COUPLING AMONG COLLOCATED LOOPS

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ABSTRACT

We analyze three orthogonal collocated loops using semi-analytical and numerical procedures. If a large number of terms is used, the currents in the loops converge to those of galvanically interconnected loops. The three loops are sensitive to positioning tolerances so that large coupling among them can occur in practice.

1. INTRODUCTION

The use of vector-sensor antennas for localization of source signals has received significant attention [1, 2]. The output of these sensors, proportional to the corresponding electric or magnetic field, is intended to be used for estimation of the source direction and polarization.

These sensors are densely packed within a small volume. Hence, coupling among the elements of sensors cannot be neglected. This coupling can cause errors in measuring the electromagnetic field. Having information about the coupling makes possible to predict and compensate the influence of the coupling by means of signal processing.

Several attempts have been made to evaluate this coupling. For example, in [2], two collocated circular loops are considered. We generalize this structure by adding the third loop. The structure described in [2] is insufficient for complete determination of a transverse plane electromagnetic wave. Namely, such a wave may be characterized by its amplitude, two parameters defining its direction of arrival (e.g., two angular spherical coordinates), and two parameters defining its polarization, i.e., a total of five scalar parameters. In general, the number of available scalar pieces of information is $2n-1$, where n is the number of ports of the vector-sensor. (One port is adopted as the reference port for phase measurement.) For $n = 2$, this amounts to three pieces of information. Hence, additional information, provided by an extra loop, is necessary. In addition, the system with two loops is insensitive for some wave polarizations. All three loops are assumed to have identical radii, their centers coincide, and the loops are located in three orthogonal planes.

We have tried to reproduce and expand the analysis method and results from [2, 3], as presented in Section 2. However, we have obtained significant discrepancies with respect to the results from [2, 3], for which we have found physical explanations.

In [2], it is shown that the coupling depends on the relative position of the generators along the loops and that it disappears when loop ports are collocated. In the case of three orthogonal loops, it is impossible to have three collocated ports. Nevertheless, we have identified a position of the ports such that the coupling among ports is theoretically negligibly small (i.e., all transmission coefficients are zero). However, in contrast to [2], there exist induced currents in each loop when the other loops are excited.

In Section 3, we present several technical problems that occur with practical implementation of such loops. In [2], the actual feeding arrangements and the matching networks for the loops were not taken into account. We analyzed some realistic feeders for the collocated loops to investigate matching, coupling, and sensitivity to tolerances.

2. ANALYSIS OF THE LOOPS

We consider three identical circular loops, denoted by L_1, L_2, and L_3, and placed in the xy, zx, and yz planes, respectively, as shown in Fig. 1. The centers of all three loops are at the coordinate origin. Let the wire radius be a and the loop radius be b. The loops are excited by generators of electromotive forces V_1, V_2, and V_3, located at positions determined by the angles $\Phi_{e1} = \Phi_1$, $\Phi_{e2} = \Phi_2$, and $\Phi_{e3} = \Phi_3$, respectively. The angles are measured along the circumference of the corresponding loop.

Following the semi-analytical approach from [2, 3], we expanded the loop currents in terms of Fourier-series harmonics. For a small number of harmonics, we obtained a good agreement with the results of [2, 3]. However, as we increased the number of harmonics, our results for the input and mutual impedances converged to significantly different values, showing much stronger coupling among the loops than predicted in [2, 3].

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We compared analytical results with numerical results obtained by [4, 5]. In the model that we used in programs [4, 5], the loops had to be slightly shifted from their original position in Fig. 1, to avoid electrical contacts, which do not exist in reality. We investigated a special case when the loops were driven by the same electromotive forces, $V_1 = V_2 = V_3 = 1\,\mathrm{V}$, located at positions $\Phi_{e1} = \Phi_{e2} = 0$, $\Phi_{e3} = \pi/2$. In all examples, $ka = 0.00423$ and $kb = 0.1$, where k is the phase coefficient in a vacuum.

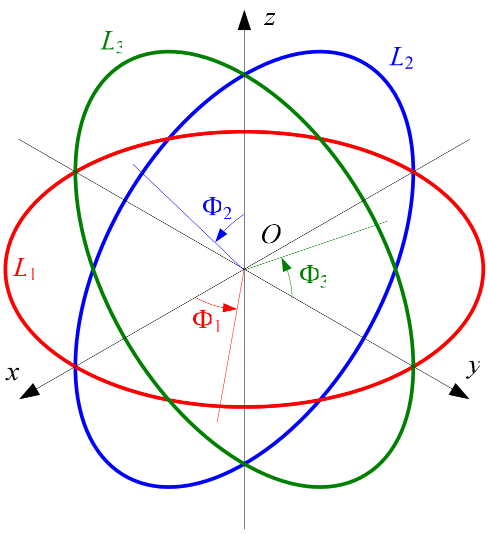

Figure 1. Three collocated loops

Due to the proximity effect, the current distribution cannot be accurately approximated by only two harmonics, as it was done in [2]. As an illustration, Fig. 2 shows the current distribution in the first loop. Similar results are obtained for the other two loops. By adding more harmonics, a better agreement is obtained, as shown in Fig. 3.

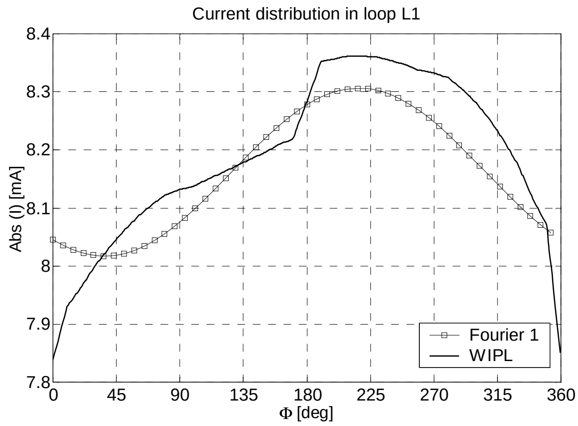

Figure 2. Current distribution in L_1 as a function of angle Φ_1, computed using fundamental and the first subsequent harmonic

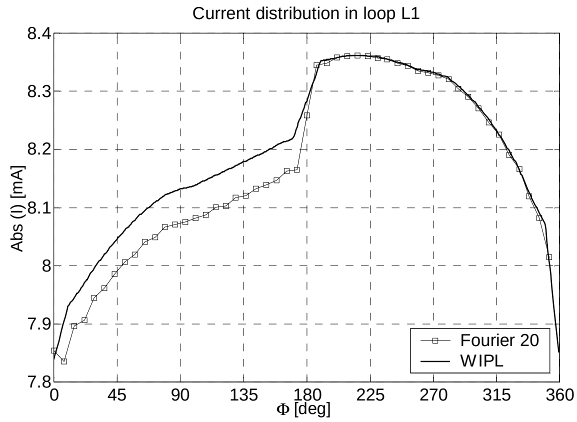

Figure 3. Current distribution in L_1 as a function of angle Φ_1, computed using fundamental and the subsequent twenty harmonics

However, further increase of the number of harmonics caused apparent divergence of the numerical results. Similar behavior was noticed for the case of two orthogonal loops as well.

For simplicity, the divergence will be illustrated on a model with only two orthogonal loops present (L_1 and L_2). We assume that only the vertical loop (L_2) is excited. In that case, the current in the horizontal loop (L_1) is reduced to the coupling current.

The lumped-element circuit that approximates the considered structure at low frequencies (quasistatic approximation) is shown in Fig. 4. For low–order approximations, the current distribution is determined by the weak capacitive coupling. Figs. 5 and 6 show the current distributions obtained with small numbers of harmonics, where the order of the highest harmonic is denoted in the legends.

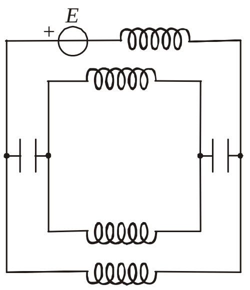

Figure 4. Equivalent circuit of two coupled loops

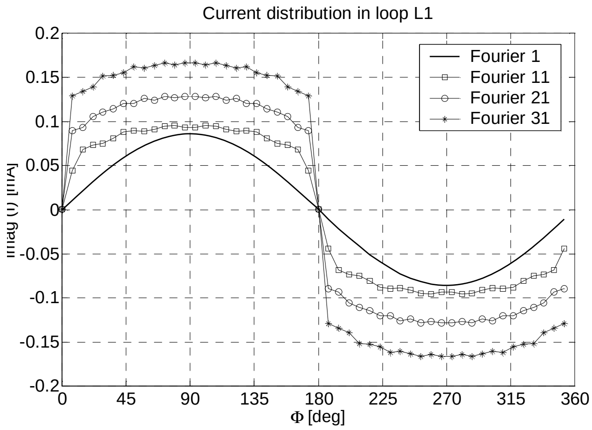

Figure 5. Current distribution in L_1 as a function of angle Φ_1 for low-order approximations (weak capacitive coupling)

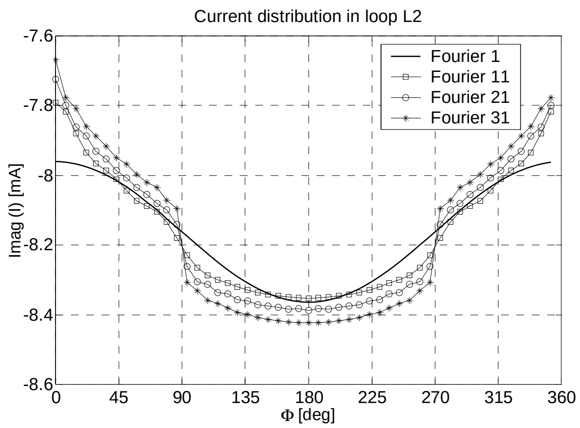

Figure 6. Current distribution in L_2 as a function of angle Φ_2 for low-order approximations (weak capacitive coupling)

More accurate representations with more harmonics increase the capacitive coupling, as shown in Figs. 7 and 8. This can be explained by the fact that the wire axes of the two loops intersect at two locations, which is not taken into account in the analysis in [2, 3]. These intersections behave as if the two loops are galvanically interconnected at the intersection points. Hence, the results of the refined simulations naturally converged to the same results as for interconnected loops. We verified this conclusion by analyzing the same loops using the programs [4, 5]. In the case of the galvanic coupling, the coupled current on loop L_1 is about 5 mA and reversed in direction as compared to the case of a weak capacitive coupling. With a further increase of the number of harmonics (more than two hundred), the results become stable. The same effect appears in the results obtained using program [5] if the loops geometrically intersect, but without specifying a galvanic coupling.

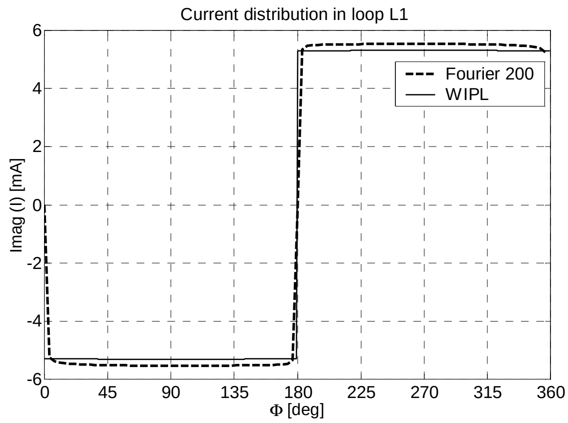

Figure 7. Asymptotic current distribution in L_1 as a function of angle Φ_1 (galvanic coupling)

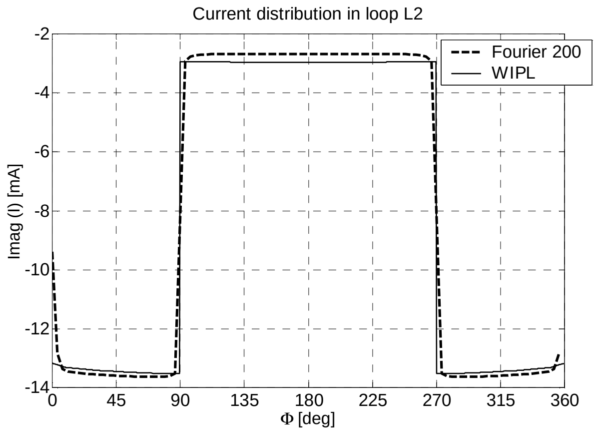

Figure 8. Asymptotic current distribution in L_2 as a function of angle Φ_2 (galvanic coupling)

3. PRACTICAL CONSIDERATIONS

In order to avoid problems presented in Section 2, we further analyze three loops that are slightly offset (for 2.5*a*), to be sure there is no artificial galvanic contact among them. The loops L_1 , L_2 and L_3 are shifted along the axes *x*, *z*, and *y*, respectively, to preserve symmetry. Such a loop disposition must also be applied in practice to let wires pass without intersections. For numerical simulations, we use programs [4] and [6].

Electrically small loops are inefficient due to losses in their conductors and in matching circuits. For example, at 47.8 MHz, for a copper conductor of radius

a=4.23 mm (which corresponds to $ka = 0.0423$) and for the loop radius b=100 mm (which corresponds to $kb = 0.1$), the efficiency of the loop is 32%. The input impedance of the loop, $Z = (0.1 + j170)\ \Omega$, is very inconvenient for matching as the real part is tiny. Hence, electrically small loops can be used only for reception of relatively strong signals that are above the noise floor of the receiver. In order to deal with a more realistic situation than in Section 2, in this section we consider the same loop around 150 MHz. At this frequency, the loop efficiency is 97%.

In this disposition, the coupling among the loops is practically negligibly small if $\Phi_{e1} = \Phi_{e2} = \Phi_{e3} = 0$. (The coupling is within the numerical noise.) Hence, the loops can be tuned independently. The input impedance of each loop is $Z = (11 + j765)\ \Omega$. It can be matched to a 50 Ω feeder using two reactive elements (which form an L-halfcell): by a capacitor (1.3 pF) connected in series with the loop and a shunt capacitor (36 pF). Assuming the quality factor of the matching capacitors to be 200, the efficiency of the matching circuit is 74%. However, the bandwidth of the matching is rather narrow. Although at 150 MHz the match is perfect, the reflection coefficient is less than −3 dB only within a 2 MHz frequency band (1.3% relative bandwidth).

An important practical problem is how to connect the loops to the receiver. In order to keep the coupling between the loops small, symmetry must be preserved for the interconnecting cables as well. We can place baluns at each loop to make a transition to coaxial lines. Geometrically, the three lines should merge to a point following the arrangement shown in Fig. 9.

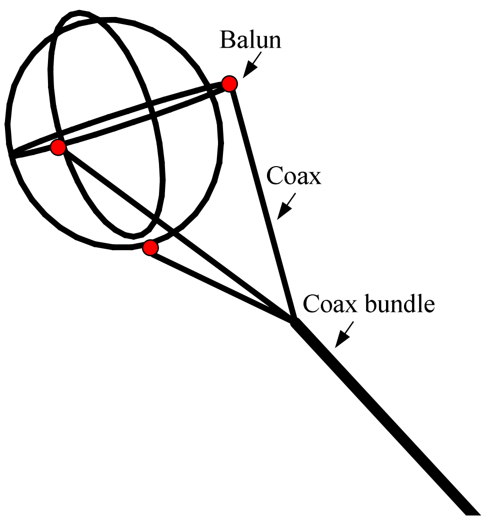

Figure 9. Arrangement of the loops and feeding coaxial cables

Any small asymmetry, however, causes enormous coupling among the loops. For example, if the symmetry of the loop positions is disturbed only for 1 mm, a coupling of 10 dB is observed, as shown in Fig. 10. This figure presents the scattering parameters of the loops with the matching circuits.

4. CONCLUSION

We analyze here three collocated loops and identify positions of the feeds in which there is no coupling among the ports. This property can be exploited for increasing channel capacity in MIMO systems [7], improving direction of arrival estimation etc. However, the implementation of systems with collocated loops should be performed with care due to some potential problems.

The first problem is theoretical, as ideally collocated loops geometrically intersect. This leads to numerical problems in their analysis. The second problem is available power. In order to have low losses in the antenna and in the matching circuit, the loops must not be small in terms of the wavelength. The third problem is the bandwidth. Even large loops are inherently narrowband. Hence, good matching can be achieved only in a very narrow frequency band. The fourth problem is the sensitivity to manufacturing tolerances. In order to keep the coupling among the antennas small, almost perfect symmetry must be accomplished. All these problems must be carefully considered in practical applications of the collocated loops.

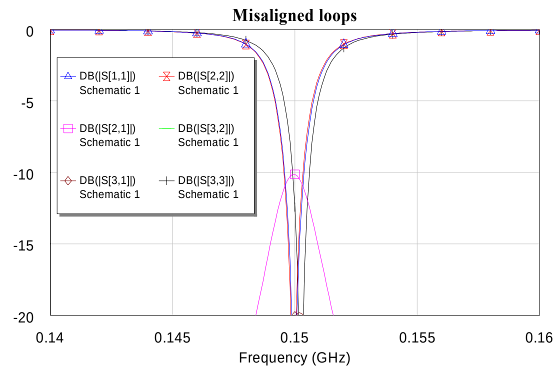

Figure 10. Scattering parameters of three loops when loops are displaced for 1 mm from symmetrical disposition

5. REFERENCES

[1] A. Nehorai and E. Paldi, "Vector-Sensor Array Processing for Electromagnetic Source Localization", *IEEE Trans. Signal Proc.*, Vol. 42, pp. 376-398, February 1994.

[2] Y. Huang, A. Nehorai, and G. Friedman, "Mutual Coupling of Two Collocated Orthogonally Oriented Circular Thin-Wire Loops", *IEEE Trans. Antennas Propagat.*, Vol. 51, pp. 1307-1314, June 2003.

[3] S. Krishnan, L.W. Li, and M.S. Leong, “Comments on 'Mutual Coupling of Two Collocated Orthogonally Oriented Circular Thin-Wire Loops'”, *IEEE Trans. Antennas Propagat.*, Vol. 52, pp. 1625-1626, June 2004.

[4] A.R. Djordjević, M.B. Baždar, V.V. Petrović, D.I. Olćan, T.K. Sarkar, and R.F. Harrington, *AWAS for Windows Version 2.0: Analysis of Wire Antennas and Scatterers*, Artech House, Boston, 2002.

[5] B. Kolundžija, J. Ognjanović, T. Sarkar, M. Tasić, D. Olćan, B. Janić, and D. Šumić, *WIPL-D Pro. v5.1*, WIPL-D, 2004.

[6] *Microwave Office 2002*, Applied Wave Research.

[7] A S. Konanur, K. Gosalia, S. H. Krishnamurthy, B. Hughes, G. Lazzi, ”Increasing Wireless Channel Capacity Through MIMO Systems Employing Co-Located Antennas”, *IEEE Trans. Microwave Theory Techn.*, Vol. 53, pp. 1837-1844, June 2005.