Magnetic-Field Coupling Characteristics of Ferrite-Coil Antennas for Low-Frequency RFID Applications

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Abstract

Low-frequency technology has been widely used for detecting objects placed underground. Low-frequency radio-frequency identification (RFID) systems provide the advantage of better propagation in lossy materials such as rocks and soil. In this paper, we assume that buried objects will be tagged with low frequency RFID passive transponders and that a reader with the large single-loop antenna will be used to detect the objects. We propose new orientation-insensitive transponder's antenna. Simulated and measured results obtained from fabricated antennas based on the new design show some advantage over the traditional design. The new antenna offers a more uniform magnetic field pattern.

Keywords: *Low-frequency RFID, double-rod, ferrite core, coils.*

1. Introduction

Conventionally, low-frequency transponders have a multiple-turn coil wound around the longitudinal axis of a cylindrical ferrite core. Therefore, this type of transponder is strongly directional, which means the transponder's reception sensitivity is highest to the signals incident from the direction parallel to the longitudinal axis of the ferrite core and lowest to the signals incident from the direction orthogonal to the longitudinal axis of the ferrite core.

RFID technology has been used in the detection of underground objects [1-3]. A simple RFID system consists of two components which communicate wirelessly. The first component, a reader, is connected to a relatively large antenna. The second component, called the tag or transponder has a small antenna. Low-Frequency (LF) band or Long-wave radio frequencies correspond to those below 500 kHz. Most publications on the RFID technology focused on transponders without a ferrite core. At LF, transponders with ferrite-core increase the magnetic field coupling between the reader's and the transponder's antennas.

It is possible to increase the overall reception sensitivity of this type of transponder's antenna by arranging two or three transponder-units that are mutually orthogonal to one another. However, it is not always practical to mount two or three transponders on one object-to-be-identified due to limited space. When two or three separate transponders are mounted in one object this way, the space occupied by the object increases and thus the object itself must be large enough to accommodate these transponders.

This paper presents one novel design that alleviates above-discussed problems that conventional cylindrical ferrite-core antennas have. Compared to the scenario where several transponder-antennas are to be used to provide the same feature, the new design would be smaller.

This type of RFID system is intended to be used to detect the buried objects in the proximity of the reader single-loop antenna in media such as rocks, wet soil, cement, etc. Typically, the transponders would be attached to the underground objects, while the reader's large single-loop antenna is placed directly on the ground surface or very near the ground surface.

RFID systems need to be designed and tuned to operate in these conditions. However, few published academic research has focused on these areas, especially for low-frequency RFID. Thus an investigation of some important parameters affecting the low-frequency RFID performance, by means of numerical simulations of transponder-reader coupling supported by the measurements, which is presented in this paper, is beneficial.

Signal attenuation has been shown to be a major factor when the frequency is above LF range [4-6]. In this research, we studied the performance of RFID systems working in the range of 125-150 kHz.

Wireless communication can be grouped into two modes: near-field and far-field communications. In the near field region, the electric and magnetic field components decay rapidly with the distance (i.e.: one over distance-cube) [8].

In low-frequency RFID systems, as distance between the reader and the transponder is much shorter than the free-space wavelength, the magnetic coupling between the reader's single-loop antenna and the transponder's coil antenna is the dominant mode of operation.

One of the research objectives was to study the near-field coupling of the low frequency RFID system as a function of various media where the transponder is buried. Experimentations were performed on a coil transponder placed underneath a large container containing the media to be studied. The experimentations were limited to small rocks and open-air. Numerical data were obtained using FEKO. FEKO is a full wave, method of moment (MoM) based simulation software for the analysis of various electromagnetic problems. FEKO calculates the electromagnetic fields by first calculating the electric surface currents on conducting surfaces and equivalent electric and magnetic surface current on the surface of a dielectric volume [7].

We analyzed the effects of the single-loop antenna's radius on the received power at the transponder-transponder's antenna in Section-2. In addition, the effect of the relative-orientation between the reader and the transponder-antenna and the effect of using a ferrite core, to the coupling, is presented. In Section 3, the proposed transponder-antenna is described.

2. Characterization of Single-Loop Antenna

Current low-frequency RFID systems operate in the near-field region, where the communicating antennas are multiple-turn antennas. In our research, the transponder-coil consists of approximately 500 turns. We used two coils with inner diameter of 0.8 cm. One coil contained a ferrite core, and another one was used without the core. The reader's antenna is a large single-loop antenna of various diameters.

The use of the ferrite core helped increase the magnetic coupling between the reader's single-loop and the transponder's coil, particularly for the LF range.

An investigation of two coils (with ferrite-core and without ferrite-core) has been conducted to compare the effect of the ferrite-core. Both have the same number of windings (500 turns). This number of turns stems from the optimal number of turns (to maximize the radiated power), calculated from equations given in [9]. The ferrite permeability was estimated to be 1300, based on typical ferrite values [10].

2.1 Effect of the Single-Loop Size and Multiple-Turn Coil Position

The single-loop's radius influences the coupling between the multiple-turn coil and the single-loop. The effect of horizontal positioning (with respect to the plane of the loop) is analyzed. Measured and simulated data are plotted in Figure 1. It shows the simulated near-field total power coupled from a single-turn loop to a ferrite-coil, taken in the air at one meter above the loop-horizontal plane. The power at the loop's output terminals is 216 mW.

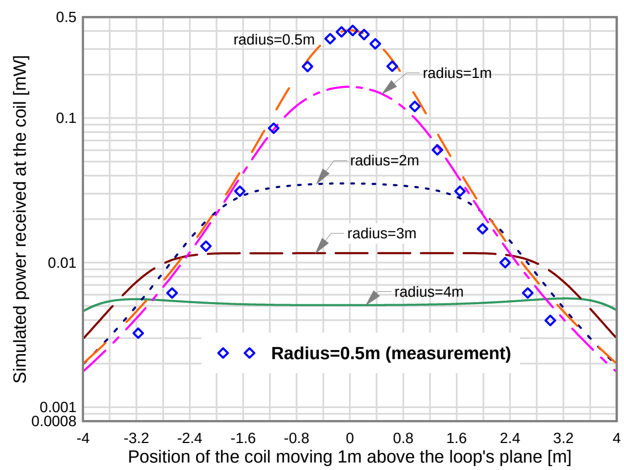

Fig. 1 Coupling between a large coil and a small coil, simulated and measured (diamond-dot), as a function of lateral position.

From our measurements and simulations, the coupled power decreases as the loop-radius increases. At LF, the wave-length equals to 2.14 km; thus the single-turn loop and the coil effective electrical-size are extremely small at this frequency, compared to the wave-length. In a two-dimensional representation, the measured results showed a similar trend as the simulated data, i.e. the coupled power peaked when the coil's position was at the center of the single-turn loop, when the loop-radius was at one meter or less, and the vertical-distance was at one meter. On the other hand, when the loop-radius was large, there were two maxima, each located near the edge of the single-turn loop, similar to results published in [11].

2.2 Effect of Ferrite and Coil-Orientation with respect to the Z-axis

The rotation of the transponder's coil can greatly affect the coupling between it and the reader's loop. Fig. 2 depicts the θ-angle of this rotation.

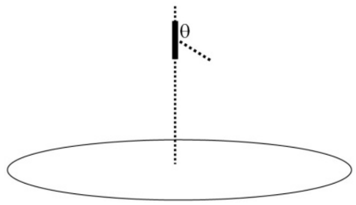

Fig. 2 Angle of rotation of the transponder.

Simulation of a coil with and without ferrite-core, when the angle of rotation is between 0 and 360°, has shown that a coil with ferrite-core (solid-line) has a magnetic coupling about 125 times greater than a coil without a ferrite-core (dashed-line), as shown in Figure 3, where the values on the left-y-axis were normalized to the maximum non-ferrite value.

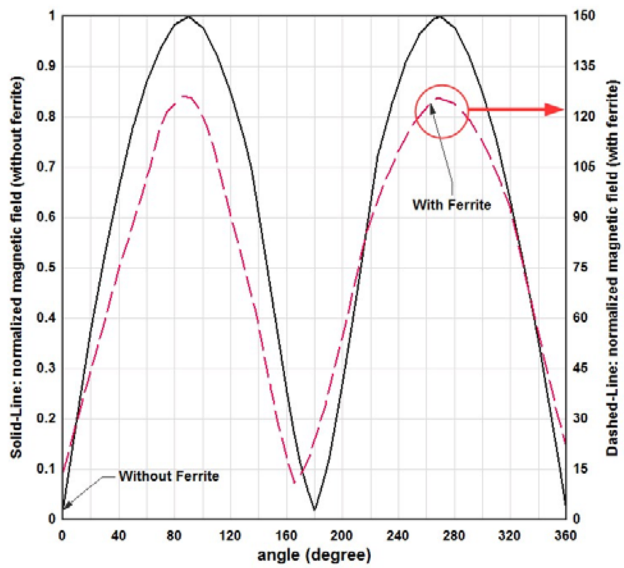

Fig. 3 Received magnetic field at the transponder's coil as a function of its orientation's angle.

This increase of the received magnetic field is due to the longitudinal shape and the permeability of the cylindrical ferrite-core.

3. Transponder-Antenna for Low-Frequency RFID

The cylindrical (rod) coil antenna is a highly directional antenna when it operates in the axial radiation mode. Two of the main parameters of the antenna are the high number of turns and the coil's circumference which is required to be much smaller than the axial length of the coil-cylinder [12].

Because of the high directivity of the cylindrical coil antenna with a very small diameter, good transmission and reception can only be guaranteed when the incoming electromagnetic waves are on the axis of the cylindrical coil. The maximum transponder's sensitivity can be improved with increased diameter, number of coil-turns, or insertion of a ferrite core [13]. However, this will increase the size and the weight of the antenna, which when used as RFID transponders, would not be desirable.

Instead, we propose the design of a dual-coil ferrite-core antenna that has a more uniform performance and is less dependent on the orientation of the cylindrical coil.

Shown in Figure 4 are two fabricated antennas: 14cm ferrite-rod length and 7cm ferrite-rod length.

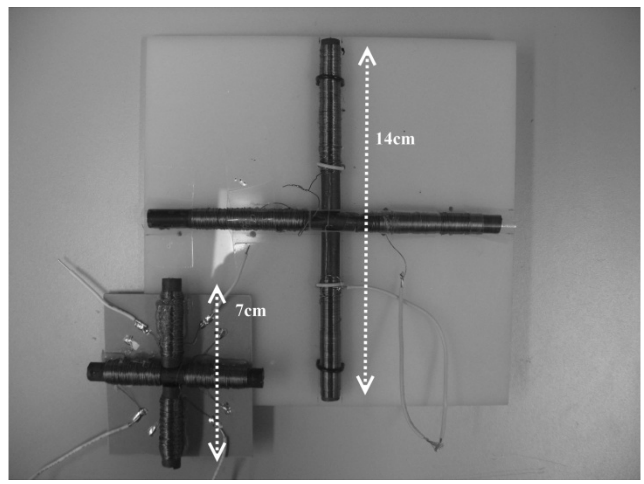

Fig. 4 Fabricated double-rod antennas (14cm version and 7cm version).

The two ferrite-cores are symmetric; one ferrite-core is cut into two equal parts, which are then attached at the center of the other ferrite-core.

The operation of a coil-antenna with a single ferrite-core has long been employed to receive magnetic field. These antennas normally consist of a coil wound on a single cylindrical core of high permeability of which the length-to-diameter ratio is very high. Provided that the magnetic flux concentration in the ferrite core is uniform, a long-cylindrical ferrite coil has an effective inductance estimated to be [14]:

$$L_{ferrite} = \pi a^2 N^2 \frac{\mu}{l} \quad (1)$$

where **μ** is the effective permeability of the coil, ***l*** is the length of the wounded ferrite-core, ***N*** is the number of coil-turns, and ***a*** is the radius of one wire-loop.

Electric field equations in the far-field of a cylindrical-coil antenna have been derived in [12].

In the vicinity of a multiple-coil antenna, the induced field is mostly magnetic. This induced magnetic field is estimated to be:

$$B_{coil} \approx \frac{\mu I l}{4\pi \, r \sqrt{r^2 + l^2}} e^{jwt} \qquad (2)$$

where $\boldsymbol{I}$ is the current in the loop, $\boldsymbol{l}$ is the length of the wound ferrite-rod, $\boldsymbol{r}$ is the distance from the observation point to the center of the rod [12].

Generally, the maximum level of transmission and reception in the near field is on the main axis of the cylindrical core, and minimum at $\theta = 90^o$ from this axis. Shown in Figure 5 is the θ-angle.

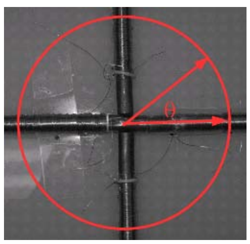

Fig. 5 Orientation's angle of rotation (θ).

During the test of our proposed dual-cylindrical ferrite-core coil antenna, each of these two antennas is connected to a power meter, and is mounted on a flat surface, acting as a receiver. Another small coil-antenna acts as the transmitter, and is connected to signal generator generating a LF signal. The distance separating the receiver and transmitter is 20cm. The transmitter is rotated around the receiver following the orientation's angle θ.

Figure 6 shows measured and simulation results (using FEKO) of the dual-cylindrical ferrite-core coil antenna versus the traditional single-cylindrical ferrite-core coil.

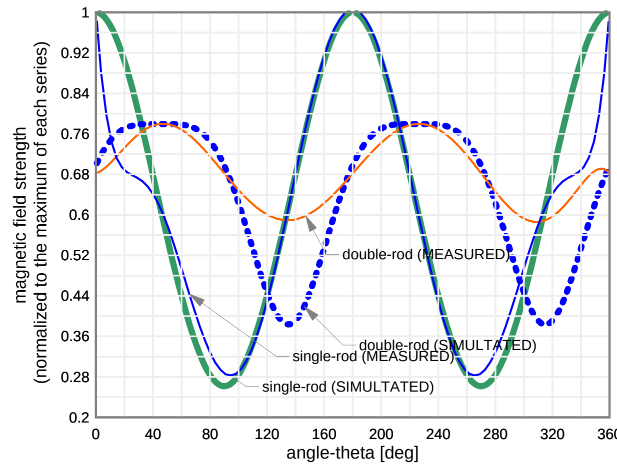

Fig. 6 Field level of the simulated and measured single-rod antenna vs. double-rod antenna (values are normalized to the maximum value of the single-rod curve).

Simulations and measurements of two types of ferrite-core antenna were performed: one with a single-rod ferrite, the other with a double-rod ferrite. Figure 6 shows the advantage of the double-rod version: its induced magnetic field is more uniform than the magnetic field of the traditional single-rod design. The magnetic field of the double-rod has maxima at 45^o and 225^o and minima at 135^o and 315^o while the maxima of the single-rod are at 0^o and 90^o. The sensitivity of the double-rod is more uniform because the difference between its maxima and minima is smaller than with the traditional single-rod antenna.

4. Conclusions

Our study focuses on improving existing transponder's antennas for LF operations using coils with ferrite and loop antennas. First, we examined the dependency of the coupling between a transponder's single-turn coil and a single-loop antenna operating at low-frequency, which indicated a significant dependence on the normal distance, the loop's size and the coil's orientation. The obtained characteristics of the received magnetic field of the coil, simulated and measured in the near-field of a single-loop antenna, are useful for future development and testing of ferrite-coil antennas used in RFID applications for buried objects. A traditional single-rod antenna has the disadvantage of having a strongly non-uniform field. Our proposed double-ferrite-rod antenna improved that aspect and was shown to provide a better uniform magnetic field.

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