

THE USE OF THE PILOT PLANT FACILITY IN TEACHING PROCESS CONTROL ENGINEERING AT MURDOCH UNIVERSITY

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ABSTRACT

The Pilot Plant at Murdoch University is equipped with a Honeywell Supervisory Control System, known as SCAN3000. The plant was designed to simulate three stages: grinding and digestion, clarification, and precipitation of the Bayer Process to manufacture alumina from bauxite.

This paper presents some examples in design and implementation of a great number of feature-based feedback PI controllers and the implementation of sophisticated control laws such as Generic Model Control (GMC), Dynamic Matrix Control (DMC), Supervisory Control and Fuzzy Control. Although all features of the pilot plant are not currently available for teaching purposes, Process Control Engineering (PCE) students still have the opportunity to operate and implement many different control strategies to various unit operations such as working with a real process to obtain real hands-on experience. A different example is the upgrade and maintenance program based on Programmable Logic Controllers (PLC) which highlights the learning and developing of skills in using PLC and Supervisory Control and Data Acquisition systems (SCADA).

INTRODUCTION

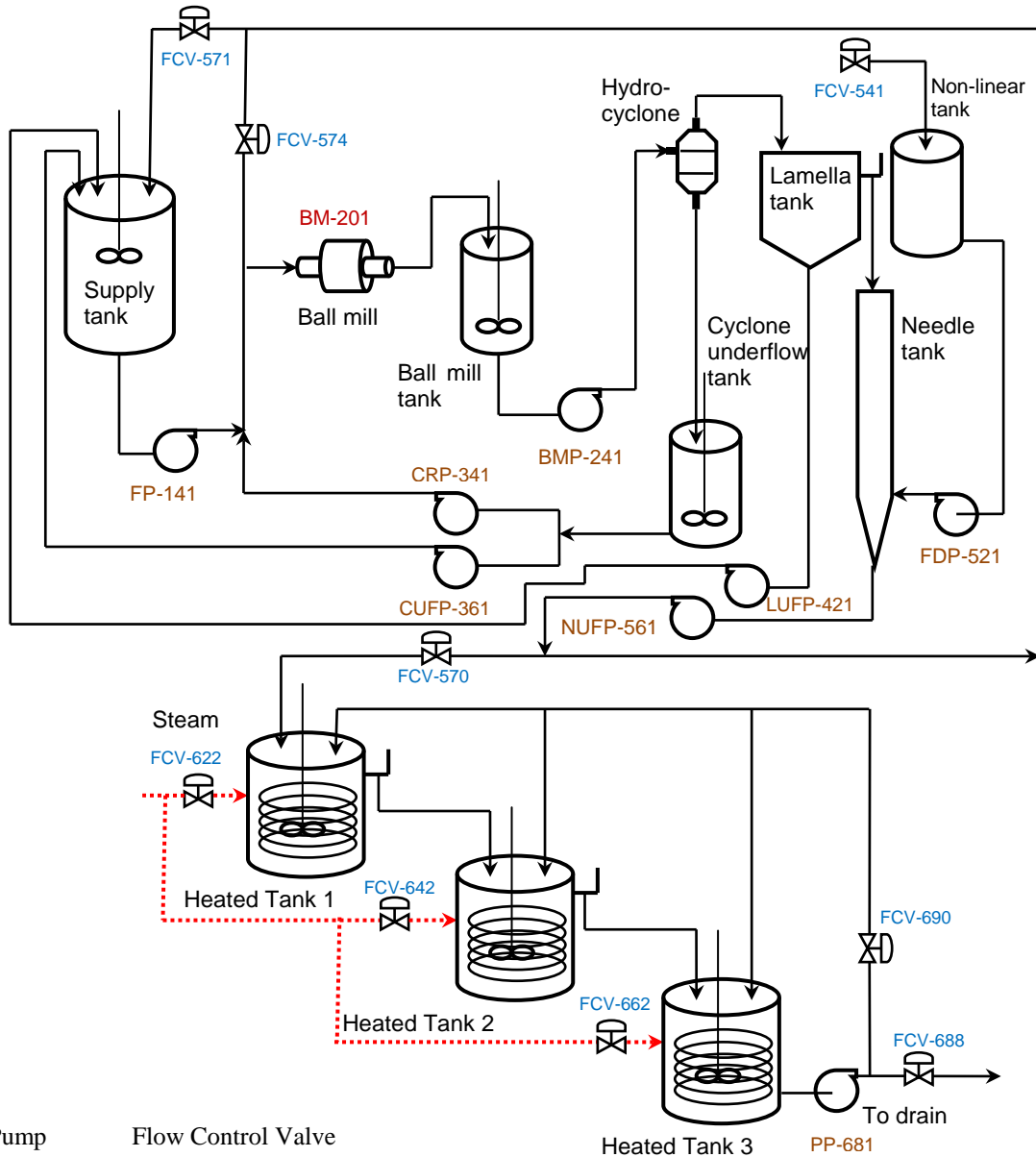
One of the perspectives in designing the Pilot Plant facility was to provide a realistic environment for the training of Process Control Engineering (PCE) students. In 1997 Alcoa of Australia, Honeywell Ltd. and Control and Thermal Engineering Pty. Ltd. joined the School of Engineering at Murdoch University to build a facility, initially to simulate the physical and chemical behaviour of a part of the Bayer Process. The actual process involves hot leaching bauxites with a sodium hydroxide solution in pressure vessels to obtain a supersaturated sodium aluminate solution.

The pilot plant at Murdoch initially used an inert solid material and water to simulate three stages: grinding and digestion, clarification, and precipitation of the Bayer Process. Over the years, engineering students have had the opportunity to operate and implement various control strategies to many unit operations such as working with a real process to obtain real hands-on experience. In addition, they have been able to explore the complex code of the Programmable Logic Controllers (PLC), developed for the existing system which controls the whole pilot plant. To understand the importance of this facility in teaching undergraduate process control engineering, a description of the plant and current projects involving learning and improvement of control strategies and operations will be presented in this paper.

PILOT PLANT DESCRIPTION

A simplified flow sheet of the pilot plant is presented in Fig.1. Two supply tanks (only one shown) having a total capacity of 4700 L are the major sources to supply the feed to the whole plant. The tanks are equipped with mechanical stirrers. In addition air is bubbled from the bottoms and the sides to avoid solids built-up in the tanks. The feed is then directed to the *Ball Mill* (BM) via the pump *FP-141* and mixed with the recycled stream from the *Cyclone Underflow Tank* (CUFT). Two recycled streams come from the *Needle Tank Underflow* (NTUF) via the pump *NUFP-561* through the flow control valve *FCV-574* to the BM and through *FCV-571*, back to one of the supply tanks. The rotation speed of the BM can be adjusted using *BM-201*. From this unit, the feed is then collected in the *Ball Mill Tank* then directed to the *Hydro-Cyclone* via *BMP-241*. A part of the solids is separated: the overflow stream going to the *Lamella Tank* and the underflow stream going to the *Cyclone Underflow Tank*. From there the concentrated feed is pumped via *CRP-341* recycled to the BM and via *CUFP-361* to the supply tank. The clarified water overflows from the *Lamella* to the *Needle Tank*. *NUFP-561* introduces the slurry to three *Heated Tanks* (HT) through *FCV-570* and recycles it back to the BM and supply tank as mentioned above. The HTs are heated by steam entering the coil via three control valves *FCV-622*, *-642* and *-662*. The outlet of the third HT is directed via *PP-681* through the control valves *FCV-688* to drain or through *FCV-690* to the first HT. Additional water, fed to the *Non-Linear Tank* through *FCV-541*, is pumped by *FDP-521* to the *Needle Tank*, to generate desired level disturbances. Eighteen control loops including 9 flow control valves (FCV), 8 pumps and 1 rotation speed can be implemented in the whole plant as illustrated in Fig.1.

In the pilot plant, flow rates, levels, temperatures and densities (if slurry feeds are used) can be measured on-line. All measurements are sent to the Honeywell Supervisory Control System, known as SCAN3000 for monitoring and control purposes. The SCAN3000 data management and control software runs on a Windows server. The Allen-Bradley PLC5/20E, which communicates with SCAN3000 through Ethernet, has 6 different inbuilt PID algorithms depending on user selections within the PLC program. Measured plant data can be transferred from SCAN3000 to Microsoft EXCEL for further processing and the results can be written to the SCAN3000 database. As a result, when running the plant in automatic mode, instead of selecting SCAN built-in algorithms, advanced control algorithms can be developed or conventional algorithms can be redesigned in EXCEL then passed to SCAN3000 to be implemented. That is one of the essential objectives of the Process Control Engineering unit, to provide students with knowledge and practical skills in controlling an industrial-like process. In addition to conventional control techniques, many sophisticated control laws such as Generic Model (GMC), Dynamic Matrix (DMC), Supervisory and Fuzzy have been explored. The following sections will highlight some examples of controlling the pilot plant from Microsoft EXCEL and a PLC-based maintenance program developed by past and current PCE students.



Pump	Flow Control Valve
FP-141	FCV-541
BM-201(*)	FCV-570
BMP-241	FCV-571
CRP-341	FCV-574
CUFP-361	FCV-622
LUFF-421	FCV-642
FDP-521	FCV-662
NUFP-561	FCV-688
PP-681	FCV-690

*Speed

Fig.1: Flow sheet of the Pilot Plant at Murdoch University (re-drawn from Murdoch Internal Website)

IMPLEMENTATION OF DIFFERENT CONTROL STRATEGIES

Implementing the simplest feature-based control scheme such as a PI controller to adequately maintain steady state flows and keeping all tank levels at their desirable set-points requires considerable knowledge of the manipulated variables in the system. In general the tanks in the plants are pure capacity systems, which are represented by a first order differential equation (1) and a transfer function in the Laplace domain shown in equation (2). In these equations, h represents the level, A the cross-sectional area of a cylindrical tank, F with subscript “in” and “out” for inlet and outlet flow rates, respectively.

$$\frac{dh}{dt} = \frac{1}{A}(F_{in} - F_{out}) \quad (1)$$

$$g(s) = \frac{-1/A}{s} \quad (2)$$

Feature-based design and implementation of Feedback Control technique

The level of a tank in the plant is generally controlled by manipulating the outlet flow rate of the tank. This desired flow rate is passed to a feedback loop, controlling the speed of a pump. The forms of PID controllers available within the Allen Bradley PLC-5 are commercial ones, which approximate the “ideal” PID form presented in many

control textbooks $MV = K_c \left\{ 1 + \frac{1}{\tau_i s} + \tau_d \right\} \varepsilon$ by $MV = K_c \left\{ 1 + \frac{1}{\tau_i s} + \frac{\tau_d s}{1 + \frac{\tau_d}{16}} \right\} \varepsilon$, as it is

impossible to obtain the exact derivative of a signal with a physical device. However, it is unnecessary to use the derivative action for pump response tuning so instead of using the algorithm of the inbuilt PID controller, the position form of a discrete PI controller (Ogunnaike and Ray, 1994) shown in equation (3) is used to calculate the value of the manipulated variable (MV), which in this case is the pump speed.

$$MV(k) = K_c \left\{ \varepsilon(k) + \frac{\Delta t}{\tau_i} \sum \varepsilon(k) \right\} \quad (3)$$

In the above controller forms, K_c is the gain of the controller; τ_i and τ_d are integral and derivative time constants, ε is the current error defined by the deviation of the process variable (PV) from its set-point; Δt is the sample time (5 seconds minimum for SCAN3000 to send values to the controller). A PI controller is commonly used as its

integral component $\frac{1}{\tau_i} \int \varepsilon(t) dt$, which is replaced by the summation $\frac{\Delta t}{\tau_i} \sum \varepsilon(k)$, can

eliminate offset in the flow. As a result the computation is easily performed in EXCEL spreadsheet and the values of calculated MV are sent to the database of SCAN3000 to adjust the speed of the corresponding pump.

The challenge of this exercise is to design up to 18 PI controllers for the pumps (P) and flow control valves (FCV) to maintain a steady flow through the whole plant. Although the selection of the controller parameters is entirely based on an individual step test for a single pump or FCV to be controlled, the conventional tuning methods do not always result in good control performances. The reasons for this are interaction between tanks, constraints posed on speed and flow rates, and disturbances coming from the back end

and noises from the front end of the plant. Similar to controlling an industrial-scale plant, good practical experiences are required for a robust performance of controlling the pilot plant.

Analytical design and implementation of Generic Model Control technique

For flow and level control only, a linear model is good enough to represent a pure capacity model with time delay. It is not necessary to deal with nonlinearity but for training purposes, Generic Model Control (GMC) strategy is implemented to control the speed of the pump, adjusting the outlet flow rate and maintaining the level of the tank at the desired set-point. The GMC algorithm provides more advantages when controlling temperatures of the heated tanks or in dealing with disturbance rejection. These are nonlinear problems with significant time-delay terms. The GMC strategy developed by Lee and Sullivan (1988) is presented in equation (4), where $f(y,u)$ is a nonlinear function describing the true process model.

$$f(y,u) = K_1 \varepsilon(t)dt + K_2 \int_0^t \varepsilon(t)dt \quad (4)$$

In equation (4), ε is the difference between the desired output y_d and the output y itself; u stands for the manipulated variable (MV); K_1 and K_2 are tuning parameters. The procedure to select appropriate values of the tuning parameters was proposed by Lee et al. (1988). In general the exact process model is rarely known. Consequently an approximate model is introduced in equation (4) then u can be solved at each time step by an algebraic method if possible, or by a numerical method. A MATLAB script file used to solve the problem of an anaerobic digester can be found in Lee et al. (1988).

$$\hat{f}(y,u) = K_1 \varepsilon(t)dt + K_2 \int_0^t \varepsilon(t)dt \quad (5)$$

As mentioned before, equation (1) representing the mathematical model of a pure capacity system, can be substituted in equation (5) to solve for the manipulated variable u .

$$\frac{1}{A}(F_{in} - F_{out}) = K_1 \varepsilon(t)dt + K_2 \int_0^t \varepsilon(t)dt \quad (6)$$

$$F_{out} = F_{in} - A[K_1 \varepsilon(t)dt + K_2 \int_0^t \varepsilon(t)dt] \quad (7)$$

For simulation, equation (7) can be solved using MATLAB or SIMULINK for outlet flow rate (F_{out}) and the liquid level in the tank (h). For implementation, the integration

$K_2 \int_0^t \varepsilon(t)dt$ is replaced by the summation $K_2 \Delta t \sum \varepsilon(k)$. (F_{out}) values can easily be

calculated in EXCEL spreadsheet and are sent back to the database of SCAN3000 to adjust the speed of the corresponding pump.

Design and implementation of model-based predictive control: Dynamic Matrix Control technique

Dynamic Matrix Control (DMC) was the first model predictive structure successfully applied to chemical processes. The DMC algorithm is based on a convolution model, which can be directly formed from the unit step response of the open-loop system. The

Dynamic Matrix Controller or (gain matrix) K_{DMC} , obtained from minimising the integral squared deviation between predicted (y_p) and desired (y_d) outputs, over a prediction horizon V , was proved to have the form as in equation (8) (Seborg et al., 2004). MV values can be then calculated from equation (9).

$$K_{DMC} = (A^T[W]A + [Q])^{-1} A^T[W] \quad (8)$$

$$\Delta MV = K_{DMC} E' \quad (9)$$

In these equations A is the dynamic coefficients matrix obtained from a unit step response of an open-loop system. W and Q are diagonal weighting matrices with an adjustable parameter w for the controlled variable and q for manipulated variable, respectively; E' is the vector of open loop predicted errors based on only past control actions. Further detail of these matrices and vectors as well as the design and implementation of the DMC technique can be found in Seborg et al. (2004).

For simulation, MATLAB can be used to find K_{DMC} in equation (8). For implementation in the pilot plant, special function for matrix manipulation must be performed in EXCEL to calculate the gain matrix then subsequently ΔMV .

Design and implementation of other sophisticated control techniques

Supervisory and Fuzzy are classified as sophisticated control techniques as the values of the control parameters are results obtained from running a simulation or an optimisation program in another software package. These results are passed to EXCEL then transferred to SCAN3000 for implementation. In supervisory control of the pilot plant, the objective function was maximised if a profit function or minimised if a cost function, to calculate the set-points of the plants. The optimisation problem was solved in MATLAB for the inlet or outlet flow rates, as manipulated variables, subject to the operating conditions of the plant. The solutions were then written from MATLAB to EXCEL using a special function in MATLAB. Alternatively in fuzzy control of the pilot plant, a visual basic program was designed to perform all calculations for the input and output memberships function. The Fuzzy Logic Toolbox in MATLAB was used only to construct the fuzzy interface system (Blay and Colson, 2009). Further details of Supervisory and Fuzzy control techniques can be found in Seborg et al. (1989) and Negnevitsky (2002).

COMPUTER BASED CONTROL SYSTEM

Similar to other industrial automated processes, the sensors and actuators of the pilot plant are physically attached to a programmable logic controller (PLC), specifically an Allen Bradley PLC-5/20E. Although only a relatively small system, it is more than complex enough from an educational standpoint. This can be appreciated by understanding the number of types of I/O supported by the system: 48 digital inputs, 41 digital outputs, 59 analog input and 20 analog outputs. The latter are attached to 10 pneumatic control valves and 10 Danfoss FC102 variable speed drives, which in turn are attached to positive displacement pumps. The PLC communicates via Ethernet to the Honeywell SCAN3000 server, which then communicates with 4 operator workstations. All the real-time control of the plant is done by the PLC via appropriate ladder logic, embedded numeric processing and dedicated PID loop blocks. The PLC program can be monitored online while the pilot plant is operating, providing a significant educational tool for students. They have been able to apply their knowledge and skills obtained from investigating simple sequential machines in the laboratory to exploring more

sophisticated and complex machines in the pilot plant. Many have already been involved in correcting and upgrading various aspects of the PLC program to include additional functionality.

DEMONSTRATIVE RESULTS

Due to the space limitation, only some results will be presented. To automatically operate the plant in a steady state mode with all tank levels and temperatures in the heated tanks at the desired set points, at least 14 control loops were designed and implemented. Thirteen of these were PI controllers including 6 flow, 5 level and 2 temperature controllers. The last one is an on-off type to top up the supply tanks. The control parameters were tuned in EXCEL spreadsheets and implemented in SCAN3000. The plant was in a stable condition if the minimum flow rates of the pumps were constrained at 15 % and their range of operating was between 75 %-90 %.

Implementation of Generic Model Control technique

The GMC technique was applied to control the level of the *Cyclone Underflow Tank* (CUFT), which had one inlet and two outlet flows as shown in Fig.1. The model of the CUFT was represented by equation (10), where V was the percentage of the liquid volume in the tank and $\varepsilon(t)$ was the difference between measured and desired volume of liquid in the tank. B , R and U respectively denoted the flow rates through the ball mill pump BMP-241, the cyclone recycle pump CRP-341 and the cyclone under flow pump CUFP-361, (Blay and Colson, 2009).

$$\frac{dV}{dt} = 0.71B - 0.56R - 0.30U \quad (10)$$

The flow rate (U) and the speed of a pump (P_U) linearly related:

$$U = 0.647P_u + 7.518 \quad (11)$$

The above equations were used with equation (5) to calculate P_U to control the level in the *CUFT*:

$$P_U = \frac{0.71B - 0.56R - 2.255 - \left[K_1 \varepsilon(t) + K_2 \int_0^t \varepsilon(t) dt \right]}{0.194} \quad (12)$$

Equations (10) and (12) were used to solve for the level of the CUFT when the set-point changed from 75 % to 60 % in SIMULINK. The block diagram is shown in Fig.2.

Implementation of Dynamic Matrix Control technique

Control problems in the pilot plant are concerned with 3 major types of variables: setting flow rates, maintaining levels and temperatures. The models representing these three types have significantly different time constants, resulting in different control and prediction horizons in designing the dynamic matrix controllers. This makes multi-input/multi-output (MIMO) DMC very challenging.

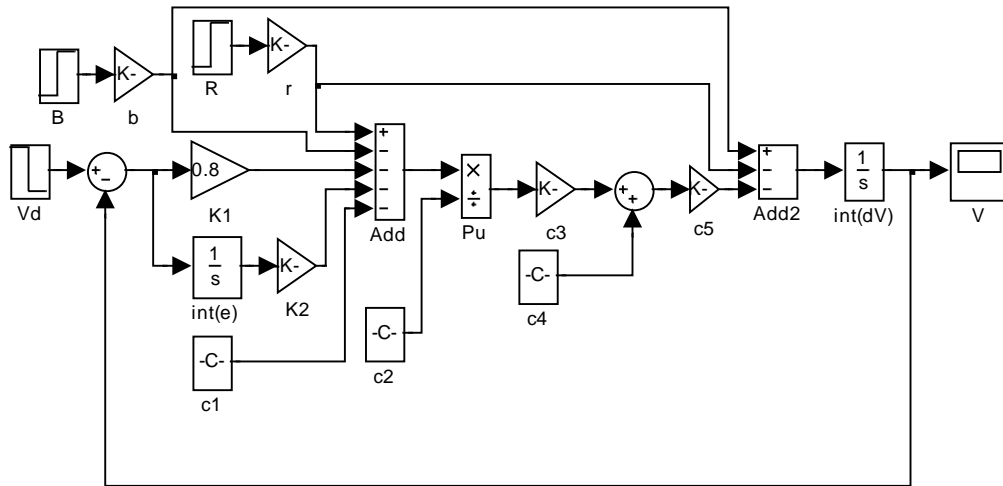


Fig.2: Block diagram of the CUFT with GMC control technique

The response of the real-time system was compared with the model in SIMULINK in Fig.3.

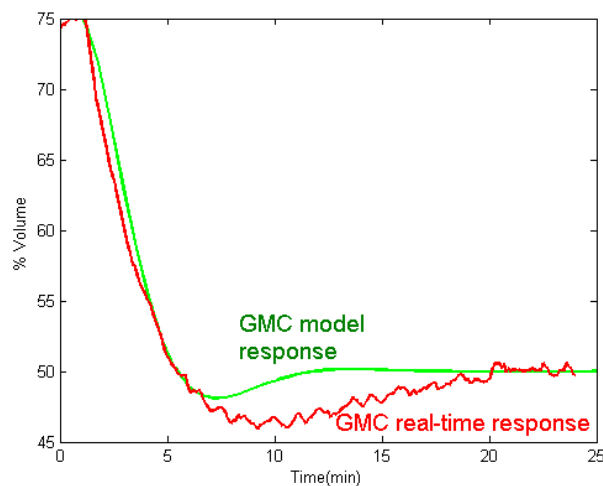


Fig.3: Response to level change from 75 to 50% in CUFT: GMC real-time compared with SIMULINK model (Real time data from Blay and Colson, 2009)

The performances of the dynamic matrix controller and the PI controller in tracking the temperature set-point of the second heated tank, by adjusting the steam valve FCV-642, are compared in Fig.4. It is suggested that the DMC technique is applicable and its performance is comparable to that of a well-tuned PI controller in temperature set-point tracking. In disturbance rejection, the flow valve FCV-570 was closed from 80% to 40% to create the disturbance. To maintain a constant flow to the first heated tank, the total flow through pump NUFP-561 must increase (i.e., the speed of the corresponding pump must increase). In this case, the performance of the PI controller is slower than that of the DMC technique because the pump speed was not directly adjusted. The comparison is shown in Fig.5.

Implementation of PLC-based upgrade and maintenance program

As mentioned previously, the pilot plant at Murdoch initially used an inert solid material and water to simulate a part of the Bayer Process. The density of the slurry feeds could be varied, measured on-line and controlled. Over the years however, the solids built up

in the pipes, valves and pumps when the plant was not continually operated. This was especially the case during the university breaks. Then, when the plant was restarted the cost both in terms of time and money could be significant. To solve the problem an automatic “maintenance” mode was designed to be included in the PLC program. The concept was that when the plant was not operated, the feed was automatically cycled through all tanks, pumps and valves. The design, implementation and commissioning of this project have been assigned to final-year students over several years.

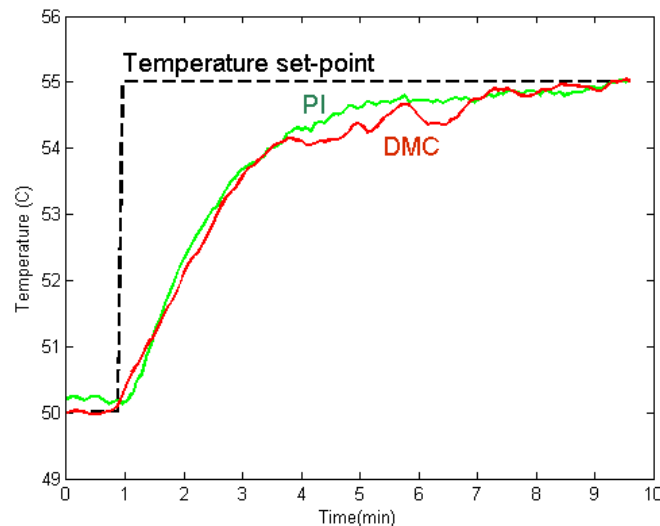


Fig.4: Response to a temperature set-point change from 50 to 55°C of second heated tank: DMC compared with PI controllers (Data from Blay and Colson, 2010)

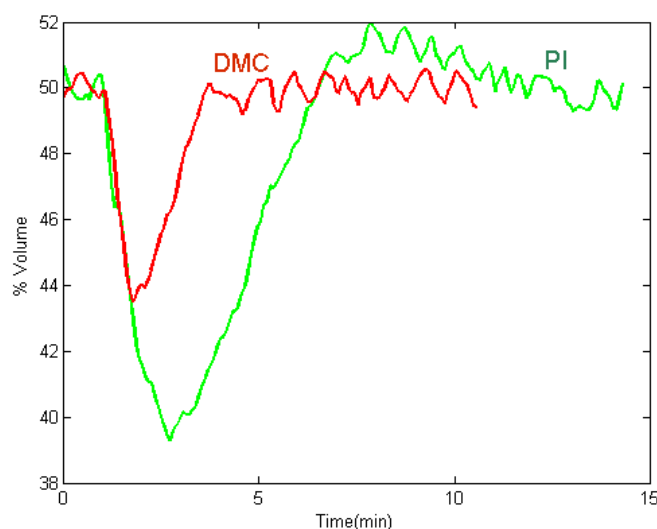


Fig.5: Response to disturbance change from 80 to 40% of FCV-570: DMC compared with PI controllers (Experimental data from Blay and Colson, 2010)

Another more ambitious project currently involves students installing the new Honeywell C300 controller in place of the old Allen Bradley PLC. This work requires a major change in the wiring and controller software. SCAN3000 system is being replaced by the new Honeywell Experion System. Additionally, rather than separate analog signals to each VSD, Modbus communication will be used. Thus the architecture of the overall control is radically different to the old system. Over the year students have been and are involved in the physical rewiring, programming, commissioning, documentation and development of all wiring and P&ID diagrams. These exercises expose students not

only to new hardware and software, but also to all aspects of a real project from design to project management.

CONCLUSION

The examples of implementation of control strategies and PLC-based maintenance and upgrade programs described in this paper highlighted the importance of the pilot plant in teaching undergraduate process control engineering at Murdoch University. PI controllers were proven to be good enough for single-input/single-output (SISO) flow, level and temperature controls but became very challenging when dealing with interacting systems. Advanced non-linear control laws such as GMC, DMC, Supervisory and Fuzzy were successfully implemented on the pilot plant. The designs and implementations of these advanced control techniques together with the implementation of the PLC-based upgrade and maintenance program have given PCE students real hands-on experiences in controlling an industrial-like process and in project design and management.

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REFERENCES

- Blay, K. and Colson, C. (2009). *Pilot Plant Case Study*. Murdoch Internal Report. School of Engineering and Energy, Murdoch University.
- Blay, K. and Colson, C. (2010). *Pilot Plant Case Study*. Murdoch Internal Report. School of Engineering and Energy, Murdoch University.
- Lee, P.L. and Sullivan, G.R. (1988). *Generic Model Control*. Computer & Chemical Engineering, 12, 573 – 580.
- Lee, P.L., Newell R.B. and Cameron, I.T. (1988). *Process Control and Management*. Blackie Academic & Professional, London.
- Negnevitsky, M. (2002). *Artificial Intelligence – A Guide to Intelligent Systems*. Addison-Wesley, New York.
- Ogunnaike, B.A. and Ray, W.H. (1994). *Process dynamics, modelling and control*. New York Oxford, Oxford University Press.
- Seborg, D.E., Edgar T.F. and Mellichamp, D.A. (2004). *Process Dynamic Control*. John Wiley & Sons, New York.
- Seborg, D.E., Edgar T.F. and Mellichamp, D.A. (1989). *Process Dynamic Control*. John Wiley & Sons, New York.