

VLSI Implementation of Fuzzy Logic Circuit

Manira Khatun

Abstract—The paper proposes the VLSI realization of a Fuzzy logic circuit. In this paper, a current-input, current-output reconfigurable MIN-MAX circuit is developed using PSPICE for application in fuzzy temperature controller.

Index Terms— Bounded difference operation, CMOS MIN circuit, CMOS MAX circuit, Current mirror, Fuzzy Logic, RFMC.

I. INTRODUCTION

Fuzzy logic is a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false, respectively). The reasons of using fuzzy logic are—conceptually easy to understand, flexible, tolerant of imprecise data, based on natural language, non-linear function of arbitrary complexity, blended with conventional control techniques, built on top of the experience of the experts.

1. Digital Implementation

The VLSI digital implementation of Fuzzy Logic systems offers several advantages issued from the sound knowledge of digital circuit design and technology. Several mature CAD (Computer Aided Design) tools allow relatively easy design automation (synthesis and simulation) reducing consequently time and cost of development. The automatic regeneration of logic levels involves high noise immunity and low sensitivity to the variances of transistor characteristics. This provides accurate and reliable data and signal processing. Binary data can be easily stored and allows realizing programmable and multistage fuzzy processing. Complex representation of fuzzy vectors and parallel structures are however required to obtain accurate and fast processing. Digital implementation of common fuzzy operation leads unfortunately rapidly to complicated, enormous VLSI circuits. The density and speed of these circuits are nevertheless continually increasing according to technological advances, so that they will become more and more efficient to implement fuzzy logic systems [1].

Digital fuzzy processors are generally designed for multipurpose applications in order to interest maximum of potential customers. They should thus implement a great and various members of fuzzy operators, membership functions and inference rules. These make them rather efficient for a large range of applications, provided that appropriate programming is possible (which supposes an appropriate internal or external memory).

Combined with an appropriate object oriented programming environment, linguistic rules derived from a human expert can be directly translated into an implementation on a chip.

The first hardware approaches of implementing fuzzy logic inference engine were the digital circuits designed by Togai and Watanabe [2]. ASIC's implementing specific architectures and specialized instructions (MIN & MAX) exhibits much enhanced processing speed relatively to regular micro processors.

Analog fuzzy values should be converted into strictly binary signals before being processed by standard digital circuits. On one hand the analog input signals should be quantized through A/D converters, and on the other hand the membership functions should be quantized to obtain their digital representations. Fuzzy sets are then storable but in the guise of stair-functions. The combination of these two round-off effect can deteriorate fuzzy processing if the fuzzy values are not represented with a sufficient number of bit. There is however a trade-off between precision and size (or speed) since the latter is proportional to the number of bit.

The inputs are furthermore sampled at the frequency of digital circuits. Sampling effects: non-continuous (or pseudo-continuous) control [3].

1.1. Application fields and future trends

Digital implementation is used in control, expert systems, robots, image recognition, diagnosis, database (interface with digital circuits), information retrieval etc. High prices must be reduced to make these processors more attractive. Some less common hardware implementations such as pulse width modulation [4] or super-conducting processor have also been implemented, and are not excluding from future developments according to technological evolution.

1.2. Analog implementation

1.2.1. Comparison between analog and digital implementation

Analog circuits present several advantages towards digital ones, especially regarding speed of processing, power dissipation and functional density. They can more over perform continuous-time processing and have particularity to be well compatible with sensors, actuators and all other analog signals. Therefore they are obviously indicated to deal with fuzzy values which are analog by nature. Some continuous representations of symbolic membership functions and some non-linear fuzzy operations can be easily synthesized by dealing with transistor characteristics. There is no need of A/D or D/A converters when implemented in a real system, provided that no specific digital signal processing is required. Analog circuits can then supplant digital controllers for some applications requiring low-cost, low-consumption, compact and high speed stand-alone chips.

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They suffer nevertheless of the lack of reliable memory cells. They are consequently not well appropriate to pipeline structures and have very restricted programmability possibilities. Fortunately, the nature of fuzzy variable systems required extensive parallelism which makes analog circuits well appropriate to precede high-speed numerous inferences and also limits the problem of error accumulation.

1.2.2. Application fields and future trends

Analog implementation is used in stable and low noise analog technologies (n-well CMOS, Bi-CMOS) having sufficient accuracy with wide frequency range.

During the last decade a growing interest in low voltage, low power circuit in standard CMOS technology can be observed because of the portable electronic devices and smart sensors. Current mode circuit's shows great future since using current as signal carriers enables it to be unrestricted by supply voltage.

1.2. Mixed implementation:

Fuzzy logic systems lend themselves well to analog integration, except for some-control and reconfiguration structures. Several switches are thus often integrated on analog circuits and commanded by digital inputs.

It can actually be attractive to increase the complementarities between digital and analog features and to merge them into a single mixed chip, in order to improve the weak points of both. A fuzzy knowledge base can be programmed in a digital memory which consists of dedicated locations and stores a variable number of parameters characterizing membership function shapes and inference rules notably. High-parallel and non-sequential analog processing is then afforded provided that D/A converters are used. A/D converters can also be used when a digital computation of the centre-of-gravity is desired.

The VLSI design group of SGC-THOMSON has also under taken the design of a hybrid controller implemented by means of a mixed analog/digital technology. It consists of a digital storage and distribution unit followed by an analog inference core. The membership grades are converted into analog values by an internal D/A. This system does not need expensive A/D and D/A converters in comparison with digital controllers. Its high speed should be suitable for very demanding real time requirements with a limited number of rules.

II. ANALOG REALIZATION

2.1. Voltage mode

Voltage mode is attractive because it makes easy to distribute a signal in various parts of a circuit. Non-linear operators such as the MIN, MAX and truncation ones are quite easy to implement in voltage mode. Multiple-input MIN and MAX circuits constructed with bipolar transistors are represented in figure-1 and figure-2 are called emitter coupled fuzzy logic gates. These basic non-linear gates present good characteristics and robustness [5]. Such circuits are impractical with MOS transistors which cause an acceptable error associated with the transition regions in which multiple devices are active. They are more complicated but have high frequency and accurate performance.

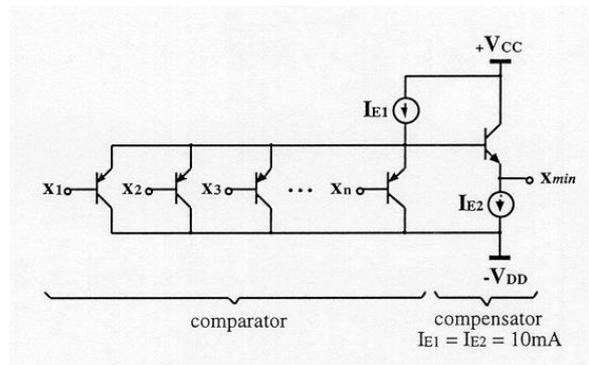


Figure-1 MIN cell, voltage mode

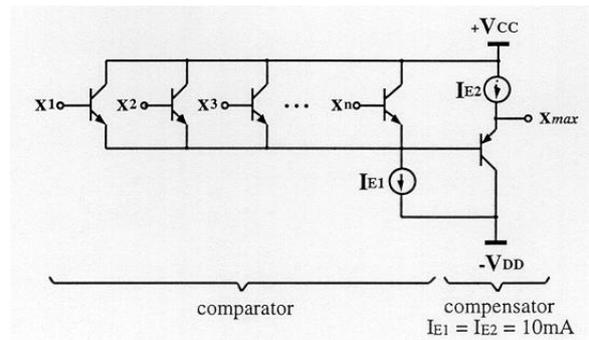


Figure-2 MAX cell, voltage mode

2.1.1. Disadvantages of voltage mode

Voltage mode fuzzy circuit implies a large stored energy into the node parasitic capacitances ($CV^2/2$) and speed is limited by charge delays of various capacitors. They are more over penalized by a certain lack of precision because signals are sensitive to changes of supply voltages. This is especially significant when the voltage range is restricted in order to limit transistor functioning to a small part of their characteristic, or when the electrical consumption should be limited. The problems mainly lie in the sizing of some components.

Several functions are very difficult to build in voltage-mode, and it is also true for some basic ones as the algebraic sum. The above described approach needs resistors to achieve additions and to convert voltages into currents. Integrated resistors are unfortunately inaccurate, cumbersome and involve significant parasitic capacitances. The truncation of the consequent and the de-fuzzification pose an important problem as regards the parallelism of the inference engine (especially when the number and size of output sets is large). This approach implies high power dissipation and large chip area, and leads to high-costs implementations.

2.2. Current mode

Current mode circuits do not need resistors and can achieve summation and subtraction in the simplest way, just by wire connections. This leads to simple and intuitive configurations, which exhibits high speed and great functional density. They are used more and more, especially for systems requiring a high level of interconnectivity (neural networks for example). High speed is provided when capacitive nodes are not subject to great voltage fluctuations. Current mode circuits have the advantages-



- a. Low power dissipation
- b. Low supply voltage
- c. Good insensitivity to the
- d. Supply voltage fluctuation.

Since, current mode circuits have a single fan-out, current repeatability is of prime importance and the distribution of signals requires multiple output current mirrors.

2.2.1. Current mirror

A current mirror is a circuit designed to copy a current through one active device by controlling the current in another active device of a circuit, keeping the output current constant regardless of loading.

An ideal current mirror is simply an ideal current amplifier. There are three main specifications that characterize a current mirror-

- a. The current level it produces
- b. Its ac output resistance which determines how much the output current varies with the voltage applied to the mirror.
- c. The minimum voltage drops the mirror necessary to make it work properly.

A current mirror implementation with n-p-n bipolar transistors using a resistor to set the reference current I_{REF} is shown in figure-3.

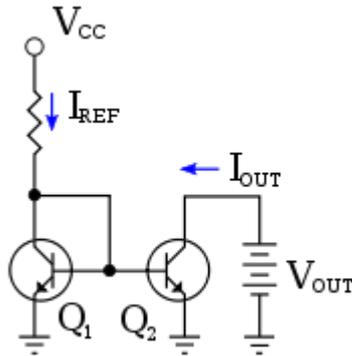


Figure-3 Current mirror implemented by BJT

Now a day, the transistors are replaced by MOSFET as the speed of MOSFET is much higher and the power dissipation is low. The n-channel MOSFET current mirror with a resistor to set the reference current I_{REF} is shown in figure-4.

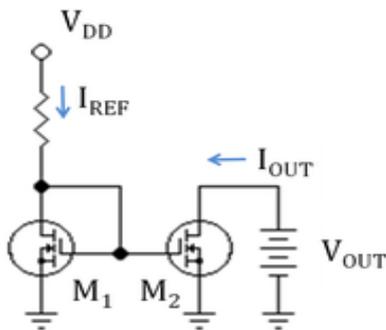


Figure-4 An n-channel MOSFET current mirror

A basic realization of multiple output CMOS current mirror is shown below.

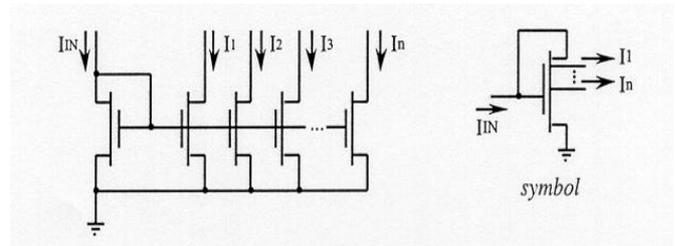


Fig-5 Basic n-output CMOS current mirror and symbolic representation

The circuit is however not suitable for synthesizing accurate functions since each output current is slightly modulated by output voltage throughout the early conductance. The output current should be independent of the output voltage, which is obtained by reducing the conductance as for the 3 common mirrors shown in fig6. The drain voltage of the transistor which imposes the current is then independent of the output voltage of the circuit. Multiple output cascade mirrors are often used but Wilson ones are preferable for low power applications because they require a single polarization voltage instead of two super-posed voltages. The Mod-Wilson mirror is obtained by adding a transistor to the Wilson mirror to improve its symmetry. This mirror provides good accuracy and input current is well reproduced with perfectly matched identical transistors. The precision of all these mirrors depends on their output resistance and on the matching of their transistors.

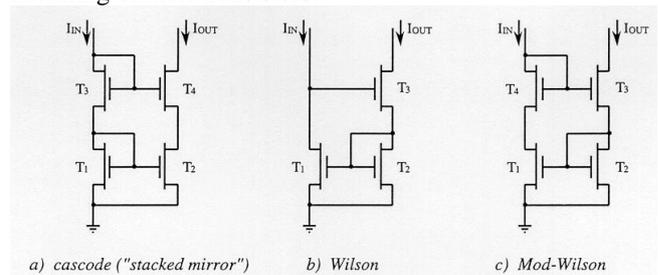


Fig-6 NMOS current mirrors

Current mirror can be used as building blocks to synthesis fuzzy logic operations and relevant processing.

In this way, nine basic fuzzy functions can be easily implemented on monolithic IC's with standard CMOS or bipolar technologies.

These current-mode basic logic cells exhibits good linearity which cannot be easily achieved in voltage- mode, and lead to fuzzy integrated systems which are globally smaller than in voltage mode.

2.2. MIN-MAX circuits

Minimum (MIN) and Maximum (MAX) operators are typically employed to define the sentence connectives in any kind of fuzzy controller. In Mamdani controller they also define the fuzzy implication and aggregation mechanism. They are also used in the fuzzification operation using membership function.

The building block of both MIN-MAX circuits is a bounded difference circuits as discuss below.

2.2.a. Bonded difference circuit

Bounded difference of two variables x and y defined as

$$x \ominus y = \begin{cases} x-y; & \text{if } x \geq y \\ 0; & \text{if } x < y \end{cases}$$



The bounded difference circuit can be obtained by the combination of a current mirror and a diode. Now, the diode can easily be realized in the CMOS circuit either by a single FET, in which gate and drain are connected together, or by a current mirror. The first solution involves inevitable voltage drops due to the channel resistance and can influence the normal logic function of the circuits. Nevertheless, the diode can be omitted in cascade connection of such circuits.

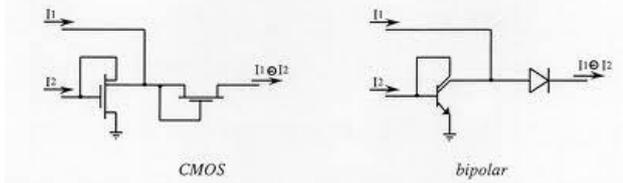


Fig-7 CMOS and Bipolar implementation of symbolic bounded difference operation

Current mirror are subdivided into two complementary types, whatever their transistors are n or p channel MOSFET. The directions of input and output currents depend on the type of the respective components (input mirror and output diode in bounded difference circuit). Thus, there are four different configurations of input and output current directions (two of which are shown in fig7 and 8).

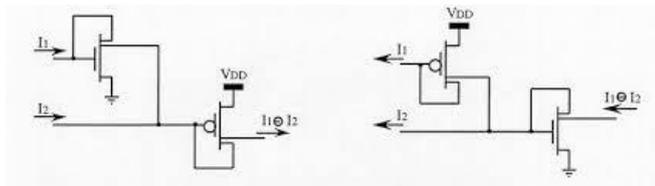


Fig-8 Two different implementations of Symbolic bounded difference operation

To each configuration corresponds a complementary one which is obtained by substituting p-channel current mirror to n-channel ones and vice-versa. Thus, this is convenient for designing circuits using fuzzy logic units, without worrying about specific current directions.

The circuits of figure-7 and figure-8 realize bounded difference operation on two values of membership functions μ_x and μ_y represented by the currents I_1 and I_2 respectively. They also realize the complement operation on I_2 , when I_1 has the maximum value. Now, as bounded difference and algebraic sum are sufficient to realize all fuzzy functions, fuzzy circuits can be designed only by specifying connections between bounded difference sub-circuits.

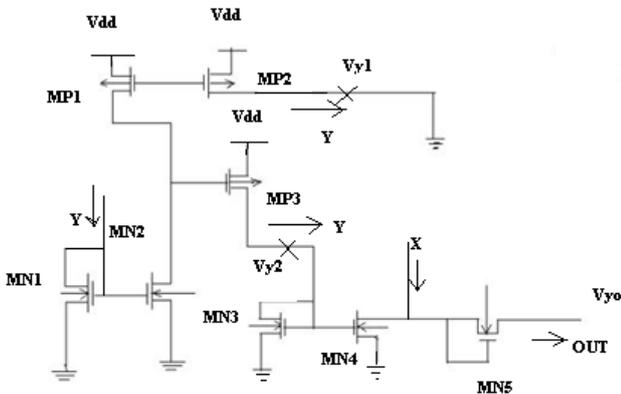


Fig-9 A Bounded Difference circuit

2.2.b. MAX-MIN circuits

MAX function of two inputs x and y can be derived by using bounded difference operator and an Add (+) Operator as follows:

$$\text{MAX}(x, y) = x \oplus y + y$$

AND

MIN function of two inputs x and y can be derived by using bounded difference operator as follows:

$$\text{MIN}(x, y) = x \ominus (x \ominus y)$$

2.2.b.1. MAX circuit

A CMOS two input MAX circuit is shown below:

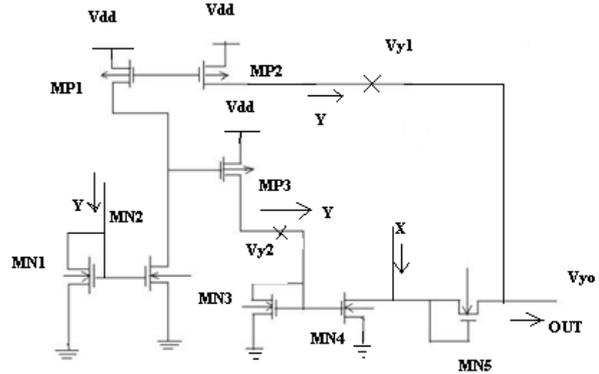


Figure-10 A two input MAX circuit

2.2. b. 2 MIN circuit

A CMOS two input MIN circuit is shown below:

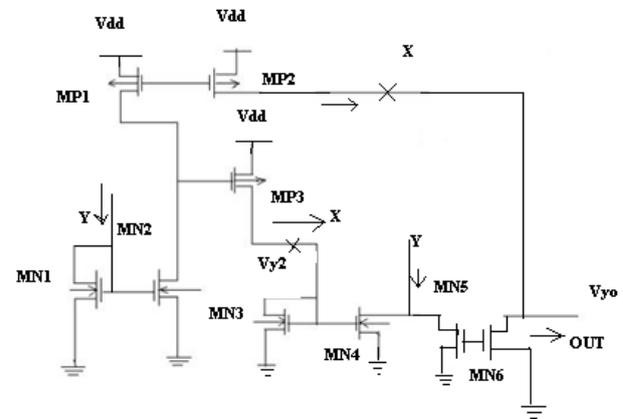


Figure-11 A two input MIN circuit

Here, both the above circuits permit only two inputs, but multiple inputs are necessary for realization of membership functions as detailed below.

MIN-MAX circuit is used in the temperature controller for developing the input and output membership functions. These membership functions can be reconfigured in terms of its shapes-the s-shape, the trapezoidal-shape, and the triangular shape.

The building block of a Reconfigurable membership function circuit (RFMC) is shown in fig12. The input-output characteristics can be assigned by external signals such as I_w , I_w' , I_h , k , k' . I_w is the first turning point of the membership function. When I_w and I_w' are same, a triangular-shape is formed. Similarly, a z-shaped is formed when I_w is zero. On the other hand, there will be a result of an S-shape if I_w is large enough. k and k' are the slopes of the membership function as shown in figure. Lastly, I_h is the maximum output current in proposed circuit. As a result, the shape of the membership function can be fine tuned.

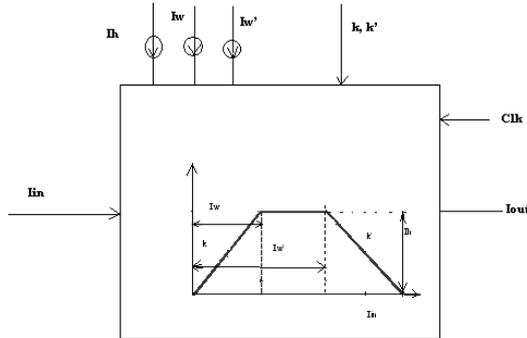


Figure- 12 Block diagram of RFMC

It is observed that for realization of the RFMC multiple-inputs are necessary. This is realized by using two-input MIN-MAX circuits connected in form of a Binary Tree as shown below:

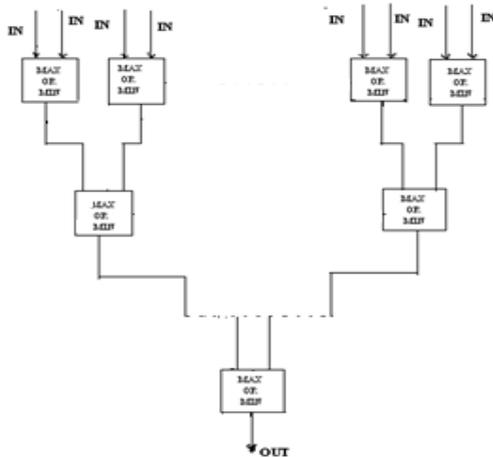


Figure-13 A binary tree realization using the typical two input circuits

II. RESULTS

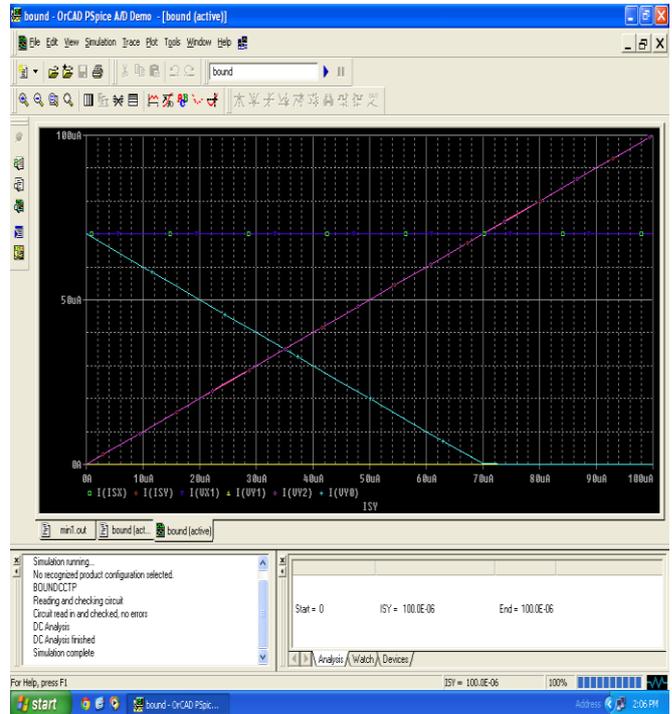


Figure-14 Inputs and outputs of Bounded Difference circuit

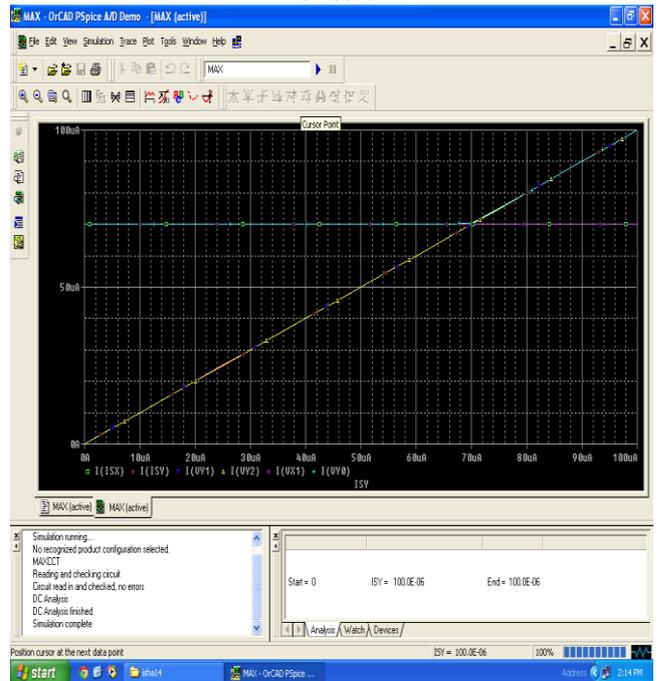


Figure-15 Inputs and outputs of MAX circuit

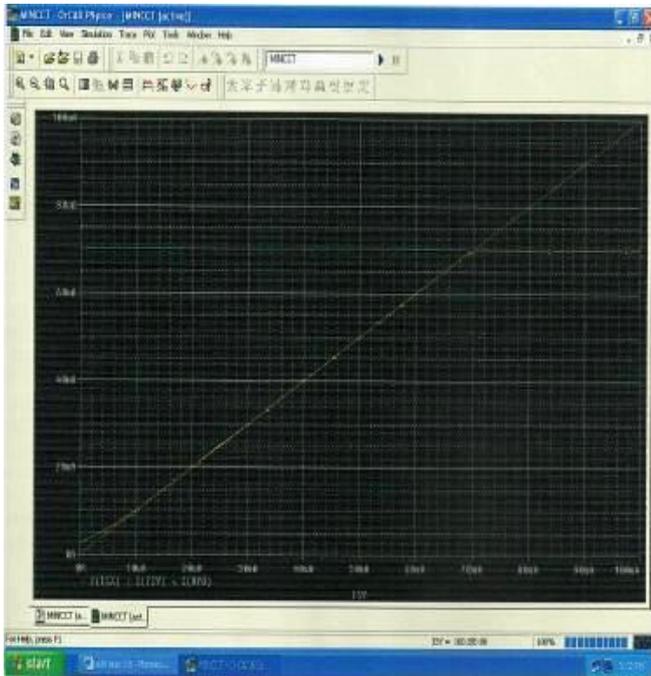


Figure-15 Inputs and outputs of MIN circuit

III. CONCLUSION

Research and development is continuing on fuzzy applications in software, as opposed to firmware, design, including fuzzy expert systems and integration of fuzzy logic with neural network and so called adaptive 'genetic' software systems with the ultimate goal of building 'self-learning' fuzzy control system.

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