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Control of Industrial Energy Systems: Mining Industry as a Case Study

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Abstract: Control of industrial energy systems is investigated in this study. In particular, common techniques used in establishing the control problems are summarized and analyzed. Due to the fact that controller design is usually based on mathematical modeling of the system to be controlled, popular methods used to model these systems mathematically are given first followed by that for controller design. The controller design is particularly classified into four levels, namely policy level, management level, system level and equipment level. This four-level control concept is elaborated in detail and a coal cleaning process of coal mining industry is studied as an illustrative example to demonstrate its applicability and usefulness to industrial systems. Controls at each level of the studied mining process are depicted and application of this four-level control to general industry process is then discussed.

Key words: Industrial energy systems; modeling techniques; four-level control; coal washing
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工业能源系统中的控制问题：以采矿业为例

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摘 要：对工业能源系统的控制问题进行了研究并对在该系统中常用的控制方法进行了总结和分析。由于控制器的设计通常是建立在系统建模的基础上的，我们首先对常用的工业能源系统建模方法进行了介绍。然后再对控制器的设计进行了探讨。特别地，我们将控制器的设计划分成了四层（决策层，管理层，系统层和设备层）并逐层进行了阐述和分析。然后，我们以洗煤过程为例对提出的四层控制概念进行了详细讨论来证明其有效性。最后，我们对提出的四层控制概念在一般工业能源系统中的应用进行了拓展讨论。

关键词：工业能源系统；建模方法；四层控制；洗煤过程

1 Introduction

Controllers for any system must be specifically designed according to the system dynamics. Modeling of the system is essential for most controller design tasks. Modern control system design techniques, especially the state-space based methods, are highly dependent on the mathematical model of the system to be controlled[1]. Therefore, modeling of the system is usually a prerequisite for controller design. A brief summary of popular techniques used to model industrial energy systems is given first.

Thereafter, the overall control problem that improves the system's performance in terms of reducing energy consumption and associated cost and maximizing system wide benefits is discussed and divided into four levels, namely policy level, management level, system level and equipment level. The controller at a specific level must address the problem specific to that level. It is formulated

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according to its specific objectives and the mathematical model of the system under investigation at that level. Policy level is the top level while equipment level is the lowest level control. From policy level to equipment level, the control tends to be more and more specific. Similarly, the scale of the control problem gets smaller and smaller from the top level to the bottom level. The effects of a lower level control usually can be seen much quicker than that of an upper level control. In addition, controls at these four levels affect each other. For instance, the policy level control affects the formulation and constraints of management level control, which again affects system level control. The system level control then determines equipment level control. This means that the four-level control exhibit a certain chain reaction. Missing control at any level will result in drastic performance depredation of the whole control system. This four-level control concept is discussed in full detail and demonstrated with an example in the main part of this paper.

In the following sections, common modeling techniques of industrial energy systems from control system perspective are summarized in Section 2. The four-level control concept is discussed in Section 3 followed by an in detail study of mining systems in two sections, Section 4 and Section 5, respectively. Some concluding remarks are given in Section 6.

2 Industrial Energy Systems from Control Perspective

Before control system approach can be applied to solve practical problems for industrial systems, a mathematical model of the system to be controlled must be obtained. This is usually done by modeling of the physical system, which is essential to most of controller design techniques, especially modern control methods. Although controller design methods that do not require a detailed model of the system exist, it has been concluded that performance of these methods can be significantly improved if a proper model of the system to be controlled is known. For many modern control techniques, such as state-space based ones, the model is a prerequisite for controller design. Therefore, process modeling is the first challenge facing control engineers. The most commonly used methods to build up such a mathematical model for industrial energy systems are discussed here.

Broadly speaking, there are two types of models used in practice to mathematically describe a physical system. The first one is first principle models and the other is data driven models.

2.1 First principle models

The most commonly used models are first principles models. These models are usually based on underlying physics of the system under consideration. For industrial systems, material balance and energy balance equations are two of the fundamental principles of building up such models. Material balance is used to model the transition of materials and energy balance is used to capture the dynamics of energy (such as thermal energy, electrical energy, chemical energy, etc.) transfer within a certain process. In most cases, the process undergoes not only one but both material and energy transitions. Therefore, both material balance and energy balance equations are required to characterize such process. Chemical reactions involving temperature changes are good examples of such processes.

Mathematically, mass balance equation for a single system component can be written as [2]

$$M_i(t+\Delta t)=M_i(t)+M_i^{\text{in}}(t)-M_i^{\text{out}}(t) \tag{1}$$

where $M_i(t)$ and $M_i(t+\Delta t)$ are the masses of the i-th component at time t and $t+\Delta t$, respectively; while $M_i^{\text{in}}(t)$ (or $M_i^{\text{out}}(t)$) is the amount of mass entered into (or left) component i during the time period $(t,t+\Delta t)$. The mass $M_i(t_0)$ at the initial time t_0 is often given.

Energy balance can be established similarly as the mass balance equation (1) either at the component level or the overall system level. That is, the two types of energy balance equations can be briefly written as the following [2]

$$\begin{aligned}E(t+\Delta t)&=E(t)+E^{\text{in}}(t)-E^{\text{out}}(t)-E^{\text{loss}}(t)\\ E_i(t+\Delta t)&=E_i(t)+E_i^{\text{in}}(t)-E_i^{\text{out}}(t)-E_i^{\text{loss}}(t)\end{aligned} \tag{2}$$

where E refers to energy (e.g., kinetic energy, potential energy), $E(t)$ or $E_i(t)$ represent the energy stored in the whole system or component i at time t, the superscripts in, out, loss represent the energy flows into, useful energy flows out from, or energy losses at the whole system or system component during the time period $(t, t+\Delta t)$.

Further, the material (energy) inflows to the i-th system or system component are usually a function of the operating status and the material (energy) outflows of the $(i-1)$-th system or system component, i.e.

$$\begin{aligned} M_i^{\text{in}}(t) &= f(u_{i-1}(t), M_{i-1}^{\text{out}}(t)) \\ E_i^{\text{in}}(t) &= f(u_{i-1}(t), E_{i-1}^{\text{out}}(t)) \end{aligned} \tag{3}$$

where $u_i(t)$ denotes the operating status of the i-th component or system. This could be a binary variable representing on/off status of the component or continues variable denoting the operating speed, temperature, etc. of the component. The model of pumping system developed in [3] and model of power dispatching problems proposed in [4] are examples of material and energy balance models. More details on this type of models from [3] and [5] will be discussed later in this study.

2.2 Data driven models

In some cases, establishing a mathematical model from first principles is very expensive technically and economically. Even if the model can be established, it is sometimes not suitable for control applications, such as computational fluid dynamics models for industrial cyclones, which are very time consuming to solve [6]. It is because of these two reasons data driven models are important to control engineers.

Data driven models are widely used in industrial control systems. These models are based on a prior knowledge about the system, according to which the structure and the parameters of the model are determined. In other words, data driven models are established through the following procedure. The initial phase is collecting and systematic treatment of available knowledge [7]. After that, a priori knowledge about the given system can be obtained through the analysis, comprising of finding all possible connections to other systems and physical laws, preceding the modeling [7]. After that a prior is used to determine the structure and parameters of the model. Lastly, experimental data is gathered to train the model built to estimate model coefficients. Neural networks, black box and grey models are some examples of this type of models.

Mathematically, this type of model can be written as

$$x = f(x, u), \tag{4}$$

where x is the key variables or states of the system, u is input to the system, and $f(\cdot)$ is a function represents the dynamics of the system under investigation.

In summary, both the first principle models and data driven models govern the dynamics of evolution of the internal system states under external excitation. From here on, equation (4) will be used as the generalized system model in this paper.

2.3 Constraints

Identifying constraints of the industrial systems is an essential part of the modeling process. These constraints outline conditions under which the model of the system remains valid. This is of particular importance for industrial systems, whose operation is usually subject to physical and operational limits.

Common constraints encountered in the operation of industrial systems can be classified into two categories, namely physical constraints and operational constraints. Physical constraints refer to those defined by physical laws, such as physical limits, energy conservation law, etc., while operational constraints refer to those introduced by operational requirements and/or rate of change of certain variables. Examples of physical constraints include the capacity limit of a storage component, energy conversion efficiency is always less than or equation to 1, the position of a linear valve can only vary within 0 %~100 %, etc. Examples of operation constraints include the rate of change of temperature at a certain component cannot be too fast in order to maintain safe operation of that component, a part to be manufactured must go through a certain sequence of machines in batch processes, etc.

All these constraints can be modeled either by equality or inequality constraints

$$\begin{aligned} g(x, u) &\le 0 \\ h(x, u) &= 0 \end{aligned} \tag{5}$$

where $g(\cdot)$ and $h(\cdot)$ are functions representing the inequality and equality constraints, respectively.

3 Application of Control Methods

Control of an industrial energy system usually aims to improve the system’s performance, in terms of production efficiency, social economic indicators, and energy consumption [8]. The general control problem can be represented by the following formulation

minimize

$$J(x,u) = J^E(x,u) + J^C(x,u) - J^B(x,u), \qquad (6)$$

subject to

$$f(x,u) = 0$$
$$g(x,u) \le 0$$
$$h(x,u) = 0$$

where $J^E(x, u)$, $J^C(x, u)$ and $J^B(x, u)$ denote energy consumption, operating cost and benefits derived from the system to be controlled, respectively. It is noticed that the model of the system comes into this formulation as an equality constraint. This is essential as it defines the dynamic evolving of the states of the system.

For control of industrial energy systems, this formulation can be termed into four levels, equipment level, system level, management level and policy level. Control at each level shares the same structure of formulation given in (6) and forms a sub-problem of the overall control problem.

Equipment is the smallest unit of any industrial systems. Control of equipment is the lowest level control. At equipment level, the objective of a control system is to minimize the deviation between desired and actual performance of the equipment by either direct manipulation of their components or by controlling of devices attached to them (usually referred to as actuators by control engineers) taking into account the equipment's operation dynamics and constraints. That is, the control input of equipment level control is usually the action of actuators connected either directly or indirectly to the equipment to be controlled. The primary goal of equipment level control is to realize the control inputs of system level control.

Control of industrial systems at system level refers to operation coordination of different system components, equipment, and/or processes in an optimal manner aiming at maximizing system wide benefits. This includes matching, sizing, scheduling and coordination of different subsystems. System level control addresses this problem by means of optimizing the desired performance of the equipment. Therefore, control input at system level is usually the optimal operating schedule, the optimal size of different system components, and desired actions of an equipment which are to be achieved by the equipment level control. Performance indicators for this level of control include energy consumption, operating cost, economic benefits, etc. Scheduling and speed matching between conveyor belts and material loading rate is one of system level control examples.

Whereas equipment and system level controls make use of what is currently available to the system, management level control decides when and in what manner to replace existing system components with better counterparts and/or to repair and service the existing components to restore them to a better performance level. Management level control is usually used by decision makers to identify possible investment in new systems and/or optimal maintenance plan for existing systems in order to obtain better performance, which could be higher revenue, less emission, etc. The scale of management level is usually longer than that of system level and equipment level control. Control on this level results in performance improvements on existing equipment and the controllers on both equipment and system levels. This is done by investing in more efficient facilities and controllers and/or proper maintenance of existing facilities to restore them to a better performance level in view of performance degradation over time. Retrofitting and maintenance of equipment and systems, where a decision must be made according to resultant benefits and investment cost, is a typical management level control problem [9]. Optimal meter planning for a sampling project over several years considering sampling precision and cost effectiveness is another example of management level control [10].

Both system level and management level control depend on policy level control, which is the top level control. At the policy level, the controllers aim to maximize social welfare or benefits of operating different system components and/or systems. The control input is usually policies, mandates, and regulations etc. that stimulate both customers and producers to operate in an optimal manner. The scale of control at this level is much larger than controls at the lower levels. Performance indicator considered at the policy level is a lumped social benefit that includes both benefits of customers and producers. For example, real-time-pricing of electricity is a policy level control that tries to maximize the benefits of electricity consumers and generation companies taking into account of social environmental indicators such as greenhouse gas emission and efficient utilization of non-renewable energy resources. Control at this level can be further classified into two sub-categories: internal policy control and external policy control. Internal policy control refers to policy regulations that originated within the entity that owns the system to be controlled and external policy control refers to policy regulations that originated from the outside of the entity.

The management and system level controls depend largely on policy level control. It can be stated that control at the policy level is a determinant of the other three controls at the lower levels.

In summary, controls at the four levels define the controls required for an industrial system from the lowest level to the top level. The control at the higher level directly affects the controls at lower levels. For instance, the policy level control affects the decision making process, which belongs to management level control, whose decision will affect the system level control and the equipment level control. This exhibits a chain reaction property.

It is interesting to notice that the effects of controllers at lower levels can be seen much faster than that of the higher level controls. For instance, the results of equipment level control can be seen immediately once implemented while the effect of a policy level control usually takes years to become apparent.

Nevertheless, for any industrial systems, an overall performance improvement can only be achieved by the combined efforts of all four-level controls. Missing proper control at any level will lead to performance deterioration due to the chain reaction effect. At the micro scale, malfunction of lower level control will results in more server damages to the system than higher level controls while the inverse is true at the macro scale.

Moreover, the control problem formulated at each level depends highly on the system model at that level. Without the required model, the control problem cannot be formulated. Therefore, the following steps outline the procedure for formulating control problem of industrial systems and reveal the importance of modeling process in the controller design:

① Mathematical modeling of the dynamics of the system to be controlled, and identifying physical and operational constraints; ② Formulate the control problem by choosing proper performance indicators and therefore an objective function; and ③ Choose a suitable control method to solve the control problem formulated.

4 Mining Industry

The mining industry is used in this study as a representative example of industrial systems because it involves many processes that exhibit essential properties that are similar to other industrial systems. Specifically, mineral processing systems of mines are covered here. Typical processes involved in mineral processing can be depicted by Fig. 1.

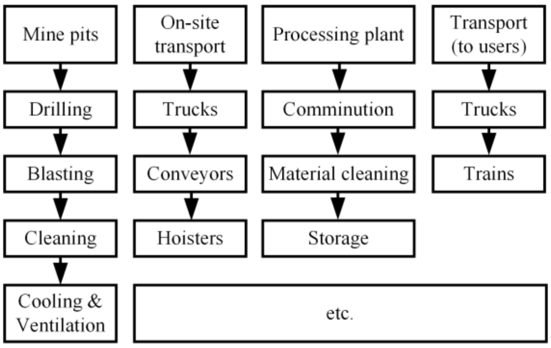

Fig. 1 Typical processed involved in mineral processing

图 1 典型选矿过程

Briefly speaking, the main processes occur at four main stages. In the first stage, mine ore is extracted from the earth by means of drilling and explosion followed by space cleaning which moves the mined ore away from the explosion site. At this stage, auxiliary processes such as cooling and ventilation are of essential importance to ensure a safe working condition for both machines and workers. The second stage is on-site material transport. The materials extracted from ore pits are transported to the processing plant for comminution and cleaning in order to get rid of undesirable impurities and obtain fine products subsequently. The main transporting methods used in this stage include hoisters, conveyor belts, truck-shovel systems, etc. After being transported to the processing plant, the materials go through the third stage, where the materials get ground to smaller particles and cleaned to remove impurities. Transport of materials from different processing machines, such as grinders and cleaning devices, is also needed at this stage. Finally, the processed materials are stored in proper stockpiles for transporting to users by trucks, trains, etc. In summary, excavation, material transport, material handling and processing, auxiliary cooling and ventilation are the main processes of a typical mine.

5 Four-level Control of a Coal Washing Circuit: A Case Study

In the following context, control of a coal washing process will be studied as a case study to demonstrate the four-level control scheme presented in Section 3.

Any of the processes involved in mining can be seen as a system for which the four-level control is essential. In this subsection, a coal washing process, which belongs to a process that runs in the processing plant, is used as a case study. In particular, the commonly used dense medium cyclone(DMC) cleaning process is investigated. The process diagram is shown in Fig. 2.

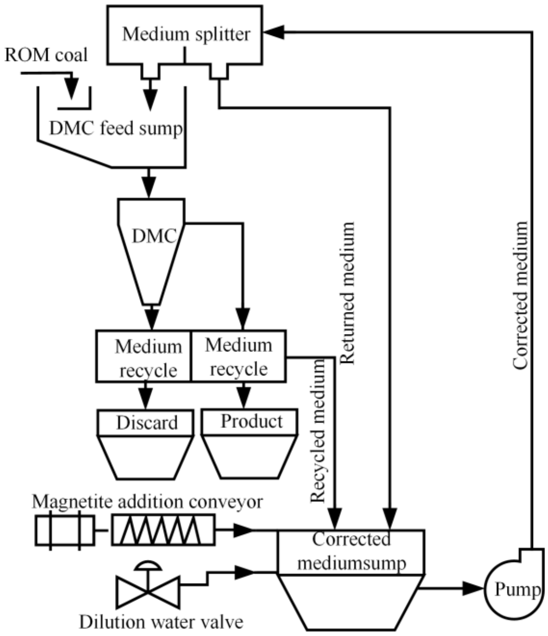

Fig. 2 Diagram of DMC coal washing circuit

图2 重介质洗煤过程示意图

In this process, run-of-mine (ROM) coal is beneficiated by the DMC in order to remove impurities such as sulfur, moisture, and volatile. For this purpose, ROM coal is mixed with a specially formulated medium solution, whose density can be adjusted by its magnetite and water contents. The mixture is then sent to the cleaning cyclone which is a density based separating equipment. Inside the DMC, the lighter carbon content of the ROM coal floats and exit at the top of the cyclone while the heavier impurities sink and exit at the bottom. The density of the dense medium is the determinant factor of the separation efficiency of the process. In practice, the density of the medium is controlled by varying the amount of magnetite and dilution water added to the corrected medium sump. It is also noticed from Fig. 2 that the medium solution is pumped from the bottom of the plant to a medium splitter, where part of the medium with correct density enters the separation process while the remaining part is returned to the corrected medium sump.

How the four-level control can be effectively applied to this process is detailed in the following subsections.

5.1 Policy Level Control

At the policy level, there are two controls, one from external and the other from the mine itself. For the process under consideration, external policy controls include carbon tax and demand response programs which are external policies that promote energy efficient and environmentally friendly operation of the processes. To be exact, carbon tax penalizes the mine for its greenhouse gas emissions which in turn forces the mine to reduce its emission and the demand response programs encourage the mine to use electricity from the utility in an optimal manner that not only results in cost savings for the mine but also a positive social impact.

Internal policy level control is also introduced to improve the performance of the processes in terms of energy efficiency, environmental impacts and economic benefits. Implementation of energy efficiency specifications that regulates procurement of new equipment is one of the internal policy controls. For example, purchase of new motors and pumps whose energy efficiency is lower than IE2 level is prohibited in one of such South African mines, which ultimately reduces energy consumption, carbon emission and energy cost of the process.

5.2 Management Level Control

Maintenance plan of the pumps used, the decision on whether to introduce measurement device to monitor the fine product quality, and decision on whether to install extra facilities to improve the energy efficiency of this process are typical problems to be addressed by management level control. Investigation on the possibility of introducing pump-storage system (PSS) to this process to improve energy efficiency is discussed here as an illustrating example [3].

It was noticed that part of the medium with correct density pumped to the DMC module is directed to flow back to the corrected medium sump without entering the separation process. This leads to energy wastes due to over pumping. It is straightforward to reduce the amount of medium pumped up to eliminate this waste. However, this is very difficult to implement as the plant manager does not want to risk the process efficiency because insufficient medium at the DMC will result in a drastic quality drop of the yield of the DMC module. Because of this, a PSS is proposed to create an additional medium circulation loop aiming at reducing energy consumption of the process. One of the PSS options presented in [3] is shown in Fig. 3, where the addition of a secondary medium sump and a pump is clearly shown. In particular, it can be seen that the differential head of the added pump *h* is much shorter than that of the existing pump *H*.

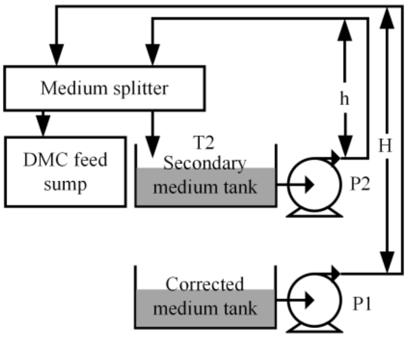

Fig. 3 Diagram PSS Option 1 from [3]

图 3 第一种 PSS 结构示意图

The purpose of management level control is to investigate the financial and economic feasibility of the proposed PSS scheme and make a final decision on whether to implement this PSS or not. This problem is formulated into the following management level control problem: minimize energy cost subject to budget limit and the maximum acceptable payback period in [3].

Solution to the problem formulated in [3] is then used to investigate the economic performance of the PSS scheme. In particular, two options of PSS are proposed and life cycle analysis of them is conducted. Results of this analysis are shown in Tab. 1, in which CC, OC, MC and SV refers to capital cost, operating cost, maintenance cost and salvage value, respectively. Option 1 and Option 2 refers to the two PSS options proposed in [3] (Option 1 is shown in Fig. 3). According to results shown in Tab. 1, including accumulative cost savings throughout the project’s lifetime and payback period of the investment, a management level decision can be made on investment in the PSS options.

Tab. 1 Summary of 10-year LCC analysis results (Rand)

表 1 10 年周期成本分析结果（南特）

	Existing	Option 1	Option 2
CC	2 250 000	24 412 275	26 262 483
OC	372 109 617	179 701 589	177 777 562
MC	16 590 331	36 812 065	41 359 556
SV	847	9 191	9 888
Accumulated saving		150 032 364	145 559 388
Payback period		2.68 years	3.30 years

Another example of the management level control is the maintenance of the pumps which determines when to maintenance the slurry pump used to pump the medium up from the bottom of the process. This maintenance control problem can be formulated as: minimize maintenance cost and maximize benefits derived from the maintenance subject to the budget limit with the control being the maintenance plan, which determines when and to what extent the equipment should be repaired/replaced.

5.3 System Level Control

To improve energy efficiency and especially fine coal quality of the coal washing process, a system level control is essential. Control at this level looks at the performance indicators of the system while considering external factors such as operating costs and the control inputs of policy and management level controls. In this study, let’s assume that due to the outcome of policy level control, the equipment used in the process adheres to external and internal policy regulations and due to the management level control, a PSS scheme is implemented.

The PSS adds one additional medium tank at the height of h to collect the medium returned by the splitter and one additional pump is used there to pump this medium up to the splitter such that energy consumption of the DMC circuit can be reduced.

The control input at this level is to determine the profile of the density of the medium used to ensure fine coal quality from the output of the circuit. This control input is also to be used by the equipment level control as the reference to manipulate the medium formulating devices. This problem is initially investigated in [5].

A controller is designed to improve the cyclone’s separation efficiency and energy consumption and associated cost without considering PSS in [5]. The controller presented therein is slightly modified to incorporate the PSS scheme in the following context.

The control general problem formulated in (6) is solved with

$$\begin{aligned} J_s^B(x_s,u_s) &= \int_0^T (x_C - x_r)^2 \mathrm{d}t \\ J_s^E(x_s,u_s) &= \int_0^T \left(\frac{u_s QgH}{1000\eta_m^1\eta_p^1} + \frac{u_s rQgh}{1000\eta_m^2\eta_p^2} \right) \mathrm{d}t \qquad (7) \\ J_s^C(x_s,u_s) &= pJ_e^E(x_s,u_s) \end{aligned}$$

where x_s is a vector containing the percentages of different components in the fine coal and discard from the output of the cyclone and u_s is the control variable representing density of the medium supplied to the DMC. Q is the flow rate of the medium, r is the percentage of medium returned from the medium splitter, g is gravitational acceleration, H is the height of the cyclone module, η_m and η_p are the efficiency of motor and pump, respectively. The superscripts 1 and 2 denote the efficiencies of the primary pump situated at the corrected medium sump and the secondary pump added by the PSS. x_C and x_r are, respectively, the actual carbon content in the fine coal from the output of the cyclone and the desired one. $J_e^B(x_s,u_s)$ in this problem denotes the deviation between desired and actual coal quality obtained, therefore the separation efficiency (benefits). $J_e^E(x_s,u_s)$ here stands for energy consumption of the pumps used to supply medium to the cyclone. For simplicity, flat rate tariff is assumed; therefore, energy cost is defined as the product of price of electricity p and energy consumed $J_e^E(x_s,u_s)$.

Using mass balance relationship, the material flows in the dense medium cyclone process can be modeled as $\dot{x}_s = f(x_s,u_s)$ (for detailed model, refer to [5]).

This model can be discretized as

$$x_s(k+1) = f(x_s(k),u_s(k)) \qquad (8)$$

where k denotes the k-th sampling instant.

In the cyclone coal cleaning process, physical constraints include the percentages of components in a mix cannot exceed the range [0 %, 100 %] and the density of the medium is also limited within $[\rho^{\min},\rho^{\max}]$. Operational constraint states that the rate of change of the medium density is confined by the $\dot{\rho}^{\max}$.

With the discretized model (8) and aforementioned constraints, a model predictive controller can be designed to regulate the density of the medium in order to improve the performance of the cyclone cleaning process.

Results of this control give the reference profile of medium density over a period of time as shown in Fig. 4, in which the dashed red line in the first subplot is the medium density profile obtained and the $x_{o,C}$ and $x_{o,ash}$, represent the percentage of carbon and ash contents in the yield, respectively and $x_{u,C}$ is the percentage of carbon content in the discard of the DMC circuit. These indicators depict the separation efficiency and yield quality of the DMC circuit.

In the case shown in Fig. 4, it can be observed that the yield quality is good because the carbon content is kept to the desired level throughout the control interval.

The medium density profile given in Fig. 4 is then to be realized by an equipment level controller.

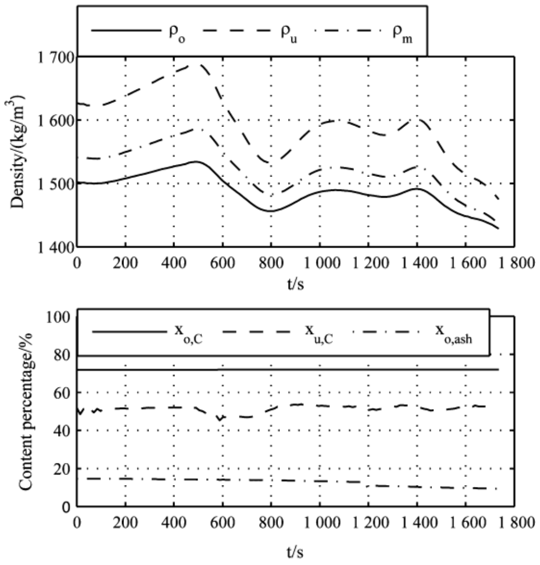

Fig. 4 System level control results

图 4 系统层控制结果

5.4 Equipment Level Control

The medium density profile obtained by the system level control must be achieved by the equipment level control which directly manipulates the medium formulating devices–one water addition valve and one magnetite addition conveyor. This control problem is explored in [11].

The medium flow in the DMC circuit is modeled by mass balance equations which can be eventually transformed into the following model [11]:

$$\dot{x}_e = f_e(x_e, u_e) \tag{9}$$

where x_e and u_e are the state variable and the control variable for the equipment level control problem, respectively. In specific, the control input u_e is a two row vector with each of its element representing the valve position of water addition valve and speed of the motor driving the magnetite addition conveyor, respectively.

This model is further linearized to be

$$\begin{aligned} \dot{x}_e &= Ax_e + Bu_e \\ y_e &= Cx_e \end{aligned} \tag{10}$$

where y_e is the density of the medium formulated in the corrected medium sump. For details of this model, please refer to [11].

After the mathematical model of the system level process is obtained, a controller is designed using model predictive control method with the following stage cost function and constraints.

Cost function takes into consideration of two indicators. The first one represents the tracking performance of the actual medium density reached by the actuators with respect to the optimized medium density set by the system level control. The second one is about the control effort required from the actuators. Therefore, the following stage cost function can be employed:

$$J_e = (y_e - u_s)^{\mathrm{T}} Q (y_e - u_s) + u_e^{\mathrm{T}} R u_e \tag{11}$$

where Q and R are weighting factors.

Constrains of this control problem consist of both physical and operational constraints. Firstly, the densities of different slurries are bounded by their physical properties. Secondly, the volume of medium in the corrected medium sump is limited by its capacity. Thirdly, from the operational point of view, the rates of change of densities are limited. Part of these constraints can be formulated as the constraint on state variable of the system as follows

$$x_e^{\min} \le x_e \le x_e^{\max} \tag{12}$$

where $x_e^{\min}$ and $x_e^{\max}$ are the lower and upper bounds.

Remaining parts of the constraints are on the magnitude and rate of change of control variables:

$$\begin{aligned} u_e^{\min} \le u_e \le u_e^{\max} \\ \dot{u}_e^{\min} \le \dot{u}_e \le \dot{u}_e^{\max} \end{aligned} \tag{13}$$

where $u_e^{\min}$ and $u_e^{\max}$ are the lower and upper bounds of the control variables. $\dot{u}_e^{\min}$ and $\dot{u}_e^{\max}$ the lower and upper limits on the rate of change of the control variables.

Implementing this controller using model predictive control method, the results achieved and the corresponding control actions when tracking an arbitrary sinusoid medium density profile are presented in Fig. 5 and Fig. 6, respectively [11].

In Fig. 5, the effectiveness of the controller to track a set medium density profile is demonstrated. It can be seen that the actual density tracks the set profile quite well.

Fig. 6 shows the speed of the motor driving the conveyor and the valve position. These two figures reveal two points. Firstly, the control is effective. Secondly, the function and objective of the equipment level control are very well illustrated.

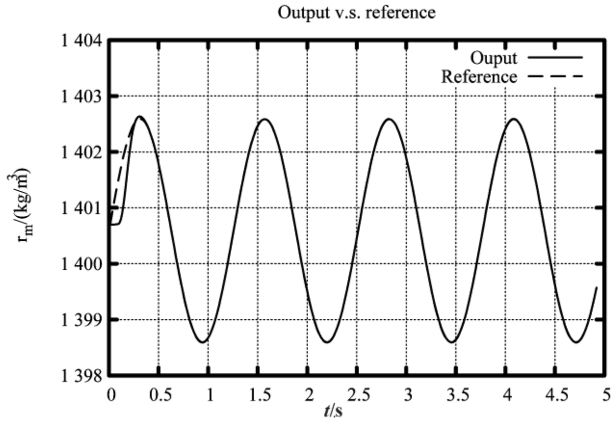

Fig. 5 Results of equipment level control5

图 5 设备层控制结果

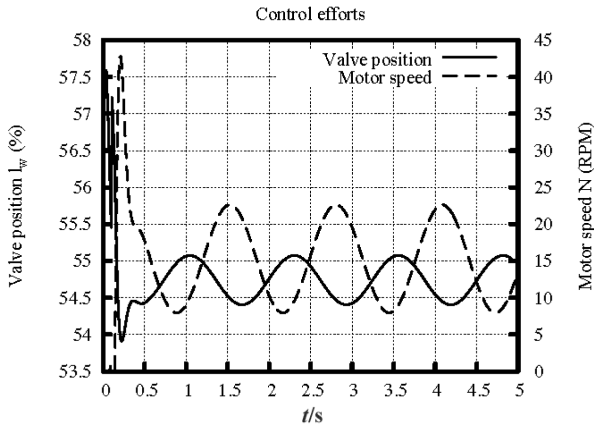

Fig. 6 Actuator actions of equipment level control

图 6 设备层控制的执行器动作

5.5 Extension to general industrial systems

Any process of the mineral processing system can be analyzed and controlled using the four-level control approach. So does any other industrial process.

Another example to demonstrate the applicability of the four-level control approach to industrial systems is the control of operation of conveyor belts in the mining systems: Policy level control for this system includes external policy on carbon emission and internal policy on throughput of the conveyors and energy efficiency on different conveyor components; management level control include making decision on investment in multiple drive conveyors and maintenance plan of the conveyor components; system level control includes optimizing operating schedule of the conveyors considering time-of-use electricity tariff and coordinating operation of different system components; equipment level control manipulates the switches installed on the conveyors and/or changes the speeds of the conveyors by means of variable speed drive if applicable. For a general industrial system, the above discussed four-level control approach can be applied in a similar manner.

6 Conclusion

This paper presents a four-level control approach to improve the performance of industrial energy systems. Common techniques to model the system to be controlled are discussed first followed by application of control system methods. The application of control system method is then categorized into four levels, namely equipment level, system level, management level and policy level. Control problems at each level are discussed, which are then followed by a case study from the mining industry. One process in the given mining system is used to demonstrate the applicability of the four-level control. After that, it is concluded that the four-level control can be applied to any industrial systems in a similar manner.

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