Interrogator For Stacked Passive Inductive Transponders


Abstract – In logistics and other applications there is a huge demand for passive inductive transponder systems that are used for “tagging” various objects. The capability to read multiple transponders quasi simultaneously is one of the main advantages when compared with other solutions. However, if the objects and thus the transponders as well are arranged in a stack – i.e. the mutual inductances of the transponder coils become very high – common transponder systems fail to operate since supply voltages induced in the passive transponders are not sufficient.

In this communication a system consisting of an interrogator and a stack of passive inductive transponders is analyzed employing network theory and computer simulations. A novel interrogator capable of reading a transponder stack is proposed and its operation verified by simulation results.

1 Introduction

Passive inductive transponders are devices capable of wireless data transmission without the need of their own power source. A magnetic powering field inducing a supply voltage in the transponder coils is generated by a power transmitter in the interrogator. The voltage is maximized if the transponders are in resonance with the transmitter frequency, since the transponder coils form a resonant circuit with a tuning capacitance [1].

There is a large range of possible applications for passive inductive transponders operating at RF frequencies, among them sensor applications [2], medical applications [3] and most important – RFID applications in logistics [4]. The RFID sales are expected to grow up to 18.6% p.a. during the next decade [5].

Especially for logistics applications it is important that several transponders can communicate with one interrogator. For example, stocktaking or counting of goods can be assisted by transponder technology. So called multitag systems are capable of this.

Multitag operation can easily be established using multitag protocols [1] as long as the distances between the transponders remain large. However, when the distances decrease the mutual inductances between the transponder coils increase. If they exceed a certain limit the system behaviour drastically differs from the single transponder case. The resonant circuits of the transponders become detuned. Since they are out of resonance, the power transmission fails and this results in insufficient supply voltages.

This problem is quite difficult to solve because the resonance frequency depends on the number of transponders, their spatial location, and their orientation: however, this is not known a priori. The worst condition is when all transponders are arranged side by side (i.e. in parallel to the flat side of the coil). In this arrangement as a stack, their mutual coupling is very high, and their resonance frequency strongly differs from the transmitter frequency. However, the transmitter frequency cannot be adjusted, since it is restricted by the ISM-band limits.

The problem is called the stack problem of passive inductive transponders. In this communication it is shown how classical linear network theory [6] and computer simulations can be employed to solve it.

The network analysis of general multitag systems is carried out in Section 2. The derived expressions form the basis for computer simulations.

In general multitag systems the number of parameters influencing the transponder resonances increases with the number of transponders N. However, for the transponder stack they can be projected onto a few quantities and thus a computer simulation can be employed. Simulation results for the stack that will be exploited for the modification are given in Section 3.

The modification that solves the stack problem is explained in Section 4. Computer simulation results show that the stack problem can be solved.

2 Network Analysis of Multitag Systems

The network model for the multigtag system is depicted in Fig. 1. The transmitter is simplified to be a voltage source $\hat{u}_0$ connected to a lossy coil. The transponders are modeled as damped resonant circuits. The current flowing in the transmitter circuit is denoted as $\hat{I}_1$, the inductance as $L_{im}$, and the transmitter coil resistance as $R_{im}$. The current in a transponder coil n is designated as $\hat{I}_n$, where $2 \leq n \leq N+1$. The inductance of the transponder coil is designated as $L_{tp}$, its resistance $R_{tp}$, and the tuning capacitance $C_{tp}$. The mutual inductance between two
The induced voltages are proportional to the currents flowing in the transponder circuits. Thus the frequencies where the induced voltages are at maximum can be determined by means of mesh current analysis where the coil currents are considered as mesh currents, and the transponder circuits and the transmitter circuit are considered as meshes. If the mesh impedance matrix $\tilde{Z}_M$ is defined as

$$\tilde{Z}_M = \begin{pmatrix} Z_{1,1} & Z_{1,2} & \cdots & Z_{1,N+1} \\ Z_{1,2} & Z_{2,2} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ Z_{1,N+1} & Z_{2,N+1} & \cdots & Z_{N+1,N+1} \end{pmatrix}$$  \hspace{1cm} (1)$$

the analysis yields.

$$\bar{Z}_{i,1} = R_{tm} + pL_{tm}$$ \hspace{1cm} (2)$$

$$\bar{Z}_{n,o} = R_{tp} + pL_{tp} + \frac{1}{pC_{tp}}$$ \hspace{1cm} (3)$$

$$\bar{Z}_{o,p} = pM_{o,p} \quad \text{for} \quad o \neq p$$ \hspace{1cm} (4)$$

The currents can now be calculated as

$$\tilde{I} = \tilde{Z}_M^{-1} \tilde{Z} \cdot \hspace{1cm} (5)$$

with

$$\tilde{Z}_M^{-1} = \frac{\tilde{A}}{\det \tilde{Z}_M}$$ \hspace{1cm} (6)$$

where $\tilde{A}$ is a matrix containing the adjuncts of $\tilde{Z}_M$. Considering $\tilde{Z}_M^{-1}$ as a function of $p$, and solving the equation

$$\det \tilde{Z}_M = 0$$ \hspace{1cm} (7)$$

yields the complex poles

$$p = \sigma_{o,y} + j\omega_{o,y},$$ \hspace{1cm} (8)$$

where the elements of $\tilde{Z}_M$ become infinite. The currents and thus the voltages reach a local maximum for $\omega_{op} = \omega_{o,y}$. The determinant is

$$\det \tilde{Z}_M = \left[ R_{tp} + pL_{tp} + \frac{1}{pC_{tp}} \right]^{N-1} \cdot \left[ R_{tm} + pL_{tm} \left( R_{tp} + pL_{tp} + \frac{1}{pC_{tp}} \right) - \sum_{a=2}^{N+1} (pM_{1,a}) \right] + \tilde{T}(p\tilde{M}),$$ \hspace{1cm} (9)$$

where $\tilde{T}(p\tilde{M})$ is an additional term that is zero when the mutual inductances between the transponder coils are also zero. That is why the transponder currents are nearly at maximum at the operating frequency when the distances between the transponders are large.

When the mutual inductances increase $T(p\tilde{M})$ the solutions of Equation 7 change. Thus the maxima of the currents appear at frequencies that depart from the resonance frequency.

Equation 7 determines the maxima for all transponders. Thus, if the current in one coil has reached a local maximum by varying the transmitter frequency, then the currents in all other transponders have reached a maximum, too.

For each transponder inserted into the reading area of the interrogator one row and one column is appended to $\tilde{Z}_M$. Thus the number of parameters influencing the possible transmitter frequencies $\omega_{o,y}$ increases with an increasing number of transponders. For a random arrangement the behaviour of the transponders cannot be predicted in general. However, if the transponders are arranged in a stack the complexity can be drastically reduced.

3 The Transponder Stack

The analyzed transponder stack is depicted in Fig. 2. The parameters $\tilde{Z}_M$ depends on are the induc-
tances, resistances, capacitances, mutual inductances, and the number of transponders \( N \). Neglecting the influence of the thickness of the coil wire the inductance of the transponder coils is determined by the number of turns \( n_{tp} \) and the coil radius \( r_{tp} \). The inductance of the transmitter coil is determined by its number of turns \( n_{tm} \) and radius \( r_{tm} \). The set of mutual inductances depends only on \( n_{tp}, r_{tp}, n_{tm}, r_{tm} \), and the distance between the transponder coils \( d_{tp} \). Thus all values of network elements can be projected onto \( N, n_{tp}, C_{tp}, r_{tp}, d_{tp}, R_{tm}, n_{tm}, \) and \( r_{tm} \).

\[ |i|/\mu A \]

Figure 2: sectional view of a transponder stack.

How do these parameters influence the resonances? Knowing the mesh currents in the transponders from Equation 5 and mutual inductances from appropriate formulae in the open literature \([6, 7]\) a computer simulation can be employed to analyze the relationship between the parameters of stacked transponders and their behaviour. Simulation results are given in Figures 3 and 4.

The number of maxima being observed is \( N \). They are spread over a frequency band between a lower frequency \( f_l \) and an upper one \( f_u \). The resonance frequency \( f_r = \frac{1}{2\pi \sqrt{L_1 C_1}} \) of a single transponder is roughly situated in the second third of it. It is the wider the smaller the quantity \( d/r_{tp} \) becomes. For

\[ d/r_{tp} > 2.3 \quad (10) \]

the effect can be neglected for the given system.

Fig. 4 shows how the width of the mentioned band depends on \( N \). The lower and upper frequency approach a lower and upper limit \( f_{l,\text{min}} \) and \( f_{u,\text{max}} \) while the number of transponders \( N \) increases.

4 Solution for the Stack Problem

The system behaviour is exclusively determined by the mesh impedance matrix \( \tilde{Z}_M \). The mesh impedance itself is determined by a limited set of parameters in a transponder stack. The coil geometries, their number of turns, the resistances, the resonant frequencies, and the distances between the transponders are once fixed by the developer. The number of transponders \( N \) cannot be fixed. It is changed every time the user inserts an additional transponder resulting in a changed \( \tilde{Z}_M \) and shifted resonance frequencies.

The solution to the stack problem is to affect \( \tilde{Z}_M \) in such a way independent of \( N \). Hence, additional meshes are to be inserted into the network. They can be formed by variable coils that are magnetically
coupled with the transponder coils and variable network elements connected to their terminals.

It is proposed to put at least one additional resonant circuit near the stack of transponders. Its coil is magnetically coupled with the transponder coils. It is tunable by either varying its capacitance or inductance. Such a device shall be designated an external tuning device.

The effect of such a device on a system can be investigated by means of computer simulation. Fig. 5 displays simulation results for the case of a single additional resonant circuit. It can be seen that the device has added an additional maximum. The location can be controlled by tuning the resonance frequency of the additional resonant circuit.

![Figure 5: Effect of the external tuning device on the system behavior](image)

The larger the number of transponders \(N\) the smaller is the average induced current and thus the voltage. Thus the transponders resonance frequency has to be chosen so that the lower frequency of the described band is

\[
f_{\text{u,min}} = f_{\text{op}},
\]

where \(f_{\text{op}}\) is the operating frequency of the transmitter. Hence, as soon as \(N\) exceeds a certain limit the induced voltage suffices to make the transponders operate. For a smaller number of transponders sufficient induced voltage can be obtained when the external tuning device is provided.

### 5 Summary

In the past one of the main problems of multitag passive transponders was the stack problem. The transponders became detuned if arranged in a stack and this lowered the induced voltage supplied by the power transmission and inhibited their operation.

In this communication we have shown how to solve the problem by employing network theory. The behaviour of the transponders is determined by the mesh impedance matrix \(\mathbf{Z}_M\) of the transponder network. Hence the coil currents of the transponders reach no maximum at the frequency of the power transmitter if they are closely coupled.

The solution proposed in this communication requires no modification of the existing passive transponders, only of the interrogator. An external tuning device has to be added. Simulation results and measurements have confirmed that the solution provides reliable operation for stacked transponders.

In theory stacks of passive inductive transponders can now be powered at a fixed frequency within an ISM band. Simulations and measurements have verified that an additional maximum can be generated by an external tuning device and its frequency can be controlled by tuning the device. A demonstrator for an interrogator for transponder stacks is now under development.

### References


