Improved Liquid Level Control Design Using Mamdani Fuzzy Inference System.

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ABSTRACT – In industrial applications such as those in petrochemicals, nuclear, etc. liquid level control is very important: hence we have elaborated a straight forward case of control scenario, that can further be applied in multiple of these areas by simply varying the design to suit each case. We have given preference to the application of fuzzy logic rather than other control methods – hence describing a lot of the background information about it. Then, we move forward to apply the Mamdani type Fuzzy Inference System in demonstrating how the logic works in controlling the liquid level in a single tank system; first using 3-rules, then, 5-rules. We have designed and simulated in MATLAB, the 3-rules and the 5-rules systems. Unlike previous works on these cases, our results show better choices in that, key performance parameters viz rise time, settling time and overshoot, are better than previous results we have seen in literatures. We achieve these better results by varying some parameters, initial conditions and improved Simulink designs; to explore the viability of our chosen method of control. This work also further proves that the FLC is a better controlling method in these areas of its application than other control methods.

Index Terms—Defuzzifier, Fuzzy Inference Systems (FIS), Fuzzy Logic Control (FLC), Liquid Level Control, Mamdani, Tank Systems.

I. INTRODUCTION

Liquid level control is essential for the proper operation of many industrial processes, including those related to petroleum, nuclear energy, chemical manufacturing, mechanical and civil engineering constructions. Otherwise, calls for emergency shutdowns and other disruptions to the efficient operation of industries would regularly arise. Due to its nonlinearities and uncertainties, liquid level control systems are complex systems depending on the mode of operation and demand in these industries. PID controllers have long dominated these industries' operational controls, but the limitations of their applications and performance have necessitated the development of stronger, more effective control systems. Fuzzy control systems are the result. In highly nonlinear systems, it is not practical to address complex problems using traditional control procedures [1]. In these fields, neural networks and fuzzy logic control have become popular over time. In terms of application, the latter has shown to give greater controls in various areas in terms of viability, flexibility, usability, robustness, etc. A type of probabilistic logic known as many-valued logic, fuzzy logic deals with approximation rather than fixed and exact reasoning. Fuzzy logic variables' truth values range from 1 to 0, unlike conventional binary sets where variables can only take true or false values. Since the truth value can be either entirely true or entirely untrue, it can also handle the idea of partial truth.

A fuzzy set is a variation on a crisp set, where crisp sets only permit complete membership or none at all whereas fuzzy sets permit partial membership. In a crisp set, a characteristic function describes whether element x is a member of set A or not. This idea is expanded by fuzzy set theory, which defines partial membership. A membership function that accepts values in the interval characterizes a fuzzy set "A" on a discourse universe "U" [1], [2]. Commonsense linguistic terms like slow, rapid, tiny, huge, heavy, low, middle, high, tall, etc. are represented by fuzzy sets. At any given time, an element can be a part of several fuzzy sets. A curve that specifies how each point in the input space is transferred to a membership value (or degree of membership) between 0 and 1 is known as a membership function. It gives an indication of how closely components in the discourse universe "U" resemble those in the fuzzy set. There are many different kinds of membership functions employed, such as sigmoid, triangular, trapezoidal, generalized bell shaped, Gaussian, and polynomial curves. In essence, a fuzzy inference system (FIS) uses fuzzy rules to define a nonlinear mapping of the input data vector into a scalar output. Input/output membership functions, FL operators, fuzzy if/then rules, aggregation of output sets, and defuzzification are all used in the mapping process [3], [4]. It is possible to think of a FIS with many outputs as a collection of independent multi-input, single-output systems. Figure 1 displays a general model of a fuzzy inference system (FIS). To produce crisp outputs, the FIS maps crisp inputs. The fuzzifier, inference engine, rule base, and defuzzifier are the four parts of the FIS that are visible in the figure. Expert-provided linguistic rules are included in the rule base. Additionally, rules can be gleaned from numerical data. The FIS can be considered as a system that maps an input vector to an output vector once the rules have been set. The fuzzifier converts the input values into associated fuzzy memberships. To activate rules that are based on linguistic factors, this is necessary. The fuzzifier uses membership functions to assess the degree to which input values belong to each fuzzy set [1], [3], [4], [5].

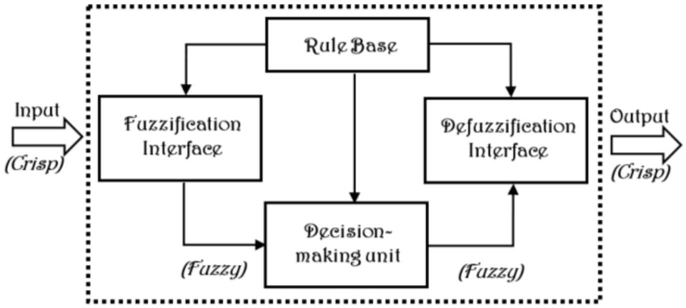


Fig. 1 – Basic block diagram of a Fuzzy Inference System (FIS)

The mapping between input fuzzy sets and output fuzzy sets is defined by the inference engine. For each rule, it establishes the extent to which the antecedent is met. Fuzzy operators are used to provide a single number that represents the outcome of the antecedent for a given rule when the antecedent has many clauses. The defuzzifier converts fuzzy sets of output into crisp numbers. The defuzzifier returns one number after receiving a fuzzy set that has a variety of output values, converting the fuzzy set into a precise number. Defuzzification techniques including the centroid, maximum, mean of maxima, height, and modified height defuzzifier are all commonly employed in practice. The centroid, which determines and provides the center of gravity of the combined fuzzy set, is the most widely used defuzzification technique. A fuzzy system is one that makes use of fuzzy mathematics. Fuzzy systems may manage language knowledge and numerical data simultaneously [6], [7]. In fuzzy control, there are primarily two categories of control rules: The Takagi Sugeno system, which is computationally efficient and performs well with optimization and adaptive techniques, is very appealing in control issues, especially for dynamic non-linear systems. Both systems are frequently used for capturing expert knowledge. The manner the crisp output is produced from the fuzzy inputs is the key distinction between Mamdani-type FIS and Sugeno type FIS [8], [9]. Sugeno-type FIS computes the crisp output using weighted average, whereas Mamdani-type FIS uses the technique of defuzzification of a fuzzy output. The Sugeno FIS lacks the expressiveness and interpretability of Mamdani output since the rules' consequences are not fuzzy [2].

However, since the weighted average took the place of the laborious defuzzification procedure, Sugeno has faster processing times. Mamdani-type FIS is frequently utilized, especially for decision support applications, due to the interpretable and intuitive nature of the rule base. Another distinction is that Sugeno FIS lacks output membership functions, but Mamdani FIS has them. Compared to Sugeno FIS, Mamdani FIS has less design flexibility because the latter can be combined with an ANFIS tool to maximize outputs [10], [11], [12]. The advantages of the fuzzy logic approach over the alternative techniques are: Fuzzy logic can efficiently use ways of reasoning that are approximate rather than exact by mimicking human thought; Fuzzy logic has the ability to accurately model nonlinear functions of any complexity; superior performance compared to traditional PID controllers; Fuzzy Logic, one of the tools used to represent a multi-input, multi-output system, is a practical approach to map an input space to an output space. It is also simple to develop and apply. Similar to traditional control systems, the fuzzy logic controller (FLC) functions as a component of the control system [13]. Fig.2 shows the FLC system with system described in state-space form [1] [2].

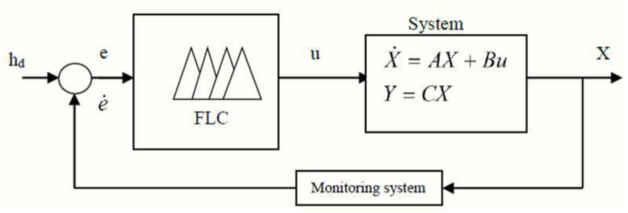


Fig. 2 – Basic block diagram of FLC, Controlling a System [2]

II. PROBLEM ANALYSIS

We will consider the following cases in this work, similar to what is depicted in [3], [4], [5]: single tank system using 3-rules; single tank system using 5-rules; single tank system using 3-rules (with variation of the maximum inflow rate); single tank system using 5-rules (with variation of the maximum inflow rate). If our aim is to maintain the water level in a tank at a certain level/height (say 5cm) the variables & quantities are defined thus: *Liquid Level (Set Point); $h = 0.05m$. Inflow Rate (Required); $q_{in} = 0.0119\ m^3/s$ or (11.9l/s). Cross-Sectional Area of the Tank; $A = 0.4m^2$. Cross-Sectional Area of the (Inflow/q_{in}) Pipe; $a = 0.012m^2$. qin (max) = 20l/s; the variations of these specifications are found in* [14]. Similar cases may be found in [10], [11], [12], [13].

In this work however, we have discovered that setting the maximum inflow, *qin (max) = 20l/s* has been an issue: it causes the huge overshoot of the 5-rule system at the beginning of operation of the system. So, to enable the operation of the system to begin smoothly, we have, in experiments, added/varied the rules, membership functions, range, etc. none of these worked. Until we discovered that it is the maximum inflow: then we varied it and arrived at *qin (max) = 14.6l/s* as a workable value that will not give any overshoot nor increase the settling time, in the 5-rules system and 12.0*l*/s for the 3-rule system. As will be seeing, our result shows a great improvement in both 3- and 5-rules systems in terms for the overshoot and settling time, which are the key parameters that required attention for a better system performance. Also, there is q_{out}. Where the liquid flow out of the tank & a sensor to sense the water level.

III. MATHEMATICAL MODEL AND BLOCK DIAGRAMS

We need the models of the TANK, the VALVE & the FLC. From the above description, the system will work according to equation (1) [14]: and we can use the system of Fig. 3, to depict the scenario.

$$\dot{h} = \frac{1}{A} q_{\text{in}} - \frac{a}{A}\sqrt{2gh} \qquad (1)$$

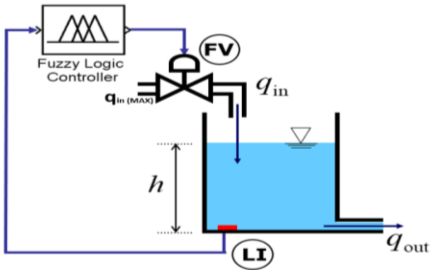


Fig. 3 – the tank system [14]

The block diagram of the system can be modeled thus: From eqn. 1, we have Fig. 4; by substituting the given values, we have Fig. 5. Moreover, we made critical design adjustments in the control block diagrams of Figs. 4 – 6, to suit our cases: an improvement from what is seen in [14].

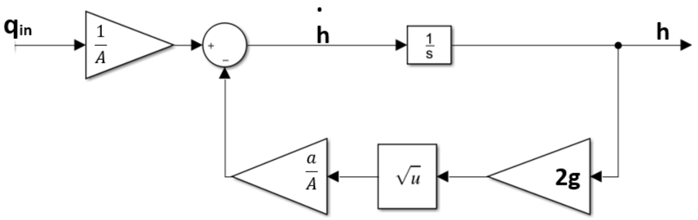


Fig. 4 – Block Diagram of the Mathematical Model of the tank system

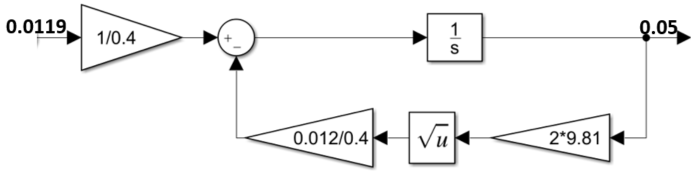


Fig. 5 – Block Diagram of the Mathematical Model the tank system; Substituting given values

The valve itself only consist of an integrator and a saturation: its input is directly from the liquid supply source to the system and its rate is controlled by the FLC controlling the valve, its output is the input to the tank; Fig. 6.

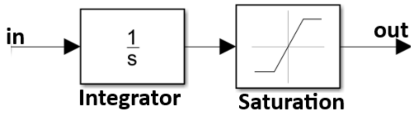


Fig.6 – Block Diagram of the VALVE System

The FLC uses the Mamdani FIS, to map the input variables to the output conditions: it is used in adjusting to give the desired q_{in} to the tank, as shown in fig. 1. Its configuration is shown & discussed in the methodology; the block diagram of the system is depicted in Fig. 7. Similarly, we could apply these concept to the two-tank system (in series) [15].

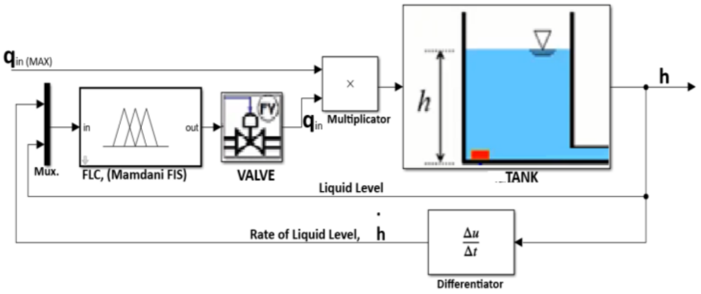


Fig.7 – the tank level system

IV. METHODOLOGY; SIMULINK DESIGNS AND SIMULATIONS

Here, we have carried out design and simulation from reviewed works, to use as a basis of prove, to show the improvements recorded in our work in trying to solve this problem; we are using the Mamdani FIS in MATLAB 2022a.

A. *The 3-rule FIS-MATLAB and SIMULINK Design & Simulation*

The diagram of fig. 8 illustrate the definition of the 3-rule membership functions (mf); table 1 further clarifies how the rules map, thus: Rule 1: IF level is okay, THEN valve is no change. Rule 2: IF level is low, THEN valve is open fast. Rule 3: IF level is high, THEN valve is close fast.

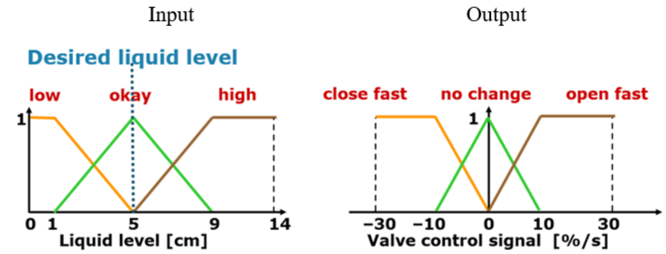


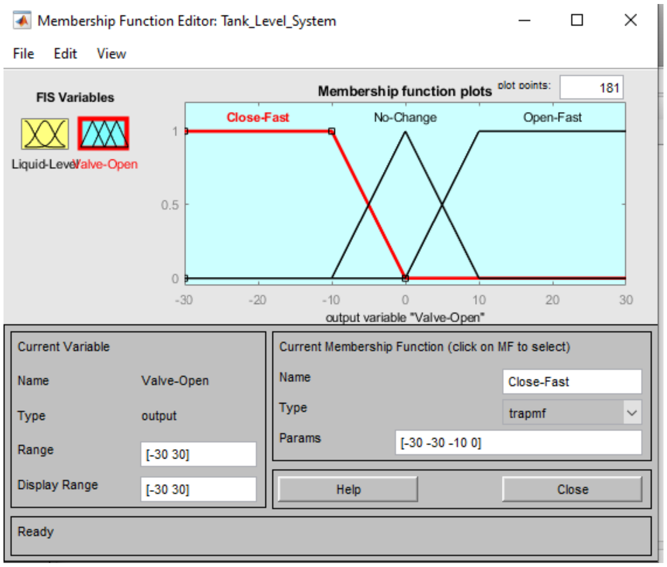
Fig. 8 – defining the 3- rules membership functions (mf)

Table 1 – the 3-rules [14]

Rule No.	Liquid Level	Valve Control Signal
1	Okay	No Change
2	Low	Open Fast
3	High	Close Fast

To configure the FIS, in MATLAB command window, type ‘fuzzy’, press the ENTER (↵) key, in the displayed dialogue box, click and change i/p 1 to ‘Liquid-Level’ & o/p 1 to ‘Valve-Open’, input the range as shown in fig. 9. Double click in turn, i/p ‘Liquid-Level’ & then, o/p 1 ‘Valve-Open’ to enter the membership functions, types, limits, etc. change the i/p ‘Liquid-Level’ range, on the graph, click the line representing membership functions mf1, mf2, mf3, change their defaults to suit your definition; Double click the Tank_Level_System, to map the rules… , i/p ‘Liquid-Level’ mapped to o/p ‘Valve-Open’, then, double-click the FLC & load the Tank_Level_System_3Rules.fis’ file to it & simulate.

For example, in our case, as depicted in Figs. 9 (a-b). We cannot present all procedure and screenshots here due to constraint; if required, contact the authors – however, knowledge of the code in this problem will help. During the execution, there were MATLAB Version inconsistencies; *(MF3='High':'trapmf',[5 9 14 Inf])* and *(MF3='Open-Fast':'trapmf',[0 10 30 Inf])*, didn’t work (complain is that inf. Is not expected), but (any finite value e.g.), *(MF3='High':'trapmf',[5 9 14 14])* and *(MF3='Open-Fast':'trapmf',[0 10 30 30])* worked.



Current Variable

Name: Valve-Open

Type: output

Range: [-30 30]

Display Range: [-30 30]

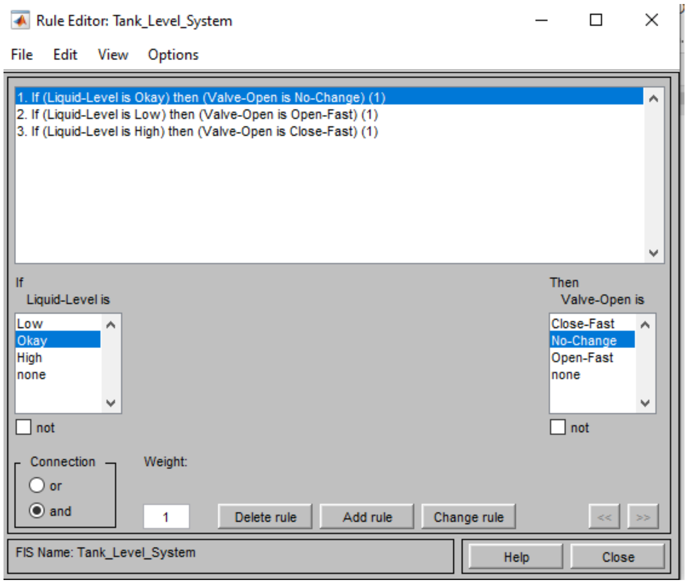
Current Membership Function (click on MF to select)

Name: Close-Fast

Type: trapmf

Params: [-30 -30 -10 0]

Fig. 9(a) – *Configuring the 3- rules FIS in SIMULINK*



1. If (Liquid-Level is Okay) then (Valve-Open is No-Change) (1)
2. If (Liquid-Level is Low) then (Valve-Open is Open-Fast) (1)
3. If (Liquid-Level is High) then (Valve-Open is Close-Fast) (1)

If Liquid-Level is: Okay

☐ not

Then Valve-Open is: No-Change

☐ not

Connection: ○ or ● and

Weight: 1

FIS Name: Tank_Level_System

Fig. 9(b) – *Rules map of the 3- rules FIS in SIMULINK*

In the 3-rule Simulink design shown in fig. 10; we used $qin\ (max) = 20l/s$ as a default value, as was prescribed in [14] and then, we later changed it and used $qin\ (max) = 12.0l/s$, as we have determined it to be better suited for this case, in order to achieve a better result.

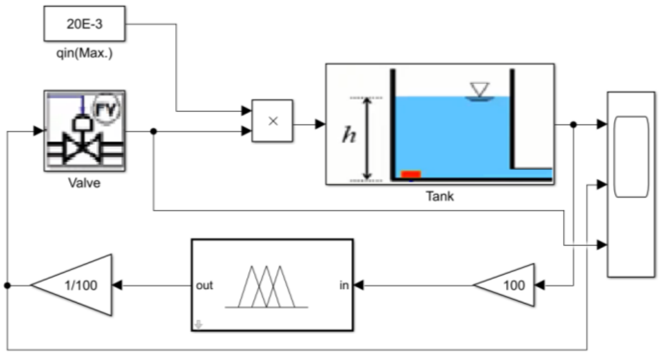


Fig. 10 – the 3-rules system SIMULINK design

B. The 5-rule FIS-MATLAB and SIMULINK Designs & Simulation

Configuring the 5-rule membership functions and rules; it is similar to how the 3-rule system was configured, only that this time we have 2-inputs and they are configured according to the graphs shown in fig. 11. The diagram of fig. 11 illustrate the definition of the 5-rule 5 mf; table 2 further clarifies how the rules map, thus: Rule 1: IF level is okay, THEN valve is no change. Rule 2: IF level is low, THEN valve is open fast. Rule 3: IF level is high, THEN valve is close fast. Rule 4: IF level is okay AND rate is negative, THEN valve is open slow. Rule 5: IF level is okay AND rate is positive, THEN valve is close slow. E.g. our case, fig. 12: see also how to add more input.

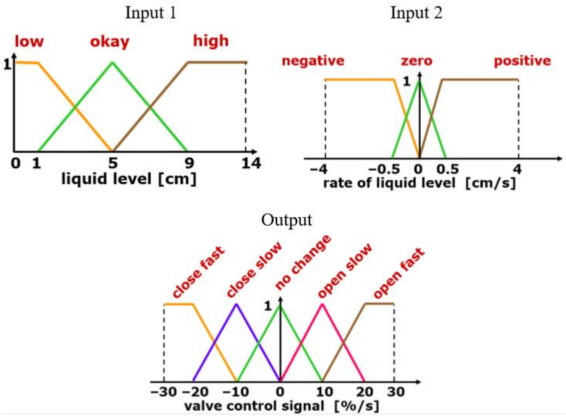
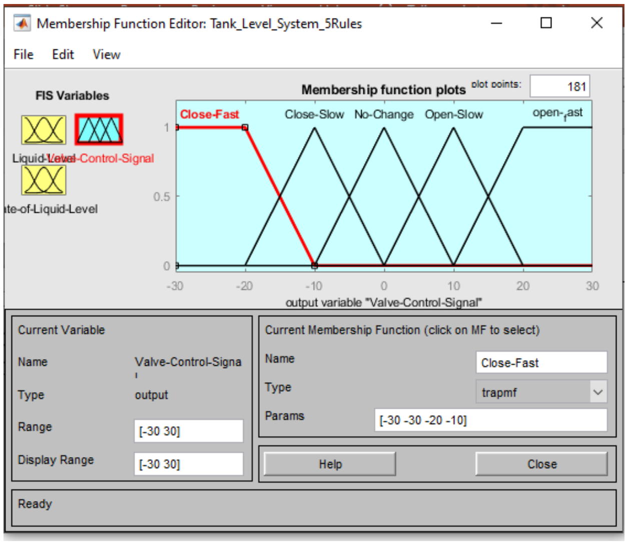


Fig. 11 – defining the 5- rules membership functions (mf) [14]

Table 2 [14], [2]

Rule No.	Liquid Level	Rate of Liquid Level	Valve Control Signal
1	Okay	-	No Change
2	Low	-	Open Fast
3	High	-	Close Fast
4	Okay	Negative	Open Slow
5	Okay	Positive	Close Slow



Current Variable

Name: Valve-Control-Signal

Type: output

Range: [-30 30]

Display Range: [-30 30]

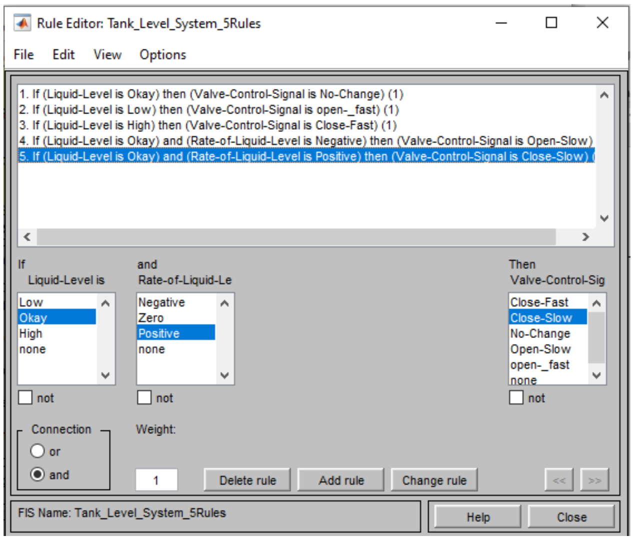
Current Membership Function (click on MF to select)

Name: Close-Fast

Type: trapmf

Params: [-30 -30 -20 -10]

Fig. 12a – configuring the 5-rules FIS in SIMULINK



1. If (Liquid-Level is Okay) then (Valve-Control-Signal is No-Change) (1)
2. If (Liquid-Level is Low) then (Valve-Control-Signal is open-_fast) (1)
3. If (Liquid-Level is High) then (Valve-Control-Signal is Close-Fast) (1)
4. If (Liquid-Level is Okay) and (Rate-of-Liquid-Level is Negative) then (Valve-Control-Signal is Open-Slow)
5. If (Liquid-Level is Okay) and (Rate-of-Liquid-Level is Positive) then (Valve-Control-Signal is Close-Slow) (

Weight: 1

FIS Name: Tank_Level_System_5Rules

Fig. 12a – Rules map of the 5- rules FIS in SIMULINK

In the simulation of the design in fig. 13, we used *qin (max) = 20l/s,* as a default value, as was prescribed in [14] and then, we later changed it and used *qin (max) = 14.5l/s*, as we have determined it to be better suited for this case, in order to achieve a better result. We have also proven that in this particular case, increasing the membership function and rules (to more than 5), does not improve the system performance; rather, it worsens it.

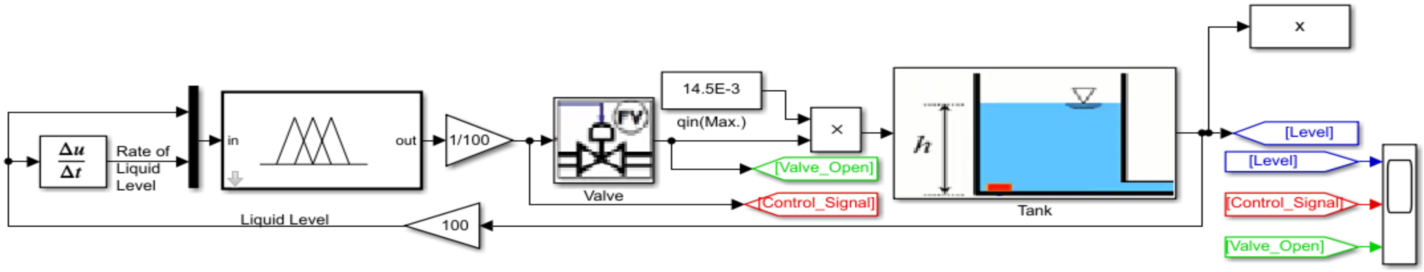


Fig. 13 – the 5-rules system SIMULINK design

V. RESULTS AND ANALYSIS

A. The 3-rule FIS-Results and Analysis

The r*esult of the 3-rule FIS using qin (max) = 20l/s* is as shown in fig. 14; the improved version of it, is as shown in fig. 15 – where we used *qin (max) = 12l/s:* from which it can be seen that, for the liquid level, which is our area of interest, the overshoot is too large and the response time, too slow. Corresponding responses of the valve control (Gain) and valve opening signals are also shown. More in section C; *Discussion and Comparison of the 3-rule and the 5-rule FIS-Results,* with corresponding data for each parameter.

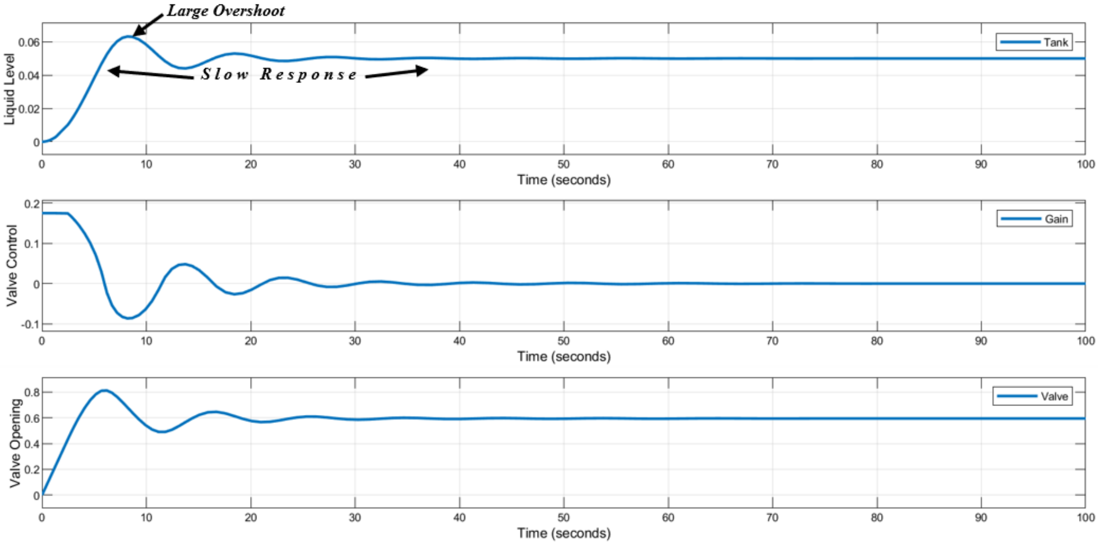


Fig. 14 – *Result of the 3-rule FIS,* (here, *qin (max) = 20l/s*)

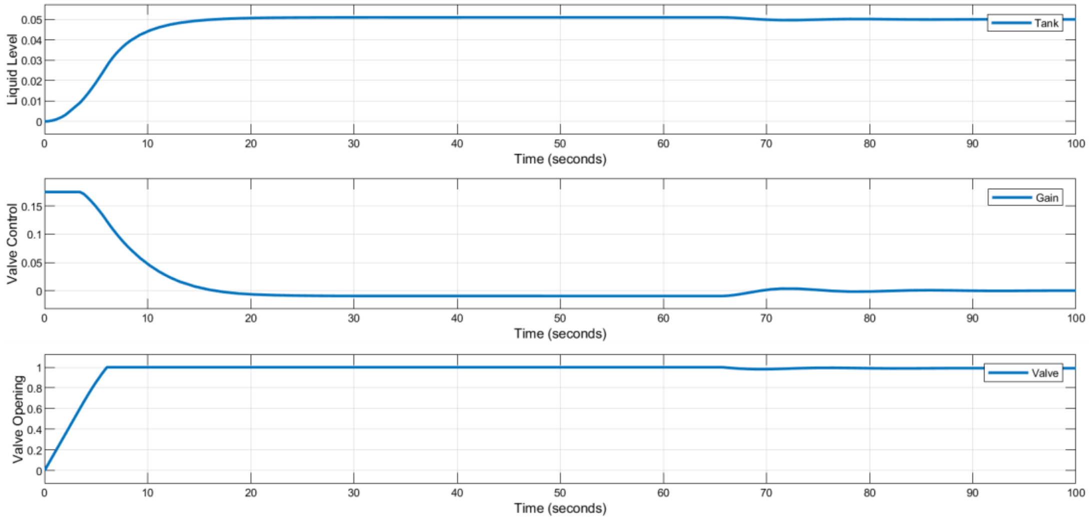


Fig. 15 – *Result of the 3-rule FIS, (with variation of the maximum inflow rate)* (here, *qin (max) = 12.0l/s*)

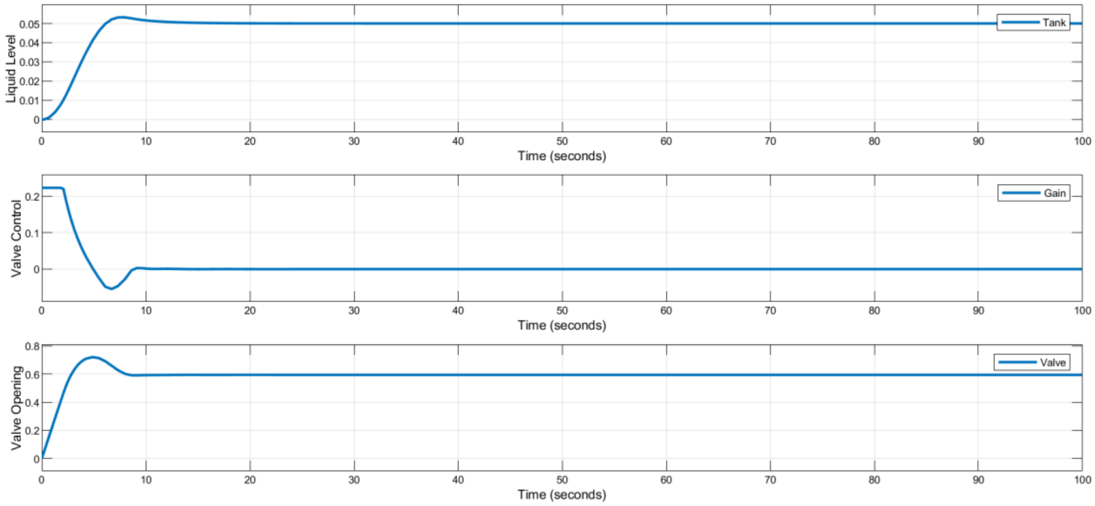


Fig. 16 – Result of the 5-rule FIS, (here, qin (max) = 20l/s)

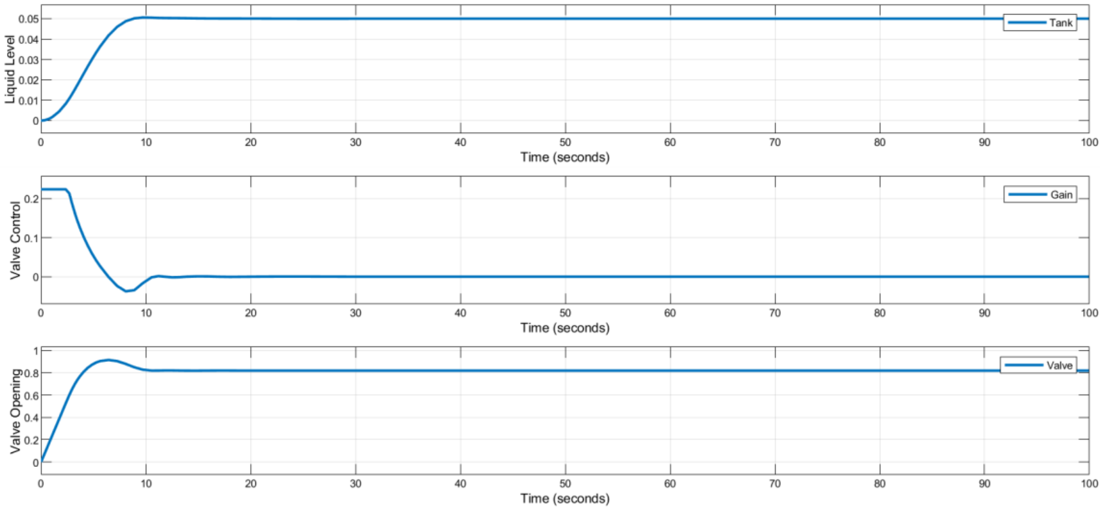


Fig. 17 – Result of the 5-rule FIS, (with variation of the maximum inflow rate) (here, qin (max) = 14.6l/s

B. The 5-rule FIS-Results and Analysis

Similar to section A above, the r*esult of the 5-rule FIS using qin (max) = 20l/s* is shown in fig. 16; the improved version of it is shown in fig. 17 – where we used *qin (max) = 14.5l/s:* from which it can be seen that, for the liquid level, which is our area of interest, the overshoot is larger and the response time, slow. Corresponding responses of the valve control and valve opening signals are also shown. A more detailed version of the liquid level result is shown in section C; *Discussion and Comparison of the 3-rule and the 5-rule FIS-Results,* with corresponding data for each parameter.

C. *Discussion and Comparison of the 3-rule and the 5-rule FIS-Results*

The 3-rules FIS with *qin (max) = 20l/s Fig 14* give a system that has a big overshoot and longer settling time – this is partly due to the huge rate and partly because the 3-rules are not enough for a more stable system here. When *qin (max) = 12l/s Fig 15*, the system performance is better as can be seen; although there occurs a little disturbance in the liquid level. The 5-rules FIS with *qin (max) = 20l/s Fig 16* give a system that has a considerably lower overshoot and lesser settling time compared to the 3-rule FIS – this has been proven to be due to the huge rate: since we can see that 5-rules are enough for the stability of the system. This fact is so proven in that when we set *qin (max) = 14.5l/s*, the system performance is at its best as can be seen from fig. 17.

Table 3: 3-Rules Results summary

qin (max) = 20l/s			*qin (max) = 12l/s*	
RiseTime	*3.8961*		*RiseTime*	*7.9965*
SettlingTime	***24.4768***		*SettlingTime*	***14.1610***
SettlingMin	*0.0440*		*SettlingMin*	*0.0462*
SettlingMax	*0.0632*		*SettlingMax*	*0.0510*
Overshoot	***26.3788***		*Overshoot*	***1.9621***
Undershoot	*0*		*Undershoot*	*0*
Peak	*0.0632*		*Peak*	*0.0510*
PeakTime	*8.1765*		*PeakTime*	*65.7384*

Table 4: 5-Rules Results summary

qin (max) = 20l/s			*qin (max) = 14.5l/s*	
RiseTime	*3.9178*		*RiseTime*	*5.2498*
SettlingTime	***11.4249***		*SettlingTime*	***8.2275***
SettlingMin	*0.0461*		*SettlingMin*	*0.0460*
SettlingMax	*0.0532*		*SettlingMax*	*0.0506*
Overshoot	***6.3928***		*Overshoot*	***1.1303***
Undershoot	*0*		*Undershoot*	*0*
Peak	*0.0532*		*Peak*	*0.0506*
PeakTime	*7.9765*		*PeakTime*	*9.7103*

However, we have tried increasing membership functions and adding more rules to the system: the results keep getting worst further proving that 5-rule FIS is sufficient to give the desired result in this case.

The novelty of this work includes experimental establishment of a better volume of the input quantity (i.e. qin (max)) for the system of each sets of rules: of which, to achieve better results for the critical control parameters such as the Overshoot, Rise time and Settling time, etc. the volume of the input quantity should be suitably determine for the 3-rules and 5-rules systems, differently. Moreover, we have made some very critical design adjustments in the control block diagrams of Figs. 4 – 6, to suit our cases: which is an improvement on what is used in [14]. Also, during the execution, we have solved many inconsistencies, due to differences in MATLAB Versions used in literature and in our work: examples include in the following settings; *(MF3='High':'trapmf',[5 9 14 inf])* and *(MF3='Open-Fast':'trapmf',[0 10 30 Inf])*, did not work (complain is that *inf.* is not expected), but (any finite value e.g.), *(MF3='High':'trapmf',[5 9 14 14])* and *(MF3='Open-Fast':'trapmf',[0 10 30 30])* were accepted.

The overall contributions, though, have been seen in the results obtained due to these experimental changes and variations; as described in paragraphs above, in this section. Furthermore, concerning the insinuation in this work, that the strategy described here can be applied in real-world industrial applications: this could be achieved by increasing the sizes of the infrastructures such as the tank, pipes valves, etc. and then re-modelling this system into a kind-of a suitable embedded system.

CONCLUSION

In this work, by applying the Mamdani FIS, we have been able to demonstrate how the logic works in controlling the liquid level in a single tank system; using the 3-rules and the 5-rules FIS, we designed and simulate in MATLAB, and have achieved better results than what we have seen in previous works. We achieve these better results by varying some parameters and initial conditions to explore the viability of our chosen method of control the result parameters are the rise time, the overshoot, and others. For further works, applying a similar strategy to two tanks, two tanks in series or more in this kind of control is promising.

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