

Simulating the Transient Response of ICCP Control Systems

JMW Baynham, R A Adey

CM BEASY, Ashurst Lodge, Southampton, Hampshire, SO40 7AA, UK

Email: j.baynham@beasy.com

Abstract

The simulation of passive and active CP systems has over the years become a straightforward matter so that it is regularly performed to aid design and to assist understanding of system behaviour. Such numerical simulation takes into account the highly non-linear effects which take place during corrosion.

This paper describes the application of CP simulation to modelling the dynamics of the complete ICCP system, including controllers, generators, anodes and reference cells.

This ICCP controller simulation allows representation of various real effects (for example time delay in response), and allows prediction of the transient behaviour of the complete ICCP system. The ICCP system may include several controllers, and multiple anodes and reference cells.

The software, which is based on the Boundary Element Method (BEM), uses “virtual instrument” technology to allow the user to manipulate individual controllers in the system, and to view the “output” of the system. The “output” can be output parameters for one or more controllers, or it can be some overall measure of response of the complete system - for example UEP signature.

Examples are given of application to multiple – controller systems.

The transient simulation runs at speeds many times faster than real-time, and so could in principle be used as part of a practical onboard control system.

Keywords

ICCP, control-system, simulation, dynamics, UEP

Introduction

The simulation of ICCP systems has been used to assist design for several years [1-4]. The *classical* method used until now involves:

- definition of the output of each anode (by prescribing either voltage or current density boundary condition)
- solution to determine the resulting UEP

The way in which the anode outputs are achieved is not considered in the classical method, and so the resulting solution represents a *snapshot* of the behaviour of the complete system.

In the work reported here, attempts are made to simulate the dynamic behaviour of the control system, including the reference cell(s), the controller(s), the power source(s), and the anode(s). The resulting solutions, which could be regarded as a series of snapshots, provide a representation of the transient behaviour of the complete system.

As in the classical method, the geometry is represented using boundary elements, and the nonlinear polarisation effects are represented using polarisation curves, all as previously reported[5,6].

The software is based on the commercial boundary element package BEASY.

Components of the System

The various components of the ICCP system are represented in the software as follows...

The Power Source

A power source has an input, and an output, and a description of how the output is related to the input. The input is the signal coming from a controller, and the output is passed on to the attached anode(s). The output may be a voltage, or a current. The *transfer function* which relates the input and the output may include a time delay, and may include various forms of response to a step change of input. There may be upper and lower limiting values of output.

The Anode Group

A group of one or more anodes is attached to a power source. The group of anodes has an input, which is the output from the power source. This group input is passed to each anode in the group, using a method which depends on the form of the input. A voltage input is passed to each anode without change, but a current input is split between the anodes using various possible methods (for example in proportions based on anode area, or in proportions which may be explicitly assigned).

The Anode

Each anode has an input, which is either a voltage or a current. The output is applied as a boundary condition on the boundary element(s) which represent the anode. The transfer function which relates the anode input and output may include a time delay, and may include various forms of response to a step change of input. There may be upper and lower limiting values of output.

The Reference Cell

A reference cell measures voltage. A cell may sample the voltage at a single position, or it may return the average of voltages sampled at a series of positions, or it may return the area-based average of voltage sampled over an area. The input to the reference cell is obtained from the classical solution to a snapshot set

of boundary conditions. The output from the reference cell is a voltage (the *process variable*, or *PV*).

The Controller

A generalised controller has input values, an output value, and a method which defines how the output is derived from the inputs.

The input typically includes the *required* voltage (the *set point* or *SP*) at the associated reference cell, and measurement(s) of *achieved* voltage at the reference cell. The output is a signal (the *control variable* or *CV*) which is passed to the power supply. The method which derives the output from the various inputs can be quite general (it can be programmed in a user-defined subroutine accessed via a *dynamic link library* or *DLL*), or it can take the form of a predefined control equation. The input to the controller is not necessarily limited to the voltage measurements at its associated reference cell.

The Sensor Point

A *sensor point* is simply a generalised position at which voltage and electric field are measured. The input to the sensor point is obtained from the classical solution to a snapshot set of boundary conditions. The output from the sensor point is a voltage, and electric field components. The output from a sensor point may be available to a generalised controller.

The Complete System

A complete system may include multiple controllers. The components attached to each separate controller (shown schematically in Figure 1) include:

- A power source
- A group of one or more anodes
- A reference cell
- Something which defines the set point

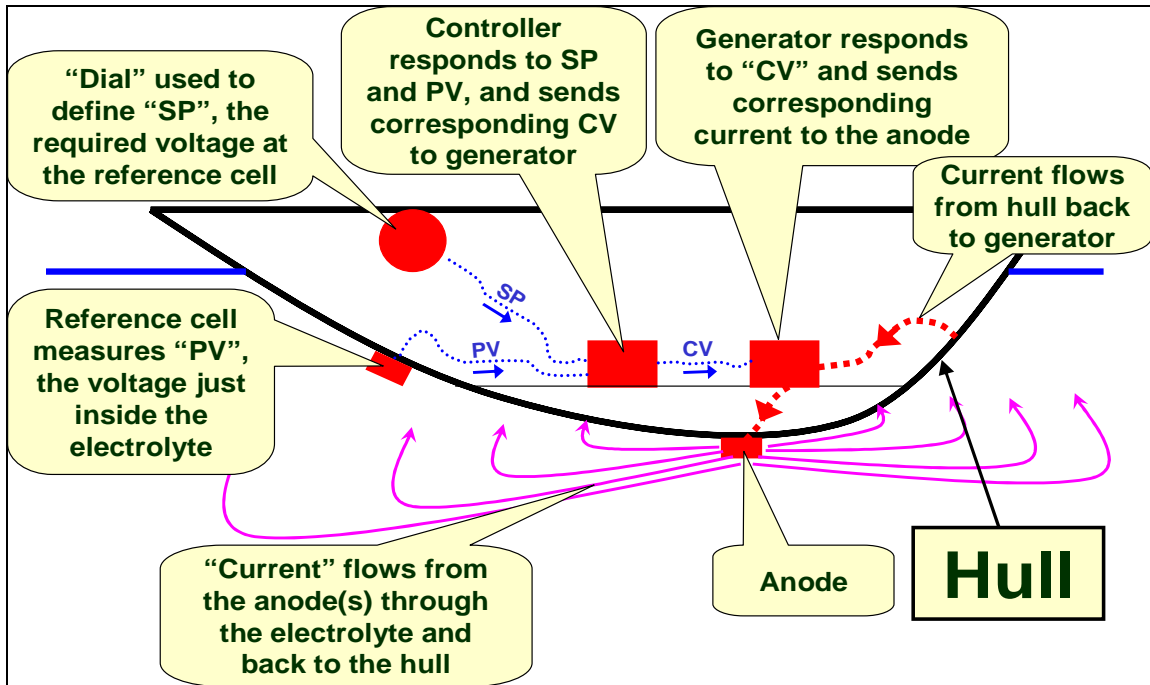


Figure 1: Schematic of a single-controller ICCP system

Simulating Start-up of the ICCP system

If initially the control system is not switched-on, the UEP predicted by the software is simply the result of galvanic effects caused by any dissimilar materials of which the ship is made. Thus the reference cells and any sensor points have an input which corresponds to the classical CP solution with all anodes turned off.

When the ICCP system is switched on, each controller immediately sees its PV and SP, and sends a value of CV to its power supply. The power supply responds, and sends output to the anodes. Current flows from the anodes into the sea water, and back to the hull, producing a change in the voltage around the hull.

The new voltage is detected by the reference cell, which passes a modified PV to the controller. The controller sees the new PV, and sends a modified value of CV to the power supply. And so on.

The mathematical description of each component is used to determine its output. The classical BEASY CP solution is used to determine the UEP (and PV) corresponding to any particular set of anode outputs.

The CP Solution and Response Surface

Clearly the time taken to determine the classical CP solution from the BEM model is crucially important to the usefulness of the ICCP System simulation as thousands of solutions are required. In practise, it has been found that for realistic hull models, the time taken is too great.

Consequently, methods were developed to build a *response surface* describing the CP solution. Then rather than performing a classical CP simulation, instead the response surface is used to determine the UEP and PV corresponding to any particular set of anode outputs. The modelling process is therefore divided into two stages, first compute the response surface from the BEM model, and then perform the simulation of the ICCP system.

Using the stored response surface method, the ICCP system simulation can operate very quickly indeed, using very limited computer resources.

Different methods can be used when constructing the response surface. The *full* response surface requires most solutions, while the *first order* response surface requires least solutions. The computational resources required to build the response surface depends upon the number of controllers, the size of the BEM model and the accuracy required.

The response surface characterises the way the UEP varies with anode output. Notice it does *not* include any of the properties of the components (power source, anodes, reference cell or controller). This means the response surface can be used for simulations using *any* component properties.

The simulator as a real-time UEP calculator

Since the simulation predicts the UEP corresponding to any set of anode outputs passed to it, the software can be used simply as a UEP calculator, which can be operated either manually or automatically. When operated automatically, the controller DLL interprets the controller inputs however it likes, and returns controller outputs derived from some other source (for example measured power supply output). Since it can run at real-time speeds, the simulation provides the means to at least *monitor* the UEP.

Regardless of whether used as a real-time UEP calculator or as an ICCP System simulator, the *frequency* at which each new set of anode outputs is passed has not yet been considered in this discussion.

When functioning simply as an automatic UEP-calculator the frequency is not relevant to the calculations. The only requirement is that the software can operate at real-time. For the 4 controller system described later, and using a 1.75GHz Pentium 4 dual processor machine, it has been found that the software can calculate UEPs at rates in excess of 1500 per second.

When functioning as an ICCP control system simulator, the frequency may or may not be relevant to the calculations. For example an external controller DLL which represents the behaviour of an analogue controller may not use the frequency when calculating its CV output value. Whether or not frequency is used depends only on the control equation used to represent the behaviour of the controller.

In the next section, there is discussion of some control equations which *do* use the frequency when determining the controller output CV value.

The Controller Equation

So far the way in which the controller works has not been discussed. Now however we give some examples of control equations which may be used...

Each of these equations assumes that a new set of PV values is available at a frequency f , which may for example be 50Hz, but could take any value. In the following:

- values which relate to a time $t-2\Delta t$ are labelled using subscript $k-2$
- values which relate to a time $t-\Delta t$ are labelled using subscript $k-1$
- values which relate to a time t are labelled using subscript k
- values which relate to a time $t+\Delta t$ are labelled using subscript $k+1$
- and so on

Note that the sampling interval T appears in the equations shown below, and that $T=1/f$.

1DOF PID

A 1 degree of freedom proportional integral differential (*1DOF PID*) control equation calculates the new controller output (CV_k) using:

$$CV_k = CV_{(k-1)} + P_k + I_k + D_k$$

Where the values of P_k , I_k , and D_k are determined as follows:

$$P_k = -K_p(PV_k - PV_{(k-1)})$$

$$I_k = K_i T e_k$$

$$D_k = -(K_d/T)(PV_k - 2PV_{(k-1)} + PV_{(k-2)})$$

and:

PV = ref cell voltage

T = sampling time interval

e = $SP - PV$

SP = required voltage

K_p , K_i , K_d = controller "constants"

k , $(k-1)$, $(k-2)$ = step numbers

2DOF PID and Trapezoidal PID

The so-called *2 degree of freedom* PID control equations and the *trapezoidal* PID control equations do basically the same thing as the 1DOF, but in modified forms.

External controller

The *external* controller is exactly that – completely unknown to the software. This is because the only interaction between the ICCP System simulation software and the external controller is via a user-defined subroutine which is contained in a dynamic link library (DLL). The external controller receives input data,

processes it somehow, and passes its output data back to the simulation software.

Thus the external controller can take any form at all.

Example: Ship hull with 4 independent controllers

A very idealised ship hull (see Figure 2) with a bronze propeller has 4 independent controllers. The anodes associated with each controller are shown in Figure 3. The controllers used here are all 2DOF PID, with controller constants initially set at:

$$\begin{aligned}K_p &= 2.4 \\K_i &= 25.0 \\K_d &= 0.01\end{aligned}$$

The sampling rate for the entire system is 50Hz.

The transfer characteristics for the anodes relate output after unit step change of input at time $t = 0$ using:

$$\begin{aligned}\text{Anode output (at } t < 0.1) &= 0 \\ \text{Anode output (at } t > 0.1) &= 1 - 0.5e^{-(t-0.1)}\end{aligned}$$

The set point is -850 mV for all controllers.

The hull coating is assumed to leak 0.1% of the bare-steel current density at any potential difference.

There are 100 sensor points arranged in a line below the centre line of the ship hull.

The power supply output is limited to the range 0 to 500 amperes.

The voltage distribution on the hull with all anodes turned off is shown in Figure 4, and the corresponding UEP signature and location of the sampling points are shown in Figure 5. These plots (of results which were obtained using the classical method with zero current density applied to the anode elements) are presented so that comparison can be made with the results obtained using the ICCP simulator.

Using the ICCP simulator, first the response surface is read, together with details of the controllers, anodes, transfer function characteristics, and so on. The transient simulation can then be started, with real-time graphing if required. With the controllers all set to manual, and the control variable set to zero, the ICCP simulator should replicate the signature obtained using the classical method, and indeed it does, as can be seen in Figure 6.

Next the controllers are all switched on, and the system is allowed to reach a steady state. The steady state UEP predicted by the simulator is shown in Figure 7.

As a final test, the steady state anode currents from the transient simulation have been applied using the classical method, and the resulting voltage distribution on the hull and UEP signature, and shown in Figure 8 and Figure 9.

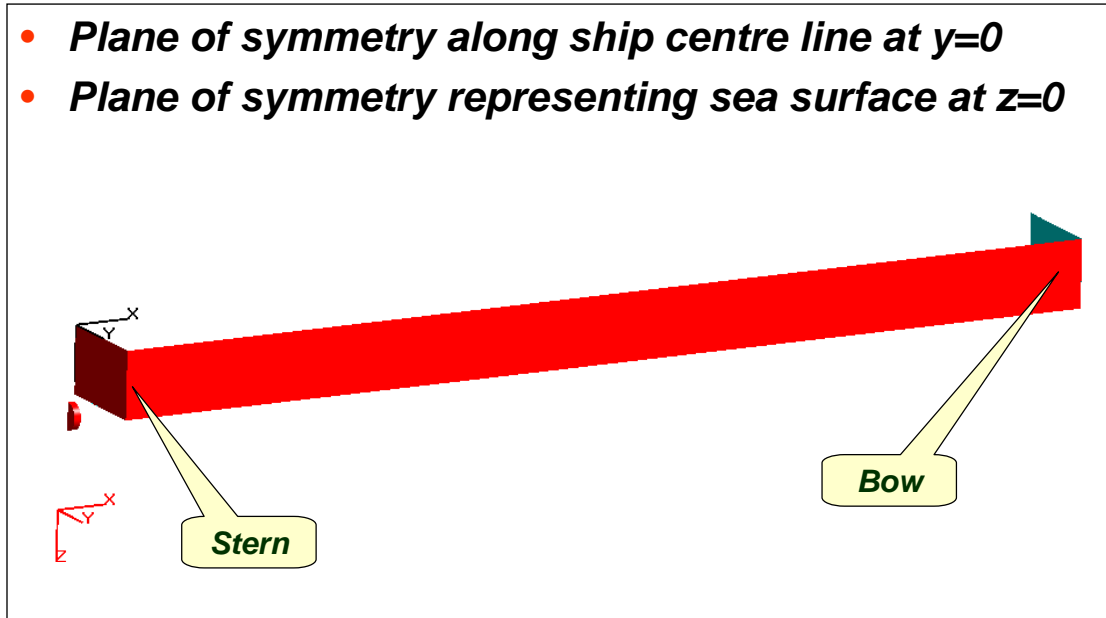


Figure 2: Geometry of hull and propeller

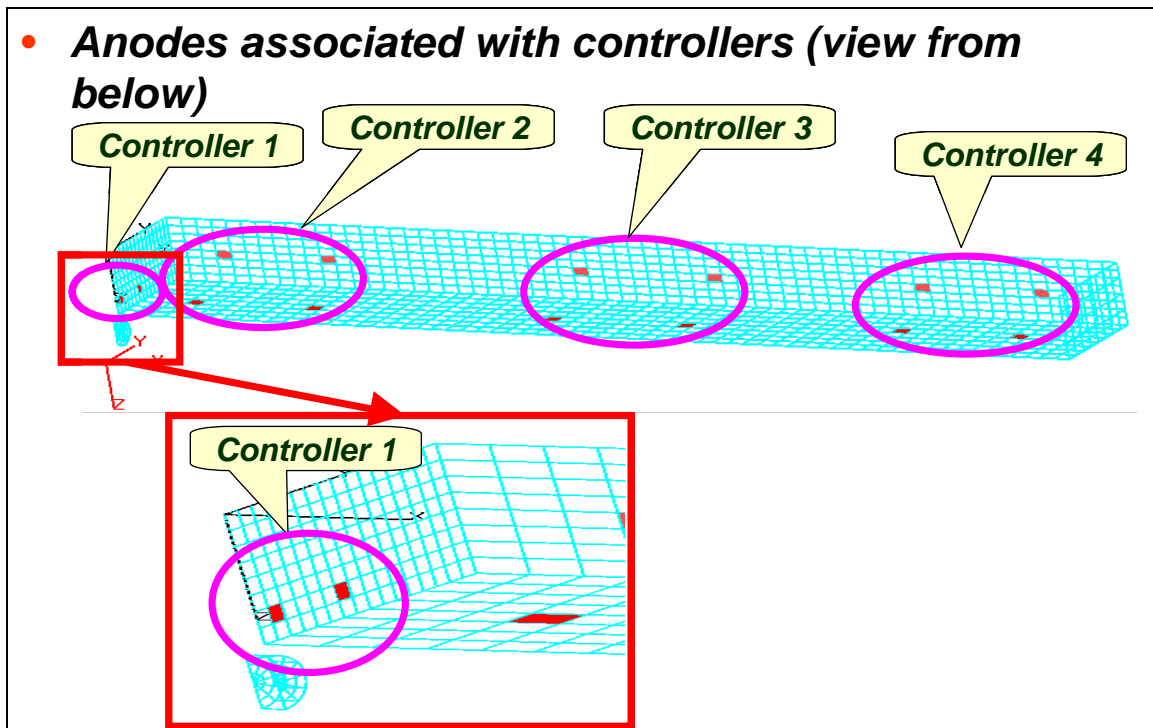


Figure 3: Showing anode positions and anode groups associated with each controller

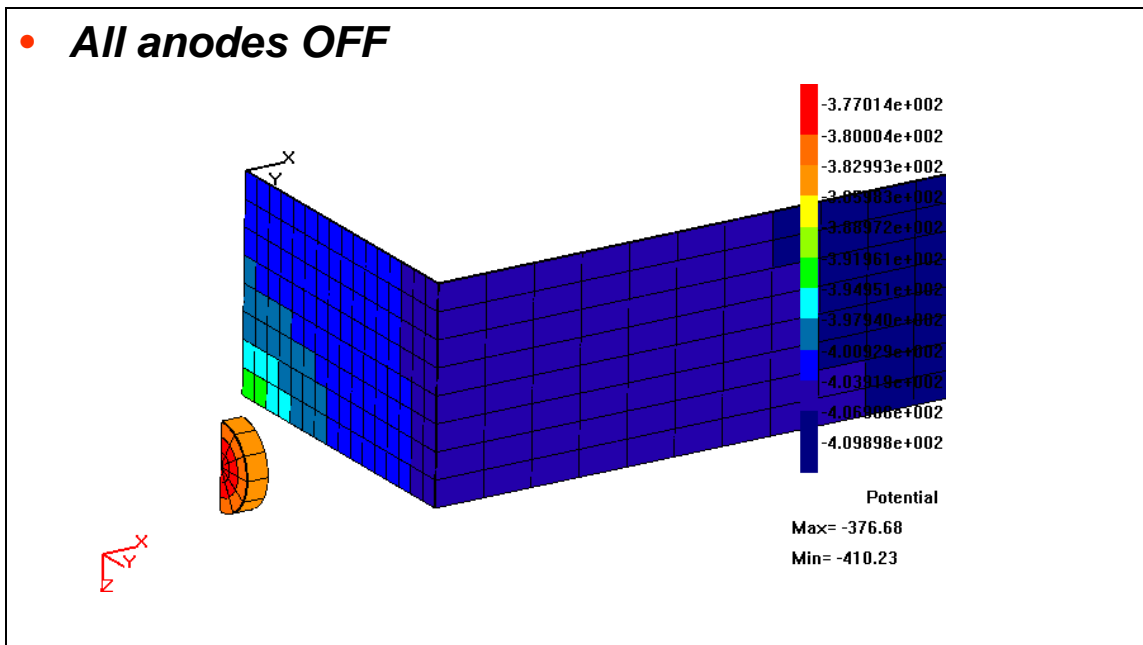


Figure 4: Potentials with all anodes turned off

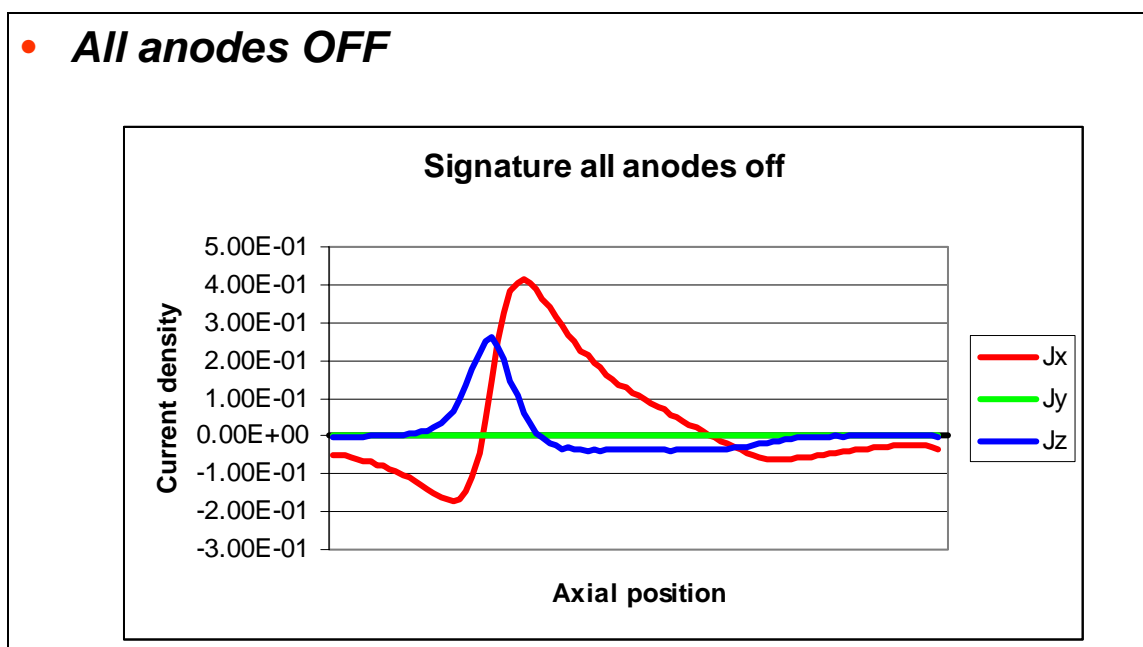


Figure 5: Signature with all anodes turned off (classical method ie direct from the BEM model)

- **Signature when all anodes are off, from ICCP Sim**

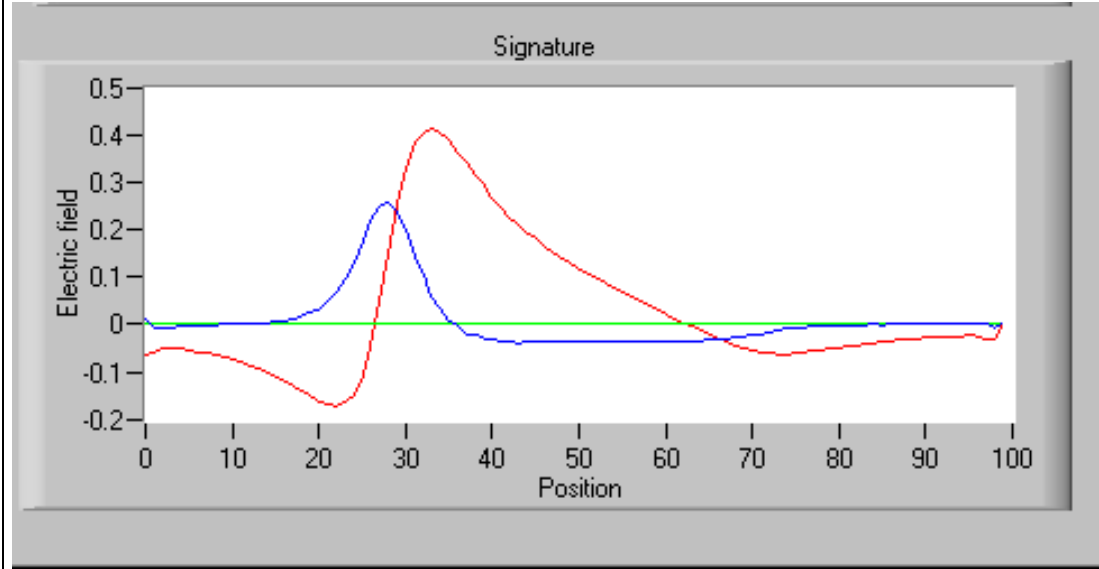


Figure 6: Signature with all anodes turned off (ICCP Sim method)

- **Signature when all anodes reach steady state, from ICCP Sim**

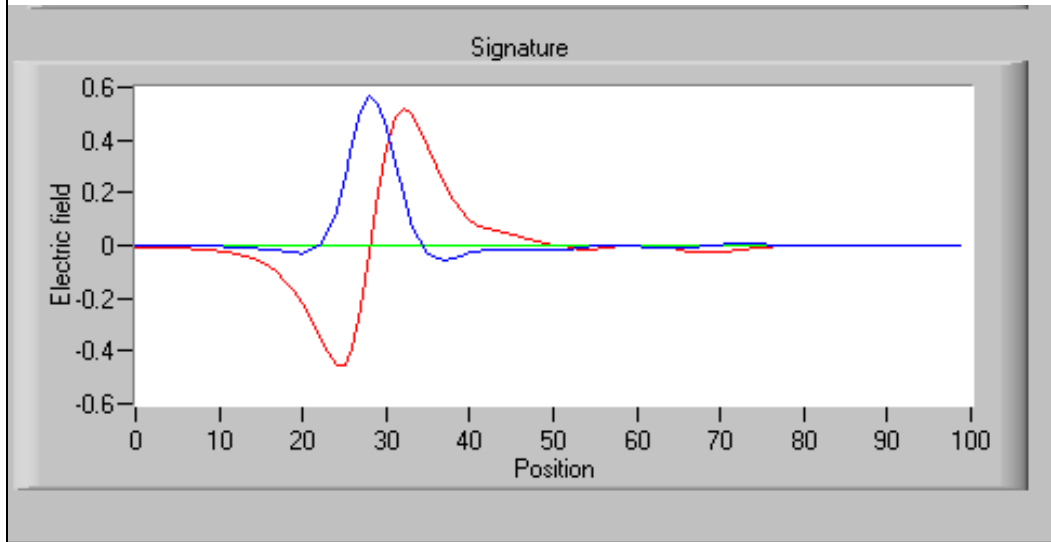


Figure 7: Signature with all controllers at steady state (ICCP Sim method)

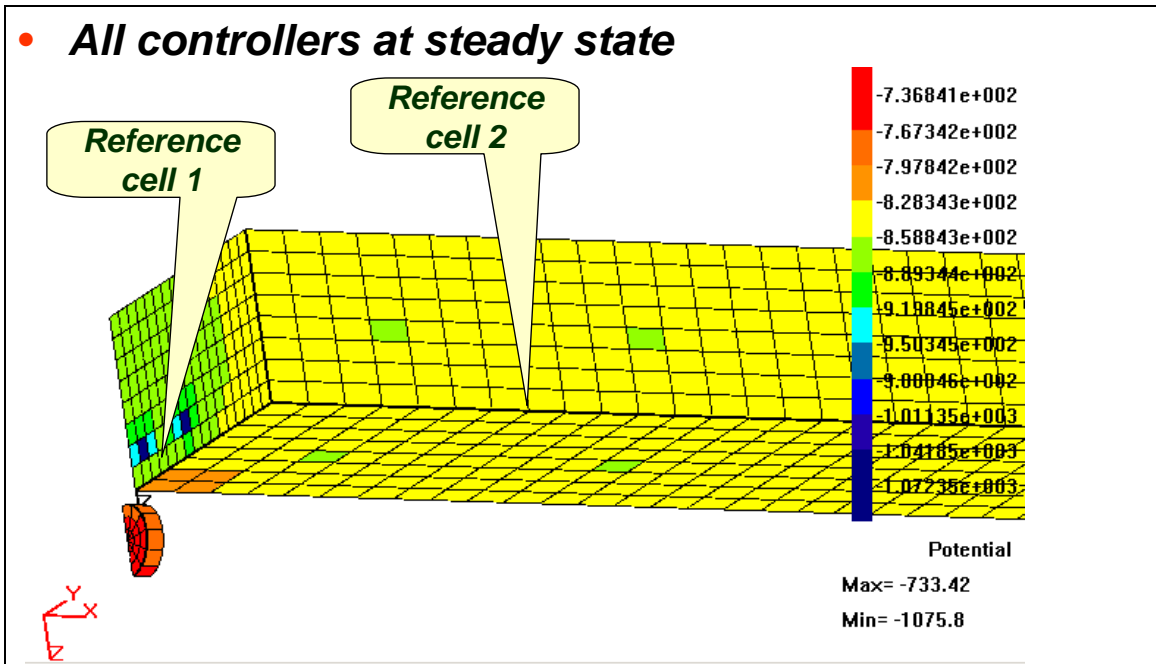


Figure 8: Potentials with all controllers at steady state (classical method)

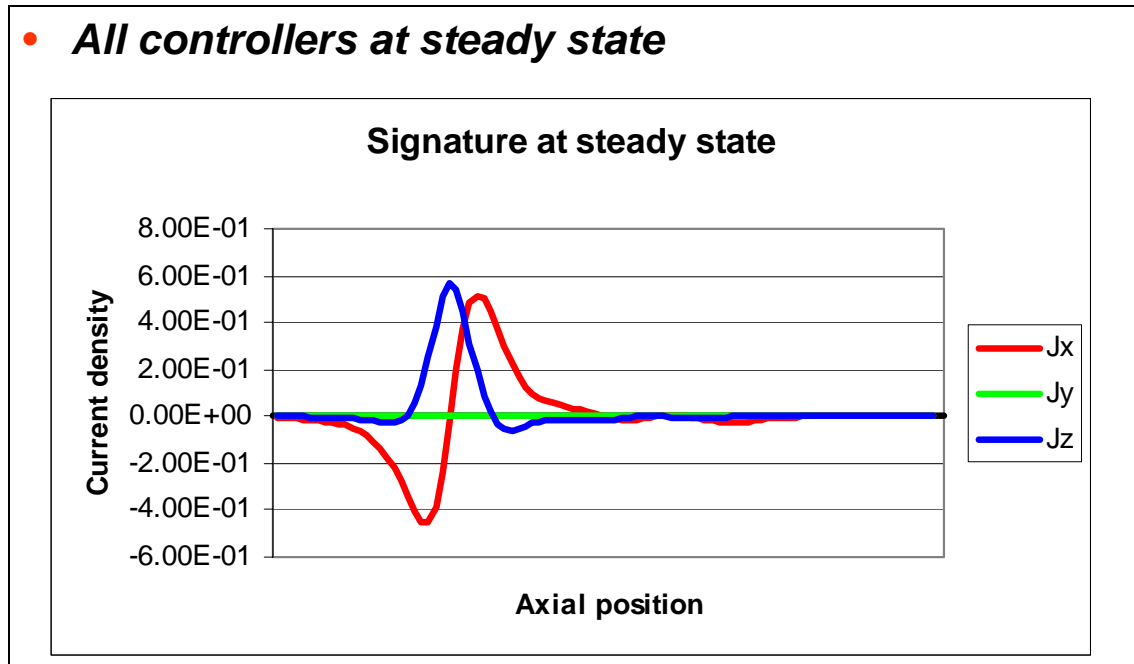


Figure 9: Signature with all controllers at steady state (classical method)

Discussion

Comparisons of Figure 5 with Figure 6, and of Figure 7 with Figure 9, show that the UEP signature calculated using the ICCP Sim method is the same as the signature calculated using the classical method. This is the expected result.

The correspondence occurs naturally in the case where all anodes are turned off, since the response surface was constructed with “*all anodes turned off*” as one of the combinations of anode outputs.

In the case where the anodes are at steady state after initial turn-on, the anode output values are *not* at values used during construction of the response surface. Hence this case confirms that ICCP Sim is producing the right answers.

The effect of the component properties

The time-delay and transient response of the various components are important to the dynamic simulations. Investigations to determine the form of transfer function most appropriate to a ship design may require calibration using experimental measurements.

Applications

Controller Tuning

One of the applications of the software is to assist in selecting the controller constants K_p , K_i and K_d for a digital controller. The values of the constants have an enormous effect on the way in which the control system responds when the ICCP system is switched on, and the result of poorly chosen values may be either very sluggish response, or at the other extreme an unstable response.

Using the controller constants described earlier, the transient response for each of controllers 1 to 4 is shown in Figure 10.

- **Transient potentials at reference cells after switch-on, using optimal constants**

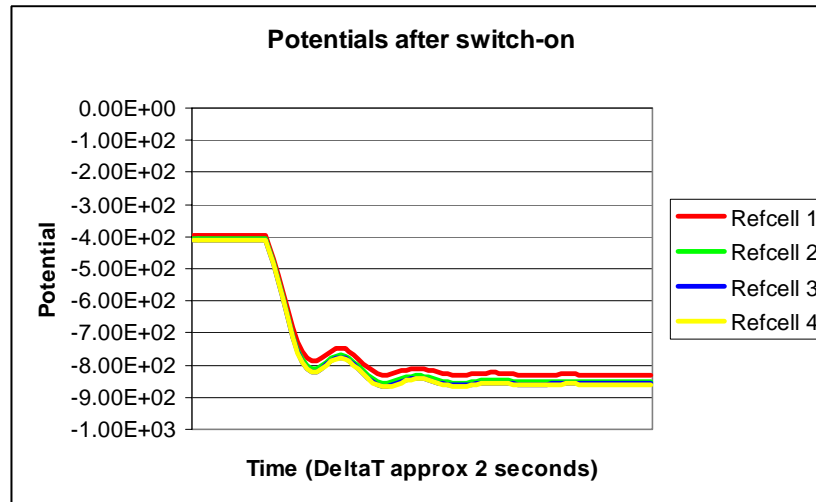


Figure 10: Transient response after switch-on, using “optimal” constants

Using non-optimal controller parameters ($K_p=4$, $K_i=25$, $K_d=.01$) the response becomes unstable as shown in Figure 11 and Figure 12.

- **Transient potentials at reference cells after switch-on, using non-optimal constants**

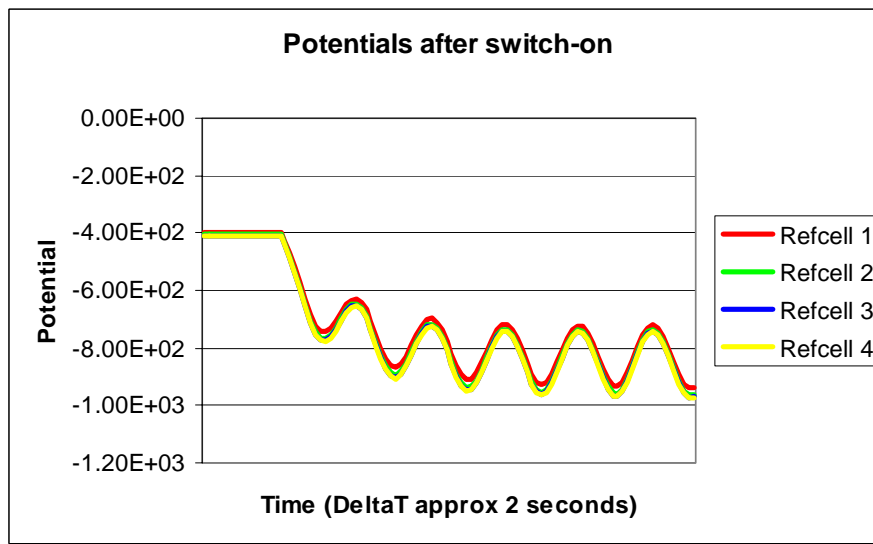


Figure 11: Transient response after switch-on, using “non-optimal” constants

- ***Transient potentials at reference cells after switch-on, using non-optimal constants***

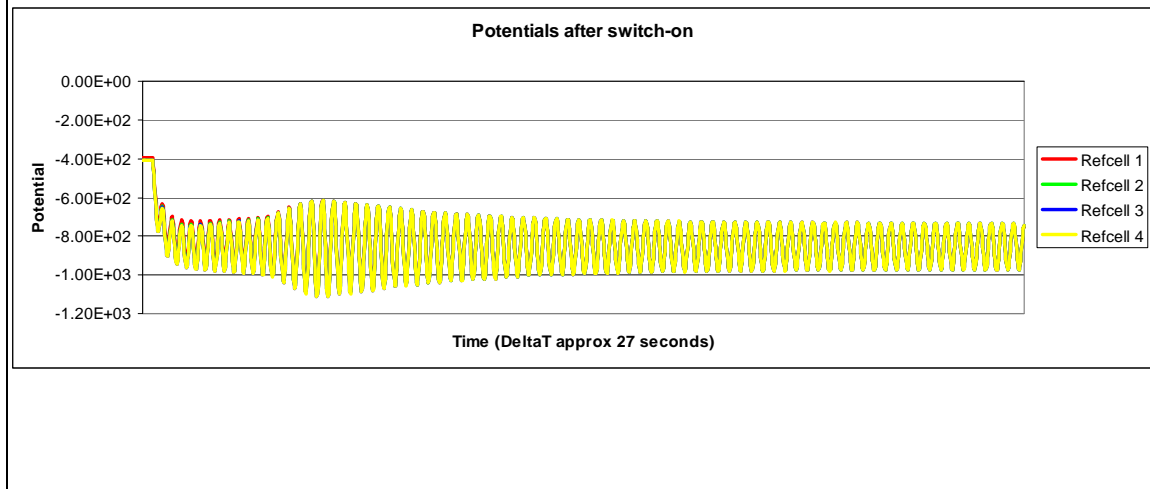


Figure 12: Transient response after switch-on, using “non-optimal” constants

There are two possible approaches to finding the optimal controller constants:

- First simply trial and error.
- Second to use tuning algorithms, such as the Ziegler Nichols methods.

The trial and error method is feasible using the software, because for the 4 controller example, it takes only 4 seconds to simulate the first two minutes after switch-on of the ICCP Control system. Thus many different trials can be performed in a short time.

Various tuning algorithms have been implemented. Although the Ziegler-Nicholls open loop reaction rate method was used to find the controller constants earlier reported as “optimal”, it is not yet clear that these methods are entirely suitable.

Controller interaction effects

Interactions may occur between multiple controllers, and investigation of such effects is necessary to understand the real cause.

A good example of interactions is given by the 4 controller example, which from Figure 10 appears to have achieved the design aim after only 1 second. However, there is in fact an interaction taking place, as can be seen from Figure 13 and Figure 14, which show variation with time of the current delivered by each controller.

It is clear that the effect of increasing controller 1 current is partly negated by simultaneous decrease of current by controllers 3 and 4. Closer inspection of the reference cell potentials (see Figure 15) clarifies what is going on: in fact the reference cell 1 potential has not reached the set point even after 4 seconds.

- **Transient total current for controllers after switch-on, using optimal constants**

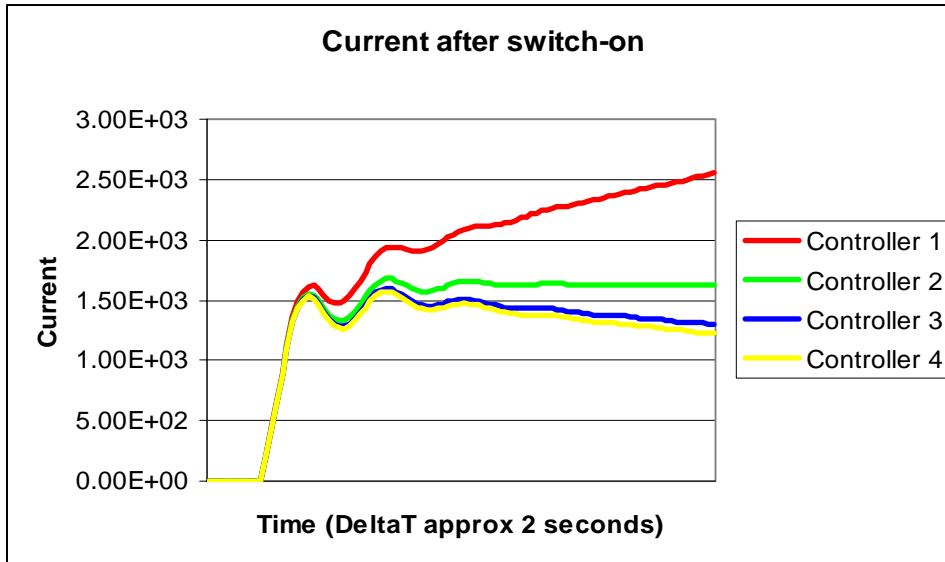


Figure 13: Variation of current for ~2 seconds after switch-on

- **Transient total current for controllers after switch-on, using optimal constants**

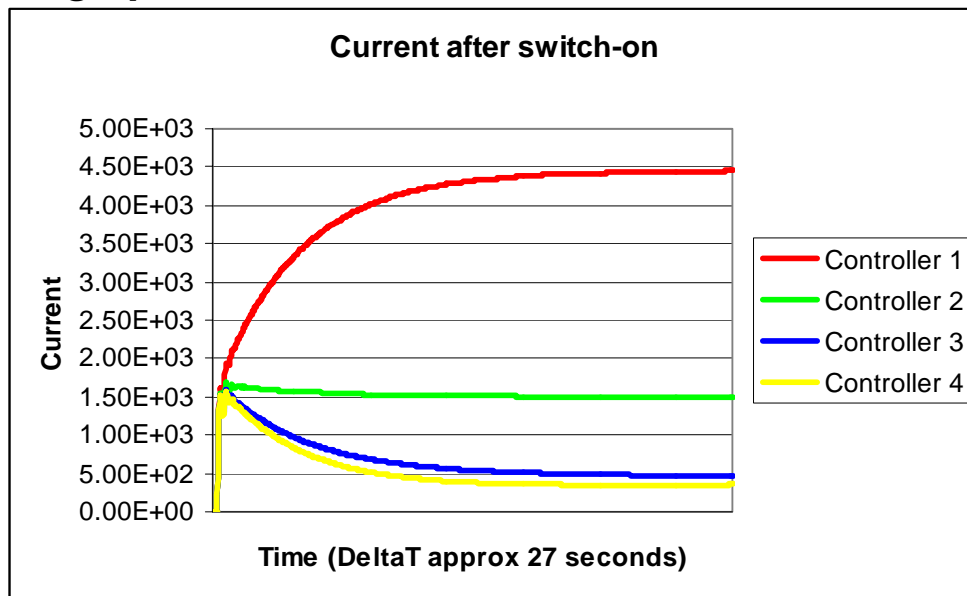


Figure 14: Variation of current for 27 seconds after switch-on

- **Transient potentials at reference cells after switch-on, using optimal constants**

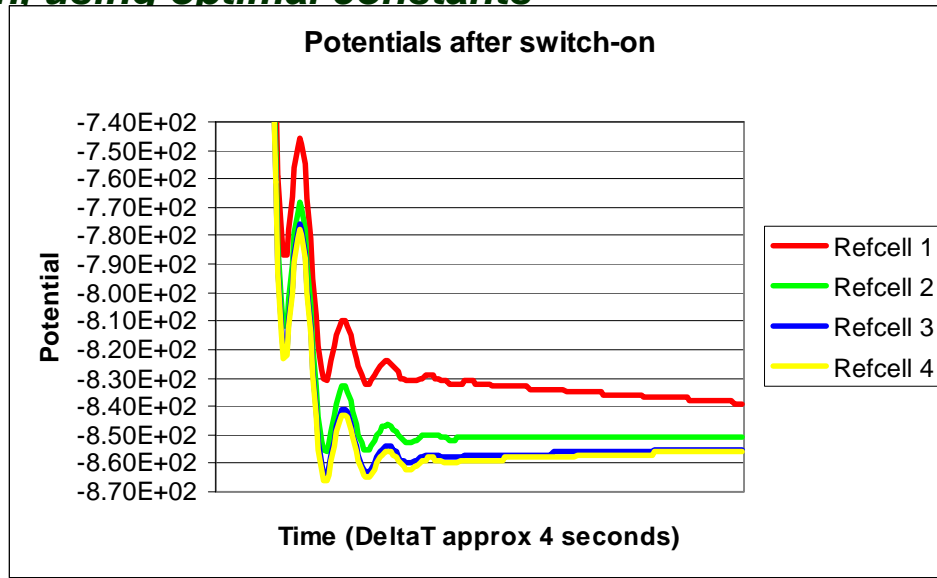


Figure 15: A closer look at reference cell voltages after switch-on

Simulating Controller Failure

The dynamic simulations can very easily represent the effect of failure during operation of one or more controllers. To achieve this, the selected controllers are turned off during the simulation and their CV is set to zero. The effect of failure of controller 2 is shown in Figure 16 and Figure 17.

- **Failure of controller 2**

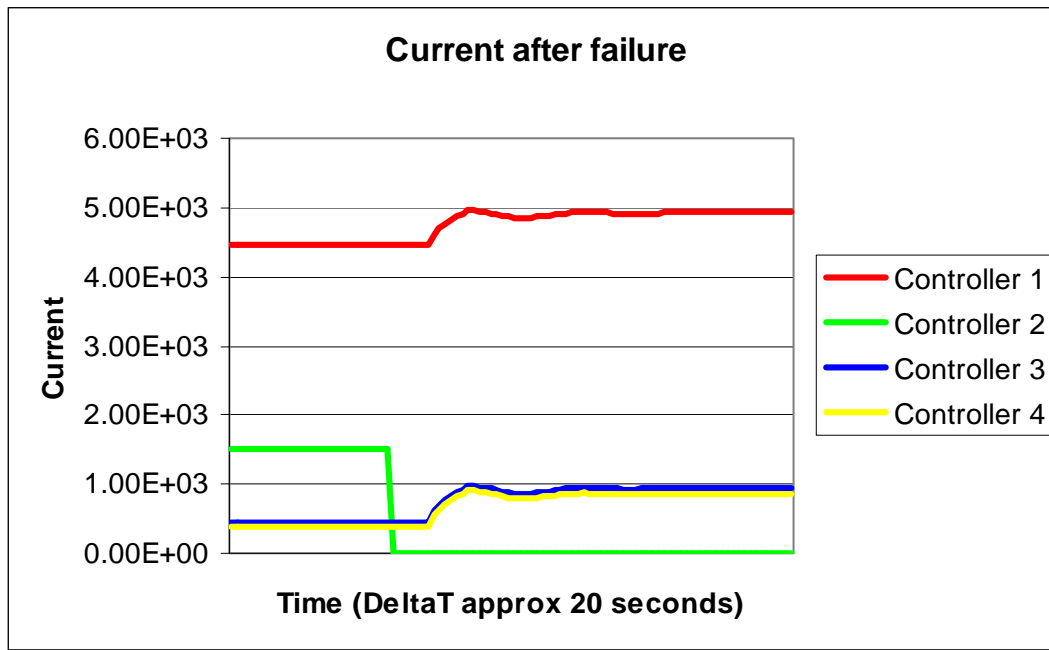


Figure 16: Effect of failure of controller 2 on controller current

- **Signature after failure of controller 2**

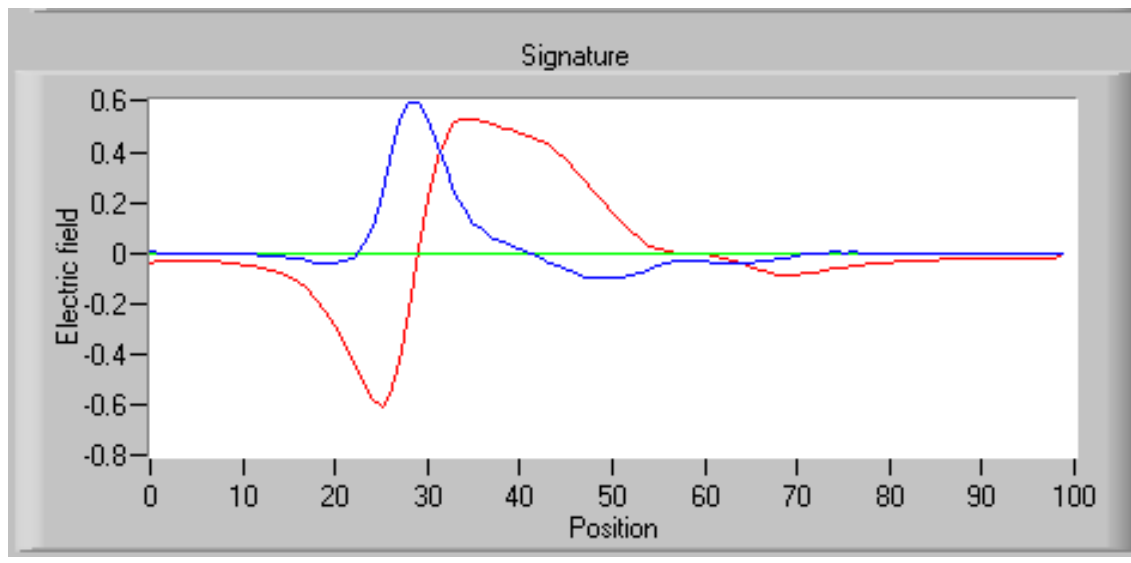


Figure 17: Signature after failure of controller 2

Conclusions

The work reported in this paper shows how a BEM model of the electric fields and corrosion electrochemistry coupled to a model of the ICCP control systems can be used to represent the transient dynamics of the system.

Simulation of the dynamics of the control system allows study of start-up behaviour, interactions between controllers, stability, and other effects.

The methodology can be used simply to predict the electric signature for any given anode outputs, and the speed of the method makes it possible to monitor the changing electric signature in real-time using very limited computing resources.

Acknowledgements

Thanks to NSWEC for their input during development of the software.

References

R.A. Adey, C.A. Brebbia and S.M. Niku. "Applications of Boundary Elements in corrosion engineering".

V.G. DeGiorgi, E.D Thomas, A.I. Kaznoff. "Numerical Simulation of impressed current cathodic protection systems", Computer Modelling for Corrosion, ASTM STP 1154,1991.

J. Trevelyan and H.P. Hack. "Analysis of stray current corrosion problems using boundary elements", Boundary Element Technology IX, 1994.

V.G. DeGiorgi, K.E. Lucas, E.D. Thomas II and M.J. Shimko. "Boundary Element Evaluation of ICCP Systems Under Simulated Service Conditions".

V.G. DeGiorgi. "Finite Resistivity and shipboard corrosion prevention system performance".

The BEASY CP User's Guide, 2004.