Adaptive Fuzzy Logic Controller for Rotary Kiln Control

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***Abstract* — *The Rotary Kiln forms the heart of the cement manufacturing plant where most of the energy is being consumed by the burning of clinker, which when powdered and mixed with gypsum gives cement. In order to assure acceptable qualities for the clinker, it is important to make sure that the raw meal fed to the rotary kiln has been properly burnt for which the temperature in the burning zone needs to be maintained at a specified range. Moreover, kiln exhibits a nonlinear behavior, which is time varying and has an inherent process lag, with complex multivariable interactions. Due to these reasons, world over, the kiln control operations are handled by expert plant operators and extreme importance is given for the control of sintering(clinkering) temperature. The multi-variable and nonlinear behavior of the kiln process makes it inadmissible for automatic control. The objective of the kiln control system is to ensure the production of desired quality clinker efficiently and to supply it to the cement mill uninterruptedly as per the demand.*

In this paper, a Fuzzy Logic Controller system is proposed to run on MATLAB, that translates the operators knowledge into membership functions that can well handle the operation of the kiln. The controller was compared with its SIMULINK model. The controller is then made adaptive by making it self-tuned even when their is a change in set point.

***Index Terms* — Rotory kiln, FLC, Adaptive, Controller, Fuzzy Logic, MATLAB, SIMULINK, Clinker .**

I. INTRODUCTION

Cement production is a complex process, composed of a series of activities requiring substantial technological support [1] . Although cement is the final product of a cement factory, the output product of kiln is called clinker. Producing clinker with high quality leads to efficiency improvement in energy consumption, input materials, and by reducing environmental pollutions.

The rotary kiln consists of a tube made from steel plate, and lined with firebrick. The tube slopes slightly (1–4°) and slowly rotates on its axis at between 30 and 250 revolutions per hour. Raw mix is fed in at the upper end, and the rotation of the kiln causes it gradually to move downhill to the other end of the kiln. At the other end fuel, in the form of gas, oil, or pulverized solid fuel, is blown in through the "burner pipe", producing a large concentric flame in the lower part of the kiln tube. As material moves under the flame, it reaches its peak temperature, before dropping out of the kiln tube into the cooler. Air is drawn first through the cooler and then through the kiln for combustion of the fuel. In the cooler the air is heated by the cooling clinker, so that it may be 400 to 800°C before it enters the kiln, thus causing intense and rapid combustion of the fuel.

A typical process of manufacturing clinker consists of three stages, in which, grinding a mixture of limestone and clay or shale to make a fine "rawmix" forms the first stage. In the second stage heating of the rawmix to sintering temperature (up to 1450 °C) takes place, in a cement kiln. And finally grinds the resulting clinker to make cement. In this second stage is the most complex stage where the rawmix is fed into the kiln and gradually heated by contact with the hot gases from combustion of the kiln fuel. Successive chemical reactions take place as the temperature rises. Free water gets evaporated at 70 to 110 °C. Minerals are decomposed into their constituent oxides; principally SiO_2 and Al_2O_3. Dolomite ($CaMg(CO_3)_2$) decomposes to $Ca(CO)_3$, MgO and CO_2 at 400 to 600 °C . From 650 to 900 °C, $Ca(CO)_3$ reacts with SiO_2 to form belite (Ca_2SiO_4). The $Ca(CO)_3$ present, decomposes to CaO and CO_2 at 900 to 1050 °C. While temperature is 1300 to 1450 °C, partial (20–30%) melting takes place, and belite reacts with calcium oxide to form alite($Ca_3O{\cdot}SiO_4$). Alite is the characteristic constituent of Portland cement. Typically, a peak temperature of 1400–1450 °C is required to complete the reaction. The partial melting causes the material to aggregate into lumps or nodules, typically of diameter 1-10 mm. This is called clinker.

In this paper, a model that behaves exactly like Cement kiln is identified using System Identification toolbox in MATLAB with kiln speed (KS), Coal feed (CF), Kiln feed (KF) and Preheater fan speed (PHFS) as inputs and Burning Zone Temperature (BZT), Torque (TOR) and Kiln inlet temperature. A Fuzzy Logic Controller is then designed to work on this system for desired set points. The system is then made adaptive to work on a range of set points.

II. CHALLENGES

A rotary kiln in a cement plant is a complex system with multi-variable interactions and non-linearities. Almost all unit operations in the cement manufacturing process constitute technical challenges towards automatic control due to their multi-variable, interacting, and nonlinear nature. Energy recycles of secondary and tertiary air flows make the system highly interactive. Sometimes a cyclical behavior is induced when coupled with feedback from the changes in the cooler under-grate pressure at the kiln outlet. These characteristics, along with large lags in the system and the lack of direct measurements of key process parameters, lead to a complex control problem that cannot be adequately addressed by conventional controllers. Additional issues include disturbances in raw material properties, heat input, conditions of the surrounding environment, and skill of the control room operator. Manual control is normal in cement plants, with heavy dependence on the knowledge and expertise of the operator. Plant performance can vary considerably based on the maturity and experience of the operator. Multi-variable interactions limit the capability of the operator to make control decisions. An increased level of automation is required to bring about yield enhancement and cost reduction.

The classical (P, PI, PID) control technique has been the basis in simple control systems. Its simplicity has been the main reason for its wide applications in industry. Since classical controllers are fixed-gain feedback controllers, they can't compensate the parameter variations in the plant and can't adapt changes in the environment. In classical conventional techniques, mathematical modeling of the plants and parameter tuning of the controller have to be done before implementing the controller. Most real systems, relevant from a control perspective, exhibit nonlinear behavior; furthermore, to model these systems are often troublesome, sometimes impossible using the laws of physics. Therefore, using a classical controller is not suitable for nonlinear control application. Proportional integrated Derivative (PID) controllers are widely used in process control applications, but they exhibit the poor performance when applied to systems, which are nonlinear, as controller tuning is difficult due to insufficient knowledge of the parameters of the system. The need to overcome such problems and to have a controller well-tuned not only for one operating point but also for a whole range of operating points has motivated this work.

III. PROBLEM DEFINITION

The main conditions to be satisfied in cement kiln operation for high quality clinker production and lower environmental impact are

- Steady burning zone temperature around the range required for complete chemical reaction
- Suitable retention time for material in kiln
- Steady suitable temperature of the preheater to ensure proper calcination in preheater which is necessary for kiln stability
- Limited amount of CO in exhaust gas which ensures proper burning of fuel

For satisfying these conditions we select 4 kiln variables or inputs as

- The burning zone temperature (BZT) :which is related to the quality of the produced clinker which should be in the range of 1350-1450 ^{o}C for good clinker.
- The Torque of the kiln (TOR) : which represents the distribution of material phases inside the kiln.
- The kiln inlet temperature (KIT): which represents the temperature at the kiln inlet, where the raw meal is fed in.

The kiln has 4 controls or the consequent's to control the kiln and produce clinker with accepted quality and low power consumption

- The kiln feed (KF): is the raw meal fed to the kiln. This represents the productivity of the kiln and ranges from 60-90 tonnes
- The coal fuel (CF): represents the fuel consumed to heat up the material which moves across the kiln and this allows the clinker minerals to form C_2S , C_3S,etc.
- Preheater (Dopol) fan speed (PHFS): This controls the flow of gases in the kiln and adjusts the oxygen percent in the system. Oxygen percentage decides the complete combustion of fuel
- Kiln speed (K.S): which controls the speed of material from the kiln inlet to the kiln outlet. It takes a range of 0.5-3.5 rpm.

The proposed controller is s1witched on after the kiln has started up and reached the normal values of the kiln operation.

IV. SYSTEM DESIGN

The inputs Kiln Feed (KF),Coal Feed (CF),Kiln Speed (KS),Pre-heater Fan Speed (PHFS) and corresponding outputs Kiln Inlet Temperature (KIT),Torque (TOR), Burning Zone Temperature (BZT) were fed to System Identification toolbox of MATLAB to get state space representation of kiln
.
The system matrix A was obtained as

$$A = [\ 0.1386\ \ -0.1335\ ;\ -0.9293\ \ -0.2274]$$

The input matrix B was obtained as

$$B = [\ 0.007706\ \ -0.13\ \ -0.01599\ \ -0.0002122\ ;\ -0.006982\ \ 1.065\ \ -1.294\ \ 0.001907\ ]$$

The output matrix C was obtained as

$$C=[\ -540\ \ -78.9;\ -559\ \ -115;\ -1365\ \ -200\ ]$$

The study of kiln response to various inputs is essential for the design of FLC. The Burning zone temperature, Kiln inlet temperature and torque for different variations of one input keeping all other inputs constant is carried out and the results and inferences are shown below

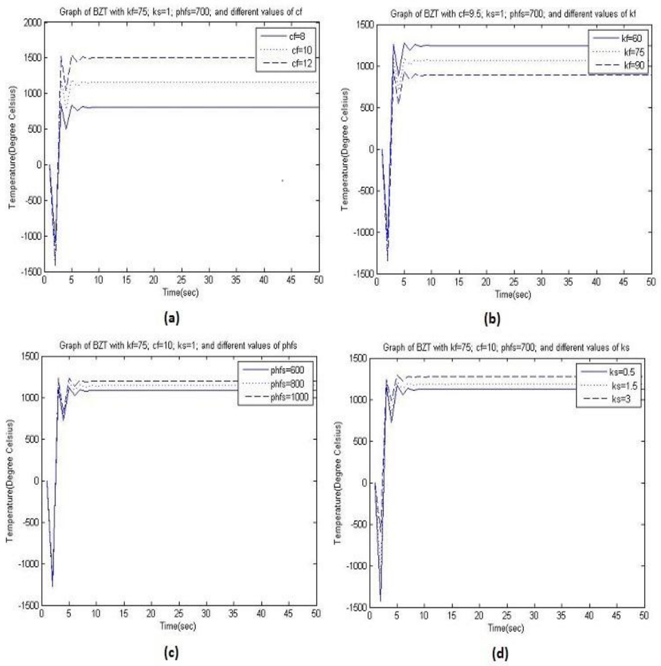


Figure 4.1 BZT at different values of (a) coal feed (b) kiln feed (c) preheater fan speed (d) kiln speed

BZT rises with a rise in coal feed, preheater fan speed, kiln speed and a fall in kiln feed. Kiln inlet temperature also behaves exactly same as Burning zone temperature, whenever there is a hike in BZT, that hike will also be reflected in KIT. So when they increase beyond set point, we have to increase the kiln feed. But coal feed and preheater fan speed are directly proportional to the burning zone temperature and kiln inlet temperature. So an increase in output temperatures requires these inputs to be increased. the torque and kiln speed are directly proportional. Considering these facts, the rules were designed.

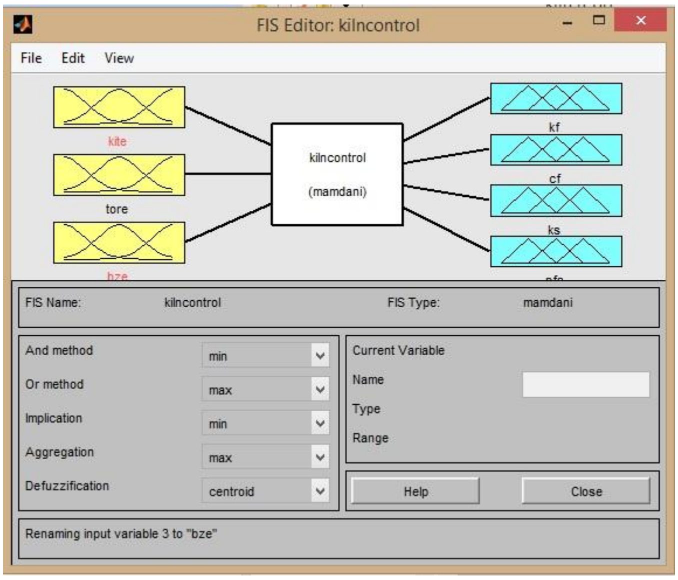
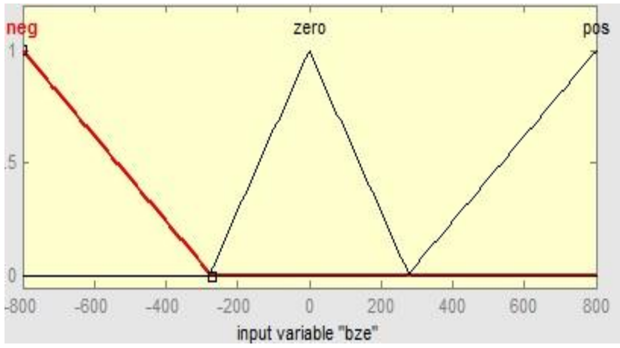
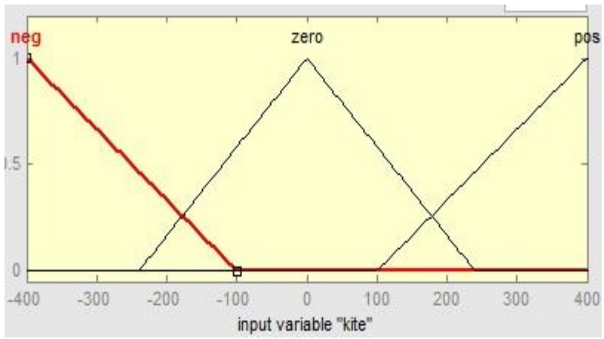


Figure 4.1 FIS editor showing 3 inputs and 4 outputs

The Fuzzy Inference System (FIS) has 3 inputs and 4 outputs. Deviations of burning zone temperature, Kiln inlet temperature and Torque from their set points forms the input to the system. For each input there are 3 membership functions pos, neg , zero denoting positive, negative and zero error regions. For each output also there are 3 membership functions low, normal, high. The triangular membership function is chosen because it is sufficient to describe data distribution of the system as well as its computational simplicity. Membership functions are designed are shown below



(a)



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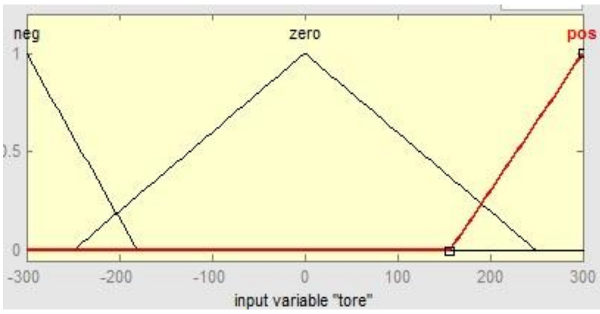


(c)

Figure 4.1 Membership functions of a) error of Burning zone temperature (b) error of Kiln inlet temperature (c) error of torque

By studying the kiln response to various inputs to the system, a set of fuzzy rules were written. As there are 3 inputs to the system, by default the number of rules becomes 27.

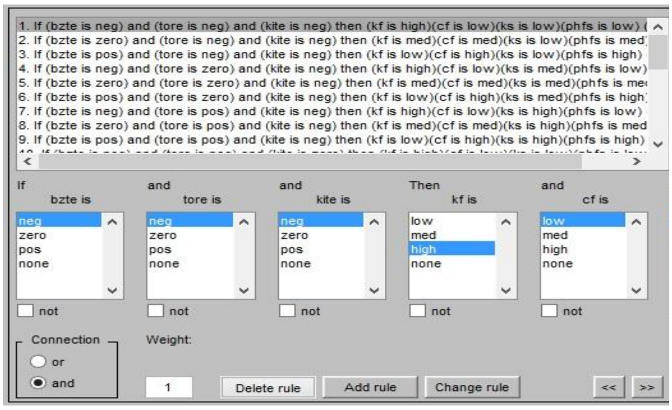


Figure 4.1 Rules editor showing fuzzy rules of the system

To make this system adaptive, the BZT setpoint is selected as the parameter that is varied. From the study it is known that the desired Burning Zone temperature for good clinkering is from 1200-1400°C. The set point with which FLC designed was 1300°C. The adaptive controller should be designed in such a way that any value of BZT set point in the range of 1200 to 1400 can make the burning zone temperature equal to the given set point.

It is not possible to edit the rules while making the system adaptive as it will change the FLC itself. So the system should be made adaptive by changing the membership functions. For simplicity, the membership function of coal feed rate alone is changed, as a small change in the coal feed rate causes a big change in BZT. Kiln feed can't be selected as it will vary the quantity of clinker obtained. Too much or too less quantity of clinker may affect the demand. The membership function of coal feed rate was manually shifted to both sides by one point to see the change in BZT. By this we can infer that the change of BZT set point in between the range 1200-1400°C can be done effectively by shifting the membership function one point in either direction.

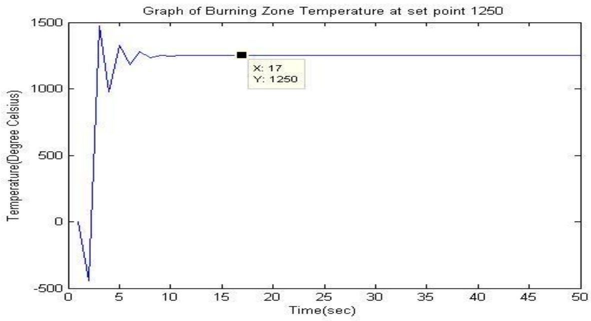
Adaptive algorithm

The adaptive algorithm designed is as follows:

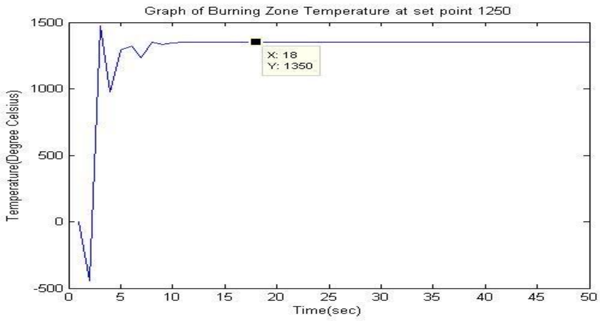
1. Define variable p=9.46 , q=10.84 and m=10
2. initialize BZTE to a non zero value greater than 1
3. Copy the FLC system and redefine the coal feed rate MF in terms of x as its mid point
4. Feed the system with a desired set point for BZT(bztset) which lies in between 1200 and 1400
5. when absolute value of BZTE greater than 1 do steps 6 and 7
6. The FLC system is made to run with x=m for 15 iterations
7. If the error bzte is positive, then x=(m+q)/2 p=m else x=(m+p)/2 and q=m
8. Run the Control system to get the desired response
9. end

V. SIMULATION RESULTS

The adaptive algorithm is simulated using Matlab and the results shows that the that the adaptation law works well and controls the BZT to the setpoints. So the controller can now work perfectly well with any burning zone temperature between 1200-1400 °C



(a)



(b)

Figure 4.1 Burning zone temperature at (a) BZT setpoint 1250 °C (b) BZT setpoint 1350 °C

VI. CONCLUSION

In this paper a fuzzy logic controller has been developed, which effectively controls the kiln variables to set of values, which can meet the desired clinker quality. The controller is then made adaptive, to adapt to the changes in burning zone temperature set points. A state space representation of kiln was identified which shows the same behavior as kiln. The responses were studied in order to design the Fuzzy logic controller. The behavior is non-linear which limits the use of ordinary controllers. The software used is MATLAB .The controller response stabilizes within 10sec which shows that a faster control action than using PID controllers. The controller is made adaptive by changing its membership function, to adapt to any setpoint of burning zone temperature (BZT) in the range 1250-1350 °C, which produces clinker of excellent quality.

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