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Dual-modality 4-terminal electrical capacitance and resistance tomography for multiphase flow monitoring.

Marco A. Rodriguez-Frias¹ and Wuqiang Yang¹, *Fellow, IEEE*

Abstract—Electrical capacitance tomography (ECT) and electrical resistance tomography (ERT) have been successfully developed to visualise dielectric and conductive distributions respectively. However, monitoring complex multiphase flows involve imaging highly dynamic distributions, constantly changing between dielectric-dominant and conductive-dominant. In this work, a dual-modality ERT/ECT system is developed for simultaneously imaging dielectric-dominant and conductive-dominant distributions. With the 4-terminal measurement configuration, the system can reduce the effect of parasitic impedances while capacitance and conductance can be simultaneously measured, using a single set of electrodes and a single data acquisition system.

Keywords—*Electrical resistance tomography (ERT), electrical capacitance tomography (ECT), 4-terminal sensing, multi-phase flow measurement, water-in-liquid ratio*

I. INTRODUCTION

Although researchers have made a great effort, measurement of complex multi-phase flows in the oil industry is still challenging and it requires integration of multiple technologies. In oil extraction, the flows are mainly composed of gas, oil and seawater. These materials present a wide range of electrical and physical properties that can be measured to estimate the water-in-liquid ratio (WLR) and gas void fraction (GVF). The most common technique for measuring the quantity of each component in the multi-phase flow is the use of oil/gas/water separators [1], which make use of the difference in density to separate the materials and provide an estimation of their quantities. Yet, the use of oil separators has several disadvantages, and the most important one is a long settling time. As the three components enter a separator, due to the big difference in density between the gas and liquid phases, the initial separation is quick, nonetheless, a foam layer could remain in the boundary between the liquid and gas phases. Within the liquid phase, the liquid mixture of water and oil requires a long time to complete the separation process. This is due to the similarity in their density and a layer of oil/water emulsion sits between the water layer and the oil layer. When the effect of gravity is not sufficient to separate the emulsion, coalescing media is used to enhance the separation process [1]. Other

important disadvantages of using separators for multiphase flow measurement are their bulky dimension and high cost.

To overcome the inherent limitations in the use of separators, inline multiphase flow meters (MPFMs) have been developed as an alternative approach. MPFMs can be grouped into two broad categories by the type of energy used to perform the measurement: (1) With radioactive sources and (2) without the use of radioactive sources. MPFMs in the first category make use of gamma densitometers to calculate GVF [2] and for flow regime identification [3-5]. This type of meters have an advantage of using hard field sensing; this allows to accurately measure the density across the transversal section of the pipe. The major disadvantages of these devices are the health and safety concerns, due to the use of a radioactive source, as well as the high cost.

MPFMs in the second category rely on the use of low energy sensing fields to measure GVF and WLR. As a consequence, the field is distorted, resulting in less accurate measurement [6]. Nonetheless, non-radioactive MPFMs have advantages of being low cost and not causing health and safety concerns. Some techniques like electrical tomography feature high temporal resolution and hence a real-time measurement of fast-changing processes like a multi-phase flow [7].

Electrical capacitance tomography (ECT) and electrical resistance tomography (ERT) have been developed to visualise dielectric and conductive distributions respectively. Both techniques rely on the measurement of the electrical properties by using the electrodes in the boundary of a region of interest [8]. In order to cover the full range from water-continuous to oil-continuous, ERT and ECT have been used together to form a dual-modality system. Dual-modality electrical tomography systems can be categorised in three groups in accordance with the use of (1) two tomographic devices with two separate sensors, (2) two tomographic measurement systems with an integrated sensor containing the two sets of electrodes in a single plane, and (3) a single tomographic measurement system and a single set of electrodes.

In the first category, dual-modality is achieved by the use of two standalone tomography systems. Two independent sensors are placed side to side along a pipe [9-14], there are two main drawbacks of this configuration: (1) two standalone acquisition systems and two sensors make the system complex and expensive; (2) data is acquired in

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different spatial and temporal locations, making it difficult to implement image reconstruction and data fusion.

In of the second category, there are systems that feature two sets of electrodes in the same plane [15-16], i.e. with an integrated ERT/ECT sensor. With these two-sensor arrays placed in the same axial plane, the main concern of measuring in different axial locations is solved. Nonetheless, despite having two-sensor arrays in the same sensing plane, the information is not captured simultaneously; both techniques cannot function at the same time due to the different types of sensing method. In this case, the information acquired by the two systems is not temporally coherent.

In the third category, there are systems composed by a single set of electrodes [17-27], i.e. integration of a single plane and a single array of sensors for a dual-modality ERT/ECT system. These systems can be built with internal electrodes [17-22] and external electrodes [23-26]. For both types of sensors in this category, integration of the dual modalities in a single plane and a single set of electrodes is achieved by using a voltage-excitation and current-sensing strategy with a 2-terminal sensing configuration. Nonetheless, with this sensing arrangement, the effect of the contact impedance and other parasitic impedances cannot be neglected. From the dual-modality systems reported with internal electrodes, the system presented by Rodriguez-Frias and Yang [17] features 4-terminal sensing, which reduces the effect of contact impedance and other parasitic impedances. Whilst, in the case of sensors with external electrodes, the contact impedance can be neglected, because the electrodes are not in contact with the material. Nonetheless, the rest of parasitic impedances in the switching stage and in the leads still have an effect on the measurement. In addition, the conductivity of the media used for testing these implementations has been low. Therefore, further research might be required to assess the feasibility of capacitive coupling of highly conductive materials, like seawater (5 Sm^{-1})

In [27], a wire-mesh sensor was presented. This sensor features a single plane of internal electrodes that are both invasive and intrusive. The wire-mesh structure can solve the problem of reduced sensibility in the central region of the sensor, and generate a more homogeneous sensitivity distribution. However, the wire-mesh works as a strainer, blocking the flow in the pipe. For this reason, such a sensor is not suitable for most oil-extraction applications.

In this paper, a new type of dual-modality ERT/ECT dual-modality system is presented. It consists of a single tomographic system and a single set of electrodes to acquire dual-modality data. It also features the use of the 4-terminal sensing technique to accurately measure the inter-electrode impedance by simultaneously measuring both voltage and current. In this way, the effect of the parasitic resistance is eliminated [28]. Simulation and experimental results are presented to validate the effectivity of the system.

II. 4-TERMINAL SENSING

A. Electrode design

4-terminal sensing is a well-known technique to measure small impedances. This technique is used to

eliminate the effect of the parasitic impedance from the measurement leads, as well as the contact impedance, which may be larger than the unknown impedance. In this sensing technique, the voltage is applied directly to a sample by using a pair of leads whilst two extra leads are used to measure the voltage in the sample. Figure 1 shows the model for the 4-terminal sensing, where Z_x is the unknown impedance, Z_p is the parasitic impedances of the leads, the switching of stage and the contact impedance. V_m is the voltage measured across the sample, V_s is the voltage applied to the sample and I_m is the current supplied to the sample. The value Z_x can be calculated by applying Ohm's law with the values of V_m and I_m .

Figure 1 Model 4-terminal sensing

The 4-terminal sensing strategy is commonly used in ERT with current-excitation and voltage-detection. In this technique, a pair of electrodes is used to inject a current into the media and another pair is used to measure the induced voltage [29]. Despite the advantages of the 4-electrode configuration, the use of small pin electrodes generates severe fringe effect and the quality of the image is greatly reduced [6], [30]. Another limitation of conventional ERT systems is the inability to measure stratified or highly bubbly flows [30]. Because ERT is not compatible with ECT in terms of sensor structure, the two techniques cannot be simply integrated as a single set of electrodes dual-modality system.

B. Electrode design

Rodriguez-Frias and Yang [31] developed a 4-terminal ERT system with voltage excitation (ERTv). The sensor structure in this system includes long rectangular electrodes, with a voltage-excitation and current-sensing strategy, making it compatible with the ECT sensing mode. As described in [31], the new sensor structure consists of a large rectangular electrode and a ring terminal for measuring the inter-electrode voltages. Figure 2 shows the electrode configuration.

Figure 2 Compound ERTv electrode [31]

Figure 3 shows the connection for the system to be integrated with the MFLI impedance analyser from Zurich Instruments and the multiplexing stage [31].

Figure 3 Electrode structure and measurement scheme [17]

The sensor uses 8 electrodes installed in the interior of the pipe wall. Screws are used to hold the electrodes in position and provide an electrical connection. Figure 4 shows the cross-sectional view of the sensor structure.

Figure 4 Cross-sectional view of the sensor structure [17]

C. Sensing strategy

The sensing strategy in the dual-modality ECT/ERT system is based on the use of one electrode as a driving source and one electrode as a sensing terminal while the rest of the electrodes remain grounded, which is the same as in single modality ECT and ERTv. While one electrode is used as a driving source, for applying a voltage, another electrode is used as a sensing electrode, to measure the resultant current. The ring terminals are used to measure the voltage between the driving and sensing electrode pair. The rest of the electrodes remain grounded. The number of independent measurements is given by

$$m = \frac{n(n-1)}{2} \quad (1)$$

where n is the number of independent measurements and m is the number of electrodes.

III. ECT MODE SENSOR MODEL

A. Parasitic capacitances

Yang *et al.* analyse the effect of parasitic capacitance for ECT sensors with external electrodes [32]. Figure 5 shows Yang's equivalent circuit for an electrode pair C_x , the parasitic capacitances C_{s1} , C_{s2} , C_{s3} and the capacitances of the pipe wall C_{w1} , C_{w2} .

Figure 5 Sensor model [32]

In order to reduce the parasitic capacitances C_{s1} and C_{s2} , capacitance measurement is performed by a stray-free trans-impedance amplifier [33] as shown in Figure 6. In addition, as suggested by Koruda, the parallel parasitic capacitance C_{s3} can be mitigated by the use of shielded cables between the measuring device and C_x .

Figure 6 Trans-impedance amplifier

The dual functionality of each electrode, as a driver or as a sensor requires the use of a switching stage, usually built with CMOS switches that allow the change for the electrode mode. Figure 7 (a) shows the switching stage. The use of this switching stage introduces an extra source of parasitic capacitances not considered by Yang's model. The C_{DS} capacitance of the CMOS switches, as seen in figure 7 (b) has an important effect in the measurement of the unknown capacitance C_x .

(a)

(b)

Figure 7 (a) C_x electrode pair and switching stage. (b) CMOS switch model [34]

In this research, the need to measure conductivity, and permittivity distributions require the electrodes to be placed inside of the pipe wall. As a result, the capacitance of the pipe wall C_{w1} and C_{w2} , as seen in Figure 5, are eliminated. However, capacitance C_{DS} of the CMOS switches still affects the measurement. Figure 8 (a) shows the complete circuit for capacitance measurement of an electrode pair C_x , where the left plate of C_x is set as the driving electrode by closing switches S1, S2 and S3; and opening switches S3, S4 and S5. The right plate of C_x is set as the sensing one by closing switches S7, S8 and S12; and opening switches S9, S10 and S11. With an OFF impedance of several $M\Omega$ [34], the open switches across the circuit generate paths of high impedance, marked with the red arrows in Figure 8 (a). Therefore, the current path flows across the series between the C_{DS} of switches S1 and S2, C_x and the C_{DS} of switches S7 and S8 as seen on the simplified model in Figure 8 (b)

Figure 8 (a) C_x electrode pair measurement circuit, (b) Simplified circuit.

Figure 9 shows the update sensor model for ECT with internal electrodes. In this model, the effect of the capacitances of the pipe wall C_{w1} and C_{w2} are not considered. The updated model includes the parasitic capacitances C_{s1} , C_{s2} , C_{s3} and the capacitances of the CMOS switches C_{DSE} for the series capacitances of S1 and S2 on the excitation side of the circuit and C_{DSD} for the series capacitances of S7 and S8 on the detection side.

Figure 9 Updated model for ECT with internal electrodes

IV. IMAGE RECONSTRUCTION

A. Sensitivity maps

In ECT and ERT, the potential distribution in the domain is governed by Laplace's equation

$$\nabla \cdot \epsilon_{(x,y)} \nabla \phi_{(x,y)} = 0 \quad (2)$$

$$\nabla \cdot \sigma_{(x,y)} \nabla \phi_{(x,y)} = 0 \quad (3)$$

where ϵ is the permittivity of the material, σ is the conductivity and ϕ is the potential on the (x,y) coordinates.

Sensitivity maps are calculated by applying

$$S_{ij}(x,y) = \int_{\rho(x,y)} \frac{E_i}{v_i} \cdot \frac{E_j}{v_j} dx dy \quad (4)$$

where S is the sensitivity, E_i is the electric field when the electrode i is driving electrode and E_j is the electric field when the j electrode is driving.

When a linear image reconstruction algorithm is implemented, the sensitivity maps are usually generated with the use of a homogeneous material filling a sensor. In this case, the potential distribution is homogeneous and stays constant regardless of the value of the permittivity or conductivity. For this reason, the sensitivity distribution for both modalities is the same and a single sensitivity distribution can be used for image reconstruction of both permittivity and conductivity [17].

B. Reconstruction algorithm

Image reconstruction is performed with the use of linear back projection (LBP) and is implemented as [36]:

$$\hat{G} = S^T \cdot M \quad (5)$$

where $\hat{G}$ is the greyscale image, S^T is the transpose of the sensitivity matrix and M is either the capacitance or the conductivity measurement vector.

V. SIMULATION AND EXPERIMENTAL RESULTS

A. 4-terminal electrical capacitance tomography

A model of a parallel plate capacitor, with 4 and 2 terminals, is used to assess the effect of the voltage variation due to the 4-terminal capacitance measurement. Figure 10 shows the 3D arrangement with the voltage measurement terminals. The parallel plate arrangement is 0.91 cm wide and the square electrodes are 16 cm^2 . The simulation consists of a parametric sweep of the permittivity of the material, from $\epsilon=0$ to $\epsilon=80$ in steps of 1.

Figure 10 3D parallel plate model, (a) Driving electrode, (b) sensing electrode

As can be seen from Figure 10, the potential at the terminals for voltage measurement diverges from the 1 V set at the driving electrode and the 0 V set at the sensing electrode. The terminals register 0.88 V and 0.11 V respectively. For this single capacitor with a homogeneous permittivity distribution, the voltage across the terminals remains constant as the permittivity of the material is increased. The effects are reflected only in the current, as seen in Figure 11 (a). While the parallel plate capacitor is simulated, the voltage measurement across the electrodes remains 1 V for the 2-terminal measurement and 0.77 V for the 4 terminal measurement. These voltage measurements remain stable with the increase of the permittivity. The current flowing through the capacitor is the same for both modalities. As the capacitance is derived by the current and voltage measurements between the electrodes, with the 4-terminal configuration, the voltage measured across the terminals is reduced and therefore the measured capacitance is proportionally increased.

Figure 11 (b) shows the percentage of the relative error for the measured capacitance C_m in relation to the theoretical capacitance C_t .

(a) I and V plots

(b) Relative error in capacitance estimation

Figure 11 C_x with 4-terminals and 2-terminals measurements

As seen from Figure 11, the voltage stays stable on both measurements. The current increases linearly with the increase in permittivity. The deviation in the voltage measurement by the use of the 4-terminals causes a constant relative error of 24% whilst the 2-wire measurement provides a 0% relative error measurement. However, for capacitance measurement in ECT, there exist parasitic capacitances that compromise the accuracy of the measurement, as seen in Figure 9, the inter-electrode capacitance is in series with the capacitance C_{DSE} and C_{DSD} . The parallel plate capacitor is modified to include two capacitors in series, each one with a value of 16 pF. This capacitance value is determined by the series of two 32 pF capacitors, a typical value for the C_{DS} of a DG411 CMOS switch. Figure 12 (a) shows the current and voltage across C_x , Figure 12 (b) shows the relative error for the estimation of C_x with both measurement techniques for the series of the three capacitors. As can be seen from Figure 12 (a), the voltage measurement with a 2-terminals configuration remains 1 V, as set by the power supply. In contrast, the voltage measurement acquired by the 4-terminals configuration reflects the change in voltage across C_x as the value of the permittivity across its plates is increased. Figure 12 (b) shows the percentage of relative error in the estimation of C_x . The error for the 4-terminals technique remains stable at 24% whilst the error for the 2-terminals measurement increases considerably as the permittivity of the dielectric inside C_x increases, reaching the highest point of 60%.

(a)

(b)

Figure 12 (a) I and V plots, (b) relative error in capacitance estimation for a series of C_{DS1} , C_x and C_{DS2} with 4-terminals and 2-terminals measurements

An experimental set up was used to further explore the effect of the parasitic capacitance C_{DSE} and C_{DSD} on imaging of permittivity distribution. Two annular distributions with

different permittivity contrasts were used. A low contrast distribution with an outer ring of air ($\epsilon = 1$) and a central core of dry sand ($\epsilon = 3$). The high contrast distribution was composed by an outer ring of air ($\epsilon = 1$) and a central core of deionised water ($\epsilon = 80$). Both data sets were acquired using the same sensor, the 4-terminals measurement was performed as shown in Figure 3. For the 2-terminals measurement, the H_{pot} terminal was connected with a bridge cable to the H_{cur} terminal. Similarly, the terminal L_{pot} was connected to the terminal L_{cur} . Figure 13 (a) shows the experimental setup and Figure 13 (b) shows the detail of the sensor with internal electrodes.

The excitation voltage and frequency were set to 3 V and 1 MHz. Figure 14 shows reconstructed images using the 4-terminals and 2-terminals techniques. Image reconstruction is performed by applying the LBP algorithm:

Figure 13 Experimental setup (a), detail of the sensor with internal electrodes (b)

Figure 14 Image reconstruction for high and low contrast distributions

The images in Figure 14 show, for both measurement techniques, similar image quality for low contrast distribution. In this case, it is expected that the error caused by the parasitic capacitance is negligible. However, in image reconstruction for the high contrast distribution, there is a considerable decrease in the image quality for the 2-terminal sensor whilst the image quality for the 4-terminals sensor remains virtually unchanged for both, high and low contrast distributions. Figure 15 shows the normalised capacitance for low (a) and high (b) contrast distributions. Normalisation is performed by:

$$C_n = \frac{C_m - C_l}{C_h - C_l} \quad (6)$$

where C_n is the normalised capacitance vector, C_m is the measurement vector, C_h is the high permittivity calibration vector and C_l is the low permittivity calibration vector.

Figure 15 Permittivity distributions, low contrast (a) and high contrast (b)

Figure 15 (a) shows how C_n of low contrast distribution for the two measurement techniques remain within a close range to each other, whereas the vectors C_n for high contrast distribution deviate considerably from each other.

As the data were acquired with the same system, using the same sensor, it is expected that the deviation seen in C_n , and therefore in the image quality, is an effect of the parasitic capacitances C_{DSE} and C_{DSD} introduced by the CMOS switches in the multiplexing stage. As stated by Yang *et al.* [32], the error introduced by such parasitic capacitance when measuring the value of C_x may be neglected for imaging low

contrast dielectric distributions. However, for dual-modality imaging, the distributions can change from fully conductive to fully dielectric as WLR and GVF change. In this case, the error introduced is too large to be neglected.

VI. CASE STUDY: MULTI-COMPONENT GAS/OIL/WATER FLOW

A. Conductivity and permittivity of an oil-water mixture.

In the oil industry, the presence of gas and water alongside the oil represents a challenge for measuring the production of wells. New oil extraction techniques generate large quantities of water alongside the oil, as water flooding is a common practice to increase the pressure in the wells. This makes monitoring the production of oil a challenging task. According to the amount of water being generated, the flow can be classified from water-continuous to oil-continuous. In a water-continuous flow, the distribution is mainly conductive. For an oil-continuous flow, the distribution is mainly dielectric. The ratio between the amounts of water and oil in the liquid phase defines WLR. In addition, the presence of gas in the flow is determined as GVF. WLR and GVF are calculated by:

$$WLR = \frac{\text{Water volume flow rate}}{\text{Total liquid volumetric flow rate}} \quad (7)$$

$$GVF = \frac{\text{Gas volume flow rate}}{\text{Total volumetric flow rate}} \quad (8)$$

The permittivity and conductivity of the liquid phase, for the oil continuous liquid phase, can be derived by:

$$\epsilon_{liq}^{oil} = \epsilon_{oil} \frac{1+2WLR}{1-WLR}, \quad \sigma_{liq}^{oil} = \sigma_{oil} \frac{1+2WLR}{1-WLR} \quad (9)$$

where ϵ_{liq}^{oil} is the resultant permittivity, ϵ_{oil} is the permittivity of the oil. σ_{liq}^{oil} is the conductivity of the resultant liquid mixture and σ_{oil} is the conductivity of the oil.

The permittivity and conductivity, for a water continuous liquid phase, can be derived by:

$$\epsilon_{liq}^{water} = \epsilon_{water} \frac{2WLR}{3-WLR}, \quad \sigma_{liq}^{water} = \sigma_{water} \frac{2WLR}{3-WLR} \quad (10)$$

where ϵ_{liq}^{water} is the resultant permittivity, ϵ_{water} is the permittivity of the water. σ_{liq}^{water} is the conductivity of the resultant liquid mixture and σ_{water} is the conductivity of the

water. Figure 16 shows the permittivity and conductivity of the resultant liquid mixture.

Figure 16 Permittivity and conductivity of the liquid phase of oil-water mixture

B. Flow conditioner

A Venturi tube can be used to form an annular flow distribution by amplifying the effect of swirl flow. Because the restriction in the diameter of Venturi's throat accelerates the flow and pushes the gas inwards, the centrifugal force pushes the liquid layer outwards, generating a central gas core and a liquid annular layer, the acceleration and swirl effect also generates the mixture of water and oil, producing an emulsion [37].

For this experiment, motor oil ($\epsilon = 2$) and water ($\sigma = 80 \text{ mS} \cdot \text{m}^{-1}$) are used as liquid components. Oil and water samples were prepared in a WLR range from 5% to 95% with 5% increments. The samples were thoroughly mixed to achieve emulsion before data were acquired for image reconstruction. An empty tube was used as a central gas core, as seen in Figure 17. Figure 18 (a) shows reconstructed images for the samples in a range of WLR from 5% to 50%. Figure 18 (b) shows reconstructed images for the samples in a range of WLR from 55% to 95%. The percentage of relative error shown in Figure 18 is calculated against the phantoms of the real distributions. Image reconstruction is performed by the LBP algorithm.

Figure 17 Empty tube as central gas core

(a) From 5% to 50% WLR, oil-continuous liquid phase

(b) From 55% to 95% WLR, water-continuous liquid phase

Figure 18 Reconstructed images for WLR samples

Figure 18 (a) shows the inability of the ERT modality to image oil-continuous distribution. While the ECT modality produces images with a low relative error. In contrast, Figure 18 (b) shows that the ERT modality provides higher quality images, with a reduced relative error in the water-continuous distribution. In this case, the ECT modality is unable to produce a meaningful image, reaching relative error levels as high as 136%. Figure 19 shows the relative error of the reconstructed images for the full range of WLR and both modalities. This agrees with the theoretical model shown in Figure 16, in which the inversion point, between oil-continuous to water-continuous, is located in the 50% WLR region. In the experimental results, the error for the ECT modality starts to increase steeply in 60% WLR, while the error for the ERT modality starts to steeply decrease, showing the change of dominance in the media, from dielectric to conductive.

Figure 19 Relative image reconstruction error for the full range of WLR for ECT and ERT modalities

VII. CONCLUSIONS

Four-terminal ECT can reduce the effect of the parasitic capacitance of the CMOS switches, which have a significant effect on the accuracy of the acquired data, more noticeable for high contrast permittivity distributions. Integration of ERT/ECT modalities, with 4-terminal sensing, allows the measurement of complex distributions in the full range of WLR. This approach can be used for monitoring multiphase flows in oil production. It is expected that with further development, this technology will allow the control and optimisation of oil extraction.

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