On-line Condition and Safety Monitoring of Pulverised Coal Mills
Using a Model Based Pattern Recognition Technique

The Final Report for BCURA Project B85A
(Period of Contract: 01/10/06 to 31/03/09)

University Project Manager:
Dr Jihong Wang

Research team:
Dr Jianlin Wei – Research Fellow
Mr Paschalis Zachariades – PhD Student
Mr. Shen Guo – Part-time Junior Research Assistant

Contact details:
School of Electronic, Electrical and Computer Engineering,
University of Birmingham, Edgbaston, Birmingham B15 2TT
Tel: 0121 4143518, Fax: 0121 4144291
E-mail: j.h.wang@bham.ac.uk

Industrial Supervisor:
Mr Dave Williamson
EDF Energy, Energy Branch, Cottam Power Station
Tel: 01522 894074, Fax: 01522 894001
E-mail: Dave.Williamson@edfenergy.com

Assisted by: Mr Mike Garwood
E.ON Engineering
Technology Centre
Tel: 02476 192713
E-mail: mike.garwood@eon-engineering.com
Web: www.eon-engineering.com
EXECUTIVE SUMMARY

Around 40% of electricity in the UK is currently generated by coal-fired power stations. Coal-fired power stations nowadays are required to operate more flexibly with more varied coal specifications and regularly use coal with higher volatile contents and biomass materials; this can increase the risks of pressurisation or fires in milling plants. The power stations are also obliged to vary their outputs in response to the changes of electricity market prices, which results in more frequent mill start-ups and shut-downs. Frequent start-ups and shut-downs of mills will also have an impact on power plant operation safety. Although the increased risks are currently being mitigated by R&D work and the implementation of increased operational controls, in many cases, coal mills are shutdown and then restarted before they have cooled adequately, which creates a potential fire hazard within the mill. Mill fires could occur if the coal stops flowing in the mill and the static deposit is heated for a period of time. The UK PF Safety Forum had recently reported an increase in the frequency of mill incidents in the UK. However, it is difficult to identify if there will be a potential fire in the mill before it happens. Mill gas outlet temperature and CO measurement are established methods of detecting fires in mills, but at present they are not very effective for detecting small fires. The CO detection system becomes ineffective when the mill is in service due to dilution effects caused by primary air flow and associated oxygen content in the mill.

Advanced distributed control and monitoring systems have been installed at almost all coal-fired power plants, which enable power plant operators to collect data from the major plant components, e.g. mills, boilers, turbines and generators. Therefore, the project is to develop a software package for condition monitoring and fire prediction through on-line implementation of a coal mill model using evolutionary computation and pattern recognition techniques.

The aim of the project is to develop a software package for on-line mill condition and safety monitoring with particular emphasis on the following objectives:

- to improve the multi-segment mill mathematical model using evolutionary computation techniques based on the on-site measurement data and to extend the current model from E-Type vertical spindle mills to other types of coal mills such as tube-ball mills and etc;
- to identify coal quality variations through recognising the variation patterns of mill model parameters and dynamics;
- to detect apparent mill defects or instrumentation problems using the on-line mill model;
- to estimate the quantity of deposit coal in the mill, which is essential for predicting potential mill fires;
- to predict potential fires through identification of the patterns of mill data and model parameter variations.

The project has achieved the originally specified objectives. The main achievements and conclusions of the project are summarised below:

- The pulverised coal mill mathematical model for E-type vertical spindle mills has been analysed and refined which was developed through a previous research project.
A multi-segment mathematical model for Tube-Ball mills is developed using on-site measurement data for mill parameter identification, in which evolutionary computation techniques are adopted. The multi-segment model covers the whole milling process from the mill start-up to shut-down. The transition from one segment to another is determined/triggered with the signals/variations of the mill status specified in the mill operation procedure.

The mill model has been verified by comparing the model predicted and measured mill variable values. Both off-line and on-line model validation has been carried out. The predicted mill outputs agree with the measured mill outputs well.

A software package has been developed for mill model on-line implementation and condition monitoring. The software has the following functions: data logging/transferring from/to the power plant computer server via a particular network - cutlass; mill model real-time implementation; predicted and measured results display; operator-friendly software interface; condition monitoring functions; parameters updating and etc.

Two associated computer programs were developed for mill parameter optimisation and identification using intelligent algorithms. Two intelligent algorithms - Genetic Algorithms and Particle Swarm Optimisation were implemented, which can be used to search the best fitted values for all the unknown mill parameters.

Completion of the project provided a software tool for mill on-line condition and safety monitoring. As this method only employs the currently available on-site measurement data without requiring any extra cost on hardware, this method is cost effective and it is easy for power plants to install. The software will run independently from all the current power plant control software and will not interfere with any current plant operations. The current software can be installed and integrate with the existing software at Cottam Power Station to serve the purpose of mill condition and safety monitoring. The software can also be used by other power stations; therefore, the project outcomes have the potential to benefit all coal fired power station Operators in the UK and other countries.
1. Introduction

Coal-fired power stations nowadays are required to operate more flexibly with more varied coal specifications and regularly use coal with higher volatile contents and biomass materials; this greatly increases the risks of explosions or fires in milling plants. The power stations are also obliged to vary their output in response to the changes of electricity demands, which results in more frequent mill start-ups and shut-downs. Frequent start-ups and shut-downs of mills will also have an impact on power plant operation safety (Scott, 1995, Fan et al 1994, Hamiane 2000). Although the increased risks are currently being mitigated by R&D work and the implementation of increased operational controls, in many cases, coal mills are shutdown and then restarted before they have cooled adequately, which creates a potential fire hazard within the mill. Mill fires could occur if the coal stops flowing in the mill and the static deposit is heated for a period of time. Fires in out-of-service mills can cause explosions on mill starts. Fires in running mills can cause explosions on shut-downs. The result of a study indicated that as many as 300 “explosions” were occurring annually in the US pulverized coal industry (Scott, 1995). The UK PF Safety Forum had recently reported an increase in the frequency of mill explosions in the UK. However, it is difficult to identify if there will be a fire in the mill. Outlet temperature and CO measurement are established methods of detecting fires in mills, but at present they are not very effective for detecting small fires. The CO detection system becomes ineffective when the mill is in service due to dilution effects caused by primary air flow and associated oxygen content in the mill.

Advanced distributed control and monitoring systems have been installed at almost all coal-fired power plants, which enable companies to collect data from the major plant components, e.g. mills, boilers and generators. The available on-site measurements for coal mills include inlet/outlet temperature, PA (primary air) differential pressures, volume flow rate of coal into mills and primary airflow rate in mills etc. For a long period of time, the data has been captured and stored in archived databases that represent the history of the mills. The data recorded a number of events of failures and accidents, which the mill experienced during a certain period of its “life time”. From the current available on-site measurement data, combustion engineers have already noticed that the mill process data tends to have been slightly different where the fires have occurred in mills. The availability of such a large volume of data presents a challenge as to how to extract the useful, task-oriented knowledge from the data. Therefore, the project is proposed to develop a software package for condition monitoring and fire prediction through on-line implementation of a coal mill model using evolutionary computation and pattern recognition techniques.

2. Development of Tube-Ball mill model for the normal grinding process

A wide range of literature survey shows that there are only a few reports on mathematical models of milling processes. A detailed milling process description can be found in Scott et al. 1995. An approximated linear transfer function model was obtained by Bollinger et al, in 1983. Mill modelling using system identification method was reported in 1984 (Corti, L. et al. 1984). With specially designed input signals, a linear discrete time model was obtained by Cheetham, et al in 1990, in which system time-delay was considered. An approximated linear time varying mill
model was derived by Fan, G.Q. et al. in 1994. A polynomial matrix model was recently reported in 2000 (Hamiane, M. et al. 2000). However, almost all the reported work describes the milling process by approximated linear mathematical models, which can not reflect the nonlinear features of coal mill systems. The complex nature of a milling process, together with the complex interactions between coal quality and mill conditions lead to immense difficulties for obtaining an effective mathematical model of a milling process.

Different from the early reported mill modelling work, the research team at Birmingham has developed a nonlinear mathematical model for vertical spindle coal mills using on-site measurement data and an evolutionary computation technique (Zhang et al. 2002, Wei et al. 2007). The team has also demonstrated a realistic technique for implementation of the model in real-time which could be used for on-line condition monitoring (Wei et al. 2006). Compared with the vertical mills, Tube-Ball mills are more complex in structure and have a much higher grinding capacity. The work for the E-type Spindle mill served the starting point for the work conducted in this project. At the same time, the previous work in vertical mill has been improved as reported in the paper of Wei et al. 2007.

The structure of a Tube-Ball mill is illustrated in Figure 2.1 (EDF Energy). Normally, there are two coal feeders for each mill. The feeder actuator positions are considered as the input variables: two feeders’ (A1 and A2) actuator positions: $A_{P1}$ (%) and $A_{P2}$ (%). The mill inlet pressure $\Delta P_{in}$, and primary air inlet temperature $T_{in}$ are also treated as the system input variables. The output variables are mill pressure $\Delta P_{out}$, outlet temperature $T_{out}$ and mill power consumed $P$. Some intermediate immeasurable variables due to lack of suitable sensors or impossible for placement of sensors are also introduced for modelling. Those variables are the mass flow rate of pulverized coal output from mill $W_{pf}$, the mass of coal in mill $M_c$, the mass of pulverized coal in mill $M_{pf}$, and the mill product pressure $\Delta P_{prod}$. The full list of the variables is given in Table 2.1.
With this organization of the data sets, the modelling study for the Tube-Ball mills has been carried out in the project. The procedure for coal mill modelling can be broken down into the following steps:

1) to derive the basic mill model dynamic equations through analyzing the milling process, applying physics and engineering principles and integrating the knowledge of experienced engineers;
2) to identify unknown parameters using intelligent algorithms based on-site measurement data;
3) to analyse the simulation results and interpret the parameters identified through the discussions between the researchers and experienced engineer;
4) to return back to Step 2 if any modification is required in order to improve the mill model or to conduct further simulation in order to validate the model.

<table>
<thead>
<tr>
<th>Input variables</th>
<th>Intermediate variables</th>
<th>Output variables</th>
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<tbody>
<tr>
<td>- A1 feeder Actuator Position $A_1$ (%)</td>
<td>- Mass of coal in mill $M_1$ (Kg)</td>
<td>- Mill outlet temperature $T_{out}$ (°C)</td>
</tr>
<tr>
<td>- A2 feeder Actuator Position $A_2$ (%)</td>
<td>- Mass of pulverised coal in mill $M_{p1}$ (Kg)</td>
<td>- Mill outlet pressure $\Delta P_{out}$ (mbar)</td>
</tr>
<tr>
<td>- Primary air temperature inlet the mill $T_a$ (°C)</td>
<td>- Mass flow rate of raw coal into the mill $W_c$ (Kg/s)</td>
<td></td>
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<tr>
<td>- Mill power consumed $P$ (Amp)</td>
<td>- Mass flow rate of pulverized coal out of mill $W_{p1}$ (Kg/s)</td>
<td></td>
</tr>
<tr>
<td>- Mill inlet pressure $\Delta P_{in,Diff}$ (mbar)</td>
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### 2.1 Mass flow analysis

In the Tube-Ball mill system, two feeders are equipped for providing raw coal flowing into the mill. Each feeder is driven by a variable speed electric motor operating at a 415V, 3Phase 50Hz power supply. Right before the feed hopper, a banker discharge valve is installed to control the mass flow. In the system, both the feeder motor current and discharge valve actuation position are measured. Based on the available measurement, the feeder current could be converted to the equivalent coal mass flow rate into the mill. It is proposed that the mass flow rate is calculated by the following equation:

$$W_c(t) = C_{f1}[K_{f1}A_{f1}(t) + 3.3] + C_{f2}[K_{f2}A_{f2}(t) + 3.3]$$

where $A_{f1}$ is the A1 Feeder Actuation Position (%); $A_{f2}$ is the A2 feeder Actuation Position (%). The parameters in (2.1) were obtained through intelligent parameter identification method algorithms. We have $K_{f1} = 32.60$, $K_{f2} = 31.64$, $C_{f1}=1$ if mill A1 feeder current $P_{f1}>1$ Amp, otherwise, $C_{f1}=0$; $C_{f2}=1$ if mill A2 feeder current $P_{f2}>1$ Amp, otherwise, $C_{f2}=0$.

The air flow system of a Tube-Ball mill can be represented by the diagram shown in Figure 2.2. From the fluid mechanism, the air blowing into the coal mill can be calculated by the following empirical equation (with the advice from E.ON):

$$W_{air} = 12.42 \cdot \sqrt{\Delta P_{in,Diff}} + 4.01$$

(2.2)
where $\Delta P_{in\_diff}$ is the mill inlet differential pressure (mbar); $W_{\text{air}}$ is the mass flow rate of inlet air (Kg/s).

Figure 2.2 Sketch of the air flow system of a Tube-Ball mill

To simplify modelling process for obtaining the quantity of coal (mass) in the mill, the coal in the mill is classified as pulverized and un-pulverized two categories only. The dynamic process of coal mass flow during the mill operation can be schematically illustrated by Figure 2.3. The raw coal is fed into the mill by the feeders for pulverizing at a mass flow rate of $W_c$. By tumbling the raw coal $M_c$ with a charge of steel balls, the pulverized coal $M_{pf}$ is produced and carried out by the warm air flow at the mill outlet with a mass flow rate of $W_{pf}$. From the mass balance point of view (see Figure 2.2), the total mass of the pulverized coal output from the mill at the flow rate $W_{pf}$ should be equal to the total mass of the raw coal mill flowing into the mill at the flow rate $W_c$ eventually.

Figure 2.3 illustration of mass flow process

Based on the principle of mass flow balance, Equations 2.3 ~ 2.5 are derived.

\[
W_{pf}(t) = K_{16} \Delta P_{out}(t) M_{pf}(t) + \left[C_{E1} P_{E1} + C_{E2} P_{E2}\right] K_{19} + 0.9
\]  

(2.3)

\[
M_c(t) = W_c(t) - K_{15} \cdot M_c(t)
\]  

(2.4)

\[
\dot{M}_{pf}(t) = K_{15} \cdot M_c(t) - W_{pf}(t)
\]  

(2.5)

where $C_{E1} = 1$ if mill A1 Exhauster current $P_{E1} >> 22$ Amp, else $C_{E1} = 0$; $C_{E2} = 1$ if mill A2 Exhauster current $P_{E2} >> 22$ Amp, else $C_{E2} = 0$; $K_{15}$ and $K_{16}$ are the unknown coefficients to be identified.

Equation (2.3) represents that the flow rate of PF (Pulverized Fuel) out of the mill $W_{pf}$ by the exhausters is proportional to the mass of pulverized coal in mill $M_{pf}(t)$ and the mill outlet differential
pressure produced by the two exhauster fans $\Delta P_{\text{out}}(t)$. Equation (2.4) represents that the changes of mass of coal in the mill $M_c(t)$ is proportional to the difference between the coal flow into mill $W_c(t)$ and a fraction of the coal pulverized $K_{15}M_c(t)$. Equation (2.5) describes that the changes of mass of pulverized fuel in mill $M_{pf}(t)$ is proportional to the difference between the fraction of pulverized coal $K_{15}M_c(t)$ and the pulverized coal flow out from the mill $W_{pf}(t)$.

2.2 Mill product pressure

While pulverizing the coal, the mill barrel rotates at around 15 rev./min. Two variable speed exhauster fans are equipped at the outlet of the mill to extract the coal flow out to the burner. The outlet pressure $\Delta P_{\text{out}}$ can be modeled by the following equation:

$$\Delta P_{\text{out}} = K_9 P_{E1} + K_{10} P_{E2} + K_{11} M_{pf} + K_{12} M_c + K_{13} \Delta P_{\text{in,Diff}} + K_{18} \Delta P_{\text{out}}$$  \hspace{1cm} (2.6)

where $K_9, K_{10}, K_{11}, K_{12}, K_{13}, K_{18}$ are the unknown coefficients to be identified.

2.3 Thermal process analysis

Distinguishing from the mineral pulverizers, the coal mills in power plants are involved with thermodynamics. Hot air is swept through the mill by two variable speed exhauster fans, and the air acts as both the drying and transporting agent for the coal. If the coal mill heating process is treated as it happens in an isolated environment as shown in Figure 2.4, the heat input into the coal mill and the heat output from the coal mill complies with the heat balance rule. The heat into the coal mill $Q_{\text{in}}$ includes the heat from raw coal $Q_{\text{coal}}$ and the heat from the hot air $Q_{\text{air}}$. The heat out from the coal mill $Q_{\text{out}}$ includes the heat outlet in the pulverized coal $Q_{\text{pf}}$ and the heat emitted from the mill body to the environment $Q_{\text{e}}$. Based on the heat balance rule, the mill outlet $T_{\text{out}}$ can be model in the following equation:

$$\dot{T}_{\text{out}}(t) = K_1 T_{\text{in}}(t) + K_2 W_{\text{coal}}(t) - K_3 W_c(t) + K_{14} P(t) - K_{20} T_{\text{out}} + K_{17} T_{\text{out}}$$  \hspace{1cm} (2.7)

where $K_1, K_2, K_3, K_{14}, K_{17}$ and $K_{20}$ are the unknown coefficients to be identified.

In summary, the complete coal mill model can be described as follows, which does not cover the start up and shut down processes.

$$W_c(t) = C_{f1} [K_{f1} A_{P1}(t) + 3.3] + C_{f2} [K_{f2} A_{P2}(t) + 3.3]$$  \hspace{1cm} (2.1)

$$W_{\text{coal}} = 12.42 \cdot \sqrt{\Delta P_{\text{in,Diff}}} + 4.01$$  \hspace{1cm} (2.2)

$$W_{pf}(t) = K_{16} \Delta P_{\text{out}}(t) M_{pf} + \left[C_{E1} P_{E1} + C_{E2} P_{E2}\right] K_{19} + 0.9$$  \hspace{1cm} (2.3)

$$\dot{M}_c(t) = W_c(t) - K_{15} \cdot M_c(t)$$  \hspace{1cm} (2.4)
\[ M_{pf}(t) = K_{15} \cdot M_c(t) - W_{pf}(t) \]  
(2.5)

\[ \Delta P_{out} = K_9 P_{E1} + K_{10} P_{E2} + K_{11} M_{pf} + K_{12} M_c + K_{13} \Delta P_{in\_Diff} + K_{18} \Delta P_{out} \]  
(2.6)

\[ \dot{T}_{out}(t) = K_7 T_{in}(t) + K_8 W_{p}(t) - K_9 W_c(t) + K_{14} P(t) - K_{20} \Delta T_{out} T_{in} + K_{17} \Delta T_{out} \]  
(2.7)

where

- \( A_{p1} \): A1 feeder actuator position (%)
- \( A_{p2} \): A2 feeder actuator position (%)
- \( \rho \): Primary air density (Kg/m³)
- \( M_c \): Mass of coal in mill (Kg)
- \( M_{pf} \): Mass of pulverized coal in mill (Kg)
- \( T_{out} \): Outlet temperature of coal mill (°C)
- \( \Delta P_{out} \): Mill outlet differential pressure (mbar)
- \( \Delta P_{in\_Diff} \): Mill product differential pressure (mbar)
- \( W_{p} \): Mass flow rate of pulverized coal outlet from mill (Kg/s)
- \( P \): Mill current (Amp)
- \( \Delta P_{in} \): Mill inlet differential pressure (mbar)
- \( W_c \): Mass flow rate of coal into mill (Kg/s)
- \( T_{in} \): Inlet temperature of coal mill (°C)
- \( W_{air} \): Primary air flow rate into coal mill (Kg/s)
- \( P_{E1} \): A1 Exhauster Motor Current (Amp)
- \( P_{E2} \): A2 Exhauster Motor Current (Amp)
- \( K_{f1}, K_{f2} \): A1 A2 feeder coefficients
- \( C_{f1}, C_{f2} \): A1 A2 feeders Boolean control coefficients
- \( C_{E1}, C_{E2} \): A1 A2 exhauster Boolean control coefficients
- \( K_1, \ldots, K_{20} \): Unknown coefficients to be identified

3. Model parameter identification using intelligent algorithms

To obtain the unknown parameters or coefficients of the mill model, intelligent algorithms are adopted for the parameter identification. Two algorithms are investigated; they are Genetic Algorithms (GAs) and Particle Swarm Optimisation. The identification process using GAs can be illustrated by the block diagram shown in Figure 3.1.

![Figure 3.1 Schematic of the model’s coefficients identification](image-url)
The on-site measurement mill data are organised into two groups; one group is used to identify the model parameters and another group is employed to verify the identified results. All the data were provided by EDF Energy, which were obtained from Cottam Power Station. The fastest sampling rate of the data is one second. One identification case is demonstrated and explained here. The model parameters are identified using the data obtained on 9th March 2008 with the period of 00:00:00 – 06:00:00am (6 hours), and the identified parameter values are listed in Table 3.1.

### Table 3.1 The identified model coefficients

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<thead>
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<td>K1</td>
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<td>K20</td>
<td>=</td>
<td>0.000003245249092</td>
<td></td>
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</table>

The model validation results are shown in Figures 3.2 ~ 3.3 with the data collected on 9th March 2008, 00:00:00 ~ 12:00:00 (12 hours). Figure 3.2 shows the system output variables and compares the simulated and the measured outputs. Figure 3.3 presents the intermediate variables, which are not measurable at the power plant. From the simulation results, we can see that the validation results are basically followed the trends of the measured outputs.

![Figure 3.2. Measured and simulated output for the data collected on 9th March 2008, 00:00:00 ~ 12:00:00 (12 hours)](image-url)
4. Development of a multi-segment coal mill model

The mathematical model described in previous sections is only suitable for the mill normal grinding process or steady-state operation stage. A multi-segment mill model is developed to cover the whole milling process from start-up to shut-down.

4.1. Coal mill start-up/shut-down operational sequences

The start-up sequence for a typical coal milling process can be divided into six different operational stages (O1 ~ O6) as shown Figure 4.1. Similarly, a typical coal mill shut-down sequence can be divided into five different operational stages (O7 ~ O11) as shown in Figure 4.2.

The overall operational stages of a coal mill in the start-up and shut-down procedures can be divided into 11 operational stages. In order to develop the model for the whole milling process, it requires a signal/flag to tell which operational stage the system is during the operation periods of start-up and shut-down. However, there is no direct indicator logged into the database to give the
information at Cottam Power Station. So the alternative signals of indirect variable values are considered, for example, A1 Feeder Motor Current A1723 and etc and the logical values of the plant operations, for example, Mill A I/L Damper Open D53, the system’s operational stages can be identified and triggered for changes. Detailed descriptions are given in the following paragraphs.

**O1: Start one exhauster at the minimum speed to purge the system.**
This operation stage can be detected by comparing the values of the exhausters’ motor currents. Because the offsets of current sensors exist, the value of exhausters’ motor current logged is a very small value (e.g. 0.0111644649878144 Amp) rather than zero when the motor is off. For triggering this operational stage, the following conditions are desired:
- A1 Exhauster Motor Current >= 1 Amp; or
- A2 Exhauster Motor Current >= 1 Amp.
An illustration of values’ variations of the two exhausters’ motor currents for starting-up are given in Figure 4.3, where P_E1 represents the A1 Exhauster Motor Current (A66), P_E2 represents the A2 Exhauster Motor Current (A73).

**O2: Initiate the pre start checking process, then start the jacking oil and lubrication oil pumps.**
For triggering this operational stage, we can look at the values of the Boolean variables of Lube Oil PP DE CB Closed Buttons (e.g. D64) and J.O. Oil PP DE CB Closed Buttons (e.g. D68). However, for the modelling purpose, these operations do not influence the model equation directly. So the trigger of this step can be skipped.

**O3: When the mill oil system are satisfactory and the inlet and outlet damper are closed, the mill motor starts**
This operation stage can be detected by comparing the values of the mill motor current. Similar to O1, the value of 1Amp is used as the threshold to tell if the motor is on. For triggering this operational stage, the following condition is desired:
- Mill Motor current P >= 1Amp.
An illustration of value variations of the mill motor current at starting-up is shown in Figure 4.4, where P represents the Mill Motor Current (A80).

![Figure 4.3. Values of A1 A2 exhausters’ motor currents at the starting-up stage](image)

![Figure 4.4. Values of mill motor currents while starting-up](image)
**O4: Start a coal feeder at the minimum speed**

There are two feeders equipped at each coal mill to feed raw coal to the mill, which are named as A1 and A2 feeders. While at the stage of starting-up of the coal mill, it will start a coal feeder at a minimum speed initially, and then the second feeder may start later depending on the load demands. The operation stage of starting a coal feeder can be detected by comparing the values of the feeders’ motor currents. Similar to O1, the value of 1Amp is used as the threshold to tell if the motor is on. For triggering this operational stage, the following conditions are to be detected:

- A1 Feeder Motor Current > 1 Amp; or
- A2 Feeder Motor Current > 1 Amp.

An illustration of values’ variations of the two feeders’ motor currents while starting-up is shown in Figure 4.5, where P_F1 represents the A1 Feeder Motor Current (A1723), P_F2 represents the A2 Feeder Motor Current (A1733).

**O5: Open the associated outlet damper; the inlet damper will open after 5 seconds**

There are two outlet dampers, named 12A1 & 12A2, equipped in each coal mill, which are associated to the exhausters A1 & A2 and controlled independently. To detect the operation of the opening of the associated outlet dampers, the following conditions are to be held:

- Mill A1 O/L Damper Open (D55) = =1, or
- Mill A2 O/L Damper Open (D57) = =1

The inlet damper 8A is controlled by the sequence system and is opened when the mill is running and one outlet damper is open. To detect the operation of the opening of the inlet damper, the following condition is expected to be true:

- Mill A I/L Damper Open (D53) = =1

An illustration of values’ variations of the three logical variables at the stage of the starting-up are shown in Figure 4.6, where D55 represents Mill A1 O/L Damper Open, D57 represents Mill A2 O/L Damper Open, and D53 represents Mill I/L Damper Open.

![Figure 4.5. Values of A1 A2 feeders’ motor currents while starting-up](image)

**O6: When the mill is running and lubricating oil flow established, the jacking oil pumps are shutdown.**

This operation is the final step for the mill start-up sequence. The operation conditions of the lubrication oil pumps and the jacking oil pumps can be detected by looking at the values of the Boolean Variable of Lube Oil PP DE CB Closed Buttons (e.g. D64) and J.O. Oil PP DE CB Open Buttons (e.g. D67) etc. However, for the modelling purpose, this operation stage does not influence the model equation directly. So the trigger of this step can be skipped.
Figure 4.6. Values of A1 A2 feeder’ motor currents while starting-up

O7: Shutdown one of the exhausters if both of them are in operating; the exhauster will purge at the maximum speed for 10 minutes and then stop.
This operation is the first step of the mill shut-down sequence. Similar to O1, the operation stage can be detected by comparing the values of the exhausters’ motor currents, wherein the following conditions are expected to be true:
- A1 Exhauster Motor Current <= 1 Amp; or
- A2 Exhauster Motor Current <= 1 Amp.
An illustration of value variations of the two exhausters’ motor currents at the starting-up is given in Figure 4.7, where P_E1 represents the A1 Exhauster Motor Current (A66), P_E2 represents the A2 Exhauster Motor Current (A73).

Figure 4.7. Values of A1 A2 exhausters’ motor currents while shutting-down

O8: Stop the coal feeders
This operation is the second step of the mill shut-down sequence. It checks the operation condition of A1 & A2 feeders, and then it will stop any of coal feeders that were running.
The operation stage of stopping a coal feeder can be detected by comparing the values of the feeders’ motor currents. Similar to O1, the value of 1Amp is used as the threshold to tell if the motor is off. For triggering this operational stage, the following conditions should be held:
- A1 Feeder Motor Current < 1= Amp; or
- A2 Feeder Motor Current < 1= Amp.
An illustration of value variations of the two feeders’ motor currents at the starting-up stage is given in Figure 4.8, where in P_F1 represents the A1 Feeder Motor Current (A1723), P_F2 represents the A2 Feeder Motor Current (A1733).
Figure 4.8. Values of A1 A2 feeders’ motor currents while shutting-down

O9: *Initiate a mill shut-down (stop): the jacking oil pumps start.*

Similar to O3, this operation stage can be detected by comparing the values of the mill motor current. For triggering this operational stage, the following condition is expected to be true:

- Mill Motor current \( P \leq 1 \)Amp.

An illustration of the values’ variations of the mill motor current while starting-up are given in Figure 4.9, where \( P \) represents the Mill Motor Current (A80).

Figure 4.9. Values of mill motor currents while shutting-down

O10: *When the jacking oil pressures are established, the mill stops and the inlet and outlet dampers are closed.*

Similar to O5, the trigger of the operation of the closures to the associated outlet dampers can be detected using the logical variables, which are shown as follows:

- Mill A1 O/L Damper Closed (D56) = 1, or
- Mill A2 O/L Damper Closed (D58) = 1

To detect the operation of the closing of the inlet damper, the following condition is expected to be true:

- Mill A I/L Damper Closed (D54) = 1

An illustration of the values’ variations of the three logical variables at the starting-up are given in Figure 4.10, where D56 represents Mill A1 O/L Damper Closed, D58 represents Mill A2 O/L Damper Closed, and D54 represents Mill I/L Damper Closed.

O11: *Shutdown the exhauster; the exhauster will purge at the maximum speed for 10 minutes and then stop.*

This operation stage is the final step of the shut-down sequence. Similar to O7, the operation stage can be detected by comparing the values of the exhausters’ motor currents, wherein the following conditions are desired to be true:

- A1 Exhauster Motor Current \( \leq 1 \) Amp; and
- A2 Exhauster Motor Current \( \leq 1 \) Amp.

An illustration of the values’ variations of the two exhausters’ motor currents while starting-up are given in Figure 4.11, where \( P_E1 \) represents the A1 Exhauster Motor Current (A66), \( P_E2 \) represents the A2 Exhauster Motor Current (A73).
Figure 4.10. Values of A1 A2 feeder’s motor currents while shutting-down

Figure 4.11. Values of A1 A2 exhausters’ motor currents while shutting-down

4.2. Multi-Segment Coal Mill Model

In the coal mill start-up and shut-down processes introduced in the previous sub-section, there are totally eleven different operation stages (see Figure 4.1). For different operational stages, the coal mill system will be described by different mathematical equations. Grouping the working conditions of the coal mill system from the different operation stages, a multi-segment coal mill model is developed, the schematic diagram of which is shown in Figure 4.12. There are five different model segments, namely Model Segment I, Model Segment II, Segment III, Segment IV, and Segment V. Detailed model equations for each segment are given below.
Model Segment I

The duration of this model segment is valid from O3 to O4. In this duration, the coal mill feeders are off, so there isn’t any raw coal ($W_c$) coming into the coal mill, see Equation (I.2). At least one of the mill exhausters is on at this duration, however, the outlet dampers (12A1 & 12A2) are all closed, so there is no pulverized coal ($W_{pf}$) outlet from the mill to the burner which can be described by Equation (I.3). Similarly, the inlet damper (8A) is still closed in this duration, there is still no hot air ($W_{air}$) inlet into the coal mill as described by Equation (I.1). As the inlet and outlet dampers are all closed, the mill body can be treated as isolated, the mill outlet pressure become the atmosphere pressure and the mill outlet temperature varies to itself, see Equation (I.6) and (I.7). The mill motor is on in this model segment, so that grinding has started. As no raw coal supplied into the mill, the raw coal remained in the coal mill from the last stage ($M_c$) reduces itself due to the grinding, and the pulverized coal inside of the mill ($M_{pf}$) increases itself consequently, see Equations (I.4) and (I.5). The whole sets of the model equations of Model Segment I are shown as follows:

\[
W_{air} (t) = 0 \quad (I.1)
\]
\[
W_c (t) = 0 \quad (I.2)
\]
\[
W_{pf} (t) = 0 \quad (I.3)
\]
\[
M_c (t) = 0 - K_{15} M_c (t) \quad (I.4)
\]
\[
M_{pf} (t) = K_{15} M_c (t) \quad (I.5)
\]
\[
\Delta P_{out} (t) = 0 \quad (I.6)
\]
\[
\dot{T}_{out} (t) = 0 + K_{17} T_{out} (t) \quad (I.7)
\]

where

\begin{itemize}
  \item $W_{air}$: Primary air flow rate into coal mill (Kg/s)
  \item $W_c$: Mass flow rate of coal into mill (Kg/s)
  \item $W_{pf}$: Mass flow rate of pulverized coal outlet from mill (Kg/s)
  \item $M_c$: Mass of coal in mill (Kg)
  \item $M_{pf}$: Mass of pulverized coal in mill (Kg)
  \item $T_{out}$: Outlet temperature of coal mill (°C)
  \item $\Delta P_{out}$: Mill outlet differential pressure (mbar)
  \item $K_{17}$: Unknown coefficients to be identified for model segment I.
\end{itemize}

Model Segment II

The duration of this model segment is valid from O4 to O5. In the duration, one of the mill feeders started running to feed raw coal into the mill for the grinding, wherein the raw coal flow rate ($W_c$) can be represented by Equation (II.2) according to the previous research. In this duration, the inlet damper (8A) and outlet dampers (12A1 & 12A2) are still closed. Consequently, there is still no $W_{air}$ inlet into the coal mill (see Equation (II.1)), likewise there is no $W_{pf}$ outlet from the mill (see Equation (II.3)). Similarly to last segment, the mill body can be treated as isolated in segment II as well, the mill outlet pressure become zeros and the mill outlet temperature varies to itself, see Equation (II.6) and (II.7). The mill motor is kept on running from the last segment, and the grinding is continued. As new raw coal supplied into the coal mill, the mass of raw coal ($M_c$) and mass of pulverized coal ($M_{pf}$) can be represented by Equations (II.4) and (II.5). The whole sets of the model equations of Model Segment II are shown as follows:

\[
W_{air} (t) = 0 \quad (II.1)
\]
\[ W_c(t) = C_{f1} \left[ K_{f1} A_{p1}(t) + 3.3 \right] + C_{f2} \left[ K_{f2} A_{p2}(t) + 3.3 \right] \]  
\[ W_{pf}(t) = 0 \]  
\[ M_c(t) = W_c(t) - K_{15} M_c(t) \]  
\[ M_{pf}(t) = K_{16} M_c(t) - 0 \]  
\[ \Delta P_{out} = 0 \]  
\[ \dot{T}_{out} = 0 + K_{17} T_{out} \]

where

- \( A_{p1} \): A1 feeder actuator position (%)
- \( A_{p2} \): A2 feeder actuator position (%)
- \( K_{f1}, K_{f2} \): A1 A2 feeder coefficients
- \( C_{f1}, C_{f2} \): A1 A2 feeders Boolean control coefficients
- \( K_{15}, K_{17} \): Unknown coefficients to be identified for model Segment II.

The other notations are same as previously stated in Segment I.

**Model Segment III**

The duration of this model segment is valid from O5 to O8. In this duration, the mill inlet damper (8A) and the outlet dampers (12A1 or 12A2) are opened; the mill motor is on; at least one of the mill feeder is on; similarly, at least one of the mill exhausters is on; This model segment represents the coal mill steady-state operation condition. Inheriting from previous research, the model equations for this segment are shown as follows:

\[ W_{in}(t) = 12.42 \sqrt{\Delta P_{in, Diff}} + 4.01 \]  
\[ W_c(t) = C_{f1} \left[ K_{f1} A_{p1}(t) + 3.3 \right] + C_{f2} \left[ K_{f2} A_{p2}(t) + 3.3 \right] \]  
\[ W_{pf}(t) = K_{16} \Delta P_{out}(t) M_{pf}(t) + \left[ C_{E1} P_{E1} + C_{E2} P_{E2} \right] K_{19} + 0.9 \]  
\[ \dot{M}_c(t) = W_c(t) - K_{15} M_c(t) \]  
\[ \dot{M}_{pf}(t) = K_{16} M_c(t) - W_{pf}(t) \]  
\[ \Delta P_{out} = K_{9} P_{E1} + K_{10} P_{E2} + K_{11} M_{pf} + K_{12} M_c + K_{13} \Delta P_{in, Diff} + K_{14} \Delta P_{out} \]  
\[ \dot{T}_{out} = K_{17} T_{in}(t) + K_{22} W_{in}(t) + K_{23} P(t) - K_{24} W_{c}(t) - K_{25} \dot{T}_{out} + K_{27} \dot{T}_{out} \]

where

- \( \rho \): Primary air density (Kg/m³)
- \( \Delta P_{in} \): Mill inlet differential pressure (mbar)
- \( P_{E1} \): A1 Exhauster Motor Current (Amp)
- \( P_{E2} \): A2 Exhauster Motor Current (Amp)
- \( P \): Mill motor current (Amp)
- \( C_{E1}, C_{E2} \): A1 A2 exhauster Boolean control coefficients
- \( K_{15}, \ldots, K_{27} \): Unknown coefficients to be identified in Segment III.

The other notations are same as previous stated in Segment II.
Model Segment IV

The duration of this model segment is valid from O8 to O10. In the duration, all the coal feeders are off, so the raw coal inlet flow rate \( W_c \) becomes zeros, see Equation (IV.2). All the other equipments are still operated as usual like the last model segment: the inlet damper 8A and the outlet dampers (12A1 or 12A2) are still opened; the mill motor is kept on running; at least one of the exhausters is kept on extracting pulverized fuel out. The model equations for this segment are shown as follows:

\[
\begin{align*}
W_{\text{air}}(t) &= 12.42 \sqrt{\Delta P_{\text{in - Diff}}} + 4.01 \\
W_c(t) &= 0 \\
W_{pf}(t) &= K_{16} \Delta P_{\text{out}}(t) M_{pf}(t) + \left[ C_{E_1} P_{E_1} + C_{E_2} P_{E_2} \right] K_{19} + 0.9 \\
M_c(t) &= W_c(t) - K_{15} M_c(t) \\
M_{pf}(t) &= K_{14} M_c(t) - W_{pf}(t) \\
\Delta P_{\text{out}} &= K_{13} P_{E_1} + K_{14} P_{E_2} + K_{11} M_{pf} + K_{12} M_c + K_{13} \Delta P_{\text{in - Diff}} + K_{14} \Delta P_{\text{out}} \\
\dot{T}_{\text{out}} &= K_{14} T_{in}(t) + K_{15} W_{\text{air}}(t) + K_{14} P(t) - 0 - K_{20} T_{\text{out}} t_{in} + K_{17} T_{\text{out}} 
\end{align*}
\]

where

\( K_{11}, \ldots, K_{20} \): Unknown coefficients to be identified in Segment IV.

The other notations are same as previous stated in Segment III.

Model Segment V

The duration of this model segment is valid from O10 to O3. In the duration, all the coal mill equipments are off: the coal feeders are off; the mill motor is off; the exhausters are off; the inlet damper (8A) and the outlet dampers (12A1 & 12A2) are all closed. The coal mill system situates in the idle stage. As the inlet and outlet dampers are all closed, the mill body can be treated as isolated, the mill outlet pressure become zeros and the mill outlet temperature varies to itself, see Equation (V.6) and (V.7). The whole set of model equations for this segment are shown as follows:

\[
\begin{align*}
W_{\text{air}}(t) &= 0 \\
W_c(t) &= 0 \\
W_{pf}(t) &= 0 \\
M_c(t) &= M_{\text{LastStage}} \\
M_{pf}(t) &= M_{pf_{\text{LastStage}}} \\
\Delta P_{\text{out}} &= 0 \\
\dot{T}_{\text{out}} &= 0 + K_{17} T_{\text{out}} 
\end{align*}
\]

where

\( M_{\text{LastStage}} \): Mass of raw coal in mill from the last segment (Kg)

\( M_{pf_{\text{LastStage}}} \): Mass of pulverized coal in mill from the last segment (Kg)

\( K_{17} \): Unknown coefficients to be identified in Segment V
The other notations are same as previous stated in Segment III.

4.3. Parameter identification and simulation study of the multi-segment model

Three start-up/shut-down data sets were collected from Cottam Power Station. Following the model parameter identification scheme as shown in Figure 3.1, the model parameters of the five segments are identified and listed in Table 4.1.

Table 4.1. The identified model parameters of the five segment models

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Segment I</th>
<th>Segment II</th>
<th>Segment III</th>
<th>Segment IV</th>
<th>Segment V</th>
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<tbody>
<tr>
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<td>N/A</td>
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<td>0.01</td>
<td>N/A</td>
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</tr>
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</tr>
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<td>0.0011</td>
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<td>0.01</td>
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<td>N/A</td>
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</tbody>
</table>

Three start-up/shut-down data sets collected from Cottam power station were selected for simulation study. The details of the data sets are given in Table 4.2.

Table 4.2. Data Sets employed for the simulation study

<table>
<thead>
<tr>
<th>Date Range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data 1</strong></td>
<td>16th Mar. 2008 00:00:00 ~ 17th Mar. 2008 00:00:00</td>
</tr>
<tr>
<td><strong>Data 2</strong></td>
<td>26th Jul. 2008 00:00:00 ~ 27th Jul. 2008 00:00:00</td>
</tr>
<tr>
<td><strong>Data 3</strong></td>
<td>28th Jul. 2008 00:00:00 ~ 28th Jul. 2008 00:00:00</td>
</tr>
</tbody>
</table>

Using the parameters identified, the model simulation results are shown in Figures 4.13~18, in which, for the normal grinding stage, the key parameters K17 & K18 updating scheme is implemented which will be described in next section. The red curves are the measured data of the system outputs and the blue curves are simulated variables.
Figure 4.13. Model simulated and measured outputs with Data set 1

Figure 4.14. Model intermediate variables with Data set 1

Figure 4.15. Model simulated and measured outputs with Data set 2
Figure 4.16. Model intermediate variables with Data set 2

Figure 4.17. Model simulated and measured outputs with Data set 3

Figure 4.18. Model intermediate variables with Data set 3
The simulation results indicated that the multi-segment mill model can capture the segment change flag/trIGGERing signals and transfer the model from one segment to the next automatically. The simulated dynamic responses can follow the measured real mill data well. The model should be sufficient to represent the mill main characteristics and features. It can be used for model based on-line condition monitoring.

5. Model based mill condition monitoring and fault detection

With the mathematical model developed, there are two possible ways for mill condition monitoring and fault detection. The first is a direct observation method by comparing the measured data with the model predicted values. A big or sudden difference between the measured and predicted indicates that some unexpected or unwanted changes may have happened in the mill. To identify if a fault happened, a two step procedure could be applied in general:

Step1: re-identifying the mill parameters;
Step 2: observing the variation trend between the measured and predicted mill variable data values after the new mill parameters were reset. If the predicted values can follow the trend of the measured values, the mill operation conditions changed but no fault happens. If there is still a big gap between the measured and predicted values, it is very likely that a fault happens and an alarm should be raised.

For example, on 9th March 2008, it is noticed that the measured and the simulated data have a big discrepancy. The model parameters were updated in time but it did not reduce the gap in between the measured and simulated data as shown in Figure 5.1. This situation should be alerted as there is a high chance of a mill fault occurred. After discussion with the plant engineers, it is identified that a big choke of biomass was fed into the mill during that period of time. The mill was choked with uneven blended biomass material. This may cause fires or an unexpected incident and will affect the combustion efficiency, so an alarm should be raised in this situation.

![Figure 5.1 Comparing the measured and simulated mill outputs for the data collected on 9th March 2008, 00:00:00 ~ 24:00:00 (24 hours)](image)

The above procedure also indicated another way of mill condition monitoring. Instead of monitoring the mill variable variations, we could update the mill parameters on-line and observe the variation trend of the mill parameters. From our simulation tests, only some model key parameter variations were influenced obviously by the mill operation condition variations. Through our analysis, a scheme is developed which will re-identify the key parameters related to $T_{out}$ or $\Delta P_{out}$ on-line but with a longer sampling period compared with the data collection frequency. One example for this parameter observation scheme is given below.
For a particular period of mill operation, initially, the mill model parameters were identified using intelligent algorithms and the values of those parameters are listed in Table 5.1. Then $\hat{K}_1$ will be updated in every 3 or 5 minutes on-line (the updating frequency can be determined for different cases). Instead of observing the mill output variations, the parameter variations were observed. Any unusual changes in the key parameter will be observed and picked up. The simulation results for three different time periods are shown in Figure 5.2–5.4.

Table 5.1. The identified model parameters

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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</tr>
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<td>0.020000000000000</td>
</tr>
<tr>
<td>$K_{15}$</td>
<td>$K_{16}$</td>
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</tr>
</tbody>
</table>

Figure 5.2. Model simulated outputs with $\hat{K}_1$ re-identified in every 5 minutes, with the data collected on 3rd July 2007, 00:00:00 ~ 12:00:00 (12 hours)

Figure 5.3. Model simulated outputs, with $\hat{K}_1$ re-identified in every 5 minutes, with the data collected on 2nd March 2008, 00:00:00 ~ 12:00:00 (12 hours)
From the above results, it can be seen that the model simulated results follow the measured data more closely while \( \hat{K}_{17} \) was updated in every 5 minutes. Also, the parameters change with time gradually but around the initially identified value.

If the value of \( \hat{K}_{17} \) changes dramatically within a very short time period or drifted away from the initial value greatly, this may indicate that there is some sudden changes in the coal mill system or some unwanted or unexpected changes. One application for mill condition monitoring using the parameter updating scheme is to identify the biomass choking. For the simulation results shown in Figure 5.1, the parameter observation scheme is applied. The figure is redrawn with the parameter variations shown alongside the results. From Figure 5.4, we can see that the values of the \( \hat{K}_{17} \) varies around -0.14 for the whole first 18 hours period, and the model simulated output of \( T_{out} \) for this first period of 18 hours matches the measured \( T_{out} \) very well. However, at around 18:30:00, the value of the \( \hat{K}_{17} \) suddenly changed rapidly, and it changed very sharply. This sudden change in the parameter \( \hat{K}_{17} \) is so obvious. This normally indicates that a big chunk of biomass materials were fed into the mill and was not blended properly. This has a potential to cause fires or other incidents so it should be reported and alarmed.

The scheme can also be used to identify the incident prior to its happening. A plugged incident happened on 4th Oct. 2007 at Cottam Power Station. The incident was analysed using this scheme. Model simulation results are presented in Figure 5.6. Monitoring the variations of the key parameters K17 and K18, it can be seen that the values of K17 and K18 move away from the average value for a “thinkable” time period before the incident in order to let the model simulated outputs follow the system measured outputs. These large offsets of K17 and K18 would become the featured pattern to indicate that mill operation condition is severely altered and an incident would be very likely to happen soon. It is also noticed that the intermediate variable of coal inside the mill increased greatly, which indicated that too much coal has been accumulated inside the mill. If the coal inside the mill and the parameter drifting can be noticed, this may be used to identify the incident earlier. The parameters were gradually drifted away from their nominal values for over 1.5 hours. If it can be identified earlier, the potential incident could be reported one hour earlier before the incident and the incident could be prevented. As only one set of incident data was obtained so more incident data are required to validate this prediction before any conclusions can
be drawn.

Figure 5.5. Model simulated outputs, with $\hat{K}_{17}$ re-identified in every 5 minutes, with the data collected on 9th March 2008, 00:00:00 ~ 24:00:00 (24 hours)

Figure 5.6. The simulation results for data obtained on the day of the incident happening
6. Intelligent parameter identification software design

6.1. Introduction

For the purpose of research and industrial user’s convenience, it is necessary to develop a user friendly interface for the implemented parameter optimisation algorithms. GUIDE (Graphical User Interface Development Environment) is adopted for creating graphical user interfaces (GUIs). The current version of GUI layout is shown in Figure 6.1. The underline program source code is demonstrated in Figure 6.2.

The GUI M-file initializes the GUI program which contains the code to perform the underline tasks before the GUI appears on the screen, such as creating data or graphics containing the call-back functions that will execute to perform the designed program functions each time when a user clicks on a GUI component. The GUI for one of our intelligent algorithms – Particle Swarm Optimisation is reported in this section.

![Figure 6.1 The design layout area](image-url)
6.2. Properties setting for PSO

A sub-window is designed for setting the algorithm parameters. On the top left of the layout area, there is a table for setting the parameters of PSO (Figure 6.3).

The meanings of those parameters are explained below:

Swarm Size: specifies how many individuals (particles) there are in each iteration.

Number of Iteration: specifies the maximum number of generations that the algorithms perform.

Maximum Velocity $V_{\text{max}}$: An upper limit is placed on the velocity in all dimensions. This upper limit prevents particles from moving too rapidly from one region in search space to another.
Social Acceleration C1 and Cognitive Acceleration C2: One of the most important parameters that drive the behaviour of PSO. C1 and C2 are positive acceleration constants. For better performance the values must be set to $2. C1 + C2 \leq 4$.

Maximum Iteration Fraction: The fraction of maximum iterations, for which the velocity is linearly varied.

Inertia Weight, Ending Velocity Weight W\_end, and Beginning Velocity Weight W\_start: Improve performance can be achieved by applying an inertia weight to the previous velocity. The weight controls the influence of previous velocities on the new velocity. Usually PSO starts with large weight which decreases over the time.

6.3. Model parameter range setting

Underneath the PSO parameter setting table, there is another table called Model Parameter Range Setting as shown in Figure 6.4. This table shows the 18 unknown parameters for identification. Each unknown coefficient has a lower and upper boundary.

![Figure 6.4. The model parameter range setting](image)

In case that the parameter value is not a clear number or exceeds the boundaries, a warning window will then pop-up to alert the users.

6.4. Using the GUI

Once the PSO parameters and the unknown coefficients boundaries are set, the next step is to load the Data. At the bottom of the layout area, there are instructions to show how to use the GUI (Figure 6.5).
Simply by clicking on the left blue button on the left of the window, the sets of Data loading sub-window will pop-up (Figure 6.6). After all the setting up completed, click on the middle button to start the optimization algorithms. Once the optimization starts, the logo window will be replaced by a graph. This graph will show the PSO optimization performance (see Figure 6.7).

The left button can be used to stop the optimization at anytime. Immediately after the button is clicked, a new window will pop-up showing the identification results (Figure 6.8).
When the optimization is totally completed, the following graphs are shown:

a. Measured and Simulated Mill Outlet Temperature
b. Measured and Simulated Mill Motor Current
c. Measured and Simulated Mill Outlet Pressure
d. Inlet raw coal flow
e. Raw coal inside of the mill
f. Outlet pulverised coal flow
g. Pulverised coal inside of the mill

These graphs shown in Figures 6.9–6.10 are typical examples.

The current version of GUI is developed from the researchers’ point of view. The interface can be modified easily on the basis of requirement from plant engineers.
7. On-line implementation and condition monitoring software development

7.1 OPC server of the Cutlass Network

At Cottam Power Station, the OPC server is in use which was developed by PowerGen in 2006. The first step towards developing the on-line condition monitoring software is to log the on-line data from the power plant server. The host computer for the monitoring software is treated as a client to the OPC server which is then connected to the OPC server via the Cutlass Network in the control room. The network connection infrastructure is shown in Figure 7.1. In our case, the Node 59 is the connecting port used for the project.

![Network infrastructure at Cottam Power Station](image)

Figure 7.1. Network infrastructure at Cottam Power Station

After successful connection with the OPC server, we can communicate with the OPC server in the Matlab software environment, which is shown in Figure 7.2. The name of the OPC server that we connected in the Cutlass Network is called the Powergen.OPCCutlass.1, which is shown on the left panel of the figure. Fourteen variables are read from the server to the Matlab OPC client for on-line implementation of coal mill model and monitoring, which is shown on the right hand panel of the figure. All these variables are using the tag numbers as they were specified at the power system. For example, \texttt{U1:A52} represents the Mill A A1 Feeder Actuation Position (%) of Unit 1.
With the successful data communication between our Matlab client and the OPC server of the power system, the coal mill model on-line implementation can be developed and it is described in the next section.

### 7.2. Mill model on-line implementation (Version1)

Based on the model discussed on Section 2~5, the model on-line implementation is carried out. The coal mill on-line implementation scheme is shown in Figure 7.3. The coal mill model is run in parallel with the real coal mill system at the power plant, and the model simulated outputs are displayed to users in synchronization with the mill measured outputs. Currently, the model parameter is set to be updated off-line by GA or PSO when it is required and the key model parameters can be updated on-line.

![Coal mill model on-line implementation scheme](image)

While the coal mill model is run in parallel with the real coal mill system at the power plant, the data acquisition mechanism is developed as shown in Figure 7.4. At Cottam Power Station, all the system variables were updated in every 5 seconds at the OPC server. Our on-line software scans the values broadcasted from the OPC server in every 0.2 seconds, and then compares the time stamp of each data point with the previous data point obtained. Once new data has arrived, the model will introduce this new data to the model, let the model program to go forward one step and then wait until the next data point arrives. Employing this data acquisition scheme, the
software can run in parallel with the real coal mill system and synchronously gain/display the output results to the users.

The main window panel of the software is shown in Figure 7.5. In general, it can be divided into four subpanels. The left hand side subpanel is the OPC Reading panel. It displays all the values of the data point read from the OPC server synchronously. Total twelve numbers of variables are read from the server in every 5 seconds time interval, which include Current Sever Time Stamp, A1 Feeder Actuation Position, A1 Feeder Actuation Position, etc.

The panel on the upper middle of the window is the control panel. It displays the logo of the Tube-Ball mill and the company information. Three control buttons are embedded for the software the starting the operation, stopping the software and saving the final results into the archived database. The panel on the lower middle of the window is the Model Equation panel. When the software is initialized, the current version of the model will be display inside this panel. And when the on-line modelling starts running, the on-line running performances are displayed dynamically to the users, where the model simulated outputs and the measured outputs are compared and displayed, which can be seen from a demo result shown in Figure 7.6.
The panel on the right hand side of the window is the Model Predicts panel. This panel displays the dynamic trend of the model predicted intermediate variables, which can not be measured from the mill. These variables are inlet raw coal flow, outlet pulverised coal flow, mass of raw coal inside of the mill, and mass of pulverized coal inside of the mill. While the on-line modelling program starts running, the values and the trends of all these variables will be dynamically display to the users, which are illustrated in Figure 7.7. After running the coal mill model on-line, users can save the results into *.xls file by clicking the ‘Save to Excel’ button. Totally each result includes 18 columns, which are the Server Time Stamp, A1 Feeder Actuation, A2 Feeder Actuation, Mill Outlet Pressure, A1 Exhaustor Current, A2 Exhaustor Current, Mill Outlet Temperature, Mill Inlet Diff, Mill Motor Current, Mill Inlet Temperature, A1 Feeder Current, A2 Feeder Current, Raw Coal Inlet Flow Rate, Pulverized Coal Outlet Flow Rate, Raw Coal Inside the Mill, Pulverized Coal Inside the Mill, Simulated Mill Outlet Temperature, and Mill Outlet CO concentration. The Version 1 software has been tested on-line at Cottam Power Station. Then the software is modified to upgrade to Version 2 (See the following section).

7.3 Further improvement of the on-line software (Version 2)

The version 1 software reported in the previous section has been modified and upgraded to Version 2. The new functions of Version 2 are:

1) expanding the software from Mill A to B, C, and D of Unit 1 and enabling the four mills running in parallel;
2) embedding the function into the software for monitoring the key parameters;
3) completed implementation of multi segment milling process modelling;
4) other new features, such as auto data save function.

![Figure 7.6. Demo results of the software on-line running](image)
7.3.1 Expanding the software from Mill A to B, C, and D in Unit 1

In the previous version of the on-line software, it is only suitable for the Mill A of Unit 1. As there are sixteen mills in four different units at the Cottam Power Station, this version of software is capable of running for four Mills (A~D) of Unit 1. The main user interface for users to select different mills is shown in Figure 7.8.
After the mill is selected, the selected mill will be brought to the front end in the OPC Reading panel. Furthermore, the system variables’ tag number will be updated accordingly. The snapshot sections after selecting different mills are illustrated in Figures 7.9 and 7.10.

Figure 7.9. OPC Reading Panel after Mill A or B was selected

Figure 7.10. OPC Reading Panel after Mill C or D was selected

7.3.2 Embeding the function of displaying the key parameters

The function of on-line upgrading the key parameters is implemented in this version. The parameters (K17 & K18) are displayed with the upgraded value on-line. The update frequency can
be selected based on the mill operation conditions. A new panel in the main platform of the software is created to display the upgraded values, which is namely ‘Adjust K17 & K18’. Locations of the panel in the main platform is highlighted in Figure 7.11.

![Figure 7.11. Adjusted K17 & K18 panel in the main platform](image)

7.3.3 Multi segment mill model on-line implementation

In order to modeling the start-up/shut-down process, a Multi-Segment coal mill model was developed. Accordingly, the on-line software was re-programmed to enable it to model the complete process including start-up and shut-down process. As introduced in Section 7.1, the system Boolean variables e.g. D56, D58 and D54, are read from the Cutlass network and adopted for the judgements of switching to be different model segments. The demonstration results of the on-line software for running a start-up ➔ steady-state ➔ shut-down process are illustrated in Figure 7.12.

7.3.4 Viewing/amending model identified parameters

A new pop-up-menu in the main platform is created to enable users to view/modify the model parameters. Benefiting from this feature, users can amend the model parameters manually, and save the modified parameter sets into *.xls files. The location of the pop-up menu is highlighted in the following figure.
Figure 7.12. Updated values of K17 & K18

Figure 1.13. Pop-up menu for viewing/modifying identified model parameters
After clicking the menu, a parameter setting window will be popped up, which will enable users to view or modify the model parameters. The pop-up window is named ‘Set Parameters’. An illustration of the pop-up dialogue is shown in Figure 7.14.

![Figure 7.14. Set Parameters window model parameters of Segment III](image)

By clicking the different push-buttons on the top of the ‘Set Parameters’ dialogue, users can view and modify the model parameters for all the model segments as shown in Figures 7.15~16.

![Figure 7.15 Set Parameters window model parameters of Segment I and Segment II](image)

![Figure 7.16 Set Parameters window model parameters of Segment IV and Segment V](image)
By clicking the ‘Load’ button, users can load a pre-defined parameter set from the existing *.xls file. The pop-up window for user to load the pre-defined parameter sets is shown in Figure 7.17. In order for convenient viewing and easy editing, the content of the pre-defined parameter file *.xls follows a specified data form, which is illustrated in Figure 7.18. Similarly, by clicking the ‘Save’ button, users can save your amended model parameters into *.xls file following the same form as illustrated in Figure 7.18.

Figure 2. Pop-up window for loading predefined model parameters

![Pop-up window for loading predefined model parameters](image)

Figure 7.18. Content of the pre-defined model parameter file *.xls

![Content of the pre-defined model parameter file *.xls](image)

7.3.5 Description of other new features

Further to the main features that were introduced above, some other new features were introduced to the new version of the on-line software. These features include:

1) Enabling and disabling the ‘Start’, ‘Pause’, ‘Stop, and ‘Save’ control button in control bar.
   Before running the coal mill model, there are no results to be saved, and also there is no running thread to be stopped or paused. So, in the control bar, only the ‘Start’ button should be activated at this moment. And other three buttons should be de-activated, see Figure 7.19.
In order to avoid users mistakenly clicking on ‘Save to Excel’ button while the mill model is still running, the ‘Save to Excel’ button is disable while the mill model is running, see Figure 7.20.

After clicking the ‘Pause’ or the ‘Stop’ button, the ‘Start’ button is re-activated again for users to re-run the program. And also, the ‘Save to Excel’ button is activated as well to enable users to save the simulated results into *.xls file. Demonstration of the control bar is shown in Figure 7.21.

2) Enabling and disabling the ‘Chose Mill’ menu and the ‘Set Parameter’ menu.
Before starting the coal mill modelling program, the ‘Chose Mill’ and the ‘Set Parameter’ menus are activated to enable users to select different mills in Unit 1 and amending different model parameters, see Figure 7.22. However, while the mill model is running on-line, these two menus should be disabled to avoid mistaken actions, see Figure 7.23. Similarly, after stopping running the modelling on-line, the ‘Chose Mill’ and the ‘Set Parameter’ menus will be re-activated again for users to choose different mills or amend the model parameters.
3) Auto-save Function

The maximum memory of the software is prepared for 12 hours’ modelling (8640 points). In the earlier versions, the program will stop automatically after running 12 hours. But for a long-time data collecting and modelling, 12 hours is not enough. Considering the memory of computer and the maximum rows of Microsoft Excel, the software is modified to save the results every 12 hours automatically to release the memory for long term operation.

8. On-line test of the software

The new version of the software was tested on-line in consequent three days from 27th Feb 2009 to 2nd March 2009. The test results are shown in Figures 8.1~8.8. From the test results, it can be seen that the software is robust enough to run in real-time and in the real power plant working environment.

From Figures 8.1~8.8, we can see the simulated mill outputs from the multi-segment mill model follow the mill measured outputs very well. Especially, all the four mills are running at the same time and all worked well. Mill B has multi times of start ups and shut downs and the mill model followed all those mill operation status satisfactorily.
Figure 8.1 The on-line test results: mill temperature and pressure outputs and the key parameters (K17 and K18) for Mill A, Unit 1 at Cottam Power Station

Figure 8.2 The on-line test results: mill intermediate variables for Mill A, Unit 1
Figure 8.3 The on-line test results: mill temperature and pressure outputs and the key parameters (K17 and K18) for Mill B, Unit 1

Figure 8.4 The on-line test results: mill intermediate variables for Mill B, Unit 1
Figure 8.5 The on-line test results: mill temperature and pressure outputs and the key parameters (K17 and K18) for Mill C, Unit 1

Figure 8.6 The on-line test results: mill intermediate variables for Mill C, Unit 1
Figure 8.7 The on-line test results: mill temperature and pressure outputs and the key parameters (K17 and K18) for Mill D, Unit 1

Figure 8.8 The on-line test results: mill intermediate variables for Mill D, Unit 1
9. Summary of achievement and conclusions

During this project, the major achievements are as summarised below:

1) The pulverised coal mill mathematical model for E-type vertical spindle mills developed in a previous project has been analysed and refined. The model has been served as a foundation for the development of the mathematical model of Tube-Ball mills.

2) A mathematical model has been developed for pulverised Tube-Ball mills using on-site measurement data by adopting evolutionary computation techniques. The model is “transparent” in terms of the physics meanings of all the variables and parameters; it can represent more complex nonlinear features of coal mills compared with the linear transfer function models reported earlier.

3) The model developed in above covers only normal grinding process so it is then extended to multi-segments to cover the whole milling process from the mill start-up to mill shut-down. The transition from one segment to another is determined/triggered by following the mill operation procedure.

4) Off-line and on-line model validation has been carried out. The predicted mill outputs agree with the measured mill outputs well. This indicates that the mill model can be used for the task of model based mill condition monitoring.

5) A software package has been developed for mill model on-line implementation and condition monitoring. The software has the following functions:
   a) auto logging data from the power plant OPC server through the cutlass network in real-time;
   b) auto sending data or model variables back to the server so they can be saved in the power plant database for future use;
   c) on-line implementation of the multi segment mill model so the model can run in parallel with the mills and the model predicted results can be reported, saved and displayed;
   d) implementation of the functions to allow the power plant engineers to initiate the software operation, to update the mill model parameters, to choose different mills for observation, to pause the program for data saving;
   e) the user friendly interface and display panel. This gives users more flexible options for software applications and allow the software to work in a safer mode;
   f) condition monitoring: i) the mill operation condition variations can be identified earlier by comparing the measured and predicted mill variable status; ii) the potential incidents could be predicted by observing the variation trends of the mill key parameters;
   g) some other functions were implemented for the convenience of using the software by the plant engineers;

6) Software for mill parameter optimisation and identification using intelligent algorithms has been developed. The software can search the best fitted values for all the mill parameters. Two intelligent algorithms were adopted and implemented, which are Genetic Algorithms and Particle Swarm Optimisation Algorithms. The software can also be adapted easily for other applications.

The software developed through this project has a potential to be used for many other coal-fired power stations so this indicates that it may have a commercial value.
10. Suggested future work

To maximise the value of the outcomes from the project deliveries, two suggested future programmes are proposed.

1) It is proposed that more mill data should be analysed which are expected to cover more data collected during the periods of mill incidents. This will enhance the software functions in mill safety monitoring and early prediction of mill incidents.

2) As great efforts have been made to develop the mill mathematical model and its software implementation, further funding should be sought to exploit more applications of this software.

11. Publications arising from the project

The results from the project have led to the following papers and presentations:


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References