Design and Evaluation of RFID Systems using the Partial Element Equivalent Circuit Method

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Abstract

Systems based on radio frequency identification (RFID) techniques are finding new markets and uses. For maximal readability, RFID-systems have to be tailored to its specific environment. In this paper, the partial element equivalent circuit (PEEC) method is used to analyze an RFID-system with reader, tag, and additional electronic circuitry. The results show how the method can be used to match antennas with discrete, external components and study the backscattered energy from the tag. The simulations are very fast which allows for studying multiple locations of the tag in order to tailor the RFID-system.

1 Introduction

When designing a radio frequency identification (RFID) system an accurate model of both the circuits and the electromagnetic properties of the antennas is desired. A magnetically coupled RFID system operating at low frequency is typically modeled using an equivalent circuit where the reader and transponder antennas are represented by an inductance. The inductance of the antennas can be calculated using either analytical expressions [1] or using a simulation software [2, 3]. In this paper, the partial element equivalent circuit (PEEC) method [4] is used to make a combined model of both the antennas and the circuits of the system.

The PEEC method is based on the integral formulation of Maxwell's equations which enables modeling of the whole system without having to discretize the air between the antennas. The conductors and dielectrics are represented by inductances, capacitances, and resistances, which makes it possible to add external components to the circuit. A combined circuit and electromagnetic solution can therefore be performed and the same equivalent circuit can be used in both the frequency and the time domain. This paper focus on modeling RFID reader antennas in the 125 kHz frequency band. The PEEC model is presented in more detail in Section 2. The procedure for designing and evaluating a RFID system using PEEC is described in Section 3. Finally, conclusions are given in Section 4.

2 The Partial Element Equivalent Circuit (PEEC) Method

This section gives an brief summary of the classical, orthogonal PEEC formulation. For further information, see [4].

The classical PEEC method is derived from the equation for the total electric field at a point written as

$$\vec{E}^i(\vec{r},t) = \frac{\vec{J}(\vec{r},t)}{\sigma} + \frac{\partial \vec{A}(\vec{r},t)}{\partial t} + \nabla \phi(\vec{r},t) \tag{1}$$

where $\vec{E}^i$ is an incident electric field, $\vec{J}$ is a current density, $\vec{A}$ is the magnetic vector potential, ϕ is the scalar electric potential, and σ is the electrical conductivity, all at observation point $\vec{r}$. By using the definitions of the scalar and vector potentials, the current- and charge-densities are discretized by defining pulse basis functions for the conductors and dielectric materials. Pulse functions are also used for the weighting functions, resulting in a Galerkin type solution. By defining a suitable inner product, a weighted volume integral over the cells, the field equation (1) can be interpreted as Kirchhoff's voltage law over a PEEC cell consisting of partial self inductances between the nodes and partial mutual inductances representing the magnetic field coupling in the equivalent circuit. The partial inductances shown as Lp_{11} and Lp_{22} in Fig. 1 are defined as

$$Lp_{\alpha\beta} = \frac{\mu}{4\pi}\frac{1}{a_\alpha a_\beta}\int_{v_\alpha}\int_{v_\beta}\frac{1}{|\vec{r}_\alpha - \vec{r}_\beta|}dv_\alpha dv_\beta. \tag{2}$$

Figure 1 also shows the node capacitances which are related to the coefficients of potential p_{ii} while ratios consisting of p_{ij}/p_{ii} leads to the current sources in the PEEC circuit. The coefficients of potentials are computed as

$$p_{ij} = \frac{1}{S_i S_j}\frac{1}{4\pi\epsilon_0}\int_{S_i}\int_{S_j}\frac{1}{|\vec{r}_i - \vec{r}_j|}\,dS_j\,dS_i. \tag{3}$$

There is also a resistive term between the nodes, defined as

$$R_\gamma = \frac{l_\gamma}{a_\gamma \sigma_\gamma}. \tag{4}$$

In (2) and (4), a is the cross section of the rectangular volume cell normal to the current direction, γ and l is the length in the current direction. Further, v represents the current volume cells and S the charge surface cells. For a detailed derivation of the method, including the nonorthogonal formulation, see [5].

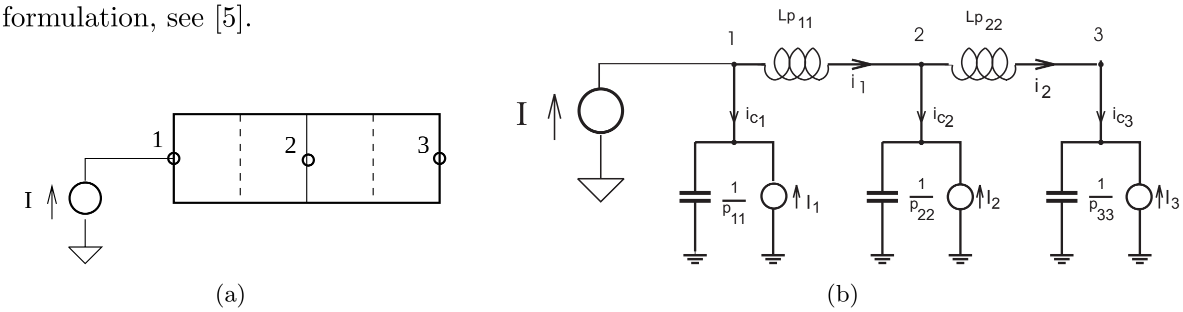


Figure 1: Metal strip with 3 nodes and 2 cells (a) and corresponding PEEC circuit (b).

As seen, the PEEC method is a framework for creating electric equivalent circuit representations of general electromagnetic problems. If a quasi-static approximation is valid, the PEEC:s can be solved to obtain the current- and potential distribution in a free/commercial SPICE-like solver with support of additional electrical components. Thus, allowing for a mixed circuit/electromagnetic solution suitable when studying RFID systems. However, for the full-wave case when retardation in electromagnetic couplings are of importance, the circuit equations [6] have to be formulated and solved in a specialized solver.

3 Design Example

The antennas studied in this paper are RFID reader antennas operating in the 125 kHz frequency band. This is a popular frequency for use in industrial environments due to its immunity to damping from dielectric materials [7]. There is however, still a possibility that metallic objects located close to the antenna interfere with the measurements and the RFID system therefore needs to be designed uniquely for each application. In this Section, the PEEC method is used in the design process of RFID reader antenna for passive tags operating in an industrial environment.

The application considered is a typical industrial situation, where the RFID tags are placed among raw material that is transported on a conveyor belt. It is then advantageous to let the conveyor belt run through the antenna, since this is a region where the magnetic field of the antenna is strong, which makes detection of the tags more likely. The antenna considered here consists of two identical square coils connected in parallel, where the region of interest is inside the coils. The distance between the coils is 1 m. This design will expand the region in which

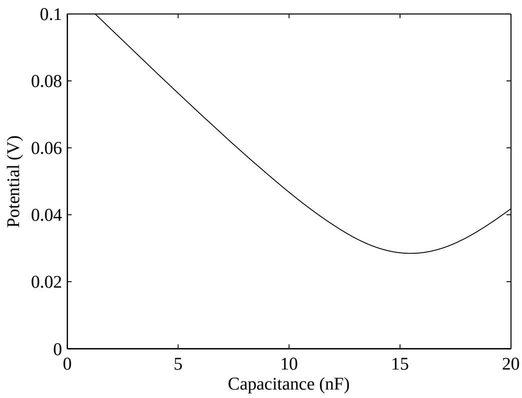


Figure 2: PEEC modeling results: The potential at the end of the coil vs. size of the capacitance connected between feed and end.

the tags can be detected, thereby further increasing the probability that the tags are detected. This is important since, in this application, the orientation of the tags cannot be controlled.

The tag used in the simulations is assumed to be a square coil with 100 turns and a wire with a square cross section of 0.1×0.5 mm. The length of the side of the innermost turn is 25 mm and the outermost turn has a side with length 56 mm. The two ends of the coil are connected via a capacitance of 1.4 nF, in order to make a matched circuit. A realistic tag will have a significantly more complex circuitry than just a capacitor, but the model used is chosen since the main interest is in comparing the backscattered energy using different reader antennas.

3.1 Matching of the Antenna

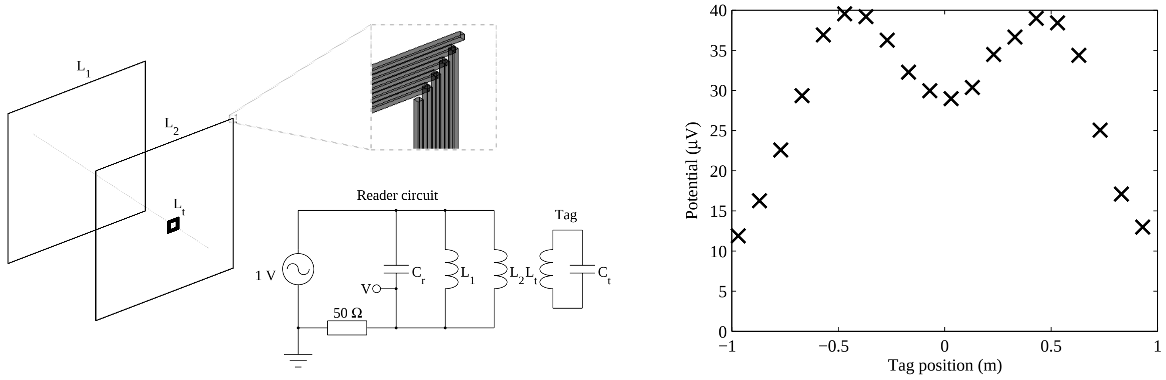
An illustration of the RFID system as well as a schematic overview is shown in Fig. 3 (a). The antenna is fed be a voltage source at one end of the coils and the other end is connected via a 50 Ω resistance to ground. This end is also where the voltage is measured, i.e. a voltage probe is placed here in the simulations. The two coils are connected to each other with a small resistance (of neglectable size) and the ends of the coils are connected to each other via a capacitance as shown in Fig. 3 (a). The size of the capacitance is chosen in order to maximize the energy dissipated by the coils. This means that the voltage measured with the probe should be minimized. Due to the mutual inductance between the two coils the size of the capacitance will depend on the distance between the coils. In Fig. 2 the simulated potential vs. capacitance is shown for a distance of 1 m between the coils. It can be seen that choosing a capacitance of 15.5 nF will maximize the energy that is dissipated.

3.2 Backscattered Energy from the Tag

In Fig. 3 (b) the energy backscattered by the tag is shown. The backscattered energy is seen as the difference of the potential measured by the reader when the tag is present compared to when tag tag is absent, and using a 1 V voltage source. The coils are located at -0.5 and 0.5 m, as seen in Fig. 3 (a), which corresponds to the two maxima seen in the figure. Using this type of antenna the region where the tag can be detected is increased without adding any extra circuits. This region can be further extended by using additional coils connected in parallel. This will, however, require another size of the capacitance in order to obtained a matched circuit.

4 Discussion and Conclusions

This paper shows the applicability of the PEEC method in studying RFID-systems. It is shown how external lumped components can be optimized for, in matching RFID-system antennas and how backscattered energy from the tag can be studied. Further, the simulations are so fast that



(a) (b)

Figure 3: PEEC modeling results: Left - An RFID reader antenna using two coils connected in parallel. The tag is moved along the dotted line located in the center of the two coils. The width of the wires are 0.1 mm for both the reader and the tag. Right - the potential at the end of the coil with a tag present.

optimization for different readers and tags are easily performed for optimal readability. One advantage with using the PEEC method is the equivalent circuit formulation allowing for the presented RFID-systems to be further studied for it's time domain characteristics using the same program.

The next step is to study more complex RFID-systems using the nonorthogonal PEEC formulation.

Acknowledgements

The authors would like to thank Process IT Innovations and ElectroTech AB for financial and technical support.

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