Perceptron Linear Function Design with CMOS-Memristive Circuits

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Abstract—In the last decade, the interest to emulation of the functionality and structure of the human brain to solve the problems related to image processing and pattern recognition, especially using Artificial Neural Network (ANN), has increased. Since the capability of ANN to compute at high-speed has been proven to be very useful for various computational problems. One of the simple ANN models is perceptron. Since the perceptron is the basic form of a neural network, the efficient implementation of analog activation functions is required. As various works introduce the design of sigmoid and tangent activation functions, the other activation functions remain an open research problem. This paper describes the design of the perception circuit with the linear activation function using operational amplifier and memristive crossbar. Additionally, the variation of performance with temperature, noise of the circuit is presented.

I. INTRODUCTION

Pattern recognition, classification, control, and optimization are the main applications of the artificial neural network [1]. Performance and ability to make decision of ANN’s mostly depend on type of the activation function and network structure. Therefore, to simplify the structure of the network, accelerate the time of convergence and the learning outcome of ANN it is necessary to design activation function that will meet these properties [2]. Various activation functions for memristive crossbar-based neural network designs have been investigated in the last decades [3], [4], [5], [6], [7], [8]. However, the implementation of the memristive neural network with linear activation function is still an open problem.

In this paper, we present the design of the linear activation function for the memristive crossbar perceptron circuit. We explore the possibility to use the linear activation function called Rectified Linear Unit (ReLU) in simple neural network design. Easier optimization, fast convergence, and high computation speed in deep networks are the main advantages of the ReLU [9].

Fig. 1 illustrates the transfer characteristics of the ReLU activation function and these characteristics described in equation (1).

\[
f(z) = \begin{cases} 
  z, & \text{if } \sum w_i x_i \geq 0 \\
  0, & \text{otherwise} 
\end{cases}
\]

(1)

The simplest model of a neuron is illustrated in the Fig 2, where the in each neuron weighted inputs are summed up in order to generate output signal.

The output of the simple neuron can be simply written in the form given in equation (2).

\[
V_O = f(\sum_{i=1}^{n} x_i w_i)
\]

(2)

Where \(x_i\) and \(w_i\) is the input and weight of the \(i\)th synapse, respectively and the function \(f\) is the activation function of the neuron [10].

Some of the neural networks use memristive crossbar technology in processors, where most of these memristive crossbars can be used to compute the dot product by consuming less power and can be used as storage for the weights. The implementation of the memristive circuits illustrated in Fig. 2 is quite simple. The inputs \((x_1, x_2, x_n)\) are voltage sources connected to respective memristors \((w_1, w_2, w_n)\), where memristors represent the weight of synaptic connections. Conductance of the memristor is multiplied with input voltage which is proportional to the currents flowing through synapses. Then, by Kirchhoff’s current law all currents are...
summed up and the output sum is evaluated by activation function [11].

The main purpose of this paper is to introduce the perceptron with Rectified Linear Unit activation function using memristive crossbar as the storage for synaptic weights.

II. METHODOLOGY

In this part of the paper memristor device will be described. In the early 1970s it was scientifically proved that there exist fourth basic circuit element that illustrate the relationship between flux $\phi$ and charge $q$ called memristor. The name of the device comes from its behavior, which similar to nonlinear resistor which has a memory [12]. The main characteristics of the device can be observed by connecting the memristor to AC source.

Conceptual view of $\text{TiO}_2$ memristor (Fig. 3), demonstrated by HP Lab in 2008, is equivalent to serially connected variable resistors. Where, high resistance state and low resistance state is denoted by $R_H$ and $R_L$. Expression of the overall memristance of the device is shown in equation (3).

$$M(p) = p \times R_H + (1 - p) \times R_L$$  \hspace{1cm} (3)

Where front position relative doping $p(0 \leq p \leq 1)$ is the ratio between doping front position and $\text{TiO}_2$ thin film thickness [13].

![Fig. 3. Memristor made of $\text{TiO}_2$. (a) Structure. (b) Equivalent circuit.](image)

III. RESULTS

A. Perceptron design

One of the main purposes of this work is to illustrate the circuit of perceptron with linear activation function. ReLU was chosen as an activation function due to its advantages compared to other activation functions. Transfer characteristics similar to ReLU function was observed in precision half wave rectifier circuit also known as superdiode (Fig. 5).

Circuit can be analyzed by considering two cases, when $V_{IN} \geq 0$ and $V_{IN} < 0$. For $V_{IN} \geq 0$, current $I_2 = I_D$, hence output voltage $V_{OUT}$ will be equal to $V_{IN}$. For $V_{IN} < 0$, the current $I_D$ will be negative, however, due to diode it will be blocked because diode will be in reverse biased mode. As a result, output voltage $V_{OUT}$ will be zero.

The transfer characteristics of the circuit obtained during simulation is shown in Fig. 6.

![Fig. 5. Precision Half Wave Rectifier.](image)

![Fig. 6. Transfer characteristics of the Precision Half Wave Rectifier.](image)

From the Fig. 4 it can be seen that the resistance of the device changes since I-V curve is not linear. However, device needs certain threshold voltage $V_{th}$ in order to change its state [14], which is equal to 1V in our model. That means the resistance of the memristor will stay constant until applied voltage will not exceed 1 volt. Also, from the Fig. 4 it can be observed that the I-V graph has three linear parts illustrating three different resistance stages. First one, which was observed in 0.8V and 1V source amplitude is $R_{initial}$, second one with higher slope is $R_{off}$ and the last is $R_{on}$. According to the sub file in LTSpice the resistance values of illustrated model is $R_{initial} = 10k\Omega$, $R_{off} = 64k\Omega$ and $R_{on} = 3k\Omega$. From the Fig. 6 it can be seen that the upper bound of the transfer characteristics is saturated. However, according to equation provided in 2 it should not. Further increase in the voltage value leads to increased current value. Since the memristor crossbar is implemented in nano level it is preferred to have lower values of current to prevent overheating and power dissipation.
using precision half wave rectifier circuit and memristive crossbar. Designed circuit was tested to noise and temperature effects and it was concluded that the circuit is able to withstand the effects of noise and temperature difference. The mathematical analysis of the given design need to be done and it is assumed that the design can be developed further.

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IV. CONCLUSION

The following paper has been proposed the perceptron linear activation function design using operational amplifier with memristive circuits. The activation function was designed

B. Noise and temperature resistance

It is always preferred to check the implemented circuit for error that can be caused by noise and temperature. Proposed neuron circuit with several memristors was simulated in LTSpice for noise and temperature error. Simulation results showed that in the region of temperature from $-50^\circ C$ to $150^\circ C$ the circuit works very well. Also, noise was added to input sources in the frequency range from 10 Hz to 100MHz. Error caused by noise in the output of the circuit was 160 $pV/Hz^{1/2}$, which can be considered as negligible change. The effect of noise on circuit is shown in Fig.8.

C. Area and power calculation

Before starting manufacturing any device the area of the device or circuit is calculated. Since the memristor crossbar is used in perceptron circuit, area calculation causes some difficulties because it will depend on the input size and other factors. However, memristor took 4 times less area than transistors, but calculations was made on 4x4 and 8x8 tiled memristor systems [15]. Further calculations of larger memristor systems is still needed.