Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 2s (2025)

Controllability Analysis of Coal Mill Pulverizer Model

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Article History:

Received: *27-09-2024*

Revised: *02-11-2024*

Accepted: *13-11-2024*

Abstract:

The most essential need for today's human life apart from food, air and water is electricity. Our life gets stuck if there is a cut-off for a few hours. The Electricity is produced in various types of power plants. Our interest is to study the process of coal-fired power plants. Coal pulverizer or coal mill play a very important role in the performance and reliability of any sub-critical or super critical coal-based power plant. The coal mill plays a crucial role in the thermal power generation process, where coal is ground into a fine powder to be used as fuel in boilers. Over the years, the modeling of coal mills has undergone significant evolution, driven by advancements in mathematical modeling techniques, computational capabilities, and a deeper understanding of the complex physical and chemical processes involved. This article discussed the controllability of coal mill pulverizer process. Controllability of this process is obtained through modern control theory.

Keywords: Coal pulverizer, Coal mill, Power plant, Controllability Analysis.

AMS Subject Classification: 93B05, 34H05, 93C10, 93C15.

1. Introduction

Electricity generation from renewable energy sources is steadily increasing as a result of greater political focus on lowering carbon dioxide emissions. However, the output from those sources varies so frequently, hence its utilization poses issues of load stabilizing. So, we understand that for traditional power plants the capability to transform manufacturing for the purpose of balance demand and network supply which becomes more essential and self-sustaining [1]. To guarantee higher grid flexibility and deduction of emissions, it is required to enhance the existing technologies. It is understood that work ability optimization of each thermal power plants is important.

Because of the abundant and sustainable coal resources, coal-fired power plants are more common than those that run on oil or natural gas. Nevertheless, the primary obstacle in the operation of these plants are the coal pulverization procedure, which leads to continual plant stops and low take-up rates [2]. In an ordinary coal-fired power station, four to eight mills of coal supply fuel to every boiler. All the control problems are brought on by insufficient sensors to identify each mill's output of ground fuel. It is also challenging to the mill to monitor input mass flow of the raw coal; typically, to do this the speed of the conveyor belt is used.

Furthermore, parameter changes are caused by fluctuating coal quality, like moisture, Hardgrove Grindability Index of coal provided to the mills, as well as normal mill wear [3]. These factors lead to simplistic and conservative mill control algorithms, which perform poorly when load requirements change or mills of coal are stopped or started. Emissions rise when the air-fuel ratio is troublesome to regulate outside of steady-state operation. Plants operating more efficiently may benefit from advanced control strategies based on measurements or estimates of flow of crushed fuel. Improved control of mill can achieve performance close to oil-fired power plant performance, claims Rees [7].

Additionally, the pulverizing process, which uses a lot of energy, can be improved, resulting in more coherent power manufacturing. Now, it is feasible to measure the flow of coal from the coal mill to the furnace with newly improved sensors. Unfortunately, at this point in time, the technology cannot be employed for direct control due to its high cost and periodic calibration requirements. Since sensors were introduced relatively recently, they are not included in the testing process for the majority of coal mill types currently in use. However, a recent work by Dahl-Sorensen and Solberg [4] demonstrated that the Kalman filter technique could be used to generate a good estimate of fuel flow using sensor fusion. The researchers applied the feeder speed but in the Kalmann filter design it was bias and unreliable powdered fuel sensors. The filter has been successfully installed and used at two Danish power plants on each mill of coal.

The mathematical modelling of coal mills and the development of pulverizing theory may be traced back to the early 1940s, when some scholars done invention on it. Austin [5] has worked and contrasted the outputs of the early research. Remarkable progress was created throughout the upcoming decades. Kersting [6], Fan and Rees [7], Palizban, O'Kelly, and Rees [8], Rees and Fan [2], Zhang et al. [9], and Wei, Wang, and Wu [10] have all given more control-oriented models.

The process was partitioned into three sub models through grinding, pneumatic conveying and classification [6]. Pressure drop data was used to verify model. He introduced a developed control scheme that changes the size of the coal particles that leaves via the classifier. Rees and Fan [2] examine the mass and heat balance in addition to the model of energy. The outputs of the inventions are motivating, even though Rees and Fan note that additional parameter recognition and authentication is needed [11]. These include new and worn mills, different load situations, different coal calorific values, and moisture. Using predictions and observations of pulverized fuel flow, these authors provide many control schemes. Just two particle sizes of raw coal and pulverized coal are examined in the grey-box mill model provided by Zhang et al. [9] and Wei et al. [10]. Piotr, Jan et al. [12] have discussed in their paper on the progress and verification of a mill model for efficient coal mill control, which could lead to greater load following capability in pulverized coal-fired power plants.

Duarte, Jéssica, et al. [13] applied unsupervised machine learning techniques to identify operating patterns based on the power plant’s historical data which leads to the identification of appropriate steam generator efficiency conditions.

Multivariable Model Predictive Control (MPC) scheme is proposed by Dadiala, Vini, Jignesh Patel, and Jayesh Barve [14] for specific industrial coal-mill. Also, simulation study is performed using validated industrial coal-mill model, and performance of MPC is compared with two other control schemes - industrial 2PI, and prior published 3PI with selective control.

Dadiala, Vini, Jignesh Patel, and Jayesh Barve [15] describes Various computational results and their analysis for the case study carried out at ESSAR thermal power plant, Hazira, Gujarat, India. It proposes more accurate mathematical model for a pulveriser and a 3PI (proportional integral) with selective control for improved performance.

Bhatt, Dhruvi S., Vini Dadiala, and Jayesh J. Barve [16] describes the first principle-based energy and mass balance mathematical models of Static-classifier and Dynamic-classifier types of industrial coal-pulverizers. In static classifier case parameters of the presented mathematical model in Matlab are estimated from the actual plant data of 150MW ESSAR power plant's coal pulverizer. The model operation is also validated. Whereas, in dynamic classifier case parametric analysis is carried out on the model simulator developed on the Matlab-Simulink platform and on the industrial coal power plant simulator tuned with actual 660MW ADANI power plant.

Djalolitdin Mukhitdinov et al. [17] have made the model to provide a robust control system for stabilizing the ball mill grinding process by accounting for nonlinearities and uncertainties in ore quality. It optimizes process performance through real-time monitoring and adaptive control.

Zhu, Mingrui, et al. [18] presented a data-driven, automated control strategy for VRM operations that reduces equipment vibration and enhances performance through real-time state monitoring and predictive modeling. Applied in a cement plant, this approach effectively optimizes VRM operations.

Cortinovis, Andrea, et al. [20] a validated coal mill model with improved control performance, showing potential for enhancing load response, handling disturbances, and enabling better integration with renewable energy sources.

Liang, Li, Wu, and Shen [21] propose a nonlinear multi-model predictive control scheme with moving horizon estimation, significantly improving control accuracy and system performance for pulverizing systems in coal-fired power plants.

Present work makes an endeavour to explore controllability analysis of mill model. Earlier, some research studies have been attained for controllability analysis of coal mill model; however, past literature doesn't provide evidence of controllability analysis of coal mill model using the concept of Transition Matrix. This paper presents the mathematical modeling and the controllability analysis of coal mill using the Mathematical analysis of controllability.

2. Methods

This section briefly discussed the coal-mill process and its mathematical modelling. A roll mill's simplified graphical representation can be found in Figure 1.

Conveyor belts are used to move raw coal, which is subsequently dropped into the mill and broken by rollers as it hits a grinding table. Fine coal particles are carried into the classifier section by prime air, which is forced from the mill's bottom. Almost all coal particles come back to the grinding table, leaving only the acceptable particles to go out the mill. With rotary classifiers, the amount of coal that swiftly exits the mill can be increased, if necessary, by regulating the rotational speed. One easily permits big particles to go by the classifier. The particles of coal that falls onto the table are reground. The mill's particle flow is depicted in the layout in Figure 1. The mathematical equations were developed for a mill's nominal grinding operation, but they also accurately represent the dynamics of start-up and shut-down. As shown in Figure 2, the particle of coal circular motion is the first step of the model.

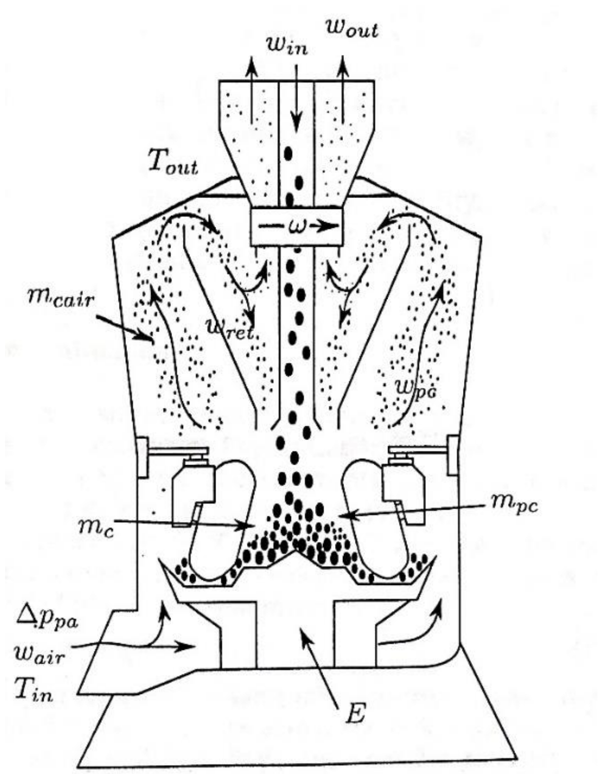

Figure 1: Flow of particles of coal in a Roll Wheel coal mill [12]

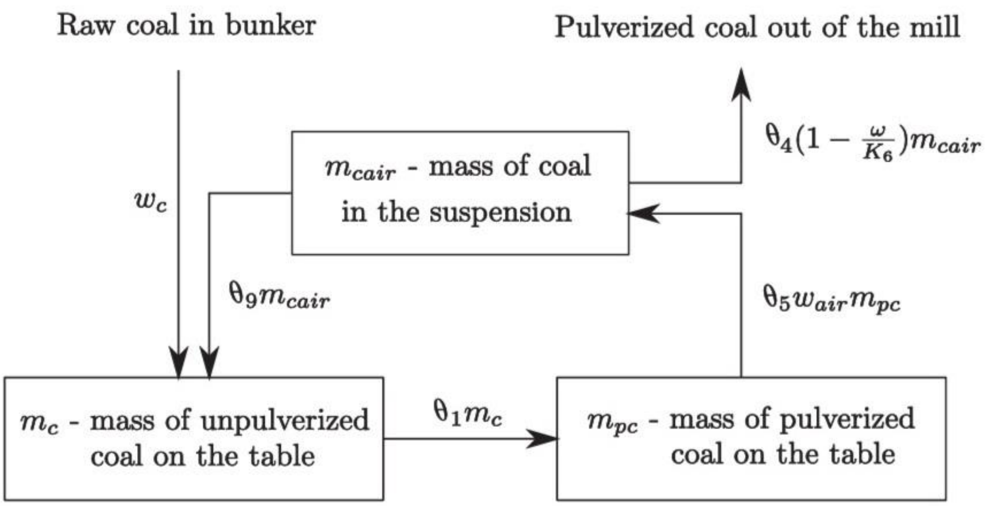

Figure 2: Circular motion of coal particles in a Mill [12]

To setup the mathematical model, consider the following parameters and variables

- $m_c(t)$ - Mass of coal pieces to be pulverized.
- $m_{pc}(t)$ - Mass of pulverized coal particle on the table.
- $m_{cair}(t)$ - Mass of particles of coal in the pneumatic transport upper side in mill.
- $w_{in}(t)$ / $w_c(t)$ - flow of mass of the raw coal.

- w_{ret}(t) - Return flow of the particles of coal declined by the classifier.
- w_{pc} - Mass of coal particle picked up by the prime air from the table.
- w_{out} - Flow of mass of pulverized coal out of the coal mill.
- w_{air} - Prime air mass of flow.
- ω - Speed of classifier.

Using the principle of continuity, the rate of change of mass of coal pieces (m_c) to be pulverized is equivalent to the mass of flow of raw coal (w_c / w_{in}) and the return flow of the particles of coal declined by the classifier (w_{ret}) and the pulverizing rate which is proportional to mass of the raw coal pieces at the pulverizing table (m_c) .

$$\frac{d}{dt} m_c(\mathrm{t}) = w_c(\mathrm{t}) + w_{ret}(\mathrm{t}) - \theta_1 m_c(\mathrm{t}) \tag{1}$$

The rate of change of mass of pulverised coal particle (m_{pc}) at the table is equivalent to the amount of mass of coal pieces (m_c) subtracted the amount of coal pieces picked up by the prime air from the table (w_{pc})

$$\frac{d}{dt} m_{pc}(\mathrm{t}) = \theta_1 m_c(\mathrm{t}) - w_{pc}(\mathrm{t}) \tag{2}$$

The mass of coal particle picked up by the prime air from the table (w_{pc}) minus flow of mass of pulverized coal out of the coal mill (w_{out}) and return flow of the particles of coal declined by the classifier (w_{ret}) are equivalent to the rate of change of mass of coal in the pneumatic transport upper side (m_{cair}) in the mill of coal.

$$\frac{d}{dt} m_{cair}(\mathrm{t}) = w_{pc}(\mathrm{t}) - w_{out}(\mathrm{t}) - w_{ret}(\mathrm{t}) \tag{3}$$

The prime air mass of flow (w_{air}) and the mass of grinded coal on the table (m_{pc}) are proportional to the mass flow of pulverized coal particles picked up by the primary air (w_{pc}) to be transferred to the classifier.

$$w_{pc}(\mathrm{t}) = \theta_5 w_{air}(\mathrm{t}) m_{pc}(\mathrm{t}) \tag{4}$$

The flow of mass of pulverized coal out of the coal mill (w_{out}) is proportional to mass of particles of coal in the pneumatic transport upper side in the mill (m_{cair}) and is affected by the classifier speed ω.

$$w_{out}(\mathrm{t}) = \theta_4 m_{cair}(\mathrm{t}) \left(1 - \frac{\omega(\mathrm{t})}{\theta_6} \right) \tag{5}$$

Where $0 < \omega(\mathrm{t}) < \theta_6$. θ_6 has the same unit as ω, making the term $\left(1 - (\omega(\mathrm{t}) / \theta_6)\right)$

a dimensionless factor.

The Mass of particles of coal in the pneumatic transport upper side in the mill m_{cair} is equivalent to the mass flow of coal coming back to pulverizing table proportional to

$$w_{ret}(\mathrm{t}) = \theta_9 m_{cair}(\mathrm{t}) \tag{6}$$

Therefore, the equation (1) , (2) and (3) can be written as,

$$\begin{aligned}
\frac{d}{dt} m_c(\mathrm{t}) &= w_c(\mathrm{t}) + \theta_9 m_{cair}(\mathrm{t}) - \theta_1 m_c(\mathrm{t}), \\
\frac{d}{dt} m_{pc}(\mathrm{t}) &= \theta_1 m_c(\mathrm{t}) - \theta_5 w_{air}(\mathrm{t}) m_{pc}(\mathrm{t}), \\
\frac{d}{dt} m_{cair}(\mathrm{t}) &= \theta_5 w_{cair}(\mathrm{t}) m_{pc}(\mathrm{t}) - \theta_4 m_{cair}(\mathrm{t}) \left(1 - \frac{\omega(\mathrm{t})}{\theta_6}\right) - \theta_9 m_{cair}(\mathrm{t})
\end{aligned}$$

Which is the Mathematical model of the coal mill system. where, $(m_c(\mathrm{t}), m_{pc}(\mathrm{t}), m_{cair}(\mathrm{t}))$ represents the states of the system.

Considering $x = (x_1, x_2, x_3) \in \boldsymbol{R}^3$ such that $x_1 = m_c(\mathrm{t})$, $x_2 = m_{pc}(\mathrm{t})$, $x_3 = m_{cair}(\mathrm{t})$ and $u_1 = w_c(\mathrm{t})$ flow of mass of the raw coal, $u_2 = w_{air}$ prime air mass of flow and

$u_3 = \omega(\mathrm{t})$ the angular velocity(speed) of the classifier is considered as the controlled inputs above equations can be written as,

$$\begin{aligned}
\dot{x}_1 &= u_1(\mathrm{t}) + \theta_9 x_3 - \theta_1 x_1 \\
\dot{x}_2 &= \theta_1 x_1 - \theta_5 u_2 x_2, \\
\dot{x}_3 &= \theta_5 u_2 x_2 - \theta_4 x_3 \left(1 - \frac{u_3}{\theta_6}\right) - \theta_9 x_3
\end{aligned}$$

These equataions rewritten as:

$$\begin{aligned}
\dot{x}_1 &= -\theta_1 x_1 + \theta_9 x_3 + u_1 \\
\dot{x}_2 &= \theta_1 x_1 - \theta_5 u_2 x_2, \\
\dot{x}_3 &= -\theta_9 x_3 - \theta_4 x_3 + \theta_5 u_2 x_2 - \frac{\theta_4}{\theta_6} x_3 u_3
\end{aligned}$$

Here, Choosing $\theta_1 = 0.0487, \theta_4 = 0.8148, \theta_5 = 0.0062, \theta_6 = 2.7855, \theta_9 = 0.5604$ [12]. The above equations can be written in the following form

$$\dot{x} = F(x,u) \tag{7}$$

where, $x = [x_1, x_2, x_3]^T$ is state, $u = [u_1, u_2, u_3]^T$ is the controller of the system and the nonlinear right-hand side $F(x,u)$ is given by

$$F(x,u)=\begin{pmatrix} -0.0487x_1+0.5604x_3+u_1 \\ 0.0487x_1-0.0062u_2x_2 \\ -1.3752x_3+0.0062u_2x_2+0.2925x_3u_3 \end{pmatrix} \quad (8)$$

It is well understood that systems of nonlinear are difficult to handle, so here nonlinear systems are approximated to linear system by using the concept of Taylor's series expansion. The linearized system obtained is of the form $\dot{x}(\mathrm{t})=A(\mathrm{t})x(\mathrm{t})+\mathrm{B}(\mathrm{t})u(\mathrm{t})$, which is widely well-known linear control system. The controllability analysis of the linear system is well known and it is discussed briefly in the next section.

2.1 Preliminaries

2.1.1 Linearization of Nonlinear System

This section is devoted to the linearization of nonlinear systems.
Consider the nonlinear system

$$\dot{x}(\mathrm{t})=f(\mathrm{t},x(\mathrm{t}),u(\mathrm{t})) \quad (9)$$

Where the state $x(\mathrm{t})$ is an n-dimensional vector, controller $\mathrm{u(t)}$ is m-dimensional vector for all t, $f:\mathrm{R}^{+}\times R^{n}\times R^{m}\rightarrow R^{n}$ is a non-linear function.
Let $(\mathrm{x}_0,\mathrm{u}_0)$ be the reference point of the system (9) then, Taylor series expansion of the function at the reference point is given by:

$$f(x_0+\delta x,u_0+\delta u)=f(x_0,u_0)+\left.\frac{\partial f}{\partial x}\right|_{(x_0,u_0)}\delta x+\left.\frac{\partial f}{\partial u}\right|_{(x_0,u_0)}\delta u+higher\,order\,terms,$$

and therefore, we have: by neglecting the higher orders terms

$$\dot{x}_0+\delta\dot{x}\approx f(x_0,u_0)+\left.\frac{\partial f}{\partial x}\right|_{(x_0,u_0)}\delta x+\left.\frac{\partial f}{\partial u}\right|_{(x_0,u_0)}\delta u,$$

simplifying, we get

$$\delta x=\left.\frac{\partial f}{\partial x}\right|_{(x_0,u_0)}\delta x+\left.\frac{\partial f}{\partial u}\right|_{(x_0,u_0)}\delta u. \quad (10)$$

Define, $x=\delta x, u=\delta u,\ A=\left.\frac{\partial f}{\partial x}\right|_{(x_0,u_0)}$ and $B=\left.\frac{\partial f}{\partial u}\right|_{(x_0,u_0)}$ the system (10) becomes:

$$\dot{x}=Ax+\mathrm{B}u. \quad (11)$$

The equation (11) is the linearized form of the corresponding nonlinear system (9).

2.1.2 Basics of Mathematical Control Theory of linear system

This section discusses the introductory concept of on mathematical control theory for the linear control system [19].

Consider linear dynamical system,

$$\dot{x}(\mathrm{t})=A(\mathrm{t})x(\mathrm{t})+\mathrm{B}(\mathrm{t})u(\mathrm{t}), \quad (12)$$

$$x(t_0) = x_0 \tag{13}$$

Where, $x_0, x(t) \in R^n$, $u \in L^2([t_0, t_1], R^m)$ and $A(t), B(t)$ are matrices of dimensions $n \times n, n \times m$ respectively. Let $\Phi(t, t_0)$ be the transition matrix generated by the corresponding homogeneous system $\dot{x}(t) = A(t)x(t)$, the solution of system (12) – (13) is given by,

$$x(t) = \phi(t, t_0)x_0 + \int_{t_0}^{t} \phi(t, s)\, B(s)u(s)\, ds \tag{14}$$

Definition 1. The system (12) and (13) is said to be Controllable over $[t_0, t_1]$, if for each pair of vectors x_0 and x_1 in R^n there is a control $u \in L^2([t_0, t_1], R^m)$ such that the solution of (12) with $x(t_0) = x_0$ satisfies $x(t_1) = x_1$.

This means there is a control u satisfying,

$$x_1 = \phi(t_1, t_0)x_0 + \int_{t_0}^{t_1} \phi(t_1, s)\, B(s)u(s)\, ds \tag{15}$$

Let $$W(t_0, t_1) = \int_{t_0}^{t_1} \phi(t_1, s)\, B(s)\, B^*(s)\phi^*(t_1, s)\, ds$$

be the controllability grammian of the system.

Theorem 1. The system defined by (12) is said to be controllable if and only if the controllability grammian $W(t_0, t_1)$ is invertible and the control u is given by

$$u(t) = B^*\, \phi^*(t_1, t)W^{-1}(t_0, t_1)[x_1 - \phi(t_1, t_0)x_0]$$

Corollary 1. Kalmann Test for Controllability (for Finite Dimensional time invariant Systems):
If matrices A and B in (12) are constants (time invariant system) then the system is controllable if and only if the rank of matrix $[B, AB, A^2B, ..., A^{n-1}B] = n$.

3. Results & Discussion

This section discusses the controllability analysis of the system represented by the equations (8). Here $u_1 = w_c(t)$ flow of mass of the raw coal, $u_2 = w_{air}$ prime air mass of flow and $u_3 = \omega(t)$ the angular velocity(speed) of the classifier are considered as the controlled inputs, which we need to control for the running the coal mill as per the requirement. Since the obtained mathematical model of the coal mill is nonlinear, so for simplicity we consider the following cases:

3.1. Controllability analysis of the mass flow of raw coal

By fixing the mass flow of prime air u_2 and the angular velocity(speed) of classifier u_3 as 0.02 and 0.0001 [19], the system becomes:

$$\begin{aligned} \dot{x}_1 &= -0.0487x_1 + 0.5604x_3 + u_1 \\ \dot{x}_2 &= 0.0487x_1 - 0.000124x_2 \\ \dot{x}_3 &= -1.3752x_3 + 0.000124x_2 \end{aligned} \tag{16}$$

Equation (16) is clearly a linear time invariant system of the form

$$\dot{x}(t) = Ax(t) + B\,u(t) \tag{17}$$

Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 2s (2025)

with $A = \begin{pmatrix} -0.0487 & 0 & 0.5604 \\ 0.0487 & -0.000124 & 0 \\ 0 & 0.000124 & -1.3752 \end{pmatrix}$ and $B = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$

So we can apply the Kalman test to check its controllability. Applying Kalman condition, the rank of the matrix $Q = [\mathrm{B}, \mathrm{AB}, \mathrm{A}^2\mathrm{B}]$,

$$Q = \begin{pmatrix} 1 & -0.0487 & 0.00237169 \\ 0 & 0.0487 & -0.002377534 \\ 0 & 0 & 0.0000060388 \end{pmatrix} = 3 = \text{dimension of the state vector}$$

Thus the system (16) is controllable and controller $u(\mathrm{t}) = \mathrm{B}^* \phi^*(\mathrm{t}_1, \mathrm{t}) W^{-1}(\mathrm{t}_0, \mathrm{t}_1)[x_1 - \phi(\mathrm{t}_1, \mathrm{t}_0) x_0]$ drives the initial state x_0 to the desired final state x_1 in finite time T. So in this case we can always control the flow of mass of the raw coal into the coal mill if we choose the other controllers, the mass flow of prime air $u_2(\mathrm{t})$ and the angular velocity(speed) of classifier $u_3(\mathrm{t})$ as 0.02 and 0.0001 [19]. That is, the initial states $x_0 = (x_1 = m_c(\mathrm{t}), x_2 = m_{pc}(\mathrm{t}), x_3 = m_{cair}(\mathrm{t}))$ of the coal mill can be always reached to the final states $x_1 = (x_1 = m_c(\mathrm{t}), x_2 = m_{pc}(\mathrm{t}), x_3 = m_{cair}(\mathrm{t}))$ in a finite time T as per the requirement of the coal mill.

For example if we choose the initial states $x_0 = (x_1 = m_c(\mathrm{t}), x_2 = m_{pc}(\mathrm{t}), x_3 = m_{cair}(\mathrm{t})) = (1,1,1)$ and the final states $x_1 = (x_1 = m_c(\mathrm{t}), x_2 = m_{pc}(\mathrm{t}), x_3 = m_{cair}(\mathrm{t})) = (2, 0, -1)$ of the coal mill, then during the finite time $[0, \mathrm{T}]$ the behaviour of the states $x(\mathrm{t})$ and the controller is given by

- $x_1 =$[1.0000, -1.5494e+06, -2.1615e+06, -2.0062e+06, -1.2781e+06, -2.0090e+05, 9.6902e+05, 1.9374e+06, 2.3665e+06, 1.8689e+06, 1.8689e+06]
- $x_2 =$[1.0000, -4.1837e+03, -1.3567e+04, -2.3989e+04, -3.2176e+04, -3.5869e+04, -3.3979e+04, -2.6755e+04, -1.5981e+04, -5.2057e+03, 0.0000]
- $x_3 =$[1.0000, 0.8540, 0.6431, 0.3407, -0.0329, -0.4284, -0.7832, -1.0380, -1.1528, -1.1237, -1.0000]

3.2. Controllability analysis of the mass flow of the prime air

In this section we fix the controller $u_1 = 0.25$ and $u_1 = 0.0001$ [19] and study the controllability analysis of the third parameter $u_2 = w_{air}$ mass flow of the prime air. Taking the numerical values of the parameter [12], $\theta_1 = 0.0487, \theta_4 = 0.8148, \theta_5 = 0.0062, \theta_6 = 2.7855, \theta_9 = 0.5604$, the coal mill system (7) can be written as

$$\dot{x}_1 = -0.0487 x_1 + 0.5604 x_3 + 0.25$$
$$\dot{x}_2 = 0.0487 x_1 - (0.0062) u_2 x_2$$
$$\dot{x}_3 = -0.5604 x_3 - 0.8148 x_3 + (0.0062) u_2 x_2 + \frac{0.8148}{2.7855} 0.0001 x_2$$

Further, simplifying the system became,

$$\dot{x}_1 = -0.0487x_1 + 0.5604x_3 + 0.25$$
$$\dot{x}_2 = 0.0487x_1 - (0.0062)u_2x_2$$
$$\dot{x}_3 = (0.0062)u_2x_2 - 1.3752x_3$$

Hence, we can see that the above system of differential equations are Non-linear, which is difficult to study directly. So, it is convenient to study its controllability if we linearize the system at the equilibrium point.

The matrices A and B obtained after linearization of the non-linear system at the equilibrium point $(x_0, u_0) = (0,0)$ is given by:

$$A = \begin{pmatrix} -0.0487 & 0 & 0.5604 \\ 0.0487 & 0.0062u_2 & 0 \\ 0 & 0.0062u_2 & -1.3752 \end{pmatrix} \ \& \ B = \begin{pmatrix} 0 \\ -0.0062x_2 \\ 0.0062x_2 \end{pmatrix}$$

After putting the equilibrium point $(x_0, u_0) = (0,0)$. We have the following:

$$A = \begin{pmatrix} -0.0487 & 0 & 0.5604 \\ 0.0487 & 0 & 0 \\ 0 & 0 & -1.3752 \end{pmatrix} \ \& \ B = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

Since all the elements of matrix B are zero, we have the Matrix $Q = [\mathrm{B}, \mathrm{AB}, \mathrm{A}^2\mathrm{B}] = 0$. So, we can not study controllability of the system by using the concept of Kalman test for this case. Hence the method fails here.

3.3. Controllability analysis of the the angular velocity(speed) of the classifier

In this section, we fix the value of the controllers $u_1 = 0.25$ and $u_2 = 0.05$ [19] and study the controllability analysis for the controller u_3, the angular velocity(speed) of the classifier. The numerical values of the parameters are $\theta_1 = 0.0487, \theta_4 = 0.8148, \theta_5 = 0.0062, \theta_6 = 2.7855, \theta_9 = 0.5604$ [12].

Thus, the equation (7) become

$$\dot{x}_1 = -0.0487x_1 + 0.5604x_3 + 0.25$$
$$\dot{x}_2 = 0.0487x_1 - (0.0062)(0.02)x_2$$
$$\dot{x}_3 = -0.5604x_3 - 0.8148x_3 + (0.0062)(0.05)x_2 + \frac{0.8148}{2.7855}u_3x_3$$

This can be simplified as follow:

$$\dot{x}_1 = -0.0487x_1 + 0.5604x_3 + 0.25$$
$$\dot{x}_2 = 0.0487x_1 - 0.000124x_2$$
$$\dot{x}_3 = 0.0031x_2 - 1.3752x_3 + 0.2925u_3x_3$$

Again, system of differential equations are Non-linear. Thus, the corresponding linearized form is obtained. The matrices A and B are derived by the process of linearization of Non-linear system at the equilibrium point $(x_0, u_0) = (0,0)$ is given by:

$$A = \begin{pmatrix} -0.0487 & 0 & 0.5604 \\ 0.0487 & -0.000124 & 0 \\ 0 & 0.0031 & -1.3752 + 0.2925u_3 \end{pmatrix} \; \& \; B = \begin{pmatrix} 0 \\ 0 \\ 0.2925x_3 \end{pmatrix}$$

at the equilibrium point $(x_0, u_0) = (0,0)$.

$$A = \begin{pmatrix} -0.0487 & 0 & 0.5604 \\ 0.0487 & -0.000124 & 0 \\ 0 & 0.0031 & -1.3752 \end{pmatrix} \; \& \; B = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

Since all the elements of the matrix B are again zero, so we have the Matrix $Q = [\mathrm{B}, \mathrm{AB}, \mathrm{A}^2\mathrm{B}] = 0$ So, we can not study controllability of the system by using the concept of Kalman test for this case also. Hence the method fails here.

4. Conclusion

This manuscript discussed the controllability analysis of coal mill pulverizer process by taking several cases. In first case the prime air mass of flow and angular velocity(speed) of the classifier are fixed and the system thus obtained are linear time-invariant system. And using the concept of linear controllability, we obtain the rank of the controllability matrix Q is 3 and the controllability grammian is invertible. Therefore, the system is controllable. That is, flow of mass of the raw coal into the coal mill can always be controlled as per the requirement. Fixing mass flow of row coal and the angular velocity(speed) of the classifier, the system becomes nonlinear, linearizing the nonlinear system at the equilibrium point, the matrix B is zero matrix and the thus the controllability cannot be studied by the above method. Similarly, by fixing the mass flow of mass of the raw coal and mass flow of the prime air, the system again become nonlinear and linearizing the system at the equilibrium point the matrix B obtained is again zero matrix. Thus, the ongoing theory of controllability cannot be applied for this case also. Thus, we conclude that we can study the controllability analysis of the coal mill pulverizer process for the flow of mass of the raw coal into the coal mill. For studying the controllability of other parameters, we should try to handle the nonlinear system directly and by not fixing any of the other control parameter.

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