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Applications of Fuzzy Logic in Sugar Industries: A Review

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Abstract*—Production of sugar from sugar cane route has been an age of old practice and the technology has been fairly stabilized in India for quite some time. In the present context where the prices of sugar cane, sugar produced and molasses are fixed by the government authorities, the only method for generating profits for sugar mills is by way of reducing manufacturing cost where steam and fuel economy plays an important role. Specialized packages are available now a days which provides savings in bagasse or steam or electricity and also improve the sugar quality. This paper reviews the development of fuzzy logic tools for various applications in sugar industry. The paper also proposes a novel concept of probabilistic fuzzy logic system for modeling and control of various control systems in sugar industry.

***Index Terms*— Fuzzy Logic, Probabilistic Fuzzy System, Steam and Fuel Economy, Sugar Quality.**

I. INTRODUCTION

The sugar industry is one of the largest sectors of the Indian economy and India is now among the largest producers and consumers of sugar in the world. After Brazil, India is world's second largest sugar producer. India's domestic sugar market is estimated at US$ 5 billion. About 45 million Indian farmers and their families are dependent on the sugar cultivation. Sugar is India's second largest agro processing industry and about 3 % of India's cultivable land is under sugar cane. The growth of India's sugar industry for the last five decades is given in Table 1[1].

India's sugar production is estimated to be 28.3 million metric tons in the marketing year 2011-12 (October – September). After two consecutive years of decline, the production started to resurge in the year 2010-11. Maharashtra contributes over one third of the country's sugar output (36%) followed by Uttar Pradesh with 25%. Tamilnadu and Karnataka are the other two important sugar producing states in the country. The maps shown in Figure 1 and Figure 2 [2] indicate the geographical distribution of the sugar mills and other co-generation units working in conjunction with them.

India's Sugar Development Fund is financing projects related to bagasse-based co-generation of power. Currently, 25 sugar mills in India are generating 250 Mega Watts of power from bagasse. The on-going projects, on completion, would generate another 700 Mega Watts. Around 300 mills have infrastructure facilities to generate a total of 4000 Mega Watts of power from bagasse [1].

TABLE I

Growth of India's Sugar Industry

Year	No. of factories in operation	Installed Capacity (Lakh tonne)	Actual sugar production (In lakh tonne)
1950-51	139	16.7	11.0
1955-56	143	17.8	18.9
1960-61	174	24.5	30.2
1965-66	200	32.3	35.4
1973-74	229	43.1	39.5
1978-79	299	59.1	58.4
1985-86	339	72.7	70.2
1990-91	377	98.5	120.5
1995-96	415	127.6	164.3
2003-04	461	185.0	170.0

II. AUTOMATION IN SUGAR INDUSTRIES

Environmental protection demands and keen competition force sugar industries to reduce energy consumption, recycle materials and energy, and optimize continuously the operation of sugar process [3]. Up to date, considerable improvements in sugar processing have been achieved. In the present context where the prices of sugar cane, sugar produced and molasses are fixed by the government authorities, the only method for generating profits for sugar mills is by way of reducing manufacturing cost where steam and fuel economy plays a vital role[4]. Plant automation packages are available now a days which provide savings in bagasse or steam or electricity and also improve the sugar quality. Examples of such packages are Juice flow stabilization system, Line sulphitation pH control system, Steam flow stabilization system, Pan automation package, Inhibition water control system etc [4].

Juice flow stabilization system is necessary due to the fluctuations of juice intakes and the volumes handled by raw

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Figure 1. Sugar map of India

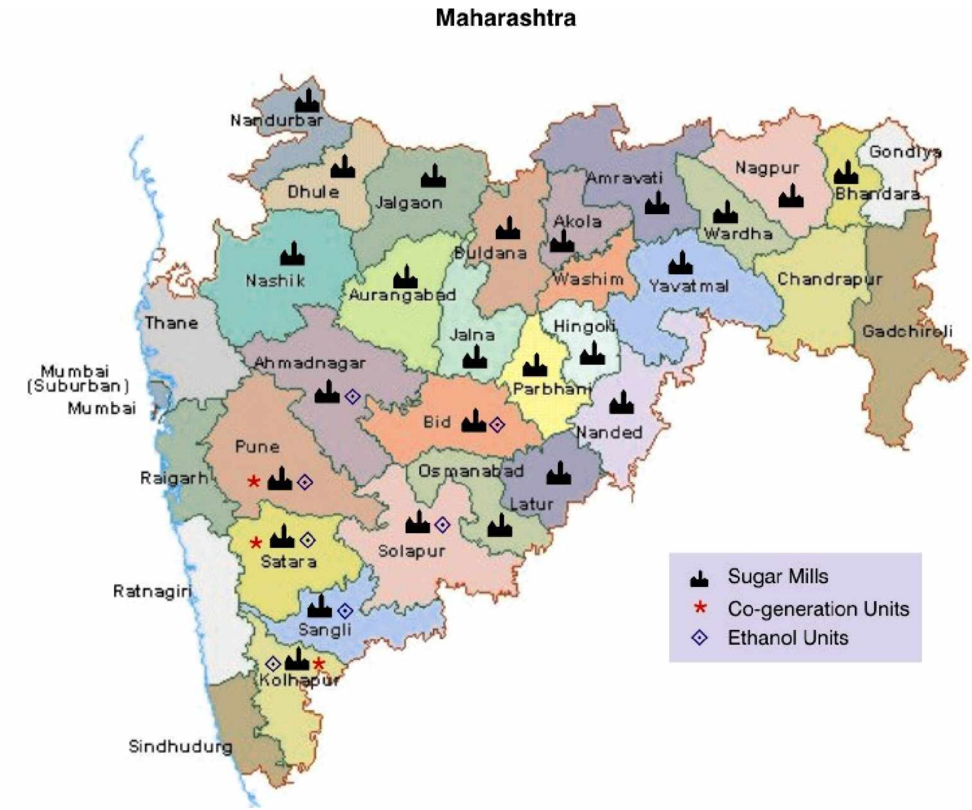

Figure 2. Sugar map of Maharashtra

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juice tanks. The system eliminates the fluctuations in juice flow to the juice heaters in spite of crushing load fluctuations and hence ensures steady state equilibrium in boiling house and also prevents the pump from dry running. It is possible to evaluate the quantity of lime to be added for the sulphitation depending on the crushing rate. The line sulphitation pH control system provides very effective clarification for the liquid phase reaction and thus improves the quality of sugar produced. Specialized systems have been designed for automation of both batch and continuous pans. The benefit of this system include consistency in pan boiling and improvement in sugar grain formation. The inhibition water control system is aimed at optimizing TCD, brix and also cutting down on down stream steam consumption. The system provides substantial savings on overall steam consumption.

Vapour stabilization system is meant for automatic control and maintaining rate of vapour to the pan section. In a sugar plant, due to non conventional operations of batch pans, the pan floor steam consumption will always be a fluctuating demand. It will affect the functioning of evaporator stations by disturbing the pressure difference of respective bleeding effects and also preceding effects. With fluctuating demand of pans, the vapour pressure in second effect followed by first effect tends to fluctuate which ultimately affect the exhaust steam pressure. These fluctuations in exhaust and vapour pressures affect the rate of evaporation in first and second effect bodies, thus resulting in fluctuations in syrup brix which further causes variation in steam demand at pan stations. This further aggravates the fluctuation in the vapour and exhaust steam pressures. Thus it becomes a vicious cycle.

On the other hand, variation in exhaust steam pressure at the process station leads to variations in the steam consumption of turbines. In order to make up the demand, the live steam is bled into the exhaust steam line through pressure reducing valves which are normally provided only with down stream controls. As the draw of live steam is instantaneous and also very high, it can not cope up with the rate of steam generation from boilers. This results in fluctuations in live steam pressure. This will again affect exhaust steam pressure at turbines. Thus the system enters into another form of vicious cycle.

Hence it is of prime importance to have vapour stabilization system in order to stabilize the exhaust steam, pan vapour and live steam pressures. Considering the system complexities and non-linear nature of the systems discussed above, soft computing tools like Fuzzy logic find wide application in modeling and control of various sugar processes. Fuzzy logic system may be able to map the physical non-linear relation of input/output model without a precise mathematical formula[12].

III. Fuzzy Logic – A Brief History

Fuzzy logic, invented by Lotfi Zadeh in the mid 1960s provides a representation scheme and a calculus for dealing with vague or uncertain concepts. It is a paradigm for an alternative design methodology which can be applied in developing both linear and non- linear systems for embedded control. Zadeh originally devised the technique as a means for solving problems in the soft sciences, particularly those that involved interactions between humans, and/or between humans and machines [6]. Since then there has been rapid developments of the theory and application of Fuzzy logic to control systems. Fuzzy logic controllers are being increasingly applied in areas where system complexities, development time and costs are the major issues[7].

In Japan, Terano, inspired by Zadeh's work introduced the idea to the research community in about 1972. This led to active research and a host of commercial applications, almost entirely in the area of physical system control. In 1990 a research institute namely LIFE (Laboratory for International Fuzzy Engineering) started functioning under the leadership of Terano[6]. The Japanese researchers have been a primary force in advancing the practical implementation of Fuzzy theory and now have more than 2000 patents in the area.

Jan Jantzen from Technical University of Denmark had outlined the various choices for an engineer to design a Fuzzy controller based on International standards[10]. He also proposes a design procedure and a tuning procedure that carries tuning rules from the PID domain over to Fuzzy single loop controller. The idea is to start with a tuned, conventional PID controller, replace it with an equivalent linear Fuzzy controller, make the Fuzzy controller non-linear and eventually fine-tune the non-linear Fuzzy controller.

The integration of probability theory and Fuzzy logic for solving engineering problems has been a recent area of interest for the researchers. Probabilistic Fuzzy logic systems are proposed for modeling and control problems[13,15]. Zhi Liu and Han Xiong Li have introduced the design of such a system with application to a robotic system[12],[14].

IV. Basic Structure Of A Fuzzy Logic Controller

The basic configuration of an FLC comprises four principal components[7].

1. Fuzzification interface
2. Rule Base
3. Inference Mechanism
4. Defuzzification Interface

A. Fuzzification

The fuzzification process can be expressed by: x= fuzzifier (x_0), where x_0 is a vector of crisp values of one input variable from the process; x is a vector of Fuzzy sets defined for the variable; and fuzzifier is a fuzzification operator with the effect of mapping crisp data to Fuzzy sets. In the application of process control, a Fuzzy logic controller requires two input parameters: error and change of error. The crisp values of error and change of error are then converted into Fuzzy terms such as [NB, NM, NS, ZE, PS, PM, PB], which can be understood by the Fuzzy inference mechanism.

B. Rule Base

The rule base holds a set of "if - then" rules that are quantified via Fuzzy logic and used to represent the knowledge that human experts may have about how to solve a problem in their domain of expertise. Each rule has the form of an IF-THEN statement. IF side of a rule contains one or more conditions, called antecedents which hold degree of membership value calculated during fuzzification. The THEN side of a rule contains one or more actions, which corresponds directly to variable called Fuzzy output.

C. Inference Mechanism

The inference mechanism has two basic tasks:

1. determining the extent to which each rule is relevant to the current situation as characterized by the input u_i, i= 1, 2,……..n
2. Drawing conclusions using current inputs u_i and the information in the rule base.
   Often more than one rule applies to the same action (Fuzzy output), in which case the common practice is to use the rule that is most true, or has the greatest strength.

D. Defuzzification

Defuzzification can be expressed by: y_{ou} = defuzzifier (y), where y is the Fuzzy control action, y_{ou} is the crisp control action; and the defuzzifier is the defuzzification operator. After taking the logical sum for all rules the Fuzzy inference engines come out with a final conclusion/action in fuzzifier. It has to be transformed in a deterministic control signal that can be used to drive the actuator/plant. The procedure to convert a Fuzzy term into a deterministic value is called defuzzification.

V. Advantages Of Fuzzy Logic Controller

Generally speaking, FLC demonstrates the following major advantages over the conventional control system[7].

1. FLC is very successful in handling system with non-linearities and various complexities without having to develop their mathematical models in an explicit form using any integral, differential or complex mathematical equations.
2. As a rule-based approach Fuzzy controlled design involve incorporating human expertise on how to control a system into a set of rule (a rule base).
3. Continuous variables may be represented by linguistic constructs that are easier to understand, making the controller easier to implement and modify. For instance, instead of using numeric values, temperature may be represented as "cold, cool, warm or hot". Complex processes can often be controlled by relative few Fuzzy rules, allowing a more understandable controller design and faster computation for real time applications.

VI. Fuzzy Logic In Chemical Processes

The implementation of Fuzzy logic has picked up momentum in chemical industries also. Fuzzy set theory had been effectively used in the evaluation of environmental performance of traditional beet sugar plants[3]. The focus was on development of a method for assessment of sugar production in order to track improvements towards environmental sustainability and zero emissions goal in beet sugar plants. Vassilis G. Kaburlasos has presented novel mathematical tools developed for improving prediction of sugar production for Hellenic sugar industry (HSI), Greece. In the context of his work a population of measurements was represented by a FIN (Fuzzy Interval Number) producing improved prediction results[9]. Fuzzy controller has been successfully developed for the production of fermentable sugars also[5]. In the report of the University of Oulu, Control Engineering Laboratory, a Fuzzy modeling of a fed batch fermentation process is described[8].

A. Fuzzy Controller for pH neutralization process

Ranganath Muthu and Elamin El Kanzi [11] with the support of the Research Council, University of Bahrain had successfully implemented a Fuzzy logic controller for a pH neutralization process which is a classic example of a highly non-linear system. Both the classical proportional plus integral (PI) controller and Fuzzy logic controller were designed for a simulated pH neutralization process. It was shown that the FLC could control the process better.

Shahin Salehi *et al* [17] has addressed an adaptive control scheme based on Fuzzy logic system for pH control. For implementation of the proposed scheme, no composition measurement is required. Stability of the closed loop system is established and it is shown that the solution of the closed loop system is uniformly ultimately bounded and under a certain condition, asymptotical stability is achieved. Effectiveness of the proposed controller has been tested through simulation and experimental studies.

B. Fuzzy Controller for Multiple Effect Evaporator

Arvin V. Pitteea *et al*[16] has carried out the modeling of a multiple effect evaporator (MEE) used to raise the concentration (brix) of sugar cane juice from a nominal value of 15 wt% to syrup with a brix of 72 wt%. The MEE under study in their work has five evaporator vessels (effects) connected in series (Figure 3). Heating steam for the first effect is exhausted from the turbine of the factory power plant. The vapour from the juice in the first vessel is used as heating source for the second vessel, and so on down the evaporator set. The vapour from the last effect is condensed in a barometric direct contact condenser. The last effect is connected to a vacuum pump thus cascading the pressures to provide the necessary temperature driving force for heat to

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flow down the MEE. Additionally steam deductions are taken from the second, third and fourth effects for heating in the vacuum pans and juice heater, the major part from the second effect which supplies the vacuum pans. In the latter, crystallization of sugar from the syrup exiting the MEE takes place.

The economy of sugar manufacturing depends strongly on the MEE because of the huge amount of thermal energy (steam) required during the process. The batch nature of the vacuum pan operation means that the demand of steam

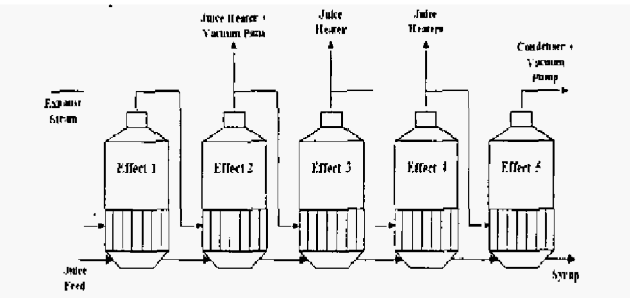

Figure 3. Multiple-Effect Evaporator Station

from the MEE station is intermittent, thus disturbing strongly the MEE. The resulting fluctuations in the brix of the syrup in turn causes the vacuum pans to have variable boiling times and steam consumption, which further disturb the MEE. Thus, there is a kind of vicious interaction between the vacuum pans and the MEE. This fluctuation in the brix of the syrup is detrimental to energy economy.

Advanced automatic control is an important factor to optimize the MEE [4]. The main objective to minimise the energy consumption is achieved by the development of a control scheme for the MEE in order to control the syrup brix to a high and constant value (72%) giving the maximum allowable evaporation. A second control objective is to stabilize the pressure of juice steam to the vacuum pans to enable the latter to function satisfactorily at all times.

The authors have proposed a scheme to control the MEE using the Fuzzy logic control. An algorithm using Genetic Algorithm (GA) is proposed and used to automatically tune the Scaling Factors (SF) and membership functions (MF) of the FLC. The development and tuning of the FLC is done in simulation on a mathematical model of the MEE which has been optimized using GA. The tuned model was then used in all simulations. Compared to manual control, this intelligent control has given substantial improvement in the control accuracy.

In general, it was found that the controlled variables Pressure 2, Brix 2 and Brix 5 were maintained at set point accurately enough in spite of disturbances. The authors have proposed further experimentation to assess the impact of GA parameters, such as the number of generations on the fitness value. They have also suggested to work on the effect of tuning of MFs of several FLCs simultaneously on the results.

C. Fuzzy Controller for Continuous Soaking Process

Wenbo Na [18] has presented a practical method to design and implement a Fuzzy Controller for temperatures of continuous soaking process in a sugar plant. A new Fuzzy control strategy is proposed to improve the control performances. The proposed strategy utilizes an innovative idea based on sectionalizing the error signal of the step response into four different functional zones. The supporting philosophy behind these four functional zones is to decompose the desired control objectives in terms of rise time, setting time and steady state error measures maintained by an appropriate PID type controller in each zone. Then Fuzzy membership factors are defined to configure the control signal on the basis of the Fuzzy weighted PID outputs of all four zones. The obtained results illustrate the effectiveness of the proposed Fuzzy control scheme in improving the performance of the implemented control systems for temperatures of continuous soaking process in sugar plant.

VII. Fuzzy Logic And Probability Theory

As stated earlier, Fuzzy logic system may be able to model a typical non-linear system without a precise mathematical formula. Consequently, Fuzzy logic controllers allow for a simpler human like approach to control system design and do not need a precise mathematical model. For non-linear systems, controlling with conventional controllers is difficult where Fuzzy logic controllers provide reasonable and effective alternative.

Modeling of real world complex system has been always a challenging problem. Complexity and uncertainty are both features of the real world systems which are treated differently in different modeling approaches[13]. Uncertainty has two different aspects which are inherently different. One aspect is statistical uncertainty which could be described by probability theory and the other one is non-statistical uncertainty which has been successfully represented using possibility theory and Fuzzy logic.

Modeling approaches would also be divided into two categories. A deterministic model of the system presents a deterministic mapping between inputs and outputs while probabilistic models are used for modeling of stochastic systems and can be characterized by the statistical properties of some random processes in the system.

Fuzzy modeling techniques are well established and are extensively used for modeling complex and non- linear deterministic system. They are not suitable, however, in their conventional form for probabilistic modeling of randomized and stochastic systems. Consequently the need for probabilistic Fuzzy modeling approach is inevitable because many of the real world complex systems may exhibit randomness in their behaviour as well[14],[15].

There is a highly flexible demand for steam when other

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co-generation units are functioning in conjunction with the sugar plant. This uncertainty has to be considered while developing the model and while deciding the control strategies [15]. The probabilistic Fuzzy logic approach can take care of such uncertainties.

VIII. CONCLUSION

This paper reviews the various modeling and control applications in sugar industries using Fuzzy logic. In all the applications discussed, FLC is an extremely successful means of controlling systems with non-linearities and various complexities. Incorporation of Fuzzy logic in such systems is feasible, versatile and has many advantages. Genetic algorithms are additionally used to tune both the scaling factors (SFs) and membership functions (MFs) of the FLCs. Probabilistic Fuzzy logic has been introduced as a general framework for combination of Fuzzy logic and probability theory for modeling and control of real world systems which exhibit randomness in their behaviour.

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