Inductive Antenna Coupling In Regenerative Receivers

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Abstract

Inductive coupling is probably the most widely used form of coupling of the antenna to the RF input tank in radio receivers. For superheterodyne receivers this topic has been treated extensively in the literature on radio receiver design. However, for regenerative receivers using inductive feedback that were quite popular as low-cost commercial receivers in Europe from the 1930s to the end of the 1940s, little can be found on the issue of inductive antenna coupling with respect to the requirements and circuit behavior that arises with regenerative circuits. In the predecessor of this paper [2] the influence of an inductively coupled electrically short antenna an regeneration has been studied focusing on the feedback behavior if the antenna tank's resonant frequency falls into the reception frequency range. In this paper, we shall focus on the more common cases where the antenna tank is driven either well below or well above it's resonant frequency. Also, we shall cover more aspects of the antenna coupling, including voltage transfer and detuning of the RF input tank.

General Considerations

A good start into the topic of inductive antenna coupling in regenerative receivers is to ponder over the following question: What is the purpose of the RF input tank and why isn't it simply replaced by a tuned[1] antenna tank that can make use of the full antenna voltage pickup? The answer to this question certainly depends on what type of receiver one is looking at.

In Superheterodyne receivers, there is the need of ganging the oscillator tank to the RF input tank. Obviously, this requires an RF input tank with well defined parameters that simply cannot be replaced by a tuned antenna tank with parameters depending heavily on the antenna and varying over a wide range. In fact, the primary design goal for the antenna to RF input tank coupling is

[1] In this paper, we shall exclusively look at electrically short antennas for the AM broadcast bands. Hence, the antenna behaves capacitively and is tuned by a variable inductor.

to prevent the antenna from overly detuning the RF input tank and thereby destroying the ganging. Voltage transfer from the antenna into the RF input tank is secondary to detuning concerns since the IF-amplifier provides an abundance of amplification.

In non-regenerative single tank tuned radio frequency (TRF) receivers the situation is different. Using a tuned antenna tank in place of the RF input tank might be feasible if the antenna loss resistance is relatively low and therefore the bandwidth of the antenna tank is still at an acceptable level. If this is not the case, a separate high Q-factor RF input tank is needed and the primary design goal of the antenna coupling is now to provide impedance matching between the antenna loss resistance and the much lower RF input tank loss resistance.

In regenerative receivers, positive feedback into the RF input tank is used to create a (virtual) negative loss resistance in the tank in order to partially compensate it's losses and reach a higher virtual Q-factor. Hence, the RF tank can be replaced by a much lossier tuned antenna tank with positive feedback applied. In theory, an arbitrarily high loss resistance of the antenna tank can be compensated by an appropriate amount of positive feedback. In practice, however, large amounts of positive feedback are difficult to control and the viable amount of feedback is typically limited to a negative loss resistance of a few hundred ohms. Nevertheless, this is sufficient for most indoor and outdoor antennas. Obviously, for homebrew regenerative receivers built, set up and operated by technically knowledgeable persons replacing the RF input tank by a tuned antenna tank is feasible and will provide a highly sensitive receiver since the full antenna voltage pickup is now used to drive the tank.

However, in commercially available receivers meant to be set up and operated by technical lay persons the user cannot be tasked with setting up an electrically short antenna of a given capacitance to be tuned by an antenna tuning coil built into the receiver. Hence, as with superheterodyne and single tank non-regenerative TRF receivers, the only way to create viable commercially available regenerative receivers is to use an RF input tank with an antenna coupled to it.

There is a wide variety of antenna coupling circuits [1]. However, the most widely used method of antenna coupling in regenerative receivers seems to be inductive coupling. In the predecessor [2] of this paper a circuit model for the regenerative receiver with inductive antenna coupling has been presented and analyzed. The focus there has been to show that the antenna tank must be operated either well above or well below it's resonant frequency since otherwise the feedback behavior is highly unfavorable [2] and we shall now focus on these two operating regions

[2]Also, the tuning behavior might be highly unfavorable since for a sufficiently high coupling factor the frequency response curve will exhibit the well known double humped shape.

of the antenna tank with respect to voltage transfer, reflected loss resistance, reflected reactance (detuning) and feedback behavior.

The Circuit Model

For the convenience of the reader, let us start by presenting the circuit model for the regenerative receiver with inductive antenna coupling that was introduced in [2] once again (figure 1).

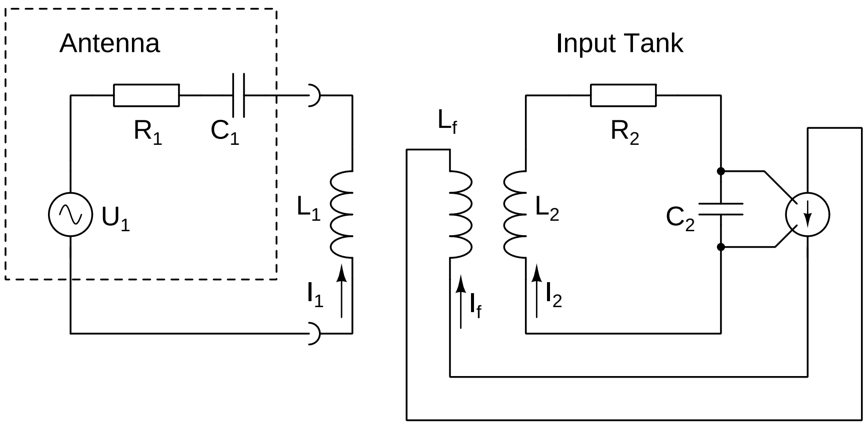

Figure 1: Antenna, RF input tank and feedback circuit

In the AM broadcast bands, the antenna is typically an electrically short wire antenna that can be modeled [3] by an ideal voltage source representing the voltage pickup U_1 of the antenna in series with the antenna's capacitance C_1 and loss resistance R_1. The antenna is in most cases connected to an antenna coil L_1 in the receiver that is inductively coupled to the RF input tank coil L_2. The losses in the RF input tank are modeled by a series loss resistance R_2.

The input voltage of the feedback device is the voltage U_{C2} across the RF input tank capacitor C_2 and it's output is connected to a feedback (tickler) coil L_f that is coupled inductively to the input tank coil L_2. The current impressed in the feedback coil is given by

$$I_\mathrm{f} = \beta U_{C2}$$

where β is the transconductance of the current source. It was shown in [2] that the current phasor I_2 in the RF input tank fulfills

$$Z I_2 = U_{12} \tag{1}$$

with

$$Z = j\omega L_2 + \frac{1}{j\omega C_2} + R_2 + M_{2\mathrm{f}}\frac{\beta}{C_2} - \frac{j\omega M_{12}\left(M_{1\mathrm{f}}\frac{\beta}{C_2} + j\omega M_{12}\right)}{R_1 + \frac{1}{j\omega C_1} + j\omega L_1} \tag{2}$$

and

$$U_{12} = \frac{-j\omega M_{12}}{R_1 + \frac{1}{j\omega C_1} + j\omega L_1} U_1 \tag{3}$$

In the above equations, M_{nm} are the mutual inductances between the coils involved that are related to their respective inductive coupling factors k_{nm} by [4]

$$M_{nm} = k_{nm}\sqrt{L_n L_m} \tag{4}$$

From equation (2) the virtual loss resistance that shows up in the RF input tank due to the applied feedback can readily be identified as:

$$R_\mathrm{f} = M_{2\mathrm{f}}\frac{\beta}{C_2} \tag{5}$$

In order to provide positive feedback, i.e. $R_\mathrm{f} < 0$, the transconductance β and the mutual inductance $M_{2\mathrm{f}}$ need to have opposite signs. It is worth noting that all results presented here are, of course, also applicable to non-regenerative receivers by simply setting $\beta = 0$. In fact, the results derived for voltage transfer, reflected loss resistance and reflected reactance are directly applicable to non-regenerative circuits since these expressions do not depend on β respectively R_f.

The equations given so far describe the behavior of the RF input tank for arbitrary driving frequencies ω. In the case of the antenna tank being driven well below it's resonant frequency $\omega_1 = 1/\sqrt{L_1 C_1}$, we have

$$\frac{1}{\omega C_1} \gg \omega L_1 \quad \text{respectively} \quad \left(\frac{\omega}{\omega_1}\right)^2 \ll 1 \tag{6}$$

For typical antenna losses R_1 and capacitances C_1, we also have

$$\left(\frac{1}{\omega C_1}\right)^2 \gg R_1^2 \tag{7}$$

On the other hand, if the antenna tank is being driven well above it's resonant frequency, we have

$$\frac{1}{\omega C_1} \ll \omega L_1 \quad \text{respectively} \quad \left(\frac{\omega}{\omega_1}\right)^2 \gg 1 \tag{8}$$

and

$$(\omega L_1)^2 \gg R_1^2 \tag{9}$$

for typical antenna losses R_1 and antenna coil inductances L_1.

Voltage Transfer

Let us first look at the voltage transfer from the antenna tank into the RF input tank. From equation (1) the complex voltage reflected into the RF input tank can readily be identified as U_{12} and the ratio of the absolute values of the voltage reflected into the RF input tank and the voltage pickup of the antenna immediately follows from equations (3) and (4) to be

$$\frac{|U_{12}|}{|U_1|} = \frac{\omega k_{12}\sqrt{L_1 L_2}}{\sqrt{R_1^2 + \left(\omega L_1 - \frac{1}{\omega C_1}\right)^2}}$$

In the case of the antenna tank being driven well below it's resonant frequency ω_1 we can use relations (6) and (7) to obtain

$$\frac{|U_{12}|}{|U_1|} = \left(\frac{\omega}{\omega_1}\right)^2 k_{12}\sqrt{\frac{L_2}{L_1}}$$

In case of the antenna tank being driven well above it's resonant frequency ω_1 using relations (8) and (9) yields

$$\frac{|U_{12}|}{|U_1|} = k_{12}\sqrt{\frac{L_2}{L_1}}$$

Obviously, when the antenna tank is driven well above it's resonant frequency, the voltage transfer into the RF input tank becomes frequency independent.

Reflected Loss Resistance

From equation (2), the loss resistance reflected from the antenna tank into the RF input tank is found to be [2]

$$R_{12} = \frac{R_1\left(\omega M_{12}\right)^2}{R_1^2 + \left(\omega L_1 - \frac{1}{\omega C_1}\right)^2}$$

For the case of the antenna tank being driven well below it's resonant frequency, applying relations (6) and (7) results in

$$R_{12} = \left(\frac{\omega}{\omega_1}\right)^4 k_{12}^2 R_1 \frac{L_2}{L_1}$$

while for the case of the antenna tank being driven well above it's resonant frequency, applying relations (8) and (9) leads to

$$R_{12} = k_{12}^2 R_1 \frac{L_2}{L_1}$$

Similar to the voltage transfer behavior, driving the antenna tank well above it's resonant frequency will make the loss resistance reflected from the antenna tank into the RF input tank independent of the driving frequency.

Reflected Reactance

Using equation (5), the imaginary part of the last summand of Z as given by equation (2) can be written as $j(X_\mathrm{f}' + X_{12})$ with

$$X_\mathrm{f}' = -\frac{\omega \frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}} L_1 R_\mathrm{f} R_1}{R_1^2 + \left(\omega L_1 - \frac{1}{\omega C_1}\right)^2} \quad \text{and} \quad X_{12} = -\frac{\omega^2 k_{12}^2 L_1 L_2 \left(\omega L_1 - \frac{1}{\omega C_1}\right)}{R_1^2 + \left(\omega L_1 - \frac{1}{\omega C_1}\right)^2}$$

From the inductive coupling factors involved in the expression for X_f, we can tell that X_f is a reactance showing up in the RF input tank due to indirect feedback [2], while X_{12} is the reactance reflected from the antenna tank into the RF input tank. We shall at this time focus on X_{12} and postpone analyzing X_f'.

In case of the antenna tank being driven well below it's resonant frequency, we can use relations (6) and (7) to obtain

$$X_{12} = \omega \cdot \left(\frac{\omega}{\omega_1}\right)^2 k_{12}^2 L_2$$

which can be interpreted as an additional, frequency dependent inductance

$$L_{12} = \left(\frac{\omega}{\omega_1}\right)^2 k_{12}^2 L_2$$

being added to the physical inductance L_2 of the RF input tank, lowering it's resonant frequency. However, in case of the antenna tank being driven well above it's resonant frequency, we can use relations (8) and (9) instead, and now obtain

$$X_{12} = -\omega k_{12}^2 L_2$$

which obviously reduces the inductance of the RF input tank to $L_2' = (1-k_{12}^2)L_2$, thereby increasing it's resonant frequency.

Indirect Feedback

Indirect feedback in regenerative receivers with inductive feedback arises due to the feedback coil[3] having some degree of coupling to the coil of the antenna tank,

[3] often called "tickler coil".

which in turn is coupled to the coil of the RF input tank. For a more in-depth introduction, the reader is referred to [2].

The effects of indirect feedback can be described by an additional resistance as well as an additional reactance showing up in the RF input tank that both depend on the amount of (positive) feedback applied. The amount of feedback applied can conveniently be described in terms of the virtual loss resistance $R_\mathrm{f} < 0$ showing up in the RF input tank as given by equation (5) rather than in terms of the transconductance β of the feedback device.

It was shown in [2] that the additional (series) resistance R'_f that appears in the RF input tank due to indirect feedback is given by

$$R'_\mathrm{f} = -R_\mathrm{f}\frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}}\frac{\omega L_1\left(\omega L_1 - \frac{1}{\omega C_1}\right)}{R_1^2 + \left(\omega L_1 - \frac{1}{\omega C_1}\right)^2}$$

It should be noted that $k_{12}k_{1\mathrm{f}}/k_{2\mathrm{f}} \geq 0$ for all possible coil arrangements [2]. The additional reactance X_f appearing in the RF input tank due to indirect feedback has been derived in the previous section to be

$$X'_\mathrm{f} = -\frac{\omega\frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}}L_1 R_\mathrm{f} R_1}{R_1^2 + \left(\omega L_1 - \frac{1}{\omega C_1}\right)^2}$$

For the case of the antenna tank being driven well below it's resonant frequency, applying relations (6) and (7) yields

$$R'_\mathrm{f} = R_\mathrm{f}\frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}}\left(\frac{\omega}{\omega_1}\right)^2 \quad \text{and} \quad X'_\mathrm{f} = -\omega\cdot\left(\frac{\omega}{\omega_1}\right)^2\frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}}C_1 R_1 R_\mathrm{f}$$

For the case of the antenna tank being driven well above it's resonant frequency, using relations (8) and (9) results in

$$R'_\mathrm{f} = -R_\mathrm{f}\frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}} \quad \text{and} \quad X'_\mathrm{f} = -\omega\cdot\left(\frac{\omega_1}{\omega}\right)^2\frac{k_{12}k_{1\mathrm{f}}}{k_{2\mathrm{f}}}C_1 R_1 R_\mathrm{f}$$

Let us first look at the additional detuning of the RF input tank that is caused by indirect feedback. The reader is reminded that the feedback device has been chosen such that no direct feedback detuning occurs [5]. From the above expressions for X'_f it becomes clear that since $R_\mathrm{f} < 0$ in both cases the inductance of the RF input tank is increased by a frequency dependent positive virtual inductance resulting in a detuning towards lower frequencies.

However, the additional loss resistance R'_f in the RF input tank caused by indirect feedback differs drastically between the two cases. Obviously, if the antenna tank is driven well below it's resonant frequency indirect feedback increases the total amount of positive feedback into the RF input tank since R'_f and R_f have the same sign. On the other hand, if the antenna tank is driven well above it's resonant frequency indirect feedback reduces the total amount of positive feedback into the RF input tank since in this case R'_f and R_f have opposite signs. The reader is again reminded that $k_{12}k_{1\mathrm{f}}/k_{2\mathrm{f}} \geq 0$ for all possible coil arrangements [2].

References

[1] K.R. Sturley, *Radio Receiver Design, JOHN WILEY & SONS*, 1943

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[4] http://en.wikipedia.org/wiki/Inductance

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