gap of 2 mm is given to place the capacitor in between C shaped microstrip line sections. So that the circuit will be the equivalent of series RLC network with two inductors and one capacitor. The layout design is exported as Electromagnetic model to perform Co-simulation between lumped and distributed sections in ADS schematic. A single C section is initially simulated to find the tuning capacitor (Ct). The capacitor (C_d) of 0.1 pF connected between two C section is used to eliminate the decoupling.

S Parameter Co-simulation is performed to obtain the return loss behavior of the proposed C shaped 1.5 Tesla RF coil structure with type1 matching circuit as shown in Fig. 6. The tuning capacitor C_t is obtained from resonance frequency relationship as indicated in Eq. (1). Figure.7 shows a return loss result of -71.778 dB at 63.87 MHz for the proposed 1.5 Tesla RF surface coil with type1 matching network having a transmission line width value of 10 mm.

Table 1: Resonance Parameters and Input Impedance

Width (mm)	Z_{in} for single C section $50x10^{-3}$ Ω	C Section Inducatnce L (nH)	Tuning Capacitor C_t (pF)	Input impedance of entire RF Coil $50x10^{-3}$ Ω
14	0.1817+ j181.7	45.277	137.14	0.2426+ j2.171
13	0.1936+ j194.5	48.467	128.12	0.2684+ j2.273
12	0.2076+ j209.6	52.229	118.89	0.3242+ j2.581
11	0.2226 + j226.5	56.441	110.02	0.3417+ j2.944
10	0.2324+ j246.5	61.424	101.09	0.3384+ j3.002
9	0.2526+ j269.3	67.106	92.531	0.3575+ j3.155
8	0.2753+ j296.1	73.784	84.156	0.3865+ j3.296
7	0.3028+ j329.0	81.982	75.740	0.4297+ j3.348
6	0.3351+ j369.1	91.974	67.512	0.4902+ j3.866
5	0.3812+ j422.0	105.16	59.049	0.5773+ j3.716
4	0.4516+ j496.2	123.65	50.219	0.6913+ j4.109

Table 2: Return Loss Behavior of RF Coil for Type1 and Type2 Matching.

Width (mm)	Type 1 Matching				Type 2 Matching				
	Shunt Capacitor C1 (nF)	Series Inductor L1 (nH)	Additional Capacitor Cad (nF)	Return Loss (dB) $-S_{11}$	Shunt Inductor L1 (nH)	Series Capacitor C1 (nF)	Additional Capacitor Cad (nF)	Equivalent Capacitor Ceq (nF)	Return Loss (dB) $-S_{11}$
14	3.1993	1.9404	22.956	66.947	1.9408	3.2001	22.956	26.1561	57.178
13	3.0416	2.0409	21.926	71.118	2.0415	3.0424	21.926	24.9684	61.016
12	2.7674	2.2430	19.309	70.358	2.2437	2.7683	19.309	22.0773	64.255
11	2.6956	2.3027	16.928	70.487	2.3035	2.6965	16.928	19.6245	68.815
10	2.7087	2.2916	16.601	71.778	2.2924	2.7096	16.601	19.3106	77.023
9	2.6353	2.3553	15.796	56.708	2.3562	2.6363	15.796	18.4323	72.495
8	2.5345	2.4490	15.120	65.282	2.4499	2.5355	15.120	17.6555	61.625
7	2.4037	2.5822	14.886	69.221	2.5833	2.4047	14.886	17.2907	80.540
6	2.2504	2.7579	12.891	75.234	2.7592	2.2515	12.891	15.1425	63.928
5	2.0736	2.9927	13.412	78.433	2.9945	2.0748	13.412	15.4868	67.999
4	1.8948	3.2747	12.129	72.856	3.2770	1.8961	12.129	14.0251	77.137

Discusion:

The design and simulation process is repeated for various width values of RF surface coil. The width values are selected as 14 mm to 4 mm, and for all the cases inductance and tuning capacitance for a resonance frequency of 63.87 MHz is evaluated using Eq.(1) as shown in Table.1. The performance of Type 1 and Type 2 Matching network are verified for various width values of RF coil. Matching Element values and corresponding return loss values are listed in Table.2 for Type1 and Type 2 matching networks.

It is very clear from Table 2 that the value of additional capacitor (Cad) depends on the Reactance of RF coil. The input reactance is inductive in nature, so in order cancel the inductive reactance exact amount of capacitive reactance is added. This is same for both type 1 and type 2 matching. The major difference between type1 and Type 2 matching are the type of shunt and series elements in the matching network and their values. Figures.8 & 9 illustrate the variation of series and shunt matching elements with respect to RF coil width ranging from 4 mm to 14 mm. It is observed that for Type1 matching network first shunt element is capacitive in nature. The same amount of capacitive reactance is used as a series element in Type 2 Matching network. The same reciprocal relationship is followed in inductor for Type 1 and Type 2 matching networks.

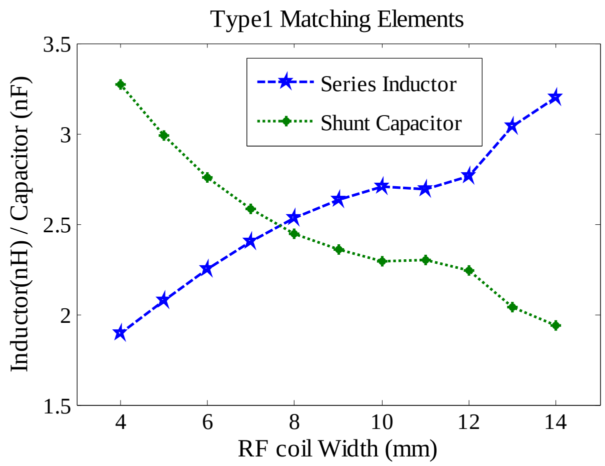

Fig. 8: Type 1 Matching element values.

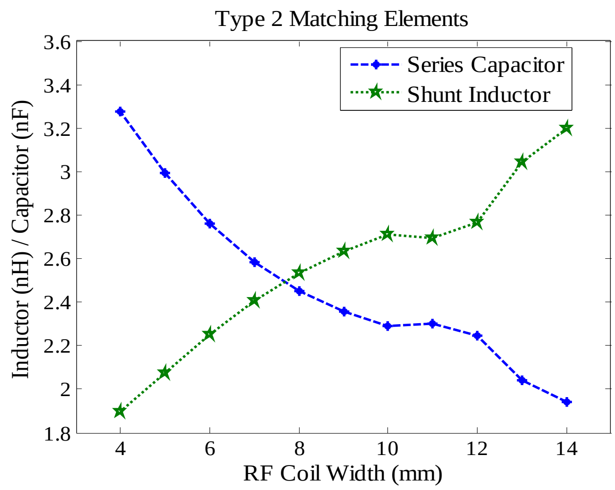

Fig.9: Type 2 Matching element values

Conclusion:

The impedance matching complication of magnetic resonance imaging RF surface coil was simplified by using the proposed L Type matching network. The design uses smith chart based evaluation to determine the inductive reactance & input impedance of the radiating structure. The matching procedures indicated are so simple for matching source impedance with real as well as complex type of load impedances. The proposed matching network is helpful in achieving desired resonance at 63.87 MHz for RF radiation as well as produces very less return loss at matching frequency. The performance of proposed Type 1 and Type 2 matching technique is verified for various width values of microstrip RF surface coil geometry. The relationship between passive matching elements is analyzed with respect to the transmission line width values of microstrip RF coil. The return loss result of S Parameter simulation shows the proposed L type-matching network performs well at 63.87 MHz for wide variety of RF coil width values.

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