

ADVANCES IN ANODE MONITORING

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Abstract - Applications for Programmable Logic Controllers and Personal Computers with the Chloralkali Industry continue to grow. Older multiplexed monitoring systems are being replaced with high speed systems that can scan an entire cell room within 2 seconds. Average cell voltages can be decreased by 0.25 V dc or more resulting in significant power savings or production increases. The newer systems can be installed as an upgrade to existing systems to minimize the impact on plant operations.

Index Terms - Anode Monitoring, Mercury Cell, Electrolytic, High Current Sensing.

I. INTRODUCTION

A. Process

The basic mercury cell process is shown in Fig. 1. Brine is circulated through an electrolytic cell containing a titanium anode and a flowing mercury cathode. The brine decomposes into gaseous chlorine and sodium which forms an amalgam with the mercury. The amalgam flows into a decomposer where water is added to form hydrogen and caustic soda. The reclaimed mercury is then recirculated through the cell.

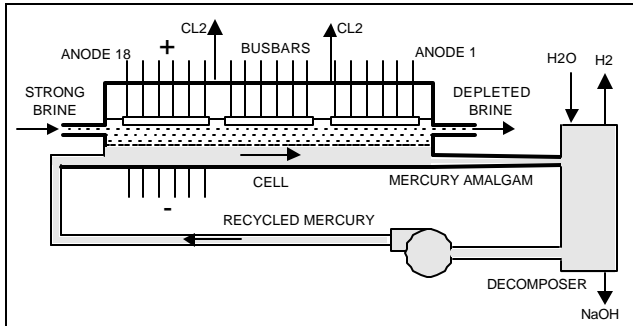
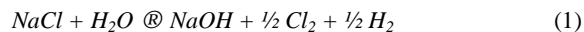


Figure 1 - Basic Mercury Cell Process

The overall reaction can be characterized as:



The process produces 1.1 tonnes of caustic soda for every tonne of chlorine. Although there are many possible configurations, we

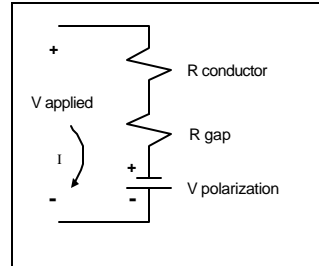


Figure 3 - Electrical Model

will examine a typical cellroom consisting of 52 cells connected in series by 18 parallel bus bars as shown in Fig. 2. The cell line load is 180 kA at 228 V dc. The cells are operated at 4.4 Vdc at a cathode current density of 11 kA/m². The total plant load is 44 MW and the cost of electricity averages 4.0 cents per kWh.

B. Electrical Model

The cell can be modeled as shown in Fig. 3. This simplified model consists of a series connection of conductor resistance, brine resistance and polarization voltage. The current is therefore:

$$I = \frac{V_{\text{applied}} - V_{\text{polarization}}}{R_{\text{copper}} + R_{\text{gap}}} \quad (2)$$

The polarization voltage $V_{\text{polarization}}$ is 3.15 Vdc. Dividing through by the anode area and rearranging we get the commonly used performance measurement:

$$k_{\text{factor}} = \frac{V_{\text{applied}} - 3.15}{I_{\text{density}}} \quad (3)$$

k_{factor} is a function of copper resistance, anode area, brine resistivity and gap distance. I_{density} is the current density in units of kA/m². A lower k_{factor} indicates attainment of a smaller gap for a given current density, hence less energy is lost in heating of the brine. k_{factors} range from 0.070 to 0.110.

C. Cellhouse Configurations

Cell configurations vary greatly from plant to plant. Some of the configurations currently in use are as follows:

- 32 cells, 18 anode buses, 180 kA
- 52 cells, 18 anode buses, 180 kA

- 70 cells, 24 anode buses, 240 kA
- 112 cells, 12 anode buses, 200 kA

II. CONTROL OBJECTIVES

The primary objectives of cell control are to:

- reduce energy consumption by reducing the gap between anode and cathode;
- achieve an even current distribution over all anodes;
- increase production by increasing current and reducing voltage. Electrical energy consumption remains constant;
- reduce instances of cell shorting and associated production loss;
- reduce maintenance costs through reduced cycling of cell operation.

III. EXISTING SYSTEMS

A. General Configuration

In a cell house consisting of 52 cells, 18 anode buses and 6 voltage taps per cell there are a total of 1248 points to be monitored. As analog-to-digital converters were relatively expensive, a multiplexing system was used to connect the monitored points with a computer usually located within the control room. The major components included:

Current sensors using millivolt voltage taps connected directly to the anode buses or Hall Effect transducers installed near the anode buses;

Voltage sensors connected across the cell;

Local Control Units to provide address decoding and multiplexing or current signals;

Interconnect cabling consisting of:

- a multiconductor Address Cable;
- a multiconductor Current Signal Cable;
- a multiconductor Voltage Signal Cable;
- a hardwired two wire alarm output for each cell;
- a two wire alarm reference cable that is daisy chained to each cell

Scanner Panel to provide address encoding and buffer signals received from the Local Control Unit;

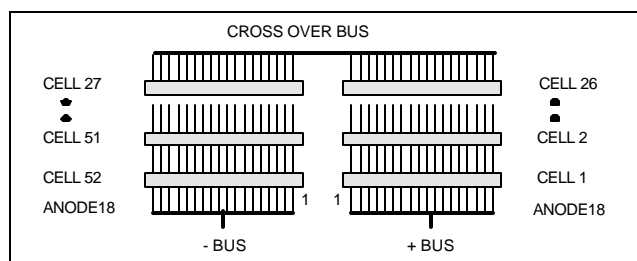


Figure 2 - Typical Cellroom Plan View

Annunciator(s) to display hardwired alarm output from each cell;
Central Computer to provide graphical display, logging and trending, and operator input.

Operation of the system is generally as follows:

- the Central Computer sends out a Binary Coded Address using 6 wires plus common on the Address Cable;
- the addressed cell confirms the address using a similar scheme;
- the addressed cell connects its current and voltage signals to the signal cables;
- the Scanner Panel provides additional buffering and filtering then forwards the analog signals to the Central Computer;
- once the analog signals are multiplexed in, the Central Computer proceeds to the next cell;
- the Isolation Panel continuously monitors the alarm cables and controls the two Annunciator Panels;

The Central Computer is usually of an older minicomputer design and programmed in Assembler. The Central Computer controls the cell scanning and provides the operator with a visual display of cell currents and voltages. There may also be one or more printers.

B. Closed Loop Control

Some cellrooms are equipped with motorized operation of the anode frames. In most cases, however, closed loop control is allowed only in the “raise” direction and operator intervention is required for operation in the “lower” direction.

IV. PROBLEMS WITH EXISTING SYSTEMS

A. Obsolescence

Existing systems are highly customized and sometimes unique. Special consideration must be paid to:

- temperature compensation;
- voltage isolation;
- accuracy
- signal conditioning, attenuation and noise;
- interfacing between various assemblies and components;
- initialization;
- computer hardware and software;

The resulting complexity makes it expensive and difficult to support these systems in the following areas:

- spare parts,
- internal training and support,
- supplier support,
- maintenance cost,
- calibration,
- modification of both hardware and software.

These problems can be addressed with currently available technology.

V. A NEW APPROACH

A. System Requirements

The following requirements were identified in the selection of a new cell monitoring system:

- the system should utilize generic hardware and software, preferably PLC's, and PC's and Windows based programming..
- the component count and the interfacing requirements between components should be minimized;
- communications should be digital in order to reduce wiring requirements and signal degradation;
- the system should be capable of scanning an entire cellroom within 2 seconds. The requirement for a separate hard wired alarm system should be eliminated.
- intelligence should be located close to each cell so that reliable closed loop control can be provided;
- the system should be upgradeable so that new technologies can be utilized as they become available;
- there should be a migration path between the existing and new system;
- the new system should be capable of higher level connectivity so that information from the monitoring system can be utilized directly by management and operations;
- installation should be simple and economical.

B. Special Considerations

Magnetic Field Strength - The magnetic field strength for a strip conductor can be found as :

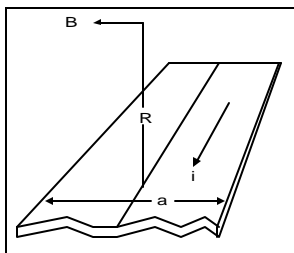


Figure 4 - Magnetic Field

$$B = \frac{\mu i}{\pi a} \tan^{-1} \frac{a}{2R}$$

where:

μ = permeability of free air
 i = total current in strip
 R = distance from strip
 a = width of strip

The calculated field strength 3/8 inch from a 10 inch wide busbar carrying 10 kA is 236 Gauss. Measured values are slightly lower at around 200 Gauss.

Effect of Magnetic Field on Electronics - The level of magnetic field found in cellrooms can affect solid state electronics. Particularly susceptible are devices that contain discrete ferrite

type inductors, for example older radio systems. Fortunately newer PLC's do not appear to be susceptible. Site testing is recommended as PLC's are not factory tested in this type of environment. Inquiries to PLC manufacturers invariably draw responses that apply to high frequency rather than dc magnetic fields.

Effect of Magnetic Field on Displays - The level of magnetic field found in control rooms is usually less than 50 Gauss. This field is strong enough to affect Cathode Ray Tubes (CRT's) through the Hall Effect. Small variations in the field can cause a "rainbow effect" with color tubes which usually prohibits their use within control rooms. The distortion on single color displays is tolerable with suitable shielding. The most common approach is to direct the lines of flux around the CRT by surrounding it with highly permeable steel. Solid state displays, particularly the Liquid Crystal Displays (LCD) are not affected by the magnetic field. They are now available in resolutions of 256 colors, 800 by 600 pixels and screen sizes of 14 inches and higher. Although expensive, prices continue to drop as availability increases.

Voltage Isolation - Chloralkali cellrooms operate at voltages of 130 to 400 V dc depending on the number of cells. Although most cellrooms are floating, single grounds can occur anywhere along the cell line. Common mode voltage isolation on the monitoring system is therefore critical. Hall Effect transducers offer several kV of isolation by virtue of the physical separation from the bus. On the other hand, direct connections, including millivolt bus taps and cell voltages, require separate isolation, usually optical.

VI. NEW SYSTEM

The new approach uses a minimum number of generic components. The system is comprised primarily of current and voltage sensors, PLC's and Man Machine Interfaces (MMI's). Refer to the Block

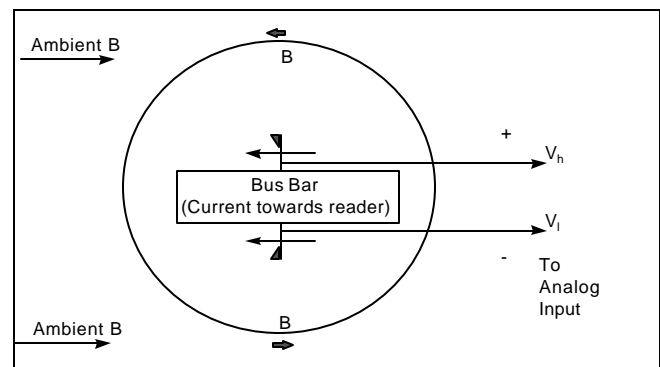


Figure 6 - Current Sensor Differential Connection

Diagram in Fig. 5.

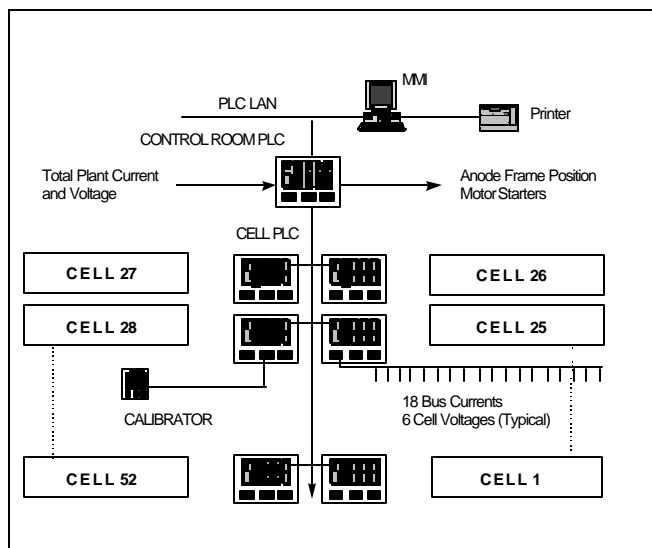


Figure 5 - New System Block Diagram

A. Current Sensors

New Hall Effect type current sensors were developed. They are powered by a 12 Vdc supply and provide a voltage output signal that is suitable for direct connection to a PLC analog input. Temperature compensation is built in and all components are contained on an integrated chip that is approximately 1/2 inch square. The sensors are hermetically sealed to protect them against the cellroom environment. They can be connected in a single or dual configuration. The latter is a differential connection that cancels ambient flux and provides a signal proportional only to the signal in the measured busbar. Referring to Fig. 6, the top sensor is mounted so that its signal increases as B increases. The bottom signal is mounted so that its signal decreases as B increases. The differential signal is derived between the two output leads. The effect of the ambient field is canceled because the output of both sensors moves in the same direction and is therefore canceled in the differential signal. The sensors are accurate to within 5% over a temperature range of -20 deg C to 80 deg C. They are capable of measuring fields from -600 to 600 Gauss and they cannot be overstressed by fields stronger than their rating. The differential signal is very linear except for small deviations near the extremes. It may be possible to improve the accuracy through software compensation in the PLC. Fig. 9 shows a picture of two current sensors and mounting hardware. The sensors are premounted on fiberglass channels that are clipped to the existing bus using threaded fiberglass rods.

B. Voltage Sensors

The voltage across each cell is measured at 6 points lengthwise along the cell. Current limiting resistors are used at the connection points to limit the fault current in case the voltage leads become shorted. Common mode isolation is provided by the PLC analog input cards.

C. PLC's

The PLC's were chosen from a mainstream manufacturer. The

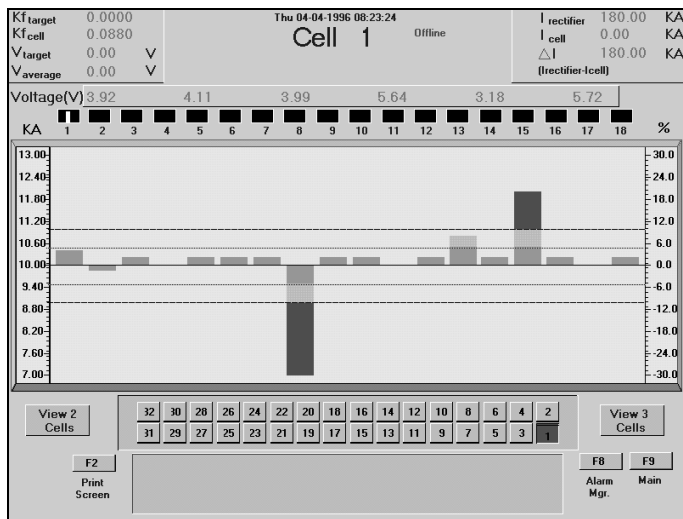


Figure 7 - MMI Screen Showing Cell Current Distribution

main selection criteria included:

- industry acceptance, support, robustness, familiarity to plant personnel;
- ability to network controllers in a peer-to-peer fashion;
- range of PLC sizes to handle from 1 to 4 cells each;
- scan time and PLC network token rotation time;
- ability to survive in cellroom environment;
- small physical size and ease of I/O connections;
- relatively low cost in comparison with custom designed equipment.

The PLC's were programmed in standard ladder logic. Only 4 types of cards were used in order to minimize stocking of spares. Fig. 10 shows a panel for a cell PLC. In addition to the PLC the panel contains quick connect terminators and a power supply for the current sensors.

D. PLC Network

The ability to communicate quickly and reliably between PLC's and MMI's is critical to the system design. It allows the communication network to be reduced from numerous multiconductor cables to a single pair. It also allows the failure prone, hardwired multiplexers to be deleted entirely.

The PLC's can be connected to service between 1 and 4 cells each. Allowing for overhead, the PLC network is capable of transferring around 10,000 registers per second. Each PLC can transfer up 100 registers each time it possesses the token and the token is rotated at the rate of approximately one PLC per 50 milliseconds. As a result data from the entire cellroom can be transferred to the MMI within 2 seconds.

E. MMI

The MMI consists of an industrial laptop with an LCD screen running a generic MMI software package. The MMI software is multiplatform meaning that it can be run on most popular operating systems including Windows 95 and NT, OS/2, HP-UX, VMS, AIX and others. As a result there is no need to "lock in" to a single computer manufacturer. Furthermore, the package can be migrated to take advantage of new computer technology as it becomes available. MMI display features include:

- full graphical interface;
- ability to enter alarm levels for each cell;
- cycling bar charts with ability to display one, two or three cells at a time;
- fixed detail bar chart;
- alarm level and target "k" factor entry (target cell voltage will be calculated from target cell "k" factor);
- summary of "cells in alarm";
- communication system status;
- parameter trends.

Fig. 7 and Fig. 8 shows sample bar chart and alarm input screens. Note the window near the bottom that shows the last 3 alarms.

Full alarming and logging capability is provided. Printed output consists of:

- alarms showing cell number, type of alarm, alarm value, time and date;
- screen dumps of graphical displays and system summary reports;
- daily shift report of:
 - cell alarm statistics;
 - ranking of the 10 worst cells;
 - average total volts, currents, average "k" factors, production and total cell down time in hours.

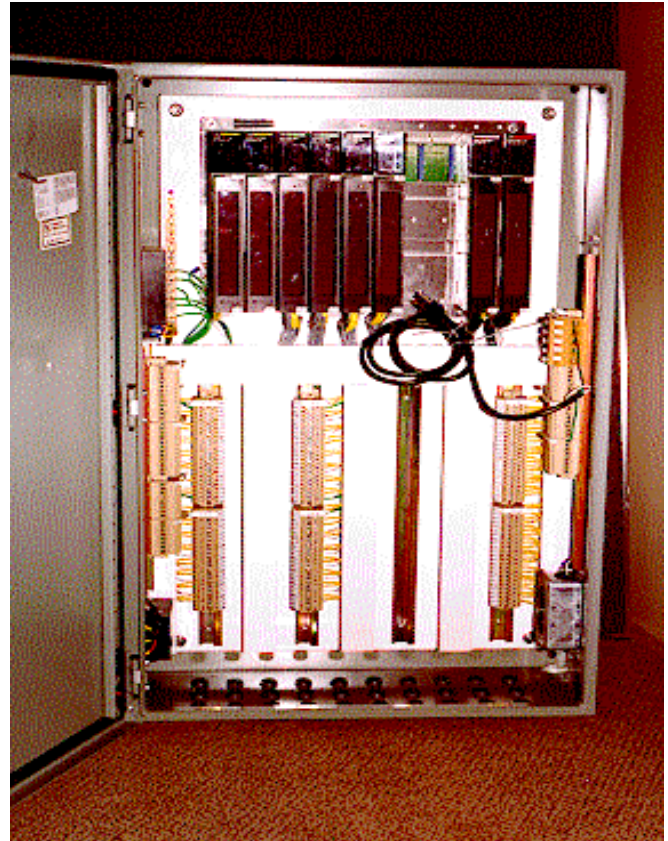


Figure 10 - PLC Panel for Mounting Adjacent to Cell

Alarm Configuration				Tue 04-02-1996 14:49:13	
Disable Alarms		Set configuration for cellhouse <input checked="" type="checkbox"/> Set configuration for cell 0 <input type="checkbox"/>			
<input type="checkbox"/> All	Current	HIHI 10.00 %	HIHI 0.00 %		
<input type="checkbox"/> KA roc	HI 5.00 %	HI 0.00 %			
<input type="checkbox"/> KA hi/hihi	LO -5.00 %	LO 0.00 %			
<input type="checkbox"/> KA lo/lo	LOLO -10.00 %	LOLO 0.00 %			
<input type="checkbox"/> V roc	ROC 10.00 % 1.0 sec.	ROC 0.00 % 0.0 sec.			
<input type="checkbox"/> V hi/hihi					
<input type="checkbox"/> V lo/lo					
<input type="checkbox"/> Inlet Temp. hi/hihi	Inlet Temp.		Outlet Temp.		
<input type="checkbox"/> Inlet Temp. lo/lo	HIHI 0.0 Deg. F	HIHI 0.0 Deg. F			
<input type="checkbox"/> Outlet Temp. hi/hihi	HI 0.0 Deg. F	HI 0.0 Deg. F			
<input type="checkbox"/> Outlet Temp. lo/lo	LO 0.0 Deg. F	LO 0.0 Deg. F			
<input type="checkbox"/> Mercury Flow	LOLO 0.0 Deg. F	LOLO 0.0 Deg. F			
<input type="checkbox"/> Cell Deviation					
Accept Configurations <input type="checkbox"/>		Rectifier Internal Deviation 0.0 %			
F1 Cell Monitor		04/02/96 14:47:33 * WARNING CELL 1 TAP 1 Voltage value high 04/02/96 14:47:33 * WARNING CELL 1 TAP 2 Voltage value high 04/02/96 14:47:33 * WARNING CELL 1 TAP 3 Voltage value high			F9 Main

Figure 8 - MMI Screen for Input of Alarm Limits

F. Calibrator

The calibrator is also a PLC based, intelligent device. In the past, the operator of the calibrator would voice his readings to a second operator who would then set potentiometers at the Local Control Unit to obtain the desired reading. With the new system the operator simply plugs into the appropriate PLC, presses a button to indicate which anode bus he is measuring, then presses a calibrate button to complete the operation. The calibration is contained entirely within the software of the PLC.

G. Actuators

Cells that are equipped with anode actuators normally use a single drive for each anode frame. A chain or shaft mechanism is then extended around the frame and connected to mechanical actuators. On cells that are not equipped with actuators, it may be feasible to install a gear motor at each corner of the frame directly on the jacking bolt.

F. Control Routines

Anode movements are closely monitored and controlled by the PLC. The control algorithms utilize both magnitude and rate of change calculations. Note in equation (2) that the cell current is inversely proportional to the gap distance. The rate of change is therefore proportional to the square of the gap distance. The real time behavior of adjacent cells is also monitored and is critical in the prevention of "traveling shorts".

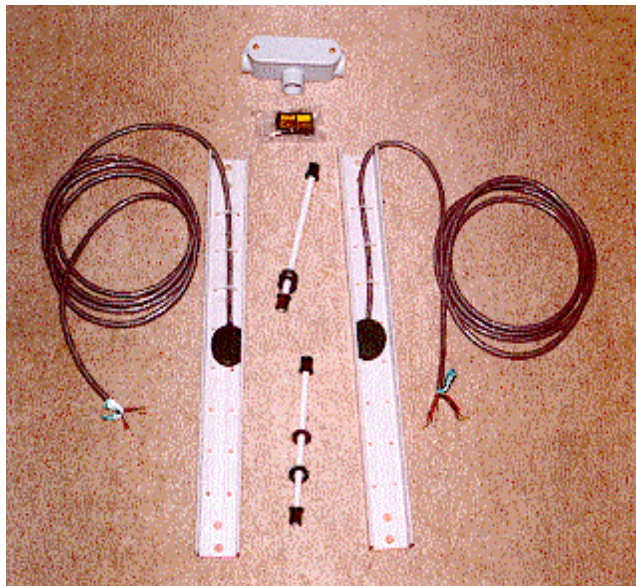


Figure 9 - Current Sensors with Mounting Brackets

VII. APPLICATIONS

A demonstration system was installed at three North American chloralkali plants. The following objectives were proven;

- reliable operation of the PLC's in a cellroom environment;
- accuracy and repeatability of the new current sensors;
- operation of large LCD screens within the control room;
- reduction of cell voltage by at least 0.25 V dc.
- automatic raising and lowering of the anode frames using gear motors mounted on the frame jacking bolts;

The achievement of automatic control was particularly significant because it showed that a very accurate level of control is provided by the PLC located next the cell. This is the benefit of the basic architecture whereby a small PLC is used to control 2 to 4 cells.

A partial system has also been installed into a South Eastern chloralkali plant. It involves replacement of the Scanner Panel, Annunciators, and Central Computer with a PLC/MMI combination. The PLC fully emulates the Scanner and reads the analog values from each cell using the existing interconnect cable system. The MMI screens and software are similar to those used on a complete new system. In fact, the plan is to provide a migration path to a new system within the next two years. The PLC/MMI combination will be reused if it is decided to install new current sensors and PLC based monitoring. The only difference that the operator will notice is that the cellroom would then be scanned in seconds instead of minutes.

VIII. RESULTS

Preliminary results indicate that the new system enables safe cell operation with balanced intercell currents and lower cell voltages. Additional experience with the applications described above are expected to confirm:

- reduced energy consumption per tonne of product;
- reduced anode-cathode shorting;
- reduced anode damage and maintenance costs;
- reduced manpower requirements;
- reduced hydrogen generation;
- improved safety;
- improved reporting of cell room operations;
- improved cell problem analysis;
- easier production rate change to take advantage of off-peak power rates;
- increased production rates;
- increased total production.

IX. FUTURE ENHANCEMENTS

The architecture of the new system is open and many enhancements are possible. These include:

A. Expansion

The PLC LAN can be expanded to include up to 63 PLC's on a single network and more if bridges are used. The I/O can be

expanded to include temperatures, pressures and concentration. It would then be possible to model the process and simulate the effect of process changes before they are implemented.

B. High Level Connectivity

The MMI's can be connected to a plant-wide computer LAN and the data available from the Anode Monitoring and Control System could be shared by a variety of users. Users could include Engineering, Accounting, Maintenance and Management. The interface could be implemented using a variety of currently available Client/Server Relational Database Servers. The MMI software "populates" the database and users query the database. The database provides a barrier between the Anode Monitoring and Control System and untrained users on the computer network.

C. Demand Control

A Demand Control System could be implemented by connecting metering pulses into the PLC system and providing outputs to the rectifier controls. The same MMI could serve the dual function of Anode Monitoring and Demand Control.

D. Rectifier Monitoring and Control

The system could be expanded to include rectifier monitoring and control. Targets would include:

- tapchanger control
- saturable core reactor control
- alarm monitoring
- diode current balance and blown fuse monitoring

X. CONCLUSIONS

The requirement for customized hardware and software continues to shrink as generic PLC's and PC's become more capable and easier to use. Concerns about reliability have been addressed by more advanced design and operating experience. In most cases the PLC/PC systems are several times more reliable than the systems they replace.

In order to reduce capital outlay and disruption to ongoing operations, existing Anode Monitoring Systems can be upgraded in several phases.

Implementation of an Anode Monitoring and Control System can result in energy savings, increased production, or a combination of the two. As the example in the Appendix shows, an average reduction of just 0.25 V dc per cell can result in a payback of many times the original capital cost.

APPENDIX

CAPITAL BUDGETING

Capital Budgeting is the process of evaluating the economics of a proposed project. The commonly used model assuming declining balance depreciation and no salvage value consists of 3 terms:

$$NPV = -C + \sum_{t=1}^n \frac{R_t(1-T)}{(1+i)^t} + C\left(\frac{dT}{d+i}\right)$$

where:

NPV	=	Net Present Value
C	=	Capital cost
R_t	=	Return to before tax net operating revenue in year t
T	=	corporate tax rate (assume 50%)
i	=	interest rate (assume 15%)
d	=	depreciation rate (assume 30%)
n	=	total life of the investment (assume 6 years)

The first term is the initial investment, paid with after tax dollars at time 0. The second term is the Net Present Value of an annual flow of after-tax revenue resulting from the investment. The third term is the after-tax savings resulting from the ability to depreciate the investment over its life.

A. Project Economics

We will consider two strategies, energy savings and increased production. In the first case we will assume that the new control system will enable the plant to operate with a voltage decrease of 0.25 V dc per cell (from 4.40 to 4.15). In the second case we will assume that the energy saving resulting from the decreased voltage is consumed by increasing the cell current. Hence the overall energy consumption is unchanged.

Assume also that:

- 1.0 tonnes of chlorine and 1.1 tonnes of caustic soda (defined as one ElectroChemical Unit or ECU) sells for a total of \$450.00;
- 3600 kWh at 4.0 cents per kWh is used to produce 1.0 tonnes of chlorine. The variable cost of production is therefore \$144.00 per tonne of chlorine;
- electrical energy accounts for approximately 40% of the cost of production;
- remaining costs of production are relatively fixed at \$216.00 per tonne of chlorine.

The incremental contributions, R_t , for three strategies; (1) do nothing (2) save power and (3) increase production, are calculated below on a per tonne of Chlorine basis. Note the third option can only be pursued if there is spare capacity in liquefaction and other plant auxiliaries.

REFERENCES

TABLE 1
INCREMENTAL CONTRIBUTIONS OF THREE
STRATEGIES

Optn	Revenue	Cost	Profit	R _t
1	\$450.00	energy \$144.00 other <u>\$216.00</u> total \$360.00	\$90.00	\$0.00
2	\$450.00	energy \$135.82 other <u>\$216.00</u> total \$351.82	\$98.18	\$8.18
3	\$477.11	energy \$144.00 other <u>\$216.00</u> total \$360.00	\$117.11	\$27.11

The installed investment cost, C, for various plant sizes is estimated as follows:

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TABLE 2
CAPITAL COST OF
MONITORING SYSTEMS

Plant Size tonne/day	150	300	450
Capital Cost	\$1.0 M	\$1.8 M	\$2.4 M

Substitution of these values into the Capital Budgeting Model yields for the three strategies:

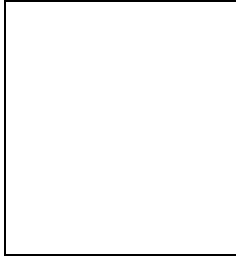
TABLE 3
NET PRESENT VALUE (NPV) OF THREE STRATEGIES

Plant Size (tonne/day)	150	300	450
Option 1	\$0.0 M	\$0.0 M	\$0.0 M
Option 2	1.86 M	3.47 M	4.91 M
Option 3	3.77 M	7.34 M	10.71 M

The NPV of the power savings (Option 2) is attractive, however, the NPV of the production increase (Option 3) is even more attractive by a factor of almost 2 to 1.

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Current Systems for the LEM group worldwide. He specializes in the application of high accuracy DC metering systems to large rectifiers and electrolysis lines. He has authored 4 IEEE papers. He is a registered Professional Engineer in the State of Ohio, and is active in the Electrochemical Subcommittee of the Petroleum and Chemical Industry (PCIC).