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Capacitively-coupled impedance measurements for ERT

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ABSTRACT

The paper explores the potential for using capacitively-coupled electrodes in electrical resistance tomography. Such electrodes are less vulnerable to corrosion and electrochemical effects that plague conventional electrical resistance tomographs utilising electrodes that are in intimate contact with the material. A model is proposed that takes account of the complex impedance of the insulating layer. The performance of the resulting passive network of components has been simulated up to 1 MHz excitation frequency. 2D finite element modelling has been used to explore the measurements that might be expected from electrodes distributed around the boundary of a vessel. Except for the adjacent measurements the modelled impedances are within 1% of those for conventional electrodes.

Keywords :electrical tomography; capacitively coupled electrodes, finite element modelling, COMSOL

1 INTRODUCTION

Electrical tomography emerged in the 1980's following the reported success of X-ray and magnetic resonance imaging in the medical field. Early work in Sheffield on electrical resistance tomography (ERT) (Barber and Brown, 1984) was followed by efforts in Manchester that extended to capacitance (ECT) and electromagnetic (EMT) modalities (Williams and Beck, 1995). The activity now attracts practitioners worldwide and progress is regularly reported at the World Congress on Industrial Process Tomography and has also been captured in a number of review articles (York, 2005; Yang, 2010; York et al, 2011).

The work reported here is primarily concerned with ERT in which, conventionally, a small number of electrodes are placed on the inner wall of a process vessel in intimate contact with the materials of interest. These materials are frequently corrosive, for instance acetic acid used in pressure filtration (York et al 2005) and nylon polymerisation (Dyakowski et al, 2000)and this can result in rapid degradation of the electrodes. In addition, with this arrangement, the measurements are subject to electrochemical effects, typically manifested as a contact impedance which is influenced by the materials present, the current density and the frequency of the signals (Geddes et al, 1971). Efforts to mitigate these effects for ERT has only attracted modest interest, for instance by McNaughtan et al(2000).Typically, measurements adopt a 4-electrode protocol. Two electrodes are used to deliver a known current, typically of the order of milli-amperes, into the region of interest. Any voltage drop across the in-series contact impedance associated with these electrodes is irrelevant as it is the current that is of interest. Two further electrodes are used to determine the potential differences around the boundary of the region which then allows associated resistances to be determined. The circuit for the voltage measurement is designed to have high input impedance such that it draws almost zero current which reduces the effect of the contact impedance. The measured voltage is therefore a good representation of the potential difference across the region of interest. In practice this arrangement is not perfect, not least because of DC offsets in the signals.

Driven by the desire to reduce electrochemical effects and corrosion of the electrodes the present work explores the use of capacitively-coupled electrodes that are covered with a protective insulating layer.The work is motivated by our interests in using electrical tomography to image the root zone of plants under the surface of the soil. Clearly, this application area presents a significant challenge due to the complex biological, chemical and physical nature of the medium which increases concerns regarding corrosion and electrochemical effects.

The remainder of the paper is organised as follows. Section 2 describes previous research into capacitively-coupled electrodes. Section 3 presents the model used here and this is followed by a discussion of the finite element modelling that has been undertaken to explore how well the model performs.

2 BACKGROUND

Capacitively-Coupled Contactless Conductivity Detection (C4D) originated in the 1980's in the field of electrophoresis(Gas, B., M. Demjanenko, and J. Vacík, 1980).Da Silva and do Lago(1998) concluded that the polarisation effects were insignificant due to no direct galvanic contact and developed an axial arrangement using two tubular electrodes around a capillary. It was found, however, that measurement frequency had a significant effect on the sensitivity of the equipment. Zemann et al (1998)also implemented a two electrode system and noted that frequencies between 20 kHz to 2 MHz provide results sensitive enough for typical electrophoresis applications. Figure 1 shows the simplified electrical equivalent of a C4D measurement where the capacitance of the insulating walls and the resistance of the medium are shown as CW and RB respectively.Vi and Vo are the input and output voltages respectively.

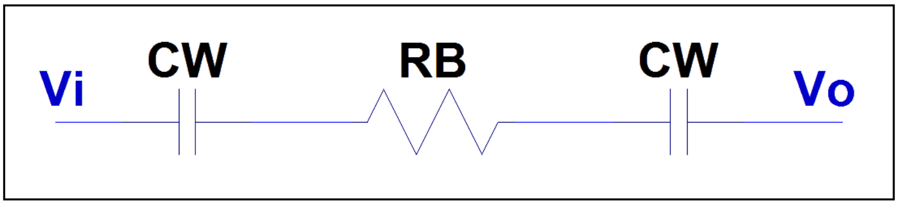

Figure 1: Simplified equivalent circuit for a C4D system

Huang et al(2009)discuss the use of a series inductor to counter capacitive effects as shown in Figure 2. They also consider the use of a shield between electrodes to reduce stray capacitance.

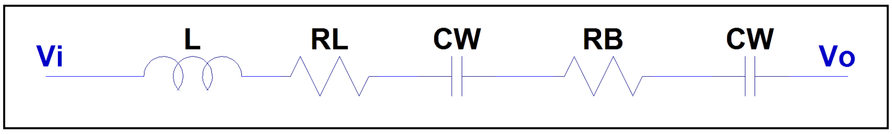

Figure 2: Equivalent C4D circuit with a series inductor (L) having resistance RL

Very little work has been reported regarding the use of C4D in electrical tomography. Wang et al (2010)utilised the C4D method to detect the presence of a plastic pipe within a water filled phantom. The apparatus was similar to that of an ECT system, with 12 large copper electrodes around the outer wall of an insulating vessel. They note that when the vessel is filled with a homogeneous conductive fluid the impedance between any two electrodes can be represented by the model shown in Figure 1, with the value of resistance RB changing dependent on the conductance of the medium and the distance between electrodes. A forward model was created to predict values of resistance, from which reconstructed images were created using the Linear Back Projection algorithm from both measurement and forward model data. The reconstructed image clearly showed the plastic pipe in the vessel but suffered from poor quality due to lack of measurement optimisation.

Kuras et al (2007) looked at the use of the C4D technique to measure underground moisture in areas where typical penetrating rods could not be inserted for contact based resistance measurements such as urban environments or hard ground. The equipment consisted of sensor arrays that were pulled along the ground to create a profile of the underground moisture content. Tomographic images were comparable with those using regular galvanic contact measurements.

3 ELECTRICAL MODEL

In contrast to the earlier work the electrical model for C4D measurements that is presented here considers both the resistance and capacitance of the wall and medium under test. The electrical equivalent circuit is shown in Figure 3, where CW and RW are the capacitance and resistance of the wall. CB and RB represent the capacitance and resistance of the bulk material within the vessel. The inclusion of parallel connected wall resistances RW and bulk capacitance CB should be noted in comparison to previous models. Considering the electrodes to be arranged as plates that are placed either side of the medium, as suggested in Figure 3, the analytical solution for the combined impedance “Z” is shown in Equation 1. In this analysis the two wall impedances are combined into a single impedance with twice the resistance (R_w = 2RW) and half the capacitance (X_W = CW/2).

$$Z = \left(\frac{1}{R_W} + \frac{1}{jX_W}\right)^{-1} + \left(\frac{1}{R_B} + \frac{1}{jX_B}\right)^{-1} = \left(\frac{R_W X_W^2}{R_W^2 + X_W^2} + \frac{R_B X_B^2}{R_B^2 + X_B^2}\right) + j\left(\frac{R_W^2 X_W}{R_W^2 + X_W^2} + \frac{R_B^2 X_B}{R_B^2 + X_B^2}\right) \quad (1)$$

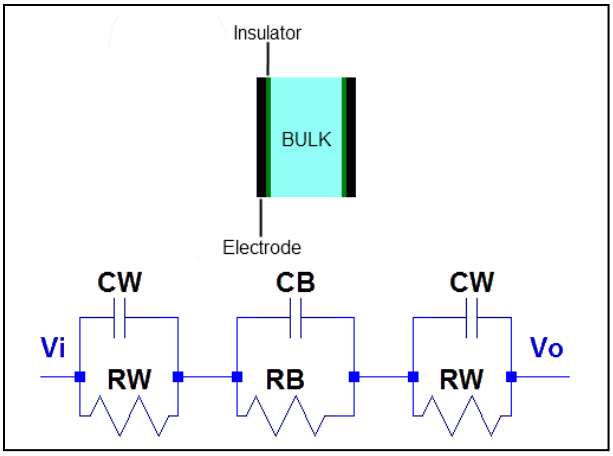

Figure 3: Equivalent Circuit for C4D

The analytical model has been simulated for electrodes having insulation resistance between 100kΩ and 1GΩ and a fixed wall capacitance of 100pF. Results are shown in Figure 4. The small circles indicate the wall transition frequency (WTF). Below this frequency current flow is primarily impeded by the wall. Above the WTF the bulk impedance dictates the current. Resistance of the bulk is inferred from the magnitude of the impedance in the plateau region above the transition frequency. For the present example this plateau lies between 40 kHz and 900 kHz. As can be seen the location of the plateau is, essentially, independent of wall resistance for the wide range of values considered. Consequently the model provides the ability to deduce the bulk resistance, as required in ERT, using insulated electrodes. In practice it is necessary to first interrogate the electrodes with multiple frequencies in order to deduce the location of the plateau.

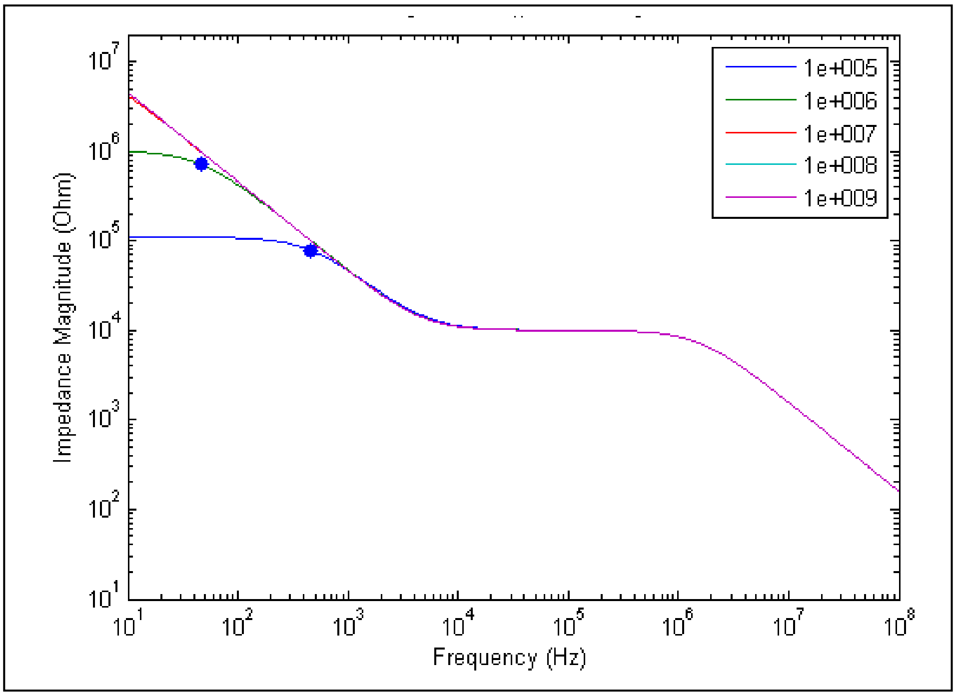

Figure 4: Simulated impedance spectra for a variety of wall resistance
C_B = 10pF, C_W = 100pF, R_B = 10 kΩ. Wall resistance = 10^5Ωto 10^9Ω

4 FINITE ELEMENT MODELLING

COMSOLMultiphysics3.5ahas been used to explore the behaviour of C4D electrodes in a tomographic configuration. Results are compared to those using "bare" electrodes in which direct galvanic contact is made between electrode and medium. A challengearises due to the contrasting dimensions in the model that arise, largely, due to the thin insulating "wall" covering on the electrodes which demands a very fine mesh granularity.Therefore, for the present initial explorations, a 2D modelling approach has been used. The solution to the 2D problem is in effect a pseudo-3D solution as COMSOL Multiphysics assumes a depth of 1 metre for the purpose of computation. The solution can be scaled appropriately according to the actual electrode height.

Initially a 2D rectangular idealised parallel plate arrangement, without fringing effects, was considered to provide a comparison with the analytical approach. Two fixed bulk dielectric constants were used representing air (ε_r=1) and water (ε_r=79) with varying conductivity values ranging from $1x10^{-9}$ to $1x10^{9}$. For each bulk conductivity/dielectric pairing, the resulting electric field distribution for a 1V excitation with a range of measurement frequencies between 10Hz and 1GHz was simulated. The complex impedance was extracted from the electric field simulation and plotted against the excitation frequency. As an example, Figure 5 shows a plot of the real component, imaginary component and magnitude of the complex impedance for a background relative permittivity of 79 and a bulk electrical conductivity of $1x10^{-3}$ S/m. The plateau where conductivity data can be extracted lies between 5 kHz and 40 kHz.

From the complex impedance spectra the 'measured' bulk conductivity can be extracted and compared to the original valuesthat were used for the simulation. For the conductivity range between $1x10^{-8}$ S/m and $1x10^{7}$ S/m these values displayed an average error of less than 1.5% and 4% for bulk dielectrics of 1 and 79 respectively.For bulk conductivities below$1x10^{-7}$ S/mand above $1x10^{7}$S/mthe simulations must be extended to include both lower and higher excitation frequencies. For practical implementation this impliesincreased demands on the necessary instrumentation.Wall resistance has beenextracted from the simulated data and the resulting values are observed to be approximately constant with a value of ~60 MΩ across the range of bulk conductivity. This suggests that,once a sensor has been characterised, further consideration of the wall resistance may not be necessary.

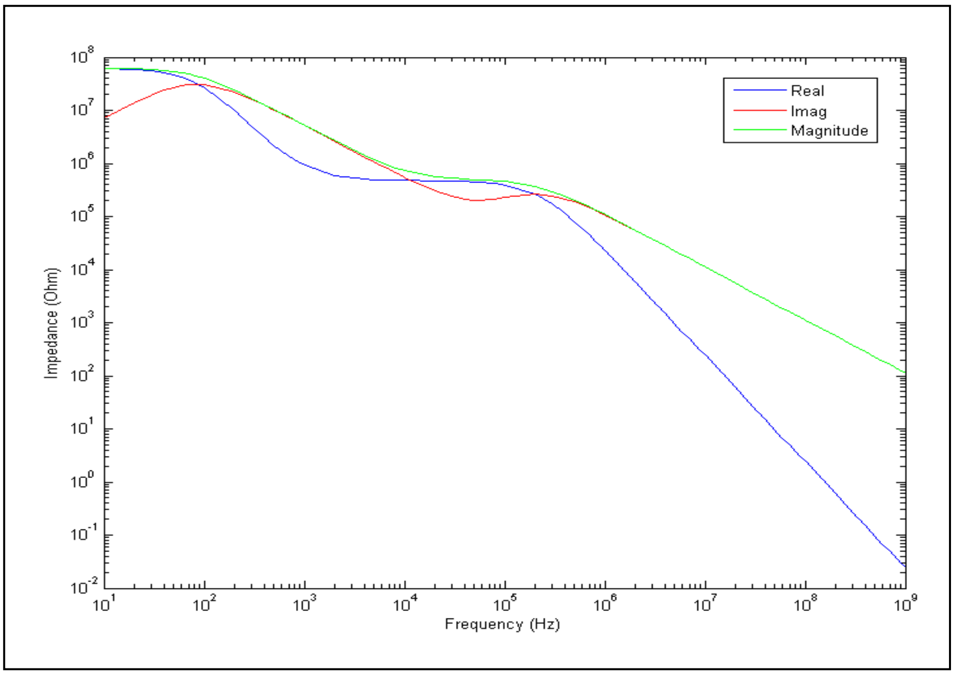

Figure 5: Real and Imaginary components and Magnitude of impedance (ε_r= 79, σ =$1x10^{-3}$ S/m)

Conventional ERT arrangements might locate 16 electrodes around a circular boundary but for the present geometry, for reasons suggested above, this presents challenges for the modelling. Therefore initial efforts to model the capacitively-coupled electrodes in a tomographic configuration have considered a hexagonal arrangement. This is sufficient to satisfy the present aim of comparing the resulting impedance values to those using conventional "bare" electrodes. A hexagonal vessel of dimension 140mm and wall thickness, corresponding to the insulating layer, of 75μm has been considered. Each of the faces of the hexagon is identified as an electrode having width 75mm. The model was simulated in 2D using an excitation voltage of 1V and a frequency of 30 kHz, selected to be located on the "plateau" region of the spectrum. Figures 6 and 7show the mesh and a sample solution for an adjacent electrode excitation respectively. Note the extremely high mesh density in the vicinity of the vessel walls.

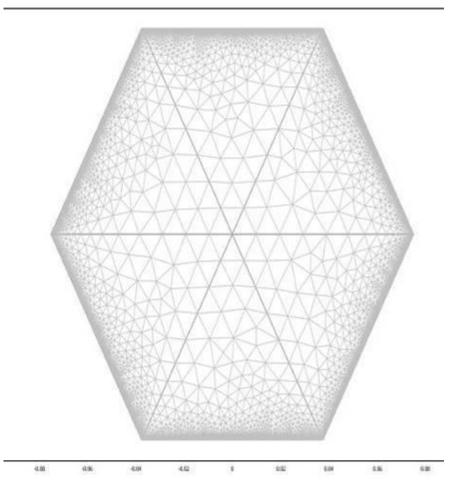

Figure 6: Mesh for hexagonal vessel

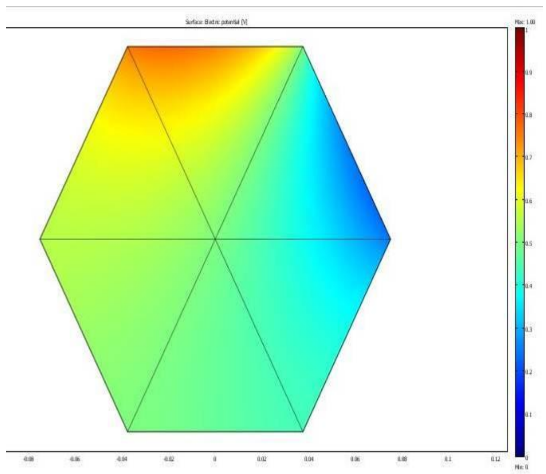

Figure 7: Potential distribution for adjacent electrodes. Red (North electrode) = high potential, Blue (North-East electrode) = low potential

Four test cases have been considered comprising bulk regions of water and air each with insulating and bare electrodes. Figures 8, 9 and 10 show the real and imaginary components of the modelled impedances for the test cases.

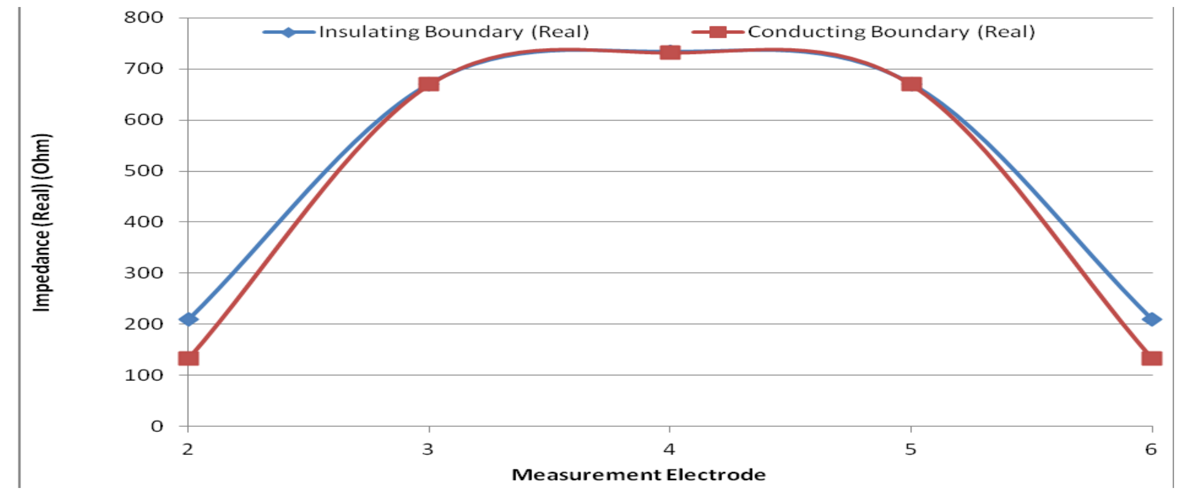

Figure 8: Modelled resistance for water

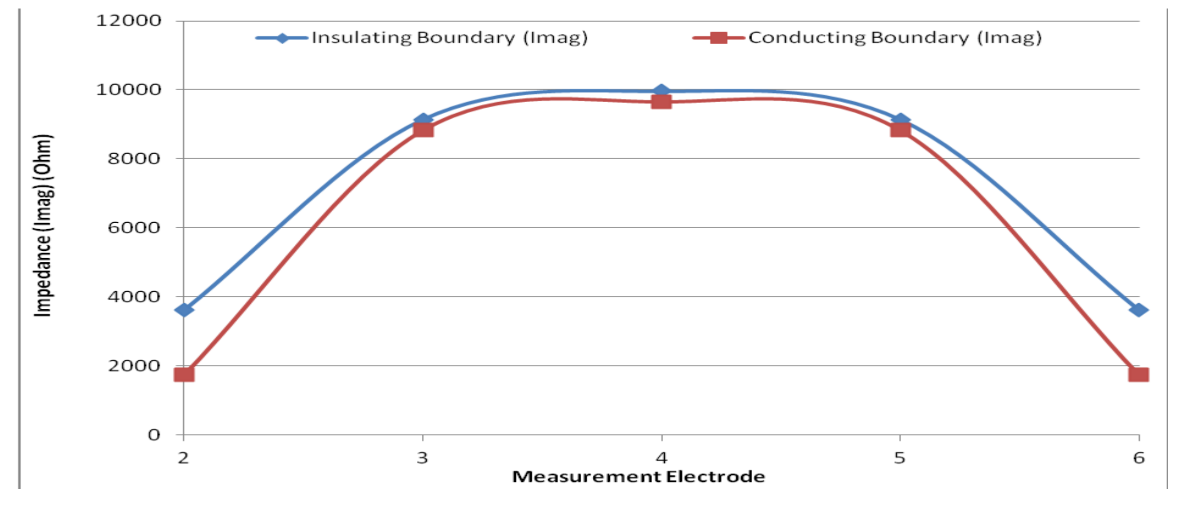

Figure 9: Modelled reactance for water

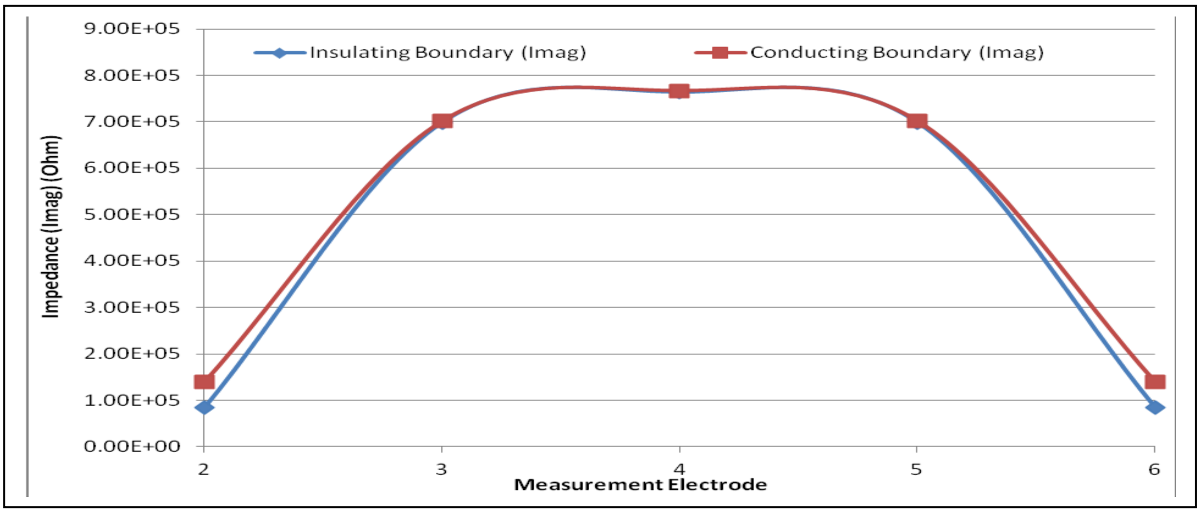

Figure10: Modelled reactance for air

As shown in Figure 8, apart from the adjacent electrodes, the modeling suggests that the capacitively coupled approach provides resistance estimates that are on average less than 1% different to those using conventional bare electrodes. The differences for the adjacent electrodes requires further exploration but may require modifications to the model. Related effects have been considered previously for ECT where the use of radial guards was proposed (Jaworski and Bolton, 2000). This approach will be considered in our future work. The results for the imaginary component, shown in Figure 9, display an average difference of 23%. It should be noted that, in reality, there are substantial challenges in measuring the imaginary component with conductive media.

As anticipated, for an insulating medium (air), there is no conducting path to provide a measurement of the real part of the impedance. However, as shown in Figure 10, the imaginary component of the impedance using the capacitively-coupled electrodes compares well under these conditions when compared with the bare electrode case. Again, excluding adjacent electrodes, average differences of less than 1% are suggested.

These results demonstrate that data collected using the proposed electrode arrangement differs very little from conventional electrode arrangements reported in the literature to date. In addition, the results demonstrate that the same electrode arrangement may be used for interrogating both conductive and insulating media, thus providing the basis for monitoring processes with both conducting and insulating phases, such as in sub-surface imaging of the root zone where there are both very wet (conducting) and very dry (insulating) phases.

5 SUMMARY

The paper reports exploration of the potential for using capacitively-coupled contactless electrodes for electrical resistance tomography. A model is suggested which, in contrast to previous reports, includes parallel connected wall resistance and bulk capacitance. Analytical consideration of the frequency response of an idealised parallel-plate capacitor suggest that a plateau region exists in the spectrum and that measurements in this region reflect the bulk resistance of the materials under consideration. Finite element modelling is compromised due to the contrasting geometries that arise, primarily due to the thin insulating layer on the electrodes. Results from 2D modelling of geometries which approximate tomographic arrangements suggest that for all except neighbouring electrodes the extracted resistances match to within 1% those using conventional bare electrodes. Future work will progress the modeling to the 3D case of more realistic geometries and results will be compared to measurements on a laboratory-based prototype.

6 ACKNOWLEDGEMENTS

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