A New Highly Controllable and Accurate Algorithm for Defuzzifier Circuit Implementation

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Abstract

Defuzzifier circuit is one of the most important parts of fuzzy logic controllers that determine the output accuracy. The Center Of Gravity method (COG) is one of the most accurate methods that so far been presented for defuzzification. In this paper, a simple algorithm is presented to generate triangular output membership functions in the Mamdani method using the multiplier/divider circuit and mirror current CMOS technology. As well as the method simplicity, the method is highly accuracy and controllable in the height, slope of output membership functions, number of rules and number of input/output membership functions cause to use mixed voltages. This method covers each type of the input fuzzifier. The proposed Circuits in this paper are implemented by a standard 0.35um CMOS technology in Hspice software.

Keywords: fuzzy logic controller, defuzzifier Center of Gravity, Mamdani defuzzification method, CMOS technology

1. Introduction

The most important application of fuzzy logic is designing controllers. Design of Fuzzy logic controllers (FLC) is much easier than non-linear controllers of similar capabilities.[1] Structure of fuzzy logic controller has several circuits. Defuzzifier circuit is the final part of the fuzzy logic controllers. Until now, several methods are presented to defuzzify parameters [2].

Defuzzification is the conversion of a fuzzy quantity to a precise quantity, just as fuzzification is the conversion of a precise quantity to a fuzzy quantity. The output of a fuzzy process can be the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variable [2]. Conventional FLCs use Center Of Gravity or Mean of Maxima defuzzification methods [1]. Among these methods, center of gravity is the most accurate and also complex method.

Mamdani and Takagi-sugeno are basic methods to implement fuzzy logic controllers [3]. Until now, center of gravity defuzzifier in the papers usually takes cumulative sum instead of integration, which only acquires an approximation of fuzzy output. Although the integration processes are rather intricate, in the sense of the mean square, fuzzy system under the integral-type center of gravity method is the best approximation [4]. In the hardware circuit implementation, the Takagi-sugeno was used more than Mamdani method since it was easier and without using integral circuits it needs need less computation. But in some cases, its limitations and disadvantages decrease its ability to be controlled by the user [5]. In some cases, these methods need circuits for normalization and were less accurate than other methods because of the common area of membership functions [6]. So far, various circuits and algorithm for defuzzifier hardware in both Takagi-sugeno [7-15] and Mamdani methods [5-6] are designed and presented.

Obviously, Mamdani method has high accuracy, especially in hardware implementation which can improve the performance of fuzzy logic controller despite of more complexity [1].
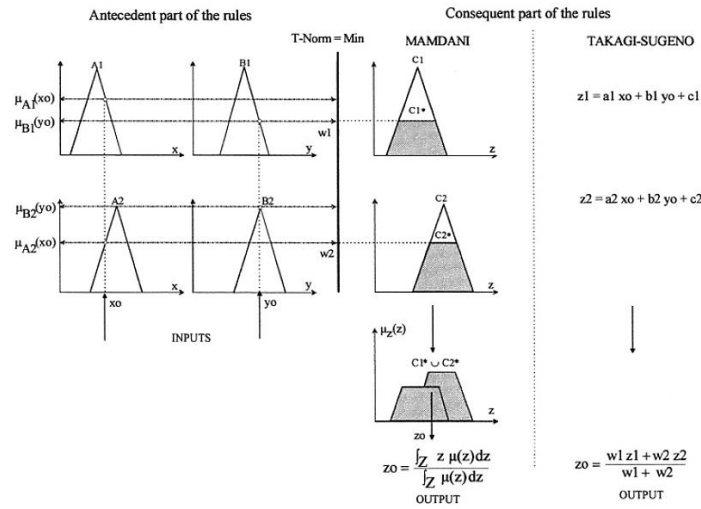

Fig.1. Comparing defuzzifier Mamdani and Takagi-sugeno center of gravity methods [3]

Fig.1 shows Diagram of Mamdani and Takagi-sugeno defuzzifier methods [3]. Clearly, Mamdani method needs to calculate the integrals to increases the output accuracy, unlike Takagi-sugeno method and consequently using this method will increase the computation. This is one of the reasons that this method is not used in hardware implementation.

This paper presents a simple Mamdani hardware implementation algorithm. The algorithm has simpler computational process than the hardware implementation of the algorithms which have been proposed so far, and do not use circuits such as square/root [5], [7] and eliminates the restrictions such as number and type of inputs [5] and hardware complexity.

The proposed algorithm introduced in Section 2 and the circuit performance is evaluated in Section 3. The simulation result of the algorithm is shown in Section 4 and finally conclusions are presented in Section 5.

3. Proposed algorithm

Mamdani defuzzification method is based on the integral calculation of $\int_a^b f(x)dx$ and $\int_a^b x.f(x)dx$ and it is shown in (1):

$$COG = \frac{\int_Z Z.\mu_{(z)}dz}{\int_Z \mu_{(z)}dz} \qquad (1)$$

Schematic of the algorithm operation is shown in Fig. 2 and the details in Fig.3. This algorithm can be applied to defuzzifier circuits that current input and current output.
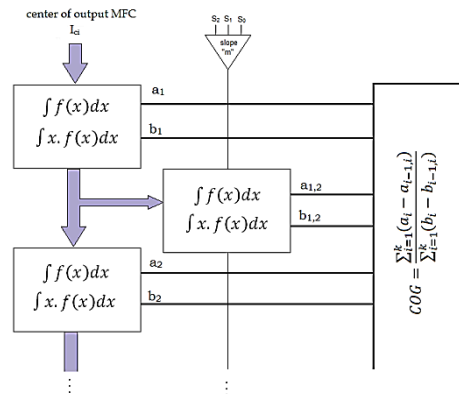

Fig.2. Proposed algorithm

In this algorithm, the integral of $\int_Z \mu_{(z)}dz$ calculated separately for all output membership functions and common area, and the integral of $\int_Z Z.\mu_{(z)}dz$ is related to the integral $\int_Z \mu_{(z)}dz$ by characteristic triangular functions and can be calculated without additional relationships.

Finally, calculated common areas are subtracted from corresponding values and numerator and denominator of the center of gravity defuzzifier are formed. In this algorithm center, slope and height of membership functions are determined by user. Fig.4 shows details of triangular membership function.
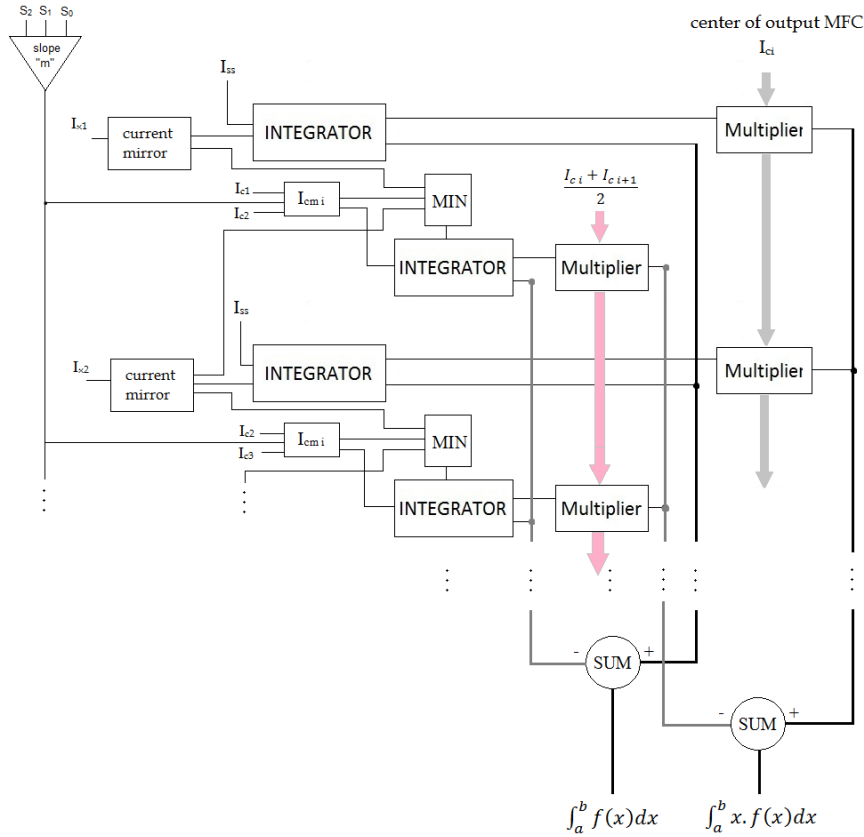
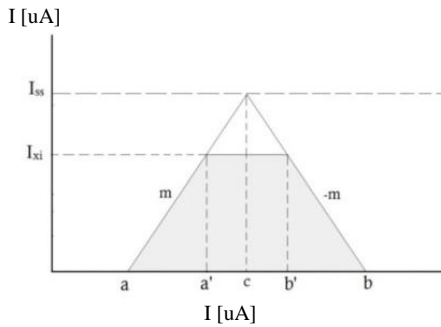Fig.3. Details of the proposed algorithm

Fig.4. Triangular membership function

According to Fig.4:

$$S = \int_a^b f(x)dx = 2 \int_a^c f(x)dx \qquad (2)$$

$$m = \frac{I_{ss}}{c-a} = \frac{I_{ss}-I_{xi}}{c-a'} \qquad (3)$$

The integral of function is the area under the function curve. According to the described characteristics in Fig.4, we have:

$$S = 2\left[\frac{(c-a)+(c-a')}{2} \times I_{xi}\right] \qquad (4)$$

$$c - a = \frac{I_{ss}}{m} \qquad , c - a' = \frac{I_{ss}-I_{xi}}{m} \qquad (5)$$

$$S = \left[\frac{I_{ss}}{m} + \frac{I_{ss}-I_{xi}}{m}\right] \times I_{xi} = [2I_{ss} - I_{xi}] \times \frac{I_{xi}}{m} \qquad (6)$$

Where, m is the slope of membership function that is controlled by digital voltage control. It should be noted that the analog current control of C is applied by the user as the location of each membership function.

To calculate the equation (6) two currents are needed. First current shows highest level function that is determined by user, and second current shows the cutting surface of membership function that comes from the rule base circuits as an input of defuzzifier circuit.

According to Fig.4 integral $A = \int_a^b x.f(x)dx$ is the product of the area under the membership function that are shown by (7) to (15):

$$A = \int_a^b x.f(x)dx \qquad (7)$$

$$A = A_1 + A_2 + A_3 \tag{8}$$

$$A_1 = \ = \frac{m}{3}\left(a'^3 - a^3\right) - \frac{\alpha}{2}\left(a'^2 - a^2\right) \tag{9}$$

$$A_2 = \int_{a'}^{b'} f_2(x)dx = \frac{I_{xi}}{2}\left(b'^2 - a'^2\right) \tag{10}$$

$$A_3 = \int_{b'}^{b} f_3(x)dx = -\frac{m}{3}\left(b^3 - b'^3\right) + \frac{\beta}{2}\left(b^2 - b'^2\right) \tag{11}$$

$$A = \frac{m}{3}\left(a'^3 - a^3\right) - \frac{\alpha}{2}\left(a'^2 - a^2\right) + \frac{I_{xi}}{2}\left(b'^2 - a'^2\right) - \frac{m}{3}\left(b^3 - b'^3\right) + \frac{\beta}{2}\left(b^2 - b'^2\right) \tag{12}$$

$$A = \frac{m}{3}\left(\left(\frac{I_{xi}}{m}\right)^3 + 3\left(\frac{I_{xi}}{m}\right)aa'\right) - \frac{\alpha}{2}\left(\frac{I_{xi}}{m}(a + a')\right) + \frac{I_{xi}}{2}\left(4c\left(\frac{I_{ss} - I_{xi}}{m}\right)\right) - \frac{m}{3}\left(\left(\frac{I_{xi}}{m}\right)^3 + 3\left(\frac{I_{xi}}{m}\right)bb'\right) + \frac{\beta}{2}\left(\frac{I_{xi}}{m}(b + b')\right) \tag{13}$$

By Calculating the equations and relationships between the line properties of triangle in Fig.3, we have:

$$A = 2c\frac{I_{xi}I_{ss}}{m} - c\frac{I_{xi}^2}{m} = c\frac{I_{xi}}{m}[2I_{ss} - I_{xi}] = c.S \tag{14}$$

$$A = \int_a^b x.f(x)dx = c\int_a^b f(x)dx = c.S \tag{15}$$

Thus, the numerator of defuzzifier in each membership functions is proportional to the area under each membership function. This feature reduces the required equations for defuzzifier and reduces the size and power of the circuit as well.

According to Fig.5, in order to calculate the numerator of adjacent membership functions of Mamdani defuzzifier, we have:
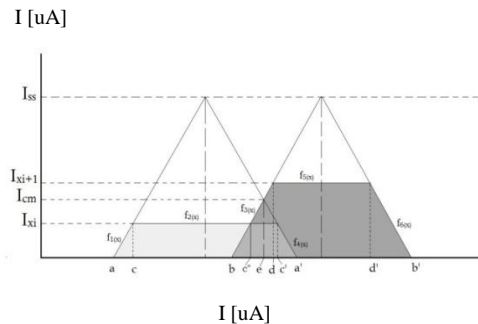
I [uA]

I [uA]

Fig.5. Properties of adjacent membership functions

$$B = \int_a^{b'} x.f(x)dx = \int_a^c x.f_1(x)dx + \int_c^{c''} x.f_2(x)dx + \int_{c''}^d x.f_3(x)dx + \int_d^{d'} x.f_5(x)dx + \int_{d'}^{b'} x.f_6(x)dx \tag{16}$$

To calculate integral $\int xf(x)dx$ of adjacent membership functions and common area according to Fig.5, we have:

$$B_1 = \int_a^{a'} x.f(x)dx = \int_a^c x.f_1(x)dx + \int_c^{c'} x.f_2(x)dx + \int_{c'}^{a'} x.f_3(x)dx \tag{17}$$

$$B_2 = \int_b^{b'} x.f(x)dx = \int_b^d x.f_3(x)dx + \int_d^{d'} x.f_5(x)dx + \int_{d'}^{b'} x.f_6(x)dx \tag{18}$$

$$B_3 = \int_b^{a'} x.f(x)dx = \int_b^{c''} x.f_3(x)dx + \int_{c''}^{c'} x.f_2(x)dx + \int_{c'}^{a'} x.f_4(x)dx \tag{19}$$

Therefore:

$$B = B_1 + B_2 - B_3$$

The *m* coefficient of numerator and denominator of defuzzifier are simplified in order to reduce the calculations. The slope effect is applied in calculation of common current, which will be explained below.

It should be noted that the slope of all membership functions are the same. It's controlled in 7 levels by 3 digital voltage controls. According to Table.1, the user generates the slop by determining the amplitude of membership function in horizontal axis.
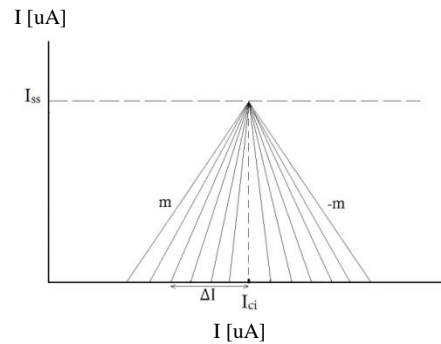
I [uA]

I [uA]

Fig.6. Generated slop by digital voltage control

Table.1
slop of membership functions

S_2	S_1	S_0	$\Delta I(\mu A)$
0	0	1	1
0	1	0	2
0	1	1	3
1	0	0	4
1	0	1	5
1	1	0	6
1	1	1	7

According to Fig.5, common area should be subtracted from calculation after calculating the required integrals of membership functions.

In order to calculate the required integral of common area, three current are required to calculate the two integrals of center of gravity defuzzifier.

According to relations (20) to (22), the first current is the common point between any two adjacent membership function that is used as the reference current of common area (I_{cm}). Minimum of three currents I_{cm}, I_{xi} I_{xi+1} as the cut-off current of common area is the second required current, and mean of currents I_{ci+1} and I_{ci} is the third current as

center of common area to calculate the defuzzifer numerator. These currents are obtained easily by simple circuit:

$$I_{ss} = -mI_{ci} + \beta_1 \rightarrow \beta_1 = I_{ss} + mI_{ci} \qquad (20)$$

$$I_{ss} = mI_{ci+1} - \alpha_1 \rightarrow \alpha_1 = mI_{ci+1} - I_{ss} \qquad (21)$$

$$I_{cm} = \frac{\beta_1 - \alpha_1}{2} = \frac{I_{ss} + mI_{ci} - mI_{ci+1} + I_{ss}}{2} = I_{ss} - m(\frac{I_{ci+1} - I_{ci}}{2}) \qquad (22)$$

In this way, the user can apply any membership functions for each rule without any restrictions. In this method, K integration process will be repeated for K output membership function and there is no need for normalized circuits.

3. Circuit Performance of algorithm

According to previous Section, the outputs of the prior blocks entered into defuzzifier circuit as current I_{xi} and according to equations (2) to (6), integral of output membership functions are calculated, with respect to the reference current I_{ss} that determines the final level of membership function. Integral of the output membership function is calculated and is multiplied in the center of output membership function to produce numerator of defuzzifer. Then, intersection current is calculated and two required integrals are calculated for these regions.

Fig.7 shows multiplier/divider circuit [16] that has been used in the algorithm. This circuit has high accuracy multiplier that is used to produce numerator and denominator of defuzzifier.
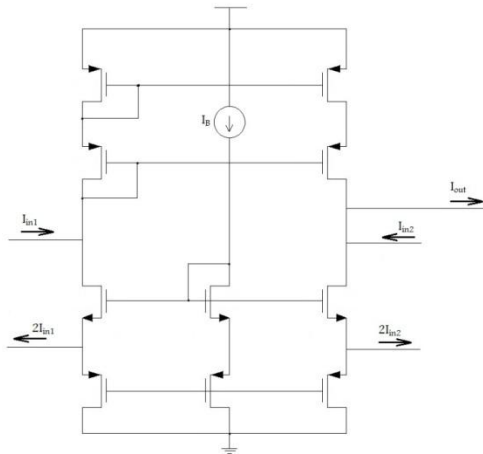

Fig.7. The multiplier circuit [16].

According to Fig.7, there are two inputs on the left and right of multiplier circuit:

$$I_{in1} = I_x + I_y \qquad (23)$$

$$I_{in2} = I_x - I_y \qquad (24)$$

The output of circuit is calculated as follows:

$$I_{out} = \frac{I_x I_y}{I_B} \qquad (25)$$

Therefore, the required inputs are considered to for desire output in the proposed integrator circuit (6) as follows:

$$I_{in1} = 2I_{ss} \qquad (26)$$

$$I_{in2} = 2(I_{ss} - I_{xi}) \qquad (27)$$

One of the advantages of this algorithm is using current mirror and multipliers circuits to calculate the numerator and denominator center of gravity of Mamdani defuzzifer method, which has simple design and reduces circuit complexity.
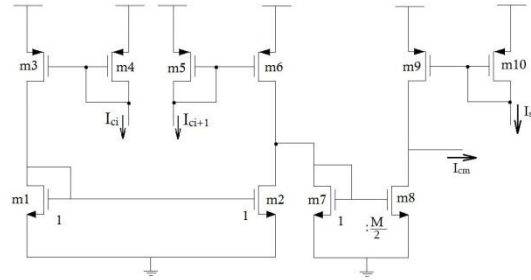

Fig.8. Require circuit to calculate common current

As mentioned, the center of output membership function is current I_{ci} which is determined by user. Distance between the centers of the membership functions are adjusted by user. The handling slope of functions is applied in this part of the circuits by the voltage control only.

4. Simulation Results

In all used simulations IB = 20uA. The simulation results of multiplier circuit are shown in Fig.9.
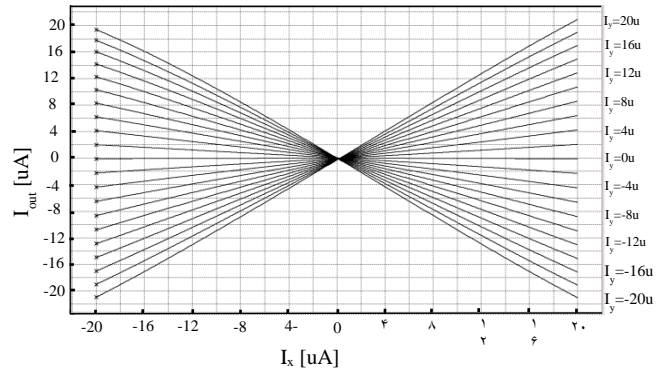

Fig.9. The simulation results of multiplier circuit

As is clear from the results, this circuit has high accuracy in multiplication, reduced size and circuit complexity due to less number of transistors. The accuracy of defuzzifier is increased due to the high accuracy of the current output. The integrated circuit is used to produce numerator and denominator center of gravity Mamdani defuzzifier.

Fig.10 shows simulation results of integral circuit that calculate denominator of defuzzifier. Acceptable error rate of the circuit is shown in Fig.11.
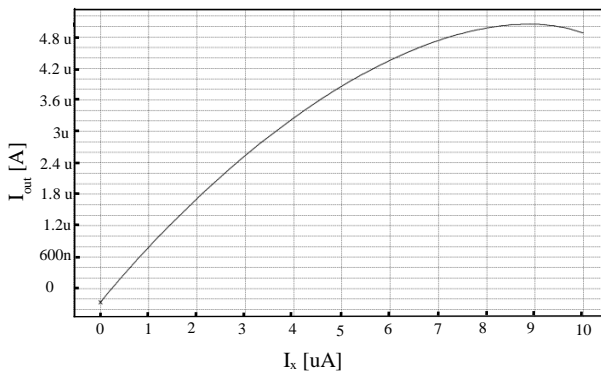

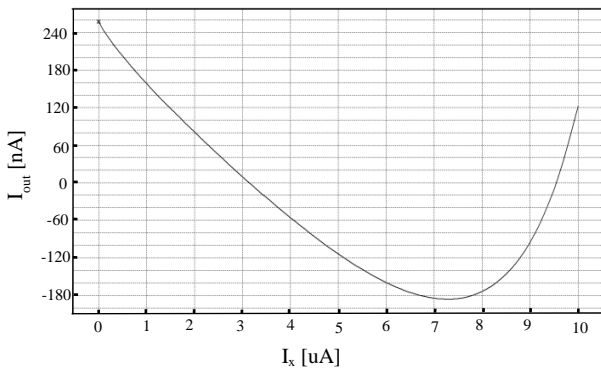Fig.10. Output of integral circuit ($I_{ss}=10u$ و $I_x=[0\ 10u]$)

Fig.11. Error of integral circuit ($I_{ss}=10u$, $I_x=[0\ 10u]$)

According to Table.1, simulation results of the intersection of two adjacent membership function circuit with $I_{ci}=10u$ and $I_{ci+1}=[10u-20u]$ are shown at Fig.12. Fig.13 for m = 2 shows high accuracy and acceptable result of the circuit.
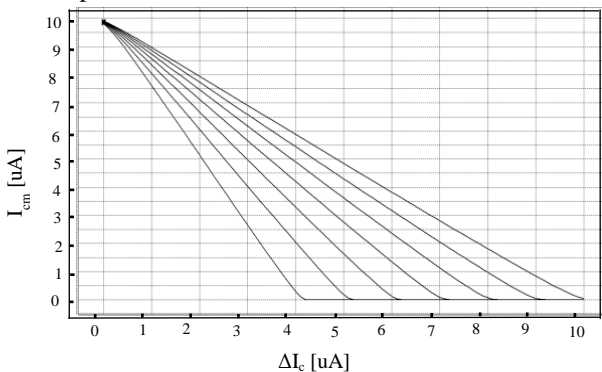

Fig.12. Simulation result of intersection memberhip functions
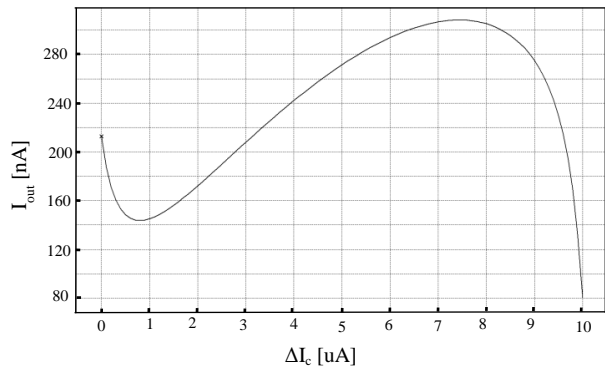

Fig.13. Error intersection circuit

According to the simulation results, the calculation of the numerator and denominator Mamdani defuzzifier shows high accuracy and good performance of the algorithm. The final result in the center of gravity defuzzifer will depend on used divider circuit. However, the size of defuzzifier circuit does not depend on the size divider circuit due to the fact that only one divider circuit is used in this algorithm but its accuracy is totally dependent.

5. Conclusion

This algorithm is new structure to implementation Mamdani defuzzifier circuit. It has high flexibility in number of input parameters such as slope, height and location of the output membership functions that is applied by the user without any changes in the circuit structure, and is programmable for various applications. This algorithm, unlike previous work never made a restriction on the type and number of fuzzifier membership functions such as triangular [12],[17] or gaussian [8-10],[13] membership functions, and this advantage cause to use the algorithm in many programmable fuzzy circuits.

According to results of the simulations, the other advantage of the algorithm is its high accuracy. Complexity reduction and high accuracy of the algorithm make it a good choice for the controllers. Consequently, employing this algorithm increase the accuracy of the controller due to implement Mamdani defuzzifier.

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