Research Journal of Engineering Sciences ISSN 2278 – 9472
Vol. **1(2),** 51-62, August **(2012)** *Res. J. Engineering Sci.*

FLC and PLC based Process Optimization and Control of Batch Digester in Pulp and Paper Mill

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Available online at: www.isca.in
Received 20th August 2012, revised 23rd August 2012, accepted 24th August 2012

Abstract

Optimization and control of a batch digester operation is necessary to improve the quality of pulp produced in the pulp and paper mill. The process involves controlling all the phases of the entire cooking cycle. Pulp and paper process is nonlinear and non stationary in nature. In such type of process it is difficult to derive and identify an appropriate dynamic model for traditional controllers due to less reliability of mathematical model of the process. So instead of conventional or advanced controller which totally depends on mathematical model of process, a fuzzy logic control strategy has been proven better option for controlling such processes. This scheme of control will evaluate certainty within uncertainty and handling the parameters within range of control the entire process continuously through fluctuations occurs. In present paper, programmable logic controller (PLC) and a fuzzy logic controller (FLC) based schemes for automation and control of pulp and paper mill batch digester has been purposed and implemented which show consistent results. The system design starts from identification of inputs, outputs and choosing the membership function for each condition from normal operation up to emergency operation of pulp and paper mill batch digester. PLC provides control of pulp digesters for the process of making pulp from wood chips. PLC are used to calculate and control the amount of chips, based on density and the digester volume; determine the quantity of cooking liquors and add the required amounts in sequence. Programmable controllers also control temperature till cooking is completed. Rs logic 500 based SLC 500 processors [CPU 1747-120 C/F] produces better stabilize and optimize operation of batch digester.

Keywords: *Fuzzification, Inference engine, defuzzification, PLC, FLC, MSF, ladder diagram.*

Introduction

Paper industry in India is the 15th largest paper industry in the world. The government regards the paper industry as one of the 35 high priority industries of the country which generating more than 1.3 million employment through agricultural activities directly and indirectly[1]. The pulp and paper industries in India have been categorized into large-scale and small-scale. Those paper industries, which have capacity above 24,000 tons per annum, are designated as large-scale paper industries. Pulp and paper are manufactured from raw materials which containing cellulose fibers[2], generally wood, recycled paper, and agricultural residues. Cellulose fibers originate from nonwood raw materials such as bagasse (sugar cane fibers), cereal straw, bamboo, reeds, esparto grass, jute, flax, and sisal. The main steps in pulp and paper manufacturing are raw material preparation, such as wood debarking and chip making, pulp manufacturing, pulp bleaching, paper manufacturing and fiber recycling. Pulp and paper mills may exist separately or as integrated operations. Manufactured pulp is used as a source of cellulose for fiber manufacture and for conversion into paper or cardboard. The manufacture of pulp for paper and cardboard employs mechanical, thermo mechanical, chemimechanical, and chemical methods. Mechanical pulping separates fibers by such methods as disk abrasion and billeting. Chemical pulps are made by cooking (digesting) the raw materials, using the Kraft (sulfate) and sulfite processes. Kraft processes produce a variety of pulps used mainly for packaging and high-strength papers and board. Wood chips are cooked with caustic soda to produce brown stock, which is then washed with water to remove cooking (black) liquor for the recovery of chemicals and energy. In the case of chemical pulps (Kraft and sulfite), the objective of bleaching is to remove the small fraction of the lignin remaining after cooking so that fibers are free and can be easily molded to the required characteristics. An alkali, such as sodium hydroxide, is necessary in the bleaching process to extract the alkali-soluble form of lignin. Pulp is washed with water in the bleaching process.

Although chemical pulping digestion processes have been widely applied in paper industry but the effective control of such processes is still an unsolvable problem. Wood chip quality variations, measurement of physical parameters problems and long process time delay make the process control difficult due to less reliability of mathematical model of such processes. Conventional controller such as PID can not be effectively used in batch processes because of its nonlinear and non stationary nature. The prime objective of the present work is to investigate and implement FLC and PLC based intelligent process control techniques to automate and optimize the batch digestion processes in pulp and paper industrial applications. The Fuzzy control is emerging as a technology that can enhance the capabilities of industrial automation and is suitable for control level tasks generally performed in programmable controllers

(PC). It is one of the recent developing methods in control that are gaining more popularity. The main reason for this popularity is that it utilizes concepts and knowledge that do not have well defined sharp boundaries; therefore it can alleviate the difficulties encountered by conventional mathematical tools in developing and analyzing complex systems.

Figure 1 shows the structure of fuzzy controller. Fuzzification is the process of converting the inputs variable values (sensor signal values) into linguistic variable values or membership function in fuzzy logic sets (fuzzy values). Rule-base of fuzzy logic breaks the control problem down into a series of IF X and Y then Z rules that define the desired system output response for given system input conditions. The number and complexity of rules depends on the number of input parameters that are to be processed and the number of fuzzy variables associated with each parameter[3-5]. Create fuzzy logic membership functions that define the meaning (values) of input/output terms used in the rules. Defuzzification is the process in which output linguistic variable value (fuzzy variable value) is translated into crisp value (real value). Fuzzy tech software 5.5[6] is used for the automatic control of pulp and paper mill batch digestion process. It contains all the editors, analyzers and tools to design a complete fuzzy logic system. It supports various fuzzy logic inference methods and algorithms. The first step in a fuzzy logic system design is the definition of the system structure. Here, we define the inputs and outputs of the fuzzy logic system and how they interact. As shown in figure 2 the small blocks on the left side are the input interfaces. The input interfaces also contain the fuzzification of the input values. The icon on the left indicates the employed fuzzification method. The small blocks on the right side are the output interfaces that contain the defuzzification method. The larger block in the middle of the screen is the rule blocks. The rule blocks each contain an independent set of fuzzy logic rules. The left column shows the variables used in the precondition of fuzzy rules. The right column shows the variables used for the conclusion of fuzzy rules. The upper box displays the condition aggregation operator. The lower box shows the result aggregation operator.

The spreadsheet rule editor shown in figure 3 represents the rule (of a rule block) as rows in a spreadsheet. Below the toolbar is the head of the spreadsheet, the [IF] and [THEN] fields, with the rule block input and output variables. A column is assigned to each input variable, showing its terms. A DoS column is assigned to each output variable, containing the degree, to which a rule is supported (degree of support = DoS) or, to put it another way, the rule's weight.

Programmable logic controller (PLC) is an industrial computer control system that continuously monitors the state of input devices and makes decisions based upon a custom program, to control the state of devices[7-9] connected as outputs. Almost any production line, machine function or process can be automated using a PLC. The speed and accuracy of the operation can be greatly enhanced using this type of control system. But the biggest benefit in using a PLC is the ability to change and replicate the operation or process while collecting and communicating vital information.

PLC provides control of pulp digesters for the process of making pulp from wood chips. PLCs are used to calculate and control the amount of chips, based on density and the digester volume; determine the quantity of cooking liquors and add the required amounts in sequence. Programmable controllers also control temperature till cooking is completed. SLC 500 Programmable Logic Controller is used in present investigation. RS Logic 500 is compatible with SLC 500 ladder programs created with any of Rockwell software's programming packages[10].

Material and Methods

The digester is an integral machine in the making of paper. Without it and the chemicals used within it, paper would not be able to be produced as quickly / efficiently. Its purpose is to cook small wood chips for several hours in order to soften them. These softened chips are then passed to a machine that whitens them to the desired shade. In addition, the quality of the paper would suffer without the benefit of being cooked and treated in the digester. The digester itself can be horizontal, upright, revolving, spherical, or cylindrical. There are two types of digesters: Kraft (sulfate) and sulfite. The sulfite digester utilizes calcium acid sulfite to aid in the process, which is usually referred to as the acid process. The Kraft process uses an alkaline system instead. The Kraft process is newer than the sulfite process, but it is used by more companies because it is less corrosive and more efficient.

In order to achieve objective of automation of paper mill batch digester, first we need to develop the process flow diagram and PandID of pulp and paper batch digestion processes. P and IDs play a significant role in the maintenance and modification of the process that it describes[3,4,9]. During the design stage, the diagram also provides the basis for the development of system control schemes, allowing for further safety and operational investigations[3,4,9,11]. Pulping process is carried out in digesters. Pulp digesters convert wood chips into pulp by the Kraft pulping process. Batch digesters fall into two categories directly heated and indirectly heated. Figure 4 show a simple process diagram of an indirectly heated batch digester. It is a closed vessel initially filled up with an aqueous mixture of sodium hydroxide and sodium sulfite (called white liquor) to remove lignin from wood chips by the Kraft reaction. Reaction temperature is controlled by manipulating the temperature and flow rate of the recirculating liquor. The principle operation in batch digester includes chip packing and steaming, liquor filling, relief of gases, cooking at maximum temperature, relief of pressure and blowing the digester. Each of these operations affects pulp properties and variations in quality.

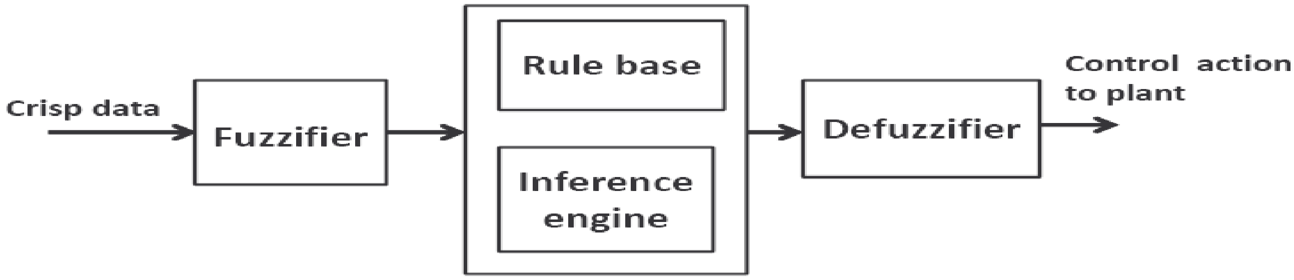


Figure-1
Structure of a fuzzy controller

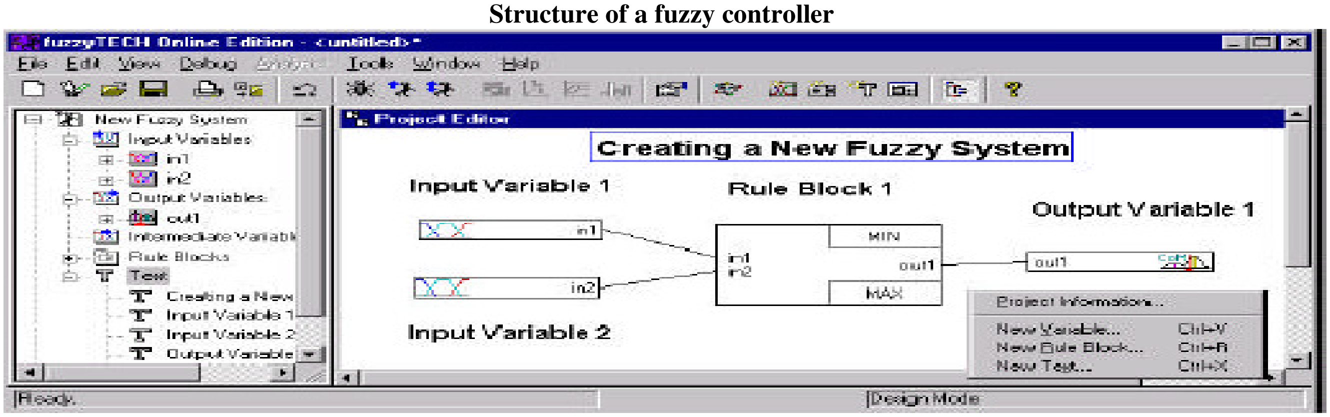


Figure-2
Text block explaining object of Fuzzy control system

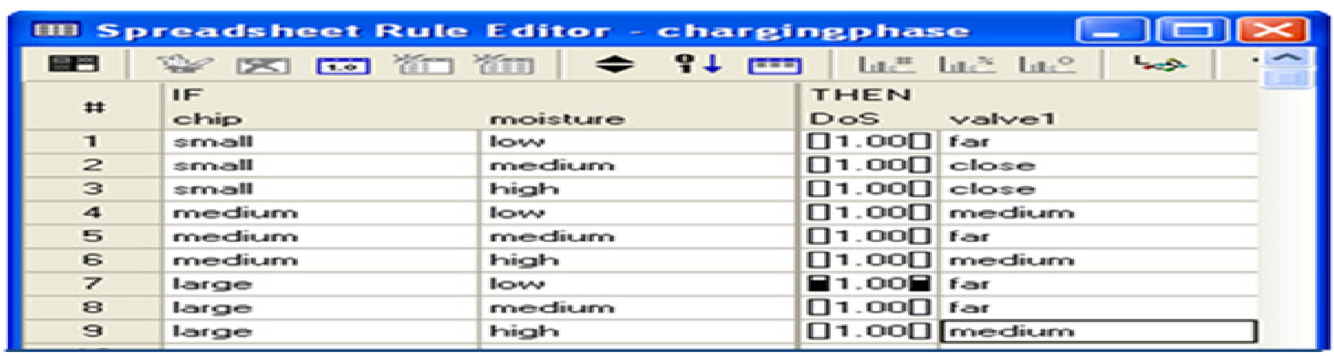


Figure-3
Rule Block Properties: Operators Dialog

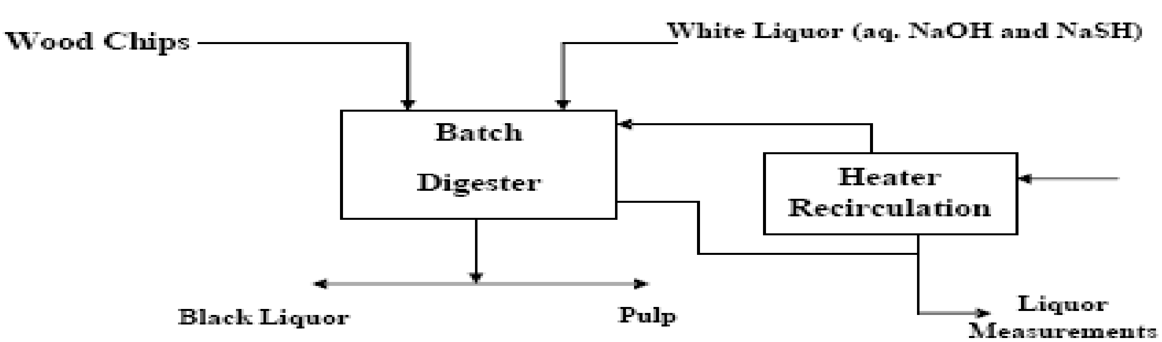


Figure-4
Schematic Flow Diagram of the Batch Pulp Digester

The figure 5 shows the Pand ID of pulp and paper mill batch digester. A batch digester can be heated in two different ways, by direct steaming or by indirect heating with forced circulation. In direct heating method, steam is injected through a valve in the bottom of digester. The difference in temperature between top and bottom makes the liquor circulate by convection, and hot liquor rises through the middle of digester, while colder liquor at the top flows down the walls to the bottom where it meets the hot steam and is reheated. Indirect heating includes a circulation system with pump, an external heat exchanger, and strainer plates in the middle section. The liquor is heated in a heat exchanger where the heating medium is steam that condenses. The hot liquor is then returned to the top and bottom of the digester. Indirect heating with forced liquor circulation avoids liquor dilution and a more uniform temperature profile throughout the digester is achieved. The liquor is normally introduced to digester at about 70^0C. Heating time varies from 30 to 120 minutes. Maximum temperature reached ranges from 160^0C to 180^0C. During heating and cooking, gases are formed. Remaining air and other non condensable gases, such as CO_2, which is released in the cooking reactions, also accumulate. These gases must be removed from the digester otherwise digester pressure will be higher than the steam pressure corresponding to liquor temperature. This “false pressure” can be lead to problem with cooking control. When predetermined cooking time is reached, partial pressure released by operating the gas relief valve and releasing gases. Once the digester has reached blowing pressure, the bottom valve is opened and content is blown in the blow tank.

The figure 6 shows the schematic of digester control/optimization. In charging phase of digester it is necessary to monitor the weight of wood chip being fed into along with its moisture. This enables us to determine the OD weight of wood chips being fed. The OD weight decides the amount of liquor to be used for cooking in digesters. Addition of liquor is usually done in a particular ratio called the liquor wood ratio. The cooking phase is the most important phase where end of the cook is to be determined accurately so that any over or under cooking of the pulp is avoided thereby resulting in good quality pulp and minimizing the wastage of raw materials. The parameters that must be maintained carefully during cooking are effective alkali concentration of the cooking liquor, liquor quantity, digester temperature and digester pressure. Cooking reactions start when chips reach the cooking temperature, about 150 - 170^oC, depending on the wood species and grade requirements. The active chemicals of the cooking liquor react with lignin in chips and convert it chemically into the compounds that dissolve in the cooking liquor. Fibers are separated into the mass since the bonding material of the chips is dissolved.

Design and developed fuzzy logic controller based scheme for automation of pulp and paper mill batch digester have been illustrated in figure 7. As shown in figure 7, there are inputs to fuzzy controller namely wood chip, moisture, liquor, temperature, pressure and outputs namely odweight, pulp, lignin, pulp blow. Valves are used to control the tempreture, pressure and pulp flow.

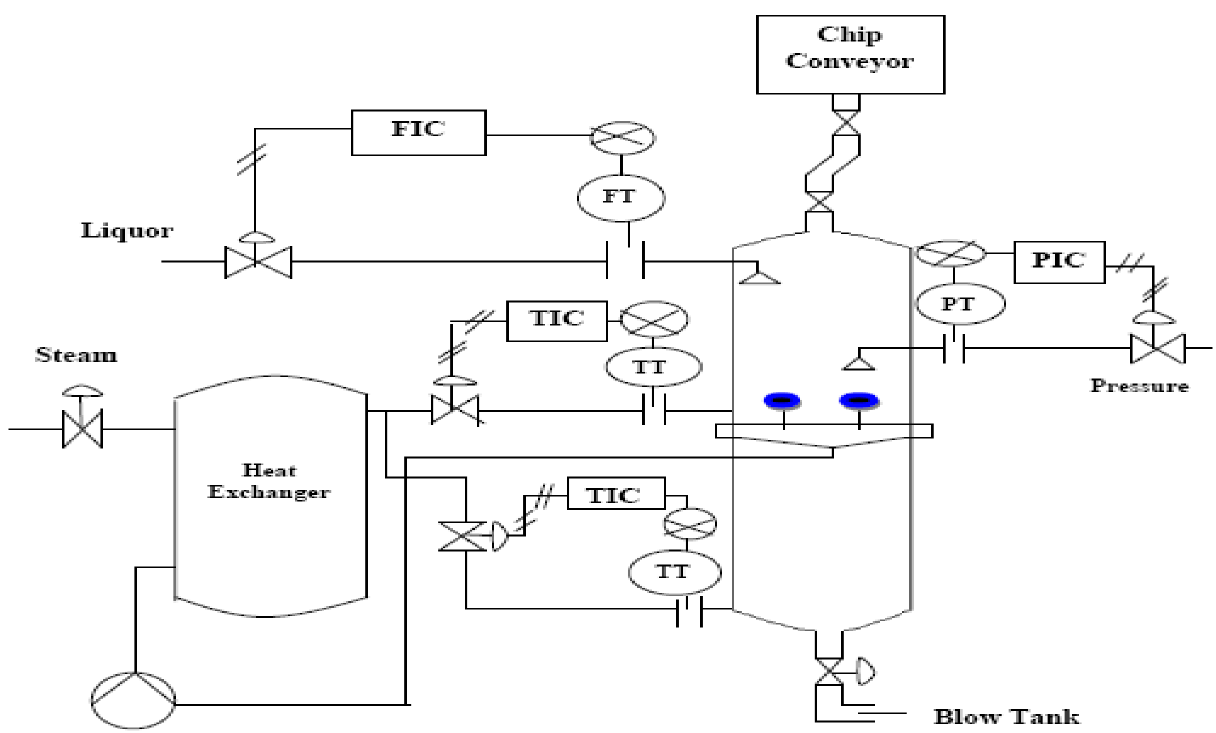


Figure-5
Pand ID of pulp and paper mill batch digester

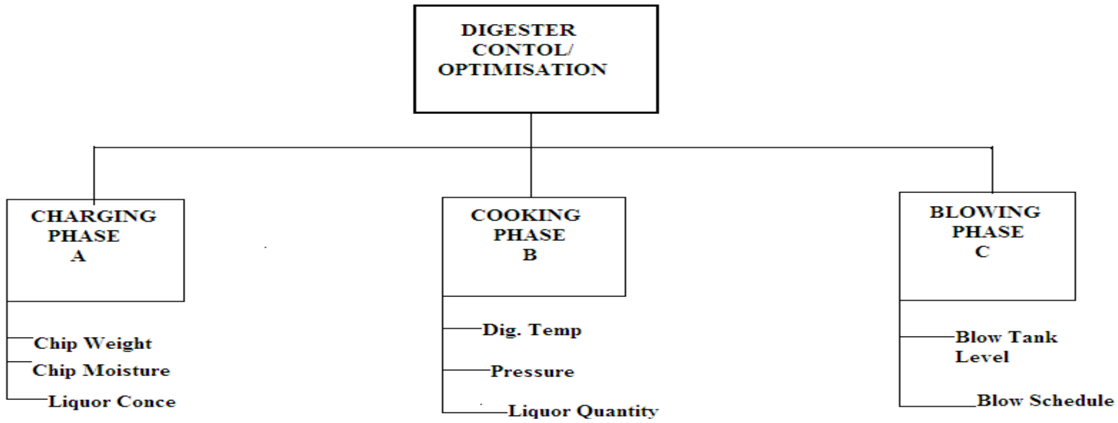


Figure-6
Digester Control/Optimization

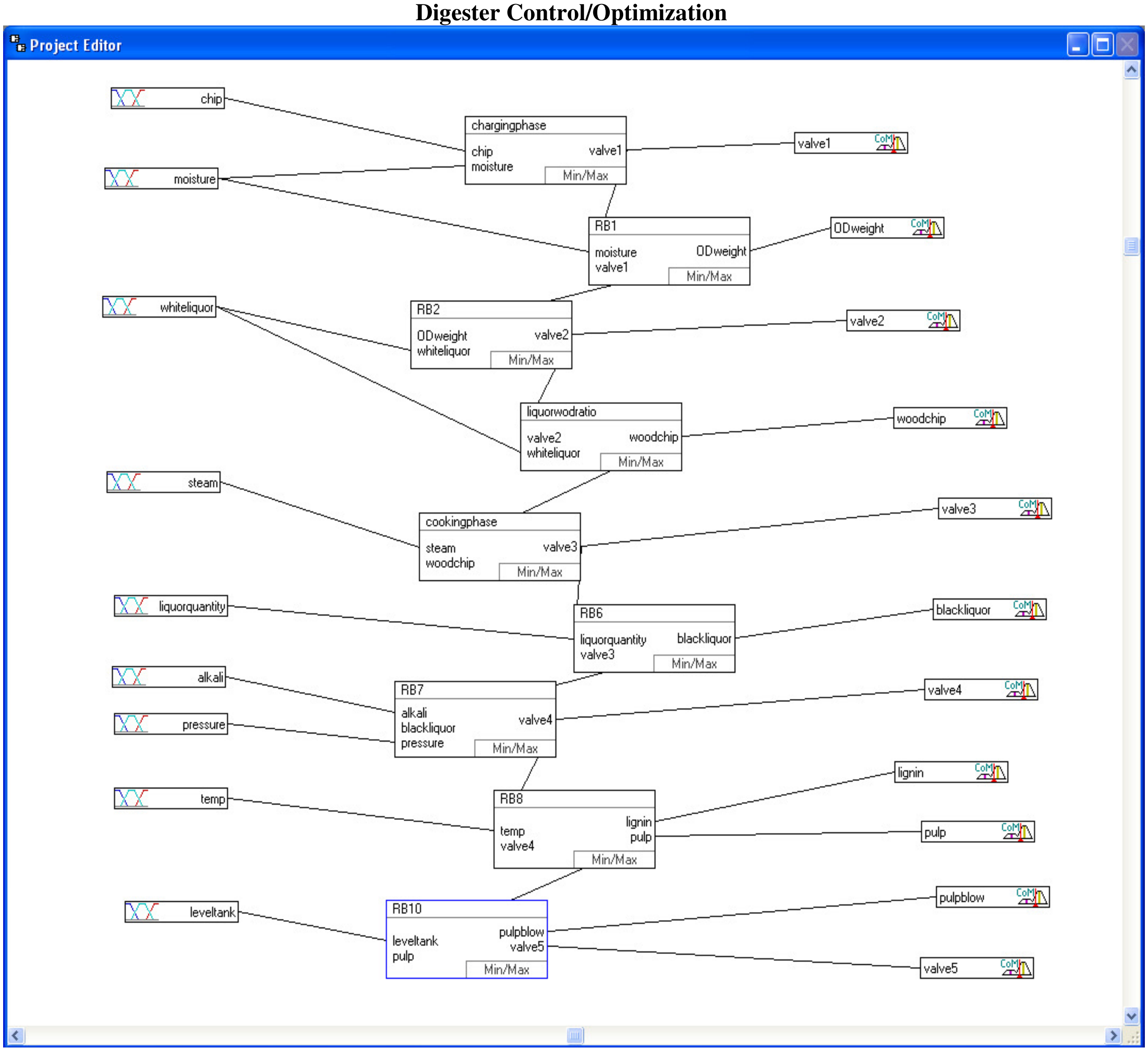


Figure-7
Fuzzy Logic Controller for batch digester

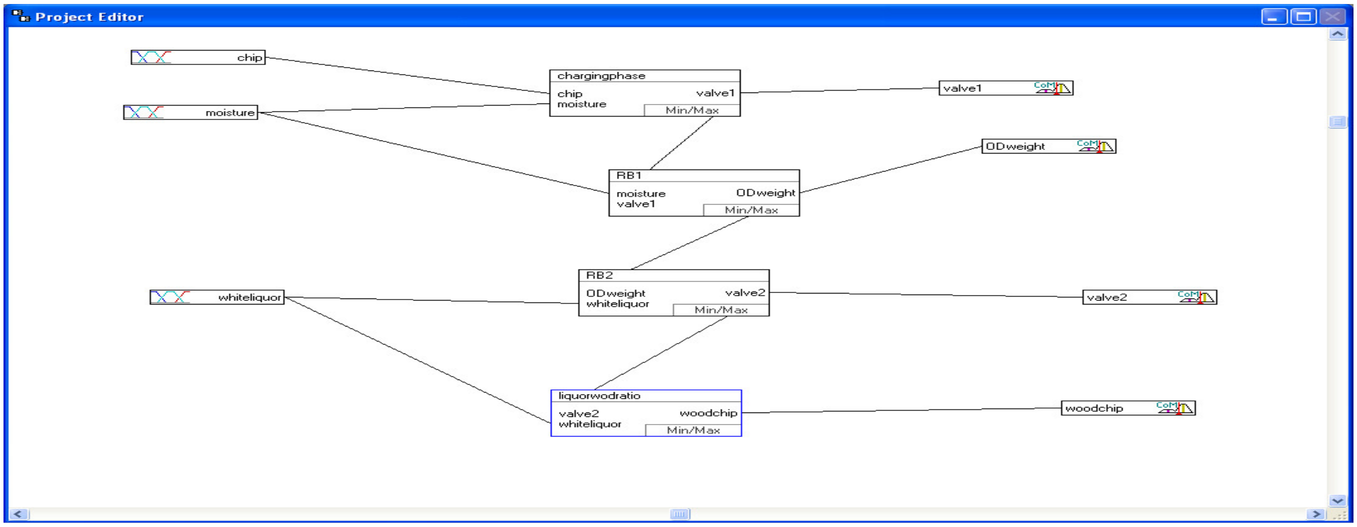


Figure-8
Fuzzy logic controller for step 1

The control loops for various steps are defined as: For Step-1: Fuzzy controller for step1 is shown in figure 8. The IF-THEN rules for step 1 are: IF chip and moisture THEN Valve1, IF OD Weight and white liquor THEN valve2, IF Moisture and Valve1 THEN OD Weight, IF valve2 and white liquor THEN wood chip

In step 1, valve 1 controls the quantity of chip fed into the digester. Control parameters are chip and moisture. To monitor the weight of chip along with moisture, OD weight is determine. In batch pulping process, wood chip and cooking liquor are loaded into a digester which is then closed. So valve 2 is used to control the concentration of woodchip and liquor. Chemical of cooking liquor react with the lignin which binds the fibers together and the lignin is dissolved. The membership function (MSF) of various parameter of step 1 are illustrated in figures 9-15.The rule editor for wood chip is shown in table 1.

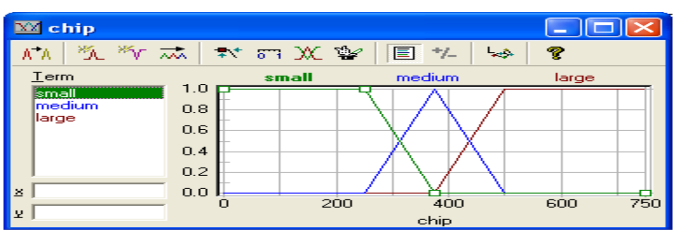


Figure-9
MSF for Chip

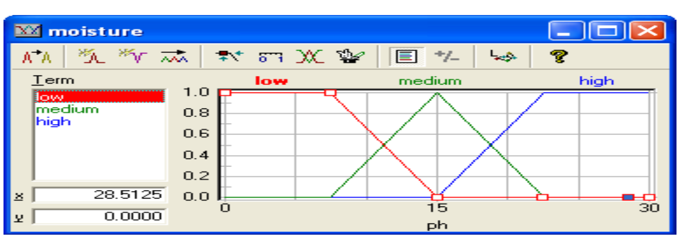


Figure-10
MSF for Moisture

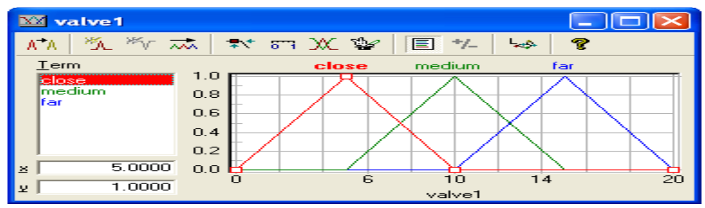


Figure-11
MSF for Valve 1

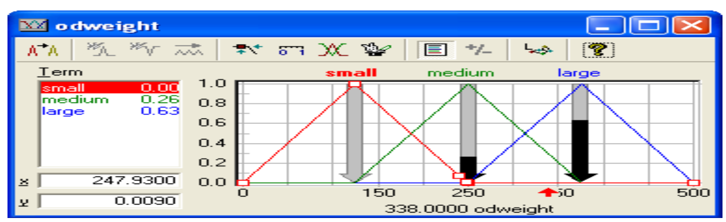


Figure-12
MSF for odweight

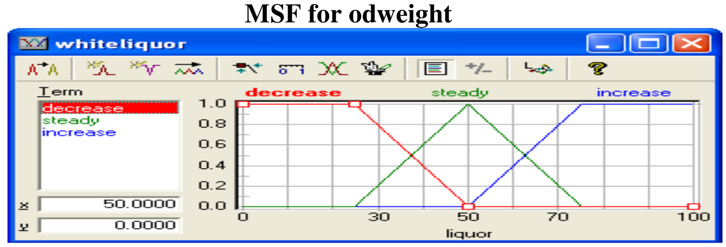


Figure-13
MSF for white liquor

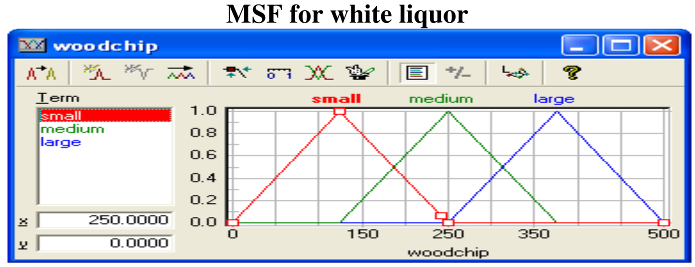


Figure-14
MSF for woodchip

For Step -2: Control loop for cooking phase: The IF-THEN rules for step 2 are: IF Wood Chip and Steam THEN Valve 3, IF black liquor and pressure THEN Valve 4, IF Liquor quantity and Valve 3 THEN Black liquor, IF Temp and Valve4 THEN Pulp THEN Lignin.

The pressure and the temperature (parameters to be maintained) within the digester are raised by admitting steam to the digester to cook the chips. Valve 3 is used to control the steam from heat exchanger. Fuzzy controller for step 2 is shown in figure 16.

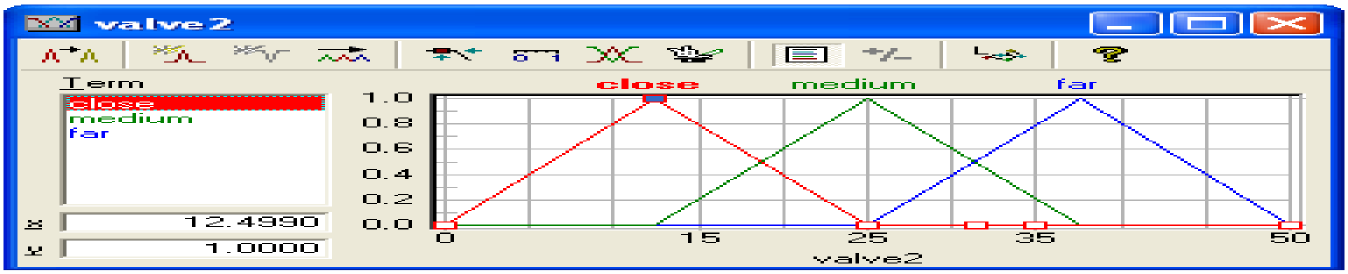
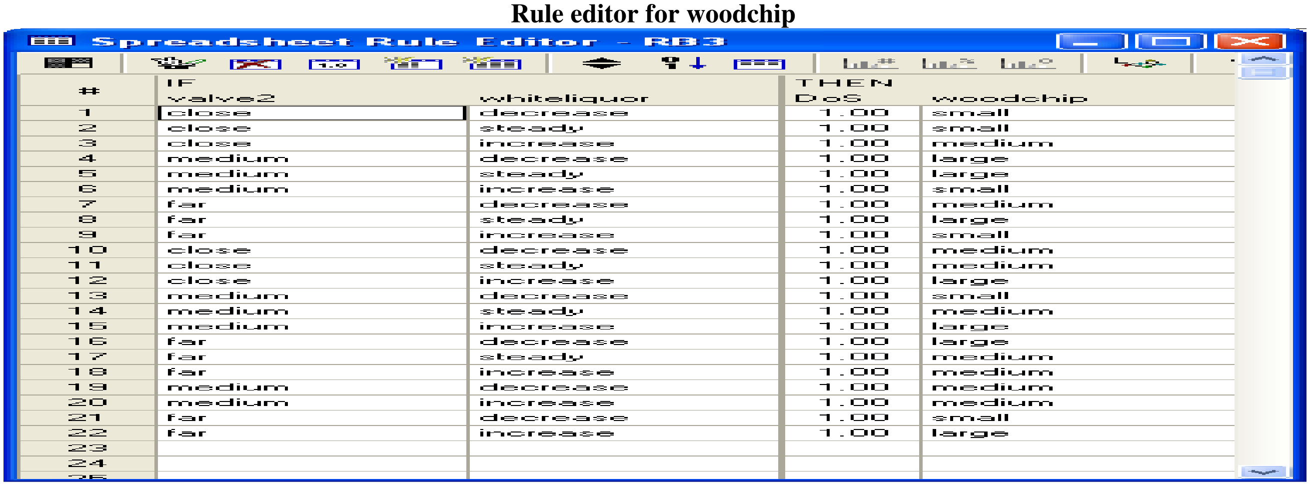


Figure-15
MSF for valve2

Table-1
Rule editor for woodchip



Spreadsheet Rule Editor - RB3

#	IF valve2	whiteliquor	THEN DoS	woodchip
1	close	decrease	1.00	small
2	close	steady	1.00	small
3	close	increase	1.00	medium
4	medium	decrease	1.00	large
5	medium	steady	1.00	large
6	medium	increase	1.00	small
7	far	decrease	1.00	medium
8	far	steady	1.00	large
9	far	increase	1.00	small
10	close	decrease	1.00	medium
11	close	steady	1.00	medium
12	close	increase	1.00	large
13	medium	decrease	1.00	small
14	medium	steady	1.00	medium
15	medium	increase	1.00	large
16	far	decrease	1.00	large
17	far	steady	1.00	medium
18	far	increase	1.00	medium
19	medium	decrease	1.00	medium
20	medium	increase	1.00	medium
21	far	decrease	1.00	small
22	far	increase	1.00	large
23				
24				

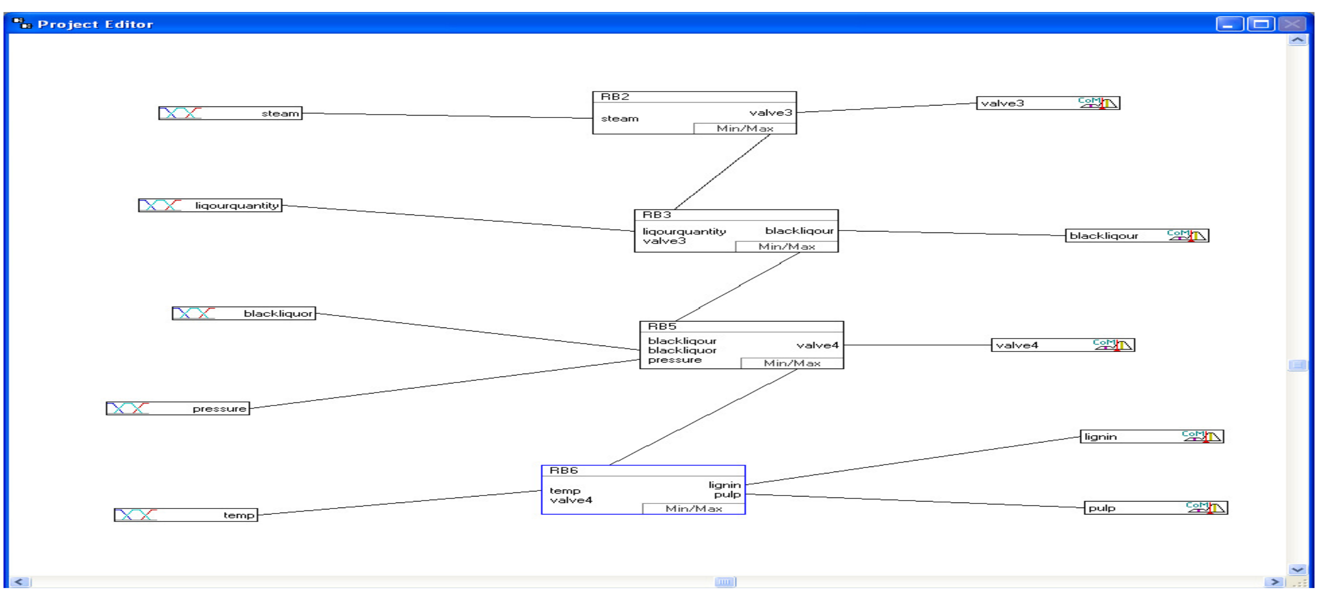


Figure-16
Fuzzy Control System for step 2

The membership function (MSF) of various parameter of step 2 are illustrated in figures 17-25. IF –THEN rule block for pulp and lignin are tabulated in table 2.

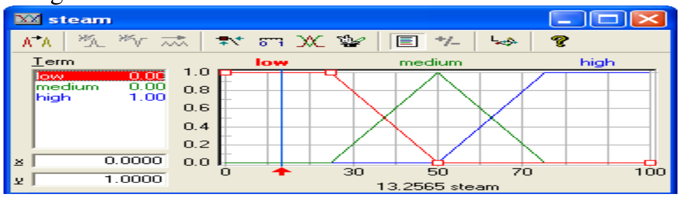


Figure-17
MSF for Steam

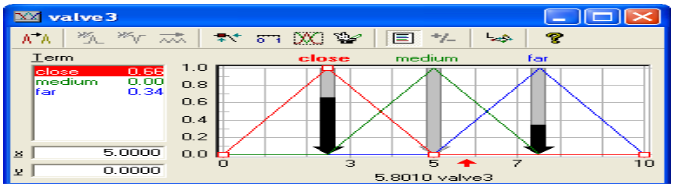


Figure-18
MSF for valve 3

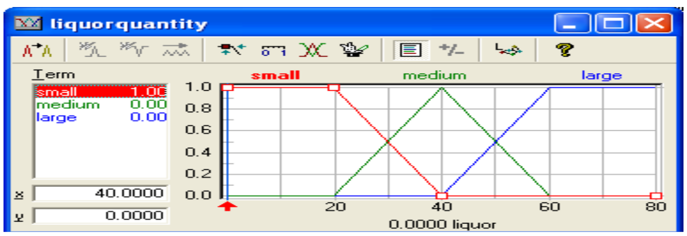


Figure-19
MSF for liquor quantity

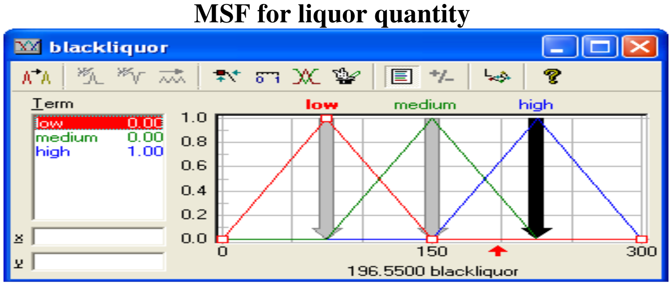


Figure-20
MSF for black liquor

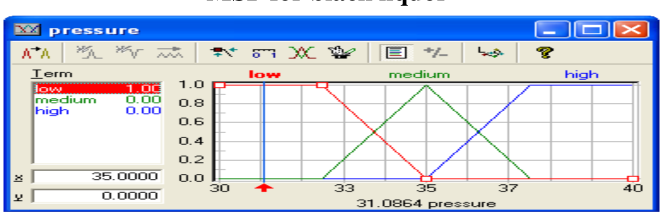


Figure-21
MSF for pressure

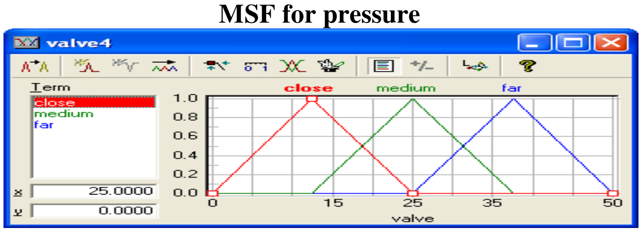


Figure-22
MSF for valve 4

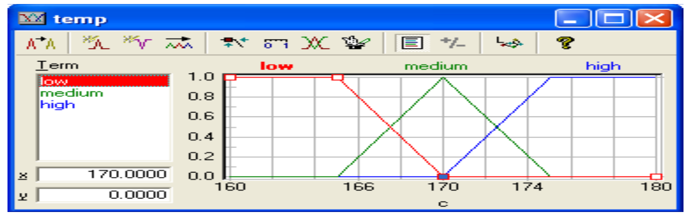


Figure-23
MSF for Temperature

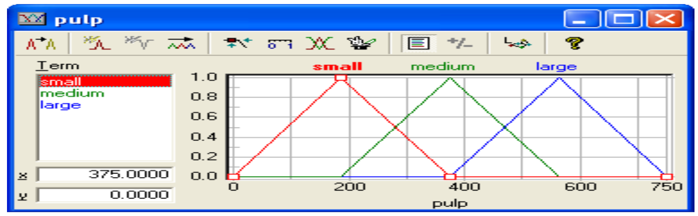


Figure-24
MSF for pulp

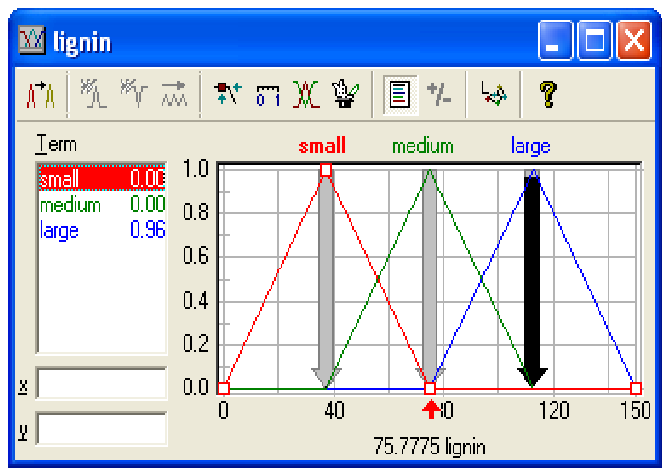


Figure-25
MSF for Lignin

Table-2
Rule editor for Pulp and lignin

Spreadsheet Rule Editor - RB5

#	IF temp	valve4	THEN DoS	lignin	THEN DoS	pulp
1	low	close	1.00	small	1.00	small
2	medium	close	1.00	small	1.00	medium
3	high	close	1.00	medium	1.00	small
4	low	medium	1.00	medium	1.00	medium
5	medium	medium	1.00	medium	1.00	small
6	high	medium	1.00	large	1.00	medium
7	low	far	1.00	medium	1.00	medium
8	medium	far	1.00	large	1.00	large
9	high	far	1.00	large	1.00	large

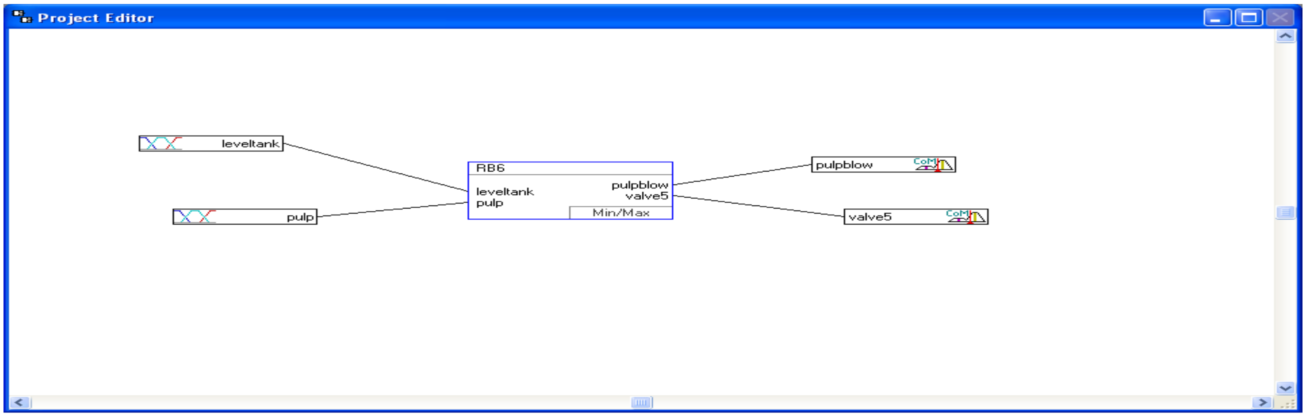


Figure-26
Fuzzy control for Step 3

For Step-3: In blow phase pulp without lignin are blow in other tank by pump and valve 5 controls the blow of pulp in tank. So parameter of that is level tank and pulp. The IF-THEN rule for step 3 is: IF level tank and pulp THEN Pulp Blow THEN Valve 5. Fuzzy control for step 3 is illustrated in figure 26 in which level tank and pulp are the input parameters. These parameters are controlled by rule table. Pulp blow and valve 5 are the output parameters. Valve 5 is used to control the pulp and level tank.

The membership function (MSF) of various parameter of step 2 are illustrated in figures 27-29. Figure 30 shows the interactive debug mode for pulp blow and valve 5.

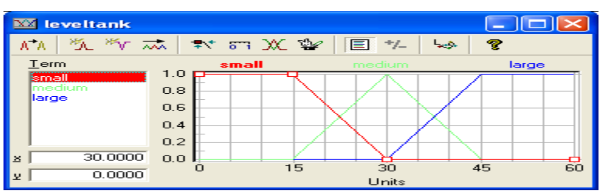


Figure-27
MSF for level tank

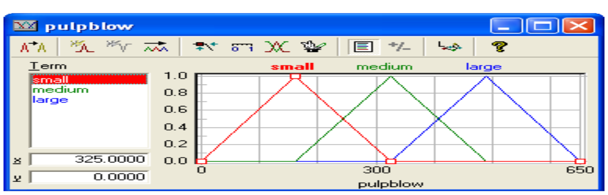


Figure-28
MSF for pulp blow

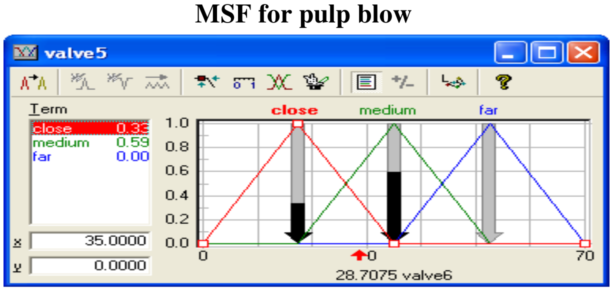


Figure-29
MSF for valve 5

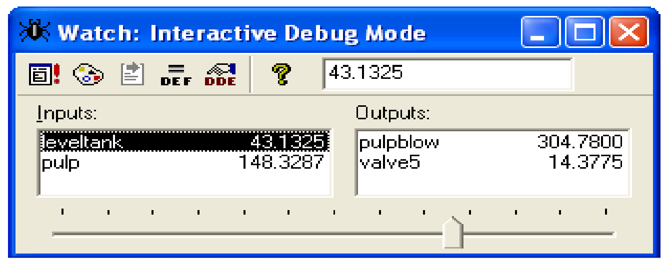


Figure-30
Interactive debug mode for pulp blow and valve5

Results and Discussion

Step 1: The Fuzzy logic system made for step 1 is made for controlling the liquor wood ratio. Liquor wood ratio is measured by controlling the flow of wood chip. Here OD weight of chip is monitored and controlled. The chips are pre-impregnated and preheated black liquor to make batch cooking more energy efficient. The cooking liquor is circulated from the middle to top and bottom to ensure a uniform cooking. Figure 31 shows the Time Plot and figure 32 shows the 3D Plot of charging phase of pulp and paper mill digester plotted between weight of wood chip, its moisture as input and OD weight as output. It infers from the time plot that variations of the parameter are agree with rule table.

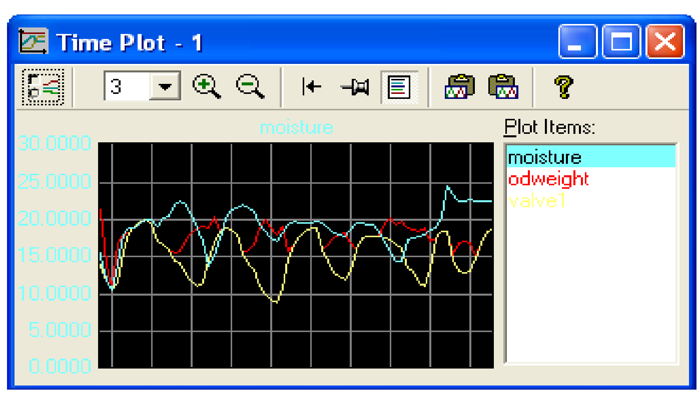


Figure-31
Time plot for od weight

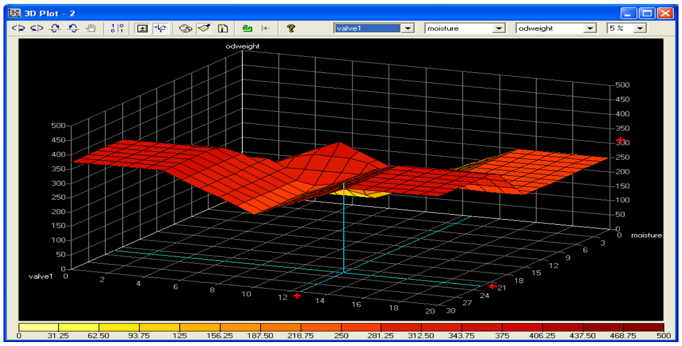


Figure-32
3D plot for odweight

Figure 33 shows the time Plot and figure 34 shows the 3D Plot of wood chip respectively plotted between the position of valve 2, concentration of white liquor as input and woodchip as output. It infers from the time plot that variations of the parameter are agree with rule table 1.

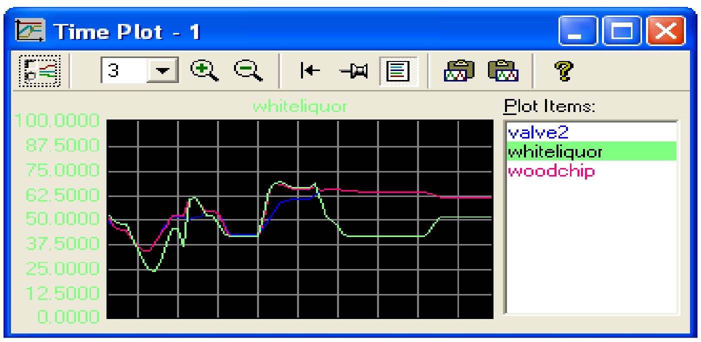


Figure-33
Time plot for wood chip

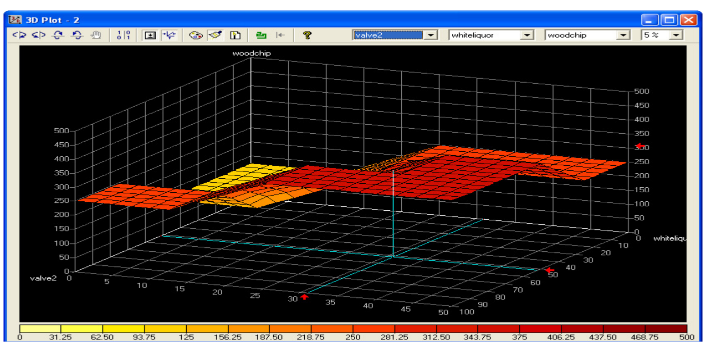


Figure-34
3D plot for wood chip

Result for Step 2: In second control system, cooking process occurs. Here temperature and pressure both are controlled to remove the lignin from pulp. Cooking reactions start when chips reach the cooking temperature, about 150 - 170ºC, depending on the wood species. Figure 35 shows the time plot and figure 36 shows the 3D Plot of lignin, and figure 37 shows the Time Plot and figure 38 shows the 3D Plot of pulp respectively. The plotted parameters here are temperature, concentration of lignin, concentration of pulp and the position of valve 4 of batch digester. It infers from the time plot that variations of the parameter are agree with rule table.

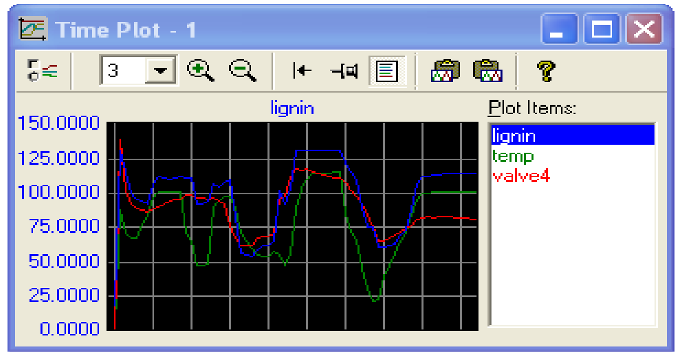


Figure-35
Time plot for lignin

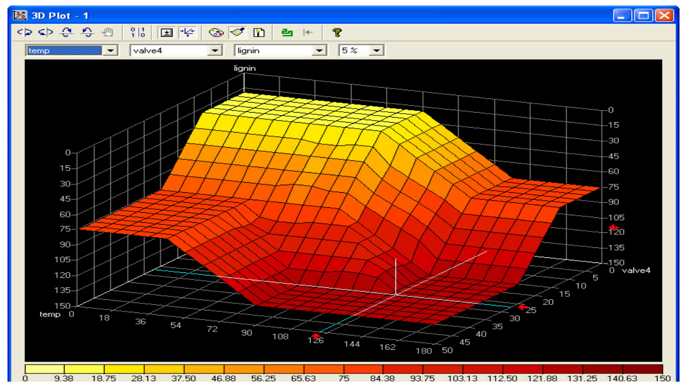


Figure-36
3D plot for lignin

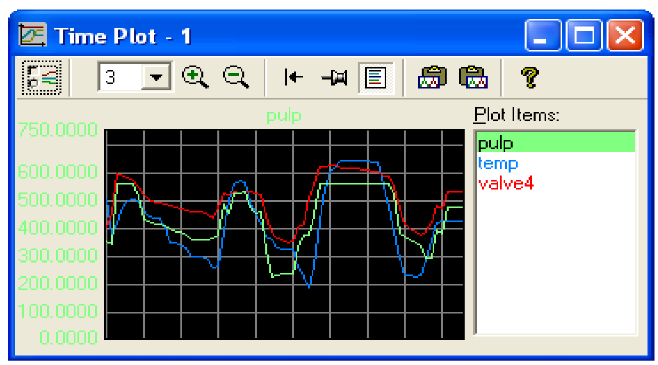


Figure-37
Time plot for pulp

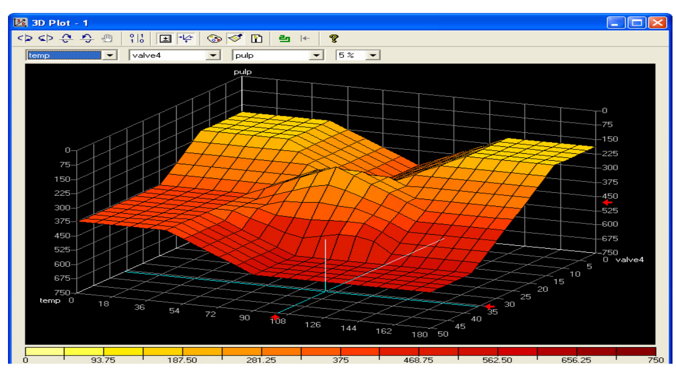


Figure-38
3D plot for pulp

Result for Step 3: In third control system, pulp is blowed from tank which is controlled by valve 5. Figure 39 shows the Time Plot and figure 40 shows the 3D Plot of pulpblow respectively. The plotted parameters here are level of the tank, concentration of pulp and quantity of pulpblow from the digester. It infers from the time plot that variations of the parameter are agree with rule table.

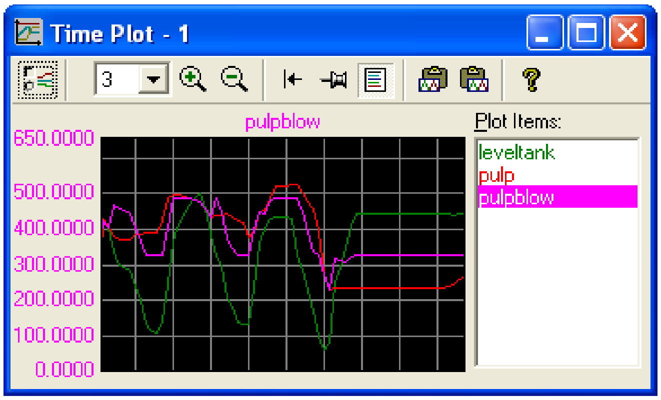


Figure-39
Time plot for pulpblow

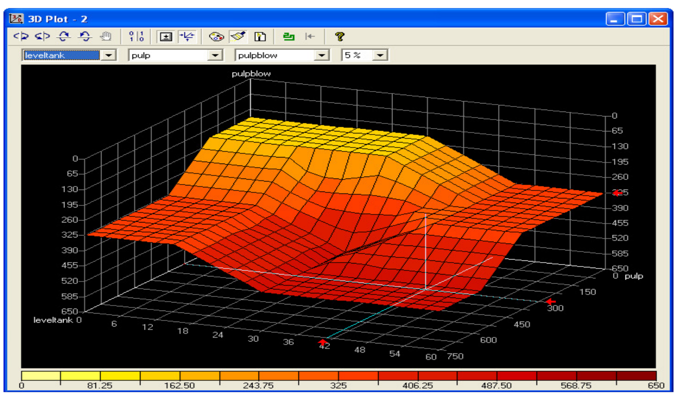


Figure-40
3D plot for pulpblow

Simulation of Batch digester using PLC: PLC includes development and design of various control loops for pulp and paper mill digester control and simulates these rungs with help of standard emulator (RS logic 500). Figure 41 illustrates the ladder diagram for batch digester. This RS ladder program is basically developed to control the temperature, pressure, liquor and chip flow in processing of digester.

Conclusion

Present paper describes the investigation and implementation of FLC and PLC based intelligent process control techniques to automate and optimize the batch digestion processes in pulp and paper mill applications. Fuzzy control system for the entire pulp and paper mill batch digester has been designed with loop identification, which shows consistent results as elaborate in previous sections. It can infer from the present work that fuzzy control system have been proven better option for controlling the nonlinear and non stationary processes and least affected by process modeling error. In addition expanded span with the help of linguistic variables give better approach for production with least errors. This shows high reliability of this process control scheme. Designed FLC and PLC based process control techniques are complete multi-level package to stabilize and optimize the pulp and paper mill batch digester operation. The functions at three stages provide safety handle automated chip and liquor charging, steam ramping, and cook and blow controls. It is the major conclusion from present work that the Rs logic 500 based SLC 500 processors [CPU 1747-120 C/F] produces better result for batch digester. The future up gradation of present batch digester will not cost much because of flexibility in programming of batch digester. PLC based automated system have high processing capability and excellent I/O systems for digital information.

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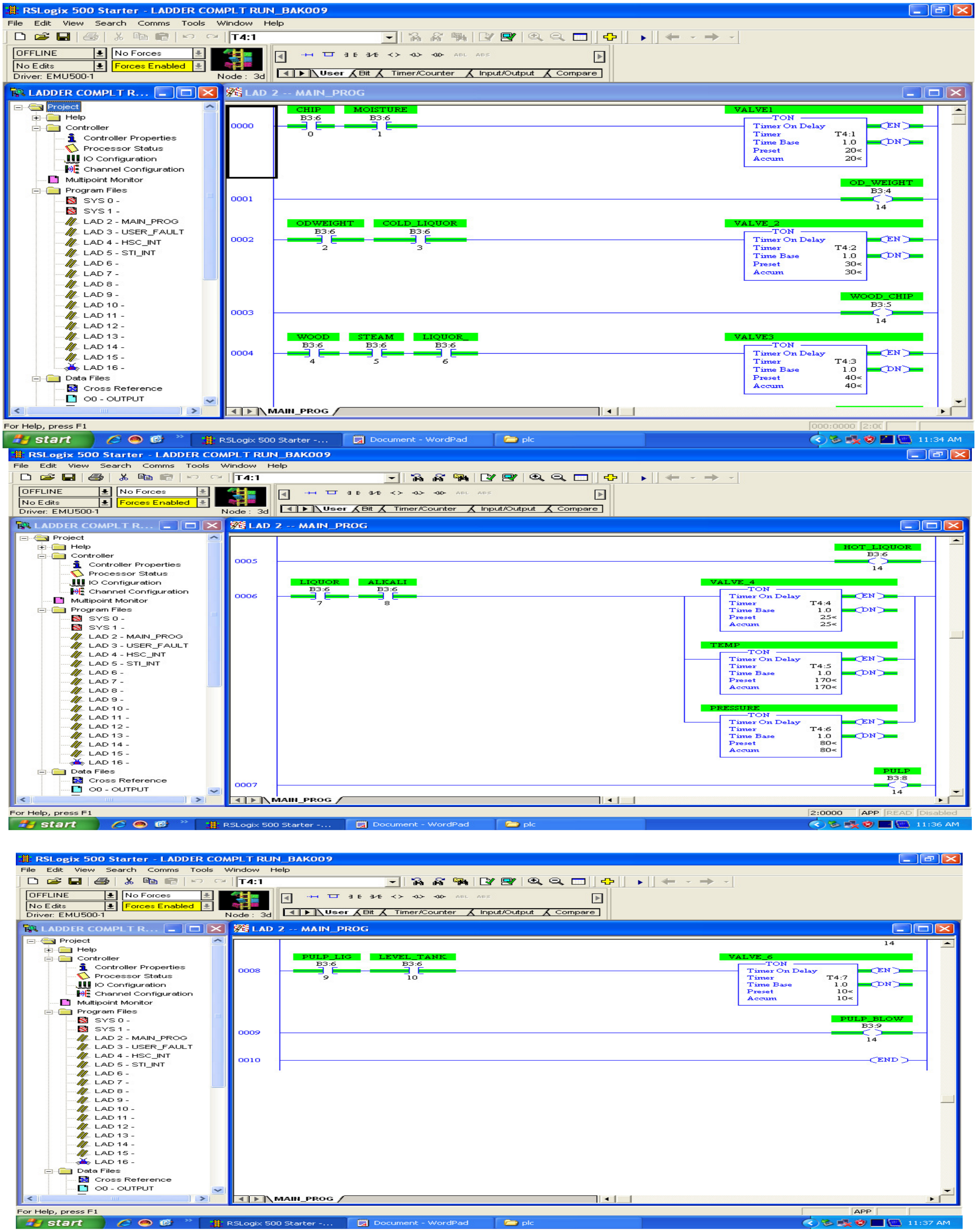

Figure -41
Ladder Diagram of Batch Digester