

# **Selection of Antenna Inductance for TI RFid's Transponder ICs**

## **Application Note**

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# Read This First

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### About This Application Note

This application note describes the selection criteria for antenna inductors to be used with ICs from TI RFid that contain an integrated transponder. Specifically, it applies to the following products:

RI-TMS37126	RAID Remote Access Identification Device
RI-TMS37F128 & RI-TMS37C128	CRAID Controller + Remote Access Identification Device

### If You Need Assistance

For more information, please contact the sales office nearest you.  
Further information can be found on our web site at: <http://www.ti-rfid.com>.

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# Introduction

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Transponder ICs such as the TMS37126 RAID (Remote Access Identification Device) and TMS37128 CRAID (Controller + Remote Access Identification Device) can handle up to three external resonant circuits for LF (Low Frequency) communication. These resonant circuits consist of an inductor, which is the antenna, and a parallel capacitor. In order to optimize the LF communication used in immobilizer and passive entry applications, the antenna circuit must be trimmed so that it resonates at the system frequency, typically 134.2 kHz or 125 kHz.

A properly trimmed resonant circuit achieves:

- optimum energy transfer
- correct response frequencies during uplink
- correct clock generation
- accurate band-pass filtering

The TMS37126 RAID is designed for use at frequencies in the range of 120kHz to 140kHz, with most systems using either 134.2kHz or 125kHz. This application note, in conjunction with the CRAID/RAID Reference Guide, describes the recommended approach to selecting external components so that optimum system performance can be achieved.

## 1.1 Related Documents

This application note should be read in conjunction with the CRAID/RAID Reference Guide (11-07-21-003).

# Important Parameters

The TMS37126 device has several parameters that must be considered during antenna selection, namely:

- the input capacitance  $C_{RFx}$  (trimming capacitors all switched off)
- the total trimming capacitance  $C_T$
- the modulation capacitance  $C_M$

Table 1 summarizes these values.

**Table 1: Important Characteristics of the TMS37126**

PARAMETER	SYMBOL	NOTE	MIN	NOM	MAX	UNIT
Input Capacitance	$C_{RF1}$	All trimming capacitors off	23	27	31.1	pF
Input Capacitance	$C_{RF2}$	All trimming capacitors off	11.9	14	16.1	pF
Input Capacitance	$C_{RF3}$	All trimming capacitors off	11.9	14	16.1	pF
Max. Trimming Capacitor ( $C_T = C_{T1} + C_{T2} + \dots + C_{T7}$ )	$C_T$	All trimming capacitors on	63.5	74.7	85.9	pF
Modulation Capacitor	$C_M$		93.5	110	126.5	pF
Modulation Capacitor (125kHz Mode)	$C_M$		119	140	161	pF

## 2.1 Important Recommended Operating Conditions

Table 2 summarizes some important Recommended Operating Conditions of TMS37126.

The resonant circuit capacitor  $C_R$  has to be selected from a range of standard values and the value of the resonant circuit inductor  $L_R$  determined by calculation. In order to select these components correctly, the parasitic capacitance of the inductor  $C_{LR}$  and the capacitances of the IC (see Table 1) must also be considered.

**Table 2: Important Recommended Operating Conditions of TMS37126**

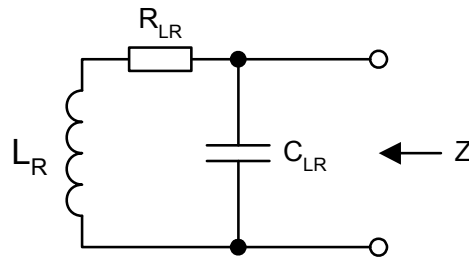
PARAMETER	SYMBOL	NOTE	MIN	NOM	MAX	UNIT
Real Inductance of Antenna ( $\Delta L_R = \pm 2.5\%$ )	$L_R$	25°C, $C_R = 470 \text{ pF} \pm 2\%$ $f = 134.2 \text{ kHz}$	2.545	2.61	2.675	mH
Capacitance of $L_R$	$C_{LR}$		4.5	7	9.5	pF
Effective Inductance of Antenna ( $\Delta L_R = \pm 2.8\%$ )	$L_R$	25°C, $C_R = 470 \text{ pF} \pm 2\%$ , Impedance Analyzer HP4192A, $f = 134.2 \text{ kHz}$	2.587	2.66	2.735	mH
Resonant Circuit Capacitor ( $\Delta C_R = \pm 2\%$ )	$C_R$		460.6	470	479.4	pF
Resonant Circuit Frequency	$f_{RES}$	25°C	134.1	134.2	134.3	kHz
Low Bit Transmit Frequency	$f_L$	25°C, $Q_{OP} = 30 \text{ to } 100$	132	134.7	136.5	kHz
High Bit Transmit Frequency	$f_H$	25°C, $Q_{OP} = 30 \text{ to } 100$	120.0	123.7	126.5	kHz

# Antenna Calculations

## 3.1 Determining the True Inductance of an Antenna

Figure 1 shows the equivalent circuit of a typical inductor, comprising a series resistance  $R_{LR}$  and a parallel capacitance  $C_{LR}$ .

**Figure 1: Equivalent Circuit of an Inductor**



By measuring the magnitude of the antenna impedance  $|Z|$  at two frequencies  $f_1$  and  $f_2$ , the antenna's true inductance  $L_R$  and its parasitic capacitance  $C_{LR}$  can be determined. The impedance of the coil should be measured at two frequencies within the typical application range, e.g.  $f_1=140$  kHz,  $f_2=120$  kHz, and the two measurement frequencies should differ by at least 20kHz to ensure decent measurement accuracy.

If the magnitude of the coil impedance measured at frequency  $f_1$  is  $|Z_1|$  and at frequency  $f_2$  is  $|Z_2|$ , then the true inductance  $L_R$  and capacitance  $C_{LR}$  of the antenna coil can be calculated using the following relationships:

$$L_R = \frac{1}{2\pi} \cdot \frac{(f_1^2 - f_2^2) \cdot |Z_1| \cdot |Z_2|}{(f_1^2 \cdot f_2 \cdot |Z_1|) - (f_2^2 \cdot f_1 \cdot |Z_2|)}$$



$$C_{LR} = \frac{1}{2\pi} \cdot \frac{(|Z_1| \cdot f_2) - (|Z_2| \cdot f_1)}{(f_1^2 - f_2^2) \cdot |Z_1| \cdot |Z_2|}$$

Note: at most practical measurement frequencies the effect of  $R_{LR}$  is negligible and therefore this term does not appear in the above expressions.

### 3.2 Determining the Inductance of a Resonant Circuit

The resonant frequency of an LC circuit is given by the following formula:

$$f_{RES} = \frac{1}{2 \cdot \pi \sqrt{L_R \cdot C_{TOT}}}$$

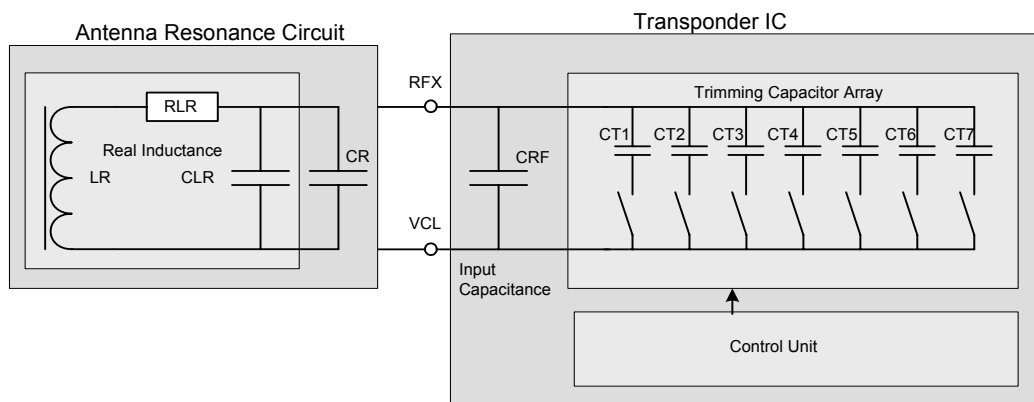
where  $C_{TOT}$  is the sum of all capacitances parallel to  $L_R$  (see Figure 2), and given by:

$$C_{TOT} = C_R + C_{LR} + C_{RF} + C_T$$

If the total capacitance is known the true inductance  $L_R$  of the antenna coil can be determined using the following relationship:

$$L_R = \frac{1}{4 \cdot \pi^2 \cdot f_{RES}^2 \cdot C_{TOT}}$$

**Figure 2: Transponder IC Trimming Capacitors**



### 3.3 Example Calculation for RF1 Input Using True Inductance

The following example shows how to calculate the true inductance needed for the RF1 input, based on the given specifications. Two scenarios have to be considered during calculation:

- Scenario 1 All capacitances are at their maximum value and therefore all trimming capacitors are switched off. This scenario yields the maximum required inductance  $L_{R(max)}$ .
- Scenario 2 All capacitances (including trimming capacitors) are at their minimum value and therefore all trim capacitors are switched on. This scenario yields the minimum required inductance  $L_{R(min)}$ .

#### 3.3.1 Scenario 1

The maximum total capacitance is given by:

$$C_{TOT(max)} = C_{R(max)} + C_{LR(max)} + C_{RF(max)}$$

$$C_{TOT(max)} = 479.4 \text{ pF} + 9.5 \text{ pF} + 31.1 \text{ pF} = 520 \text{ pF}$$

The value of inductance used must be such that the nominal resonant frequency can still be achieved, and is given by:

$$L_{R(max)} = \frac{1}{4\pi^2 \cdot f_{RES}^2 \cdot C_{TOT}}$$

$$L_{R(max)} = \frac{1}{4\pi^2 \cdot 134.2 \text{ kHz}^2 \cdot 520 \text{ pF}} = 2.705 \text{ mH}$$

#### 3.3.2 Scenario 2

The minimum total capacitance is given by:

$$C_{TOT(min)} = C_{R(min)} + C_{LR(min)} + C_{RF(min)} + C_{T(min)}$$

$$C_{TOT(min)} = 460.6 \text{ pF} + 4.5 \text{ pF} + 23.0 \text{ pF} + 63.5 \text{ pF} = 551.6 \text{ pF}$$

$$L_{R(min)} = \frac{1}{4\pi^2 f_{RES}^2 \cdot C_{TOT(min)}}$$

$$L_{R(min)} = \frac{1}{4\pi^2 \cdot 134.2 \text{ kHz}^2 \cdot 551.6 \text{ pF}} = 2.550 \text{ mH}$$

The nominal inductance is simply the average of the minimum and maximum values calculated above, and is given by:

$$L_{R(nom)} = \frac{L_{R(max)} + L_{R(min)}}{2}$$

$$L_{R(nom)} = \frac{2.705 \text{ mH} + 2.550 \text{ mH}}{2} = 2.628 \text{ mH}$$

The maximum allowed tolerance is therefore  $\pm 2.9\%$ . If the tolerance is tighter, the inductance can be reduced, which has advantages for charge functions (described later in this document).

For example, if  $L_{R(nom)} = 2.61 \text{ mH} \pm 2.5\%$ , then the maximum frequency, if all components are at their maximum value and all trimming capacitors are switched off, is given by:

$$f_{RES(max)} = \frac{1}{2\pi\sqrt{L_{R(max)} \cdot C_{TOT(max)}}}$$

$$f_{RES(max)} = \frac{1}{2\pi\sqrt{2.675 \text{ mH} \cdot 520 \text{ pF}}} = 134.9 \text{ kHz}$$

Because  $f_{RES(max)} > 134.2 \text{ kHz}$  the resonant frequency can be trimmed to its optimum value by switching on additional trimming capacitors.

If all components are at their minimum value and all trimming capacitors are switched on:

$$f_{RES(min)} = \frac{1}{2\pi\sqrt{L_{R(min)} \cdot C_{TOT(min)}}}$$

$$f_{RES(min)} = \frac{1}{2\pi\sqrt{2.545 \text{ mH} \cdot 551.6 \text{ pF}}} = 134.3 \text{ kHz}$$

The resonance frequency is still within the trimming tolerance  $f_{RES(nom)}$  of  $\pm 100 \text{ Hz}$  (see Table 1).

### 3.4 Example Calculation for RF1 input using Equivalent Inductance

If measurement and calculation of the real inductance  $L_R$  and capacitance  $C_{LR}$  of the antenna is inconvenient, use of the equivalent inductance  $L_{Requ}$  may be preferred. The equivalent inductance can be measured directly with an Impedance Analyzer at the desired resonant frequency. Antenna manufacturers typically only provide this value.

The total capacitance is now the sum of all capacitances in parallel with  $L_R$  without the capacitance of the antenna  $C_{LR}$ :

$$C_{TOT} = C_R + C_{RF} + C_T$$

#### 3.4.1 Scenario 1

In this case all trimming switches are switched off during trimming and the maximum total capacitance is given by:

$$\begin{aligned} C_{TOT(max)} &= C_{R(max)} + C_{RF(max)} \\ C_{TOT(max)} &= 479.4 \text{ pF} + 31.1 \text{ pF} = 510.5 \text{ pF} \end{aligned}$$

The antenna inductance must be chosen such that even if all trimming capacitors are switched off the nominal resonant frequency can still be achieved, and is given by:

$$\begin{aligned} L_{Requ(max)} &= \frac{1}{4\pi^2 \cdot f_{RES}^2 \cdot C_{TOT(max)}} \\ L_{Requ(max)} &= \frac{1}{4\pi^2 \cdot 134.2 \text{ kHz}^2 \cdot 510.5 \text{ pF}} = 2.755 \text{ mH} \end{aligned}$$

#### 3.4.2 Scenario 2

The second case to be considered is when all capacitances and  $L_R$  are at their minimum value. In this case all trimming capacitors will be switched on and the total capacitance is given by:

$$\begin{aligned} C_{TOT(min)} &= C_{R(min)} + C_{RF(min)} + C_{T(min)} \\ C_{TOT(min)} &= 460.6 \text{ pF} + 23.0 \text{ pF} + 63.5 \text{ pF} = 547.1 \text{ pF} \end{aligned}$$

$$L_{\text{Requ}(\min)} = \frac{1}{4\pi^2 \cdot f_{\text{RES}}^2 \cdot C_{\text{TOT}(\min)}}$$

$$L_{\text{Requ}(\min)} = \frac{1}{4\pi^2 \cdot 134.2 \text{ kHz}^2 \cdot 547.1 \text{ pF}} = 2.571 \text{ mH}$$

The nominal inductance is simply the average of the minimum and maximum values calculated above, and given by:

$$L_{\text{Requ}(\text{nom})} = \frac{L_{\text{R}(\max)} + L_{\text{R}(\min)}}{2}$$

$$L_{\text{Requ}(\text{nom})} = \frac{2.755 \text{ mH} + 2.571 \text{ mH}}{2} = 2.663 \text{ mH}$$

The allowed tolerance ( $\pm 3.5\%$ ) is higher than the tolerance allowed for the real inductance  $L_{\text{R}}$  ( $\pm 2.9\%$ ), because the variation of  $C_{\text{LR}}$  is now included in  $L_{\text{Requ}}$ .

If the antenna is selected with a tighter tolerance, its inductance can be reduced. Also, additional inductance or capacitance changes caused for example by coil assembly can be taken into account.

For example, if  $L_{\text{Requ}(\text{nom})} = 2.66 \text{ mH} \pm 2.8\%$  the maximum frequency, when all components are at their maximum value and all trimming capacitors are switched off, is given by:

$$f_{\text{RES}(\max)} = \frac{1}{2\pi \sqrt{L_{\text{Requ}(\max)} \cdot C_{\text{TOT}(\max)}}}$$

$$f_{\text{RES}(\max)} = \frac{1}{2\pi \sqrt{2.734 \text{ mH} \cdot 510.5 \text{ pF}}} = 134.7 \text{ kHz}$$

Because  $f_{\text{RES}(\max)} > 134.2 \text{ kHz}$ , the resonance frequency can be trimmed to its optimum value by switching on additional trimming capacitors.

If all components are at their minimum value and all trimming capacitors are on:

$$f_{\text{RES}(\min)} = \frac{1}{2\pi \sqrt{L_{\text{Requ}(\min)} \cdot C_{\text{TOT}(\min)}}}$$

$$f_{\text{RES}(\min)} = \frac{1}{2\pi \sqrt{2.586 \text{ mH} \cdot 547.1 \text{ pF}}} = 133.8 \text{ kHz}$$

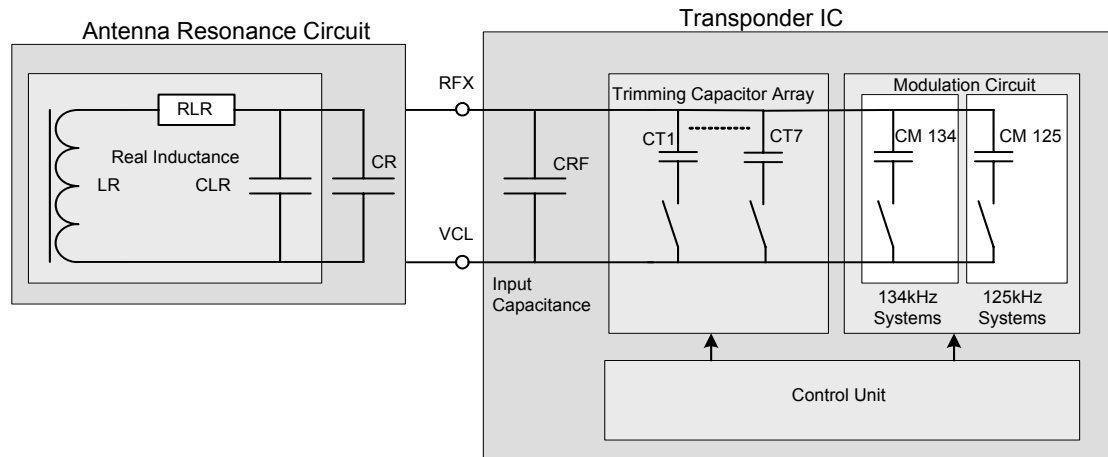
Because  $f_{\text{RES}(\max)} < 134.2 \text{ kHz}$ , the resonant frequency can still be trimmed to its optimum value by switching off additional trimming capacitors. In this case a margin of  $\pm 400 \text{ Hz}$  is available for additional frequency changes.

# Frequency Shift Keying

## 4.1 134.2 kHz Systems

During TI-compatible immobilizer functions Frequency Shift Keying (FSK) is used for the transponder response. For this purpose a modulation capacitor  $C_M$  is switched in parallel to the resonant circuit in order to reduce the frequency for high-bit transmission (see Figure 3).

**Figure 3: Transponder IC Modulation Capacitor for Frequency Shift Keying**



The nominal response frequency is slightly higher than the resonant frequency because certain periods are shorter due to the adaptive pluck function of the transponder IC. From the specification (see Table 1) it can be seen that the nominal response frequency during low-bit  $f_{L(nom)}$  transmissions is 0.5 kHz higher than the nominal resonant frequency  $f_{RES(nom)}$ :

$$f_{L(nom)} = f_{RES(nom)} + 0.5 \text{ kHz}$$

$$f_{L(nom)} = 134.2 \text{ kHz} + 0.5 \text{ kHz} = 134.7 \text{ kHz}$$

The average reduction in period is therefore 28 ns.

If the resonant circuit is trimmed exactly to  $f_{RES(nom)}$ , then the total capacitance is given by:

$$C_{TOT(nom)} = \frac{1}{4\pi^2 \cdot f_{RES(nom)}^2 \cdot L_{R(nom)}}$$

$$C_{TOT(nom)} = \frac{1}{4\pi^2 \cdot 134.2 \text{ kHz}^2 \cdot 2.61 \text{ mH}} = 538.9 \text{ pF}$$

If the nominal  $C_M$  is switched on, the resonant frequency will be:

$$f_{RES(nom)} = \frac{1}{2\pi\sqrt{L_{R(nom)} \cdot (C_{TOT(nom)} + C_{M(nom)})}}$$

$$f_{RES(nom)} = \frac{1}{2\pi\sqrt{2.61 \text{ mH} \cdot (538.9 \text{ pF} + 110 \text{ pF})}} = 122.3 \text{ kHz}$$

Assuming same average period reduction because of the pluck function, the resulting nominal high bit frequency is given by:

$$f_H = \frac{1}{\frac{1}{f_{RES(high)}} - 28 \text{ ns}}$$

$$f_H = \frac{1}{\frac{1}{122.3 \text{ kHz}} - 28 \text{ ns}} = 122.7 \text{ kHz}$$

which is equivalent to a frequency shift of 12.0 kHz.

## 4.2 125 kHz Systems

TI-compatible transponder communication requires a frequency shift of at least 11 kHz. In order to satisfy this requirement in 125 kHz systems, the TMS37126 can be configured so that the value of the modulation capacitor  $C_{M(125 \text{ kHz})}$  is increased to 140 pF.

Example: if the nominal resonant frequency is 125 kHz, then the response frequency for a low-bit is given by:

$$f_{L(nom)} = \frac{1}{\frac{1}{f_{RES(nom)}} - 28 \text{ ns}}$$

$$f_{L(nom)} = \frac{1}{\frac{1}{125 \text{ kHz}} - 28 \text{ ns}} = 125.4 \text{ kHz}$$

and the total capacitance needed to achieve this frequency is given by:

$$C_{TOT(nom)} = \frac{1}{4\pi^2 \cdot f_{RES(nom)}^2 \cdot L_{R(nom)}}$$

$$C_{TOT(nom)} = \frac{1}{4\pi^2 \cdot 125 \text{ kHz}^2 \cdot 2.61 \text{ mH}} = 621.1 \text{ pF}$$

When the modulation capacitor  $C_{M(125 \text{ kHz})}$  is switched on, the resonant frequency is given by:

$$f_{RES(high)} = \frac{1}{2\pi \sqrt{L_{R(nom)} \cdot (C_{TOT(nom)} + C_{M(nom)})}}$$

$$f_{RES(high)} = \frac{1}{2\pi \sqrt{2.61 \text{ mH} \cdot (621.1 \text{ pF} + 140 \text{ pF})}} = 112.9 \text{ kHz}$$

and the resulting nominal high bit frequency is therefore given by:

$$f_{H(nom)} = \frac{1}{\frac{1}{f_{RES(high)}} - 28 \text{ ns}}$$

$$f_{H(nom)} = \frac{1}{\frac{1}{112.9 \text{ kHz}} - 28 \text{ ns}} = 113.3 \text{ kHz}$$

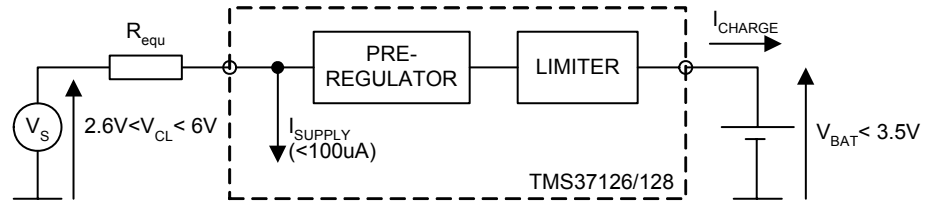
This corresponds to a frequency shift of 12.1 kHz.



# Using Other Inductance Values

The modulation capacitor for 125 kHz operation can also be used in 134.2 kHz systems to realize inductance values different from the recommended ones. This can be important for battery charge functions. The maximum available charge current is limited by the inductive coupling, which depends on the distance between the receiver and the transmitter and the transmitter's field strength. Figure 4 shows an equivalent circuit describing the electromagnetic coupling between a transmitter and a transponder. It consists of a voltage source  $V_S$  with source resistance  $R_{equ}$ .

**Figure 4: Equivalent Circuit Describing Electromagnetic-Coupled System**



The unloaded voltage source  $V_S$  of an arrangement with transponder ferrite coil depends on the field strength at the transponder and the antenna characteristics.

This can be described with the following formula:

$$V_S = \frac{2\pi \cdot \mu_0 \cdot \mu_{ROD} \cdot F_V \cdot N_{TRP} \cdot r_{ROD}^2 \cdot \pi \cdot Q_{TRP} \cdot 10^{(H[dB\mu A/m] / 20)}}{10^6}$$

Where:

$\mu_0$  = Magnetic Field Constant

$\mu_{ROD}$  = Effective Rod Permeability

$F_V$  = Flux Distribution Averaging Factor of Transponder Antenna

$N_{TRP}$  = Number of Transponder Antenna Windings

$r_{ROD}$  = Radius of rod

$Q_{TRP}$  = Quality factor of transponder

The Equivalent Source Resistance  $R_{equ}$  depends on the resonant frequency  $f_{RES}$ , the transponder antenna inductance  $L_R$  and the antenna quality factor  $Q_{TRP}$ , as follows:

$$R_{equ} = 2\pi \cdot f_{RES} \cdot L_R \cdot Q_{TRP}$$

The input voltage at the charge regulator circuit has to be above a certain limit for the circuit to function correctly, so the difference between the source voltage  $V_S$  and the input voltage  $V_{CL}$ , and the value of  $R_{equ}$  determine the maximum available current  $I_{equ}$ , as follows:

$$I_{equ} = \frac{V_S - V_{CL}}{R_{equ}}$$

In the case of high field strengths, which are required for charging operations,  $V_{CL}$  is much lower than  $V_S$  and can be neglected. In order to increase  $I_{equ}$  either  $V_S$  must be increased or  $R_{equ}$  must be decreased.

## 5.1 Reduction of $R_{equ}$

$R_{equ}$  is decreased if either  $Q_{TRP}$  or  $L_R$  is decreased. However, since reducing  $Q_{TRP}$  also reduces the source voltage  $V_S$ , reducing  $Q_{TRP}$  is of limited value in increasing charge current.

Only a reduction of  $L_R$  is therefore important, but it also has an effect on the source voltage  $V_S$ . A reduction of  $L_R$  means reducing number of turns  $N_{TRP}$ , but this effect is less dramatic because  $L_R$  is given by:

$$L_R = \frac{N_{TRP}^2 \cdot \mu_0 \cdot \mu_{ROD} \cdot r_{ROD}^2 \cdot \pi}{l} \cdot \frac{l_C}{l}$$

Where:

$l_C$  = Length of windings

$l$  = Length of rod

and therefore  $N_{TRP}$  is only reduced by the square-root of  $L_R$  reduction.

## 5.2 Increasing $V_S$

As previously explained, increasing  $N_{TRP}$  in order to increase  $V_S$  is not recommended. Increasing the permeability of the rod  $\mu_{ROD}$  is also of limited use, if the length to diameter ratio  $m$  is less than ten and ferrite material permeability is greater 1000, which is typically the case. Figure 5 shows a diagram out of magnetic circuit theory literature, which can be used to determine  $\mu_{rod}$ , based on material permeability  $\mu$  and length:diameter ratio  $m$ .

The best way to increase charge current (besides decreasing inductance) is to increase the coil length  $l$  and rod radius  $r_{ROD}$ .

## 5.3 Combinations of components and configurations

In the next table some possible combinations of  $L_R$  and  $C_R$  are shown using different modulation capacitors  $C_M$ :

**Table 3: Various Component Combinations**

$f_{RES}$ (kHz)	$L_R$ (mH)	$C_{LR}$ (pF)	$C_R$ (pF)	$C_T$ (pF)	$C_{RF1}$ (pF)	$C_M$ (pF)	$f_{RES}$ (kHz)	Shift (kHz)
134.2	2.61	7.00	470	35.0	27.0	110	122.3	12
134.1	2.24	7.00	560	35.0	27.0	110	123.7	10
134.1	2.05	7.00	620	35.0	27.0	140	122.2	12
134.1	1.88	7.00	680	35.0	27.0	140	123.1	11
134.1	1.72	7.00	750	35.0	27.0	140	123.9	10

Note: If the inductor capacitance  $C_{LR}$  is different  $L_R$  must be adapted accordingly.

**Figure 5: Determination of Rod Permeability**