An Industrial Application of Multivariable Linear Quadratic Control to a Cement Mill Circuit

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***Abstract*— There are a variety of control strategies that one may consider for mill circuit control and often several methods for implementing each strategy.**

Ideally, the control strategy selected and methodology used in it's implementation should not only optimize circuit performance in terms of productivity but also be able to optimize quality.

A linear quadratic multivariable controller has been applied to milling circuits and these goals successfully accomplished.

The results are a stable circuit with mill and separator optimized, producing a consistent quality product of a predictable fineness. This enables one to use cement quality as the single circuit control set point.

I. INTRODUCTION

THE MAJORITY of cement finish grinding is done by ball mills in closed circuit with a separator. Ball mill product is fed to the separator where finished product is separated off. The oversize material, often referred to as the circulating load, is returned to the mill. There is an optimum value of the circulating load to ensure ball mill efficiency. Constant fines and rejects flow ensure minimum variation in product quality. Such a circuit needs to be controlled, or the amount of material entering the circuit will deviate significantly from what is leaving the circuit, and the circuit will run either empty or full.

When considering mill circuit-control strategies, emphasis is usually placed on stabilizing one flow, having one measured variable and one controlled variable. Control systems of this type, usually utilizing a proportional integral derivation (PID) controller, are based on the assumption that what is exiting the system is equal to what is entering the system. Over an extended period this is undoubtedly true, but on the shorter term this is rarely the case.

When the circuit circulating load is held constant, as for example in a circuit where the elevator power is monitored and mill fresh feed varied to keep it constant, or the rejects rate is monitored and the mill fresh feed varied to keep total feed constant, what leaves the circuit is constantly changing. Constant total mill feed, or constant separator feed, does not imply constant fines production. True stabilized flow is only possible when the rejects flow rate and the fines flow rate are both monitored and stabilized. The concept of measuring and controlling fines flow in addition to rejects flow is unique, and offers the consequential benefit of fineness stabilization and subsequently fineness prediction.

In modern grinding circuits featuring variable speed separators and reliable material flow meters, it is now possible, by utilizing mulitvariable control theory, to optimize the mill grinding performance and the finished product quality by ensuring correct total mill feed and stable separator flows (see Fig. 1).

II. CONTROL STRATEGY

Traditional strategies for mill control have used PI controllers, monitoring one value to control another. A popular method is to vary the mill fresh feed to keep the elevator power constant. This essentially is constant separator feed. The ratio between fines and rejects may, and probably will, be constantly changing. In more recent times with the rejects flow rate being monitored, a popular strategy has been to vary fresh feed to keep the sum of the rejects flow rate and the fresh feed rate constant. This is essentially constant mill feed rate. The response time is slow however, the typical residence time for a mill being in the order of 10 min, so that a deviation from set point will require 10 min and more for corrective action to become effective. A similar strategy has been to vary mill feed to keep just rejects constant. This again has a significant lag.

An in-depth study has shown that to optimize a circuit for performance and quality, it is the cement flows that must be stabilized. The total flow to the separator must be held constant so that the ratio of separator feed to separator air is constant. The separator rejects flow must be kept constant so that the ratio of rejects to fresh feed at the mill inlet is maintained at the optimum. This ensures an optimized material level in the mill and flowability of material through the mill. The fines flow will thus also be constant. This ensures that the fines to air ratio on the separator is invariant.

The efficiency of a grinding circuit is dependent on three key conditions:

- an optimum and constant level of material in the mill;
- constant air to material ratios for the separator material flows;

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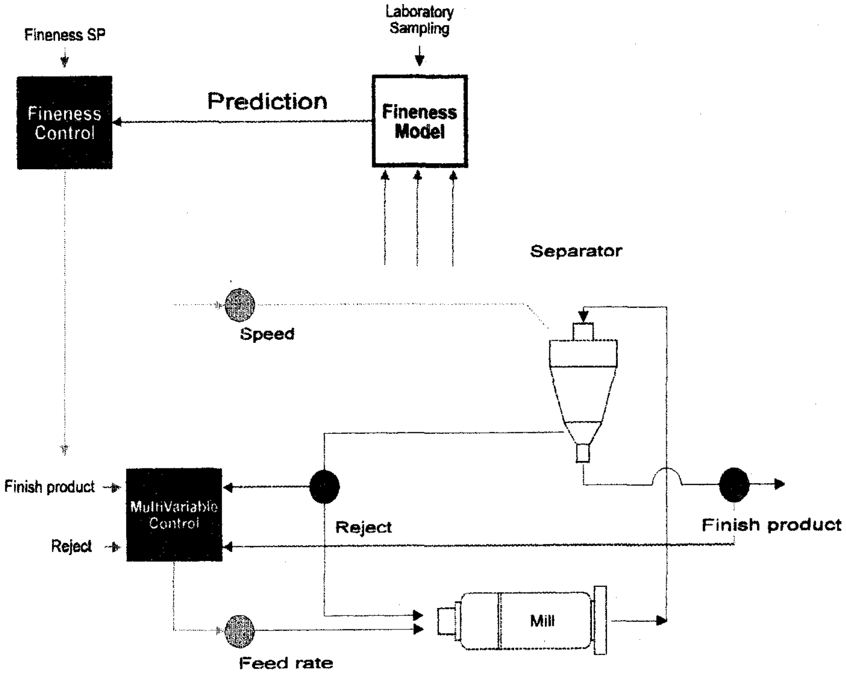

Fig. 1. An industrial application of multivariate linear quadratic control to a cement mill circuit.

- a constant and optimum ratio between fresh feed and rejects at the mill inlet.

Clearly, the requirements are thus that the separator rejects flow must be kept constant and the separator fines flow must be kept constant. This will ensure total separator feed, and thus the mill discharge itself is constant. As the goal is to control two flows, there needs to be two manipulated variables. Research has shown that the optimum strategy is to keep fines and rejects flows constant by varying the separator speed and mill fresh feed.

A very significant aspect of this control strategy is that it allows the fineness to be predicted. The implications of this are covered later.

Variations in the separator speed produce almost instantaneous changes in the fines and rejects flow rates. Changes in the fresh feed rate result in much slower changes in the circuit, but also result in changes to both separator fines flow rate and separator rejects flow rate. To ensure constant flows without significant deviations, manipulation of the separator speed in conjunction with the fresh feed rate is essential. A change in a single measured flow will require action by both manipulated variables.

There are many other factors influencing the performance and quality of the grinding circuit. Critical to the quality aspect is the separator venting air. The ratio of separator feed to separator air is important; changes will result in performance and quality variations. At this point it is considered that the separator venting air is constant.

Numerous tests were carried out to analyze a circuit's reaction. Two key results were obtained. First, it was shown that it is possible to make stochastic models of a grinding circuit. Using these mathematical models, specific circuit reactions can be simulated, and the interrelations between actions and reactions within the circuit can be studied. Second, it was shown that strong interrelations can be observed between the actions, separator speed and fresh material feed rate, and the reactions, the separator fines and rejects flow rates. Thus follows the observation that to effectively control the fines and rejects flow, the manipulated variables need to be the separator speed and the mill fresh feed.

III. METHODOLOGY

The methodology employed to achieve constant material flows is to vary the separator feed and the fresh feed to achieve these goals. Clearly, with two controlled variables and two manipulated variables, a single PID will not suffice. Neither will two PID's. A change in separator speed will result in changes in both rejects and fines flows (one increased and the other decreased), and similarly changes in the fresh feed rate will result a changes in both flows—in this case, both in the same direction.

Thorough investigation indicated that the optimum method was to employ a linear quadratic multivariable controller. Linear quadratic multivariable control theory is not new, but it's application to milling circuits is, and was successfully implemented to satisfy the desired requirements of constant flow, and ultimately fineness prediction.

The controller maintains the stability of the two flows by acting simultaneously on the separator speed and the mill fresh feed (see Fig. 2).

Of the alternative methodologies available such as fuzzy logic, expert systems, and others, none was more applicable to the implementation of the constant flow strategy with two controlled variables and two manipulated variables than the linear

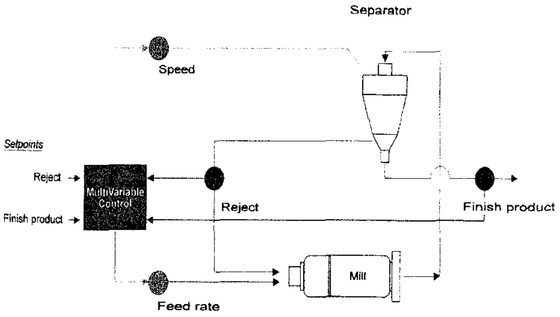

Fig. 2. The controller maintains the stability of the two flows by acting simultaneously on the separator speed and the mill fresh feed.

quadratic multivariable controller. This is an ideal application of multivariable controller theory: two controlled variables and two manipulated variables, with strong and predictable relationships between them, and where the interrelationship between them can be determined and modeled.

Consider the circuit operating under the influence of this control system. The set points are the rejects flow rate and the fines flow rate. The fines flow set point is chosen to give the required fineness, the rejects flow rate chosen to ensure adequate mill material loading and circulating load. The optimum value for these set points are found by testing, and will be dependent on many factors, some of which are the mill length to diameter ratio, the clinker grindability characteristics, the ball charge graduation and condition, and many others.

It must never be forgotten, however, that any control system operates within the limitations of the mechanical installation. The grinding is still done in the mill, the separation in the separator. The primary mechanical elements of the circuit need be in good shape for the circuit to operate successfully.

IV. IMPLEMENTATION

To implement the multivariable controller requires the following procedure.

1) The dynamics of the circuit are mathematically modeled.
2) A simulator based on the mathematical model describing the circuit dynamics is generated.
3) From this model the parameters for the multivariable controller are developed using analytical software.
4) The controller is tested in the simulator.
5) The controller is installed at the plant and tested on the actual circuit.

Clearly, prior and subsequent to installation, all instrumentation needs to be in good order and calibrated.

The stochastic models describing the circuit dynamics are generated by performing two step tests on the milling circuit. With the circuit running in a natural and steady state, the feed is reduced in a step-wise manner. The response of the flow of the separator fines and the separator rejects are recorded. In the second test, the separator speed is reduced in step. Again the separator fines and separator rejects are recorded.

The results of a feed step test are in Fig. 3. The feed is reduced from approximately 115 t/h to 80 t/h. Both the flow rate of the separator rejects and the separator fines are reduced, decaying slowly to a new equilibrium. At equilibrium, the separator fines flow rate will again be equal to the fresh feed rate. The separator rejects find their own value. The climb in the separator feed as the feed is cut is a result of poor speed stabilization on the separator control loop and is not a part of the test. Had the separator loop been properly stabilized, the separator speed would have been invariant with separator feed.

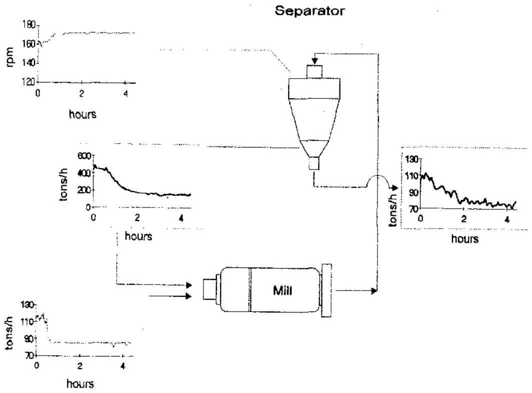

Fig. 3. Results of a speed step test.

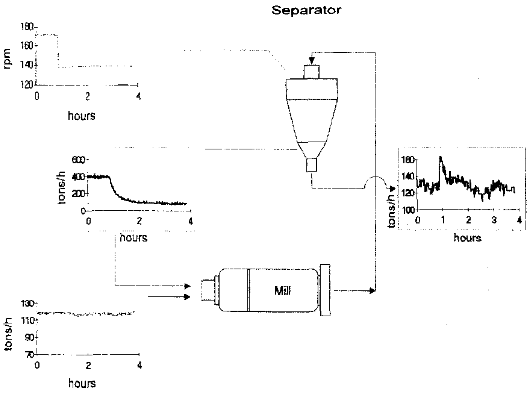

Fig. 4. Results of a separator speed step test.

The results of a separator speed step test are in Fig. 4. With the circuit running steadily, the separator speed is decreased stepwise. The fresh feed and other circuit parameters are held constant. Initially there is an increase in the amount of material leaving the circuit, but as the new equilibrium is approached, the amount of material leaving the circuit must decrease again, and after several oscillations, equal the amount of material entering the circuit. The rejects flow rate decreases and finds a new equilibrium.

It is interesting that all circuits show similar characteristics, and the general form of the mathematical model is the same in all cases. The step tests yield the specific constants required for the modeling of a particular installation.

For each cement type, if the fineness is significantly different between the types, new step tests need to be performed. Although the controller will control at set points away from the step test parameters, they may not be the optimum. After a model is developed for each cement quality (fineness), the multivariable controller parameters are calculated

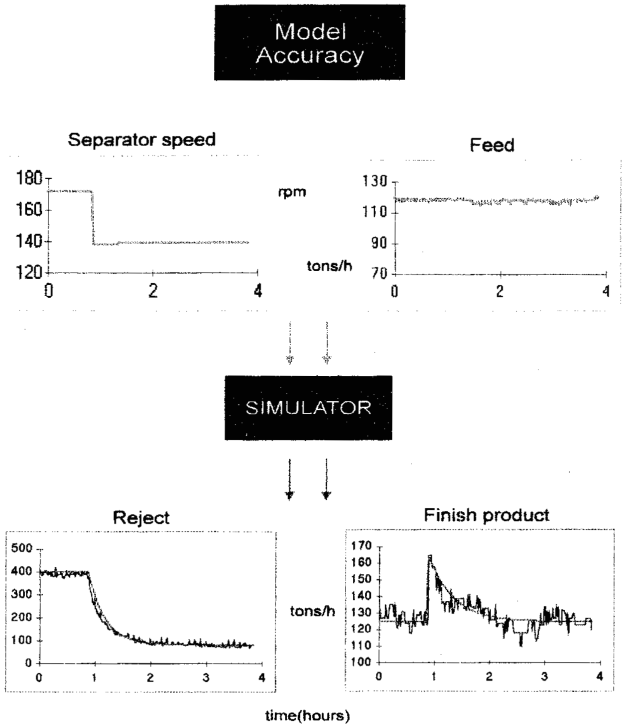

Fig. 5. The model predicted response of the circuit to the separator speed step.

for the various cement qualities. The controller parameters are generated from the mathematical model using analytical software. Cement qualities of similar fineness would use the same models, and hence the same multivariable parameters. Unlike PI controllers which may have just proportional and reset adjustments, multivariable controllers require a matrix of parameters, and the parameters are determined by computer analysis of the process dynamics, in this case, on the simulator developed from the step tests. Tuning by trial and error is not practical. The quality of the models are easily tested by comparing the model predicted step test results against those obtained in the actual step test.

On the graphs in Fig. 5, the smooth lines on the rejects and finished product plots against time are the model predicted response of the circuit to the separator speed step. The wavy lines are the actual measured response of the circuit.Any fine tuning can be done at this stage without interference to plant operation. In fact, once the step tests are complete, the model and controller generation are done off site. When the controller is operating well on the simulator, the system is installed on site.

For operation around the target fineness, the separator fines flow rate set point is changed to change product fineness. Reducing the separator fines flow rate set point will result in a lower mill through put and a finer product. Increasing the separator fines flow rate set point will increase the mill through put, resulting in a coarser product.

For different qualities, for which different step tests were done, and for which different models and controller parameters were generated, the operator switches to another cement type. With this selection, the appropriate controller is activated, together with the appropriate set points. The strategy of constant flows implemented with linear quadratic multivariable controllers, allows the prediction of the fineness of product from the circuit, and this enables one to move to the next level of control where the set point is product fineness rather than the fines and rejects flows.

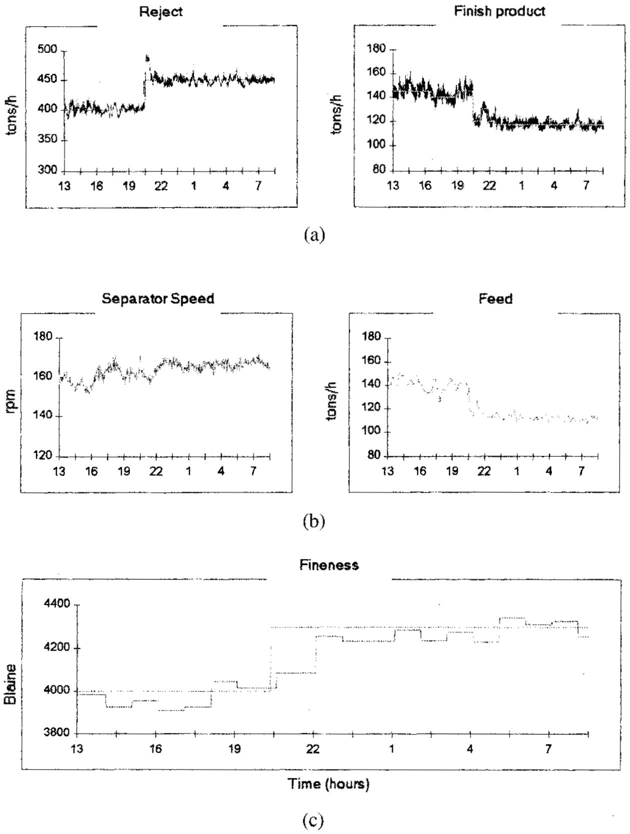

Fig. 6. The control system applied to an industrial circuit. (a) How the controlled flows follow the set point lines. (b) the actions taken by the control system on the separator speed and feed rate. (c) As the separator speed changes, the fineness stays very close to the target line.

V. RESULTS

Results from industrial installations have been consistent with expectations. Installations on several grinding circuits have confirmed the capability of the strategy to stabilize a circuit, even under severe perturbations, and the effectiveness of the methodology in implementing the strategy.

The graphs in Fig. 6(a)-(c) are of the control system applied to an industrial circuit. The circuit ran for 24 h and during this time produced two types of cement. The upper two graphs [Fig. 6(a)] show how the controlled flows follow the set point lines. The set point lines are the straighter lines. The set point for the rejects is 400 t/h for the first type of cement and 450 t/h for the second. The finish product set point is changed manually according to the measured fineness.

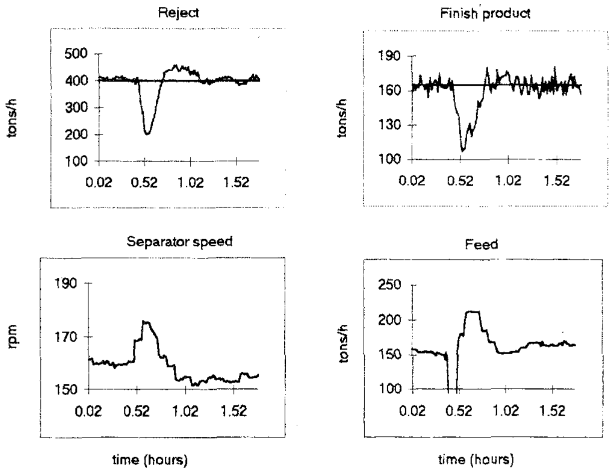

Fig. 7. The response resulting from a feed starvation.

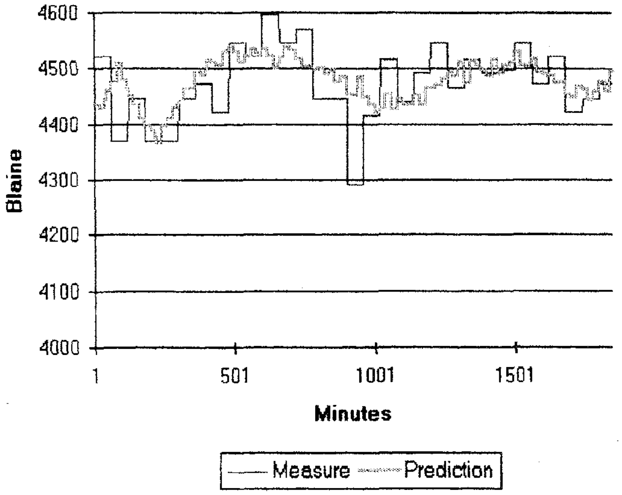

Fig. 8. Fineness.

The graphs in the middle [Fig. 6(b)] are the actions taken by the control system on the separator speed and feed rate. As the separator speed changes, fineness variations could be expected, but as seen on the lower graph [Fig. 6(c)], the fineness stays very close to the target line. The line with the single step from 4000 to 4300 at 20h30 is the blaine set point line. The other stepped line is the measured blaine line. This is without any form of fineness control. Only because both the fines and rejects flows are stabilized, are the fineness variations stabilized. Significant variations in blaine do not occur with separator speed changes under the constant flow strategy.

VI. RESPONSE TO PERTURBATIONS

In the case of circuit fluctuations, the control system acts appropriately and smoothly. The graphs below show the response resulting from a feed starvation. As the feed bin empties, the fresh feed to the mill is interrupted, but the rest of the circuit continues to operate. The mill continues to grind and material leaves the circuit as finished product. There is less and less material in the circuit. In this case, the finished product decreases by 60 t/h and the rejects drop to 200 t/h.

With the feed reestablished, the controller acts aggressively on the fresh feed and the separator speed to reestablish the finished product flow and the rejects flow. Aggressive action on separator speed in particular brings a fast response to the circuit. The rapid stabilization of the product flow ensures that major deviations of blaine from the target blaine do not occur. Trying to reestablish a circulating load by acting on the fresh feed only takes significantly longer than acting on the fresh feed and separator speed simultaneously, and significant blaine deviations can occur as the finished product flow rate falls below the set point.

VII. FINENESS PREDICTION

When the circuit is running with stabilized flows, it is possible to predict the fineness. Measured fineness is input into the system. This measured data is collected and used to construct a fineness prediction software module. This module will predict the fineness of the product produced for the values of the manipulated variables determined by the multivariable controller.

On the graph in Fig. 8, one sees a superimposed plot of the fineness prediction and the measured fineness. The measured values, the longer steps, is the analysis of a composite sample of product taken every hour. The line with the short steps is the fineness prediction. The circuit was running without any action being taken to try and control the blaine; the set point for the product flow rate, which would normally be manipulated to control the fineness, is not being changed.

The graphs show good correlation. An exception occurs just before 1000 min, when the measured value for the blaine deviates some 150 points below the predicted values. With no action taken, the actual and predicted values trended together again, indicating that the measured value was likely at fault, either due to sampling error or measurement error. Fineness prediction eliminates unnecessary changes often made to circuits when the blaine appears to be deviating away from it's goal. In many instances blaine changes are made unnecessarily, introducing instability into the circuit.

VIII. FINENESS CONTROL

With the fineness control engaged, the fineness becomes the control set point. The sketch in Fig. 9 illustrates how this is realized. The fineness control compares the fineness prediction to the fineness set point. The output from this is to the product flow set point. With the fineness control engaged, the product flow set point is lowered to increase the blaine, or increased to lower the blaine, these changes being near the fineness (quality) of the cement type that is selected.

The graph in Fig. 10 shows an 18-h production run with the fineness controller engaged. The error between the fineness predictor and the fineness set point determines the fines flow rate set point. On the upper curve, the stepped line is the product flow set point as asked for by the fineness control module, and the wavy line the measured flow rate. The lower

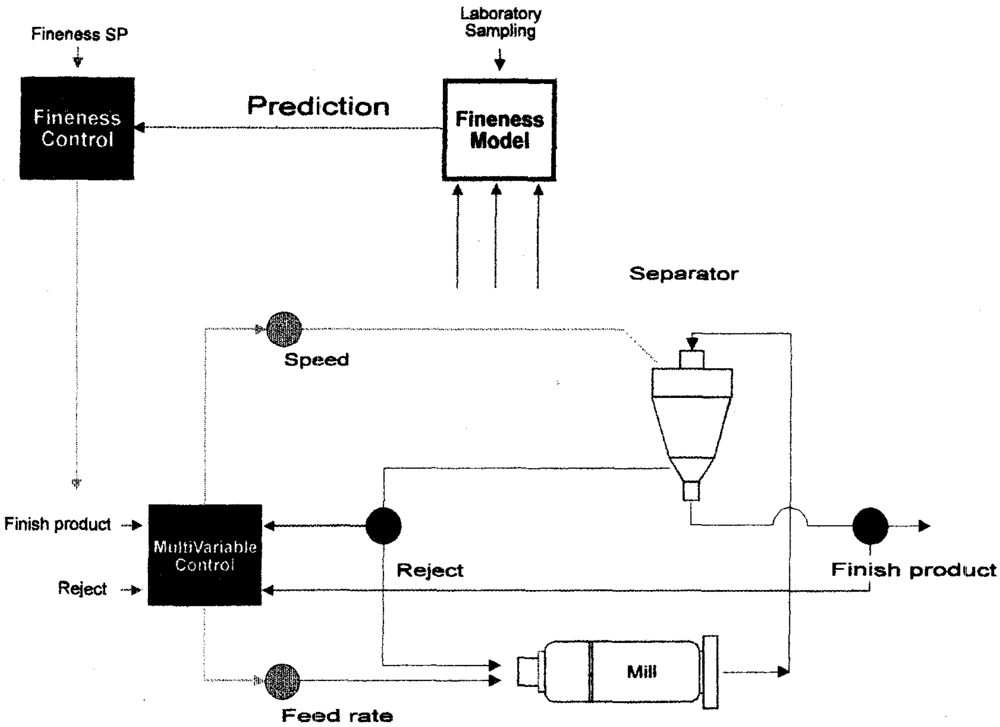

Fig. 9. The fineness control compares the fineness prediction to the fineness set point.

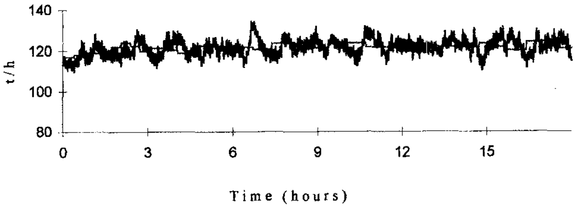

Fig. 10. Finished product flow rate.

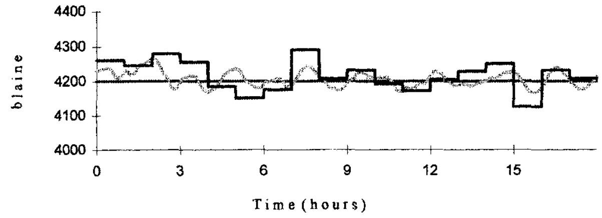

Fig. 11. Fineness.

curve is of measured blaine and predicted blaine, the measured blaine being the stepped line, and curved line the predicted blaine. Correlation is excellent.

With fineness control, product samples continue to be taken. The operator inputs the measured fineness into the system. A software module compares the average of the predicted values to the measured values. If a constant offset is observed, the fineness prediction module is adjusted accordingly. If the measured values are on either side of the predicted values, as is seen on the graph in Fig. 11, no action is taken by the offset module on the prediction module. This is in effect a constant updating of the fineness predictor modeling.

IX. HARDWARE

For the system to be applied, one requires a circuit consisting of the ball mill in closed circuit with a variable-speed (high-efficiency) separator. All product must be generated in the separator, i.e., derived from one source. Clearly fineness prediction will not be possible in any circuit were material is added to the product from a source other than the separator. Modern high-efficiency separator circuits are generally suitable.

The circuit would ideally require the following equipment (Fig. 12):

- command and measure of the mill fresh feed;
- measure of the separator rejects (tailings) flow rate;
- command and measure of the separator speed;
- command and measure of the air flow through the separator;
- measure of the mill absorbed power;
- measure of first compartment sound;
- measure of product flow rate.

At a minimum the separator speed must be controlled. The mill fresh feed, the product (fines) flow rate, the separator rejects flow rate, the separator speed and the separator air flow (or at least the separator fan absorbed power) are essential. Additional useful, but not essential information, is mill sound, mill absorbed power, pressure drop across the mill, mill outlet

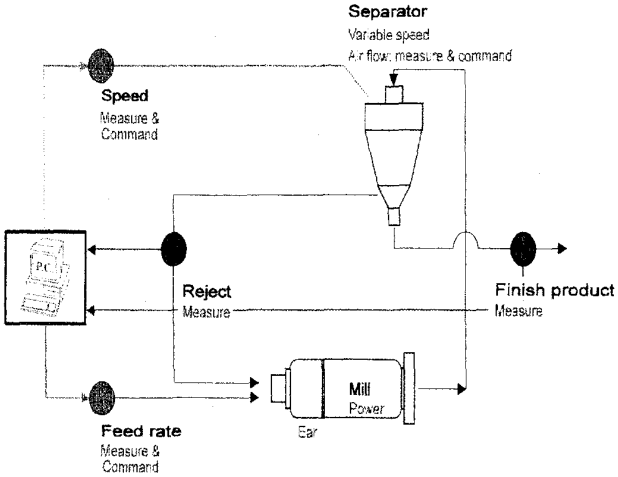

Fig. 12. Requirements.

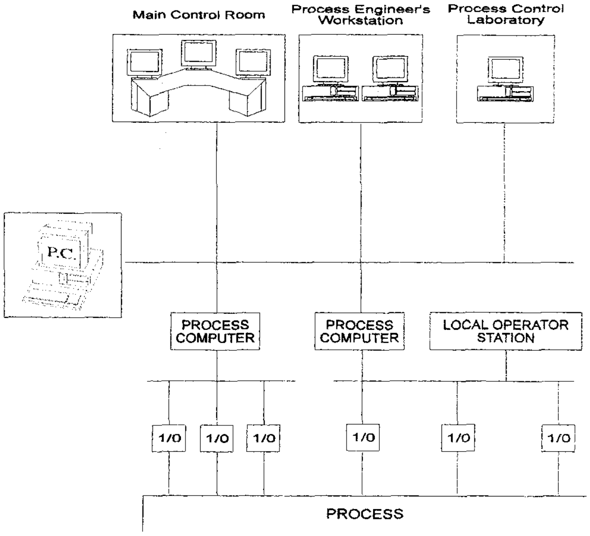

Fig. 13. Typical installation.

temperature, etc. Clearly, all mechanical systems need to be in good order.

The control system software itself operates on a regular PC. It can be interfaced with the existing control system. Supervisory software is commercially available with a variety of drivers, able to communicate with most commercially available PLC's etc. A typical installation may be as seen in Fig. 13.

In the case of there being no existing system, the 4–20-mA or 0–10-V signals can be brought directly to the PC via analogue to digital converters. These are freely available. It was because of the ability of the PC to interface with a diverse variety of communication protocols that led to its choice. With just a change in software driver the same basic system can be used in a variety of environments.

The PC minimum requirements are requirements are the following:

- a 486, 33-Mz 8-Mbyte RAM, and 100-Mbyte hard disc;
- an operating system DOS 5.0;
- Windows 3.1.

More powerful machines are more flexible, especially in terms of hard-disc storage. The system stores data for historical reference, and larger disc space means, of course, more history. Faster systems will facilitate quicker changes of graphic screen, etc.

X. LIMITATIONS

For any control system to operate well, the basic equipment needs to be in good order. No grinding is done in the separator. No grinding is done in the PC! If the mill fails to grind (material accumulating in the mill), the control will break down. The multivariable controller will respond to a fall in both fines and rejects by calling for more feed. Without some other intervention, material accumulation in the mill will eventually lead to back spilling.

Modules to accommodate these are integrated into the software as applicable to the particular installation. It is for this reason that additional information, such as first compartment sound, mill absorbed power, elevator power, etc., are useful, if not necessary. Using this information, the regular controller can be interrupted to accommodate breakdown within the grinding process itself.

The control system will attempt to get the optimum from the system, and shortcomings within the mechanical installation will quickly become apparent. A mill circuit with optimum equipment will be further optimized by the control system, but the control system will not be able to over come mechanical shortcomings within the equipment.

XI. CONCLUSION

The research program leading to the application of the multivariable controller to a grinding circuit was initiated by cement producers expressing the need to improve their grinding operations. The collaboration between a grinding research center, a cement manufacturer, and control system specialists instigated the development of a complete solution for the entire grinding circuit. The system is designed according to the specific circuit models, and is tailor-made and tuned for a particular circuit.

The system applies modern technologies, but remains practical in its application. The system ensures steady flows of material in the mill and separator and this improves the constancy of the finished product fineness. The system provides a smooth reliable control even in difficult conditions and during transitions from one quality to another The second level of control, the fineness control, ensures a consistent quality (fineness) of production.

Rising production costs and tighter requirements on quality require that control systems are able to address quality as well as productivity issues. Producing at higher-than-required blaines to negate fineness variations is an expensive alternative to producing consistent and predictable quality product.

Vincent Van Breusegem was born in Charleroi, Belgium, in 1960. He received the B.S.Eng. and the Ph.D. degrees, both from the Catholic University of Louvain, Louvain-la-Neuve, Belgium, in 1984 and 1987, respectively. From 1984 to 1993, he was with the Laboratoire d'Automatique, Dynamique et Analyse des systmes, as a Research Assistant. From 1991 to 1993, he was a Senior Research Assistant of the Belgian Fund for Scientific Research. Since September 1993, he has been with the Bureau Economique de la Province de Namur, a public economic development agency.

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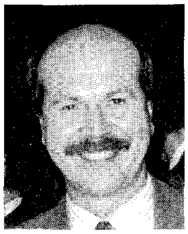
During 1987 and 1991, she worked on two industrial projects involving the optimization and regulation of a fed-batch bioreactor with application of adaptive nonlinear control and a cement grinding process with multivariable LQ control. She is currently a research fellow of the Universities of Birmingham and Newcastle-upon-Tyne in the U.K. Her research interests are in the control, identification and identifiability of nonlinear systems, especialy of biochemical systems.



George Bastin received the B.S.Eng. and Ph.D. degrees from the Catholic University of Louvain, Louvain-la-Neuve, Belgium.

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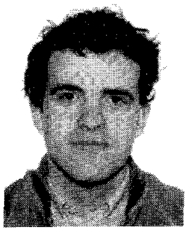
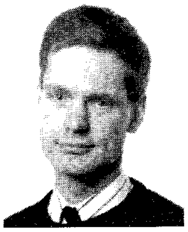


Vincent Werbrouck was born in Belgium in 1964. He obtained the B.S. degree in mechanical engineering from the Catholic University of Louvain, Louvain-la-Neuve, Belgium. He received the M.S. degree in automation from the Université des sciences et techniques du Languedoc, France, at the Laboratoire d'Automatique et de microélectronique de Montpellier in 1987.

He worked as a researcher at the Automation Laboratory of the Catholic University of Louvain, Louvain-la-Neuve, Belgium, during 1988, and in the Automation Laboratory of the Belgian Army during 1989. He is now Research and Development Manager at Slegten, a member of the Magotteaux Group, and he developed a control system for cement grinding installation.



Cédric de Pierpont received the B.S. degree in mining engineering from the Catholic University of Louvain, Louvain-la-Neuve, Belgium, in 1987.

He trained in Spain, in an open-cast coal mine for a few months, then he worked for Schlumberger,, a petroleum service company, in Taiwan. He also worked two years in an Owens Corning fiberglass factory to improve operators' work environments. In 1991, he joined Slegten, a member of the Magotteaux Group, to work on process control for the mining and cement industries.