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Differential Inductive Sensing System using a Differential Transformer with Shielded and Split Primary Coil

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Introduction

In this work, we show a differential transformer for the determination of the electrical and dielectric properties of a sample using a split primary coil and magnetic shielding through a highly permeable ferrite layer for improved sensitivity. Preliminary results show an increase in sensitivity of 12.2 % compared to a transformer with one primary coil and without shielding.

Differential transformers are widely used in sensing technologies. Typically, a differential transformer consist of three coils located on a ferrite core. The center coil is the primary coil and is excited by an ac voltage or an ac current. Due to the excitation, a primary magnetic flux is generated. The outer coils are the secondary coils and are connected differentially in series. In many applications, the ferrite core is movable. This allows a very precise displacement, force or pressure sensor to be realized [1–8].

Another field of application results with a ferrite core fixed symmetrically to the coils. If a sample is placed closer to one of the two secondary coils, its electrical and dielectric properties can be measured. Fig. 1 a) shows such a differential transformer schematically. The primary magnetic flux induces eddy and displacement currents into the sample depending on its permittivity and conductivity. These currents cause a secondary magnetic flux. Due to the lower distance to one of the secondary coils compared to the other, a higher voltage is induced into the closer coil. Thus, an output voltage U_o is generated that can be measured at the terminals of the differentially connected secondary coils. [9] shows the possibility to separate U_o into a real part depending on the permittivity of the sample and into an imaginary part depending on the conductivity of the sample. Because of the differential connection and the symmetrical setup, the primary magnetic flux induces a voltage in the upper and the lower secondary coil with the same magnitude but different sign, resulting in an output voltage of the connected secondary coils of zero. This allows the weak eddy and displacement currents to be measured with a high resolution. Such a differential transformer with fixed ferrite core can be used for determining the biomass in a bioreactor, the tissue properties or for continuous monitoring of blood properties – e.g. the sodium concentration during the dialysis treatment [9–14]. [15] has even shown the possibility of measuring directly through a tubing, making it very promising for applications such as continuous and contactless monitoring of sodium in the blood during dialysis treatment. The sodium concentration measurement in blood is realized via blood conductivity measurement, since sodium has the strongest impact on the plasma conductivity (therefore the measuring frequency must be below the β-dispersion, which is at about 1 MHz) [16–23].

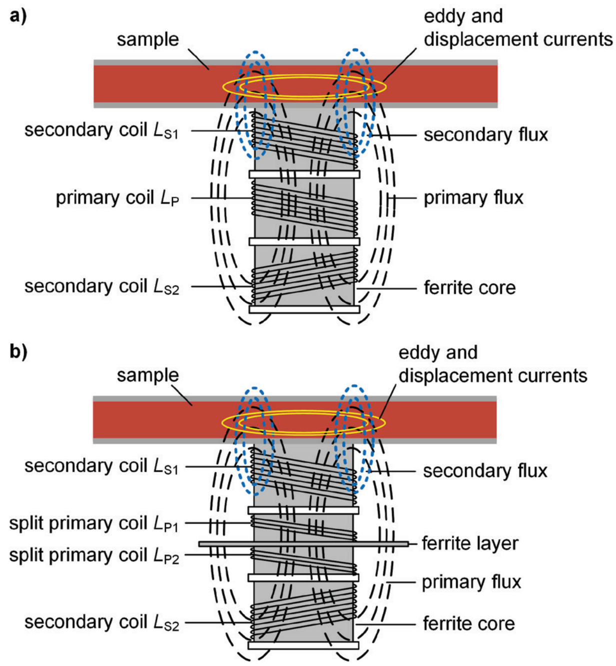

Fig. 1: (a) Schematic depiction of a differential transformer in single-primary coil configuration consisting of the secondary coils L_{S1} and L_{S2} connected differentially in series and the primary coil L_P. (b) Differential transformer with two split primary coils L_{P1} and L_{P2}. A ferrite layer is located between the two primary coils to shield the secondary flux from L_{S2}.

In order to achieve high sensitivity, it is an advantage to place the primary coil as close as possible to the sample, as this causes the sample to be penetrated strongly by the primary magnetic flux, and thus high eddy and displacement currents are induced in the sample. This increases the field strength of the secondary flux. However, due to the symmetrical design of the transformer, the secondary coil L_{S2} must also be placed closer to the sample. As a result, this secondary coil is also penetrated by more secondary flux. Due to the differential connection of the two secondary coils, this has a negative effect on the sensitivity. In [12] it was therefore shown how to set the optimum distance between the coils.

To further attenuate the secondary magnetic flux at the position of the lower secondary coil, this paper presents a new approach with a primary coil split into two coils and a ferrite layer added between the two primary coils so that the secondary field is shielded from the secondary coil L_{S2}. A schematic illustration of this setup can be seen in Fig. 1 b). This setup improves the sensitivity of the differential transformer by 12.2 % compared to the setup shown in Fig. 1 a).

Methods and Materials

Concept

The differential transformer with split and shielded primary coils is compared to a PCB (printed circuit board) differential transformer from [12] using one single primary coil L_P. This single primary coil transformer has n_S = 542 turns for each secondary coil and n_P = 42 turns for the primary coil. The distance between the upper and lower secondary coils is 17.5 mm. The primary coil is exited with a voltage U_P = 1 V_{PP} (peak to peak) at a frequency of 155 kHz. Since the sensitivity of the differential transformer depends on the ratio of the secondary inductance L_S to the primary inductance L_P, and only the effect of the shielding is to be investigated here, this ratio should not be changed by splitting the single primary coil L_P into two primary coils L_{P1} and L_{P2}. This condition can be achieved by two basic configurations.

First, each of the two primary coils can be the same as in the single primary differential transformer. That means both the upper primary coil L_{P1} and the lower primary coil L_{P2} have 42 turns each. Each coil is excited with U_P = 1 V_{PP} at 155 kHz. This corresponds to a parallel configuration of both coils. The mutual inductance M between the primary coils is

$$M = k \cdot \sqrt{L_{P1}L_{P2}}, \quad (1)$$

where k is the coupling factor ($0 \le k \le 1$) [24]. The total inductance L_{para} of the coupled primary coils with the same winding direction that are connected in parallel is given by [24] as

$$L_{para} = \frac{L_{P1}L_{P2} - M^2}{L_{P1,para} + L_{P2,para} - 2M}. \quad (2)$$

If equation (1) is substituted into equation (2) and assuming that L_{P1} and L_{P2} are very well coupled via the ferrite core ($k \to 1$) and $L_{P1} = L_{P2} = L_P$, the total inductance L_{para} is given as

$$L_{para} = \lim_{k\to 1} \frac{L_P^2 - k^2 L_P^2}{2L_P - 2kL_P} = L_P. \quad (3)$$

This gives the same inductance for the two primary coils connected in parallel and coupled via the ferrite core as for the single primary coil differential transformer.

Second, each primary coil now has a reduced number of turns to n_P = 21. Both coils L_{P1} und L_{P2} are now connected in series. The total excitation voltage is U_P = 1 V_{PP} at 155 kHz. Thus, compared to the single primary coil transformer the total number of turns of the primary coils is unchanged. Since the inductance of a coil depends quadratic on the number of turns, the inductances of the individual coils is $L_{P1} = L_{P2} = L_P / 4$. For magnetically coupled coils connected in series with the same winding direction, the total inductance L_{seri} results according to [24] to

$$L_{seri} = L_{P1} + L_{P2} + 2M = \frac{1}{4}L_P + \frac{1}{4}L_P + \frac{1}{2}k \cdot L_P. \quad (4)$$

Again, assuming that k tends to one, it follows from equation (4) that $L_{seri} = L_P$.

Thus, it is expected that both configurations – the series connection with halved number of turns per primary coil and the parallel connection of two coils, which are identical to the single primary coil differential transformer – provide the same results. Both configurations are compared in the following using numerical simulations.

Simulations

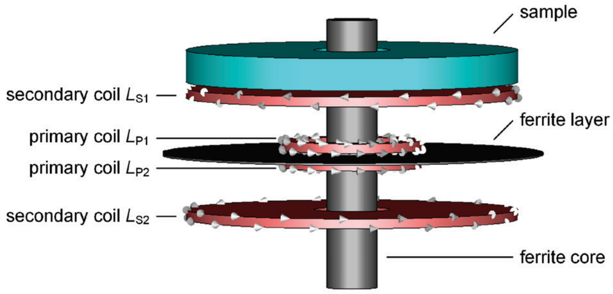

Fig. 2: CST-EM Studio simulation model for simulation of the differential transformer with split and shielded primary coil. The white cones indicate the winding direction. The ferrite layer has a thickness of 0.3 mm, a radius of 30 mm and a relative permeability of μ_r = 300.

The increase in sensitivity by inserting a ferrite layer with a high relative permeability between the split primary coil is simulated for the two configurations described above using *CST-EM Studio*. The model corresponds to the PCB differential transformer with two primary coils L_{P1} and L_{P2} and is shown in Fig. 2. The number n_S of the turns of each secondary coil is 542. The distance between the upper and the lower secondary coil is also the same as with the single primary coil transformer (17.5 mm). To simulate the parallel connection of L_{P1} and L_{P2}, each primary coil has 42 turns and is wound in the same direction. Both primary coils are excited with a voltage of 1 V_{PP} at 155 kHz. To simulate the series configuration of both coils, the number of turns of L_{P1} and L_{P2} is reduced to 21 each, while exciting each coil with 0.5 V_{PP} at 155 kHz. Between the two primary coils L_{P1} and L_{P2} a 0.3 mm thick ferrite layer with a radius of 30 mm and a relative permeability μ_r = 300 is located. The relative permeability of the ferrite core is μ_r = 300 as well. In order to investigate the exact impact of the ferrite layer, each simulation is performed with and without the ferrite layer between L_{P1} and L_{P2}.

As mentioned before, the imaginary part of the output voltage U_o depends on the conductivity of the sample. To determine the sensitivity, the conductivity of the sample is varied between 1 S/m and 2 S/m.

Experimental Setup

The PCB differential transformer with split and shielded primary coil is compared to the PCB differential transformer with the single primary coil from [12]. For both transformers, the secondary coils have 542 turns and are placed with a distance of 17.5 mm to each other. The excitation voltage is in each case 1 V_{PP} at 155 kHz.

As already shown by the theoretical preliminary considerations, and later also proven by the simulation results, the configurations of series connection with halved number of turns n_P / 2 or the parallel connection with n_P turns are equivalent. Hence, the experimental investigations are only realized in the parallel configuration. A photograph of the differential transformer with split and shielded primary coil is shown in Fig. 3.

The primary coils L_{P1} and L_{P2} have 42 turns each and are connected in parallel. In the single primary coil configuration, which is used as a reference, L_P also has 42 turns.

DI-water (deionized-water) solutions with different sodium chloride (NaCl) concentrations are used as a sample with varying conductivity. The concentration range is increased from 100 mmol/L in 10 mmol/L steps up to 150 mmol/L. The sensitivity is given by the slope of the linear regression of the imaginary part of the output voltage U_o.

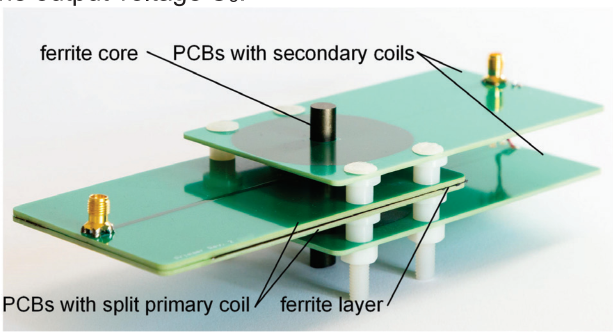

Fig. 3: Photograph of a differential transformer with split and shielded primary coil used for the experimental investigations. Each coil is realized on a separate printed circuit board (PCB). Here, the primary coils L_{P1} and L_{P2} have the same number of turns n_P = 42 as L_P of the single primary coil differential transformer from [12]. L_{P1} and L_{P2} are connected in parallel.

Results

Simulations

Initially, the simulations were conducted with two primary coils in series and in parallel configuration without ferrite layer. The results of this simulation are shown in Fig. 4 (parallel configuration: blue line; series configuration: red dashed line).

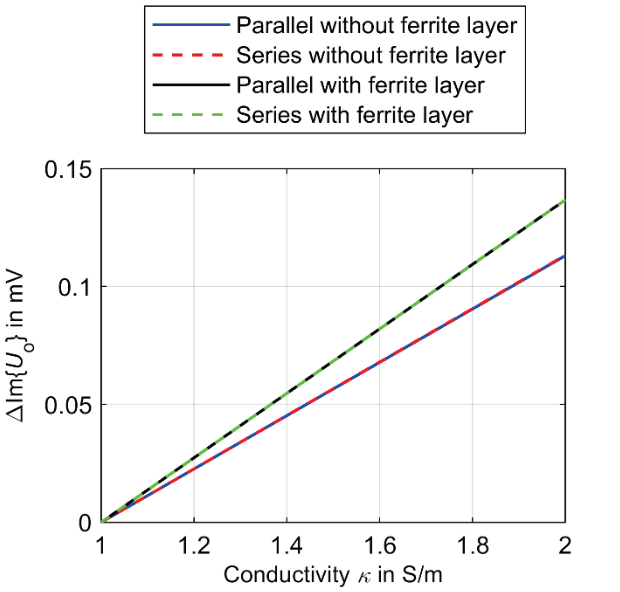

Fig. 4: Simulated variation of the imaginary part of the output voltage U_o depending on the conductivity of the sample using the simulation model from Fig. 2. For the parallel configuration, n_P is 42 turns and the excitation of each coil is 1 V_{PP}. For the series configuration n_P = 21 turns and the excitation is 0.5 V_{PP} per primary coil. Both configurations were simulated with and without a 0.3 mm thick ferrite layer between the primary coils. The relative permittivity of the ferrite layer is μ_r = 300.

As expected from the theoretical considerations, both configurations have almost the same sensitivity. For the parallel configuration, the simulated sensitivity is 113.2 µV/S/m and for the series connection, the simulated sensitivity is 113.4 µV/S/m.

Afterwards, the 0.3 mm thick ferrite layer with a radius of 30 mm and a μ_r = 300 was added between L_{P1} and L_{P2}. The simulated sensitivity is now increased for both configurations to 136.8 µV/S/m (series configuration: green dashed line; parallel configuration: black line). Thus, the sensitivity increases by about 20 % adding the ferrite layer.

Measurements

As can be seen in Fig. 5, the differential transformer with split and shielded primary coil has a sensitivity of 215.7 mV/mol/L (red), while the differential transformer in single coil configuration has lower sensitivity of 192.2 mV/mol/L (blue). Thus, in the experiment, the sensitivity of the differential transformer with split and shielded primary coils is 12.2 % higher compared to the single primary coil differential transformer.

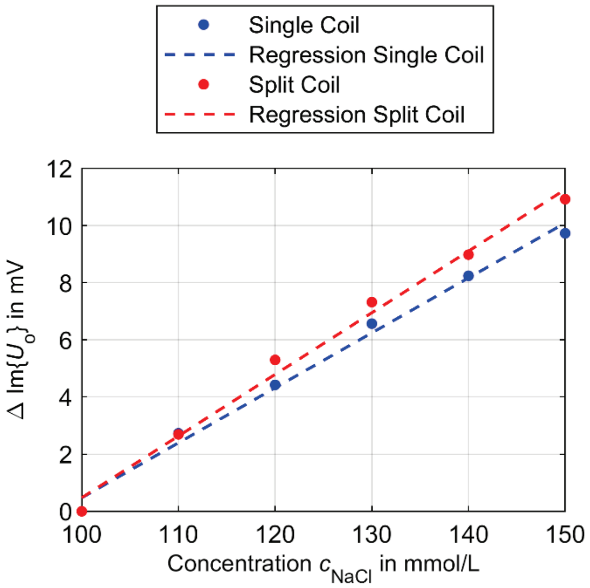

Fig. 5: Comparison between the differential transformer with a single primary coil from [12] (blue) and the differential transformer with a split and shielded primary coil from Fig. 3 (red). The dots are the measured variation of the imaginary part of the output voltage U_o depending on the NaCl concentration of the sample in DI-water. The dashed lines are the linear regressions to the measured values (the slopes represent the sensitivities).

Conclusion

In this paper, a concept for sensitivity enhancement of a differential transformer is presented. To achieve this, the primary coil of the transformer is split into two coils and a ferrite layer with a high relative permittivity is added between the two primary coils. Thus, the lower secondary coil being further away from the sample than the upper secondary coil is shielded more from the secondary flux. Due to the differential configuration of the secondary coils, this has a positive effect on the sensitivity.

There are two basic configurations for the connection of the split primary coils, allowing the total inductance of the primary coil not to be changed compared to a single primary coil differential transformer, so that an increase in sensitivity is solely attributed to the shielding. On the one hand, the same coil as for a single primary coil differential transformer can be used twice. These coils must then be connected in parallel. On the other hand, it is also possible to halve the number of turns of the coils and connect both coils in series.

Experimental investigations have shown that the differential transformer with split and shielded primary coils has a sensitivity of 215.7 mV/mol/L, exceeding the sensitivity of a single primary coil differential transformer by 12.2 %.

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