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Performance and Application Studies of an Electrical Resistance Tomography System

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Abstract - *Electrical resistance tomography has been developed to the stage where commercial instruments are now available. There are a number of approaches to transferring this technology from the institutions where it has been developed to interested users. This paper examines the approach of offering a consultancy service. This typically includes the mounting of pilot plant experiments, aimed at the evaluation of the use of process tomography to gain a deeper insight into a process of interest. Applications include a range of processes in which complex flows and inter-actions take place which are ill understood. The major interest has been to enhance knowledge of the internal behaviour of the process with a view to optimising design. The paper reviews the development of electrical resistance instruments, the technology transfer process, the detailed facilities of the instrument used, and the capabilities of the software employed. It will also illustrate its use through a illustrative case study in which a detailed insight of a process has been achieved.*

Keywords: Electrical resistance tomography, instrumentation, reconstruction software, interpretation software

1. INTRODUCTION

The goal of electrical impedance tomography is to obtain the impedance distribution in the domain of interest and apply this information to improve the overall performance of a process.

The impedance distribution information is obtained by injecting currents or applying voltages on the domain and measuring voltages or current via a number of electrodes that are mounted non-intrusively but invasively on its boundary. An accurate and stable data acquisition system (DAS) is a core requirement and typically incorporates: signal sources; an electrode multiplexer array; voltage sensing; signal demodulators; system controller. Such complexity is necessary due to: -

- low amplitude measurements required at the boundary, of the order of millivolts or less, whose dynamic changes are of the order of microvolts;
- large number of electrode channel operations, for example a minimum of 104 measurements are needed for 16 electrodes, with high common mode voltages.

At this early stage in the application of the technology, the improvement in process performance varies from case to case. Thus whilst a standard instrument format can be devised to extract information, a flexible approach must be taken to translate this information into enhanced performance.

2. BACKGROUND TO EIT INSTRUMENTS

The first instruments to use the principle of EIT were built by biomedical research groups in North America and Europe for use in clinical observations. In contrast to visualisation of organic systems, an EIT system for tomographic visualisation in process applications must offer maximum flexibility to suit a range of applications, for example: miscible liquid and/or liquid-solid mixing processes; cyclonic and dense medium separation; and, hydraulic transportation in pipelines.

The current *ITS* instrument has been developed from research and development at UMIST, UK, beginning in the early 1990's. The current *ITS* system is based upon a specification to maintain flexibility and accuracy over a diverse range of process parameters:

- injected alternating current bandwidth - 75 Hz up to 153.6 kHz;
- injected alternating current amplitude - 0 to 30 mA (peak-to-peak);
- various current injection methods - adjacent, opposite, multi-reference, and conducting boundary strategies;
- a maximum of 64 electrodes either in a single, or over multiple planes.

To suit a wide range of process vessel size and electrical conductivity, there is a need to vary the amplitude of injected currents in order to optimise the measurement signal-to-noise ratio (SNR). Also, for slowly changing processes, such as sedimentation in a viscous medium, more accurate measurements are facilitated at lower frequencies of injected current hence the motivation for the ranges given in the first two requirements above.

The requirement to accommodate several different methods of injecting alternating current is readily achievable by utilising more than one current source/sink pair. The adjacent and opposite electrode pairs methods only require one current source and sink pair thereby minimising the complexity of the associated circuitry. Conversely, the multi-reference method requires that all but one of the electrodes have an identical fixed amplitude current source attached to it. The corresponding voltage measurement is taken across a grounded load connected to the free electrode. The conducting boundary strategy is an alternative method in which the current injection is performed between one of the electrodes and the conducting boundary. The resultant boundary voltages being measured from each of other electrodes with respect to the conducting boundary.

The final specification enables up to 64 fixed-amplitude current sources to be attached to the process vessel. These can be arranged across several layers, to meet the requirement of the multi-layered imaging, or across a single layer to enhance the spatial resolution which is proportional to the number of unique measurements.

3. TECHNOLOGY TRANSFER APPROACH

There are a number of well-understood approaches to the transfer to technology from research institutions to the open market. In the case of new instrumentation, typical mechanisms include:

- developing well manufactured instruments which consistently deliver well-understood outputs. Publishing these specifications, together with case notes on applications. Selling instruments to expert, interested users
- collaborative research between research institutions and interested users leading to one-off technology licensing arrangements
- providing a service which supports organisations interested in applying the new technology, but where the organisation does not have the appropriate in-house skills to manage the application.

The third approach is generally the one adopted by *ITS*. It requires close dialogue with interested users to ensure that applications selected are amenable to process improvement through tomography. Whilst this takes time it provides an opportunity for *ITS* to build a deeper understanding of the application and it provides the company the opportunity of fine-tuning the application and increasing its confidence in achieving its particular goals.

Over the last two years the process has developed along the following structure, with an iterative loop in developing the tomography system itself. Once process benefits have been achieved, then there is greater confidence in the company for applying tomography elsewhere in its business.

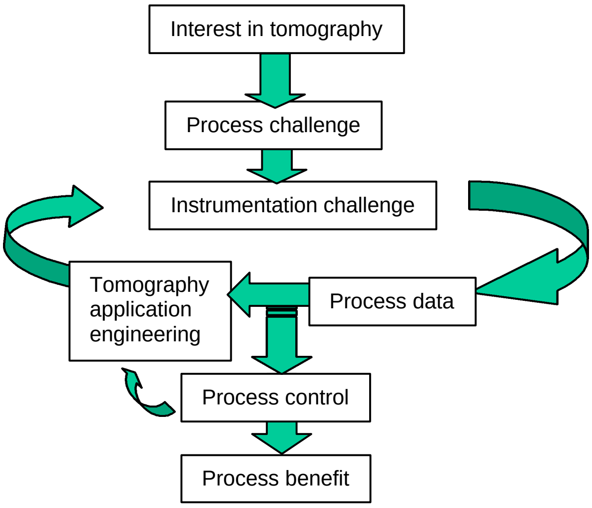


Figure 1 – Technology transfer process.

In reviewing the central loop of the above process, the key areas of information required are:

- access to process plant (including safety)
- flow conditions (rate and composition)
- time-scale of process measurement
- measurement output (homogeneity, gas hold-up, relative concentration etc)
- process control methodology.

The process control methodology is often refined in the course of the technology transfer process. As illustrated in Figure 1.

These refinements relate to the extent to which a single control variable is required for the need for full three dimensional visualisation of the process behaviour. The proper design of sensor electrode systems is a most critical part of the process.

4. SYSTEM OVERVIEW

The *ITS* EIT system is shown in schematic form in Figure 2 below, commencing at the bottom left corner with the voltage generator (1); and then, in a clockwise direction, the electrode current injection unit (2) which drives each electrode on the process vessel, and its control module (3). This is followed by the voltage measurement, demodulation and filtering unit (4). Finally the microcontroller (5) coordinates the various sub-systems.

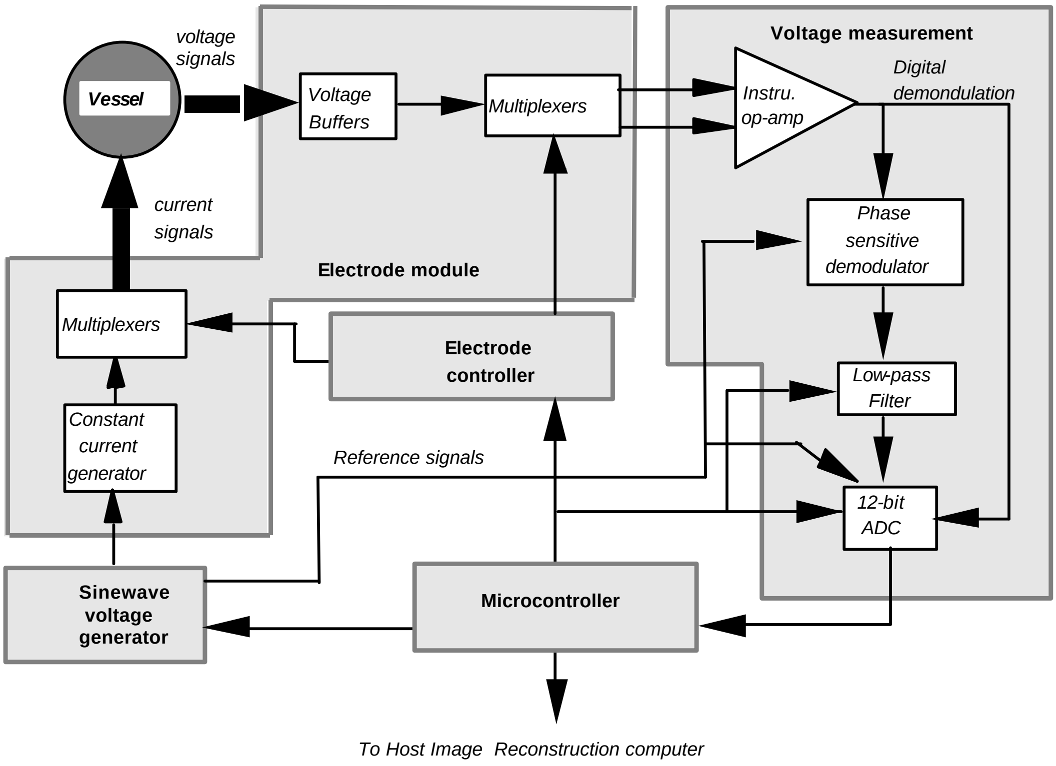


Figure 2 – Structure of the ITS measurement system.

The system is housed on five Eurocard printed circuit boards (PCBs) and one or more electrode modules to form a complete system. A single-chip microprocessor, an Intel i8052AH, controls the operation of the system. This embeds assembly language routines for real-time data acquisition and control. A 64-way backplane is utilised for digital signal transfer and control between each board and the microcontroller. The system can be extended to accommodate 8 voltage generators, 8 measurement boards and up to 64 electrodes with an additional 64 memory-mapped address spaces.

The sinewave voltage generator (1) is a key sub-system. To minimise the number of harmonic components in the 'interrogating' injection signal, the voltage generator is required to produce a sinewave-shaped output at the desired frequency. Important attributes of the voltage generator are: -

- *good amplitude stability* - the amplitude must remain stable (to ±0.1%) for the entire duration of the sequential measurement procedure;
- *low harmonic distortion* - the phase sensitive demodulator uses the oscillator output to synchronously rectify the measured voltage signal. An error can be introduced by the rectified noise contribution from the harmonic coefficients. This can be reduced through a switching demodulator, in that only odd-

numbered harmonics cause errors, or a digital demodulator in combination with a digital function generator.

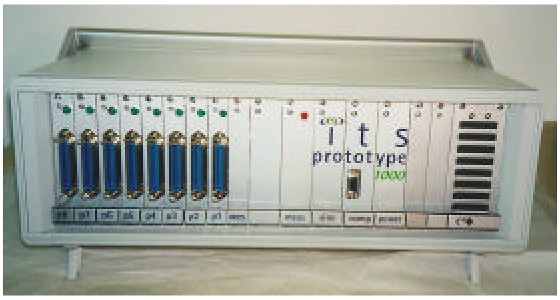


Figure 3 – Photo of instrument.

The *ITS* system offers maximum flexibility through a software-based staircase function generator. The digitised sinewave signal can be stored as a variable number of samples, typically 16 or 32, depending on the required accuracy of the reconstituted signal, with a rate of 32 samples per cycle giving a much lower total harmonic distortion. Any small errors arising are effectively removed by a second order Butterworth low-pass filter.

An electrode module allows an advantageous close linkage between the tomographic measurement system and the process plant.

5. TECHNICAL DESIGN FEATURES AND PERFORMANCE

In order to obtain the voltage measurement from the boundary of the domain of interest, an electrical signal, in the form of a voltage or current, is necessary in order to 'probe' the domain. The design of this system is a critical factor to suit a wide variety of process applications. The four-electrode measurement technique is utilised in the majority of applications to minimise the errors caused by contact impedance at the electrode-process material interface. The transient time arising from the contact impedance is also affected when a voltage injection is adopted. A current injection strategy is therefore selected in the *ITS* instrument. The device also has a trigger function that is important for data collection e.g. gating to a mixing, chemical or other process transient.

The voltage controlled current source (VCCS) is one of the most critical aspects of a current injection EIT system. After careful evaluation the VCCS adopted in the *ITS* instrument is based on an optimal positive feedback architecture designed to deliver the flexibility and transient performance required with a matched phase error of less than 0.7°. The electrode connection utilises a driven shield technique necessary to minimise the stray capacitance associated with the connectors.

Through the use of these sophisticated compensation techniques the current amplitude and bandwidth of the VCCS extends linearly from 0 to 30 mA (peak-peak) and from 75 Hz to 153.6 kHz. The voltage measurement circuitry is shown schematically in Figure 4. It extends from voltage buffers in the electrode module to the digital data output from the ADC.

One of the most problematic measurement errors arises from common mode voltage (CMV) due to limitations in operational amplifiers. The design delivers a nominal common mode rejection ratio (CMRR) of -73 dB at a gain of 1000 times at a frequency of 100 kHz.

Demodulation is achieved either by switched, or by digital mode. It is well known that the phase shift of the reference signal must be less than 1.266° to achieve 12-bit accuracy in switched mode. Demodulation for the quadrature part is much more sensitive than for the in-phase part when the phase shift is small. For example, a quadrature signal deviated by only 0.015° can be located with a 12-bit ADC. Therefore, the unit is initially calibrated at the quadrature position for the injection current phase, and then the correction phase is subtracted by 90° to

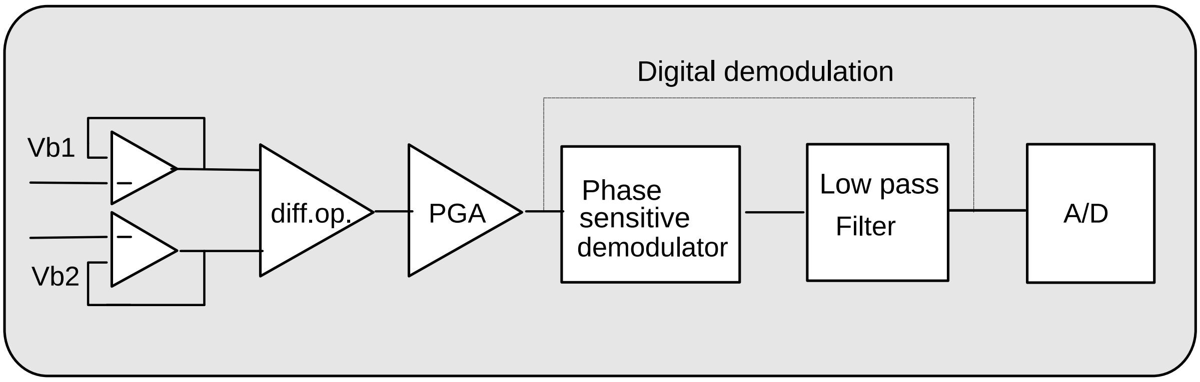


Figure 4 - Measurement, demodulation and filtering sub-systems

represent the reference phase at the demodulator for in-phase demodulation. The minimum adjustable phase shift is 0.7° through control by the microcontroller and 5ns delay by manual delay line adjustment.

The overall accuracy of the voltage measurements is governed by the resolution of the analogue to digital converter (ADC). A 12-bit ADC has a resolution of 1/4096 or approximately 0.025% of the full range of input signal is used which combines adequate resolution with good access speed.

The data collection speed of an EIT system is mainly limited by the filter in the voltage measurement stage, and its associated couplings, when analogue demodulation is adopted. The *ITS* design modules are available to satisfy differing requirements. The fastest speed of collection for 1 frame of 104 measurements is 40ms at 38.4kHz, using the digital demodulation option, and 150ms using the analogue demodulation option.

Control is achieved using embedded software for the single-chip Intel i8052AH microcontroller, which also offers a variety of useful software development options to allow customisation for specific industrial requirements.

The repeatability and stability of the data acquisition system are important for a system targeted to industrial use. Repeatability for a nominal instrument was investigated by acquiring 100 frames of data sequentially from a test vessel filled with mains tap-water (0.096 mS/cm conductivity at room temperature of 23.1°C) using a current of 5 mA (absolute value). The maximum deviations were found to be less than 0.5%.

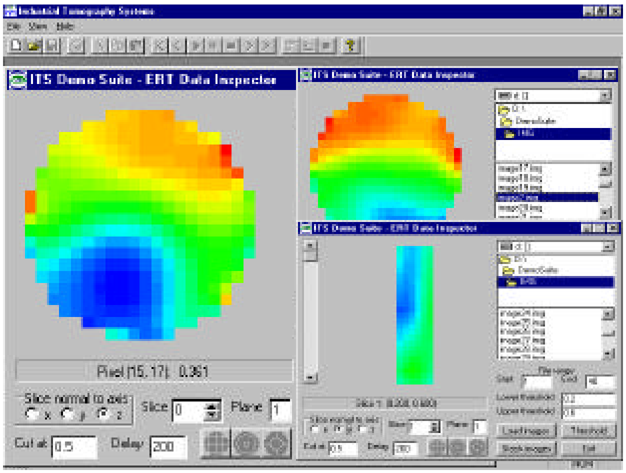
Stability was also examined using the same experimental conditions through the comparison of two frames of data acquired with an intervening interval of two hours. The deviation due to instability was found to be less than 0.6% after two hours. The averages of the repeatability and the stability values are lower than 0.2 %. The key features are summarised in Table 1.

Microcontroller	Intel 80C52AH
Clock speed	11.0592 MHz
Internal memory	32 Kbytes ROM, 32 Kbytes RAM
Sinewave generator	zero order hold staircase wave
Oscillator	9.8304 MHz
Number of samples	32
Harmonic content	-65 dB @ 38.4 kHz for 2^{nd} order
Max. no. of generators	8
Injection frequency	75 Hz - 153.6* kHz (in 12 steps) (* 156.3 kHz frequency is a reference only)
Injecting current	0 - 30 mA(peak to peak) (in 256 steps)
Harmonic	-59 db @ 38.4 kHz for 2^{nd} order
Current injection methods	For single electrode module only: - Adjacent Opposite Conducting boundary Multireference
Max. number of electrodes	64
Measurement range	-10 V to +10 V (peak to peak)
Sensitivity	4.88 V at gain ×1000
CMRR	> -70 db @ 153.6 kHz
Accuracy	± 0.5% (at 0.6 kHz to 76.8 kHz)
Repeatability	< 0.5% per 100 frames (at 9.6 kHz, 21.8 °C)
Stability	< 0.6% (at 9.6 kHz, 2 hours @23.8 °C)
Max. no. of measurements	8
ADC resolution	12 bits
Sample window	0.3 S
Conversion speed	3 S
Mode of measurement	sequential / 8 channels parallel
Type of demodulation	switched or digital demodulation
Phase shift compensation	0.7° to 180°
Speed of acquisition for one frame	< 40 ms (digital demodulation, at 38.4 kHz) < 150 ms (switched demodulation at 38.4 kHz)
Serial data interface	RS-232C, Baud rate 2400 – 76800
Physical construction of PCBs	Eurocard, fibre glass base
Power consumption	< 0.15A, 220-240V AC

Table 1: Key Features

6. USER INTERFACE AND SOFTWARE

The measurement system is driven by a Microsoft Windows interface that can be used for both measurement and data analysis (on and off line). The Windows approach offers the ability to set up multiple experiments and to easily compare current and historical data. Data reconstruction and analysis software is supplied in a library format with different modules. Figure 5 shows a data analysis module (Data Inspector™) which allows reconstructed images to be sliced, animated and interrogated at the pixel level or by filtering data to user-supplied models. An example is given below. Raw voltage measurements can also be analysed using statistical methods. The analysis library is under continued development.



Pixel (15, 17): 0.361

Slice 0

Plane 1

Cut at 0.5

Delay 200

Figure 5 - Windows data viewer showing two tomographic slices in z plane and one image of ten slices stacked in y plane

7. CASE STUDY

To demonstrate the ability of the approach in typical industrial applications, we will consider here the first stage in a feasibility study of applying ERT to a bubble column. The target set was to see what information could be obtained from the *simplest possible* array of electrodes on the behaviour of a spargered column. Considering only one ring of electrodes retrofitted into a column section (Figure 6), the P1000 measurement method was used in conjunction with an independent (calibration) method of injected gas flux to predict:

- gas hold up
- homogeneity of gas bubble dispersion
- flow state of the column

Gas was injected at different rates whilst monitoring the response from the 16 electrodes at a frame rate of 1 Hz. This represents a low specification and demand on the instrumentation but was used to assess the capabilities of such a minimal specification.

Figure 7 shows the results. Figure 7(a) provides a time-scrolling animation of the gas distribution, as identified with an iso-contour visualisation, with the instantaneous (current time) image at the top of the stack. The light coloured regions correspond to non-conducting gas phase. The squat appearance of the bubble clouds is due to the low image rate deployed. Figure 7(b) shows the analysis of the process inputs (i.e. gas valve position) (lower graph) and image-derived data. This consists of an estimate of the instantaneous local gas hold-up from average conductivity (middle) and a statistical assessment of the homogeneity (top graph). The user has control over the time averaging and other features. Different methods can be used to assess the uniformity of the bubble behaviour. The method used here is based on proprietary ITS Data Inspector software based on a ranking of time-variations in a pixelated regions.

Figure 6 Bubble column with 16-electrode single plane sensor in centre of vessel

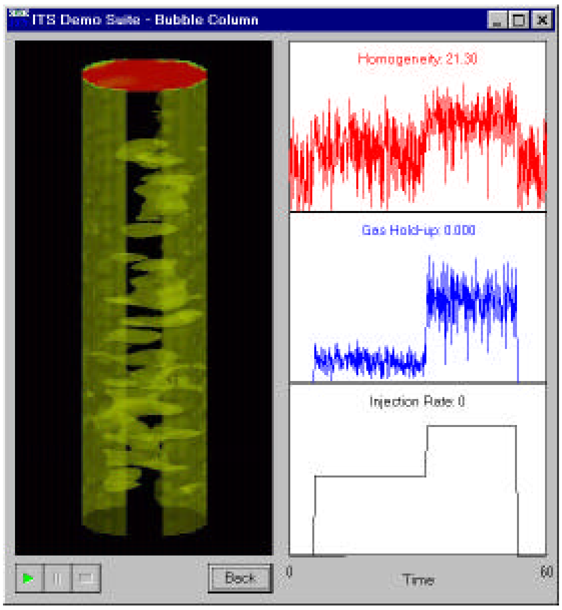


Figure 7 (a) Animation Showing, gas hold-up and homogenetiy

Figure 7 (b) Data analysis,

The methodology has proved effective in characterising the bubble column. By using multiple sensors arranged on such columns, the axial and radial properties of the bubble column can be assessed. Use of time-space data also enables velocity-based information to be derived. Further examples of this approach will be published in the future.

8. CONCLUSION

The approach to the development of electrical resistance in a process-user environment has been described. Close interaction with industries has ensured measurements and interpretation of resulting data conforms to industrial needs. This has resulted in significant modification to process practice – for example, making more use of process user-knowledge and a prior information. As the international user-base develops, we anticipate a continued rapid development.