J. S. Afr. Inst. Min. Metall., vol. 90, no. 7.
Jul. 1990. pp. 173-181.

Multivariable control of a run-of-mine milling circuit*

by D.G. HULBERT†, I.K. CRAIG†, M.L. COETZEE‡, and D. TUDOR§

SYNOPSIS

The paper describes how a multivariable control scheme was developed and implemented for the run-of-mine milling circuit at a gold mine belonging to Vaal Reefs Exploration & Mining Company Limited.

The key variables that are controlled are slurry level in the sump, mass of material in the mill, and product size. The control scheme has resulted in reliable control of the dynamics of the plant, and has provided a good basis for the optimization of plant operation by the selection of suitable setpoints.

SAMEVATTING

Die referaat beskryf die ontwikkeling en inbedryfstelling van 'n veelveranderlikebeheerskema vir die maalkring vir onbehandelde erts by 'n goudmyn wat aan Vaal Reefs Exploration & Mining Company Limited behoort.

Die sleutelveranderlikes wat beheer word, is die vlak van die flodder in die opgaartenk, die massa materiaal in die meul, en die grootte van die produk. Die beheerskema het gelei tot die betroubare beheer van die dinamika van die aanleg en het 'n goeie grondslag gelê vir die optimering van die bedryf van die aanleg deur die keuse van geskikte stelpunte.

Introduction

The run-of-mine (ROM) milling unit at No. 7 shaft at Vaal Reefs gold mine is being used in an investigation into the automatic control of ROM milling. The aim of the project is the development and implementation of an advanced control scheme that will yield significant economic benefits from the optimized or improved operation of a ROM milling circuit.

The control of milling circuits has been the subject of research for many years. The research is of particular importance to the mining and mineral-processing industry, the cost of milling often being a significant component of the total production cost. The techniques used for control depend on the availability of reliable measurements, suitable hardware and software for the implementation of control, and specialized expertise for the design of the control scheme. Advances in all these fields have led to the beneficial use of many old and new ideas in the exploitation of ROM milling.

As a milling circuit is used to grind material to a fine product, it seems logical that a measurement of product size could be very useful in the control and evaluation of milling. Some years ago, the use of a continuous particle-size monitor (PSM) in industrial milling circuits became possible, and the usefulness of this instrument was recognized[1]. The dynamic response of the product size of a milling circuit can be fairly complex, leading to oscillations when conventional control techniques are applied[1]. The introduction of multivariable techniques for the control of product size has led to a control scheme that has been operating successfully for several years at East Driefontein gold mine[2,3].

The control of ROM milling is more difficult than the control of conventional milling circuits because the feed rate of the main grinding medium, rocks from the ore, cannot be made independent of the feed rate of the ore itself. This results in the loss of a degree of freedom. If a ROM milling circuit is run semi-autogenously, as is the case with the circuit at Vaal Reefs, some compensation for the loss of control can be achieved by variations in the addition of steel balls. However, steel is consumed at a much lower rate than rocks and, unless there is a facility for the removal of balls, the addition of balls tends to be a one-sided control action that is not of much use in the short term.

The multivariable controller used for the control of ROM milling differs from that currently implemented at East Driefontein. The newer controller has special facilities to deal with the specific characteristics of ROM milling, including those for startup, shutdown, and the limiting of control action.

The ROM Milling Circuit

A diagram of the milling circuit is given in Fig. 1. About 100 t of gold-bearing ore per hour is milled by the circuit to produce a material containing about 70 to 75 per cent material smaller than 75 μm. The ROM mill is operated in closed circuit with a hydrocyclone, and the product is pumped to thickeners. The gold is subsequently extracted by a leaching process.

The mill is 9,15 m long and 4,88 m in diameter, and is supported by pressurized-oil circumferential bearings. Pulp flows out of the mill through an end-discharge grate. The mill has lifter bars and solid white-iron liners. It is operated at 91 per cent of critical speed.

Pulp is discharged from the mill into a sump, where

---

* Presented at the Colloquium on Milling, which was held by The South African Institute of Mining and Metallurgy in Randburg in June 1987.

† Mintek, Private Bag X3015, Randburg, 2125 Transvaal.

‡ Anglo American Research Laboratories, P.O. Box 106, Crown Mines, 2025 Transvaal.

§ Formerly of Vaal Reefs Exploration & Mining Co. Ltd, Private Bag X5010, Vaal Reef, 2621 Transvaal.

ISSN 0038-223X/3.00 + 0.00.

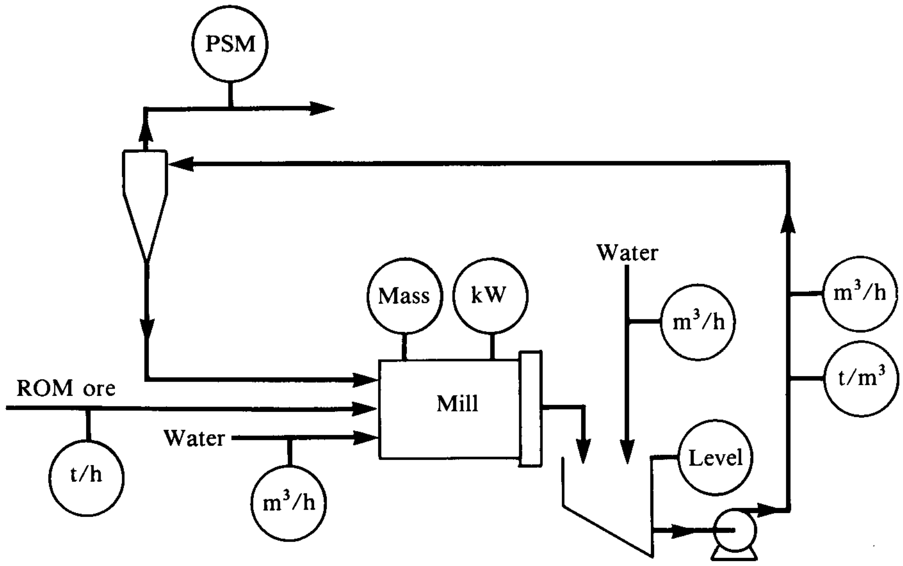

Fig. 1—Milling circuit and measurements

it is mixed with added water and then pumped to a hydrocyclone with an internal diameter of 1,05 m. The underflow from the cyclone, additional water, and fresh ore are fed into the mill.

The plant was designed and constructed in such a way that the sporadic or uncontrolled addition of water to the milling circuit is minimized. Belt-wash water and slurry from spillage and floor washing are processed by a rotor scoop that produces a slurry containing fine material and most of the water, and a cake of solids with a little water. The slurry is combined with the product of the milling circuit, and the cake is deposited on the ore-feed belt.

Procedure Followed

The procedure that was adopted for the project was based on similar procedures that Mintek had used successfully in other projects involving the application of process control to industrial plants. Although the project has been backed by a continuing investigation into the characteristics of milling by means of mechanistic modelling and simulation, its main thrusts can be summarized by the following stages:

- Instrumentation and logging
- Basic control loops
- Perturbation tests on the plant
- Dynamic modelling
- Design of a controller
- Preparation of controller hardware and software
- Implementation of the controller
- Measurement of long-term performance
- Optimization of the control scheme
- Evaluation of optimized control.

The project was split into three phases, ending with the design and implementation of the controller, and the evaluation of optimized control. The preparation of the controller hardware and software was carried out under a separate project; as multivariable control becomes more widely applied, suitable multivariable-control systems will become commercially available at reasonable cost. This paper describes the first two phases of the project, up to the stage at which the multivariable control scheme was implemented on the ROM milling circuit at Vaal Reefs.

Instrumentation and Logging

Although the quality of the instrumentation was fairly good at the start of the project, a concerted effort was made to achieve even more reliable and accurate instrumentation. Accuracy was important during the perturbation tests on the plant, in that measurements taken over a relatively short period were required to reflect the dynamic characteristics of the milling circuit that could be expected for many years of future operation. Correct deductions regarding the technical and economic features of controlled milling also depend critically on the quality of the instrumentation. Fig. 1 shows the milling circuit and the on-line measurements.

The ore is drawn from silos through Langlaagte chutes by a variable-speed belt that transports the ore to the mill. The belt is slow-moving, and the cross-sectional profile of the solids on the belt does not vary significantly. The feed rate of the solids is determined from combined measurements of belt speed and mass, the latter being measured by a radiometric weigher on the belt near the inlet of the mill.

The flowrates of water and slurry are all measured by magnetic-induction flowmeters. In the case of the slurry, an alternating-current flowmeter was installed to avoid problems of noisy measurements, which often occur when direct-current flowmeters are applied to slurry streams.

The level of the slurry in the sump was measured by means of a bubble tube, and was calibrated on a percentage scale approximately covering the full range of operation. The mass of material in the mill, or mill load, was measured according to the oil pressures on the various slipper-pads of the mill bearings, by means of a system designed and installed by Vecor. The mill load was measured in terms of percentages. In the scale used, 68 per cent corresponded to a mill filling at which, when the mill was stopped, the surface of the charge was level with the lower lip of the 1,05 m diameter inlet aperture. A variation of 1 per cent in the scale of the mill load corresponded to a change in the load of about 3 t.

The particle size and solids content of the product from the milling circuit were measured by an Autometrics PSM300. When it is properly calibrated, this instrument can give an adequate on-line measurement of the percentage of solid material smaller than 75 μm. However, it requires careful maintenance and a reliable supply of clean water at a suitable pressure.

All the on-line measurements on the plant were logged at intervals of 30 seconds during perturbation tests, and at intervals of 10 minutes at other times. Suitable analogue and digital filtering was carried out.

Basic Control Loops

Each of the inflowing streams of solids and water was controlled by a proportional–integral (PI) controller. The volumetric flowrate of slurry flowing to the cyclone was also controlled by a PI controller involving adjustment of the pump speed. The setpoints for these four controllers were as follows:

(i) Feed rate of water to the sump, SFW ($m^3.h^{-1}$)
(ii) Feed rate of solids, MFS ($t.h^{-1}$)
(iii) Flowrate of slurry to the cyclone, CFF ($m^3.h^{-1}$)
(iv) Feed rate of water to the mill inlet, MFW ($m^3.h^{-1}$).

SFW, MFS, CFF, and MFW were 'plant inputs' that could be manipulated so that the milling circuit as a whole could be controlled. The PI controllers of the four plant inputs can be regarded as 'slave' controllers that can receive setpoints from a multivariable controller operating at a higher level.

The slave controllers were tuned to operate with response times of a few seconds so that the responses could be considered, for practical purposes, to be instantaneous relative to the response times of the multivariable-control scheme. The fast responses and the control according to calibrated measurements tended to make the analysis of milling characteristics and multivariable control independent of the physical characteristics associated with the actuators.

With only the four slave controllers in operation, the milling circuit did not operate stably. While the multivariable controller was not in operation, the use of two additional controllers was therefore necessary. One of these controlled the level in the sump by the adjustment of SFW. The other controlled the mill load by the adjustment of MFS.

Perturbation Tests on the Plant

Dynamic tests had to be carried out so that sufficient information could be obtained for the derivation of a suitable dynamic model of the plant. Perturbations were made in the plant inputs SFW, MFS, CFF, and MFW, and the responses of all the on-line measurements were logged.

Thirty-four tests were carried out over a period of about two months. Each test consisted of a period in which the operation of the plant was allowed to settle, following by a period during which the plant responded to a single step or a series of steps in the setpoint of one of the slave PI controllers. Fairly large steps were made so that the responses of the measurements would be large enough compared with their noise levels, but this was done in such a way that the plant was kept running within a practical region of operation. Particular care was taken to eliminate the effects of disturbances where possible.

At least five successful runs corresponding to each of the four plant inputs were carried out. More were carried out in cases where the measured responses were not clear or not consistent. Although an ideal set of tests might have consisted of individual runs each having perturbations in only one of the plant inputs, the inherent instability of the plant necessitated the simultaneous variation of more than one plant input in many instances.

Dynamic Modelling

The results obtained from the perturbation tests were used for the derivation of a linear dynamic model, which characterized the relationship between the plant inputs and four 'plant outputs':

(i) Product size, PSM (% < 75 μm)
(ii) Mill load, LOAD (%)
(iii) Slurry level in the sump, SLEV (%)
(iv) Density of feed to the cyclone, CFD (t/m^3).

The model was in the form of a matrix of Laplace transforms, $G(s)$, relating changes in plant outputs to changes in plant inputs, where the changes are relative to any suitable set of fixed base-levels.

Fig. 2 shows some measured results and the fitted model corresponding to a perturbation test in which SFW was varied while the other plant inputs were kept constant. In this instance, the response of SLEV was modelled by an integrator of the form A/s. The value of A was obtained by software that minimized the sum of squares of the differences between the model and the measurement, with respect to the values of A and the base-level of SFW (which would correspond to a steady SLEV).

Fig. 3 illustrates the method by which data were processed from a test in which SFW and CFF were both varied. In this case, the theoretical response was calculated (by means of the previously derived model) to correspond to what would have occurred if SFW had been kept constant. The effective response of SLEV to CFF and the fitted model are shown in Fig. 3. The response of SLEV to CFF was also modelled by an integrator.

From all the estimates of parameters, suitable means were calculated for the derivation of the following dynamic model of the plant:

$$\begin{bmatrix} g_{11}(s) & g_{12}(s) & g_{13}(s) & g_{14}(s) \\ g_{21}(s) & g_{22}(s) & g_{23}(s) & g_{24}(s) \\ g_{31}(s) & g_{32}(s) & g_{33}(s) & g_{34}(s) \\ g_{41}(s) & g_{42}(s) & g_{43}(s) & g_{44}(s) \end{bmatrix} \begin{bmatrix} \Delta\overline{\mathrm{SFW}} \\ \Delta\overline{\mathrm{MFS}} \\ \Delta\overline{\mathrm{CFF}} \\ \Delta\overline{\mathrm{MFW}} \end{bmatrix} = \begin{bmatrix} \Delta\overline{\mathrm{PSM}} \\ \Delta\overline{\mathrm{LOAD}} \\ \Delta\overline{\mathrm{SLEV}} \\ \Delta\overline{\mathrm{CDF}} \end{bmatrix}.$$

Each element in the matrix, $G(s)$, is a transfer function between an input–output pair. A graphical representation of the model is given in Fig. 4, which indicates the responses of each of the plant outputs to single positive step changes in each of the plant inputs. In the diagram, the times at which the step was made are marked by short vertical lines on the curves, an hour's response being shown in each case; the graphs were scaled in an optimum way consistent with the scaling of plant inputs and outputs. It is clear that the system is interactive, each input giving rise to responses in more than one output.

The response of the power drawn by the mill was nonlinear and not amenable to modelling by linear transfer functions. The modelling of the power and its use in the control scheme, which is being investigated under phase 3 of the project, is beyond the scope of this paper.

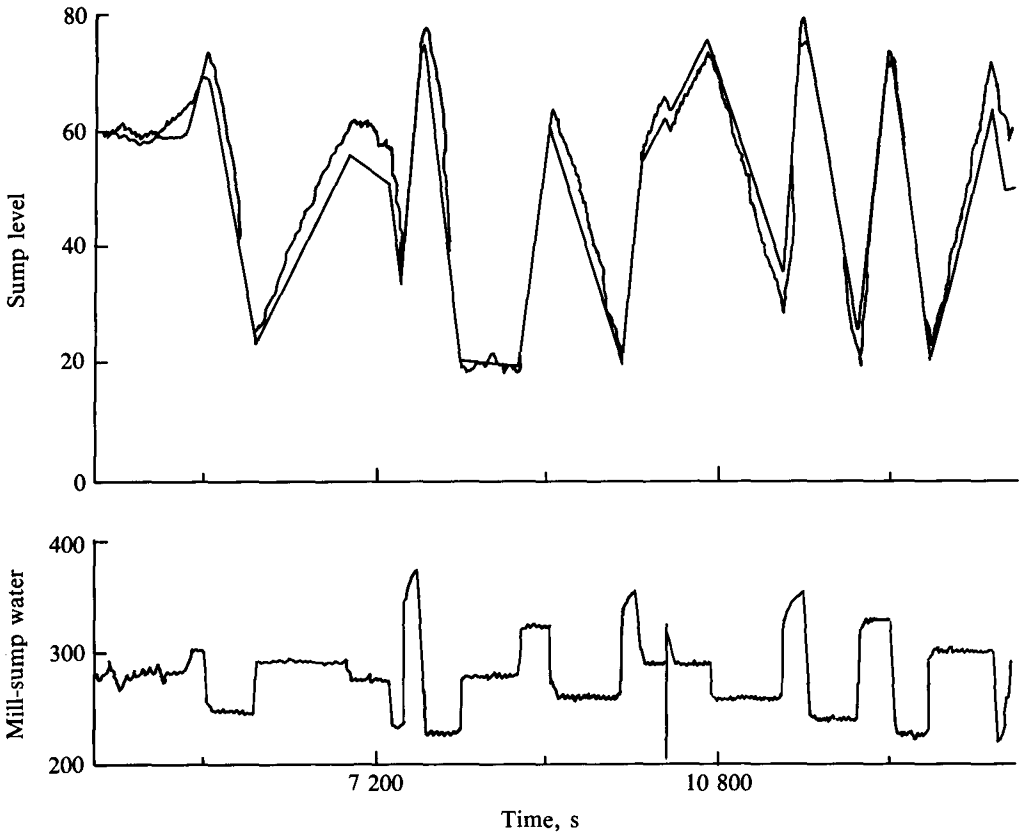

Fig. 2—Response of the sump level to mill-sump water

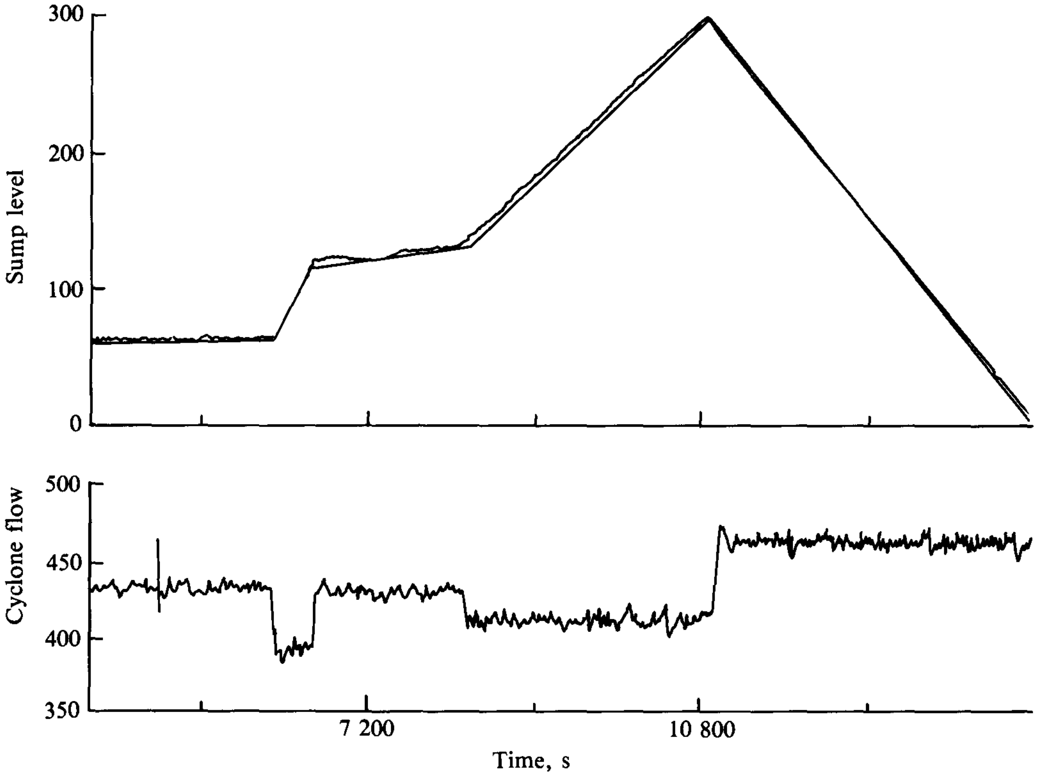

Fig. 3—Response of the sump level to the flow of cyclone feed

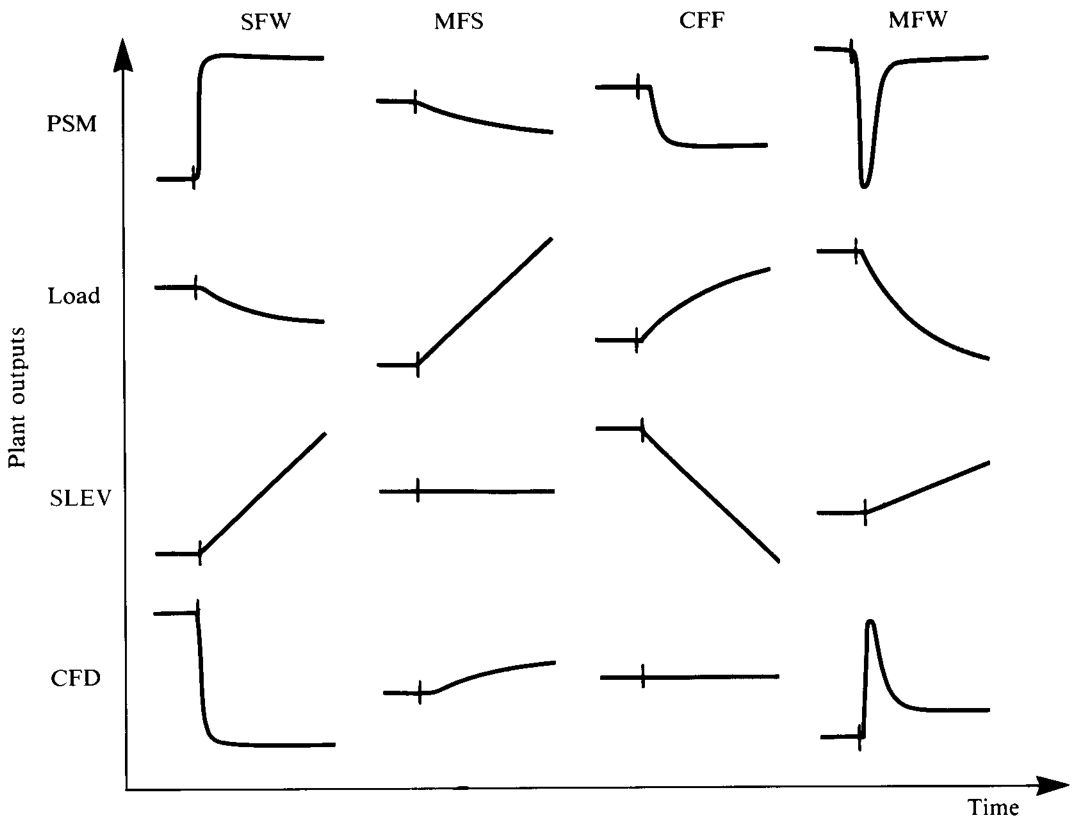

Fig. 4—Array of responses to step changes

Design of the Controller

Stabilization of the milling circuit requires the control of LOAD and SLEV, because these variables would otherwise drift to extremes at which the operation of the plant would be unacceptable. Control of the quality of the product as measured by PSM was also considered desirable. Although the control of CFD or the deduced density of the mill discharge was investigated, the selection of a fourth plant output to be controlled was deferred pending the analysis of long-term measurements of milling performance that is currently under way.

The response of PSM to MFW comprised a dead-time lag, followed by a large and rapid transient reaction with a smaller long-term effect. This response leads to difficulties in the design of rugged fast-acting control schemes, and MFW was therefore omitted as a primary control action in the multivariable controller. On the other hand, SFW, MFS, and CFF were found to be suitable control actions for the design of a multivariable controller to control PSM, LOAD, and SLEV.

The model for the 3 × 3 system considered is thus represented by the upper left 3 × 3 minor of the 4 × 4 matrix given above. The model was processed by use of Mintek's software[4] for the interactive design of a multivariable controller by inverse Nyquist array (INA) methods. Fig. 5 shows the structure of the control system. Each plant output is associated with a setpoint and a PI control element. The output from one of these PI elements is an intermediate variable representing corrective action that must result in a modification of the corresponding plant output. The matrix compensator, K, was designed in such a way that the corrective action for one plant output leads to dynamic changes in a number of plant inputs, but results in significant changes in only the one plant output concerned. K can be represented by the following matrix:

$$\begin{bmatrix} 17{,}72 & \dfrac{123{,}5}{1+2484s} & \dfrac{-3{,}804}{1+1193s} \\ 0 & 82{,}17 & 0 \\ 14{,}97 & \dfrac{104{,}6}{1+2465s} & \dfrac{-6{,}56-3994s}{1+1193s} \end{bmatrix}.$$

In the case of SLEV, a special non-linear operator is applied to the input of its PI element. The input is multiplied by its own absolute value, which makes the effective gain of the control dependent on the magnitude of the deviation of SLEV from its setpoint. This 'error squared' control is particularly effective in the utilization of the buffering potential of a sump, so that control of the level is achieved with small, relatively smooth changes in the control action.

The simulated response of the controlled system to changes in setpoints is shown in Fig. 6. The responses of PSM and LOAD are fast and stable. The response of SLEV is smooth and slow in this case because the nonlinear element of the controller would result in fast action only if a large change were required.

During periods in which a control action in a multivariable controller is constrained (e.g. when a valve is fully open), there is one less degree of freedom for the control of plant outputs, and it is likely that one or more plant outputs will deviate from their setpoints. In applications of single-variable and some multivariable control-

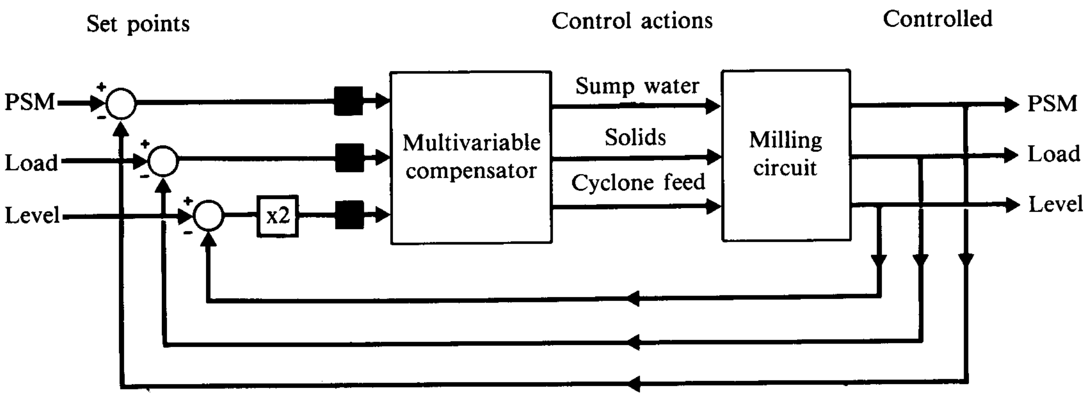

Fig. 5—The multivariable-control scheme

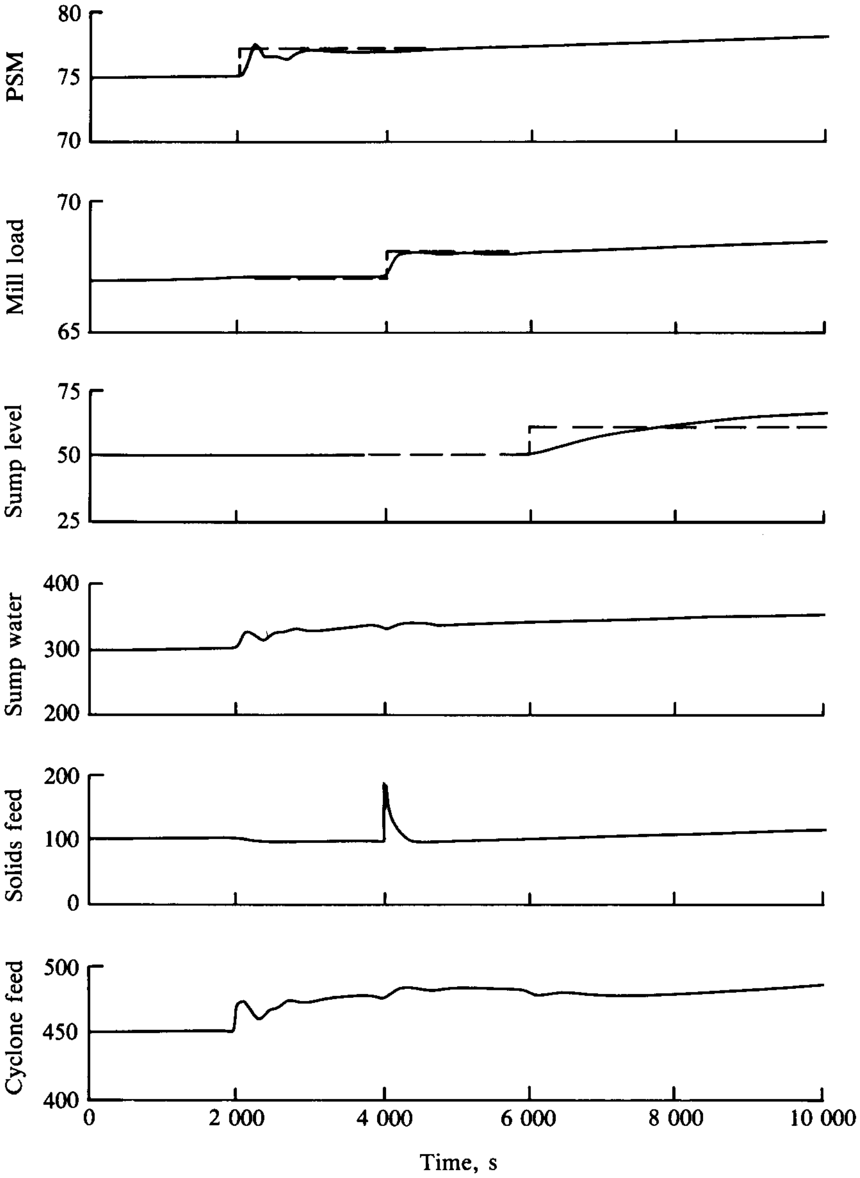

Fig. 6—Simulated responses with multivariable control

lers, the use of an incremental implementation with a simple limiting of the control actions might be adequate. However, the plant that was being controlled in this case was open-loop unstable and, when a control action was limited, a technique was provided for the preferential control of LOAD and SLEV at the expense of PSM when necessary.

Preparation of Controller Hardware and Software

Although a control system was commercially available for the implementation of a multivariable controller for conventional milling, new techniques had to be developed for ROM milling. As a temporary measure, a personal computer, linked by suitable hardware to the instrumentation of the plant, was used for the monitoring and control of the ROM milling circuit.

Before the start of this project, the milling circuit was controlled by a set of conventional analogue PI controllers. Additional wiring was installed and connected to a multiple-pole switch to provide for either the old configuration of PI controllers, or the set of slave controllers for SFW, AMFS, CFF, and AMFW with remote setpoints originating from a Micromac interface. The analogue measurements on the plant were connected through suitable analogue filters to the Micromac. A Sperry personal computer was linked to the Micromac, and was used to implement data logging and multivariable control.

The operating system used on the Sperry was CCPM/86, which is a multitasking system, and MACBASIC was run under this system. The software was written in modular form so that its development and modification could be facilitated, particularly as more than one person was involved with the programming.

Implementation of the Controller

Before being installed on the plant, the hardware and software were tested fully by the monitoring of their performance when connected to a computer simulation of the plant. The computer that was used to simulate the plant was interfaced with hardware to input and output 4 to 20 mA signals representing control actions and measurements on the plant.

In the first test of the multivariable controller on the plant, the parameters for the controller were fixed according to the theoretical design, the setpoints were specified at values that differed a little from the corresponding values on the plant, and the controller was then turned on. All three of the plant outputs, PSM, LOAD, and SLEV, were driven to their setpoints by the controller. A step change in the setpoint for PSM was the made, and the controlled plant responded accordingly, except that there was some oscillation of the PSM measurement about the new setpoint. As a result of the sensitivity of the PSM control loop, the gain for the loop (an on-line tuning factor) was reduced slightly for subsequent runs. Further tests were carried out in which the gain and integral constants for each of the three loops were fine-tuned.

The multivariable controller was designed to have a perfectly bumpless startup. This was achieved by the elimination of any initial proportional control action that might have been taken by the multivariable controller on startup when the plant measurements were not initially at their setpoints. (This is also normal practice with most conventional controllers.) The fully bumpless startup tended to result in a rather long delay before the controller established the correct operating level for the solids feed. This was essentially the result of the relatively low integral action that had to be used for the load-control loop, which has the most important influence on the solids feed. The controller was subsequently made to use a base value of 90 t/h for the solids feed, and immediate proportional action in the load-control loop on startup. This was found to give a smooth startup with good control of the load.

Fig. 7 illustrates the results of a five-hour test in which changes were made in the setpoints. The three plant outputs followed their setpoints fairly well. After a few tests had been carried out to confirm that the multivariable controller could be left unattended for long periods, it was accepted for continuous use in the normal operation of the plant. The operating staff of the plant were favourably impressed by the control scheme, which resulted in better control of the product size and coincided with an increase in throughput.

In the above statement about throughput, the term *coincided* was used deliberately in order to avoid premature claims of what multivariable control can do. In a previous investigation[1], Mintek found that a milling circuit can be operated at high or low throughputs with the same product size simply by the selection of good or bad setpoints for the control scheme. As the optimization of setpoints is still being investigated at Vaal Reefs, any improvement in throughput at that stage could simply be attributed to the 'luck of the draw'.

On the other hand, improvements were achieved in the control of product size, and the quality of the product would have improved in economic terms. The use of multivariable control resulted in an estimated reduction in the standard deviation of PSM 10-minute averages from about 5 per cent to about 3 per cent of material smaller than 75 μm.

Fig. 8 shows a two-day period of operation with multivariable control. The minor oscillations that are visible on some of the responses were due to too much integral action in the control of the load, and this was subsequently corrected. Over the two-day period, the setpoint for the PSM was 75, the average value resulting was 75,3, and the standard deviation of 10-minute averages was 1,2 per cent of material smaller than 75 μm, which is exceptionally good for a ROM milling unit. The corresponding values for the load and the sump level were setpoints of 71 and 60 per cent, measurements of 71,0 and 60,1 per cent, and standard deviations of 0,2 and 3,5 per cent respectively. The average solids feed was 113 t/h.

Conclusion

The multivariable control system applied to the ROM milling circuit at No. 7 shaft of Vaal Reefs provides stable control of the dynamics of the circuit while controlling the product size at a specified setpoint, or as close as practically possible to it. The controller has also provided a convenient set of setpoints that can be used in subsequent optimization of the plant. The controller has been in continuous operation at Vaal Reefs since March 1987.

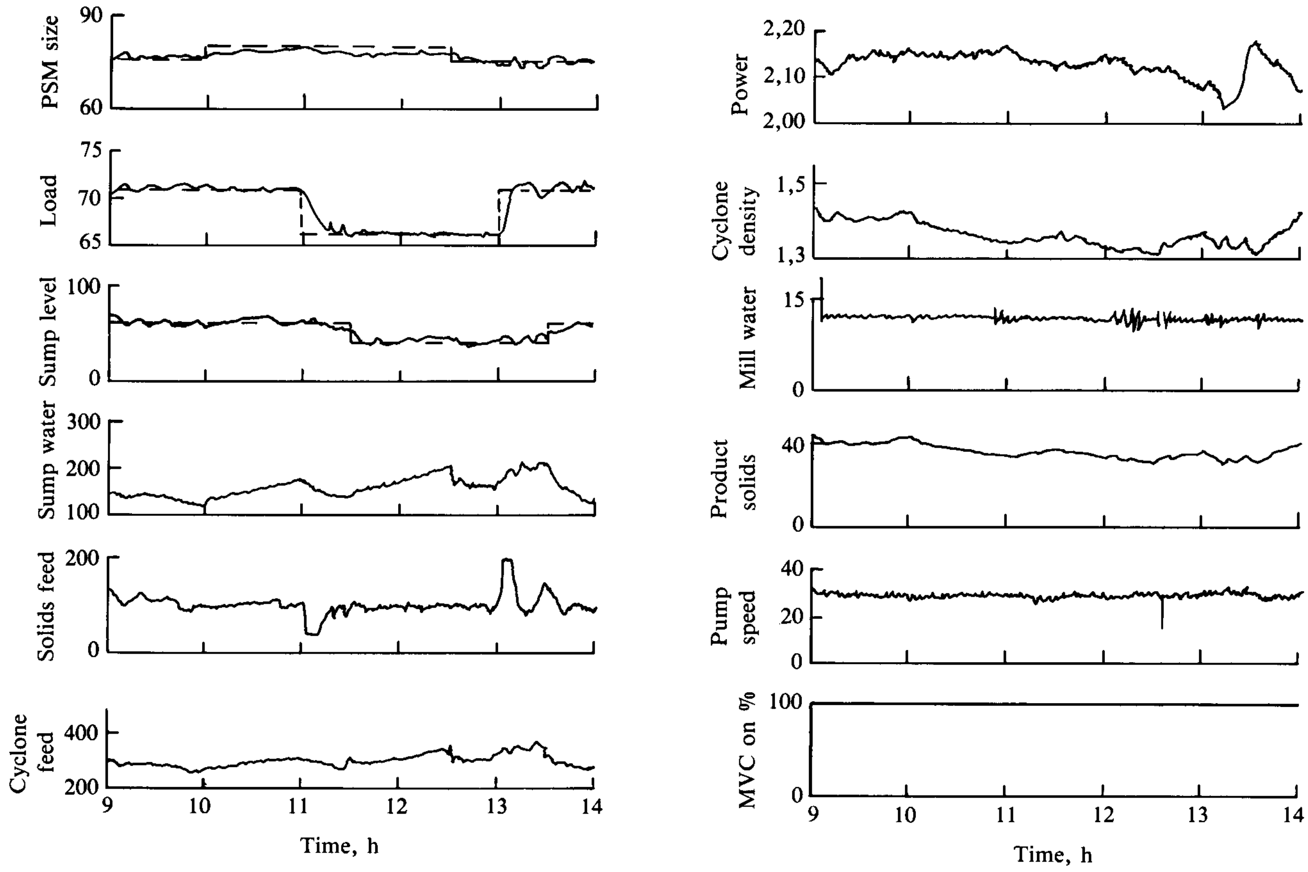

Fig. 7—Responses to changes in setpoints

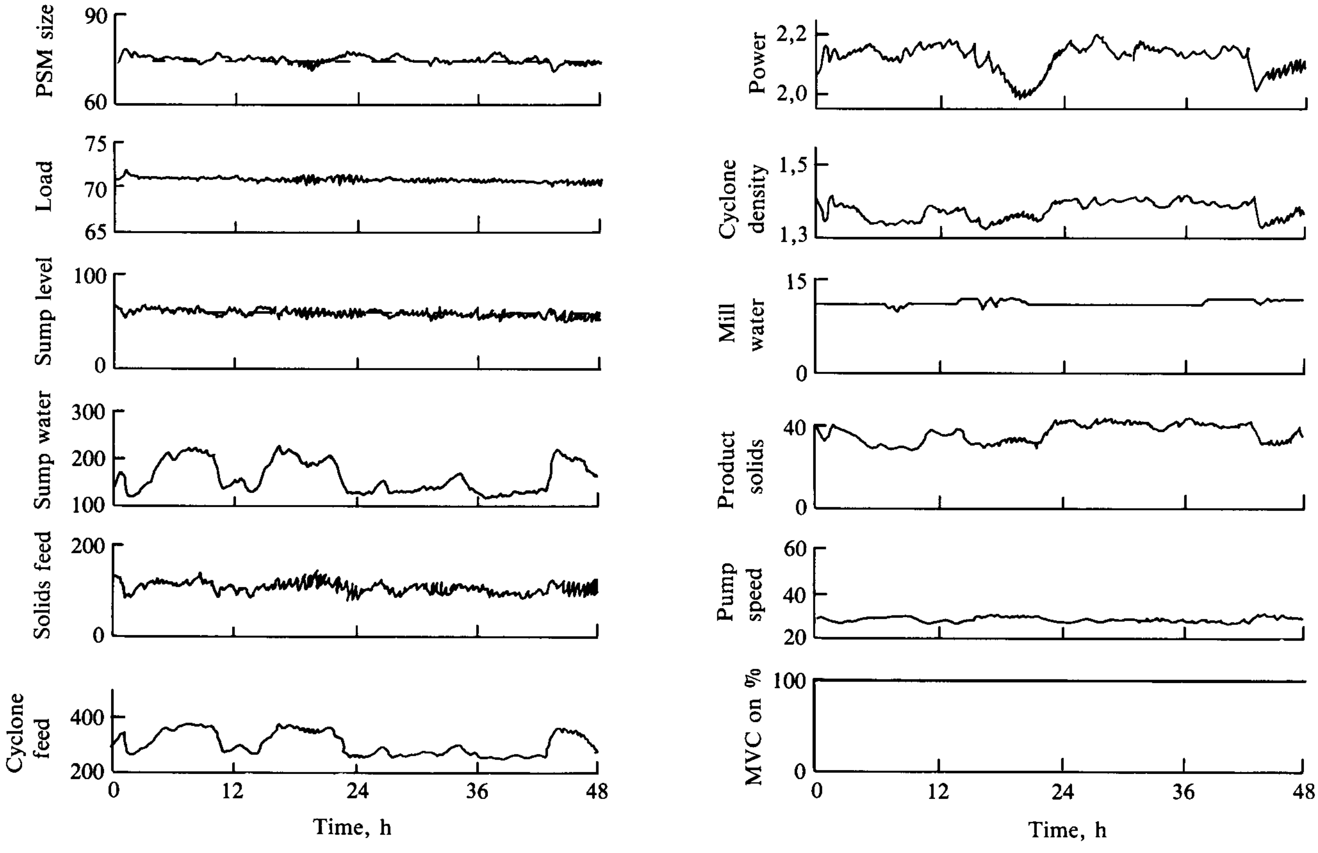

Fig. 8—Two-day period with multivariable control

This is probably the first application in which a direct measurement of the product size of a ROM milling circuit has been controlled successfully. A good two-day period of operation with a setpoint of 75 per cent material smaller than 75 μm resulted in a measured average size of 75,3 per cent smaller than 75 μm and a standard deviation of 1,2 per cent. The solids throughput has been satisfactory with multivariable control.

Although some optimization has been achieved by the dynamic control of product size and internal plant variables, the optimum selection of setpoints has still to be determined. Phase 3 of this project is currently being undertaken to complete the optimization of the operation of the plant by the derivation of a scheme for the selection of setpoints that maximizes performance in terms of throughput and other relevant criteria.

Acknowledgements

This paper is published by permission of Mintek, the Anglo American Research Laboratory, and Vaal Reefs Exploration & Development Ltd.

References

1. Mokken, A.H., Blendulf, G.K.I., Blendulf, K.A.G., and Cowin, N.R. A study, by continuous monitoring of particle size in the cyclone overflow, of factors influencing run-of-mine mill performance. *J. S. Afr. Inst. Min. Metall.*, May 1975. pp. 249–256.
2. Hulbert, D.G. Multivariable control and optimization of the operation of a milling circuit at East Driefontein gold mine. Randburg, Mintek, *Report* M98. May 1983. 20 pp.
3. Gossman, G.I., Hulbert, D.G., Koudstaal, J., Braae, M., and Buncombe, A. The application of computer control to a gold-milling circuit at East Driefontein gold mine. *Proceedings, Twelfth Congress of the Council of Mining and Metallurgical Institutions.* Glen, H.W. (ed.). Johannesburg, The South African Institute of Mining and Metallurgy, 1982. pp. 817–825.
4. Hulbert, D.G. Software for the design of multivariable control systems by use of the inverse Nyquist array. Randburg, Mintek, *Report* M31. Jun. 1982. 35 pp.

Investigation into Waste and Pollution

The Department of Environment Affairs has commissioned the CSIR to investigate the present status of waste management and pollution control in South Africa. The designated project team will report on the legislation, application, and administration of legislation and shortcomings in the areas of waste management and pollution.

The Department initiated the study as a result of experience and observation of problems and shortcomings in these areas. The Committee for Wastes and Pollution of the Council for the Environment strongly supports the actions taken by the Department.

In the past, different waste, pollution, and other environmental problems were regarded as separate problems, rather than as integrated fragments of a whole, which led to diverse legislation on waste management and pollution. Effective environmental protection can be achieved only with the rationalization of relevant legislation and the development of uniform criteria.

Various groups will be approached to participate in the study. These include waste producers and processors, controlling bodies, research organizations, and action groups. Recognized experts in environmental legislation will assist in identifying problems in the existing legislation, law enforcement, and judgements. The investigation will cover a wide spectrum and will include marine, air, water, and land pollution, but will not include pollution as a result of noise or radioactive wastes. An in-depth study on hazardous waste is already in progress, also sponsored by the Department of Environment Affairs, and will be included in the investigation. The Foundation for Research Development (FRD) of the CSIR is co-ordinating the investigation into hazardous waste.

All organizations, individuals, or industries involved in any capacity or who have an interest in the fields of waste management and pollution control are invited to assist by co-operating with the CSIR in this investigation. As part of an information-gathering exercise, the CSIR has sent out questionnaires to identified industries, authorities, and other interested parties. Individuals and organizations who wish to contribute to this survey in the interests of environmental protection can do so by contacting

The Waste Management Study
INFOTEK
CSIR
P.O. Box 395
Pretoria 0001.

Tel: Tina James at (012) 841-3083;
telefax (012) 86-2869.